RECLAMATION

Managing Water in the West

Technical Memorandum No. PAP-1171

Research Priorities for Mechanical Components of Hydropower Units

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations & Laboratory Services Group
Denver, Colorado

September 2018

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BUREAU OF RECLAMATION
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Hydraulic Investigations & Laboratory Services, 86-68560

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Research Priorities for Mechanical Components of Hydropower Units

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Acronyms and Abbreviations

CFR	comprehensive facility review
CO_2	carbon dioxide
FEA	finite element analysis
FIST	Facilities Instructions, Standards, and Techniques
HVAC	heating, ventilation, and air conditioning
O&M	operation and maintenance
PFR	periodic facility review
PRO	Power Resources Office
Reclamation	Bureau of Reclamation
ROV	remotely operated vehicle
RQ	research question
SCADA	Supervisory Control and Data Acquisition
TSC	Technical Service Center

Symbols

#	number
%	percent

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EXECUTIVE SUMMARY

The main objective of this research roadmap is to determine where future research efforts should be focused in order to provide the greatest benefit for Bureau of Reclamation (Reclamation) powerplants. In this report, we explore the existing needs of hydropower systems from a mechanical and hydraulic perspective to identify key research needs. This will help Reclamation address the needs of aging infrastructure to improve and maintain system reliability [1].

The Mechanical Hydropower Research Roadmap is included in Appendix B, which provides a comprehensive description of the research need, including the adverse outcome, 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 for each category:

- Penstocks
    - Improve durability and extend service life for coatings materials in high-velocity environments.
    - Improve coating materials for application in low temperature and humid conditions.
    - Develop or advance inspection and coating application and repair methods for large pipes and penstocks with difficult-to-access or dangerous geometries (e.g., complex geometry, steep slopes, drops, etc.). Inspection methods should improve data quality and reduce inspection time.
- Gates and Valves
    - Improve durability and extend service life for coatings materials in locations prone to high velocity, erosion, and cavitation.
    - Develop or improve inspection methods for submerged equipment (e.g., bulkheads, trashracks, gates, valves, etc.). Inspection methods should improve data quality and reduce inspection time.
    - Consider alternative materials or techniques to improve corrosion protection for existing structures and equipment.

- Turbine Runner and Wicket Gates

    - Develop or improve existing tools to recommend effective operational limits that can distinguish erosive (damaging/ metal or material loss) cavitation from non-erosive cavitation.

    - Integrate detection tools into existing Supervisory Control and Data Acquisition (SCADA) or monitoring systems.

    - Improve cavitation repair methods for turbine runners that are cost effective, minimize outage time, and are durable and repairable.

- Auxiliaries

    - Consider alternative materials or techniques to improve corrosion protection for auxiliary systems.

    - Improve or advance inspection methods for auxiliary systems (e.g., cooling water; heating, ventilation, and air conditioning [HVAC]; fire protection; oil piping, and equipment systems). Inspection methods should improve data quality and reduce inspection time.

- Generators

    - Compile information on best practices or guidelines on rotor cracking and loose poles from industry.

- Shafts and Bearings

    - Improve oil level measurement accuracy and robustness for unsteady oil reservoir depths, hydraulic conditions, or difficult applications during unit operation.

    - Identify or consolidate information for oil quality standards (viscosity, temperature, moisture, contaminants) and performance in Reclamation's powerplants.

    - Consolidate information on oil containment and leak detection for different oil systems.

INTRODUCTION

The Bureau of Reclamation's (Reclamation) Research and Development Office enacted several research (mapping) endeavors in order to strategically identify the organization's evolving scientific and engineering research needs. Hydropower facilities are considered Reclamation mission-critical infrastructure (or asset) as described by Policy and Administration. 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].

Reclamation's needs for aging infrastructure related to hydropower are addressed under the current mapping effort. The "Bureau of Reclamation Asset Management Plan" reiterates that this is "central to the mission objectives of operation and maintenance (O&M) projects" [1]. Therefore, 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?

The current roadmap addresses these research questions with a focus on mechanical components and systems of Reclamation hydropower units. A concurrent roadmap that addresses electrical powerplant components in development with power systems has been completed.

RESEARCH METHOD

This roadmap was developed using the same methods as the pilot study roadmap from 2014 [2]. The study proceeds in several phases as shown on Figure 1. A committee of seven hydropower experts from the Technical Service Center (TSC), Power Resources Office (PRO), Research and Development Office, and the Mid-Pacific Region was formed. Their role was to help collect and clarify survey data, score research needs for prioritization, and fill information gaps where appropriate.

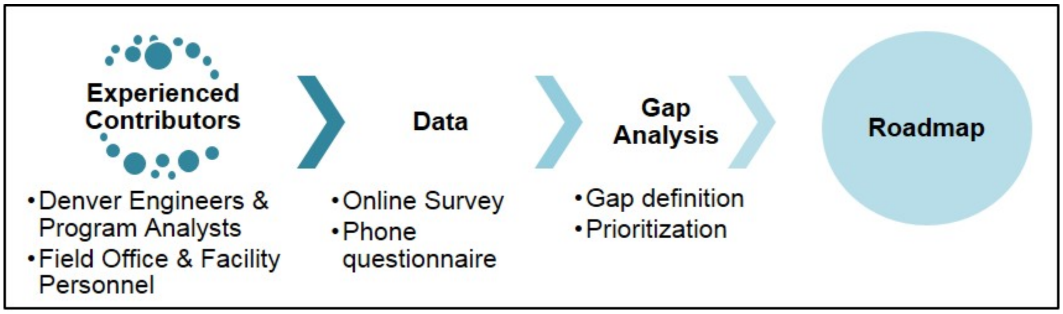

Figure 1. Process for Infrastructure Sustainability Roadmap.

First, data were collected for the three RQs from Reclamation hydropower engineers, analysts, operators, and maintenance personnel from all five regions as well as Denver's TSC and PRO Offices. This was done through an online survey (SurveyMonkey®) as well as phone conversations. Survey questions were categorized into basic component and system groups (Table 1 and Appendix A).

Table 1. Powerplant component and system categories

Category	Components
Turbine runner and wicket gates	Turbine runner, wicket gates, air admission systems, shear pins, and pertinent components
Penstocks	Main penstocks, supports, bifurcations, scroll case, stay vanes, draft tube, expansion joints, and connections
Gates and valves	Head gates, stop logs and bulkheads, isolation gates and valves, and emergency shutoffs
Shafts and bearings	Turbine shaft, generator shaft and connections, thrust bearings, and upper and lower guide bearings
Auxiliaries	Cooling water systems, fire protection systems, and oil and lubrication systems
Generators	Spider arms, rotor and stator supports, and mechanical connections
Governors	Aging mechanical governors and mechanical components of electrical governors
Instrumentation and controls	Instrumentation and controls related to mechanical and hydraulic monitoring (shaft runout, vibration, cavitation, unit discharge, pressure, and temperature)

Next, survey data were collated, and responses with similar issues and concerns were grouped together and coded. This required some interpretation by the committee in order to develop accurate statements shown in the roadmap. Each code is a summarized description of the statements made by respondents, which helped developed statements under the "Causal Analysis" for RQ #1 and the "Gap

Analysis" for RQs #2 and #3. Based on information from the "Causal" and "Gap" analyses, the committee formed "Research Needs" statements according to each component and coded response.

The final analysis of the roadmap included prioritizing research needs using a scoring system. Information from survey responses were quantified by "Frequency," which represents how often they appeared in survey results, and the "Concern," which was ranked by each respondent. These were normalized and averaged to give a score (0–3) for both frequency and concern. The "Gap Analysis" and "Research Needs" were given a score by each committee member (0–5). The sum of the four individual scores provided the total score for each research need pertaining to a certain component and adverse outcome. Each research need was ranked in the roadmap, with the highest total score representing the greatest priority (Table B-1, Appendix B).

RESULTS

Survey Response

Thirty-six participants responded either through the online survey or by phone. Table 2 and Figures 2 and 3 compare Reclamation's hydropower inventory to the survey respondents by region. These show a representation from each region, especially the Lower Colorado, Mid-Pacific, and Pacific Northwest Regions, which correspond to a significant portion of Reclamation's hydropower production. These results add confidence to the accuracy and effective application of research needs produced by this roadmap.

Table 2. Comparison of Reclamation's hydropower inventory to survey participants by region and office

HYDROPOWER BY REGION					SURVEY RESULTS	
Region/Office	**Plants**	**Units**	**Capacity (megawatts)**	**Capacity (%)**	**Number of Respondents**	**Percent of Respondents**
Great Plains	20	42	1,008	6.8%	3	8.3%
Lower Colorado	3	28	2,454	16.7%	6	16.7%
Mid-Pacific	10	26	1,910	13.0%	10	27.8%
Pacific Northwest	10	56	7,537	51.2%	9	25.0%
Upper Colorado	9	22	1,816	12.3%	3	8.3%
Technical Service Center	–	–	–	–	4	11.1%
Power Resources Office	–	–	–	–	1	2.8%
Total =	**52**	**174**	**14,725**	**100%**	**36**	**100%**

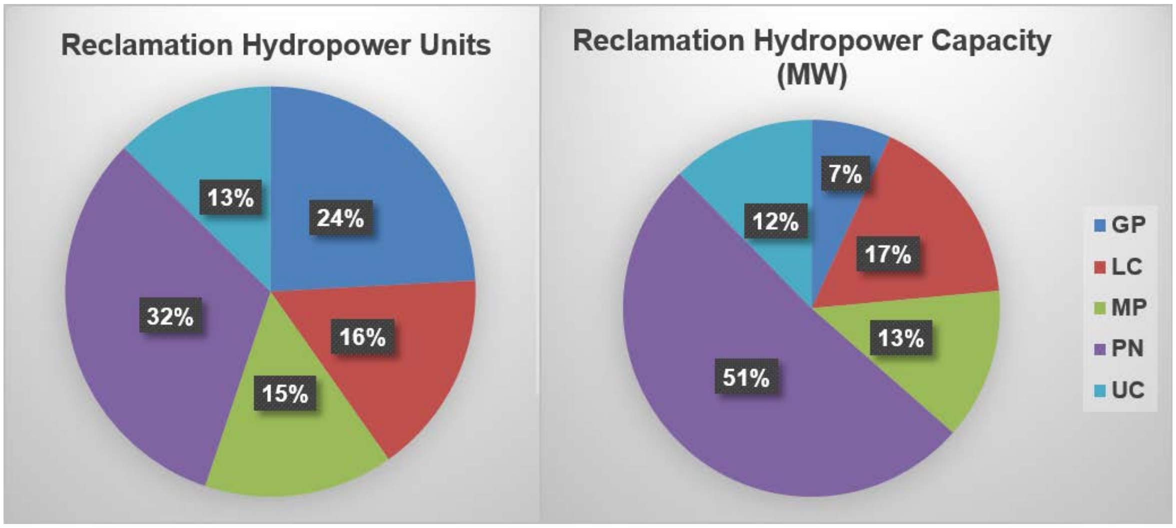

Figure 2. Plot of hydropower for each region in Reclamation.
Great Plains (GP), Lower Colorado (LC), Mid-Pacific (MP), Pacific Northwest (PN), and Upper Colorado (UC).

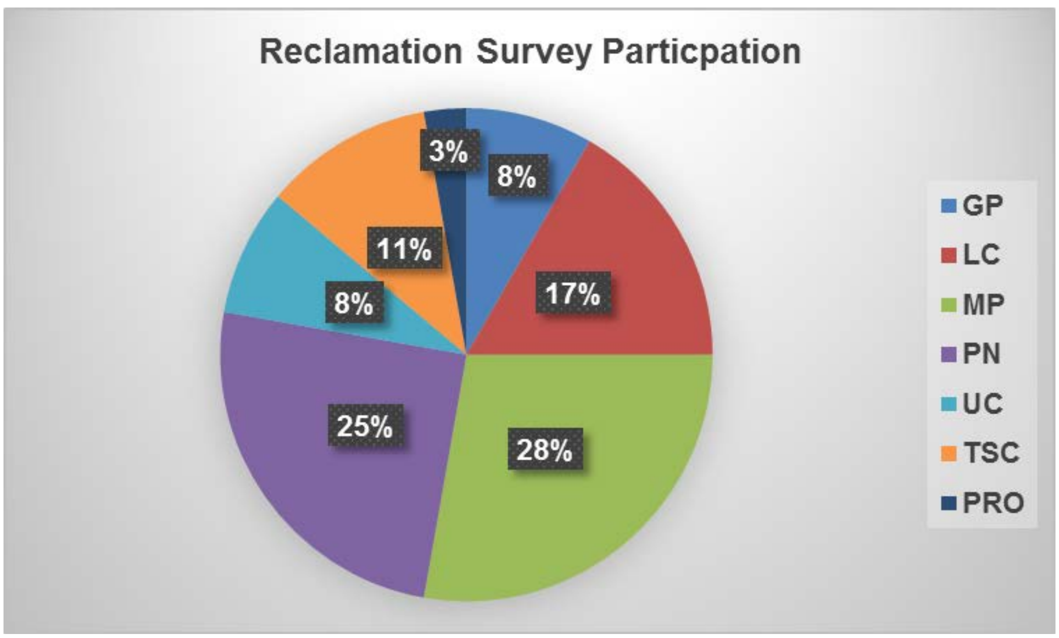

Figure 3. Distribution of Reclamation survey respondents.
Great Plains (GP), Lower Colorado (LC), Mid-Pacific (MP), Pacific Northwest (PN), Upper Colorado (UC), Denver's Technical Service Center (TSC), and Denver's Power Resources Office (PRO).

Roadmap Results

Table B-1 (Appendix B) shows the Mechanical Hydropower Research Roadmap. Results in this table show the prioritized "Research Needs," with additional information in the "Causal" and "Gap Analysis" columns. The most significant need resulting from this study is coatings and corrosion protection. This need was identified for multiple components and systems, including penstocks, gates and valves, turbine runners, and auxiliary systems. Another significant research need is cavitation, including detection, prediction, protection, and repairs. Table B-1 shows detailed rankings and information for all identified research needs.

Due to the increasing age of Reclamation's fleet, overhauls are becoming more frequent. Approximately half of the hydraulic turbines have been replaced, and 70% of the generating units have been rewound. Survey responses and TSC experience indicate that new technology can be used to speed up the alignment and overhaul process of our equipment for both generator rewinds and turbine overhauls, leading to efficiency and reduced outage schedules.

Administrative and O&M Findings

A significant pattern noted in the survey results was repeated issues and concerns related to administration, operation, and maintenance practices more than research. The main issues were:

- Lack of technical expertise, training, and experience
- Lack of funding and personnel
- Delayed procurement and other administrative processes
- Standard parts and equipment no longer available due to the age of the system or components
- "Time-based" maintenance programs instead of more effective "condition-based" maintenance (the need for standardized monitoring systems and practices required for condition-based maintenance)

In many survey responses, these issues were the root cause of extended outage time, deferred or lack of maintenance, and errors in maintenance or operation. While these issues may not be directly related to a research need, we considered it important to include them in the roadmap due to the frequency of these concerns from multiple survey respondents. An "O&M or Program Needs" column was included in the far right of Table B-1 (Appendix B) for related notes and comments.

REFERENCES

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

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

[3] B. Merten, "Research Roadmapping Framework to Enhance Infrastructure Sustainability," Bureau of Reclamation, Denver, CO, *in preparation*.

[4] Power Resources Office, *Reclamation Hydropower Inventory*, Denver, CO: Bureau of Reclamation, 2017.

APPENDIX A

Questionnaire

The Technical Service Center (TSC), in conjunction with the Research and Development Office, is preparing a research roadmap to identify ongoing research needs. This questionnaire allows us to take a closer look at Reclamation's infrastructure from its subset of "Powerplants" and related features. This information will be used to determine where future research efforts should focus, with a goal of providing the greatest benefit to the organization as a whole.

You were selected to participate in this questionnaire based on your knowledge and experience with Powerplants. We appreciate your time and hope that you will complete it by June 5, 2015. It contains eight topic areas with five questions each. There are two additional questions: one for contact information (in case an answer requires clarification) and the second for any additional comments that you may have that were not addressed in the questionnaire. There are a total of 47 questions. The estimated time needed to complete this is 1 hour. You do not have to fill-in all boxes. In this questionnaire, you are free to navigate backward/forward, edit responses, stop/restart later, discuss answers with colleagues, etc. Your careful and well-constructed insight is appreciated.

Thank you for taking valuable time out of your day to contribute to this effort. For questions or concerns, please contact Josh Mortensen at 303-445-2156 or jmortensen@usbr.gov. If you experience technical difficulties, please contact Bobbi Jo Merten at 303-445-2380 or bmerten@usbr.gov.

Thanks,
Josh Mortensen
Hydraulic Investigations & Laboratory Services, 86-68460
Technical Service Center
Bureau of Reclamation

Turbine

Includes turbine runner, wicket gates, air admission, & all components from the turbine shaft down.

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

Figure A-1. Example of survey questionnaire for turbines.

APPENDIX B

Mechanical Hydropower Research Roadmap

Table B-1. Reclamation's Mechanical Hydropower Research Roadmap

#	Causal Analysis				Frequency and Concern				Gap Analysis			Research Needs		Total	O&M or Program Needs
	Component	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	Penstocks	Penstock walls begin to corrode	Corrosion of metal piping	Coatings failure, galvanic corrosion, or end of service life	48	3.00	9 Maj 5 Mod 6 Min 1 Nn	2.05	Visual Inspections, coatings replacement or repair, and cathodic protection	Coating systems that perform well over an extended service life (20–40 years) Ability to apply coatings in low-temperature, humid, and wet environments Improved methods or tools (ROVs, etc.) for faster and safer inspections and repair of coatings in pipes or penstocks that are difficult or dangerous to access (e.g., steep slopes or large diameters that require rope or scaffolding)	3.75	a) Improve durability and extend service life for coatings materials in high-velocity environments. b) Improve coating materials for application in low-temperature, humid, and wet conditions. c) Develop or advance inspection and coating application and repair methods for large pipes and penstocks with difficult or dangerous geometries (e.g., complex geometry, steep slopes, drops, etc.). Inspection methods should improve safety and data quality, and reduce inspection time.	3.63	**12.4**	
2	Gates and valves	Gates and valves leak or become inoperable	Corrosion of metal equipment and components	Coatings failure, galvanic corrosion, or end of service life	48	3.00	9 Maj 5 Mod 6 Min 1 Nn	2.05	Visual Inspections, coatings replacement or repair, and cathodic protection	Coating systems that perform well in high-velocity or cavitating environments Improved methods or tools (ROVs, etc.) for better and faster inspections of hard-to-access components (bulkheads, submerged equipment, etc.) Improved cathodic protection systems that work in conjunction with coatings systems	3.34	a) Improve durability and extend service life for coatings materials in locations prone to high velocity and cavitation. b) Develop or improve inspection methods for submerged equipment (e.g., bulkheads, trashracks, gates, valves, etc.). Inspection methods should improve data quality and reduce inspection time. c) Consider alternative materials or techniques to improve corrosion protection for existing structures and equipment.	3.80	**12.2**	

Table B-1. Reclamation's Mechanical Hydropower Research Roadmap

#	Causal Analysis				Frequency and Concern				Gap Analysis			Research Needs		Total	O&M or Program Needs
	Component	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	
3	Turbine runner and wicket gates	Damage from cavitation	Pitting damage on turbine runner and draft tube caused by cavitation formation	Operating outside of normal range for prolonged periods of time or poor runner design	27	1.69	3 Maj 3 Mod 2 Min 2 Nn	1.70	Time-based repair outages, weld repair, improved runner design, and runner replacement	Cavitation monitoring and/or prediction of damage for condition-based maintenance Improved methods of stainless steel repair (overlay, maintain runner blade contours, etc.)	4.00	a) Develop or improve existing tools to set effective operational limits that can distinguish erosive (damaging/metal or material loss) cavitation from non-erosive cavitation. b) Integrate detection tools into existing Supervisory Control and Data Acquisition (SCADA) or monitoring systems. c) Improve wireless technology (power and data transmission) to allow for long-term data monitoring from rotating components. d) Improve methods to allow faster and cheaper cavitation repairs for turbine runners. e) Utilize new technologies (laser scanning, etc.) to ensure cavitation repairs do not alter blade geometry or degrade the units' performance or efficiency.	4.42	**11.81**	
4	Auxiliaries	Leaky auxiliary piping systems	Corrosion of metal piping and equipment	Coatings failure, galvanic corrosion, or end of service life	48	3.00	9 Maj 5 Mod 6 Min 1 Nn	2.05	Visual Inspections, coatings replacement or repair, and cathodic protection	Improved cathodic protection systems that work in conjunction with coatings systems Improved methods or tools (borescopes, acoustics, etc.) for better and faster inspections in auxiliary piping systems that are difficult to access or inspect visually	2.71	a) Consider alternative materials or techniques to improve corrosion protection for auxiliary systems. b) Improve or advance inspection methods for auxiliary systems (e.g., cooling water, heating, ventilation, and air conditioning [HVAC]; fire protection, oil piping, and equipment systems). Inspection methods should improve data quality and reduce inspection time.	3.17	**10.93**	Life expectancy analysis to identify service life of piping systems
5	Turbine runner and wicket gates	Corrosion of turbine runner and submerged components	Corrosion of metal components	Coatings failure, galvanic corrosion, or end of service life	48	3.00	9 Maj 5 Mod 6 Min 1 Nn	2.05	Visual inspections, component replacement, cathodic protection, coatings replacement, and spot repair	Coating systems that perform well over an extended service life (20–40 years) and can be applied in low-temperature and humid environments Improved methods and tools for inspections and coating repair in difficult to access areas Improved cathodic protection systems that work in conjunction with coatings systems	2.63	a) Improve durability and extend service life for coatings materials that can be applied in low-temperature and wet conditions. b) Advance application techniques to improve worker safety and reduce time and costs. c) Consider alternative materials or techniques to improve corrosion protection for runners, wicket gates, and other submerged components.	2.83	**10.51**	

Table B-1. Reclamation's Mechanical Hydropower Research Roadmap

#	Causal Analysis				Frequency and Concern				Gap Analysis			Research Needs		Total	O&M or Program Needs
	Component	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	
6	Auxiliaries	Reduced performance of auxiliary piping systems	Piping becomes clogged, and flow is reduced or eliminated	Colonization of live invasive species or dead shell debris clog pipe system	11	0.69	2 Maj 2 Md 2 Mn	2.00	Ultraviolet or chemical treatments for live invasive species Strainer and filter technology for small piping systems (smaller than 3-inch diameter)	Proven live species treatment technology with lower maintenance and operational costs Improved strainer or filtration systems that are self-cleaning or require less maintenance	3.17	a) Develop or advance effective invasive mussel treatment technologies that require low maintenance and costs. b) Reduce maintenance time for debris removal methods or tools for auxiliary piping systems (e.g., self-cleaning strainer systems).	4	**9.86**	
7	Generators	Cracking, loose rim and poles	Cracks form in spider arm supports, poles, and other mechanical attachments	Excessive vibration and fatigue Design issues (dovetail design)	11	0.69	1 Maj 2 Md 1 Mn 1 Nn	1.60	Visual, ultrasonic, and dye penetrant testing and inspections Operational stress and vibration testing and repair (grind and reweld cracks)	Condition-based maintenance by vibration monitoring on generator units Information on other standard industry practice for safety and reliability (update Facilities Instructions, Standards, & Techniques (FIST) or Standard Commissioning Guideline)	3.17	a) Compile information on best practices or guidelines on rotor cracking and rim and pole issues from industry. b) Improve wireless technology (power and data transmission) to allow for long-term data monitoring from rotating components.	3.92	**9.37**	Update FIST or Standard Commissioning Guideline Life expectancy analysis
8	Turbines, gates and valves, and shafts and bearings	Problems with oil and lubrication systems	Oil level is either insufficient or not measured accurately Oil supply becomes contaminated.	Leaks, quantity readings are inaccurate due to changing reservoir depths during operation Becomes contaminated due to dirt, moisture, etc.	34	2.13	2 Maj 5 Md 3 Mn 4 Nn	1.36	Oil monitoring – FIST (temperature, level, etc.) Oil filtration systems, quality sampling evaluation	Improved oil level sensing and integrating data into SCADA or health monitoring system (oil temperature, flow, level, etc.). Faster and better oil quality sampling or monitoring methods or processes. Environmental and performance properties of food-grade greases	2.92	a) Improve oil level measurement accuracy and robustness for unsteady oil reservoir depths, hydraulic conditions, or difficult applications during unit operation. b) Identify or consolidate information for oil quality standards (viscosity, temperature, moisture, contaminants) and performance in Reclamation's powerplants. c) Consolidate information on oil containment and leak detection for different oil systems (collaborations with U.S. Army Corps of Engineers).	2.80	**9.20**	FIST update (industry standards for cleanliness, flushing techniques)
9	Turbines	Excessive shaft runout	Excessive operation in the rough zone	Unclear limits of rough zone operation or incorrect air injection operation	4	0.25	1 Md 1 Mn	1.50	Run out measurements and air injection	Update FIST to include newer technologies and techniques to monitor rough zone operation and runout (See row 15) Improved machine condition monitoring information	3.00	a) Consolidate updated information technologies and techniques on rough zone operating limits and runout measurements. b) Advance generalized test procedures for defining rough zone operation limits that can be applied to site-specific units. c) Improved machine condition monitoring capabilities (more details and advanced programming).	3.54	**8.29**	Standardized techniques and updated technologies for run out measurements and rough zone operation Life expectancy analysis

Table B-1. Reclamation's Mechanical Hydropower Research Roadmap

#	Causal Analysis				Frequency and Concern				Gap Analysis			Research Needs		Total	O&M or Program Needs
	Component	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	Gates and valves	Excessively worn or failed equipment	Deferred or lack of inspection, maintenance, and operational testing	Excessive time and effort required for inspection, maintenance of equipment that is difficult to access Excessive time, effort or risk required for operational testing of large gates and valves	13	0.81	1 Md 1 Mn	1.50	FIST standards and engineering analyses for inspection, maintenance, and operational testing	Improved methods and equipment (e.g., ROVs, sonar) for faster and more thorough inspections of submerged structures (bulkheads, gates, temperature control devices, trashracks, etc.) Condition-based maintenance by monitoring and integrating data into SCADA (number of gate operations, hydraulic system pressures, flows, etc.)	2.67	a) Develop or advance inspection methods for submerged equipment (e.g., bulkheads, trashracks, gates, and valves.) Inspection methods should improve data quality and reduce inspection time. b) Improved inspection methods and techniques for enhanced safety and reduced costs for submerged or inaccessible equipment and features.	3.10	**8.06**	Improved recordkeeping and analysis of maintenance and operational testing for predictive maintenance tasks
11	Gates and valves	Gates or valves leak	Failure or end of service life of gate seats, seals, gaskets, and packing	Normal wear and tear, end of service life, damage from cavitation or erosion	15	0.94	1 Maj 7 Md 1 Mn	2.00	Inspections, repair and replace with currently available sealant products	Improve leak detection or low flow technology or application on closed systems Information on sealants, gaskets, packing, products, etc., to provide long service life for various conditions (temperature, pressure, drying, aging, ozone, ultraviolet, etc.)	2.08	a) Improve leak detection or low flow technology (see Pipes Roadmap). b) Develop general guidelines from consolidated information on seats, seals, and gaskets from Reclamation powerplants.	2.92	**7.94**	
12	Turbine runner and wicket gates	General wear and failure of components or extended outage time	Lack of or deferred maintenance	Lack of funding or personnel Delays due to procurement or administrative processes Parts and equipment not readily available for aging units and systems	8	0.50		0.00	Existing procurement procedures and administrative processes	Expedited or streamlined administrative processes Information or guidance on rehabilitation versus replacement Technology to accurately inspect major components on site to improve repair/ replacement decisions, reducing the risk of unknown conditions and reducing the risk of costly modifications to the contract	3.92	a) Identify and prioritize major system components for which rehabilitation versus replacement decisions are often needed. b) Evaluate and compare rehabilitation versus replacement of major system components (cost benefit analysis). c) Improve and expedite repair or replacement decision making for major components using newer technologies (laser scanning, photogrammetry, etc.).	3.33	**7.75**	Update FIST with new maintenance information Standardized procedures for maintenance records and analysis Engineering expertise and tools for rehabilitation versus replacement decisions (FEA, fatigue analysis, life expectancy analysis, etc.)
13	Gates and valves	Leaky stop logs and bulkheads	Stop logs or bulkheads do not seal in the guides or seat	Swelling or shifting of logs and/or guides; damaged rollers, wheels, and chains; removal and debris becomes lodged in seat	4	0.25	1 Md	2.00	CFR-PFR Power O&M Program and FIST manual	Information and discussion at Power O&M conference (share best practices, etc.) Information and proper documentation of proper seal for particular gates or stop logs Debris removal systems (see row 22)	2.17	a) Improved debris removal systems (see the "Debris" section, row 22). b) Determine root causes of leaks in stop log and bulkhead equipment and identify current seal products or other technologies that could best prevent leaks for each root cause (see "Seat and Seal" section, row 11).	2.50	**6.92**	Information and discussion at Power O&M conference (share best practices, etc.) Information and proper documentation of proper seal for particular gates or stop logs
14	Generators and auxiliaries	Reduced performance or	Insufficient flow through cooler	Corrosion in coils, insufficient design or	3	0.19	2 Md	2.00	Time-based cleaning and maintenance	Improved cooler design and maintenance guidelines	2.17	a) Identify and consolidate information on common air cooler designs and	2.33	**6.69**	Upgrades to FIST on air cooler operation

Table B-1. Reclamation's Mechanical Hydropower Research Roadmap

#	Causal Analysis				Frequency and Concern				Gap Analysis			Research Needs		Total	O&M or Program Needs
#	Component	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	O&M or Program Needs
		failure of air cooler system		capacity					Repair and rebuild cooler system			capacities with respective problems and solutions.			and maintenance
15	Turbine runner and wicket gates	Failed or obsolete air admission systems	Air admission system either doesn't work or isn't properly implemented for optimized performance	Lack of knowledge for optimized air admission for rough zone/cavitation reduction	2	0.13		0.00	Time-based maintenance and component replacement	Updated/automated air admission systems Understand air admission impacts to unit operation and performance	3.33	a) Develop generalized test procedure for testing and optimization of air admission systems that can be applied to site-specific systems.	3.17	**6.50**	Education and communication of air admission system O&M
16	Auxiliaries	Fire prevention systems underperform or are inoperable	System components seize up or become clogged	Aging of system and components and debris in system Aging or obsolete CO_2 systems	4	0.25	1 Mn	1.00	Replace or refurbish pumps and system components Periodic system testing and flushing of piping Manual weighing of CO_2 bottles	Improved methods to quantify CO_2 levels Identify need or feasibility to transition to water-based systems (FIST update) Self-cleaning or automatic straining systems for deluge-type systems	2.80	a) Compile information and develop guidelines on current fire protection systems and current industry practice for hydropower plants. b) Improve CO_2 quantification and monitoring to reduce time and costs, and improve reliability.	2.33	**6.38**	Update FIST based on current industry practice New FIST 5-3
17	Turbine runner and wicket gates	Failure of shear pins	Cracking then shearing of pins	Age and metal fatigue	6	0.38		0.00	Visual inspections, time-based maintenance and replacement, and compressed air alarms	Condition monitoring for condition-based maintenance	2.83	a) Develop or improve current detection systems to reduce false alarms and identify initial cracks or fatigue before full pin failure. b) Implement higher strength shear pins with a greater service life.	3.21	**6.04**	Develop program to identify life expectancy and replacement practices
18	Generators	Additional downtime for clean up	Contaminants (dirt, carbon dust, brake dust, etc.) accumulate in the generator	Excessive brake dust due to incorrect brake speeds or operation	2	0.13	1 Mn	1.00	Regular clean up	Identify safe and environmentally friendly cleaning products for generators Brushes (carbonless, reduce carbon dust)	2.25	a) Identify new technologies or methods for preventing excessive brake dust in generators (see Electrical Roadmap).	2.17	**5.55**	
19	Generators and auxiliaries	Degradation to generator windings or mechanical components	Excessive moisture, condensation, or poor air quality	Generators, heaters, or dehumidifiers are abandoned, forgotten, or not maintained Inadequate performance of HVAC systems					Plant HVAC units	Understanding of air quality on generator windings and other mechanical and electrical components Determine current performance of existing HVAC units	2.67	a) Determine air quality impacts on mechanical and electrical components and develop guidelines for HVAC or generator heater performance and design for Reclamation.	2.83	**5.50**	Add HVAC and generator heater information to FIST
20	Turbine runner and wicket gates	Worn or failed bushings, bearings, wear rings, etc.		Lack of maintenance and/or too much time in rough zone Insufficient or contaminated lubrication	19	1.19	3 Maj 1 Md 1 Mn	2.40	Visual inspections and time-based maintenance Attempts to limit number of unit startups and time in rough zone	Root-cause analysis, continuous monitoring for condition-based maintenance	2.25	a) Determine viability of environmentally friendly lubricants and of greaseless bushings and components. b) Develop and apply condition monitoring capabilities for various systems and components.	3.17	**5.42**	
21	Instrumentation and controls	Increased maintenance		Lack of comprehensive real-time information					SCADA and common monitoring	Comprehensive information of unit and systems that indicate	2.83	a) Determine how to bring common instrumentation signals into general	2.58	**5.42**	Update FIST with modern technologies,

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	Component	**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**	
		and failure							instrumentation and techniques	overall unit health in real time (vibration, flow, pressure, temperature, cavitation, etc.)		SCADA systems in use in Reclamation plants to comprehensively assess the overall health of the unit and auxiliary systems.			software programs, or methods for comprehensive unit health monitoring
22	Penstocks	Reduced flow to penstocks or poor performance of intake equipment	Pipes or intakes become clogged, and flow is reduced	Debris from reservoir clogs trashracks, stop logs, and other system components					Log booms, trash rakes, and other debris removal systems	Compilation of experience or best practices with different debris removal systems with various types of debris (grass, algae, logs, woody debris, mussels, etc.)	2.33	a) Identify and consolidate information on common debris problems and solutions within Reclamation for specific debris types versus facility features.	3.00	**5.33**	
23	Turbine runner and wicket gates	Leaks through packing	Packing failure, adjustment or replacement	Deteriorated packing material, overtightening	8	0.5	1 Maj 2 Md	2.33	Visual and time-based inspections and maintenance, replace with mechanical seal with feedback system (effective but expensive)	More modern shaft packing design	1.75	a) Identify and consolidate information on common packing components, materials and methods, and design.	2	**4.25**	Education and communication on types and methods of packing for various facilities and equipment
No Research and Development Need Statements															
	Governors; instrumentation and controls	Inoperable instrumentation	Electrical components fail or lose calibration	Lack of proper preventive maintenance and calibration program, end of service life	10	0.63	1 Maj 3 Md 2 Mn 1 Nn	1.57	Maintain stockpile of replacement components	More durable and repeatable electronic components Governors – develop electronics and programming that is compatible with off-the-shelf components	2.83	a) See Electric Hydropower Roadmap.	2.83	7.87	Consider options of standardizing equipment throughout Reclamation
	Turbine Runner and Wicket gates	Extended outage time	Incorrect maintenance or operator error	Lack of technical expertise, training, and experience	14	0.88	1 Maj 1 Md 2 Nn	1.25	Current project and scheduling tools	Proper training, mentorship, and knowledge transfer for both engineers and craftsman rather than trial and error	3.33	a) See "O&M or Program Needs."	2.33	7.80	Proper training, mentorship, and knowledge transfer for both engineers and craftsman rather than trial and error