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Improving Efficiency and Capacity of Hydro-Turbines in the Western United States, Hoover Dam

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IMPROVING EFFICIENCY AND CAPACITY OF HYDRO-TURBINES
IN THE WESTERN UNITED STATES
- HOOVER DAM -

By

Jonathan Gamaliel Sanchez

A thesis submitted in partial fulfillment
of the requirements for the

Master of Science in Mechanical Engineering

Mechanical Engineering Department
Howard R. Hughes, College of Engineering
The Graduate College

University of Nevada, Las Vegas
May 2012

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THE GRADUATE COLLEGE

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Jonathan Gamaliel Sanchez

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ABSTRACT

Improving Efficiency and Capacity of Hydro-Turbines In the Western United States - Hoover Dam –

by

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Professor of Department of Mechanical Engineering
University of Nevada, Las Vegas

The goal for this thesis is to minimize clearances and tolerances, in order to prevent water leakage. A proper seal on the seal rings does not let excess water flow through the turbine runner, thus conserving more water and wasting less energy. Moreover, water leakage past worn wear plates allows for an extra load for the turbine when operating in condense mode. When the wicket gates are closed, water leakage past worn plates wastes mechanical energy in the water; thus, decreasing the efficiency of the Francis turbine, especially when operating at partial loads. Furthermore, the wicket gates also known as guide vanes can increase the efficiency of the turbine in their relation to their laminar profile and proper seal.

Water is a very vital resource in today's society. This thesis illustrates how existing hydro machinery can be improved to reduce the dependency on fossil fuels as an electric energy source. This study provides actual examples of improvements using the generating units located at Hoover Dam. Hoover Dam located in Boulder City, NV is part of the Lower Colorado Region, of the U.S. Department of the Interior Bureau of Reclamation.

Overhauling a hydro unit to obtain better efficiency is very similar to overhauling a vehicles engine to improve the vehicles fuel economy. Modifying and replacing three major hydro-machinery components: seal rings, wear plates, and wicket gates, improves the efficiency of Hoover Dam units by an average of 2 percent. This increase in capacity equates to an additional 8,000 MW-hrs per year per unit. The wholesale market value of this increase in energy and capacity, roughly equates to about \$290,000 per unit per year [1]. Engineering design, calculations, and performance test were conducted to improve the parameters of the seal rings, wear plates, and wicket gates. MATLAB[®] and MS Excel computer software was used to analyze testing results and provide data and calculation results.

This study focuses mainly on the seal rings, wear plates, and wicket gates. In order to achieve a 2% efficiency gain and about a 3% to 5% capacity gain per unit, the dimensions of the wear plates and seal rings were changed to have tighter clearances, and the wicket gate design and profile were changed by increasing the angle of attack by 2 degrees, and by increasing the trailing edge gap by 0.02 inches. Additionally, the servo motors were stroke 2.5 feet more to achieve the 2 percent increase in efficiency.

As water levels keep on dropping in the Colorado River, future research and analysis can be allocated in a new turbine runner design for low head operation ranges. Additionally, there are a few other mechanical and electrical components that can be modified or alternated to monitor and improve capacity efficiency.

ACKNOWLEDGEMENTS

I want to thank my committee members who were more than generous with their expertise and precious time. A special thanks to Dr. Yitung Chen, my committee chairman for his countless hours of reflecting, reading, encouraging, and most of all patience throughout the entire process. I am forever grateful, thanks for all your support Dr. Chen and may God bless you. Thank you Dr. Robert F. Boehm, Dr. Hui Zhao, and Dr. Yahia Baghzouz for agreeing to serve on my committee, and for all your help and support.

I would like to acknowledge and thank my school division and the US. Dept. of the Interior, Bureau of Reclamation – Hoover Dam, for allowing me to conduct my research and providing me with any assistance requested, especially the Hoover Engineering Group. Special thanks go to the members of the UNLV Mechanical Engineering department for their continued support, and the staff and employees at Hoover Dam for supporting me throughout this process.

Special thanks go to Mr. Daniel A. Pellouchoud, PE, for believing in me since day one. Not only are you a great engineer, a great mentor, but also a great friend. You helped me throughout the process and established parameters that I could follow. Big thanks go to you and also thank you for inspiring me, coaching me, training me, and supporting me throughout the process. You once told me to “Never give up, never, never, never give up”; and those words have surely paid-off.

Last but not least, I wish to thank my family, friends, church member and colleagues for their ongoing support and encouragement during my time at the University of Nevada, Las Vegas and over the course of the research presented. Thank you all for your prayers, your motivating and encouraging words, and for extending out a hand when help was needed. You all made this possible and I am forever grateful.

DEDICATION

To the four pillars of my life: God, my parents, my siblings, and my sweetheart. Without your support, guidance, and encouraging words this will not have been possible.

Whenever I was down You lifted me up, whenever I was weak You gave me strength, whenever I was lost and confused You provided me with guidance. Walking with You, God, through this journey has given me right to say, “I can do all things through Christ which strengthen me.”

Dad and Mom, thanks for your support, faith, and encouragement. Thanks for always being there for me, in the good and in bad times. You are truly an inspiration to me, and your great sacrifice and effort has paid off. You taught me how to become the person that I am today, and I am proud to be your son.

Elias and Esther, you too have a big part on this accomplishment. You have challenged me to achieve what I have until this day. My desire is that I can set a good example for you both as an older brother, and to see you two achieve much more than what I have accomplished.

Sara, my love; I love you with all my heart. Thanks for supporting and encouraging me to keep on going. Thank you so much for your patience, caring, commitment, and teaching me that I should never surrender. Without your love and understanding I would not be able to make it.

To God be all the glory, all the honor, and all the praise.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The United States Department of the Interior, Bureau of Reclamation, with full support from power customers, is completing major projects to improve plant generating capacity and efficiency available from the existing renewable hydro generation resources at Hoover Dam.

Hoover Dam, located in Boulder City, NV has seventeen commercial generators. The nameplate capacity rating of all these generators combined is 2074 megawatts (MW_e). The current capacity of all the generators at Hoover Dam is 1885 MW_e with a Lake Mead elevation of 1134 ft on January 2012. Lower lake levels result in less capacity available from these units. More flow and change in net head, allow for more capacity and power to be produced at Hoover Dam.

Capacity improvements at Hoover Dam are focused on allowing an increase in the maximum amount of water allowed to flow into the turbines at low lake levels. Additional water flow translates into additional horsepower capability at the turbine and it allows for additional electrical capacity for the overall plant.

Wicket gates or guide vanes are large steel gates which can be opened or closed to control the flow of high pressure water to a hydro turbine. The wicket gate system consists of 24 large steel gates arranged like a cylindrical venetian blinds around the turbine. A method used to improve the flow capacity to the turbines, and the power

output capacity is to replace the old cast steel wicket gates with new stainless steel wicket gates to allow more water to flow through the turbine. The new gates have a more streamlined flow profile when compared to the old gates, and are designed with a larger maximum opening.

The benefits from the increased capacity provide payback of project investments within a few years. Using a conservative wholesale market price for capacity (\$2660 per MW-month), the value of 70 megawatts of new capacity added at Hoover Dam is \$2.2 million per year.

Another strategic goal for Reclamation at Hoover Dam is to improve hydro unit operating efficiencies. Major turbine overhauls have been underway since October 1999 for the purpose of restoring machinery to a more efficient operating condition.

Overhauling a hydro unit to obtain better efficiency is equivalent to overhauling an automobile engine to improve fuel economy. Hoover unit efficiencies improve in an average of 2 percent after a turbine overhaul. The improved efficiency results in more energy production using the same amount of water. An additional 8,000 megawatt-hours per year per unit for each unit overhauled has been gained. The wholesale market value of this added energy is \$290K per unit per year. If the 8,000 MW-hrs were produced at a conventional power plant, more than 14,000 barrels of crude oil would be burned to produce the amount of added electrical energy which results from one unit overhaul. Major turbine overhauls include work such as modifying and replacing seal rings and wear plates to reduce high-pressure leakage of water through the wicket gate system which occurs when the hydro units are shut down. Preventing the leakage of water, results in more water available in the future to produce valuable electrical energy. The

wholesale market value from reducing leakage through wicket gates at Hoover is \$200K per unit per year. If the energy produced by the saved water were produced by burning oil at a conventional power plant, over 10,000 barrels of crude oil would be burned to produce the amount of electrical energy produced by the “saved” water. [2]

1.2 Background of Hydropower

What is hydropower? Hydropower is a form of energy that is renewable, reliable, and efficient. This form of energy does not directly emit greenhouse gases or other air pollutants into the environment; therefore it greatly reduces our carbon foot print here on planet Earth.

Water has always been one of mankind’s most vital resources. We use water for cleaning, cooking, irrigation and for recreational activities. While the human body can go weeks without food, it can only survive for a couple of days without water consumption [3]. However, water can be used as an energy source, known as hydro-electric power or simply hydropower.

Some of the first recorded mentions of hydropower go back over 2,000 years ago to ancient Greece and Egypt, where water wheels were connected to grindstones to turn wheat into flour. The invention of the electrical generator in the late 1800’s created a new way to utilize hydropower for the growth of civilization. By combining water turbines to generators with belts and gears, a reliable source of electricity was created that could be used to power factories and businesses around the world.

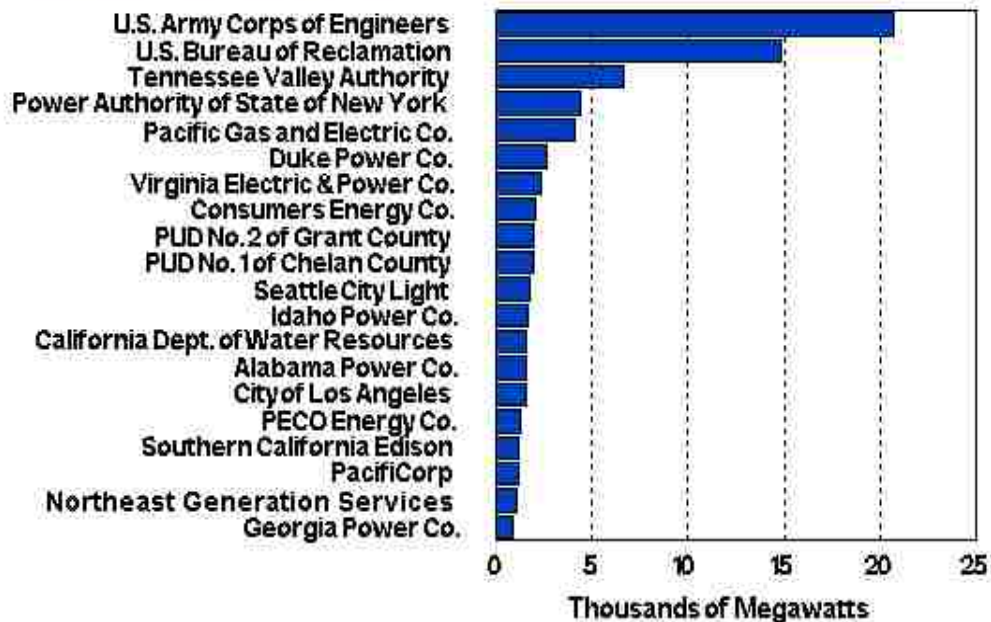
Water development meant far more than irrigation. In the twentieth century, the United States Department of the Interior, Bureau of Reclamation responded to the call for multipurpose water development. Its vast network of irrigation projects, dams, reservoirs, canals, and aqueducts supplied rural and urban water users, and, most of all, supplied an industrializing society the many-faceted resources of hydropower [4].

The United States Department of the Interior, Bureau of Reclamation also known as Reclamations is known as the largest water resource management in the West. It accounts for 348 reservoirs that deliver 30 million acre feet of water annually. It serves water to about one-third of the West's irrigated agriculture that is roughly about 31 million people. Reclamation is responsible and in charge of 50 hydroelectric power plants, that is 194 generating units that total an installed capacity of 14,778 megawatts (MW_e). The total installed capacity makes Reclamation the tenth largest power utility in the United States; it provides electricity for roughly 9 million people.

Figure 1 shows the major producers of hydropower from largest to smallest. The producers include: the U.S. Army Corps of Engineers producing roughly 21 thousands of MW_e , the U.S. Bureau of Reclamation producing roughly 15 thousands of MW_e , the Tennessee Valley Authority producing roughly 7 thousands of MW_e , the Power Authority of State of New York producing roughly 4.5 thousands of MW_e , the Pacific Gas and electric Co. producing roughly 4 thousands of MW_e , the Duke Power Co. producing roughly 2.5 thousands of MW_e , the Virginia Electric & Power Co. producing roughly 2.25 thousands of MW_e , Consumers Energy Co. producing roughly 2 thousands of MW_e , PUD No.2 of Grant County producing roughly 1.97 thousands of MW_e , PUD

No.1 of Chelan County producing roughly 1.97 thousands of MW_e, the Seattle City Light producing roughly 1.95 thousands of MW_e, the Idaho Power Co. producing roughly 1.94 thousands of MW_e, the California Dept. of Water Resources producing roughly 1.5 thousands of MW_e, the Alabama Power Co. producing roughly 1.5 thousands of MW_e, the City of Los Angeles producing roughly 1.5 thousands of MW_e, the PECO Energy Co. producing roughly 1.25 thousands of MW_e, the Southern California Edison producing roughly 1 thousands of MW_e, the PacifiCorp producing roughly 1 thousands of MW_e, the Northeast Generation Services producing roughly 0.75 thousands of MW_e, and the Georgia Power Co producing roughly 0.5 thousands of MW_e.

Major Producers of Hydropower Hydroelectric Generation Capacity in Megawatts



Includes Pumped Storage

Figure 1: Major Producers of Hydropower, Hydroelectric Generation Capacity in MW_e [4].

There are several benefits of hydropower. Hydropower can be considered as a renewable source of energy, as it relies on water, and water can be renewed through the water cycle. Hydroelectricity's ability to be dispatched quickly to meet peak electricity demand have made it one of the most valuable renewable energy sources worldwide; additionally, it is low-cost, and it produces near-zero emissions [5]. In the 1920's hydroelectric plants supplied as much as 40% of the electric energy produced, today hydropower only accounts for about 7% of the nation's total energy produced.

Hydropower is an essential contributor in the national power grid because of its ability to respond quickly to rapidly varying loads or systems disturbances. Base load plants with steam systems powered by combustion or nuclear processes cannot accommodate for rapid varying loads. Hydropower has grown over the last century from 45 hydroelectric facilities in 1886 to more than 2,000 facilities in 50 states and Puerto Rico. The hydropower facilities throughout the United States contribute approximately 80,000 MW_e to our nation's electrical capacity [6]. Reclamation's fifty-eight hydro-electric power plants throughout the Western United States produce an account for an average of 42 billion kWh per year. This amount of electricity is enough to meet the needs of more than 14 million people. Hydropower is also one of the most economic energy resources and it is not affected by market fluctuations or embargos, which helps support our nation's energy independence. Hydropower has also non-power benefits than any other generation sources. It provides flood control, water supply for irrigation districts, navigation and recreational activities. The hydropower projects in the United States, accounts for more than 47,000 miles of shoreline; 2,000 water access sites; 28,000 tent, trailer, and recreational vehicle sites for camping; 1,100 miles of trails, and 1,200 picnic areas.

While there are many advantages to hydroelectric production, the industry faces several unique environmental challenges. Potential environmental impacts include changes in aquatic and stream side habitats; alteration of landscapes through the formation of reservoirs; effects on water quality and quantity; interruption of migratory patterns for fish; and injury or death of fish passing through the turbines. Hydropower is mainly criticized for its negatively environmental impacts on local ecosystems and its environments.

Hydropower alters the natural flow of a river, which in turn changes the aquatic habitat. It converts a river ecosystem into a lake ecosystem overnight. Damming a river creates a change and damages the river's natural animal life and natural plant life. Additionally, hydropower is not as cheap as we often think. While hydropower saves up in the cost of fuel, as there is with coal and oil, there is a heavy cost for construction, upkeep, and land rights.

Money is also invested in water delivery and usage between Mexico and the United States. The United States Department of the Interior, under the Bureau of Reclamation handles those water rights and water relations between both countries. An estimated amount of 1.5 million acre feet of water is delivered to Mexico yearly. The Colorado River Compact of 1922, also known as the "Law of the River" defines the relationship between the upper basin states and lower basin states.

The Colorado River Compact of 1922 - The cornerstone of the "Law of the River", this Compact was negotiated by the seven Colorado River Basin states and the federal government in 1922. It defined the relationship between the upper basin states, where most of the river's water supply originates, and the lower basin states, where most of the water demands were developing. At the time, the upper basin states were concerned that plans for Hoover Dam and other water development projects in the lower basin would, under the Western water law doctrine of prior appropriation, deprive them of their ability to use the river's flows in the future.

The states could not agree on how the waters of the Colorado River Basin should be allocated among them, so the Secretary of Commerce Herbert Hoover suggested the basin be divided into an upper and lower half, with each basin having the right to develop and use 7.5 million acre-feet (maf) of river water annually. This approach reserved water for future upper basin development and allowed planning and development in the lower basin to proceed.

Hydropower and pumped-storage hydroelectricity is often used in combination with dams to generate electricity. What is a dam? A dam is a barrier that is used to store water. It is also known as a reservoir. In the United States, there are about 80,000 dams of which only about 2,400 produce power. The other dams are used for recreation, irrigation, farming, flood control, and water supply. Hydropower facilities or plants can

be categorized under the following distinctive categories: impoundment, diversion or run-of-river, and pumped storage.

The most commonly seen and used type of dam is the impoundment facility.

Figure 2 demonstrates an impoundment plant which uses a dam to store water in the reservoir. Water released from the reservoir is transported through pipes, also known as penstocks, where the water flows through a turbine runner, which causes the runner to spin a generator which in turn creates electricity. The water at an impoundment facility may be released to meet changing electricity needs or to maintain a constant reservoir level, flood control. Hoover Dam is considered to be an impoundment dam.

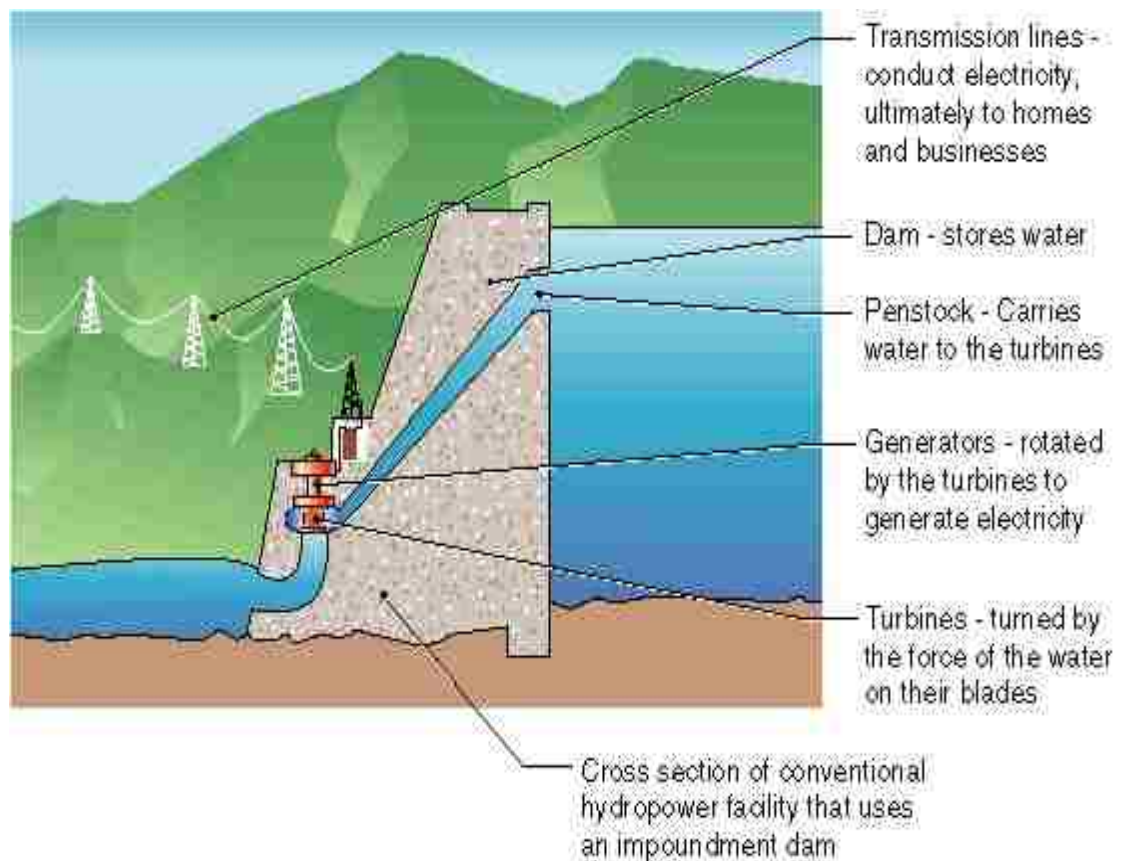


Figure 2: Schematic of an Impoundment Dam [6].

Figure 3 shows the major components found on hydro-unit. This demonstrates a cut-view of the reservoir and how water enters the plan from the forebay (lake) traveling through all the hydro-components, and finally exiting back into the tailrace (river).

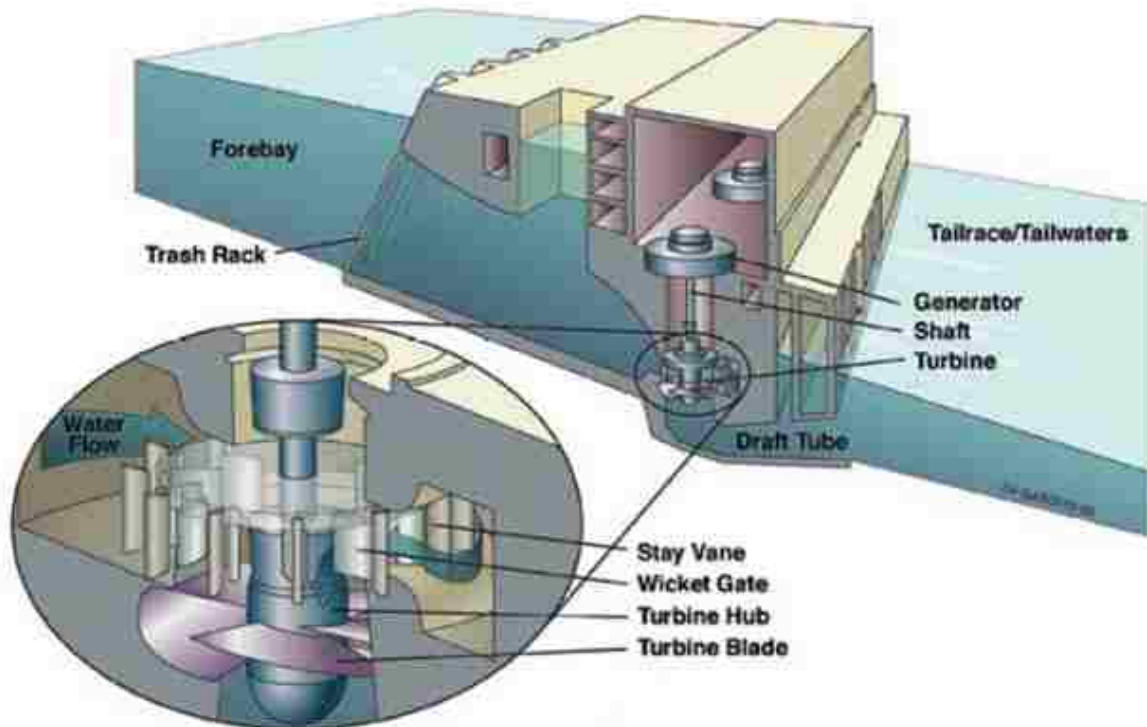


Figure 3: Hydropower Unit Components [6].

A diversion plant channels a portion of a river through a canal or penstock. A diversion facility is sometimes referred to as a run-of-river plant. A run-of-river plant uses water within the natural flow range of the river, requiring little or no impoundment. A run-of-river, facility channels a portion of a river through a canal or penstock.

These facilities are usually built on rivers with steady natural flows or regulated flows discharged from upstream reservoirs. These units have little or close no storage capacity, thus, hydropower is generated using the river flow and water head. Run-of-river hydropower plants are less appropriate for rivers with large seasonal fluctuation. These facilities may not always require the use of a dam.

Last but not least, Figure 4 shows how pumped storage hydropower plants store water in a lower reservoir after it is released from an upper reservoir to drive the turbine and generate power. The water is then pumped back to the upper reservoir for reuse. Pumping the water back to the upper reservoir requires energy. Pumped storage systems are considered flexible sources of electricity generation. Pumped storage plants are not net energy producers; in contrast, pumped storage plants provide energy storage and electricity at its peak demand times. The units generate electricity when demand and price are higher, during peak hours, and pump water back to the upper reservoir when electricity demand and price are lower.

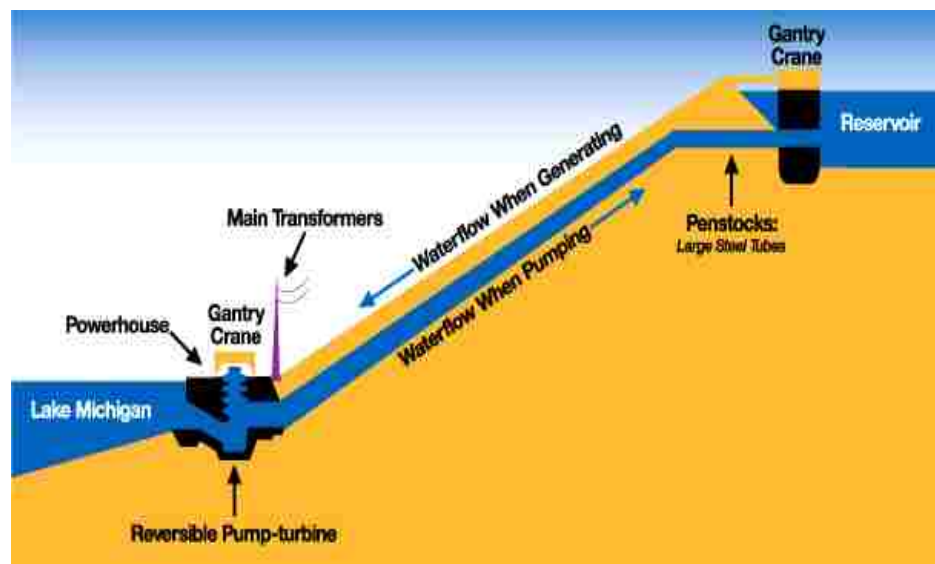


Figure 4: Schematic of a Pumped Storage Facility [7].

Hydropower facilities range in size from large power plants that supply many consumers with electricity to small plants that individuals operate for their own energy needs or to sell power to utilities. Therefore, hydropower plant can also be categorized based on their capacities.

Large hydropower plants typically have a capacity of more than 30 MW_e, Hoover Dam for example, has a nameplate capacity of 2,074 MW_e. Small hydropower plants have a generation capacity of 1 to 30 MW_e, and micro hydropower plants have a generation capacity of less than 100 kW_e. A small micro hydropower plant can produce enough electricity for a home, farm, ranch, or village [6].

How does hydropower work? First of all hydropower is obtained from water at work, water in motion. Hydropower can be seen as a form of solar energy, as the sun powers the hydrologic cycle which gives the planet Earth its water. Following the hydrologic cycle, atmospheric water reaches the earth's surface as precipitation, rain. Some water from the rain evaporates, but a big percentage of the water from the rain either penetrates into the soil or it becomes a surface runoff. Water from the rain and snow pack eventually reaches ponds, rivers, oceans, reservoirs, and lakes where evaporation occurs constantly. Water vapor passes into the atmosphere by evaporation then circulates, condenses into clouds, and some returns to earth as precipitation. Thus, completing the water cycle, and allowing hydropower to be called a form of sustainable and reliable energy.

As the First Law of Thermodynamics states, energy cannot be created or destroyed, it can only change forms. In hydropower when electricity is generated, no new energy is created, but simply one form of energy is converted into another form. To generate electricity, water must be in motion. This form of energy is called kinetic or moving energy.

When the flowing water turns the blades in a turbine runner, the form of energy is then changed to mechanical energy or machine energy. The turbine runner then turns a vertical shaft which is connected to a big generator rotor. The turning of the runner causes the generator rotor to turn, thus converting the mechanical energy into another energy form, electricity.

Hydropower plants are located on rivers, streams, and canals, but for a reliable water supply, the usage and maintenance of dams is necessary. Dams store water for later release, for purposes such as irrigation, domestic and industrial use, and of course power generation. The reservoir behind the dam acts much like a battery, storing water to be released as needed in order to generate power.

Figure 5 shows the major hydro components found in a typical hydro-unit. The generator that produces electricity when falling water is converted into mechanical energy to drive the generator. The stator being a stationary component is composed of copper coils. The rotor is connected to the turbine generator shaft that spins the entire unit from the mechanical energy received by the turbine runner. Additionally, the rotor is composed of electromagnets also referred to as poles. The wicket gates act as guide vanes which control the flow of water from the scroll case into the turbine runner.

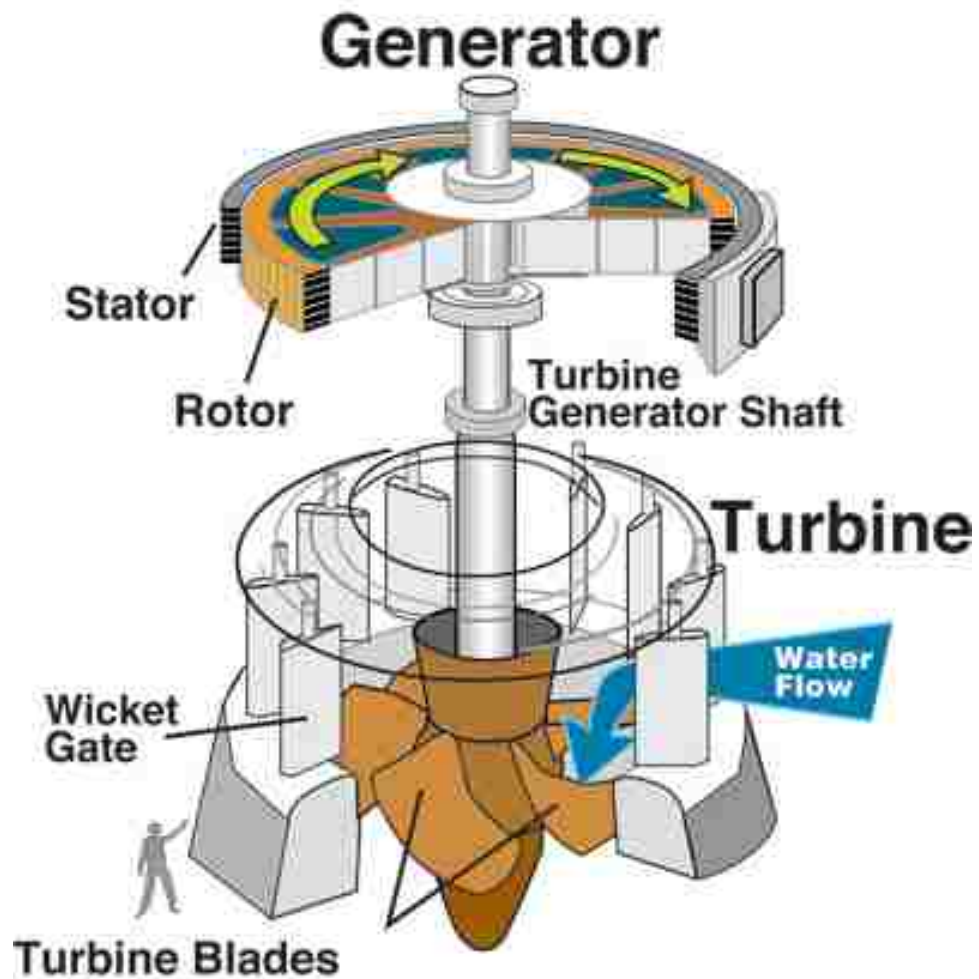


Figure 5: Hydropower Generating Unit Components [Web].

The differential altitude between the lake and the river creates the net head. The greater the net head, the more pressure the reservoir can be accounted for. A pipe also known as penstock carried the water from the reservoir to the turbine. The fast-flowing water then pushes the turbine blades or buckets, which causes the turbine to rotate the rotor, the moving part of the electric generator. When coils of wire on the rotor sweep past the generator's stationary coil (stator), electricity is produced [8]. This concept was

first discovered by scientist Michael Faraday in 1831 when he found that electricity could be created by rotating magnets within copper coils.

Figure 6 shows a schematic inside a hydropower plant. It's a cut-view section that demonstrates how the water flows from the reservoir into the dam, and is finally converted into electrical energy in where the electricity is transported through the power lines.

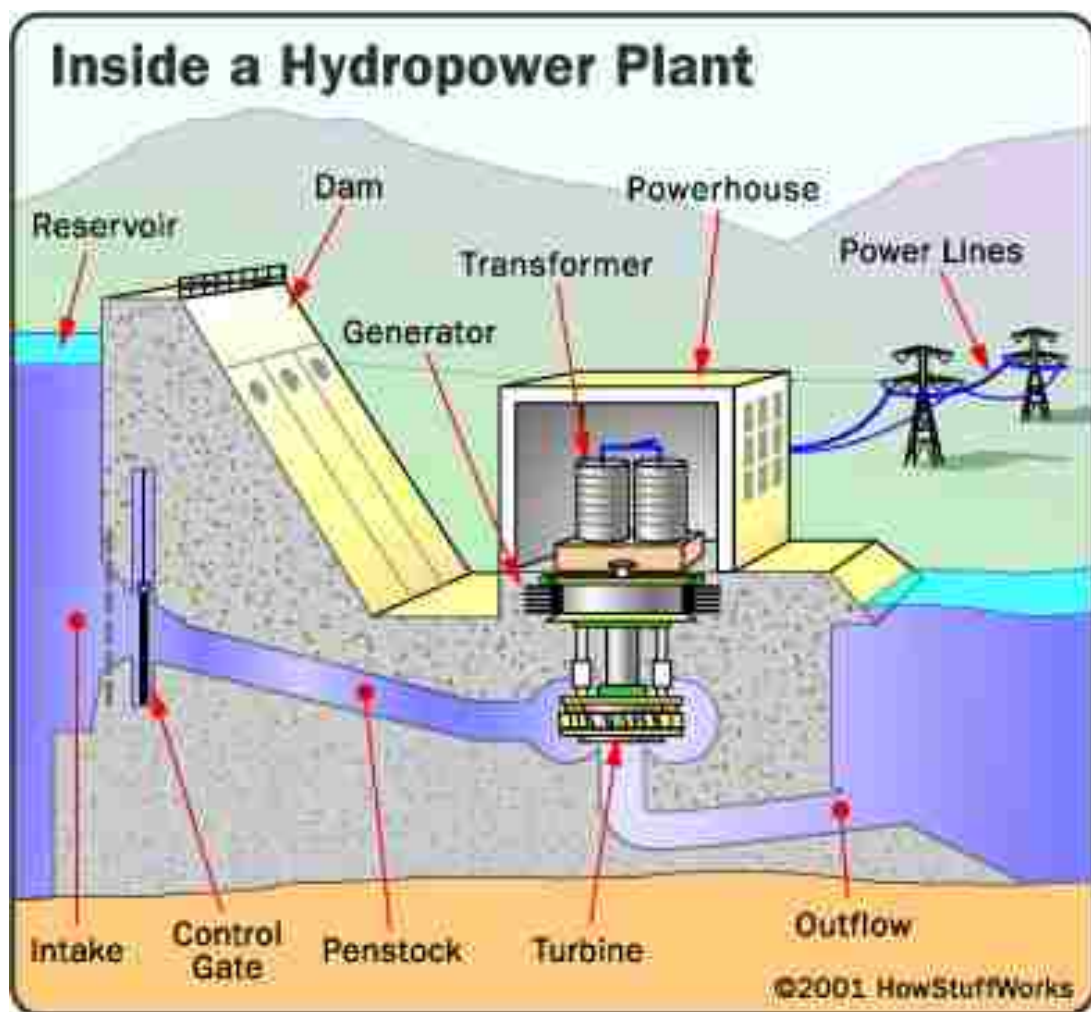


Figure 6: Inside a Hydropower Plant [7].

1.3 Background of Hoover Dam

The United States Department of the Interior, Bureau of Reclamation main purpose is to manage the water in the West, and utilize its structures and construction projects for flood control, water irrigation, and for the production of hydro-electric power. Reclamation's consumers include: farmers, cities, tribes, power, recreation, fish and wildlife, and foreign countries.

Figure 7 shows the United States Department of the Interior Bureau of Reclamation's jurisdiction. Reclamation's jurisdiction includes the seventeen Western States, which are: Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington, and Wyoming. These seventeen states then make up five regions: Great Plains, Lower Colorado, Mid Pacific, Pacific Northwest, and Upper Colorado.



Figure 7: U.S. Dept. of the Interior, Bureau of Reclamation Jurisdiction [9].

Hoover Dam pertains to the Lower Colorado Region. The Lower Colorado Region encompasses southern Nevada, southern California, most of Arizona, a small corner of southwest Utah and a small section of west-central New Mexico. The Lower Colorado Regional office is located in Boulder City, Nevada. There are also other offices within our region located in Phoenix, Arizona (Phoenix Area Office, PXAO); Yuma, Arizona (Yuma Area Office, YAO); Temecula, California (Southern California Area Office, SCAO); and at Hoover Dam (Lower Colorado Dams Office, LCDO).

The LCDO Area Office consists of Hoover Dam, Davis Dam, and Parker Dam, and their associated power plants and other facilities on the Lower Colorado River. Hoover Dam, Davis Dam, and Parker Dam were completed in 1935, 1953, and 1938, respectively. These three facilities were essential to the economic growth of the Southwest, and continue to sustain that growth today. The three dams annually deliver an average of 7.5 million acre feet of Colorado River water to urban and agricultural water users, including Indian Tribes, in Arizona, Nevada, and California, and 1.5 million acre feet of water to Mexico. Hoover, Davis, and Parker, also protect downstream communities from floods and together annually generate an average of more than 6.5 billion kilo-watt-hours (kWh) of electricity that it's distributed to the three states [9]. A kWh is a unit of work or energy equal to that done by one kilowatt of power acting for one hour. A kilowatt is 1,000 watts or 1.34 horsepower.

The primary parts of a generating unit are: the exciter, the rotor, the stator, the shaft, and the turbine. The exciter is itself a small generator that makes electricity, which is sent to the rotor, charging it with a magnetic field. The rotor is a series of

electromagnets, also known as and called poles. The rotor is connected to the shaft, so that the rotor rotates when the shaft rotates. The stator is a coil of copper wire. It is stationary. The shaft connects the exciter and the rotor to the turbine.

Hoover Dam spelled security for southern California's Imperial Valley, power and water for Los Angeles, and even promised to make Nevada a viable state [4]. Hoover Dam generates, on average, about 4 billion kWh of hydroelectric power each year for use in Nevada, Arizona, and California - enough to serve 1.3 million people. From 1939 to 1949, Hoover power plant was the world's largest hydroelectric installation; today, it is still one of the country's largest. Each power plant wing is 650 feet long (the length of almost 2 football fields) and rise 299 feet (nearly 20 stories) above the power plant foundation. In all of the galleries of the plant there are 10 acres of floor space. There are seventeen main turbines in the Hoover Power plant -- nine on the Arizona wing and eight on the Nevada wing. The original turbines were replaced through an uprating program between 1986 and 1993. The plant has a nameplate capacity of about 2,080 MW_e. This includes the two station-service units (small generating units that provide power for plant operations), which are rated at 2.4 MW_e each. With the main units having a combined rated capacity of 2,991,000 horsepower (hp), and two station-service units rated at 3,500 horsepower each, the plant has a rated capacity of 2,998,000 horsepower. The water reaches the turbines through four penstocks, two on each side of the river. Wicket gates control water delivery to the units. Maximum head (vertical distance the water travels), at maximum lake level is around 590 feet; minimum net head, 420 feet; and average net head, 510 to 530 feet.

The installation of the last generating units was completed in 1961. A plant uprating was completed in 1993, so presently there are fifteen 178,000 horsepower, one 100,000 horsepower, and one 86,000 horsepower Francis-type vertical hydraulic turbines in the Hoover power plant. There are also thirteen 130,000 kW_e, two 127,000 kW_e, one 61,500 kW_e, and one 68,500 kW_e generators.

All machines are operated at 60 cycles. The two 2,400 kW_e station-service units are driven by Pelton turbine runners. Pelton turbine runners are a form of impulse turbine runners. An impulse turbine runner is a horizontal or vertical wheel that uses the kinetic energy of water striking its buckets or blades to cause rotation. The wheel is covered by a housing and the buckets or blades are shaped so they turn the flow of water about 170 degrees inside the housing. After turning the blades or buckets, the water falls to the bottom of the wheel housing and flows out. These provide electrical energy for lights and for operating cranes, pumps, motors, compressors, and other electrical equipment within the dam and power plant.

The machinery was transported from the canyon to the power plant by an electrically operated cableway of 150 tons rated capacity, with a 1,200-foot span across the canyon. This cableway lowered all heavy and bulky equipment. The cableway is still used when necessary. The average annual net generation for Hoover power plant for 1947 through 2008 was about 4.2 billion kilowatt-hours. The ten-year annual average for 1999 through 2008 was about 4.2 billion kilowatt-hours. The maximum annual net generation at Hoover power plant was 10,348,020,500 kilowatt-hours in 1984, while the minimum annual net generation since 1940 was 2,648,224,700 kilowatt-hours in 1956.

The power plant is operated and maintained by the Bureau of Reclamation. The power customer for Hoover Dam include the States of Arizona and Nevada; City of Los Angeles; Southern California Edison Co.; Metropolitan Water District of Southern California; California cities of Glendale, Burbank, Pasadena, Riverside, Azusa, Anaheim, Banning, Colton, and Vernon; and the city of Boulder City, Nevada.

The energy generated at Hoover dam is allocated as follow:

Arizona - 18.9527 %

Nevada - 23.3706 %

Metropolitan Water District of Southern California - 28.5393 %

Burbank, CA - 0.5876 %

Glendale, CA - 1.5874 %

Pasadena, CA - 1.3629 %

Los Angeles, CA - 15.4229 %

Southern California Edison Co. - 5.5377 %

Azusa, CA - 0.1104 %

Anaheim, CA - 1.1487 %

Banning, CA - 0.0442 %

Colton, CA - 0.0884 %

Riverside, CA - 0.8615 %

Vernon, CA - 0.6185 %

Boulder City, NV - 1.7672 %

To pay all operation, maintenance and replacement costs (including interest expense and repayment of investments) to meet the requirements of the project. The cost of construction completed and in service by 1937 was repaid from power revenues by May 31, 1987, except for costs relating to flood control. Repayment of the \$25 million construction costs allocated to flood control will be repaid by 2037. Any features added after May 31, 1987 will be repaid within 50 years of the date of installation or as established by Congress. In addition, Arizona and Nevada each receive \$300,000 annually in lieu of taxes.

Hoover Dam is not only a national landmark but it is also known as one of the seven civil engineering wonders of the world. The project was authorized under the Boulder Canyon Project Act of 1928. Its authorized cost was of \$165,000,000 with the first \$25,000,000 being allocated for flood control as specified by the Boulder Canyon Project Authorization.

Preparation for the construction site of Hoover Dam, required for four diversion tunnels to be blasted and bored through the canyon walls, two on the Arizona side and two on the Nevada side. Excavation began in June of 1931 and it was completed in November of 1933. The construction site tunnels are 56 feet in diameter and they are lined with three foot thickness of concrete, leaving the final diameter of the tunnel to be 50 ft. in diameter. The combined length of all four diversion tunnels is approximately three miles in length.

The Colorado River was diverted into the fourth tunnel on November 14, 1932. Additionally, two coffer dams were built. The first coffer dam was 100 feet high and was located upstream between the construction site and the downstream exit of the diversion tunnels. The excavation from the river bed, to the bed rock below, was approximately a total of 135 ft.

The dam itself is a concrete arch-gravity type of dam. An arch-gravity dam is a dam with the characteristics of both an arch dam and a gravity dam. Meaning that the dam curves upstream in a narrowing curve, thus directing most of the water against the canyon rock walls; therefore, the force of gravity seen by the dam, compresses the dam downward. Registry of the first concrete pour at Hoover Dam dates back to June 6, 1933. The construction project was continuous and did not stop until the dam was all complete on May 29, 1935. The dam was completed, two years ahead of schedule. In order to accelerate the curing process of the concrete, an ammonia 1,000 ton chilling plant was constructed on the lower coffer dam to provide chilled brine that was pumped through piping throughout each of the lifts. Each concrete lift was cured enough to be stripped of its forms every 72 hours. The total amount of concrete in the dam itself equals approximately 3.25 million cubic yards that is about 6,600,000 tons of concrete. There is enough concrete in the dam to pave a 3 inch thick, 18 ft. wide highway from San Francisco, California to New York City, New York. Believe it or not the concrete continues to cure, until this day. The life span of the concrete is estimated to be around 2,000 years that is 1,925 years to go from the year 2012. Hoover Dam is 726.4 ft. in height from bedrock to the roadway; 1,244 ft. between the canyon walls at its widest

point; 660 ft. at its base, and 45 ft. thick at its crest. The Nevada-Arizona State line is located right at the center of the dam's crest [1].

Hoover Dam's powerhouse/power plant contains two power plant wings. One located in Nevada with eight commercial generators and one station service generator that provides the power for the power plant. Likewise, another wing is located on the Arizona side. The Arizona wing contains nine commercial generators and one station service generator. The approximate length of each wing is about 650 feet, and eight stories high. As mentioned before there is a total of 17 commercial generators. Each generator is water wheel driven by a stainless steel Francis turbine runner. The total nameplate capacity for the plant is 2,074 MW_e.

Hoover Dam is truly a unique power plant; each unit is unique from the others. The rotors on units N1 through N8 and A1, A2, A5, and A7 rotate at 180 revolutions per minute (rpm). These 12 units combined develop approximately 178,000 horsepower. The rotors have 40 electromagnetic poles. The rotors on units A3 and A4 rotate at 200 rpm and have 36 electromagnetic pole pieces. The two station service units differentiate in that they have Pelton type turbine runners instead of Francis type turbine runners. These two station service units, A0 and N0 rotate at 300 rpm and have 24 electromagnetic pole pieces. Additionally, all generators except for N7, A5, A7, and A8 are rated at 133,333 kilo-volt ampere (KVA) and 16,500 volts. Units N7 and A5 are rated at 130,256 KVA and 16,500 volts, and unit A9 is rated at 70, 256 KVA and 16,500 volts. The main excitation voltage is 250 VDC. The main shaft that connects the turbine runner and the

generator rotor, is 38 inches in diameter, weighs approximately 114 tons, and is about 65 ft. in length.

The intake towers are the inlets for the water to flow through the dam and to the power plant into the units. There is a total of four intake towers, one for each upper and lower penstock on each wing of the power plant. Each intake tower is built on a rock shelf, and is approximately 395 ft. tall. It has a diameter of 82 ft. and it tapers to the top with a final diameter of 63 ft.

The four main penstocks located in the dam are 30 ft. in diameter, and constructed from a 2.75 inch boiler steel plate. Each pipe section varies in length from 11 ft. to 30 ft.. Each section interlocks with adjacent sections, and is connected by the use of friction-fit steel pins, which were inserted from inside the penstock and pressed into position with a hydraulic ram. There is approximately 272 pins per each joint. The penstocks that branch off from the big penstocks are also known as laterals. Each lateral is 13 ft. in diameter and supply water into the scroll case and finally the generating unit.

The spillways are located at each side of the dam, one in Nevada and the other one in Arizona. Each spillway connects to one of the original diversion tunnel. Each spillway is approximately 650 ft. long, 750 ft. wide and 170 ft. deep. The spillways act as a flood control passage in case the lake ever goes up high enough, as high as 1,232 ft. In such event the spillways will diverge the water from the lake into the river, preventing the water to top over the dam. Each spillway is regulated by four (16 ft. X 100 ft.) drum gates. Each drum gate weighs approximately 500,000 pounds.

Figure 8 shows Hoover Dam at its whole. In the figure one can see the two wings of the power house for Nevada and Arizona as well as the face of the dam, which holds back Lake Mead. Additionally, the figure shows the Stoney Gates tunnel that allow the water to flow back into the river once it has gone through the generating units and the Spill Way tunnels that will allow the water to bypass the dam in the event of an overflow.



Figure 8: Hoover Dam [2].

Figure 9 shows the Hoover Power Plant. This photograph was taken in the Nevada Wing of the Powerhouse. Nine hydro-generating units are shown. Eight commercial units and one in-house unit that provides power for the power plant's electrical needs and use.



Figure 9: Hoover Power Plant, Nevada Wing [2].

1.4 Research Objectives

Efficiency is the amount of electrical power generated over known water flow. After studying, analyzing, and researching how valuable the water is for our daily use, one comes to realize that we have to do our best and use water efficiently and effectively.

Hydro-turbine generating units are units that use the water flow and force to spin a magnetic generator which in result produces electricity. This thermodynamic system can be assumed to be an open system; however, there are some losses and factors that must be accounted for in determining the complete and total output efficiency.

Every year or so there is a turbine overhaul in a certain unit at Hoover Dam. Ideally, every unit should get overhaul every 10 to 15 years, depending on the inspection results and wear and tear circumstances. Since there is 17 generating units at Hoover Dam, a unit overhaul takes place every year. During a unit overhaul, many factors and machine components are inspected, tested, and replaced.

Hoover Engineering believes that the efficiency of Hoover's generating units can be increased by having tighter clearances and tighter tolerances in the turbine runner seal rings, turbine pit wear plates, and by modifying the design of the wicket gates, by reducing the wicket gate camber profile. These factors will not only increase the overall plant efficiency, but in the long run it will benefit Hoover Dam, and its customers. Better efficiency means more power that can be produced utilizing the same water intake and water flow.

In Figure 10 one can see a new set of wear plates ready to be installed in the turbine pit. A Hoover hydro-unit is composed of 24 wicket gates; therefore, there is a total of eight sets of three bore holes per unit. This makes it easier for the hydro-electric mechanics to mobilize and install each set.



Figure 10: Wear plate ready for bolting above and below wicket gates [2].

Figure 11 shows two sets of wear plates being installed on the turbine pit and below the stay vanes and wicket gates. Note the head cover has not been installed yet, Figure 13 will show the installation of the top and bottom wear plates.



Figure 11: New wear plates bolted below wicket gates [2].

Figure 12 shows the head cover upside down while Hoover's hydro-electric mechanics install the wear plates.



Figure 12: Hydro-Electric Mechanics (HEM's) working on the wear plates that are attached to the units head cover [2].

Figure 13 demonstrates the top and bottom wear plates once installed inside the turbine pit. The white walls shown are the stay vanes that allow the water to flow into the turbine runner once the water has been guided by the wicket gates.



Figure 13: New wear plates installed at top and bottom of the turbine pit [2].

Figure 14 show both the stationary seal ring and the top portion of the wear plates after restoration.

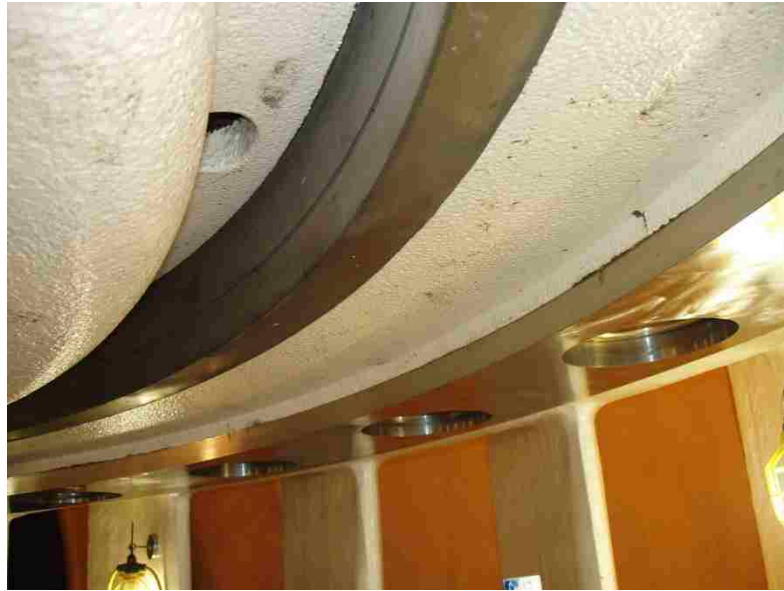


Figure 14: Restoration of Seal Rings (top left) and Wear Plates (top right) [2].

Figure 15 shows a comparison between a new stainless steel wicket gate and an existing cast steel wicket gate. Note that the stainless steel wicket gate has a slimmer profile.



Figure 15: New Stainless Steel Wicket Gate (left) vs. Old Cast Steel Wicket Gate (right) [2].

Figure 16 shows the new stainless steel wicket gates being installed inside the turbine pit.



Figure 16: New Wicket Gates being installed [2].

The Laws of Thermodynamics will be applied to analyze the tighter clearances and design modifications, that will help improve the capacity and efficiency of a hydro-turbine unit. Data from MATLAB[®] and MS Excel will be used to analyze the dimensions, tolerances, and clearances for the seal rings, wear plates, and wicket gates. Tighter dimension and clearances will be the main focus for the seal rings and wear plates. A change in camber, possibly the chord, and the angle of attack will be parameters taken into account for the wicket gate analysis.

1.5 Literature Review

Similar studies in analyzing and studying the wicket gates have been done by the United States Army Corps of Engineers. A study done at Lower Granite Lock & Dam to evaluate potential environmental and performance gains that can be achieved in Kaplan turbine units, through non-structural modifications to stay vanes and wicket gate assemblies [10], was done back in 2005.

The wicket analysis was done by VA Tech Hydro [11], similar to the design modifications and studies done at Hoover Dam. The analysis report showed that in order to achieve their efficiency gains, the minimal losses are reached by a rotation of approximately 1.0 degrees; and that the stay vane trailing edge is extended to minimize the gap between the stay vane and the wicket gate.

CHAPTER 2

EXERGY ANALYSIS

2.1 Laws of Thermodynamics

Thermodynamics plays an important role when analyzing and designing thermal design systems. The first law of thermodynamics states the change in the amount of energy contained within a system during some interval time is equal to the difference of the net amount of energy transferred in across the system boundary by heat transfer during the time interval and the net amount of energy transferred out across the system boundary by work during the time interval. The first law of thermodynamics is expressed in Eq. (2.1),

$$\Delta E = Q - W \quad (2.1)$$

In Eq. (2.1), ΔE , represents the change of energy found on the system (ft-lbs), Q , represents the amount of heat done on or created by the system (Btu), and W , represents the amount of work done on or created by the system (ft-lb_f).

In analyzing the energy balance, one considers a process in where the system and the environment come to equilibrium. The energy balance for the overall system as seen in Eq. (2.1), includes the kinetic, potential, and internal energies of the system. Analyzing how energy is lost throughout the system helps one understand the overall energy balance. For example, when a diesel engine turns a generator, the engine's mechanical energy is converted into electricity. The electricity is still concentrated, but not all of the mechanical energy is converted to electricity. Some of the energy is lost through heat,

and friction that is lost through all the mechanical components. The generator wires are heated up by internal friction as electrons flow through them. The generator cooling fan heats up more air by blowing it over the generator to keep it cool. All of this heat expands into the air around the generator. The energy is still there, however, it is no longer useful to the system.

In average a generator converts about 90 to 98 percent of the mechanical energy received into electrical energy, or electricity. The remaining 2 to 10 percent of the energy that is lost becomes low grade energy, or a less effective form of energy.

As the electrical energy flows through the transmission lines into the power generating substations and into our homes, the wires are heated by the flowing electrons. This result in more energy lost. Finally the electrical energy reaches our homes, in where the energy is converted into heat or mechanical energy.

The second law of thermodynamics states that the change in the amount of entropy contained with the system during some interval is equal to the difference between the net amount of entropy transferred in across the system boundary during the time interval and the amount of entropy produced within the system during the time interval. For simplicity, the second law of thermodynamics is expressed by Eq. (2.2),

$$\Delta s = \left(\frac{1}{T} \right) \delta Q \quad (2.2)$$

In Eq. (2.2), Δs represents the change of entropy in the system (S.I. units are [kJ/kg · K] and English are [Btu/lb·°R]), T is the absolute temperature at the part of the

boundary of the system (S.I. units are [$^{\circ}\text{C}$] and English are [$^{\circ}\text{F}$]), and δQ represents the heat transfer at a part of the system boundary (S.I. units are [J] and British are [Btu]).

Looking at a hydropower generating unit, the first and second law of thermodynamics can be applied in many distinctive ways. First and foremost, one must account for all mass flow rate, energy balance, and mass balance. Certain assumptions are made in this case study. Hoover Dam, is both a regulating and peak hydropower generating plant, therefore, the units do not run at a constant mode. Hoover Dam is frequently, changing its power output, by adjusting the amount of water intake. The plants power output is regulated based on the power customer's need and also based on the water capacity and flow that the dams downstream desire. It is safe to assume however, that a specific unit will operate constantly at full capacity, meaning that the wicket gates will be 100% open, allowing for maximum flow and maximum power output from the generating unit, based on the existing net head.

Another assumption that is accounted for is a constant head. Lake Mead has been increasing lately, during the past year. Back on October 2010, the lake was at El. 1080 ft., and recently on January 2012, the lake is at El. 1133 ft.. The value of the net head is the difference between the river (Tailbay) and lake (Forebay) elevations. For consistency and comparison feasibility the net head used in this thesis is 490.36 ft. The baseline calculations will reflect that net head parameter, unless noted otherwise; 490.36 ft was the net head value obtained on November 2011.

Table 1, shows the distinctive parameters used for the thermodynamic analysis of this case study. Some of these values were obtained from the Fundamentals of Engineering Thermodynamics, 6th Ed. textbook written by Michael J. Moran and Howard D. Shapiro [12], and others from Hoover Dam SCADA software.

Table 1: Hydropower Unit Variable Parameters.

Variable	Value	Units
Net Head, z	490.36	ft
Gravity Constant, g	32.2	ft/s ²
Water Density, ρ_f	62.4	lb/ft ³
Water Mass, m	62.4	lbs
Water Temperature, T_f	60	°F
Constant Volumetric Flowrate, Q	3100	cfs
Constant Mass Flow Rate, $m_{\dot{}}$	193440	lb _m /s
Constant Pressure, p_0	212	psi

For this case analysis MATLAB[®] and MS Excel were used for data gathering and numerical analytical programming. MATLAB[®] coding and MS Excel data and results will be referred to in later sections. By using the above parameters listed in Table 1, one is able to obtain the distinctive energy balance, mass balance, entropy balance, and exergy balance values that are applicable to this study.

2.2 Calculating the Thermodynamic Exergy

What is exergy? As defined by the textbook written by Moran and Shapiro, exergy is the maximum theoretical work obtainable from an overall system consisting of a system and the environment as the system comes into equilibrium with the environment. In other words into the work passes the dead state. The work developed is fully available for lifting a weight or, equivalently as mechanical work or electrical work. The exergy of a system for control volumes at steady states is given by Eq. (2.3):

$$0 = \sum_j \left(1 - \frac{T_0}{T_j} \right) \dot{Q} - \dot{W}_{cv} + \sum_i \dot{m}_i e_{fi} - \sum_e \dot{m}_e e_{fe} - \dot{E}_d \quad (2.3)$$

T_0 = temperature on the environment ($^{\circ}\text{R}$)

T_j = temperature on the boundary ($^{\circ}\text{R}$)

\dot{Q} = heat transfer rate (Btu/s)

\dot{W}_{cv} = energy transfer by work of the control volume (Btu/s)

\dot{m} = mass flow rate (lb_m/s)

$e_f = h - h_0 - T_0(s - s_0) + 0.5(V^2) + gz$ (ft-lb)

The control volume was treated as an incompressible fluid; therefore, the temperature and pressure remained constant. Thus e_f , represents only the kinetic and potential energy of the system. Eq. (2.3) allows one to calculate for the exergy of the control volume, setting the first term of the equation to zero. Figure 17 demonstrates the control volume that was analyzed in the parametric study at steady state 1, and steady state 2. A single unit was analyzed, therefore the volumetric flow rate was kept constant through both steady states.

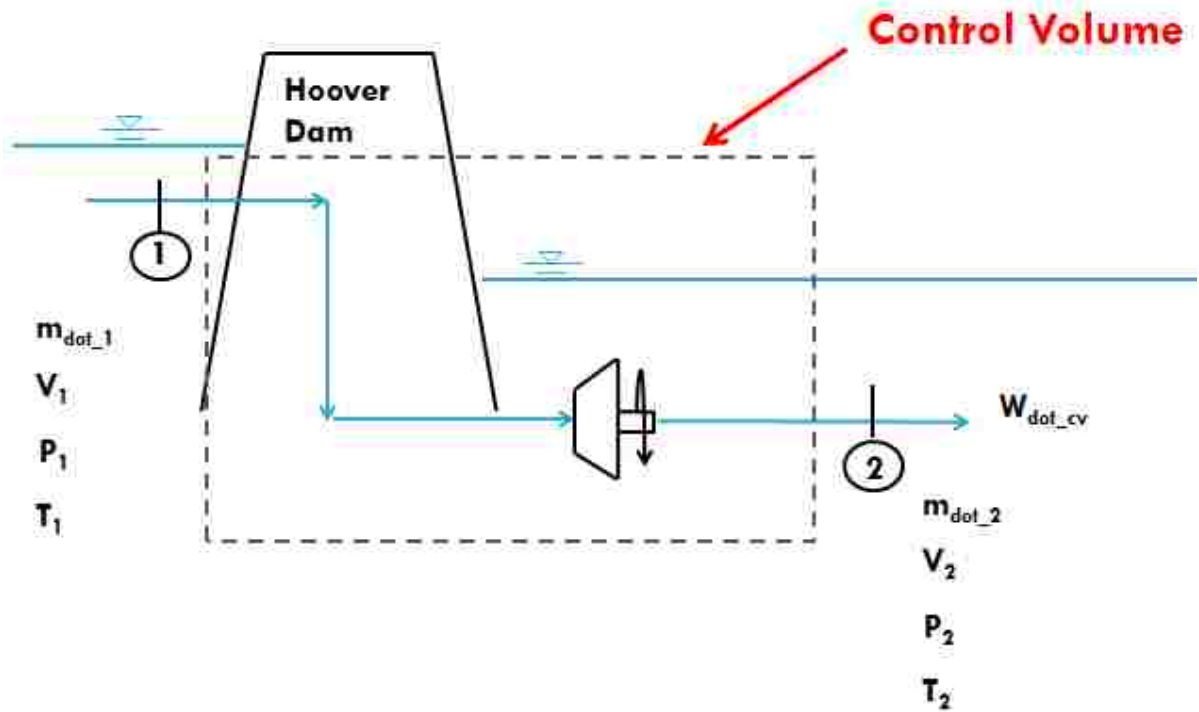


Figure 17: Control Volume Used in Parametric Analysis

The distinctive parametric values analyzed in this study were the mass flow rate, the velocity at the inlet and outlet, the pressure seen by the system, and the water temperature of the system. As mentioned before, a constant $T=60^\circ\text{F}$ and mass flow rate of $\dot{m}=193440$ lb_m/s , were obtained by using volumetric flow rate value of $Q=3100$ cfs and a net head of $z=490.36$ ft. Additionally, the medium in the control volume was taken to be as an incompressible fluid, meaning that the temperature and the pressure remained constant; thus, allowing for the first term in Eq. (2.3) to be cancelled out.

As seen in Figure 17, steady state 1 accounts for the parameters as the water flows from the lake and into the 30 ft. diameter penstock. Steady state 2 accounts for the water flow from the turbine outlet and into the river.

Eq. (2.4) demonstrates Eq. (2.3) when simplified to account for an irreversible and adiabatic system.

$$0 = -\dot{W}_{cv} + \dot{m} \left[\left(\frac{V_1^2 - V_2^2}{2} \right) + g(z_1 - z_2) \right] - \dot{E}_d \quad (2.4)$$

\dot{W}_{cv} = energy transfer by work of the control volume, c.v. (Btu/s)

\dot{m} = mass flow rate (lb_m/s)

V_1 = velocity coming into system (ft/s)

V_2 = velocity coming out of the system (ft/s)

z_1 = forebay/lake elevation (ft)

z_2 = tailbay/river elevation (ft)

\dot{E}_d = exergy destruction due to irreversibilities (Btu/s)

V_1 and V_2 were calculated by setting the volumetric flow rate coming in to the system to be equal with the volumetric flow rate coming out of the system. Eq. (2.5) shows how to calculate for velocity, using a volumetric flow rate of, $Q=3100$ cfs.

Additionally, an area of 706.86 ft^2 was used for steady state 1, accounting for an entry water flow into a 30 ft. diameter penstock, and an area of 113.10 ft^2 was used for steady state 2, accounting for an exit water flow from the turbine outlet.

$$Q = AV \quad (2.5)$$

Q = volumetric flow rate (cfs)

A = area for the flow passage (ft²)

V = velocity of the water flow (ft/s²)

Eq. (2.4) allows one to solve for the system exergy destruction, \dot{E}_d . The exergy destruction represents all the losses accounted for in the system, losses such as friction losses, fluid losses, pressure losses etc. After solving for the exergy destruction, one is able to solve for the entropy production, $\dot{\sigma}_{cv}$ of the system. Eq. (2.6) demonstrates how to solve for the entropy production, using the absolute temperature and the exergy destruction due to irreversibilities.

$$\dot{E}_d = T_0 \dot{\sigma}_{cv} \quad (2.6)$$

\dot{E}_d = exergy destruction due to irreversibilities (Btu/s)

T_0 = temperature on the environment ($^{\circ}\text{R}$)

$\dot{\sigma}_{cv}$ = entropy production (Btu/s- $^{\circ}\text{R}$)

Solving for Eq. (2.4) and Eq. (2.6) allows one to obtain the exergetic turbine efficiency of the system. This exergetic turbine efficiency value will be used to calculate the parametric study analysis discussed in Chapter 4. Eq. (2.7) shows how to calculate for the exergetic turbine efficiency value, using the results from steady state 1 and steady state 2.

$$\eta_{\text{turbine-exergetic}} = \frac{\frac{\dot{W}_{cv}}{\dot{m}}}{\frac{\dot{W}_{cv}}{\dot{m}} + \frac{\dot{E}_d}{\dot{m}}} \quad (2.7)$$

\dot{W}_{cv} = energy transfer by work of the control volume, c.v. (Btu/s)

\dot{m} = mass flow rate (lb_m/s)

\dot{E}_d = exergy destruction due to irreversibilities (Btu/s)

Table 2 demonstrates the results of the exergy analysis before and after a unit's overhaul. The wicket gate guide vein opening and the seal ring and wear plate clearances were modified to obtain a better efficiency and plant capacity. These parameters and modifications will be discussed in Chapter 3.

Table 2: Exergy Parametric Study Analysis Comparison

Case Study	Q (cfs)	Net Head (ft.)	Exergetic Efficiency (%)	Power Produced (MWe)	Power Max Capacity (MWe)	Unit Efficiency (%)
Pre-Overhaul	3100	490.36	96.93	124.656	130	95.89
Post-Overhaul	2745	490.36	96.93	124.656	130	95.89

Table 2 demonstrates that after a unit's overhaul the same amount of power can be produced with a smaller volumetric flow rate.

In calculating the thermodynamic exergy analysis of a hydropower unit, there are several aspects of the thermodynamic exergy analysis that must be taken into account [12].

1. Exergy is a measure of the departure of the state of a system from that of the environment. It is therefore, an attribute of the system and environment together. However, once the environment is specified, a value can be assigned to the exergy in terms of property values for the system only, so exergy can be regarded as a property of the system. This classifies exergy as an extensive property.
2. The value of exergy cannot be negative. If a system were at any state other than the dead state, the system would be able to change its condition spontaneously toward the dead state; this tendency would cease when the dead

state was reached. No work must be done to effect such a spontaneous change. Accordingly, any change in state of the system to the dead state can be accomplished with at least zero work being developed, and thus the maximum work or exergy cannot be negative.

3. Exergy is not conserved but is destroyed by irreversibilities. A limiting case is when exergy is completely destroyed, as would occur if a system were permitted to undergo a spontaneous change to the dead state with no provision to obtain work. The potential to develop work that existed originally would be completely wasted in such a spontaneous process.
4. Exergy has been viewed thus far as the maximum theoretical work obtainable from an overall system of system plus environment as the system passes from a given state to the dead state. Alternatively, exergy can be regarded as the magnitude of the minimum theoretical work input required to bring the system from the dead state to the given state.
5. When a system is at the dead state, it is thermal and mechanical equilibrium with the environment and the value of exergy is zero. The contents of a system at the dead state are permitted to enter into chemical reaction with environmental components and in so doing develop additional work. This contribution to exergy is called chemical exergy.

As mentioned before exergy is the maximum theoretical value of the work obtainable as the system comes into equilibrium with the environment that is when the system passes to the dead state. The system plus the environment is referred to as the overall system. The boundary of the overall system is located so there is no energy transfer across it by heat transfer: $Q = 0$. Moreover, the boundary of the overall system is located so that the volume remains constant, even though the volumes of the system and environment can vary. The work is the only energy transfer across the boundary of the overall system and is fully available for lifting a weight, turning a shaft, or producing electricity in the surroundings. Next, the energy and entropy balances are applied to determine the maximum theoretical value for the work.

CHAPTER 3

HYDRO-MACHINE PARAMETER IMPROVEMENTS

3.1 Correlated Variables

Generation of hydropower can be said that is driven by two factors. The water levels in the reservoir and the efficiency in transforming the water energy's into electrical power. The relationship between the water levels in the lake and power generation is divided into demand (energy conversion efficiency) and capacity (Hoover Dam capacity). Mechanical factors that affect the efficiency of the Energy Conversion System (ECS) and methods in how to increase the power plants efficiency reducing the Energy Conversion Gap (ECG) were analyzed. The ECG is the difference between the designed efficiency and the current efficiency.

Previous researches have studied distinctive methods in how to improve power plant efficiency, but most of them are focused in alternating or modifying explicit software programs. At Hoover Dam the operations and engineering group have a computer system called SCADA (Supervisory Control And Data Acquisition). SCADA is a computer system in an industrial plant that provides process control for machinery and data for monitoring machinery operations. Additionally, SCADA systems are used in power plants to start and stop units, and control MW_e , voltage, and unit operating mode (i.e. either in condense mode or generate mode). In condense mode the commercial units act as a motor, in where it does not provide power, but it takes power from the system. Since Hoover Dam it's both a regulating and generating plant, the units are often put in-line and off-line. Generating mode helps facilitate the process by keeping the units

spinning and in reserve ready to go for whenever more power is required. The units can easily be put online in about 15 seconds, as oppose as to having to start up a unit from complete stand-by mode which can take much longer than 15 seconds. When the units are on-line then they act as a big generator that produces and supplies as much as 130 MW_e of power.

Hoover turbines are generally 85% to 95% efficient when operated in the best range for a given head. With three different groupings of unit efficiencies, the best efficiency occurs from around 90 MW_e to about 130 MW_e for a majority of the units at Hoover Dam. Very low turbine efficiency occurs at loads below 50 MW_e. Hence, that is the reason why the units are put in condense mode. It is more convenient to put the units off-line, then risking the changes of seeing and experimenting rough zones and cavitation problems when operating our units at low loads.

3.2 Hydro-Machinery Components

The machinery components for this study were seal rings, wear plates, and wicket gates. A proper seal on the seal rings does not let excess water flow through, thus conserving more water and wasting less energy. Water leakage past worn wear plates puts an extra load on a turbine runner when operating in condense mode. Additionally, water leakage past worn plates decreases the efficiency of the Francis turbine, especially when operating at partial loads and the wicket gates are closed.

3.2.1 Seal Rings

Turbine runner seal rings have both stationary and rotating components. The rotating components are attached to the turbine runner itself and the stationary components are attached to the turbine pit itself. Additionally, there is upper and lower rotating and stationary components. The seal rings main function is to reduce water leakage around the shroud of the runner and between the crown plate of the runner and the turbine cover plate. When the unit is operating as a synchronous condenser the runner seal chamber is supplied with penstock water through two 4-inch pipes, which are capable of delivering about 3 cfs of water to each seal chamber. The sealing water acts as a cooling medium to prevent heating and seizing of the runner bands in case the stationary and revolving metal components come in contact.

In the original design the use of two metals of different characteristics was desirable in the event of accidental contact between the rotating and stationary rings. The stationary seal rings were made out of stainless steel. These were made in segments of a ring and bolted to the stationary seats. The runner seals were made of carbon steel forged into a ring and shrunk on the runner bands [14].

The seal rings are now being manufactured and produced out of a Nitronic 60 material. Nitronic 60 is an all-purpose metal (austenitic stainless). This fully austenitic alloy was originally designed as a temperature alloy, and subsequently has good high temperature properties for temperatures around 1800 °F. The oxidation resistance of Nitronic 60 is similar to Type 309 Stainless Steel, and far superior to Type 304 Stainless Steel. This grade is best known for its wear and galling resistance.

The additions of Silicon and Manganese have given this alloy a matrix to inhibit wear, galling, and fretting even in the annealed condition. Higher strengths are attainable through cold working the material and are still fully austenitic after severe cold-working. This working does not enhance the anti-galling properties as is normal for carbon steels and some stainless steels. The benefit to the cold or hot work put into the material is added strength and hardness, and the wear resistance does not decrease noticeably. Chromium and Nickel additions give it comparable corrosion to 304 and 316 stainless steels, while having approximately twice the yield strength. The high mechanical strength in annealed parts permits use of reduced cross sections for weight, and cost reductions through the use of thinner stock.

As mentioned before a proper seal and tight tolerances on the seal rings do not let excess water flow through the system. A better seal conserves more water, and reduces the energy wasted. Hoover Engineering's goal is to try and keep tight tolerances, while avoiding contact with the other metal components. Additionally, the goal is to replace the seal rings with a Nitronic 60 material, machine new radial surfaces concentric, and restore the design clearance to improve the unit efficiency.

Figure 18 shows the stationary seal ring inside the turbine pit. A turbine runner is composed of a total of four seal rings. Two upper seal rings and two lower seal rings. The upper seal rings are composed of a stationary seal ring that remains stationary and a rotating seal ring that rotates with the turbine runner. The same applies for the lower seal rings. The lower seal rings are composed of a stationary seal ring that remains stationary and a rotating seal ring that rotates with the turbine runner.



Figure 18: Lower Seal Ring [2].

Figure 19 shows the seal ring being machined in the Big Cincinnati machine at Hoover's Machine Shop.



Figure 19: Machining the turbine runner seal rings on the Cincinnati [2].

Figure 20 shows the turbine runner on top of the Big Cincinnati machine in Hoover's Machine Shop. The turbine runner is being turned and machined to achieve the final clearances and tolerances for the seal rings.



Figure 20: Turning runner on the Cincinnati for final seal ring clearances [2].

3.2.2 Wear Plates

Wear plates are the turbine components that are located in the upper and lower portions of the wicket gates. The original design was made out of chrome-vanadium steel, but recent designs call out for Nitronic 60 material. The top and bottom distributor wearing plates are renewable, and the runner seal clearance is 0.060 inches and the distributor-plate clearance is 0.015 inches.

When studying and analyzing the wear plates, one notices that high pressure water flow at 250 psi causes water erosion that damages and wears out the wear plates. Water leakage past worn plates puts extra load on turbine when operating in condense

mode. Furthermore, once the wicket gates are closed the water leakage that passes through the worn wear plates, wastes the energy in the water. The water leakage past worn wear plates decreases the efficiency of turbine runner, especially when operating at partial loads.

Figure 21 demonstrates a corroded section of a wear plate. Sever corrosion affects the efficiency of the unit tremendously as it is more exposed to water leakage that might lead to cavitation. Cavitation is the vaporization of fluids due to pressure loss which forms vapor pockets, and upon collapse, produces vibrations, noise, and destruction of the surrounding walls [13].



Figure 21: Damaged and Corroded wear plates [2].

Figure 22 is a series of photographs that show the wear plates once they have been refurbished. If the wear plates are not replaced with new ones, then all the corrosion is removed and the wear plates are restore to their original condition.



Figure 22: Refurbished Nitronic 60 wear plates [2].

3.2.3 Wicket Gates (Guide Vanes)

Wicket gates control the flow of water from the input pipes, that is water from the penstock and then into the scroll case to the turbine runner. Wicket gates are also referred to as paddles or guide vanes. Modifying the existing wicket gate to have a slimmer profile and tighter clearances reduces the water leakage between them. This was achieved by analyzing the wicket gate as an airfoil, and taking into account the airfoil's chord length, camber, and the angle of attack.

The tighter clearances reduce water leakage, and store more water in the reservoir for future use whenever the water is not required. Figure 23 shows that when the wicket gates are pinched shut under normal operating conditions each gate is subject to a system of forces. These forces cause bending about the horizontal and vertical axes.

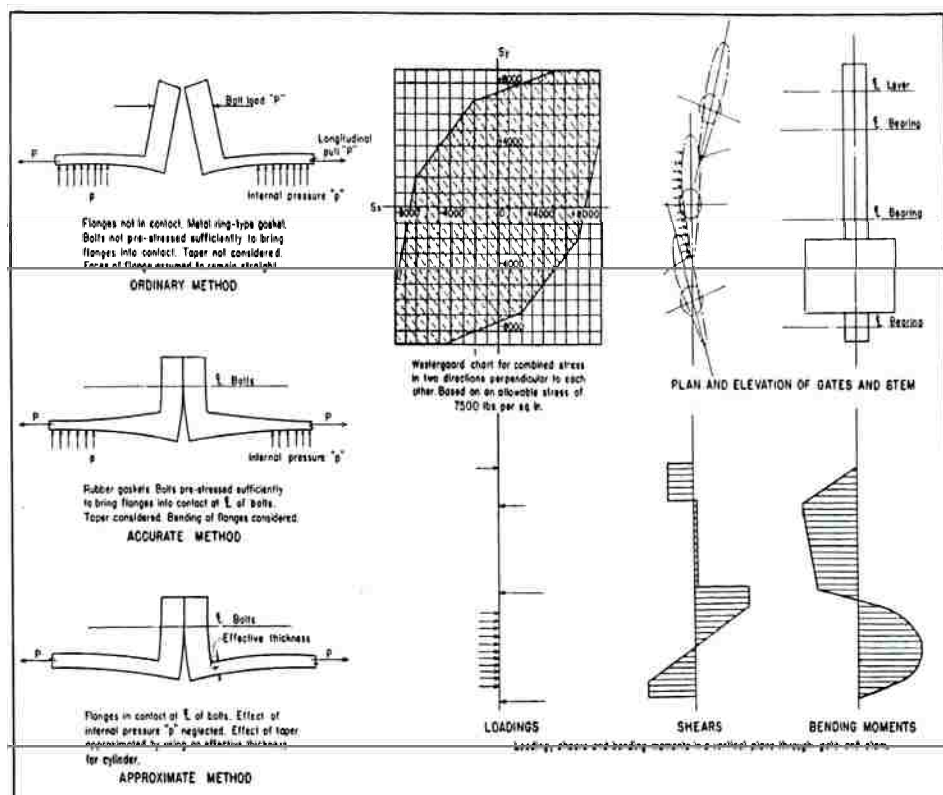


Figure 23: Check Stress Analysis for Turbine Flanges and Gates [2].

As seen in Figure 23, the gate stem is subjected to torsion and shear as well as bending about a horizontal axis. Each gate stem is provided with three bronze-bushed grease-lubricated guide bearings, one located in the lower cover or curb plate and the other two located in the top cover or crown plate. Additionally, one is located above the stuffing box and the other one is located below the stuffing box. A shearing pin is located between each gate stem and the gate shifting rings which is strong enough to withstand the maximum operating forces that the system will see, but this shear pin will break or yield and protect the rest of the mechanism from injury in case one or more of the gates becomes locked. The shear pins are designed to fail under double shear and have a vee-grooved configuration at the shear plane to reduce bending of the pin. This facilitates the removal of the broken parts.

The design of the wicket gates itself is such that in case any individual gate becomes disconnected from the gate-shifting mechanism, no part of the gate can come in contact with the turbine runner. The mechanism and the connections that control the wicket gates are mounted on the shift ring located inside the turbine pit.

When one modifies the wicket gate profile to make them squeeze tighter, it prevents leakage but also it result in a bigger guide vane opening (GVO). This is achieved by reducing the wicket gate airfoil camber profile. More flow results in more power. Lately, Hoover's goal has also been to replace the old cast-steel wicket gates with new thinner profile wicket gates made out of a stainless steel material. The wicket gates need a tighter squeeze to conserve energy and reduce water leakage. As Lake Mead goes down, the plant's output is reduced. According to a study done by VA Tech Hydro, the

new optimized wicket gate profile will increase peak efficiency by 1.00 to 1.25 %, resulting in a 5 % unit capacity increase.

Figure 24 shows that with an optimal head of 490 ft. to get a 90.25% efficiency the gates have to be open approximately 0.893” roughly 10% of gate opening, with a water flow of 1.28 cfs. Additionally, the wicket gate operational opening is limited by opening and closing time rate factors. The ranges used for this study are: 0%, 10%, 70%, 80%, 90%, and 100% of wicket gate opening.

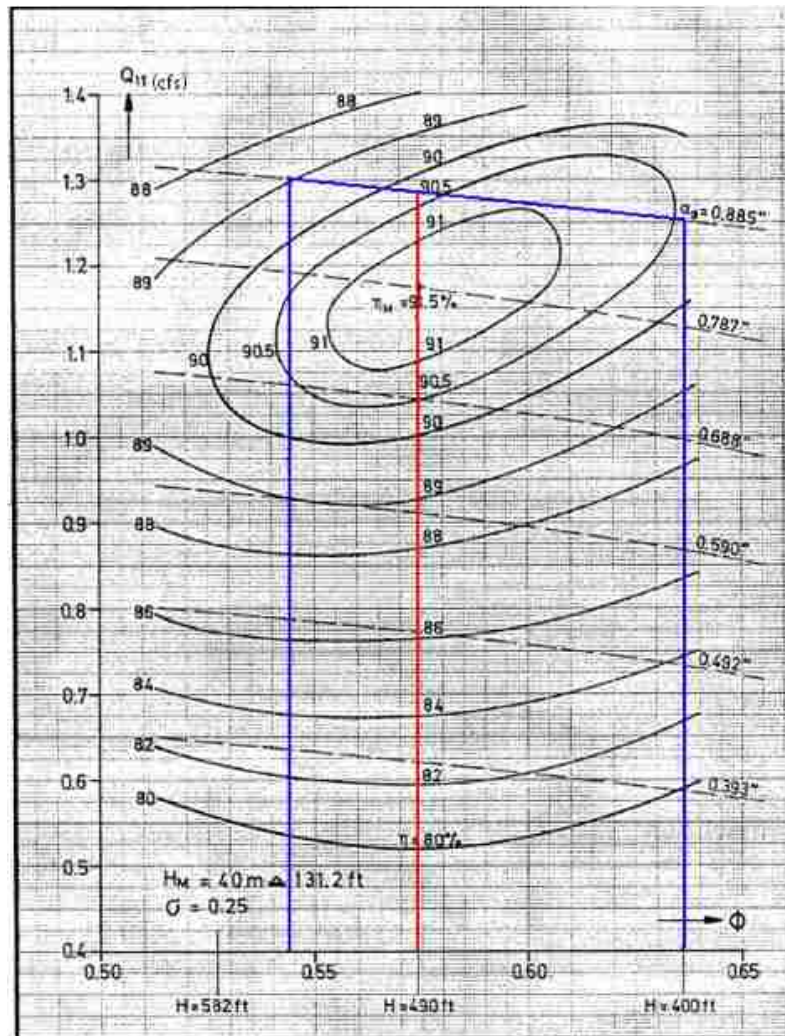


Figure 24: Hoover Dam Mussel Curve, showing an operating range of 400 ft to 550 ft [2].

The standard operating rate of the wicket gates is limited to a 15 second opening time frame that allows the wicket gates to open from 0% open to 100% open. The 15 second time frame is restricted to a certain interval to prevent vibration and water hammer to occur in a 130 MW_e unit. Water hammer is a pressure surge that results when a fluid in motion is forced to come to a stop or change fluid flow direction.

VA Tech Hydro did a study for distinctive variations and profiles of a new and optimized wicket gate design made with a stainless steel material. Figure 25 shows a sleeker profile, with an asymmetrical shape and a thin trailing edge. The black outline is the existing profile (d_0), while the red outline is the proposed designed asymmetrical slimmer profile (d_1). In this profile the parameters that were analyzed were the airfoil camber and angle of attack.

Overall, in order to achieve the 2 percent average efficiency, the angle of attack will need to be increased by 2 degrees, and the trailing edge gap by 0.02 inches. Additionally, the servo motors will have to be stroke 2.5 feet more to achieve the 2 percent increase in efficiency.

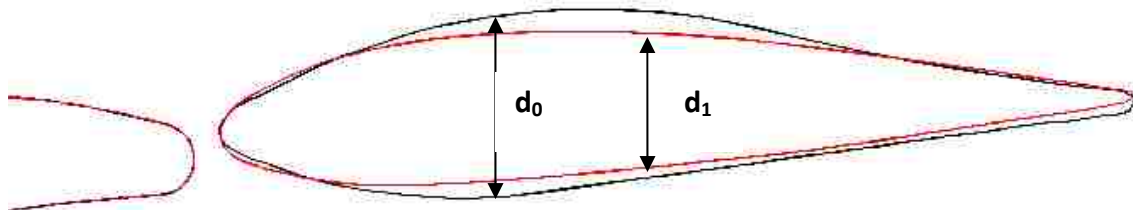


Figure 25: New Optimized Wicket Gate – VA Tech Hydro Profile A (Asymmetrical Shape) [11].

Figure 26 shows another design similar to Figure 24, however, with a slight difference in the wicket gate profile. Instead of having an asymmetrical shape the profile has a symmetrical shape. The black outline is the existing profile (d_0), while the green outline is the proposed designed symmetrical slimmer profile (d_2). In this profile the parameters that were analyzed were the airfoil camber and angle of attack. The asymmetrical is a little off center from the nose of the wicket gate profile. Studies showed that a profile with a symmetrical shape is not as efficient as a profile with an asymmetrical shape. In a symmetrical shape the flow of water tries to bypass a congruent shape and flow around the wicket gates, thus increasing the possibility of eddy currents and possible corrosion.

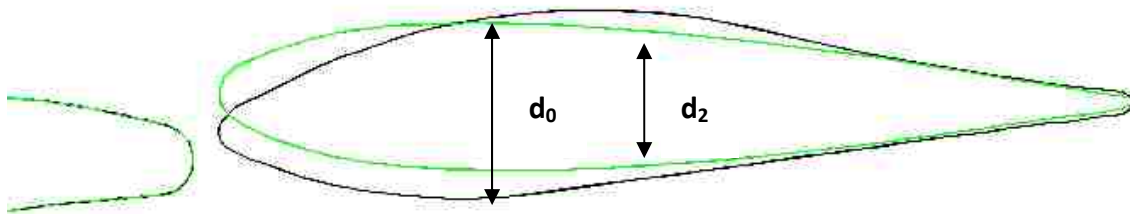


Figure 26: New Optimized Wicket Gate – VA Tech Hydro Profile B (Symmetrical Shape) [11].

Wicket gates act like Venetian blinds that let the sun shine go through a window. The more one opens the blinds the more sun shine one allows for to enter the room. Wicket gates are very similar alike in the concept of letting more water flow through. As seen in the picture below the more the wicket gates are open, the more output power our generating units can produce. However, in a perfect scenario in order to produce more power the wicket gates will be 100 % open at all times, to allow for more water flow to enter the turbine. This concept is hard to follow at Hoover Dam, since Hoover is a special

unique plant that generates and regulates power at the same time. Therefore, Hoover's power demand varies and fluctuates depending on the time of day and seasonal time of the year.

Figure 27 shows the water energy coming into the scroll case and into the turbine runner. The water flow is however control by the twenty-four (24) wicket gates around the unit which control the flow of water. More water flow into the unit allows for more power to be generated.

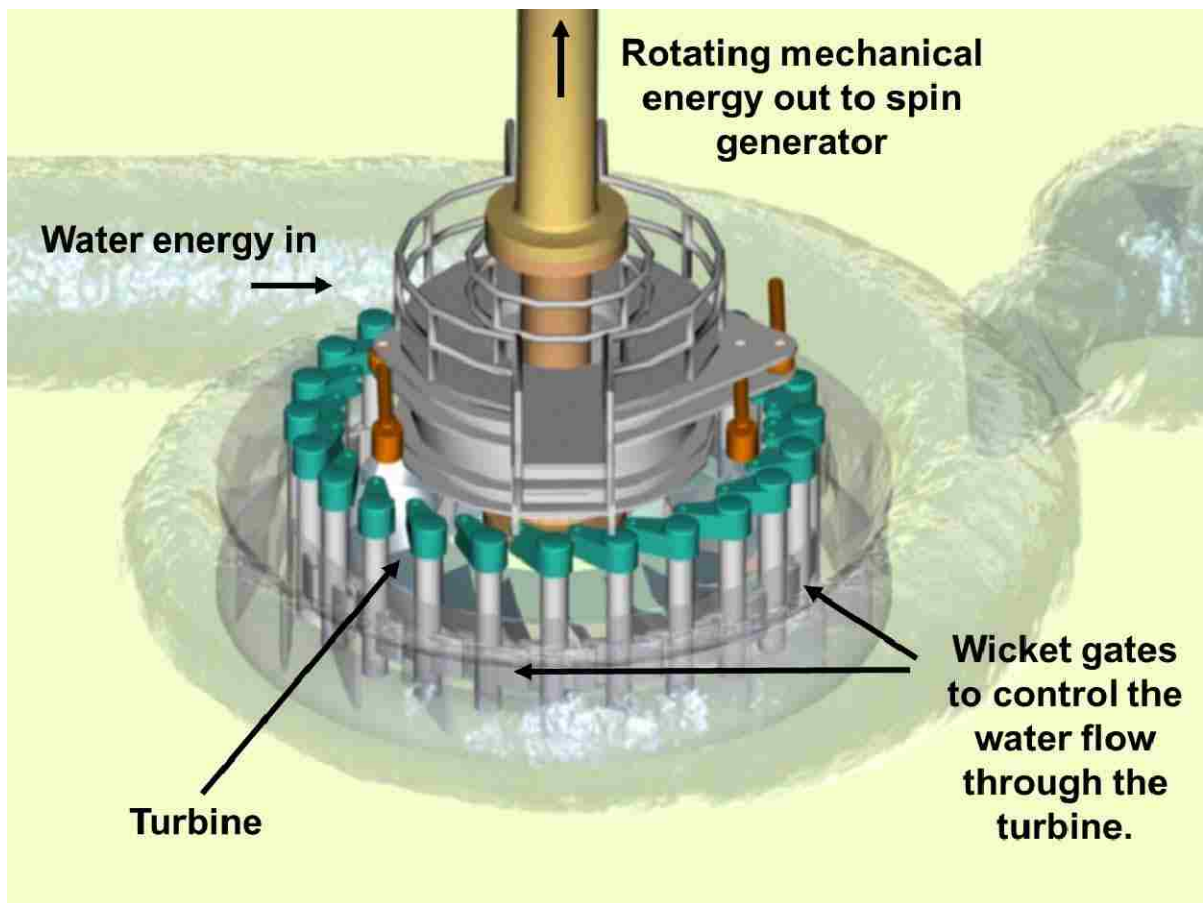


Figure 27: Wicket Gate Function Schematic [2].

Figure 28 below clearly demonstrates the importance of tight tolerances on the turbine runner stationary and rotating seal rings in both the upper and lower portions of the runner. Furthermore, the precise measurements of the wear plates are extremely important to prevent excess water leakage through the wicket gate profile. The photograph also demonstrates how the nose and tail of the wicket gate profile come in contact with each other once the wicket gates are close. If there is an excessive gap between the nose and tail of the wicket gate, then energy will be wasted. It is Hoover Engineering's goal for the new wicket gate profile to have a tighter squeeze on the gates once they are closed.

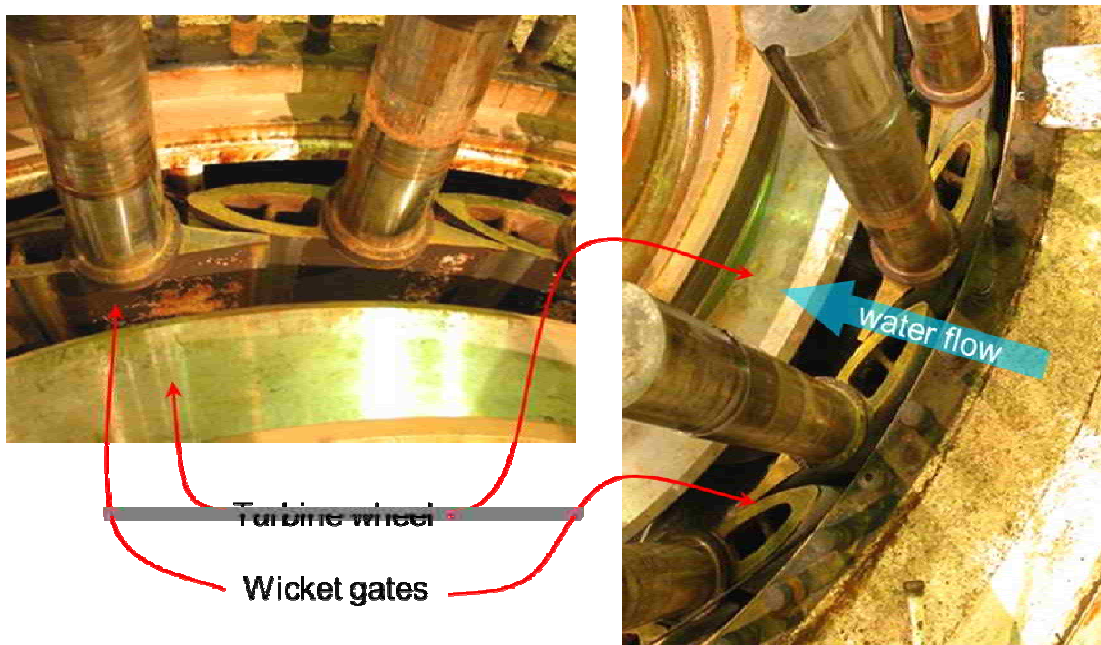


Figure 28: Wicket Gate and Turbine Runner Arrangement [15].

A large passage area, also known as the Guide Vane Opening (GVO), allows for more water flow to pass through the wicket gates. In having a bigger GVO and a thinner hydraulic profile, the new wicket gate made out of stainless steel will increase the maximum flow rate to the turbine from 3,400 cfs to 3,600 cfs. The end results are a capacity increase of 7 MW when the lake levels are below 1,180 ft. of elevation [1].

Figure 29 shows how the water passage area or the GVO (A_0) affects the amount of water flow (cfs) that goes into a unit. More water flow creates more power.

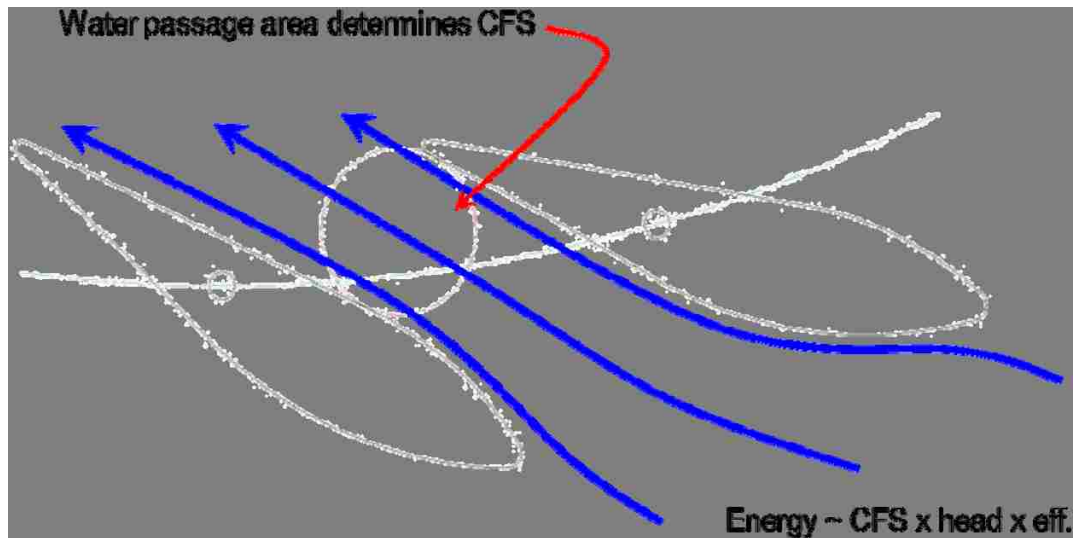


Figure 29: Existing Wicket Gate - 1930's Mild Steel Castings with Stainless Steel Inlays [15].

Figure 30 reiterates the idea that a larger GVO (A_1) creates more water flow which in turn creates more power. That's why having a slimmer wicket gate profile it's truly beneficial in increasing efficiency and capacity of Hoover Dam.

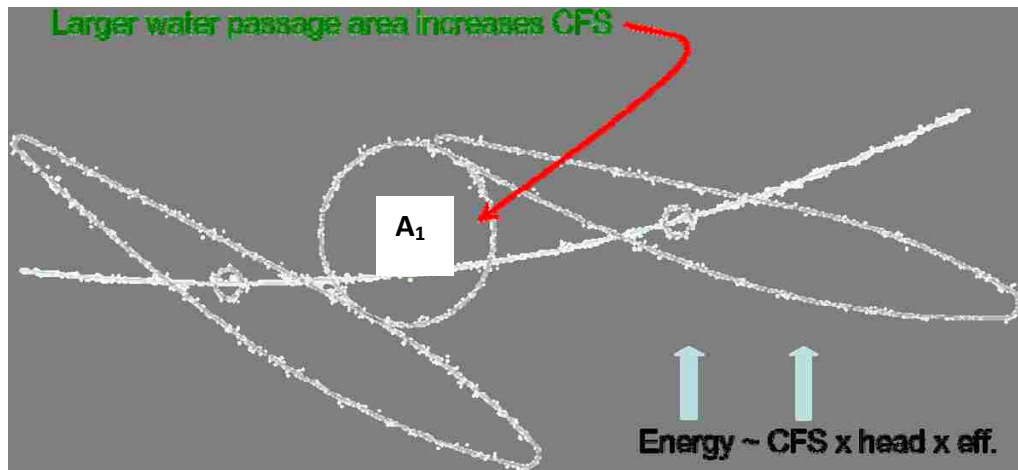


Figure 30: New Wicket Gate – Modern, Thinner Design all Stainless Steel [15].

Figure 31 compares the old cast steel wicket gate design (d_0 and A_0) with the new slimmer profile stainless steel wicket gate design (d_1 and A_1). Additionally, the GVO with the new stainless steel wicket gate design increases by 12%.

Note how $d_0 > d_1$, but $A_0 < A_1$. As mentioned previously a larger GVO (A_1) creates more water flow which in turn creates more power.

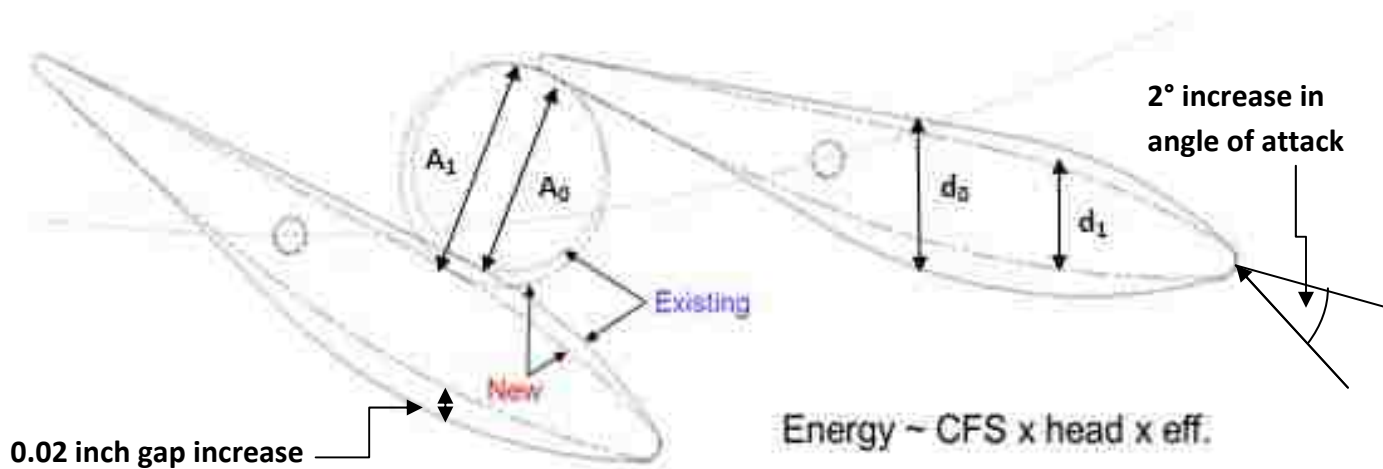


Figure 31: Comparing Existing and New Wicket Gate Profile and Guide Vane Opening [15].

Another possible solution in increasing power capacity is to over stroke the wicket gates. Over stroking the wicket gates involves modifying the existing wicket gate mechanism, by extending the wicket gate servo motor linear travel by about 1 to 4 inches of travel. This slight modification, involves machining or moving the wicket gate servo motor stop nuts back further. By doing so, the servomotor arm is allowed to travel up to 4 more inches, allowing the wicket gates to have a bigger GVO when opened and a tighter squeeze when closed. The modification of over stroking the wicket gates allows a larger GVO, which allows for a flow rate increase from 2,900 cfs to 3,400 cfs, that is a 500 cfs flow rate increase.

Figure 32 shows the green wicket gate linkage mechanism that operates the gates to open and close. The orange rod is part of the servo motor components which hydraulically operates the gates to open or close.



Figure 32: Wicket Gate Servo Motor Arm and Wicket Gate Mechanism [2].

Figure 33 shows the green shift ring and orange rod servo motors. The wicket gate mechanism is linked to the shift ring in order to be hydraulically operated to open or close.



Figure 33: Wicket Gate Servo Motor Arm and Shift Ring Mechanism [2].

Figure 34 shows the wicket gate mechanism that is linked to the shift ring, which is hydraulically operated by the servo motors.



Figure 34: Wicket Gate Linkage Mechanism [2].

In Figure 35, note the wicket gate level arms sticking out of the turbine pit. In this figure the shift ring and turbine guide bearing have been removed. This figure also shows the two orange servo motors that hydraulically operate the wicket gates.



Figure 35: Turbine Pit Area, without the Wicket Gate Shift Ring [2].

Other benefits of the new wicket gate profile and modifications, include less turbine cavitation at the leading edges of the turbine runners, because of the uniform velocities across the newly design wicket gates. The new wicket gates prevent the wear plates to experience less damage from leakage in comparison to the old cast-steel wicket gate design.

Figure 36 shows a typical Hoover Dam turbine runner. This runner is being stayed in the power house wing, for future modifications and repairs in the runner's buckets.



Figure 36: Turbine Runner being staged for further modifications and repairs [2].

Figure 37 shows cavitation on the bottom portion (low pressure side) of the N3 turbine's runner bucket No. 14.



Figure 37: Erosion caused by cavitation seen on the turbine runner bucket [25].

Cavitation occurs when the pressure of water flow drops and forms vapor bubbles. In cavitation the vaporization of fluids due to pressure loss forms vapor pockets, and upon collapse, produces vibrations, noise, and destruction of the surrounding walls [13].

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Results

Overhauling a hydro unit to obtain better efficiency is very similar to overhauling a vehicles engine to improve the vehicles fuel economy. Modifying and replacing the three major hydro-machinery components: seal rings, wear plates, and wicket gates, improves the efficiency of Hoover Dam units by an average of 2 %, and a capacity increase of 3% to 5%. In order to achieve such results the dimensions of the wear plates and seal rings were changed to have tighter clearances, and the wicket gate design and profile were changed by increasing the angle of attack by 2 degrees; additionally, the trailing edge gap of the wicket gate was increased by 0.02 inches. The servo motors were also stroked 2.5 feet more to achieve the 2 percent increase in efficiency. This increase in efficiency and capacity equates to an additional 8,000 MW-hrs per year per unit. The wholesale market value of this increase in energy and capacity, roughly equates to about \$290,000 per unit per year.

By preventing water leakage in the hydro-power generating unit more water becomes available to produce more electrical energy. By installing new modified and machined seal rings, wear plates, and wicket gates, the operating clearances between the moving parts is reduced, thus, the water leakage throughout the unit is reduced as well. This results in a reduction of downstream water leakage and it improves the unit's control accuracy.

The estimated wholesale market value at Hoover Dam from reducing water leakage through the wicket gates is approximately \$200,000 per unit per year. That is a total savings of \$3,400,000 a year for the 17 power-generating units at Hoover Dam.

Additionally, by preventing water leakage in the hydro-power generating unit more water becomes available to produce more electrical energy. In installing new modified and machined seal rings, new wear plates, and new wicket gates, the operating clearances between the moving parts is reduced, thus, minimizing the water leakage throughout the unit, and also minimizing energy losses. This results in a reduction of downstream water leakage and it improves the unit control accuracy. Table 3 demonstrates how the power plant capacity increases by installing new wicket gates for units that have been previously overhauled.

Table 3: Hoover Power Plant Projected Capacity Increases Achieved [2].

Unit Number	Date	Modification	Capacity Increase when Lake Mead is below 1145 (MW _e)
A6	July 21, 2010	New Stainless Steel Wicket Gates	5
N3	May 26, 2011	New Stainless Steel Wicket Gates	10

4.2 MATLAB® Coding

The computer software used was MATLAB® which is developed by MathWorks. Some coding was programmed in MATLAB®, but some data collection and analysis was done in Excel. The MATLAB® codes show analysis of hydro-unit variables necessary for an efficiency study. The exergy process analysis was discussed in Chapter 2.

4.2.1 Baseline Calculations MATLAB® Coding

The baseline parameters were coded in MATLAB® using English units. To account for the head of water elevation one must first take the difference between the Forebay (Lake) elevation and the Tailbay (River) elevation.

Eq. (4.1) shows one how to calculate for the total net head, given $F_{El.} = 1125.27$ ft and $T_{El.} = 634.91$ ft.

$$H = F_{El.} - T_{El.} \quad (4.1)$$

H = net head of water elevation (ft)

$F_{El.}$ = forebay (lake) elevation (ft)

$T_{El.}$ = tailbay (river) elevation (ft)

Having obtained the net head of the system, $H = 490.36$ ft. one can substitute Eq. (4.1) into Eq. (4.2) to obtain the pressure coming into the system.

Eq. (4.2) demonstrates the conversion from net head into psi.

$$z = \left(\frac{1}{2.307} \right) H \quad (4.2)$$

H = net head of water elevation (ft); using a value of 490.36 ft. for net head.

z = pressure coming into the system (psi); the value obtained is 212.5531 psi.

The following parameters are values obtained from Hoover Dam SCADA software. For study analysis these values will be kept constant, unless otherwise noted.

Eq. (4.3) denotes the gravity coefficient of the system.

$$g = 32.2 \text{ ft} / \text{s}^2 \quad (4.3)$$

g = gravity constant (ft/s²)

Eq. (4.4) denotes the density of water of the system.

$$\rho_{H_2O} = 62.4 \text{ lb} / \text{ft}^3 \quad (4.4)$$

ρ_{H_2O} = density of water (lb/ft³)

Eq. (4.5) denotes the temperature of the water of the system.

$$T_{H_2O} = 60^\circ \text{ F} \quad (4.5)$$

T_{H_2O} = temperature of water (°F)

Eq. (4.6) denotes the volumetric flow rate coming in to the system, at the time when the net head was 490.36 ft.

$$Q_{in} = 12042 \text{ cfs} \quad (4.6)$$

Q_{in} = volumetric flow rate coming in into the system (cfs)

The mass flow rate coming in into the system can be obtained by substituting Eq. (4.4) and Eq. (4.6) into Eq. (4.7).

$$\dot{m}_{in} = \rho_{H_2O} Q_{in} \quad (4.7)$$

\dot{m}_{dot_in} = mass flow rate coming in into the system (cfs)

ρ_{H_2O} = density of water (lb/ft³)

Q_{in} = volumetric flow rate coming in into the system (cfs)

Thus, the value obtained for the mass flow rate coming in, $\dot{m}_{dot_in}=751421$ lb_m/s. The same procedures were done to obtain the value for the mass flow rate coming out of the system, with the only exception that Q_{out} was used for the volumetric flow rate. The value obtained from SCADA for $Q_{out}=9341$ cfs, meaning that the value for, $\dot{m}_{dot_out} = 582878$ lb_m/s, see Eq. (4.9) for procedures.

Eq. (4.8) denotes the volumetric flow rate coming out of the system.

$$Q_{out} = 9341 \text{ cfs} \quad (4.8)$$

Q_{out} = volumetric flow rate coming out of the system (cfs)

The mass flow rate coming out of the system can be obtained by substituting Eq. (4.4) and Eq. (4.8) into Eq. (4.9).

$$\dot{m}_{out} = \rho_{H_2O} Q_{out} \quad (4.9)$$

\dot{m}_{dot_out} = mass flow rate coming out of the system (cfs)

ρ_{H_2O} = density of water (lb/ft³)

Q_{out} = volumetric flow rate coming out of the system (cfs)

In order to obtain the mass flow rate for the overall system Eq. (4.9) is subtracted from Eq. (4.7), see Eq. (4.10) for mathematical procedure.

$$\dot{m}_{baseline} = \dot{m}_{out} - \dot{m}_{in} \quad (4.10)$$

\dot{m}_{dot} = mass flow rate of the system (cfs)

\dot{m}_{dot_out} = mass flow rate coming out of the system (cfs)

\dot{m}_{dot_in} = mass flow rate coming in into the system (cfs)

Thus, the value obtained for the mass flow rate, $\dot{m}_{dot_baseline} = 168542 \text{ lb}_m/\text{s}$.

4.2.2 Parametric Analysis Calculations MATLAB® Coding

A baseline value of $Q_{baseline}=2701$ cfs was used for the baseline calculations, when there was a net head of 490.36 ft. However, in order to keep the parametric study constant a volumetric flow rate of $Q_{system}=3100$ cfs will be used in Eq. (4.13) for the comparison parametric study.

Eq. (4.11) will be used to compare the turbine exergetic efficiency, with the actual efficiency obtain from an actual unit. The $P_{produced}$ was obtained from the exergy study analysis at $H=490.36$ ft., $Q=3100$ cfs, and $\eta_{turbine_exergetic_efficiency}$.

$$\eta_{turbine} = \frac{P_{produced}}{P_{capacity}} \quad (4.11)$$

$\eta_{turbine}$ = efficiency of turbine unit (%)

$P_{produced}$ = overall power produced by unit (MW_e)

$P_{capacity}$ = capacity of power that a unit can produce, stator max capacity (MW_e)

Eq. (4.12) shows the volumetric flow rate of the system that was used in the comparison analysis for the distinctive power outputs.

$$Q_{system} = 3100 cfs \quad (4.12)$$

Q_{system} = volumetric flow rate of the system (cfs)

Eq. (4.13) shows how to calculate for power in a hydro unit.

$$P_{system} = \eta_{turbine_exergetic} \left[Q_{system} (H) (\rho_{H_2O}) \left(\frac{1hp}{550 ft-lb/sec} \right) \left(\frac{0.747 kW}{1hp} \right) \left(\frac{1MW_e}{1000 kW_e} \right) \right] \quad (4.13)$$

$\eta_{turbine_exergetic}$ = turbine exergetic efficiency (%)

Q_{system} = volumetric flow rate of the system (cfs)

H = net head of water elevation (ft)

ρ_{H_2O} = density of water (lb/ft³)

From Eq. (4.13), $P_{system} = 124$ MW. This power produce is not the maximum power that the unit is capable of producing, the stator is rated for a 130 MW_e max power output. This power output is lower than 130 MW_e due to the low net head and low volumetric flow rate into the system.

(Please refer to Appendix B (B-1) and (B-2) to reference the MATLAB[®] Coding)

Solving for the mass balance, energy balance, and exergy balance requires solving for the unit's kinetic energy, potential energy, internal energy, and the heat transferred. Parameters from Table 1, were used to perform some of the required calculations.

Eq. (4.14) demonstrates how to calculate for the kinetic energy of the system.

$$KE = \frac{1}{2} mv^2 \quad (4.14)$$

KE = kinetic energy of the system (ft-lb)

m = mass of water (lb) (*62.4 lbs in a cubic feet)

v = velocity of the fluid medium in the system (ft/s)

Eq. (4.15) demonstrates how to calculate for the kinetic energy of the system.

$$PE = mgH \quad (4.15)$$

PE = potential energy of the system (ft-lb)

m = mass of water (lb) (*62.4 lbs in a cubic feet)

g = gravity constant (ft/s²)

H = net head of water elevation (ft)

The system was taken to be an adiabatic process; therefore, there was no heat transfer and internal energy is kept constant. $Q_{\text{heat}} = 0$, adiabatic and $U = 0$, constant internal energy.

Eq. (4.16) demonstrates how to calculate for the overall energy of the system.

$$E = PE + KE + U \quad (4.16)$$

E = overall energy of the system (ft-lb)

PE = overall potential energy of the system (ft-lb)

KE = overall kinetic energy of the system (ft-lb)

U = overall internal energy of the system (ft-lb)

Now, one can calculate for the mass balance, energy balance, and exergy balance of the system. Eq. (4.17) demonstrates how to find the mass balance in the system.

$$\dot{m} = \rho_{H_2O} Q_{\text{system}} \quad (4.17)$$

$m_{\dot{o}t}$ = mass balance of the system

ρ_{H_2O} = density of water (lb/ft³)

Q_{system} = volumetric flow rate of the system (cfs)

Substituting Eq. (4.4) and Eq. (4.12) into Eq. (4.17), one obtains $m_{\dot{o}t} = 193,440 \text{ lb}_m/\text{s}$.

Overhauling a unit allows for more volumetric flow rate which increases power capacity; thus, increasing the energy balance, mass balance, and the exergy balance increasing the maximum useful work of the system.

4.2.3 Seal Ring Calculations MATLAB[®] Coding

Table 4 shows the parameters used for calculating the clearance dimensions for the upper and lower rotating seal rings.

Table 4: Seal Ring Clearances Parameter Values [2]

Variable	Value	Units
Young Modulus, E	2.62×10^7	psi
Ultimate Tensile Strength, S_{ut}	11100	psi
Yield Strength, S_y	60000	psi
Density, ρ	0.274	lbm/in ³
Temperature Range, α	8.8×10^{-6}	in/in/°F
Coefficient of Static Friction, μ_s	0.7	
Seal Design Clearance, X_{seal}	0.04	in
Maximum Allowable Stress, σ_{max}	10000	psi
Runaway Speed, N_o	340	rpm

Due to proprietary rights the data results were not shared, but the clearances obtained were decreased from 0.05 to 0.150 inches.

Eq. (4.18) demonstrates how to calculate for the final inside diameter of the seal ring.

$$ID_{ofSealRing} = OD_{runner} \left(\frac{1 - \sigma_{max}}{E} \right) \quad (4.18)$$

$ID_{sealring}$ = final inside diameter of rotating seal ring (in)

OD_{runner} = outside diameter of runner (in)

σ_{max} = maximum allowable stress (psi)

E = Young Modulus (psi)

Eq. (4.19) demonstrates how to calculate for the final inside diameter of the seal ring tongue.

$$ID_{ofSealRingTongue} = ID_{sealring} - 2(X_{tongue}) \quad (4.19)$$

$ID_{sealring_tongue}$ = final inside diameter of rotating seal ring tongue (in)

$ID_{sealring}$ = final inside diameter of rotating seal ring (in)

X_{tongue} = thickness of rotating seal ring tongue (in)

Eq. (4.20) demonstrates how to calculate for the final outside diameter of the seal ring.

$$OD_{ofSealRing} = ID_{stationary} - 2(X_{seal}) \quad (4.20)$$

$OD_{sealring}$ = final outside diameter of rotating seal ring (in)

$ID_{stationary}$ = inside diameter of stationary seal ring (in)

X_{seal} = rotating seal ring design clearance (in)

Eq. (4.21) demonstrates how to calculate for the inside diameter of the rotating seal ring at the installation temperature.

$$ID_{installation} = ID_{sealring} (1 + \alpha(T_{installation} - T_{ambient})) \quad (4.21)$$

$ID_{installation}$ = inside diameter of rotating seal ring at installation temperature (in)

ID_{sealring} = final inside diameter of rotating seal ring (in)

α = temperature range @ 75 °F to 200 °F (in/in/°F)

$T_{\text{installation}}$ = rotating seal ring installation temperature (°F)

T_{ambient} = rotating seal ring ambient temperature (°F)

Eq. (4.22) demonstrates how to calculate for clearances between the inside diameter of the rotating seal ring to the outer diameter of the turbine at the installation temperature.

$$ID_{\text{clearances}} = ID_{\text{installation}} - ID_{\text{sealring}} \quad (4.22)$$

$ID_{\text{clearances}}$ = inside diameter of rotating seal ring to the outside diameter of runner (in)

$ID_{\text{installation}}$ = inside diameter of rotating seal ring at installation temperature (in)

ID_{sealring} = final inside diameter of rotating seal ring (in)

Eq. (4.23) demonstrates how to calculate for clearances between the inside diameter of the rotating seal ring tongue to the outer diameter of the turbine at the installation temperature.

$$ID_{\text{clearances tongue}} = ID_{\text{installation}} - 2X_{\text{tongue}} - OD_{\text{runner}} \quad (4.23)$$

$ID_{\text{clearances tongue}}$ = inside diameter of rotating seal ring tongue to the outside diameter of runner (in)

$ID_{\text{installation}}$ = inside diameter of rotating seal ring at installation temperature (in)

X_{tongue} = thickness of rotating seal ring tongue (in)

OD_{runner} = outside diameter of runner (in)

Eq. (4.24) demonstrates how to calculate for the average diameter of the rotating seal ring at the cross section installed.

$$D_{avg} = OD_{runner} + OD_{sealring} \quad (4.24)$$

D_{avg} = average diameter of rotating seal ring at the cross section installed (in)

OD_{runner} = outside diameter of runner (in)

$OD_{sealring}$ = final outside diameter of rotating seal ring (in)

Eq. (4.25) demonstrates how to calculate for the centrifugal stress at the runaway speed.

$$\sigma_{cf} = \left(\frac{\rho \left(\frac{N_o \pi D_{avg}}{60} \right)^2}{386} \right) \quad (4.25)$$

σ_{cf} = centrifugal stress at the runaway speed (psi)

ρ = density of material (lbm/in³)

N_o = runaway speed (rpm)

D_{avg} = average diameter of rotating seal ring at the cross section installed (in)

Eq. (4.26) demonstrates how to calculate for the factor of safety against a seal ring separation at the runaway speed.

$$FS_{sealring} = \frac{\sigma_{max}}{\sigma_{cf}} \quad (4.26)$$

$FS_{sealring}$ = factor of safety against a seal ring separation at the runaway speed

σ_{max} = maximum allowable stress (psi)

σ_{cf} = centrifugal stress at the runaway speed (psi)

(Please refer to Appendix B (B-3) to reference the MATLAB[®] Coding)

4.2.4 Pre-Overhaul and Post-Overhaul Calculations MATLAB® Coding

Data values were obtained from the Hoover Dam SCADA software see Table 5 and Table 6 for results.

(Please refer to Appendix B (B-4) to reference the MATLAB® Coding)

Figure 38 shows a plot of unit capacity with the data normalized at 490.36 ft of net head. Power (MW_e) is plotted on the vertical axis, while the Volumetric Flow Rate (cfs) is plotted on the horizontal axis. Figure 37 shows that in order for a unit to produce 130 MW_e of power there must be a volumetric flow rate of at least 3300 cfs

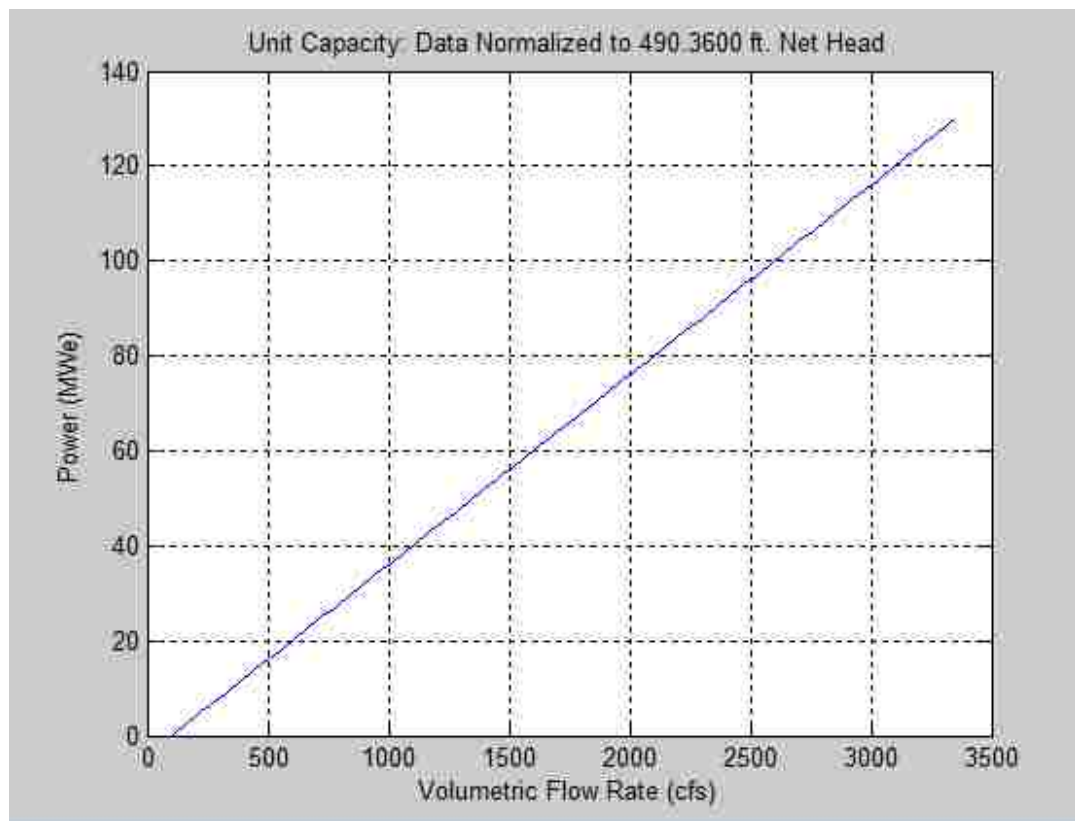


Figure 38: MATLAB® plot of Unit Capacity - Data Normalized to 490.36 ft. of net head.

Figure 39 shows a plot of unit efficiency with the data normalized at 490.36 ft of net head. Efficiency (%) is plotted on the vertical axis, while the Volumetric Flow Rate (cfs) is plotted on the horizontal axis. Figure 38 shows that a unit is 78 % efficient when it produces 130 MW_e of power.

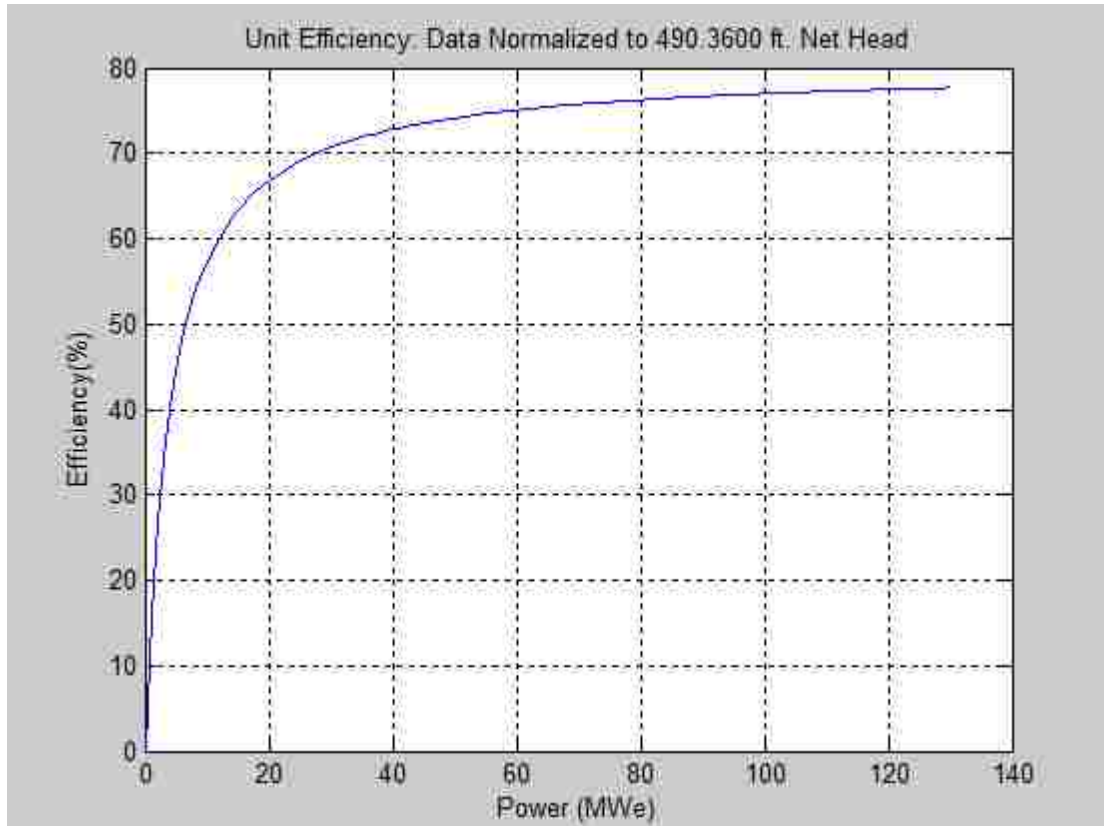


Figure 39: MATLAB[®] plot of Unit Efficiency - Data Normalized to 490.36 ft. of net head.

Table 5 demonstrates the values obtained from the SCADA software at Hoover Dam, prior to the unit overhaul. Certain values were analyzed and will be plotted in Figures 40 and 41 to compare data results pre-overhaul and post-overhaul. The parameters analyzed were: the stroke of the servo motors measured out in inches, the percent of the servo motor in an open position, the volumetric flow rate of water flow

through the unit measured out in cfs, the power generated by the unit as a result of the volumetric flow rate, the elevation of both the Forebay and Tailbay measured out in feet at the time the data was recorded, the net head parameter equals the difference between the Forebay elevation and Tailbay elevation, and lastly the units efficiency. Since the SCADA software records data values in a certain time rate, the data used was recorded when servo opening percent values were at 10, 70, 80, 90, and 100 percent. Additionally, the volumetric flow rate values and the efficiency values have been normalized to account for a net head of 490.36 ft. As mentioned previously, 490.36 ft of net head was the net head available on November 2011, when the performance tests were analyzed.

Table 5: Stabilized Readings, Prior to Unit Overhaul

Note: (The values recorded represent the data without new seal rings, without new wear plates and without any new wicket gates)

Servo Stroke (inches)	Servo Opening (percent)	Flow (cfs)	Power (MWe)	Forebay El. (ft.)	Tailbay El. (ft.)	Net Head El. (ft.)	Efficiency (percent)
1.25	10	336.68	1.4629	1138.5	643.37	495.12	10.482
8.75	70	2385	85.406	1138.5	643.66	494.83	86.387
10	80	2713.6	99.458	1138.5	644.01	494.48	88.418
11.25	90	3054.4	111.94	1138.5	644.36	494.13	88.41
12.5	98.9	3299.2	119.62	1138.5	645.2	493.28	87.466

Table 6 demonstrates the values obtained from the SCADA software at Hoover Dam, after the unit overhaul. Certain values were analyzed and were plotted in Figures 40 and 41 to compare results, pre-overhaul and post-overhaul. The parameters analyzed were: the stroke of the servo motors measured out in inches, the percent of the servo

motor in an open position, the volumetric flow rate of water flow through the unit measured out in cfs, the power generated by the unit as a result of the volumetric flow rate, the elevation of both the Forebay and Tailbay measured out in feet at the time the data was recorded, the net head parameter equals the difference between the Forebay elevation and Tailbay elevation, and lastly the units efficiency. Since the SCADA software records data values in a certain time rate, the data used was recorded when servo opening percent values were at 10, 70, 80, 90, and 100 percent. Additionally, the volumetric flow rate values and the efficiency values were normalized to account for a net head of 490.36 ft.

Table 6: Stabilized Readings, After Unit Overhaul

Note: (The values recorded represent the data with new seal rings, with new wear plates and with new wicket gates)

Servo Stroke (inches)	Servo Opening (percent)	Flow (cfs)	Power (MWe)	Forebay El. (ft.)	Tailbay El. (ft.)	Net Head El. (ft.)	Efficiency (percent)
1.25	10	277.38	1.1926	1126.5	643.37	488.26	10.372
8.75	70	2313.8	82.828	1126.5	643.66	487.71	86.355
10	80	2650.6	97.048	1126.5	644.01	487.41	88.327
11.25	90	2994	110.07	1126.5	644.36	487.23	88.684
12.5	100	3330.2	121.12	1126.5	645.2	487.01	87.738

Figure 40 shows the pre-overhaul and post-overhaul results. Figure 39 compares the overall unit capacity data. Pre-Overhaul data is in blue and Post-Overhaul data is in red. The Volumetric Flow Rate (cfs) of the unit is plotted in the x-axis and the amount of

Power (MW_e) generated by the unit is plotted in the y-axis. In Figure 39 one can see that at a flow of 3000 cfs, after a unit's overhaul the capacity increases by around 4 MW_e .

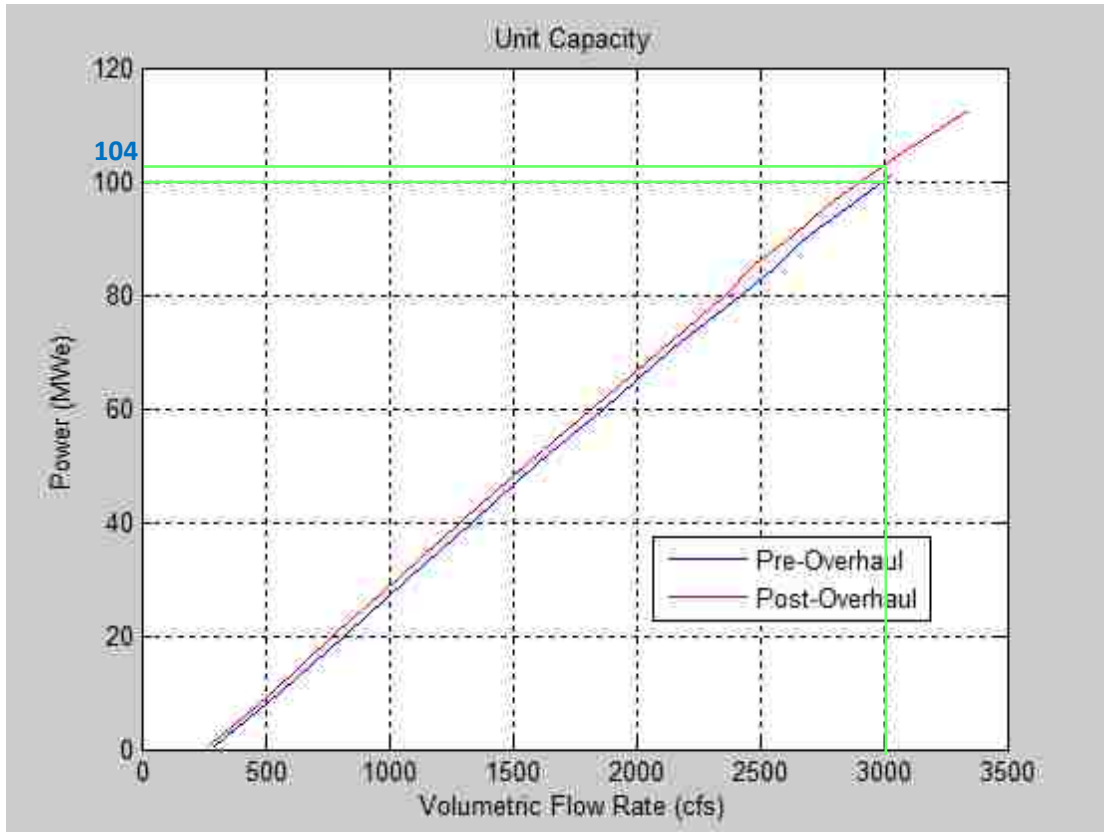


Figure 40: MATLAB[®] plot of Unit Capacity – Pre-Overhaul vs. Post-Overhaul Data.

Figure 41 compares the overall unit efficiency data. Pre-Overhaul data is in blue and Post-Overhaul data is in red. The Power (MW_e) generated by the unit is plotted in the x-axis and the unit recorded Efficiency (%) is recorded in the y-axis. In Figure 40 one can see that at 80 MW_e of power produced by the unit, after a unit's overhaul the efficiency increases by around 2%.



Figure 41: MATLAB[®] plot of Unit Efficiency – Pre-Overhaul vs. Post-Overhaul Data.

4.3 Discussion

Water is a vital resource to everyone, especially if you live out in the desert. It is extremely important to use the water efficient. At Hoover Dam, one of the main goals is to reduce water leakage in order to prevent energy from getting wasted. Capacity improvements at Hoover Dam are focused on allowing an increase in the maximum amount of water allowed to flow into the turbines at lower net heads.

As discussed in this study there are various mechanical components as well as electrical components that can be modified or alternated to improve capacity efficiency,

however, the three major components that this study focuses on are the seal rings, wear plates, and wicket gates. As water levels keep on dropping in the Colorado River, future research and analysis can be allocated in a new turbine runner design for low head operation ranges. Additionally, there are a few other mechanical and electrical components that can be modified or alternated to monitor and improve capacity efficiency.

The benefits from the increased capacity provide payback of project investments within a few years. Using a conservative wholesale market price for capacity, the value of 70 MW_e of new capacity added at Hoover Dam is an increase of approximately \$2.2 million per year in capital.

To reference back turbine overhauls include work such as modifying and replacing seal rings and wear plates to reduce high-pressure leakage of water through the wicket gate system which occurs when the hydro units are shut down. Preventing the leakage of water, results in more water available in the future to produce valuable electrical energy. The wholesale market value from reducing leakage through wicket gates at Hoover is approximately \$200,000 per unit per year.

CHAPTER 5

CONCLUSION

5.1 Findings

Modifying and replacing the three major hydro-machinery components: seal rings, wear plates, and wicket gates, improves the efficiency of Hoover Dam units by an average of 2 percent. This increases a unit's capacity by 3 percent to about 5 percent. The increase in capacity equates to an additional 8,000 MW-hrs per year per unit. The wholesale market value of this increase in energy and capacity, roughly equates to about \$290,000 per unit per year.

Engineering design, calculations, and performance test were utilized to improve the parameters of the seal rings, wear plates, and wicket gates. MATLAB[®] and MS Excel computer software was used to analyze numerical analytically results and data plots.

The goal to minimize clearances, in order to prevent water leakage, create a proper seal on the seal rings which do not let excess water flow through, thus, conserving more water and wasting less energy. Furthermore, the new wicket gates design increases the efficiency of the turbine unit due to their laminar profile and proper seal. By increasing the angle of attack by 2 degrees, and increasing the trailing edge gap by 0.02 inches, as well as stroking the servo motor arms 2.5 feet further the 2 percent increase in unit efficiency was achieved.

5.2 Suggestions

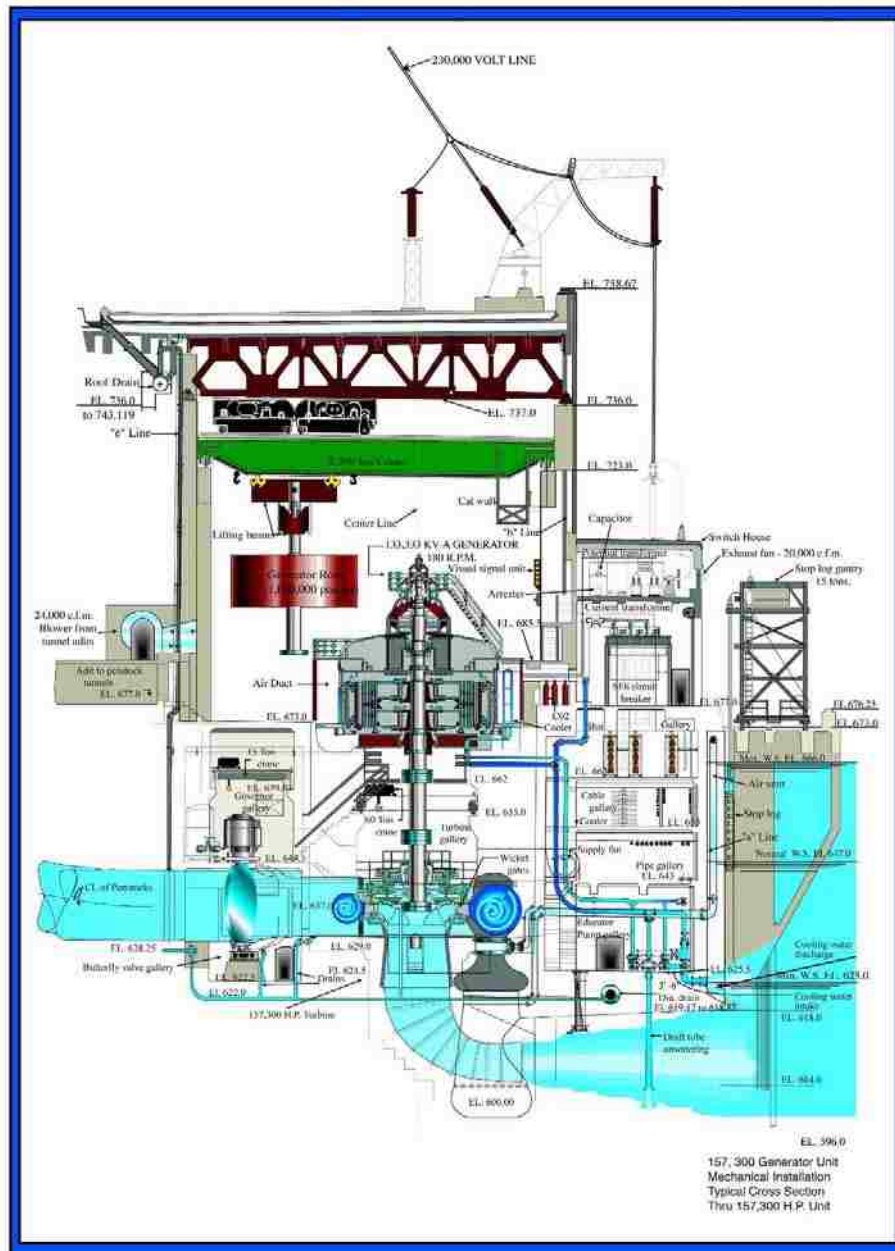
The seal rings, wear plates, and wicket gates were the three major hydro-components analyzed in this thesis. Future system analysis should examine modifications and new design of low-head turbine runners. As water levels keep on dropping in the Colorado River, future research and analysis can be allocated in a new turbine runner design for low head operation ranges. Additionally, there are a few other mechanical and electrical components that can be modified or alternated to monitor and improve capacity efficiency.

It is strongly recommended to continue with the overhaul procedures at Hoover Dam. After all, it is a great investment that will pay back by itself, and it will maintain the generating units running properly and stable for many more years of hydro power to be produced.

EXHIBITS

Exhibit 1: Figures

Exhibit E-1 shows a cut section of a typical Hoover generator unit. It shows all the different powerhouse elevations with all the major components. Exhibit E-1 shows that the generating unit is approximately 100 ft. tall.



E-1: Cross-Section of a typical Hoover Dam Generator Unit [25].

APPENDICES

Appendix A: Glossary (Principles of Hydro-Electric Power)

A-1: Utility Definitions

<i>Base Load</i>	The minimum load over a given period of time.
<i>Capability</i>	"The maximum load which a machine, apparatus, station, or system can carry under specified conditions for a given time interval.
<i>Capacity</i>	The load from which a machine, apparatus, station, or system is rated.
<i>Demand</i>	The load at the terminals of an installation or system averaged over a specified interval of time. Demand is expressed in kilowatts, kilovolt amperes or other suitable units.
<i>Energy</i>	That which does or is capable of doing work. It is measured in terms of the work it is capable of doing; electric energy is usually measured in kilowatt-hours.
<i>Load Factor</i>	The ratio of the average load over a designated period to the peak load occurring in that period.
<i>Off-Peak Energy</i>	Electric energy supplied during periods of relatively low system demands as specified by the supplier.
<i>On-Peak Energy</i>	Electric energy supplied during periods of relatively high system demands as specified by the supplier.
<i>Peaking Capacity</i>	Generating capacity available to assist in meeting that portion of peak load which is above base load.

<i>Plant Factor</i>	The ratio of the average load on the plant for the period of time considered to the aggregate rating of all the generating equipment installed in the plant.
<i>Rating</i>	Limits placed on operating conditions of a machine apparatus, or device based on its design characteristics. Such limits as load, voltage and frequency may be given in the rating.
<i>SCADA</i>	Supervisory Control and Data Acquisition (SCADA) is an industrial control computer system that monitors infrastructure, or facility-based processes.
<i>Spinning Reserve</i>	That reserve generating capacity connected to the bus and ready to take load.
<i>Station Service</i>	Auxiliary and other facilities for station use in a generating, switching, converting, or transforming station.
<i>Variable Costs</i>	Costs associated with operation or utilization of plant.

A-2: Electrical Definitions

<i>Ampere (Amp)</i>	The basic unit of current or electron flow.
<i>Base Load</i>	The minimum load over a given period of time.
<i>Battery</i>	A group of several cells connected together as a unit for furnishing electric current.
<i>Boost</i>	Raise or attempt to raise voltage.

<i>Bus</i>	A bus conductor, or group of conductors, is a switchgear assembly which serves as a common connection for three or more circuits. NOTE: The conductors of a bus are usually in the form of a bar.
<i>Collector Rings</i>	Metal rings suitably mounted on the rotating member of an electric machine, serving through stationary brushes bearing thereon, to conduct current into or out of the rotating member.
<i>Current Transformer</i>	A small transformer for measuring heavy currents in power leads. The primary is in series with the power lead and full rated current in the primary gives 5 amps in the secondary. (Never open the secondary circuit of a current transformer when the primary is energized.)
<i>Efficiency</i>	The ratio of output to input power, generally expressed as a percentage.
<i>Electric Generator</i>	A machine which transforms mechanical power into electrical power.
<i>Electric Motor</i>	A machine which transforms electric energy into mechanical energy.
<i>Exciter</i>	An auxiliary DC generator which supplies energy for the field excitation of another electric machine.
<i>Frequency (F)</i>	The number of complete cycles per second existing in any form of wave motion; such as the number of cycles per second of an alternating current. See Hertz.
<i>Generating Station</i>	A plant wherein electric energy is produced from some form of energy (e.g. chemical, mechanical, or hydraulic) by means of suitable apparatus.

<i>Generator</i>	A machine that converts mechanical energy into electrical energy.
<i>Ground Bus</i>	A bus used to connect a number of grounding conductors to one or more grounding electrodes.
<i>Ground Current</i>	Any current flowing in the earth.
<i>Grounding Switch</i>	A form of air switch by means of which a circuit or a piece of apparatus may be connected to ground.
<i>Hertz</i>	Replaces cycle as the basic unit of frequency.
<i>High Voltage</i>	Above 600 volts.
<i>Hot</i>	Energized electrically referring to pieces of electrical equipment, buses or lines.
<i>House Turbine</i>	A turbine installed to provide a source of auxiliary power.
<i>Kilowatt Hour (kW-hr)</i>	A unit of energy equal to 1000 watthours.
<i>Lag</i>	The amount one wave is behind another in time; expressed in electrical degrees.
<i>Lead</i>	The opposite of lag. Also, a wire or connection.
<i>Load</i>	The impedance to which energy is being supplied.
<i>Megawatt (MW)</i>	One million watts.
<i>Pole</i>	One of the ends of a magnet where most of its magnetism is concentrated.

<i>Power</i>	The rate of doing work or the rate of expending energy. The unit of electrical power is the watt.
<i>Rotor</i>	The rotating member of a machine.
<i>Solenoid</i>	An electric conductor wound as a helix with a small pitch, or as two or more coaxial helices.
<i>Spinning Reserve</i>	That reserve generating capacity connected to the system and ready to take load.
<i>Static</i>	A fixed nonvarying condition; without motion.
<i>Static Electricity</i>	A stationary charge of electricity.
<i>Stator</i>	The part of a machine which contains the stationary parts of the magnetic circuit with their associated windings.
<i>Transformer</i>	An electric device which by electromagnetic induction transforms electric energy from one or more circuits to one or more other circuits at the same frequency, usually with changed values of voltage and current.
<i>Trip</i>	An accessory or the act of divorcing a piece of equipment from its source of energy.
<i>Var</i>	Reactive volt-amperes.
<i>Volt</i>	The unit of electromotive force.
<i>Watt</i>	A unit of electric power produced by a current of one ampere at one volt.

<i>Watt-Hour</i>	A unit of electrical energy equal to one watt of power acting for one hour.
A-3: Mechanical Definitions	
<i>Accumulator</i>	A pressure vessel divided into two chambers by means of a rubber diaphragm, having a liquid stored under pressure in one chamber and nitrogen gas in the other.
<i>Bearing</i>	A bushing, sleeve, box, or shell within which the shaft rotates.
<i>Cavitation</i>	Vaporization of fluids due to pressure loss which forms vapor pockets, and upon collapse, produces vibrations, noise, and destruction of the surrounding walls.
<i>Draft Tube</i>	An airtight pipe or channel extending downward into the tailrace from a turbine wheel located above it, to make the whole fall available.
<i>Efficiency</i>	The ratio of the useful work output of a machine to the total work input.
<i>Energy</i>	The capacity of a body to do work.
<i>Foot Pound</i>	The English unit of work and energy.
<i>Horsepower</i>	The English unit of power, equal to work done at the rate of 550 footpounds per second or 33,000 foot-pounds per minute.
<i>Hydromotor</i>	A liquid operated mechanism by which hydraulic forces are converted into mechanical energy. Such motors are used as valve operators, etc.
<i>Labyrinth Seal</i>	Device for restricting leakage along a turbine shaft.

<i>Lantern Ring</i>	An open metal ring between rings of packing in a stuffing box used to admit a sealing or lubricating fluid.
<i>Power</i>	The amount of work done in a given interval of time.
<i>Rotor</i>	The rotating member of a machine.
<i>Servomotor</i>	A mechanism controlled by governor oil to operate inlet valves on a turbine.
<i>Stop Log</i>	One of a set of timber pieces, usually square, which serve to form a dam to check the flow of water.
<i>Trip</i>	An accessory or the act of divorcing a piece of equipment from its source of energy.
<i>Venturi</i>	A primary device used for establishing, pressure differentials used in the measurement of flow through pipes.

Appendix B: MATLAB® Coding

B-1: Baseline Calculation MATLAB® Coding

```
%% Variables for Baseline Calculations

% Pressure
River_Elevation=634.91; %Elevation of Mohave River (ft). As of 11/28/11
%                               OPS Daily Operating Report

Lake_Elevation=1125.27; %Elevation of Lake Mead in (ft). As of 11/28/11
%                               OPS Daily Operating Report

Head=Lake_Elevation-River_Elevation; %Head of Water Elevation (ft).
%                               Head=490.3600 (ft).

z=(1/2.307)*Head; %Pressure coming into the system (psi)
%                               Note:(1/2.307) is conversion factor
%                               from ft. to psi.
%                               z=212.5531 (psi)

% Gravity Constant
gravity_EE=32.2; %(ft/s^2)

% Water Parameters
H20_density=62.4; %Density of Water (lb/ft^3)
H20_temperature=60; %Temperature of water (deg. F)
H20_mass=62.4; %Pounds in a cubic feet.
H20_volume=1; %Volume is accounted for a ft^3.

% Mass flow-in and Volumetric Flow Rate-in
H20_volumetricflowrate_in=12042; %Hoover Dam Water Intake (cfs).
%                               OPS Daily Operating Report.
%                               Based on 5.4 Million gpm.
%                               Multiply 5.4 Million gpm by 0.00223
%                               to get cfs.

mdot_in=H20_density*H20_volumetricflowrate_in; %(lb/s)

% Mass flow-out and Volumetric Flow Rate-in
H20_volumetricflowrate_out=9341; %Hoover Dam Water Release (cfs). As of
%                               11/28/11, OPS Daily Operating Report
mdot_out=H20_density*H20_volumetricflowrate_out; %(lb/s)

% Change in Mass flow rate and Change in Volumetric Flow Rate
mdot=mdot_in-mdot_out; %(lb/s)
H20_volumetricflowrate_cfs=H20_volumetricflowrate_in-
H20_volumetricflowrate_out; %(cfs)
```

```

% Unit Conversion Factors
hp_ftlbsec=550; % Horsepower in (ft.-lbf)/sec)
hp_kW=0.7457; % Horsepower in (kW)
kW=0.001; % Megawatts (MW)
MW=1000; % kilowatts (kW)

% Hydro-Power Calculation

% Power: MW = efficiency[(Q,cfs)*(Head, ft)*(H2O density,lbf/ft^2)
% *(((1 hp)/(550 ft-lb/sec))*(((0.7457 kW)/(1 hp))))
% *(((1 MW)/(1000 kW)))]

Power_Produced=124*MW;
Power_Capacity=130*MW;
efficiency=(Power_Produced)/(Power_Capacity)
% efficiency=0.9538;

Power_MW=(efficiency)*(H2O_volumetricflowrate_in*Head*H2O_density*(1/hp
_ftlbsec)*(hp_kW)*(kW));

% Unit Capacity: Power(MW) vs. Flow (cfs)[Per unit]
% z=212.5531 psi

cfs_perunit=[100:25:3350];
Power_MW_perunit=[0:1:130];
cfstoMW=H2O_volumetricflowrate_in*H2O_density*Head*(1/hp_ftlbsec)*(hp_k
W)*(kW);

% Unit Efficiency: Efficiency (%) vs. Flow (cfs)[Per unit]
% z=212.5531 psi

cfstoMW_plot=cfs_perunit*(H2O_volumetricflowrate_in*Head*H2O_density*(1
/hp_ftlbsec)*(hp_kW)*(kW))*(1/1000000);
efficiency_plot=(Power_MW_perunit./cfstoMW_plot);

%% Plots

% Plot of Unit Capacity (Data Normalized to 490.3600 ft. Net Head)
figure (1)
plot(cfs_perunit,Power_MW_perunit); grid
title('Unit Capacity: Data Normalized to 490.3600 ft. Net Head')
xlabel('Volumetric Flow Rate (cfs)'); ylabel('Power (MWe)');

% Plot of Unit Efficiency (Data Normalized to 490.3600 ft. Net Head)
figure (2)
plot(Power_MW_perunit,efficiency_plot); grid
title('Unit Efficiency: Data Normalized to 490.3600 ft. Net Head')
xlabel('Power (MWe)'); ylabel('Efficiency(%)');

```

```

%% Balance Equations Variables

% Gravity Constant
g_EE=gravity_EE;    %32.2 (ft/s^2)

% Water Temperature
T=H20_temperature;    %T=60 deg. F

% Kinetic Energy (ft-lb)
KE_ftlb=(1/2)*H20_mass*velocity^2;    %(ft-lb), Mass is accounted for a
%                                     ft^3 which is 62.4 lbs.
% KE=455.5531 (ft-lb)

% Potential Energy (ft-lb)
PE_ftlb=H20_mass*gravity_EE*Head;
%PE_ftlb=9.8527e+005

% Heat Transfer on System
Q=0; %Adiabatic process, no heat transfer

% Mass Balance, mdot(in)=mdot(out)
mdot=mdot_in-mdot_out;    %(lb/s)
% mdot=1.6854e+005    %(lb/s)

% Energy Balance, (d=DELTA) dKE+dPE+dU=Q-W (English)
W_ftlb=KE_ftlb+PE_ftlb+U_ftlb;    %(ft-lb)
% W_ftlb=1.9715e+006    %(ft-lb)

```

B-2: Exergy and Parametric Study MATLAB® Coding

```

clear all
clc
format bank

%% Baseline

Power_MW_max=130;
W_dotMW_max=Power_MW_max;    %MW
kW1=1000;% 1000 kW in 1 MW
W_dotBTUsec=(W_dotMW_max*kW1)*(3413/1)*(1/3600)    %BTU/sec
W_dot=W_dotBTUsec;
Q=3100;    %cfs
ro=62.4;    %lb/ft^3
m_dot=ro*Q    %lbm/s
ft2s2_btusec=4e-5;    %BTU/s
g=32.2;    %ft/s^2
To=60;    % deg. F
To_R=To+460;    % deg. R
lbmsec_btusec=(m_dot)*(1/32.714)*(1/1.285e-3)*g;    %BTU/s
d1=30;    %30 ft pipe section at control volume inlet
d2=12;    %12 ft pipe section at control volume outlet
A1=(pi*d1^2)/4;    %Area of state 1
A2=(pi*d2^2)/4;    %Area of state 2
V1=Q/A1;    %ft/s
V2=Q/A2;    %ft/s

```

```

z1=1125.27; %ft
z2=634.91;
z=z1-z2; %ft
hp_ftlbsec=550; % Horsepower in [(ft.-lbf)/(sec)]
hp_kW=0.7457; % Horsepower in (kW)
kW=0.001; % Megawatts (MW)
MW=1000; % kilowatts (kW)

%% Data Calculation

% Solving for exergy destruction STATE 1 to STATE 3
% Ed_dot=W_dot-((m_dot)*((0.5*(V1^2-V2^2)*(1/25026.84158))-((m_dot*4e-
5)*g*(z1-z3)*(1/25026.84158))))
Ed_dot=W_dot-(m_dot*(((V1^2-
V2^2)/(2))*ft2s2_btusec))+((g)*(z))*ft2s2_btusec)) % (Btu/sec)

% Solving for system irreversibilities
sigma_cv=(Ed_dot/To_R) % (Btu/sec-deg. R)

% Solving for exergetic turbine efficiency
turbine_exergetic_efficiency=((W_dot)/(m_dot))/(((W_dot)/(m_dot))+((Ed
_dot)/(m_dot))))*100

% Solving for energy coming in to the system
energyin=m_dot*(((V1^2-
V2^2)/(2))*ft2s2_btusec))+((g)*(z))*ft2s2_btusec))

% Solving for power produced
Power_MW_produced=(turbine_exergetic_efficiency/100)*(Q*z*ro*(1/hp_ftlb
sec)*(hp_kW)*(kW));
W_dotMW_produced=Power_MW_produced;

% Solving for unit efficiency taken into account max capacity and power
produced
unit_efficiency=((W_dotMW_produced)/(W_dotMW_max))*100;

%% Post-Overhaul
table=[Q,m_dot,V1,V2,z1,z2,z,turbine_exergetic_efficiency,Power_MW_prod
uced,Power_MW_max,unit_efficiency];
%% Table

disp('
Table 5: Exergy Analysis Parametric Study Results')
fprintf('\n')
fprintf('\n')
disp('Volumetric Flow Rate    Mass Flow Rate    Velocity S1    Velocity
S2    Forebay El.    Tailbay El.    Net Head El.    Exergetic
Efficiency    Power Produced    Power Max Capacity    Unit Efficiency')

```



```

disp('          (cfs)                (lbm/s)                (ft/s)                (ft/s)
(ft.)          (ft.)                (ft.)                (percent)
(MWe)          (MWe)                (percent)')
fprintf('\n')
fprintf('          %4.2f                %8.2f                %4.2f                %4.2f
%4.2f          %4.2f                %3.2f                %3.2f                %2.3f
%2.2f          %2.2f                %2.3f',table)
fprintf('\n\n')

```

B-3: Seal Ring Calculation MATLAB® Coding

```

%% UNIT CALCULATION FOR UPPER AND LOWER ROTATING SEAL RINGS
%% UNIT CALCULATION GENERAL DATA VALUES

E=2.62e+007; % Young's Modulus (psi)

S_ut=111000; % Ultimate Tensile Strength (psi)

S_y=60000; % Yield Strength (psi)

rho=0.2754; % Density (lbm/in^3)

alpha=8.80e-006; % Temperature Range @ 75 to 200 deg. F (in/in/deg. F)

mu_s=0.7; % Co-efficient of Static friction (in/in/deg.F)

X_seal=0.04; % Seal design clearance - Radial (in.)

sigma_max=10000; % Maximum Allowable Stress (psi)

N_o=340; % Runaway Speed (rpm)

%% UNIT VARIABLES FOR UPPER ROTATING SEAL RING

%Data

OD_runner_upper=; % Outside Diameter of Runner (in)

OD_runnertongue_upper=; % Outside Diameter of Runner Tongue
% Grove (in)

ID_stationary_upper=; % Inside Diameter of Stationary Ring (in)

X_tongue_upper=; % Thickness of Seal Ring Tongue

H_upper=; % Height of Seal Ring (in)

T_ambient_upper=; % Ambient Ring Temperature in Machine Shop (deg. F)

T_operation_upper=; % Average Ring Temperature in Operation (deg. F)

T_installation_upper=; % Ring Temperature for Installation (deg. F)

```

```

%Find

% Inside Diameter of Ring (in)
ID_final_upper=(OD_runner_upper).*((1-((sigma_max)./(E))));

% Inside Diameter of Ring Tongue (in)
ID_tongue_upper=(ID_final_upper)-2*(X_tongue_upper);

% Outside Diameter of Ring (in)
OD_final_upper=(ID_stationary_upper)-2*X_seal;

% Inside Diameter of Ring @ Installation Temperature (in)
ID_installation_upper=(ID_final_upper)*(1+alpha*(T_installation_upper-
T_ambient_upper));

% Clearance between the inside Diameter of RIng to the OD of Turbine @
Installation % Temperature
Delta_ID_upper=ID_installation_upper-ID_final_upper;

% Clearance between Inside Diameter of Ring Tongue to the OD of Turbine
@ % Installation Temperature
Clearance_ID_upper=(ID_installation_upper)-(2*X_tongue_upper)-
OD_runner_upper;

% Average Diameter of Ring Cross Section Installed (in)
D_c_upper=(OD_runner_upper+OD_final_upper)/2;

% Centrifugal Stress at the Runaway Speed (psi)
sigma_cf_upper=(rho*((N_o*pi*D_c_upper)/60)^2)/386;

% Factor of Safety Against Ring Separation at the Runway Speed
FS_cf_upper=(sigma_max/sigma_cf_upper);

%% UNIT VARIABLES FOR LOWER ROTATING SEAL RING

%Data

OD_runner_lower=; % Outside Diameter of Runner (in)

OD_runnertongue_lower=; % Outside Diameter of Runner Tongue
% Grove (in)

ID_stationary_lower=; % Inside Diameter of Stationary Ring
% (in)

X_tongue_lower=; % Thickness of Seal Ring Tongue

H_lower=; % Height of Seal Ring (in)

T_ambient_lower=; % Ambient Ring Temperature in Machine Shop (deg. F)

T_operation_lower=; % Average Ring Temperature in Operation (deg. F)

T_installation_lower=; % Ring Temperature for Installation (deg. F)

```

```

%Find

% Inside Diameter of Ring (in)
ID_final_lower=(OD_runner_lower).*((1-((sigma_max)./(E))));

% Inside Diamter of Ring Tongue (in)
ID_tongue_lower=(ID_final_lower)-2*(X_tongue_lower);

% Outside Diameter of Ring (in)
OD_final_lower=(ID_stationary_lower)-2*X_seal;

% Inside Diameter of Ring @ Installation Temperature (in)
ID_installation_lower=(ID_final_lower)*(1+alpha*(T_installation_lower-
T_ambient_lower));

% Clearance between the inside Diameter of RIng to the OD of Turbine @
Installation % Temperature
Delta_ID_lower=ID_installation_lower-ID_final_lower

% Clearance between Inside Diameter of Ring Tongue to the OD of Turbine
@ % Installation Temperature
Clearance_ID_lower=(ID_installation_lower)-(2*X_tongue_lower)-
OD_runner_lower

% Average Diameter of Ring Cross Section Installed (in)
D_c_lower=(OD_runner_lower+OD_final_lower)/2

% Centrifugal Stress at the Runaway Speed (psi)
sigma_cf_lower=(rho*((N_o*pi*D_c_lower)/60)^2)/386

% Factor of Safety Against Ring Seperation at the Runway Speed
FS_cf_lower=(sigma_max/sigma_cf_lower)

```

B-4: Pre-Overhaul and Post-Overhaul Calculation MATLAB® Coding

```
%% DATA
%% Pre-Overhaul Data

Pre_Servo_Stroke=[1.25, 8.75, 10, 11.25, 12.5];
% Servo Stroke of wicket gates measured in inches.

Pre_Servo_Percent_Open=[10, 70, 80, 90, 98.9];
% Percent of opening of Servo Stroke.

Pre_CFS=[338.31, 2396.54, 2726.75, 3069.15, 3315.20];
% Recorded amount of Flow during testing analysis.

Pre_MW=[1.47, 85.82, 99.94, 112.48, 120.20];
% Recorded amount of Power during testing analysis.

Pre_Forebay=[1138.49, 1138.49, 1138.49, 1138.49, 1138.48];
% Recorded Forebay (lake) elevation during testing analysis.

Pre_Tailbay=[643.37, 643.66, 644.01, 644.36, 645.20];
% Recorded Tailbay (river) elevation during testing analysis.

Pre_NetHead=Pre_Forebay-Pre_Tailbay;
% Recorded Net Head (lake-river) during testing analysis.

Pre_NormalizedHead=490.36;
% Data was taken prior to a Net Head elevation of 490.36 ft. therefore,
% the data has been normalized.

Pre_CFS_Normalized_Matrix=((Pre_CFS'))*sqrt(((490.36)/(Pre_NetHead')));
% Data for CFS was normalized and factored in to correct values.

Pre_CFS_Normalized_Vector=Pre_CFS_Normalized_Matrix(:,1)';
% Zeroes were deleted from CFS matrix and left only with
% desired values.

Pre_MW_Normalized_Matrix=((Pre_MW'))*sqrt(((Pre_NormalizedHead)/(Pre_NetHead')));
% Data for MW was normalized and factored in to correct values.

Pre_MW_Normalized_Vector=Pre_MW_Normalized_Matrix(:,1)';
% Zeroes were deleted from MW matrix and left only with
% desired values.

Pre_Efficiency_Factor_Matrix_11=(1/(0.00000135582.*Pre_CFS_Normalized_Vector(1,1)*62.35*Pre_NormalizedHead));
% Data for Efficiency was normalized and factored in to correct values.

Pre_Overall_Efficiency_11=Pre_Efficiency_Factor_Matrix_11*Pre_MW_Normalized_Vector(1,1);
% Efficiency of element (1,1) from Efficiency Matrix was evaluated.
```

```

Pre_Efficiency_Factor_Matrix_12=(1/(0.00000135582.*Pre_CFS_Normalized_V
ector(1,2)*62.35*Pre_NormalizedHead));
% Data for Efficiency was normalized and factored in to correct values.

Pre_Overall_Efficiency_12=Pre_Efficiency_Factor_Matrix_12*Pre_MW_Normal
ized_Vector(1,2);
% Efficiency of element (1,2) from Efficiency Matrix was evaluated.

Pre_Efficiency_Factor_Matrix_13=(1/(0.00000135582.*Pre_CFS_Normalized_V
ector(1,3)*62.35*Pre_NormalizedHead));
% Data for Efficiency was normalized and factored in to correct values.

Pre_Overall_Efficiency_13=Pre_Efficiency_Factor_Matrix_13*Pre_MW_Normal
ized_Vector(1,3);
% Efficiency of element (1,3) from Efficiency Matrix was evaluated.

Pre_Efficiency_Factor_Matrix_14=(1/(0.00000135582.*Pre_CFS_Normalized_V
ector(1,4)*62.35*Pre_NormalizedHead));
% Data for Efficiency was normalized and factored in to correct values.

Pre_Overall_Efficiency_14=Pre_Efficiency_Factor_Matrix_14*Pre_MW_Normal
ized_Vector(1,4);
% Efficiency of element (1,4) from Efficiency Matrix was evaluated.

Pre_Efficiency_Factor_Matrix_15=(1/(0.00000135582.*Pre_CFS_Normalized_V
ector(1,5)*62.35*Pre_NormalizedHead));
% Data for Efficiency was normalized and factored in to correct values.

Pre_Overall_Efficiency_15=Pre_Efficiency_Factor_Matrix_15*Pre_MW_Normal
ized_Vector(1,5);
% Efficiency of element (1,5) from Efficiency Matrix was evaluated.

Pre_Overall_Efficiency_Vector=[Pre_Overall_Efficiency_11,
Pre_Overall_Efficiency_12, Pre_Overall_Efficiency_13,
Pre_Overall_Efficiency_14, Pre_Overall_Efficiency_15];
% All the evaluated Efficiency values were put into a vector for
% simplicity.

Pre_Overall_Efficiency_Percent=100*Pre_Overall_Efficiency_Vector;
% Efficiency is converted into percent.

```

```

%% Post-Overhaul Data

Post_Servo_Stroke=[1.25, 8.75, 10, 11.25, 12.5];
% Servo Stroke of wicket gates measured in inches.

Post_Servo_Percent_Open=[10, 70, 80, 90, 100];
% Percent of opening of Servo Stroke.

Post_CFS=[276.79, 2308.89, 2644.88, 2987.60, 3323.10];
% Recorded amount of Flow during testing analysis.

Post_MW=[1.19, 82.65, 96.84, 109.83, 120.86];
% Recorded amount of Power during testing analysis.

Post_Forebay=[1126.48, 1126.48, 1126.46, 1126.47, 1126.47];
% Recorded Forebay (lake) elevation during testing analysis.

Post_Tailbay=[638.22, 638.77, 639.05, 639.24, 639.46];
% Recorded Tailbay (river) elevation during testing analysis.

Post_NetHead=Post_Forebay-Post_Tailbay;
% Recorded Net Head (lake-river) during testing analysis.

Post_NormalizedHead=490.36;
% Data was taken prior to a Net Head elevation of 490.36 ft. therefore,
% the data has been normalized.

Post_CFS_Normalized_Matrix=((Post_CFS'))*sqrt(((490.36)/(Post_NetHead')));
% Data for CFS was normalized and factored in to correct values.

Post_CFS_Normalized_Vector=Post_CFS_Normalized_Matrix(:,1)';
% Zeroes were deleted from CFS matrix and left only with
% desired values.

Post_MW_Normalized_Matrix=((Post_MW'))*sqrt(((Post_NormalizedHead)/(Post_NetHead')));
% Data for MW was normalized and factored in to correct values.

Post_MW_Normalized_Vector=Post_MW_Normalized_Matrix(:,1)';
% Zeroes were deleted from MW matrix and left only with
% desired values.

Post_Efficiency_Factor_Matrix_11=(1/(0.00000135582.*Post_CFS_Normalized_Vector(1,1)*62.35*Post_NormalizedHead));
% Data for Efficiency was normalized and factored in to correct values.

Post_Overall_Efficiency_11=Post_Efficiency_Factor_Matrix_11*Post_MW_Normalized_Vector(1,1);
% Efficiency of element (1,1) from Efficiency Matrix was evaluated.

Post_Efficiency_Factor_Matrix_12=(1/(0.00000135582.*Post_CFS_Normalized_Vector(1,2)*62.35*Post_NormalizedHead));
% Data for Efficiency was normalized and factored in to correct values.

```

```

Post_Overall_Efficiency_12=Post_Efficiency_Factor_Matrix_12*Post_MW_Nor
malized_Vector(1,2);
% Efficiency of element (1,2) from Efficiency Matrix was evaluated.

Post_Efficiency_Factor_Matrix_13=(1/(0.00000135582.*Post_CFS_Normalized
_Vector(1,3)*62.35*Post_NormalizedHead));
% Data for Efficiency was normalized and factored in to correct values.

Post_Overall_Efficiency_13=Post_Efficiency_Factor_Matrix_13*Post_MW_Nor
malized_Vector(1,3);
% Efficiency of element (1,3) from Efficiency Matrix was evaluated.

Post_Efficiency_Factor_Matrix_14=(1/(0.00000135582.*Post_CFS_Normalized
_Vector(1,4)*62.35*Post_NormalizedHead));
% Data for Efficiency was normalized and factored in to correct values.

Post_Overall_Efficiency_14=Post_Efficiency_Factor_Matrix_14*Post_MW_Nor
malized_Vector(1,4);
% Efficiency of element (1,4) from Efficiency Matrix was evaluated.

Post_Efficiency_Factor_Matrix_15=(1/(0.00000135582.*Post_CFS_Normalized
_Vector(1,5)*62.35*Post_NormalizedHead));
% Data for Efficiency was normalized and factored in to correct values.

Post_Overall_Efficiency_15=Post_Efficiency_Factor_Matrix_15*Post_MW_Nor
malized_Vector(1,5);
% Efficiency of element (1,5) from Efficiency Matrix was evaluated.

Post_Overall_Efficiency_Vector=[Post_Overall_Efficiency_11,
Post_Overall_Efficiency_12, Post_Overall_Efficiency_13,
Post_Overall_Efficiency_14, Post_Overall_Efficiency_15];
% All the evaluated Efficiency values were put into a vector for
%simplcity.

Post_Overall_Efficiency_Percent=100*Post_Overall_Efficiency_Vector;
% Efficiency is converted into percent.

```

```
%% TABLES
```

```
%% Pre-Overhaul Table
```

```
disp('Table 3: Stabilized Readings, Prior to Unit Overhaul')
disp('      Note: (The values recorded represent the data without
new seal rings, without new wear plates')
disp('      and without any new wicket gates)')
fprintf('\n')
disp('Servo Stroke      Servo Opening      Flow      Power      Forebay
El. Tailbay El. Net Head El. Efficiency')
disp(' (inches)          (percent)      (cfs)      (MWe)      (ft.)
(ft.)      (ft.)      (percent)')
fprintf('\n')
tablePre=[Pre_Servo_Stroke; Pre_Servo_Percent_Open;
Pre_CFS_Normalized_Vector; Pre_MW_Normalized_Vector; Pre_Forebay;
Pre_Tailbay; Pre_NetHead; Pre_Overall_Efficiency_Percent];
disp(tablePre')
```

```
%% Post-Overhaul Table
```

```
disp('Table 4: Stabilized Readings, After Unit Overhaul')
disp('      Note: (The values recorded represent the data with new
seal rings, with new wear plates')
disp('      and with any new wicket gates)')
fprintf('\n')
disp('Servo Stroke      Servo Opening      Flow      Power      Forebay
El. Tailbay El. Net Head El. Efficiency')
disp(' (inches)          (percent)      (cfs)      (MWe)      (ft.)
(ft.)      (ft.)      (percent)')
fprintf('\n')
tablePost=[Post_Servo_Stroke; Post_Servo_Percent_Open;
Post_CFS_Normalized_Vector; Post_MW_Normalized_Vector; Post_Forebay;
Pre_Tailbay; Post_NetHead; Post_Overall_Efficiency_Percent];
disp(tablePost')
```



```

%% DATA FOR PLOTS (PRE-OVERHAUL vs. POST-OVERHAUL)

prex_capacity=[293.5543869, 563.994155, 824.9794444, 1078.877906,
1342.327087, 1604.030412, 1870.696168, 2142.474334, 2431.724913,
2556.818498, 2670.594957, 2850.743578, 3037.321823];
prey_capacity=[0.5, 9.865, 20.0025, 29.884375, 40.08875, 50.396875,
59.755625, 70.19625, 80.13687375, 84.87749938, 89.59999938,
95.28249813, 101.159375];
postx_capacity=[272, 517, 777, 1043, 1291, 1558, 2090, 2362, 2483,
2636, 2767, 2912, 3074, 3341];
posty_capacity=[0.54, 9.66, 20.07, 30.26, 40.32, 50.41, 69.84, 79.85,
85.5, 90.41, 95.52, 100.24, 105.16, 112.6];

prex_efficiency=[9.865, 20.0025, 29.884375, 40.08875, 50.396875,
59.755625, 70.19625, 80.13687375, 84.87749938, 89.59999938,
95.28249813, 101.159375];
prey_efficiency=[46.68262709, 64.71496054, 73.95545156, 79.77233298,
83.9555221, 85.39943515, 87.64979257, 88.19142979, 88.87155098,
89.79701207, 89.40520469, 89.03212675];
postx_efficiency=[0.54, 9.66, 20.07, 30.26, 40.32, 50.41, 69.84, 79.85,
85.5, 90.41, 95.52, 100.24, 105.16, 112.60];
posty_efficiency=[5.263913101, 49.52164837, 68.44893436, 76.8699843,
82.72744976, 85.68740759, 88.49840352, 89.51676923, 91.12266174,
90.82384784, 91.35899871, 91.14437454, 90.5626378, 89.20243704];

%% PLOTS (PRE-OVERHAUL vs. POST-OVERHAUL)

% Unit Capacity: Pre-Overhaul vs. Post-Overhaul Plot
figure (3)
plot(prex_capacity,prey_capacity,'-b',postx_capacity,posty_capacity,'-
r'); grid
legend('Pre-Overhaul','Post-Overhaul',0)
title('Unit Capacity')
xlabel('Volumetric Flow Rate (cfs)'); ylabel('Power (MWe)');
axis(0,3500,0,130)

% Unit Efficiency: Pre-Overhaul vs. Post-Overhaul Plot
figure (4)
plot(prex_efficiency,prey_efficiency,'-
b',postx_efficiency,posty_efficiency,'-r'); grid
legend('Pre-Overhaul','Post-Overhaul',0)
title('Unit Efficiency')
xlabel('Power (MWe)'); ylabel('Efficiency (%)');

```

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Improving Efficiency and Capacity of Hydro-Turbines in the Western United States,
Hoover Dam

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