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 2017

MISSION STATEMENTS

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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.

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BUREAU OF RECLAMATION

Technical Service Center, Denver, Colorado
Hydraulic Investigations & Laboratory Services, 86-68560

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Research Priorities for Mechanical Components of Hydropower Units

Prepared by: Josh Mortensen, P.E. — Date
Hydraulic Engineer, Hydraulic Investigations & Laboratory Services 86-68560

Checked by: Erin Foraker — Date
Renewable Energy Research Coordinator, Research & Development Office, 08-10000

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

Peer Review: Robert Einhellig, P.E. — Date
Manager, Hydraulic Investigations & Laboratory Services Group, 86-68560

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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 Reclamation Powerplants. In this report, we explore the existing needs of hydropower systems from a mechanical & 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 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 & extend service life for coatings materials in high velocity environments
    - Improve coating materials for application in low temperature & humid conditions
    - Develop or advance inspection & coating application & repair methods for large pipes & penstocks with difficult-to-access or dangerous geometries (eg. complex geometry, steep slopes, drops, etc.) Inspection methods should improve data quality & reduce inspection time

- Gates & Valves
    - Improve durability & extend service life for coatings materials in locations prone to high velocity, erosion, & cavitation
    - Develop or improve inspection methods for submerged equipment (eg. bulkheads, trashracks, gates, valves, etc.) Inspection methods should improve data quality & reduce inspection time
    - Consider alternative materials or techniques to improve corrosion protection for existing structures & equipment

- Turbine Runner & 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 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 (eg. cooling water, HVAC, Fire Protection, oil piping & equipment systems). Inspection methods should improve data quality & reduce inspection time.

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

- Shafts & Bearings
    - Improve oil level measurement accuracy & robustness for unsteady oil reservoir depths, hydraulic conditions or difficult applications during unit operation
    - Identify or consolidate information for oil quality standards (viscosity, temp, moisture, contaminants) & performance in Reclamation's Powerplants
    - Consolidate information on oil containment & 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 (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].

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 & 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 & 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 in Figure 1. A committee was formed of seven hydropower experts from TSC, PRO, R&D, and the MP Region. Their role was to help collect and clarify survey data, score research needs for prioritization, and fill information gaps where appropriate.

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).

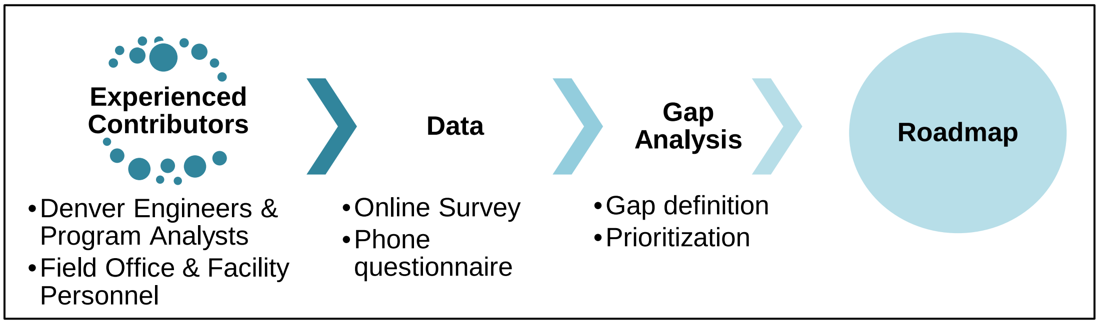

Figure 1. Process for infrastructure sustainability roadmap.

Table 1. Powerplant component and system categories

Turbine Runner & Wicket Gates	Turbine runner, wicket gates, air admission systems, shear pins & pertinent components
Penstocks	Main penstocks, supports, bifurcations, scroll case, stay vanes, draft tube, expansion joints & connections
Gates & Valves	Head gates, stop logs & bulkheads, isolation gates & valves, & emergency shutoffs
Shafts & Bearings	Turbine shaft, generator shaft & connections, thrust bearings, & upper & lower guide bearings
Auxiliaries	Cooling water systems, fire protection systems, oil & lubrication systems
Generators	Spider arms, rotor & stator supports & mechanical connections
Governors	Aging mechanical governors and mechanical components of electrical governors
Instrumentation & Controls	Instrumentation & controls related to mechanical & hydraulic monitoring (shaft runout, vibration, cavitation, unit discharge, pressure, & 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 3, Appendix B).

RESULTS

Survey Response

Thirty-six participants responded either through the online survey or by phone. Table 2 and Figures 2 & 3 compare Reclamation's hydropower inventory to the survey respondents by region. These show a representation from each region, especially the LC, MP, and PN 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 (MW)**	**Capacity %**	**# of Respondents**	**% of Respondents**
GP	20	42	1,008	6.8%	3	8.3%
LC	3	28	2,454	16.7%	6	16.7%
MP	10	26	1,910	13.0%	10	27.8%
PN	10	56	7,537	51.2%	9	25.0%
UC	9	22	1,816	12.3%	3	8.3%
TSC	-	-	-	-	4	11.1%
PRO	-	-	-	-	1	2.8%
Total =	**52**	**174**	**14,725**	**100%**	**36**	**100%**

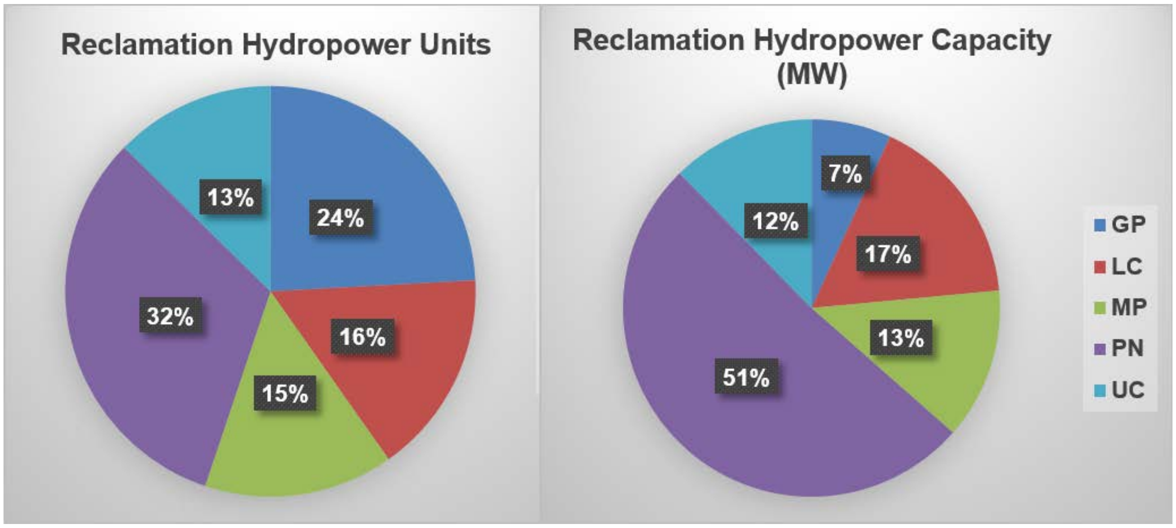

Figure 2. Plot of hydropower for each region in Reclamation. Great Plains (GP), Lower Colorado (LC), Mid-Pacific (MP), Pacific Northwest (PN), and Upper Colorado (UC).

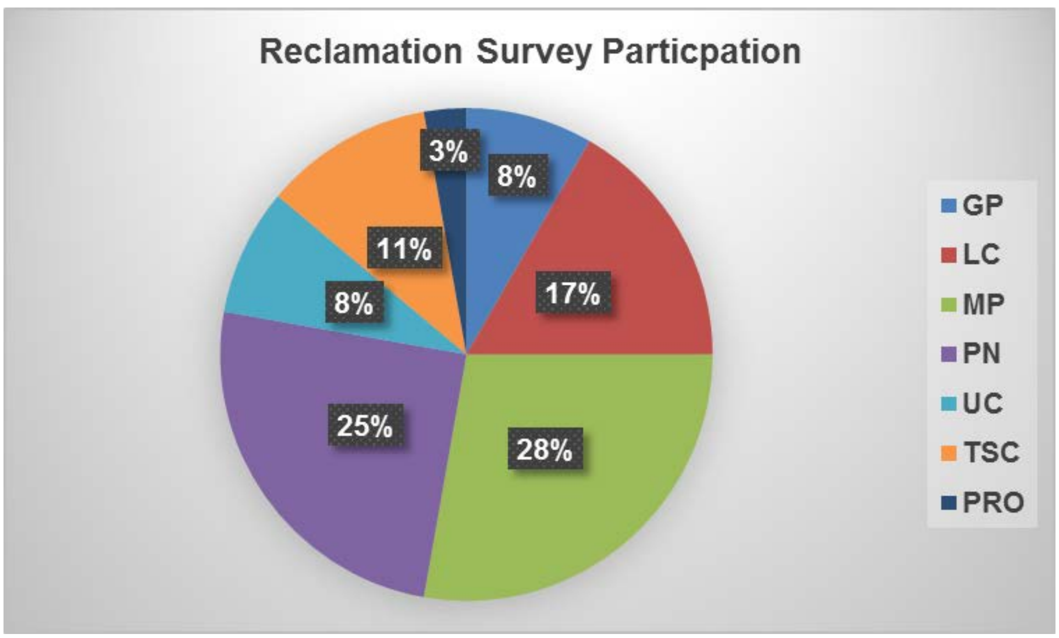

Figure 3. Distribution of Reclamation survey respondents. Great Plains (GP), Lower Colorado (LC), Mid-Pacific (MP), Pacific Northwest (PN), Upper Colorado (UC), Denver's Technical Service Center (TSC), and Denver's Power Resources Office (PRO).

Roadmap Results

The Mechanical Hydropower Research Roadmap is shown in Table 3 of Appendix B. 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 & valves, turbine runners, and auxiliary systems. Another significant research need is cavitation including detection, prediction, protection, and repairs. Detailed rankings and information for all identified research needs are shown in Table 3.

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 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 survey results were repeated issues and concerns related to administration, operation, and maintenance practices more than research. The main issues were:

- Lack of technical expertise, training, & 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 3 for related notes & comments (Appendix B).

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 8 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/re-start 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 and 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 4. Example of survey questionnaire for turbines.

APPENDIX B: Mechanical Hydropower Research Roadmap

Table 3. Reclamation's Mechanical Hydropower Research Roadmap

#	**Causal Analysis**				**Frequency & 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, & cathodic protection	Coating systems that perform well over an extended service life (20-40 years) Ability to apply coatings in low-temp, humid, & wet environments Improved methods or tools (ROV's, etc.) for faster & safer inspections & repair of coatings in pipes or penstocks that are difficult or dangerous to access (eg. steep slopes or large diameters that require rope or scaffolding)	3.75	a) Improve durability & extend service life for coatings materials in high velocity environments b) Improve coating materials for application in low temperature, humid, & wet conditions c) Develop or advance inspection & coating application & repair methods for large pipes & penstocks with difficult or dangerous geometries (eg. complex geometry, steep slopes, drops, etc.) Inspection methods should improve data quality, reduce inspection time, & safety	3.63	**12.43**	
2	Gates & Valves	Gates & valves leak or become inoperable	Corrosion of metal equipment & 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, & cathodic protection	Coating systems that perform well in high velocity or cavitating environments Improved methods or tools (ROV's, etc.) for better & 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 & extend service life for coatings materials in locations prone to high velocity & cavitation b) Develop or improve inspection methods for submerged equipment (eg. bulkheads, trashracks, gates, valves, etc.) Inspection methods should improve data quality & reduce inspection time c) Consider alternative materials or techniques to improve corrosion protection for existing structures & equipment	3.80	**12.22**	
3	Turbine Runner & Wicket gates	Damage from cavitation	Pitting damage on turbine runner & 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, & runner replacement	Cavitation monitoring &/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 SCADA or monitoring systems c) Improve wireless technology (power and data transmission) to allow for	4.42	**11.81**	

#	Causal Analysis				Frequency & 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	
												long term data monitoring from rotating components d) Improve methods to allow faster & 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	Auxiliaries	Leaky auxiliary piping systems	Corrosion of metal piping & 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, & cathodic protection	Improved cathodic protection systems that work in conjunction with coatings systems Improved methods or tools (borescopes, acoustics, etc.) for better & 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 (eg. cooling water, HVAC, Fire Protection, oil piping & equipment systems) Inspection methods should improve data quality & reduce inspection time	3.17	**10.93**	Life expectancy analysis to identify service life of piping systems.
5	Turbine Runner & Wicket gates	Corrosion of turbine runner & 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 & spot repair	Coating systems that perform well over an extended service life (20-40 years) & can be applied in low-temperature & humid environments Improved methods & tools for inspections & coating repair in difficult to access areas Improved cathodic protection systems that work in conjunction with coatings systems	2.63	a) Improve durability & extend service life for coatings materials that can be applied in low temperature & wet conditions b) Advance application techniques to improve worker safety & reduce time & costs c) Consider alternative materials or techniques to improve corrosion protection for runners, wicket gates, & other submerged components	2.83	**10.51**	

#	**Causal Analysis**				**Frequency & 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 & 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	UV or chemical treatments for live invasive species Strainer & filter technology for small piping systems (smaller than 3-inch diameter)	Proven live specie treatment technology with lower maintenance & 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 & costs b) Reduce maintenance time for debris removal methods or tools for auxiliary piping systems (eg. self-cleaning strainer systems)	4	**9.86**	
7	Generators	Cracking, loose rim and poles	Cracks form in spider arm supports, poles, & other mechanical attachments	Excessive vibration & fatigue Design issues (dovetail design)	11	0.69	1 Maj 2 Md 1 Mn 1 Nn	1.60	Visual, ultrasonic, & dye penetrant testing & inspections Operational stress & vibration testing & repair (grind & re-weld cracks)	Condition-based maintenance by vibration monitoring on generator units Information on other standard industry practice for safety & reliability (update 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 & valves, Shafts & Bearings	Problems with oil & 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 & integrating data into SCADA or health monitoring system (oil temp, flow, level, etc.). Faster & better oil quality sampling or monitoring methods or processes. Environmental & performance properties of food-grade greases	2.92	a) Improve oil level measurement accuracy & robustness for unsteady oil reservoir depths, hydraulic conditions or difficult applications during unit operation b) Identify or consolidate information for oil quality standards (viscosity, temp, moisture, contaminants) & performance in Reclamation's Powerplants c) Consolidate information on oil containment & leak detection for different oil systems (collaborations with Army Corps of Engineers)	2.80	**9.20**	FIST update (industry standards for cleanliness, flushing techniques)

#	Causal Analysis				Frequency & 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	
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 & air injection	Update FIST to include newer technologies and techniques to monitor rough zone operation & runout (See air admission/injection section) Improved Machine Condition Monitoring (MCM) information	3.00	a) Consolidate updated information technologies & techniques on rough zone operating limits & runout measurements b) Advance generalized test procedures for defining rough zone operation limits that can be applied to site specific units c) Improved MCM capabilities (more details and advanced programming)	3.54	**8.29**	Standardized techniques & updated technologies for run out measurements & rough zone operation Life Expectancy Analysis
10	Gates & Valves	Excessively worn or failed equipment	Deferred or lack of inspection, maintenance, & operational testing	Excessive time & effort required for inspection, maintenance of equipment that is difficult to access Excessive time, effort or risk required for operational testing of large gates & valves	13	0.81	1 Md 1 Mn	1.50	FIST standards & engineering analyses for inspection, maintenance, & operational testing	Improved methods & equipment (eg. ROV, Sonar) for faster & more thorough inspections of submerged structures (bulkheads, gates, temperature control devices, trashracks, etc.) Condition based maintenance by monitoring & integrating data into SCADA (# of gate operations, hydraulic system pressures, flows, etc.)	2.67	a) Develop or advance inspection methods for submerged equipment (eg. Bulkheads, trashracks, gates, & valves.) Inspection methods should improve data quality & reduce inspection time. b) Improved inspection methods & techniques for enhanced safety & reduced costs for submerged or inaccessible equipment & features	3.10	**8.06**	Improved record keeping & analysis of maintenance & operational testing for predictive maintenance tasks
11	Gates & Valves	Gates or valves leak	Failure or end of service life of gate seats, seals, gaskets, & packing	Normal wear & tear, end of service life, damage from cavitation or erosion	15	0.94	1 Maj 7 Md 1 Mn	2.00	Inspections, repair & 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 (temp, pressure, drying, aging, ozone, UV, etc.)	2.08	a) Improve leak detection or low flow technology (See Pipes roadmap) b) Develop general guidelines from consolidated information on seats, seals, & gaskets from Reclamation Powerplants	2.92	**7.94**	
12	Turbine Runner & Wicket gates	General wear & 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 & equipment not readily available for	8	0.50		0.00	Existing procurement procedures & administrative processes	Expedited or streamlined administrative processes Information or guidance on rehabilitation vs. replacement	3.92	a) Identify and prioritize major system components for which rehab vs. replacement decisions are often needed b) Evaluate & compare rehabilitation vs. replacement of major system components (cost benefit analysis)	3.33	**7.75**	Update FIST with new maintenance information Standardized procedures for maintenance records & analysis Engineering

#	Causal Analysis				Frequency & 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	
				aging units & systems						Technology to accurately inspect major components on site to improve repair/replacement decisions reducing the risk of unknown conditions and reducing risk of pricey modifications to the contract		c) Improve and expedite repair or replacement decision making for major components using newer technologies (laser scanning, etc.).			expertise & tools for rehab vs. replacement decisions (FEA, fatigue analysis, life expectancy analysis, etc)
13	Gates & Valves	Leaky stop logs & bulkheads	Stop logs or bulkheads do not seal in the guides or seat	Swelling or shifting of logs &/or guides, damaged rollers, wheels, & chains, removal & debris becomes lodged in seat	4	0.25	1 Md	2.00	CFR-PRF Power O&M program & FIST manual	Information & discussion at Power O&M conference (share best practices, etc.) Information & proper documentation of proper seal for particular gates or stop logs. Debris removal systems - see debris section	2.17	a) Improved debris removal systems (see debris section, row 23) b) Determine root causes of leaks in stop log & bulkhead equipment & identify current seal products or other technologies that could best prevent leaks for each root cause (See seat & seal section, row 11)	2.50	**6.92**	Information & discussion at Power O&M conference (share best practices, etc.) Information & proper documentation of proper seal for particular gates or stop logs.
14	Generators & Auxiliaries	Reduced performance or failure of air cooler system	Insufficient flow through cooler	Corrosion in coils, insufficient design or capacity	3	0.19	2 Md	2.00	Time based cleaning & maintenance Repair & rebuild cooler system	Improved cooler design & maintenance guidelines	2.17	Identify & consolidate information on common air cooler designs & capacities with respective problems & solutions	2.33	**6.69**	Upgrades to FIST on air cooler operation & maintenance
15	Turbine Runner & 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 & component replacement	Updated/automated air admission systems. Understand air admission impacts to unit operation & performance	3.33	Develop generalized test procedure for testing & optimization of air admission systems that can be applied to site specific systems	3.17	**6.50**	Education & communication of air admission system operation & maintenance
16	Auxiliaries	Fire prevention systems underperform or are inoperable	System components seize up or become clogged.	Aging of system & components & debris in system Aging or obsolete CO_2 systems	4	0.25	1 Mn	1.00	Replace or refurbish pumps & system components Periodic system testing & flushing of piping Manually weigh 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 & develop guidelines on current fire protection systems & current industry practice for hydropower plants b) Improve CO_2 quantification & monitoring to reduce time & costs, & improve reliability	2.33	**6.38**	Update FIST based on current industry practice New FIST 5-3

#	Causal Analysis				Frequency & 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	
17	Turbine Runner & Wicket gates	Failure of shear pins	Cracking then shearing of pins	Age & metal fatigue	6	0.38		0.00	Visual inspections, time-based maintenance & replacement, & compressed air alarms	Condition monitoring for condition-based maintenance	2.83	a) Develop or improve current detection systems to reduce false alarms & 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	Contaminates (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 & environmentally friendly cleaning products for generators Brushes (carbonless, reduce carbon dust)	2.25	Identify new technologies or methods for preventing excessive brake dust in generators (see electrical roadmap)	2.17	**5.55**	
19	Generators & Auxiliaries	Degradation to generator windings or mechanical components	Excessive moisture, condensation or poor air quality	Generator heaters or dehumidifiers are abandoned, forgotten or not maintained Inadequate performance of HVAC systems					Plant HVAC units	Understanding of air quality on generator windings & other mechanical & electrical components. Determine current performance of existing HVAC units	2.67	Determine air quality impacts on mechanical & electrical components & develop guidelines for HVAC or generator heater performance & design for Reclamation	2.83	**5.50**	Add HVAC & generator heater information to FIST
20	Turbine Runner & Wicket gates	Worn or failed bushings, bearings, wear rings, etc.		Lack of maintenance &/or too much time in rough zone. Insufficient or contaminated lubrication.	19	1.19	3 Maj 1 Md 1 Mn	2.40	Visual inspections & time-based maintenance. Attempts to limit number of unit startups & time in rough zone.	Root-cause analysis, continuous monitoring for condition-based maintenance	2.25	a) Determine viability of environmentally friendly lubricants & of greaseless bushings & components b) Develop & apply condition monitoring capabilities for various systems & components	3.17	**5.42**	
21	Turbine Runner & Wicket gates	Leaks through packing	Packing failure, adjustment or replacement	Deteriorated packing material, overtightening	8	0.50	1 Maj 2 Md	2.33	Visual & time-based inspections & maintenance, replace with mechanical seal with feedback system (effective but expensive)	More modern shaft packing		Identify & consolidate information on common packing materials & methods		**4.25**	Education & communication on types & methods of packing for various facilities & equipment

#	Causal Analysis				Frequency & 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	
22	Instrumentation & Controls	Increased maintenance & failure		Lack of comprehensive real time information					SCADA & common monitoring instrumentation & techniques	Comprehensive information of unit & systems that indicate overall unit health in real time (vibration, flow, pressure, temperature, cavitation, etc.)	2.83	Determine how to bring common instrumentation signals into general SCADA systems in use in Reclamation plants to comprehensively assess the overall health of the unit and auxiliary systems	2.58	**5.42**	Update FIST with modern technologies, software programs, or methods for comprehensive unit health monitoring
23	Penstocks	Reduced flow to penstocks or poor performance of intake equipment	Pipes or intakes become clogged & flow is reduced	Debris from reservoir clog trashracks, stop logs, & other system components					Log booms, trash rakes, & 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	Identify & consolidate information on common debris problems & solutions within Reclamation for specific debris types vs. facility features	3.00	**5.33**	
24	Turbine Runner & Wicket gates	Leaks through packing	Packing Failure, adjustment or replacement	Deteriorated packing material, overtightening	8	0.5	1 Maj 2 Md	2.33	Visual & time-based inspections & maintenance, replace with mechanical seal with feedback system (effective but expensive)	More modern shaft packing design	1.75	Identify & consolidate information on common packing components, materials & methods, & design	2	**4.25**	Education & communication on types & methods of packing for various facilities & equipment
No R&D Need Statements															
	Governors; Instrumentation & 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 & repeatable electronic components Governors – develop electronics & programming that is compatible with off-the-shelf components	2.83	See Electric Hydropower Roadmap	2.83	7.87	Consider into options of standardizing equipment throughout Reclamation
	Turbine Runner & Wicket gates	Extended outage time	Incorrect maintenance or operator error	Lack of technical expertise, training, & experience	14	0.88	1 Maj 1 Md 2 Nn	1.25	MS projects and scheduling	Proper training, mentorship, & knowledge transfer for both engineers & craftsman rather than trial & error	3.33	(see O & M Needs)	2.33	7.80	Proper training, mentorship & knowledge transfer for both engineers & craftsman rather than trial & error