

Optimizing the Corps' Hydroelectric Generation On the Columbia River: A Multi-Faceted Effort

The Hydroelectric Design Center of the U.S. Army Corps of Engineers seeks to increase the efficiency of hydroelectric generation at projects on the Columbia and Snake rivers through a number of activities. These activities — from field retrofits to research and development — are producing positive results.

By Rodney J. Wittinger

The Hydroelectric Design Center of the U.S. Army Corps of Engineers is leading or coordinating a variety of efforts in the field and laboratory to optimize the efficiency of its 112 Kaplan turbines. These generating units are located at hydroelectric projects on the Columbia and Snake rivers in the Pacific Northwest. With the exception of recent turbine replacement programs, almost 95 percent of the Kaplan turbines in the Corps' system are at least several decades old. During those decades, the original means of measuring aspects of turbine performance — from position-

Rod Wittinger, P.E., is a mechanical engineer and serves as a turbine expert in the U.S. Army Corps of Engineers' Hydroelectric Design Center in Portland, Ore. He participates in or coordinates with each of the organizations listed in the acknowledgments at the end of this article, and he oversees applied research and implementation of improvements to optimize hydroelectric generation within the Corps' Pacific region of the U.S.

Peer Reviewed

This article has been evaluated and edited in accordance with reviews conducted by two or more professionals who have relevant expertise. These peer reviewers judge manuscripts for technical accuracy, usefulness, and overall importance within the hydroelectric industry.

ing wicket gates to the blade angles, head, and power — have degraded. Additionally, civil characteristics (e.g., the smoothness of the walls of turbine water passages) have deteriorated.

To correct these deficiencies, the design center defined five areas where field retrofits can be applied to improve efficiency. These are:

- Calibrating and standardizing wicket gate openings and turbine blade angles;
- Measuring power output;
- Installing new instruments to measure the head at individual generating units;
- Upgrading governor mechanisms and controls; and
- Index testing of all turbines to determine relative efficiency profiles.

The design center formed a new central test group to perform field tests. The Corps anticipates that the capability of the group will expand within the next two years to allow two test teams to be in the field simultaneously.

At the same time, the Corps launched laboratory and field research in six areas of particular concern. A Hydro Optimization Team sponsored by Bonneville Power Administration (BPA), a federal power marketing agency, was formed to find a way of measuring — to a high degree of accuracy — the absolute flow through a generating unit. This team is considering experiments to determine the effect on unit efficiency of refurbishing turbine water passages. Addi-

tionally, plant efficiencies may be increased through research in four areas: properly sharing total load among individual generating units, modifying wicket gates and stay vanes, testing of minimum gap runners, and extending the length of draft tubes.

FIELD RETROFITS

Calibrations and standardization

As the Kaplan units aged, their mechanical control linkages changed. For example, restoring cables have a tendency to stretch with time. Consequently, the Corps initiated a program to recalibrate the control linkages of each unit prior to and after index testing to assure that mechanical operation agrees with electrical instrumentation reporting.

In addition, the Corps is standardizing calibration protocols and procedures system-wide. Previously, a measurement of the servomotor stroke had been used as an indicator of the wicket gate opening. The actual opening of the wicket gates, however, is not an exact linear function of the stroke of the servomotor, but is usually a shallow S-shaped curve. Further, this curve differs slightly for each unit; often, the value of actual wicket gate opening and servomotor stroke are not coincident. Variations or deviations exceeding 5 percent in position have been measured between the two when compared to original erection engineer's settings. To address this problem, the Corps initiated a program to permanently mount transducers (digital absolute angle encoders from Stegman) on three different wicket gate stems for every Kaplan unit to measure wicket gate angle.

Standardization of measuring angles applies to the runner blades as well. Historically, there has not been a standard method among manufacturers to measure blade angle. Most used two points on the

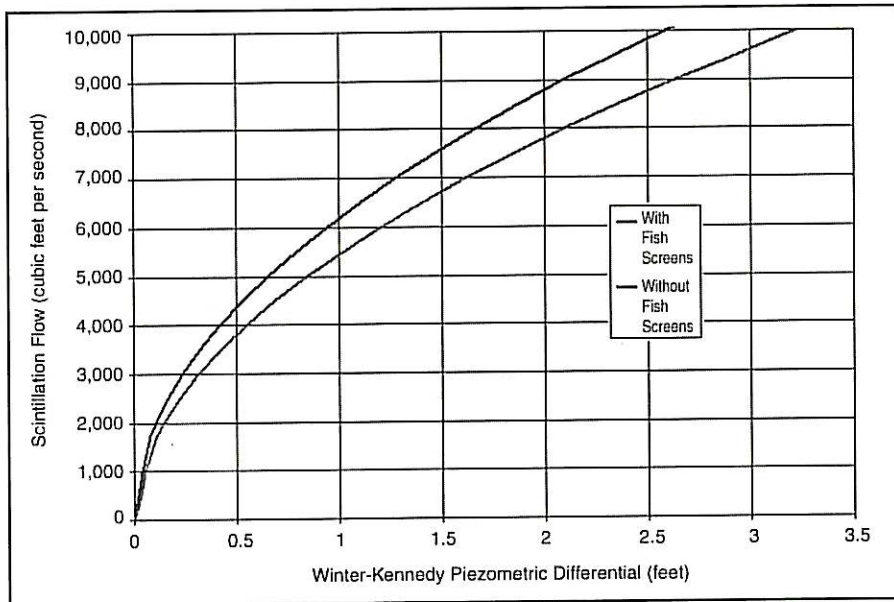


Figure 1: This graph shows the differences in Winter-Kennedy calibration curves for Unit 5 at McNary Dam with and without fish screens.

blade surface — near the outer leading and trailing edges — to form a hypo-

tenuse. However, to form the lower leg of a triangle, some used a direct horizon-

tal distance or the curved distance around the blade periphery, while others used a projection of that distance. Now, the method of measuring blade angle on all of the Corps' Kaplan turbines is being standardized to define the flat "over travel" (the most closed position possible) angular position to the horizontal.

The method is simple for on-site maintenance staffs to perform. The establishment of this minimum angle allows the governor to position the runner blades to the desired operating angle through a standard control algorithm.

The Corps expects that these standardization efforts will significantly improve unit, plant, and system outputs by eliminating inconsistencies, errors, and lack of information on adjustments by placing the correct information and tools in maintenance staff's hands. Our experience to date indicates that individual units can be improved in efficiency by as much as 7 percent by simply keeping a unit mechanically and electronically "tuned."

Visit us at Waterpower XIII, Booth 422



Specialist for custom engineered Trash Rakes

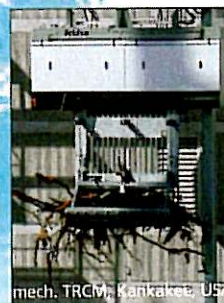
See the advantages you get from our machines!

- Reduction of head loss thus increasing efficiency
- Reduction of manpower dedicated to trash removal
- Removal of sedimentation
- Improvement of safety and working conditions
- Various auxiliary functions

New!! The largest hydraulic boom-operated TRCM under construction.

Künz

Kuenz America Inc.
8625-B Barefoot Industrial Rd., Raleigh, NC 27617
Phone 919 783 8427 Fax 919 783 8804
e-mail: kuenzamerica@kuenz.com, web: www.kuenzamerica.com



Solutions in Water Power of

- Hydraulic TRCM
- Cable-operated TRCM
- Powerhouse Cranes
- Gantry Cranes
- Gates
- Bottom outlets
- Stop-logs
- ...YOUR MACHINE??

Innovative and efficient solutions worldwide

CIRCLE 390 ON READER SERVICE CARD

Measuring power output

Another parameter being investigated is the accuracy of the power output measurement. Power is needed to determine efficiency. The accuracy of a power measurement depends, in part, on the accuracy of the calibrations of the power transformers and current transformers. We found that many power transformer and current transformer metering circuits have been overloaded (burdened) or modified, thus affecting the measurements. In addition, in almost all cases investigated, the original calibration certificates of accuracy have been lost or destroyed. The Corps initiated a program to check the calibrations of all the power transformers and current transformers.

New instrumentation for measuring head

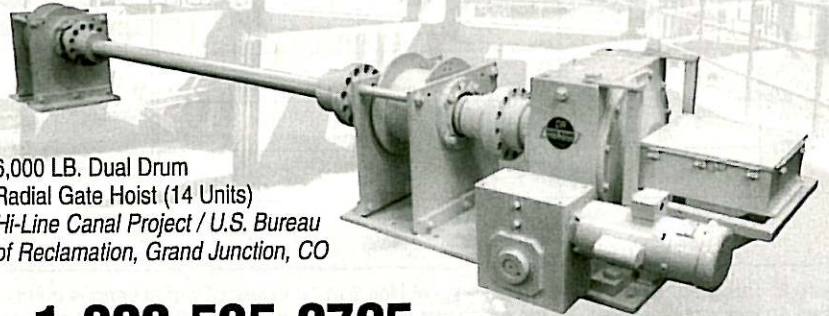
The Corps is installing new and replacement head measuring instrumentation, using digital pulse radar transducers from OHMART, at every Corps project containing Kaplan turbines on the Columbia and Snake river systems. With the advent of electronic 3-D governors, the blade angle of a Kaplan may be positioned to an exact optimum angle for any given wicket gate opening and head. The head on an individual unit in a powerhouse, however, can vary from the head on another unit. This variation is due to such physical differences as a "tilt" of the water surface elevation across the powerhouse and whether adjacent units are generating simultaneously. The width of the Columbia River exacerbates any tilting effect. Operation of adjacent units, lock operation, and spill may affect the velocity head at the intake of the measured unit, as well as the surface elevation at the draft tube discharge.

The original instrumentation system for measuring head consisted of only two still wells, often located at one end of the powerhouse — one for the forebay and one the tailrace. Thus, the original instrumentation no longer provides sufficient accuracy to take full advantage of the 3-D cam capability and modern technology. As a minimum, forebay and tailwater transducers from OHMART are being installed on every other unit at every powerhouse. The expected return is a minimum of 0.25 percent in plant efficiency and a minimum net worth benefit for the Federal Columbia River Power System of \$28 million.

GATE HOISTS

Hoist-only packages for radial, tainter and bulkhead gate projects

- Ideal for contractors and gate OEM's
- Gate position indicators
- Modular units designed to meet application requirements
- Fan brakes and manual modes
- Gearbox and actuator style drives
- Single and double drum designs
- Optional sheave banks and blocks



6,000 LB. Dual Drum Radial Gate Hoist (14 Units)
Hi-Line Canal Project / U.S. Bureau of Reclamation, Grand Junction, CO

1-800-535-2725

Ask about our other product lines including stainless steel hoists and cranes



DAVID ROUND, INC.

32405 AURORA RD., CLEVELAND, OH 44139
TEL (440) 248-4700 • FAX (440) 248-8544
WEB SITE www.davidround.com
E-MAIL info@davidround.com

CIRCLE 270 ON READER SERVICE CARD



Provides a positive bank-to-bank barrier

Security for your equipment and restricted spaces



Durable & unsinkable Modular Floating Barricade

Stops logs, debris, & boats

- Log, debris, and watercraft barriers
- Dam safety and security barricades
- Highly visible line of demarcation
- Patent pending composite construction
- Premium marine friendly materials
- Full-length stainless steel strength and ballast member with MIG welded fitments
- Permanently molded-on floatation body is unsinkable and highly puncture resistant
- Flexible and shock absorbing connectors have no metal-to-metal wear points
- Draft is 3" with 13" of freeboard
- Each module is 120" long, 16" in diameter, and weighs approximately 100 lbs.
- Visit us at www.goodinnovation.com for more information

A product of Good Innovation, LLC
3090 Stanhope Way - Sacramento, CA 95833-1028
Phone: (916) 920-8620 - Fax: (916) 920-8618



High system strength



Waterborne security

CIRCLE 431 ON READER SERVICE CARD

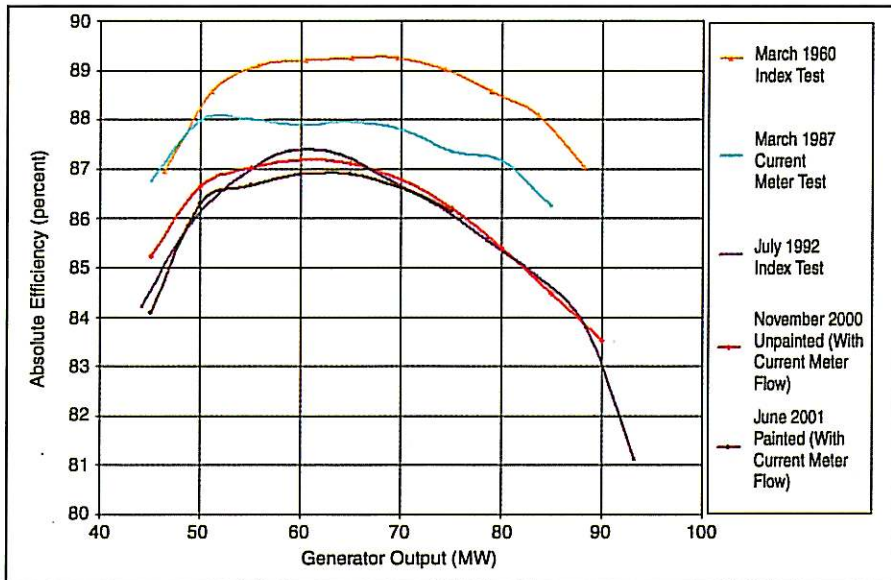


Figure 2: This graph compares the efficiency of Unit 9 at The Dalles Dam at various points during 40 years of operation. As the graph shows, the unit's efficiency decreased 2.4 percent during the period.

Governor upgrades

A program is presently in place to upgrade the existing individual governors on each Kaplan unit to operate with modern 3-D cams. Originally, governors on the Kaplan turbines were mechanical with 2-D cams. They were retrofitted with first generation electronic 3-D cams in the 1980s. These existing systems are now obsolete. Currently, the Corps is installing modern Corps designs with considerably more functionality. These include many user friendly features, significantly improved accuracy, and communication with a master control system. Other features include self-optimization capability, error checking, and redundancy. In addition, upgrading to digital governor components is underway. We expect efficiency improvements of up to 5 percent on an individual unit basis, with a system improvement in excess of 1 percent. This efficiency improvement is a result of the turbine actually operating "on cam" for the actual site hydraulic conditions.

Index testing

Index testing is a method of determining the relative efficiency profile of a hydraulic turbine. The name is derived because the volumetric flow rate is not usually measured in absolute terms, such as cubic feet per second, but is measured by "indexing" it against some other known parameter. The commonly used indexing parameter on Corps Kaplan turbines is the Winter-Kennedy piezometer system. Similar to "elbow taps," a pair of piezometer taps on the inner and outer radii and the same radial plane of a semi-spiral case will have a pressure differential proportional to the square of the flow rate. Determining the relative efficiency profile provides an ability to determine the optimum operation, so that the governor can position the turbine blades to their optimum angle for any given wicket gate opening and head.

If the absolute flow rate in a Kaplan turbine can be measured by an independent method at the same time the

Winter-Kennedy piezometers are being measured, then that piezometer system can be calibrated to measure in terms of absolute flow. Initially, engineers thought that the required installation of the various types of fish diversion devices in a turbine intake rendered any calibration of the Winter-Kennedys useless. Subsequent investigations found that there is a different calibration for the Winter-Kennedys for each different configuration of the intake. However, that calibration appears constant and the Winter-Kennedys can be used to measure absolute flow, provided they are regularly calibrated for each different intake configuration.

As a numerical example, on Unit 5 at the 980-MW McNary Dam, without any type of fish screens in the intake, the Winter-Kennedy piezometers have a calibration equation as follows:

$$Q = 5,443D^{0.5193}$$

where:

Q equals flow rate in cubic feet per second (cfs); and

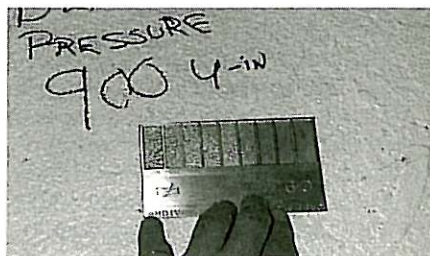
D equals piezometric differential in feet of water.

However, when "long" screens, also known as extended submerged bar screens (ESBS), are installed, the calibration equation is changed as follows:

$$Q = 6,180D^{0.5062}$$

In other words, at a flow of 10,000 cfs, the piezometric differential without screens would be 3.23 feet and with screens it would decrease to 2.59 feet. This decrease in deflection would indicate less angular momentum available to be converted into shaft power. It also emphasizes the need for different calibration equations when fish diversion devices are installed in the turbine intakes. Figure 1 shows the calibrations of the Winter-Kennedys with and without fish screens.

Historically, index test data were reduced graphically by hand plotting. This dated to the older American Society of Mechanical Engineers Test Code (PTC18-1949), which stipulated the use of the "smooth curve" data reduction technique. In this technique, the efficiency profiles for the individual fixed blades are not drawn through the calculated efficiency data points. Instead, the values of power and flow, absolute or relative, are each plotted versus servomotor stroke. These are well-behaved, positively sloped curves. Then, each curve is interrogated at the same values of servo stroke, such that the efficiency curve may be constructed more accu-



Rough, corroded blades can cause reduced efficiency in Kaplan turbines. The photo on the left shows an unpainted blade surface on Unit 9 at The Dalles Dam; the blade is shown on the right after it was sand blasted and painted.

rately than plotting directly could draw it. Taking this one step further, the Corps developed a computer program to do this plotting and curve construction more accurately than previously could even be done by hand.

The use of this graphical computer data reduction program allowed a detailed examination of Unit 9 at the 1,807-MW The Dalles project. Over the past 40-plus years, this unit had been index tested on a relative flow basis three times, as well as tested once on an absolute basis by current meters. The Corps team reexamined this test data to determine the peak efficiencies as though the unit was operating with an optimum cam in the governor during each test. The peak efficiency of this unit has decreased 2.4 percent, with most occurring in the first eight years of operation. It is hypothesized that the initial decrease is due to a roughening of the surfaces of the water passages caused by corrosion. From the test results, it is clear that as Kaplan turbines age and peak efficiency is reduced, the optimum cam also changes. This demonstrates the need to index test and adjust Kaplan turbines on a periodic basis, though there is no recommended standard. Figure 2 shows the decrease of peak efficiency as The Dalles Unit 9 aged.

In order to achieve this frequency of testing on all Corps' Kaplan turbines in the Pacific Northwest, a new central test group was formed within the Hydroelectric Design Center. The Corps anticipates that this group will be further expanded to enable it to have two test teams — of two to three people each — in the field simultaneously.

LABORATORY AND FIELD RESEARCH

Measuring absolute and relative flow

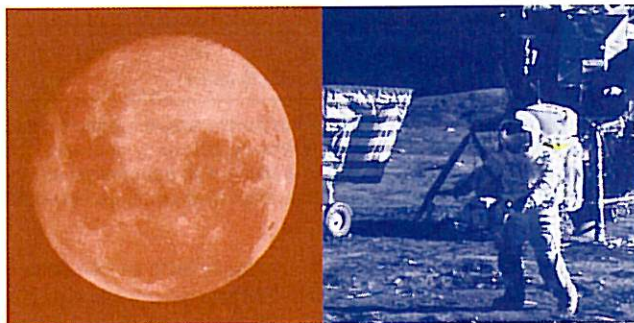
In order to determine the efficiency of a turbine or to conduct optimizations at a powerhouse, the absolute flow rate in a turbine must be measured to a high degree of accuracy. This is particularly difficult on run-of-the-river Kaplan turbines in which the cross-sectional area is continually changing over the length of the water passages and may contain fish diversion devices. Historically, current meters mounted on a frame in the intake took these measurements, but this is unfeasible with fish-screened intakes.

More recently, as an applied research

project, the Corps applied the acoustic scintillation method of measuring flow by using transducers mounted on a frame in the intake gate slot on five Corps projects. Basically, this method times the passage of a particular turbulence pattern over a short distance. However, the uncertainty of the absolute measurement of flow obtained by this method is unknown, and there are clear indications of variable bias — likely related to boundary or inlet conditions.

This measurement system does appear satisfactory in determining relative flow for calibration of the Winter-Kennedy taps in defining the optimum "on cam" curve. Using acoustic scintillation to calibrate Winter-Kennedy taps appears satisfactory for use in unit self-optimization algorithms. In order to quantify and possibly decrease the uncertainty associated with this method of measuring absolute flow, a Corps-sponsored scintillation peer review committee has been formed

impossible possible



There are two types of people, those who looked to the moon and said "impossible" and those who said "possible." The same is true of today's energy market. Deregulation, a rapidly evolving market and a technologically challenging climate can seem insurmountable, but not to us. With 2 years of phenomenal growth and success as Kinectrics and an extra 90 years as Ontario Hydro we've proven that impossible markets can flourish. Profits can be healthy. Work forces can evolve. When the word impossible comes to mind, call us at 416-207-6000 or www.kinectrics.com.

Chances are good we'll point skyward and say "everything's possible."



Stop by and see us at Waterpower XIII in Booth #931.

into energy

ideas

CIRCLE 232 ON READER SERVICE CARD

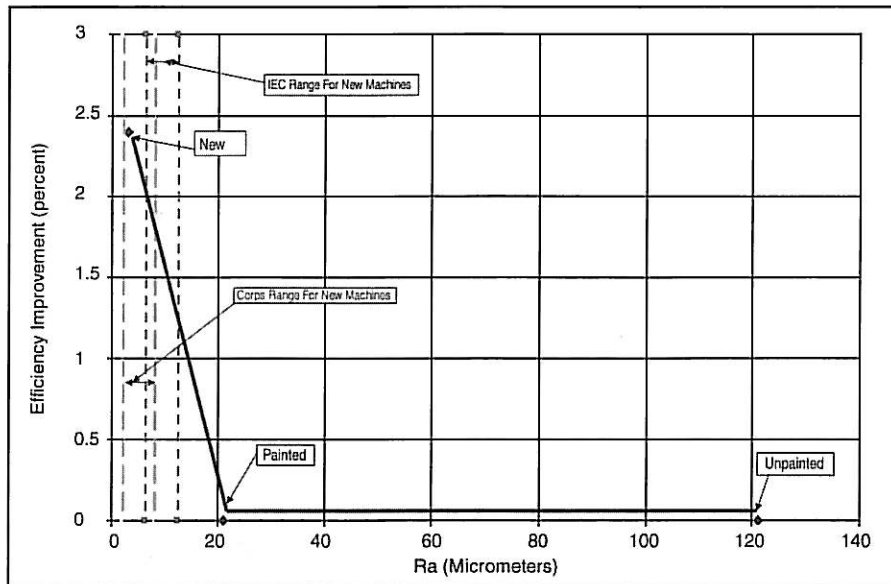


Figure 3: This graph shows the correlation of the roughness of turbine blades to the efficiency of the machine at Unit 9 at The Dalles Dam. While no efficiency gain was obtained from the first sand blasting and painting of the blade, the blade was determined still to be three times rougher than when it was first placed in service, leading to continued lowered efficiency.

with active participation from the Hydroelectric Design Center. Recommendations of the committee concerning application in absolute flow measurements will be published in late 2003.

The Corps also is investigating other alternate or new methods of measuring absolute flow. The well-known technique of "time of travel" has potential, as well as other techniques. The "time of travel" does not refer to the velocity of the water, but to the velocity of an acoustic wave in the water. Corps engineers proposed an alternate method of mounting acoustic transducers; this method will be evaluated at one or two as-yet unselected projects in the near future. Technical specifications are being developed for laboratory evaluation of various absolute flow measurement methods while they are subjected to various hydraulic flow conditions.

Refurbishing turbine water passages

In another area of applied research, experiments have been and are being conducted in an attempt to define the effect on efficiency of refurbishing the water passages of a Kaplan turbine. At various projects, an unexplained turbine performance loss has occurred when recent results are compared to previous acceptance test results. This loss is currently theorized to be a result of rough, corroded water passage surfaces or blade profile changes resulting from operation, or a combination of the two. If the

magnitude of the losses due to surface degradation are significant, simply refurbishing the surfaces may return a substantial portion of lost revenue, negating the need for turbine runner replacement. In that The Dalles Units 1-14 have experienced an unexplained 2.4 percent loss in performance and had several historical field tests including a current meter test, this site was selected as a test case for the hypothesis.

Consequently, in November 2000, the Corps index tested Unit 9 at The Dalles after determining the surface roughness of the existing components. The following year, the water passage surfaces of this unit were sand blasted and painted with a Corps standard vinyl painting system (5-E-Z). Based on weighting the surface roughness of the individual turbine elements by the submerged surface area, the Corps estimated that the unpainted turbine had an average absolute surface roughness (Ra) of 121 micro-meters (4,764 micro-inches). The average absolute roughness of the painted turbine was measured as (Ra) 21 micro-meters (827 micro-inches). However, when this unit was tested again in June 2001, no change in efficiency could be detected. The photos on page 84 show the unpainted and painted blade surfaces.

A subsequent analysis concluded that the surface roughness of the painted turbine was still about three times rougher than that of the original turbine when first placed in service (64 to 250 micro-inches). Figure 3 shows the correlation

between roughness versus efficiency at The Dalles Unit 9. Consequently, the Corps plans to refurbish the water passages of this turbine to near their original installed condition; selection of a vendor for this task awaits funding. If comparative tests on this turbine do ultimately show an efficiency improvement, the conclusion will be that maintenance of the water passages of a turbine needs to be done on a periodic basis. We have found that to neglect such maintenance for decades and then attempt to refurbish a turbine to a sufficient degree is a difficult task. If the hypothesis is proven, a more robust investigative program likely will be undertaken to better define the benefits and costs for surface finish improvements. Retesting of the repainted Dalles units is not presently scheduled.

Developing a control algorithm for plant optimization

Research shows that overall powerhouse efficiency can be maximized by the way that a given total load is shared among the individual generating units. Even though the units in a powerhouse may nominally be the same, they do have individual differences. We found in one instance that supposedly identical units in the same powerhouse can approach a 4 percent difference in peak efficiency. Thus, for any given powerhouse load setpoint, unit availability, and head, there is one unique way to individually load the different units to maximize the combined powerhouse efficiency. That is, generating a given load at a given head while using a minimum amount of water maximizes the efficiency of a powerhouse.

Researchers at the Hydroelectric Design Center and consultant Lee Sheldon developed a computer algorithm to select the one optimum way to share load from among the infinite number of possible combinations. That algorithm has been incorporated into a computer program named "T2 Optimizer." This program will, in turn, be incorporated in the next two years into the new GDACS (Generic Data Acquisition and Control System) presently being installed to control generation on the Columbia and Snake river systems. (See "Taking Control on the Columbia: Enhancing Reliability through Automation," *Hydro Review*, March 2002, pages 12-19).

Modifying wicket gates and stay vanes

In conventional, vertical-shafted tur-

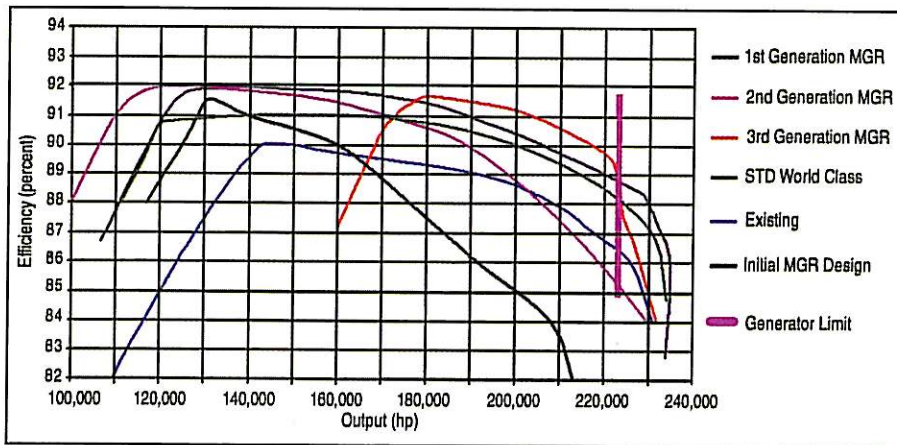


Figure 4: These plots compare the efficiency of four minimum gap runner designs against the efficiency of the original machine and modern standard Kaplan design. Machine output in horsepower is measured on the horizontal lines, while efficiency in percent is tracked on the vertical lines.

bins, the distributor section is composed of the wicket gates, an upper and lower stay ring, and stay vanes. While the purpose of the wicket gates is to control flow, the purpose of the stay vanes is primarily structural. They are placed around and upstream of the wicket gates to transmit the loading on the roof of the spiral or semi-spiral case

to the powerhouse foundation. Consequently, stay vanes are designed separately from wicket gates and located to allow unit disassembly. Since they are located in the flow regime, however, they are usually given some type of hydraulic streamline shape. The Corps has used Computational Fluid Dynamics (CFD) and physical turbine model-

ing to investigate the interaction between stay vanes and wicket gates. The investigation includes both performance improvements and environmental enhancement to improve downstream fish passage. The Corps found that modifying the stay vanes to shadow the wicket gates provided beneficial effects on turbine performance — up to 2 percent gains in efficiency — and the potential of environmental improvements.

Testing of minimum gap runners

Continuing applied research and field testing of minimum gap runner designs are providing efficiency gains for the Corps' generating units (along with additional benefits in safely passing migrating anadromous fish). In order to achieve a minimum gap runner configuration, slots and gaps in the runner are minimized, hidden, or covered. For example, on the outer periphery, the discharge ring is no longer a cylindrical shape, but is spherical. That way, no matter what angle the blade is positioned, the gap is minimized. Further, design of the runner hub is modified by maintaining a spherical relationship be-

Power Plant Problems? Need Real Solutions? Call Phoenix!

Quick fixes or temporary solutions can cause bigger problems later on.

For over 20 years the engineers at Phoenix have been providing real hydro plant solutions for control and electrical systems.

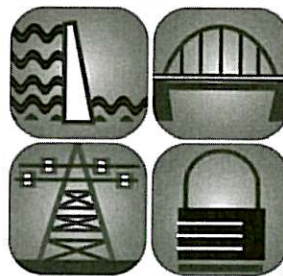
- Improve plant performance & reliability
- Complete system troubleshooting
- Automation work and system rehab
- New protection & control systems
- New plant SCADA systems
- Non-proprietary, open systems
- Remote control and data logging
- New governors and excitation systems
- Complete plant electrical design and supply
- Maintenance contract and servicing plans

Phoenix
Power Control, Inc.

To discuss your solutions, call 360-794-8550 or email
John Claybrook - jclaybrook@phoenixcontrol.com
or Herb Vernon - hvern@phoenixcontrol.com

CIRCLE 346 ON READER SERVICE CARD

Foos & Associates



We lead the industry in homeland security, applying state-of-the-art risk assessment methods to civil sites

as well as state and federal facilities. No one has more experience in conducting and providing technical review on vulnerability studies. We can help you to meet FERC security requirements, too.

Count on us to provide full-service infrastructure protection services, including threat assessments for any of your security studies. We're licensed to use both RAM-DSM and RAM-T.SM

Foos & Associates, LLC

1092 Country Club Road, Camp Hill, PA 17011
Phone: 717.571.3412 Fax: 717.303.0126

FoosAssociates@comcast.net www.FoosAssociates.com

CIRCLE 245 ON READER SERVICE CARD

tween the blade and the hub.

This design is being successfully used at the 518-MW Bonneville First Powerhouse. While even the first minimum gap runner developed produced a gain in efficiency over the existing Kaplan runner, subsequent designs led to further increases in efficiency. Figure 4 provides a comparison of output versus efficiency for four minimum gap runner designs, the existing Kaplan, and the standard Kaplan.

Extending draft tubes

In order to minimize construction costs, Corps projects historically have been designed and built with short draft tubes. This was achieved by leaving a residual amount of post whirl in the flow leaving the runner so that the expansion angle of the draft tube could be increased. However, this design also resulted in high fluid velocities and velocity heads at the exits of the draft tubes. Prototype biological testing indicates that draft tubes and their downstream discharge areas may be extremely important for juvenile fish passage. Consequently, hydraulic turbine models have been and are being used to investigate the benefits of modifying draft tubes or adding many different types of draft tube extensions, both for performance improvements and biological enhancements. Performance benefits include increased efficiency and reduction in the inception of cavitation. These performance benefits are site-specific.

Site-specific biological benefits may result from closing the draft tube bulkhead slots at the draft tube roof. Researchers found that a significant percentage of migrants apparently find their way into the draft tube bulkhead slots and can stagnate there. Both fish passing downstream through turbines and fish attempting to migrate upstream by entering the draft tube exits can wind up in isolated bulkhead slots for an unknown amount of time. Draft tube extensions have benefits in the reduction of the back roll and reducing the tailrace discharge boil to produce a smooth downstream transition from turbine passage to ambient river conditions. Current biological investigations are planned or have been performed in an attempt to quantify the indirect component of turbine fish passage. ■

Mr. Wittinger may be contacted at U.S. Army Corps of Engineers, Hydroelectric Design Center, 333 S.W. First Avenue, P.O. Box 2946, Portland, OR 97208-


2946; (1) 503-808-4280; E-mail: rodney.j.wittinger@usace.army.mil.

Acknowledgment

The author acknowledges the contributions to the article by consultant Lee Sheldon, P.E., and staff of the U.S. Army Corps of Engineers, Engineering and Design Research Center, as well as by representatives of the following:

Corps of Engineers' Turbine Survival Program; Corps' Bonneville I Rehabilitation Program; Corps' The Dalles Units 1-14 Rehabilitation Program; U.S. Department of Energy's Advanced Hydropower Turbine Systems Program; Bonneville Power Administration; and Pacific Northwest Turbine Working Group and Hydropower Optimization Team (two multi-organization efforts).

Visit us at Waterpower XIII, Booth 915



Specialist in the Hydroelectric Field

*servicing domestic and
international clients since 1978*

Digital Governors
and Positioners
Electric or Hydraulic
Retrofit or New

Pump replacements

- Integrated Solutions
- Turnkey Projects
- Control, Protection, Metering
- High Speed Networking and Communications
- Excitation
- Switchgear
- Plant and Unit Auxiliary Systems

North American Hydro
1323B Everest Ave.
Schofield, WI 54476
USA

Tel: 715.359.0209
Fax: 715.359.1049
Email: schofield@nahydro.com
Web: www.nahydro.com

CIRCLE 218 ON READER SERVICE CARD