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Performance Testing Multiple Units of Similar Hydraulic Design

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14. ABSTRACT
Performance test each unit at a powerplant that has similar hydraulic design. Analyze the available performance test data and historical operating data for a selected set of Reclamation hydropower facilities to estimate potential for increased value and reliability from multi-unit optimization informed by regular performance testing under historical dispatch and water availability scenarios.

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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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Performance Testing Multiple Units of Similar Hydraulic Design

Science and Technology Program
Research and Development Office
Final Report No. ST-2022-300-01

prepared by

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Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology Program

Final Report ST-2022-300-01

Performance Testing Multiple Units of Similar Hydraulic Design

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Acronyms and Abbreviations

ASME	American Society of Mechanical Engineers
DOE	Department of Energy
HFI	Hydropower Fleet Intelligence
HPPi	Hydro Performance Processes, Inc.
ORNL	Oak Ridge National Laboratory
Reclamation	Bureau of Reclamation
USBR	United States Bureau of Reclamation

Measurements

cfs	cubic foot per second (ft^3/s)
°F	degree Fahrenheit
ft	feet
ft/s^2	feet per second squared
hp	horsepower
kW	kilowatt
lb/ft^3	pounds per cubic foot
MW	Megawatt
MWh	Megawatt-hour
psi	pounds per square inch (lbs/in^2)

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Executive Summary

Do hydraulically similar hydroelectric units have identical performance characteristics? Can high accuracy ASME PTC 18 performance testing on each unit identify performance differences? Can detailed analysis of archival unit data and turbine manufacturer's predicted performance give enough information on specific unit performance characteristics? Can we use this data to optimize operations at multiple unit powerplants?

Seeking an answer to these questions, U.S. Bureau of Reclamation (USBR) with Oak Ridge National Lab (ORNL) and Hydro Performance Processes, Inc. (HPPi) investigated two multi-unit powerplants to test each unit, gather historical data, analyze the data, and provide optimization improvements.

USBR performed a performance test on each unit at a multiple unit powerplant with similar hydraulic designs. ORNL analyzed the available performance test data and historical operating data for a selected set of Reclamation hydropower facilities. They estimated the potential increased value and reliability for multi-unit optimization, informed by regular performance testing under historical dispatch and water availability scenarios. Optimization scheduling at the two powerplants also outlined the optimized generating efficiencies.

Reclamation should continue to identify powerplants that would benefit from an optimization study for water conservation and generation schedule analysis for increased revenue and optimized water usage. Evaluating exiting units that have not had recent turbine runner replacements could provide better efficiency and water use information to power and water customers. Additional studies should be performed to provide more information for our power and water customers on the costs of starts/stops, balanced versus unbalanced unit scheduling, and impacts to maintenance and overhaul scheduling.

1. Introduction

1.1 Background

As the demand for clean energy and water increases, optimizing a hydropower plant's energy production and water usage is becoming increasingly important. This can be a challenging problem so solve, even in hydropower plants with identical units. Unit specific hydraulic performance can depend on operational wear or differing tolerances of turbine components. In addition, operational constraints can limit hydropower plant optimization due to wildlife, water delivery, power demands, and water quality.

This research considers operation optimization of two powerplants, each with multiple identical units: Flaming Gorge Powerplant and Palisades Powerplant. This study initially included testing of Glen Canyon Units 1 through 8, but this could not be completed due to unit outages during the project timeframe.

Flaming Gorge Powerplant contains three vertical-shaft Francis hydraulic turbine units. The turbines were designed and manufactured by James Leffel & Company originally units were placed into commercial operation in 1964. The original 36,000 kW generators were uprated in 1992 to 50,650 kW. In 2003, a contract was awarded to VA Tech Hydro of Charlotte, NC, now Andritz Hydro, to furnish a model tested hydraulic design with three new stainless steel runners and a complete turbine rehabilitation. Unit 1 was returned to commercial operation in 2008, Unit 2 in 2007 and Unit 3 in 2006.

Palisades Powerplant contains four vertical-shaft Francis hydroelectric generation units. The units were designed and manufactured by S. Morgan Smith and were put into commercial operation in 1957. The original 30,000 kW generators were uprated to 44,000 kW each in the mid 1990's. In April 2011, a contract was awarded to Andritz Hydro to furnish a model tested hydraulic design with four new stainless steel runners and complete a turbine rehabilitation. Unit 1 was returned to commercial operation in 2013. Unit 4 was returned to commercial operation in 2014. Unit 3 was returned to commercial operation in 2015. Unit 2 was returned to commercial service in 2017.

1.2 Previous Work

No previous work completed by USBR.

1.3 Problem

Hydropower plants with multiple identical units may assume each unit has identical hydraulic performance characteristic. This assumption can affect the optimization scheme for achieving the highest powerplant efficiency for the power and water demands of that system.

1.4 Objectives

The Western United States has experienced an enormous increase in demand for water conservation and improved hydropower generation. The desired outcome of this study is to optimize multiple unit powerplants to provide a larger benefit to power and water customers, and stakeholders. This research effort is separated in two phases, outlined below.

Phase 1 – Performance Testing Multiple Units of Similar Hydraulic Design and Comparing to Other Data Sources.
The objective of Phase 1 was for USBR to perform field efficiency testing of the hydroelectric generating units at one multi-unit powerplant and report on the results. The results include performance testing of the units at the reservoir elevation available at the time of the test. Data to include test points throughout the wicket gate range from speed-no-load to 100 percent wicket gate opening or generator limit. Data is presented in tabular form, as well as graphically to illustrate the unit-to-unit differences in turbine performance. Flaming Gorge Units 1, 2, and 3 were tested November 2015. Palisades Units 1, 2, 3, and 4 were tested September 2018.

ORNL performed quantification of optimization benefits from detailed unit performance testing at multiunit hydropower facilities. Using the performance test data collected for each unit at Palisades and Flaming Gorge, ORNL collected historical data and provided comparisons to the test data. Optimization for unit operations at the specific powerplant was analyzed.

ORNL collected data for more than a year for their analysis. The extended data collection and analysis was important for unit optimization.

Phase 2 - Improved Hydropower Value through Data Analysis.
The objective of Phase 2 was to continue the data analysis for Palisades and Flaming Gorge using collected historical plant operational data. Additional operational data was gathered from Palisades and Flaming Gorge to improve the Phase 1 analysis.

Previous work from the selected four-unit hydropower plants provided individual unit performance characteristics derived from historical data (i.e., unit power, head, and unit flow). ORNL and its partners used results from USBR's September 2018 field performance tests, unit characteristics derived from the correlation analyses, the expected unit characteristics based on previous USBR performance testing, and the turbine manufacturers' predicted performance characteristics to detect any significant difference among these sources. The Hydroplant Performance Calculator [March et al., 2014], developed during the Department of Energy (DOE) funded Hydropower Advancement Project at ORNL and now part of the Foundational Concepts resource within the DOE-funded Hydropower Fleet Intelligence (HFI) project, was used to automate operational efficiency analyses and scheduling analyses for historical data from September 2018 to June 2019. These analyses evaluated and quantified the potential reductions in generation associated with differences in individual unit performance characteristics for the analyzed plants.

Extension of field test program planning and analyses by ORNL and its partners supported USBR in the evaluation and practical implementation of identified opportunities for generation improvements.

ORNL and its partners prepared a confidential final report on the costs and benefits of a performance test program, including field test results, analysis results, guidance for USBR on the frequency and type of unit performance testing, and cost-effective online performance monitoring. The report discussed implications for the optimization of water and power resources. Content from this report will be used to produce a formal use case example document for the DOE HFI project.

1.5 Study Partners

Brennan T. Smith - Oak Ridge National Laboratory
Patrick March - Hydro Performance Processes Inc.
Paul Wolff - WolffWare Ltd.
Palisades Powerplant
Flaming Gorge Powerplant
CPN Regional and Area Office
UCB Regional and Area Office

2. Results

2.1 Phase 1 – Performance Testing Multiple Units of Similar Hydraulic Design and Comparing to Other Data Sources.

Phase 1 objective is met which is summarized below and detailed in the referenced appendices.

Appendix A: Flaming Gorge Powerplant Unit 1, 2, and 3 Turbine Performance Test Report – Durham and Kummet, November 2016

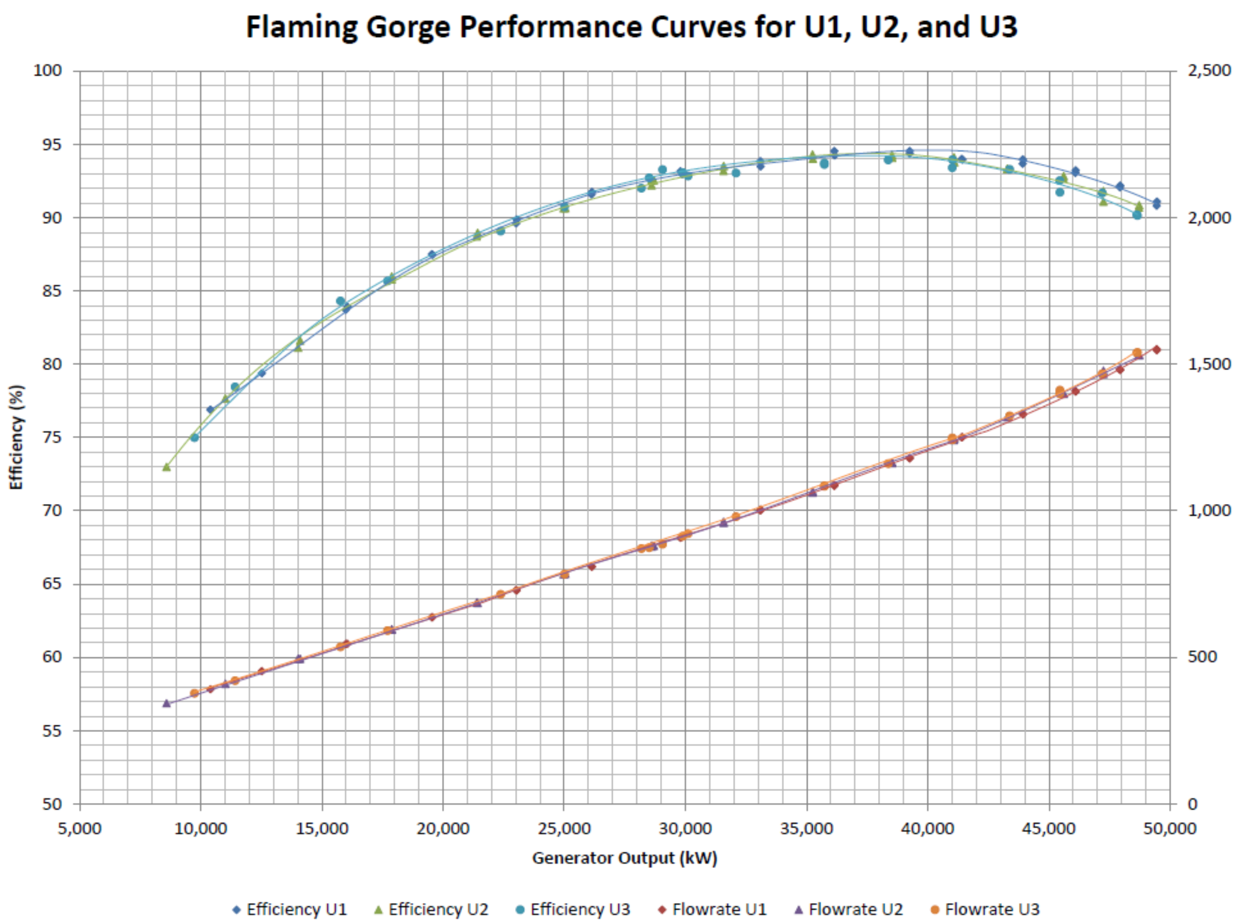


Figure 1: Flaming Gorge Unit 1, 2, and 3 field efficiency testing of the hydroelectric generating units in one multi-unit powerplant and report on the results.

Initial performance analyses for USBR's Flaming Gorge powerplant used hourly archival data from 2008 to 2015 and Reclamation's field efficiency test results from November 2015. The performance curves derived from efficiency tests and from the archival data correspond closely. A comparison between the turbine manufacturer's expected performance curves and the derived performance curves resulted in an average annual energy difference of 1.6 percent, corresponding to $190,000 per year in power revenue loss. Operation efficiency analyses for Flaming Gorge show the potential for modest annual improvements from improved unit dispatch, corresponding to an increase in power revenue of $48,000 per year. Generation scheduling analyses for Flaming Gorge show the potential for significant annual improvements from improved scheduling, corresponding to an increase in power revenue of $210,000 per year.

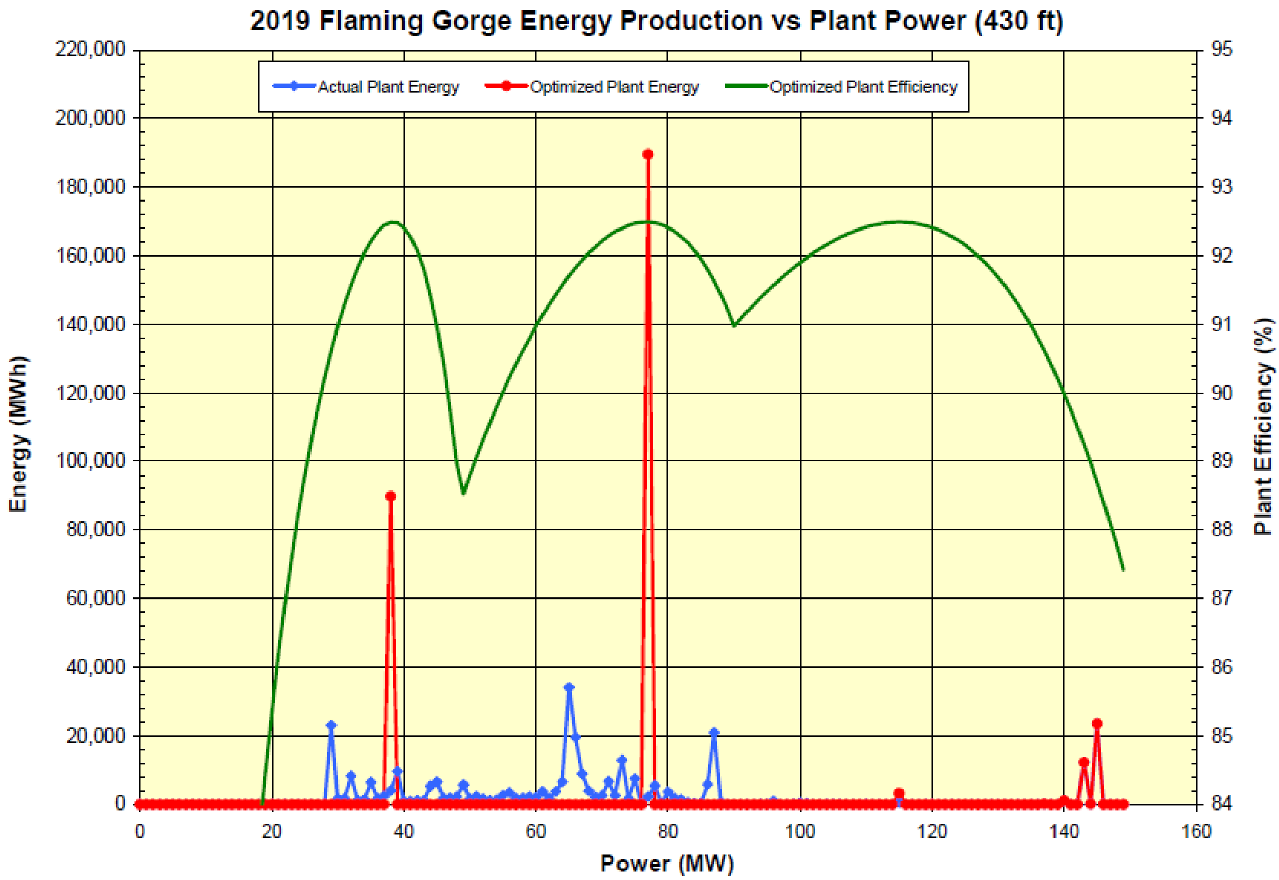


Figure 3: Flaming Gorge Optimized Operation Benefit from Detailed Unit Performance Testing at Multiunit Hydropower Facilities.

Appendix B: Palisades Powerplant Unit 1, 2, 3, and 4 Turbine Performance Test Report – Durham Kummet, and Johnson, 2021

Flaming Gorge Performance Curves for Unit 1, 2 and 3. Generator output on the x-axis, efficiency on the left y-axis, flowrate on the right y-axis.

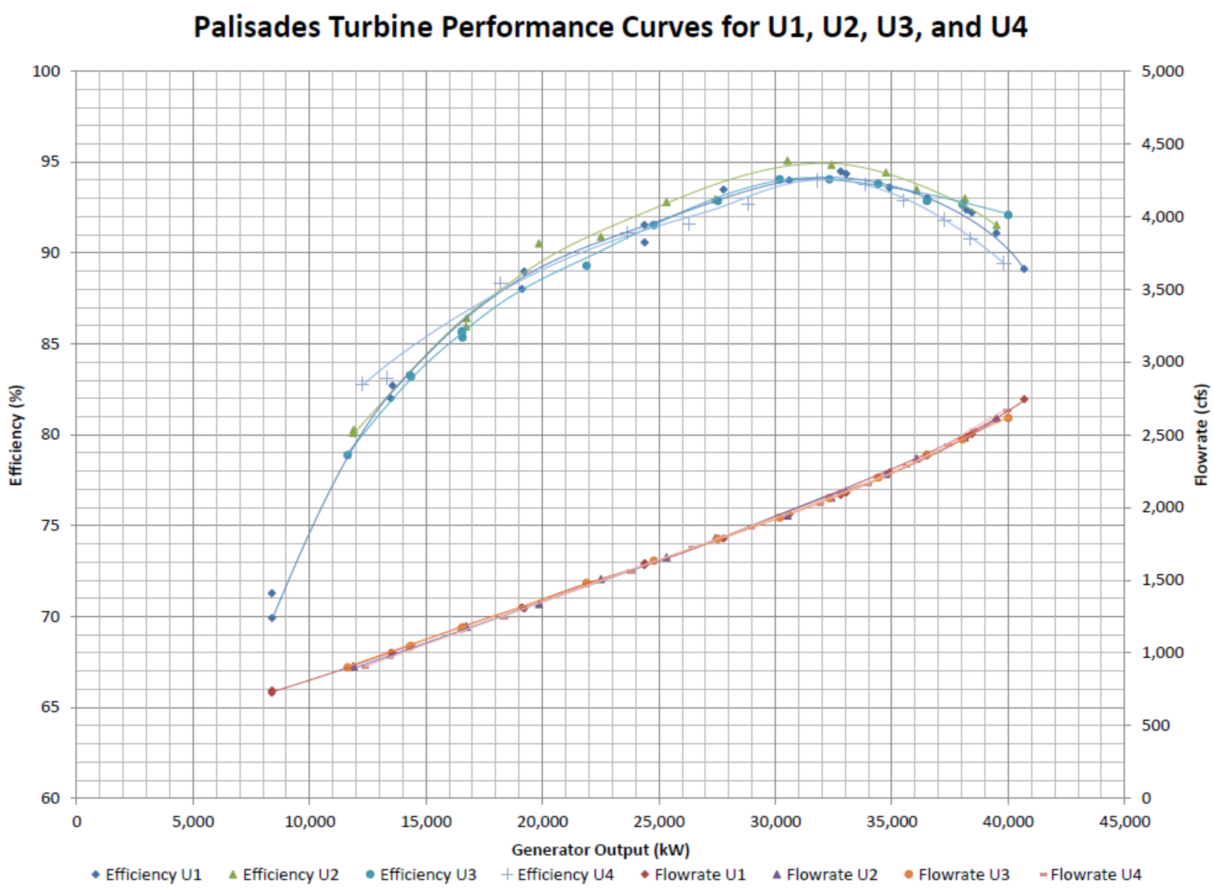


Figure 2: Palisades Unit 1, 2, 3, and 4 field efficiency testing of the hydroelectric generating units in one multi-unit powerplant and report on the results.

Initial performance analyses for USBR's Palisades powerplant used fifteen-minute increment archival data for 2014 to 2018 and Reclamation's field efficiency test results from June 2014 and September 2018. The turbine manufacturer's expected performance curves for Palisades and the performance curves derived from efficiency tests and archival data correspond closely. Operation efficiency analyses for Palisades show the potential for modest annual improvements from improved unit dispatch with the new units, corresponding to an increase in power revenue of $23,700 per year. Generation scheduling analyses for Palisades show the potential for significant annual improvements from improved scheduling, corresponding to an increase in power revenue of $277,000 per year.

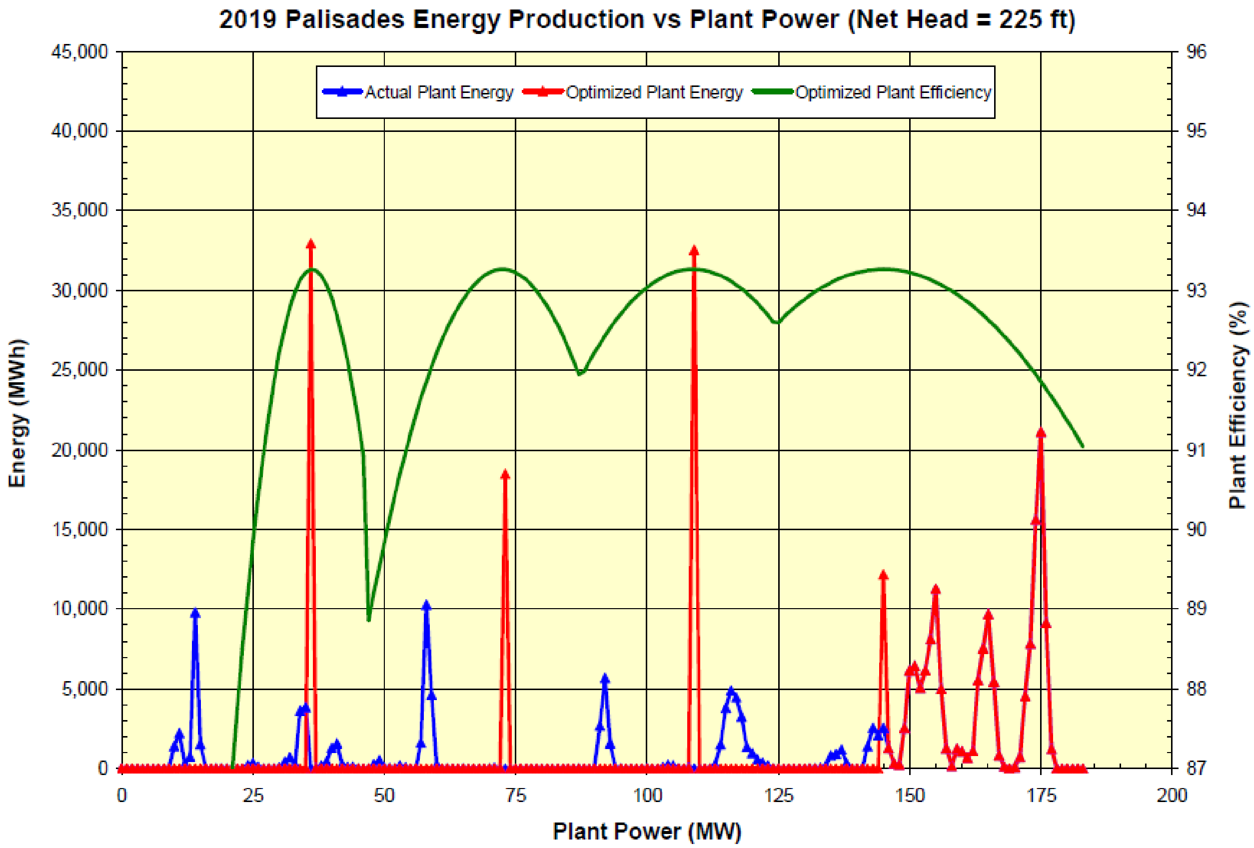


Figure 4: Palisades Optimized Operation Benefit from Detailed Unit Performance Testing at Multiunit Hydropower Facilities.

2.2 Phase 2 - Improved Hydropower Value through Data Analysis.

Phase 2 objective is met which is summarized below and detailed in the referenced appendix.

Appendix C: Quantifying the Potential Value of Unit Characteristics Based on Field Efficiency Tests and Archival Data Analyses, March and Wolff, Final Report FR2101, November 2021.

Recent performance analyses for USBR's Flaming Gorge powerplant used hourly archival data from 2008 to 2015 and Reclamation's field efficiency test results from November 2015 to derive unit characteristics and using 2018 to 2019 archival data. The estimated lost revenue opportunity and reduced maintenance costs for 2018 to 2019 range from $76,727 to $82,892, indicating a small but achievable potential improvement from improved optimization at Flaming Gorge. Generation scheduling analyses show the potential for significant annual improvements of approximately 1.0 percent, corresponding to a generation increase of 10,546 MWh and a power revenue increase of $312,366 for 2018 to 2019. Recommended best efficiency operating points for Flaming Gorge versus gross head achieve some or most of the potential generation improvements from improved scheduling.

Recent performance analyses for Palisades summarized the recent performance analyses derived from the 2008 to 2015 archival analyses, Reclamation's September 2018 field tests, and generation scheduling analyses based on the 2018 and 2019 archival data. Updated flow analyses confirmed the results from previous flow analyses and show that the unit efficiencies from field tests agree closely with the efficiencies derived from archival data and the turbine manufacturer's predictions. Operation efficiency analyses showed that the potential efficiency improvements due to improved optimization, while meeting the actual power versus time, are modest, ranging from a low of 0.20 percent for 2020 to a high of 0.39 percent for 2019, with a three-year total lost energy opportunity of 7,210 MWh and a three-year total lost revenue opportunity of $213,559. Major efficiency loss events, approximately two-thirds of the potential improvements identified by the operation efficiency analyses, occurred because too many or too few units were operating, because the units are not operating at equal loads, or both. This increased generation from improved optimization could be achieved without any significant effect on the number of start/stops for the Palisades units. The potential efficiency improvements due to improved generation scheduling are significant, ranging from a low of 0.57 percent for 2018 (partial year) to a high of 1.98 percent for 2021 (partial year), with a three-year total Lost Energy Opportunity of 21,557 MWh and a three-year total lost revenue opportunity of $638,519. Opportunities for scheduling improvements occur primarily during October to April each year. Recommended best efficiency operating points for Palisades versus net head were provided to achieve some or most of the potential generation improvements from improved scheduling.

3. Discussion

Optimizing power generation and water usage is essential to fulfilling USBR's mission. In recent years, increases in power and water demands coupled with continual climate change has a significant impact on the operational availability of generating units. Western United States watersheds are receiving less water each year, therefore, less water inflow at Reclamation's hydroelectric plants and dams.

It is essential that Reclamation continues to identify powerplants that would benefit from an optimization study for water conservation and power generation schedule analysis to address the water and power needs of the Western United States. Historical data collection and analysis with on-site unit performance testing will positively benefit the majority of USBR hydropower plants. Water releases can also be better optimized by studying individual powerplants with respect to the timing of water release and power demand. In addition, a benefit can be realized from evaluating exiting units that have not had recent turbine runner replacements to provide better efficiency and water use information to power and water customers.

Additional studies should be performed to provide up-to-date and accurate information to power and water customers on the costs of starts/stops, balanced versus unbalanced unit scheduling, and impacts to maintenance and overhaul scheduling.

4. References

March, P., P. Wolff, E. Foraker, and S. Hulet, "Quantification of Optimization Benefits from Detailed Unit Performance Testing at Multiunit Hydropower Facilities," Proceedings of HydroVision International 2017, Tulsa, Oklahoma: PennWell Corporation, July 2017.

March, P., P. Wolff, E. Foraker, and S. Durham, "Quantifying the Potential Value of Unit Characteristics Based on Field Efficiency Tests and Archival Data," Proceedings of HydroVision International 2019, Tulsa, Oklahoma: PennWell Corporation, July 2019.

Appendix A

Flaming Gorge Powerplant Unit 1, 2, and 3 Turbine Performance Test Report –Durham and Kummet, November 2016

RECLAMATION
Managing Water in the West

Flaming Gorge Powerplant
Unit 1, 2, and 3 Turbine Performance Test Report

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, CO

November 2016

Mission Statements

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.

INTRODUCTION

Flaming Gorge Powerplant contains three vertical-shaft Francis hydraulic turbine units. The turbines for built originally by James Leffel & Company originally rated 48,000 horsepower at 350 feet and 240 rpm. The units were put into commercial operation in 1964. The original 36,000 kW generators have been uprated in 1992 to 50,650 kW.

In 2003 contract No. 03-CC-40-8011 was awarded to VA Tech Hydro of Charlotte, NC, now Andritz Hydro, to furnish a model tested hydraulic design for three new stainless steel runners and rehabilitation. Unit 1 was returned to service in 2008, Unit 2 in 2007 and Unit 3 in 2006. Unit 1 was tested for efficiency and power output on November 3, 2015, Unit 2 was tested November 4, 2015 and Unit 3 was tested November 5, 2015 by personnel of the Bureau of Reclamation, Technical Service Center.

RESULTS

Turbine performance testing is accomplished by simultaneously measuring the generator power output, spiral case pressure, tail water pressure, turbine discharge, and servomotor stroke. Turbine efficiency is calculated from these measurements. The contract allowed a test uncertainty tolerance of +/- 1.0% on the calculated efficiency.

Results of the performance testing:

Results at Peak Efficiency:				
Unit	Net Head	Peak Efficiency	Turbine Power	Servomotor Stroke
1	423 feet	94.54 %	53,462 horsepower	75 %
2	423 feet	94.31%	48,041 horsepower	70 %
3	423 feet	93.94 %	55,869 horsepower	79 %

Results at Full Gate:				
Unit	Net Head	Full Gate Efficiency	Turbine Power	Servomotor Stroke
1	421 feet	91.08 %	67,295 horsepower	100 %
2	421 feet	90.85%	66,307 horsepower	100 %
3	421 feet	90.18 %	66,183 horsepower	100 %

TEST EQUIPMENT

All performance data was recorded using a digital data acquisition system. The system consists of a laptop computer, a Hewlett-Packard Model 34970A digital scanning voltmeter, a printer, and various transducers. The computer utilizes an IEEE-488 interface card to communicate over a GPIB bus to control the other devices in the system. It also records all data on disk. The voltmeter was used to convert the analog signals from the transducers to digital form for processing and storage by the computer. The voltmeter has a capability of 6-1/2 digit accuracy and each reading was integrated over a time period equal to 10 power line cycles to maximize electrical noise rejection. The scanner was used to connect the transducers to the voltmeter and serves as a programmable switching device allowing the voltmeter to read each transducer individually. The printer was used to provide hardcopy output of the data as it was generated during the test and provide a second form of permanent storage.

Turbine spiral case pressure; tailwater pressure; and generator output voltage, amperage, and watts were measured with transducers that have analog output. Flow rate was measured with a four path Accusonic Technologies Inc. Model 7510 acoustic flowmeter. The flowmeter transducers are located in the penstock upstream from the inlet to the turbine spiral casing extension. Recording transducer outputs for approximately seven minutes while the unit operates at a steady state condition makes up a test run. Each run was an average of 300 instantaneous measurements for spiral case inlet pressure, tailwater pressure, watt transducer output, generator volts and amps, and gate position. The flowmeter updated approximately 64 times during a test run.

HEAD

Turbine spiral case pressure was measured at the net head taps in the penstock casing extension. The four net head piezometer taps were manifolded together and piped up to the governor cabinet so that the average pressure at the section was recorded. A piezometer traverse could not be performed prior to the test.

Tailwater elevation was measured using a pressure transducer connected to an unused cooling water discharge pipe to the tail race located close to the unit under test. Both transducers were calibrated with a Fluke 718 pressure calibrator prior to testing at site. Cooling water which is normally tapped off the unit spiral case was taken from the cross connection to an adjacent unit so as not to reduce measured water through the turbine during the test.

Net head on the turbine was computed by subtracting the tailrace pressure elevation (corrected for velocity head at the draft tube exit) from the spiral case inlet pressure elevation (corrected for velocity head at the location of the piezometer taps). Pressure measurements were converted from pounds per square inch to feet of water by using a weight of water taken from the ASME Performance Test Code, PTC 18-2011 for the elevation and latitude for the powerplant and the temperature of water measured during the test. Calculated pressure elevations were verified against the control room water surface elevation meters.

The dimensions of the penstock at the piezometer section and draft tube at the exit were taken from drawing No. 591-D-279 which were used to obtain the areas to correct the pressure measurements for velocity head.

H_n	Net Head (ft)	$H_n = (H_i - H_o)*[1-(\rho_a/\rho)] + H_{vi} - H_{vo}$
H_i	Inlet Head (ft)	$H_i = (P_i * C) + P_{ie}$
H_o	Outlet Head (ft)	$H_o = (P_o * C) + P_{oe}$
H_{vi}	Inlet Velocity Head (ft)	$H_{vi} = Q^2 / (A_i^2 * 2 * G)$
H_{vo}	Outlet Velocity Head (ft)	$H_{vo} = Q^2 / (A_o^2 * 2 * G)$
ρ_a	Density of air (lbm/ft^3)	
ρ	Density of water (lbm/ft^3)	
P_i	Inlet Pressure (lb/in^2)	
P_o	Outlet Pressure (lb/in^2)	
P_d	Draft tube pressure (lb/in^2)	
P_h	High Pressure (lb/in^2)	
P_{ie}	Inlet Pressure Transducer Zero Elevation (ft)	
P_{oe}	Outlet Pressure Transducer Zero Elevation (ft)	
G	Local Gravity (ft/s^2)	
Q	Flowrate (ft^3/s)	
A_i	Area of Spiral Case Extension (ft^2)	
A_o	Area of Draft Tube Outlet (ft^2)	
C	Conversion factor from Pressure (lb/in^2) to (ft) of H_2O	

Turbine net head computation - Formulas and a sample computation for computing turbine net head for Unit 1 Run No. 21:

A_i = 63.434 ft^2 (area of spiral case at piezometer taps)
A_o = 195.223 ft^2 (area of draft tube outlet)
G = 32.1431 ft/s^2
ρa = 0.043 lbm/ft^3
ρ = 62.44 lbm/ft^3
P_i = 173.30 lb/in^2
P_o = 4.317 lb/in^2
Q = 1179.02 ft^3/s
C = 2.312

Water temperature during test = 51.5º F (10.8º C)
Elevation of spiral case pressure transducer = 5622.3 feet
Elevation of draft tube pressure transducer = 5594.36 feet

$H_i = (173.30 * 2.312) + 5622.3 = 6023.01$ ft
$H_o = (4.317 * 2.312) + 5594.36 = 5604.34$ ft
$H_{vi} = (1179.02)^2 / ((63.434)^2 * 2 * 32.1431) = 5.37$ ft
$H_{vo} = (1179.02)^2 / ((195.223)^2 * 2 * 32.1431) = 0.57$ ft

$H_n = (6023.01 – 5604.34)*[1-(0.043/62.44)] + (5.37 – 0.57) = 423.19$ ft

POWER

Power output from the turbine was determined by using the generator as a dynamometer. Generator input was determined by measuring the generator output in kilowatts, adding the generator losses, and converting to horsepower. Power output from the generator was measured using the two-wattmeter method with a Scientific Columbus polyphase watt transducer. Scientific Columbus transducers are also used to measure generator current and voltage for the power factor calculation. The transducers for measuring voltage, current and power were connected to the secondary side of the instrument transformers used in the metering circuits for the instruments on the unit control boards. The potential transformers have a ratio of 100:1 and the current transformers have a ratio of 600:1. Generator inefficiencies were obtained from the 1993 uprate acceptance test report and added to the measured generator output to obtain generator input horsepower.

G_L	Generator Loss (kW)	$G_L = K0 + (K1 * G_o) + (K2 * G_o^2) + (K3 * G_o^3)$
G_o	Generator Output Reading (kW)	
G_i	Generator Input (kW)	$G_i = T_o = G_o + G_L$
T_o	Turbine Output (hp)	$T_o = G_I * X$
K3	Electrical coefficient K3 for K3 $*KW^3$	
K2	Electrical coefficient K2 for K2 $*KW^2$	
K1	Electrical coefficient K1 for K1 *KW	
K0	Electrical coefficient K0	
X	Conversion factor from kW to hp	X = 1.34102

Turbine power output computation - Formulas and a sample computation for computing turbine power output for Unit 1 Run No. 21 follows:

Test data for the generator indicated the following relationship between power output from the generator in kilowatts and total losses in kilowatts:

G_L, (kW) = $412.2 + (4.465 \times 10^{-4} * G_o) + (1.20 \times 10^{-7} * G_o^2)$

(Generator losses include core loss, stray loss, copper loss, and friction and windage loss)

G_o = 39,252.12 kW

$G_L = 412.2 + (4.465 \times 10^{-4} * 39{,}252.12) + (1.20 \times 10^{-7} * 39{,}252.12^2) = 614.61$ kW

$G_i = T_O$ = 39,252.12 kW + 614.61 kW = 39,866.73 kW

T_o = 39,866.73 kW = 53,462.16 hp

FLOW RATE

Flow rate was measured during the performance test with an Accusonic Technologies time-of-flight acoustic flowmeter system. The flowmeter uses acoustic transducers fed through the penstock wall and arranged in 4 chordal paths in two crossing planes. The measurement section is 45 feet downstream of a slight vertical reducing bend. This represents approximately 5 diameters of straight penstock. The vertical reducing bend is approximately 10 degrees with a reducing section from 10 feet diameter to 9 feet diameter. The calculated flows were recorded by the data acquisition in the plant control room. The clocks in the computer and flowmeter were synchronized prior to the performance test. The beginning time for each test run and the time for each flowmeter update are recorded. The data obtained from the digital output of the flowmeter was averaged, during data reduction, over the data acquisition period for each test run. This data was used in the final calculation of the test results.

EFFICIENCY

$E = (D * W) * 100 / (H_n * Q * \gamma)$

E	Efficiency (%)
D	Conversion factor (550)
W	Power Output (hp)
H_n	Net Head (ft)
Q	Flow rate (ft^3/s)
γ	Weight of Water (lb/ft^3)
g	Local Gravity (ft/sec^2)

Efficiency computation - The peak efficiency for Unit 1 Run No. 21 is as follows:

$$E = (550 * 53,462.16) * 100 / (423.19 * 1179.02 * 62.3368)$$

$$\mathbf{= 94.54\ \%}$$

UNCERTAINTY ANALYSIS

Systematic Uncertainty

The uncertainty was evaluated using the square root of the sum of the squares of the individual uncertainties.

Head
Bureau of Reclamation standard for plant floor elevation deviation = +/-0.125 inch = .0104 ft
Estimated maximum uncertainty in the difference in floor elevations = +/-0.25 inch = .0208 ft
Diameter of Penstock at casing extension section = 9 ft
Difference between inlet and outlet transducer elevations = 28 ft

Hp = standard for plant floor elev. deviation / diameter of casing extension / net head * 100
Hp = 0.0104 / 9 / 423.19 * 100 = <u>0.00027 %</u>

Hm = Est. max uncertainty in the diff in floor elev. / diff. in transducer elev. / net head * 100
0.0208 / 28 / 423.19 * 100 = <u>0.00018 %</u>

Accuracy of Druck DPI-261 pressure transducer (200 lb/in^2 range) = 0.04% of full scale
(used for spiral case pressure measurement)

200 * 0.0004 * (144 / 62.262) / 423.19 * 100 = <u>0.044 %</u>

Accuracy of Druck DPI-261 pressure transducer (25 lb/in^2 range) = 0.04% of full scale
(used for draft tube pressure measurement)

25 * 0.0004 * (144 / 62.262) / 423.19 * 100 = <u>0.0055 %</u>

Total systematic uncertainty of head measurement:
$E_h = (0.00027^2 + 0.00018^2 + 0.044^2 + 0.0055^2)^{0.5}$ = +/-0.044 %

Power
Systematic error for power measurement instruments:
Scientific Columbus watt/watt-hour transducer = 0.1%
Potential transformers = 0.3%
Current transformers = 0.3%
Generator loss curve = 0.1%

Total systematic uncertainty of power measurement:

$E_P = (0.3^2 + 0.3^2 + 0.1^2 + 0.1^2)^{0.5}$ = +/-0.45%

Flowrate
According to the Accusonic procedure for determining systematic uncertainty for the flowmeter transducer installation, the following variables require analysis:

- Path length measurement
- Path angle measurement
- Pipe radius measurement
- Travel time measurement
- Velocity profile uncertainty

Contract flowmeter systematic uncertainty $E_f = 0.5\%$

Efficiency
The systematic uncertainty for efficiency is estimated as:
$E_e = (0.044^2+0.45^2 +0.50^2)^{0.5} = +/-0.672\ \%$

Random Uncertainty

The random uncertainty was calculated using the formula, for Unit 1 Run #21:

$t * S_d / (n)^{0.5}$ / mean value, where t is the student t-coefficient for the 95% confidence level, and S_d is the standard deviation of the n measurements.

Head
Mean of 300 spiral casing pressure measurements = 173.3 lb/in^2
Standard deviation = 0.145 lb/in^2

Random uncertainty = $(2 * 0.145) / 300^{0.5} / 173.3 * 100 = 0.0096$ %

Mean of 300 draft pressure measurements = 4.32 lb/in^2
Standard deviation = 0.059 lb/in^2

Random uncertainty = $(2 * 0.059) / 300^{0.5} / 4.32 *100 = 0.158$ %

Total random uncertainty, head = $(0.0096^2 + 0.158^2)^{0.5} = 0.158$ %

Power
Mean of 300 power measurements = 39,141 kW
Standard deviation = 41.7 kW

Random uncertainty = $(2 * 41.7) / 300^{0.5} / 39{,}141 *100 = 0.0123$ %

Flowrate
The random uncertainty for the flowrate used in the calculation of Run No. 21:

Mean of 75 flowrate measurements = 1,085.05 cfs
Standard deviation = 16.04 cfs

Random uncertainty = $(2 * 16.04) / 144^{0.5} / 1{,}085.05 *100 = 0.341$%

Efficiency
Random uncertainty = $(0.158^2 + 0.0123^2 + 0.341^2)^{0.5} = 0.376$ %

Total uncertainty (systematic and random) = $(0.672^2 + 0.376^2)^{0.5}$ = **+/- 0.77%**

Report prepared by:

Shanna M. Durham

Shanna M. Durham, Mechanical Engineer

11/30/2016

Date

Peer reviewed by:

Mark Kummet

Mark Kummet, Mechanical Engineer

11/30/2016

Date

Flaming Gorge U1

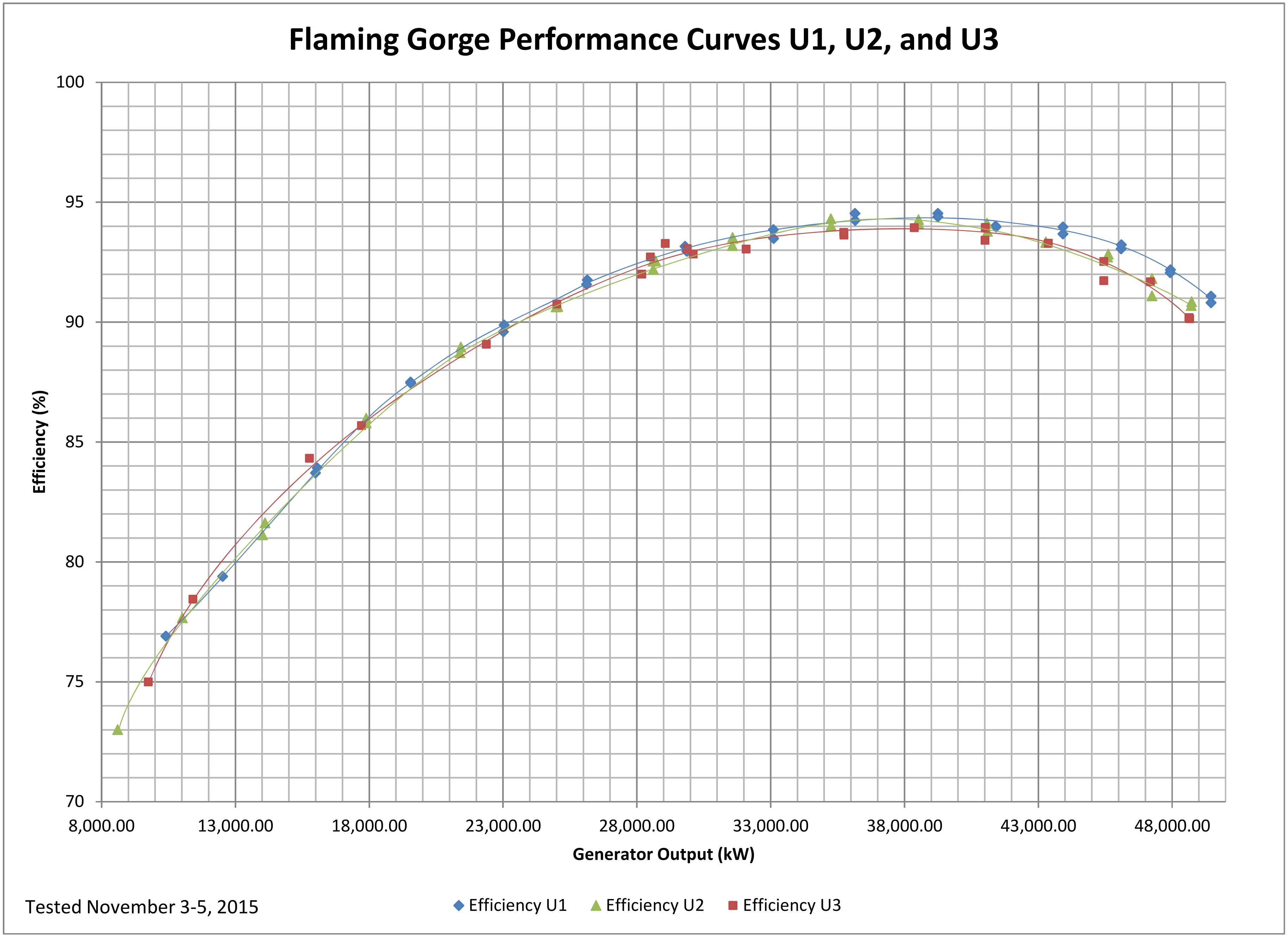
Run #	Flowrate (cfs)	Spiral Case Pressure (psi)	Draft Tube Pressure (psi)	Generator Output (kW)	Horsepower (HP)	Case Pressure Elevation (ft)	Draft Tube Pres. Elevation (ft)	Net Head (ft)	Efficiency (%)	Servo Stroke (%)
1	1,547.65	170.88	4.27	49,453.89	67,294.71	6,027.05	5,605.23	421.18	91.09	100
2	1,551.41	170.94	4.25	49,449.92	67,289.32	6,027.24	5,605.19	421.39	90.81	100
3	1,408.80	171.90	4.24	46,092.31	62,733.05	6,027.81	5,604.99	422.20	93.06	89
4	1,406.67	171.91	4.24	46,106.32	62,752.05	6,027.80	5,604.98	422.19	93.23	89
5	1,250.88	172.91	4.27	41,406.10	56,379.94	6,028.52	5,604.87	423.02	94.01	79
6	1,251.89	172.91	4.27	41,419.56	56,398.19	6,028.51	5,604.89	423.00	93.97	79
7	1,088.57	173.81	4.28	36,155.77	49,270.47	6,029.11	5,604.76	423.73	94.25	70
8	1,085.05	173.81	4.27	36,151.58	49,264.80	6,029.10	5,604.73	423.74	94.54	70
9	907.54	174.67	4.27	29,802.58	40,679.46	6,029.71	5,604.58	424.51	93.16	60
10	911.62	174.66	4.27	29,871.00	40,771.91	6,029.71	5,604.58	424.52	92.95	61
11	729.94	175.38	4.28	23,013.55	31,513.45	6,030.22	5,604.49	425.13	89.60	51
12	728.56	175.38	4.28	23,040.04	31,549.19	6,030.20	5,604.48	425.10	89.88	51
13	546.53	176.06	4.26	16,059.00	22,139.36	6,030.87	5,604.34	425.92	83.92	41
14	545.72	176.03	4.27	15,991.30	22,048.18	6,030.79	5,604.36	425.83	83.71	41
15	636.37	175.64	4.30	19,545.52	26,836.92	6,030.32	5,604.48	425.23	87.50	46
16	637.06	175.64	4.31	19,556.08	26,851.15	6,030.31	5,604.50	425.21	87.46	46
17	809.30	175.05	4.32	26,148.30	35,743.89	6,029.93	5,604.64	424.68	91.76	55
18	810.29	175.02	4.32	26,123.64	35,710.60	6,029.87	5,604.64	424.62	91.57	55
19	1,000.87	174.22	4.32	33,101.47	45,138.71	6,029.35	5,604.77	423.97	93.86	65
20	1,004.97	174.18	4.31	33,106.25	45,145.17	6,029.30	5,604.75	423.93	93.49	65
21	1,179.02	173.30	4.32	39,252.12	53,462.16	6,028.73	5,604.92	423.19	94.54	75
22	1,180.62	173.32	4.31	39,250.18	53,459.54	6,028.79	5,604.92	423.25	94.39	75
23	1,332.55	172.43	4.30	43,918.69	59,785.40	6,028.21	5,605.04	422.54	93.68	84
24	1,328.70	172.42	4.30	43,922.66	59,790.78	6,028.17	5,605.04	422.50	93.97	84
25	1,480.31	171.45	4.27	47,938.31	65,237.61	6,027.57	5,605.14	421.79	92.19	95
26	1,482.10	171.44	4.27	47,929.68	65,225.91	6,027.57	5,605.15	421.79	92.06	95
27	453.63	176.16	4.35	12,519.92	17,374.98	6,030.75	5,604.50	425.64	79.39	35
28	391.73	176.27	4.43	10,404.20	14,528.68	6,030.79	5,604.68	425.51	76.90	31

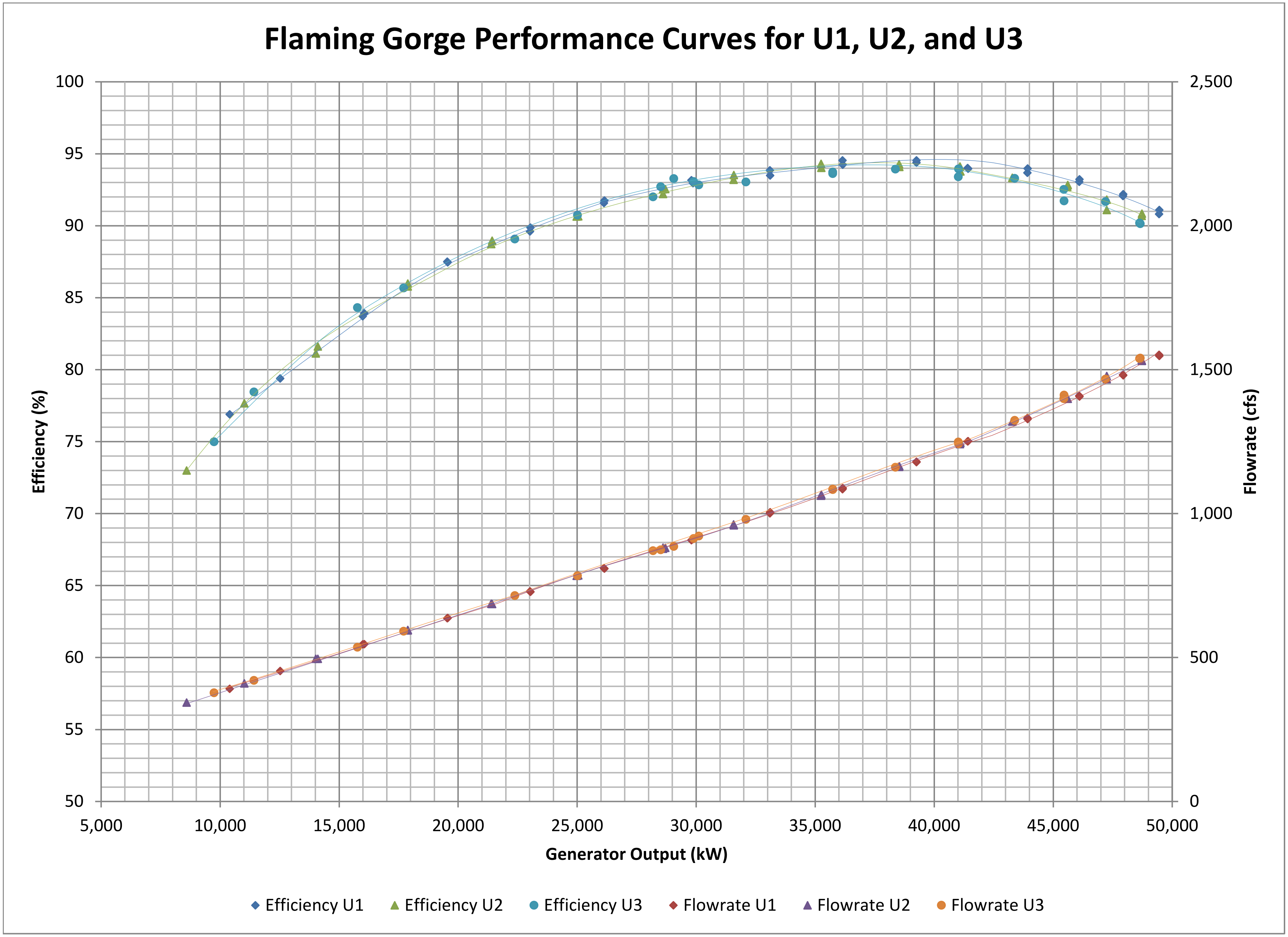
Flaming Gorge U2

Run #	Flowrate (cfs)	Spiral Case Pressure (psi)	Draft Tube Pressure (psi)	Generator Output (kW)	Horsepower (HP)	Case Pressure Elevation (ft)	Draft Tube Pressure Elevation (ft)	Net Head (ft)	Efficiency (%)	Servo Stroke (%)
1	1,530.31	170.95	4.21	48,725.90	66,306.52	6,018.62	5,604.19	421.07	90.85	100
2	1,533.12	170.88	4.22	48,716.28	66,293.46	6,026.80	5,605.09	420.94	90.69	100
3	1,399.12	171.91	4.21	45,613.04	62,082.97	6,027.65	5,604.89	421.98	92.83	91
4	1,400.30	171.90	4.21	45,590.21	62,052.01	6,027.67	5,604.90	421.98	92.71	90
5	1,241.36	172.89	4.25	41,082.24	55,941.15	6,028.32	5,604.83	422.71	94.12	81
6	1,246.25	172.89	4.26	41,098.35	55,962.99	6,028.36	5,604.84	422.74	93.78	81
7	1,061.76	173.91	4.28	35,247.48	48,041.45	6,029.07	5,604.73	423.55	94.31	70
8	1,065.65	173.84	4.29	35,256.61	48,053.80	6,028.95	5,604.74	423.43	94.02	71
9	881.00	174.75	4.27	28,698.47	39,187.77	6,029.67	5,604.57	424.31	92.55	61
10	878.32	174.76	4.28	28,605.70	39,062.44	6,029.66	5,604.57	424.30	92.54	60
11	881.68	174.74	4.27	28,610.75	39,069.27	6,029.65	5,604.56	424.29	92.20	61
12	685.98	175.48	4.28	21,424.66	29,370.40	6,030.17	5,604.46	424.91	88.96	51
13	686.70	175.50	4.29	21,392.15	29,326.57	6,030.22	5,604.47	424.95	88.73	51
14	495.93	176.05	4.27	14,105.30	19,508.75	6,030.64	5,604.34	425.49	81.62	40
15	495.81	176.08	4.28	14,015.03	19,387.23	6,030.70	5,604.36	425.54	81.12	40
16	343.60	176.40	4.32	8,595.02	12,095.91	6,030.95	5,604.41	425.73	73.00	31
17	410.22	176.21	4.33	11,017.56	15,353.69	6,030.70	5,604.44	425.46	77.67	35
18	595.56	175.73	4.29	17,885.87	24,600.31	6,030.31	5,604.43	425.08	85.79	46
19	594.04	175.79	4.28	17,887.42	24,602.39	6,030.44	5,604.41	425.23	85.99	46
20	785.75	175.14	4.33	25,043.14	34,252.09	6,029.95	5,604.63	424.52	90.65	56
21	783.99	175.14	4.32	24,981.16	34,168.44	6,029.94	5,604.62	424.53	90.63	55
22	959.32	174.39	4.32	31,577.17	43,077.82	6,029.39	5,604.72	423.87	93.53	65
23	962.55	174.40	4.31	31,572.91	43,072.06	6,029.43	5,604.72	423.92	93.19	65
24	1,162.12	173.35	4.33	38,527.66	52,481.14	6,028.66	5,604.93	422.94	94.27	76
25	1,164.63	173.35	4.33	38,535.12	52,491.25	6,028.68	5,604.94	422.95	94.08	76
26	1,319.89	172.44	4.28	43,284.34	58,925.44	6,028.04	5,604.97	422.28	93.34	85
27	1,320.52	172.43	4.28	43,294.13	58,938.70	6,028.02	5,604.97	422.28	93.31	85
28	1,478.30	171.43	4.25	47,244.86	64,296.65	6,027.41	5,605.09	421.55	91.09	95
29	1,467.07	171.43	4.25	47,247.73	64,300.55	6,027.30	5,605.08	421.45	91.81	95

Flaming Gorge U3

Run #	Flowrate (cfs)	Spiral Case Pressure (psi)	Draft Tube Pressure (psi)	Generator Output (kW)	Horsepower (HP)	Case Pressure Elevation (ft)	Draft Tube Pressure Elevation (ft)	Net Head (ft)	Efficiency (%)	Servo Stroke (%)
1	1,539.93	171.07	4.34	48,661.06	66,218.51	6,027.17	5,605.37	421.18	90.14	100
2	1,538.26	171.08	4.33	48,634.83	66,182.91	6,027.16	5,605.35	421.20	90.18	100
3	1,411.45	171.93	4.33	45,455.16	61,868.85	6,027.64	5,605.18	421.88	91.73	89
4	1,399.11	172.00	4.32	45,451.94	61,864.48	6,027.69	5,605.16	421.93	92.52	90
5	1,248.84	172.95	4.32	41,017.70	55,853.72	6,028.30	5,605.00	422.73	93.40	79
6	1,242.16	172.94	4.31	41,029.20	55,869.29	6,028.24	5,604.97	422.69	93.94	79
7	1,084.64	173.84	4.30	35,741.72	48,710.18	6,028.87	5,604.80	423.50	93.62	70
8	1,083.21	173.84	4.29	35,740.39	48,708.37	6,028.87	5,604.76	423.54	93.73	70
9	885.45	174.68	4.27	29,064.37	39,682.07	6,029.29	5,604.55	424.19	93.27	59
10	715.39	175.35	4.28	22,380.28	30,659.22	6,029.78	5,604.48	424.76	89.08	50
11	535.77	175.83	4.27	15,771.54	21,752.22	6,030.01	5,604.34	425.14	84.31	40
12	377.65	176.21	4.24	9,750.78	13,649.92	6,030.30	5,604.22	425.56	74.98	29
13	420.49	176.11	4.23	11,420.85	15,896.20	6,030.22	5,604.22	425.47	78.44	35
14	591.00	175.68	4.28	17,716.77	24,372.47	6,029.90	5,604.41	424.96	85.68	45
15	784.30	175.09	4.28	25,019.79	34,220.58	6,029.56	5,604.51	424.51	90.74	54
16	979.76	174.31	4.28	32,089.92	43,770.98	6,029.13	5,604.65	423.92	93.04	65
17	1,161.12	173.41	4.30	38,373.29	52,272.14	6,028.56	5,604.85	423.14	93.93	75
18	1,323.36	172.49	4.30	43,384.53	59,061.25	6,028.01	5,605.04	422.39	93.28	85
19	1,467.41	171.54	4.32	47,200.46	64,236.40	6,027.39	5,605.24	421.55	91.68	95
20	921.83	174.55	4.29	30,115.21	41,101.90	6,029.24	5,604.64	424.05	92.83	61
21	871.06	174.77	4.31	28,191.94	38,503.57	6,029.39	5,604.65	424.19	92.00	58
22	912.82	174.59	4.31	29,893.37	40,802.14	6,029.27	5,604.67	424.05	93.06	61
23	874.09	174.74	4.31	28,511.42	38,935.09	6,029.34	5,604.64	424.16	92.71	59


Flaming Gorge Performance Curves U1, U2, and U3
100
95
90
85
80
75
70
Efficiency (%)
8,000.00
13,000.00
18,000.00
23,000.00
28,000.00
33,000.00
38,000.00
43,000.00
48,000.00
Generator Output (kW)
Tested November 3-5, 2015
Efficiency U1
Efficiency U2
Efficiency U3

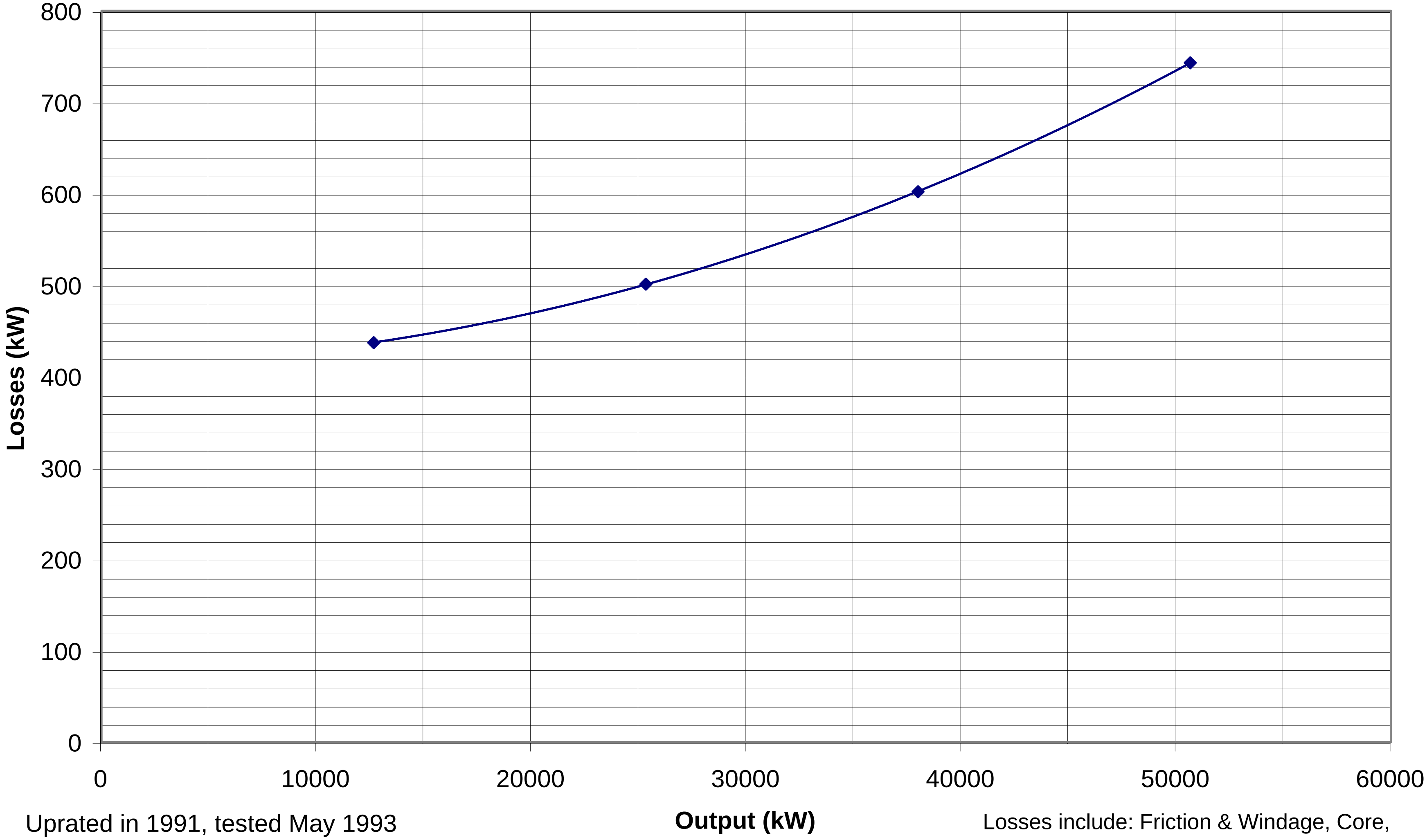


Flaming Gorge Performance Curves for U1, U2, and U3
Efficiency (%)
Flowrate (cfs)
Generator Output (kW)
100
95
90
85
80
75
70
65
60
55
50
2,500
2,000
1,500
1,000
500
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
50,000
Efficiency U1
Efficiency U2
Efficiency U3
Flowrate U1
Flowrate U2
Flowrate U3

Flaming Gorge Generator Losses

$y = 1.201E-07x^2 + 4.462E-04x + 4.122E+02$

$R^2 = 1.000E+00$

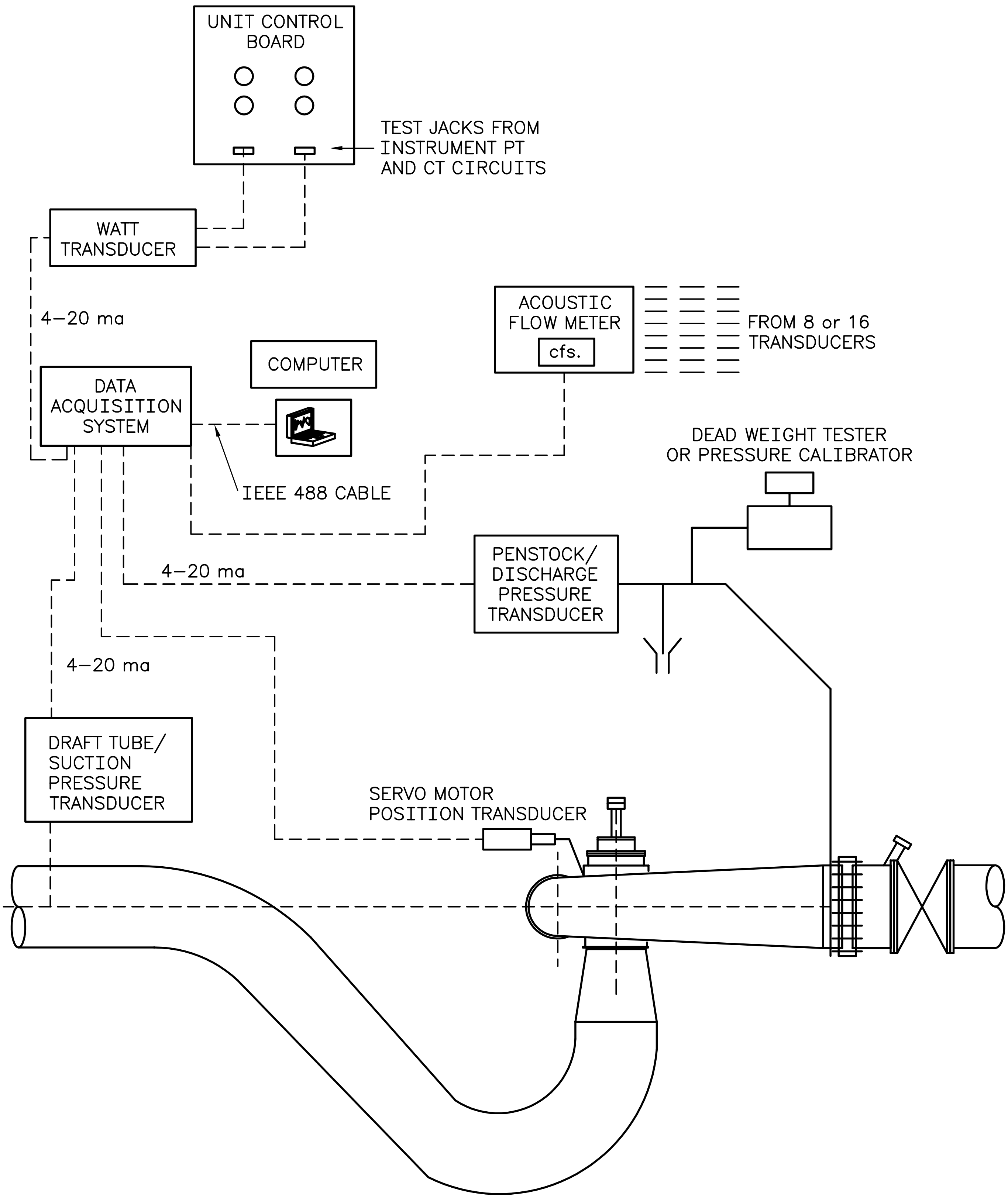


Uprated in 1991, tested May 1993

Losses include: Friction & Windage, Core, Armature, and Stray Load Losses

TURBINE AND PUMP TEST SCHEMATIC (TYPICAL)

BUREAU OF RECLAMATION—HYDRAULIC EQUIPMENT GROUP, D-8420



GATE OPENING MEASUREMENTS (To 0.001 inches except as noted) Date______________________

SERVO. STROKE (1): IN %	IN INS. (2)	0 (*) Top	Bottom	Av.	Area	10 (11.27) Top	Bottom	Av.	Area	20 (22.55) Top	Bottom	Av.	Area
		0 0/32" (3)				31/32"				1 15/16"			
GATE (4)	**HEIGHT**	HORIZ. WIDTH TOP	BOTTOM	AV.	AREA	HORIZ. WIDTH TOP	BOTTOM	AV.	AREA	HORIZ. WIDTH TOP	BOTTOM	AV.	AREA
1-2	19.258	.000	.000	.000	.000	17/32	17/32	17/32	10.230	1 11/32	1 11/32	1 11/32	25.878
2-3	19.256	.000	.000	.000	.000	17/32	17/32	17/32	10.229	1 11/32	1 11/32	1 11/32	25.876
3-4	19.256	.000	.000	.000	.000	19/32	19/32	19/32	11.434	1 3/8	1 3/8	1 3/8	26.477
4-5	19.257	.000	.000	.000	.000	19/32	19/32	19/32	11.435	1 3/8	1 3/8	1 3/8	26.478
5-6	19.256	.000	.000	.000	.000	9/16	9/16	9/16	10.832	1 3/8	1 3/8	1 3/8	26.477
6-7	19.255	.000	.000	.000	.000	19/32	19/32	19/32	11.426	1 3/8	1 3/8	3/8	26.476
7-8	19.255	.000	.000	.000	.000	19/32	19/32	19/32	11.426	1 13/32	1 13/32	13/32	27.076
8-9	19.254	.000	.000	.000	.000	19/32	19/32	19/32	11.433	1 13/32	1 13/32	13/32	27.075
9-10	19.256	.000	.000	.000	.000	19/32	19/32	19/32	11.434	1 13/32	1 13/32	1 13/32	27.078
10-11	19.254	.000	.000	.000	.000	9/16	9/16	9/16	10.830	1 3/8	1 3/8	1 3/8	26.474
11-12	19.255	.000	.000	.000	.000	9/16	9/16	9/16	10.831	1 3/8	1 3/8	1 3/8	26.476
12-13	19.258	.000	.000	.000	.000	9/16	9/16	9/16	10.833	1 3/8	1 3/8	1 3/8	26.480
13-14	19.256	.000	.000	.000	.000	19/32	19/32	19/32	11.434	1 13/32	1 13/32	1 13/32	27.078
14-15	19.255	.000	.000	.000	.000	19/32	19/32	19/32	11.434	1 13/32	1 13/32	1 13/32	27.076
15-16	19.261	.000	.000	.000	.000	19/32	19/32	19/32	11.437	1 13/32	1 13/32	1 13/32	27.085
16-17	19.263	.000	.000	.000	.000	19/32	19/32	19/32	11.438	1 3/8	1 3/8	1 3/8	26.487
17-18	19.256	.000	.000	.000	.000	19/32	19/32	19/32	11.434	1 3/8	1 3/8	1 3/8	26.477
18-19	19.255	.000	.000	.000	.000	19/32	19/32	19/32	11.434	1 3/8	1 3/8	1 3/8	26.476
19-20	19.257	.000	.000	.000	.000	9/16	9/16	9/16	10.832	1 3/8	1 3/8	1 3/8	26.478
20-1	19.255	.000	.000	.000	.000	9/16	9/16	9/16	10.831	1 3/8	1 3/8	1 3/8	26.476
		TOTAL		Sq. ins.	.000				222.647				531.954
		AREA		Sq. ft.	.000				1.546				3.694

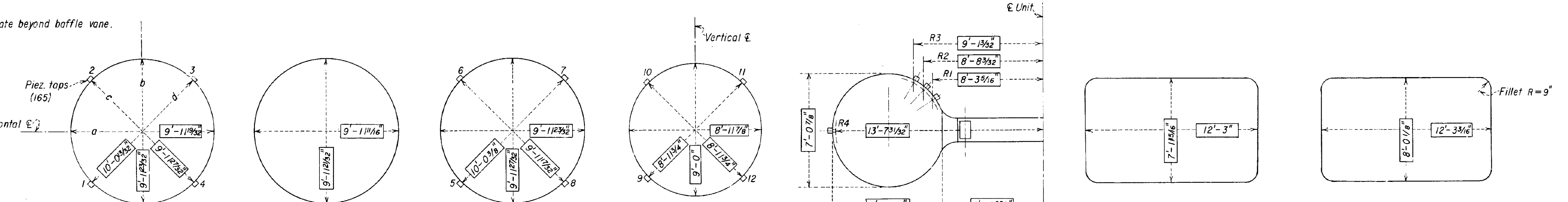
GATE (4)	30 (33.82) 2 29/32" Top	Bottom	Av.	Area	40 (45.01) 3 7/8" Top	Bottom	Av.	Area	50 (56.36) 4 27/32" Top	Bottom	Av.	Area
1-2	2 5/32	2 5/32	2 5/32	41.524	3 3/32	3 3/32	3 3/32	59.578	4	4	4	77.032
2-3	2 5/32	2 5/32	2 5/32	41.520	3 3/32	3 3/32	3 3/32	59.574	3 31/32	3 31/32	3 31/32	76.423
3-4	2 7/32	2 7/32	2 7/32	42.725	3 5/32	3 5/32	3 5/32	60.776	4	4 1/16	4 1/32	77.625
4-5	2 3/16	2 3/16	2 3/16	42.125	3 1/8	3 1/8	3 1/8	60.178	4	4	4	77.028
5-6	2 3/16	2 3/16	2 3/16	42.123	3 1/8	3 3/32	3 7/64	59.875	4	4	4	77.024
6-7	2 7/32	2 7/32	2 7/32	42.723	3 5/32	3 5/32	3 5/32	60.773	4 1/16	4 1/16	4 1/16	78.223
7-8	2 7/32	2 7/32	2 7/32	42.723	3 1/8	3 1/8	3 1/8	60.172	4 1/32	4 1/32	4 1/32	77.621
8-9	2 3/16	2 3/16	2 3/16	42.118	3 1/8	3 1/8	3 1/8	60.169	3 31/32	3 31/32	3 31/32	76.415
9-10	2 7/32	2 7/32	2 7/32	42.725	3 5/32	3 5/32	3 5/32	60.776	4 1/16	4 1/16	4 1/16	78.228
10-11	2 7/32	2 7/32	2 7/32	42.719	3 3/16	3 3/16	3 3/16	61.372	4 3/32	4 3/32	4 3/32	78.820
11-12	2 5/32	2 5/32	2 5/32	41.518	3 1/16	3 1/16	3 1/16	58.968	3 31/32	3 31/32	3 31/32	76.419
12-13	2 7/32	2 7/32	2 7/32	42.728	3 5/32	3 5/32	3 5/32	60.782	4 1/16	4 1/16	4 1/16	78.236
13-14	2 5/16	2 9/32	2 19/64	44.229	3 1/4	3 1/4	3 1/4	62.582	4 3/16	4 5/32	4 11/64	80.336
14-15	2 1/4	2 1/4	2 1/4	43.324	3 1/4	3 1/4	3 1/4	62.579	4 1/8	4 1/8	4 1/8	79.427
15-16	2 7/32	2 7/32	2 7/32	42.734	3 3/16	3 3/16	3 3/16	61.394	4 1/32	4 1/32	4 1/32	77.645
16-17	2 3/16	2 3/16	2 3/16	42.138	3 1/8	3 3/32	3 7/64	59.896	3 31/32	3 31/32	3 31/32	76.449
17-18	2 7/32	2 7/32	2 7/32	42.725	3 5/32	3 5/32	3 5/32	60.776	4 1/16	4 1/16	4 1/16	78.228
18-19	2 7/32	2 7/32	2 7/32	42.723	3 3/16	3 3/16	3 3/16	61.375	4 3/32	4 1/16	4 5/64	78.524
19-20	2 3/16	2 3/16	2 3/16	42.125	3 1/8	3 1/8	3 1/8	60.178	4	4	4	77.028
20-1	2 1/4	2 1/4	2 1/4	43.324	3 3/16	3 3/16	3 3/16	61.375	4 1/32	4 1/32	4 1/32	77.621
TOTAL (Sq. ins.)				850.593				1213.148				1554.452
AREA (Sq. ft.)				5.907				8.425				10.795

GATE (4)	60 (67.64) 5 13/16" Top	Bottom	Av.	Area	70 (78.91) 6 25/32" Top	Bottom	Av.	Area	80 (90.18) 7 3/4" Top	Bottom	Av.	Area
1-2	4 31/32	4 31/32	4 31/32	95.687	5 31/32	5 31/32	5 31/32	114.945	6 27/32	6 27/32	6 27/32	131.796
2-3	4 15/16	4 15/16	4 15/16	95.077	5 15/16	5 15/16	5 15/16	114.333	6 25/32	6 25/32	6 25/32	130.579
3-4	4 31/32	4 31/32	4 31/32	95.677	6	6	6	115.536	6 7/8	6 7/8	6 7/8	132.385
4-5	4 29/32	4 29/32	4 23/32	94.481	5 15/16	5 15/16	5 15/16	114.338	6 13/16	6 13/16	6 13/16	131.188
5-6	4 15/16	4 15/16	4 15/16	95.077	5 15/16	5 15/16	5 15/16	114.333	6 13/16	6 13/16	6 13/16	131.182
6-7	5 1/32	5 1/32	5 1/32	96.876	6 1/32	6 1/32	6 1/32	116.131	6 29/32	6 29/32	6 29/32	132.979
7-8	4 31/32	4 31/32	4 31/32	95.672	5 31/32	5 31/32	5 31/32	114.927	6 7/8	6 7/8	6 7/8	132.378
8-9	4 7/8	4 7/8	4 7/8	93.863	5 27/32	5 27/32	5 27/32	112.515	6 11/16	6 11/16	6 11/16	128.761
9-10	5 1/32	5 1/32	5 1/32	96.881	6	6	6	115.536	6 29/32	6 29/32	6 29/32	132.986
10-11	5 1/32	5 1/32	5 1/32	96.871	6 1/32	6 1/32	6 1/32	116.125	6 7/8	6 7/8	6 7/8	132.371
11-12	4 29/32	4 29/32	4 29/32	94.469	5 27/32	5 27/32	5 27/32	112.520	6 3/4	6 3/4	6 3/4	129.971
12-13	5	5	5	96.290	5 31/32	5 31/32	5 31/32	114.945	6 25/32	6 25/32	6 25/32	130.592
13-14	5 1/8	5 1/8	5 1/8	98.687	6 3/32	6 3/32	6 3/32	117.340	6 31/32	6 31/32	6 31/32	134.189
14-15	5 3/32	5 3/32	5 3/32	98.079	6 3/32	6 3/32	6 3/32	117.334	6 31/32	6 31/32	6 31/32	134.182
15-16	4 15/16	4 15/16	4 15/16	95.101	5 15/16	5 15/16	5 15/16	114.362	6 27/32	6 27/32	6 27/32	131.817
16-17	4 15/16	4 15/16	4 15/16	95.111	5 7/8	5 7/8	5 7/8	113.170	6 25/32	6 25/32	6 25/32	130.626
17-18	5 1/32	5 1/32	5 1/32	96.881	5 31/32	5 31/32	5 31/32	114.934	6 15/16	6 15/16	6 15/16	133.589
18-19	5 1/16	5 1/32	5 3/64	97.178	6 1/32	6	6 1/64	115.830	6 29/32	6 29/32	6 29/32	132.979
19-20	4 15/16	4 15/16	4 15/16	95.081	5 29/32	5 29/32	5 29/32	113.736	6 13/16	6 13/16	6 13/16	131.188
20-1	5	5	5	96.275	5 31/32	5 31/32	5 31/32	114.927	6 13/16	6 13/16	6 13/16	131.175
TOTAL (Sq. ins.)				1919.314				2297.216				2636.913
AREA (Sq. ft.)				13.328				15.952				18.312

GATE (4)	90 (101.45) 8 23/32" Top	Bottom	Av.	Area	100 (112.73) 9 11/16" Top	Bottom	Av.	Area	GATE-FACING PLATE CLEARANCE (5) Gate (4)	Top	Bottom
1-2	7 13/16	7 13/16	7 13/16	150.453	8 23/32	8 23/32	8 23/32	169.905	1	.011	.010
2-3	7 7/8	7 7/8	7 7/8	151.641	8 23/32	8 23/32	8 23/32	167.887	2	.008	.009
3-4	7 7/8	7 7/8	7 7/8	151.641	8 13/16	8 13/16	8 13/16	169.694	3	.011	.010
4-5	7 3/4	7 3/4	7 3/4	149.242	8 23/32	8 23/32	8 23/32	167.896	4	.008	.010
5-6	7 27/32	7 27/32	7 27/32	151.038	8 25/32	8 25/32	8 25/32	169.091	5	.011	.010
6-7	7 15/16	7 15/16	7 15/16	152.837	8 7/8	8 7/8	8 7/8	170.888	6	.008	.008
7-8	7 15/16	7 15/16	7 15/16	152.837	8 13/16	8 13/16	8 13/16	169.685	7	.009	.008
8-9	7 25/32	7 25/32	7 25/32	149.819	8 21/32	8 21/32	8 21/32	166.666	8	.008	.008
9-10	7 31/32	7 31/32	7 31/32	153.445	9 29/32	8 29/32	8 29/32	171.498	9	.011	.010
10-11	7 15/16	7 15/16	7 15/16	152.829	8 13/16	8 13/16	8 13/16	169.676	10	.010	.008
11-12	7 25/32	7 25/32	7 25/32	149.827	8 5/8	8 5/8	8 5/8	166.074	11	.010	.009
12-13	7 7/8	7 7/8	7 7/8	151.657	8 3/4	8 3/4	8 3/4	168.508	12	.011	.011
13-14	7 15/16	7 15/16	7 15/16	152.845	8 7/8	8 7/8	8 7/8	170.897	13	.013	.011
14-15	8	8 1/32	8 1/64	154.340	8 7/8	8 7/8	8 7/8	170.888	14	.010	.011
15-16	7 13/16	7 13/16	7 13/16	150.477	8 11/16	8 11/16	8 11/16	167.330	15	.011	.010
16-17	7 3/4	7 23/32	7 47/64	148.988	8 5/8	8 5/8	8 5/8	166.143	16	.009	.010
17-18	7 29/32	7 29/32	7 29/32	152.242	8 27/32	8 27/32	8 27/32	170.294	17	.010	.011
18-19	7 3/32	7 29/32	7 15/16	152.837	8 7/8	8 7/8	8 7/8	170.888	18	.011	.013
19-20	7 25/32	7 25/32	7 25/32	149.842	8 11/16	8 11/16	8 11/16	167.295	19	.011	.008
20-1	7 13/16	7 13/16	7 13/16	150.430	8 3/4	8 3/4	8 3/4	168.481	20	.007	.009
TOTAL (Sq. ins.)				3029.267				3377.675			
AREA (Sq. ft.)				21.037				23.456			

(1) Use temporary machinists scale - 1/32" graduations.
(2) Inches from "no squeeze". Record to nearest 1/32". "No squeeze" means servomotor cylinders are bled of oil pressure.
(3) Squeeze is the additional servomotor piston movement in the closing direction from the point where the gates just touch closed to where the pistons strike the cylinder head.
SQUEEZE = ___1/4"___ inches.
(4) Number gates in direction of flow, starting at first gate beyond baffle vane.
(5) Measure with gates closed.

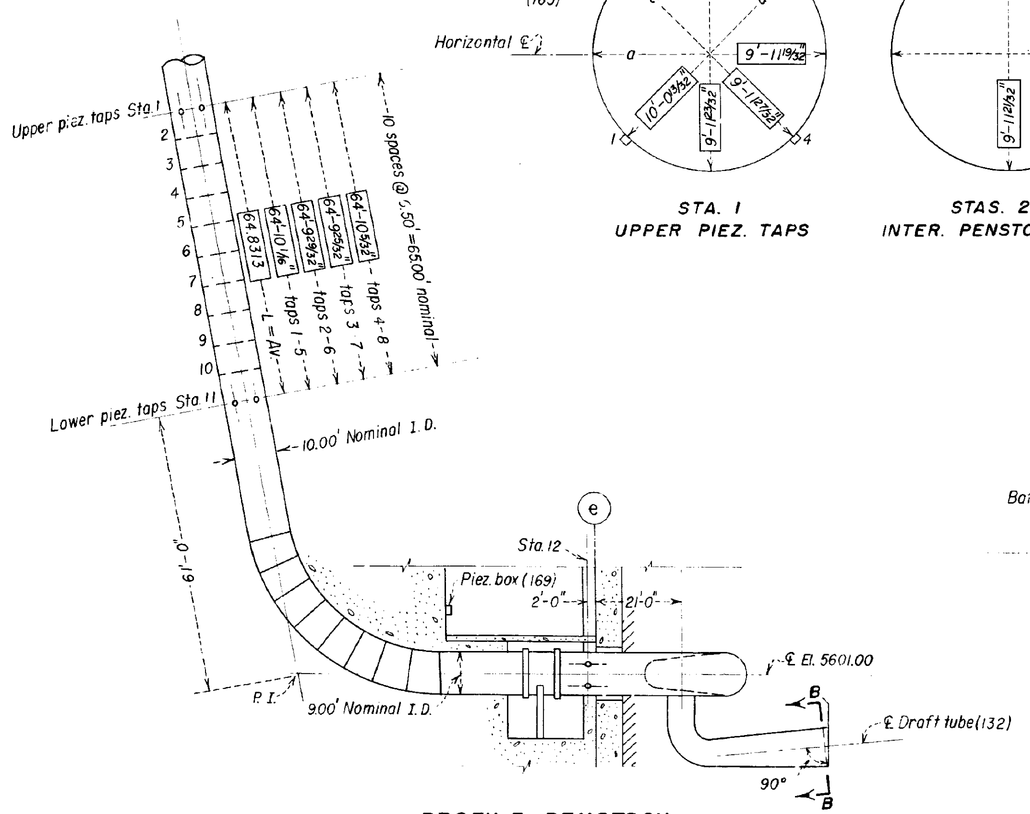
* Figures in parenthesis indicate servomotor stroke as percent of final maximum setting of servomotor stroke which is 8 19/32".



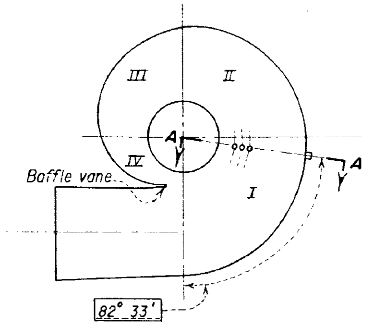
STA. 1 UPPER PIEZ. TAPS — STAS. 2-10 INTER. PENSTOCK SECTS. — STA. 11 LOWER PIEZ. TAPS. — STA. 12 CASING INLET TAPS — SECTION A-A FLOW INDEX TAPS — SECTION B-B DRAFT TUBE OUTLET

Net area = 195.223

WATERWAY CROSS-SECTIONS (to 0.01 feet) LOOKING UPSTREAM Date____________



PROFILE - PENSTOCK



SPIRAL CASE PLAN

PENSTOCK VOLUME								
STA.	a	b	c	d	AREA (1)	AV. AREA	DIST. (2)	VOL. CU. FT.
1	9-11 19/32	9-11 23/32	9-11 27/32	10-0 13/32	78.401			
						78.338	6.50	509.197
2	9-11 15/16	9-11 21/32			78.275			
						78.224	6.50	508.456
3	9-11 13/16	9-11 5/8			78.173			
						78.203	6.50	508.319
4	9-11 23/32	9-11 13/16			78.233			
						78.2535	6.50	508.647
5	10-0	9-11 19/32			78.274			
						78.3255	6.50	509.116
6	10-0 1/16	9-11 11/16			78.377			
						78.224	6.50	508.456
7	9-11 21/32	9-11 5/8			78.071			
						78.173	6.50	508.124
8	9-11 7/8	9-11 23/32			78.275			
						78.2955	6.50	508.920
9	9-11 23/32	9-11 15/16			78.315			
						78.2745	6.50	508.784
10	9-11 11/16	9-11 27/32			78.234			
						78.300	6.3313	495.740
11	9-11 23/32	9-11 27/32	9-11 17/32	10-0 3/8	78.366			
						TOTAL	L (3)	5073.759
12	8-11 7/8	9-0	8-11 3/4	8-11 3/4	63.434			

(1) Use $A = \frac{\pi ab}{4}$ for stations 2-10 inclusive.
Use $A = \frac{\pi(ab+cd)}{4 \times 2}$ for stations 1, 11 and 12.
(2) Use L - (9 x 6.50) for dist. 10 to 11.
(3) L = Average of measurements.
(See Profile - Penstock).

WEARING RING CLEARANCE — Date________ (TO 0.001 INCHES)					
QUADRANT	U/S I	E II	D/S III	IV W	AV.
NEAR GATE NO.					
UPPER RINGS	.035	.030	.030	.028	.031
LOWER RINGS	.030	.030	.030	.030	.030

REFERENCE DRAWINGS

PENSTOCKS 591-D-165
PIEZOMETER PIPING 591-D-169
NEAT LINES OF DRAFT TUBE 591-D-132

GENERAL NOTES

1. Make field measurements as near as practicable to the date of placing unit in operation.
2. Dimensions shown ←[ ]→ to be measured.
3. Latitude of plant is 40° 55'.
4. Average temp., penstock metal during measurement [15 °C]
5. Draft tube discharge dimensions may be obtained from as built records.

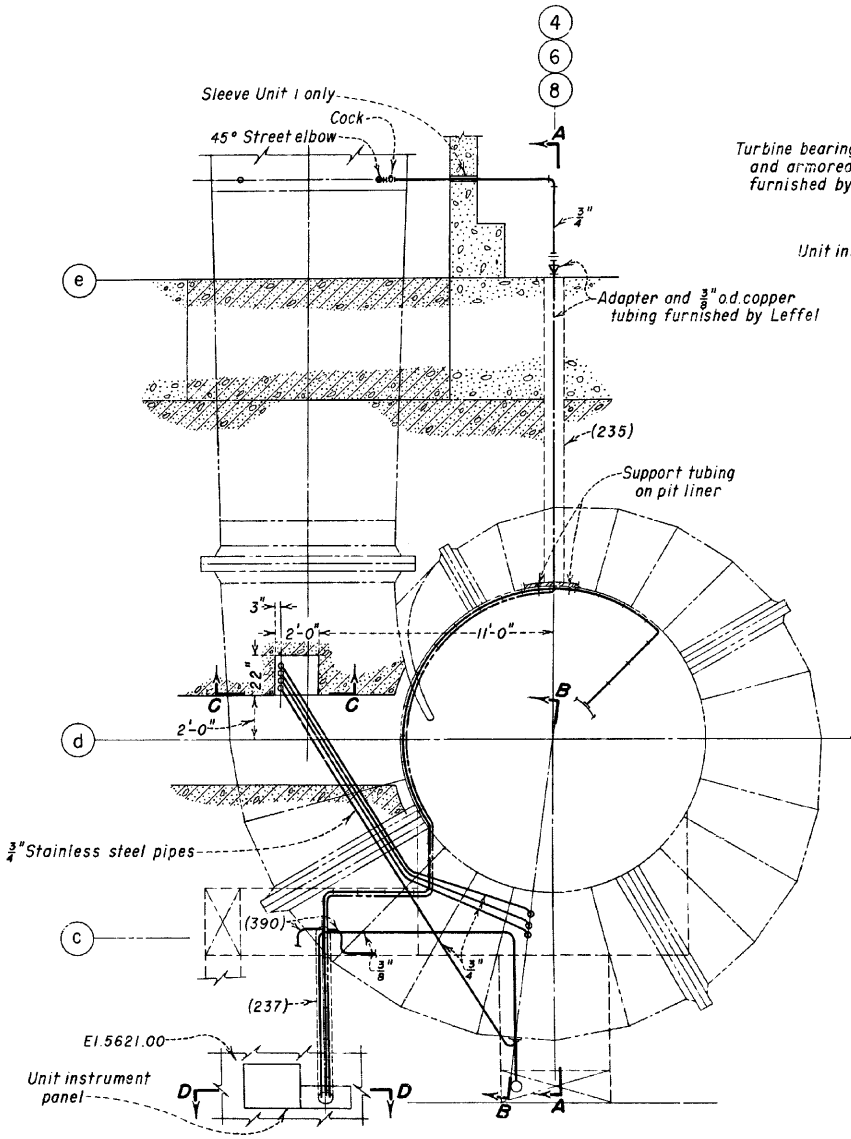
11-25-64 D-V.B.N.	REVISED SERVOMOTOR STROKE MEASUREMENTS TO INDICATE FINAL SETTING.
4-15-64 D-V.B.N.	ADDED MEASUREMENTS AND DATA.

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
GREEN DIV. - FLAMING GORGE UNIT -- UTAH-WYOMING

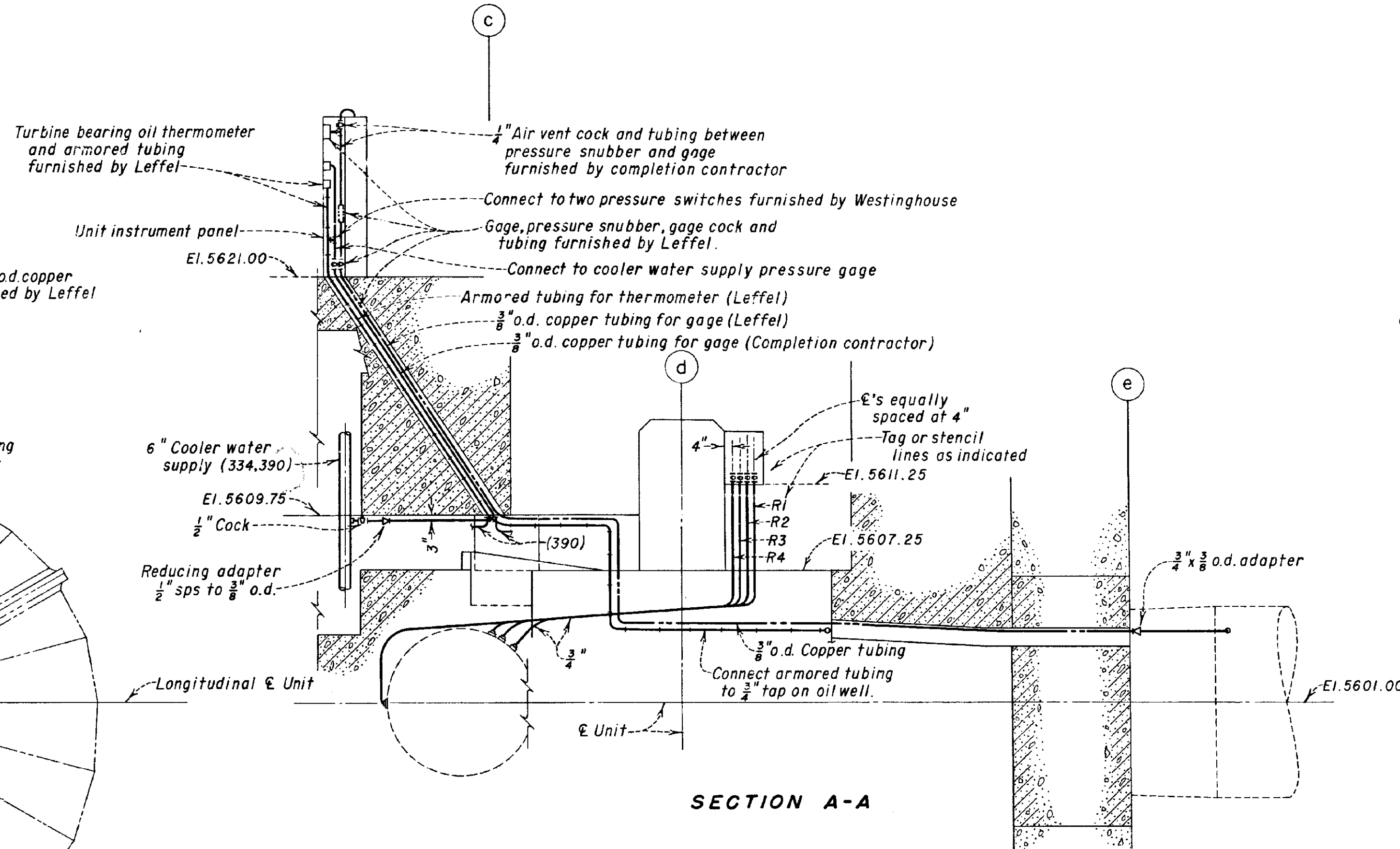
FLAMING GORGE POWER PLANT
TURBINES AND AUXILIARIES
UNIT NO. 3
WATER PASSAGE CALIBRATIONS

DRAWN B.S. — SUBMITTED C.R. Wilderson
TRACED J.C.B. — RECOMMENDED [signature]
CHECKED R.H.K. — APPROVED J. A. Winter, CHIEF, HYDRAULIC MACHINERY BRANCH

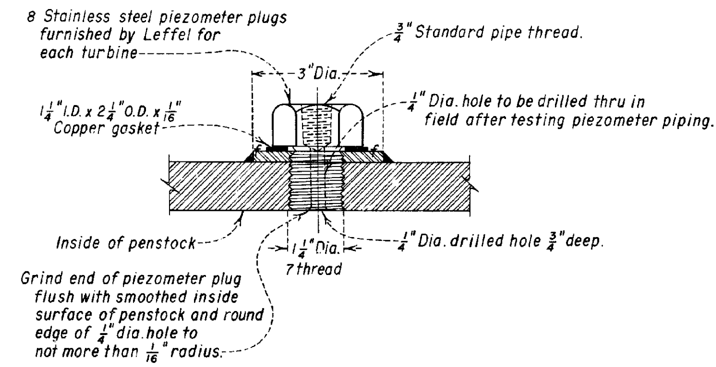
DENVER, COLORADO, SEPTEMBER 4, 1958 — 591-D-279



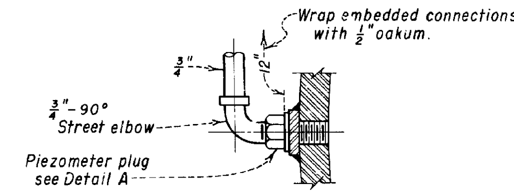
PLAN UNITS 1, 2 AND 3



SECTION A-A



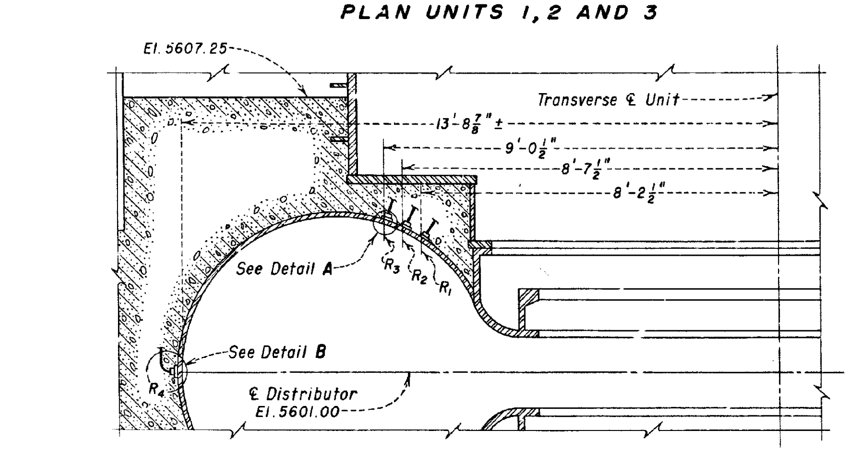
DETAIL A



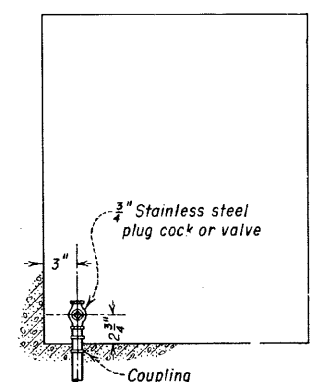
DETAIL B

NOTES

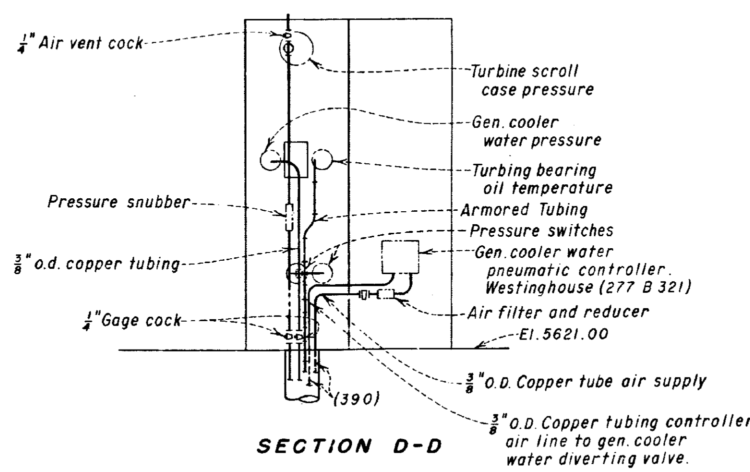
1. All pipe fittings and cocks to conform to Material Schedule, 591-D-134.
2. All piezometer lines to slope continously upward from tap.
3. Before test, remove paint and grind smooth inside of spiral case surface for 6" all around and 18" upstream of piezometer. Repaint to suit original paint after test.



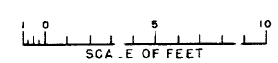
SECTION B-B



SECTION C-C



SECTION D-D



6-27-62	D-V.B.N.	ADDED DWG. NO. 390 AS REFERENCE FOR 6" COOLER WATER SUPPLY LINE NOTE.
12-29-61	D-B.R.M.	ADDED PNEUMATIC CONTROLLER AND PIPING AT UNIT INSTRUMENT PANEL

UNITED STATES
DEPARTMENT OF THE INTERIOR
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COLORADO RIVER STORAGE PROJECT
GREEN DIV.-FLAMING GORGE UNIT--UTAH-WYOMING

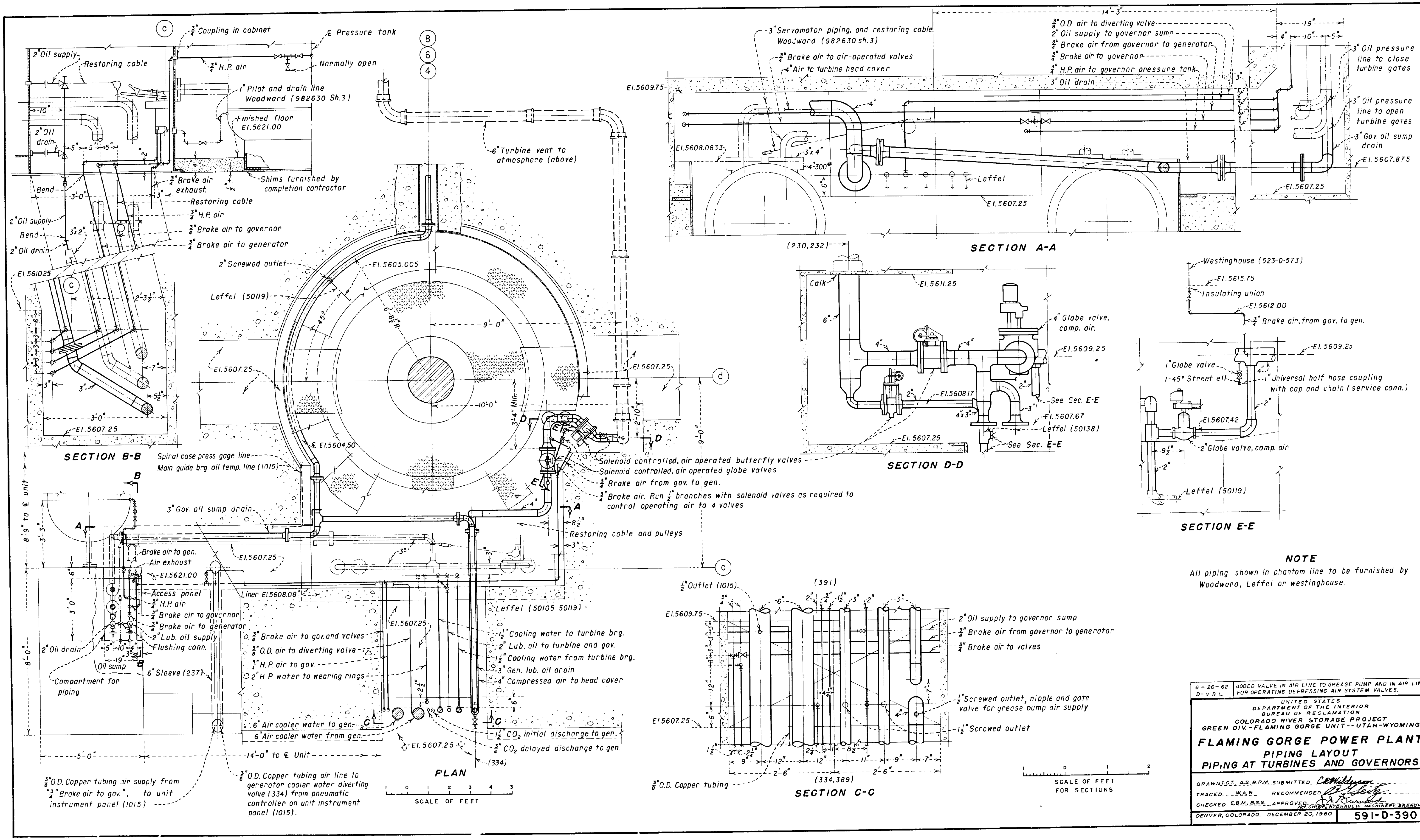
FLAMING GORGE POWER PLANT

PIPING LAYOUT
PIEZOMETER AND GAGE PIPING

DRAWN B.R.M. SUBMITTED C.R. Wilderson
TRACED W.G.C. RECOMMENDED [signature]
CHECKED B.G.S. APPROVED [signature] CHIEF, HYDRAULIC MACHINERY BRANCH

DENVER, COLORADO, MARCH 30, 1961 — 591-D-1015

7-330
(21 x 36)



SECTION B-B
2" Oil supply
Restoring cable
3/4" Coupling in cabinet
℄ Pressure tank
3/4" H.P. air
Normally open
1" Pilot and drain line Woodward (982630 Sh.3)
Finished floor El.5621.00
2" Oil drain
Shims furnished by completion contractor
3/4" Brake air exhaust
Restoring cable
3/4" H.P. air
3/4" Brake air to governor
3/4" Brake air to generator
Bend
2" Oil supply
2" Oil drain
El.5607.25
6" Turbine vent to atmosphere (above)
2" Screwed outlet
Leffel (50119)
El.5605.005
El.5607.25
El.5604.50
Spiral case press. gage line
Main guide brg. oil temp. line (1015)
3" Gov. oil sump drain
Solenoid controlled, air operated butterfly valves
Solenoid controlled, air operated globe valves
3/4" Brake air from gov. to gen.
3/4" Brake air. Run 1/2" branches with solenoid valves as required to control operating air to 4 valves
Restoring cable and pulleys
Brake air to gen.
Air exhaust
El.5621.00
Access panel
3/4" H.P. air
3/4" Brake air to governor
3/4" Brake air to generator
2" Lub. oil supply
Flushing conn.
2" Oil drain
Oil sump
Compartment for piping
6" Sleeve (237)
Liner El.5608.08
Leffel (50105 50119)
3/4" Brake air to gov. and valves
3/8" O.D. air to diverting valve
3/4" H.P. air to gov.
2" H.P. water to wearing rings
1 1/2" Cooling water to turbine brg.
2" Lub. oil to turbine and gov.
1 1/2" Cooling water from turbine brg.
3" Gen. lub. oil drain
4" Compressed air to head cover
6" Air cooler water to gen.
6" Air cooler water from gen.
1 1/2" CO2 initial discharge to gen.
3/4" CO2 delayed discharge to gen.
El.5607.25
(334)
14'-0" to ℄ Unit
3/8" O.D. Copper tubing air supply from "3/4" Brake air to gov.", to unit instrument panel (1015)
3/8" O.D. Copper tubing air line to generator cooler water diverting valve (334) from pneumatic controller on unit instrument panel (1015).
PLAN
SCALE OF FEET
SECTION A-A
3" Servomotor piping, and restoring cable Woodward (982630 sh.3)
3/4" Brake air to air-operated valves
4" Air to turbine head cover
3/8" O.D. air to diverting valve
2" Oil supply to governor sump
3/4" Brake air from governor to generator
3/4" Brake air to governor
3/4" H.P. air to governor pressure tank
3" Oil drain
3" Oil pressure line to close turbine gates
3" Oil pressure line to open turbine gates
3" Gov. oil sump drain
El.5609.75
El.5608.0833
El.5607.875
El.5607.25
Leffel
SECTION D-D
(230,232)
Calk
El.5611.25
4" Globe valve, comp. air
El.5609.25
El.5608.17
El.5607.67
Leffel (50138)
See Sec. E-E
El.5607.25
SECTION E-E
Westinghouse (523-D-573)
El.5615.75
Insulating union
El.5612.00
3/4" Brake air, from gov. to gen.
El.5609.25
1" Globe valve
1-45° Street ell
1" Universal half hose coupling with cap and chain (service conn.)
El.5607.42
2" Globe valve, comp. air
Leffel (50119)
SECTION C-C
(391)
1/2" Outlet (1015)
El.5609.75
El.5607.25
2" Oil supply to governor sump
3/4" Brake air from governor to generator
3/4" Brake air to valves
1/2" Screwed outlet, nipple and gate valve for grease pump air supply
1 1/2" Screwed outlet
3/8" O.D. Copper tubing
(334,389)
SCALE OF FEET FOR SECTIONS
NOTE
All piping shown in phantom line to be furnished by Woodward, Leffel or Westinghouse.
6-26-62 D-V.B.I. ADDED VALVE IN AIR LINE TO GREASE PUMP AND IN AIR LINE FOR OPERATING DEPRESSING AIR SYSTEM VALVES.
UNITED STATES DEPARTMENT OF THE INTERIOR BUREAU OF RECLAMATION
COLORADO RIVER STORAGE PROJECT
GREEN DIV.-FLAMING GORGE UNIT--UTAH-WYOMING
FLAMING GORGE POWER PLANT
PIPING LAYOUT
PIPING AT TURBINES AND GOVERNORS
DRAWN I.G.T., A.S., R.R.M. SUBMITTED
TRACED W.A.W. RECOMMENDED
CHECKED E.B.M., B.G.S. APPROVED
CHIEF, HYDRAULIC MACHINERY BRANCH
DENVER, COLORADO, DECEMBER 20, 1960
591-D-390

AMETEK

REPAIR REPORT

04/22/2015

RMA Number JD2394

Customer Name Bureau of Reclamation - Mid Pacific Region

Substation Name

	Product Line	Description	Part Number	Rev	Serial Number
1	TRANSDUCER PRODUCTS	Scientific Columbus Analog Transducer	(1) Digilogic Watt Transducer model: DL31K5A2		63774
2	TRANSDUCER PRODUCTS	Scienific Columbus Analog Xducer	(1) Digilogic Watt Transducer Model: DL342K5A2		63773
3	TRANSDUCER PRODUCTS	Scientific Columbus Analog Xducer	(1) Exceltronic Current Xducer model: 4044A4 (THREE PHASE)		63775
4	TRANSDUCER PRODUCTS	Scientific Columbus Analog Xducer	(1) Exceltronic Voltage Transducer model: 3588A4 (THREE PHASE)		63776

Customer Description of Problem	Calibration only.
As Found Condition	No problems found.
Repairs Performed	Retested and recalibrated all units.
Cause of Failure	None.
Further Actions Required	None.

QA Tech/Eng	

ISO 9001:2008 (10101/2)

FLUKE®

Certificate of Calibration

Everett Service Center

Certificate Number:	127014		
Data Type:	Found-Left	**Calibration Date:**	13-Apr-2015
Result Summary:	In Tolerance	**Calibration Due:**	13-Apr-2016
Manufacturer:	Fluke	**Certificate Date:**	13-Apr-2015
Model:	718 300G	**Temperature:**	22.7 °C
Serial Number:	9798074	**Humidity:**	35.3 %
Description:	Pressure Calibrator		
Procedure:	Fluke 718: (1 year) ACAL/ZCAL VER /7250xi/RPM4	**Revision:**	2.3
Customer:	US DEPT OF THE INTERIOR		
City:	DENVER	**Country:**	US
State:	CO		
Purchase Order:	CCS HULSE	**RMA:**	30759537

This calibration is traceable to the International System of Units (SI), through National Metrology Institutes (NIST, PTB, NRC, NPL, etc.) , ratiometric techniques, or natural physical constants. This certificate applies only to the item identified and shall not be reproduced other than in full, without the specific written approval by Fluke Corporation. Calibration certificates without signature are not valid. The calibration has been completed in accordance with Fluke Electronics Corporation Quality System Document 111.0 Revision 118 8/2014 and/or Fluke 17025 Quality Manual QSD 111.41 Revision 005 9/2014.

The Data Type found in this certificate must be interpreted as:

- As - Found Calibration data collected before the unit is adjusted and / or repaired.
- As - Left Calibration data collected after the unit has been adjusted and / or repaired.
- Found-Left Calibration data collected without any adjustment and / or repair performed.

COREY DINARDI
Issued By

Certificate of Calibration

KEYSIGHT TECHNOLOGIES

Keysight Calibration

Certificate Number 1-6756422897-1

Model Number	34970A
Manufacturer	Keysight Technologies Inc
Description	Data Acquisition/Switch Unit. GPIB, RS232
Serial Number	SG41007166
Date of Calibration	9 Apr 2015
Procedure	STE-50114553-B.01.01
Temperature	(23 ± 5) °C
Humidity	(50 ± 30) %RH

Customer
US Department of the Interior
6th Ave and Kipling Ct Bldg 67 86-68420
Denver Federal Ctr
DENVER CO 80225
United States

Location of Calibration
Keysight Technologies Inc
EMG Support Operation
10090 Foothills Blvd.
Roseville CA 95747-7102
United States

This certifies that the equipment has been calibrated using applicable Keysight Technologies procedures in compliance with a quality management system registered to ISO 9001:2008.

As Received Conditions
The measured values of the equipment were observed IN SPECIFICATION at the points tested.

Action Taken
- No corrective actions were necessary.

As Completed Conditions
The measured values of the equipment were observed IN SPECIFICATION at the points tested.

A team of engineers and metrologists develops performance tests procedures and selects specific instruments considering the uncertainty of measurement. In this report, conformance statements of "Passed" or "Failed" are determined by simple comparison of observed measurements to the warranted specifications. Uncertainty of measurement is not reported.

Remarks or Special Requirements

This calibration certificate may reference instruments manufactured by HP, Agilent and Keysight as being manufactured by Keysight Technologies, Inc.

The test limits stated in the report correspond to the published specifications of the equipment, at the points tested.

Based on the customer's request, the next calibration is due on 9 Apr 2016.

Keysight Technologies Inc
EMG Support Operation
10090 Foothills Blvd.
Roseville CA 95747-7102
United States

Wes Fischbach Roseville Serv. Cntr. Mgr.

Traceability Information

Technician ID Number 00813497

Measurements are traceable to the International System of Units (SI) via national metrology institutes (e.g., NIST, NPL, PTB, NMIJ, NRC, KRISS, SIRIM, etc.) that are signatories to the CIPM Mutual Recognition Arrangement.

This certificate shall not be reproduced, except in full, without prior written approval of the laboratory.

Calibration Equipment Used

Model Number	Model Description	Equipment ID	Cal Due Date	Certificate Number
3325B	Synthesizer/Function Generator	3325B13927	26 Jul 2015	1-5274770623-1
5720A	Calibrator	5720A35204	9 Oct 2015	1-6229391658-1
5725A	Amplifier	5725A40001	9 Oct 2015	1-6229391950-1

Appendix B

Palisades Powerplant Unit 1, 2, 3, and 4 Turbine Performance Test Report – Durham, Kummet, and Johnson, 2021

Palisades Powerplant Units 1, 2, 3, and 4 Performance Test Report

U.S. Department of the Interior June 2021

INTRODUCTION

Palisades Powerplant contains four vertical-shaft Francis hydroelectric generation units. The units were originally built by S. Morgan Smith and were put into commercial operation in 1957. The original 30 MW generators were uprated to 44 MW each in the mid 1990's.

In April 2011 a contract was awarded to Andritz Hydro to furnish a model tested hydraulic design, four new stainless steel runners, and complete a turbine overhaul. Unit 1 was returned to commercial service in 2013. Unit 4 was returned to commercial service in 2014. Unit 3 was returned to commercial service in 2015. Unit 2 was returned to commercial service in 2017.

All four units were tested for turbine performance the week of September 24, 2018 by personnel of the Bureau of Reclamation, Technical Service Center.

RESULTS

Turbine performance testing is accomplished by simultaneously measuring the generator power output, scroll case pressure, tailwater pressure, turbine discharge, and servomotor stroke in accordance to ASME PTC 18-11 Hydraulic Turbines and Pump-Turbines Performance Test Code. Turbine efficiency is calculated from these measurements.

Results of Unit 1, 2, 3, and 4 performance tests:

Results at Peak Efficiency:				
Unit #	Net Head	Peak Efficiency	Turbine Power	Servomotor Stroke
1	200 feet	94.49 %	44,710 hp	75 %
2	199 feet	95.08 %	41,623 hp	74 %
3	200 feet	94.06 %	41,173 hp	74 %
4	201 feet	94.01 %	43,322 hp	74 %

Results at Full Gate Efficiency:				
Unit #	Net Head	Full Gate Efficiency	Turbine Power	Servomotor Stroke
1	200 feet	89.13 %	55,419 hp	100 %
2	199 feet	91.54 %	53,810 hp	100 %
3	200 feet	92.09 %	54,491 hp	100 %
4	201 feet	89.44 %	54,227 hp	100 %

All four units have an eight-path acoustic time-of-flight flowmeter installed in the penstock. The overall test uncertainty (systematic and random components) calculated at +/- 0.88 percent. For the Unit 1 test, during mid-range operation the air admission valve was either in normal original operation or clamped full open which resulted in a slight increase of efficiency at 50 to 60 percent gate opening.

TEST EQUIPMENT

All performance data was recorded using a digital data acquisition system. The system consists of a laptop computer, a Hewlett-Packard Model 34970A digital scanning voltmeter, a printer, and various transducers. The computer utilizes an IEEE-488 interface card to communicate over a GPIB bus to control the other devices in the system. It also records all data to the computer. The voltmeter was used to convert the analog signals from the transducers to digital form for processing and storage by the computer. The voltmeter has a capability of 6-1/2-digit accuracy and each reading was integrated over a time period equal to 10 power line cycles to maximize electrical noise rejection. The scanner was used to connect the transducers to the voltmeter and serves as a programmable switching device allowing the voltmeter to read each transducer individually. The printer was used to provide hardcopy output of the data as it was generated during the test and provide a second form of permanent storage.

Turbine scroll case pressure; tailwater pressure; and generator output; including voltage, amperage, and watts were measured with transducers that have analog output. Flowrate was measured with an eight cordal path in two crossing planes Accusonic Technologies ultrasonic flowmeter. The Accusonic 8510+ flowmeter located in the control room was connected to a laptop and Accuflow recorded the flowrates. The flowmeter transducers are located in the penstock approximately 20 feet upstream from the unit centerline and approximately 10 feet downstream of a butterfly valve, reference Drawing No. 456-D-185. Recording transducer outputs for approximately seven minutes while the unit operates at a steady state condition makes up a test run. Each run was an average of 300 instantaneous measurements for scroll case inlet pressure, tailwater pressure, watt transducer output, generator volts and amps, and gate position. The flowmeter updated approximately 85 times during a test run.

HEAD

Turbine scroll case pressure was measured at the net head taps in the turbine casing extension. The four net head piezometer taps were manifolded together so that the average pressure at the section was recorded. All piezometer lines were flushed free of rust and debris prior to the test.

Tailwater elevation was measured using a pressure transducer connected to the Unit 4 cooling water discharge line which was offline for the testing Units 1 through 3. Unit 2 cooling water discharge line, that was offline, was utilized for the tailwater pressure of Unit 4. During some of the testing all four units was required to meet flow and power requirements. During the test it was agreed upon to use the control room tailwater elevation reading for the test results. Both transducers were calibrated with a Fluke 718 pressure calibrator prior to testing and after all of the test runs were completed. Cooling water, which is normally tapped off the unit penstock downstream of the flow measurement section, was shut off and a back-up cooling water supply was used during data acquisition. Normal cooling water supply is measured by the flowmeter but does not pass through the runner to make power.

Net head on the turbine was computed by subtracting the tailwater pressure elevation from the casing inlet pressure elevation, corrected for velocity head at the location of the piezometer taps. Pressure measurements were converted from pounds per square inch to feet of water by using a weight of water taken from the ASME Performance Test Code, PTC 18 for the elevation and latitude for the powerplant and the temperature of water measured during the test.

The dimensions of the penstock at the piezometer section and draft tube at the exit were taken from drawings (Drawings No. 456-D-1116 and 456-D-58) which were used to obtain the areas to correct the pressure measurements for velocity head.

H_n	Net Head (ft)	$H_n = H_i - H_o + H_{vi} - H_{vo}$
H_i	Inlet Head (ft)	$H_i = (P_i{*}C) + P_{ie}$
H_o	Outlet Head (ft)	$H_o = (P_o{*}C) + P_{oe}$
H_{vi}	Inlet Velocity Head (ft)	$H_{vi} = Q^2 / (A_i^2 * 2 * G)$
H_{vo}	Outlet Velocity Head (ft)	$H_{vo} = Q^2 / (A_o^2 * 2 * G)$
P_{ie}	Inlet Pressure Transducer Zero Elevation (ft)	
P_{oe}	Outlet Pressure Transducer Zero Elevation (ft)	
G	Local Gravity (ft/s^2)	
Q	Flowrate (ft^3/s)	
A_i	Area of Casing Extension (ft^2)	
A_o	Area of Draft Tube Outlet (ft^2)	
C	Conversion factor from Pressure (psi) to (ft) of H_2O	

Turbine net head computation - Formulas and a sample computation for computing turbine net head for Run No. 17 for Unit 1:

A_i = 122.719 ft^2 (area of casing at piezometer taps)
A_o = 349.5 ft^2 (area of draft tube outlet)
G = 32.1509 ft/s^2
P_i = 88.66 psi
P_o = 3.89 psi
Q = 2086.19 ft^3/s
C = 2.31

Water temperature during test = 61º F (16º C)
Elevation of casing pressure transducer = 5366.80 feet
Elevation of draft tube pressure transducer = 5366.73 feet

$H_i = (88.66 * 2.31) + 5366.80 = 5571.97$ ft

$H_o = 5376.18$ ft

$H_{vi} = (2086.19)^2 / ((122.719)^2 * 2 * 32.1509) = 4.49$ ft

$H_n = 5571.97 - 5376.18 + 4.49 = 200.28$ ft

POWER

Power output from the turbine was determined by using the generator as a dynamometer. Generator input was determined by measuring the generator output in kilowatts, adding the generator losses, and converting to horsepower. Power output from

the generator was measured using the two-wattmeter method with a Scientific Columbus polyphase watt transducer. Scientific Columbus transducers are also used to measure generator current and voltage for the power factor calculation. The transducers for measuring voltage, current and power were connected to the secondary side of the instrument transformers used in the metering circuits for the instruments on the unit control boards. The potential transformers have a ratio of 100:1 and the current transformers have a ratio of 500:1. Generator inefficiencies were obtained from the 1991 General Electric test report and added to the measured generator output to obtain generator input horsepower.

G_L	Generator Loss (kW)	$G_L = K0 + (K1 * G_o) + (K2 * G_o^2)$
G_o	Generator Output Reading (kW)	
G_i	Generator Input (kW)	$G_i = T_o = G_o + G_L$
T_o	Turbine Output (hp)	$T_o = G_i * C$
K2	Electrical coefficient K2 for $K2*KW^2$	
K1	Electrical coefficient K1 for K1*KW	
K0	Electrical coefficient K0	
C	Conversion factor from kW to hp	C = 1.341022

<u>Turbine power output computation</u> - Formulas and a sample computation for computing turbine power output for Run No. 17 for Unit 1 follows:

Test data for the generator indicated the following relationship between power output from the generator in kilowatts and total losses in kilowatts:

G_L (kW) $= 343.875 + (4.055 \times 10^{-5} * G_o) + (1.759 \times 10^{-7} * G_o^2)$

(Generator losses include core loss, stray loss, copper loss, and friction and windage loss)

$G_o = 32{,}806$ kW

$G_L = 343.875 + (4.055 \times 10^{-5} * 32{,}806) + (1.759 \times 10^{-7} * 32{,}806^2) = 534.52$ kW

$G_I = T_O = 32{,}806$ kW + 534.52 kW = 33,340.52 kW

T_o = 33,340.52 kW * 1.341022 = 44,710.37 hp

FLOW RATE

Flowrate was measured with an Accusonic Technologies 8510+ system ultrasonic flowmeter. The flowmeter uses acoustic transducers fed through the penstock wall which are arranged in eight chordal paths in two crossing planes. The flowmeter transducers are located in the penstock approximately 20 feet upstream from the unit centerline and approximately 10 feet downstream of a butterfly valve, reference Drawing No. 456-D-185. The installed flowmeters have an estimated uncertainty value of +/- 0.50 percent. The clocks in the computer and flowmeter were synchronized prior to the performance test. The beginning time for each test run and the time for each flowmeter update were recorded. The data obtained from the digital output of the flowmeter was averaged, during data reduction, over the data acquisition period for each test run. This data was used in the final calculation of the test results. The flowmeter was set to produce new flowrate values at approximately two second intervals. Backup or emergency cooling water upstream of Units butterfly valve was used during the test.

EFFICIENCY

$$E = (D * W) * 100 / (H_n * Q * \gamma)$$

E	Efficiency (%)
D	Conversion factor (550)
W	Power Output (hp)
H_n	Net Head (ft)
Q	Flow rate (ft^3/s)
γ	Weight of Water (lb/ft^3)
g	Local Gravity (ft/sec^2)

<u>Efficiency computation</u> - The efficiency for Run No. 17 for Unit 1 is as follows:

E = (550 * 44,710) * 100 / (200.28 * 2,086.19 * 62.29)

= 94.49 %

Uncertainty Analysis for the Palisades Unit 1 Turbine Test

Systematic Uncertainty

The uncertainty was evaluated using the square root of the sum of the squares of the individual uncertainties.

Head
Bureau of Reclamation standard for plant floor elevation deviation = +/-0.125 inch = 0.0104 ft
Estimated maximum uncertainty in the difference in floor elevations = +/-0.25 inch = 0.0208 ft
Diameter of Penstock at casing extension section = 12.5 feet
Difference between inlet and outlet transducer elevations = 0.07 feet

Hp = standard for plant floor elev. deviation / diameter of casing extension / net head * 100
Hp = 0.0104 / 12.5 / 200.28 * 100 = 0.00042 %

Hm = Est. max uncertainty in the diff in floor elev. / diff. in transducer elev. / net head * 100
0.0208 / 0.07 / 200.28 * 100 = 0.1486 %

Accuracy of Druck DPI-261 pressure transducer (200 psi range) = 0.04% of full scale
(used for casing pressure measurement)

200 * 0.0004 * (144 / 62.289) / 200.28 * 100 = 0.0923 %

Accuracy of Druck DPI-261 pressure transducer (25 psi range) = 0.04% of full scale
(used for draft tube pressure measurement)

25 * 0.0004 * (144 / 62.289) / 200.28 * 100 = 0.0115%

Total systematic uncertainty of head measurement:
$E_h = (0.00042^2 + 0.01486^2 + 0.0923^2 + 0.0115^2)^{0.5}$ = +/-0.1753 %

Power
Systematic error for power measurement instruments:
Scientific Columbus watt/watt-hour transducer = 0.1%
Potential transformers = 0.3%
Current transformers = 0.3%
Generator loss curve = 0.1%

Total systematic uncertainty of power measurement:

$E_P = (0.3^2 + 0.3^2 + 0.1^2 + 0.1^2)^{0.5}$ = +/-0.45%

Flowrate
According to the Accusonic procedure for determining systematic uncertainty for the flowmeter transducer installation, the following variables require analysis:

- Path length measurement
- Path angle measurement
- Pipe radius measurement
- Travel time measurement
- Velocity profile uncertainty

Estimated flowmeter systematic uncertainty E_f = +/-0.50%

Efficiency
The systematic uncertainty for efficiency is estimated as:
$E_e = (0.1753^2+0.45^2 +0.50^2)^{0.5}$ = +/-0.693%

Random Uncertainty

The random uncertainty was calculated using the formula, for Run No. 17 for Unit 1:

$t*S_d/(n)^{0.5}$/mean value, where t is the student t coefficient for the 95% confidence level

S_d is the standard deviation of the n measurements

Head
Mean of 300 casing pressure measurements = 88.663 psi
Standard deviation = 0.282 psi

Random uncertainty = $(2 * 0.282) / 300^{0.5} / 88.663 * 100 = 0.0367$ %

Mean of 300 draft tube pressure measurements = 3.88 psi
Standard deviation = 0.1296 psi

Random uncertainty = $(2 * 0.1296) / 300^{0.5} / 3.88 * 100 = 0.385$ %

Total random uncertainty, head = $(0.0367^2 + 0.385^2)^{0.5} = 0.387$ %

Power
Mean of 300 power measurements = 32,806 kW
Standard deviation = 94.35 kW

Random uncertainty = $(2 * 94.35) / 300^{0.5} / 32{,}806 *100 = 0.0332$ %

Flowrate
The random uncertainty for the flowrate used in the calculation:

Mean of 85 flowrate measurements = 2,086.19 cfs
Standard deviation = 35.47 cfs

Random uncertainty = $(2 * 35.47) / 85^{0.5} / 2{,}086.19 *100 = 0.369$%

Efficiency
Random uncertainty = $(0.387^2 + 0.0332^2 + 0.369^2)^{0.5} = 0.535$ %

Total uncertainty (systematic and random) = $(0.693^2 + 0.535^2)^{0.5}$ = **+/- 0.88%**

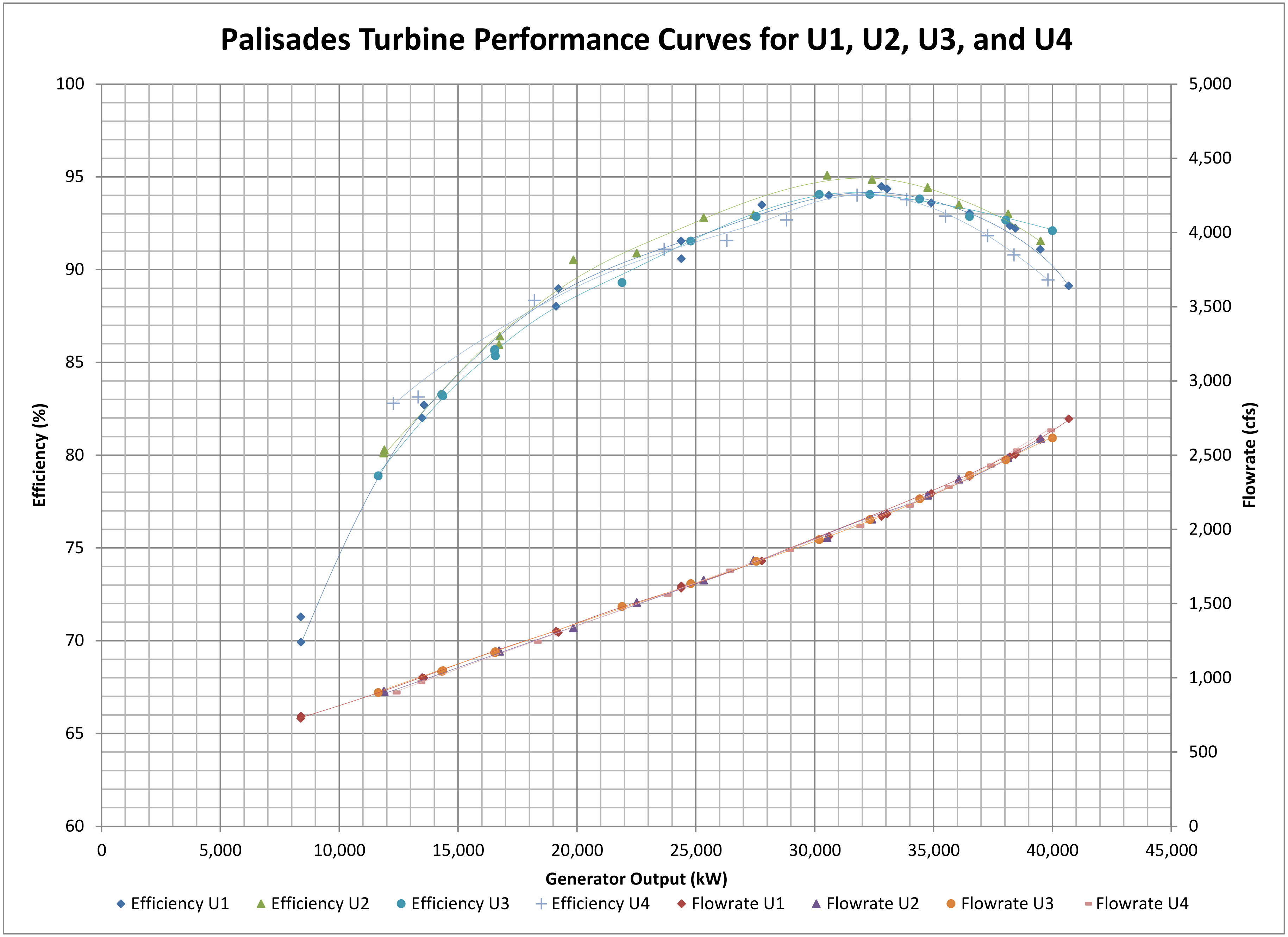
Report prepared by:

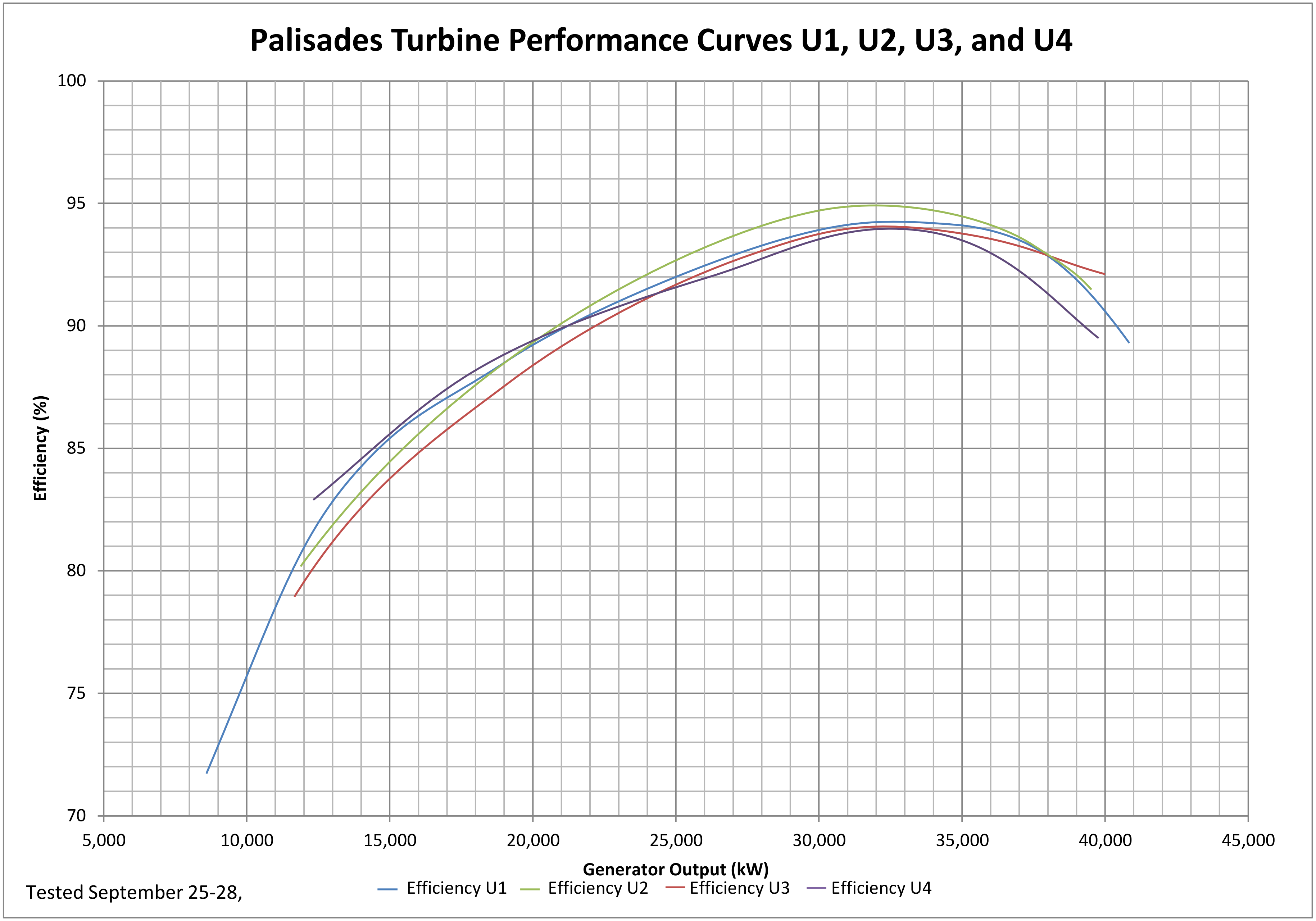
____
Shanna Durham, PE, Mechanical Engineer

Peer reviewed by:

____
Mark Kummet, PE, Mechanical Engineer

____
Zach Johnson, Mechanical Engineer


Palisades Turbine Performance Curves for U1, U2, U3, and U4
Efficiency (%)
Flowrate (cfs)
Generator Output (kW)
100
95
90
85
80
75
70
65
60
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
5,000
10,000
15,000
20,000
25,000
30,000
35,000
40,000
45,000
Efficiency U1
Efficiency U2
Efficiency U3
Efficiency U4
Flowrate U1
Flowrate U2
Flowrate U3
Flowrate U4



Tested September 25-28,

Palisades U1

Run #	Servo Stroke (%)	Spiral Case Pressure (psi)	Draft Tube Pressure (psi)	Net Head (ft)	Generator Output (kW)	Turbine Output (horsepower)	Flowrate (cfs)	Corrected* Generator Output (kW)	Corrected* Turbine Output (hp)	Corrected* Flowrate (cfs)	Efficiency (%)
1	100	87.10	3.44	200.04	40,689	55,419	2,745	40,678	55,403	2,744	89.13
2	95	87.47	3.44	200.08	39,497	53,798	2,606	39,473	53,765	2,606	91.09
3	91	87.76	3.44	200.20	38,444	52,366	2,504	38,386	52,287	2,503	92.23
4	85	88.13	3.44	200.34	36,512	49,741	2,356	36,419	49,614	2,354	93.04
5	80	88.35	3.46	200.23	34,909	47,564	2,241	34,848	47,481	2,240	93.60
6	76	88.68	3.45	200.39	33,045	45,035	2,103	32,949	44,904	2,101	94.35
7	71	89.02	3.43	200.61	30,604	41,724	1,954	30,463	41,533	1,951	94.00
8	66	89.15	3.45	200.18	27,779	37,897	1,788	27,741	37,845	1,787	93.49
9	60	89.52	3.44	200.57	24,392	33,313	1,619	24,289	33,172	1,617	90.58
10	60	89.43	3.40	200.32	24,386	33,305	1,604	24,328	33,225	1,602	91.54
11	51	89.73	3.91	199.99	19,213	26,314	1,306	19,214	26,316	1,306	88.98
12	51	89.72	3.93	200.01	19,121	26,190	1,313	19,119	26,188	1,313	88.03
13	41	89.98	3.94	199.77	13,488	18,592	1,002	13,511	18,624	1,003	82.00
14	41	90.04	3.91	199.94	13,563	18,694	998	13,569	18,702	998	82.71
15	32	90.19	3.93	199.79	8,389	11,728	741	8,403	11,747	742	69.92
16	32	90.18	3.94	199.69	8,379	11,715	727	8,399	11,742	727	71.28
17	75	88.66	3.89	200.28	32,806	44,710	2,086	32,737	44,617	2,085	94.49
18	90	87.70	3.92	199.94	38,216	52,056	2,489	38,232	52,078	2,489	92.38

*Corrected power and flowrate to 200 feet net head using Homology laws

Palisades U2

Run #	Servo Stroke (%)	Spiral Case Pressure (psi)	Draft Tube Pressure (psi)	Net Head (ft)	Generator Output (kW)	Turbine Output (horsepower)	Flowrate (cfs)	Corrected* Generator Output (kW)	Corrected* Turbine Output (hp)	Corrected* Flowrate (cfs)	Efficiency (%)
1	99	86.79	3.66	198.64	39,506	53,810	2,612	39,914	54,365	2,621	91.54
2	95	87.12	3.62	198.69	38,140	51,953	2,482	38,518	159,670	2,490	93.01
3	88	87.44	3.66	198.50	36,074	49,146	2,338	36,483	151,258	2,347	93.49
4	84	87.66	3.70	198.57	34,755	47,355	2,229	35,130	145,667	2,237	94.43
5	78	87.95	3.65	198.72	32,412	44,176	2,069	32,727	135,740	2,076	94.85
6	74	88.19	3.66	198.77	30,529	41,623	1,944	30,812	127,839	1,950	95.08
7	69	88.37	3.64	198.61	27,430	37,424	1,790	27,718	115,086	1,796	92.95
8	64	88.50	3.72	198.41	25,329	34,581	1,658	25,634	106,505	1,665	92.80
9	59	88.62	3.69	198.22	22,515	30,775	1,508	22,818	94,916	1,515	90.89
10	54	89.02	3.76	198.38	19,854	27,180	1,336	20,098	83,730	1,342	90.53
11	49	89.59	3.78	199.32	16,749	22,989	1,178	16,835	70,320	1,180	86.41
12	49	89.53	3.74	199.23	16,722	22,953	1,183	16,819	70,254	1,186	85.96
13	39	89.80	3.68	199.20	11,901	16,455	908	11,973	50,376	910	80.29
14	39	89.81	3.70	199.33	11,873	16,417	908	11,933	50,211	909	80.10

*Corrected power and flowrate to 200 feet net head using Homology laws

Palisades U3

Run #	Servo Stroke (%)	Spiral Case Pressure (psi)	Draft Tube Pressure (psi)	Net Head (ft)	Generator Output (kW)	Turbine Output (horsepower)	Flowrate (cfs)	Corrected* Generator Output (kW)	Corrected* Turbine Output (hp)	Corrected* Flowrate (cfs)	Efficiency (%)
1	100	87.33	4.11	199.72	40,007	54,491	2,616	40,092	54,607	2,617	92.09
2	94	87.78	3.59	200.03	38,040	51,817	2,468	38,031	51,804	2,468	92.67
3	90	88.05	3.58	200.16	36,517	49,748	2,363	36,473	49,688	2,362	92.86
4	84	88.39	3.58	200.17	34,424	46,906	2,205	34,381	46,847	2,204	93.81
5	78	88.68	3.58	200.22	32,325	44,058	2,066	32,272	43,985	2,064	94.05
6	74	88.92	3.58	200.20	30,197	41,173	1,930	30,152	41,112	1,929	94.06
7	69	89.19	3.57	200.24	27,539	37,572	1,784	27,489	37,504	1,783	92.86
8	64	89.36	4.18	199.93	24,795	33,858	1,633	24,809	33,877	1,634	91.53
9	59	89.60	4.17	200.02	21,897	29,940	1,480	21,894	29,935	1,480	89.30
10	49	90.07	4.21	200.33	16,571	22,749	1,175	16,530	22,693	1,174	85.35
11	49	90.07	4.12	200.33	16,548	22,718	1,169	16,507	22,661	1,168	85.62
12	49	90.06	4.11	200.31	16,545	22,714	1,168	16,507	22,662	1,167	85.69
13	45	90.19	4.14	200.30	14,360	19,768	1,047	14,328	19,723	1,046	83.20
14	45	90.18	4.14	200.25	14,315	19,707	1,043	14,288	19,669	1,043	83.27
15	39	90.30	4.16	200.23	11,648	16,114	901	11,628	16,086	900	78.88

*Corrected power and flowrate to 200 feet net head using Homology laws

Palisades U4

Run #	Servo Stroke (%)	Spiral Case Pressure (psi)	Draft Tube Pressure (psi)	Net Head (ft)	Generator Output (kW)	Turbine Output (horsepower)	Flowrate (cfs)	Corrected* Generator Output (kW)	Corrected* Turbine Output (hp)	Corrected* Flowrate (cfs)	Efficiency (%)
1	100	87.63	4.32	200.70	39,813	54,227	2,667	39,605	53,944	2,662	89.44
2	94	87.98	4.35	200.79	38,385	52,286	2,532	38,159	51,978	2,527	90.79
3	89	88.26	4.30	200.90	37,272	50,773	2,430	37,021	50,432	2,424	91.83
4	84	88.64	4.32	201.08	35,498	48,364	2,286	35,213	47,975	2,280	92.89
5	79	88.92	4.28	201.17	33,868	46,151	2,160	33,573	45,750	2,154	93.77
6	74	89.18	4.35	201.17	31,782	43,322	2,022	31,505	42,943	2,016	94.01
7	69	89.46	4.30	201.19	28,818	39,304	1,861	28,562	38,955	1,855	92.68
8	65	89.61	4.36	201.00	26,304	35,900	1,722	26,108	35,633	1,718	91.58
9	60	89.85	4.29	201.02	23,668	32,334	1,559	23,487	32,087	1,555	91.09
10	50	90.14	4.39	200.60	18,211	24,962	1,244	18,129	24,849	1,242	88.33
11	41	90.46	4.34	200.76	13,323	18,370	972	13,247	18,265	970	83.14
12	38	90.47	4.38	200.59	12,276	16,960	901	12,222	16,885	900	82.80

*Corrected power and flowrate to 200 feet net head using Homology laws

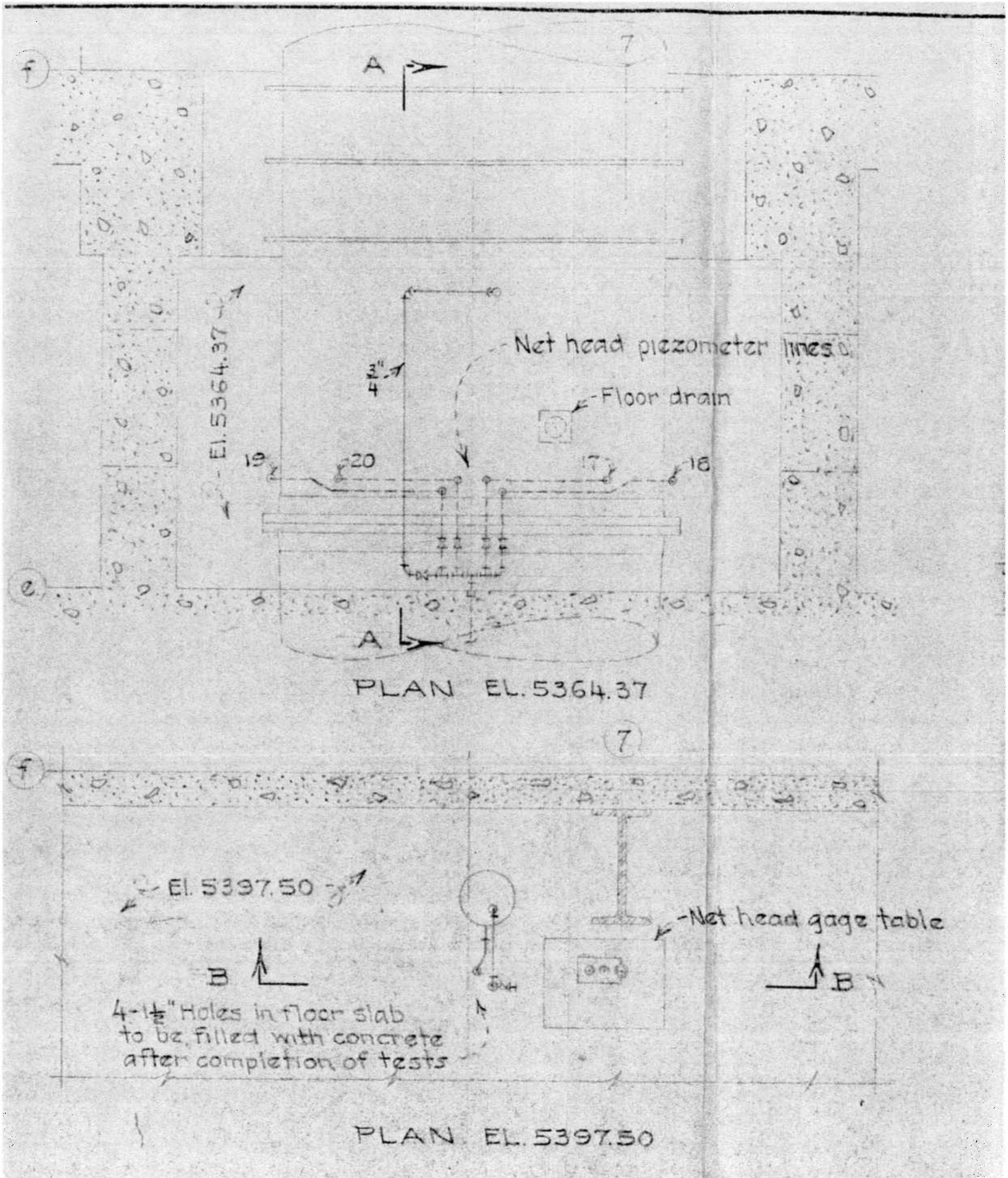
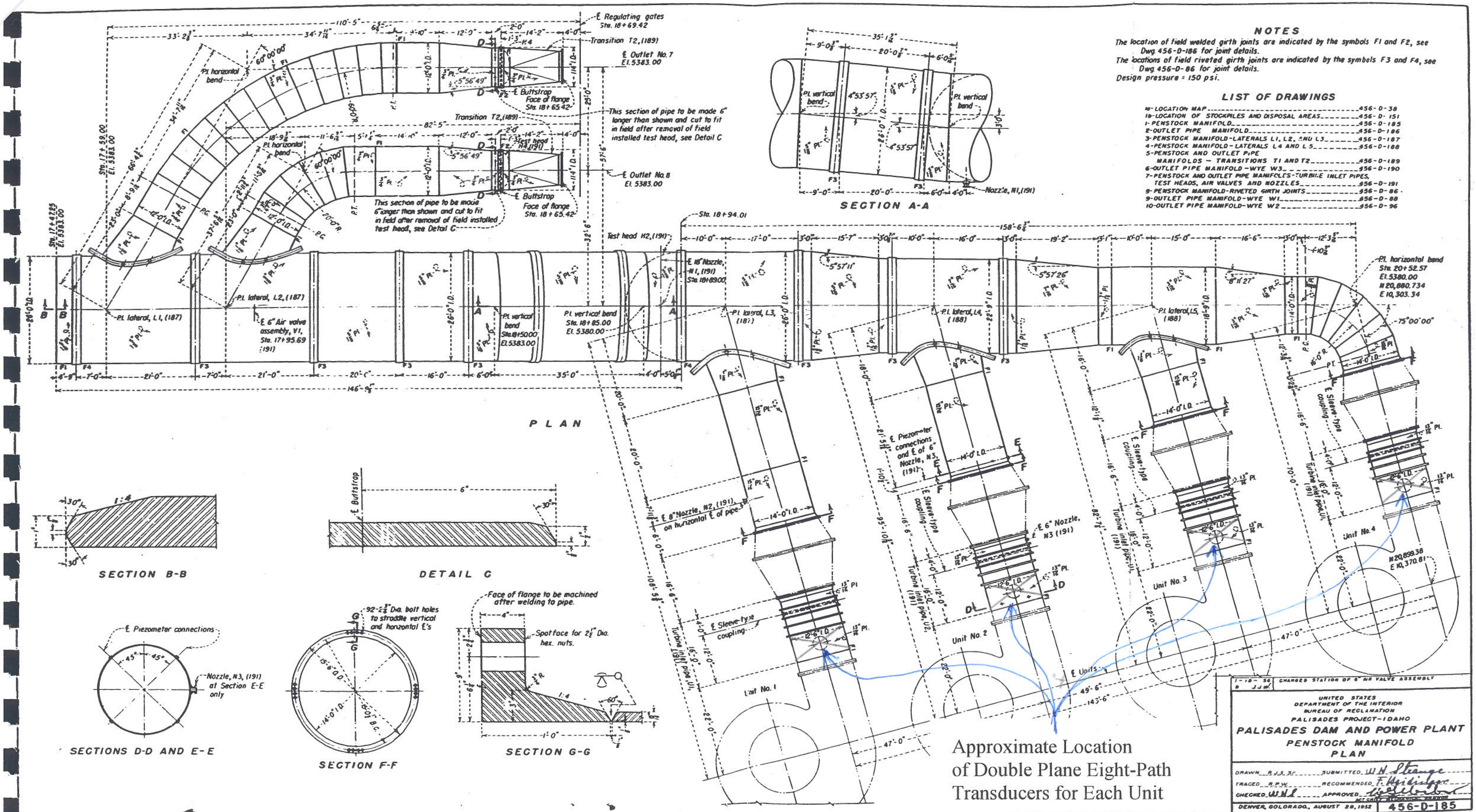


FIGURE 1

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
PALISADES POWERPLANT
TURBINE ACCEPTANCE TEST
NET HEAD MANOMETER


NOTES
The location of field welded girth joints are indicated by the symbols F1 and F2, see Dwg. 456-D-186 for joint details.
The locations of field riveted girth joints are indicated by the symbols F3 and F4, see Dwg. 456-D-86 for joint details.
Design pressure = 150 psi.
LIST OF DRAWINGS
1a-LOCATION MAP 456-D-38
1b-LOCATION OF STOCKPILES AND DISPOSAL AREAS 456-D-151
1-PENSTOCK MANIFOLD 456-D-185
2-OUTLET PIPE MANIFOLD 456-D-186
3-PENSTOCK MANIFOLD-LATERALS L1, L2, AND L3 456-D-187
4-PENSTOCK MANIFOLD-LATERALS L4 AND L5 456-D-188
5-PENSTOCK AND OUTLET PIPE MANIFOLDS — TRANSITIONS T1 AND T2 456-D-189
6-OUTLET PIPE MANIFOLD-WYE W3 456-D-190
7-PENSTOCK AND OUTLET PIPE MANIFOLDS-TURBINE INLET PIPES, TEST HEADS, AIR VALVES AND NOZZLES 456-D-191
8-PENSTOCK MANIFOLD-RIVETED GIRTH JOINTS 456-D-86
9-OUTLET PIPE MANIFOLD-WYE W1 456-D-88
10-OUTLET PIPE MANIFOLD-WYE W2 456-D-96
SECTION A-A
PLAN
SECTION B-B
DETAIL C
SECTIONS D-D AND E-E
SECTION F-F
SECTION G-G
Unit No. 1
Unit No. 2
Unit No. 3
Unit No. 4
Approximate Location
of Double Plane Eight-Path
Transducers for Each Unit
UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
PALISADES PROJECT-IDAHO
PALISADES DAM AND POWER PLANT
PENSTOCK MANIFOLD
PLAN
DENVER, COLORADO, AUGUST 28, 1952
456-D-185

CALIBRATION OF TURBINE WICKET GATE OPENINGS FOR UNIT 2

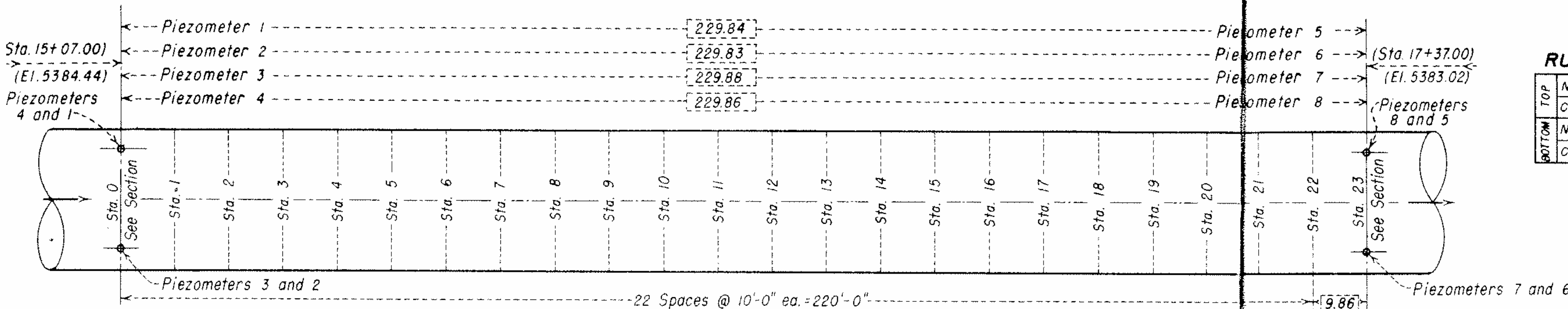
PISTON STROKE – PERCENT (INCLUDING SQUEEZE)		GATES CLOSED FULL PRESSURE				GATES CLOSED ZERO PRESSURE				10			
PISTON STROKE – INCHES (INCLUDING SQUEEZE)		.000				.233				1.344			
GATE MEASUREMENT	DISTRIBUTOR HEIGHT – INCHES	TOP	CENTER	BOTTOM	AREA	TOP	CENTER	BOTTOM	AREA	TOP	CENTER	BOTTOM	AREA
1-2	25.632		.000			.0	.0	.0		.7656	.7656	.7656	19.621
2-3	25.633					.0	.0	.0		.7500	.750	.7187	18.954
3-4	25.630					.0	.0	.0		.7343	.7343	.7343	18.819
4-5	25.629					.0	.0	.0		.750	.7343	.7343	18.953
5-6	25.629					.0	.0	.0		.7343	.7343	.7343	18.819
6-7	25.628					.0	.0	.0		.7656	.7656	.7656	19.621
7-8	25.630					.0015	.0015	.000	.02563	.7656	.7656	.7656	19.621
8-9	25.629					.0	.0	.0		.7343	.7343	.7343	18.819
9-10	25.626					.0	.0	.0		.750	.750	.7343	19.087
10-11	25.628					.0	.0	.0		.7187	.7187	.750	18.686
11-12	25.629					.003	.004	.004	.09397	.750	.7343	.750	19.087
12-13	25.627					.0	.0	.0		.750	.7343	.750	19.087
13-14	25.627					.015	.000	.000	.12814	.750	.750	.7343	19.087
14-15	25.627					.0	.0	.0		.7343	.7343	.7343	18.819
15-16	25.636					.0	.0	.0		.750	.750	.750	19.221
16-17	25.625					.004	.003	.003	.08542	.7343	.750	.7656	19.221
17-18	25.626					.0	.0	.0		.7187	.7343	.7343	18.685
18-19	25.627					.003	.002	.000	.04271	.7343	.7343	.7343	18.819
19-20	25.627					.0	.0	.0		.7343	.7343	.750	18.953
20-1	25.628					.0	.0	.0		.750	.750	.750	19.221
TOTAL AREA – SQ. IN.					.000				.37587				381.200
TOTAL AREA – SQ. FT.					.000				.00261				2.647

PISTON STROKE – PERCENT (INCLUDING SQUEEZE)	20				30				40			
PISTON STROKE – INCHES (INCLUDING SQUEEZE)	2.781				4.125				5.500			
GATE MEASUREMENT	TOP	CENTER	BOTTOM	AREA	TOP	CENTER	BOTTOM	AREA	TOP	CENTER	BOTTOM	AREA
1-2	1.8437	1.8437	1.8437	47.251	2.9531	2.9531	2.9218	75.416	4.0468	4.1093	4.0312	104.115
2-3	1.8593	1.8593	1.8437	47.518	2.9218	2.9062	2.9268	74.791	4.0156	4.0312	4.0468	103.314
3-4	1.8281	1.8281	1.8281	46.851	2.8906	2.8593	2.875	73.681	4.00	4.0156	4.00	102.648
4-5	1.8125	1.8281	1.8281	46.718	2.8906	2.8906	2.875	73.949	4.00	4.00	4.0156	102.648
5-6	1.8281	1.8281	1.8281	46.851	2.9062	2.9062	2.8906	74.349	4.0312	4.0312	4.0312	103.314
6-7	1.8437	1.8437	1.8437	47.251	2.9062	2.9062	2.9062	74.482	4.0156	4.00	4.00	102.648
7-8	1.7968	1.7968	1.7968	46.049	2.8906	2.8906	2.8906	74.082	4.0312	4.0156	4.0312	103.181
8-9	1.7968	1.7968	1.7968	46.049	2.875	2.875	2.8906	73.815	4.0156	4.0156	4.0312	103.048
9-10	1.8125	1.8125	1.8125	46.452	2.875	2.8593	2.875	73.548	3.9843	3.9843	3.9843	102.112
10-11	1.8125	1.8125	1.8125	46.452	2.875	2.875	2.875	73.682	4.00	4.00	4.0156	102.648
11-12	1.8125	1.8125	1.8125	46.452	2.8593	2.8593	2.875	73.414	4.00	4.00	4.0156	102.648
12-13	1.7812	1.7812	1.7812	45.649	2.8593	2.8593	2.8593	73.280	3.9687	3.9687	3.9687	101.712
13-14	1.7812	1.7968	1.7968	45.916	2.8593	2.8593	2.8437	73.147	3.9843	3.9843	3.9843	102.112
14-15	1.7812	1.7812	1.7812	45.649	2.8437	2.8437	2.8593	73.013	3.9687	3.9687	4.00	101.980
15-16	1.8125	1.8125	1.8125	46.452	2.875	2.875	2.8906	73.815	4.0156	4.0468	4.0937	103.848
16-17	1.7968	1.7968	1.7968	46.049	2.8906	2.8906	2.8906	74.082	4.0156	4.00	4.0156	102.781
17-18	1.7812	1.7812	1.7812	45.649	2.8593	2.8593	2.8593	73.280	3.9687	3.9687	4.00	101.980
18-19	1.7968	1.7812	1.7812	45.783	2.8906	2.8593	2.8593	73.547	3.9843	3.9843	4.00	102.246
19-20	1.7968	1.7968	1.7968	46.049	2.8593	2.8593	2.875	73.405	3.9843	3.9843	4.00	102.246
20-1	1.8281	1.8437	1.8281	46.985	2.8906	2.8906	2.875	73.949	4.00	4.00	4.0156	102.648
TOTAL AREA – SQ. IN.				928.075				1476.727				2053.877
TOTAL AREA – SQ. FT.				6.445				10.255				14.263

PISTON STROKE – PERCENT (INCLUDING SQUEEZE)	50				60				70			
PISTON STROKE – INCHES (INCLUDING SQUEEZE)	6.875				8.250				9.687			
GATE MEASUREMENT	TOP	CENTER	BOTTOM	AREA	TOP	CENTER	BOTTOM	AREA	TOP	CENTER	BOTTOM	AREA
1-2	5.250	5.3125	5.250	135.084	6.375	6.4843	6.375	164.317	7.5625	7.6406	7.6093	194.884
2-3	5.1875	5.2031	5.1875	133.082	6.3437	6.3593	6.3281	162.581	7.5312	7.5625	7.5156	193.149
3-4	5.1562	5.1406	5.1406	131.880	6.3593	6.3593	6.3281	162.714	7.5312	7.5812	7.50	192.748
4-5	5.2187	5.1875	5.1875	133.215	6.3906	6.3593	6.3593	163.248	7.5156	7.5156	7.50	192.482
5-6	5.2031	5.1562	5.2343	133.214	6.3125	6.3437	6.3437	162.048	7.4687	7.50	7.50	191.948
6-7	5.1406	5.1562	5.1875	132.281	6.3125	6.3125	6.3593	162.181	7.5156	7.50	7.4843	192.214
7-8	5.1875	5.1875	5.1718	132.815	6.2968	6.2968	6.3281	161.646	7.5625	7.6406	7.5937	194.751
8-9	5.2031	5.2031	5.2031	133.348	6.3437	6.3281	6.3281	162.314	7.5625	7.5625	7.5625	193.817
9-10	5.1406	5.1875	5.1562	132.281	6.2812	6.2968	6.3125	161.367	7.5156	7.5156	7.5625	193.016
10-11	5.1718	5.1562	5.1562	132.280	6.3593	6.3593	6.375	163.115	7.5625	7.5625	7.5781	193.950
11-12	5.1562	5.2187	5.1875	132.948	6.3906	6.4062	6.3593	163.649	7.5937	7.6093	7.5625	194.483
12-13	5.1093	5.0937	5.1093	130.811	6.3125	6.3125	6.3125	161.781	7.5312	7.5312	7.5312	193.015
13-14	5.1406	5.1562	5.1562	132.013	6.3906	6.375	6.375	163.516	7.5468	7.5468	7.5468	193.415
14-15	5.125	5.1406	5.1718	131.880	6.3593	6.3437	6.375	162.981	7.5156	7.5156	7.5156	192.615
15-16	5.125	5.2343	5.250	133.348	6.3437	6.4375	6.3906	163.783	7.50	7.6093	7.5312	193.415
16-17	5.1562	5.1562	5.1718	132.280	6.375	6.4062	6.4062	163.916	7.5937	7.5625	7.5625	194.084
17-18	5.1093	5.1406	5.1875	131.880	6.2968	6.3437	6.3593	162.313	7.5312	7.5468	7.5312	193.148
18-19	5.1406	5.1875	5.1406	132.147	6.3437	6.3437	6.3437	162.518	7.5312	7.5781	7.5468	193.549
19-20	5.1406	5.1406	5.1718	132.013	6.3437	6.3437	6.3593	162.714	7.4843	7.4843	7.5781	192.614
20-1	5.1562	5.1562	5.1562	132.147	6.2968	6.2812	6.2812	161.112	7.4687	7.50	7.50	191.948
TOTAL AREA – SQ. IN.				2.650.947				3253.814				3865.245
TOTAL AREA – SQ. FT.				18.409				22.596				26.842

PISTON STROKE – PERCENT (INCLUDING SQUEEZE)	80				90				100				GATES CLOSED FULL PRESSURE	
PISTON STROKE – INCHES (INCLUDING SQUEEZE)	11.031				12.437				13.812				CLEARANCE BETWEEN GATES AND FACING PLATES	
GATE MEASUREMENT	TOP	CENTER	BOTTOM	AREA	TOP	CENTER	BOTTOM	AREA	TOP	CENTER	BOTTOM	AREA	TOP	BOTTOM
1-2	8.7031	8.7812	8.7031	223.716	9.875	9.9375	9.9062	253.916	11.0468	11.0468	11.0000	282.715	.008	.004
2-3	8.6718	8.7031	8.6562	222.381	9.8437	9.8437	9.8125	252.057	10.9687	10.9687	10.9843	281.246	.005	.007
3-4	8.6562	8.6093	8.6093	221.046	9.750	9.7343	9.7187	249.490	10.8750	10.8593	10.8437	278.309	.004	.007
4-5	8.625	8.625	8.6406	221.181	9.7812	9.7187	9.7343	249.748	10.8125	10.8437	10.9687	278.710	.005	.006
5-6	8.625	8.6562	8.6718	221.714	9.750	9.7656	9.7968	250.416	10.8593	10.9375	10.9375	279.645	.007	.006
6-7	8.5937	8.5937	8.6093	220.379	9.750	9.7656	9.7812	250.273	10.8593	10.9062	10.9375	279.377	.003	.005
7-8	8.5937	8.5937	8.5937	220.245	9.7343	9.7656	9.7812	250.158	10.8437	10.8437	10.8750	278.176	.004	.005
8-9	8.625	8.6093	8.625	220.849	9.7812	9.7812	9.7812	250.682	10.9375	10.9375	10.9218	280.179	.006	.004
9-10	8.6093	8.6093	8.6093	220.645	9.8125	9.8437	9.8906	252.389	10.9062	10.9375	10.9375	280.045	.003	.005
10-11	8.7187	8.7187	8.6875	223.182	9.7812	9.7656	9.8281	250.940	10.9062	10.8750	10.9218	279.377	.007	.006
11-12	8.6562	8.6562	8.6562	221.847	9.8281	9.875	9.8437	252.418	11.1718	11.0156	10.9687	283.248	.002	.006
12-13	8.7031	8.7031	8.7031	223.049	9.7656	9.7656	9.7656	250.263	10.9531	10.8593	10.9531	279.911	.006	.006
13-14	8.625	8.625	8.6718	221.447	9.7187	9.7187	9.8125	249.862	10.9218	10.8906	10.9375	279.778	.008	.009
14-15	8.625	8.625	8.6718	221.447	9.7812	9.7812	9.8281	251.063	10.9375	10.9062	10.9687	280.312	.007	.003
15-16	8.625	8.7187	8.7343	222.782	9.750	9.8437	9.875	251.820	10.9375	11.1718	11.0312	283.115	.004	.008
16-17	8.7187	8.7031	8.7031	223.182	9.7812	9.7968	9.8125	251.044	10.9062	10.9062	10.9375	279.778	.004	.006
17-18	8.625	8.6562	8.6875	221.896	9.7968	9.8125	9.7656	250.920	10.8593	10.8906	10.9062	278.977	.004	.007
18-19	8.7031	8.6562	8.6718	222.381	9.7812	9.7968	9.8593	251.463	10.9687	10.9843	10.9843	281.379	.006	.003
19-20	8.5937	8.6093	8.6875	4434.611	9.750	9.7656	9.8437	250.797	10.9062	10.8750	11.1718	281.513	.004	.003
20-1	8.5937	8.5781	8.5937	220.112	9.7187	9.750	9.7187	249.338	10.9062	10.8906	10.8906	279.244	.004	.004
TOTAL AREA – SQ. IN.				4434.611				5019.057				5605.059	.00505	.0055
TOTAL AREA – SQ. FT.				30.796				34.855				38.924	AVERAGE	AVERAGE

The difference between PISTON STROKE-INCHES for gates closed-full pressure readings and gates closed-zero pressure readings represents the squeeze from [195] psi governor oil closing pressure.

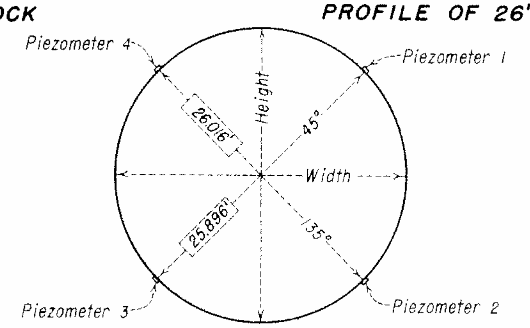


PROFILE OF 26'-0" I.D. PENSTOCK

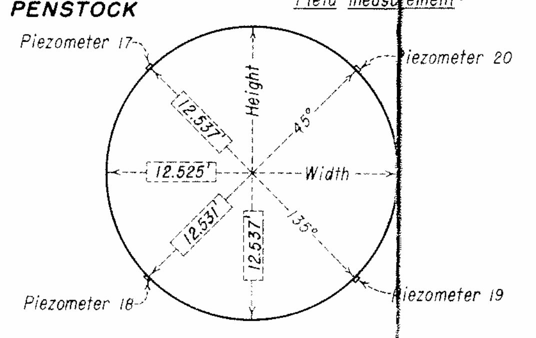
CALIBRATION OF PENSTOCK

STATION	HEIGHT	WIDTH
0	25.930	26.062
1	25.960	25.984
2	25.995	25.969
3	25.980	26.005
4	25.970	25.984
5	26.000	25.984
6	26.010	25.964
7	26.010	25.989
8	25.990	25.995
9	25.965	26.005
10	25.925	26.026
11	25.970	26.016
12	25.955	26.036
13	25.900	26.057
14	25.905	26.063
15	25.935	26.042
16	25.915	26.021
17	25.950	26.00
18	25.935	25.979
19	25.985	25.958
20	25.975	25.958
21	25.985	25.964
22	25.990	25.984
23	25.960	25.974

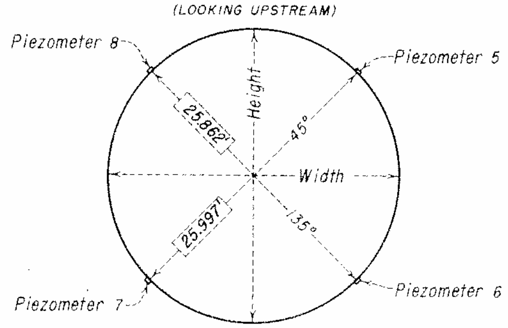
Average temperature of penstock metal during calibration [40°F].
Take measurements normal to ℄ of penstock.
Dimensions in this table to be correct within 0.05 inch.



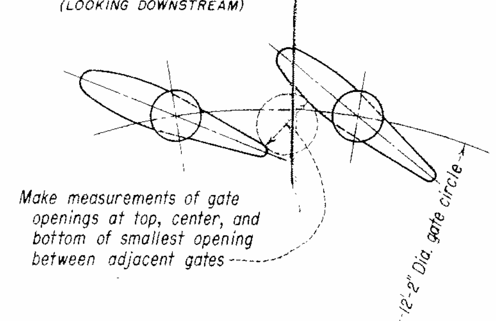
PENSTOCK SECTION AT STATION 0
(LOOKING UPSTREAM)



SPIRAL CASE INLET SECTION AT STATION 24
(LOOKING DOWNSTREAM)



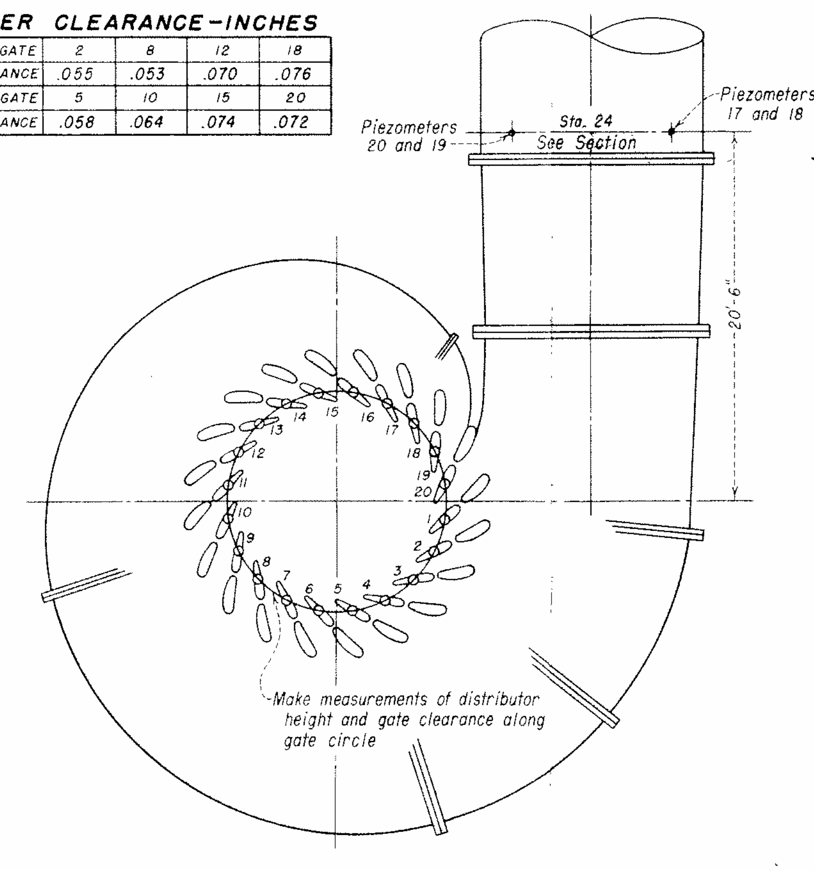
PENSTOCK SECTION AT STATION 23
(LOOKING UPSTREAM)



PLAN OF WICKET GATES

RUNNER CLEARANCE – INCHES

TOP	NEAR GATE	2	8	12	18
TOP	CLEARANCE	.055	.053	.070	.076
BOTTOM	NEAR GATE	5	10	15	20
BOTTOM	CLEARANCE	.058	.064	.074	.072



PLAN OF SPIRAL CASE

DRAFT TUBE EXIT AREA

3 Openings @ 11.95 ft. x 9.75 ft. each
Total Net Area = 349.5 sq. ft.

without fillets

NOTES

Make penstock calibrations as soon as practicable.
Spacing of penstock piezometer taps based on governor setting of 8 seconds.
Units 1 thru 4 supplied from a common penstock.
Make turbine calibrations immediately prior to placing unit in operation.
The latitude of the power plant is [43°20'N]

Net Hd Taps

REFERENCE DRAWINGS

U.S.B.R. DRAWINGS:
- PALISADES DAM–GENERAL PLAN AND SECTIONS 456-D-117
- POWER TUNNEL (PENSTOCK) LINER 456-D-36, 37
- PENSTOCK PIEZOMETER PIPING 456-D-87, 851
- TURBINE INLET PIPING 456-D-1110
- WATER PASSAGE CALIBRATION– UNITS 1, 3, AND 4 .... 456-D-1115, 1117, 1118

S. MORGAN SMITH COMPANY (TURBINE) DRAWINGS:
- DISTRIBUTOR PLAN 5840-QD-1
- DISTRIBUTOR SECTION 5840-QE-1
- SPIRAL CASE 1006-TO-1
- ELBOW DRAFT TUBE 5846-J1-1
- GATE MECHANISM ASSEMBLY 5128-L-1
- 20 GATE LAYOUT 3828-WE-1
- WICKET GATE 3828-WG-1

8-15-57 D FAG LWY — CALIBRATION DATA ADDED IN ACCORDANCE WITH PROJECT LETTER OF AUGUST 8, 1957

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
PALISADES PROJECT–IDAHO

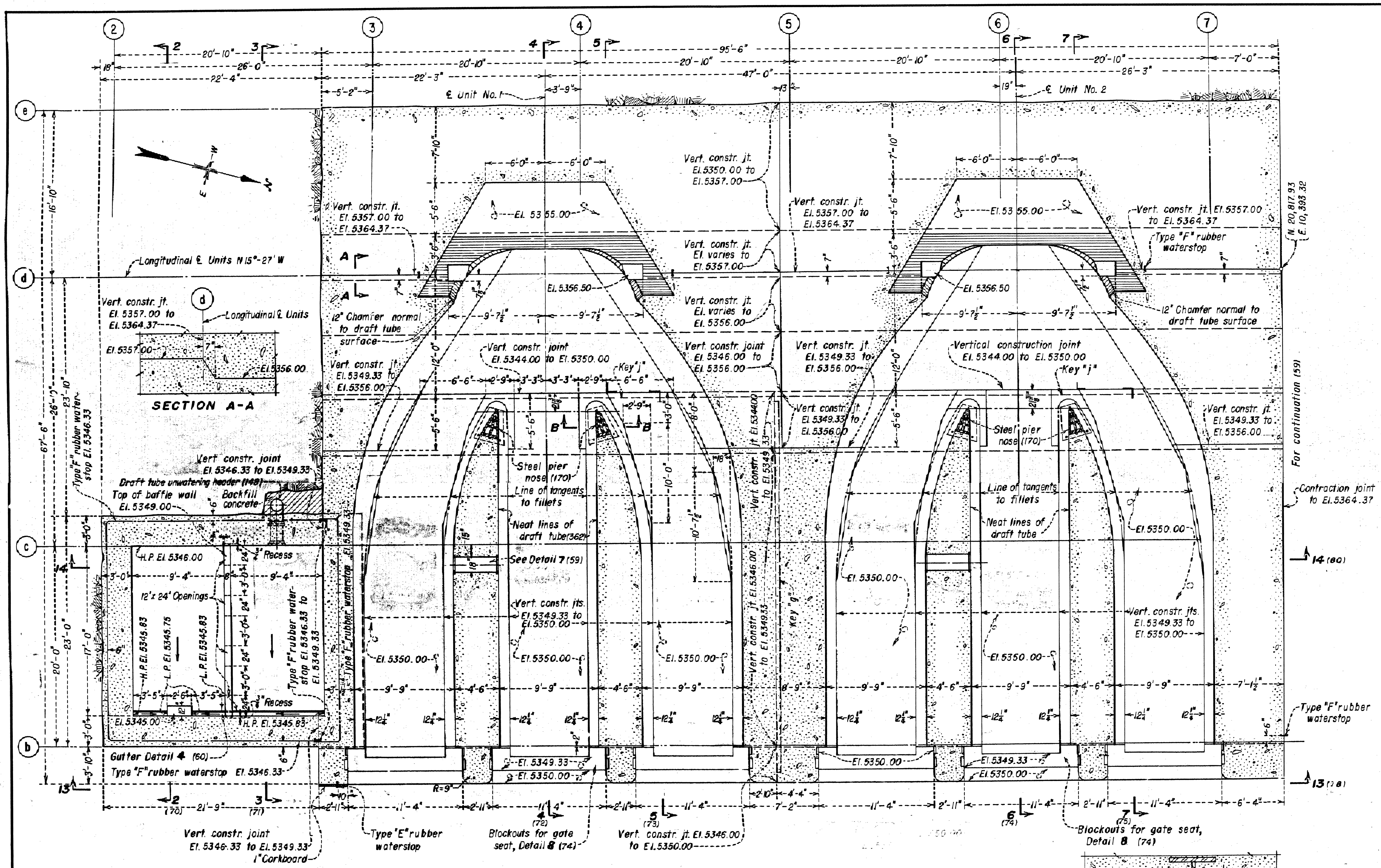
PALISADES POWER PLANT
UNIT 2
TURBINES AND AUXILIARIES
PENSTOCK AND TURBINE WATER PASSAGE CALIBRATION

DRAWN F.T. SUBMITTED E. H. Johnson
TRACED F.F.M. RECOMMENDED J. H. Durnard
CHECKED FAG APPROVED I. D. Winter
CHIEF, HYDRAULIC MACHINERY BRANCH

DENVER, COLORADO, NOVEMBER 24, 1954
SHEET 2 OF 4

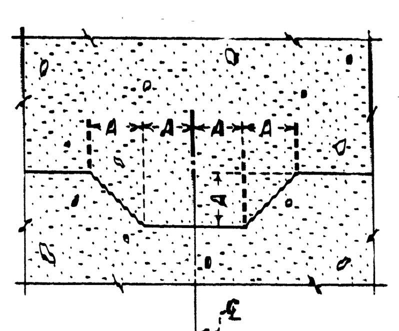
456-D-1116

GPO 849027



PLAN ALONG ℄ OF DRAFT TUBE

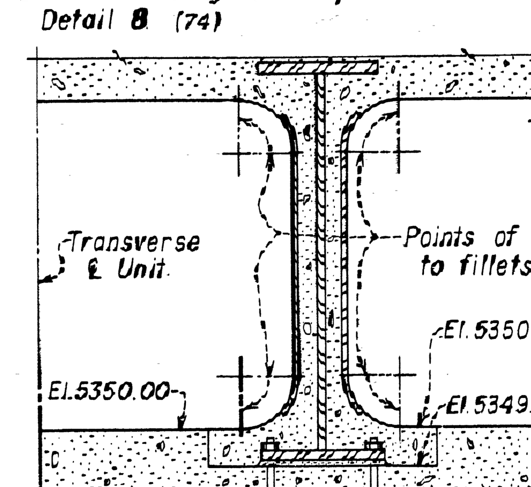
SCALE OF FEET



KEY DETAILS

KEY	THICKNESS OF WALL OR SLAB	A	KEY	THICKNESS OF WALL OR SLAB	A
a	8" to 12"	1.0"	h	43" to 47"	4.5"
b	13" to 17"	1.5"	j	48" to 52"	5.0"
c	18" to 22"	2.0"	k	53" to 57"	5.5"
d	23" to 27"	2.5"	m	58" to 62"	6.0"
e	28" to 32"	3.0"	n	63" to 67"	6.5"
f	33" to 37"	3.5"	p	68" to 72"	7.0"
g	38" to 42"	4.0"	r	73" to 77"	7.5"

SCALE OF FEET (SECTIONS A-A & B-B)



SECTION B-B

GENERAL NOTES

All exposed edges of concrete structures shall be chamfered ¾" unless otherwise shown.
Numerals in parenthesis (59) following section letters or notes indicate the drawing number upon which the section or detail is drawn.
Dimensions in parenthesis on plans are beam sizes. Beam and slab depths to be measured from the top of the structural slab.
Dimensions given for the depth of recesses are from the face of the structural concrete.
Rubber waterstops shown on sections or elevations to be continuous by splicing and connecting to other waterstops.
Construction joints marked "optional" are suggested and may be omitted by the contractor, if approved by the construction engineer.
For embedded conduits and grounding cables see electrical drawings.
Embedded pipe and pipe sleeves smaller than 6" are not shown, see piping drawings.
All concrete shall have a 28 day compressive strength of 3000 lbs. per sq. in.
Concrete shall be allowed to contract before placing adjacent lifts.
For location and setting of anchor bolts, see steel fabrication drawings.
Thickness shown for walls and slabs adjacent to rock surfaces are minimum dimensions.
For floor finish, see "Finish Schedules" on architectural drawings.
Corkboard in all joints at top of partitions shall not be painted.
Dimensions not shown are the same as for similar details shown elsewhere on the drawing.
All dimensions to a joint are to the ℄ of the joint.
Keys are located in center of wall or slab unless otherwise noted.
H.P. and L.P. indicate High Point and Low Point of finished concrete.

NOTE

For reinforcement, see 456-D-421, 422 & 427.

REFERENCE DRAWINGS

LOCATION ---------- 456-D-38
DAM-GENERAL PLAN AND SECTIONS ---------- 456-D-117-118
SPILLWAY AND OUTLET WORKS-GENERAL PLAN ---------- 456-D-120
PENSTOCK ANCHOR BLOCK ---------- 456-D-129
GENERAL ARRANGEMENT ---------- 456-D-49 TO 54 INCL.
LIST OF STRUCTURAL DRAWINGS ----------
BUILDING DETAILS ---------- 456-D-55
RUBBER WATER STOPS ---------- 40-D-4567
ARCHITECTURAL PLANS AND ELEVATIONS ---------- 456-D-98
HEATING AND VENTILATING ---------- 456-D-886
SANITARY PIPING ---------- 456-D-794
STRUCTURAL STEEL ---------- 456-D-145
HATCH COVERS, FRAMES, METAL STAIRS ETC. ---------- 456-D-174
TRANSFORMER TRACK CROSSOVER AND SOLEPLATE ---------- 40-D-5048
SEPTIC TANK AND DISPOSAL FIELD ---------- 456-D-852
EMBEDDED PIPES AND PIPE SLEEVES ---------- 456-D-202
NEAT LINES OF DRAFT TUBE ---------- 456-D-362
ERECTION OF SPIRAL CASE AND DRAFT TUBE LINER ---------- 456-D-814
EMBEDDED CONDUITS ---------- 456-D-567
GROUNDING SYSTEM NETWORK ---------- 456-D-94
DRAFT TUBE PIER NOSE COLUMN ---------- 456-D-170
TRANSFORMER AND GANTRY CRANE TRACK ---------- 456-D-171 TO 173 INCL.

5-12-55 D T.Q.Q. — LABELED - BACKFILL CONCRETE

REV. 2-20-53 | 4-7-53 | 8-7-53
REV. 2-27-52 | 9-25-52 | TR. & REV. 1-28-53

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
PALISADES PROJECT- IDAHO

PALISADES POWER PLANT
UNITS 1 AND 2
SUBSTRUCTURE - OUTLINE
PLAN ALONG ℄ OF DRAFT TUBE

DRAWN R.H.O. - J.S.P. SUBMITTED S. Thompson
TRACED R.T.S. RECOMMENDED Samuel Judd
CHECKED [signature] APPROVED O. L. Rice
ACT. CHIEF DESIGNING ENGINEER

DENVER, COLORADO, NOVEMBER 2, 1951 — 456-D-58

Job No. 1-456-11-01-01

Appendix C

Quantifying the Potential Value of Unit Characteristics Based on Field Efficiency Tests and Archival Data Analyses, March and Wolff, Final Report FR2101, November 2021

Final Report FR2101

Quantifying the Potential Value of Unit Characteristics Based on Field Efficiency Tests and Archival Data Analyses

Prepared by
Patrick A. March, Hydro Performance Processes Inc.
Paul J. Wolff, WolffWare Ltd.

Prepared for
U. S. Bureau of Reclamation
Oak Ridge National Laboratory

Subcontract 4000183047, Modification 1

November 2021

1. Introduction

Accurate unit and plant performance characteristics are essential for proper operation and optimization of hydroelectric power plants. Accurate flow measurement is a key component for determining accurate unit and plant performance characteristics, and careful attention to unit flow measurements can improve operational efficiencies and generation [ORNL, 2011; EPRI, 2014; EPRI, 2015; March et al., 2016]. In addition, the unit and plant performance information must be properly utilized by operators and/or control systems.

Do nominally identical units have identical performance characteristics for each unit? Can detailed analyses of archival unit data provide useful performance characteristics? Compared to a turbine manufacturer's predicted performance, do characteristics based on field tests and/or archival data analyses provide additional value for optimizing multiunit hydroelectric power plants?

To answer these questions, the U. S. Bureau of Reclamation has conducted or commissioned multiple investigations at two multiunit plants, including the 150 MW Flaming Gorge Project and the 176 MW Palisades Project. Under the current project (ORNL Subcontract 4000183047, Mod. 1), Hydro Performance Processes Inc. (HPPi) is supporting Oak Ridge National Laboratory (ORNL) to provide Reclamation with additional analyses of Palisades archival data (Task 1), with additional analyses of Flaming Gorge archival data (Task 2), and with additional review and evaluation of the practical implementation of the identified opportunities for generation improvements (Task 3).

The initial performance analyses for Flaming Gorge are described in Section 2.1, and the initial performance analyses for Palisades are described in Section 2.2. Section 2.3 describes the recent performance analyses for Flaming Gorge, and Section 2.4 describes the recent performance analyses for Palisades. Section 3 provides detailed results from all of the performance analyses, and Section 4 provides recommendations to Reclamation based on these performance analyses. Section 5 lists the technical references. Technical Memorandum TM1901, *Quantifying the Potential Value of Unit Characteristics Based on Field Efficiency Tests and Archival Data Analyses,* is included as Appendix A [March et al., 2019a]. Technical Memorandum TM2101, *Implementing Identified Opportunities for Generation Improvements at Reclamation's Flaming Gorge Dam and Powerplant*, is included as Appendix B [March and Wolff, 2021a]. Technical Memorandum TM2102, *Operation Efficiency and Generating Scheduling Analyses for Reclamation's Palisades Dam and Powerplant*, is included as Appendix C [March and Wolff, 2021b].

2. Overview of Previous Results

2.1 Initial Performance Analyses for Flaming Gorge

March et al. [2017], March et al. [2019a], and March et al. [2019b] summarize the initial performance analyses for Flaming Gorge using hourly archival data from 2008 - 2015 and Reclamation's field efficiency test results from November 2015. The performance curves derived from efficiency tests and from the archival data correspond closely. A comparison between the turbine manufacturer's expected performance curves and the derived performance curves shows an average annual energy difference of 1.6%, corresponding to $190,000/year in power revenue loss. Operation efficiency analyses for Flaming Gorge show the potential for modest annual improvements from improved unit dispatch, corresponding to an increase in power revenue of $48,000/year. Generation scheduling analyses for Flaming Gorge show the potential for significant annual improvements from improved scheduling, corresponding to an increase in power revenue of $210,000/year.

2.2 Initial Performance Analyses for Palisades

March et al. [2019a] and March et al. [2019b] summarize the initial performance analyses for Palisades using fifteen-minute archival data for 2014 - 2018 and Reclamation's field efficiency test results from June 2014 and September 2018. The turbine manufacturer's expected performance curves for Palisades and the performance curves derived from efficiency tests and archival data correspond closely. Operation efficiency analyses for Palisades show the potential for modest annual improvements from improved unit dispatch with the new units, corresponding to an increase in power revenue of $23,700/year. Generation scheduling analyses for Palisades show the potential for significant annual improvements from improved scheduling with the new units, corresponding to an increase in power revenue of $277,000/year.

2.3 Recent Performance Analyses for Flaming Gorge

March and Wolff [2021a] summarizes the recent performance analyses for Flaming Gorge using hourly archival data from 2008 - 2015 and Reclamation's field efficiency test results from November 2015 to derive unit characteristics and using 2018 - 2019 archival data. The estimated Lost Revenue Opportunity and reduced maintenance costs for 2018 - 2019 range from $76,727 to $82,892, indicating a small but achievable potential improvement from improved optimization at Flaming Gorge. Generation scheduling analyses show the potential for significant annual improvements of approximately 1.0%, corresponding to a generation increase of 10,546 MWh and a power revenue increase of $312,366 for 2018 - 2019. Recommended best efficiency operating points for Flaming Gorge versus gross head are provided to help Reclamation in achieving some or most of the potential generation improvements from improved scheduling.

2.4 Recent Performance Analyses for Palisades

March and Wolff [2021b] summarizes the recent performance analyses for Palisades. Unit characteristics derived from the 2008 - 2015 archival analyses and Reclamation's September 2018 field tests were used for operation efficiency analyses and generation scheduling analyses based on the 2018 and 2019 archival data. Flow analyses confirm the results from previous flow analyses and show that the unit efficiencies from field tests agree closely with the efficiencies derived from archival data and with the turbine manufacturer's predictions. Operation efficiency analyses show that the potential efficiency improvements due to improved optimization, while meeting the actual power versus time, are modest, ranging from a low of 0.20% for 2020 to a high of 0.39% for 2019, with a three-year total Lost Energy Opportunity of 7,210 MWh and a three-year total Lost Revenue Opportunity of $213,559. Major Efficiency Loss Events, constituting approximately 2/3 of the potential improvements identified by the operation efficiency analyses, occur because too many or two few units are operating, because the units are not operating at equal loads, or both. This increased generation from improved optimization could be achieved without any significant effect on the number of start/stops for the Palisades units. The potential efficiency improvements due to improved generation scheduling are significant, ranging from a low of 0.57% for 2018 (partial year) to a high of 1.98% for 2021 (partial year), with a three-year total Lost Energy Opportunity of 21,557 MWh and a three-year total Lost Revenue Opportunity of $638,519. Opportunities for scheduling improvements occur primarily during October to April in each year. Recommended best efficiency operating points for Palisades versus net head are provided to help Reclamation in achieving some or most of the potential generation improvements from improved scheduling.

3. Detailed Summary of Results from Performance Analyses

3.1 Flow Analyses

Comparison of Archival Analyses and Field Test Results:

Flow analyses for Flaming Gorge and Palisades show that the unit efficiencies from field tests agree closely with the efficiencies derived from the archival data, as illustrated by the Palisades Unit 1 example in Figure 3.1. Other units at both plants demonstrate similarly close agreement between the unit efficiencies from field tests and the efficiencies derived from the archival data [March et al., 2019a; March et al., 2019b; March and Wolff, 2021a; March and Wolff, 2021b].

Comparison of Archival Analyses and Field Test Results with Turbine Manufacturer's Predictions:

For Palisades, good agreement was observed among the archival analyses, the field test results, and the turbine manufacturer's predictions, as shown in Figure 3.1 [March et al., 2019a; March et al., 2019b]. However, for Flaming Gorge, there was approximately a 1.6% difference between the archival analyses, the field test results, and the turbine manufacturer's predictions, as shown in Figure 3.2 [March et al., 2017; March et al., 2019a; March et al., 2019b].

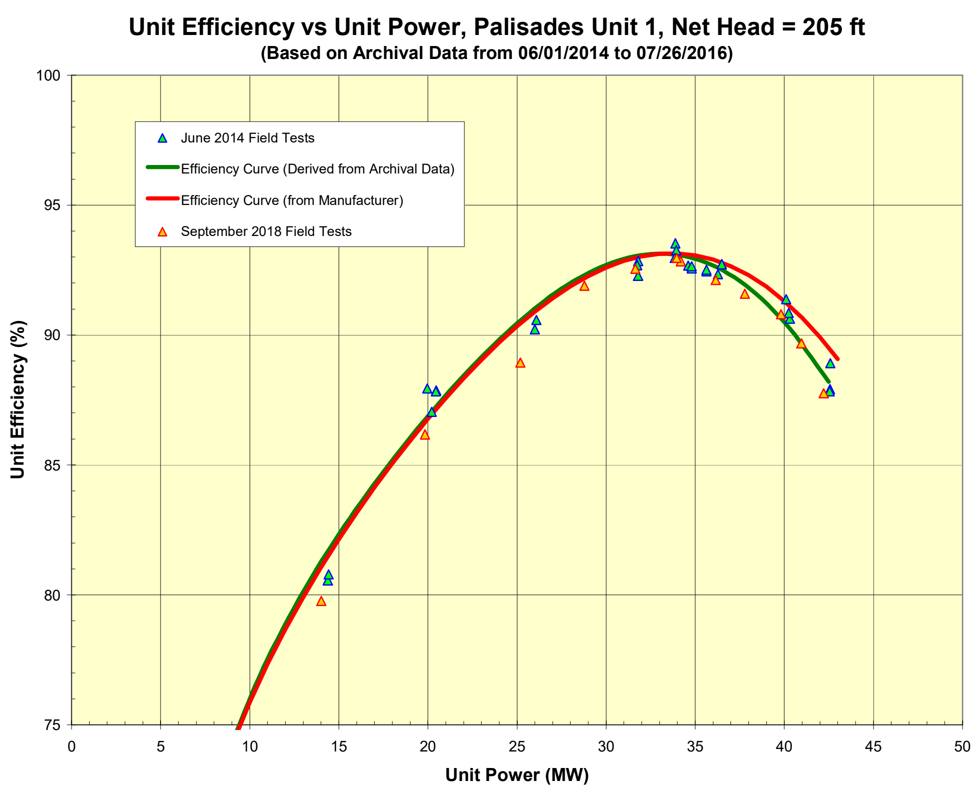


Figure 3.1: Performance Comparison for Palisades Unit 1 at Net Head of 205 ft

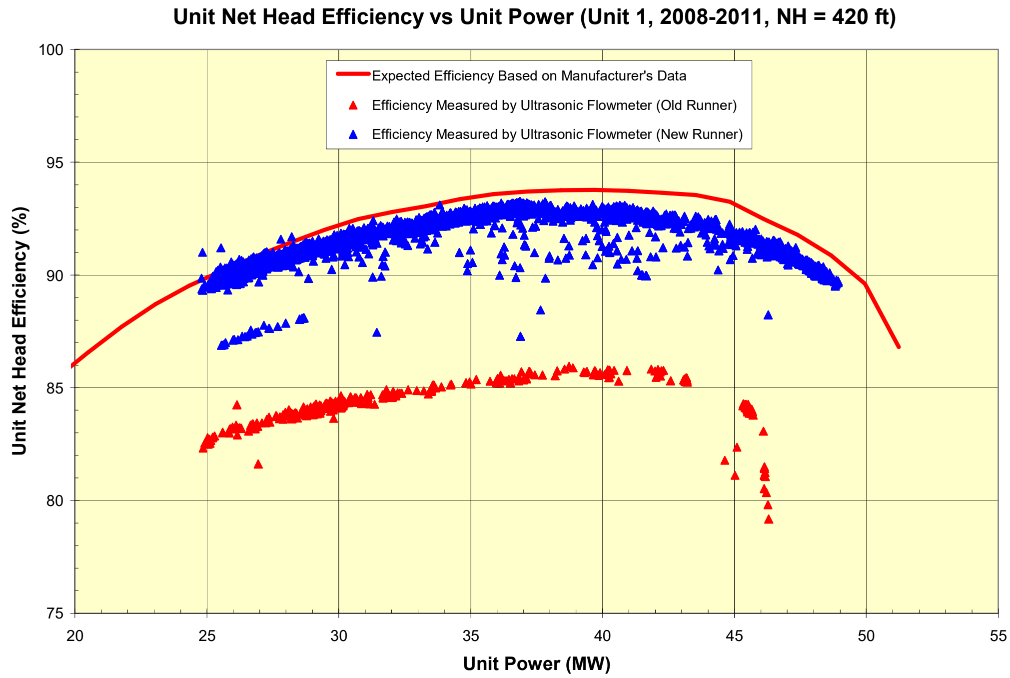


Figure 3.2: Expected and Measured Efficiency versus Power for Flaming Gorge

Both the field efficiency tests and the archival analyses provide additional details on unit performance that are important for contractual issues related to unit acceptance and also for the actual operation and optimization of the plants.

Flow Correlation Analyses:

March and Wolff [2021b] describes how an initial review of the flow correlation analyses for Palisades revealed low flow correlation efficiencies over an extended period of time for Palisades Unit 1 due to a malfunctioning flowmeter, as illustrated at a net head of 225 ft in Figures 3.3 and 3.4. Consequently, only data from 2013 to 2016 was usable for the Unit 1 flow analyses. Figure 3.5 and Figure 3.6 present the corresponding flow correlation efficiencies and efficiency versus power results for Unit 1 with the bad flowmeter data removed.

These results illustrate the value of flow correlation analyses in identifying potential problems with performance-related instrumentation (i.e., flow, power, head). Previously, results from Flaming Gorge demonstrated the value of flow analyses in identifying trash rack fouling [March et al., 2017; March et al., 2019a; March et al., 2019b].

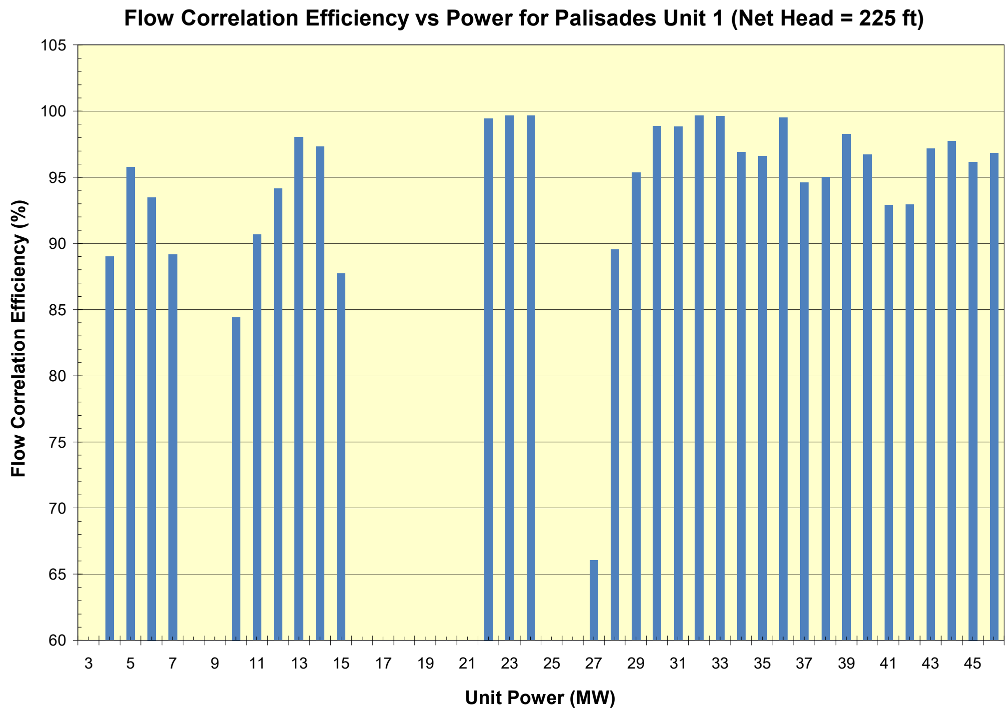


Figure 3.3: Flow Correlation Efficiency versus Power for Palisades Unit 1 at Net Head of 225 ft with All Flow Data Included (2013 – 2021)

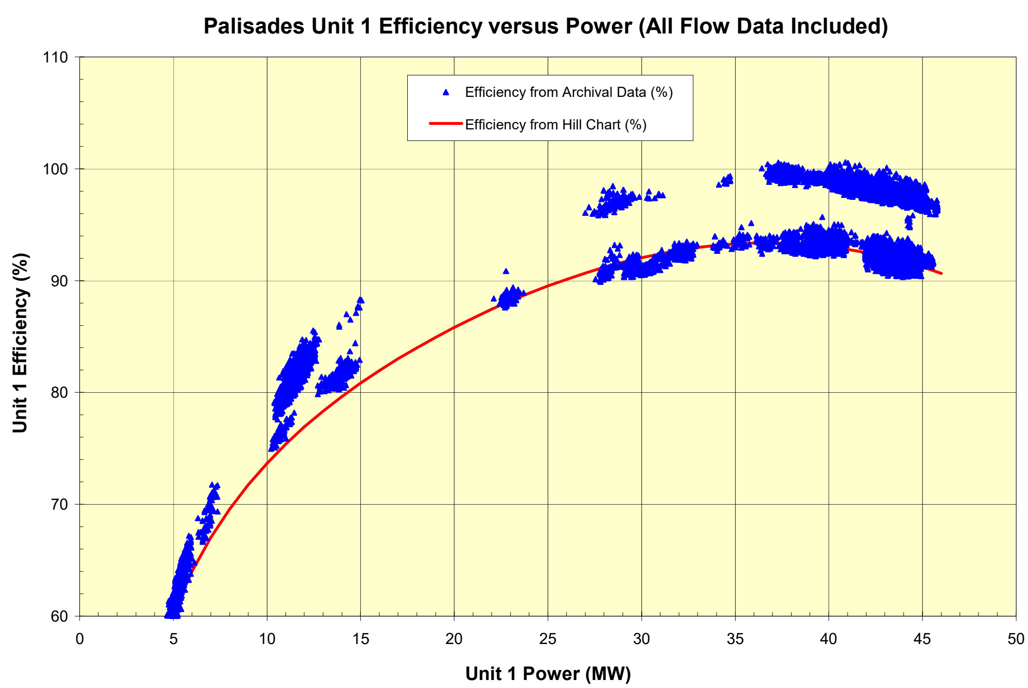


Figure 3.4: Unit Efficiency versus Power for Palisades Unit 1 at Net Head of 225 ft with All Flow Data Included (2013 – 2021)

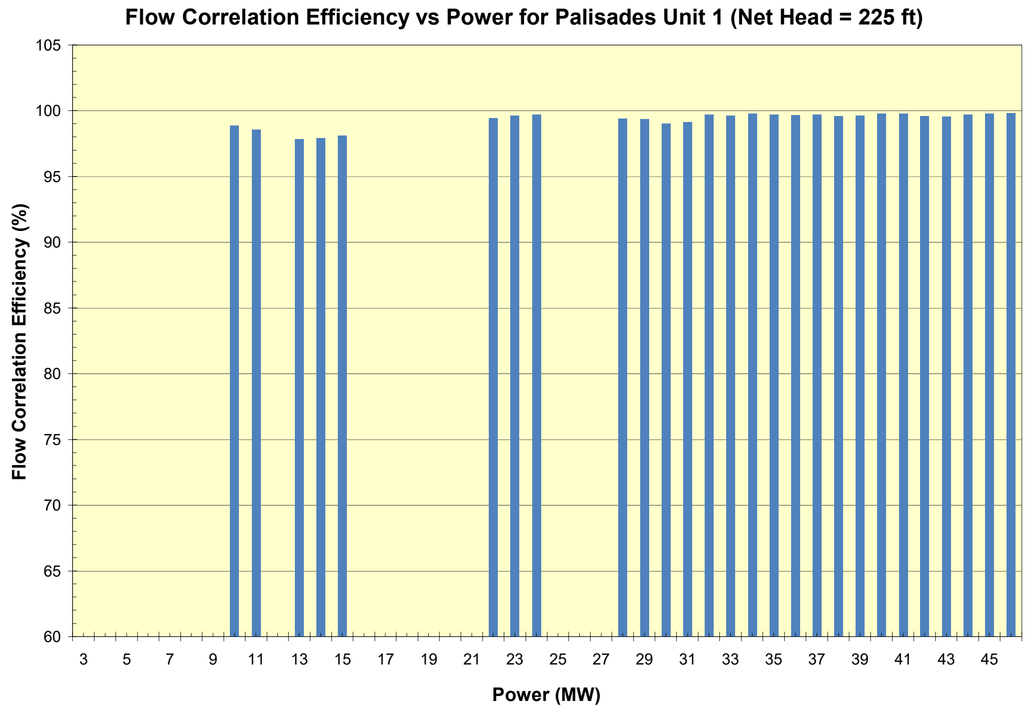


Figure 3.5: Flow Correlation Efficiency versus Power for Palisades Unit 1 at Net Head of 225 ft with Bad Flow Data Removed (2013 – 2016)

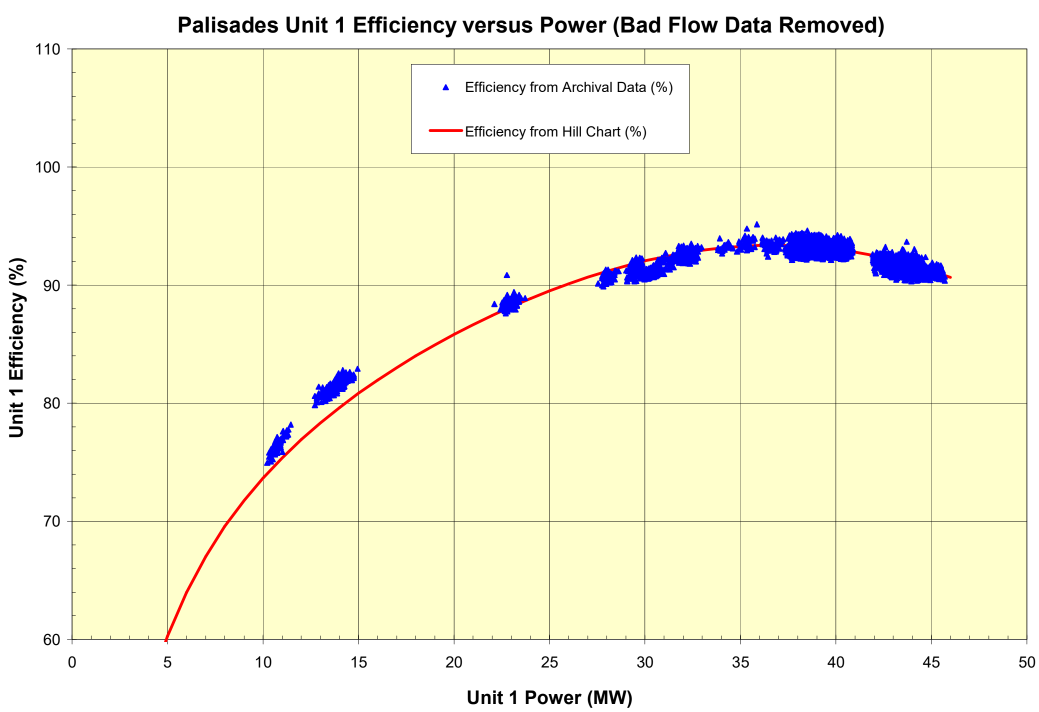


Figure 3.6: Unit Efficiency versus Power for Palisades Unit 1 at Net Head of 225 ft with Bad Flow Data Removed (2013 – 2016)

Combined Unit Characteristics:

March and Wolff [2021b] describes how the individual unit performance characteristics for Palisades Units 1, 2, 3, and 4, derived from the archival data, were aggregated to provide combined unit performance characteristics. Combined unit characteristics, assuming equal performance for all units, were developed from the September 2013 through June 2021 fifteen-minute archival data for unit flow, unit power, headwater, and tailwater using the Hydroplant Performance Calculator [March et al., 2014]. Combined unit characteristics, assuming equal performance for all units, were also developed from the turbine manufacturer's hill curves. Both sets of combined unit characteristics were used for operation efficiency analyses and generation scheduling analyses with archival operating data for June 2018 through June 2021. The operation efficiency results and the generation scheduling results are similar for the combined unit characteristics based on the turbine manufacturer's hill curves and the combined unit characteristics derived from the archival data.

Optimized dispatch has been shown to be an effective hedge against the potential for energy losses and revenue losses due to uncertainty in unit characteristics [EPRI, 2014; EPRI, 2015; March et al., 2016; March et al., 2019a; March et al., 2019b]. By assuming equal unit performance and combining the unit curves, optimized dispatch is simplified with virtually no effect on the optimized plant efficiency curves. The equal performance assumption also ensures that each unit is interchangeable in the dispatch order, avoiding unequal wear which could result from the preferential dispatch of an insignificantly more efficient unit.

Comparison of Multi-path Acoustic Flowmeters and Winter-Kennedy Relative Flowmeters:

Details of the comparison of multi-path acoustic flowmeters and Winter-Kennedy relative flowmeters are provided in March et al. [2019a] and March et al. [2019b]. Piezometers called Winter-Kennedy taps, originally developed by Reclamation, are commonly positioned at inner and outer radii of the turbine scroll case and used to provide an effective and inexpensive measurement of relative flow rate [Winter, 1933; March and Almquist, 1995; ASME, 2011]. With properly designed and installed Winter-Kennedy taps, the flow rate is directly proportional to the square root of the differential pressure between the taps. During Reclamation's September 2018 field tests at Palisades, pressure differentials from Winter-Kennedy piezometers (using tap R2, inside radius of the scroll case, and tap R3, outside radius of the scroll case) for each unit were recorded for comparison with the unit's corresponding multi-path acoustic flowmeter. The Winter-Kennedy differential pressures for Unit 1 and Unit 3 erroneously produced a varying Winter-Kennedy flow coefficient that trended upward with increasing flow rates, perhaps due to leaking piezometer lines or due to bad pressure measurements. For Unit 2 and Unit 4, the turbine manufacturer's value for flow rate at the best efficiency point and the tested head was used to calibrate the Winter-Kennedy flow coefficient for each unit. As shown in Figure 3.7, the flows measured with the calibrated Winter-Kennedy flowmeters corresponded closely to the flows measured with multi-path acoustic flowmeters for Palisades Unit 2 and Unit 4.

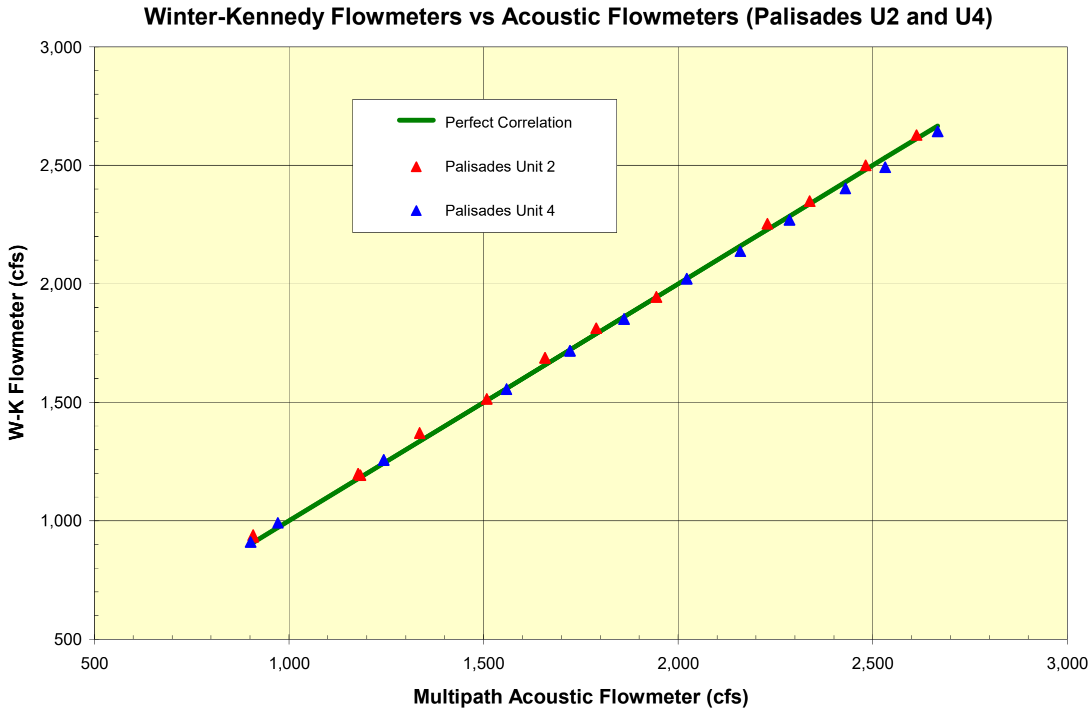


Figure 3.7: Comparison of Results from Winter-Kennedy Flowmeters and Multi-path Acoustic Flowmeters for Palisades Unit 2 and Unit 4

3.2 Operation Efficiency Analyses

Operation Efficiency Results:

March et al. [2017], March et al. [2019a], and March et al. [2019b] provide results from initial operation efficiency analyses for Flaming Gorge and Palisades. At Flaming Gorge, a potential for modest annual improvements from improved unit dispatch was identified, corresponding to an increase in power revenue of $48,000/year. The initial operation efficiency analyses for Palisades also identified the potential for modest annual improvements from improved unit dispatch with the new units, corresponding to an increase in power revenue of $23,700/year. Subsequently, March and Wolff [2021a] provided an estimated Lost Revenue Opportunity and reduced maintenance costs for Flaming Gorge ranging from $76,727 to $82,892 for 2018 - 2019. March and Wolff [2021b] used 2018 - 2019 Palisades archival data for operation efficiency analyses showing that potential efficiency improvements due to improved optimization, while meeting the actual power versus time, are modest, ranging from a low of 0.20% for 2020 to a high of 0.39% for 2019, with a three-year total Lost Energy Opportunity of 7,210 MWh and a three-year total Lost Revenue Opportunity of $213,559.

Efficiency Loss Events:

The identification of Efficiency Loss Events is an important component of the operation efficiency analyses. An Efficiency Loss Event occurs when the optimized dispatch remains constant for multiple time steps, and the gain in energy due to optimization is greater than a chosen threshold. Typically, Efficiency Loss Events are the most easily obtainable efficiency improvements due to optimized dispatch. March and Wolff [2021b] describes results from the 2018 - 2021 operation efficiency analyses for Palisades, which were also reviewed for Efficiency Loss Events with the threshold set at 50 MWh. At Palisades, the major Efficiency Loss Events constituted approximately 2/3 of the potential improvements identified by the operation efficiency analyses. The events occur because too many or two few units are operating, because the units are not operating at equal loads, or both. This potential for increased generation from improved optimization could be achieved without any significant effect on the number of start/stops for the Palisades units.

3.3 Generation Scheduling Analyses

Generation Scheduling Results:

March et al. [2017], March et al. [2019a], and March et al. [2019b] provide results from initial generation scheduling analyses for Flaming Gorge and Palisades. Initial generation scheduling analyses for Flaming Gorge show the potential for significant annual improvements from improved scheduling, corresponding to an increase in power revenue of $210,000/year. Similarly, the initial generation scheduling analyses for Palisades show the potential for significant annual improvements from improved scheduling with the new units, corresponding to an increase in power revenue of $277,000/year. March and Wolff [2021a] provides results from 2018 - 2019 generation scheduling analyses for Flaming Gorge, showing the potential for significant annual improvements of approximately 1.0%, corresponding to a generation increase of 10,546 MWh and a power revenue increase of $312,366 for 2018 - 2019. March and Wolff [2021b] provides results from 2018 - 2021 performance analyses for Palisades, showing potential efficiency improvements due to improved generation scheduling which range from a low of 0.57% for 2018 (partial year) to a high of 1.98% for 2021 (partial year), with a three-year total Lost Energy Opportunity of 21,557 MWh and a three-year total Lost Revenue Opportunity of $638,519. Opportunities for scheduling improvements at Palisades occur primarily during October to April in each year.

Recommended Operating Points:

Table 3.1 provides recommended best efficiency operating points for Flaming Gorge versus gross head, and Table 3.2 provides recommended best efficiency operating points for Palisades versus net head. These operating points for both plants can help Reclamation to achieve some or most of the potential generation improvements from improved scheduling. When multiple units are operating at either plant, the load should be split equally among the units.

Table 3.1: Recommended Best Efficiency Operating Points for Flaming Gorge versus Gross Head

Gross Head (ft)	Number of Units Operating	Plant Power (MW)	Plant Flow (cfs)
410	1	37	1,161
410	2	74	2,322
410	3	111	3,483
420	1	37.5	1,145
420	2	75	2,290
420	3	112.5	3,435
430	1	38	1,132
430	2	76	2,264
430	3	114	3,396
440	1	39	1,140
440	2	78	2,280
440	3	117	3,420

(Note: When multiple units are operating, the load should be split equally among units.)

Table 3.2: Recommended Best Efficiency Operating Points for Palisades versus Net Head

Net Head (ft)	Number of Units Operating	Plant Power (MW)	Plant Flow (cfs)
135	1	25	2,393
135	2	50	4,787
135	3	75	7,180
135	4	89	8,494
145	1	25	2,233
145	2	50	4,415
145	3	75	6,698
145	4	99	8,845
155	1	28	2,325
155	2	56	4,649
155	3	84	6,974
155	4	111	9,227
165	1	27	2,130
165	2	54	4,260
165	3	80	6,310
165	4	107	8,440
175	1	27	1,991
175	2	54	3,982
175	3	82	6,047
175	4	108	7,965
185	1	28	1,927
185	2	56	3,854
185	3	85	5,849
185	4	114	7,844
195	1	32	2,078
195	2	64	4,156
195	3	96	6,235
195	4	128	8,313
205	1	35	2,176
205	2	70	4,353
205	3	106	6,591
205	4	141	8,767
215	1	35	2,073
215	2	70	4,146
215	3	106	6,278
215	4	141	8,351
225	1	36	2,032
225	2	72	4,065
225	3	108	6,097
225	4	145	8,186
235	1	39	2,113
235	2	78	4,225
235	3	118	6,392
235	4	156	8,450
245	1	43	2,230
245	2	86	4,461
245	3	128	6,639
245	4	171	8,869

(Note: When multiple units are operating, the load should be split equally among units.)

4. Recommendations Based on Performance Analyses

Reclamation's hydroelectric power plants, including Flaming Gorge and Palisades, typically have high quality, well-maintained instrumentation for the plants' on-line systems, including multi-path acoustic flowmeters for each unit. Consequently, Reclamation's plants produce an accurate and valuable archival data set. Gaps that were identified as part of these performance analyses, and recommendations based on those gaps, include the following:

1. Based on results from Flaming Gorge and Palisades, Reclamation should consider computing and reviewing hydro performance indicators for each plant in the Reclamation system. Three important performance indicators for consideration include flow correlation analyses, operation efficiency analyses, and generation scheduling analyses.
2. Reclamation should consider computing and reviewing flow correlation analyses for each plant on a monthly basis to ensure that unit characteristics are accurate over the entire operational range and that the unit instrumentation is functioning properly. Results from Flaming Gorge and Palisades demonstrate that flow correlation analyses can identify problems with performance-related instrumentation (such as the multi-path acoustic flowmeters), provide an indication of trash rack fouling, and provide guidance if additional field performance testing is necessary.
3. Reclamation should consider computing and reviewing operation efficiencies for each plant on monthly intervals. This would help to ensure that the unit dispatch is well optimized for all plants.
4. For Palisades, major Efficiency Loss Events, constituted approximately 2/3 of the potential improvements identified by the operation efficiency analyses. These events occurred because too many or too few units were operating, because the units were not operating at equal loads, or both. This increased generation from improved optimization could be achieved without any significant effect on the number of start/stops for the Palisades units. The identification of Efficiency Loss Events is an important component of the operation efficiency analyses, and the methodology can be applied to other Reclamation plants.
5. Reclamation should consider implementing the methodology of Osburn [2014] to develop estimates of start/stop costs that are specific to Flaming Gorge and Palisades. This would help to ensure improved evaluation of the start/stop-related maintenance costs compared to the potential benefits from optimization improvements. The methodology can also be applied to other Reclamation plants.
6. Reclamation and its partners should consider modifications to the generation scheduling for Flaming Gorge and Palisades. Recommended best efficiency operating points versus head are provided in Section 3.3 for these plants. Where the optimized plant power scheduling is feasible, Reclamation should consider computing and reviewing the generation scheduling efficiencies on a monthly basis to ensure that the generation scheduling is well optimized. If successfully implemented at these plants, Reclamation should extend the practices and procedures to additional plants.
7. Results from Palisades Unit 2 and Unit 4 showed close agreement between flows measured with Winter-Kennedy flowmeters and flows measured with multi-path acoustic flowmeters. A comparison of Winter-Kennedy flowmeters and multi-path acoustic flowmeters could be conducted for the Palisades units and at other Reclamation plants to determine long term stability and relative maintenance costs.

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Appendix A

Technical Memorandum TM1901

Quantifying the Potential Value of Unit Characteristics
Based on Field Efficiency Tests and Archival Data Analyses

July 2019

Technical Memorandum TM1901

Quantifying the Potential Value of Unit Characteristics Based on Field Efficiency Tests and Archival Data Analyses

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Do nominally identical units have identical performance characteristics for each unit? Can detailed analyses of archival unit data provide useful performance characteristics? Compared to a turbine manufacturer's predicted performance, do characteristics based on field tests or archival data analyses provide additional value for optimizing multiunit hydroplants? To answer these questions, the U. S. Bureau of Reclamation has conducted investigations at two multiunit hydroplants, the 150 MW Flaming Gorge Project and the 176 MW Palisades Project. Flaming Gorge units were upgraded, and expected performance characteristics were supplied by the turbine manufacturer. Detailed unit efficiency tests were conducted for Flaming Gorge Units 1-3 in November 2015. Modified Flaming Gorge unit characteristics were developed from hourly archival data (i.e., HW, TW, unit power, unit flow) for 2008-2015. Palisades Units 1-4 were upgraded, and expected performance characteristics were supplied by the turbine manufacturer. Detailed unit efficiency tests were conducted for Palisades Unit 1 in June 2014 and for Units 1-4 in September 2018. Unit performance characteristics for Palisades were also developed from fifteen-minute archival data for 2014-2018. Optimization analyses compared actual unit operations for multiyear periods using unit performance characteristics based on the turbine manufacturers' predictions and characteristics based on multiyear archival data. Performance characteristics derived from archival data correlated well with field measurements for both plants. The manufacturer's curves and the derived performance curves correlated well for Palisades but showed an average annual energy difference of 1.6% for Flaming Gorge. Generation scheduling analyses showed the potential for significant annual improvements of $210,000/year at Flaming Gorge and $277,000/year at Palisades.

1. Introduction

Accurate unit and plant performance characteristics are essential for proper plant operation and optimization. Accurate flow measurement is a key component for determining accurate unit and plant performance characteristics, and careful attention to unit flow measurements can improve operational efficiencies and generation [EPRI, 2015]. In addition, the unit and plant performance information must be properly utilized by operators and/or control systems. For example, during unit upgrades proper performance management requires application of old and new unit characteristics in a timely manner to maximize plant efficiency and generation.

Typically, owners/operators of hydroelectric powerplants assume that a "family" of nominally identical units has identical performance characteristics for each unit. However, multiple factors can influence a unit's performance and affect the validity of that assumption. For example, differences in construction of intakes, penstocks, spiral cases, stay vanes, wicket gates, throat rings, and draft tubes can lead to performance differences among units with identical turbine designs. Performance for individual units can be significantly affected by the cleanliness of trash racks, as demonstrated by previous analyses of the USBR's three-unit Flaming Gorge plant [March et al., 2012]. Turbine fabrication errors, different operating experiences, and different maintenance experiences (e.g., cavitation repairs) can impact the performance of nominally identical units. Localized irregularities in composition can lead to localized cavitation damage, blade distortion, and blade cracking, which can also affect performance adversely. In addition, unit performance results may be obtained at a few opportunistic heads and then scaled across the full operational range, leading to potential errors in plant optimization, reduced generation, and reduced water in storage.

3. Description of Plants

2.1 Flaming Gorge Dam and Powerplant

The USBR's Flaming Gorge Dam and Powerplant was selected for the initial case study of a research project to evaluate and quantify potential operational and maintenance-related optimization benefits from detailed unit performance testing and optimized dispatch at several USBR hydropower facilities. Flaming Gorge Dam and Powerplant is located on the Green River in Daggett County, Utah. The Flaming Gorge Reservoir has a capacity of 3,788,700 acre-ft, and the plant has the 16th largest generation capacity (151 MW) among the 53 USBR plants. Flaming Gorge was constructed as part of the Colorado River Storage Project (CRSP) to provide storage and distribution of water to the upper Colorado River basin. Construction on the dam began in 1958, and Flaming Gorge was commissioned for operation in 1964.

The plant has three Francis turbine generating units. Originally, each unit had a rating of 36 MW. The generators were uprated between 1990 and 1992, and the turbines were modernized between 2005 and 2007. The current rating for each unit is 50 MW at a design net head of 440 ft. In addition, three large selective withdrawal structures were installed on the upstream face of the dam over the penstock intakes and trash rack structures in 1978, and the GSU transformers were replaced with larger capacity transformers in 2001. Some results from the initial case study analyses are reported elsewhere [March et al., 2012; March et al., 2017]. Figure 2-1 shows a photograph of the Flaming Gorge Dam and Powerplant.

Figure 2-1: USBR's Flaming Gorge Dam and Powerplant

2.2 Palisades Dam and Powerplant

The USBR's Palisades Dam and Powerplant, shown in Figure 2-2, was selected for an additional case study. Palisades is located on the Snake River in eastern Idaho, near the Idaho-Wyoming border. The Palisades Reservoir has a capacity of 1,200,000 acre feet, and the Palisades Powerplant has the 13th largest generation capacity among the 53 USBR plants. The plant currently has four Francis turbine generating units producing 44 MW at a head of 225 ft, with an average annual plant generation of 906,720 GWh. During the period of archival data for this paper (June 21, 2006, through August 31, 2016), Units 1, 3, and 4 were upgraded with new turbines. Unit 2 was also upgraded later in 2016.

Figure 2-2: USBR's Palisades Dam and Powerplant

3. Related Literature

There has been relatively little treatment in the technical literature of the potential benefits from detailed performance testing for each one of a set of nominally identical units. Lamy and Néron [2003] discuss a variation of the pressure-time methodology as an approach to reducing field test costs for measuring performance of each unit at multiunit hydroplants. The authors note, "…tests done in different powerhouses at Hydro-Québec have shown that turbines assumed to be identical often have non-negligible differences in their turbine efficiency. This is particularly true for units produced before modern day blade manufacturing techniques using numerically controlled machine tools. Hydro-Québec is now turning to using individualized unit efficiency curves to improve plant efficiency [Lamy and Néron, 2003]." Curves are provided for each individual unit at three plants, including a five-unit plant, a nine-unit plant, and an eight-unit plant. For the five-unit plant (noted as "a plant in which particularly large differences in turbine efficiency are present amongst units reputed to be identical"), turbine efficiencies varied from 92.1% to 92.5%, and turbine power levels at best efficiency varied from 43 MW to 46 MW. For the nine-unit plant, turbine efficiencies varied from 95.0% to 95.3%, and turbine power levels at best efficiency varied from 264 MW to 270 MW. For the eight-unit plant, turbine efficiencies varied from 93.8% to 94.6%, and turbine power levels at best efficiency varied from 290 MW to

305 MW. Unfortunately, the scatter associated with the actual test data for these three plants is not provided in the paper, no statistical analyses are provided, and no quantification is provided for the potential benefits from utilizing the individual unit characteristics.

Similar to Lamy and Néron [2003], Almquist et al. [2005] examines the relatively inexpensive implementation of variations on the pressure-time methodology for comparing the performance among units of nominally identical design. Four variations were examined, and a preferred low-cost method called the "simple biased method" was identified for additional examination. However, only the standard code-compliant (see [ASME, 2011]) pressure-time methodology provided consistent, accurate results. Almquist et al. [2005] provides no quantification for the potential benefits from utilizing individual unit characteristics.

EPRI [2015] presents the first comprehensive examination of the effects of uncertainty in unit characteristics on the optimization of multiunit hydroplants. Operational data and unit performance data from sixteen hydroelectric plants analyzed during previous studies provided the basis for scaled unit characteristics in generalized two-unit, three-unit, five-unit, and seven-unit plant configurations with Francis units, diagonal flow units, fixed propeller units, and Kaplan units. Operational data from the sixteen hydroelectric plants also formed the basis for generalized annual generation patterns. Three annual generation patterns, including an hourly generation pattern, a moderate automatic generation control (AGC) generation pattern, and a heavy AGC generation pattern, were developed from the data. Operation and optimization for the two-unit, three-unit, five-unit, and seven-unit plant configurations were evaluated under the hourly generation pattern and the moderate AGC generation pattern with unit performance uncertainties of 1%, 2.5%, and 5% and with unit commitments based on equal unit power, simple operational rules, and unconstrained optimization. EPRI [2015] concludes that energy losses and revenue losses due to uncertainty in unit characteristics can be substantial for multiunit plants. For the plant configurations and unit types included in the analyses, annual energy losses based on flow modification uncertainties and power modification uncertainties are similar. For Francis plants, annual energy losses vary with assumed uncertainty from approximately 0.3%–1.2% for the two-unit plant configuration, from approximately 0.2%–1.3% for the three-unit plant configuration, from approximately 0.2%–1.4% for the five-unit plant configuration, and from approximately 0.3%-1.5% for the seven-unit plant configuration. Results demonstrate that optimized dispatch is an effective hedge against the potential for energy losses and revenue losses due to uncertainty in unit characteristics. The Francis unit results from the evaluations are also provided in March et al. [2016].

4. Overview of Performance Analyses

The performance analyses computed for this paper are based on a set of tools to quantify unit and plant performance and to enable the investigation of potential opportunities for operations-based and equipment-based performance improvements, leading to additional generation. The following subsections briefly address the processes and methodologies used for the quantitative performance analyses. Additional details are available in ORNL [2011], EPRI [2015], and elsewhere [March and Wolff, 2003; March and Wolff, 2004; EPRI, 2008; EPRI, 2012a; EPRI, 2012b; EPRI, 2012c; EPRI, 2012d; March et al., 2012; March et al., 2014; EPRI, 2014; March et al., 2016].

4.1 Data for Performance Analyses

The primary data required for performance analyses include unit characteristics and facility operational data, which are discussed in this subsection.

Hydroelectric generating facilities convert the potential energy of stored water and the kinetic energy of flowing water into a useful form, electricity. This fundamental process for a hydroelectric generating unit is described by the generating efficiency equation, defined as the ratio of the power delivered by the unit to the power of the water passing through the unit. The general expression for the efficiency (η) is

$$\eta = \frac{P}{\rho g Q H}$$

where P is the output power, ρ is the density of water, g is the acceleration of gravity, Q is the water flow rate through the unit, and H is the head across the unit.

Efficiency curves provide guidance for the effective use of a hydropower unit or facility. The points of most efficient operation can be identified, and the efficiency penalty for operating away from the optimum can be quantified and evaluated relative to the potential economic benefits from generating at a different power level.

Typically, facility operational data is obtained from multiple sources, including plant personnel, central engineering staff, and load control personnel. The essential operational data for correlation analyses, operation efficiency analyses, and generation scheduling analyses include:

1. Timestamp;
2. Unit Power;
3. Unit Flow;
4. Headwater Level;
5. Tailwater Level; and
6. Unit Status (e.g., available, unavailable, condensing).

Figure 4-1 provides an example of unit characteristics previously computed from operational data for Flaming Gorge Unit 1 [March et al., 2012]. The expected efficiency versus unit power level is shown as the red line, and the measured efficiencies versus the unit power levels are shown as the blue triangles. The results indicate that the performance for the unit is approximately 1% lower than the expected performance, and the shape for the actual efficiency curve is somewhat flatter than expected. Figure 4-1 also shows limited performance results from flow measurements for Unit 1 before it was upgraded, providing a graphic indication of the significant performance gains achieved by the upgrade at Flaming Gorge.

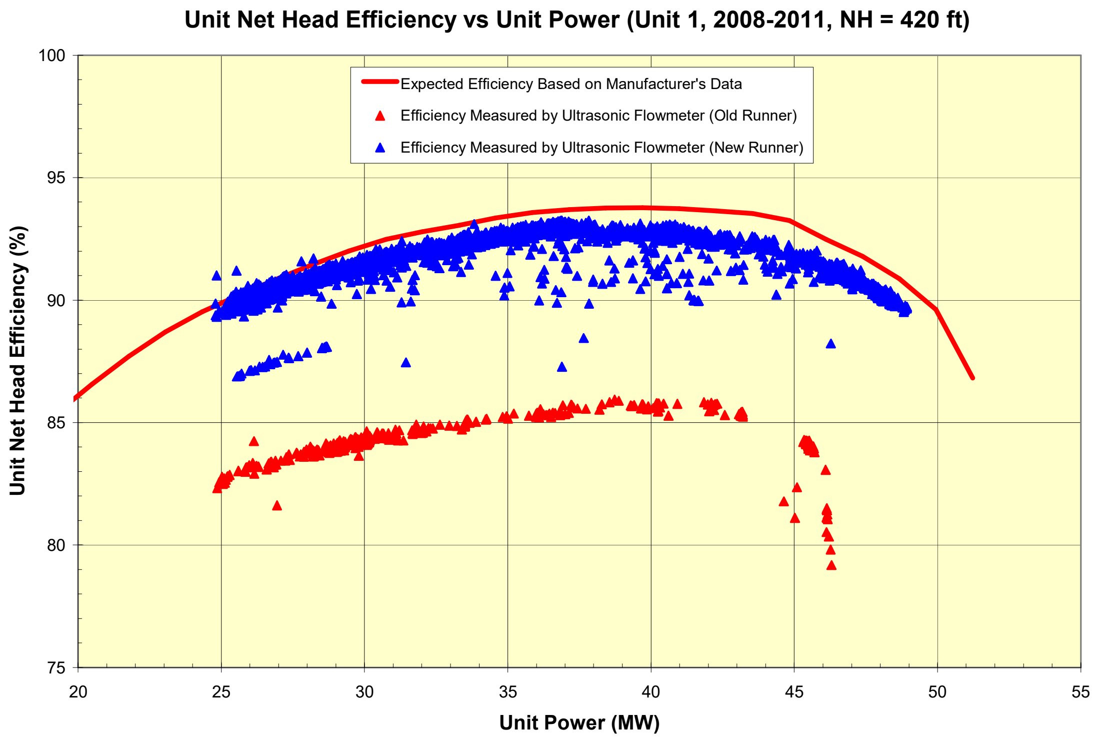

Figure 4-1: Example of Expected and Measured Efficiency versus Power

4.2 Tools for Performance Analyses

The primary tool used for conducting performance analyses is the Hydroplant Performance Calculator (HPC). The HPC was developed to enable standardized metrics for hydro plant performance [March et al., 2014]. The Hydroplant Performance Calculator includes: (1) a setup module, HPC PlantBuilder, for developing unit and plant performance characteristics; and (2) a multi-unit optimization and analysis module, HPC Analyzer, for calculating operation efficiencies, generation scheduling analyses, and flow analyses. The data needs for HPC PlantBuilder and HPC Analyzer include unit performance data and facility operational data, as described in Section 4-1.

Figure 4-2 provides a graphical overview of HPC PlantBuilder, and Figure 4-3 provides a graphic overview of HPC Analyzer.

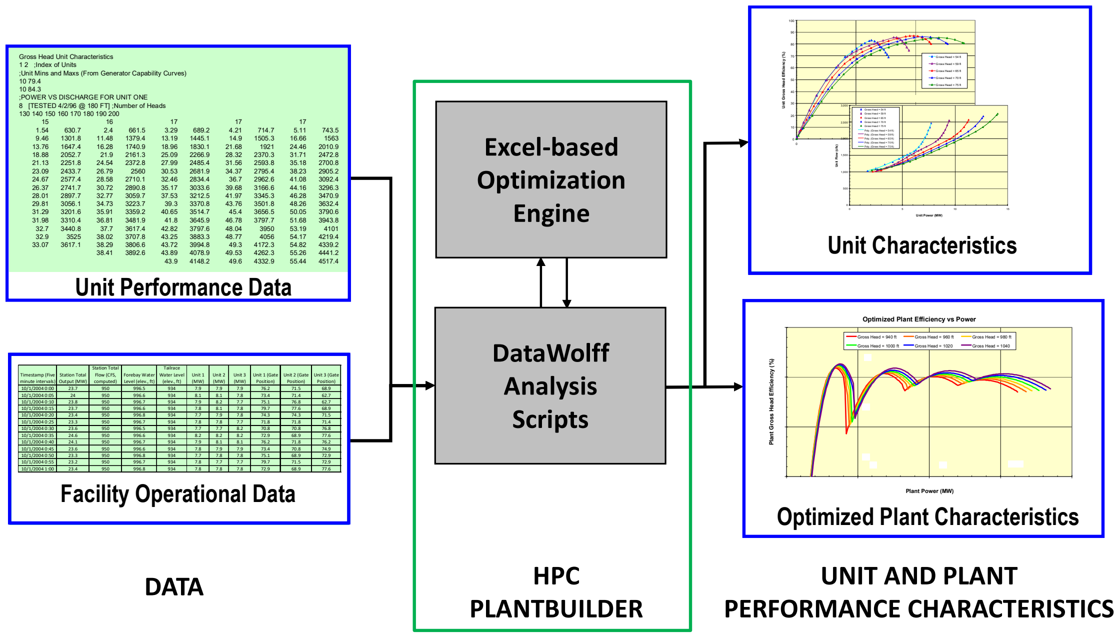

Figure 4-2: Overview of HPC PlantBuilder

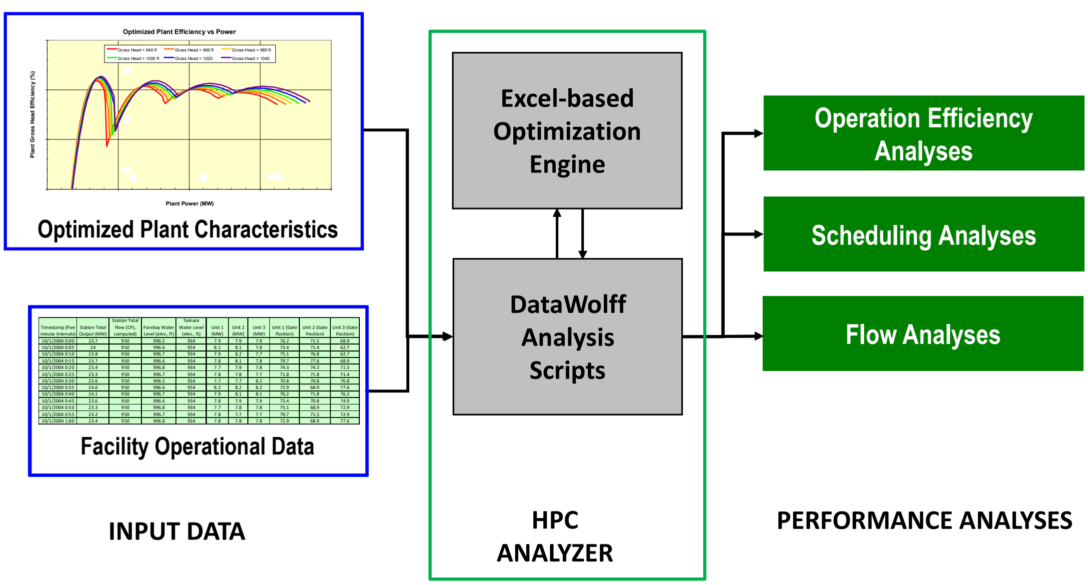

Figure 4-3: Overview of HPC Analyzer

Input data for the HPC PlantBuilder includes unit performance data (generator efficiency; turbine power and turbine flow versus head) and facility operational data (unit power and head versus time; unit flow versus time). The input data for HPC PlantBuilder also includes plant latitude, plant elevation at the turbine centerline, and average water temperature. These values are used to compute the acceleration of gravity, g, and the water density, ρ [ASME, 2011]. Additional details are available in EPRI [2015] and elsewhere [March et al., 2012; March et al., 2014; EPRI, 2014]. An Excel interface for HPC PlantBuilder provides an efficient, consistent, and systematic approach to creating unit and plant performance characteristics from performance data and plant operational data.

Input data for the HPC Analyzer includes optimized plant performance data, as computed by HPC PlantBuilder, and facility operational data (unit power and head versus time). For this paper, HPC Analyzer was used to compute operation efficiency analyses and generation scheduling analyses, as described in ORNL [2011] and March et al. [2014].

5. Results from Performance Analyses

5.1 Flow Correlation Analyses

Flaming Gorge: Hourly measurements of flow rate (cfs) from ultrasonic time-of-flight flowmeters were available for each unit at Flaming Gorge for the period from January 2008 through November 2015. Additional hourly measurements included unit power (MW), headwater elevation (ft), and tailwater elevation (ft). Flow correlation analyses were used to derive unit performance characteristics for comparison with expected unit performance characteristics from the turbine manufacturer (VA TECH) and measured unit efficiencies from field performance tests conducted by USBR personnel in November 2015.

Figure 5-1 provides results from the flow correlation analyses for Flaming Gorge Unit 1, using archival data from January 2008 through November 2015. The red line in Figure 5-1 shows the computed Unit 1 efficiency curve at a gross head of 420 ft, derived from 2008-2015 hourly archival data for unit flow, unit power, headwater, and tailwater. The small blue triangles show average efficiency values computed from the archival data at 0.5 MW intervals, and the black error bars show the precision error for the 2008-2015 archival data for the given power level. Below about 25 MW, significant scatter can be observed in the efficiency results because operation in this range is typically a transient condition during ramp-up and ramp-down. Consequently, the hourly flow data is not adequate to characterize these transitions. The green triangles show the Unit 1 efficiencies measured during the November 2015 field performance tests. The unit efficiencies from the field tests agree closely with the efficiencies derived from the archival data.

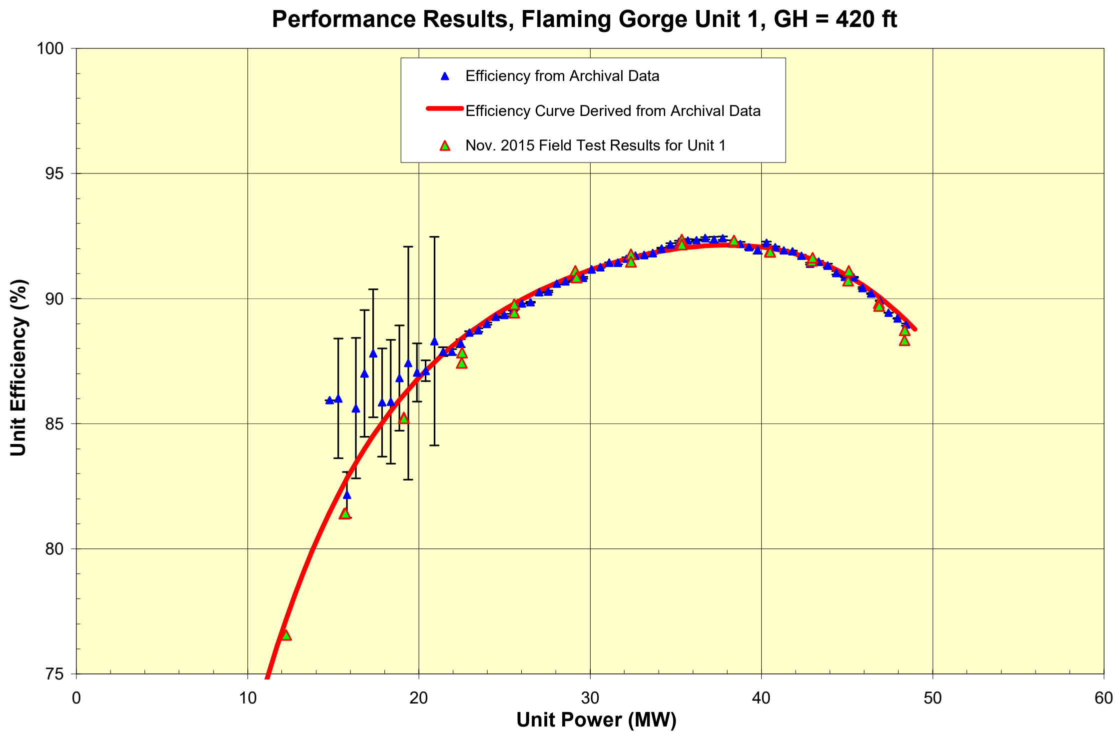

Figure 5-1: Performance Results for Flaming Gorge Unit 1 (Gross Head = 420 ft)

Similarly, Figures 5-2 and 5-3 provide results from the flow correlation analyses for Flaming Gorge Unit 2 and Unit 3, respectively. As with Unit 1, the unit efficiencies from the field tests for Unit 2 and Unit 3 agree closely with the corresponding derived efficiencies. For Unit 2, additional scatter in the derived efficiency values can be observed in some of the data above a power level of 25 MW. Similar results, observed with previous 2008-2011 analyses of Flaming Gorge archival data for Unit 2, were attributed to occasional trash rack fouling events [March et al., 2012].

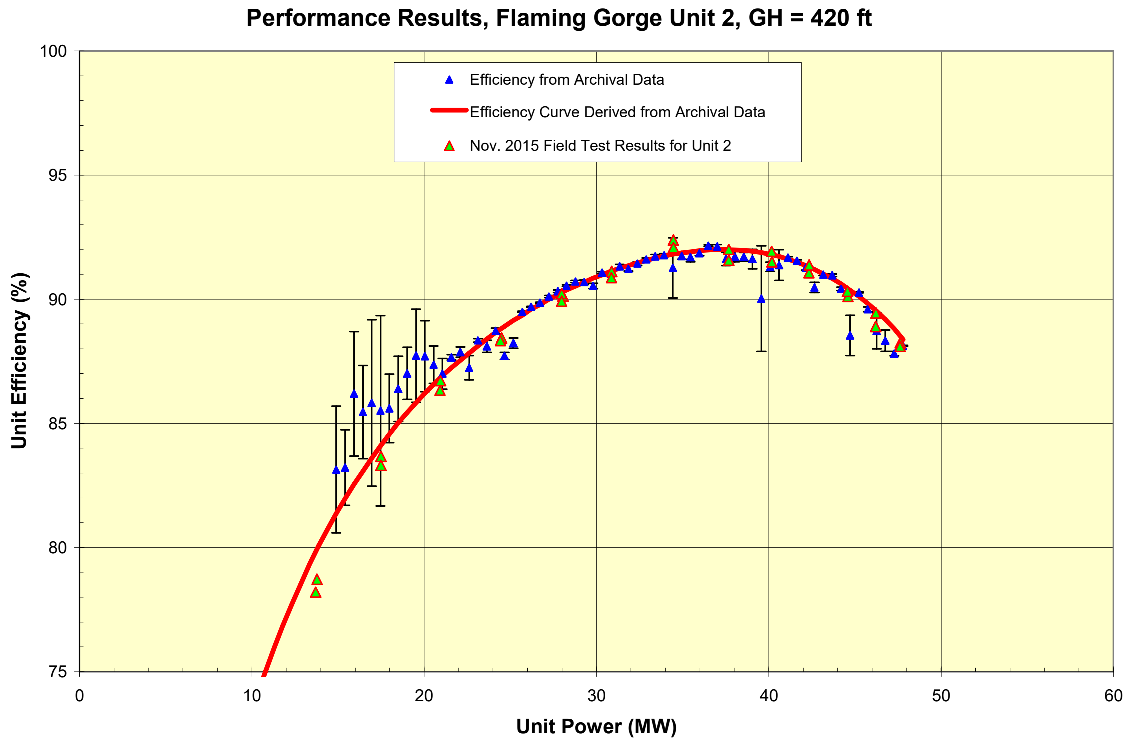

Figure 5-2: Performance Results for Flaming Gorge Unit 2 (Gross Head = 420 ft)

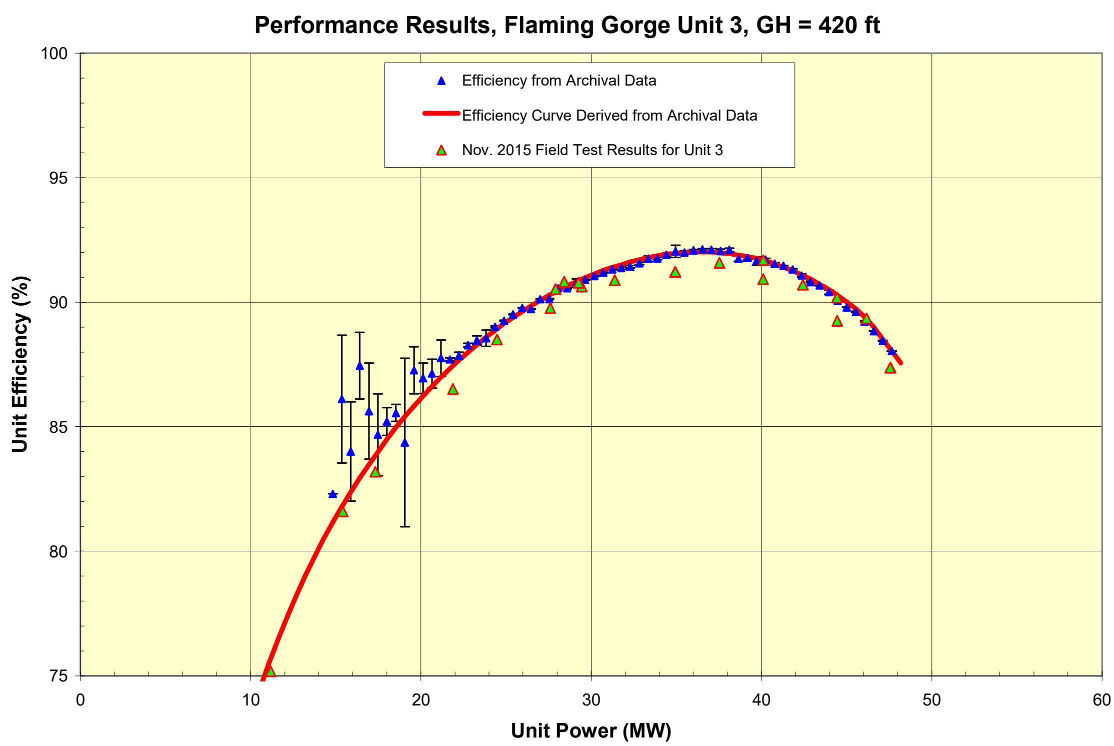

Figure 5-3: Performance Results for Flaming Gorge Unit 3 (Gross Head = 420 ft)

Figure 5-4 shows a comparison among curve fits of performance results for Flaming Gorge at a gross head of 420 ft. The red line in Figure 5-4 is the expected performance provided by the turbine manufacturer. The blue line shows the Unit 1 derived performance curve from the 2008 – 2015 archival data, the green line shows the Unit 2 derived performance curve, and the gold line shows the Unit 3 derived performance curve.

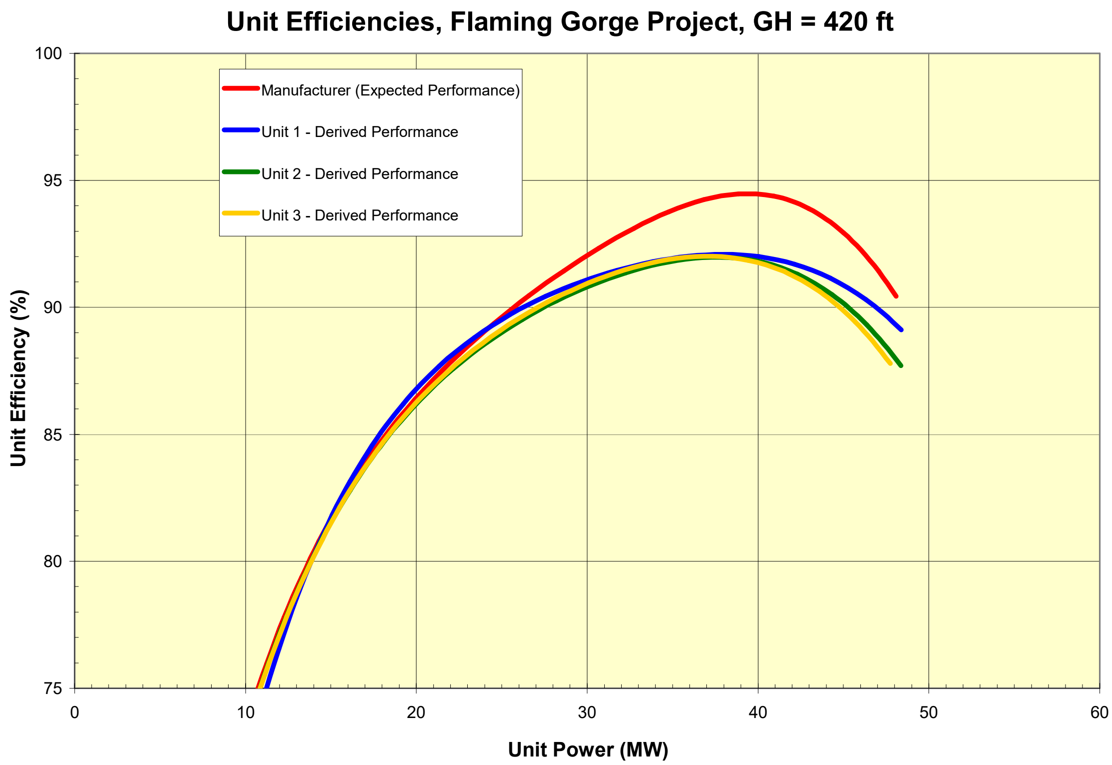

Figure 5-4: Comparison of Unit Performance Curves for Flaming Gorge (Gross Head = 420 ft)

The Hydroplant Performance Calculator was used to develop optimized plant efficiency curves based on the unit characteristics from the turbine manufacturer and based on the derived unit characteristics. Typical optimized plant efficiency curves for Flaming Gorge, at a gross head of 420 ft, are provided in Figure 5-5. Note the shift in the power levels for minimum and maximum values of optimized plant efficiency for the turbine manufacturer’s efficiency curve compared to the derived efficiency curve.

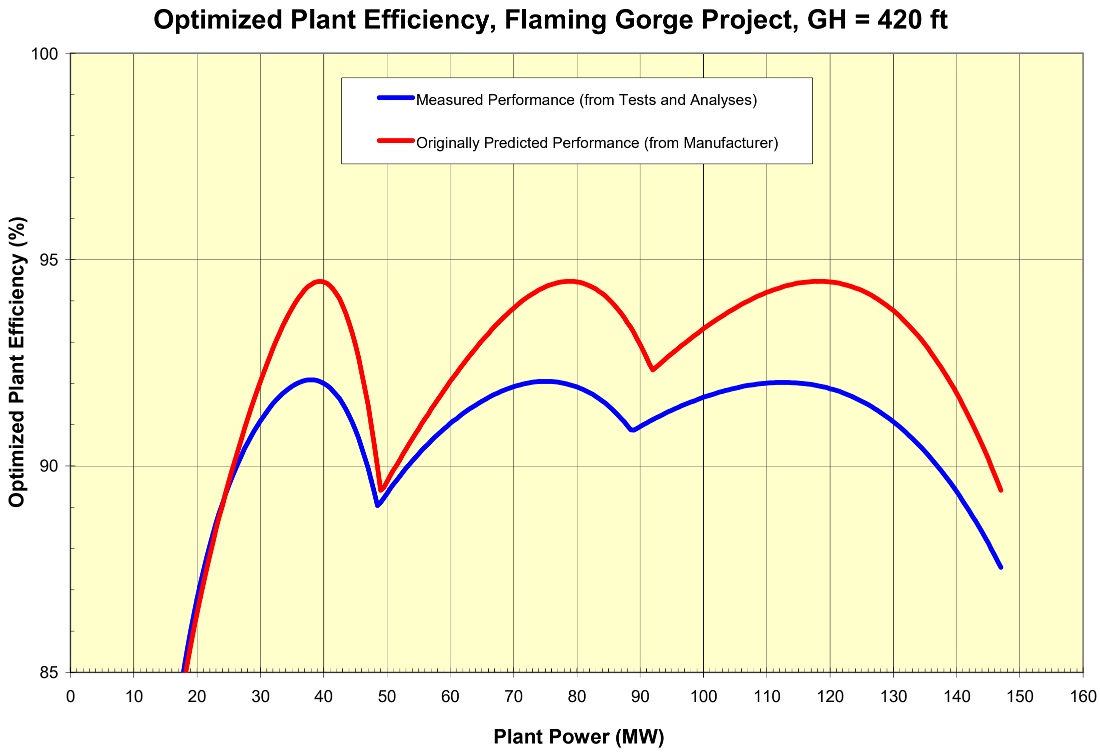

Figure 5-5: Comparison of Plant Performance Curves for Flaming Gorge (Gross Head = 420 ft)

Palisades: Fifteen-minute measurements of flow rate (cfs) from ultrasonic time-of-flight flowmeters were available for each unit at Palisades for the period from June 2006 through July 2015. Additional fifteen-minute measurements included unit power (MW), headwater elevation (ft), and tailwater elevation (ft). Correlation analyses were used to derive unit performance characteristics for comparison with expected unit performance characteristics from the turbine manufacturer (Andritz) and measured unit efficiencies from field performance tests field performance tests conducted by USBR personnel for Unit 2 (original unit) in December 2008, for Unit 1 in November 2014, and for Units 1 - 4 (new units) in September 2018.

Multiyear energy production analyses have shown that most of Palisades' generation occurs at a net head of 225 ft. Figure 5-6 provides results from the flow analyses for Palisades Unit 1 (new unit), using archival data from September 2013 through May 2015. The red line in Figure 5-6 shows the computed Unit 1 efficiency curve at a net head of 225 ft, derived from fifteen-minute archival data for unit flow, unit power, headwater, and tailwater. The green line in Figure 5-6 shows the efficiency curve provided by the turbine manufacturer. The small blue triangles show average efficiency values computed from the archival data at 0.5 MW intervals, and the black error bars show the precision error in the archival data for the given power level. The efficiency curve derived from the archival data agrees closely with the efficiency curve provided by the turbine manufacturer.

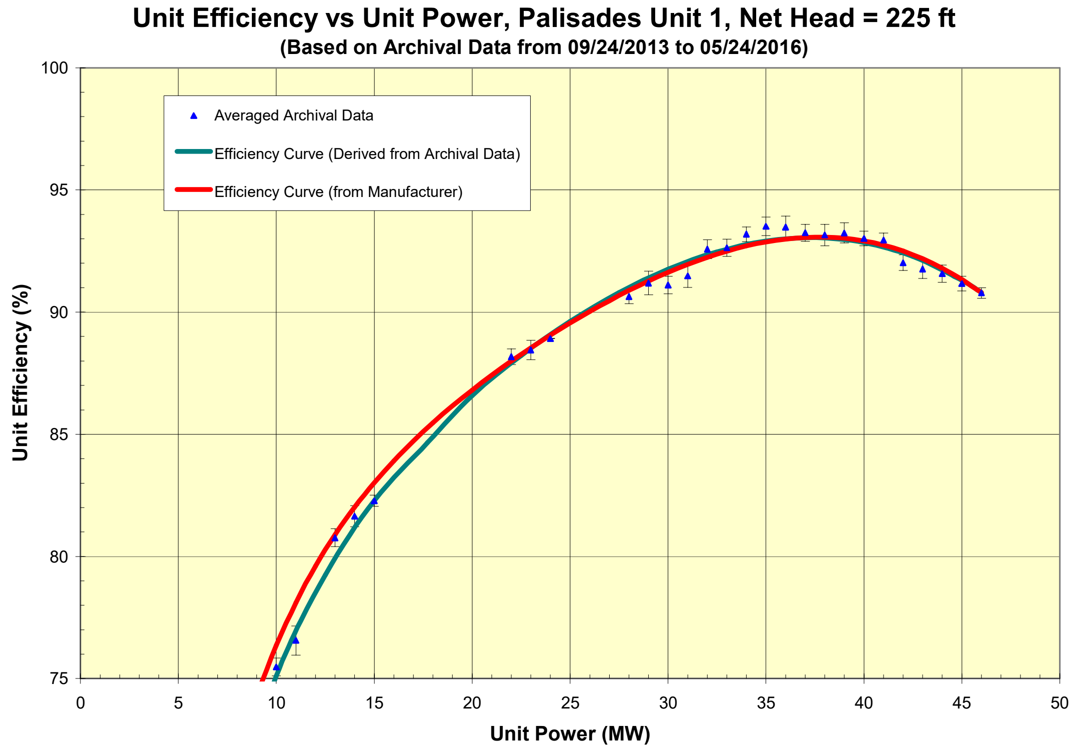

Figure 5-6: Performance Results for Palisades Unit 1 (Net Head = 225 ft)

Similarly, Figure 5-7 provides results from the flow analyses for Palisades Unit 2 (new unit) at a net head of 225 ft, based on archival data from June 2006 through July 2015. As with Unit 1, the Unit 2 (new unit) efficiency curve derived from the archival data (green line) agrees closely with the efficiency curve provided by the turbine manufacturer (red line). Similar results were also obtained for Palisades Unit 3 (new unit) and Unit 4 (new unit). Figure 5-7 shows the reasonable agreement between the efficiency values computed from archival data for Unit 2 (original unit, blue triangles) and the expected efficiency curve based on USBR flow tables (red dotted line) for the original units.

Figure 5-8 provides results from the flow analyses for Palisades Unit 1 (new unit) at a net head of 205 ft based on archival data from June 2014 through July 2016. Similar to results at a net head of 225 ft, the efficiency curve derived from the archival data (green line) agrees closely with the efficiency curve provided by the turbine manufacturer (red line). Results from the Unit 1 field tests (new unit, June 2014, green triangles; new unit, September 2018, gold triangles) agree closely with the efficiency curve derived from the archival data and the efficiency curve supplied by the turbine manufacturer. Similar agreement among field tests, efficiency curves derived from the archival data, and efficiency curves supplied by the turbine manufacturer was also observed for Palisades Unit 2 (new unit), Unit 3 (new unit), and Unit 4 (new unit).

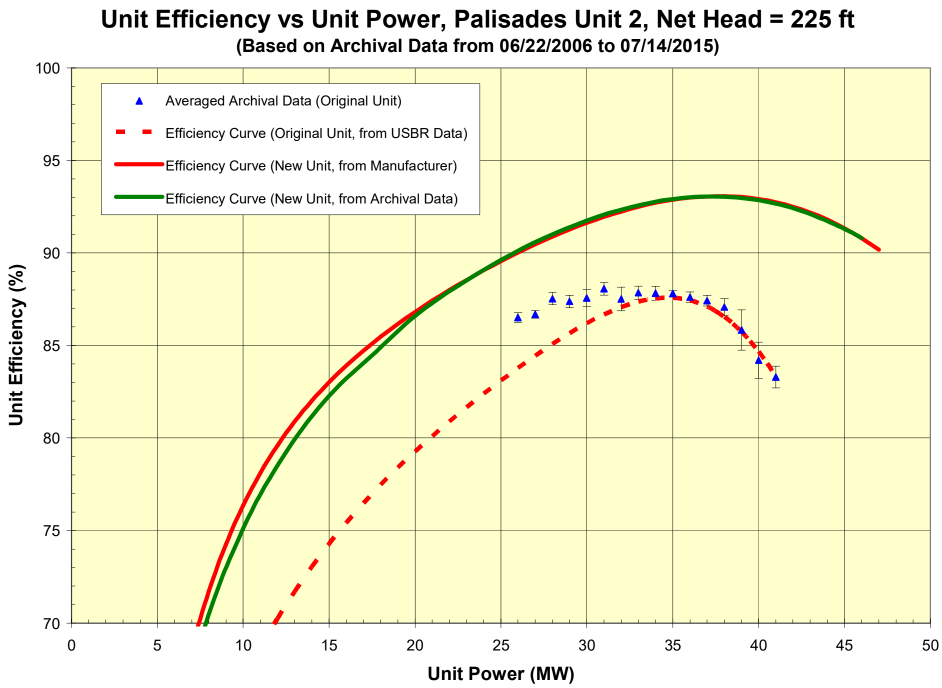

Figure 5-7: Performance Results for Palisades Unit 2 (Original Unit and New Unit) Net Head = 225 ft

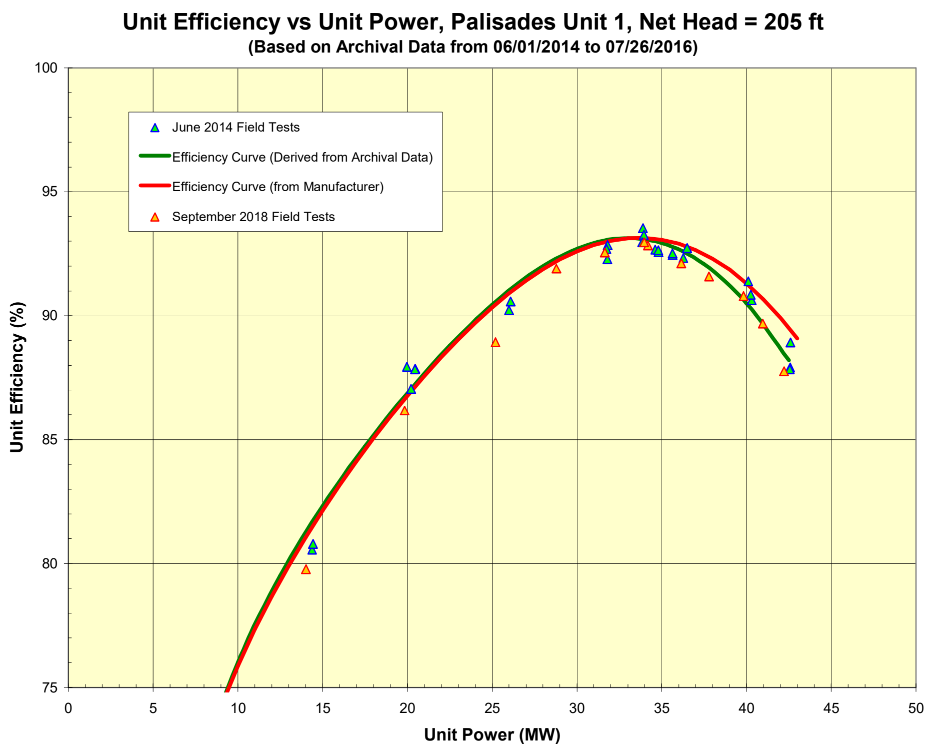

Figure 5-8: Performance Results for Palisades Unit 1, Net Head = 205 ft

Figure 5-9 provides efficiency values at a net head of 190 ft computed from archival data from August 2006 through September 2015 for Unit 2 (original unit, blue triangles), the expected efficiency curve based on USBR flow tables (red line) for the original units, and results from December 2008 field tests. The averaged efficiency values derived from the archival data are about one percent higher than the expected efficiencies from the USBR flow tables, and the efficiencies from the field tests are about one percent lower than the expected efficiencies.

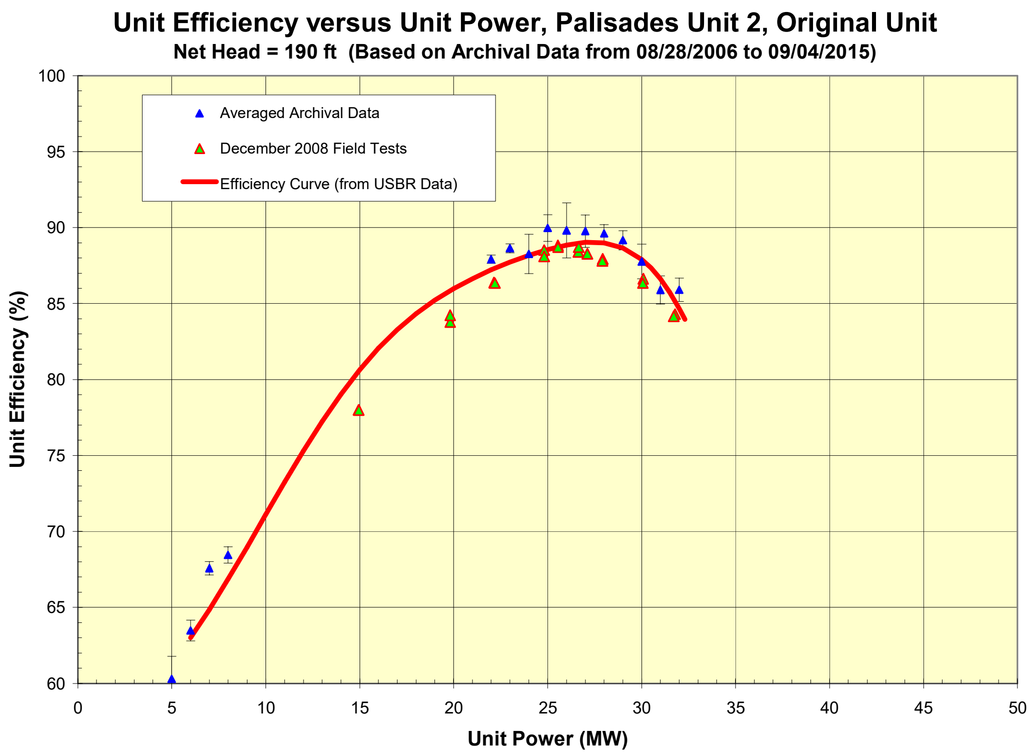

Figure 5-9: Performance Results for Palisades Unit 2, Original Unit
Net Head = 190 ft

Palisades Flow Method Comparisons: Piezometers called Winter-Kennedy taps are commonly positioned at inner and outer radii of the turbine scroll case and used to provide an effective and inexpensive measurement of relative flow rate [Winter, 1933; March and Almquist, 1995; ASME, 2011]. With properly designed and installed Winter-Kennedy taps, the flow rate is directly proportional to the square root of the differential pressure between the taps. During the September 2018 field tests, pressure differentials from Winter-Kennedy piezometers (using tap R2, inside radius of the scroll case, and tap R3, outside radius of the scroll case) for each Palisades unit were recorded for comparison with the corresponding multi-path ultrasonic flowmeter. The Winter-Kennedy differential pressures for Unit 1 and Unit 3 produced a varying Winter-Kennedy flow coefficient that trended upward with increasing flow rates, perhaps due to leaking piezometer lines or due to bad pressure measurements. For Unit 2 and Unit 4, the turbine manufacturer's value for flow rate at the best efficiency point and the tested head was used to calibrate the Winter-Kennedy flow coefficient for each unit. As shown in Figure 5-10, the flows measured with the Winter-Kennedy flowmeters corresponded closely to the flows measured with multi-path ultrasonic flowmeters for Palisades Unit 2 and Unit 4.

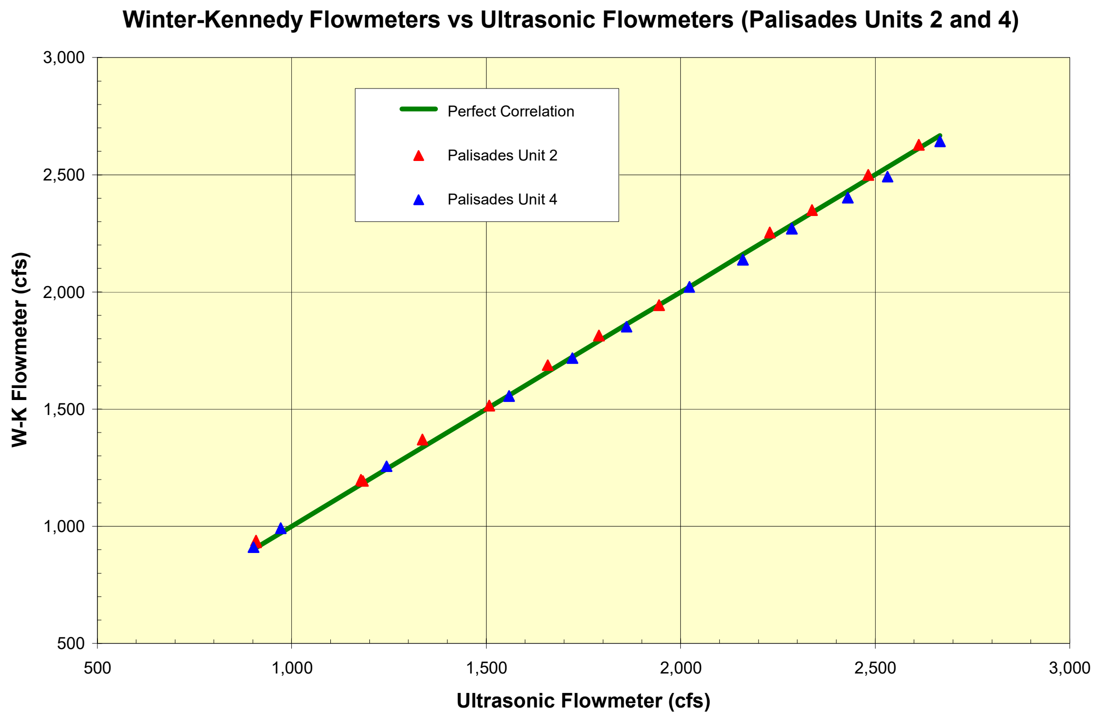

Figure 5-10: Comparison of Results from Winter-Kennedy Flowmeters and Ultrasonic Flowmeters for Palisades Unit 2 and Unit 4 (Based on September 2018 Field Tests)

5.2 Operation Efficiency Analyses

Operation efficiency analyses use unit efficiency characteristics and archival operations data to determine how closely the actual dispatch matches the optimized dispatch. Detailed computational steps for determining the operation efficiency are discussed elsewhere [ORNL, 2011]. At each time step of the archival data, the optimized plant efficiency is computed, apportioning the total plant power among the available units to maximize the plant efficiency while meeting the necessary constraints (e.g., matching the actual plant power, matching the head, and operating each unit within minimum and maximum power limits). Energy gains due to water savings from optimized dispatch are computed by assuming that the water is converted into energy at the optimized plant efficiency and head for the time step in which the computed energy gain occurs.

Flaming Gorge: Operation efficiency analyses were computed with the HPC for Flaming Gorge using the 2008-2015 hourly archival data of unit flow, unit power, headwater, and tailwater, the derived unit characteristics, and the optimized plant performance curves (see Figure 5-5). Results from these operation efficiency analyses are summarized in Table 5-1.

Table 5-1: Summary of Operation Efficiency Analyses for Flaming Gorge (2008-2015)

Year	Total Lost Energy Opportunity (MWh)	Total Lost Revenue Opportunity ($)	Total Water Conservation Opportunity (acre-ft)	Actual Energy Production (MWh)	Potential Increase in Energy Production (%)
2008	1,708	51,236	4,185	368,495	0.5
2009	997	29,907	2,402	457,274	0.2
2010	1,084	32,533	2,602	395,614	0.3
2011	3,198	95,954	7,544	674,662	0.5
2012	1,641	49,220	3,869	97,612	1.7
2013	809	24,283	2,002	299,601	0.3
2014	1,284	38,515	3,046	418,674	0.3
2015	1,988	59,646	4,720	450,339	0.4
TOTAL (2008-2015)	**12,710**	**381,293**	**30,370**	**3,162,271**	**0.4**

Overall, the potential efficiency improvements due to improved optimization, while meeting the actual power versus time, are modest, ranging from a low of 0.2% for 2008 to a high of 1.7% for 2012, with an average of 0.4% and an eight-year total of 12,710 MWh. The 1.7% efficiency improvement for 2012 is based on a partial data set that includes data from 1/1/2012 through 2/23/2012. The water conservation opportunity ranges from a low of 2,002 acre-ft/year for 2013 to a high of 7,544 acre-ft/year for 2011, with an eight-year total of 30,370 acre-ft.

Palisades: For the operation efficiency analyses, the HPC was used with efficiency curves derived from the fifteen-minute archival data for the upgraded turbines (Units 1, 3, and 4) and efficiency curves derived from the USBR flow tables for the original units. The analyses focus on three time periods, including: (1) 2008 through 2012, before any unit upgrades; (2) October 2, 2013, through October 31, 2017 (393 days), with Unit 1 upgraded, Units 2 and 3 not upgraded, and Unit 4 out of service; and (3) September 5, 2015, through July 21, 2016 (311 days), with Units 1, 3, and 4 upgraded and Unit 2 out of service. Optimized plant efficiency curves were computed for each combination of units.

Examples of the optimized plant efficiency curves at a net head of 225 ft are provided in Figure 5-11 for each of the three time periods and the corresponding unit configurations. For the first time period, four nominally identical (original) units were available, and the optimized plant efficiency curve in Figure 5-11 (red line) shows four peaks. The first peak corresponds to one-unit operation, the second peak corresponds to two-unit operation, and so forth. The peaks become broader as more units are added. For the second time period, one new unit (Unit 1) and two original units (Unit 2 and Unit 3) were available. The optimized plant efficiency curve in Figure 5-11 (green line) shows an initial, higher efficiency peak for Unit 1 operation (new unit), followed by two lower efficiency peaks corresponding to Units 2 and 3 (original units). For the third time period, three new units (Unit 1, Unit 3, and Unit 4) were available. The optimized plant efficiency curve in Figure 5-11 (blue line) shows a high efficiency peak for the first unit operation (Unit 1, Unit 3, or Unit 4), followed by two high efficiency peaks corresponding to the other two new units.

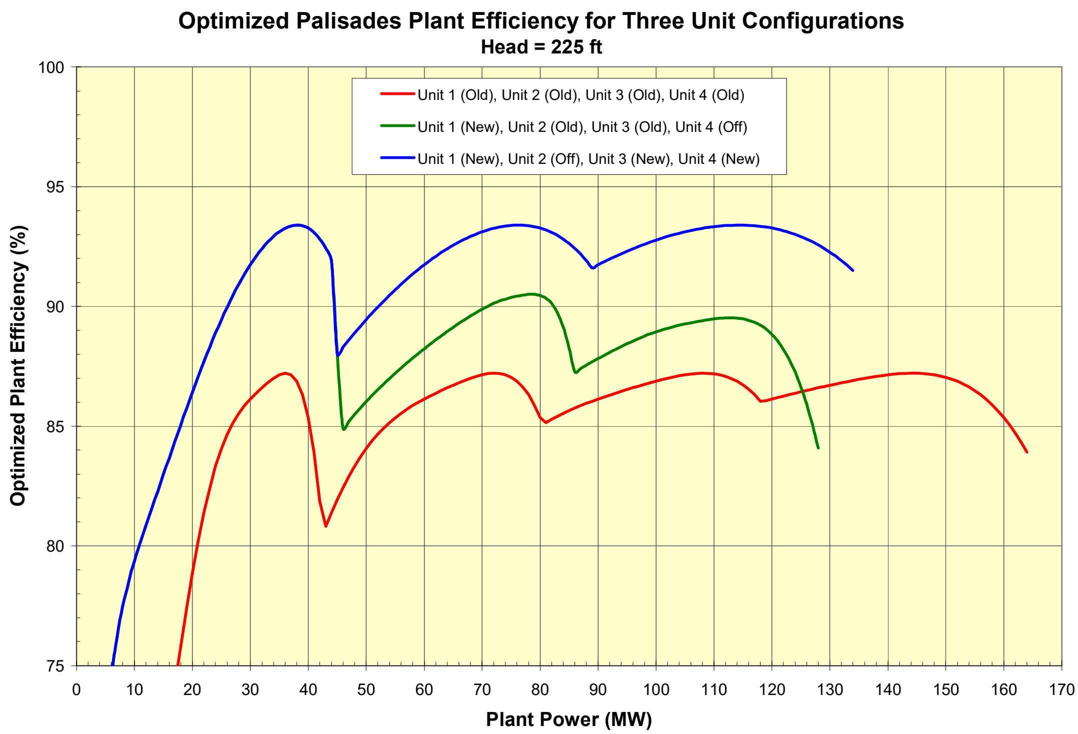

Figure 5-11: Optimized Palisades Plant Efficiency Curves for Three Analysis Periods

Operation efficiency analyses were computed with the HPC for the three Palisades unit configurations and the corresponding time periods. Results from the operation efficiency analyses for Palisades are summarized in Table 5-2 for the first (2008-2012) time period and in Table 5-3 for the second (October 2, 2013, through October 31, 2014) and third (September 5, 2015, through July 21, 2016) time periods.

Table 5-2: Summary of Operation Efficiency Analyses for Palisades (2008-2012)

Year	**Total Generation** (MWh)	**Lost Energy Opportunity** (MWh)	**Lost Revenue Opportunity** $	**Water Conservation Opportunity** (acre-feet)
2008	550,590	3,144	93,125	18,848
2009	683,980	1,943	57,552	9,252
2010	590,200	11,275	333,966	60,285
2011	786,720	10,656	315,631	51,171
2012	670,500	13,085	387,578	61,915

Note: Lost Revenue Opportunity assumes an energy value of $29.62/MWh.

Table 5-3: Summary of Operation Efficiency Analyses for Palisades
(2013-2014 and 2015-2016)

Dates	Number of Days	Total Generation (MWh)	Lost Energy Opportunity (MWh)	Lost Revenue Opportunity $	Water Conservation Opportunity (acre-feet)
10/02/2013 to 10/31/2014	393	523,500	9,244	273,809	51,180
09/14/2015 to 07/21/2016	311	413,240	403	11,937	2,326

Note: Lost Revenue Opportunity assumes an energy value of $29.62/MWh.

The potential efficiency improvements due to improved optimization, while meeting the actual power versus time, were significant for the 2008-2012 time period. The lost energy opportunity ranged from a low of 1,943 MWh (lost revenue opportunity of $57,552, water conservation opportunity of 9,252 acre-feet) for 2009 to a high of 13,085 MWh (lost revenue opportunity of $387,578, water conservation opportunity of 61,915 acre-feet) for 2012, with a five-year total of 40,103 MWh (lost revenue opportunity of $1,187,851, water conservation opportunity of 201,469 acre-feet). For the 393-day time period from October 2, 2013, through October 31, 2014, the potential efficiency improvements due to improved optimization were also significant. During this second analysis period, the total lost energy opportunity was 9,244 MWh (lost revenue opportunity of $273,809, water conservation opportunity of 51,180 acre-feet). For the 311-day time period from September 5, 2015, through July 21, 2016, the potential efficiency improvements due to improved optimization were minimal. During this third analysis period, the total lost energy opportunity was 403 MWh (lost revenue opportunity of $11,937, water conservation opportunity of 2,326 acre-feet). Additional operation efficiency analyses for operation with the four new units at Palisades will be performed in the future.

5.3 Generation Scheduling Analyses

Generation scheduling analyses evaluate how closely the actual plant powers align with the overall peak efficiency curves for the entire plant. The steps for computing the generation scheduling analyses are shown elsewhere [ORNL, 2011]. Individual unit characteristics combine to create an overall plant efficiency curve that is the maximum plant efficiency achievable for any given power with optimized plant dispatch. By scheduling plant power levels to align with peak operating efficiency regions when hydrologic conditions, market conditions, and other restrictions permit, more efficient energy generation is achieved.

Flaming Gorge: Figure 5-12 provides typical results from the scheduling analyses conducted for Flaming Gorge, showing 2010 results for a gross head of 420 ft. The optimized plant gross head efficiency for 420 ft, based on the derived unit characteristics, is shown in green. The actual 2010 monthly generation versus plant power at that head is shown in blue, and the optimized 2010 monthly generation versus plant power at that head is shown in red. The actual generation values (blue triangles) tend to occur at a wide variety of power levels corresponding to specific release flows. The optimized generation values (red triangles) correspond to the peak efficiencies for one-unit, two-unit, and three-unit operation.

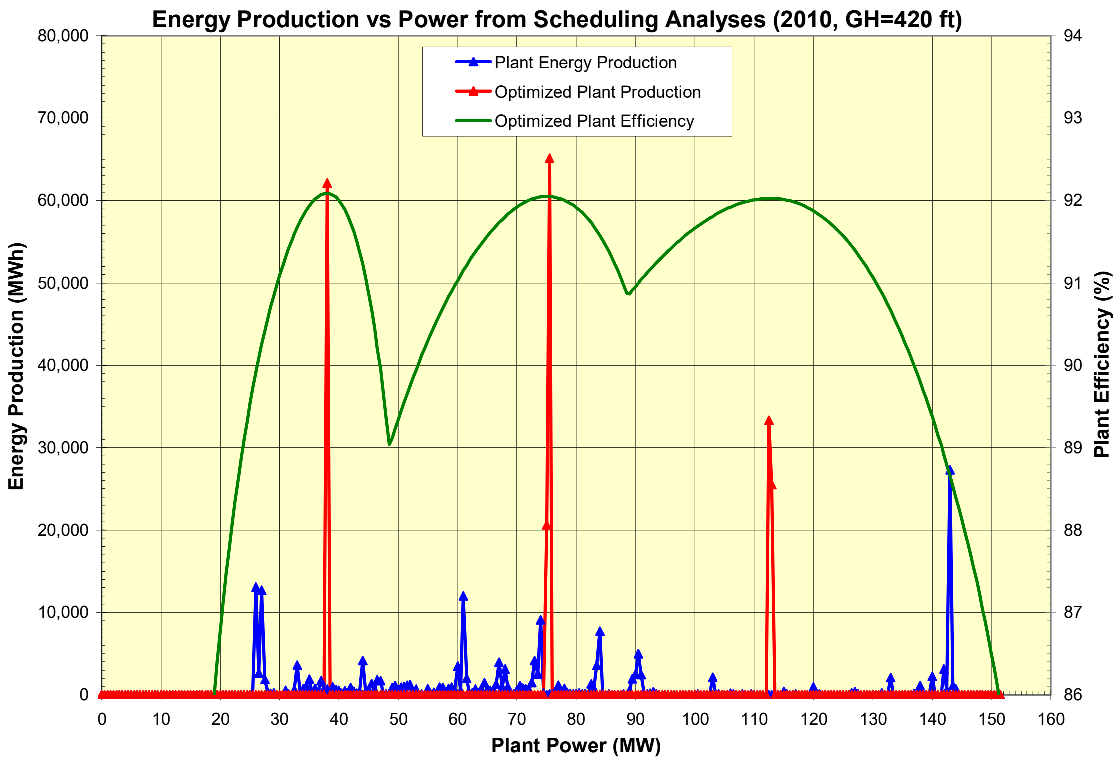

Figure 5-12: Typical Energy Production versus Power from Generation Scheduling Analyses (2010, Gross Head = 420 ft)

Results from these scheduling analyses are summarized in Table 5-4. The potential generation improvements are significant, ranging from a low of 1,254 MWh (1.3%) in 2012 to a high of 15,286 MWh (2.3%) in 2011, with an average of 1.8% and an eight-year total of 55,963 MWh. The water conservation opportunity ranges from a low of 2,936 acre-ft/year for 2012 to a high of 36,341 acre-ft/year for 2011, with an eight-year total of 133,320 acre-ft.

Table 5-4: Summary of Scheduling Analyses for Flaming Gorge (2008-2015)

Year	Total Lost Energy Opportunity (MWh)	Total Lost Revenue Opportunity ($)	Total Water Conservation Opportunity (acre-ft)	Actual Energy Production (MWh)	Potential Increase in Energy Production (%)
2008	7,830	234,895	18,744	368,495	2.1
2009	5,355	160,656	12,722	457,274	1.2
2010	6,032	180,956	14,292	395,614	1.5
2011	15,286	458,591	36,341	674,662	2.3
2012	1,254	37,614	2,936	97,612	1.3
2013	7,103	213,101	17,228	299,601	2.4
2014	7,590	227,697	18,092	418,674	1.8
2015	5,512	165,368	12,965	450,339	1.2
TOTAL (2008-2015)	**55,963**	**1,678,878**	**133,320**	**3,162,271**	**1.8**

Palisades: Figure 5-13 provides typical results from the generation scheduling analyses conducted for Palisades, showing 2010 results for a net head of 185 ft. The optimized plant efficiency for 185 ft, based on unit characteristics derived from the archival data, is shown in green. The actual 2010 generation versus plant power at that head is shown in blue, and the optimized 2010 generation versus plant power at that head is shown in red.

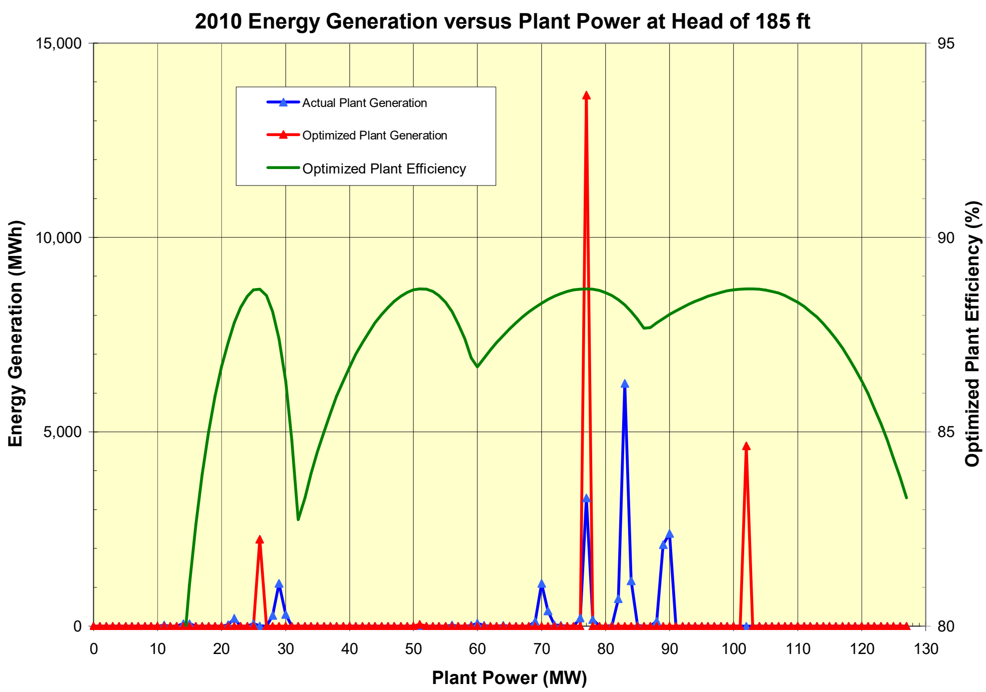

Figure 5-13: Typical Energy Generation versus Plant Power from Palisades Generation Scheduling Analyses (2010, Head = 185 ft)

The actual generation values (blue triangles) tend to occur at a wide variety of power levels, presumably corresponding to specific release flows, including minimum flow releases. The optimized generation values (red triangles) correspond to the peak efficiencies for one-unit, two-unit, three-unit, and four-unit operation.

Results from generation scheduling analyses for Palisades are summarized in Table 5-5 for the first (2008-2012) time period and in Table 5-6 for the second (October 2, 2013, through October

31, 2014) and third (September 5, 2015, through July 21, 2016) time periods. The potential generation improvements due to improved generation scheduling, while meeting the same flow release for each time step, were significant for the 2008-2012 time period. The lost energy opportunity ranged from a low of 1,233 MWh (lost revenue opportunity of $36,521, water conservation opportunity of 7,002 acre-feet) for 2008 to a high of 11,075 MWh (lost revenue opportunity of $328,042, water conservation opportunity of 68,733 acre-feet) for 2010, with a five-year total of 27,543 MWh (lost revenue opportunity of $815,824, water conservation opportunity of 155,487 acre-feet). For the 393-day time period from October 2, 2013, through October 31, 2014, the potential efficiency improvements due to improved optimization were significant. During this second analysis period, the total lost energy opportunity was 6,323 MWh (lost revenue opportunity of $187,287, water conservation opportunity of 42,883 acre-feet).

Table 5-5: Summary of Generation Scheduling Analyses for Palisades (2008-2012)

Year	**Total Generation** (MWh)	**Lost Energy Opportunity** (MWh)	**Lost Revenue Opportunity** $	**Water Conservation Opportunity** (acre-feet)
2008	550,590	1,233	36,521	7,002
2009	683,980	8,385	248,364	48,278
2010	590,200	11,075	328,042	68,733
2011	786,720	3,909	115,785	18,572
2012	670,500	2,941	87,112	12,902

Note: Lost Revenue Opportunity assumes an energy value of $29.62/MWh.

Table 5-6: Summary of Generation Scheduling Analyses for Palisades (2013-2014 and 2015-2016)

Dates	**Number of Days**	**Total Generation** (MWh)	**Lost Energy Opportunity** (MWh)	**Lost Revenue Opportunity** $	**Water Conservation Opportunity** (acre-feet)
10/02/2013 to 10/31/2014	393	523,500	6,323	187,287	42,883
09/14/2015 to 07/21/2016	311	413,240	9,347	276,858	54,734

Note: Lost Revenue Opportunity assumes an energy value of $29.62/MWh.

For the 311-day time period from September 5, 2015, through July 21, 2016, the potential generation improvements due to improved generation scheduling, while meeting the same flow release for each time step, were significant. During this third analysis period, the total lost energy opportunity was 9,347 MWh (lost revenue opportunity of $276,858, water conservation opportunity of 54,734 acre-feet). Most of this potential generation increase is associated with plant operation under low flow conditions. Additional generation scheduling analyses for operation with the four new units at Palisades will be performed in the future.

6. Summary

6.1 Summary of Results

The U. S. Bureau of Reclamation has conducted investigations at two multiunit hydroplants, the 152 MW Flaming Gorge Project and the 176.6 MW Palisades Project, to evaluate the value from unit performance testing and from unit performance characteristics derived from archival unit data. Flaming Gorge units were upgraded, and expected performance characteristics were supplied by the turbine manufacturer. Detailed unit efficiency tests were conducted for Flaming Gorge Units 1-3 in November 2015. Modified Flaming Gorge unit characteristics were developed from hourly archival data (i.e., HW, TW, unit power, unit flow) for 2008-2015. Palisades Units 1-4 were upgraded, and expected performance characteristics were supplied by the turbine manufacturer. Detailed unit efficiency tests were conducted for Palisades in June 2014 and September 2018. Unit performance characteristics for Palisades were also developed from fifteen-minute archival data for 2014-2018. Optimization analyses compared actual unit operations for multiyear periods using unit performance characteristics based on the turbine manufacturers' predictions and characteristics based on multiyear archival data. Generation scheduling analyses showed the potential for significant annual improvements at both plants.

Results are summarized below:

1. Performance characteristics derived from archival data correlated well with results from field efficiency tests for Flaming Gorge and Palisades.
2. For Flaming Gorge, a comparison between the turbine manufacturer's expected performance curves and the derived performance curves shows an average annual energy difference of 1.6%, corresponding to $190,000/year in power revenue loss.
3. For Palisades, the turbine manufacturer's expected performance curves and the performance curves derived from archival data corresponded closely.
4. Operation efficiency analyses for Flaming Gorge show the potential for modest annual improvements from improved unit dispatch, corresponding to an increase in power revenue of $48,000/year.
5. Operation efficiency analyses for Palisades show the potential for modest annual improvements from improved unit dispatch with the new units, corresponding to an increase in power revenue of $23,700/year.
6. Generation scheduling analyses for Flaming Gorge show potential for significant annual improvements from improved scheduling, corresponding to an increase in power revenue of $210,000/year.
7. Generation scheduling analyses for Palisades show the potential for significant annual improvements from improved scheduling with the new units, corresponding to an increase in power revenue of $277,000/year.

6.2 Suggested Actions based on Results

Flaming Gorge and Palisades have high quality, well-maintained instrumentation for the plants' on-line systems, including multi-path ultrasonic flowmeters for each unit. Consequently, these plants produce an accurate and valuable archival data set. Gaps that were identified as part of these analyses, and recommendations based on those gaps, include the following:

1. Flaming Gorge and Palisades do not currently compute and review hydro performance indicators. Three important performance indicators for consideration include the operation efficiency, the generation scheduling efficiency, and flow correlation analyses.
2. The operation efficiencies should be computed and reviewed on monthly intervals. This would help ensure that the unit dispatch is well optimized for both plants.
3. Modification to the power schedules for both plants should be reviewed by the USBR. If the USBR determines that optimized plant power scheduling is feasible, the generation scheduling efficiencies should be computed and reviewed on a monthly basis to ensure that the generation scheduling is well optimized for both plants.
4. Flow correlation analyses should be computed and reviewed on a monthly basis to ensure that unit characteristics are accurate and that the unit instrumentation is functioning properly for both plants. In addition, flow correlation analyses can be a useful component for a predictive maintenance program, including identification of trash rack fouling.
5. Results from Palisades Unit 2 and Unit 4 showed close agreement between flows measured with Winter-Kennedy flowmeters and flows measured with multi-path ultrasonic flowmeters. A comparison of Winter-Kennedy flowmeters and multi-path ultrasonic flowmeters could be conducted for the Palisades units to determine long term stability and relative maintenance costs.

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Appendix B

Technical Memorandum TM2101

Implementing Identified Opportunities for Generation Improvements at Reclamation's Flaming Gorge Dam and Powerplant

September 2021

Technical Memorandum TM2101

Implementing Identified Opportunities for Generation Improvements at Reclamation's Flaming Gorge Dam and Powerplant

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Subcontract 4000183047, Modification 1

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1. Introduction

Previous work by Oak Ridge National Laboratory (ORNL) and Hydro Performance Processes Inc. (HPPi) identified potential opportunities for generation improvements at Reclamation's Flaming Gorge Dam and Powerplant [March et al., 2017; March et al., 2019]. Under the previous project, Reclamation conducted efficiency tests for Flaming Gorge Units 1, 2, and 3 in November 2015. HPPi developed detailed unit characteristics from Reclamation's archival data (2008-2015), including HW, TW, unit power, and unit flow. The derived unit characteristics and the Hydroplant Performance Calculator [March et al., 2014] were used to produce operation efficiency analyses and generation scheduling analyses.

Results from the previous project are summarized below [March et al., 2017]:

1. Performance characteristics derived from archival data correlate well with field measurements.
2. A performance comparison between the manufacturer's curves and the derived performance curves shows an average annual energy difference of 1.6%, corresponding to a power revenue loss of $190,000/year.
3. Operation efficiency analyses show the potential for modest annual improvements of approximately 0.4% from improved unit dispatch, corresponding to a $48,000/year power revenue increase and a 2008-2015 greenhouse gas emissions reduction of 8,764 metric tons of Carbon Dioxide Equivalent [EPA, 2016].
4. Generation scheduling analyses show potential for annual improvements of approximately 1.8%, corresponding to a power revenue increase of $210,000/year and a 2008-2015 greenhouse gas emissions reduction of 38,589 metric tons of Carbon Dioxide Equivalent [EPA, 2016].

Under the current project (ORNL Subcontract 4000183047, Mod. 1), HPPi is supporting ORNL to provide Reclamation with a more detailed review and evaluation of the practical implementation of the identified opportunities for generation improvements at Flaming Gorge.

5. Overview of Performance Analyses

The performance analyses computed for this technical memorandum are based on a set of tools to quantify unit and plant performance and to enable the investigation of potential opportunities for operations-based and equipment-based performance improvements, leading to additional generation. The following subsections briefly address the processes and methodologies used for the quantitative performance analyses. Additional details are available in ORNL [2011], EPRI [2015], and elsewhere [March and Wolff, 2003; March and Wolff, 2004; EPRI, 2008; EPRI, 2012a; EPRI, 2012b; EPRI, 2012c; EPRI, 2012d; March et al., 2012; March et al., 2014; EPRI, 2014; March et al., 2016].

2.1 Data for Performance Analyses

The primary data needs for performance analyses include unit characteristics data and facility operational data, which are discussed in this subsection.

Hydroelectric generating facilities convert the potential energy of stored water and the kinetic energy of flowing water into a useful form, electricity. This fundamental process for a hydroelectric generating unit is described by the generating efficiency equation, defined as the ratio of the power delivered by the unit to the power of the water passing through the unit. The general expression for the efficiency (η) is

$$\eta = \frac{P}{\rho g Q H}$$

where P is the output power, ρ is the density of water, g is the acceleration of gravity, Q is the water flow rate through the unit, and H is the head across the unit.

Efficiency curves provide guidance for the effective use of a hydropower unit or facility. The points of most efficient operation can be identified, and the efficiency penalty for operating away from the optimum can be quantified and evaluated relative to the potential economic benefits from generating at a different power level.

Typically, facility operational data is obtained from multiple sources, including plant personnel, central engineering staff, and load control personnel. The essential operational data for correlation analyses, operation efficiency analyses, and generation scheduling analyses include:

1. Timestamp;
2. Unit Power;
3. Unit Flow;
4. Headwater Level;
5. Tailwater Level; and
6. Unit Status (e.g., available, unavailable, condensing).

2.2 Tools for Performance Analyses

The primary tool for conducting performance analyses is the Hydroplant Performance Calculator (HPC). The HPC was developed to enable standardized metrics for hydro plant performance [March et al., 2014]. The Hydroplant Performance Calculator includes: (1) a setup module, HPC PlantBuilder, for developing unit and plant performance characteristics; and (2) a multi-unit optimization and analysis module, HPC Analyzer, for calculating operation efficiencies, generation scheduling analyses, and flow analyses. The data needs for HPC PlantBuilder and HPC Analyzer include unit performance data and facility operational data, as described in the previous subsection.

Figure 2-1 provides a graphical overview of HPC PlantBuilder, and Figure 2-2 provides a graphic overview of HPC Analyzer. Input data for the HPC PlantBuilder includes unit performance data (generator efficiency; turbine power and turbine flow versus head) and facility operational data (unit power and head versus time; unit flow versus time).

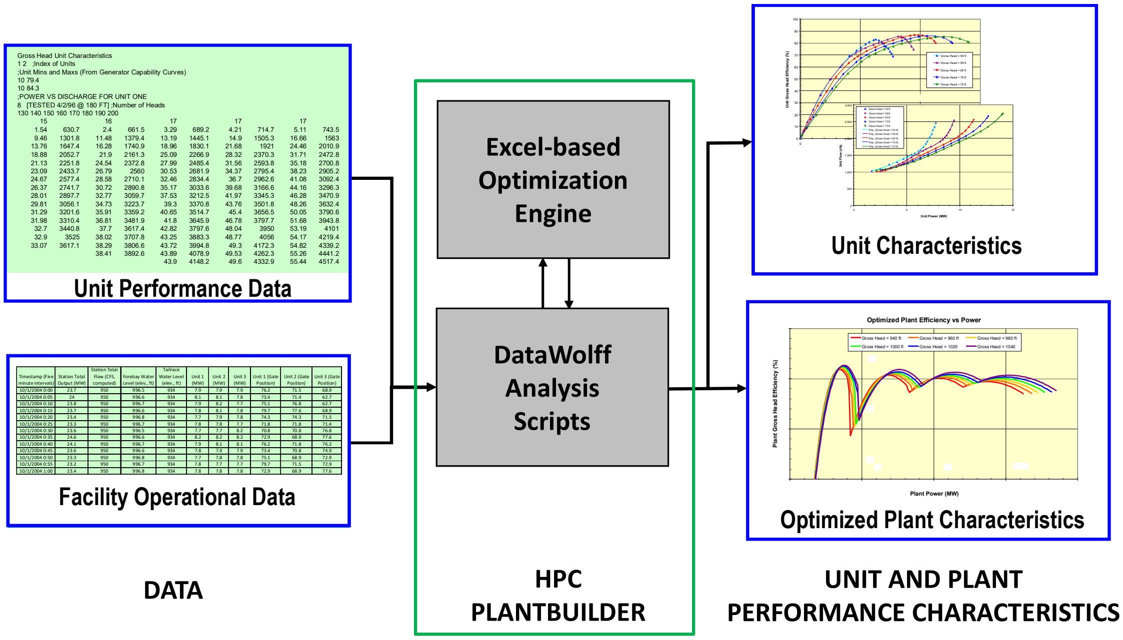

Figure 2-1: Overview of HPC PlantBuilder

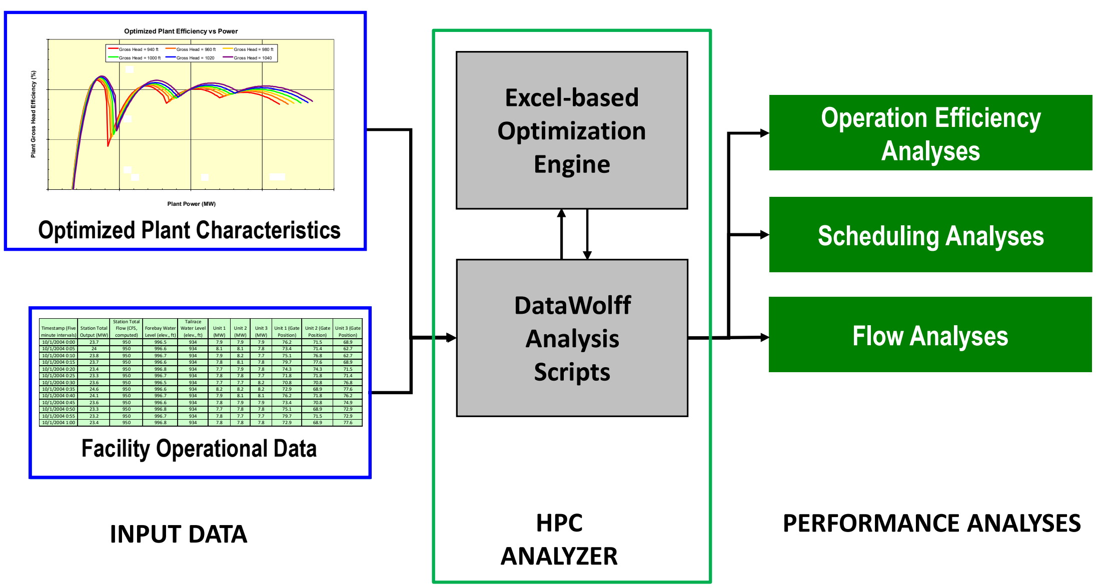

Figure 2-2: Overview of HPC Analyzer

The input data for HPC PlantBuilder includes plant latitude, plant elevation at the turbine centerline, and average water temperature. These values are used to compute the acceleration of gravity, g, and the water density, ρ [ASME, 2011]. Additional details are available in EPRI [2015] and elsewhere [March et al., 2012; March et al., 2014; EPRI, 2014].

An Excel interface for HPC PlantBuilder provides an efficient, consistent, and systematic approach to creating unit and plant performance characteristics from performance data and plant operational data. Input data for the HPC Analyzer includes optimized plant performance data, as computed by HPC PlantBuilder, and facility operational data (unit power and head versus time). For this project, HPC Analyzer was used to compute operation efficiency analyses and generation scheduling analyses, as described in ORNL [2011] and March et al. [2014].

3. Results from Performance Analyses

3.1 Previous Flow Analyses

Previous flow analyses for Flaming Gorge have shown that the unit efficiencies from field tests agree closely with the efficiencies derived from the archival data, as shown by the example in Figure 3.1 [March et al., 2017].

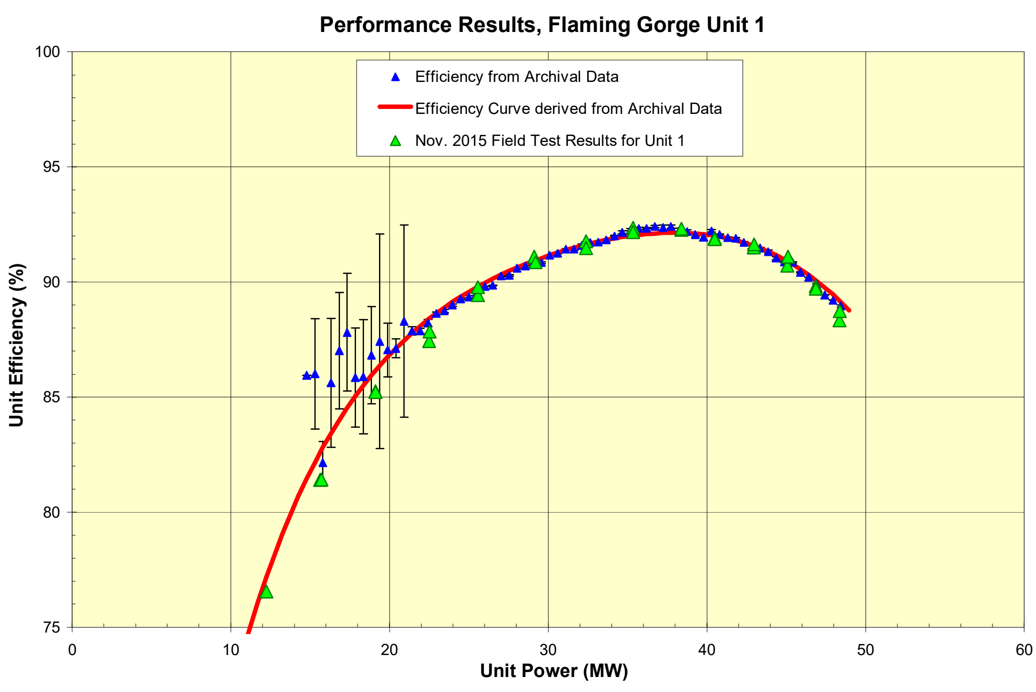

Figure 3.1: Performance Comparison for Flaming Gorge Unit 1 (GH = 420 ft)

Figure 3.1 provides results from previous flow analyses for Flaming Gorge Unit 1, using data from January 2008 through November 2015. The red line in Figure 3.1 shows the computed Unit 1 efficiency curve at a gross head of 420 ft, derived from 2008-2015 hourly archival data for unit flow, unit power, headwater, and tailwater using head loss information from the USBR's field tests. The small blue triangles show average efficiency values at 0.5 MW intervals, and the black error bars show the precision error for the 2008-2015 archival data for the given power level. Below about 25 MW, significant scatter can be observed in the efficiency results because operation in this range is typically a transient condition during ramp-up and ramp-down. Consequently, the hourly flow data is not adequate to characterize these transitions. The green triangles show that the Unit 1 efficiencies measured during the November 2015 field performance tests agree closely with the efficiencies derived from the archival data, with similar results for the other units [March et al., 2017].

The HPC was used to develop optimized plant efficiency curves based on combined unit characteristics derived from the 2008-2015 archival analyses and the November 2015 field tests. By assuming equal unit performance and combining the unit curves, optimized dispatch is simplified with virtually no effect on the optimized plant efficiency curves. This also ensures that each unit is interchangeable in the dispatch order, avoiding unequal wear which could result from the preferential dispatch of an insignificantly more efficient unit. These optimized plant efficiency curves are provided in Figure 3.2 for gross heads of 410 ft, 420 ft, 430 ft, and 440 ft. Note that the maximum plant efficiencies are achieved for a gross head of 430 ft.

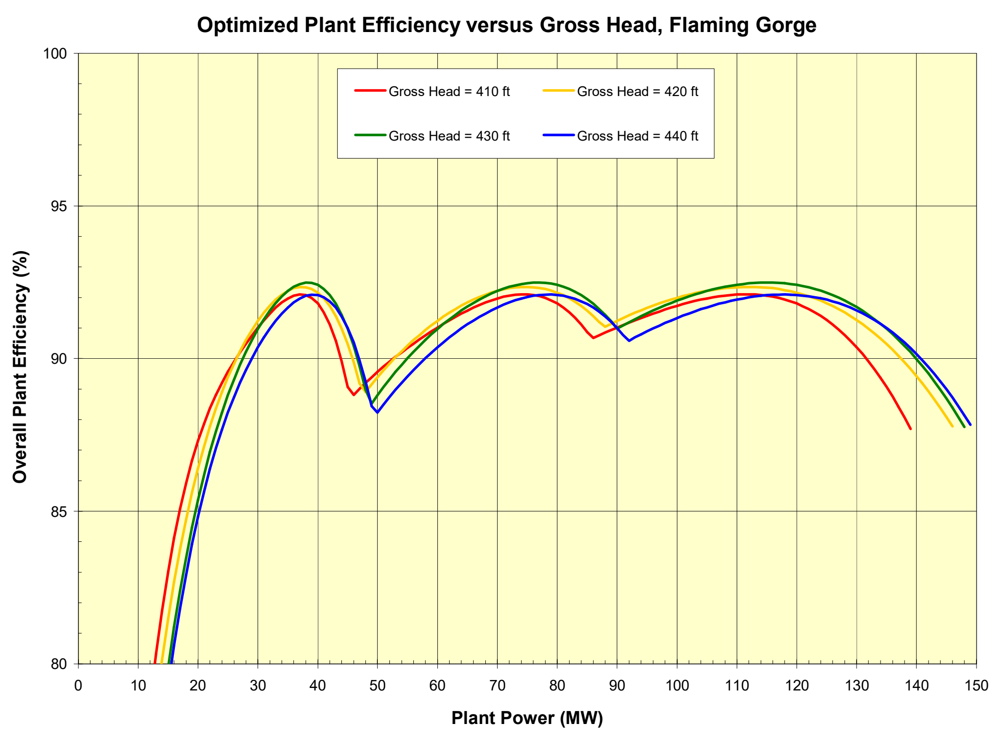

Figure 3.2: Optimized Plant Efficiency versus Gross Head for Flaming Gorge, Based on Unit Efficiencies Derived from 2008-2015 Archival Data and Field Test Data

3.2 Operation Efficiency Analyses

Operation efficiency analyses use unit efficiency characteristics and archival operations data to determine how closely the actual dispatch matches the optimized dispatch. Detailed computational steps for determining the operation efficiency are discussed elsewhere [ORNL, 2011]. At each time step of the archival data, the optimized plant efficiency is computed, apportioning the total plant power among the available units to maximize the plant efficiency while meeting the necessary constraints (e.g., matching the actual plant power, matching the head, and operating each unit within minimum and maximum power limits). Energy gains due to water savings from optimized dispatch are computed by assuming that the water is converted into energy at the optimized plant efficiency and head for the time step in which the computed energy gain occurs.

For this project, hourly measurements of flow rate (cfs) from acoustic time-of-flight flowmeters were available from archival data for each unit at Flaming Gorge during a more recent analysis period from January 2018 through December 2019. Additional hourly measurements in the archival data included unit power (MW), headwater elevation (ft), and tailwater elevation (ft). Operation efficiency analyses were computed with the HPC Analyzer for Flaming Gorge using the 2018-2019 hourly archival data of unit flow, unit power, headwater, and tailwater; the head loss information from Reclamation's field tests; and the unit characteristics derived from the 2008-2015 archival analyses and the November 2015 field tests. Results from these recent operation efficiency analyses are summarized in Table 3.1 and shown in Figures 3.3 and 3.4.

Table 3.1: Summary of Operation Efficiency Analyses for Flaming Gorge (2018-2019)

Year	Total Lost Energy Opportunity (MWh)	Total Lost Revenue Opportunity ($)	Total Water Conservation Opportunity (acre-ft)	Actual Energy Production (MWh)	Potential Increase in Energy Production (%)
2018	3,602	$106,678	8,563	586,938	0.61
2019	2,407	$71,281	5,808	496,280	0.48
TOTAL (2018-2019)	**6,009**	**$177,959**	**14,371**	**1,083,218**	**0.55**

Overall, the potential efficiency improvements due to improved optimization, while meeting the actual power versus time, are modest, ranging from a low of 0.48% for 2018 to a high of 0.61% for 2019, with an average of 0.55% and a two-year total of 6,009 MWh. The water conservation opportunity ranges from a low of 5,808 acre-ft/year for 2019 to a high of 8,563 acre-ft/year for 2018, with a two-year total of 14,371 acre-ft. These results from Flaming Gorge operation efficiency analyses are comparable to results from previous analyses for 2008-2015 [March et al., 2017].

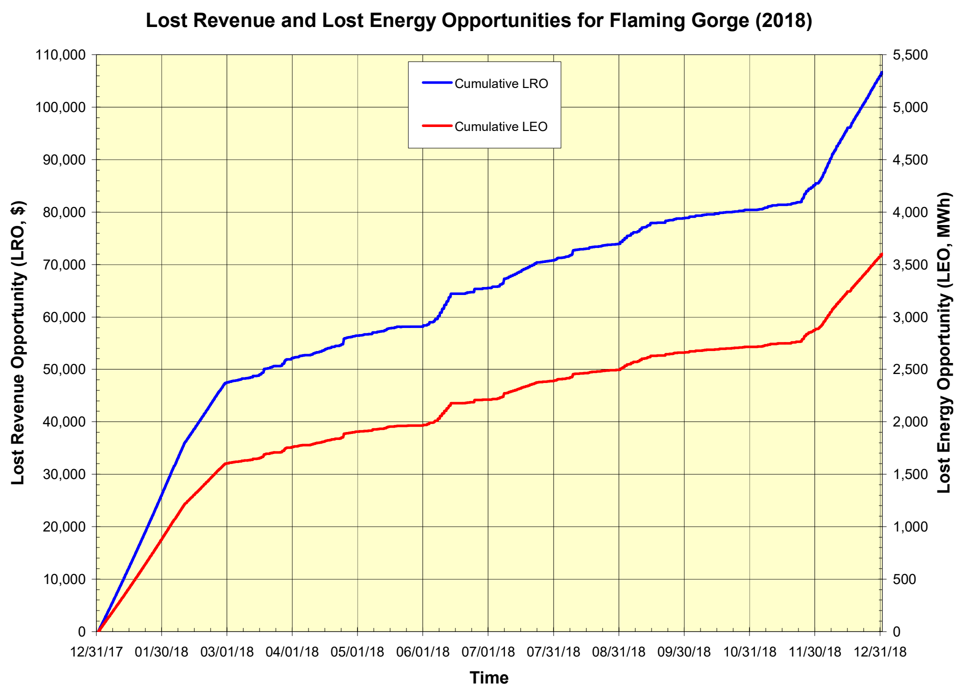

Figure 3.3: Results from Flaming Gorge Operation Efficiency Analyses, 2018

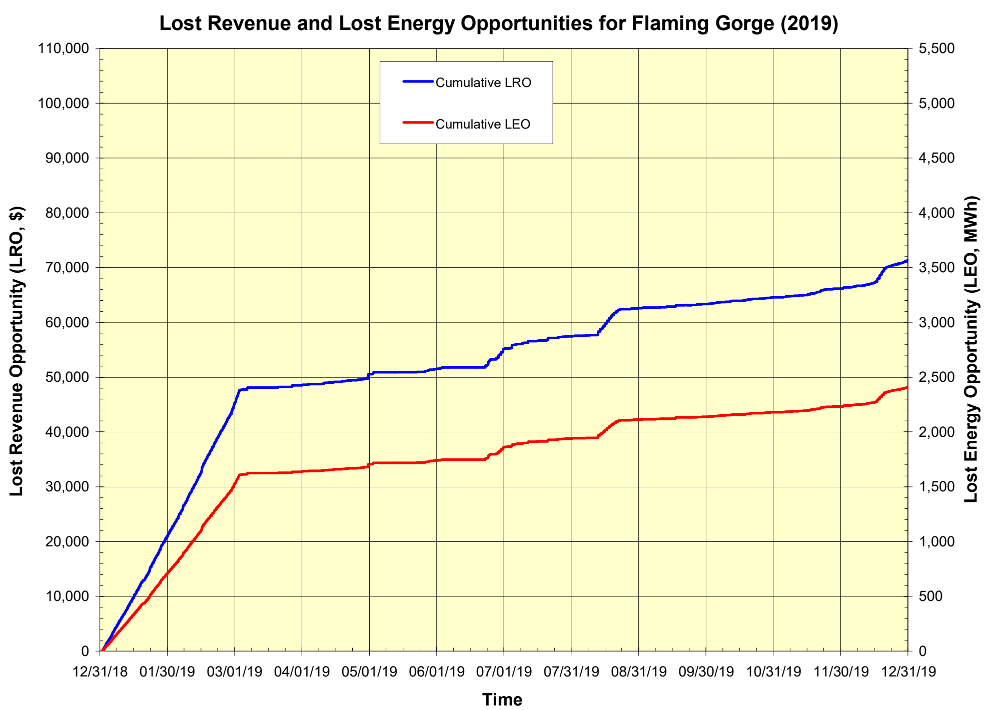

Figure 3.4: Results from Flaming Gorge Operation Efficiency Analyses, 2019

The practical implementation of generation improvements from improved optimization should be balanced with consideration of the potential for additional maintenance costs due, often, to increased start/stops of the units. In Osburn [2014], Reclamation provides a methodology for plant-specific estimates of start/stop costs and concludes that the typical cost is approximately $274 to $411 per start/stop. This range of start/stop costs provides some insight into the results from the 2018-2019 operation efficiency analyses for Flaming Gorge. Table 3.2 provides a range of estimated start/stop costs using the information provided by Osburn [2014].

Table 3.2: Estimates of Start/Stop Costs for Flaming Gorge (2018-2019)

Year	Actual Plant Start/Stops	Optimized Plant Start/Stops	Additional Start/Stops (Optimized - Actual)	Cost with Start/Stop at $274	Cost with Start/Stop at $411	Total Lost Revenue Opportunity ($)
2018	695	989	294	$80,556	$120,834	$106,678
2019	778	1,038	260	$71,240	$106,860	$71,281
TOTAL (2018-2019)	**1,473**	**2,027**	**554**	**$151,796**	**$227,694**	**$177,959**

The 2018 operation efficiency analyses show 695 actual plant start/stops, 989 optimized plant start/stops, and 294 additional plant start/stops. These additional plant start/stops correspond to increased maintenance costs ranging from $80,556 to $120,834, compared to a total lost revenue opportunity of $106,678. The 2019 operation efficiency analyses show 778 actual plant start/stops, 1,038 optimized plant start/stops, and 260 additional plant start/stops. These additional plant start/stops correspond to increased maintenance costs ranging from $71,240 to $106,860, compared to a total lost revenue opportunity of $71,281.

However, the operation efficiency analyses for 2018-2019 also show patterns of operation which can be examined in more detail. For example, between January 1, 2018, and February 10, 2018, Flaming Gorge operated at a gross head of approximately 420 ft and a plant power of approximately 92 MW, which was supplied by two units operating at approximately 46 MW each with a plant efficiency of approximately 89.9%. The optimized operation requires three units operating at approximately 30.7 MW each with a plant efficiency of approximately 91.5%, as shown in Figure 3-5. Assuming that three units were available for operation during this time period, the Lost Energy Opportunity of 1,229 MWh for this time period could have been achieved with three-unit operation without additional start/stops.

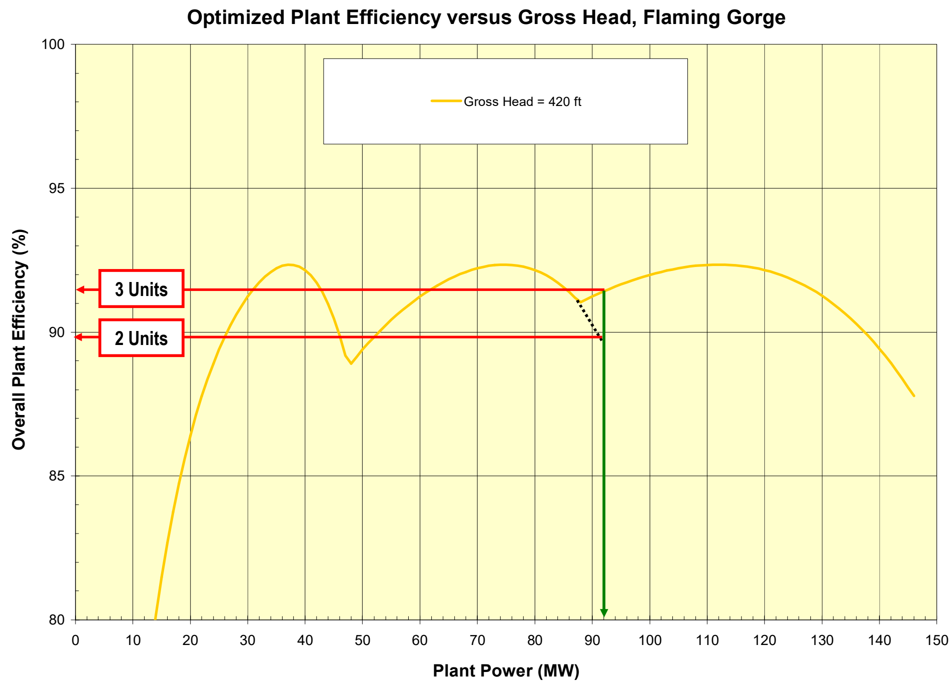

Figure 3.5: Actual and Optimized Operation of Flaming Gorge for January 1, 2018, through February 10, 2018

An additional review of the operation efficiency results was conducted by summarizing the results by day and deleting all days in which the optimized operation required more start/stops than the actual operation. A summary of this review for 2018 and 2019 is provided in Table 3.3.

Table 3.3: Refined Estimates of Start/Stop Costs for Flaming Gorge (2018-2019)

Year	Days when Actual Start/Stops Exceeds Opt Start/Stops	Actual Plant Start/Stops	Optimized Plant Start/Stops	Additional Start/Stops (Optimized - Actual)	Cost with Start/Stop at $274	Cost with Start/Stop at $411	Lost Energy Opportunity (MWh)	Lost Revenue Opportunity ($)
2018	208	157	133	-24	-$6,576	-$9,864	1,724	$51,071
2019	268	167	146	-21	-$5,754	-$8,631	450	$13,326
TOTAL (2018-2019)	**476**	**324**	**279**	**-45**	**-$12,330**	**-$18,495**	**2,174**	**$64,397**

For 2018, there were 208 days when the optimized operation required the same or fewer start/stops than the actual operation, with 157 actual start/stops and 133 optimized start/stops resulting in reductions of estimated maintenance costs ranging from $6,576 to $9,864. For 2019, there were 268 days when the optimized operation required the same or fewer start/stops than the actual operation, with 167 actual start/stops and 146 optimized start/stops resulting in reductions of estimated maintenance costs ranging from $5,754 to $8,631. The total Lost Revenue Opportunity and reduced maintenance costs for 2018-2019 corresponding to these days ranged from $76,727 to $82,892, indicating a small but significant potential improvement from improved optimization at Flaming Gorge.

3.3 Generation Scheduling Analyses

Generation scheduling analyses evaluate how closely the actual plant powers align with the overall peak efficiency curves for the entire plant. The steps for computing the generation scheduling analyses are shown elsewhere [ORNL, 2011]. Individual unit characteristics combine to create an overall plant efficiency curve that is the maximum plant efficiency achievable for any given power with optimized plant dispatch. By scheduling plant power levels to align with peak operating efficiency regions when hydrologic conditions, market conditions, and other restrictions permit, more efficient energy generation is achieved.

Generation scheduling analyses were computed with the HPC Analyzer for Flaming Gorge using the 2018-2019 hourly archival data of unit flow, unit power, headwater, and tailwater; the head loss information from Reclamation's field tests; and the unit characteristics derived from the 2008-2015 archival analyses and the November 2015 field tests. Results from these recent generation scheduling analyses are summarized for 2018 and 2019 in Figures 3.6 and 3.7, respectively. Opportunities for scheduling improvements occur throughout each year.

Figures 3.8 and 3.9 provide typical results from the 2018 scheduling analyses conducted for Flaming Gorge, showing results for gross heads of 420 ft and 430 ft. In each figure, the optimized plant gross head efficiency for the head, based on the derived unit characteristics, is shown in green. The actual monthly generation versus plant power at that head is shown in blue, and the optimized monthly generation versus plant power at that head is shown in red. The actual generation values (blue triangles) tend to occur at a wide variety of power levels corresponding to specific release flows. The optimized generation values (red triangles) correspond to the peak efficiencies for one-unit, two-unit, and three-unit operation.

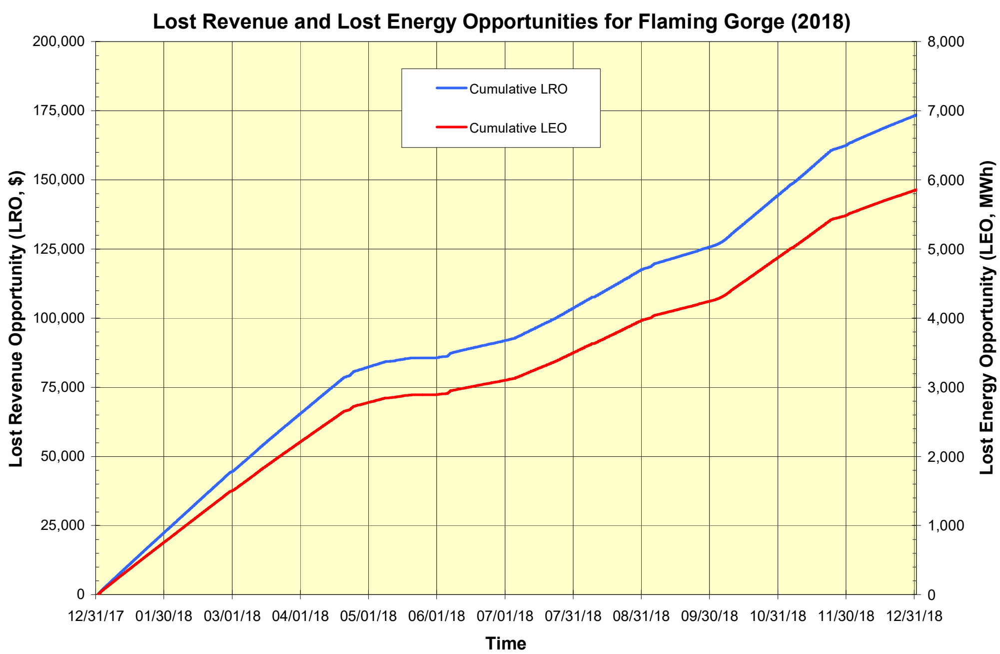

Figure 3.6: Results from Flaming Gorge Generation Scheduling Analyses, 2018

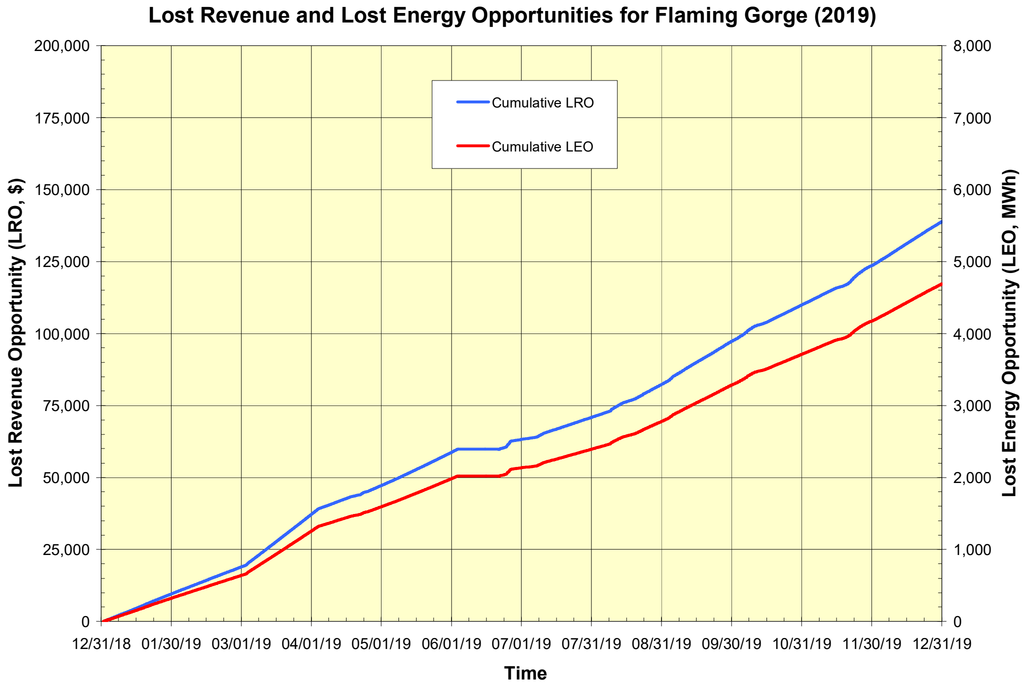

Figure 3.7: Results from Flaming Gorge Generation Scheduling Analyses, 2019

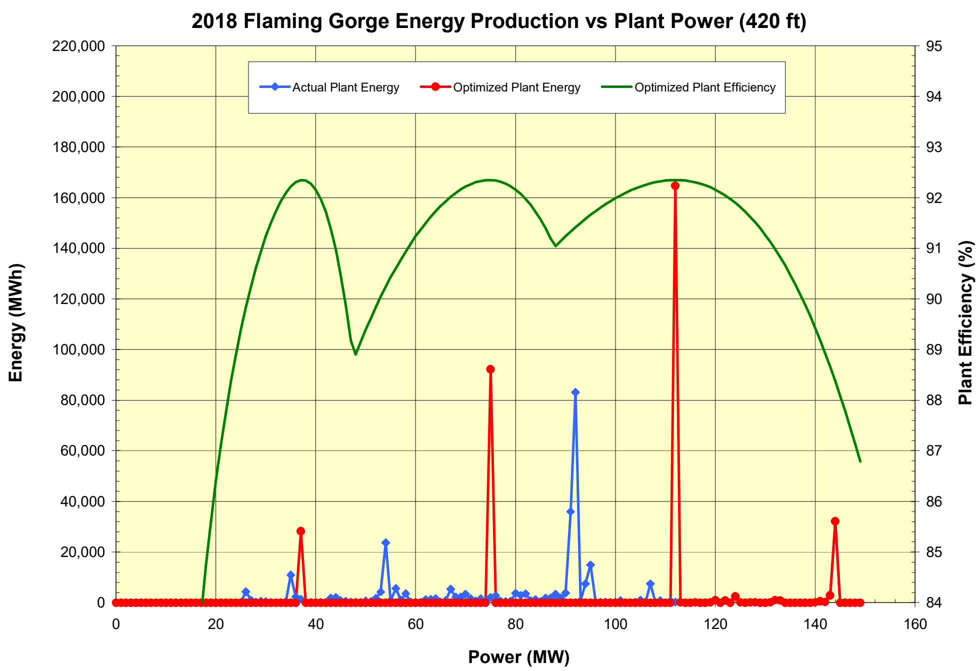

Figure 3.8: Typical Energy Production versus Power from Generation Scheduling Analyses (2018, Gross Head = 420 ft)

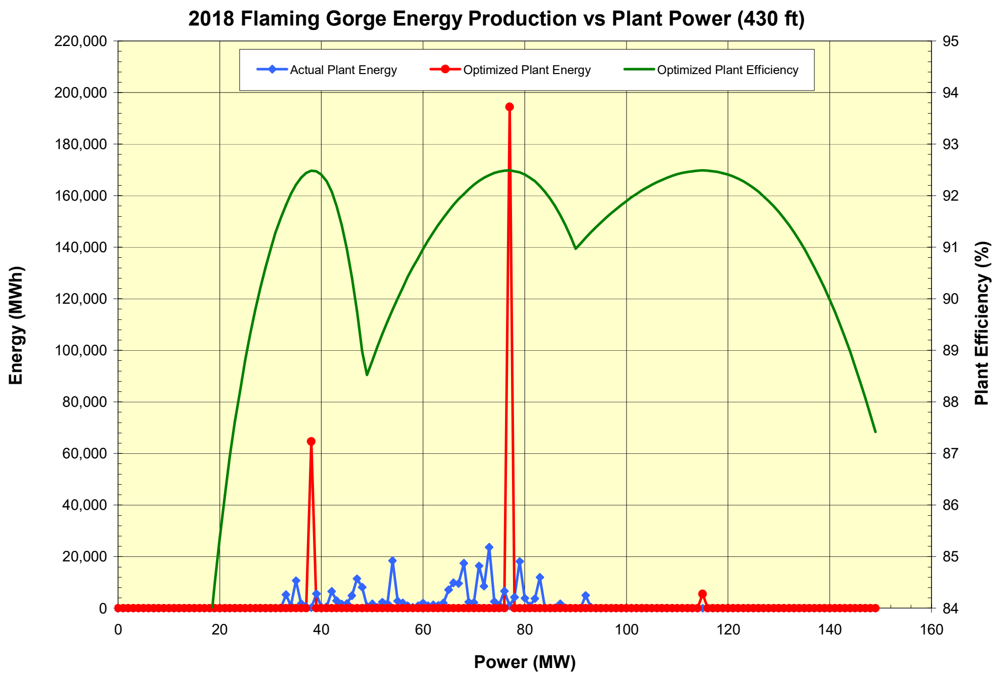

Figure 3.9: Typical Energy Production versus Power from Generation Scheduling Analyses (2018, Gross Head = 430 ft)

Similarly, Figures 3.10 and 3.11 provide typical results from the 2019 scheduling analyses conducted for Flaming Gorge, showing results for gross heads of 420 ft and 430 ft.

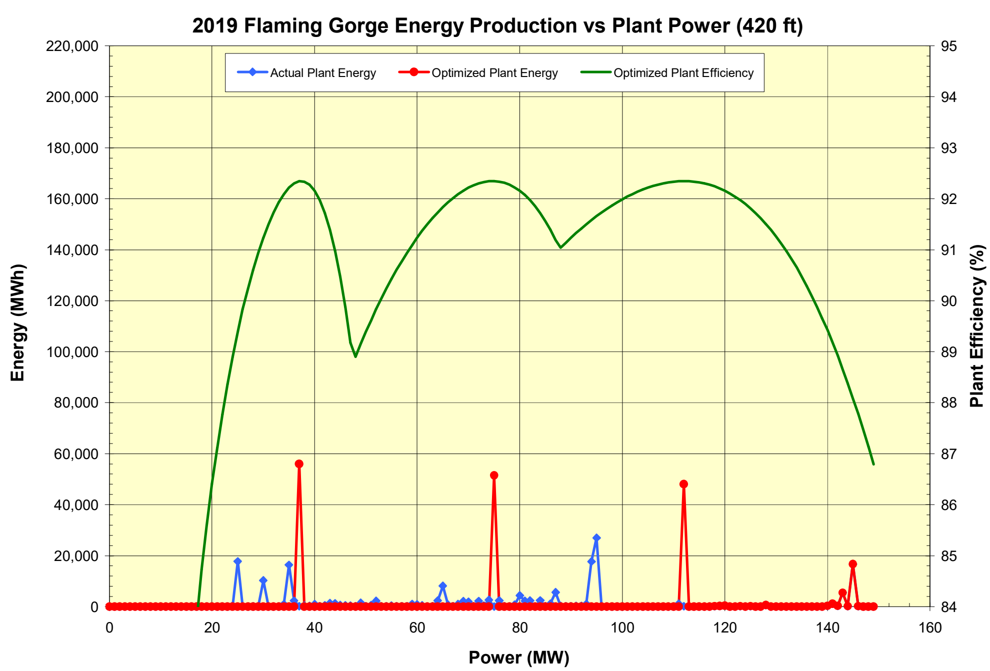

Figure 3.10: Typical Energy Production versus Power from Generation Scheduling Analyses (2019, Gross Head = 420 ft)

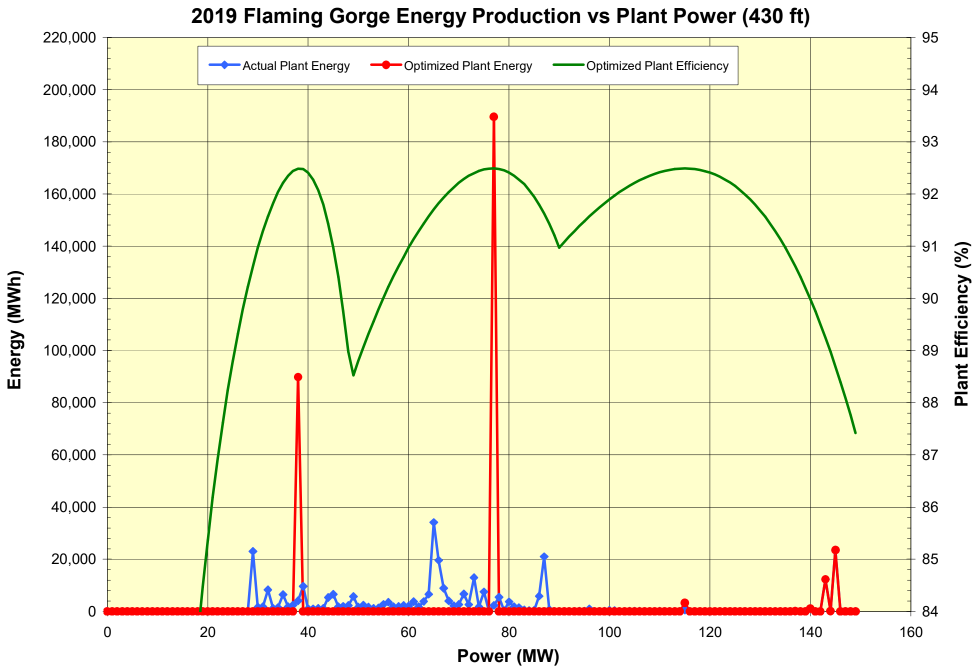

Figure 3.11: Typical Energy Production versus Power from Generation Scheduling Analyses (2019, Gross Head = 430 ft)

Results from the 2018 and 2019 generation scheduling analyses are summarized in Table 3.4. The potential generation improvements are significant, ranging from a low of 4,688 MWh (0.94%) in 2019 to a high of 5,858 MWh (1.0%) in 2018, with an average of 0.97% and a two-year total of 10,546 MWh. The water conservation opportunity ranges from a low of 10,973 acre-ft/year for 2019 to a high of 13,728 acre-ft/year for 2018, with a two-year total of 24,701 acre-ft.

Table 3.4: Summary of Scheduling Analyses for Flaming Gorge (2018-2019)

Year	Total Lost Energy Opportunity (MWh)	Total Lost Revenue Opportunity ($)	Total Water Conservation Opportunity (acre-ft)	Actual Energy Production (MWh)	Potential Increase in Energy Production (%)
2018	5,858	$173,515	13,728	586,938	1.00
2019	4,688	$138,851	10,973	496,280	0.94
TOTAL (2018-2019)	**10,546**	**$312,366**	**24,701**	**1,083,218**	**0.97**

To achieve some or most of the potential generation improvements from improved scheduling, the units at Flaming Gorge should be dispatched at their best efficiency points, according to head. Table 3.5 provides guidance, based on the unit characteristics derived from the 2008-2015 archival analyses and the November 2015 field tests, on the best efficiency plant power and plant flow for gross heads of 410 ft, 420 ft, 430 ft, and 440 ft.

Table 3.5: Recommended Best Efficiency Operating Points for Flaming Gorge versus Gross Head

Gross Head (ft)	Number of Units Operating	Plant Power (MW)	Plant Flow (cfs)
410	1	37	1,161
410	2	74	2,322
410	3	111	3,483
420	1	37.5	1,145
420	2	75	2,290
420	3	112.5	3,435
430	1	38	1,132
430	2	76	2,264
430	3	114	3,396
440	1	39	1,140
440	2	78	2,280
440	3	117	3,420

(Note: When multiple units are operating, the load should be split equally among units.)

4. Results from 2018 and 2019 Performance Analyses

4.1 Summary of Results

Unit characteristics derived from the 2008-2015 archival analyses and the November 2015 field tests were used for operation efficiency analyses and generation scheduling analyses based on the 2018 and 2019 archival data.

Results are summarized below:

1. The estimated Lost Revenue Opportunity and reduced maintenance costs for 2018-2019 ranged from $76,727 to $82,892, indicating a small but achievable potential improvement from improved optimization at Flaming Gorge.
2. Generation scheduling analyses show the potential for significant annual improvements of approximately 1.0%, corresponding to a generation increase of 10,546 MWh and a power revenue increase of $312,366 for 2018-2019.
3. Table 3.5 provides recommended best efficiency operating points for Flaming Gorge versus gross head. These operating points can help Reclamation to achieve some or most of the potential generation improvements from improved scheduling. When multiple units are operating, the load should be split equally among the units.

4.2 Suggested Actions Based on Results

Flaming Gorge has high quality instrumentation for the plant's on-line systems, including flow measurements and producing accurate and valuable archival data sets. Gaps that were identified as part of these analyses, and recommendations based on those gaps, include the following:

1. Reclamation should consider implementing the methodology of Osburn [2014] to develop estimates of start/stop costs that are specific to Flaming Gorge.
2. Table 3.5 provides recommended best efficiency operating points for Flaming Gorge versus gross head, and these recommendations should be followed whenever possible. If multiple units are operating, the load should be split equally among the units.
3. Flaming Gorge does not currently compute and review hydro performance indicators. Three important performance indicators for consideration include the operation efficiency, the generation scheduling efficiency, and the correlation efficiency, as recommended in March et al. [2017].

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Appendix C

Technical Memorandum TM2102

Operation Efficiency and Generating Scheduling Analyses for Reclamation's Palisades Dam and Powerplant

October 2021

Technical Memorandum TM2102

Operation Efficiency and Generating Scheduling Analyses for Reclamation's Palisades Dam and Powerplant

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Subcontract 4000183047, Modification 1

October 2021

1. Introduction

Previous work by Oak Ridge National Laboratory (ORNL) and Hydro Performance Processes Inc. (HPPi) identified potential opportunities for generation improvements at Reclamation's Palisades Dam and Powerplant [March et al., 2019a; March et al., 2019b]. Under the previous project, Reclamation conducted field efficiency tests for Unit 2 (original unit) in December 2008, for Unit 1 (new unit) in November 2014, and for Units 1 - 4 (new units) in September 2018. HPPi developed detailed unit characteristics from Reclamation's field test data and from archival data for June 2006 through July 2015, including HW, TW, unit power, and unit flow. The derived unit characteristics and the Hydroplant Performance Calculator [March et al., 2014] were used to produce operation efficiency analyses and generation scheduling analyses for Palisades.

Results from the previous project are summarized below [March et al., 2019a; March et al., 2019b]:

1. Performance characteristics derived from archival data correlated well with results from field efficiency tests for Palisades.
2. The turbine manufacturer's expected performance curves, the performance curves derived from archival data, and the field test results corresponded closely.
3. Operation efficiency analyses for Palisades showed the potential for modest annual improvements from improved unit dispatch with the new units, corresponding to an increase in power revenue of $23,700/year.
4. Generation scheduling analyses for Palisades showed the potential for more significant annual improvements from improved scheduling with the new units, corresponding to an increase in power revenue of $277,000/year.

Under the current project (ORNL Subcontract 4000183047, Mod. 1), HPPi is supporting ORNL to provide Reclamation with additional analyses of Palisades archival data (Task 1) and with additional review and evaluation of the practical implementation of the identified opportunities for generation improvements (Task 3).

2. Overview of Performance Analyses

The performance analyses computed for this technical memorandum are based on a set of tools to quantify unit and plant performance and to enable the investigation of potential opportunities for operations-based and equipment-based performance improvements, leading to additional generation. The following subsections briefly address the processes and methodologies used for the quantitative performance analyses. Additional details are available in ORNL [2011], EPRI [2015], and elsewhere [March and Wolff, 2003; March and Wolff, 2004; EPRI, 2008; EPRI, 2012a; EPRI, 2012b; EPRI, 2012c; EPRI, 2012d; March et al., 2012; March et al., 2014; EPRI, 2014; March et al., 2016].

2.1 Data for Performance Analyses

The primary data needs for performance analyses include unit characteristics data and facility operational data, which are discussed in this subsection.

Hydroelectric generating facilities convert the potential energy of stored water and the kinetic energy of flowing water into a useful form, electricity. This fundamental process for a hydroelectric generating unit is described by the generating efficiency equation, defined as the ratio of the power delivered by the unit to the power of the water passing through the unit. The general expression for the efficiency (η) is

$$\eta = \frac{P}{\rho g Q H}$$

where P is the output power, ρ is the density of water, g is the acceleration of gravity, Q is the water flow rate through the unit, and H is the head across the unit.

Efficiency curves provide guidance for the effective use of a hydropower unit or facility. The points of most efficient operation can be identified, and the efficiency penalty for operating away from the optimum can be quantified and evaluated relative to the potential economic benefits from generating at a different power level.

Typically, facility operational data is obtained from multiple sources, including plant personnel, central engineering staff, and load control personnel. The essential operational data for correlation analyses, operation efficiency analyses, and generation scheduling analyses include:

1. Timestamp;
2. Unit Power;
3. Unit Flow;
4. Headwater Level;
5. Tailwater Level; and
6. Unit Status (e.g., available, unavailable, condensing).

2.2 Tools for Performance Analyses

The primary tool for conducting performance analyses is the Hydroplant Performance Calculator (HPC). The HPC was developed to enable standardized metrics for hydro plant performance [March et al., 2014]. The Hydroplant Performance Calculator includes: (1) a setup module, HPC PlantBuilder, for developing unit and plant performance characteristics; and (2) a multi-unit optimization and analysis module, HPC Analyzer, for calculating operation efficiencies, generation scheduling analyses, and flow analyses. The data needs for HPC PlantBuilder and HPC Analyzer include unit performance data and facility operational data, as described in the previous subsection.

Figure 2-1 provides a graphical overview of HPC PlantBuilder, and Figure 2-2 provides a graphic overview of HPC Analyzer. Input data for the HPC PlantBuilder includes unit performance data (generator efficiency; turbine power and turbine flow versus head) and facility operational data (unit power and head versus time; unit flow versus time).

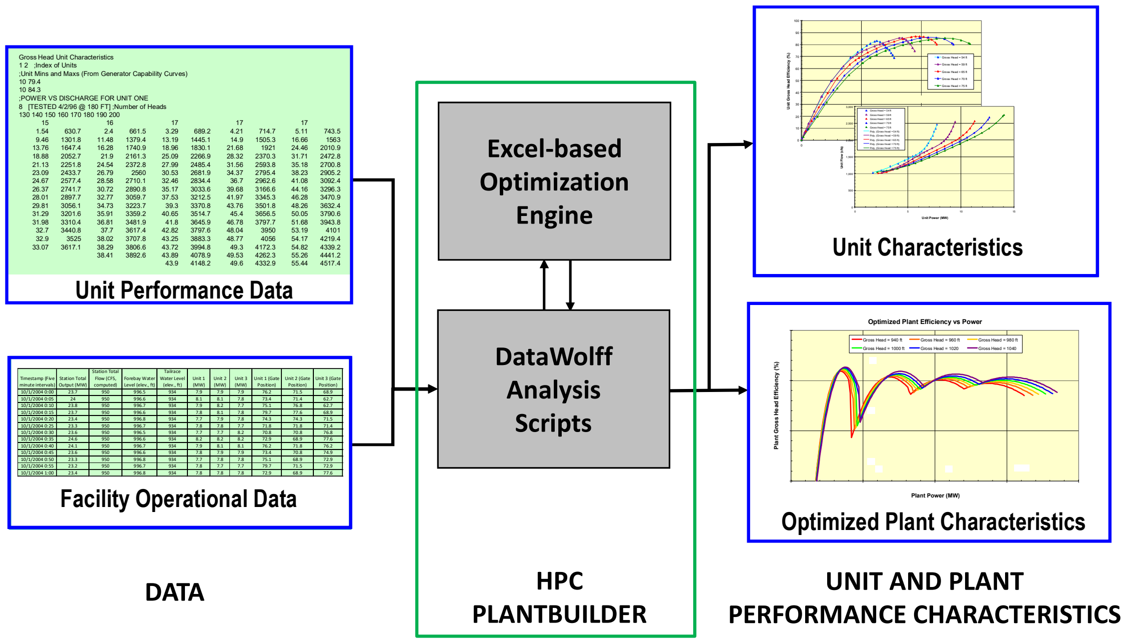

Figure 2-1: Overview of HPC PlantBuilder

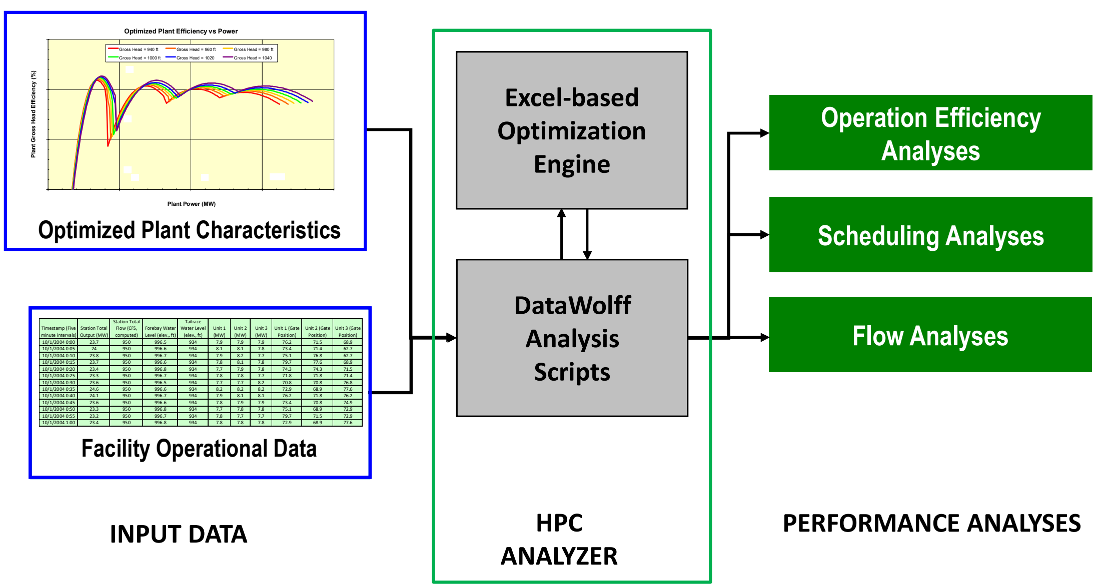

Figure 2-2: Overview of HPC Analyzer

The input data for HPC PlantBuilder includes plant latitude, plant elevation at the turbine centerline, and average water temperature. These values are used to compute the acceleration of gravity, g, and the water density, ρ [ASME, 2011]. Additional details are available in EPRI [2015] and elsewhere [March et al., 2012; March et al., 2014; EPRI, 2014].

An Excel interface for HPC PlantBuilder provides an efficient, consistent, and systematic approach to creating unit and plant performance characteristics from performance data and plant operational data. Input data for the HPC Analyzer includes optimized plant performance data, as computed by HPC PlantBuilder, and facility operational data (unit power and head versus time). For this project, HPC Analyzer was used to compute operation efficiency analyses and generation scheduling analyses, using the methodology described in ORNL [2011] and March et al. [2014].

3. Results from Performance Analyses

3.1 Previous Flow Analyses

Previous flow analyses for Palisades have shown that the unit efficiencies from field tests agree closely with the efficiencies derived from the archival data and with the turbine manufacturer's predictions, as shown by the Unit 1 example in Figure 3.1. The other units provided similar performance results [March et al., 2019a; March et al., 2019b].

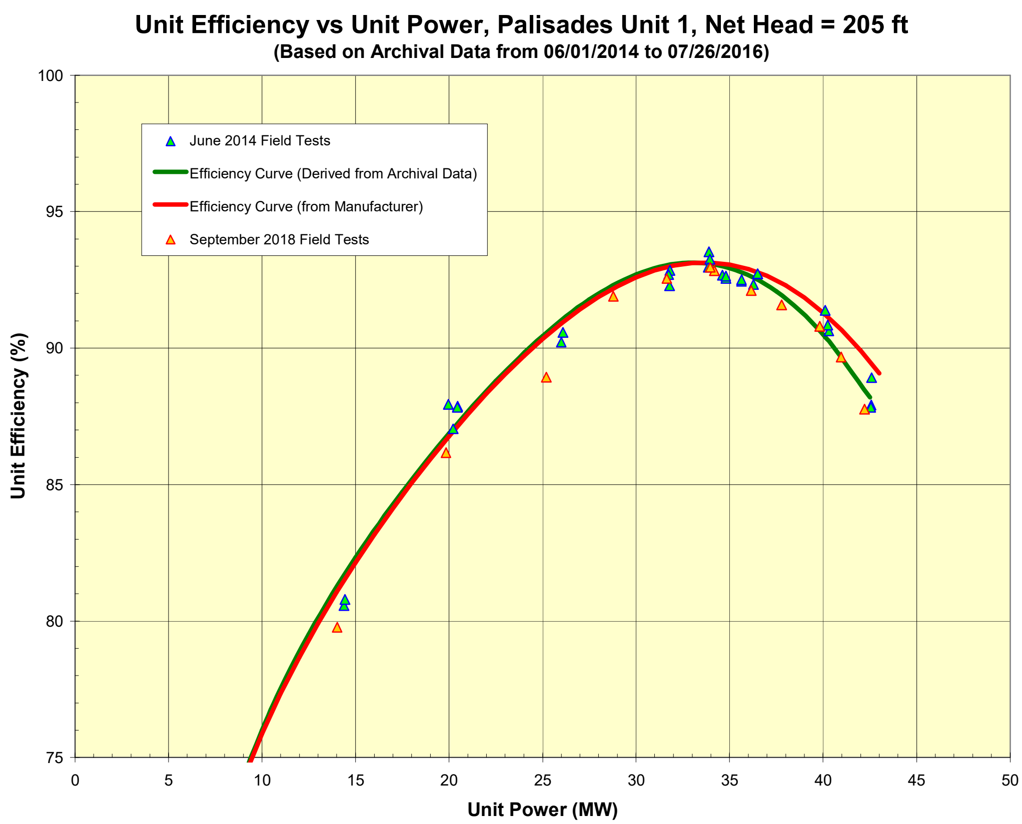

Figure 3.1: Performance Comparison for Palisades Unit 1 at Net Head of 205 ft

Some of the data scatter shown in Figure 3.1 is presumably due to flow profile effects on Palisades' acoustic flowmeters. Figure 3.2 provides a diagram of the Palisades penstock layout and the location for each unit's double plane eight-path acoustic transducers. Figure 3.3 shows four-unit and one-unit velocity streamlines from the turbine manufacturer's CFD analyses [Lemay et al., 2017]. As noted in Lemay et al. [2017], "The bifurcations were found to introduce a significant non-uniformity in the flow at the casing inlet, which is more substantial when multiple units are operated in parallel than for single unit operation." So, different combinations of unit operation could provide additional uncertainty in the flow measurements used for both the archival analyses and the field tests which could contribute to the observed data scatter.

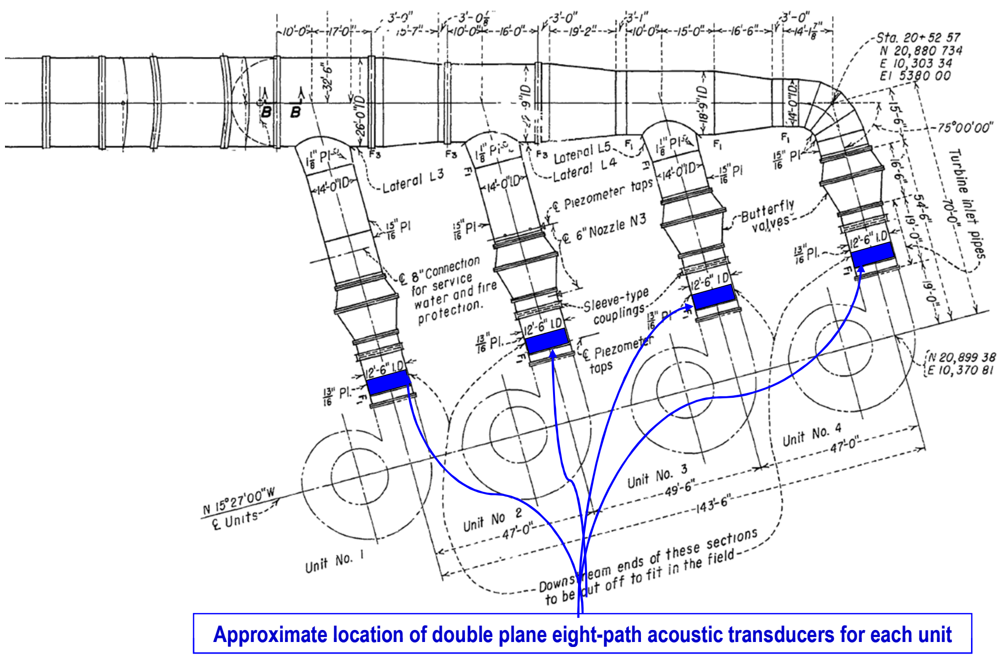

Figure 3.2: Location of Multi-path Acoustic Flowmeter Transducers for Palisades Units

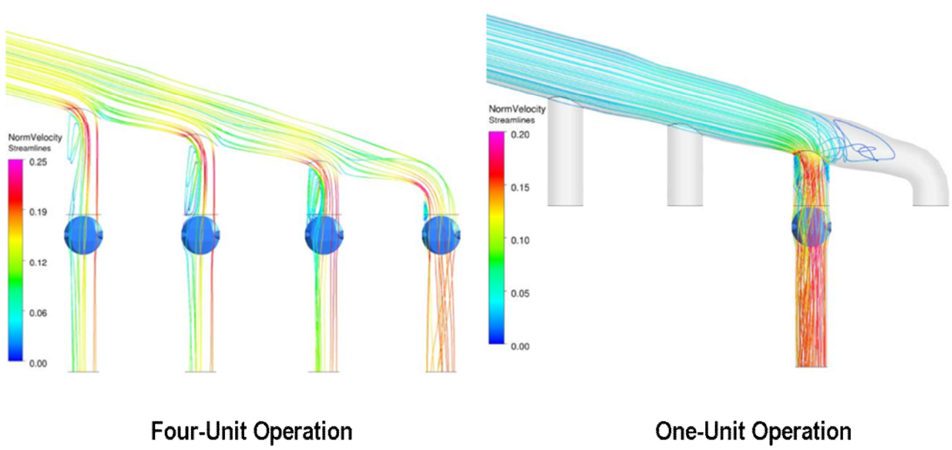

Figure 3.3: Velocity Streamlines from CFD Analyses [Lemay et al., 2017]

3.2 Flow Analyses for the Current Project

Fifteen-minute measurements of flow rate (cfs) from acoustic time-of-flight flowmeters were available for each unit at Palisades for the period from September 2013 through June 2021. Additional fifteen-minute measurements included unit power (MW), headwater elevation (ft), and tailwater elevation (ft). Flow correlation analyses were used to derive individual unit performance characteristics. An initial review of the flow correlation analyses revealed low flow correlation efficiencies over an extended period of time for Unit 1 due to a malfunctioning flowmeter, as illustrated at a net head of 225 ft in Figure 3.4 and Figure 3.5. Consequently, only data from 2013 to 2016 was usable for the Unit 1 flow analyses. Figure 3.6 and Figure 3.7 present the corresponding flow correlation efficiencies and efficiency versus power results for Unit 1 with the bad flowmeter data removed. These results illustrate the value of flow correlation analyses in identifying potential problems with performance-related instrumentation (i.e., flow, power, head).

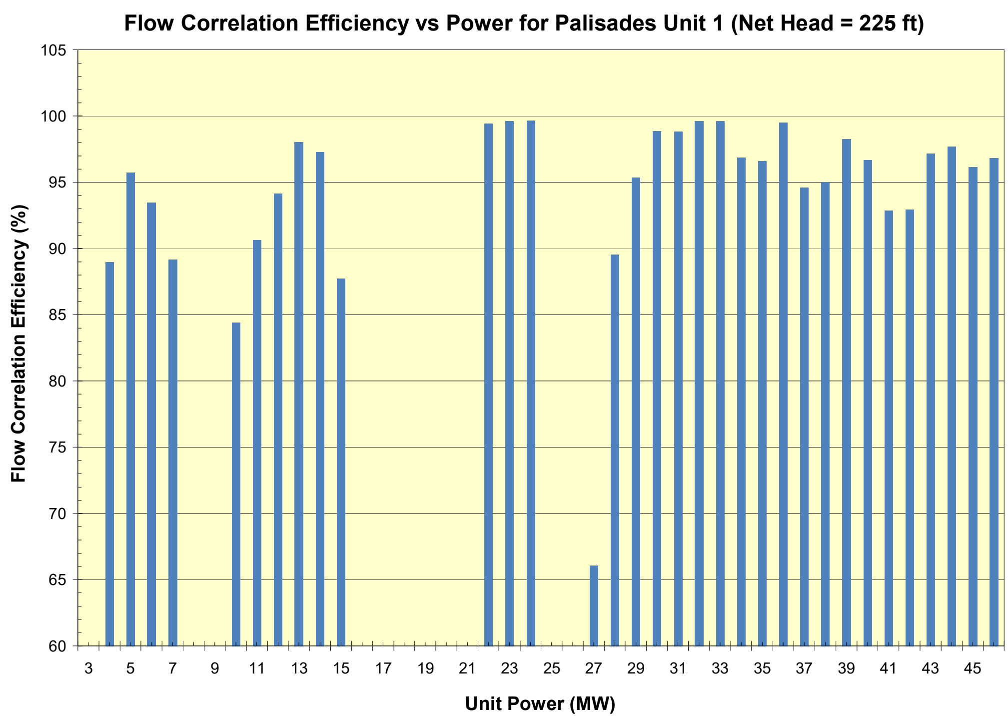

Figure 3.4: Flow Correlation Efficiency versus Power for Palisades Unit 1 at Net Head of 225 ft with All Flow Data Included (2013 – 2021)

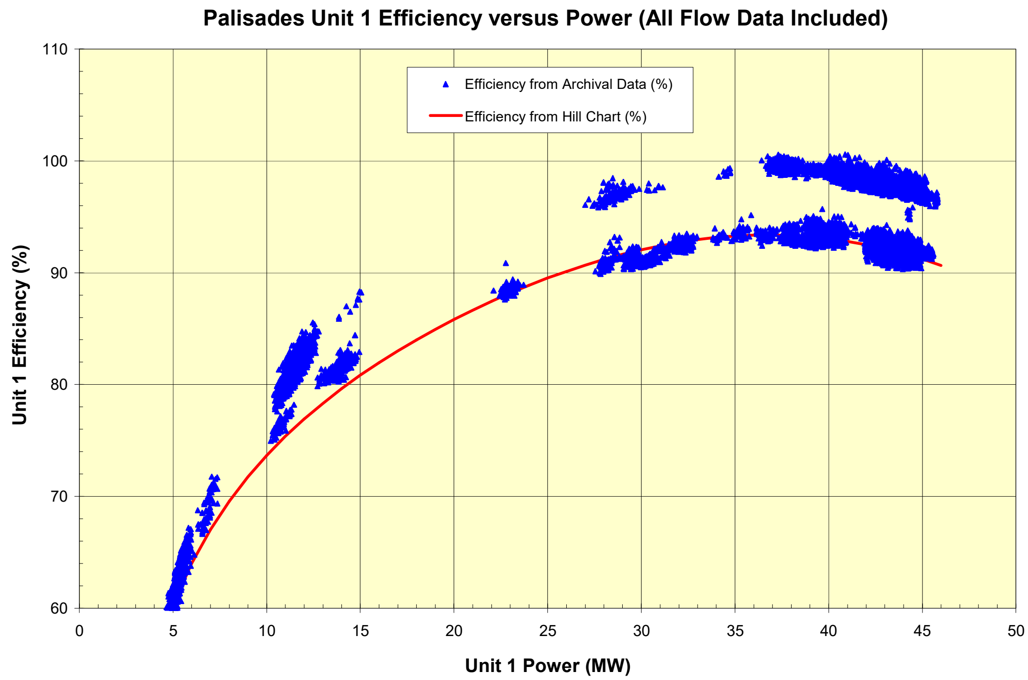

Figure 3.5: Unit Efficiency versus Power for Palisades Unit 1 at Net Head of 225 ft with All Flow Data Included (2013 – 2021)

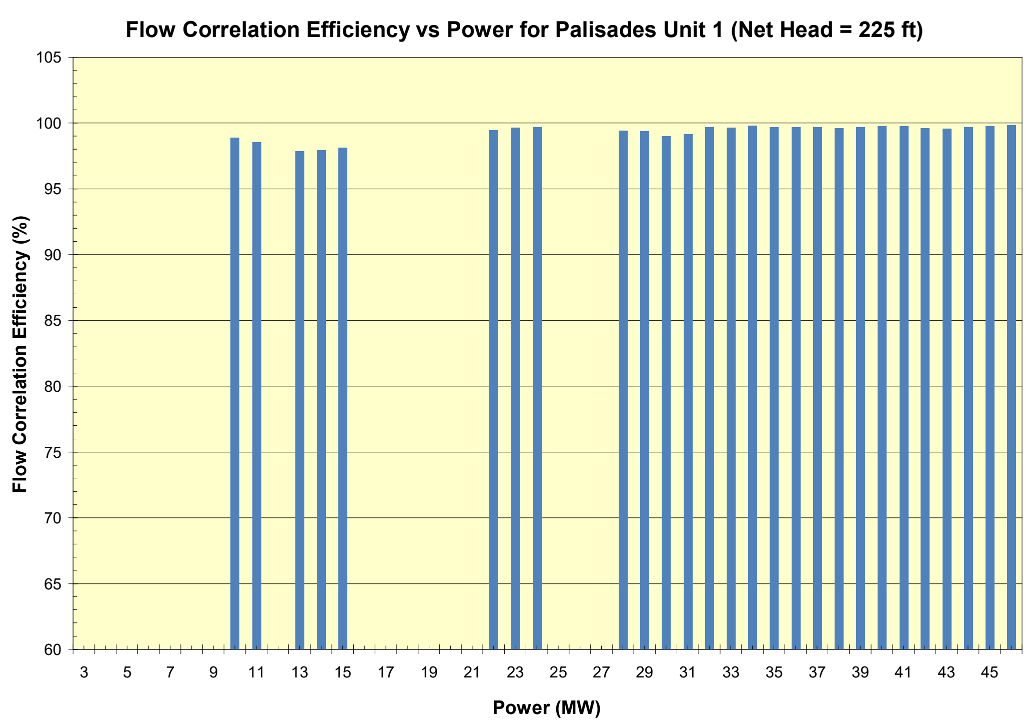

Figure 3.6: Flow Correlation Efficiency versus Power for Palisades Unit 1 at Net Head of 225 ft with Bad Flow Data Removed (2013 – 2016)

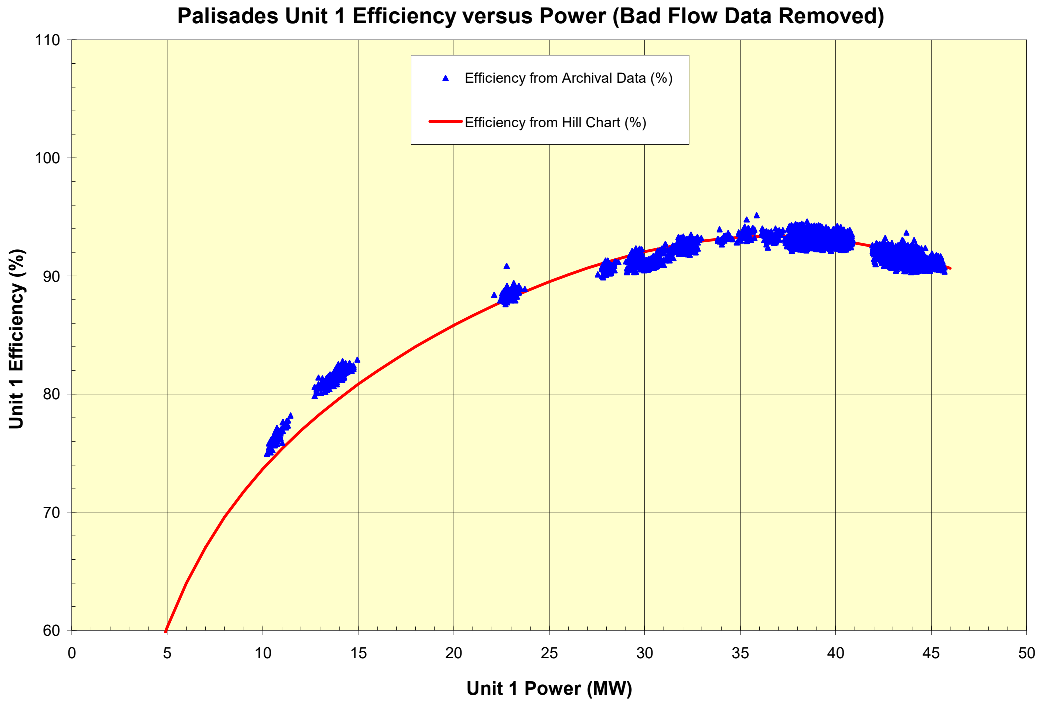

Figure 3.7: Unit Efficiency versus Power for Palisades Unit 1 at Net Head of 225 ft with Bad Flow Data Removed (2013 – 2016)

3.3 Operation Efficiency Analyses

Operation efficiency analyses use unit efficiency characteristics and archival operations data to determine how closely the actual dispatch matches the optimized dispatch. Detailed computational steps for determining the operation efficiency are discussed elsewhere [ORNL, 2011]. At each time step of the archival data, the optimized plant efficiency is computed, apportioning the total plant power among the available units to maximize the plant efficiency while meeting the necessary constraints (e.g., matching the actual plant power, matching the head, and operating each unit within minimum and maximum power limits). Energy gains due to water savings from optimized dispatch are computed by assuming that the water is converted into energy at the optimized plant efficiency and head for the time step in which the computed energy gain occurs.

The individual unit performance characteristics for Units 1, 2, 3, and 4 derived from the archival data, as discussed in Section 3.2, were aggregated to provide combined unit performance characteristics. By assuming equal unit performance and combining the unit curves, optimized dispatch is simplified with virtually no effect on the optimized plant efficiency curves. This also ensures that each unit is interchangeable in the dispatch order, avoiding unequal wear which could result from the preferential dispatch of an insignificantly more efficient unit. The HPC was used to develop optimized plant efficiency curves based on these combined unit characteristics derived from the archival analyses.

For this project, operation efficiency analyses were computed with the HPC Analyzer for Palisades using fifteen-minute archival data (June 2018 through June 2021) of unit flow, unit power, headwater, and tailwater and the combined unit characteristics derived from the archival analyses as discussed above. In addition, operation efficiency analyses were also computed for Palisades using the same archival data for plant operations (June 2018 through June 2021) and the combined unit characteristics based on the hill curves from the turbine manufacturer. Results from these recent operation efficiency analyses are summarized in Table 3.1 for the derived unit characteristics and in Table 3.2 for the unit characteristics based on the hill curves. Figures 3.8 and 3.9 show Lost Energy Opportunity and Lost Revenue Opportunity results from operation efficiency analyses for the two complete years (2019 and 2020), based on the derived unit characteristics.

Table 3.1: Summary of Operation Efficiency Analyses for Palisades Using Unit Characteristics Based on Hill Curves (2018 - 2021)

Analyses Based on Prototype Efficiency Curves from Hill Chart				
Year	Operation Efficiency Analyses			
	Efficiency Improvement (%)	Lost Energy Opportunity (MWh)	Lost Revenue Opportunity ($)	Water Conservation Opportunity (millions of cubic feet)
2018 (partial)	0.29	1,578	$ 46,729	347
2019	0.44	2,384	$ 70,601	496
2020	0.29	1,542	$ 45,662	298
2021 (partial)	0.12	622	$ 18,421	118
TOTAL	**N/A**	**6,126**	**$ 181,413**	**1,259**

Table 3.2: Summary of Operation Efficiency Analyses for Palisades Using Unit Characteristics Derived from Archival Data (2018 - 2021)

Analyses Based on Modified Efficiency Curves from Archival Analyses				
Year	Operation Efficiency Analyses			
	Efficiency Improvement (%)	Lost Energy Opportunity (MWh)	Lost Revenue Opportunity ($)	Water Conservation Opportunity (millions of cubic feet)
2018 (partial)	0.30	1,902	$ 56,337	450
2019	0.39	3,012	$ 89,211	632
2020	0.20	1,646	$ 48,758	321
2021 (partial)	0.21	650	$ 19,253	124
TOTAL	**N/A**	**7,210**	**$ 213,559**	**1,527**

Because unit efficiencies from field tests agree closely with the efficiencies derived from the archival data and with the turbine manufacturer's predictions (i.e., hill curves), the operation efficiency results in Table 3.1 and Table 3.2 are similar to each other. As shown in Table 3.2, the potential efficiency improvements due to improved optimization, while meeting the actual power versus time, are modest, ranging from a low of 0.20% for 2020 to a high of 0.39% for 2019, with a three-year total Lost Energy Opportunity of 7,210 MWh and a three-year total Lost Revenue Opportunity of $213,559.

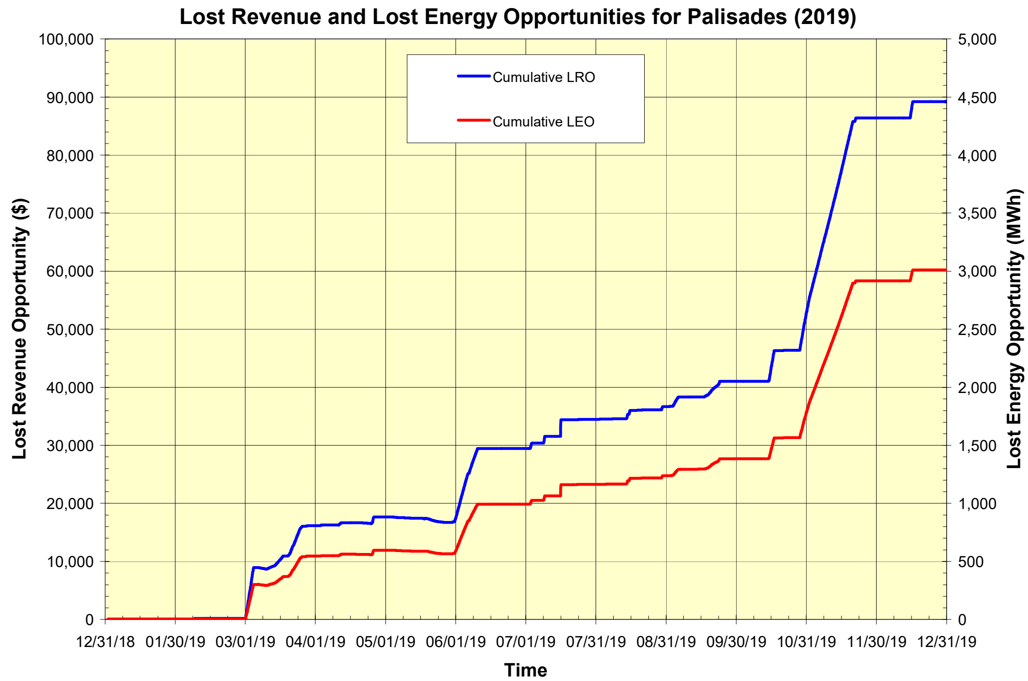

Figure 3.8: Results from Palisades Operation Efficiency Analyses, 2019

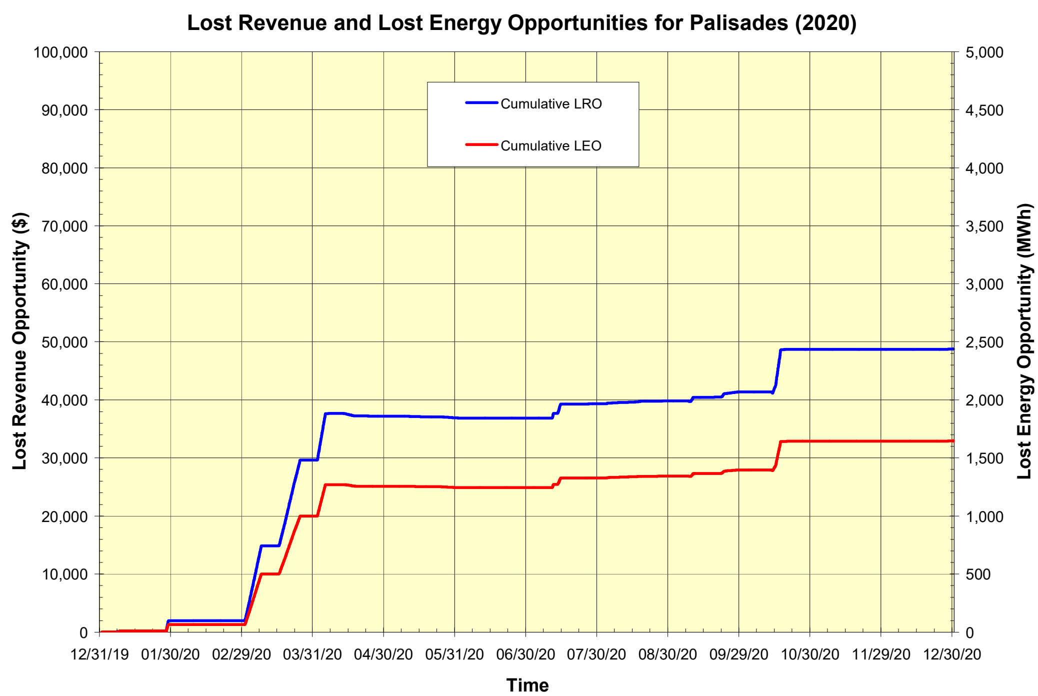

Figure 3.9: Results from Palisades Operation Efficiency Analyses, 2020

The results from the 2018 – 2021 operation efficiency analyses were also reviewed for Efficiency Loss Events. An Efficiency Loss Event occurs when the optimized dispatch remains constant for multiple time steps, and the gain in energy due to optimization is greater than a chosen threshold (set at 50 MWh for these analyses). Typically, Efficiency Loss Events are the most easily obtainable efficiency improvements due to optimized dispatch. Table 3.3 summarizes the major Efficiency Loss Events identified from the 2018 – 2021 analyses.

Table 3.3: Summary of Major Efficiency Loss Events for Palisades (2018 - 2021)

Start Time	End Time	Energy Loss (MWh)	Optimized Unit Dispatch Configuration	Number of Units On	Description of Energy Loss Event
04/26/18 07:15	05/26/18 10:45	994.8	Unit 1,Unit 2,Unit 3,Unit 4	4	Optimized configuration requires four units. But, one unit is off, and the other three units are operating at unequal loads.
08/18/18 01:00	09/18/18 08:45	530.8	Unit 1,Unit 2,Unit 3,Unit 4	4	Four units are operating but not at equal loads, with Unit 3 up to 20 MW lower than the other units.
10/17/18 22:00	10/25/18 16:15	376.8	Unit 1	1	Two units are operating when one unit would be more efficient.
01/31/19 12:00	03/07/19 14:00	215.3	Unit 1	1	Two units are operating at unequal loads when one unit would be more efficient.
10/14/19 21:00	11/07/19 15:00	520.6	Unit 1	1	Two units are operating at unequal loads when one unit would be more efficient.
11/07/19 16:00	12/31/19 23:45	630.7	Unit 1	1	Two units are operating at unequal loads when one unit would be more efficient.
01/01/20 00:00	03/09/20 09:45	448.6	Unit 1	1	Two units are operating at unequal loads when one unit would be more efficient.
03/09/20 10:00	03/25/20 23:45	457.9	Unit 1,Unit 2	2	Three units are operating when two units would be more efficient.
03/26/20 00:00	04/05/20 19:45	250.1	Unit 1,Unit 2,Unit 3	3	Four units are operating when three units would be more efficient.
02/25/21 21:00	04/14/21 18:15	305.2	Unit 1	1	Two units are operating, sometimes at unequal loads, when one unit would be more efficient.

These Efficiency Loss Events occur because too many or two few units are operating, because the units are not operating at equal loads, or both. There may be availability or maintenance issues associated with some of these events. Also, the practical implementation of generation improvements from improved optimization must be balanced with the potential for additional maintenance costs due, often, to increased start/stops of the units. However, the Lost Energy Opportunity for these Efficiency Loss Events is two-thirds of the total Lost Energy Opportunity identified in the operation efficiency analyses. So, increased generation from improved optimization could be achieved without any significant effect on the number of start/stops for the Palisades units.

3.4 Generation Scheduling Analyses

Generation scheduling analyses evaluate how closely the actual plant powers align with the overall peak efficiency curves for the entire plant. The steps for computing the generation scheduling analyses are shown elsewhere [ORNL, 2011]. Individual unit characteristics combine to create an overall plant efficiency curve that is the maximum plant efficiency achievable for any given power with optimized plant dispatch. By scheduling plant power levels to align with peak operation efficiency regions when hydrologic conditions, market conditions, and other restrictions permit, more efficient energy generation is achieved.

For this project, generation scheduling analyses were computed with the HPC Analyzer for Palisades using fifteen-minute archival data (June 2018 through June 2021) of unit flow, unit power, headwater, and tailwater and the combined unit characteristics derived from the archival analyses. In addition, generation scheduling analyses were also computed for Palisades using the same archival data for plant operations (June 2018 through June 2021) and the combined unit characteristics based on the hill curves from the turbine manufacturer. Results from these recent generation scheduling analyses are summarized in Table 3.4 for the unit characteristics based on the hill curves and in Table 3.5 for the derived unit characteristics.

Table 3.4: Summary of Generation Scheduling Analyses for Palisades Using Unit Characteristics Based on Hill Curves (2018 - 2021)

Analyses Based on Prototype Efficiency Curves from Hill Chart				
Year	Generation Scheduling Analyses			
	Efficiency Improvement (%)	Lost Energy Opportunity (MWh)	Lost Revenue Opportunity ($)	Water Conservation Opportunity (millions of cubic feet)
2018 (partial)	0.69	3,719	$ 110,158	828
2019	1.09	7,366	$ 218,178	1,496
2020	0.71	5,752	$ 170,368	1,252
2021 (partial)	1.55	4,631	$ 137,158	997
TOTAL	**N/A**	**21,468**	**$ 635,862**	**4,573**

Table 3.5: Summary of Generation Scheduling Analyses for Palisades Using Unit Characteristics Derived from Archival Data (2018 - 2021)

Analyses Based on Modified Efficiency Curves from Archival Analyses				
Year	Generation Scheduling Analyses			
	Efficiency Improvement (%)	Lost Energy Opportunity (MWh)	Lost Revenue Opportunity ($)	Water Conservation Opportunity (millions of cubic feet)
2018 (partial)	0.57	3,413	$ 101,079	769
2019	0.98	7,073	$ 209,509	1,484
2020	0.61	5,116	$ 151,533	1,149
2021 (partial)	1.98	5,955	$ 176,398	1,358
TOTAL	**N/A**	**21,557**	**$ 638,519**	**4,760**

Because unit efficiencies from field tests agree closely with the efficiencies derived from the archival data and with the turbine manufacturer's predictions (i.e., hill curves), the generation scheduling results in Table 3.4 and Table 3.5 are similar to each other. As shown in Table 3.5, the potential efficiency improvements due to improved generation scheduling are significant, ranging from a low of 0.57% for 2018 (partial year) to a high of 1.98% for 2021 (partial year), with a three-year total Lost Energy Opportunity of 21,557 MWh and a three-year total Lost Revenue Opportunity of $638,519.

Figures 3.10 and 3.11 show Lost Energy Opportunity and Lost Revenue Opportunity results from the generation scheduling analyses for the two complete years (2019 and 2020), based on the derived unit characteristics. Opportunities for scheduling improvements occur primarily during October to April in each year.

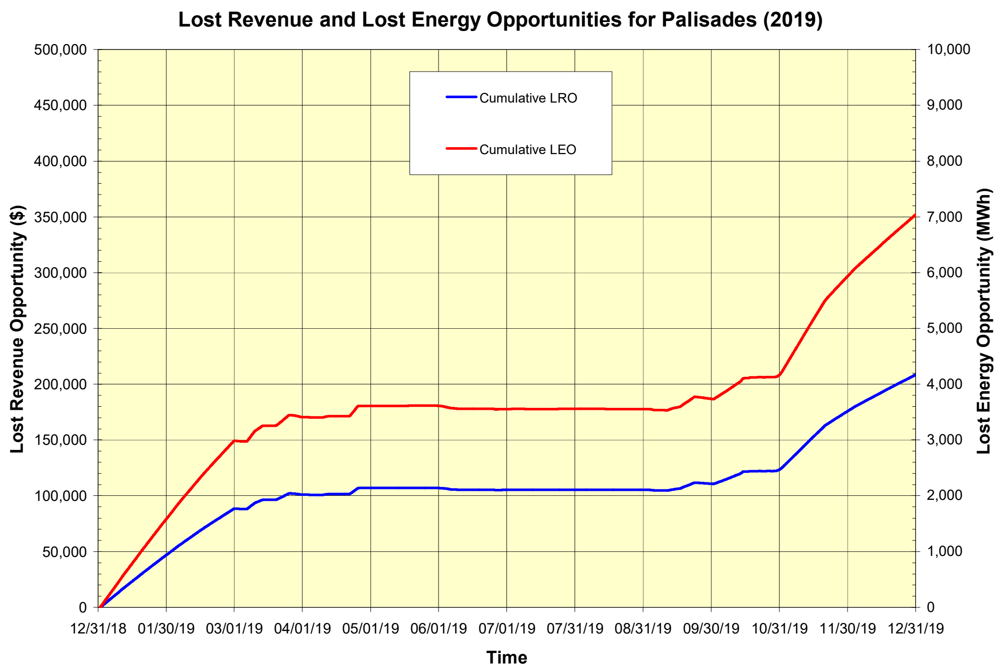

Figure 3.10: Results from Palisades Generation Scheduling Analyses, 2019

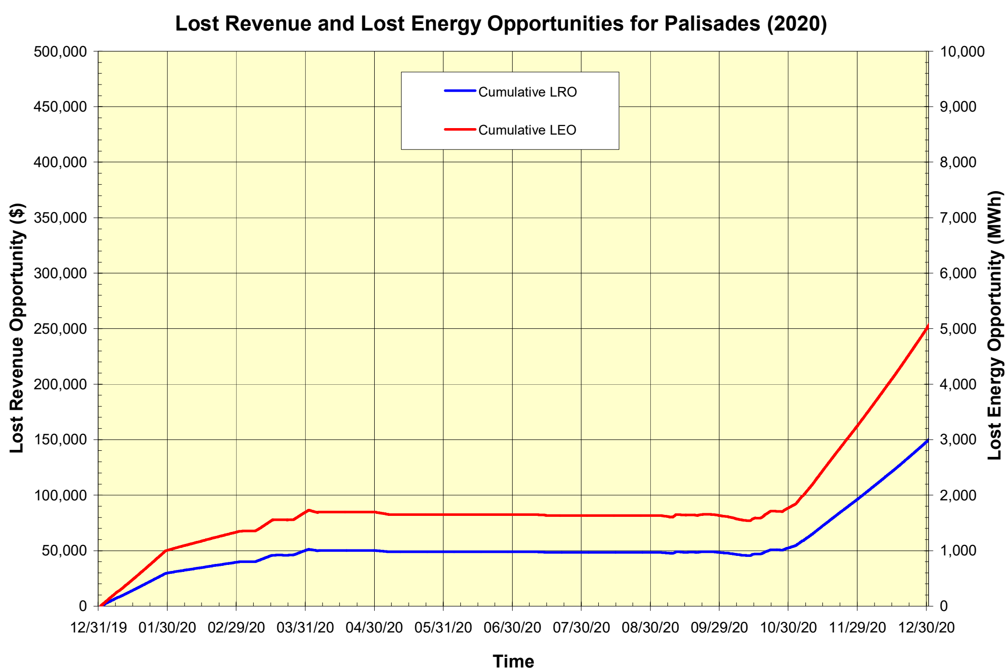

Figure 3.11: Results from Palisades Generation Scheduling Analyses, 2020

Results from the 2018 - 2021 generation scheduling analyses are summarized by net head in Table 3.6. For the two years with data for the entire year, the largest potential generation improvements occur at net heads of 225 ft and 235 ft for 2019 and at net heads of 205 ft and 215 ft for 2020.

Table 3.6: Summary of Scheduling Analyses for Palisades by Net Head (2018 - 2021)

Generation Scheduling Results for Palisades				
Net Head (ft)	2018 (Partial Year)	2019	2020	2021 (Partial Year)
	Computed Energy Increase (MWh)	Computed Energy Increase (MWh)	Computed Energy Increase (MWh)	Computed Energy Increase (MWh)
135	0	0	0	0.4
145	0	0	0.4	0
155	0	0	0	0
165	0	0	0	0.3
175	10.3	0	0	0
185	57.8	0	0	0
195	264.0	4.4	640.5	0
205	870.4	187.9	1,707.7	0
215	1,593.9	151.3	1,084.2	1,405.8
225	605.4	3,506.0	1.3	2,858.1
235	9.3	3,218.6	623.6	1,690.8
245	1.4	4.8	1,058.3	0

Figures 3.12 and 3.13 provide results from the 2019 scheduling analyses conducted for Palisades, showing results for net heads of 225 ft and 235 ft. In each figure, the optimized plant net head efficiency for the head, based on the derived unit characteristics, is shown in green. The actual monthly generation versus plant power at that head is shown in blue, and the optimized monthly generation versus plant power at that head is shown in red. The actual generation values (blue triangles) tend to occur at a wide variety of power levels corresponding to specific release flows. The optimized generation values (red triangles) correspond to the peak efficiencies for one-unit, two-unit, three-unit, and four-unit operation.

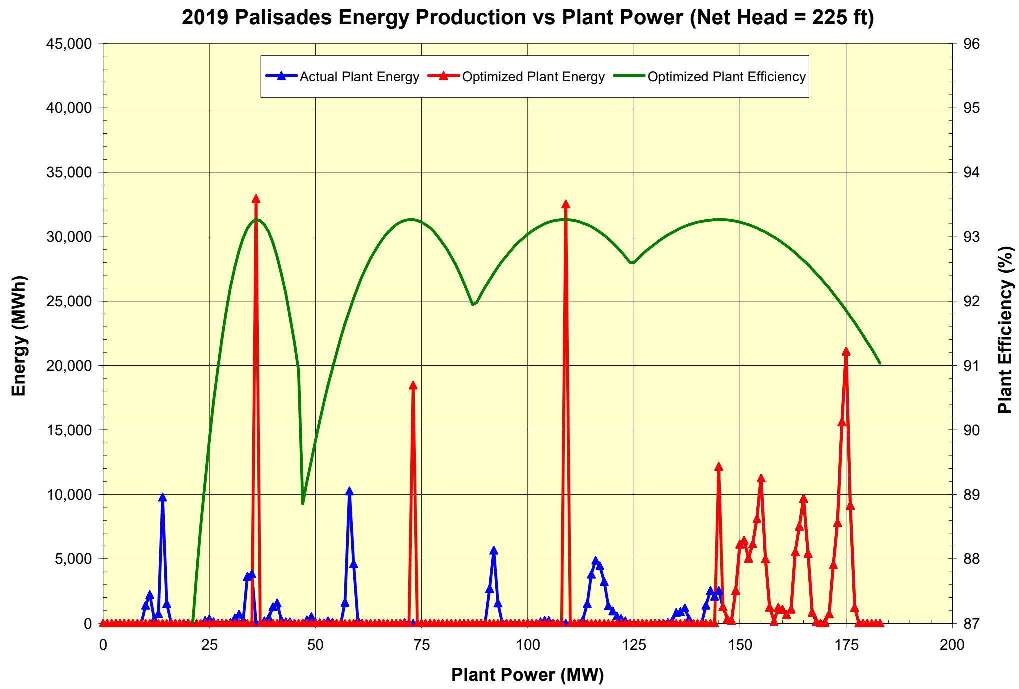

Figure 3.12: Energy Production versus Power from Palisades Generation Scheduling Analyses (2019, Net Head = 225 ft)

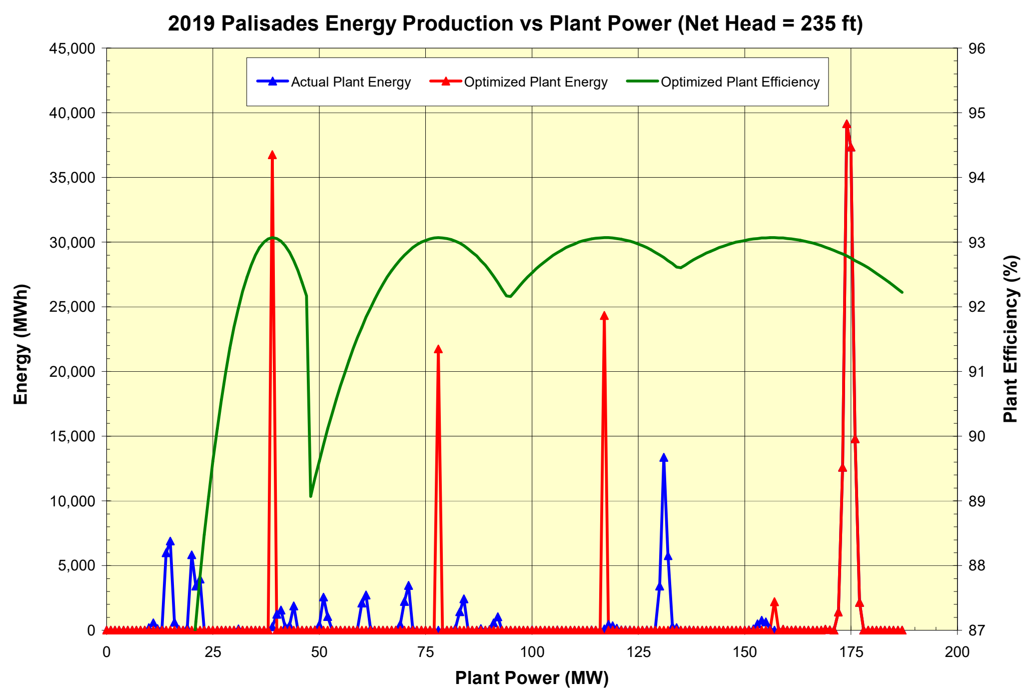

Figure 3.13: Energy Production versus Power from Palisades Generation Scheduling Analyses (2019, Net Head = 235 ft)

Similarly, Figures 3.14 and 3.15 provide typical results from the 2020 scheduling analyses conducted for Palisades, showing results for net heads of 205 ft and 215 ft.

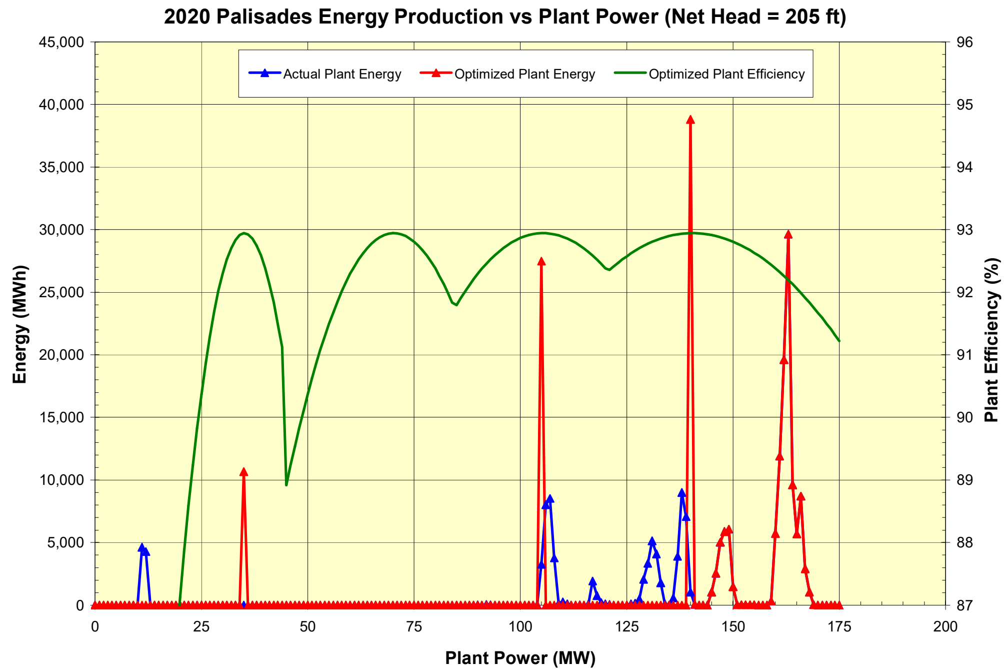

Figure 3.14: Energy Production versus Power from Palisades Generation Scheduling Analyses (2020, Net Head = 205 ft)

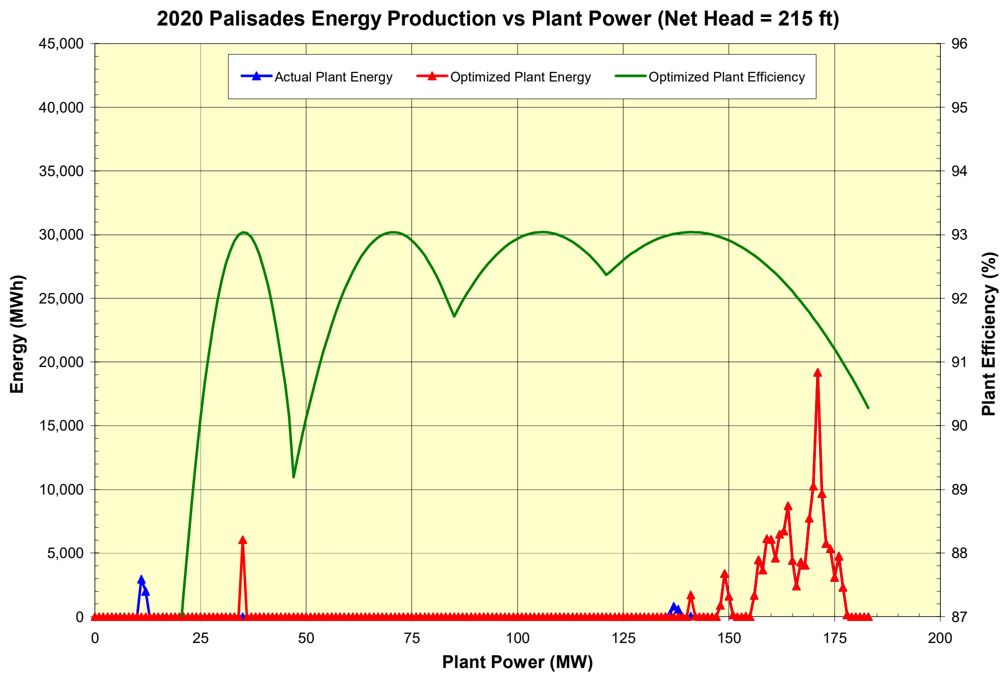

Figure 3.15: Energy Production versus Power from Palisades Generation Scheduling Analyses (2020, Net Head = 215 ft)

To achieve some or most of the potential generation improvements from improved scheduling, the units at Palisades should be dispatched at their best efficiency points, according to head. Table 3.7 provides guidance on the best efficiency plant power and plant flow for net heads of 135 ft, 145 ft, 155 ft, 165 ft, 175 ft, 185 ft, 195 ft, 205 ft, 215 ft, 225 ft, 235 ft, and 245 ft, based on the unit characteristics derived from the 2018 - 2021 archival analyses.

Table 3.7: Recommended Best Efficiency Operating Points for Palisades versus Net Head

Net Head (ft)	Number of Units Operating	Plant Power (MW)	Plant Flow (cfs)
135	1	25	2,393
135	2	50	4,787
135	3	75	7,180
135	4	89	8,494
145	1	25	2,233
145	2	50	4,415
145	3	75	6,698
145	4	99	8,845
155	1	28	2,325
155	2	56	4,649
155	3	84	6,974
155	4	111	9,227
165	1	27	2,130
165	2	54	4,260
165	3	80	6,310
165	4	107	8,440
175	1	27	1,991
175	2	54	3,982
175	3	82	6,047
175	4	108	7,965
185	1	28	1,927
185	2	56	3,854
185	3	85	5,849
185	4	114	7,844
195	1	32	2,078
195	2	64	4,156
195	3	96	6,235
195	4	128	8,313
205	1	35	2,176
205	2	70	4,353
205	3	106	6,591
205	4	141	8,767
215	1	35	2,073
215	2	70	4,146
215	3	106	6,278
215	4	141	8,351
225	1	36	2,032
225	2	72	4,065
225	3	108	6,097
225	4	145	8,186
235	1	39	2,113
235	2	78	4,225
235	3	118	6,392
235	4	156	8,450
245	1	43	2,230
245	2	86	4,461
245	3	128	6,639
245	4	171	8,869

(Note: When multiple units are operating, the load should be split equally among units.)

4. Results from 2018 - 2021 Performance Analyses

4.1 Summary of Results

Unit characteristics derived from the 2008-2015 archival analyses and the September 2018 field tests were used for operation efficiency analyses and generation scheduling analyses based on the 2018 and 2019 archival data.

Results are summarized below:

1. Flow analyses confirm results from previous flow analyses and show that the unit efficiencies from field tests agree closely with the efficiencies derived from archival data and with the turbine manufacturer's predictions.
2. Results from flow analyses demonstrate their value in identifying potential problems with performance-related instrumentation (i.e., flow, power, head).
3. Combined unit characteristics, assuming equal performance for all units, were developed from the September 2013 through June 2021 fifteen-minute archival data for unit flow, unit power, headwater, and tailwater.
4. Combined unit characteristics, assuming equal performance for all units, were also developed from the turbine manufacturer's hill curves.
5. Both sets of combined unit characteristics were used for operation efficiency analyses and generation scheduling analyses with archival operating data for June 2018 through June 2021. The operation efficiency results and the generation scheduling results are similar for the combined unit characteristics based on the turbine manufacturer's hill curves and the combined unit characteristics derived from the archival data.
6. Operating efficiency analyses show that the potential efficiency improvements due to improved optimization, while meeting the actual power versus time, are modest, ranging from a low of 0.20% for 2020 to a high of 0.39% for 2019, with a three-year total Lost Energy Opportunity of 7,210 MWh and a three-year total Lost Revenue Opportunity of $213,559.
7. Major Efficiency Loss Events, constituting approximately 2/3 of the potential improvements identified by the operation efficiency analyses, occur because too many or too few units are operating, because the units are not operating at equal loads, or both. This increased generation from improved optimization could be achieved without any significant effect on the number of start/stops for the Palisades units.
8. The potential efficiency improvements due to improved generation scheduling are significant, ranging from a low of 0.57% for 2018 (partial year) to a high of 1.98% for 2021 (partial year), with a three-year total Lost Energy Opportunity of 21,557 MWh and a three-year total Lost Revenue Opportunity of $638,519. Opportunities for scheduling improvements occur primarily during October to April in each year.
9. Table 3.7 provides recommended best efficiency operating points for Palisades versus gross head. These operating points can help Reclamation to achieve some or most of the potential generation improvements from improved scheduling. When multiple units are operating, the load should be split equally among the units.

4.2 Suggested Actions Based on Results

Palisades has high quality instrumentation for the plant's on-line systems, including flow measurements, and typically produces accurate and valuable archival data sets. Gaps that were identified as part of these analyses, and recommendations based on those gaps, include the following:

1. The identified Efficiency Loss Events should be investigated, and improvements should be implemented where possible.
2. Reclamation should consider implementing the methodology of Osburn [2014] to develop estimates of start/stop costs that are specific to Palisades for fully evaluating the potential maintenance costs associated with improved optimization.
3. Table 3.7 provides recommended best efficiency operating points for Palisades versus net head, and these recommendations should be followed whenever possible. If multiple units are operating, the load should be split equally among the units.
4. Palisades does not currently compute and review hydro performance indicators. Three important performance indicators for consideration include the operation efficiency, the generation scheduling efficiency, and the flow correlation efficiency, as recommended in March et al. [2019a].

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