RECLAMATION

Managing Water in the West

Technical Memorandum No. 8540-2016-09

Research Priorities to Enhance Pipeline Infrastructure Sustainability

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Materials and Corrosion Laboratory
Denver, Colorado

August 2017

MISSION STATEMENTS

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Technical Memorandum No. 8540-2016-09

Research Priorities to Enhance Pipeline Infrastructure Sustainability

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Materials and Corrosion Laboratory
Denver, Colorado

August 2017

BUREAU OF RECLAMATION
Technical Service Center, Denver, Colorado
Materials and Corrosion Laboratory, 86-68540

Technical Memorandum No. 8540-2016-09

Research Priorities to Enhance Pipeline Infrastructure Sustainability

BOBBI JO MERTEN Digitally signed by BOBBI JO MERTEN
Date: 2017.08.22 12:16:32 -06'00'

Prepared by: Bobbi Jo Merten, Ph.D. — Date
Chemist, Materials and Corrosion Laboratory, 86-68540

JOHN SWIHART Digitally signed by JOHN SWIHART
Date: 2017.08.23 15:12:55 -06'00'

Checked by: Jay Swihart, P.E. — Date
Civil Engineer, Materials and Corrosion Laboratory, 86-68540

SHARON LEFFEL Digitally signed by SHARON LEFFEL
Date: 2017.08.24 08:53:52 -06'00'

Editorial Approval: Sharon Leffel — Date
Technical Writer/Editor, Economics and Technical
Communications Group, 86-68270

WILLIAM KEPLER Digitally signed by WILLIAM KEPLER
Date: 2017.08.24 10:24:34 -06'00'

Peer Review: William F. Kepler, Ph.D., P.E. — Date
Manager, Materials and Corrosion Laboratory, 86-68540

ACRONYMS AND ABBREVIATIONS

FY	fiscal year
P&A	Policy and Administration
Reclamation	Bureau of Reclamation
ROV	remotely operated vehicle
RQ	research question
SCADA	supervisory control and data acquisition
TSC	Technical Service Center

CONTENTS

Tables

Figures

Attachments

EXECUTIVE SUMMARY

Addressing the needs of aging infrastructure is critical to system reliability [1]. Research roadmapping enables us to determine where future research efforts should be focused in order to provide the greatest benefit. In this report, we explore the existing needs of aging infrastructure and identify key research needs, establishing a framework for research roadmapping. A research roadmap for pipeline infrastructure is included in attachment B, which provides comprehensive descriptions of research needs, including adverse outcomes, currently used mitigation practices, and the outstanding needs for tools, technology, etc. The intent of this information is to provide a thorough explanation of the research need to researchers in this area. The highest priority need statements are listed below:

- Pipe Body
    - Better instrumentation on remotely operated vehicles for evaluating metallic pipe deficiencies, detecting leaks, and faster data analysis
    - Investigate the aging processes of plastic pipe and develop or evaluate nondestructive testing techniques for detecting cracks and other deficiencies
    - Investigate nonmetallic pipes for large-diameter and high-pressure use
- Pipe Coating
    - Better remotely operated vehicle instrumentation and faster data analysis for evaluating pipe coatings, including film thickness
    - More field testing of different pipe coatings and linings
    - Robotic coating preparation and application
    - Coal tar enamel repair and replacement options

- Tunnel Liner
  - Evaluate the durability and chemistry of available high abrasion-resistant lining materials
  - Identify or evaluate cost effectiveness and constructability of alternatives to pressure grouting
  - New or improved environmentally friendly methods to clean minerals from weep holes, drains, etc.
- Siphon Corrosion Detection
  - Demonstrate low- or no-power tools or sensors for detecting or monitoring metallic corrosion in concrete siphons
  - Evaluate a reliable power source for corrosion protection techniques
- Leaking Pipe Joint
  - Improved methods for managing pipe joint leaks, both temporary and permanent
  - Evaluate the impact of thrust restraints on polyvinyl chloride pipe creep deformation; for example, observe the long-term performance of a Megalug on pressurized pipe
- Techniques or methods to notify personnel of flooded vaults in remote locations
- Literature review of state-of-the-art for various pipe construction inspections; produce updated training videos for field use when aligning pipe
- Tunnel Seepage
  - New or improved methods to retrofit drainage systems in tunnels
  - Faster and more accurate survey methods to determine the location of underground water

- New or improved methods to clean large-diameter siphons robotically, such as one similar to a pipe pig

- Tunnel Geotechnical

    - Evaluate alternative tunnel support methods for cost, constructability, and durability

    - Evaluate the feasibility of soil tunnel and heavy ground design and construction methods, a including literature review

    - Faster and more accurate investigation methods for collecting geological and geotechnical properties

INTRODUCTION

The Bureau of Reclamation's (Reclamation) Research and Development Office enacted several research roadmapping endeavors in order to strategically identify the organization's evolving scientific and engineering research needs. As an example, "Addressing Climate Change in Long-Term Water Resources Planning and Management, User Needs for Improving Tools and Information" addressed interagency impacts of climate change [2]. In addition, the "Desalination and Water Purification Technology Roadmap – A Report of the Executive Committee" identified opportunities for growing water supply challenges [3]. Ecohydraulics roadmapping is ongoing.

The needs of Reclamation's aging infrastructure are addressed under the current research project. The "Bureau of Reclamation Asset Management Plan" reiterates that this is "central to the mission objectives of operation & maintenance projects" [1]. Therefore, these three research questions (RQ) are of key interest:

RQ #1: What are the common reasons for reduced service life, extraordinary maintenance, or failure of Reclamation's infrastructure components?

RQ #2: What mitigation practices are currently used by Reclamation to address these failures or extend the working life of the infrastructure components?

RQ #3: What additional tools, measures, and technology, or improvements in existing technology, might allow us to extend the service life for all reserved and constructed Reclamation infrastructure components?

Table 1 provides Reclamation's mission-critical infrastructure (or assets) as described by Policy and Administration (P&A). Mission critical is defined as "a facility or piece of equipment that if unavailable or inoperable, would substantially detract from the achievement of Reclamation's business objectives" [1]. The use of the component categories (as listed in table 1) allows us to focus on each infrastructure type separately. Furthermore, the answers to RQ #1 are more apparent for their corresponding major components.

A parallel project, under which we are evaluating powerplant infrastructure, is ongoing under Project Manager Erin Foraker (Renewable Energy Research Coordinator, Reclamation). The focus of this project is on aging infrastructure from the perspective of its engineering disciplines. Therefore, the categories listed as "Other" in table 1 lie outside the scope of the existing framework; these categories may be approached by similar means at a later date.

Table 1.—Reclamation mission-critical assets

Category	Components
Dams	Dams, spillways, outlet works, gates (for dam operation)
Canals	Canals, laterals, reservoirs, gates, crane/lifts, trashrack structures, siphons, diversion dams, flow meters
Pipelines	Pipelines, surge tanks, associated components (with pipeline)
Powerplants	Gates, penstocks, turbines, excitation, generators, step-up transformers, auxiliaries, instrumentation and controls, unit breaker/switchgear, draft tubes
Pumping plants	Intake units, tanks, pump casings, motors, auxiliaries, instrumentation and control, discharge pipes
Other	Supervisory control and data acquisition (SCADA) systems, communication systems, associated land, etc.

RESEARCH METHOD

The "Research Roadmapping Method & Pilot Study" describes research method development [4]. The research roadmapping project proceeds in several phases. Table 2 provides the estimated timeline for the individual projects by fiscal year (FY) and quarter.

Table 2.—Roadmapping schedule

Category	FY13		FY14				FY15				FY16			
	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Pipelines	Pilot study								Draft roadmap				Roadmap vetting	
Canals			Draft roadmap						Roadmap vetting					
Dams			Draft roadmap						Roadmap vetting					
Pumping plants							Draft roadmap				Roadmap vetting			
Powerplants	Draft roadmaps for protection systems, mechanical systems, etc. (one per year through FY19)													

Figure 1 summarizes the roadmapping method. SurveyMonkey® provided a means for obtaining data for the three RQs. Subject matter experts, including Technical Service Center (TSC) engineers and field office personnel—regional and area—contributed to these datasets.

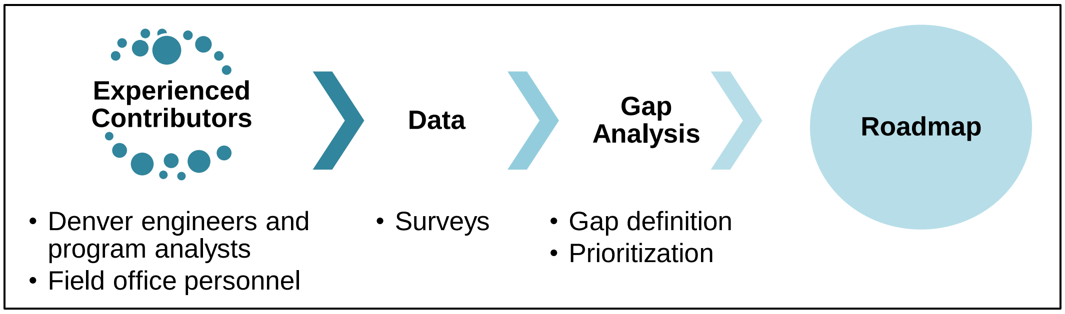

Figure 1.—Process for infrastructure sustainability roadmap.

The questionnaire data were collated, and similar responses were grouped together and coded. Some interpretation of responses was required. Each code is a summarized description of the statements made by respondents. These codes appear in the draft roadmap as "adverse outcomes" for RQ #1. In addition, these answers informed the development of the "causal analysis." Expert input from TSC engineers and P&A program analysts provided clarification and filled information gaps where appropriate. The final analysis of the roadmap included calculated statistics for "normalized frequency" and "average concern."

RQs #2 and #3 provided the "gap analysis" information. Again, TSC and P&A personnel reviewed the accuracy and completeness of the coded information.

Finally, the coded information for all three RQs aided in the development of the "research needs" for each adverse outcome. TSC and P&A personnel then scored the "gaps in existing tools" and "research needs." These two categories address the size of the gaps in existing tools and the value of anticipated research results, respectively.

This work resulted in four categories of quantitative information: frequency, concern, gaps in existing tools, and research needs. The respective rankings for these categories are 0–3, 0–3, 0–5, and 0–5. The four categories were summed, and the draft roadmap table was sorted from the highest to lowest score. The highest score represents the highest necessity for research.

TSC and P&A personnel evaluated the research needs for each adverse outcome and reduced the information to a short list of highest priority research needs.

RESULTS

Thirty-two survey responses were included in the analysis. Denver personnel represented 19 percent of the survey respondents and included the following groups:

- Water Conveyance
- Mechanical Equipment
- Materials and Corrosion
- Asset Management

The remaining 81 percent of the survey respondents represent Reclamation field offices. The geospatial location of these personnel is critical to ensure that all of Reclamation's needs are included. For instance, climatic stresses (weather) vary greatly from region to region. Respondents represent all five regions and hold offices in the following locations:

- Glendale, Arizona
- Byron, California
- Camarillo, California
- Fresno, California
- Sacramento, California
- Shasta Lake, California
- Alamosa, Colorado
- Grand Junction, Colorado
- Loveland, Colorado
- Heyburn, Idaho
- Hungry Horse, Montana
- Boulder City, Nevada
- Bismarck, North Dakota
- Hermiston, Oregon
- Klamath Falls, Oregon
- Rapid City, South Dakota
- Sioux Falls, South Dakota
- Lake City, Utah
- Provo, Utah
- Yakima, Washington

Personnel from the TSC's Water Conveyance, Mechanical Equipment, and Materials and Corrosion Groups and from the Mid-Pacific Region participated in the survey analysis and roadmap development.

Attachment B provides the compiled survey results as the draft roadmap. This attachment includes the additional editing for accuracy and completeness provided by TSC and P&A personnel. Furthermore, it is prioritized based on the statistics for frequency (normalized:nrm) and concern (average:avg) as well as the rankings for sufficiency of current tools and research needs — provided by TSC and P&A personnel. The roadmap provides the average of these ranking results.

Table 3 provides the short list of highest priority research needs. The goal is for researchers in these respective areas to develop and implement solutions. A process for instituting the ensuing research projects is in progress.

Table 3.—Survey results for highest priority research needs

Structure	Research need statement
Pipe body	A) Better instrumentation on remotely operated vehicles for evaluating metallic pipe deficiencies, detecting leaks, and faster data analysis B) Investigate the aging processes of plastic pipe and develop or evaluate nondestructive testing techniques for detecting cracks and other deficiencies C) Investigate nonmetallic pipes for large-diameter and high-pressure use
Pipe body	A) Better remotely operated vehicle instrumentation and faster data analysis for evaluating pipe coatings, including film thickness B) More field testing of different pipe coatings and linings C) Robotic coating preparation and application D) Coal tar enamel repair and replacement options
Tunnel	A) Evaluate the durability and chemistry of available high abrasion-resistant lining materials B) Identify or evaluate cost effectiveness and constructability of alternatives to pressure grouting C) New or improved environmentally friendly methods to clean minerals from weep holes, drains, etc.
Siphon	A) Demonstrate low- or no-power tools or sensors for detecting or monitoring metallic corrosion in concrete siphons B) Evaluate a reliable power source for corrosion protection techniques

Table 3.—Survey results for highest priority research needs

Structure	Research need statement
Pipe joint	A) Improved methods for managing pipe joint leaks, both temporary and permanent B) Evaluate the impact of thrust restraints on polyvinyl chloride pipe creep deformation; for example, observe the long-term performance of a Megalug on pressurized pipe
Appurtenances (valves, meters, etc.)	Techniques or methods to notify personnel of flooded vaults in remote locations
Pipe joint	Literature review of state-of-the-art for various pipe construction inspections; produce updated training videos for field use when aligning pipe
Tunnel	A) New or improved methods to retrofit drainage systems in tunnels B) Faster and more accurate survey methods to determine the location of underground water
Siphon	New or improved methods to clean large-diameter siphons robotically, such as one similar to a pipe pig
Tunnel	A) Evaluate alternative tunnel support methods for cost, constructability, and durability B) Evaluate the feasibility of soil tunnel and heavy ground design and construction methods, including a literature review C) Faster and more accurate investigation methods for collecting geological and geotechnical properties

REFERENCES

[1] "Bureau of Reclamation Asset Management Plan," Bureau of Reclamation, Policy and Administration, Fiscal Year 2011, September 2012.

[2] Brekke, L.D., "Addressing Climate Change in Long-Term Water Resources Planning and Management, User Needs for Improving Tools and Information," Bureau of Reclamation, Science and Technology Program, Technical Report, January 2011.

[3] "Desalination and Water Purification Technology Roadmap – A Report of the Executive Committee," Bureau of Reclamation, Desalination & Water Purification Research & Development Program, Report #95, January 2003.

[4] Merten, B., "Research Roadmapping Method & Pilot Study," Bureau of Reclamation, Technical Memorandum No. MERL-2014-53, September 2014.

ATTACHMENT A

Pipeline Questionnaire

The Technical Service Center and the Research Office are seeking your assistance with a short survey (see link below) on "Aging Infrastructure Sustainability – Pipelines." You have been identified as a desired participant based on your knowledge and experience with pipelines. Your input is greatly appreciated. The survey should not take too much time (about 1 hour). Responses are due December 31, 2015.

https://www.surveymonkey.com/r/JTDC3RH

In addition to completing the survey, please forward this email (cc me) to other people in the Bureau of Reclamation who you feel are qualified to complete the survey. The more responses we get, the better the results will be.

Thank you in advance for your time, and let me know if you have any questions.

Jay Swihart, P.E.
Bureau of Reclamation – Technical Service Center
303-445-2397

Aging Infrastructure - Pipelines Roadmap

Pipe Body

2. List the most common reasons for maintenance (scheduled and unscheduled), failure, reduced service life, or replacement in descending order.

1 ________

2 ________

3 ________

4 ________

5 ________

3. Describe the level of concern for the number one reason listed in Question 2.

- ○ Major: Very expensive, extended interruption of service, delivery demands not met
- ○ Moderate: Expensive, brief interruption of service
- ○ Minor: Above and beyond regular maintenance budget, no interruption of service
- ○ None: Covered by regular maintenance budget and not interruption of service
- ○ Other (please specify) ________

4. What mitigation practices are currently used at Reclamation to address these issues (maintenance, failures, extension of service life)?

1 ________

2 ________

3 ________

4 ________

5 ________

5. What additional tools, measures, and technology (or improvements in existing technology) are needed?

1 ________

2 ________

3 ________

4 ________

5 ________

6. Additional comments on answers above

____

Figure A1.—Pipeline questionnaire example, shown for pipe body.

ATTACHMENT B

Research Roadmap

Table B1.—Prioritized draft research roadmap for pipeline infrastructure

#	Causal analysis (pipeline infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
#	Structure	Adverse outcome	Process	Cause	Frq	Nrm 0–3	Conc. data	Avg 0–3	Available tools	Gaps in existing tools	L – H 0–5	Results are high value	L – H 0–5	0–16
1	Pipe body	Pipe corroding	Metallic corrosion of pipe body, pinhole develops, degradation of plastic pipe	Corrosive water or soil, failed coatings, cathodic protection system not maintained, erosion	17	3.00	4 Maj 1 Mod 1 Min 1 Other	2.50	Scheduled inspections, monitor wall thickness, repair or replace coatings and cathodic protection systems, crawler cameras, soil resistivity testing, replace, reline, or repair material with alternative (e.g., replace steel siphon with concrete)	Anticorrosion technology to extend service life, internal pipe inspection, acoustic monitoring, better materials for repair and replacement of pipe and coatings, better and more used cathodic protection, more accessibility of crawler cameras, improved remote inspection technology, improved nondestructive testing techniques, larger diameter and higher pressure pipe types that are not corrosive, ensure access points for pipe inspections in future installations	3.88	**A) Better instrumentation on remotely operated vehicles (ROVs) for evaluating metallic pipe deficiencies, detecting leaks, and faster data analysis** **B) Investigate aging processes of plastic pipe and develop or evaluate nondestructive testing techniques for detecting cracks and other deficiencies** **C) Investigate nonmetallic pipes for large-diameter and high-pressure use**	3.94	**13.31**
2	Pipe body	Deteriorated or failed pipe protective coating	Coating degrades	Coating service life surpassed, improper application or material	8	1.41	3 Maj 1 Mod 2 Other	2.75	Inspection by camera or walkthrough, scheduled maintenance, replace coating	Pipe diver ROV, a simple tool that field personnel can use to determine coating types and best applications, ability to inspect large pipelines remotely, factor in the constructability of new coating systems on certain pipes, ongoing testing of new coatings, better coatings with improved life expectancy and adhesion, more field testing of different pipe coatings, linings for embedded pipe systems (cleaning, lining techniques, procedures, materials, contracts), improved coating application methods to ensure good coating quality and decreased downtime, better inspection practices	3.50	**A) Better ROV instrumentation and faster data analysis for evaluating pipe coatings, including film thickness** **B) More field testing of different pipe coatings and linings** **C) Robotic coating preparation and application** **D) Coal tar enamel repair and replacement options**	4.13	**11.79**
3	Tunnel	Deteriorated or failed lining	Concrete condition changes by cracking, spalling, eroding, etc.	Construction defect, rebar corrosion, freeze-thaw, abrasion erosion, wear and tear, environmental factors, chemical reactions (including alkali aggregate reaction and sulfate attack), weep failure, etc.	13	2.29	2 Maj 1 Mod 2 Min	2.00	Periodic inspection; repair products, including abrasion-resistant coatings and composites; repair lining; design concrete for all possible loads and environmental conditions; crack repair using grout materials; stabilize or protect from corrosion; periodic weep cleaning; water jetting	Testing new crack repair materials, increased testing and use of materials such as fiber reinforced polymers, improved and safer abrasion-resistant coatings	3.00	**A) Evaluate durability and chemistry of available high abrasion-resistant lining materials** **B) Identify or evaluate cost effectiveness and constructability of alternatives to pressure grouting** **C) New or improved environmentally friendly methods to clean minerals from weep holes, drains, etc.**	3.50	**10.79**
4	Siphon	Corroding siphon	Corrosion of siphon	Coating damage or failure, corrosive water or soil, construction defect, corrosion of wires, freeze-thaw, wear and tear, environmental factors, chemical reactions (including alkali aggregate reaction and sulfate attack), etc.	9	1.59	3 Maj 2 Mod	2.58	Periodic inspections, repair damaged coating, cathodic protection, replacement, monitoring of prestressed concrete cylinder pipe using electromagnetic testing or other nondestructive methods, repair leaks with grout, ROVs, inspectors during construction, slip lining, fiber reinforced polymer repairs	Pipe crawler device or diver, improved remote inspection techniques, testing of new coating materials, better understanding of appropriate types of material to be used for pipelines and siphons, use cast-in-place pipe more often, improved and less expensive methods to inspect and monitor, fiber reinforced polymer repair materials to pipe interior, identifying and testing new repair methods and materials, improved data analysis methods	3.16	**A) Demonstrate low- or no-power tools or sensors for detecting or monitoring metallic corrosion in concrete siphons** **B) Evaluate reliable power source for corrosion protection techniques**	3.10	**10.43**

Table B1.—Prioritized draft research roadmap for pipeline infrastructure

#	Causal analysis (pipeline infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
#	Structure	Adverse outcome	Process	Cause	Frq	Nrm 0–3	Conc. data	Avg 0–3	Available tools	Gaps in existing tools	L – H 0–5	Results are high value	L – H 0–5	0–16
5	Pipe joint	Leaking pipe joint	Pipe joint leaks through flaw	Failed seals, improper thrust restraint, corroding sleeve type coupling, or cracked pipe joint as a result of manufacturing, construction, degradation, operation, or design flaws	7	1.24	1 Maj 2 Mod	2.33	Inspections (manufacturer, construction, and maintenance), leak detection equipment, tightening of joints, replacement of sleeve type couplings, periodic maintenance to adjust fitting, pipe clamp (clam shell), foam injection	Engineering planning to make joints more accessible, better understanding of service life of products (easy to use charts/graphs), pipe crawler unit would help in performing routine maintenance, combine thrust restraint method standards for each pipe type into one standard, improved technology for fit-over repairs in which the existing fitting is left in place and a repair is fitted over the fitting, considering methods for internal repair of bad joints, better inspection capabilities	3.06	**A) Improved methods for managing pipe joint leaks, both temporary and permanent** **B) Evaluate the impact of thrust restraints on polyvinyl chloride pipe creep deformation; for example, observe the long-term performance of a Megalug on pressurized pipe**	3.56	**10.20**
6	Appurtenances (valves, meters, etc.)	Corroding appurtenance	Corrosion of appurtenance	Inadequate corrosion prevention, failed coatings or linings, galvanic corrosion, erosion, poor water seal around stem	11	1.94	2 Maj 2 Mod	2.50	Expensive overhaul practices, preventative maintenance, corrosion control, inspection, coating repair, replacement	Best materials for the water chemistry, improved remote inspection technology, better coatings, valves that do not leak at the stems	2.56	**Techniques or methods to notify personnel of flooded vaults in remote locations**	2.56	**9.57**
7	Pipe joint	Pipe joint misalignment	Pipe joint becomes misaligned	Alignment offset during installation, improper construction, differential settlement, flooding and other natural hazards	14	2.47	3 Mod 1 Min	1.75	Quality assurance inspection of joints during construction, pressure testing joints	Better training for personnel who put piping together – both maintenance techniques and vibration dampening; vigilant construction inspectors and survey crews at the time of inspection; improved knowledge of current and new material for pipe joints; increased training and knowledge of joint type, installation, and construction; update Technical Service Center publication for construction inspector training (i.e., Basic Mechanical Inspection: First-Stage Installation, January, 1989, Unit VIII: Inspecting Penstocks, Tanks, and Piping to be Embedded)	2.69	**Literature review of state-of-the-art for various pipe construction inspections; produce updated training videos for field use when aligning pipe**	2.50	**9.41**
8	Tunnel	Uncontrolled tunnel seepage	Tunnel subject to uncontrolled moisture or water flow	Groundwater intrusion or seepage, unidentified geology or fault line	3	0.53	1 Maj 1 Min	2.00	Drainage systems, prevent or clean clogged drains, electro-osmotic pulse system	Injection products to better seal and bond concrete cracks, better concrete repair methods, new or improved methods to retrofit drainage systems	3.31	**A) New or improved methods to retrofit drainage systems in tunnels** **B) Faster and more accurate survey methods to determine location of underground water**	3.31	**9.16**
9	Pipe joint	Deteriorated or failed joint seal	Seals, gaskets, packing degrade	Seal material is not suitable or service life is surpassed, defective product	4	0.71	1 Mod	2.00	Pipe pressure testing, manage the leak, repair joint, chemical grout, replace gaskets, weld repairs, sleeve repairs, add dye or tracers to the water to ensure pipe is the leak source	Acoustic monitoring sensors to locate leaks during pressure testing, methods/techniques to manage a leaking joint to get it safely to a maintenance cycle in which it can be serviced, ongoing research on use of new joint material and coatings, etc.	3.19	A) Improved gasket or joint materials B) Better or more economical methods or techniques to locate leaks	3.13	**9.02**

Table B1.—Prioritized draft research roadmap for pipeline infrastructure

#	Causal analysis (pipeline infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
#	Structure	Adverse outcome	Process	Cause	Frq	Nrm 0–3	Conc. data	Avg 0–3	Available tools	Gaps in existing tools	L – H 0–5	Results are high value	L – H 0–5	0–16
10	Pipe body	Observed or detected pipe leakage	Pipe leaks through defect	Inadequate corrosion prevention or physical damage	4	0.71	2 Mod	2.00	Pipe bandaids, repairs, replace, stock replacement pipe, Geographic Information System pipe locations	Availability of pipe location services and tools, technology that helps with difficult to find leaks and damage, better repair techniques, improved documenting of pipe location, bulkhead sealing techniques for intakes at 200+ feet	3.00	More economical leak detection methods[1]	3.19	**8.90**
11	Tunnel	Corroding tunnel	Tunnel material degrades	Coating damage or failure, corrosive water or soil, water leakage, excess moisture	5	0.88	1 Maj 1 Mod 1 Min	2.00	Recoating, periodic inspection, coating repairs, cathodic protection system	Better coatings, better cathodic protection, quicker methods for inspection without dewatering	2.94	New or improved methods for inspection without dewatering[2]	3.06	**8.88**
12	Siphon	Leaking siphon joint	Siphon leaks through joint	Damaged or deteriorated seals or water-stops, pipe or geotechnical slippage on steep grade	5	0.88	1 Maj 2 Mod 1 Other	2.33	Restrain with concrete blocking to prevent joint movement, repair leaks with grout, joint testing during construction, Weko seals, foam injection, inspections (manufacturer, construction, and maintenance), leak detection equipment	Acoustic monitoring	2.75	A) Improved temporary methods for managing siphon joint leaks B) Improved permanent siphon joint repair methods, materials, and techniques[3]	2.75	**8.71**
13	Siphon	Loss of siphon capacity	Siphon volume decreases	Sedimentation, silt, debris, plugging by rock, landslide, or other	9	1.59	1 Maj 2 None	1.00	Hydroexcavation cleaning, trashracks placed at entrance and exit, remove rock deposits	Better cameras to video siphons, hydrovac units to clean conduits	2.88	**New or improved methods to clean-large-diameter siphons robotically, such as one similar to a pipe pig**	3.00	**8.47**
14	Tank (regulating, elevated, etc.)	Deteriorated or failed tank coating	Coating degrades	Coating service life surpassed, improper application or material, physical damage	13	2.29	1 Maj 6 Mod 1 Min	2.00	Recoating, coating maintenance, try to use the longest lasting coating, regular inspections, ROV inspections	Long-lasting membrane liners; long-lasting coatings; improvements on educating inspectors on best coatings, application processes, and signs of failure; a coating that will last 50 years or more without requiring recoating; improved coatings for spot patching with older coatings; inspection techniques for water-filled tanks (large water storage tanks); identify and test coatings with improved properties	3.06	N/A	0.83	**8.19**
15	Tunnel	Geotechnical tunnel failure	Tunnel stability or function decreases	Landslide or abutment movement, spalling of rock-bolted support tunnel, portal slope fails due to landslide, soil or rock fault shift (i.e., earthquake)	3	0.53	2 Mod	2.00	Better location for placement, thorough analysis of the geology, 3-dimensional point scanning of tunnel during excavation, construction, and as built	Greater understanding of surrounding geology, other portal and tunnel crown support system such as McNally Support System	2.31	**A) Evaluate alternative tunnel support methods for cost, constructability, and durability** **B) Evaluate feasibility of soil tunnel and heavy ground design and construction methods, including literature review** **C) Faster and more accurate investigation methods for collecting geological and geotechnical properties**	2.94	**7.78**

[1] Included in Item 1 research need statement.
[2] Included in Item 1 research need statement.
[3] Included in Item 5 research need statement.

Table B1.—Prioritized draft research roadmap for pipeline infrastructure

#	Causal analysis (pipeline infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
#	Structure	Adverse outcome	Process	Cause	Frq	Nrm 0–3	Conc. data	Avg 0–3	Available tools	Gaps in existing tools	L – H 0–5	Results are high value	L – H 0–5	0–16
16	Pipe body	Deteriorated or failed concrete pipe	Concrete condition changes by cracking, spalling, prestressed wire breaks, etc.	Freeze-thaw, wear and tear, environmental factors, corrosion, abrasion erosion, chemical reactions, including sulfate attack	5	0.88	1 Maj 1 Mod	2.50	Repair, replace prestressed concrete pipe with steel or cast-in-place concrete, electromagnetic testing and acoustic monitoring of prestressed concrete pipe, slip lining, fiber reinforced polymer repairs	Concrete repair on pressurized pipes, review other research efforts occasionally	1.94	Concrete repair methods or techniques for concrete pipes in service	2.25	**7.57**
17	Tank (regulating, elevated, etc.)	Corroding or leaking tank	Corrosion of tank	Corrosive water or soil, failed coatings, improper cathodic protection system or system not maintained, galvanic corrosion, deteriorated gaskets on glass bolted tanks	14	2.47	4 Mod 1 Min	1.80	Wall thickness monitoring, repair or replacement of the tanks, regular inspections, cathodic protection, weld repair, maintain cathodic protection system	Improved methods of corrosion prevention of tanks, remote inspection technology, increased operation and maintenance of cathodic protection systems in accordance with standard operating procedure	2.44	N/A	0.67	**7.37**
18	Appurtenances (valves, meters, etc.)	Leaking or seized valve or gate	Valve or gate does not seal or is inoperable	Material is not suitable or seal service life is surpassed, lack of exercising, cavitation, stem misaligned, sediment abrasion	14	2.47	2 Maj 4 Mod 1 Other	2.33	Routinely exercise valves, maintain mechanical equipment, inspections, limit velocity through valves, replace, set limits on openings	Valve exerciser machine, robust training for maintenance and engineering staff on how to care for and properly install valves and metering, educate users on why they should operate gates correctly, better gate designs, inform stakeholders of value of full travel exercising, ensure proper material and equipment selection	1.94	N/A	0.33	**7.07**
19	Pipe joint	Corroding or eroding pipe joint	Corrosion or erosion of pipe joint material	Debris in the water, general corrosion, erosion corrosion, galvanic corrosion, failed coating	11	1.94	2 Maj 2 Mod	2.50	Recoating, coating repair, concrete repair products, cathodic protection, crawler camera, replace components, inspections, weld repair	Awareness of galvanic corrosion, pressure pipe concrete repairs, cheaper slip lining, better materials to withstand aging and the elements, greater understanding of coatings in industry, better coatings, crawler camera, defined standards to quantify damage to pipe, less corrosive or erodible materials for pipes and fittings	2.19	N/A	0.33	**6.96**
20	Tank (regulating, elevated, etc.)	Physical damage to tank	Tank receives damage	Heavy equipment, vandalism, ballistic damage, natural disasters, lightning	5	0.88	–	0.00	Protection from external damage using bollards, lightning arrestors, fencing and anticlimb guards to prevent vandalism, security cameras and sensors	Improved repair methods and techniques, identify and test construction materials, such as fiber-reinforced plastics, to offer ballistic improvements and decreased need for coatings	2.94	A) Regular unmanned aerial vehicle patrols of remote assets, such as tanks, to identify any issues at the site B) New or improved quick-repair methods to mitigate physical damage	3.06	**6.88**
21	Appurtenances (valves, meters, etc.)	Deteriorated or failed appurtenance seal	Seals, gaskets, packing degrade	Seal material is not suitable or service life is surpassed; defective product; chemical degradation, including chlorine/chloramine; sediment abrasion	4	0.71	2 Mod	2.00	Inspection, replacement	Tougher seals	2.13	Review literature on chloramine-resistant seals and determine best practices for cost and performance	2.00	**6.84**

Table B1.—Prioritized draft research roadmap for pipeline infrastructure

#	Causal analysis (pipeline infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
#	Structure	Adverse outcome	Process	Cause	Frq	Nrm 0–3	Conc. data	Avg 0–3	Available tools	Gaps in existing tools	L – H 0–5	Results are high value	L – H 0–5	0–16
22	Tank (regulating, elevated, etc.)	Loss of tank capacity	Tank volume decreases	Sediment, buildup of material, algae	2	0.35	–	0.00	Tank cleaning, repair, replacement	Increased internal inspection of tanks, better access for cleaning and maintenance without taking the tank out of service or personnel entering confined space	2.81	New or improved methods to clean tanks robotically	3.44	**6.60**
23	Pipe body	Damaged pipe received	Pipe service life reduced	Physical damage during installation, improper construction, defective product, improper storage	10	1.76	1 Maj 1 Mod	2.50	Replacement, repairs, factory or construction inspections	Improved construction practices and management, monitoring to ensure pipeline construction adheres to specification and design, more inspectors during construction, more field testing during installation	1.75	N/A	0.50	**6.51**
24	Appurtenances (valves, meters, etc.)	Failed appurtenance operator or meter	Loss of operator or meter function	Wear and tear, corrosion, sediment	3	0.53	–	0.00	Meter cleaning, replacement, periodic inspections	Non-inline water meters, penstock flow meters that do not leak and are easier to repair and to get to work correctly, more consistent maintenance of meters, operators, and other instruments	2.44	N/A	0.83	**3.80**
25	Pipe joint	Failed or loosened pipe joint fasteners	Bolts loosen or fail	Wear and tear, vibration, corrosion	2	0.35	–	0.00	Replacement, ultrasonic thickness inspection of bolts for cracks	N/A	0.57	Improved pipe joint fasteners	1.63	**2.55**