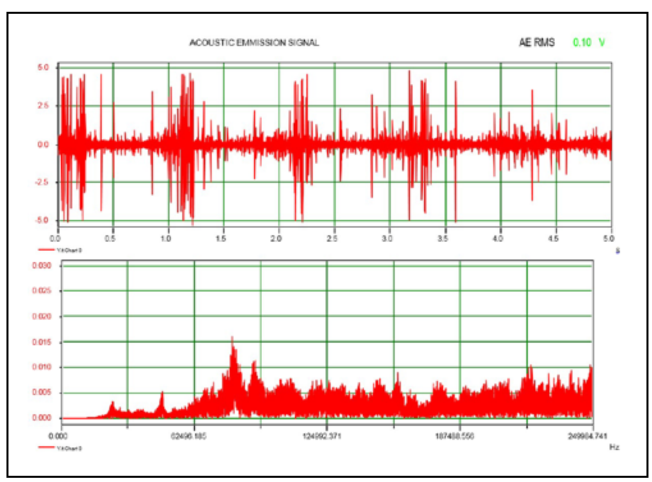
RECLAMATION

Managing Water in the West

Cavitation Detection Technology for Optimizing Hydraulic Turbine Operation and Maintenance

Research and Development Office
Science and Technology Program
(Final Report) ST-2015-2944-01



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Bureau of Reclamation
Research and Development Office

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Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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14. ABSTRACT
This research project focuses on the continued development and testing of a better cavitation detection system for hydraulic turbines and pumps as well as improved test methodology and techniques. Reclamation's research work is directed toward taking high frequency vibratory and acoustic measurements from the turbine and turbine runner shaft and comparing these measurements with those from more traditional fixed locations including low frequency measurements such as from pressure transducers. This research was conducted on hydroelectric generators at several Reclamation powerplants.

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This study was conducted for the U. S. Bureau of Reclamation under Reclamation's Research and Development Office (R&D), Science and Technology Program Project 2295, '*Cavitation Detection Technology for Optimizing Hydraulic Turbine Operation and Maintenance*'.

Primary research was performed by the Technical Service Center Electrical and Mechanical Engineering Division (86-68400) with participation by team members from the Mechanical Equipment Group (86-68410) and Hydropower Diagnostics and SCADA Group (86-68450). Additional services and peer review was received from the Engineering and Laboratory Services Division (86-68500), Hydraulic Investigations and Laboratory Services Group (86-68560).

Reclamation's Principal Investigator was Mr. John Germann, Mechanical Engineer, with the Mechanical Equipment Group. Other team members were Mr. James DeHaan, Electrical Engineer, PE, Hydropower Diagnostics and SCADA Group; Mr. Bryan Hampson, Electrical Engineer, Hydropower Diagnostics and SCADA Group; Mr. Josh Mortensen, Hydraulic Engineer and Mr. Warren K Frizell, Hydraulic Engineer, with the Hydraulic Investigations and Laboratory Services Group. Mr. Seth Gregg participated under a postgraduate program administered through the Colorado School of Mines.

Field research was conducted at the following Reclamation Powerplants:

Judge Francis Carr Powerplant, Northern California Area Office, Redding, California with the cooperation and assistance of Mr. Donald Bader, Area Manager and Mr. Joseph Ascoli, Chief, Mechanical Maintenance and others;

Flaming Gorge Powerplant, Flaming Gorge Field Division, Dutch John, Utah with the cooperation and assistance of Mr. Steven Hulet, Manager;

Upper Molina Powerplant, Curecanti Field Division, Colbran, Colorado with the cooperation and assistance of Mr. George Hoard, Powerplant Supervisor II;

Flatiron Powerplant, Eastern Colorado Area Office, Loveland, Colorado with the cooperation and assistance of Mr. Tom Moritz, Mechanical Engineer;

Grand Coulee Powerplant Grand Coulee Power Office, Grand Coulee, Washington, with the cooperation and assistance of Mr. Coleman Smith, Power Manager and Mr. Daniel Booker, Third Powerplant, Supervisory Facility Operations Specialist and others.

Executive Summary

This report outlines the progress and achievements of the subject research. This 2015 through 2017 research project was funded by Reclamation's Science and Technology (S&T) office.

Cavitation is the phenomenon where vapor bubbles form within local fluid flow in low pressure regions and subsequently collapse when they reach areas of higher pressure as they are carried by dynamic flow. Cavitation in hydraulic machines such as hydroelectric turbines, negatively effects the machine's performance and may cause severe erosive damage of components such as the runner or draft tube. Although the use of advanced computer modeling design techniques and modern steel alloys have vastly improved turbine resistance to cavitation, cavitation continues to be an ongoing issue in the hydroelectric industry. Today, turbines are often required to operate at less than ideal conditions as the result of extreme reservoir levels driven by floods and drought and increased water delivery or electrical power system requirements to supplement renewable energy demands. Operating at these off-designed conditions can promote damaging cavitation in the hydro machine turbine.

The U. S Bureau of Reclamation has been conducting research designed to better detect damaging turbine cavitation. The emphasis of this on-going work is to develop reliable techniques and instrumentation for cavitation detection that can be used as a machine condition monitoring tool and allow plant operations to avoid running in cavitation producing conditions. Online cavitation monitor(s) that uses accelerometers and acoustic emission (AE) sensors have been developed to identify, alarm, and record cavitation activity over long-term operations. This allows better prediction of cavitation behavior over varying unit operations and reservoir elevations and allows operations to avoid cavitation induced zones. The monitor ties into Reclamation's newly developed machine condition monitor which allows for continuous monitoring and long-term trending of cavitation signals.

Reclamation's research team is also producing successful test techniques and methodology in testing for damaging cavitation. A shaft mounted cavitation detector, which is used for initial short duration tests, has been developed to better quantify damaging cavitation. This detector uses a shaft-mounted accelerometer and acoustic emission sensor, and a wireless transmitter to send high frequency signals from the turbine shaft. This system, along with sensors located in more traditional locations has improved the accuracy and reliability of detecting cavitation within the turbine. Further research is being conducted to utilize data taken during short term diagnostic tests and long-term measurement campaigns to produce an algorithm(s) that effectively correlates cavitation measurements to actual cavitation damage found in the hydro turbine.

Over the past thirty or so years, considerable research has been conducted on the cavitation phenomenon. Almost exclusively, this research has been generated by academia, hydraulic laboratories or turbine manufacturers and is often somewhat theoretical in nature. Reclamation has a unique opportunity and advantage to build upon these research accomplishments of others because of the vast number of hydro machines in Reclamation's fleet. Reclamation currently owns, operates and maintains 53 hydroelectric powerplants with 176 generators. Academic and manufacturing sources do not have this vast resource which allows conducting active cavitation research on fully operational prototype machines that are in service. Cavitation research lacks in this critical area because of the unavailability to access full size operational units. A partial goal of this Reclamation research program is to translate this vast amount of research that has been and is being conducted in the laboratory and academic arena and use it to produce proven, practical applications and uses for Reclamation and hydroelectric power generator producer's hydro generators.

Active cavitation research during the 2015 through 2017 research term focused on the turbines and runners at several Reclamation field sites that were prime candidates for this type of research. These units either exhibited existing cavitation issues on their turbines or runners, or operations desired to operate the units in suspected cavitation 'zones' where management was concerned with potential damage.

Contents

Figures

Introduction

Fiscal Year (FY) 2017 concluded Project 2295, '*Cavitation Detection Technology for Optimizing Hydraulic Turbine Operation and Maintenance*', a three-year extensive research study started in 2015. This research was funded through the U. S. Bureau of Reclamation, Research and Development office, Science and Technology program. This successful project investigated different methods to detect cavitation in hydraulic turbines. The objective of this research campaign is to identify suitable techniques to detect cavitation in hydraulic turbines and through this technology, quantify the damaging erosion and other adverse effects due to the cavitation. As part of this study, researchers investigated the most suitable locations and types of sensors to be used, aiming to characterize differing types of cavitation and the operating conditions that produce them. An accurate and functional permanent cavitation monitoring system was developed for continuous and cumulative monitoring of cavitation erosion damage. This effort has led to many benefits to Reclamation.

- New knowledge on cavitation erosion detection and monitoring; the sensors to be used, their best location and better data acquisition and analysis techniques.
- A better knowledge of hydropower unit behaviors and subsequent methods to mitigate adverse conditions. By being able to better optimize hydropower generation relative to cavitation damage, operation and maintenance costs and outage time can be reduced. This also allows for better optimization of the unit's operating range allowing more flexibility in operations.
- The development of accurate and functional permanent cavitation monitoring systems that can integrate into Reclamations new generator machine condition monitors.
- Initial investigations into algorithm(s) that potentially correlate cavitation damage to the cavitation measurements being taken leading to the ability to effectively quantify cavitation erosion rates.
- The start of research into unit condition assessment including turbine runner residual life predictions and remaining life expectancy for hydroelectric generators.
- Improved cavitation monitoring and avoidance technologies such as the use of air injection techniques to mitigate turbine rough zones.

Background on Cavitation Phenomena in Hydraulic Turbines

The term cavitation is often used to describe the phenomenon of liquid-to-gas and gas-to-liquid phase changes that occur when the local fluid dynamic pressures in areas of accelerated fluid flow drop below the vapor pressure of the local fluid [1]. Within hydro machinery, the occurrence of cavitation almost always has a negative effect, often leading to severe erosive damage to turbine components such as the runner, reduction in efficiency, and vibration and noise problems. This leads to high maintenance and repair costs, revenue loss due to downtime and power replacement costs, decreased operating efficiencies, and reduction of equipment service life.

There are different types of cavitation that can occur in hydraulic turbines. Different cavitation will produce different results depending on the design and operating condition of the turbine [2]. In Francis turbines, the turbine design utilized at most Reclamation sites, leading edge cavitation, traveling bubble cavitation, von Karman vortex cavitation and draft tube swirl are commonly exhibited. Each of these different types of cavitation exhibit different characteristics [3].

Leading edge cavitation is very aggressive and can quickly erode the runner blades. Traveling bubble cavitation characteristics are high noise, reduced efficiency and blade erosion on the lower runner blades. Von Karman vortex cavitation can result in cracking to the trailing edge of the blade and finally, draft tube swirl generates pressure pulsation that can cause strong and sometimes violent vibrations in the turbine and powerhouse and power swings.

Cavitation can be observed visually during model testing of the runner where cavitation can be induced under controlled conditions. Unfortunately, these applied conditions and the resulting cavitation intensity does not always effectively translate to the prototype runner. Also, Reclamation has numerous older units with runners in operation where model tests were not performed. Therefore, it is necessary to develop reliable and accurate indirect detection techniques that can successfully be used on actual powerplant units.

Previous Reclamation Work on Cavitation Research

Reclamation has a long history of proactive research investigating flow phenomenon in hydraulic turbines. Reclamation conducted extensive research on the fundamentals of draft tube surging in its Denver hydraulics laboratory during the late 1960’s through early 1980s [4] and [5]. Reclamation first used acoustic emission transducers in 1991 on a model hydraulic turbine to detect the high-frequency acoustic energy released by cavitation [6]. Since then, Reclamation has successfully expanded its knowledge in this area by using accelerometers, AE and other sensors to test for and detect the occurrence of cavitation on a number of its hydro turbines.

Reclamation started researching cavitation detection in actual hydro machines in 2003 through 2005 at its Grand Coulee power facility. This early work was performed both independently and through collaborative agreements with Hydro Resource Solutions LLC, and Korto Cavitation Services [7] and [8]. Reclamation used acoustic emission sensors and accelerometers to perform basic cavitation investigations on the 750 MW units located in the Third Powerplant. The effect of using air injection techniques to mitigate cavitation was also briefly studied. Also, two commercially available cavitation monitors were purchased and tested. These early monitors used a simplistic approach and did not perform well. This was due to the complexity of cavitation and their inability to distinguish different types of cavitation and damaging cavitation from non-erosive cavitation within the fluid stream. Recognizing the lack of knowledge in this area and the short comings of these systems helped lead Reclamation into further pursuing research toward the cavitation phenomenon and its impact on hydraulic machines.

Early S&T funded research in 2005 helped determine a turbine over-gating problem at a hydroelectric plant in central Wyoming where cavitation had caused extensive damage to the two Francis turbine runners at the plant   In-field repairs on the runners and cavitation zone operating restrictions allowed for the units to remain operational for an additional eight years until new runners could be procured and installed.

In 2005, Reclamation researchers investigated the source of a loud ‘booming’ noise which was emanating from the tail race area of one of its hydroelectric plants in northern Colorado. The loud noise started after the removal of vortex diffusers (draft tube fins) from the draft tube of one of the power plant units. Tests helped determine that the noise was caused by the collapsing vortex within the draft tube. As a result of the cavitation test findings, a recommendation was made to unwater the tail race, where significant cavitation induced damage to one of the concrete draft tube splitter piers was discovered.

The pier was repaired, the draft tube vortex diffusers were reinstalled and the unit was retested the following year. Post testing found a significant reduction in acoustic emissions after these corrections were made.

In another case, operational tests using acoustic emission and accelerometers were conducted on a submerged 42” diameter outlet works tube valve where damaging downstream cavitation was occurring. These tests led to the recommendation to increase the vent piping diameter to avoid further cavitation.

These early successes using acoustic emission sensors and accelerometers helped prove the effectiveness of these instruments and associated analysis techniques in detecting cavitation related problems and validated the need to continue research in the detection and control of cavitation in Reclamation’s hydroelectric turbines.

In 2013, Reclamation’s Technical Service Center (TSC) and its Northern California Area Office (NCAO) partnered to conduct cavitation detection research at the Judge Francis Carr (J. F. Carr, Carr) powerplant. This research was funded through the S&T research program. Tests were performed in 2013 and 2014 to determine if it was possible to detect and measure cavitation-induced vibration and acoustic signals created by the cavitation that was causing severe erosion on the turbine blades. Research activities conducted were successful and from the data obtained, cavitation restriction zones were placed on the operation of the two units.

A shaft mounted cavitation detector was developed to focus on damaging cavitation when performing short duration diagnostic tests. Reclamation uses this system to take measurements off of the rotating shaft in the turbine pit. Online cavitation monitors were developed and installed to monitor and map cavitation conditions over long-term operation of the J. F. Carr units in late 2014. The technology and instrumentation used for these monitors can be used on any hydroelectric turbine with cavitation issues.

As a further product of this S&T cavitation research funding, numerous research papers have been written for technical magazines and the findings presented at various conferences. Also, two master’s level students (Dias in 2014 and Greg in 2016) from the Colorado School of Mines achieved their Master’s degrees in Mechanical Engineering through two theses’ written on cavitation [9] and [10]. Their work was based off of this Reclamation cavitation research.

Methodology

Direct detection of cavitation is possible only if measuring or detecting instruments can access the cavitating region of the flow passages. This is quite difficult to achieve in a hydroelectric turbine that is fully contained and under high water pressure. Due to the difficulties in direct detection methods, several indirect methods can be used.

Reclamation’s current approach for accurately detecting cavitation occurring within a turbine focuses toward taking indirect, high frequency vibratory and acoustic measurements from stationary locations outside the turbine, and from the turbine runner shaft. A variety of sensor types mounted at different locations are used to better understand and quantify the different cavitation types and the damage that they create. Cavitation produces broadband high-frequency noise. This noise is emitted when the cavities collapse violently and high-pressure peaks are generated.

Cavitation is a spatially unsteady process that is difficult to assess. However, the unsteady process tends to repeat itself each revolution. Turbine pressures, shaft runout, vibratory and acoustic signatures are all analyzed both in the time-domain and frequency-domain. This allows for use of full-wave rectification spectral analysis as a viable signal process technique. Accelerometer and acoustic emission signals are band pass filtered, full-wave rectified and Fourier transformed to obtain the power spectrum. When bandpass filtered and rectified, discrete frequency tones at the shaft and blade passage frequencies are evident. If cavitation is occurring, these discrete frequencies become elevated [11]. Reclamation researchers use this signal processing technique to analyze the vibratory and acoustic measurements and confirm that cavitation is occurring.

First, short term diagnostic tests are conducted where each unit is operated through its full operating range by varying the wicket gate opening, and if possible, the head. Accelerometers and acoustic emission sensors are placed in various stationary locations to determine the best location to measure the type of cavitation that may be occurring. The generator is then slowly ramped up from start, through speed-no-load, to full load.

With the information gleaned from the diagnostic tests, online cavitation monitors and a generator machine condition monitor can then be installed to measure cavitation occurring over long term operations through varying reservoir and tail water elevations.

Research Results

Research activities for this project during the 2015 through 2017 period were conducted at several field sites as well as in Reclamation's hydraulics laboratory.

1. Ongoing research continues to explore cavitation issues on the turbine runners at J. F. Carr powerplant located in northern California. These units have been a primary focus of past Reclamation cavitation research, the latest being similar research funded through an earlier (2013-2014) S&T study; "*Cavitation Detection Techniques for Optimizing Hydraulic Turbine Operation and Maintenance, X2836*" [12]. The turbine runners at this two-unit powerplant exhibit an especially aggressive form of erosive cavitation on the lead edge of the runner vanes. For this reason, these units are an excellent research platform for field studies.

   The reader may want to access archived documents and reports written about this earlier research. This information can be accessed by contacting the S&T department through this website.

   Work at J. F. Carr resulted in the successful construction, installation and testing of online cavitation monitors to identify, alarm, and trend cavitation activity over long-term operations. Two cavitation monitors and a machine condition monitor were designed, parts procured and instrumentation fabricated for installation on Units 1 & 2 at J. F. Carr powerplant. Final installation and testing of two cavitation monitors was completed in January 2015. The installation of these monitors allows for better prediction of cavitation behavior over varying unit operations and changing reservoir elevations. The two cavitation monitors transmit data to a single machine condition monitor which stores data and monitors other unit parameters. The cavitation monitors produce an alarm whenever a unit is operating in a high intensity cavitation zone. Alarms are given on the machine condition monitor screen, the unit annunciator board and at Reclamation's Central Valley Operations Control Center.

   Cavitation data is also routinely saved to allow for trending and further in-depth analysis. The monitors integrate time and cavitation intensity that occurs while operating within a cavitation zone and this information is saved for trending purposes. Both monitors have been actively collecting data since their installation. Reclamation continues to improve on the hardware and software of these machine condition monitors and the cavitation monitors associated with these units. It is Reclamation's intent to install the cavitation monitors at other facilities where cavitation may be an issue.

   Initial on-site testing was performed during a four-day test period from June 27 to June 30, 2014. A complete set of additional on-site cavitation tests were conducted on the two units while on site in January 2015. The June cavitation testing was scheduled in a narrow time window between the completion of turbine maintenance repair work and the critical need for both units to be operational for water delivery due to the California drought conditions. The Carr tests were very successful. Not only were baseline cavitation signatures documented, but the new prototype permanent cavitation monitor was also tested. A comparison of current cavitation activity that was occurring on the newly repaired runners with that found on the damaged runners prior to repairs was made. These tests have led to a better understanding of cavitation and what is required to accurately detect and quantify the resulting damage.

Figure 1. Cavitation display screen from a cavitation monitor at J F Carr powerplant.

Figure 2. Displayed cavitation data from the cavitation monitor at J F Carr. powerplant.

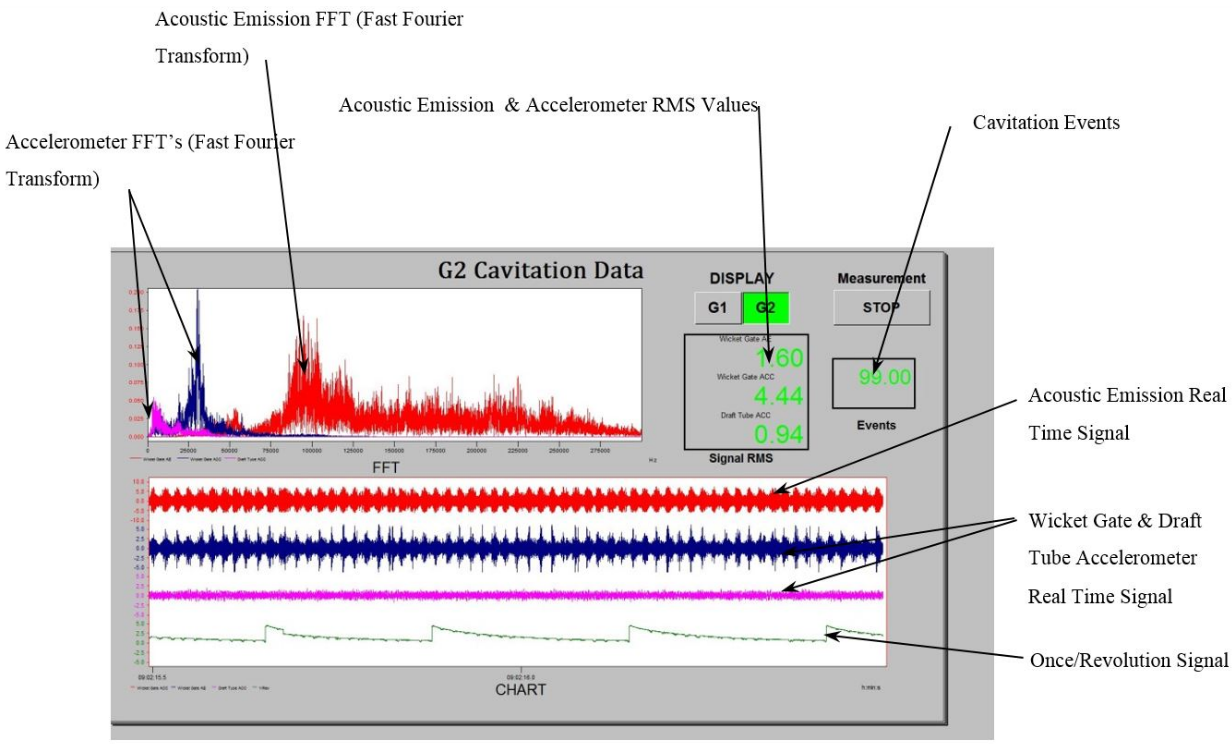

Figure 3. A display screen for analyzing typical signals generated from the cavitation monitor. Note that the real time signals display cavitation on each runner blade and its intensity.

A detailed report of this work was written, published and presented at the 2016 Hydrovision conference in Minneapolis, Minnesota [12]. A similar presentation was also given at the 2016 Power Operation & Maintenance workshop in Mussel Shoals, Alabama, in August of 2016. The technical paper that was written for the Hydrovision conference is attached in the Appendix of this final report. This paper describes in more detail the J. F. Carr studies and the cavitation monitors that were developed for this facility.

2. A Colorado School of Mines student, Mr. Seth Gregg, who was selected by the industries Hydro Fellowship Committee for scholarship and advanced studies, completing his master's thesis on research related to turbine cavitation and its detection [10]. Mr. Gregg worked with the Reclamation cavitation team to complete this work. The Hydro Fellowship program allows for a unique partnership between the hydroelectric community and academic studies. Mr. Gregg's thesis, entitled, "*Feature Selection and Adaptive Threshold for Automated Cavitation Detection in Hydroturbine*" focused on advanced cavitation signal analysis techniques and was completed at the end of the spring semester in 2016. Data obtained from the J. F. Carr plant were used in this work.

   His findings lead to several additional publications and journal articles. In addition to his thesis, Mr. Gregg presented his findings in a paper entitled "*Machine Learning for*

Cavitation Detection: A Step Toward Predicting Cavitation Erosion Rates on Hydroturbine Runners", at the 2016 Hydrovision conference [13]. A technical journal article was subsequently published in the May 2017 entitled, "*Feature Selection for Monitoring Erosive Cavitation on a Hydroturbine*", in the International Journal of Prognostics and Health Management [14]. A magazine article entitled, "*Machine Learning: A Tool for Predicting Cavitation Erosion Rates on Turbine Runners"*, was published in the April 2017 addition of Hydro Review magazine [15]. Lastly, a second journal paper entitled "*A Method for Automated Cavitation Detection with Adaptive Thresholds*" has been recently submitted, and is being considered for publication by the International Journal of Prognostics and Health Management. Mr. Gregg's findings were very beneficial and well received by the hydroelectric community. The results from this work will be incorporated into Reclamation's cavitation program. Several of these articles are posted in designated link provided in the section entitled "Products that Support the Final Report."

3. In 2016 cavitation tests were performed on a small Pelton wheel turbine at Lower Molina powerplant. Tests on this unit will provide cavitation data on this particular style of turbine runner. Specifically, tests tried to isolate cavitation occurring on a single bucket on the wheel. Further details and tests results of this study are also documented in the "Products that Support the Final Report" section of this report.

4. In 2016, a series of tests were conducted on a turbine at Reclamation's Flaming Gorge Powerplant. By testing different types of turbine runners with different forms of cavitation activity and assessing the resulting damage, a wider knowledge base on the cavitation phenomenon was achieved. This provides us with a better understanding of detection possibilities and the ability to relate detected activity to quantified damage.

   The data from the Flaming Gorge tests are still being analyzed. Findings from this work indicates the complexity of this research as both the J. F. Carr and Flaming Gorge results indicated areas where further research needs to take place. In some particular respects, measurement results were not as expected. The cavitation phenomenon is very complex. This is not uncommon, as research by others have also measured results that are not fully understood.

   Cavitation data was taken during two test periods at the Flaming Gorge Powerplant. The first test were conducted in early November, 2015. Each unit was tested as part of a larger efficiency study to accurately measure performance unit and plant performance characteristics. This study, entitled "*Quantification of Optimization Benefits from Detailed Performance Testing of Multiunit Hydropower Facilities*", was conducted by Reclamation, WolffWare, Ltd and Hydro Performance Process's Incorporated and partially funded by Reclamation's S&T program and Department of Energy, Oak Ridge National Laboratory [16]. Proximity sensors were installed on each unit to measure shaft runout. Accelerometers and AE sensors were also mounted on each unit draft tube to measured turbine vibration and acoustic emissions.

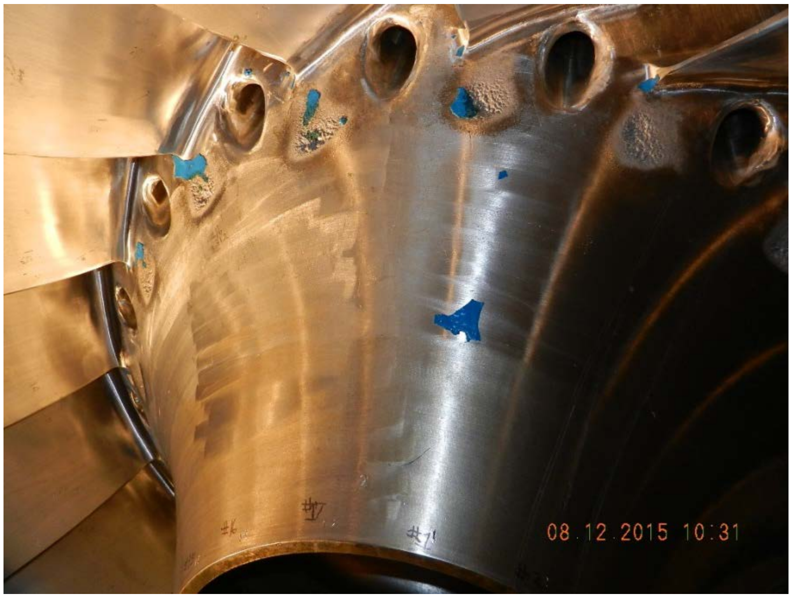

Figure 4. Typical cavitation damage downstream of the turbine runner air vent at Flaming Gorge powerplant.

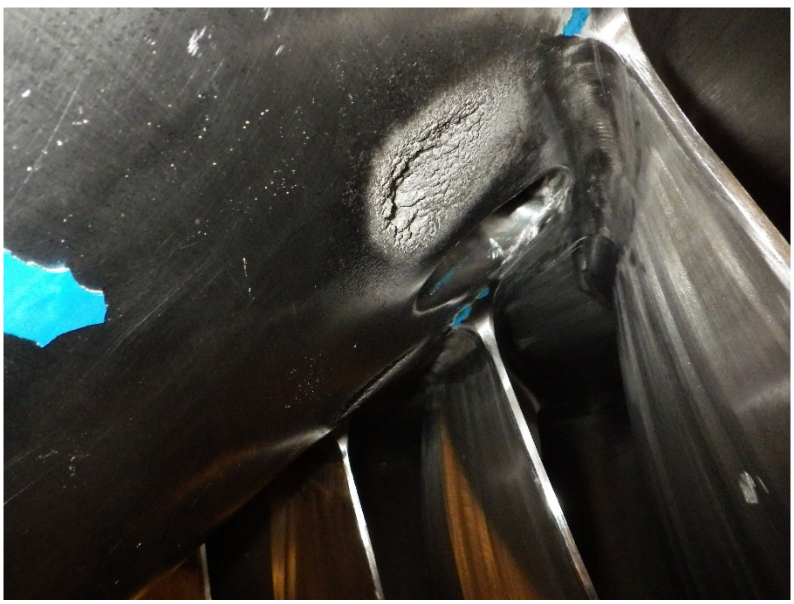

Figure 5. Additional cavitation damage downstream of the turbine air vent at Flaming Gorge powerplant.

5. In 2017 Reclamation entered into a three-year cooperative research project for extensive cavitation testing at the Grand Coulee Hydroelectric Complex, Third Powerhouse using generator unit G24, a 805 mw hydro unit. This ongoing three-year project, as currently structured, was entered into by Reclamation and Alstom Renewable US LLC (Alstom) through Cooperative Research and Development Agreement (CRADA) 17-CR-PN-1009.

Reclamation's Technical Service Center (TSC) cavitation research team is an active participant in this work; reviewing tests and procedures, taking independent measurements, and providing research support and consultation with Alstom on this research. Their participation in this work for 2017 was funded through the current S&T project. Continued participation in this research project is funded through a new research proposal that was recently approved. The scope of this study examines two areas. The first is the study of cavitation and the second is the measurement of residual stresses. Grand Coulee G24, one of the largest generators in the world was selected for the cavitation tests. As part of the cavitation tests, the addition of air injection, used to mitigate vibration and cavitation, was also added to the scope.

Figure 6. Grand Coulee Third Powerhouse. Cavitation and residual stress research is taking place at this facility as part of an agreement with Alstom Renewables, US (photo provided by Alstom).

This study is intended to further the research on cavitation on a prototype/field turbine and examine external noise as an indicator of cavitation. Through past research performed by Alstom an algorithm was developed that determines damaging cavitation from non-damaging. Reclamation was able to collaborate with Alstom by participating in the field study of Grand Coulee G24. This research will help to verify that this phenomenon translates well into field performance and enable improvement to the algorithm where necessary.

Additionally, many hydropower facilities are impacted by high vibration when operating in rough zones. Minimizing this vibration through air injection offers operators more operational flexibility. Air injection tests were conducted on the unit to measure whether air would mitigate the unwanted effects of the vortex (swirl) cavitation that is present in the unit. Reclamation's cavitation team participated in all tests and provided Alstom with accelerometer and acoustic emissions data.

Field cavitation measurements were completed on Grand Coulee G24 during the final two weeks of September 2017. Data analysis and final results have not been completed, but preliminary results indicate an appreciable benefit from air injection over certain gate opening ranges. The initial stage of this study with analysis of data indicating cavitation mapping and air injection benefits will be completed in 2018.

A study of residual stress is also being performed. The study is intended to further understand fatigue impacts on turbine runner life. Alstom will perform several non-destructive tests on the turbine runner to develop methods for measuring residual stress. The residual stress measurements using this non-destructive method will help to better evaluate the impact of operating conditions on the hydro component's life expectancy.

Residual stress measurements are scheduled to be conducted in early 2018. During the 2018 study a data acquisition system is schedule to be installed on hydro generator G24. The Alstom machine condition monitor will monitor and quantify cavitation data supplied from fixed sensors through the water season. The final year of the study, 2019 will analyze this data and produce a final report.

Figure 7. Grand Coulee Unit G24 turbine shaft with attached AE sensor and accelerometer, and wireless data transfer system.

Please contact the Science and Technology office or the principle investigator regarding questions related to this particular research.

Cavitation tests were conducted in March 2017 at Flatiron Powerplant, Eastern Colorado Area Office, Loveland, Colorado to identify cavitation that was thought to be occurring on the wicket gates of the unit 1 and unit 2 turbines. Field tests were conducted on Unit 1 including gathering and analyzing vibratory and acoustic data from sensors attached to the wicket gate stem. Although Unit 1 was tested, a unit outage for testing of the second unit could not be obtained. The completion of this project is still pending. Field measurements on Unit 2 and completion of the study is hoped to be accomplished in 2018.

6. In 2017, a one-year research project entitled, "*Cavitation Detection – Method Development to Detect Damaging Cavitation*", X1708, [17]was funded through Reclamation's Science and Technology program. This study, which was performed by the Hydraulic Investigations and Laboratory Services Group, investigated cavitation within a laboratory venue with the objective of determining if damaging vs. non-damaging cavitation could be detected through broadband acoustic emission measurements. A lab-scale test facility was constructed and a broadband AE sensor was installed and tested. Cavitation was induced on metal samples (mild steel) by a submerged jet. Laboratory tests were conducted under more controlled conditions than those expected with field measurements on full size prototype hydro turbines. Results showed that a difference in damaging and non-damaging cavitation activity can be detected at the lab scale and recommended that further testing be conducted on a prototype hydro turbine. This research highly compliments the field research performed under this study.

Conclusions and Recommendations

Cavitation in hydraulic machines is a complex phenomenon that is highly damaging. Cavitation detection is of major importance to Reclamation and warrants an expanding research role. This research explored newly developing techniques to detect, monitor and track cavitation activity occurring within turbine runners. The research furthers the technology behind the measurement and studying of the cavitation on hydroelectric turbines through direct analysis of high frequency vibrations and acoustics measured at Reclamation sites such as the J. F. Carr powerplant, Grand Coulee powerplant, Fremont Canyon powerplant, Flaming Gorge powerplant, and at other Reclamation facilities.

This research will ultimately lead to decreased outage times for cavitation repair and greater longevity of turbine runners and components. This will ultimately create increased power generation, reduced maintenance costs and extend the longevity of the turbine.

Products that Support the Final Report

Research products that include specific and more in depth reports, conference presentations and journal articles related to the individual in-house and field research conducted and that are referenced in this report and the section, "Research Results" can be found on the following share drive: https://drive.google.com/open?id=0Bw_9TNNswzJPSmhhdnJVX3EzSFk/2944 Additional Products

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Data Sets that Support the Final Report

- Data for this project can be found on the following share drive: Q:\Mechanical\O&M\jgermann\cavitation
- Point of Contact: John Germann, jgermann@usbr.gov, 303-445-2295
- DasyLab test files and worksheets, spreadsheets, word documents, reference reports
- Keywords: cavitation detection, cavitation monitor, hydroelectric, hydraulic turbines, acoustic emissions
- Approximate total size of all files: 1.0 Tbytes