RECLAMATION
Managing Water in the West

Technical Memorandum No. MERL-2015-50

Research Priorities to Enhance Pumping Plant Infrastructure Sustainability

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

June 2015

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. MERL-2015-50

Research Priorities to Enhance Pumping Plant Infrastructure Sustainability

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

June 2015

BUREAU OF RECLAMATION

Technical Service Center, Denver, Colorado
Materials Engineering and Research Laboratory, 86-68180

Technical Memorandum No. MERL-2015-50

Research Priorities to Enhance Pumping Plant Infrastructure Sustainability

Prepared by: Bobbi Jo Merten, Ph.D. Chemist, Materials Engineering and Research Laboratory, 86-68180	6-24-2015 Date
Checked by: Jay Swihart Civil Engineer, Materials Engineering and Research Laboratory, 86-68180	6-24-2015 Date
Editorial Approval: Sharon Leffel Technical Writer/Editor, Economics, Planning, and Technical Communications Group, 86-68270	6-24-2015 Date
Peer Review: William F. Kepler, Ph.D., P.E. Manager, Materials Engineering and Research Laboratory, 86-68180	6/24/15 Date

Acronyms and Abbreviations

FY	fiscal year
IR	infrared
O&M	operation and maintenance
P&A	Policy and Administration
PVC	polyvinyl chloride
Reclamation	Bureau of Reclamation
ROV	remotely operated vehicle
RQ	research question
SCADA	supervisory control and data acquisition
TSC	Technical Service Center
UT	ultrasonic testing

CONTENTS

Page

Executive Summary ES-1

Introduction 1
Research Method 2
Results 4
References 7

Tables

Table | Page

1 Reclamation mission-critical assets 2
2 Roadmapping schedule 2
3 Need statements for highest priority research needs 5

Figures

Figure | Page

1 Process for infrastructure sustainability roadmap. 3

Attachments

Attachment

A Pumping Plants Questionnaire
B Research Roadmap

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 peer-reviewed pumping plant infrastructure roadmap 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 potential researchers in this area. The highest priority need statements are listed below:

- Buried and Encased Pipe
    - Research and develop longer service life interior pipe coatings that can be applied at low temperatures and high humidity
    - Review and reassess uses of noncorrosive materials, such as polyvinyl chloride, for buried and encased pipe
- Investigate nondestructive inspection tools, such as ultrasonic testing, to improve efficiency and effectiveness of inspections in hard to access areas
- Pump Economics
    - Investigate the economics of repairing versus replacing pumps and pump impellers (the Bureau of Reclamation's [Reclamation] Technical Service Center [TSC] has a pumping plant assets inventory data file)
    - Investigate the economics of variable frequency drives with regard to operational parameters, equipment and installation costs, and future utility costs (high power factor)
    - Identify and modify machine condition monitoring techniques used for powerplants to be applicable for pumping plants
- Investigate composite materials for intake equipment, such as structural fiberglass, including lifecycle cost and benefit-cost analyses

- Investigate methods to improve the repairability of bolted steel tanks – AWWA D103 – in regard to their susceptibility to ballistic defect

- Evaluate and develop a supervisory control and data acquisition (SCADA) system design and troubleshooting best practices; keep security challenges in mind; and maintain security compliance. Recommended contacts: TSC Hydropower Services, Power Resources Office, and Central Valley Operations Office

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 (O&M) 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

	FY13		FY14				FY15				FY16			
Category	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Pipelines	Pilot study									Draft roadmap				
Canals			Draft roadmap						Roadmap vetting					
Dams			Draft roadmap											
Pumping Plants							Draft roadmap							
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.

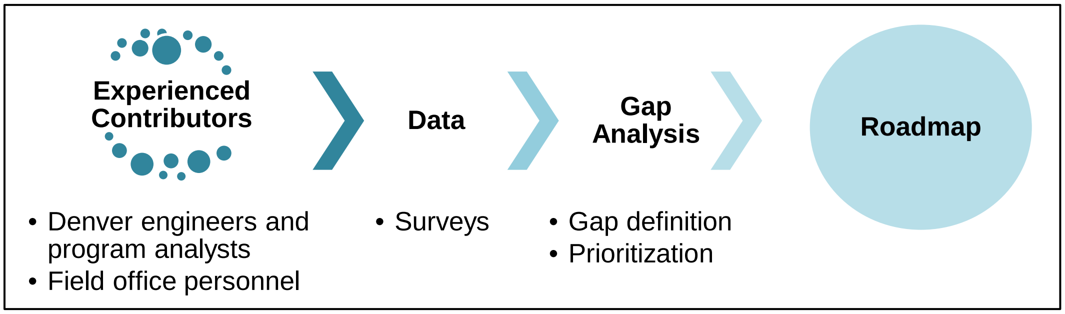


Figure 1.—Process for infrastructure sustainability roadmap.

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

Twenty survey responses were included in the analysis. Denver personnel represented 15 percent of the survey respondents and included the following groups:

- Mechanical Equipment
- Plant Structures

Hydraulic Equipment, Materials Engineering, Mechanical Equipment, Hydropower Diagnostics and SCADA, Hydropower Technical Services, Asset Management, and Electrical Design personnel participated in the survey analysis and roadmap development but did not complete surveys.

The remaining 85 percent of the survey respondents represent 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:

- Yuma, Arizona
- Folsom, California
- Durango, Colorado
- Loveland, Colorado
- Boise, Idaho
- Bismarck, North Dakota
- Bisti, New Mexico
- Boulder City, Nevada
- Hermiston, Oregon
- Klamath Falls, Oregon
- Casper, Wyoming
- Cody, Wyoming

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.

Several items are struck-through in the roadmap table. Item 19's content was included with Item 1 during the final scoring exercise. Items 22 and 23 lacked an adverse outcome and had no identified research need.

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.—Need statements for highest priority research needs

Structure	Research Need Statement
Buried and encased pipe	A) Research and develop longer service life interior pipe coatings that can be applied at low temperatures and high humidity B) Review and reassess uses of noncorrosive materials, such as polyvinyl chloride, for buried and encased pipe
Buried and encased pipe	Investigate nondestructive inspection tools, such as ultrasonic testing, to improve efficiency and effectiveness of inspections in hard to access areas
Pumps	A) Investigate the economics of repairing versus replacing pumps and pump impellors (Reclamation's TSC has a pumping plant assets inventory data file) B) Investigate the economics of variable frequency drives with regard to operational parameters, equipment and installation costs, and future utility costs (high power factor) C) Identify and modify machine condition monitoring techniques used for powerplants to be applicable for pumping plants
Intake equipment	Investigate composite materials for intake equipment, such as structural fiberglass, including lifecycle cost and benefit-cost analyses
Tanks	Investigate methods to improve the repairability of bolted steel tanks - AWWA D103 – in regard to their susceptibility to ballistic defect
Instrumentation	Evaluate and develop SCADA system design and troubleshooting best practices; keep security challenges in mind; and maintain security compliance. Recommended contacts: TSC Hydropower Services, Power Resources Office, and Central Valley Operations Office

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

Pumping Plants Questionnaire

Last year, the Research Office prepared a questionnaire (see link below) on "Aging Infrastructure Sustainability – Pumping Plants." We have received some responses, but need more for a statistically meaningful sample. You have been identified as a desired participant based on your knowledge and experience with pumping plants.

Your input is greatly appreciated. The survey should not take too much time (about 1 hour), and I do have a small budget for this project.

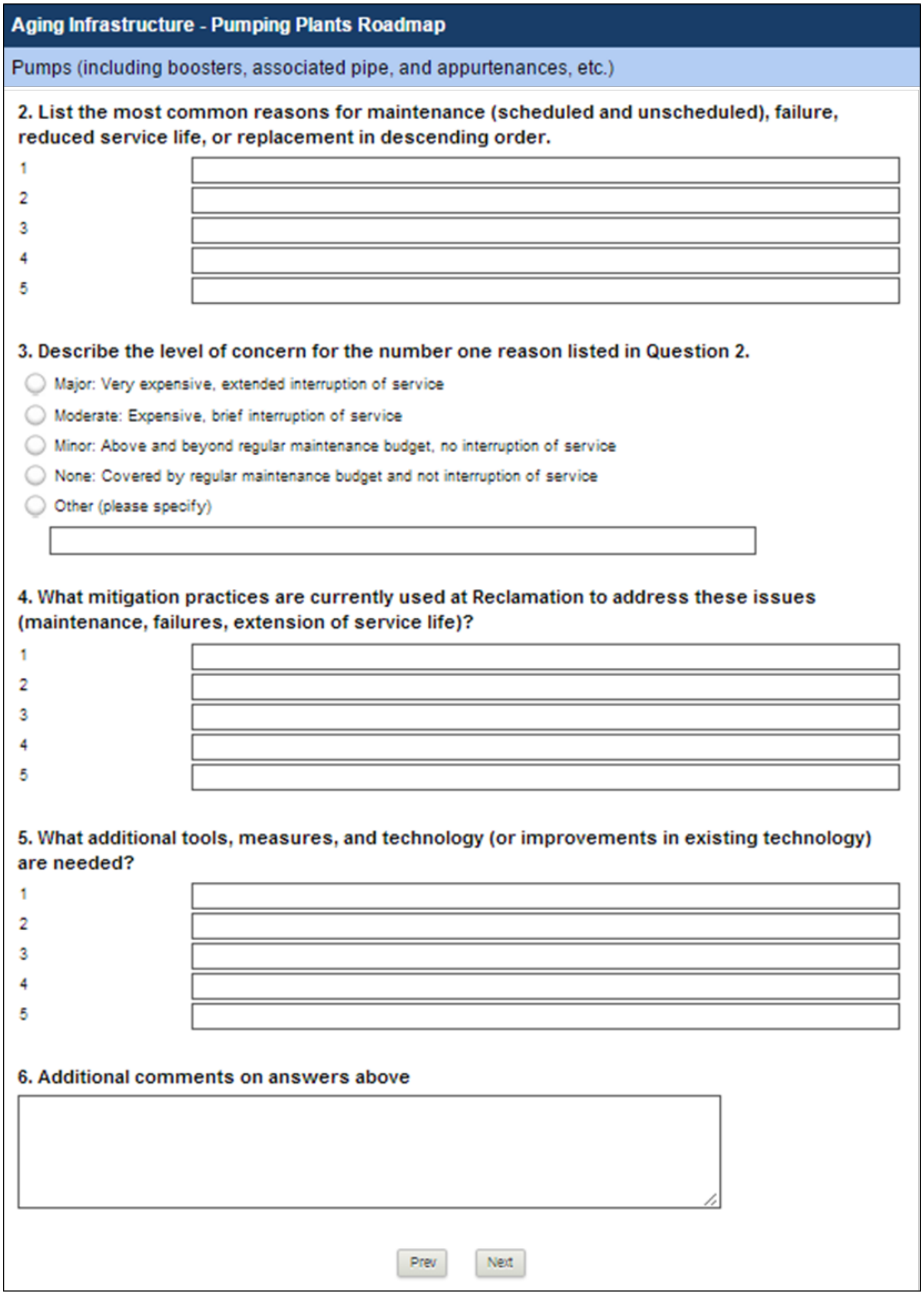
In addition to completing the survey, would each of you please send me names of other people in Reclamation that you feel are qualified to complete the survey? The more responses we get, the better the results will be.

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

https://www.surveymonkey.com/s/75T7J2M

PS - Respondents who previously completed the survey will shortly have the opportunity to update their answers (if desired) via a separate email.

Jay Swihart, P.E.
Reclamation – TSC
303-445-2397



Aging Infrastructure - Pumping Plants Roadmap

Pumps (including boosters, associated pipe, and appurtenances, etc.)

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
- 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

Prev Next

Figure A1.—Pumping plants questionnaire example, shown for pumps.

ATTACHMENT B

Research Roadmap

Table B1.—Prioritized draft research roadmap for pumping plant infrastructure

	Causal analysis (Pumping Plants 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	Buried and encased pipe (including valves, etc.)	Corroding pipe or valve	Corrosion of metalwork	Inadequate corrosion prevention, failed coatings, galvanic (dissimilar metals) corrosion, cavitation, corrosion cell where pipe is embedded into concrete	14	3.00	1 None 3 Maj 2 Mod 1 Min	2.33	Cathodic protection, recoating, current coating specs, monitoring cathodic protection, remotely operated vehicles (ROVs), new coatings to replace coal tar linings, in-situ line, apply coating to concrete/pipe transition	Better coating techniques, better coatings, better cathodic protection, improved inspection techniques and equipment, improved material selection—use polyvinyl chloride (PVC) for drain lines	2.67	**A) Research and develop longer service life interior pipe coatings that can be applied at low temperatures and high humidity** **B) Review and reassess uses of noncorrosive materials, such as PVC or composites, for buried and encased pipe**	3.17	11.17
2	Buried and encased pipe (including valves, etc.)	Leaking or failed pipe	Pipe or joint leaks, reduced wall thickness	Inadequate corrosion prevention, leaking joint	7	1.50	1 None 3 Maj	3.00	Ultrasonic tests, replace coating materials, install Weko-seals, pipeline camera inspections	Improved inspection techniques… robots, etc., user-friendly ROVs, better packing materials, ultrasonic testing (UT) technology that can be used without the costs of bringing engineers to the regional office, 5-year program to do predictive UT	3.00	**Investigate nondestructive inspection tools, such as UT, to improve efficiency and effectiveness of inspections in hard to access areas**	3.25	10.75
3	Pumps (including boosters, associated pipe, appurtenances, etc.)	Metal loss of pump components	Corrosion or cavitation	Abrupt change in pressure causes cavitation, abraded coatings, failed coatings, erosion corrosion, microbiological corrosion of martensitic steel (410 stainless)	12	2.57	1 Oth 2 Maj 1 Min	2.33	Regular maintenance to repair cavitation and coatings, replace impellers and/or pumps, stainless weld repairs	Better materials and design, more efficient pumps, cavitation detection, pipe thickness inspection, workshops, better welding technologies for cavitation repair of bronze impellers, new coating technologies for pump waterways	2.75	**A) Investigate the economics of repairing versus replacing pumps and pump impellors (Reclamation's TSC has a pumping plant assets inventory data file)** **B) Investigate the economics of variable frequency drives with regard to operational parameters, equipment and installation costs, and future utility costs (high power factor)** **C) Identify and modify machine condition monitoring techniques used for powerplants to be applicable for pumping plants**	3.00	10.65
4	Intake equipment (trashracks, gates, etc.)	Corroded or failed trashracks or gates	Corrosion of metalwork or warping of plastic trashracks	Inadequate corrosion prevention, failed coatings, under-engineered trashrack	14	3.00	1 Maj 2 Mod 3 Min	1.67	Cathodic protection, recoating, weld repair, replacement	Improved trashrack materials, better corrosion and cavitation indicators, more effective cathodic protection, improved ability to fluctuate reservoirs for inspection, improved ability to conduct underwater inspections	2.67	**Investigate composite materials for intake equipment, such as structural fiberglass, including lifecycle cost and benefit-cost analyses** Evaluate and advance methods and technologies to perform underwater inspections	3.25	10.59
5	Tanks (storage, air, etc.)	Corroding tank	Loss of wall thickness	Inadequate corrosion prevention, failed coatings or linings	10	2.14	1 None 3 Maj 2 Mod 2 Min	2.14	Visual inspections, UT, recoating, installing cathodic protection	Glass-lined bolted panels are least expensive but most difficult to repair – only method is to replace panel	2.21	**Investigate methods to improve the repairability of bolted steel tanks - AWWA D103 – in regard to their susceptibility to ballistic defect**	2.71	9.20
6	Instrumentation (SCADA, etc.)	Occasional SCADA failure or disconnection	SCADA software or connectivity issues	Software upgrades, technology upgrades, programming issues, no standardized SCADA	5	1.07	1 Maj	3.00	Recruit and retain good SCADA engineers, software updates, Hydromet	Improve software compatibility with operating systems, standardize SCADA, plan for bandwidth growth, improve personnel skills regarding SCADA/automation	2.32	**Evaluate and develop SCADA system design and troubleshooting best practices; keep security challenges in mind; and maintain security compliance. Recommended contacts: TSC Hydropower Services , Power Resources Office, and Central Valley Operations Office**	2.50	8.89
7	Pumps (including boosters, associated pipe, appurtenances, etc.)	Guide bearing failure	Bearings degrade	Degradation of bearings or bushings or pump misalignment	6	1.29	1 Mod	2.00	Repair or replacement, vibration monitoring	Vibration monitoring, vibration analysis education and tools (PEB42 provides guides for vibration monitoring)	2.58	Evaluate machine condition monitoring system installed at Mt. Elbert (pump and generating) to determine if any adjustments are needed for use in pumping plants	2.75	8.62

Table B1.—Prioritized draft research roadmap for pumping plant infrastructure

#	Causal analysis (Pumping Plants Infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
8	Intake equipment (trashracks, gates, etc.)	Plugged trashracks	Debris in the water builds up on trashrack	No or failed trash removal system, excessive debris, change in type of debris	5	1.07	1 None 1 Mod 2 Min	1.33	Trashrack rakes, log booms, periodic minor cleaning at high pool, deep cleaning at low pool, hand cleaning	Improved trashrack cleaning system or log booms, improved debris removal systems, procedures for utilizing riverflow to remove debris using applicable modeling tools (passive debris removal), how does debris affect hydraulics of the pump?	2.83	Investigate the relationship between operational parameters for pumps and intake or sump hydraulic changes due to debris Evaluate potential intake designs to divert debris downstream – needs to be flexible to a wide variety of debris loads and should not affect downstream areas	3.17	8.40
9	Plant structure and foundation	Deteriorated structural concrete or joint failure	Concrete condition changes by cracking, spalling, etc.	Freeze-thaw, wear and tear, environmental factors, abrasion erosion, chemical reactions (including alkali aggregate reaction and sulfate attack), etc.	8	1.71	2 Mod 2 Min	1.50	Repair or replace, grout repair on joints, epoxy injections, electro-osmotic pulse	Injection products to better seal and bond concrete cracks, better concrete repair methods	2.60	Improved understanding of concrete repair material properties and performance of the composite system as well as methods to prevent cracking of repair materials Better tools to treat the underlying cause of concrete deterioration (Ensure any research efforts are not duplicates of past efforts or existing knowledge – see Reclamation/TSC's Guide to Concrete Repair book)	2.40	8.21
10	Pumps (including boosters, associated pipe, appurtenances, etc.)	Electrical component or pump motor failure	Inadequate pump performance or loss of pump use	Submersible electric motor failure, pump component failed or degraded	7	1.50	1 Oth 1 Maj 1 Mod 1 Min	2.00	Temperature probe monitoring, infrared (IR) scanning program, UT	Machine condition monitoring and failure diagnostics, thermography program for electrical and mechanical, prolong electric motor life	1.83	Evaluate and demonstrate all available failure diagnostic methods used for powerplants, IR scanning, ramp testing, UT, etc.) and determine the best methods for use at pumping plants; there may be a unique method for each size: small – medium – large	2.83	8.16
11	Intake equipment (trashracks, gates, etc.)	Gate leakage	Inadequate gate seal performance	Seal material is not suitable or seal service life is surpassed, debris caught in seal, dissimilar metals between gate and frame	4	0.86	2 Mod	2.00	New seals, coatings, cavitation repair	Improved sealing (music note – Teflon type) materials including cladding (thin layer of tougher material on exterior) and fiber reinforcement, improved geometry of seals, including interference fit versus material, clamping bars, etc.	2.40	Evaluate the state of the art for seal materials for isolation slide gates; currently using brass, but composites may be an alternative	2.20	7.46
12	Plant structure and foundation	Water leaks through roof or wall	Roof or wall waterproofing performance changes	Roof/wall material is not suitable or service life is surpassed, repair material or method not suitable, inadequate maintenance of materials	5	1.07	2 Mod	2.00	Surface sealants or coatings, replace, repair, mitigation through flashings, waterproofing membranes, etc.	Injection products, sealants, or coatings to better seal and bond concrete cracks as well as other roofing materials, easier to apply materials (low temperature cure, etc.)	2.30	Review state of the art for roofing repairs and repair methods	1.70	7.07
13	Instrumentation (SCADA, etc.)	Failed instrumentation or equipment	Failed or inadequate performance of instrumentation	Faulty wiring, failed breakers, transformers, fuses, conductors, switches, controls, relays, protections circuits, sensors, etc.	7	1.50	1 Oth 1 Mod 2 Min	1.33	Repair or replacement, replace with improved components, testing	More smart components and sensors, better user friendly software, electrical technology advancing very fast and resulting in almost annual maintenance cost to continue monitoring service, more aggressive planned replacement of aged electrical and electronic equipment, thermography program	1.92	Re-evaluate current sensors at Reclamation and determine if new sensor applications would be beneficial	2.25	7.00
14	Buried and encased pipe (including valves, etc.)	Leaking or failed valve	Valve seats, seals, bearings, and packing degrade	Material is not suitable or seal/packing service life is surpassed, lack of exercising	6	1.29	1 Min	1.00	Replace valve seals, repair seals and motor components, recoat, operate valves in a timely manner, annual exercising	Better seals, computer-generated monitoring systems detecting meltdowns of equipment, lubricant acceptable with drinking water	2.00	Investigate environmental friendly hydraulic oils	2.17	6.46

Table B1.—Prioritized draft research roadmap for pumping plant infrastructure

#	Causal analysis (Pumping Plants Infrastructure)				Frequency and concern				Gap analysis			Research needs		Total
15	Tanks (storage, air, sumps, etc.)	Contaminated tank or sump	Spills and leakage migrate to sump	Equipment failure, spills, leaks, pressure or other indicator gauge fails; sensor not yet available to fill need	1	0.21	–	0.00	Troubleshoot and replace sensors, redundant alarm	Smart sensors – sensor that initiates action based on data sensed; detecting oil or other contaminants in sump water before discharging downstream (discharge permits may be put in place)	2.92	Identify and evaluate methods for removing oil and other contaminants (skimmers, etc.) and determine most efficient way to quantify oil and contaminant in sumps (what methods did/does oil industry use for wells and major clean-up operations?)	2.58	5.71
16	Plant structure and foundation	Plant damage by natural events, wildlife, or humans	Landslides, erosion, settlement	Seismic events, storm events, differential settlement, vandalism, etc.)	5	1.07	–	0.00	Committees to write codes for structural designs, mud jacking	Methods and practices for mitigating differential settlement, ballistic-resistant materials	2.17	Evaluate best methods and practices for mitigating differential settlement Evaluate best methods and practices for retrofitting buildings for updated ballistic resistance requirements	2.25	5.49
17	Intake equipment (trashracks, gates, etc.)	Deteriorated concrete around frames/guides	Concrete condition changes by cracking, spalling, etc.	Metal guide corroding, freeze-thaw, wear and tear, environmental factors, abrasion erosion, alkali aggregate reaction, sulfate attack, chemical reactions, etc.	2	0.43	–	0.00	Concrete repair, replace guides	Better materials—nonmetallic guides, improved concrete repair methods	2.08	Evaluate nonmetallic (noncorrosive) guides to minimize future maintenance	2.42	4.93
18	Intake equipment (trashracks, gates, etc.)	Gate does not function properly	Gate motor fails or gate becomes misaligned	Lack of full travel exercising of gates, operating in unbalanced or harsh conditions	5	1.07	1 Maj	3.00	New actuator seals, bushings, shaft replacement, motor refurbishment, test equipment, preventative maintenance	N/A	0.00	N/A	0.00	4.07
19	~~Plant structure and foundation~~	~~Deteriorated metalwork~~	~~Corrosion of metalwork~~	~~Inadequate corrosion prevention, corrosive water, maintenance inaccessibility~~	~~5~~	~~1.07~~	~~1 None~~ ~~1 Mod~~ ~~1 Min~~	~~1.50~~	~~Cathodic protection systems, replace coatings~~	~~Better cathodic protection, consider new pipe materials when replacing old auxiliary piping~~	-		-	2.57
20	Intake equipment (trashracks, gates, etc.)	Changes to ecosystem or regulations	Becomes habitat of invasive or endangered species	Invasive species enter ecosystem or Endangered Species Act requirements change	2	0.43	–	0.00	Adapt to changes, nonphysical fish barriers, fish screens	Foul-resistant coatings or materials	1.75	None	0.00	2.18
21	Pumps (including boosters, associated pipe, and appurtenances, etc.)	Seal or wear ring failure	Leaking seals	Degradation of seal or wear rings	4	0.86	–	0.00	Repair or replacement, aluminum bronze on stationary ring and stainless steel on impeller	Improved seal material and design	0.75	N/A	0.33	1.94
22	~~Tanks (storage, air, etc.)~~	~~Recertification required~~	~~Pressure vessel inspection~~		~~2~~	~~0.43~~	~~1 None~~	~~0.00~~	~~Pressure vessel testing~~	~~Training for tank maintenance~~	-		-	0.43
23	~~Tanks (storage, air, etc.)~~		~~Maintenance of isolation and relief valves and gauges~~		~~2~~	~~0.43~~	–	~~0.00~~	~~Monthly exercising, install to allow maintenance~~		-		-	0.43