TURBINE VENTING FOR DISSOLVED OXYGEN IMPROVEMENTS AT BULL SHOALS, NORFORK, AND TABLE ROCK DAMS

E. Dean Harshbarger[1], M. ASCE
Bethel Herrold[2]
George Robbins[3], M. ASCE
James C. Carter[4]

Introduction

The Southwestern Power Administration (SWPA) has utilized turbine venting modifications designed and installed by the Tennessee Valley Authority (TVA) to significantly improve the dissolved oxygen content (DO) in the turbine discharges from Bull Shoals, Norfork, and Table Rock Dams. This improvement has allowed the turbine generators to be operated at higher power outputs while meeting target DO levels in the discharges.

Project Locations

A map showing the location of Bull Shoals, Norfork, and Table Rock Dams is shown on Figure 1. All three of the dams are authorized for flood control and power generation and are also operated for water supply and recreational purposes. As mitigation for the loss of the warm water fishery, a cold water trout fishery has been developed below each project.

Bull Shoals Dam is situated in north central Arkansas 115 miles north of Little Rock at mile 418.6 on the White River. The power facilities consist of four 40-MW and four 45-MW turbine/generator units. All eight turbines are of the Francis type. Units 1-4 are identical and have similar, but slightly different geometry than Units 5-8. The plant hydraulic capacity with all eight units operating is 27,600 cfs. Typical maximum turbine discharge during normal operating

[1] Technical Specialist, TVA, Water Management, Clean Water Initiative, P.O. Box 1649, Norris, TN 37828
[2] Hydraulic Engineer, Southwestern Power Administration, Tulsa, OK
[3] Hydraulic Engineer, Southwestern Power Administration, Tulsa, OK
[4] Mechanical Engineer, Tennessee Valley Authority, P.O. Box 1649, Norris, TN

conditions is 24,000 cfs. The gross head on the turbines during the low DO season is about 200 feet.

Norfork Dam is situated in north central Arkansas at mile 4.8 on the North Fork of the White River. The power facilities consist of two 40-MW generators driven by two identical Francis turbines. The plant hydraulic capacity with two units operating is 7,300 cfs. The typical maximum turbine discharge is 6,200 cfs. The gross head on the turbines during the low DO season is about 180 feet.

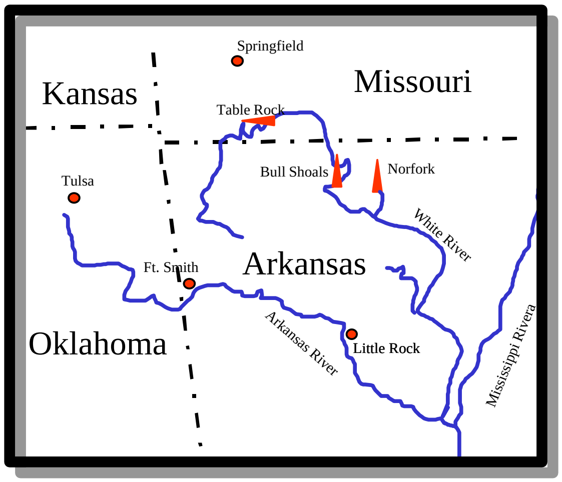

Figure 1. Location of Bull Shoals, Norfork, and Table Rock Dams

Table Rock Dam is located in southern Missouri, 40 miles south of Springfield at mile 528.8 on the White River. The power facilities consist of four 50-MW generators driven by Francis turbines. The turbines for Units 1 and 2 are identical and slightly different in geometry from the Unit 3 and 4 turbines. The maximum turbine discharge during normal operations is 15,100 cfs. Typical maximum turbine discharge during normal operating conditions is 12,700 cfs. The gross head on the turbines during the low DO season is about 200 feet.

Description of Problem

Because of thermal stratification of the reservoir water during the summer months, the water at the turbine intake level of the reservoirs becomes low in DO. When water is discharged through the turbines in late summer and fall, low DO in the tailwaters occurs unless mitigation measures are utilized. Figure 2 shows mean annual variation in the intake DO at the three dams based upon data obtained from 1991 through 1996.

The turbines at all three projects induce increased quantities of air when operated at reduced load. Voluntary de-rating of the turbines by SWPA has been used since 1991 to maintain a minimum DO of 4 mg/L in the discharge. De-rating is costly, however, because it reduces the capability of the projects to meet peaking power demands and forces the turbines to operate at less than maximum efficiency.

Operating the turbines at less than best efficiency also has a detrimental effect on structural vibration and cavitation damage.

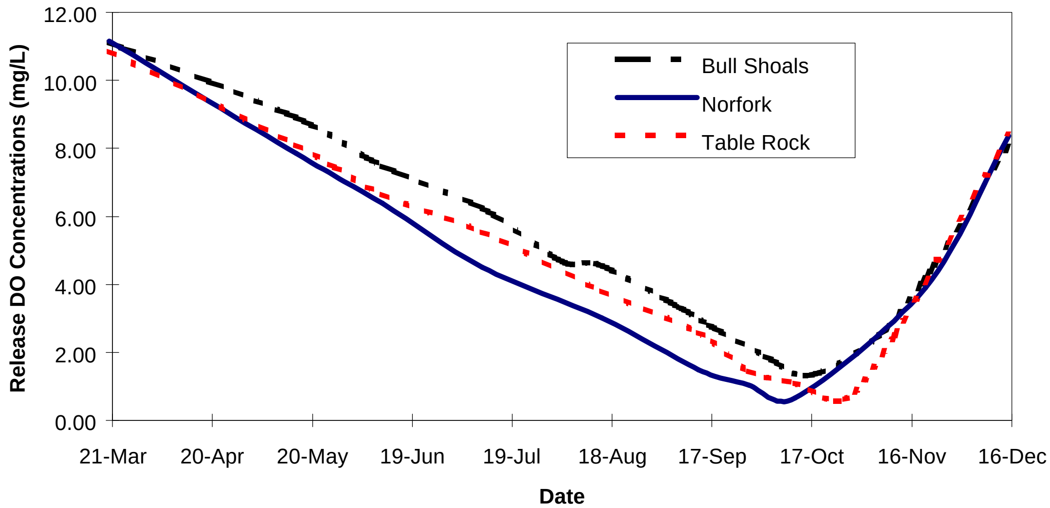

Figure 2. Mean Annual Dissolved Oxygen Variations at Bull Shoals, Norfork, and Table Rock Dams

Turbine venting techniques were applied to increase the amount of air induced and to expand the range of turbine operations at which significant quantities of air would be induced for aeration. These techniques involved the design and installation of baffles over the thrust relief openings of the turbines, adding new openings in the turbine headcovers and the addition or modification of air supply piping to the turbine headcover. Because of differences in unit design, geometry, turbine setting, head, flows and operating conditions, the modifications were very site specific and differed somewhat for the three projects.

Turbine Venting Modifications

Bull Shoals

Turbine venting modifications at Bull Shoals consisted of the installation of baffles over the thrust relief openings on the turbine hub and the addition of an 8-inch diameter pipe to supply air under the turbine headcover. A photograph of the “hub baffles” used on Unit 5 is shown in Figure 3. The proximity of the thrust relief openings on the hub to the downstream edge of the turbine blades precluded the effective application of curved, streamlined hub baffles. Therefore, flat plate baffles were utilized. These 4-inch high baffles were fabricated from ¼-inch flat steel plate and were welded onto the hub over the eight existing thrust relief openings. The baffles were oriented to create maximum negative pressure over the openings when the turbine wicket gates were opened to produce maximum turbine efficiency (best gate). An additional air supply was provided by cutting additional

Figure 3. Hub Baffles Installed at Bull Shoals Dam

openings in the headcover and adding additional air supply piping. This new piping bypassed the existing vacuum breaker system so that it could continue to function as intended. The bypass pipe system contained a check valve to prevent back flow of water, a butterfly valve for on/off operation and was equipped with a bell mouth entrance to increase flow and reduce pipe entrance noise. A schematic of typical bypass piping is shown in Figure 4. Units 5-8 were fitted with 8-inch diameter bypass systems, while because of space limitations, 6-inch diameter systems were installed on Units 1-4.

<u>Norfork</u>

The nose cone or hub of the turbine shaft at Norfork differed from the hub at Bull Shoals in that the lower portion of the cone was truncated and the end was sealed. This effectively reduced the induced air flow. The venting modifications at Norfork included removing the seal plate from the bottom of the hub, installing flat plate baffles over the thrust relief openings, and adding a vacuum breaker bypass piping system.

The proximity of the thrust relief openings on the hub to the downstream edge of the turbine blades precluded the effective application of curved, streamlined hub baffles. Therefore, flat plate baffles such as shown in Figure 5 were utilized. These baffles were made of ¼-inch steel and extended about 3 inches high over the surface of the hub. An additional opening through the headcover was provided and bypass piping similar to that at Bull Shoals was installed. The assembly was compact enough to fit below the existing floor grating in the turbine wheel pit.

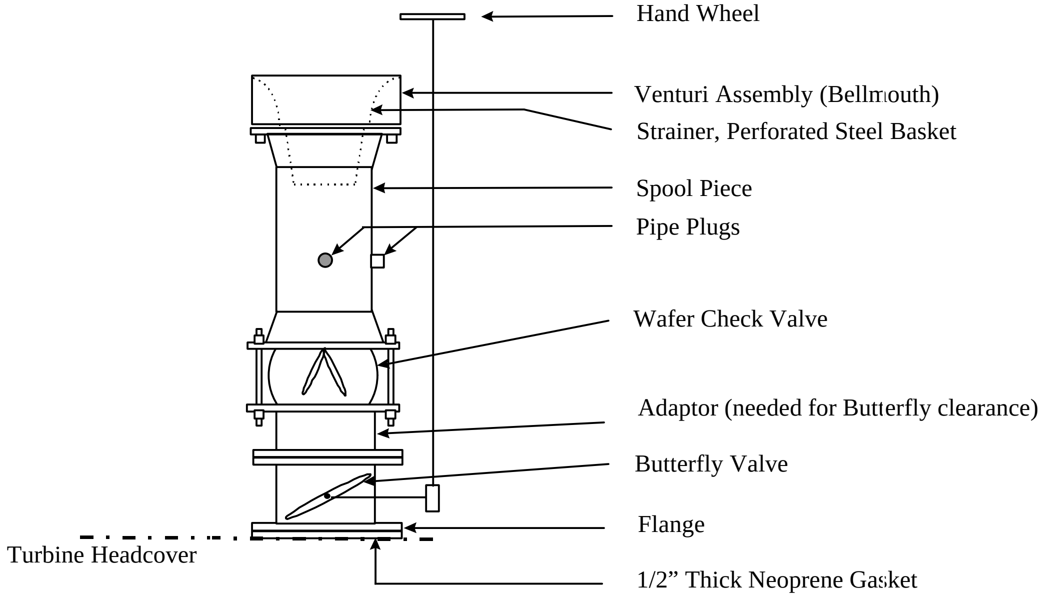

Figure 4. Bypass Piping Installed at Bull Shoals Dam

Figure 5. Hub Baffles Installed at Norfork Dam

Table Rock

The thrust relief openings on the turbine hubs at Table Rock consisted of 32, 1-inch diameter holes equally spaced around the periphery of the hub a few inches below the turbine blades. In addition, a narrow slot was present between the runner crown and the hub. To enhance air induction, the thrust openings were enlarged to 1-½-inch diameter and were shielded by a 4-inch high flat plate baffle ring located just upstream of the openings. In addition, a 1-½-inch high "booster" baffle ring was added upstream from the crown/hub slot and modifications were made in the existing 10-inch diameter vacuum breaker system to allow additional air to be drawn from the wheel pit area. No additional openings were cut in the headcover. Modifications to the Table Rock Unit 2 turbine are shown on Figure 6.

Figure 6. Modifications Made to the Hub on Table Rock Unit 2

Results

Bull Shoals

In July 1996, hub baffles designed by TVA were installed on Unit 5. Tests were conducted before and after the installation so that the effects of the baffles could be evaluated. During these tests, induced air flow, generator output, water flow, and other parameters were measured over a range of wicket gate openings for single-unit and eight-unit operation. The significance of the eight-unit tests is that the increased tailwater elevation reduces the head available for inducing air flow because of increased back pressure.

Figure 7 shows the relationship of air flow to water flow before and after baffle installation when only Unit 5 was operating. During the pre-baffle tests, because of limitations of the air flow instrumentation used, no air flow data was obtained for wicket gate openings less than about 60 percent (corresponding to water flows of about 3,200 cfs). However, the data taken for flows greater than 3,200 cfs indicates that before the modifications were made, air flow decreased rapidly as water flow increased, and was nearly zero for about 3,700 cfs (best operating gate). After the modifications were made, the data indicate that air flow was greater than 80 cfs over the full range of wicket gate openings tested and did not change appreciably as water flow increased.

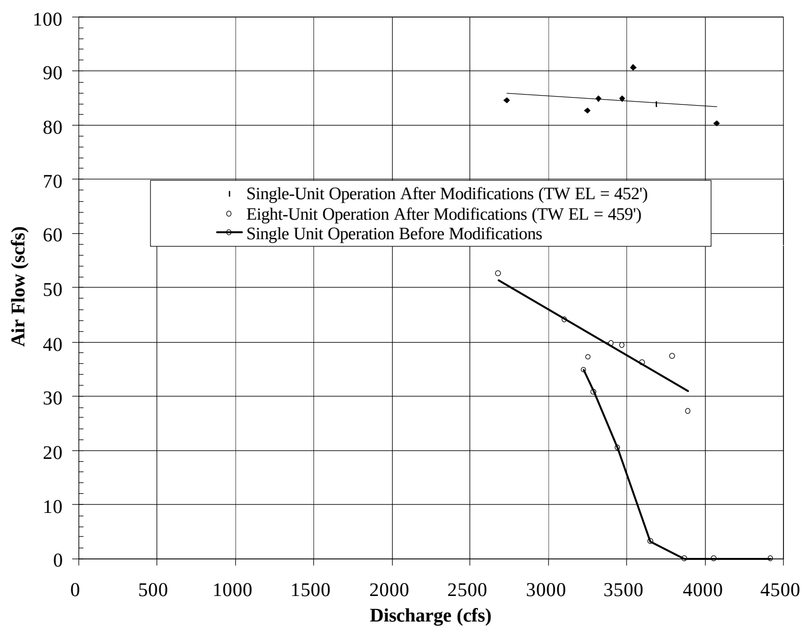

Figure 7. Effect of Modifications on Induced Air for Single and Multi-Unit Operation

Increased tailwater elevation reduces the head available for inducing air. Since tailwater elevation increases with the number of units in operation, the worst case for air induction therefore occurs when all eight units are operating at maximum discharge. Figure 7 also shows post-modification data obtained with all eight units operating (tailwater elevation 459) and with only Unit 5 operating (tailwater elevation 452.0). These data indicate that for eight-unit operation with about 2,700 cfs discharge through Unit 5, air flow was around 50 cfs. When all eight units were operating, and the discharge through Unit 5 was about 3,900 cfs, air flow was about 30 cfs. At about 3,400 cfs, which is the most efficient operating condition, the air flow was about 40 cfs.

Inadequate water flow measurements prevented the calculation of the effects of the modifications on unit generation efficiency. However, the measured relationship of water flow to unit generating efficiency before and after modifications shown on Figure 8 indicate that the modifications decreased power output by about 1 to 1.5 MW at low wicket gate opening and less than 1 MW for

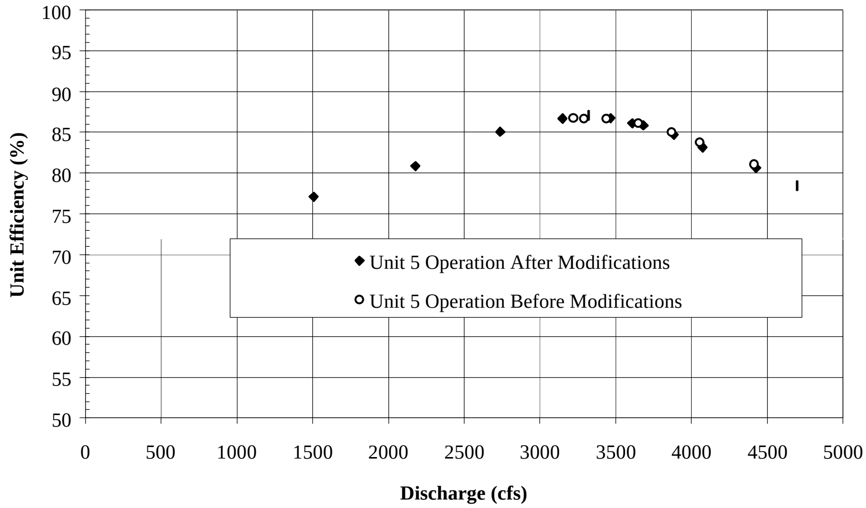

Figure 8. Effect of Modifications on Unit Efficiency, Bull Shoals

gate openings above about 65 percent. Based on the DO data obtained and estimates of oxygen uptake efficiency, the increased air flow is expected to result in DO uptakes on the order of 2 to 3 mg/L for single-unit operation and 1 to 2 mg/L for eight-unit operation.

Norfork

The effect of the modifications on induced air for Norfork unit one is shown in Figure 9. These data indicate that before the modifications, air flow was less than about 18 cfs for wicket gate openings of 30 to about 75 percent and for higher gate openings the induced air flow was below 10 cfs. After the modifications, the induced air flow was in the range of 50 cfs for all wicket gate openings. This increased air flow resulted in DO uptakes of 2.5 to 3 mg/L. Increased tailwater elevation caused by two-unit operation at Norfork reduced the DO uptake over that for single-unit operation by less than 0.5 mg/L. .

The effect of the additional air flow on unit efficiency at Norfork is shown on Figure 10. These data indicate that below best gate operation the air flow decreased generation efficiency, near best gate operation there was little change, and above best gate the presence of the air slightly improved unit generation efficiency.

Table Rock

The relationship of air flow to wicket gate opening for Unit 2 before and after the turbine venting modifications is shown on Figure 11. These data indicate that the modifications increased air flow 20 cfs or more over the full range of operation. This increase in air flow corresponds to a DO uptake increase of about 2 to 3 mg/L.

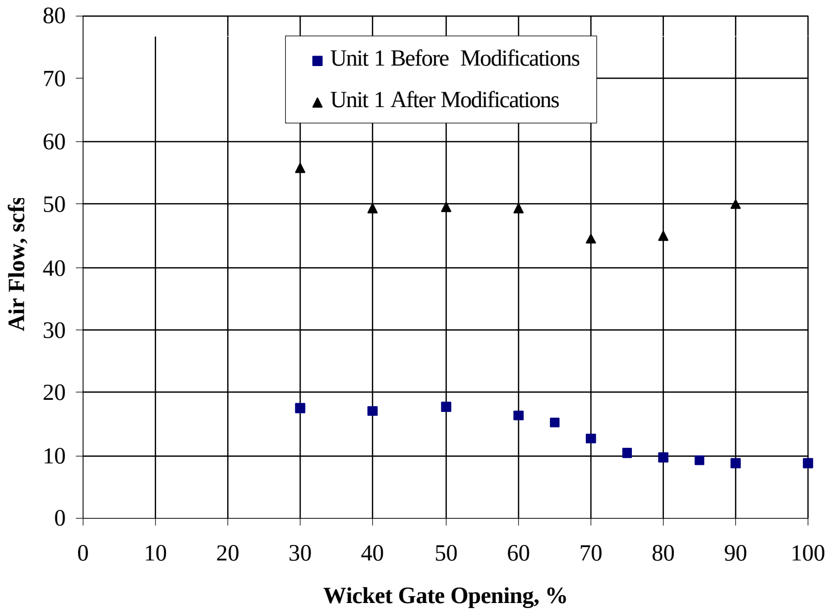

Figure 9. Effect of Modifications on Induced Air for Single-Unit Operation, Norfork

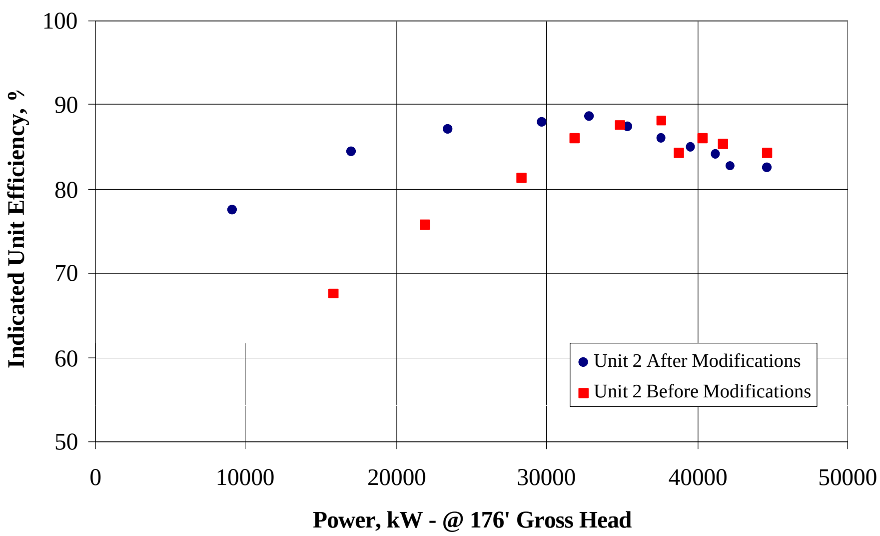

Figure 10. Effect of Modifications on Unit Efficiency, Norfork

The effect of the modifications on generating efficiency is shown on Figure 12. The modifications and additional air flow had apparently little effect.

Summary

SWPA has utilized turbine venting modifications designed and installed by TVA to significantly improve the DO in the turbine discharges from Bull Shoals, Norfork, and Table Rock Dams. At these projects, turbine venting has proven to be an effective, economical method to help meet DO targets and improve plant peaking capacity and operational versatility during the low DO season. Increase in DO uptakes of as much as 3 mg/L have been obtained. The modifications made to the turbines are site-specific and are tailored to the particular configuration and site characteristics. The effects on generation are minimal, increased cavitation damage has not occurred, and the systems are virtually maintenance free.

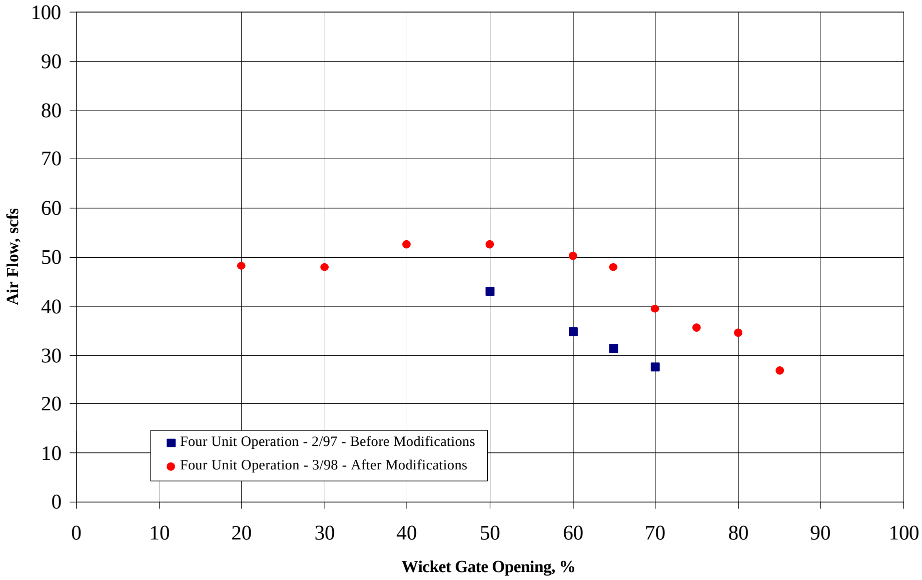

Figure 11. Effect of Modifications on Induced Air for Four-Unit Operation, Table Rock

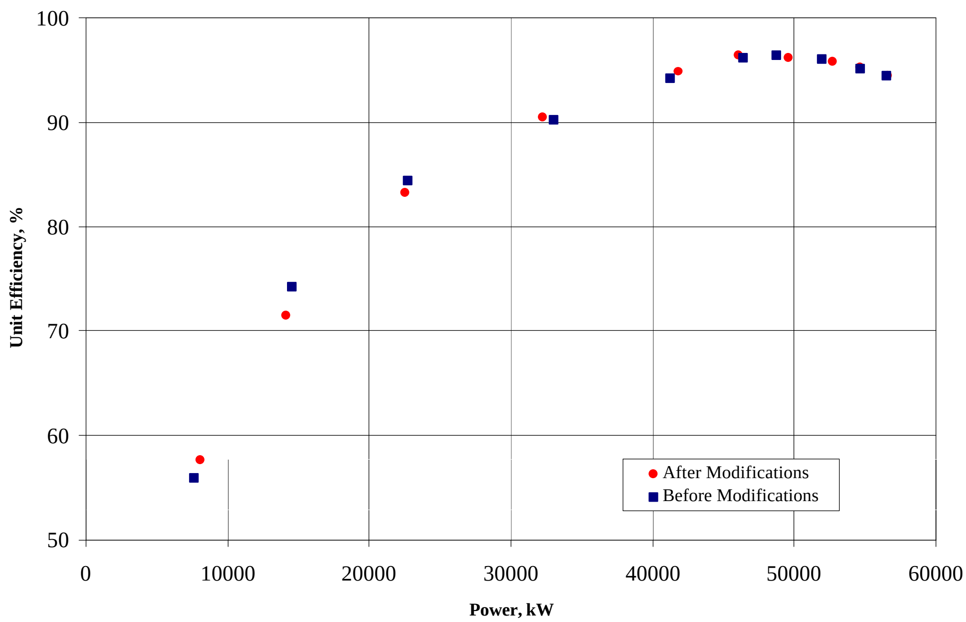

Figure 12. Effect of Modifications on Unit Efficiency, Table Rock