Spiral Drain

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APPENDICES

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1.0 Introduction

The northern spiral drain at the University of British Columbia (UBC) campus is a remarkable engineering design. Installed 71 years ago, the spiral drain has managed to drain storm and groundwater run-off from half of the UBC campus without a single maintenance procedure. Although the system still operates effectively and as designed, the UBC Social, Ecological, Economic Development Studies (SEEDS) program in association with UBC Campus Planning realized that there was an opportunity to improve the system by adding a component of sustainability into the design. In September of 2007, the manager of the SEEDS program, Brenda Sawada, approached the Mechanical Engineering Department with a proposal to utilize the spiral drain water flow and hydropower technology to generate electricity from the northern spiral drain system.

This report summarizes the objectives, design process and conclusions of the spiral drain project. The three stages of the design phase (preliminary, conceptual, and detailed) are presented. Next, the final power generation design is presented followed by a discussion of the economics and other important considerations. As well, the proof-of-concept constructed by the design team is presented along with a brief summary of the construction process. Finally, concluding remarks for the project and future opportunities are presented.

2.0 Project Objectives

The main focus of the UBC Northern Spiral Drain project was sustainability, specifically how to utilize the previously untapped natural rainfall on UBC's campus to generate power in an innovative and environmentally friendly way. As such, the main objective of the project was to generate electricity from the water flow in UBC's northern drainage system while minimizing impacts to the surrounding environment. Because the spiral drain is located in Pacific Spirit Park, much care was taken to ensure that the final design did not negatively affect the natural beauty of the park. Although power generation was the main objective, other opportunities to improve the value of the design presented themselves throughout the project. Two such examples were increasing the drainage capacity of the system to a higher storm level, and filling the currently drained pond in front of the Museum of Anthropology to act as a reservoir. Significant thought was directed towards incorporating these other facets into the project, however the main objective of the project was sustainable power generation and it remained the primary objective throughout.

3.0 Project Design

3.1 Preliminary Design

The initial scope of this project involved generating power from the spiral drain, storing the power during the winter months, and utilizing the power for composting toilet facilities located on Wreck beach during the summer months. The team decided to focus on the power generation aspect as this was the first step to achieving the overall goal of the project. To determine the feasibility of the project the team performed a preliminary power calculation based on maximum rainfall data. According to these calculations, the maximum available power was approximately 1.5 MW (see Appendix C.1 for these calculations). Although unrealistic, this estimate did prove the feasibility of the project, namely that power generation is a possibility. Research into small-scale hydro determined that no existing systems utilize storm water run-off as a flow source, however the spiral drain system does share conditions that have been proven to work well with run of the river (ROTR) technology. Therefore the design team focused research efforts on ROTR technologies and installations. For further detail on our preliminary design phase refer to Appendices A.1 and A.2 for the Proposal and Background Research.

3.2 Conceptual Design

The main functional aspects of the design are the power generation mechanism and the location of the powerhouse. Because of the high head and varying, moderate flow rates of the spiral drain system, a Turgo impulse turbine was chosen by the team. Possible locations for the power house were narrowed down to the throttling at the base of the vertical shaft, the outflow pipe near Wreck beach, or building a separate pipe system to be located at a specified design location. Choosing this location depended on many factors including cliff stability, accessibility, cost, visual impact, and safety of the Wreck beach users. To evaluate the options a weighted scoring matrix and concepts were scored based on power generation, maintenance requirements, safety, and difficulty of installation among others. From the scoring matrix, it was determined that the separate pipe system was the best option. Further, this allowed for the existing spiral drain to be used as an overflow in case rainfall exceeds the capacity of the generation system. Please see Appendix A.3 for the Conceptual Alternatives Report.

3.3 Final Design

Once the conceptual design was completed, the team performed detailed technical analysis to determine the sizing of the components and more accurately predict the expected power production. Rainfall data collected by UBC over the last 5 years was used to accurately predict the expected flow rates. This, combined with a more in-depth head loss calculation, allowed the team to design the transmission shaft, the penstock, and size a commercially available Turgo turbine. All other necessary components such as generators, battery packs, and control system were found through commercial suppliers. See Appendix A.5 for more information on the final design.

4.0 Demonstration Model

A small-scale demonstration model of the spiral drain system and the basic final design was constructed by the team in the later stages of the project. Every effort was made to scale the model through dimensional analysis which would have allowed for technical measurements to be taken and scaled up to the full-size system. However once the dimensional analysis was been completed, it became clear that it was physically impossible to scale the model in this way (see Appendix C.10 for calculations). For this reason, the model's main purpose was to showcase the basic functioning of the final design and illustrate a few key aspects:

- The Turgo turbine design
- Using the current spiral drain system as an overflow
- Other important components of the design such as valves, nozzles, and shaft assembly

The materials and components for the prototype were chosen to provide good visualization of the design while approximating the actual system as close as possible. Great efforts were also made to keep the costs as low as possible due to a budget of $500 given by the UBC Mechanical Engineering Department. In the end, the design team concluding on clear acrylic piping for the main pipe system and supply tanks, wood 2x4's for the support structure, and ABS pipe with a submersible sump pump for the return system. As well, a small-scale genuine Turgo turbine runner was obtained from a supplier in Utah. Figure 1 below is a solid model of the completed prototype.

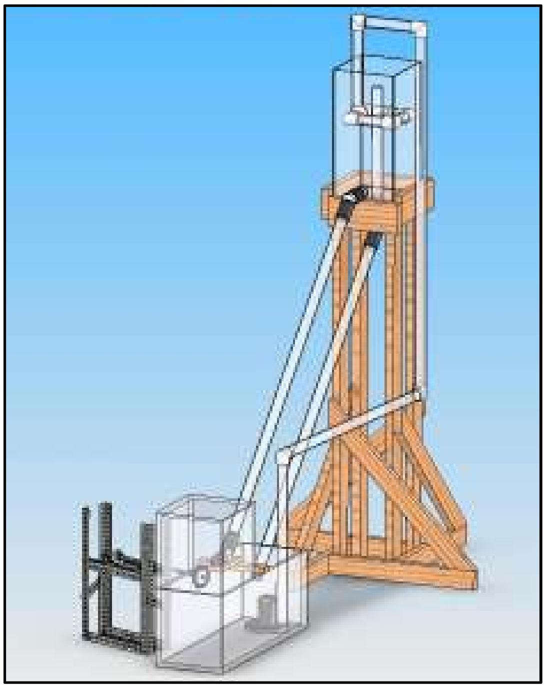

Figure 1 – Solid Model of Prototype

5.0 Conclusions and Recommendations

The final design consists of two 6’’penstock pipes starting at the spiral drain collection chamber and ending at a powerhouse location on Wreck beach which has yet to be determined. The system utilizes a Turgo impulse turbine to harness the water flow energy and a battery pack/generator system to convert the power the electricity. The current drainage system is used as an overflow pipe during times of severe storms.

All told, the system is expected to cost in the area of $190,000 for parts and installation. Analysis estimates the system is capable of producing approximately 130 kW for an average of 325 hours a year giving a total energy of 42.25 MWh per year. This equates to approximately $3,000 of electrical power at the current price of $0.07/kWh. If the electricity is used to run toilet facilities and eliminate the need for pit toilets, the team estimates additional savings of $20,000/year in pumping and maintenance. With this in mind, the project has the possibility of becoming economic in 8-10 years.

If adequate funding is available, the team recommends that the project is seen through to implementation. At present time, significant sustainable energy is being wasted in the current system. This project will capture the wasted energy and will also improve UBC’s reputation as a front-runner in sustainable development. As well, it opens up the possibility of better toilet facilities on Wreck beach without having to run power lines down the cliff side. Although the team believes this project to be a good investment, a number of items must be taken care of before the project is installed.

Because of the high initial costs of the project, the team recommends that more detailed research is undertaken to determine the flow rates of water through the drainage system. The final numbers quoted for this project were obtained using rainfall data and are probably only valuable as estimates. Before implementation of the project, the team recommends that flow measurements are taken in the main lines right before entry into the spiral drain collection chamber.

As well, the team recommends that the electrical power conversion unit be designed. The current team stopped analysis and design at the transmission shaft from the turbine; a suitable generator and power storage unit will need to be designed for the system. This can be completed by other project teams in future years but will likely need to include electrical engineers and not solely mechanicals.

Finally, the team recommends the design and location of the powerhouse be finalized. This decision will be up to UBC Campus Planning and Metro Vancouver. The current team recommends that the powerhouse be located in one of the already existing concrete structures on the beach as this would avoid the need for new infrastructure. As well, a team of civil engineers will need to be assembled to design the powerhouse.

With some more analysis and design, the team expects this project to be a success and contribute positively to the University of British Columbia’s community and development.

Appendices

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1.0 Introduction

The northern spiral drain at the University of British Columbia (UBC) is a hydraulic system responsible for draining half of the campus's storm and groundwater run-off. Brenda Sawada, manager of the UBC Social, Ecological, Economic Development Studies program (SEEDS), requested the UBC Mechanical Engineering department to investigate the possibility of power generation from the spiral drain system. Prior to detailed conceptual design it is essential for the project team to have a good understanding of the design problem. This requires in-depth research of existing designs, patents, and key technologies related to the problem. The purpose of this report is to present the initial research findings for the UBC Northern Spiral Drain Energy Recovery Project.

2.0 Existing Designs

Research into existing designs was conducted through the Engineering Village database and Google. At present time, there are no hydraulic power generation systems using storm drain flow as input however research has shown that it is not necessary to design the spiral drain energy generation system from the bottom up. There are two applicable systems already in use: run of the river systems and flutter power generation devices.

Run-of-the-river systems are typically used in small towns not serviced by power grids. The systems incorporate a small turbine and divert water from a river. Energy is extracted from the natural elevation difference (West Wales Eco Center, 1999).

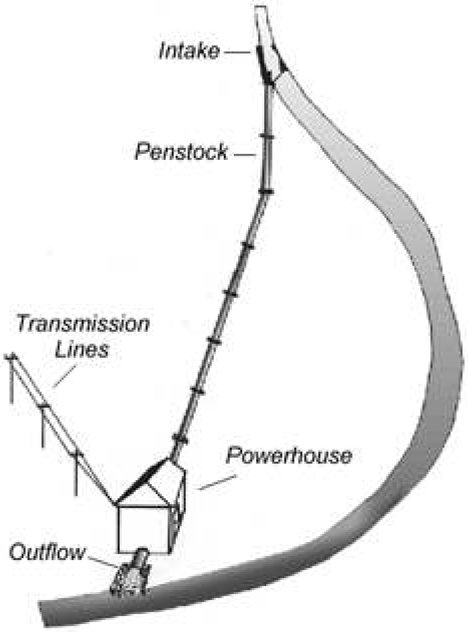

Figure 1 – Typical Run of the River Installation

The horizontal section of the UBC northern spiral drain bears much resemblance to a running river; therefore the water flow can be diverted into a turbine. The main advantage of this system is that it satisfies the fail safe criteria; if the turbine blocks the flow it simply diverts back through the spiral drain. The shortcoming is that there needs to be a consistent head and flow rate for the turbine to perform efficiently. In order to address this requirement, a series of turbines can be installed (Petricec et al., 1985) or variable speed hydroelectric generation can be implemented (Fraile-Ardanuy et al., 2006). The first alternative addresses the limited budget concerns of this project because small centrifugal pumps with the attachment of a generator are inexpensive alternatives to expensive turbines (**Williams, 1999).**

Flutter power generation involves harnessing the energy from the oscillation of thin airfoils (Frayne, 2007). The vibration in the high tension strip of metal caused by wind is called aeroelastic flutter. Although the original device is made to harness wind energy, the idea behind this system can be applied to water as well since both mediums are viscous fluids. The advantage to flutter power is the ease of implementation. However it would be difficult to accurately predict the power generation and failure cycle because this technology is still relatively new. As a result, it will be difficult to create a budget proposal. The disadvantage of a flutter power system stems from the uncertainty of the technology.

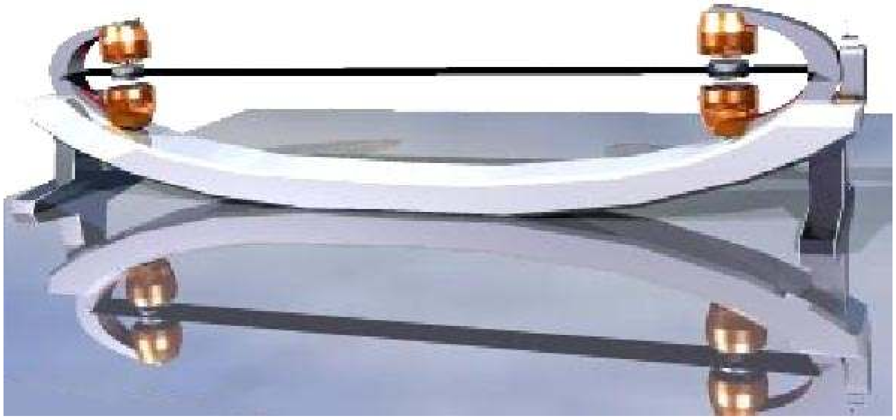

Figure 2 – Flutter Power Wind Generation Mechanism

3.0 Patents

A patent search in the United States Patent Database was performed using the website http://www.freepatentsonline.com in order to gain insight to existing technologies available for energy recovery from storm drains. Although no patents were found regarding hydro generation from storm water, relevant patents were available which dealt with run of the river hydro and small scale hydro generation. Since the aim of this project is not to develop a new product, existing patents do not restrict freedom to operate.

US Patent number 7,233,078 B2, filed March 4, 2005, describes a miniature hydroelectric generation system used to power portable water treatment systems or plumbing fixtures that draw water from a pressurized water supply, such as a domestic water line. As water enters the generation system, part of it is diverted to a nozzle and discharged into a Pelton turbine. The patent describes several arrangements of the nozzle and turbine, as well as methods to reduce friction and increase efficiency. Many of the ideas described within this patent can be easily scaled up and applied to the discharge of the throttling pipe in the spiral drain.

US Patent number 20,070,222,219 A1, filed March 23, 2006, describes a turbine designed to function in open channel flow. The turbine is an impulse type turbine mounted in the vertical plane with fins dipping into an enclosure designed to speed up the flow of the water by the use of a converging – diverging nozzle. A similar system may be implemented in the outflow pipe of the spiral drain, where the flow is essentially open channel flow.

US Patent number 6,192,821 B1, filed March 16, 1998, describes a hydroelectric generator mounted underneath an outboard motor of a boat in order to generate power for onboard electronics. The generator consists of a propeller turbine and electric generator enclosed in a tube. The entire assembly is placed underwater, and as the boat travels forwards, the flow of water spins the turbine, generating electricity. Turbine-generator assemblies similar to the one described in this patent may be placed in line with the flow at the outflow pipe of the spiral drain. Multiple units may be used all along the outflow pipe in order to reuse the water as it flows out to the ocean.

4.0 Use Patterns and Functionality

Please see the following page for a high level descriptive diagram of the spiral drain turbine system.

The spiral drain turbine system is relatively simple with a single input, the storm drain flow, and a single output, electrical power. As well, the turbine system will likely generate some noise and installation facilities may impact the landscape of the beach.

The only expected users to have direct interaction with the system are maintenance crews. Their interaction with the system will consist of regular scheduled maintenance to ensure the system is operating correctly. Maintenance procedures will consist of inspection of the filtration system, inspection of the bearings, and inspection of the turbine blades. Any component that is adversely affecting the system will be then be replaced.

Users of the beach and surrounding park area may be indirectly affected by the system due to noise generation and change of landscape.

5.0 Key Technologies

5.1 Turbine Technology

To begin research of relevant technologies a simple search on Wikipedia was performed to get a general understanding of the various technologies involved. The search phrase used in Wikipedia was “hydro turbine,” which returned a page entitled *Water Turbine*. This page contained useful information on the classification of turbines and various application examples of each turbine design. The turbine application chart seen below in Figure 3 was also found on this page. The two classifications of turbines relevant to this project are:

- **Reaction Turbines**
  Reaction turbines extract energy by decreasing the pressure of the water flow as it passes through the turbine. They require that the turbine be completely encased or submerged in the flow in order to contain the suction. Reaction turbines work well with low to medium head applications. Examples of reaction turbines are: Francis, Kaplan, Tyson, and Water Wheels.
- **Impulse Turbines**
  Impulse turbines operate on the principle of conservation of momentum. As water hits the blades of the turbine it changes direction and thus imparts a force on the turbine blade. Impulse turbines are typically used in very high head applications. Examples of impulse turbines are: Pelton, Turgo, and Crossflow.

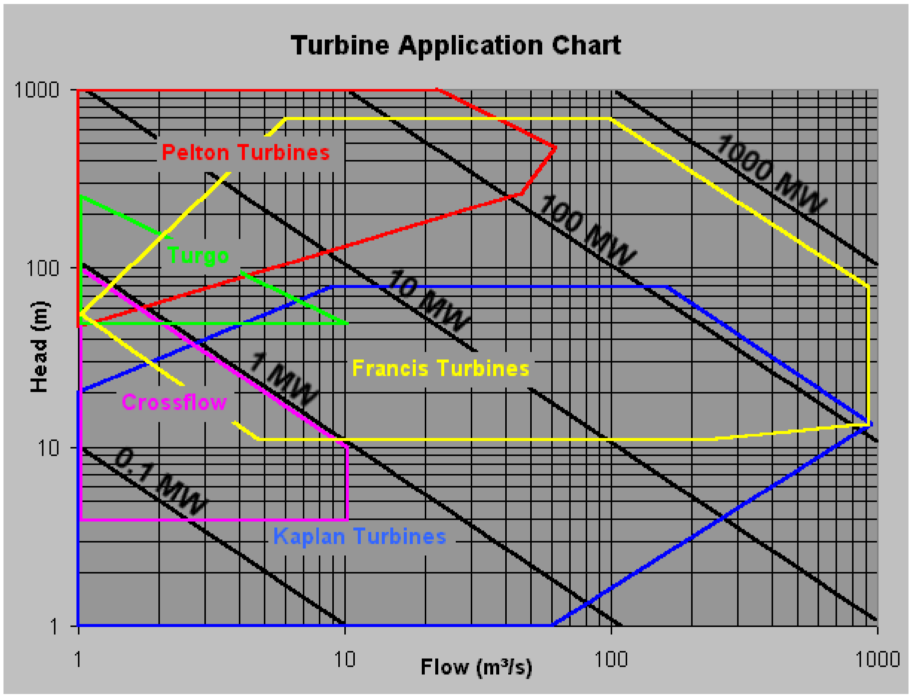

Figure 3 – Turbine Application Chart

From the information gathered, the research of key technologies was narrowed down to reaction turbines. Using Academic Search Premier through the UBC Library webpage, a subject search was conducted using the word “turbine.” This search turned up an article titled *Modeling of Micro Turbine Power Generation Systems*. This article details the design of control systems used in micro turbine power generation systems and could provide valuable insight during the design process.

Academic Search Premier was also searched using “hydro power” as the search phrase. This search provided an article titled *Small Hydro Power: Technology and Current Status* which contains much of the same information as the Wikipedia site but goes into substantially more detail.

Because of the emphasis on clean energy in modern society, there is considerable research being undertaken in micro-turbine design for its low impact on the environment.

5.2 Generator Technology

Although generator design is not in the scope of this project, the technology was researched briefly to provide a general knowledge base for the design team. One online article and one engineering handbook were consulted.

Cunningham and Fife state that AC direct systems consist of a turbine and generator supplying power directly to appliances. Governing of the power can be controlled by off the shelf components. The power must be monitored so that when the appliances are not in use, the power is sent to an alternate load (such as a heating unit). AC direct systems are simple to design however they must be capable of handling all the power loads at any one time, including surges from appliance start-up, otherwise electrical systems failure will occur.

Also discussed in the article by Cunningham and Fife are battery based generation systems. Battery based systems require less power generation due to the fact that AC systems must cover instantaneous power requirements whereas battery based systems only need to cover the average power requirements. This also leads to the conclusion that battery based generation systems are better at dealing with inconsistent power generation due to the fact that they can operate appliances off of stored power when no power from the turbine is available.

Penche and de Minas discuss the two common generator types: synchronous and asynchronous. Asynchronous generators can only operate when tied to a power grid as they draw their excitation current from the grid. Synchronous generators are equipped with DC excitation and therefore can operate independent of a power grid. Asynchronous generators are used when the power output of the generator represents a small fraction of the power system load, for example if the generator were tied into a large power grid. Synchronous generators are used in the alternate scenario, when the generator supply represents a large portion of the power system load.

6.0 Conclusions

Background research of existing designs, patents, and key technologies has provided valuable insight into the technologies that are available for the UBC Northern Spiral Drain Energy Recovery Project.

Initial research has not changed the evaluation criteria developed in the project proposal however it has illuminated which general conceptual designs to pursue. Detailed metrics and specifications will be developed. Preliminary research has provided some of the tools necessary to prepare a system performance specification and concomitant economic cost and benefit.

Research for this project will be an ongoing process as concepts are developed and refined.

Purpose

This report has been prepared in response to a request from the University of British Columbia (UBC) Social, Ecological, Economic Development Studies Program (SEEDS) for the Department of Mechanical Engineering to investigate the possibility of power generation from the UBC northern spiral drain system. This report is intended for Brenda Sawada, manager of the UBC SEEDS program, and David Grigg, primary consultant for this project from the UBC Campus Planning office.

This report outlines the conceptual design phase of the UBC Northern Spiral Drain Energy Recovery Project. Research of other micro-hydro sites is presented, as well as discussion of key functional aspects of the design. Complete concepts are generated and compared using evaluation criteria and concept scoring. Finally, the best concept is put forth for future work into detailed design.

Abstract

The northern spiral drain at the University of British Columbia (UBC) is a hydraulic system responsible for draining half of the campus's storm and groundwater run-off. Brenda Sawada, manager of the UBC Social, Ecological, Economic Development Studies program (SEEDS) requested that the UBC Mechanical Engineering Department investigate the possibility of power generation from the spiral drain water flow. This report details the analysis of conceptual alternatives completed by the project design team.

Three run-of-the-river hydro power sites were identified as "existing products," as no power generation schemes based off of drainage systems could be found through research. Canyon Creek utilizes 170ft of head and a Pelton turbine to generate an average of 350kW. This site has similar characteristics to the spiral drain site and therefore will be a good comparison for the final design. Brandywine Creek is a 7.6MW site located north of Whistler, BC. Although much larger in capacity, it offers good insight into penstock and structural design. Finally, a home installation by Harold Lunner was analyzed. Water to wire efficiency was calculated to be 65%, a value that the design team hopes to improve upon for this project.

Functional aspects of the design were determined to be turbine design, powerhouse location, filtration, and flow control. Filtration and flow control were classified as secondary design criteria due to their dependence on what turbine is used and where it is located. Two classes of turbines were looked at in detail: impulse and reaction. Impulse turbines are designed for higher head applications and utilize the flow momentum to generate power. Reaction turbines are designed for lower head applications and utilize pressure difference to generate power. The design team identified three potential locations where a turbine powerhouse could be located: on the beach near the outflow pipe, in the cliff near the throttling pipe, or in a separate newly designed pipe system parallel to the current drainage system.

In order to generate complete concepts, the "best" turbine design was chosen for each potential location. This choice was based on technical feasibility and site characteristics (flow rate, head, etc.)

Four concepts were identified as promising candidates: a Kaplan turbine in the outflow location, a Crossflow turbine in the throttling pipe location, a Turgo turbine in a separate system, or a flutter power mechanism in the outflow. Detailed energy analysis was completed for each location to determine available hydraulic power. Each concept was compared against the evaluation criteria of power generation, installation difficulty / cost, effect on surroundings, maintenance, flow restriction, power storage / transmission, and safety. Weighting for each criterion was chosen by general consensus among the design team and a scoring matrix was generated to determine the best concept.

Although it has high installation costs, the Turgo turbine in a separate pipe system was chosen as the best candidate to proceed forward with into detailed design. This concept allows for good flow control, prediction of power, and allows for more design freedom and innovative thinking. The design team will proceed forward with implementing a Turgo turbine in a separate pipe system.

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1.0 Introduction

The northern spiral drain at the University of British Columbia (UBC) is a hydraulic system responsible for draining half of the campus's storm and groundwater run-off. Brenda Sawada, manager of the UBC Social, Ecological, Economic Development Studies program (SEEDS) requested that the UBC Mechanical Engineering Department investigate the possibility of power generation from the spiral drain water flow. The UBC Northern Spiral Drain Energy Recovery project is tasked with solving how electrical power could be generated from the water flow. This report details the analysis of conceptual alternatives completed by the project design team.

The generalized problem statement for the project was identified as follows:

> *Generate power from the northern spiral drain flow with minimal effects to the surrounding environment and minimal changes to the current system.*

The project team is focused around designing a system that takes the northern spiral drain flow as input and creates electrical power as an output. The system is expected to have direct interaction with maintenance crews who will perform inspections to ensure the system is operating at its full potential. As well, the system may have indirect interaction with the public users of the nearby beach through noise generation and change of landscape. The system is only expected to be operational through the winter months when storm and groundwater run-off is at its highest due to storm season. A successful design solution will economically and safely generate power from the northern spiral drain flow with minimal maintenance and upkeep, and minimal effect on the surrounding environment.

This document provides an overview of the analysis of conceptual alternatives, specifically benchmarking, concept generation, concept selection, concept validation, and final conclusions. Recommendations are made for which conceptual designs to pursue as the project continues forward into the detailed design phase.

2.0 Benchmarking

Existing run-of-the-river micro hydro power generating sites are the closest designs in existence that can be specified as “existing products” as research was unable to discover any power generation sites based off of drainage systems. Three run-of-the-river designs were investigated mainly to offer insight into this type of hydro power generation. The three sites are Canyon Hydro, Brandywine Creek, and Harold Lunner’s installation**.**

Canyon Hydro utilizes a creek with nine months of predictable flow rate; the three summer months of downtime are used for maintenance. A 4.125 inch diameter nozzle directed at a Pelton turbine is used to harness the 170ft of available head. The Pelton turbine is rated at 350kW however the system was designed to be expandable. With one Pelton turbine operating a full return on investment was expected within less than seven years. On a side note, the article stated it was typically only possible to predict the rain fall over five year intervals. Canyon Hydro had similar operating conditions to the spiral drain. However, the spiral drain was designed as an energy dissipating structure and not a running creek. It is expected to have extra installation or construction cost in the beginning.

Brandywine Creek is a 7.6 MW site located north of Whistler in BC, Canada which annually produces in the range of 38,000 to 42,000 MWh. This system utilizes a three meter high weir and 4.5 km long penstock to create a head of 282 m. The project took less than one year to build. A 20 year purchase contract was signed with BC Hydro and the system is predicted to generate over $50,000,000 during this 20 year period. Although this system is several times the capacity of the spiral drain, it gives good insight into penstock and structural design.

The final system analyzed was installed by Harold Lunner, who bought an off-the-shelf integrated turbine-generator product called a Stream Engine. The operating system consisted of a flow rate of 10 liters per second directed through two 22 mm nozzles which generated 459 W. The generator harnessed the energy of an eight meter head and was fed by a 150 mm diameter pipe, 200 m long. The calculated efficiency in this system from water to electricity was 65% which gives a rough estimate of expected efficiency. This design shows that available hydraulic power is not a realistic estimation of power generation ability.

All run-of-the-river sites found by research were very different from the northern spiral drain system and could only offer high level insight into hydro power generation. Most run-of-the-river sites, as implied by the name, are based off of rivers or creeks and not drainage systems.

3.0 Functional Concept Generation

Early in the concept generation phase it was realized that two primary functional design questions existed. Firstly, how will the energy of the spiral drain flow be harnessed to create electrical power? Secondly, where will the power generation mechanism be located within the spiral drain system? It should be noted that many other functional aspects of the design exist such as flow control, filtration and mechanical-to-electrical power conversion, however the design of these systems is dependent on what type of hydro power generation mechanism is used and where it is located. Because of this dependence, these functional aspects were deemed secondary and conceptual design efforts were focused on the two primary functional design questions. Discussed below are different hydro power generation mechanisms and possible implementation locations within the spiral drain system.

3.1 Hydro Power Generation Mechanisms

3.1.1 Turbines

All information on turbines was obtained from the Layman's Guidebook on How to Develop a Small Hydro Site (Penche and de Minas, 1998).

3.1.1.1 Impulse Turbines

Impulse turbines are used for relatively higher head applications and operate on the principle of converting water pressure into kinetic energy, usually in the form of a high speed jet. The jet is usually created by a nozzle with a needle valve to control the flow. This high speed jet is directed at a turbine runner designed to capture the maximum amount of energy from the flow. Three popular impulse turbine designs exist: Pelton, Turgo, and Crossflow. See Figure 1 below for a basic design schematic.

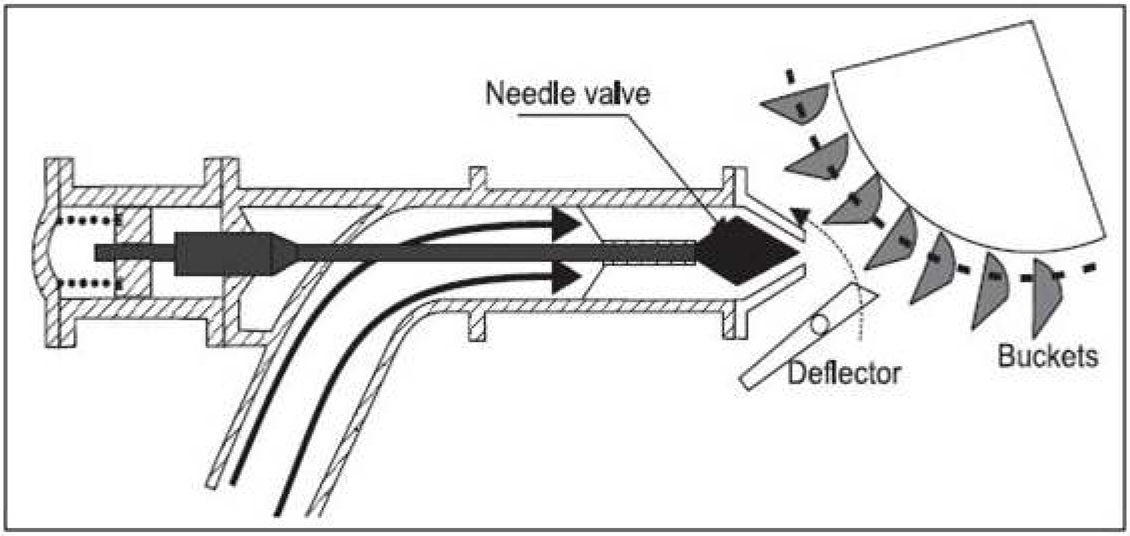

Figure 1 – Schematic of an Impulse Turbine

Pelton turbines implement a bucket structure designed for the high speed jet to be in plane with the turbine runner. Figure 2 below shows the Pelton bucket design. Pelton turbines are designed for high head applications and are limited by the fact that water exiting the buckets impinges on the adjacent buckets, thereby limiting the maximum runner speed of the turbine.

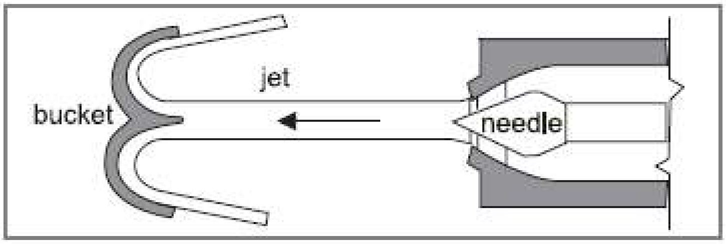

Figure 2 – Pelton Turbine

Turgo turbines are applicable for medium to high head applications and operate similar to Pelton turbines however the buckets are designed to take the high speed jet flow at a 20° angle (see Figure 3 below). Because the bucket design allows for water flow to pass through the bucket from one side to the other, the outflow does not impinge on adjacent buckets and Turgo turbines are not limited by runner speed. Higher running speed increases the possibility of direct coupling between the turbine and generator which can improve efficiency and maintenance costs.

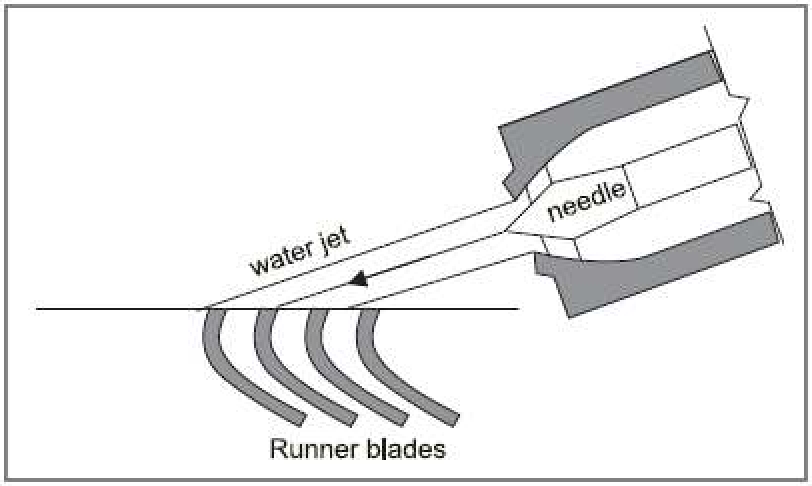

Figure 3 – Turgo Turbine

Crossflow turbines operate differently from the Pelton and Turgo designs. The runner is constructed of two parallel disks connected together by numerous curved blades. The flow is directed through the runner in two stages, the first allowing for minor reaction and the second causing major shock loss and transfer of kinetic energy from the flow to the turbine runner. Crossflow turbines can be implemented with a typical efficiency of 80% across a wide range of flow rates (20 litres/s to 10m^3/s) and wide range of heads (1m to 200m). See Figure 4 below for a typical design.

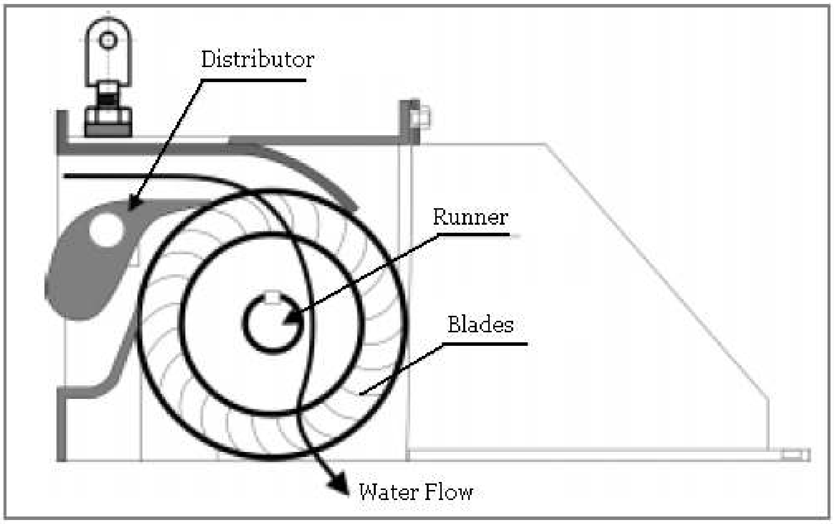

Figure 4 – Crossflow Turbine

3.1.1.2 Reaction Turbines

Reaction turbines operate on the principle of a pressure difference across the turbine blades. This pressure difference exerts a force on the blade and causes it to rotate thus the runners of reaction turbines need to be fully encased within a structure that can withstand the pressure of the fluid. Reaction turbines are typically used for applications with relatively low to medium head but relatively high flow rates. The two most common reaction turbines in use today are Francis turbines and Kaplan turbines.

Francis turbines are the most common type of turbines and range in size from two feet in diameter to up to ten meters in diameter. Figure 5 below shows a schematic of a typical Francis turbine installation.

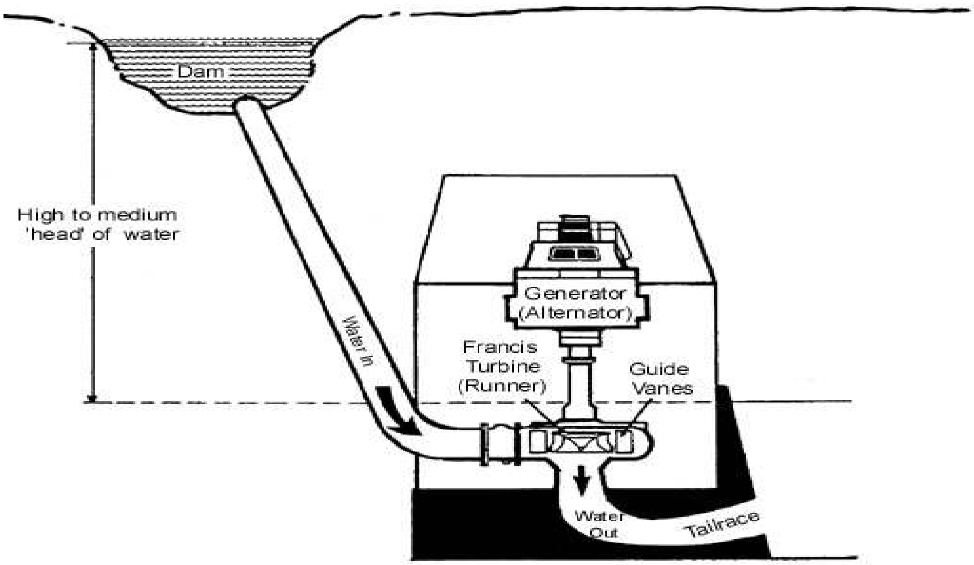

Figure 5 – Typical Francis Turbine Installation

Francis turbines use a radial enclosure around the runner to create a flow that is tangential to the rotation of the runner. To keep the velocity constant along the enclosure, the cross sectional area of the enclosure is decreased. The speed of the runner can be adjusted through the use of guide vanes which allow the flow to be adjusted to more tangential or more axial thus changing the speed of the runner.

Kaplan turbines are axial flow turbines meaning that the flow of water is parallel to the axis of the runner. They are essentially a propeller attached to a generator. A typical Kaplan turbine installation can be seen below in Figure 6.

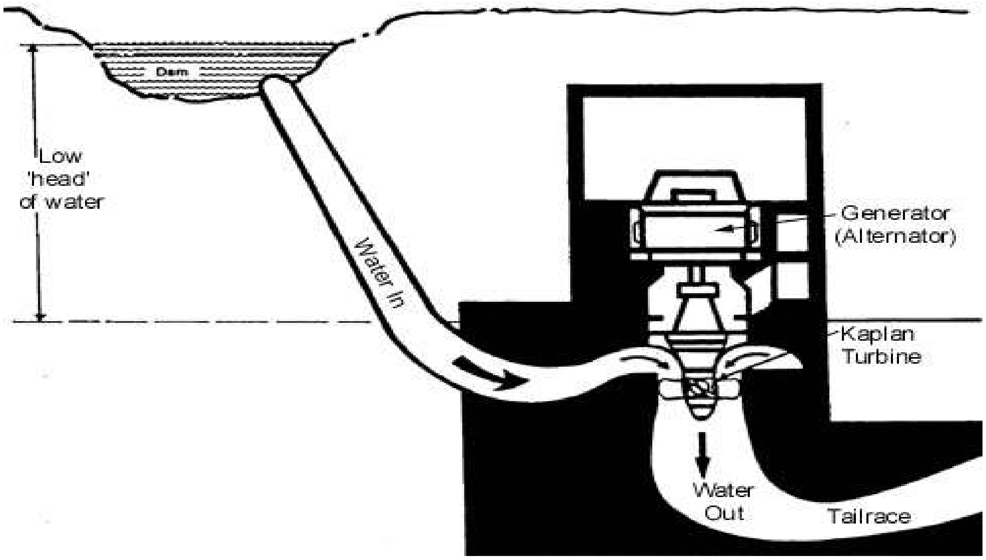

Figure 6 – Typical Kaplan Turbine Installation

Both Francis and Kaplan turbines utilize a draft tube on their outlet which acts as a diffuser and reduces the kinetic energy of the exit stream by reducing the velocity. Generally this is achieved through a conical expansion. The expansion cannot be too large or flow separation may occur, causing large losses in the system. The recommended maximum diffuser angle is about 7^{o}. A well designed draft tube allows the turbine to be mounted above the elevation of the tail water without a loss of head.

3.1.2 Flutter Power Generation Mechanisms

Flutter power generators are a relatively recent development in wind power generation. A thin, flexible membrane is stretched between two supports and sized such that it will produce considerable aerodynamic flutter when air flows past it. To produce electricity, magnets are attached to the membrane which moves in and out of a coil of wire as the membrane vibrates. This technology is intended to produce 30mW – 100W of power for rural areas and third world countries. Research has shown no records of flutter power being used for micro-hydro generation however it might be possible to adapt this technology to the spiral drain project. (Frayne, 2007)

Figure 7 – Flutter Power Mechanism

3.2 Implementation Locations / Systems

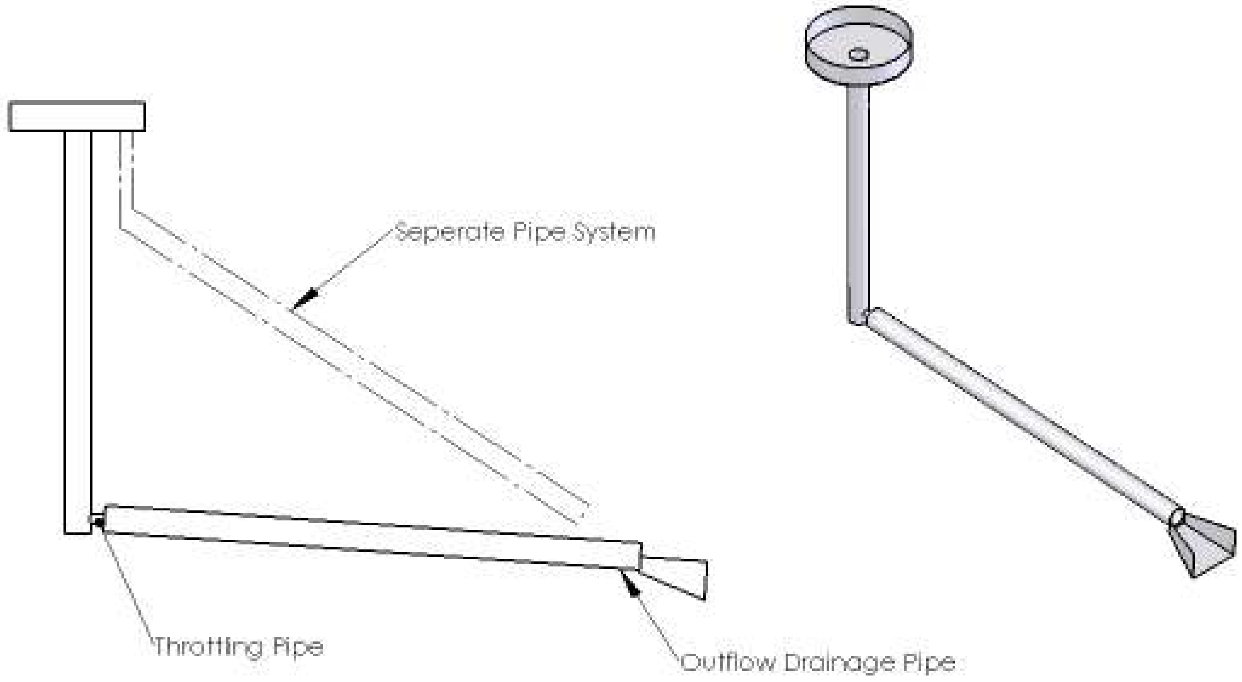

Figure 8 – Model of Spiral Drain Locations

3.2.1 Outflow Drainage Pipe

Located at the bottom of the cliff face on Wreck Beach is a small access station to the outflow drainage pipe of the spiral drain system, consisting of a small concrete structure and a manhole. This site is one possible location for installing a hydro power generation system. The advantage of this site is that it is easily accessed; the amount of excavating / drilling required to reach the spiral drain system is minimal. However due to the large diameter of the outflow pipe (4 ft) and an opening to allow for groundwater seepage, the design team expects open channel flow through the drainage pipe which reduces the available head for hydro power generation considerably (Penche and de Minas, 1998). Further, frictional losses to the flow would be maximized due to the power generation system being located near the end of the spiral drain system.

3.2.2 Throttling Pipe

Located at the base of the spiral drain is a throttling pipe whose purpose is to ensure that no solid build-up blocks the drain output. The smaller internal diameter of the throttling pipe causes a head of water to develop in the bottom of the spiral drain, leading to accelerated velocities through the pipe. This location is advantageous for hydro power generation as pressure head is available and full pipe flow through the throttling pipe is expected. As well, frictional losses to the flow would be minimized as this location is right at the start of the outflow drainage pipe. The downside of this location is that it requires a separate access shaft be drilled from the surface or an access tunnel be excavated from the beach, two options which require more than a 250 ft distance be covered through solid earth.

3.2.3 Separate Pipe System

Instead of installing a power generation system within the existing spiral drain structure the possibility also exists to design a separate pipe system which would act in parallel with the current system. This would allow for maximum utilization of available head as well as correct sizing of a pipe to ensure consistent fully developed pipe flow, and allow for more control of the flow rate and velocities. In essence, this would allow for much more design freedom and optimization of the power generation system. In addition, a new pipe system would increase the drainage capacity of the current system. Conversations with David Grigg of UBC Campus Planning have concluded that a new piping system would have to travel underground due to environmental concerns in Pacific Spirit Park. Therefore installing a new piping system would require a significant amount of drilling which would increase capital costs of the project. Further, this could endanger the geologically sensitive cliff side.

4.0 Complete Concept Generation

Due to the specific design of a turbine for a certain head and flow rate, each hydro power generation mechanism is only applicable to certain locations in the spiral drain system. For example, impulse turbines (Pelton, Turgo) are designed for high head which makes them unsuitable for use in the outflow pipe location where open channel flow is expected. Technical feasibility can be used as a form of concept screening; Table 1 below details which concepts are technically feasible.

	Outflow Pipe	Throttling Pipe	Separate Pipe System
Pelton Turbine	-	-	+
Turgo Turbine	-	-	+
Crossflow Turbine	-	+	+
Francis Turbine	-	+	+
Kaplan Turbine	+	+	+
Flutter Power Generation	+	+	+

+ Feasible - Infeasible

Table 1 – Concept Feasibility

By analyzing the drawings of the spiral drain system (see Appendix D.1 for a drawing) and discussing the flow expectations at each potential location in the spiral drain system, the “best” hydro power generation mechanism was chosen for each site.

Based on the design of the spiral drain system, specifically the groundwater seepage basin located directly above the throttling pipe, open channel flow is expected in the outflow pipe. Because of this, very little head is expected to be available in the outflow pipe making almost every turbine design technically infeasible. A Kaplan turbine can operate on as little as 2 meters of head and is likely the only turbine design to have potential at this location (Penche and de Minas, 1998)

Based on a study completed by Northwest Hydraulic Consultants and discussions with David Grigg of UBC Campus Planning, the head characteristic at the throttling pipe location is expected to oscillate about an average value which is dependent on storm severity. Under maximum capacity the full spiral drain head of 59.6 meters is expected to be available however this will only occur during a one in ten year storm or worse. Under normal operating conditions the average level of head is expected to vary between a few meters and this maximum value. Because of this expected inconsistency, a Crossflow turbine is likely the best option for this location as it can operate under widely varying conditions with the same efficiency.

As shown in Table 1 a separate pipe system could be designed to fit any turbine design. However if the capital were to be invested in a pipe system parallel to the spiral drain it would be advantageous to utilize the maximum amount of head available; this would generate more power and likely reduce the time for return on investment. If a pipe system were to be installed from the collecting cistern on the cliff top down to the beach level, the total head available is 60 meters making this location situation for an impulse turbine. Due to the inconsistent flow rates expected, the best choice was chosen to be the Turgo design for its variable flow rate capacity. This also allows for direct coupling to a generator which improves efficiency (Penche and de Minas, 1998).

As stated previously, flutter power generation has not been implemented in water flows however the design team felt it should be investigated to determine if it had been an overlooked technology at previous run-of-the-river sites. Flutter power generation is not expected to generate as much power as a turbine system and therefore the outflow pipe was chosen as an implementation location to minimize excavating costs.

Based on this high level analysis and discussion of concepts, the four concepts chosen to proceed into more detailed concept scoring were:

- Kaplan turbine in the outflow pipe
- Crossflow turbine in the throttling pipe
- Turgo turbine in a separate pipe system
- Flutter power generation mechanism in the outflow pipe

5.0 Concept Evaluation

5.1 Evaluation Criteria

Evaluation criteria were chosen based on the important aspects of the design as well as design requirements and constraints. Evaluation criteria were analyzed briefly during the proposal stage of the project and little has changed since this preliminary assessment. A short discussion of each evaluation criteria can be seen below.

5.1.1 Power Generation

The main focus of the UBC Northern Spiral Drain Energy Recovery Project is to generate power from the spiral drain flow therefore concepts will be scored on the amount of available power. Data for maximum flow through the spiral drain is readily available (Northwest Hydraulic Consultants, 1998) and although calculations using this flow rate will not be indicative of normal operating conditions, they will allow for a relative comparison of the concepts.

5.1.2 Installation Difficulty / Cost

Due to the geographic sensitivity of the UBC cliff side (Trow Associates, 2004) the amount of excavating, drilling, and tunneling must be kept to a minimum. Concepts will be evaluated based on their expected difficulty of installation and amount of work required. Installation cost will also be considered as a lower installation cost increases the strength of the business case for implementation.

5.1.3 Effect on Surroundings

Environmental impacts such as noise generation, change of landscape, and destruction of habitat will be used to evaluate the concepts. The UBC SEEDS Program is committed to sustainable practices and it would be counteractive to generate power at the expense of the environment.

5.1.4 Maintenance Requirements

The power generation system used for this project is expected to be located in a remote location, either deep in a tunnel or shaft, or down the cliff side on Wreck Beach. For this reason, the amount of maintenance required to ensure correct operation of the system must be kept to a minimum. Maintenance is also expected to be a significant cost in the life cycle of the system, another reason to minimize it.

5.1.5 Flow Restriction

The current spiral drain is rated for a one in ten year storm however recent upgrades to the surrounding area have increased the overall system's capacity to a one in seventy year storm (Northwest Hydraulic, 1998). Flow restrictions of the power generation system must be kept to a minimum to ensure this capacity does not decrease. Any overflow of water from the drainage system could cause severe damage to the geographically sensitive cliff side (Trow Associates, 2004).

5.1.6 Power Storage / Transmission

Concepts will be graded on their ability to store power and the range of power storage systems available. Thought will also be given to how easy it is to transport the power to its expected location of use, Wreck Beach.

5.1.7 Safety

Safety of the power generation system both for the maintenance crews, users of Pacific Spirit Park, and surrounding wildlife populations is of vital importance to the project. Safety will be considered heavily in concept analysis.

5.2 Evaluation of Concepts

5.2.1 Kaplan Turbine in Outflow Pipe

Figure 9 below shows the proposed implementation of this concept.

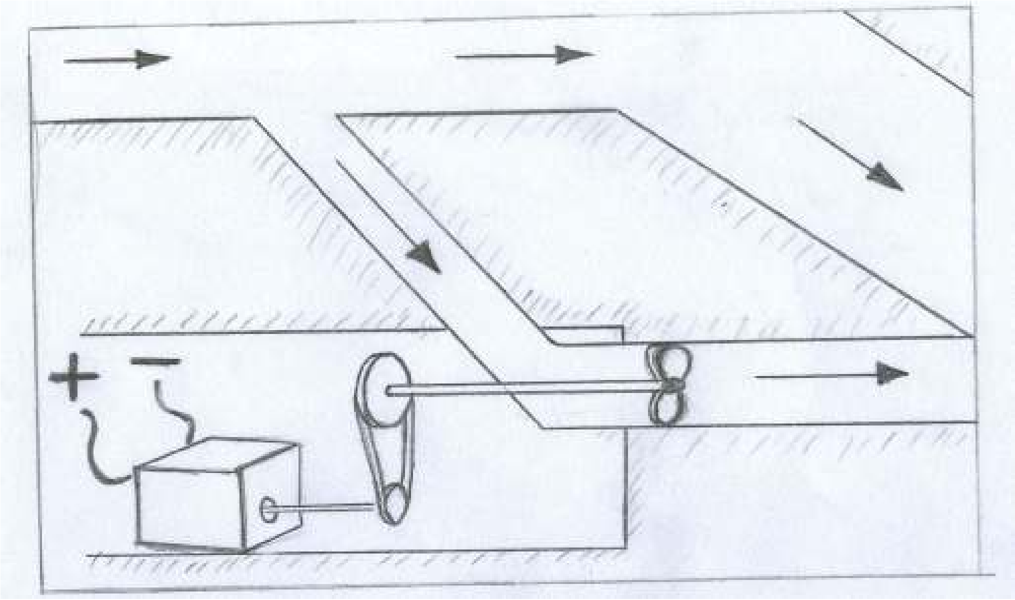

Figure 9 – Sketch of Kaplan Turbine in Outflow Pipe

Technical analysis of this location has shown that the flow in the outflow pipe will likely translate from open channel flow to fully developed pipe flow around 0.15m^3/s however this analysis was based on numerous assumptions due to the fact that no actual data for this location exists (see Appendix C.7 for the full detailed calculation). As well due to the inconsistent nature of storm water run-off there is expected to be significant transient effects at this location meaning the flow might transition between open channel flow and pipe flow often. Estimating the available power for this concept is difficult and rife with uncertainty however calculations have shown the available power ranges from 0 kW to 280 kW depending on head back-up in the drainage system and flow rate.

Installation of this concept would require excavation at the beach around the site of the exposed outflow pipe for construction of a facility to house the turbine and the bypass pipe system. The powerhouse would need to house the turbine equipment and power storage elements, and is estimated at 10 square meters. The structure would likely be built of concrete. Costs of installation would include the turbine, piping and associated valves, excavation, concrete, and construction labour.

There is expected to be an effect to the beach surroundings from this concept. Noise generation is expected from the turbine and associated power components, however this can likely be minimized if soundproofing is installed (AcoustiBlok, 2007). The powerhouse can likely be constructed mostly below ground however some change of landscape and destruction of habitat is expected due to the excavation.

Maintenance requirements for the Kaplan turbine will be regular inspections of the turbine blades, bearings, and filters. The turbine will also need to be shutdown during the summer months where less flow through the drainage system is expected, and started up once the winter months are nearing. Some form of flow control will also be needed to ensure the turbine is operating in an efficient range however this control could be applied through automatic equipment (Penche and de Minas, 1998).

No flow restriction is expected for this concept as the turbine will be located in a bypass pipe. The spiral drain capacity will not be detrimentally affected.

Due to inconsistent available power and the need for a system operating outside of a power grid, power storage and transmission will be provided by a synchronous generator connected to a battery storage system (Cunningham, 2006). If the storage system is large enough, power can be stored in the battery pack until final usage. Otherwise the battery pack will be used to power a compressor to generate compressed air for storage, or will be used to power a fuel cell to generate hydrogen for storage.

This concept is expected to pose no safety risks to the public as long as it is housed in an appropriate facility. Maintenance crews will be exposed to rotating machinery and pressurized piping however risks can be mitigated with proper design and installation.

5.2.2 Crossflow Turbine in Throttling Pipe

See Figure 10 below for a sketch of this concept.

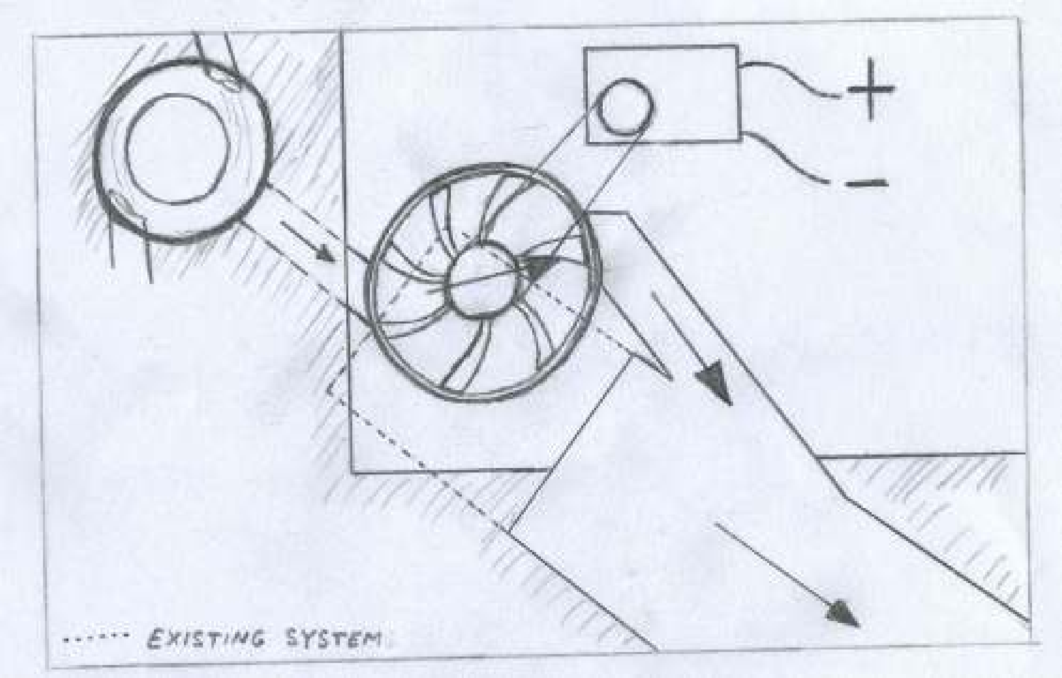

Figure 10 – Sketch of Crossflow Turbine in Throttling Pipe

Due to the uphill gradient of the throttling pipe a build-up of head would be required in the spiral drain before flow would continue through the throttling pipe into the outflow pipe. For this reason, fully developed pipe flow is expected in the throttling pipe at all times with varying levels of head and flow rate depending on storm severity. Because of this variation technical analysis was completed over a range of head and flow rates. The available hydraulic power for this concept ranged from 0-115 kW depending on storm severity. See Appendix C.4 for a detailed calculation.

The throttling pipe is located 50 m into the cliff side from the beach and 60 m down from the cliff top. To access the pipe would require either a hole be drilled from the cliff top or a tunnel be dug out from the cliff side at the beach. Both of these options would require a large amount of excavation and capital input. As well, once this location was reached a large enough space to build the powerhouse would need to be excavated. The powerhouse for this concept is expected to be of similar size to the outflow pipe concept, around 10 square meters. Costs for installation of this concept would include a significant amount of excavation work, concrete, construction labour, the turbine, modifications to the throttling pipe for turbine implementation and associated piping and valves.

Effects to the surroundings would be minimal for this concept as long as proper implementation procedures are followed. Special care must be taken during excavating procedures to ensure that the fragile cliff side remains intact. Because the powerhouse would be located deep within the cliff no noise generation is expected at the beach or cliff top. As well, the only noticeable change of landscape would be the entrance to the access tunnel, consisting of a small concrete structure and doorway.

Maintenance requirements for the Crossflow turbine will be regular inspections of the turbine blades, bearings, and filters. The turbine will also need to be shutdown during the summer months where less flow through the drainage system is expected, and started up once the winter months are nearing. Some form of flow control will also be needed to ensure the turbine is operating in an efficient range however this control could be applied through automatic equipment (Penche and de Minas, 1998).

The Crossflow turbine will be located within the current spiral drain system therefore some flow restriction will be present as the flow travels through the turbine. This will likely reduce the capacity of the storm drain somewhat however the extent will not be known until the turbine has been specified. A bypass system could be built at this location to negate this effect however a design would need to be implemented that properly controlled the flow through the two different pipes.

Due to inconsistent available power and the need for a system operating outside of a power grid, power storage and transmission will be provided by a synchronous generator connected to a battery storage system (Cunningham, 2006). If the storage system is large enough, power can be stored in the battery pack until final usage. Otherwise the battery pack will be used to power a compressor to generate compressed air for storage, or will be used to power a fuel cell to generate hydrogen for storage.

This concept is expected to pose no safety risks to the public as the facilities would be located deep within the cliff and only authorized personnel would have access to them. Maintenance crews will be exposed to rotating machinery and pressurized piping however safety risks can be mitigated by proper design and installation.

3.2.3 Turgo Turbine in Separate Pipe System

See Fig. 11 below for a sketch of this concept.

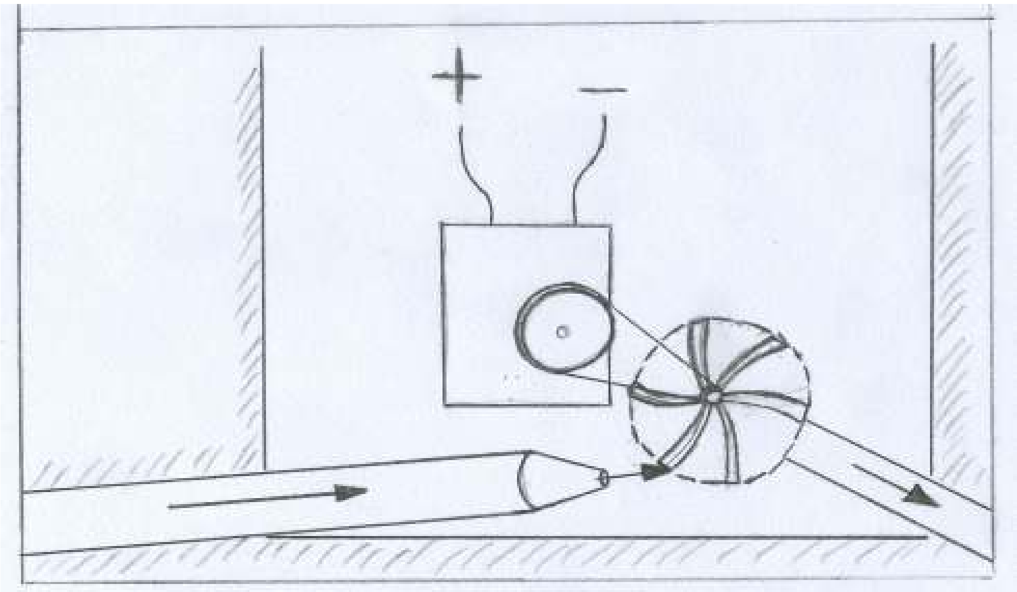

Figure 11 – Sketch of Turgo Turbine in Separate Pipe System

If a separate pipe system was built down the cliff side in parallel to the current spiral drain system the full height of the cliff side could be harnessed for power generation. Varying flow rates would be expected due to inconsistencies of storm water flow however as long as proper control and design techniques were used a constant head could be expected at the bottom of the cliff. Technical analysis was completed for a range of flow rates assuming constant head. Because a separate system allows for design freedom, a range of pipe diameters was also covered. Depending on storm severity and pipe diameter, the range of available hydraulic power was 0-300 kW. See Appendix C.5 for a detailed calculation.

Installation for this concept would be costly and require a large amount of work. Conversations with David Grigg of UBC Campus Planning have brought to light that construction work down the cliff side is prohibited, meaning that the separate piping system would have to travel underground. The powerhouse to house the turbine and associate power generation components would likely be located at the beach, requiring some excavation. There have been discussions with the client about housing the turbine and assorted components in the existing concrete structures on the beach, built for defensive purposes in World War II. This would eliminate the construction of a new powerhouse and excavation at the beach however some uncertainty still exists about whether this is possible. Therefore costs for installation would include significant drilling costs, penstock pipe, the turbine and associated valves, control equipment, excavation, concrete, and construction labour.

Effect on the surrounding for this concept will likely be small, consisting only of a concrete structure located at the beach. As stated above, the penstock pipe will travel underground. Part of the structure can likely be located underground to reduce change to the beach landscape. Some noise generation is expected from the turbine equipment however this can be reduced by soundproofing (AcoustiBlok, 2007). It should be noted that drilling the penstock pipe through the unstable cliff side could cause major environmental effects; extreme care should be taken.

If designed correctly, the penstock and valves will be able to control the flow meaning the system will be mostly automated. In other words no work need to done to operate the system. Maintenance procedures will consist of regular inspections of the turbine blades, bearings, and filtration system. As well, the system will be shut down during the slow summer months.

In terms of flow restriction this concept is ideal because it will have no equipment housed in the current spiral drain system and will actually increase the drainage capacity by adding a second stream in parallel. Some consideration has been given to sizing the penstock pipe specifically to increase the drainage capacity of the spiral drain system to a one in two hundred year storm; however power generation is the main focus of the project and increased drainage capacity will not be considered if it hampers the power generation abilities of this concept.

Due to inconsistent available power and the need for a system operating outside of a power grid, power storage and transmission will be provided by a synchronous generator connected to a battery storage system (Cunningham, 2006). If the storage system is large enough, power can be stored in the battery pack until final usage. Otherwise the battery pack will be used to power a compressor to generate compressed air for storage, or will be used to power a fuel cell to generate hydrogen for storage.

Building a separate pipe system is expected to pose minimal safety risks to the public as long as the turbine equipment is housed in an appropriate structure and the penstock pipe is sized correctly for the pressure. Maintenance crews will be exposed to rotating machinery and pressurized piping however risks can be mitigated by proper design and installation.

3.2.4 Flutter Power Mechanism in Outflow Pipe

No flutter power generation mechanism is currently designed for hydraulic flows however an idea from the design team was to utilize an airfoil type device with a canard to counteract the pitching moment. As flow passes by the mechanism, the airfoil would oscillate back and forth between two mechanical stops and a set of magnets in a linear inductor would be used to generate current. See Figure 12 below for a sketch.

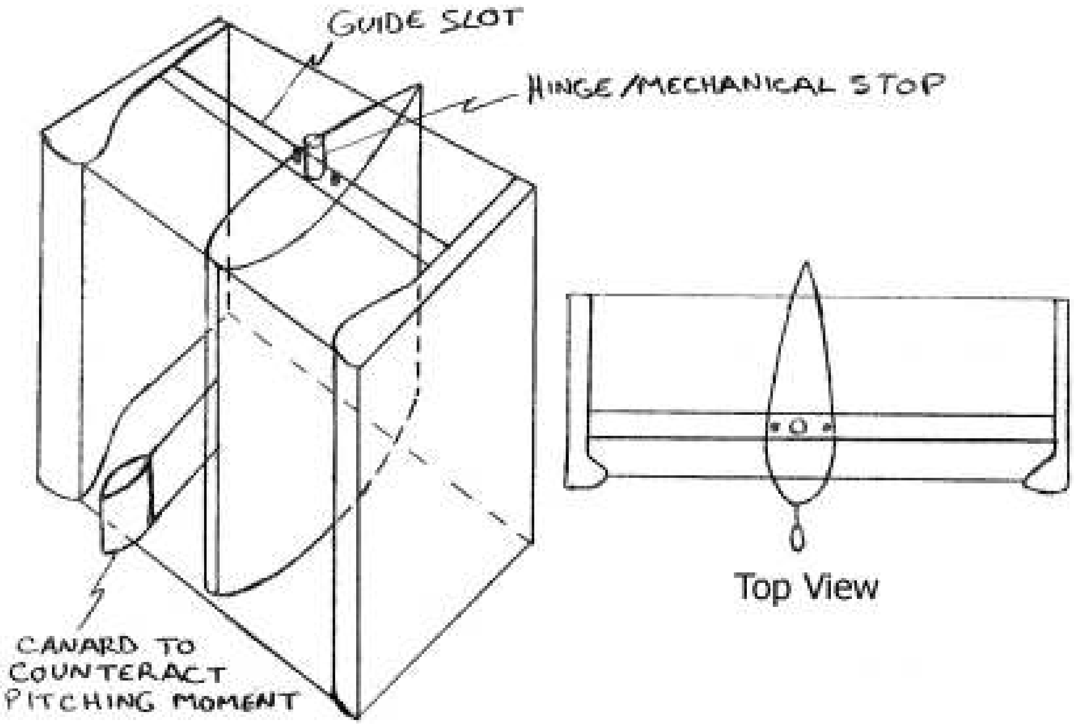

Figure 12 – Sketch of Flutter Power Concept

Power generation calculations for this mechanism were rudimentary at best due to the fact that this is a new idea. From our best estimations, at the maximum storm drain capacity flow rate the mechanism will generate 300 W of power (see Appendix C.2 for a detailed calculation). As expected, this is much lower than concepts utilizing turbines.

Installation costs for this concept would be low. The mechanism would need to be developed and constructed however this will likely be lower than buying a commercially available turbine. Further, very little excavation would be needed as the mechanism would be designed to fit within the manhole located at the beach outflow pipe location. A structure would need to be constructed for the electrical elements however this would be smaller than a full powerhouse. Another beneficial aspect is that the concept would work without fully developed pipe flow as force would still be imparted to the mechanism if open channel flow were present. Therefore no flow control would be needed. Installation costs would consist of excavation, concrete, the cost of the mechanism, and labour costs.

Flutter power generation would have little effect on the surroundings. A small structure to house electrical equipment would be needed however this could be located underground. Therefore no change in landscape is expected and noise generation would be minimal, if any. As well because no large excavations are expected, dangers to the fragile cliff side during installation are non-existent.

Maintenance procedures for this concept are difficult to provide as no such mechanism exists. The system would operate automatically so no operation would be needed. Maintenance would likely consist of regular inspection of the mechanism to ensure the foils were travelling smoothly and the magnets were in place.

Because the mechanism would be located directly in the outflow pipe this concept would cause some flow restriction, reducing the capacity of the spiral drain. A bypass pipe could be built however this would increase installation costs.

The resonating motion of the flutter mechanism and the linear inductor will generate an AC current which can be used to charge a battery pack. The battery pack can be drained for final usage or can be used to power a compressor for compressed air storage, or a fuel cell for hydrogen storage. No generator is needed in this system as the linear inductor inherent in the flutter mechanism generates current.

Safety risks for this concept are minimal. No rotating machinery is involved and normal operating conditions of the outflow pipe are expected to be open channel flow meaning no pressurized piping.

5.3 Concept Scoring

5.3.1 Evaluation Criteria Weighting

Analysis of the problem statement and much discussion amongst the design team provided the following weights for evaluation criteria:

Evaluation Criteria	Weight
Power Generation	25%
Installation Difficulty / Cost	20%
Effect on Surroundings	15%
Maintenance	10%
Flow Restriction	10%
Power Storage and Transmission	5%
Safety	15%

Table 2 – Evaluation Criteria and Weights

Power generation was chosen to have the highest weight as it is the main focus of this project. Installation was chosen to have the next highest as high installation costs will prevent this project from ever being implemented. Effect on surroundings and safety were chosen next in line as they are very important aspects of the design but are not essential to the project being implemented. Maintenance and flow restriction were weighted next as again they are important to the design but not as essential as the other design aspects. Power storage and transmission does have some effect on the conceptual choice but it is minimal.

5.3.2 Scoring Matrix

Concepts were scored on a scale of 0 to 10 for each of the evaluation criteria, with 0 being the worst score and 10 being the best. Scores were decided upon by general consensus amongst the design team and were based on the discussions on concepts in the previous sections. Please see the following page for the full concept scoring matrix.

Evaluation Criteria	Weight	Kaplan Turbine in Outflow Pipe	Crossflow Turbine in Throttling Pipe	Turgo Turbine in Separate System	Flutter Mechanism in Outflow Pipe
Power Generation	0.25	4	5	10	0
Installation Difficulty / Cost	0.2	7	1	1	8
Effect on Surroundings	0.15	5	8	5	7
Maintenance	0.1	5	5	4	7
Flow Restriction	0.1	6	3	10	2
Power Storage	0.05	6	5	6	6
Safety	0.15	5	7	5	9
WEIGHTED SCORES	1	5.3	4.75	**5.9**	5.2

Table 3 – Concept Scoring Matrix

6.0 Conclusions

All told, our highest scoring concept was utilizing a Turgo turbine in a separately constructed pipe system. Although this concept has high installation costs and will be difficult to implement, it is the easiest system to predict and control the flow characteristic and also provides the highest power generation of all the concepts. As well, because another pipe would be added to the current system the drainage capacity of the northern spiral drain would actually increase, providing another operational safeguard against overflow and cliff erosion. Also of note, if the separate pipe system was designed to travel through the existing concrete structures on the beach it would eliminate the need to construct a powerhouse for the turbine and associated components. This would greatly lower the overall capital costs and difficulty of implementing this system.

Because of predictability, ease of flow control, high power generation, and increased drainage capacity, the Turgo turbine in a separate pipe system was chosen as the best concept. The design team will proceed forward with detailed design of this system including design of the penstock pipe and associated structures, flow control and shut-off valves, filtration system, and turbine installation. Every effort will be made to reduce capital costs and maintenance requirements while maximizing power generation and safety. The design team is optimistic that this concept will be able to solve the problem statement of the UBC Northern Spiral Drain Energy Recovery Project.

Abstract

The northern spiral drain at the University of British Columbia (UBC) is a hydraulic system responsible for draining half of the campus's storm and groundwater run-off. Brenda Sawada, manager of the UBC Social, Ecological, Economic Development Studies program (SEEDS) requested that the UBC Mechanical Engineering Department investigate the possibility of power generation from the spiral drain water flow. This report details the preliminary technical analysis completed by the project design team.

Based on the analysis of conceptual alternatives, the design chosen to proceed forward with into the detailed design phase was building a separate pipe system off of the current drainage system and diverting the flow through a turbine. Two main systems of the design were identified: the electro mechanical system and the flow control system. The electro mechanical system consists of the turbine, the generator, and the gears, shafts, and bearings which connect the two machines. The flow control system consists of three different pipes: the penstock, the outflow, and the overflow. Two gate valves, a needle valve, and a deflector are also used in the flow control system.

Due to a lack of rainfall data, detailed flow calculations could not be completed and hydraulic calculations had to proceed as a function of flow rate. A fixed static head of 80 meters was assumed and calculations were completed to determine pipe diameter and hydraulic power for different flow rates. As well, the maximum overpressure from the water hammer effect was calculated for differing pipe diameters and valve closing times. Future calculations needed to finalize the technical analysis were identified as flow calculations, mechanical component design, and turbine sizing.

Failure modes, effects, causes, and probability were identified and analyzed. The most damaging failure was shown to be a plug in the overflow pipe, however numerous other failures had the potential to be catastrophic. It was determined that correct design of machinery components and piping could mitigate many of the system's failure modes. As well, it would be beneficial to utilize a redundant overflow system and a trash rack to prevent large material from damaging the system.

Although operating flow rates have not yet been calculated, a "best guess" estimate was completed by the design team. If the flow rate is 10% of the maximum capacity of the drain, a steel pipe with an internal diameter in the range of 6-8 inches is a likely choice. Steel was chosen due to the 1.2 MPa of pressure seen from the water hammer effect. At this flow rate of 0.3 m^3/s, this pipe would generate approximately 18 kW.

Rainfall data and flow calculations are the next crucial step in the project's development. Once the data is obtained and the calculations are completed, the design team can move forward to sizing the turbine and the associated mechanical components, as well as finalized power estimates and pipe sizes.

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List of Figures

1.0 Introduction

The northern spiral drain at the University of British Columbia (UBC) is a hydraulic system responsible for draining half of the campus's storm and groundwater run-off. Brenda Sawada, manager of the UBC Social, Ecological, Economic Development Studies program (SEEDS) requested that the UBC Mechanical Engineering Department investigate the possibility of power generation from the spiral drain water flow. The UBC Northern Spiral Drain Energy Recovery project is tasked with solving how electrical power could be generated from the water flow. This report details the preliminary technical analysis of the concept chosen for the final design.

Based on analysis of conceptual alternatives completed by the design team, the concept chosen for detailed design was constructing a separate pipe system off of the current drainage system and diverting the flow through a Turgo turbine to generate power. Of all the designs looked at, this concept allowed for maximum power generation and design freedom (please see the report previously completed by the design team titled *"Conceptual Alternatives Report"* for a more detailed discussion). This design has four main functions to satisfy in order to be successful, namely divert the flow from the current drainage system, carry the flow down the Wreck Beach cliff side, control the flow rate, and generate power.

This document provides an analysis of the system architecture detailing the assemblies and components involved in the design. Following this is a discussion of the technical analysis completed for this project including models, calculations, and design variables, and finally an analysis of failure modes and effects. Conclusions are presented and recommendations for future work are discussed.

2.0 Design Architecture

2.1 Assemblies and Components

Two main systems are inherent in the design, the electro mechanical system and the flow control system. These two systems, their components, and their connections are described below.

2.1.1 Electro Mechanical System

The electro mechanical system is composed of two main standard components, the turbine and the generator. The turbine and generator are connected through a gearing system consisting of gears, shafts, and bearings to support the assembly. Gears will likely be attached to the shafts by keyways and bearings will use an adapter sleeve mount and tapered inner ring. Both the turbine and generator will utilize a mounting bracket and bolt assembly to connect them securely to their specified locations in the powerhouse.

2.1.2 Flow Control System

The flow control system is composed of two main components, the piping and the valves. Three main assemblies of pipe are present: the penstock pipe, the outflow pipe, and the overflow pipe. All three pipe assemblies will have seals and fittings associated with them. Four valves will be used in the system. A gate valve will be present at both the entrance and exit of the penstock pipe and will be used when complete shutdown of the system is needed. A needle valve will be present at the exit of the penstock pipe to govern the flow rate to the turbine, and finally a deflector will be used to divert the flow away from the turbine in case of emergency.

2.1.3 System Connections

The electro mechanical system and flow control system are connected through two interactions. Firstly, the water flow travelling through the piping and valves is accelerated and directed towards the turbine blades. The momentum of the flow acts on the turbine blades, and therefore connects the two systems together. Secondly, a governor will connect the two systems through a series of sensors to measure turbine speed and an actuator to control the needle valve. The governor will also have sensors to measure reservoir depth and shut off the needle valve if the reservoir reserves are dwindling.

2.2 Schematic Diagram and Flow Sheet

Please see the following pages for a schematic diagram and flow sheet of the components.

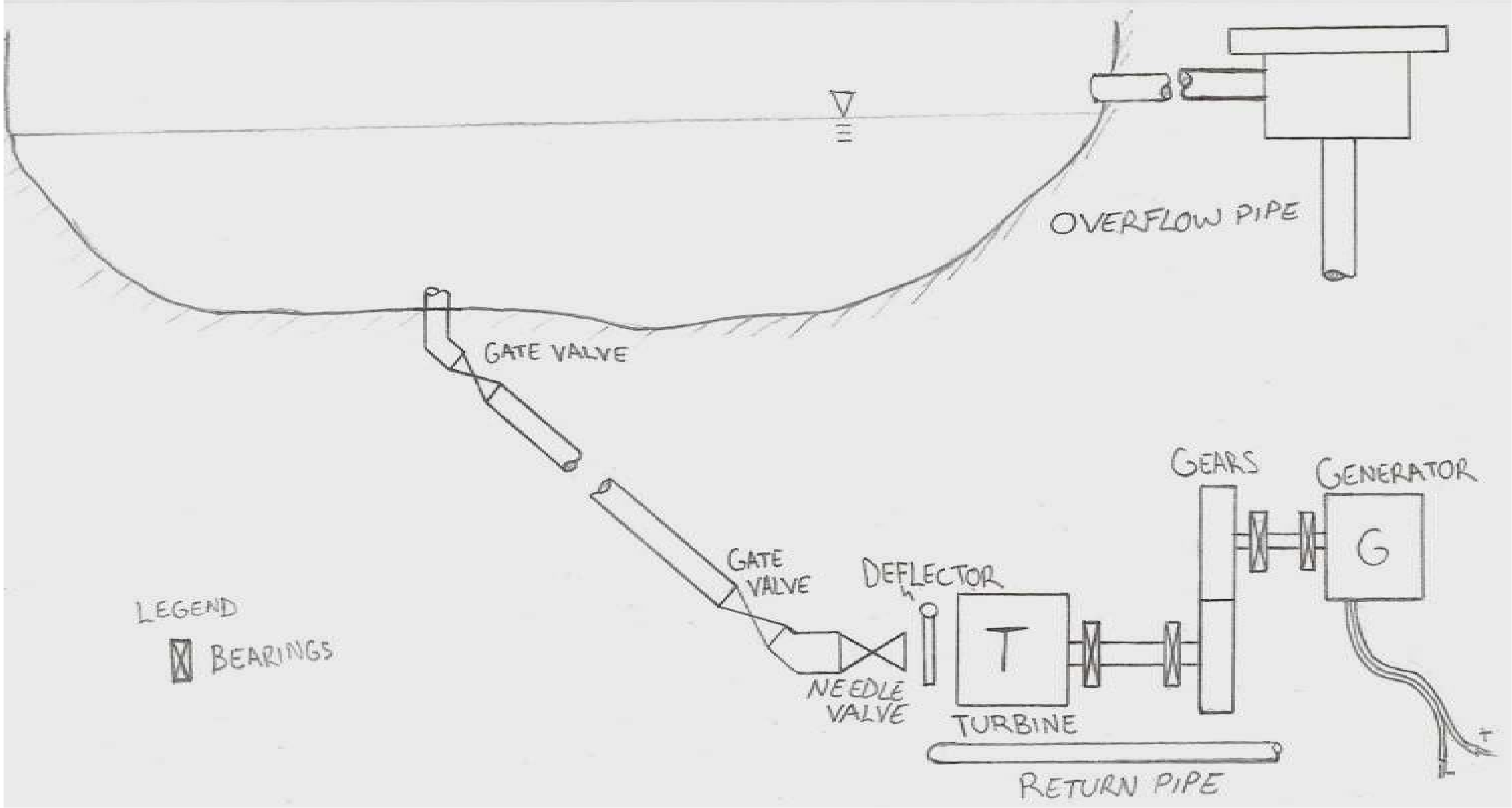

Figure 1 – Schematic Drawing of Spiral Drain System

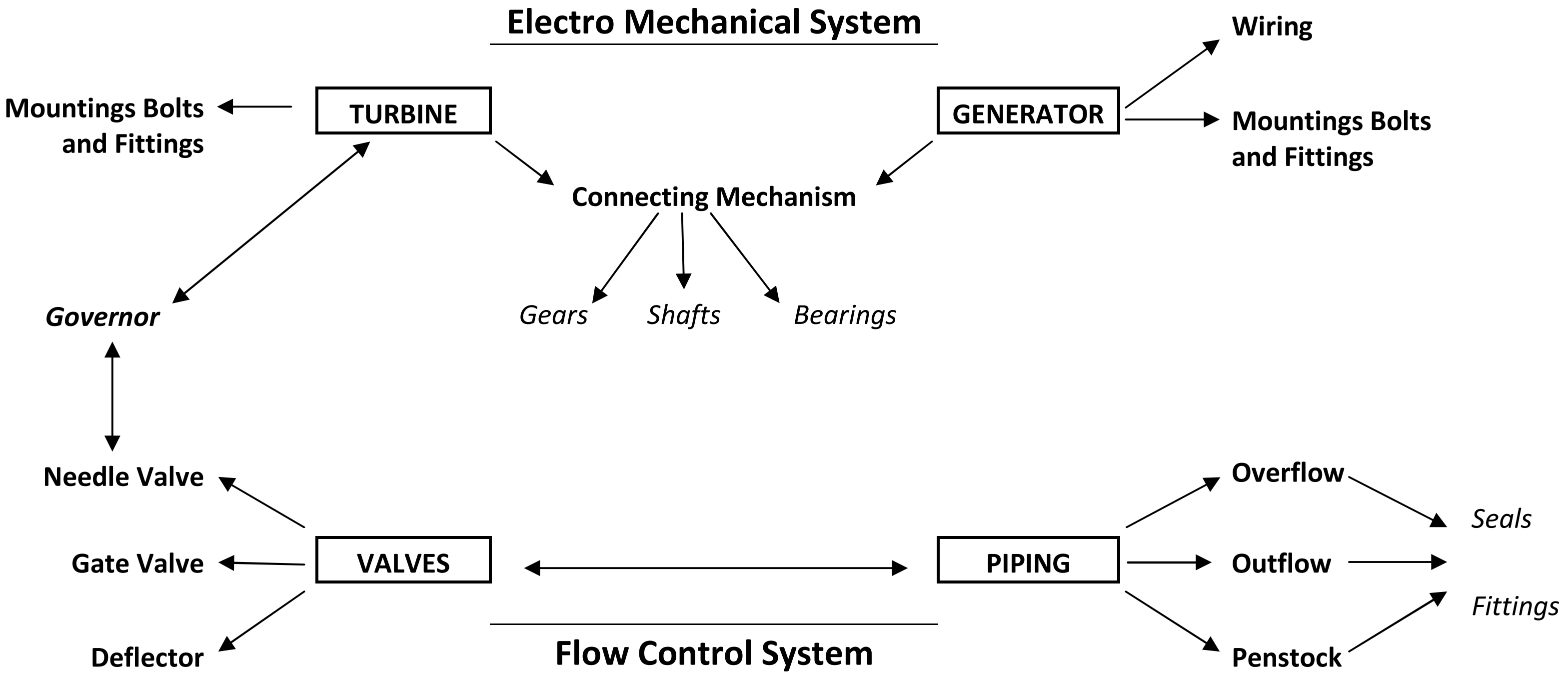

Figure 2 – Component Flow Sheet

3.0 Parametric Design

3.1 Models and Simulations

Due to a lack of detailed rainfall data, hydraulic calculations were completed as a function of flow rate. Further, because the turbine will be sized based on flow rate mechanical calculations for shaft design and assorted other mechanical components will be forthcoming. A discussion of future calculations and analytical work can be seen in section 3.1.3.

3.1.1 Hydraulic Power and Pipe Diameter Calculations

Please see Appendix C.8 for the detailed calculations.

The main parameter that needed to be determined for the system was the diameter of the penstock pipe running between the reservoir and the turbine. The diameter of the penstock depends largely on the expected flow through the system as it will limit the maximum flow that can reach the turbine. In order to estimate the expected flow rate through the system, detailed rainfall data is needed. At present time, detailed rainfall data is still being procured so a mathematical model was used to determine pipe diameter as a function of flow rate and a subsequent graph was created (see Fig. 3 on the following page).

For this calculation the length of the penstock was assumed to be L = 150 meters. This approximation is based on the schematic drawing provided by the client and the assumption that the penstock pipe will be underground. A minor loss coefficient was calculated assuming that there are three 90 degree elbows, three 45 degree elbows, and 2 gate valves; this gave us a minor loss coefficient of K = 2. From the schematic of the current spiral drain system the available static head was estimated as h_{avail} = 80m. The pipe was assumed to be new steel which gave a surface roughness value of ε= 0.046mm. A previous study of the spiral drain system determined the maximum flow rate capacity to be Q_{max}=128.3 ft^3/s (3.342 m^3/s) (Northwest Hydraulic Consultants 1998). Figure 3 on the following page shows the percentage of maximum flow the system can handle as a function of the pipe diameter. It should be noted that the hydraulic power available from the system will display the same shape as it is a function of flow rate.

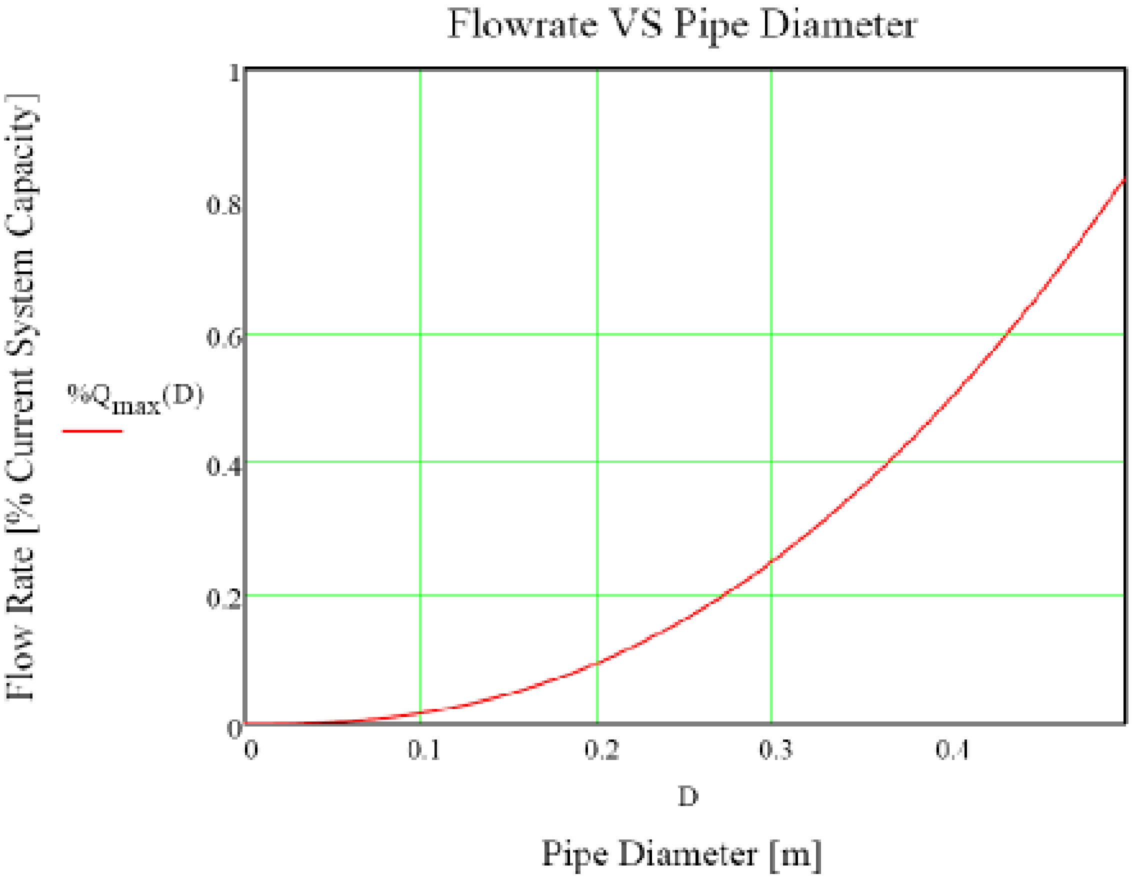

Figure 3 – Graph of Flow Rate vs. Pipe Diameter

As the diameter of the pipe is increased, the flow rate through the system increases exponentially. This is because an increase in the diameter increases the Reynolds number and decreases the ratio of roughness over diameter, both of which lead to a decrease in friction factor and therefore greater flow for the given fixed head.

Once detailed rainfall data is obtained, the range of flow rates that the system is seeing can be calculated and a pipe diameter can be chosen to facilitate the operating conditions.

3.1.2 Overpressure Calculation

In order to facilitate pipe selection, the maximum operating pressure of the penstock pipe is needed. To determine this maximum pressure, the water hammer effect was examined. Water hammer involves the sudden change in the momentum of the flow such as when a valve is closed too quickly.

Initially a water flow is travelling with a velocity and an associated momentum. When a valve is closed the water wants to continue moving due to this momentum however the closed valve does not allow this and the water's kinetic energy goes into "piling up" the water behind the valve. The kinetic energy is converted into pressure energy which causes the water behind the valve to slightly compress and also causes the pipe to expand slightly. This occurs along the length of the pipe until all the kinetic energy is converted into both pressure energy of the compressed water and strain energy of the expanded pipe. Next, a pressure wave unloading the pipe and compressed water travels along the pipe towards the reservoir. This causes the water to momentarily flow back towards the reservoir, which in turn causes a negative pressure behind the valve, which in turn causes the pipe behind the valve to contract. The process then repeats itself until the pipe friction in the system dampens out the pressure waves (Penche 1998). To calculate the maximum pressure for various valve closure times the Allievi formula was used as can be seen in Appendix C.8. This calculation produced the graph in Figure 4 showing the pressure rise for various pipe diameters and closure times.

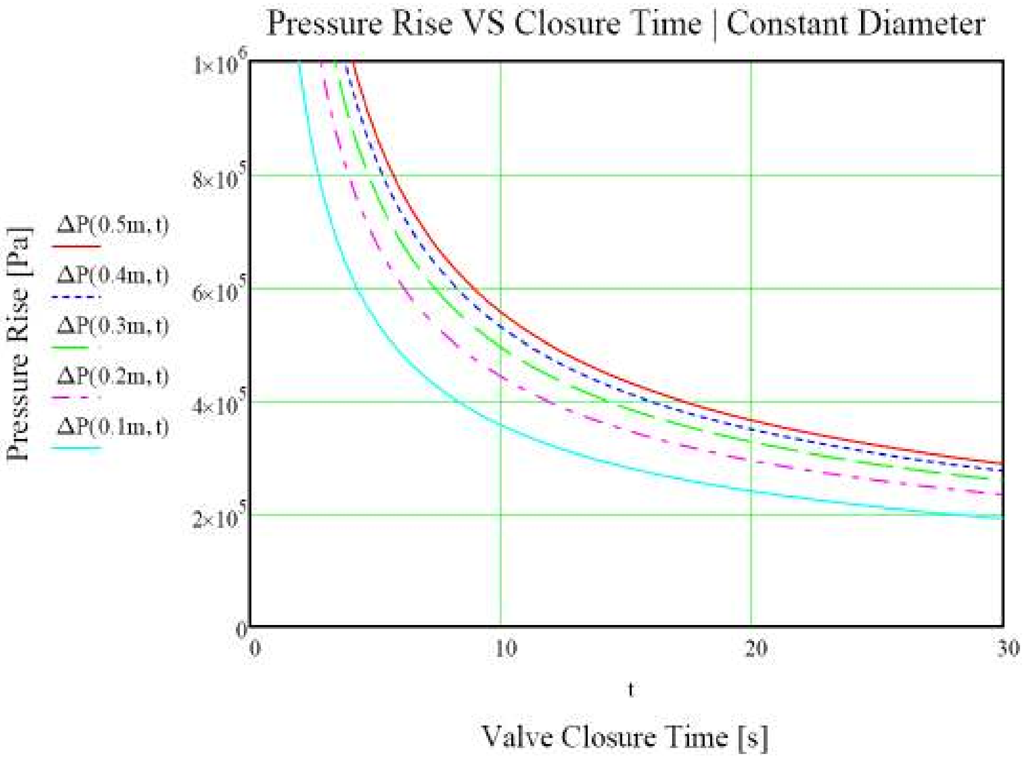

Figure 4 – Pressure Rise vs. Valve Closure Time

If a flow of 10% of the maximum capacity is assumed for normal operating conditions, the required pipe diameter is 0.2 meters (from Fig. 3). If a gate valve was closed over 10 seconds, the penstock pipe would see a maximum pressure of about P_{Max}=1.225 MPa.

3.1.3 Future Calculations

As stated before, rainfall data has yet to be obtained. Once rainfall data is obtained, an estimation of the normal operating conditions of the system can be completed and the internal diameter of the penstock can be decided upon. The maximum pressure of the system will determine the penstock thickness and material. As well, once the flow rate has been estimated a turbine design can be chosen and the associated mechanical components (shafts, gears, bearings) can be designed. In short, before any more technical analysis of the system can be completed the expected flow rates to the system must be determined. Work is presently being undertaken by the design team to complete this calculation.

3.2 Failure Modes and Effects Analysis

3.2.1 Failure Modes Effects Causes and Probability Analysis (FMECPA)

Please see Appendix F for the detailed FMECPA sheet.

3.2.2 Design Considerations

The failure modes, effects, causes, and probability analysis completed by the design team illuminated a number of important design considerations. These considerations must be taken into account when detailed component design is undertaken so as to minimize the risks of catastrophic failure.

Firstly, the piping must be designed to handle the range of pressures expected including overpressures from water hammer and excessive flow rates. Due to the fragile nature of the cliff side (Trow), any failure in piping resulting in water seepage has the potential to greatly enhance the cliff side erosion or in the worst case scenario, cause a landslide. It is critical that all piping is designed for the variation of operating conditions to ensure that no leaks or other failures threaten the fragile environment where this system will be located.

Secondly, it is critical that all machinery components and piping are designed correctly and are sufficiently strong enough to handle the range of operating conditions. Any failure of the rotating machinery whether it is the turbine blades, connecting shafts, or gearing system, has the potential to cause massive damage to all components contained within the powerhouse. It is essential to design the machinery components for shock loading, start-up and shut-off loading, fatigue loading, and corrosion resistance in order to prevent damage to the powerhouse components.

Finally, the FMECPA determined that the most critical failure of the system is a plug in the overflow pipe. Because the overflow is only utilized as a backup during more severe storms, it is likely that a plugged pipe would not be noticed until right before catastrophic failure is imminent. Once someone notices the flow is not exiting through the overflow pipe, the storm would already be in full swing and the reservoir would be in danger of spilling water down the cliff face (as it would have nowhere else to go). Therefore, it would be beneficial to have a redundant overflow system. Another option could be to incorporate regular testing of the overflow pipe for plugging into the maintenance procedures. The severity of an overflow pipe plug also proves the need for a trash rack to prevent larger debris from entering the pipe systems.

4.0 Conclusions

Although the range of operating flow rates for the system has yet to be defined, a rough estimate of 10% of the maximum capacity produces a penstock diameter of approximately 20 centimeters. At this size and assuming a gate valve closure rate of 10 seconds, the penstock will be subjected to approximately 1.2 MPa of pressure. Taking into account that the site location does not allow for a surge tower, research into pipe strengths has shown that this maximum pressure will likely limit the pipe material to steel. In summary, preliminary analysis has shown that a reasonable expectation for the penstock pipe would be a steel pipe in the range of 6 – 8 inches internal diameter, giving a flow rate of approximately 0.3 m^3/s and producing 18 kW of hydraulic power. The design team believes this to be a sound estimate however it is important to stress that this is only a preliminary assessment and that more concrete values cannot be achieved until rainfall data is obtained and operating conditions are determined. Work is currently underway to complete this calculation.

Component design for this system is critical, as evidenced by the failure modes, effects, causes, and probability analysis completed by the project team. It is clear that all mechanical components and pipes must be correctly designed for all operating conditions as a failure of any component could be catastrophic to either the cliff side, the power generation system, or both. As well, the FMECPA illuminated the need for a redundant overflow system and trash rack to reduce the risk of overflow during the more severe storms. If proper care is taken during the detailed design phase, many of the risks associated with this design can be mitigated.

Many other technical aspects of the system still need to be clarified; however they depend on rainfall data. Once detailed rainfall data is obtained, the design team will proceed with flow rate calculations, turbine sizing, and mechanical component design.

Table of Contents

1.0 Introduction

The northern spiral drain at the University of British Columbia (UBC) is a hydraulic system responsible for draining half of the campus's storm and groundwater run-off. Brenda Sawada, manager of the UBC Social, Ecological, Economic Development Studies program (SEEDS) requested that the UBC Mechanical Engineering Department investigate the possibility of power generation from the spiral drain water flow. The UBC Northern Spiral Drain Energy Recovery project is tasked with solving how electrical power could be generated from the water flow. This report provides a summary of the components needed for the final design and an estimation of costs.

2.0 Final Design Components

2.1 Turbine Runner

The concept design phase of the Spiral Drain project concluded upon a Turgo turbine runner as the ideal choice for the expected flow conditions. A Turgo runner manufacturer, Hartvigsen-Hydro, was located in Kaysville, Utah and through discussions with the manufacturer the design team was able to decide upon a specific runner. A picture of a smaller sized but similarly designed runner can be seen below. The cost estimate provided by the manufacturer was $7000.

Figure 1 – Turgo Runner Design

2.2 Transmission Shaft

Based on rainfall data obtained from UBC Campus Planning, the design team was able to develop numerous scenarios for expected flow through the spiral drain. The final design choice was based on maximum power generation and set the flow rate to $0.257 m^3/s$ through a 6'' diameter penstock and nozzled through a 3.75" exit diameter. A design speed of 1200 RPM was chosen and the torque applied to the shaft was obtained through power calculations. The shaft material and shaft size were decided upon by a fatigue stress analysis, see Appendix C.9 for detailed calculations.

Through an online steel supplier, 15-5PH centerless ground stainless steel (annealed condition) round stock was found. The strength was adequate for the stress condition and final cost for a 4ft bar of 2.5" stock was $680.45.

For a detailed drawing of our shaft, see Appendix D.2.

2.3 Bearing Assembly

SKF was the chosen bearing manufacturer due to the design team's previous experience with their product and support staff. Detailed below is the bearing assembly. See Appendix E for drawings and information of the components.

2.3.1 Bearings

Self aligning ball bearings (SABBs) were chosen as the bearing design. SABBs have self aligning capabilities making the requirements for shaft alignment less stringent. As well, SABBs work well with the designed speed and loading condition. Full bearing selection calculations were completed by the design team and all the requisite conditions (minimum load, limiting speed, service life, lubrication) were met by the SKF 1313 EKTN9 and SKF 1210 EKTN9. The SKF 1313 EKTN9 is larger in size and therefore has a higher load capacity; it was chosen as the fixed bearing, responsible for taking the axial loads of the shaft. SKF was contacted for a quote and listed the bearings at $186.88 and $109.34.

2.3.2 Bearing Housings

SAF housings with adapter sleeve mount were chosen for the bearings. SAF housings are easy to install with two standardized bolt holes for mounting. As well, the split block design of the SAF housing allows for easy maintenance and inspection. The designations for the chosen two housings are SAF 1613 and SAF 1510. SKF quoted the housings at $597.43 and $461.78 respectively.

2.3.3 Auxiliary Components

The final remaining components of the bearing assembly are fixing rings, seals, and adapter sleeves. Fixings rings of designation SR 13-0 are required for the SAF housing chosen, and triple ring seals come standard with the housings. Adapter sleeves of designation HA 213 and HA 210 are needed for mounting the bearings. Adapter sleeves were quoted at $131.96 and $75.42 respectively, and fixing rings at $39.08 each.

2.4 Battery Pack

A 24 volt bank off-grid battery pack was chosen to operate the power storage equipment (which will likely be a fuel cell). A battery pack is needed to handle the fluctuations in power generation due to inconsistencies in the spiral drain flow rate. An online supplier was found and quoted a battery pack at $4100.00.

2.5 Generator

The design team is currently in contact with a supplier for a generator for the system. Numerous designs have been looked at but the final decision has yet to be made.

2.6 Penstock Pipe

In order to reduce frictional losses in the penstock pipe, the design team decided upon two 6" steel pipes to transport the rainfall flow down the cliff side to the powerhouse. A steel pipe supplier was found online and a cost estimate was given at $204.00 per meter of pipe. The design team expects about 150m of pipe per penstock, bringing the total estimated cost to $72,000.

2.7 Valves

Three valves are needed in the final design: two gate valves for system shut-off and a needle valve for control. A 6" gate valve design was found on McMaster Carr for $841.79 a unit. A supplier of needle valves for the system is still being sought.

3.0 Installation and Labour

3.1 Machining Labour

The only machined component of the design is the transmission shaft. In order to machine the shaft, the 2.5'' round stainless steel stock will need to be dropped to a diameter of 2-3/16" for the larger step and 1-11/16" for the main diameter. As well, a circumferential slot will need to be machined for a retaining ring. Both of these operations will require lathe work. A keyway will also need to be put in the shaft near the shoulder. This will require either an end mill or sled runner (a sled runner is the preferred machine as it reduces stress concentrations in the shaft). Finally, the shaft surface will need to be ground finished to reduce stress concentrations. All told, the design team estimates the machining work to be approximately 8 hours. At a cost estimate of $70/hr, this equates to $560.

3.2 Excavation Labour

Because the penstock pipes will be travelling underground, a considerable amount of excavation is needed to drill the penstock lines down to the powerhouse on the beach. David Grigg of UBC Campus Planning estimated a total cost of approximately $40,000 (including piping) for each 6" line. This equates to about $12,000 in labour and excavation costs per line, and $24,000 total for the project.

3.3 Installation Labour

Construction of the powerhouse and installation of the turbine, shaft, bearings, piping, and valves is estimated to take 800 hours. This equates to a 10 man crew working two full work weeks. Due to the industrial nature of the construction and installation, cost was estimated at $80 per worker per hour, bringing the total cost of powerhouse construction and installation to $64,000.

4.0 Cost Summary

Sub-System	Description	Components	QTY	Unit	Price/unit	Total Cost
Reservoir to Turbine		Piping	300	m	$240.00	$72,000.00
		Gate Valve	2	ea	$841.79	$1,683.58
		Needle Valve	1	ea	TBA	TBA
	Excavation, including labor	Design and Installation	1	ea	$24,000.00	$24,000.00
	Installation of piping components	Labor	40	hr	$75.00	$3,000.00
Power House		Turgo Turbine	1	ea	$7,000.00	$7,000.00
	Shaft raw materials	2-1/2"OD 4' L Circular Stock, Center-Less Ground, 15-5 Anneal Stainless	1	ea	$680.45	$680.45
	Shaft machining labor	Machinist Labor	8	hr	$70.00	$560.00
		Generator	1	ea	TBA	TBA
	Bearings Total Cost	Bearings	1	set	$296.22	$296.22
		Bearing Housing	1	set	$1,059.21	$1,059.21
		Adapter Sleeves	1	set	$207.30	$207.30
		Fixing Rings	1	set	$78.16	$78.16
	Crew of 5, 20 days	Installation labor	800	hr	$80.00	$64,000.00
	C&D, AT-27, 2 volt cells, 1500 amp/hour	Off Grid Batteries	1	ea	$4,100.00	$4,100.00
						$178,664.92

5.0 Conclusions

The estimated cost of our system is $178,664.92; this includes most of the components as well as installation and labour. As stated above, the design team has already secured suppliers for most of the components of the system meaning if the client, UBC Campus Planning, decides to proceed with this project they will already have a list of available suppliers. The design team will continue seeking suppliers for the remaining components and will update the client and the design specifications as available. More accurate cost estimates can be obtained if needed.

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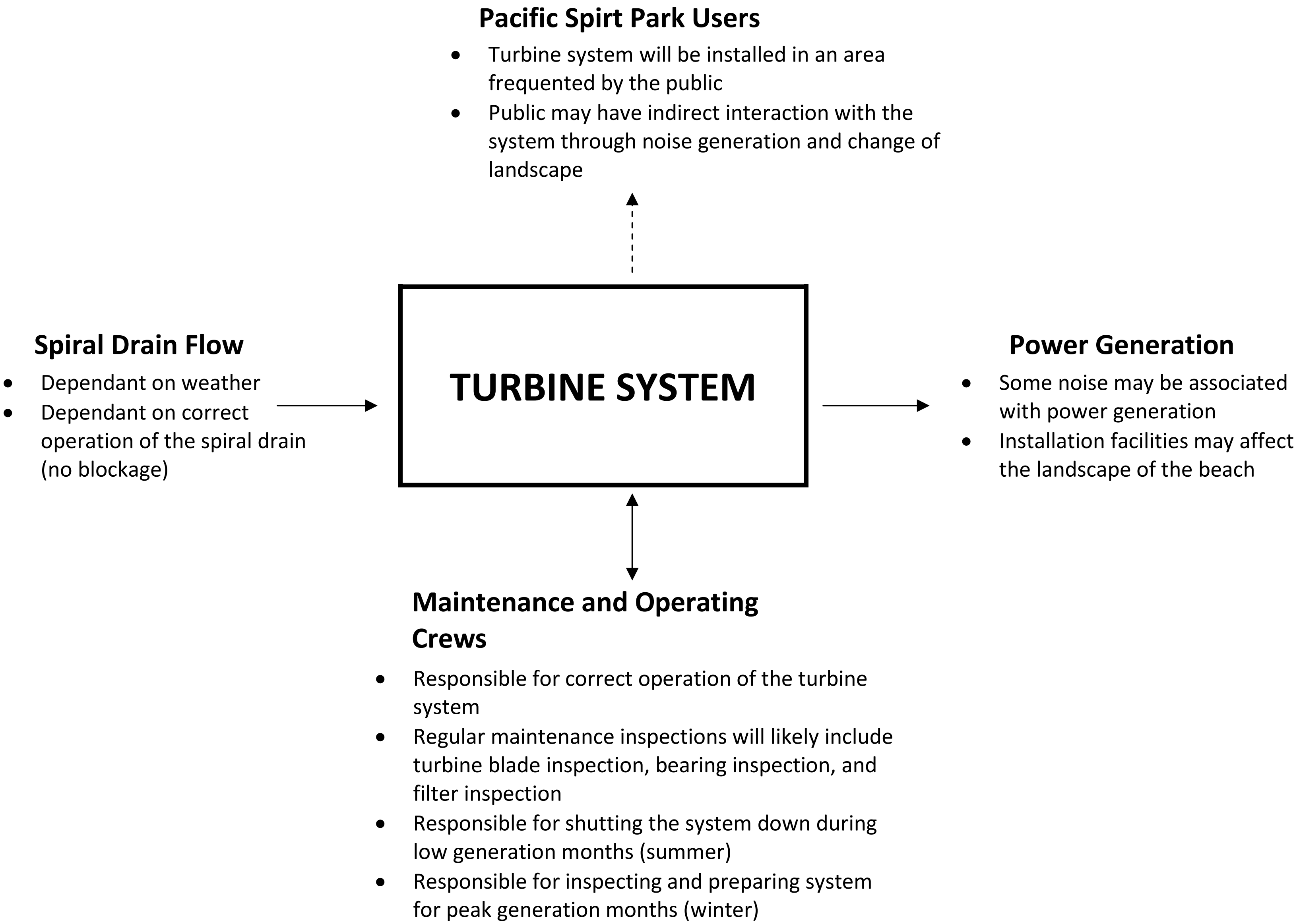

Pacific Spirt Park Users

- Turbine system will be installed in an area frequented by the public
- Public may have indirect interaction with the system through noise generation and change of landscape

Spiral Drain Flow

- Dependant on weather
- Dependant on correct operation of the spiral drain (no blockage)

TURBINE SYSTEM

Power Generation

- Some noise may be associated with power generation
- Installation facilities may affect the landscape of the beach

Maintenance and Operating Crews

- Responsible for correct operation of the turbine system
- Regular maintenance inspections will likely include turbine blade inspection, bearing inspection, and filter inspection
- Responsible for shutting the system down during low generation months (summer)
- Responsible for inspecting and preparing system for peak generation months (winter)