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Micro Hydroelectric Power Generation

An Undergraduate Honors College Thesis

in the

Department of Chemical Engineering
College of Engineering
University of Arkansas
Fayetteville, AR

by

Roberto Arraya

4/29/2012

This thesis is approved.

Thesis Advisor:

Dr. R. C. Penney 4/24/12

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Dr. William Roy Penney

Thesis Committee:

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DESCRIPTION OF INDIVIDUAL CONTRIBUTIONS Roberto Arraya

The WERC CREW team was comprised of 4 members. The project consisted of building a lab-scale experiment that adequately demonstrated that power could be generated given the amount of head and flow available from a major wastewater user in NM. The project also consisted of making a presentation to a panel of judges, creating a pamphlet to distribute to judges and people interested in learning about the project, and making a poster presentation to demonstrate the bench-scale unit.

Although the project would not have come to fruition without the contribution of all 4 members, each individual had to be self-motivated and support the team individually. My individual contributions were the following:

1) Performed the preliminary calculations using GoogleEarth© of the basin located in the NM Intel plant to determine the level drop required to maintain adequate surge.

2) Investigated different possible incentives that could aid the economics of implementing this project. These included federal, state and local incentives. However, only one incentive was discovered. The incentive allows for the local utility to purchase electrical power at $0.12/kWhr. This enabled the project to show economic promise.

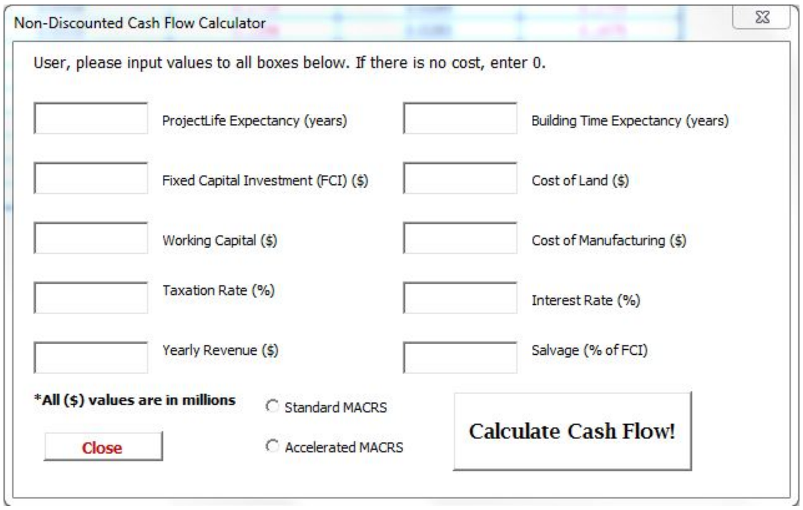
3) Determined the revenues involved with producing power for both scenarios.

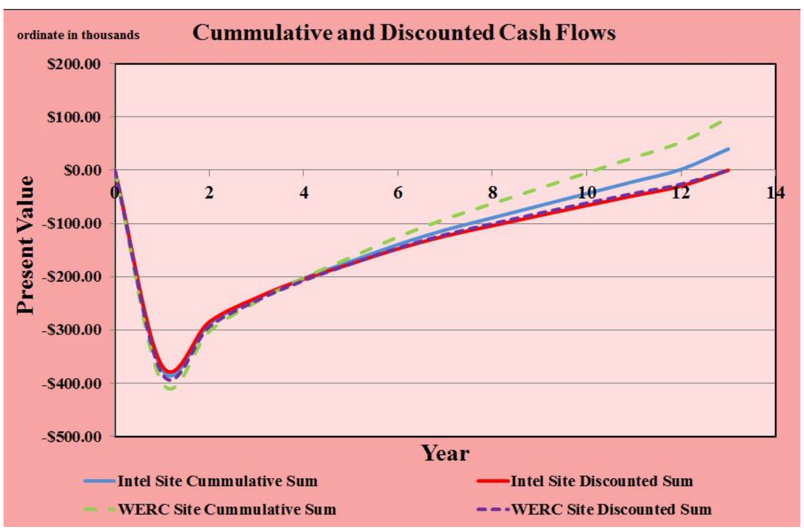
Revenue Estimations

Revenue	Head (ft)	Power Output (kW)	Unit Price for Electricity ($/kWhr)	Operating time (hrs/year)	Revenue ($/year)
WERC Task premises	150	43.54	0.12	8500	44,412
Surrogate Location	120	34.32	0.12	8500	35,011

4) Constructed the power generation unit while the other team members built the efficiency measuring unit. This included cutting the wood, painting and screwing it together, connecting the circuitry for the light display, placing the pillow block bearings and designing the Plexiglas encasing.

5) Built a VBA excel worksheet that performed the entire economic analysis and cash flow for any scenario. With this sheet, I was able to determine all the required information needed to perform a proper cash flow analysis. The sheet automatically created a tabulated cash flow and a diagram of the cash flow involved given the economic parameters. The cash flow also included the ability to use a standard MACRS or an aggressive MACRS to improve economic profitability.





6) Researched all the regulations (federal, state, local) involved with implementation of this project. This meant reading through tax codes, plumbing codes, and safe-water prevention regulations for NM.

7) The poster and presentation were a team effort. However, the pamphlet was made by two team members including myself. The pamphlet was a great success and helped people follow the overall scope of the project by excluding extraneous information.

APPENDIX

Micro-Hydroelectric Power Generation

TASK # 6

WERC Creating Renewable Energy from Wastewater
CREW

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

A major industrial water user in New Mexico discharges approximately 3.8 million gal of wastewater per day. The topology of the site provides an elevation difference of about 150 ft between the plant site and the entrance to the municipal sewage line; this flow and elevation difference is sufficient to produce about 40 kW of electrical power using a water turbine/electrical generator set to extract power from the flowing stream.

This report includes designs and economic analyses for two distinct cases. One case is based on the written premises of the task; whereas, a second case is based on a real surrogate site, which is Intel's Rio Rancho (near Albuquerque, NM) plant, which does discharge about 3.8 million gal per day and has about 120 ft of head available for power generation.

After analyzing several turbine technologies, the Pelton wheel turbine was determined to be the most economical means for generating commercial electrical power. Pelton Wheel turbines operate most efficiently with a constant head and flow. Because the wastewater discharge for the task varies from 0.5 – 4 MM gal/day, an integrated study of the flow fluctuations determined that a surge tank of 27,000 gal was required to maintain a steady flow as input to the turbine. The task premises did not include any existing storage for the discharge stream; consequently, a 27,000 gal surge tank was provided for the task premises site. The surrogate site has a surge basin with a surface area of 17,000 ft^2. This surface area requires only a 3 in level change to accommodate 27,000 gal of surge; consequently, no surge tank was included in the surrogate site case.

The surge provides the turbine with a steady flow of 2,400 gpm and a constant head of 120 ft. The purchased turbine system selected by CREW has an overall (mechanical + electrical) efficiency of 68%. For the task premises scenario, 40 kW is produced, and for the surrogate site scenario, 30 kW is produced.

The economic analysis provides the following tabular results:

Summary	Fixed Capital Investment	Working Capital	Yearly Revenue	IROR (%)	Simple Payout (years)
WERC Task premises	**$381,902**	**$16,676**	**$44,412**	**4.3**	**8.6**
Surrogate Location	**$358,826**	**$15,590**	**$35,011**	**2.0**	**10.2**

The WERC task premises case is most economical with an IROR of 4.3%. This return is marginal for earnings projects under normal circumstances. However, interest rates are now at historically lower levels, and are projected to remain low for several years. The surrogate location IROR is about 2.0%, which is considered as a reasonable return for a minimal risk project with today's economic environment. This energy recovery initiative is a "Green" project, which inherently lowers the acceptable IROR for environmentally conscious industries.

This project will require about 12 months to complete once funds are available.

INTRODUCTION

As energy costs continue to rise, the CO_2 level in the atmosphere continues to increase, and the World's fossil fuels are depleted, reliable new sources of energy will be needed. Hydroelectric power generation is a clean, effective means of generating "green" renewable energy that will continue to be a viable supplement to energy demands long into the future. Any environmentally friendly hydroelectric possibility must be exploited to the maximum. Task 6 addresses the use of hydroelectric power in the most environmentally friendly manner by producing electricity utilizing a high efficiency Pelton Wheel turbine and generator.

In 1870, Lester Allan Pelton[1] revolutionized hydroelectric power with the invention of the Pelton Wheel, a high efficiency turbine that converts momentum of a water jet stream to mechanical power and, through an electrical generator, electricity. Pelton Wheels operate by passing a working fluid through a nozzle, which converts pressure energy to kinetic energy. The kinetic energy of the fluid is then converted to mechanical work by impingement of the fluid jet upon the buckets of the Pelton Wheel. The Pelton Wheel drives a rotating shaft, which is connected to the drive shaft of an electric generator. The speed of the Pelton Wheel, at optimum efficiency, operates at a peripheral bucket velocity of ½ the nozzle velocity[1, 12]; at this optimum condition, the fluid leaves the bucket with minimal velocity.

DESIGN CONSIDERATIONS FOR TASK 6

The design considerations are to:

1. Design a flexible, scalable system using appropriate sponsor input.
2. Address the efficiencies of the hydraulic turbine and the electrical generator.
3. Generate at least 5–15 kW (20–40 is more reasonable) of electric power.
4. Designs were requested for 10–200 ft of head and ½–4 MM gal/day of hydraulic load; however, with adequate surge, head and flow are constant at 150 ft and 3.8 MM gal/day.

5. Include an economic analysis which provides proof that the project is economical.
    a. The task sponsors specified a 5 year project life. However, to receive full benefits of government subsidies, the project life must be 12 years; thus the assumed project life is 12 years.
6. One design consideration for the project was "Ability to handle solid waste"; this was interpreted to mean 'handling dissolved solids and readily suspendible particulates.'
7. Provide a time-line, from construction to full operation, for the proposed project.
8. Discuss the risks, safety and legal, associated with the design and implementation of the project.

HYDROELECTRIC POWER GENERATION

After surveying the literature and consulting with experts in the field of hydroelectric power generation, a wide variety of turbine/generator combinations were identified that could possibly accommodate the conditions required for this design.

Turbine Technologies

Micro-hydroelectric turbine technologies, for the purposes of this report, refer to any turbine/generator system producing less than 100 kW. Technologies considered for implementation included: Gorlov helical turbines, gravitational water vortex turbines, Francis-Kaplan turbines, and Pelton Wheel turbines.

Figure 1 – Gorlov Turbines[3]

Gorlov turbines (Fig. 1) are helical bladed turbines that are primarily used in large volume, low head situations, such as a river where a dam is not a viable option. The Gorlov turbine is typically used with large free flowing water sources. Gorlov turbines were rejected for this approach primarily because of the low efficiency (≈ 35%) which is well below the effectiveness of other micro-hydroelectric power generation methods.[2] In addition, the geometry of Gorlov turbines does not fit the inlet and outlet pipe geometry of Task 6.

Figure 2 – Vortex Power Generation[4]

Gravitational water vortex turbines (Fig. 2) are a micro-hydroelectric technology used at low heads (2.5-10 ft). They create a swirling vortex that is used to drive an impeller. They were rejected primarily because of their inability to effectively handle the high heads (115-150 ft) and inlet and outlet piping particular to this task.[4]

Francis—Kaplan turbines (Fig. 3), are commonly used in hydroelectric power generation. "*Reaction turbines run fully immersed in water, and are typically used in low-head (pressure) systems with high flow*".[5] As the fluid passes through the turbine, the fluid transfers energy to the turbine blades, creating angular momentum that rotates a central shaft and generates electricity. Francis—Kaplan turbines are highly efficient (up to 90%), can be used at high and low heads, 30–2,100 ft, and are capable of handling high flow rates. These characteristics make the Francis—Kaplan turbines an excellent choice for hydroelectric power generation.[5]

Figure 3 – Francis-Kaplan Turbine[6]

Pelton Wheel turbines (Fig. 4) are impulse turbines that "*operate in air, driven by one or more high-velocity jets of water. Impulse turbines are typically used with high-head systems and use nozzles to produce the high-velocity jets*".[1] The momentum of the fluid is then captured and converted to power by a series of precisely designed buckets connected to a rotating shaft. Pelton Wheel turbines are second to the Francis-Kaplan turbines in efficiency (80-90%) and are ideal for systems with low flow rates and high heads.[7]

Figure 4 – Pelton Wheel Turbine[8]

After consulting with experts in the field of hydroelectricity, the Pelton Wheel was chosen as the preferred technology. Although the Francis—Kaplan turbine is an efficient solution that meets the demands of the project, Francis turbines are more typically used in large scale operations, such as dams. The relatively small size of the turbine for this project (40 kW) makes the Pelton Wheel the most efficient and economically viable solution for the project.

Electricity Transmission Technologies

Electricity transmission, either single or three-phase, is another design aspect of the project. The Pelton Wheel system selected for this project generates electricity via three-phase power generation. Since three-phase current is the most efficient means of transmission[9] and the electricity grid of the power company is three-phase, three-phase transmission was selected. A phase-lock loop system was selected and included in the project to align the phases of the generated power with the power of the electrical utility.

BENCH SCALE APPARATUS

Experimental Apparatus

The bench scale apparatus consisted of two independent systems mounted on a 32 in by 96 in pressboard table, which was supported by two plastic sawhorses. Figure 5 shows a Process Flow Schematic (PFS) of the experimental apparatus.

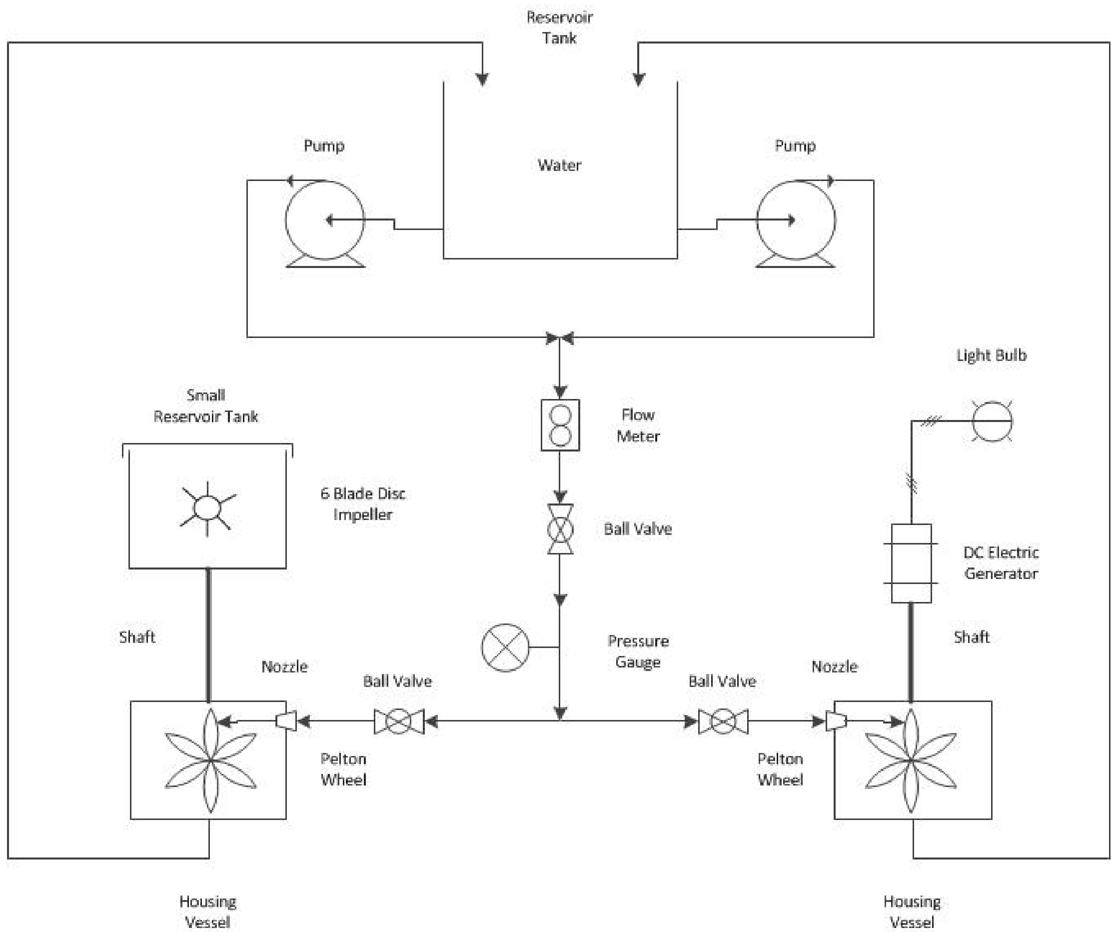

Figure 5. Bench Scale PFS

Figures 6 and 7 show the power measurement and the electrical generation portions of the bench scale apparatus, respectively.

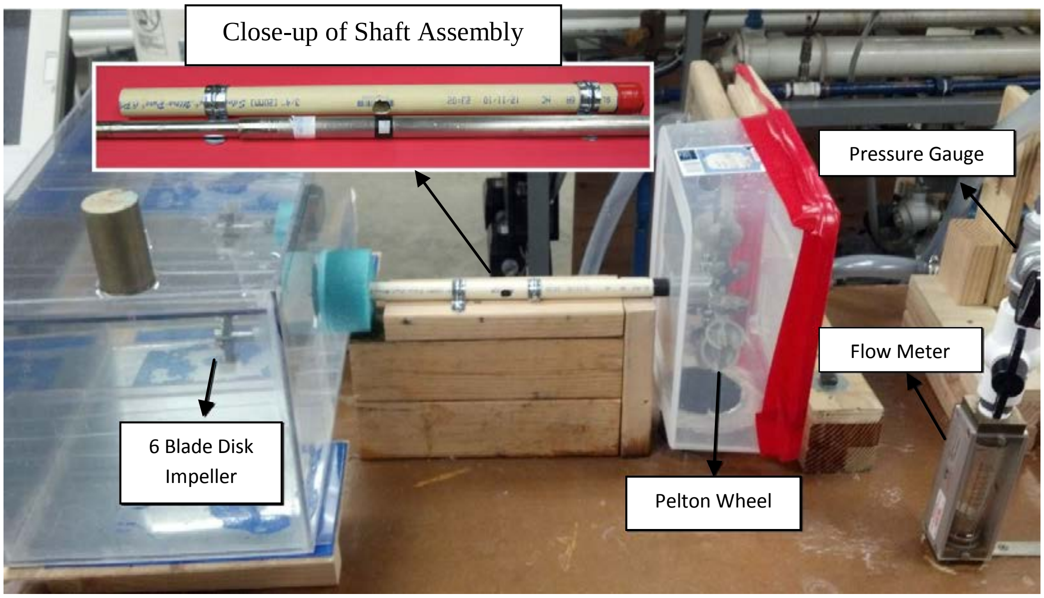

Figure 6. Power Measuring Unit

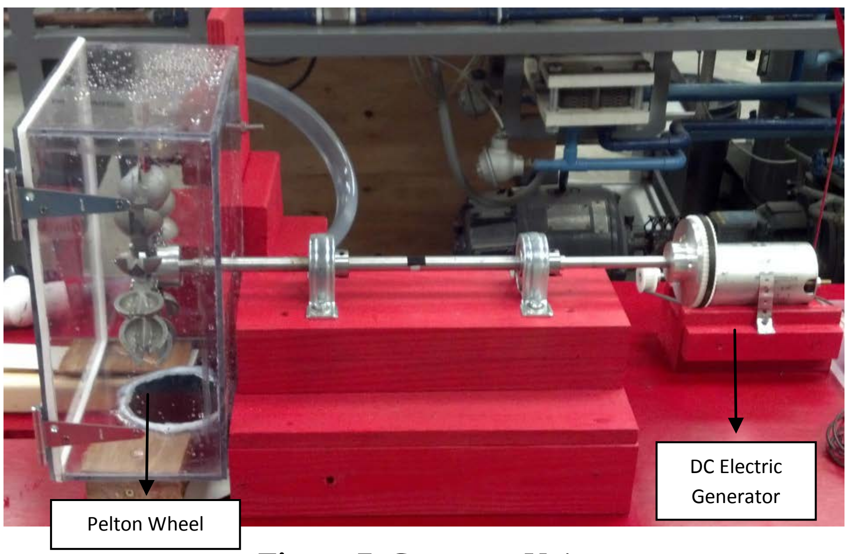

Figure 7. Generator Unit.

A 40 gal reservoir (beneath the table) provided feed for two, in parallel-centrifugal pumps (16 gpm at 10 ft head) which moved the fluid through a 15 gpm rotameter, then through a restriction valve, past a pressure gauge, and through a nozzle. These components were used to control and measure the flow and measure the nozzle inlet pressure. Downstream of the pressure gauge the flow was split, by a tee and two ball valves, so either system could be operated.

Power Measurement

The 8 in Pelton Wheel was attached to a 3 ¼ in diameter 6 blade disk impeller, which was submerged in a water tank, through a 5/8 in SS drive shaft. The drive shaft was machined to

½ in on either end to accommodate ½ in holes in the Pelton Wheel and the 6 blade disk impeller. To contain the water exiting the Pelton Wheel, a Plexiglas container (6 in x 11.5 in x 15 in) surrounded the Pelton Wheel. This shielding had a ¾ in diameter hole drilled in its shaft side to accommodate a ¾ in PVC shaft support tube and provide a water tight seal between the PVC tube and the storage container side. The short side of the storage container was fitted with a 1 3/8 in hole for the jet from the nozzle to enter, as shown in Figure 8.

The nozzle (25/64 in ID) was a brass coupling from a ½ in male pipe thread to a 3/8 in hose barb. The fitting was screwed into a galvanized steel ½ in to 1 in bushing. The bushing was screwed into a 1 in NPT to 1 in hose barb plastic coupling. The nozzle could be adjusted to any desired orientation by rotating it in a vertical plane and by lateral movement of the nozzle support stand through a slot in the support table.

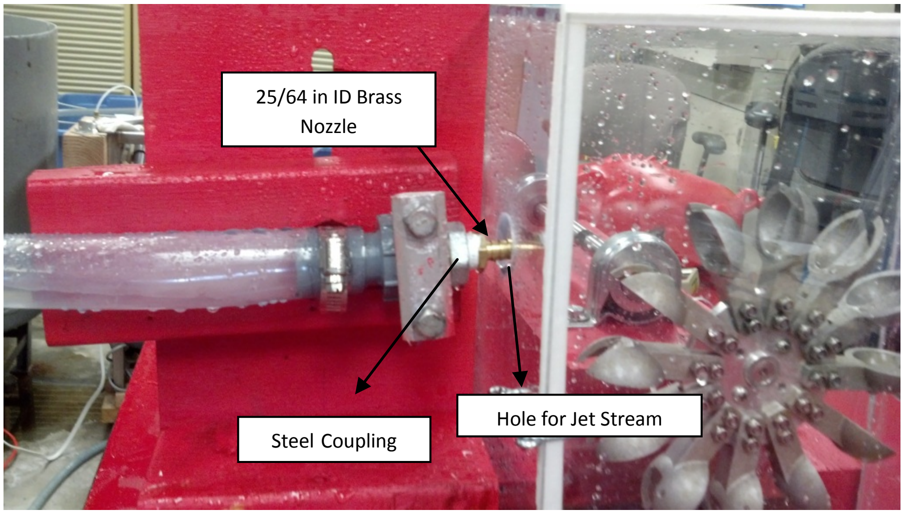

Figure 8. Nozzle with adjustable bracket.

The 5/8 in drive shaft was supported and enclosed in a 3/4 in PVC tube (Fig. 6). Near either end of the tube, the shaft was wrapped with Teflon tape which provided a low friction bearing surface between the shaft and the PVC tube. The clearance between the PVC tube and the Teflon tape was kept to a minimum to prevent shaft wobble.

The Pelton Wheel speed was measured with an electronic tachometer whose light source was focused on a section of silver tape on the rotating shaft. As explained later, the rotational speed was used to calculate the power consumed by the 6 blade disk impeller.[10]

The water tank (12 in x 12 in x 24 in) in which the 6 blade disk impeller operated was constructed from 1/8 in thick Plexiglas. It consisted of 4 built-in, 1 in wide baffles, which prevented swirl and fully baffled the vessel.

Electric Generator (Figure 7)

The generator unit was similar in design to the power measurement unit. The Pelton Wheel shield was a 6 in x 11.5 in x 15 in polypropylene storage vessel. The 5/8 in drive shaft was supported by two 5/8 in pillow block bearings. The power output of the drive shaft was attached to a 4 in diameter toothed pulley which drove a 1.5 in toothed pulley by means of a toothed belt. The electric generator drive shaft was attached to the 1.5 in toothed pulley. At the maximum rotation speed of the Pelton Wheel (1015 RPM), the generator produced 50 mA at 70 V and 3.5 W.

The power produced by the generator was made visual in Fig. 10 by lighting a bank of LED strips (5 in series) which were encased in a plastic Razorback hog hat.

Figure 10. LED Hog Hat.

Experimental Procedure

Safe operating procedures were important when using pressurized equipment and moving parts. Care was taken to ensure that the Pelton Wheels, the 6 blade disk impeller, and the DC electric generator were all clear of any obstructions before the system was powered. Since the apparatus was designed so that only one system could be operated at a time, the valves were positioned properly before operating the system. The pumps were started one at a time due to high starting currents. Once the pumps were operating, the nozzle of the desired system was adjusted to generate maximum shaft speed, producing maximum Pelton Wheel power.

The nozzle location was adjusted by moving it laterally and by rotating it around the axis of its holder to obtain the maximum operating speed. These adjustments were made by tapping either the nozzle holder or the support base with a suitable hammer.

LAB EXPERIMENTATION

Overview

Laboratory experiments were conducted using both the power measurement device and the electric generator.

Turbine and Impeller System

The bench-scale turbine and impeller system was used to determine the combination of nozzle size and 6 blade disk impeller diameter which gave the highest mechanical efficiency of the Pelton Wheel. With a specific nozzle and a specific 6 blade disk impeller installed, both pumps were started with all valves open except the appropriate system isolation valve was closed. The nozzle pressure and nozzle flow rate were recorded. The nozzle location was adjusted to produce maximum shaft speed. Table 1 presents the experimental data and reduced results for all runs made using the power measurement apparatus.

The maximum efficiency of 50% was realized using a 25/64 in nozzle and a 3.25 in diameter 6 blade disk. The efficiency results agreed with literature[11, 12] findings, both gave the optimum ratio of Pelton Wheel peripheral speed to jet velocity (Velocity Ratio in Table 1) of 50%. Power consumed by the 6 blade disk impeller was in the range of 39-49 W.

The optimum nozzle location of the nozzle exit is given by the measurements below:

1. The nozzle centerline is in a plane containing the centerline of the Pelton Wheel buckets.
2. 3 3/8 in above the drive shaft horizontal plane.
3. 5 1/2 in from the drive shaft vertical plane.
4. The nozzle centerline points slightly downward at an angle of 6 degrees with the vertical plane through the nozzle tip.

Data Reduction

The reduced data in Table 1 were calculated using the following procedure:

$A_n = \pi D_n^2/4$	[nozzle flow area, m^2]	(1)
$V_j = Q/A_n$	[jet velocity, m/s]	(2)
$\Delta H = V_j^2/2g$	[head to power the jet, m]	(3)
$M_j = \rho Q$	[jet mass flow rate, kg/s]	(4)
$P_j = M_j V_j^2/2g$	[jet power, W]	(5)
$P_i = N_p \rho N^3 D_i^5$	[impeller power, W]	(6)
$\eta = P_i/P_j$	[efficiency, impeller power to jet power]	(7)
$V_{tw} = \pi N D_{pw}$	[Pelton Wheel peripheral speed, m/s]	(8)
$\zeta = V_{tw}/V_j$	[velocity ratio]	(9)

Table 1. Experimental and Reduced Results

Trial	Nozzle Dia. (in)	Impeller Dia. (in)	Pressure (psig)	Flow (gpm)	Jet Velocity (ft/s)	N (RPM)	Velocity Ratio (ζ)	Efficiency (η)	Jet Power (W)	Produced Power (W)
I	17/64	2.625	32	9.85	58.7	1119	0.519	43%	99.4	42.7
II	17/64	2.75	32	9.85	58.7	1085	0.504	49%	99.4	49.2
III	17/64	3.25	32	9.85	58.7	815	0.378	48%	99.4	48.0
IV	17/64	3.75	32	9.85	58.7	597	0.277	39%	99.4	38.6
V	25/64	2.625	18	16	44.1	1000	0.612	33%	91.1	30.5
VI	25/64	2.75	18	16	44.1	978	0.604	40%	91.1	36.0
VII	25/64	3.25	18	16	44.1	800	0.494	50%	91.1	45.4
VIII	25/64	3.75	18	16	44.1	625	0.386	49%	91.1	44.3

Turbine and Generator System

A 17/64 in nozzle was used with the turbine generator system. The nozzle was adjusted to give maximum shaft speed which produced maximum light output of the LEDs. At these conditions, the power produced was 3.5 W (50 mA at 70 V).

FULL SCALE DESIGN

Overview

In accordance with the theme of the task, two sites were considered for full scale design: (1) a site based on task premises and (2) a real site based on the Intel Rio Rancho plant.

WERC Task Premises Site

The full scale WERC task premise design consisted of a 27,000 gallon surge tank, an elevation change of 150 ft, a level control system for the tank, approximately 1,300 ft of 14 in rigid PVC piping, a Pelton Wheel turbine/generator unit producing 43.5 kW, 900 ft of 6 gauge electrical wire, and a 3-phase lock loop system.

Intel Site

The full scale Intel design consisted of a 17,000 ft^2 pre-existing basin, a level control system for the basin, approximately 1,600 feet of 14 in rigid PVC piping, a 34 kW turbine/generator unit, 900 ft of 6 gauge electrical wire, and a 3-phase lock loop system.

Intel's manufacturing facility FAB 11X was chosen as a surrogate site for the full scale design. This facility was selected because (1) it is a major industrial water user in the state of

New Mexico, using approximately 3.8 million gal per day and (2) it contains an elevation drop of 120 ft inside Intel's property, both within the range of the sponsor specifications. Figure 11 shows one possible placement for the turbine system, as well as necessary piping and wiring routes. As shown in Figure 11, the elevation profile of the water pipe from Intel to the turbine unit shows an elevation drop of 105 ft, as shown in blue. This could be easily increased to 120 ft by installing the turbine unit below grade. The water would then flow northeast to a sewer line, shown in green. The electric power line routes are shown in yellow.

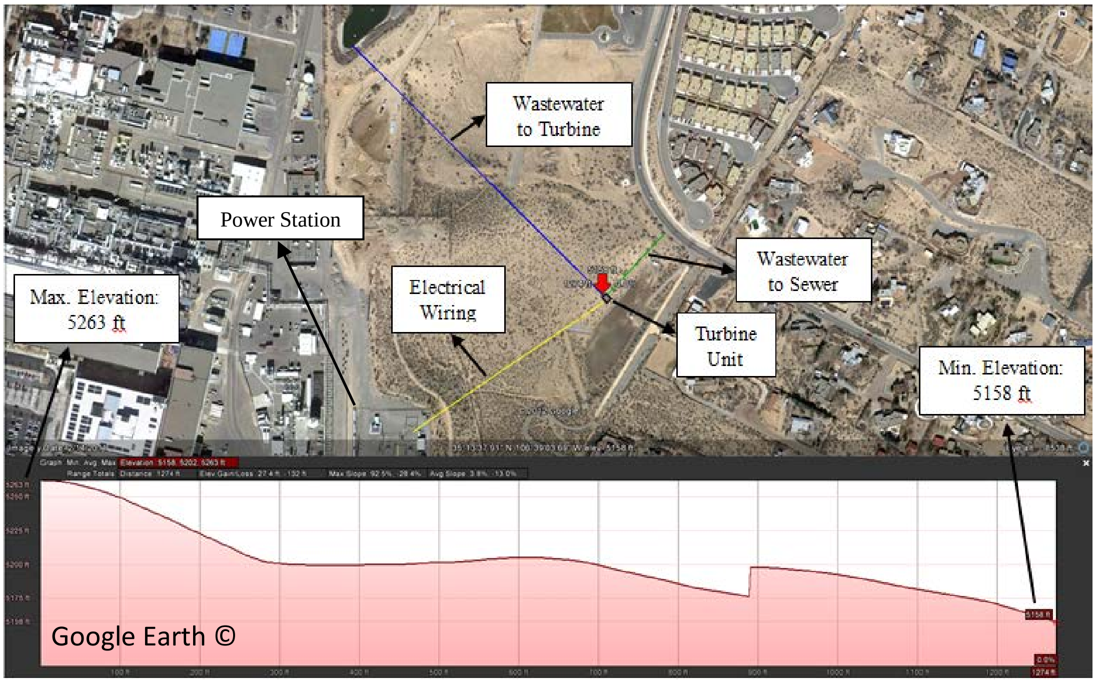

Figure 11. Overhead View of Turbine Unit at Intel New Mexico in Rio Rancho, NM.

Based on the parameters of the surrogate site and the turbine, a Bernoulli balance shows that 110 ft of head is available at the turbine. With an efficiency of 68%, the turbine will produce 34 kW. These calculations are shown in Tables A3 and A4 in the appendix.

Turbine

The turbine/generator for both scenarios consisted of a commercially available, quoted Pelton Wheel turbine/generator unit. The turbine has a 15 in diameter SS wheel and dual, hydraulically actuated nozzles. The generator is a 56 kW, 600 RPM, 480 VAC, 3 phase, 60 Hz, brushless, induction machine. The control package for the turbine integrates the power produced into the local electrical utility and provides protective relays up to North American utility grid standards. It is PLC based, including automated head level control, and is designed to automatically restart following a grid failure. A schematic of the turbine unit is shown in Figure 12. The overall efficiency of the turbine, from nozzle to electricity, is approximately 68%.

The turbine was designed for 2,430 gpm and 150 ft of head. Six gauge electrical wiring is required.

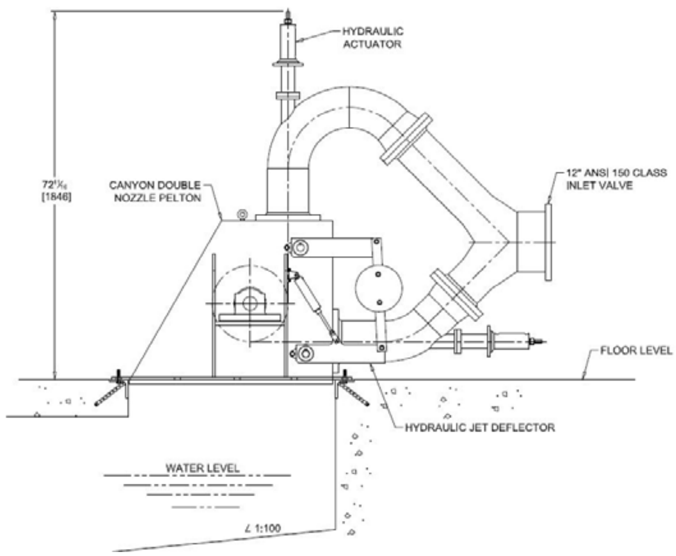

Figure 12. Manufacturer's Schematic-Pelton Wheel Turbine

Surge Tank

The surge tank for the theoretical site was designed using flow data provided by the task sponsor. Seven months of flow data were provided, at five minute intervals. An Excel computer program was written to determine surge tank requirements. A 27,000 gal tank with a set point level of 36% delivered the surge requirements. The use of this tank supplied a constant flow of 2,430 gpm to the turbine. The surge tank will never exceed a level of 90% nor drop below a level of 10%. Figure 13 shows volume within the tank over time.

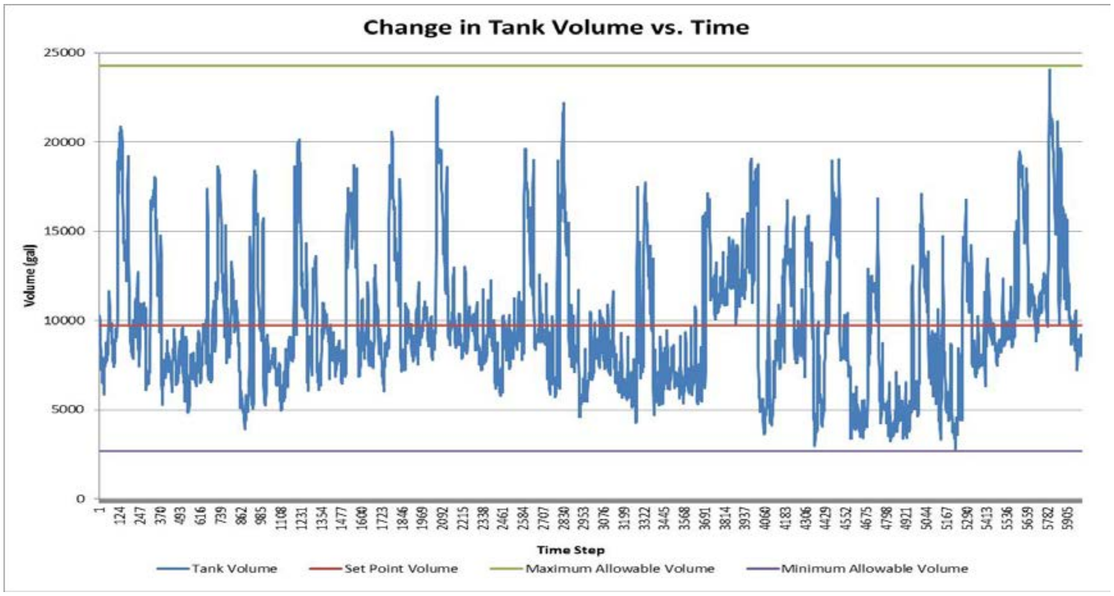

Figure 13. Fluctuations in surge tank volume over time.

Adding a surge tank to the system eliminates the problem of variable flow rates and available head to the turbine, conditions which reduce turbine efficiency. The surge tank also serves as a settling vessel, removing particulates from the wastewater. The existing wastewater line should serve as a bypass line should the surge tank begin to overflow.

Figure 14. - Photograph using Google Earth© of the nearby basin at the surrogate location.

Google Earth© was used to estimate the surface area covered by the basin and the depth that was required to serve as an alternate surge tank. The values estimated for the length of the base and height of the triangular shaped basin are shown in Fig. 14. The volume required for the surge tank is approximately 27,000 gal. The basin has a surface area of 17,000 ft^2; thus, a depth of only 0.2 ft (2.5 in.) is required to handle a surge of 27,000 gal (3,600 ft^3). Conservatively, at least 1 ft of depth would compensate for evaporation.

ECONOMICS

Two scenarios were analyzed in order to determine the incremental economics. The case scenarios included: 1) The Rio Rancho Intel plant location and 2) The WERC task 6 premises site.

The revenue for this project consists of produced electricity purchased by PNM, the New Mexico electric utility. A nearby power station is visible in Figure 11. This location is where the electricity enters the power grid. The return of electrical power to the grid qualifies the project under the U.S. Department of Energy's incentive programs. The specific applicable incentive program is called the *Small and Medium System Renewable Energy Certificate Purchase Program* [13]. The criteria for eligibility is that the system produces between 10-100kW, that the system be installed after January 1, 2012, and that the project life must be at least 12 years.[13] The selling price for produced electricity is mandated at $0.12/kW-hr. Other incentives were investigated, however, none were discovered which met all eligibility criteria. The revenue associated with both scenarios is shown in Table 3.

Table 3: Revenue estimations for both scenarios

Revenue Estimations					
Revenue	Head (ft)	Power Output (kW)	Unit Price for Electricity ($/kWhr)	Operating time (hrs/year)	Revenue ($/year)
WERC Task premises	150	43.54	0.12	8500	44,412
Surrogate Location	120	34.32	0.12	8500	35,011

An incremental economic analysis of all capital costs incurred along with a description of each item is outlined in Tables 4 and 6, for the surrogate and WERC task premise scenarios, respectively. The major components of the capital cost include the turbine, generator, control system, surge tank, and piping, plus installation of these items.

Intel Location Scenario

The surrogate case scenario utilizes wastewater from the Rio Rancho Intel plant. The project involves a battery limits unit; this type of profitability analysis is called retrofitting.[14] Implementation of the described technology at the specified location would include the purchase of a turbine, generator, and control system. The specifications for the system were a gross head of 150 ft and a design flow of 5.4 ft^3/s (3.5 MM gal/day). The net head across the turbine was 142 ft with an output of 43.5 kW.

The delivery time for the turbine/generator system is 20 weeks. The project can be implemented about 1 year after funding is available. The lifetime of the turbine/generator set is at least 12 years (100,000 hr).

The surge tank need not be purchased at the surrogate location, since the actual location has a nearby basin next to a water treatment plant, with sufficient depth to handle the required surge capacity of 27,000 gal.

The total equipment and material costs for the surrogate location is approximately $312,000. Direct costs include delivery, installation, and construction. Installation costs were determined using the total number of required workers, their average pay, an average 8 hr workday (unless otherwise noted), and specified time duration. Indirect costs are comprised of engineering, supervision, and legal consultation. Legal costs were estimated as 4% of the purchased equipment cost. Within the year required to build the project, a 2 to 3 month period is assumed for engineering work. For the proposed technology, a project manager would be responsible for directing all design, engineering, and supervision. Working capital is required to operate a plant and finance the first few months of operation before revenues begin.[14] Working capital was included as 5% of the purchased equipment cost.

The incremental cost of land is negligible because the location of the project is within the Intel plant. The operating costs for this project are minimal because there is no cost for the wastewater. Labor costs are negligible because an existing operator can monitor the operation within an existing control room. Maintenance costs for the turbine/generator set are negligible. On-stream time for the unit was assumed to be 97%.

Intel is a profitable public company[15], consequently their incremental income tax rate is 35%; this tax rate was used in the economic analysis. The equipment depreciation schedule is based on the federal tax depreciation currently in use in the United States. The system uses a 5-year Modified Accelerated Cost Recovery System (MACRS).[14] Business incentives exist to reduce taxable income. The IRS allows certain assets to have an accelerated depreciation schedule in order to encourage capital investment. A standard MACRS depreciation schedule allows only 20% of the depreciable capital in the first year. However, this energy saving project qualifies for 50% depreciation in the first year. The following years must follow the standard MACRS depreciation schedule.[16]

A discounted cash flow method was used to perform the economic analysis. This method discounts all cash flows year by year back to time zero. The interest rate of return (IROR, or sometimes referred to as the internal rate of return) is determined when the discounted net present value of the project is zero.[14] A cash flow for both scenarios is presented below in Tables 5 and 7 for the task premise scenario and the surrogate location, respectively.

Table 4. Outlined summary of costs for the surrogate location

Surrogate Location Capital Costs		
Item	Description	Cost
Equipment		
Turbine/Generator/Control System	PeltonTurbine, 56 kW, 600rpm, 480 VAC, 3 phase, 60 Hz, control panel to parallel generator	$150,000
Housing for Turbine Materials	Slabs, cinder blocks supports	$1,000
Piping	Total 1600 ft in place, unit price $100/ft	$160,000
Electrical	Total 900 ft, unit price $89.3/100ft , Gauge 6AWG, OD 0.249 in. , Amps 65 , Jacket Nylon, PVC	$804
Total Equipment Costs		**$311,804**
Direct Costs		
Delivery Costs		
Electrical	1 truckload, 9 spools, 100ft/spool, electrical wire	$2,000
Construction Materials	Local supplier, housing for turbine	$200
Installation Costs		
Piping and Electric	10 workers, $20/hr, 8hr/day, 4 days	$6,400
Surge tank	4 craftsmen, $30/hr, 8hr/day, 5 days	$4,800
Turbine	Included in Price quote	$0
Contractor's Fees		
Construction	5 days, backhoe rental ($150/day) and gas costs, $4/gal Diesel, 1 tank/day, 20 gal/tank	$1,150
Total Delivery Cost		**$2,200**
Total Installation Costs		**$11,200**
Total Construction Costs		**$1,150**
Total Direct Costs		**$14,550**
Indirect Costs		
Engineering/Supervision	$100,000/year salary for project manager and supervisors, assuming 2 to 3 months time	$20,000
Legal	4% of Purchased Equipment Cost	$12,472
Total Indirect Costs		**$32,472**
Working Capital		
Contingency	5% of Purchased Equipment Cost	$15,590
Total Capital Costs for the surrogate location		
Fixed Capital Investment	Sum of Equipment, Direct Costs and Indirect Costs	**$358,826**
Total Capital Investment	Sum of Fixed Capital Investment and Working Capital	**$374,416**

Table 5. Discounted cash flow table for the surrogate location

End of year	Investment	Depreciation	Revenue	Taxable Income	Manufacture Costs	After Tax Net Income	After Tax Cash Flow	Non-Discounted Cash Flow	Cummulative Sum	Discounted Cash Flow	Discounted Sum
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	-374.42	0.00	0.00	0.00	0.00	0.00	0.00	-374.42	-374.42	-367.25	-367.25
2	0.00	179.41	35.01	-144.40	0.00	264.96	85.55	85.55	-288.86	82.31	-284.94
3	0.00	71.77	35.01	-36.75	0.00	119.64	47.87	47.87	-240.99	45.18	-239.76
4	0.00	43.06	35.01	-8.05	0.00	80.89	37.83	37.83	-203.16	35.02	-204.75
5	0.00	25.84	35.01	9.18	0.00	57.64	31.80	31.80	-171.36	28.87	-175.88
6	0.00	25.84	35.01	9.18	0.00	57.64	31.80	31.80	-139.56	28.32	-147.56
7	0.00	12.92	35.01	22.09	0.00	40.20	27.28	27.28	-112.28	23.83	-123.73
8	0.00	0.00	35.01	35.01	0.00	22.76	22.76	22.76	-89.53	19.50	-104.23
9	0.00	0.00	35.01	35.01	0.00	22.76	22.76	22.76	-66.77	19.13	-85.10
10	0.00	0.00	35.01	35.01	0.00	22.76	22.76	22.76	-44.01	18.76	-66.34
11	0.00	0.00	35.01	35.01	0.00	22.76	22.76	22.76	-21.26	18.40	-47.94
12	0.00	0.00	35.01	35.01	0.00	22.76	22.76	22.76	1.50	18.05	-29.89
13	0.00	0.00	35.01	35.01	0.00	39.85	39.85	38.35	39.85	29.83	-0.06

All values except years in thousands ($)

WERC Task Premises Scenario

The total cost for the WERC task premises includes a surge tank. The overall equipment and material costs are estimated to be $223,000. The surrogate scenario was used as a basis for the assumptions made in the WERC task premise scenario. All parameters involved should essentially remain the same. The following assumptions are to be noted:

1) The length of pipe chosen is the same for both scenarios to maintain a comparable basis.

2) The cost of land is negligible in both scenarios.

Table 6. Purchased equipment cost for the WERC task premise location.

WERC Task Premise Capital Costs		
Item	Description	Cost
Equipment		
Turbine/Generator/Control System	PeltonTurbine, 56 kW, 600rpm, 480 VAC, 3 phase, 60 Hz, control panel to parallel generator	$150,000
Surge Tank	27,000 gallon Galvanized Tank: FRB	$21,708
Housing for Turbine Materials	Slabs, cinder blocks supports	$1,000
Piping	Total 1600 ft in place, unit price $100/ft	$160,000
Electrical	Total 900 ft, unit price $89.3/100ft , Gauge 6AWG, OD 0.249 in. , Amps 65 , Jacket Nylon, PVC	$804
Total Equipment Costs		**$333,512**
Direct Costs		
Delivery Costs		
Electrical	1 truckload, 9 spools, 100ft/spool, electrical wire	$2,000
Surge Tank	Materials required for surge tank, use local supplier	$500
Construction Materials	Housing materials required for housing	$200
Installation Costs		
Piping and Electric	10 workers, $20/hr, 8hr/day, 4 days	$6,400
Surge tank	4 craftsmen, $30/hr, 8hr/day, 5 days	$4,800
Turbine	Included in Price quote	$0
Contractor's Fees		
Construction	5 days, backhoe rental ($150/day) and gas costs, $4/gal Diesel, 1 tank/day, 20 gal/tank	$1,150
Total Delivery Cost		**$2,700**
Total Installation Costs		**$11,200**
Total Construction Costs		**$1,150**
Total Direct Costs		**$15,050**
Indirect Costs		
Engineering/Supervision	$100,000/year salary for project manager and supervisors, assuming 2 to 3 months time	$20,000
Legal	4% of Purchased Equipment Cost	$13,340
Total Indirect Costs		**$33,340**
Working Capital		
Contingency	5% of Purchased Equipment Cost	$16,676
Total Capital Costs for WERC task premise		
Fixed Capital Investment	Sum of Equipment, Direct Costs and Indirect Costs	**$381,902**
Total Capital Investment	Sum of Fixed Capital Investment and Working Capital	**$398,578**

Table 7. Discounted cash flow table for the WERC task premise location.

End of year	Investment	Depreciation	Revenue	Taxable Income	Manufacture Costs	After Tax Net Income	After Tax Cash Flow	Non-Discounted Cash Flow	Cummulative Sum	Discounted Cash Flow	Discounted Sum
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	-398.58	0.00	0.00	0.00	0.00	0.00	0.00	-398.58	-398.58	-382.11	-382.11
2	0.00	190.95	44.41	-146.54	0.00	286.65	95.70	95.70	-302.88	87.96	-294.15
3	0.00	76.38	44.41	-31.97	0.00	131.98	55.60	55.60	-247.28	48.99	-245.16
4	0.00	45.83	44.41	-1.42	0.00	90.74	44.91	44.91	-202.37	37.93	-207.23
5	0.00	27.50	44.41	16.92	0.00	65.99	38.49	38.49	-163.88	31.17	-176.06
6	0.00	27.50	44.41	16.92	0.00	65.99	38.49	38.49	-125.39	29.88	-146.18
7	0.00	13.75	44.41	30.66	0.00	47.43	33.68	33.68	-91.71	25.07	-121.11
8	0.00	0.00	44.41	44.41	0.00	28.87	28.87	28.87	-62.84	20.60	-100.52
9	0.00	0.00	44.41	44.41	0.00	28.87	28.87	28.87	-33.97	19.75	-80.77
10	0.00	0.00	44.41	44.41	0.00	28.87	28.87	28.87	-5.10	18.93	-61.84
11	0.00	0.00	44.41	44.41	0.00	28.87	28.87	28.87	23.77	18.15	-43.69
12	0.00	0.00	44.41	44.41	0.00	28.87	28.87	28.87	52.63	17.40	-26.29
13	0.00	0.00	44.41	44.41	0.00	28.87	28.87	45.54	98.18	26.31	0.02

All values except years in thousands ($)

Summary

An acceptable interest rate for large corporations has traditionally been in the range of 8%-11%.[17] The WERC task premises case is the more economical of the two cases considered here with an IROR of 4.3%. This return is marginal for earnings projects under normal circumstances. However, interest rates are now at historically lower levels, and are projected to remain low for several years. The surrogate location IROR is about 2.0%. The project involves minimal risk and gives an attractive margin over the interest payments for borrowed funds. This energy recovery initiative is a "Green" project, which inherently lowers the acceptable IROR for environmentally conscious industries.

Table 8. Summary of the most pertinent values of the economic analysis.

Summary	Fixed Capital Investment	Working Capital	Yearly Revenue	IROR (%)	Simple Payout (years)
WERC Task premises	$381,902	$16,676	$44,412	4.3	8.6
Surrogate Location	$358,826	$15,590	$35,011	2.0	10.2

REGULATIONS

Environmental and Legal Considerations

Installation of the proposed system must comply with all state and federal laws. The construction of the pipelines and connection of the new pipelines to existing sewer lines must comply with the New Mexico Department of Health, the New Mexico Environmental department, and must abide by all plumbing codes.

The proposed technology will comply with the environmental regulations of New Mexico. These regulations can be found under the *New Mexico Environmental Protection Ground and Surface Water Protection (Title 20, Chapter 6, Part 2, Sec. 20.6.2.1- 20.6.2.5299)* issued by the *Water Quality Control Commission*. The current discharge of wastewater from the plant is approximately 3.8 million gal per day.[19] The *Ground Water Quality Bureau* and the *Surface Water Quality Bureau must be notified of the intent to alter the character of any existing water contaminant discharge, and must file plans and specifications of the modifications or construction involved (Title 20, Chapter 6, Part 2, Sec. 20.6.2.1201-20.6.2.1203).* For more information on applicable laws, refer to the references section[20,21].

The toxicity of the wastewater is high and could be deleterious if exposed to the general public[20]. If the areas nearby are residential, and they are residential near the Intel Rio Rancho plant, the pollution of drinking water sources in the vicinity could be catastrophic. Therefore, pipeline integrity must be continuously monitored. Pathogens in waste water can produce illness through ingestion, inhalation or even dermal absorption (skin contact). Sewage water contains various harmful toxicants, including, but not limited to, inorganic chemicals (ex. arsenic, chromium), organic chemicals (ex. acrylamide, benzene), radionuclides (ex. radium 226), disinfectants (ex. chlorine dioxide), disinfection byproducts (ex. bromate, trihalomethanes) and others.[20] Even minimal exposures could be potentially hazardous to nearby residents. To control possible problems with erosion and sediment control, a storm water pollution prevention plan must be in place prior to construction.

Worker Safety

Worker safety is paramount. Accident prevention and proper training are essential during the installation and operation of the proposed system. The system utilizes high flow rates and achieves moderately high pressures. For this reason, operators must be knowledgeable about the operation and maintenance requirements for the turbine and generator systems. Operation, cleaning, and maintenance must comply with the following OSHA regulations; *Occupational Safety and Health Standards (Sec. 1910.1-1910.1450), Construction Regulations Sec. 1926.1-1926.1501, Recordkeeping Regulations (Sec. 1904.4.0 – 1904.46), Personal Protective Equipment and Training (Sec. 1910, 1915, 1917, 1918, 1926) and Electrical Installations (1910, Subpart S).* Personal protective equipment shall be provided to all employees (when required by federal, state, and city laws) working on machinery. The system is automated; therefore, workers must be aware of electrical dangers and moving parts. Material Safety Data Sheets (MSDS) must be readily available to inform workers of the toxicants in the wastewater streams. Before operation on equipment, a safety lock-out/tag-out system must be in place, and all electrical connections with the machinery must be severed.

Community Involvement

A town hall meeting will be held prior to beginning construction on the project to inform the public of the potential hazards associated with the implementation of the project. Warning signs will clearly mark dangerous areas during and after construction. A pamphlet will be distributed in the surrounding areas communicating the potential hazards related to the project. Also, a representative from the parent corporation will be made available to answer any and all questions pertaining to the installation of this project. To further inform the public, a newspaper advertisement will be placed in the local newspaper (ex: Rio Rancho observer). Due to the relatively small scale of the project, the cost of this community outreach program will be negligible.

CONCLUSIONS AND RECOMMENDATIONS

1. Extensive research of potential technologies that apply to the concept of hydroelectric renewable energy was conducted. The technology that was best suited for WERC Task # 6 was determined to be a Pelton-Wheel type turbine.
2. The bench-scale apparatus adequately modeled the ability to convert kinetic energy produced from a wastewater stream to usable electric power by means of a turbine/generator system. The apparatus also demonstrated that the efficiency of Pelton Wheel turbine can be measured and quantified.
3. The efficiency of the Pelton Wheel system is highly dependent on the location of the impinging jet stream on the buckets. To maximize the efficiency, the nozzle velocity and bucket speed must be selected to yield a velocity ratio (bucket peripheral velocity/jet velocity) of ½.
4. A 27,000 gal surge tank is required to smooth the wastewater flow fluctuations into a constant flow, which optimizes the Pelton Wheel efficiency.
5. Incentives are essential to improve the project economics. Currently, the only available incentives allow electricity to be returned to a nearby electrical grid for a price of $0.12/kW-hr. The project is considered "Green", making it highly desirable by U.S. industry.
6. The project is minimal risk. Consequently, the most environmentally friendly U.S. companies would find the means to implement the project.
7. The revenues for the projects are $35,000 and $44,000 per annum for the surrogate location and WERC task premises location, respectively.
8. The total capital costs incurred, including direct costs, indirect costs, working capital, and fixed capital investment for the surrogate and the WERC task premise scenarios are $374,000 and $399,000, respectively.
9. The overall interest rate of return for the surrogate and the WERC task premises scenarios are 2.0% and 4.3%, respectively. The current low interest rates provide a basis for careful consideration of the projects' economic viability.
10. The simple payout for the surrogate and the WERC task premises scenarios are 10.2 and 8.6 years, respectively.

11. It is recommended that the equipment or materials be purchased locally to minimize transportation and delivery costs.
12. All applicable laws (Federal, City, and State) must be researched, reviewed, and properly considered before implementing the proposed technology.
13. All calculations are estimates and are subject to change depending on the different conditions or locations where the technology may be applied. Extensive analysis of the specific circumstances is necessary to optimize the efficiency of the equipment and to reduce the economic and environmental impact of the venture.

APPENDIX

Table A1. Calculations for the efficiency of the Pelton Wheel.

Stat	Rule
Co	;CALCULATE THE VOLUMETRIC FLOW RATE
Sa	M=(GPM*ρ_e)/(7.48*60*2.205)
Sa	Vol = GPM/60/7.48
Sa	M_e=(GPM*ρ_e)/(7.48*60)
Co	;CALCULATE THEORETICAL NOZZLE VELOCITY
Sa	Anoz = pi()*(Dnoz/12)^2/4
Sa	Vol = v_t*Anoz
Sa	v = v_t*1.03
Co	;HEAD BALANCE
Sa	ΔH = v^2/(2*g)
Co	;CALCULATE PELTON WHEEL SHAFT TO TURBINE RATIO
Sa	Vt = VelRatio*v ; http://en.wikipedia.org/wiki/Pelton_wheel - See Subsection Optimal wheel speed
Co	;CALCULATE THE POWER OUTPUT
Sa	Pjet = P/η
Co	;CALCULATE THE REVOLUTIONS PER SECOND
Sa	Vt = Pi()*N*2*(r/12)
Co	;CALCULATE THE REVOLUTIONS PER MINUTE
Sa	RPM = N*60
Co	;CALCULATE THE DIAMETER OF THE IMPELLER REQUIRED
Sa	Din = D/0.0254 ; meters to inches
Sa	D = (P/(Np*ρ*N^3))^(1/5)
Co	;CALCULATE THE MASS FLOW RATE
Sa	Pjet = (745/550)*M_e*v^2/(2*gc)

Table A2. Variables involved in efficiency calculations.

Sta	Input	Name	Output	Un	Comment
					PROPERTIES
	32.2	g			Gravitational acceleration, ft/s^2
	32.2	gc			Gravitational constant (English), lbm ft/s^2 lbf
	62.4	ρ_e			Density of water, lbm/ft^3
	1000	ρ			Density of Water, kg/m^3
					RADIUS
	3.125	r			Radius of pelton wheel (turbine), in
		R			Radius of pelton wheel (turbine), m
					DIAMETERS
	.265625	Dnoz			Diameter of nozzle, in
	2.75	Din			Diameter of impeller, in
		D	.06985		Diameter of impeller, m
					AREAS
		Anoz	.00038		Nozzle cross-sectional area, ft^2
					HEAD
		ΔH	53.583		Recoverable head, ft
					VELOCITIES
		v_t	57.032		Theoretical velocity of impinging jet stream, ft/s
		v	58.743		Actual jet stream velocity, ft/s
		Vt	29.589		Optimal shaft speed, ft/s
		VelRatio	.5037		Velocity Ratio
					REVOLUTIONS
	1085	RPM			Revolutions per minute, RPM
		N	18.083		Revolutions per second, RPS
					POWER
	5	Np			Power Number for impeller
		P	49.163		Power of impeller, W
		Pjet	99.4		Power of jet stream, W
					EFFICIENCY
		η	.4946		Energy Transfer Efficiency
					FLOW RATES
		M	.6211		Mass flowrate, kg/s
		M_e	1.3695		Mass flowrate, lb/s
	9.85	GPM			Volumetric flowrate, gpm
		Vol	.02195		Volumetric flowrate, ft^3/s

Table A3. Calculations for the power produced by the turbine.

Rule
A = pi() * (D/12)^2 / 4; Pipe flow area
koD = k / (D/12); Relative roughness
a = .094 * koD^.225 + 0.53 * koD; Constant in Wood equation
b = 88 * koD^.44; Constant in Wood equation
c = 1.62 * koD^.134; Constant in Wood equation
IF Nre > 2200 THEN f = (a + b * Nre^(-c))/4 ELSE f = 16/Nre;Wood Equation for f
Mdot = V * A * ρ; Mass flow rate
Pterm = (Pb - Pa) * 144 / ρ; Pressure term in Bernoulli equation
Zterm = (g/gc) * (Zb - Za); Elevation term in Bernoulli equation
Va = V;Velocity at system entrance
Vb = V; Velocity at system exit
Vterm = (Vb^2 - Va^2) / (2*gc);Velocity term in Bernoulli equation
NuWp = -(Pterm + Zterm + Vterm + hf); Available head at the turbine
Wp = NuWp * η; Turbine specific power
P_turb = Wp*Mdot/550*0.735; Power produced by the turbine

Table A4. Variables involved in the power calculations.

St	Input	Name	Output	Un	Comment
	32.2	g			Gravity, ft/s^2
	32.2	gc			Gravitational constant, lbm/lbf ft/s^s
	1	μ			Viscosity, cp
	62.4	ρ			Density, lbm/ft^3
	2430	GPM			Volumetric flow rate of waste water, gpm
		Nre	585127		Reynolds number in pipe
		A	.93942		Pipe flow area, ft^2
	.000005	k			Pipe roughness, ft
		koD	4.57E-6		Relative roughness, k/D
		a	.005913		Constant in Wood Eq.
		b	.393478		"
		c	.311865		"
F		f	.003042		Fanning friction factor
		V	5.7636		Velocity at point in system, ft/s
		Va	5.7636		Velocity at system entrance, ft/s
		Vb	5.7636		Velocity at system exit, ft/s
	120	Za			Elevation of system entrance, ft
	0	Zb			Elevation of system exit, ft
	0	Pa			Pressure at system entrance, psia
	0	Pb			Pressure at system exit, psia
		Pterm	0		Pressure head, ft
		Zterm	-120		Elevation head, ft
		Vterm	0		Velocity head, ft
		Mdot	337.861		Mass flow rate, lbm/s
	13.124	D			Pipe diameter, in
	1300	L			Length of straight pipe, ft
		Wp	75.1231		Turbine specific power, (ft-lbf/s)/lbm/s
		NuWp	110.475		Available head at the turbine, ft
	.68	η			Turbine efficiency
		P_turb	33.9184		Power produced by turbine, kW

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