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.

2. 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.

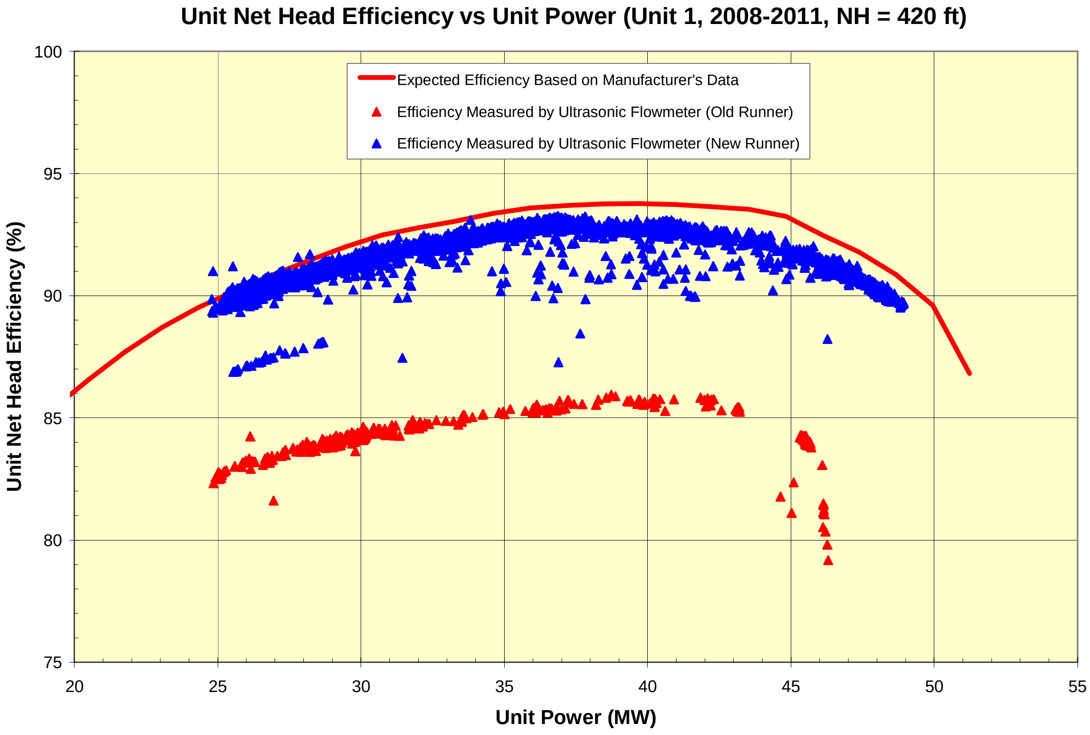

Figure 4-1: Example of Expected and Measured Efficiency versus Power

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.

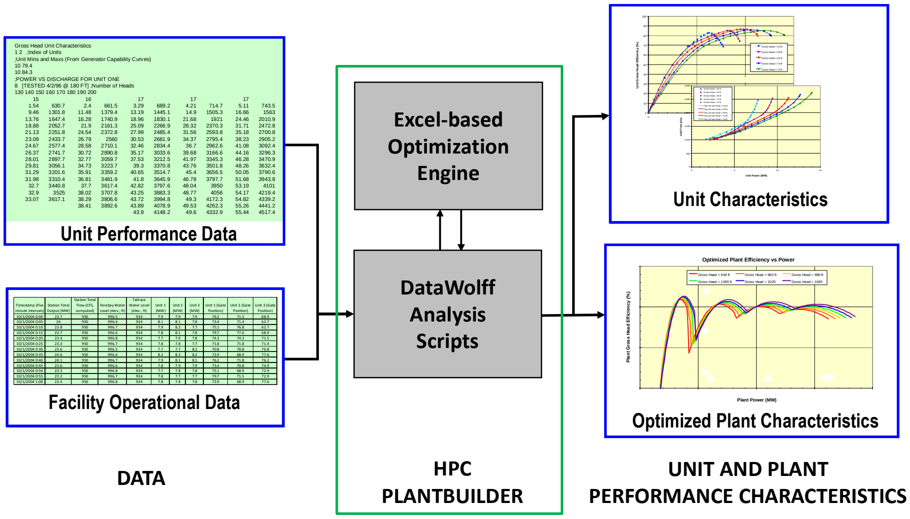

Figure 4-2: Overview of HPC PlantBuilder

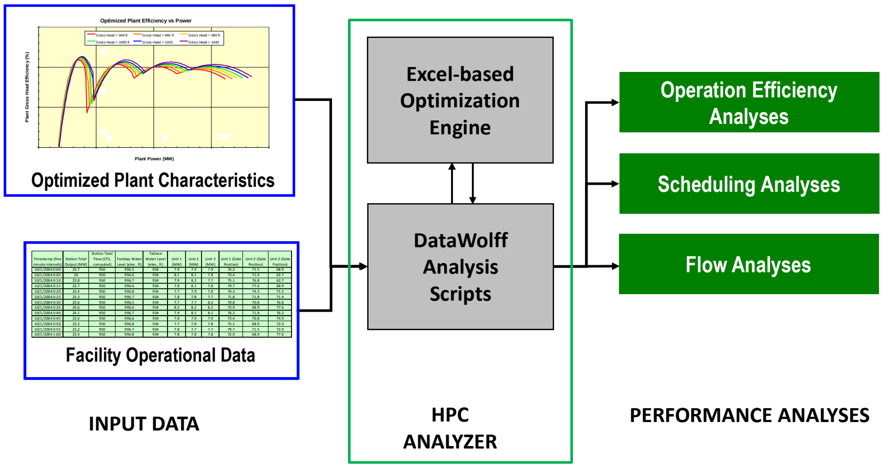

Figure 4-3: Overview of HPC Analyzer

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.

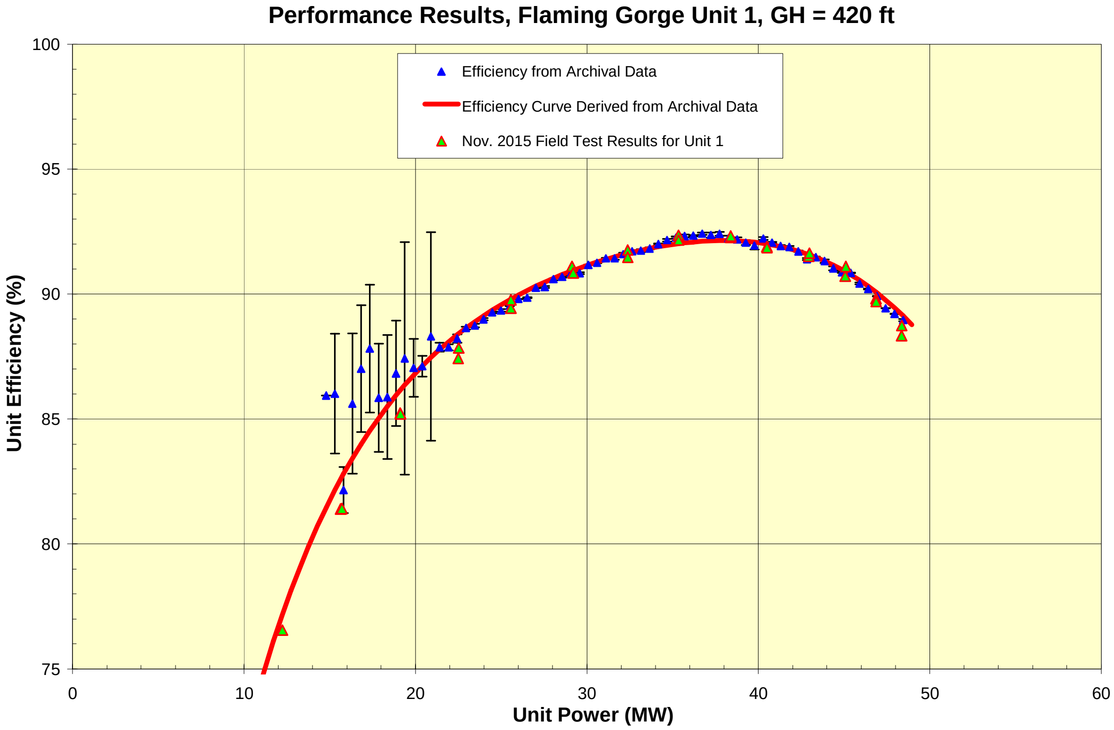

Figure 5-1: Performance Results for Flaming Gorge Unit 1 (Gross Head = 420 ft)

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].

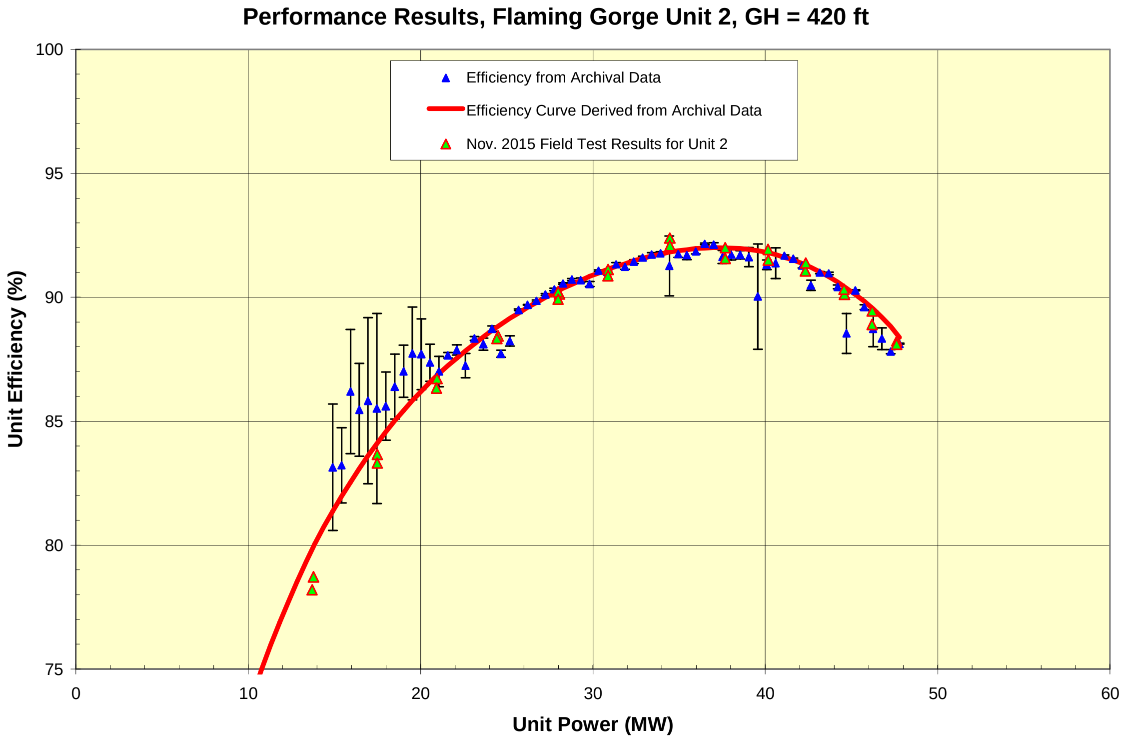

Figure 5-2: Performance Results for Flaming Gorge Unit 2 (Gross Head = 420 ft)

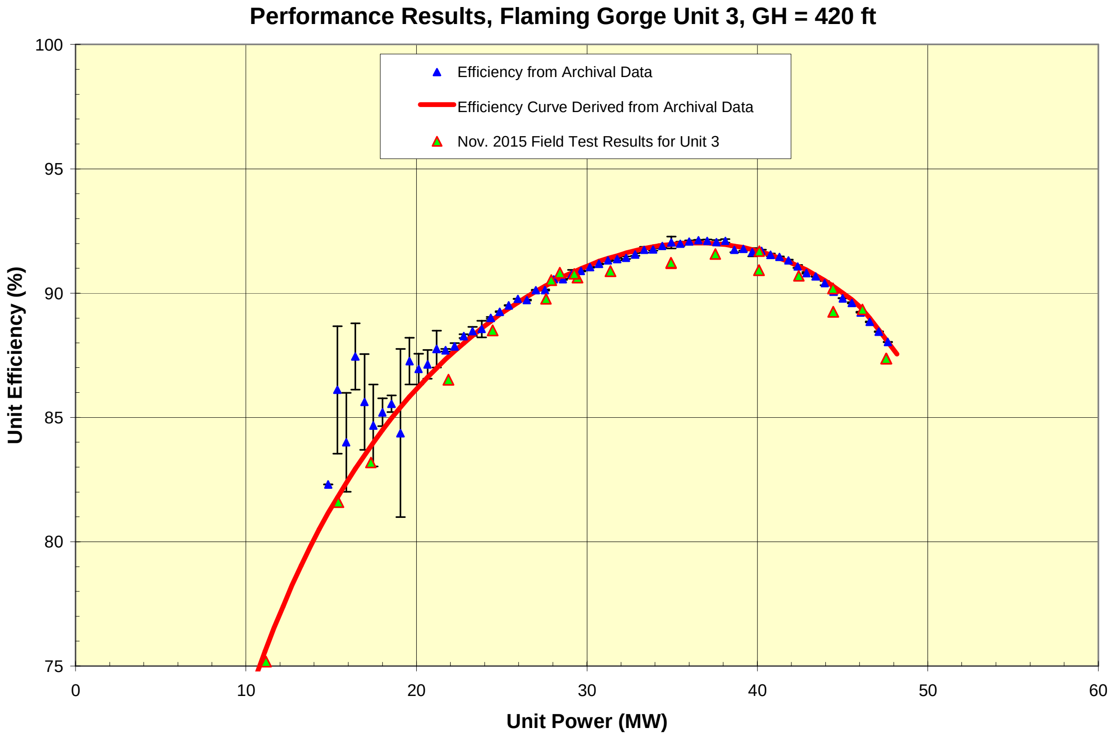

Figure 5-3: Performance Results for Flaming Gorge Unit 3 (Gross Head = 420 ft)

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.

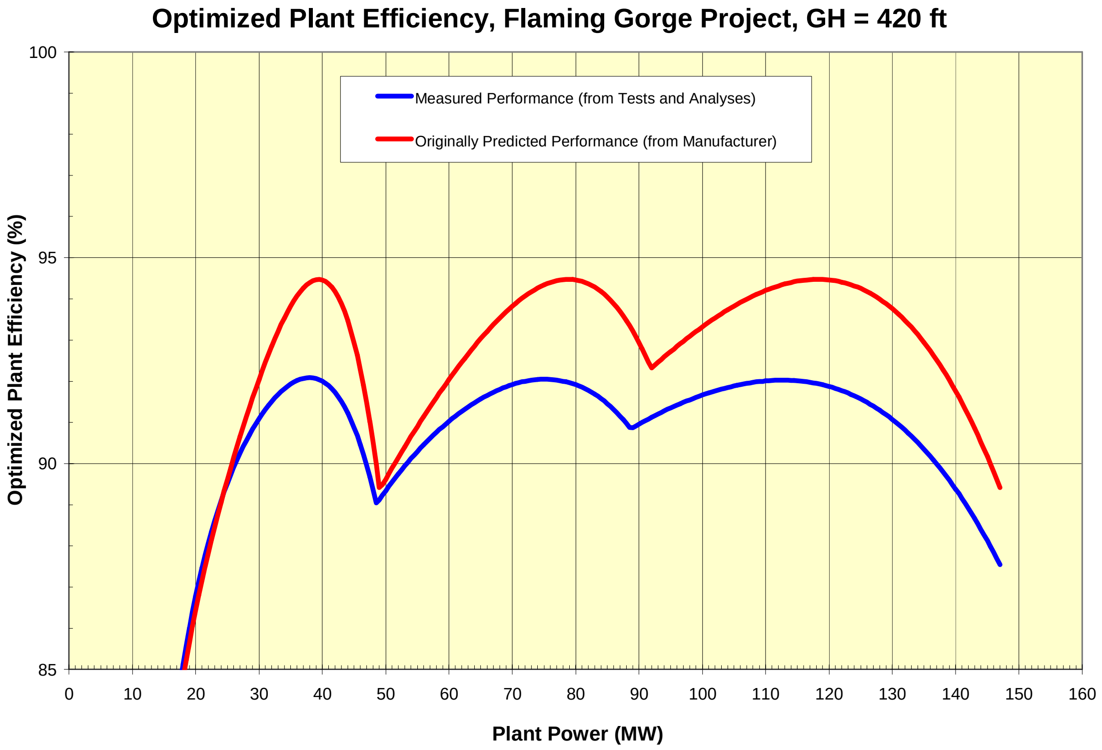

Figure 5-5: Comparison of Plant Performance Curves for Flaming Gorge (Gross Head = 420 ft)

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.

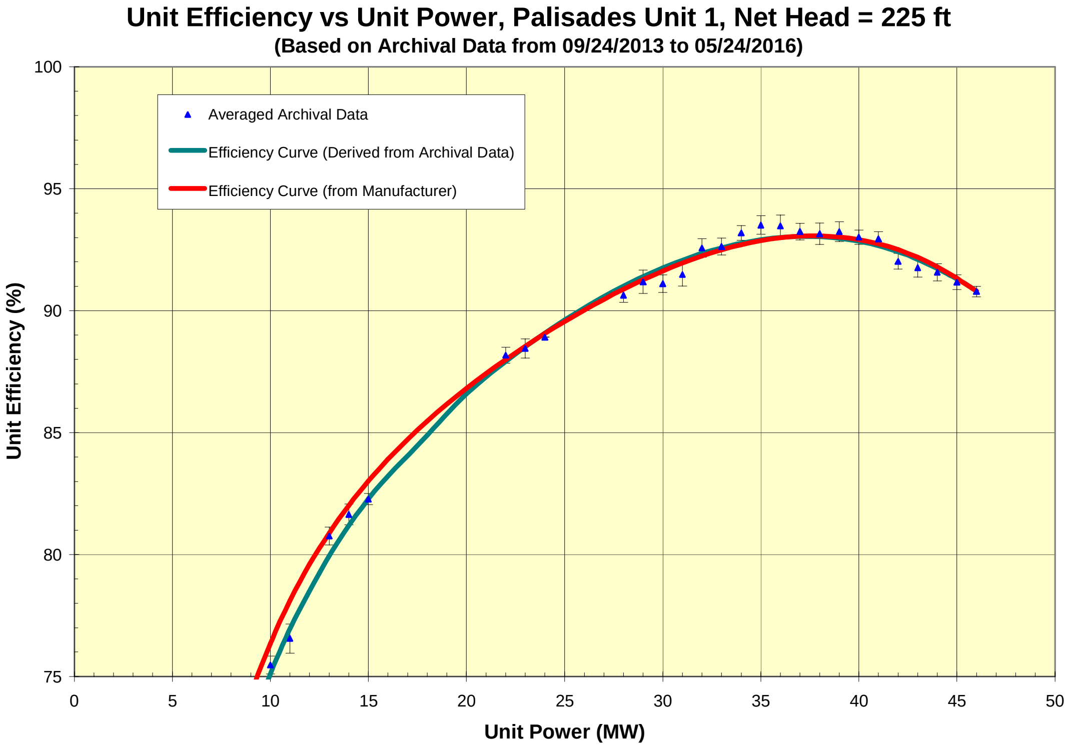

Figure 5-6: Performance Results for Palisades Unit 1 (Net Head = 225 ft)

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).

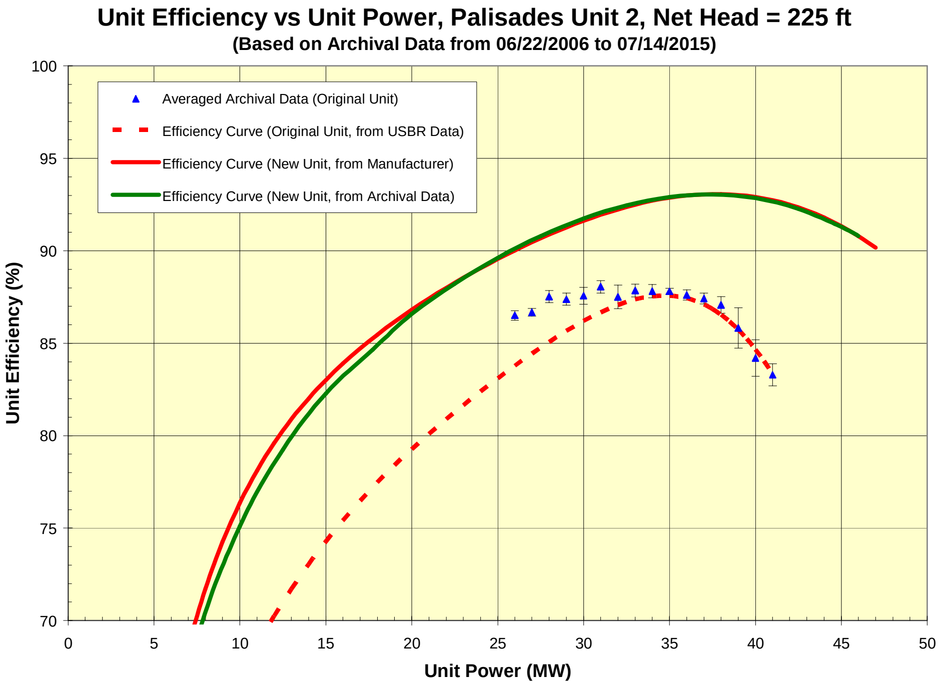

Figure 5-7: Performance Results for Palisades Unit 2 (Original Unit and New Unit)
Net Head = 225 ft

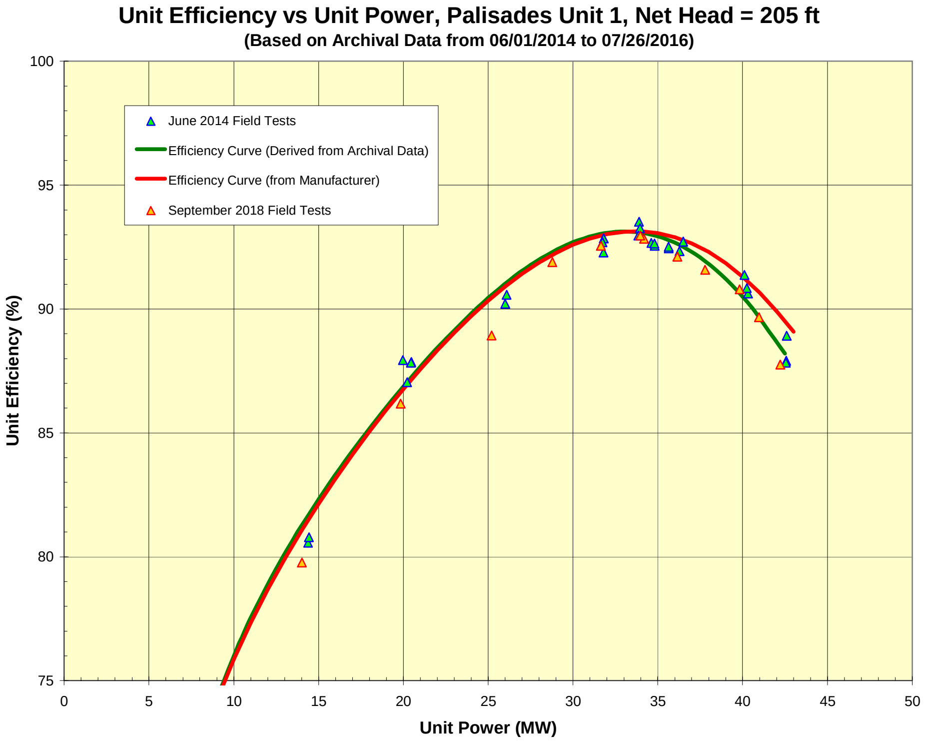

Figure 5-8: Performance Results for Palisades Unit 1, Net Head = 205 ft

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.

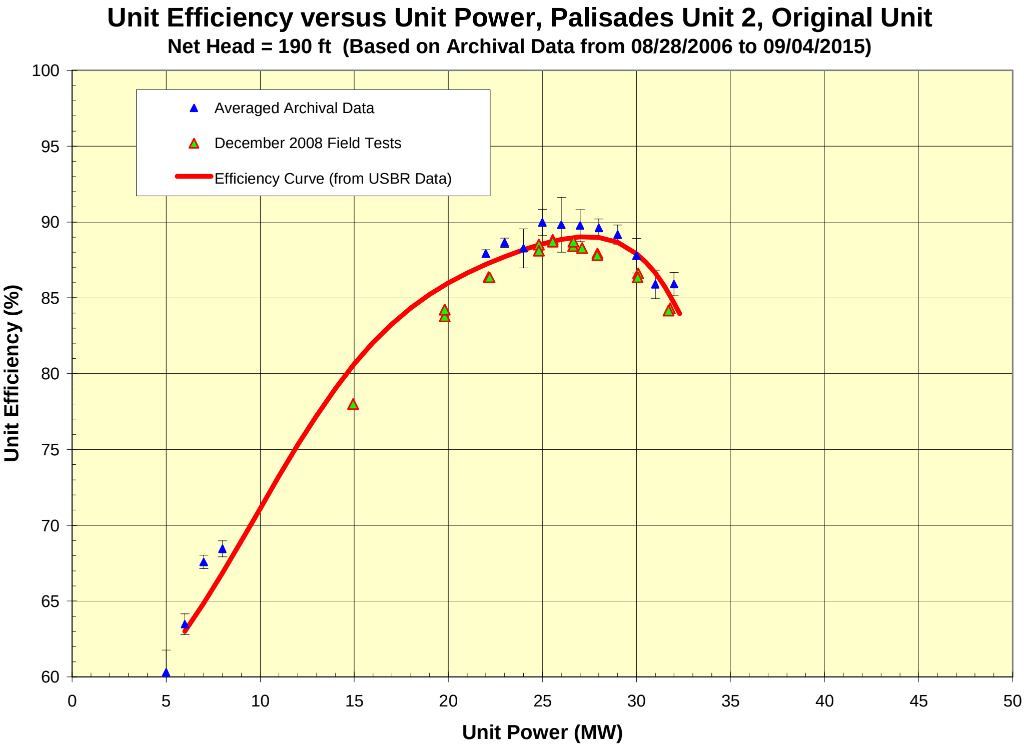

Figure 5-9: Performance Results for Palisades Unit 2, Original Unit
Net Head = 190 ft

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.

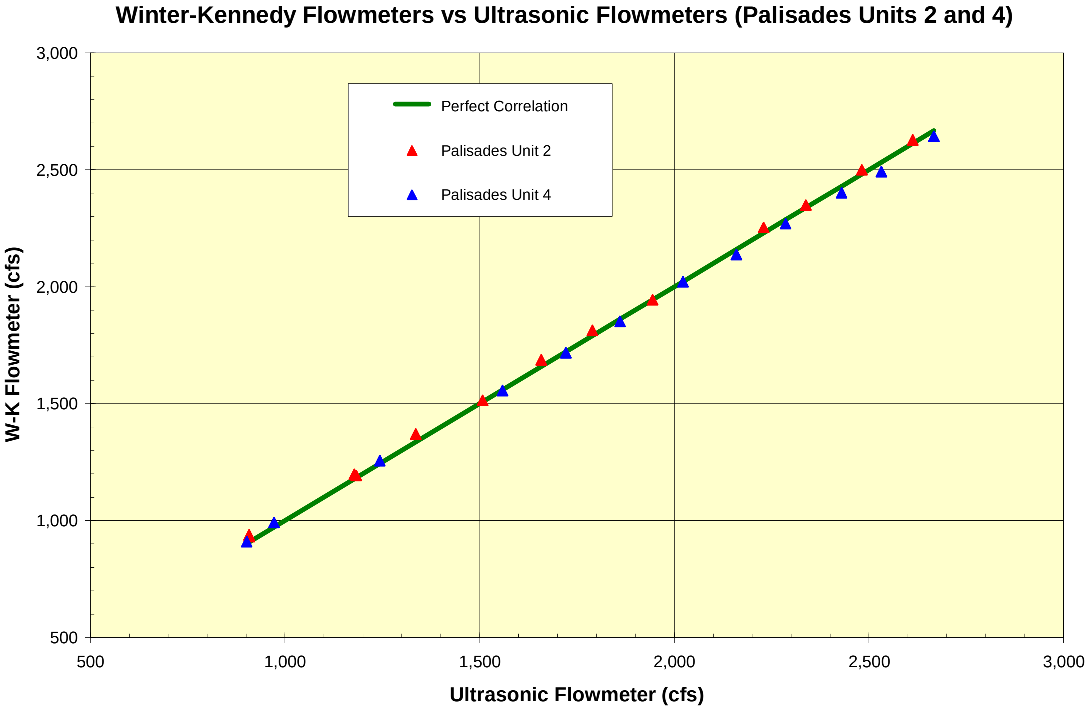

Figure 5-10: Comparison of Results from Winter-Kennedy Flowmeters and Ultrasonic Flowmeters for Palisades Unit 2 and Unit 4 (Based on September 2018 Field Tests)

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.

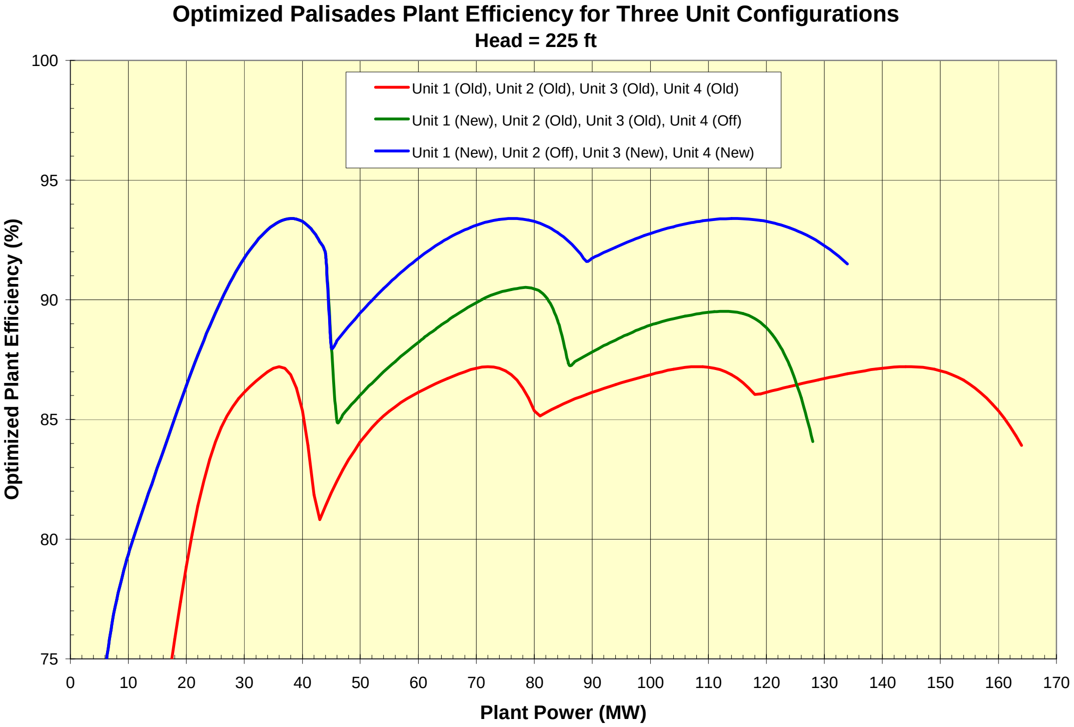

Figure 5-11: Optimized Palisades Plant Efficiency Curves for Three Analysis Periods

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.

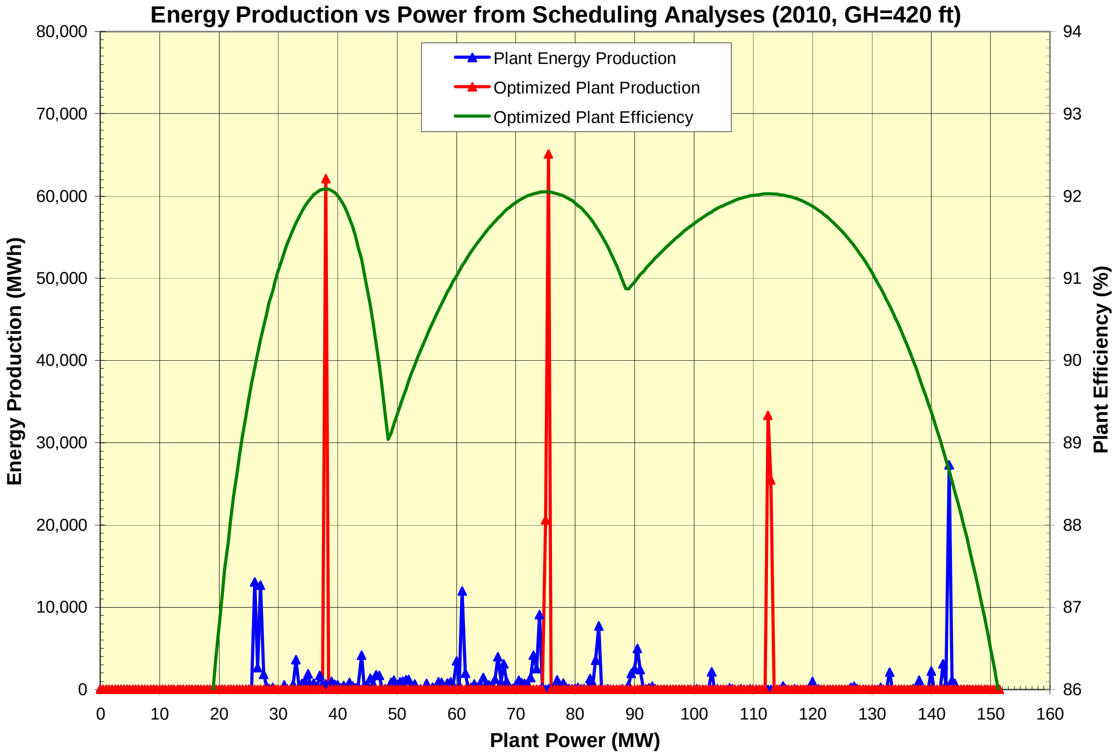

Figure 5-12: Typical Energy Production versus Power from Generation Scheduling Analyses (2010, Gross Head = 420 ft)

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.

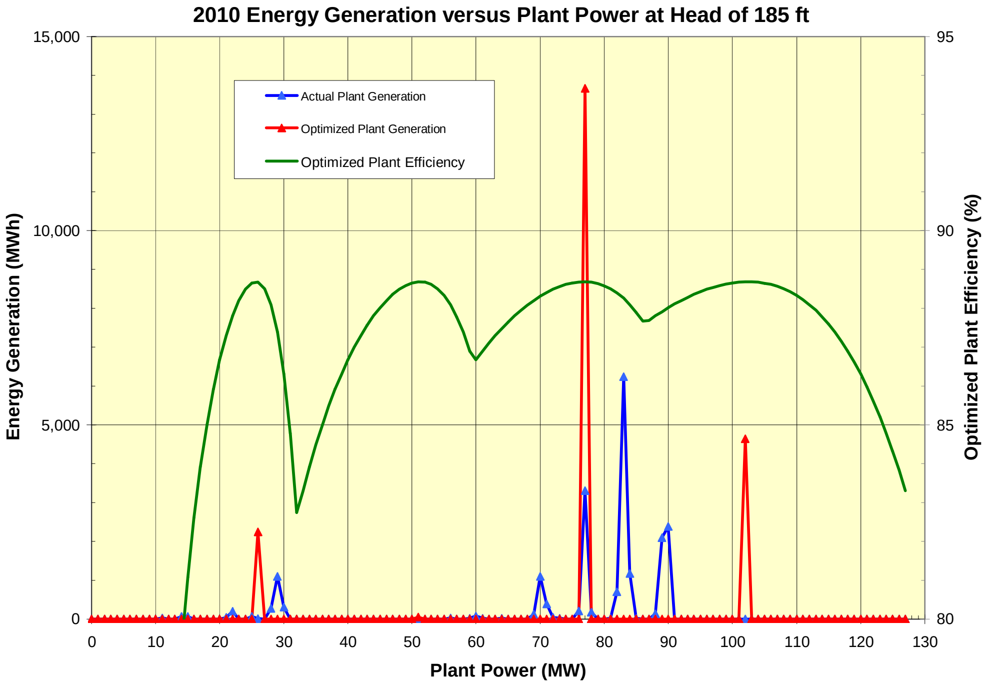

Figure 5-13: Typical Energy Generation versus Plant Power from Palisades Generation Scheduling Analyses (2010, Head = 185 ft)

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.

7. References

Almquist, C. W., T. A. Brice, J. S. Adams, and P. A. March, "Economical Flow Measurement for Optimal Dispatch," *Proceedings of Waterpower XIV*, Kansas City, Missouri: HCI Publications, July 2005.

ASME, *Performance Test Code 18: Hydraulic Turbines and Pump-Turbines*, ASME PTC 18-2011, New York, New York: American Society of Mechanical Engineers (ASME), 2011.

EPRI, *Hydropower Technology Roundup Report - Case Study on Hydro Performance Best Practices*, Palo Alto, California: Electric Power Research Institute, Report No. 1015807, December 2008.

EPRI, http://epri.com/hydrogrid, 2012a.

EPRI, *Results from Case Studies of Conventional Hydroelectric Plants: Quantifying the Value of Hydropower in the Electric Grid*, Palo Alto, California: Electric Power Research Institute, Report No. 1023143, August 2012b.

EPRI, *Results from Case Studies of Pumped-Storage Plants: Quantifying the Value of Hydropower in the Electric Grid*, Palo Alto, California: Electric Power Research Institute, Report No. 1023142, August 2012c.

EPRI, *Effects of Markets and Operations on the Suboptimization of Pumped Storage and Conventional Hydroelectric Plants*, Palo Alto, California: Electric Power Research Institute, Report No. 1023782, December 2012d.

EPRI, *Evaluating the Effects of Uncertainty in Unit Characteristics on the Operation and Optimization of Multiunit Hydroplants*, Palo Alto, California: Electric Power Research Institute, Report No. 3002003700, December 2014.

EPRI, *Evaluating the Effects of Uncertainty in Unit Characteristics on the Operation and Optimization of Francis, Diagonal Flow, Fixed Propeller, and Kaplan Hydroplants*, Palo Alto, California: Electric Power Research Institute, Report No. 3002006158, December 2015.

Lamy, P., and J. Néron, "A Different Approach in Measuring Individual Turbine Efficiencies in Multiple Unit Powerplants," *Proceedings of Waterpower XIII*, Kansas City, Missouri: HCI Publications Inc., July 2003.

March, P. A., and C. W. Almquist, "Flow Measurement Techniques for the Efficient Operation of Hydroelectric Powerplants," *National Institute of Standards and Technology, Metrology for the Americas Conference*, Miami, FL, November 1995.

March, P. A., and P. J. Wolff, "Optimization-Based Hydro Performance Indicator," *Proceedings of Waterpower XIII*, Kansas City, MO: HCI Publications Inc., July 2003.

March, P. A., and P. J. Wolff, "Component Indicators for an Optimization-Based Hydro Performance Indicator," *Proceedings of HydroVision 2004*, Kansas City, Missouri: HCI Publications Inc., August 2004.

March, P. A., P. J. Wolff, B. T. Smith, Q. F. Zhang, and R. Dham, "Data-Based Performance Assessments for the DOE Hydropower Advancement Project," *Proceedings of HydroVision 2012*, Tulsa, Oklahoma: PennWell Corporation, July 2012.

March, P. A., P. J. Wolff, B. T. Smith, P. O'Connor, "Developing and Verifying a Hydroplant Performance Calculator," *Proceedings of HydroVision 2014*, Tulsa, Oklahoma: PennWell Corporation, July 2014.

March, P., P. Wolff, and S. Rosinski, "Evaluating the Effects of Uncertainty in Unit Characteristics on the Operation and Optimization of Francis, Diagonal Flow, Fixed Propeller, and Kaplan Hydroplants," *Proceedings of HydroVision International 2016*, Tulsa, Oklahoma: PennWell Corporation, July 2016.

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.

ORNL, *Performance Assessment Manual, Hydropower Advancement Project, Rev. 1,* Oak Ridge, Tennessee: Oak Ridge National Laboratory (ORNL), December 2011.

Winter, I. A., “Improved Type of Flow Meter for Hydraulic Turbines,” *Proceedings of the ASCE*, April 1933.