Development of a Kaplan Turbine for Utilization on the Kunhar River Basin, Pakistan - A Case Study

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Declaration

We certify that this research work titled "*Development of a Kaplan Turbine for Utilization on the Kunhar River Basin – A Case Study"* is our own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources is acknowledged and has been properly referred in the appendices of this report.

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Language Correctness Certificate

This thesis is based on the format which has been provided by the university. It has been assessed by an English Language expert and it is free of typing, syntax, semantic, grammatical and spelling mistakes.

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Copyright Statement

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Abstract

Almost 89 percent of hydropower potential despite being the cheapest source of electricity generation is still untapped in Pakistan. The Khyber Pakhtunkhwa province has the huge capacity for installing of hydropower to generate maximum electricity, followed by Gilgit Baltistan as compared to rest the country, but the potential has not been utilized in a proper way to meet the growing energy demand in these provinces and rest of the areas. These facts were revealed in a study report on "Energy" prepared by Sarhad Chamber of Commerce and Industry (SCCI). According to statistical data of the report, the total hydropower resources of Khyber Pakhtunkhwa are about 24,736 MW in various short, medium and long term projects, followed by Gilgit Baltistan with capacity of total hydro power generation of 21,125 MW. Punjab comes next with a total installed capacity of 7,291 MW, followed by Azad Jammu Kashmir (AJK) with capacity of 6,291 MW, then Sindh with 193 MW, and finally Balochistan with less hydropower producing potential, and an installed capacity of just 1 MW. Despite efforts by both the provincial and federal governments, this vast hydel power generation potential from the country's rivers and streams remains untapped. The aim of this project titled, "Development of a Kaplan Turbine for Utilization on the Kunhar River Basin, Pakistan – A Case Study" is therefore, to conduct a study/assessment on a local site in the Northern Areas of Pakistan and then provide a viable solution to harness this major energy reserve. Different hydro turbine types have been considered, and a selection has been made based on the conditions of an assessed site on the Kunhar River Basin, Pakistan. Design Parameters of a Kaplan Turbine have been calculated, an airfoil selection procedure has been followed and dimensional analysis has also been conducted to scale-down the turbine model, while keeping it similar in design to the actual theoretical turbine design presented for use on-site. Finally, a working prototype of the scaled-down Kaplan Turbine has also been manufactured to assess its performance parameters and determine its efficiencies under different variable conditions. In the end, various recommendations have been made to optimize the performance of the designed systems.

Key Words: *Hydro, Power, Hydel Power Potential, Renewable Energy, Kaplan Turbine, Airfoil Selection, Turbine Design, Kunhar River Basin, Pakistan, Northern Areas of Pakistan*

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CHAPTER 1: INTRODUCTION

The research work in this dissertation has been presented in two parts. The first part is related to the literature review and then the detailed investigation of the construction technicalities and feasibility assessment of developing a hydro-electric turbine for power generation applications in the Northern Areas of Pakistan. For this, a case study has been conducted on the Kunhar River Basin in the Malakandi Region near Balakot in the Kaghan Valley in the Northern Areas of Pakistan. The second part of this dissertation deals with the detailed design, airfoil selection and dimensional analysis of a scaled-down prototype of the theoretical turbine presented in the case study. The objective of this part is to study the performance parameters and efficiency of the experimental prototype and suggest recommendations for the actual full-scale design.

1.1 Problem Statement

The client – Fairy Land Hotel and Resort at Malakandi, Balakot was approached by NUST SMME faculty to discuss the possibility of setting up a demonstrative turbine prototype at the behest in the land area on the River Kunhar to provide them with a sustainable, self-sufficient and renewable source of energy. The power requirement of the Hotel was estimated to be 25 Kilo-Watts, and the site had to be assessed on whether extraction of this energy from the river was a possibility or not.

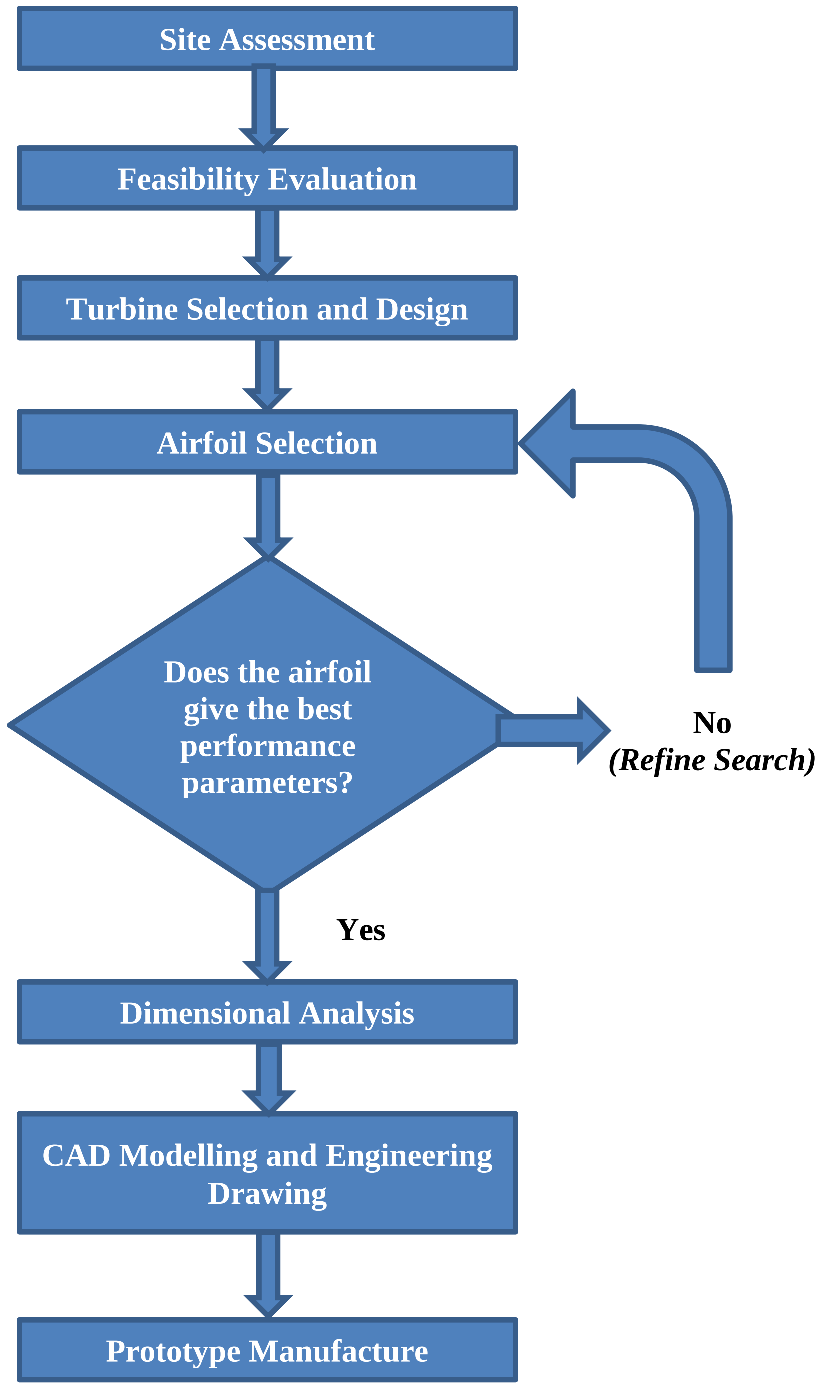
The first part of this project was to assess the site presented to us for the potential of Hydel Power, and then conduct its feasibility study. This was followed by turbine selection and detailed calculation of all design parameters. The turbo machine which we chose for further research and development with regards to our case study was a reaction-type Kaplan turbine whose principle is to extract energy from a running-water river stream and convert it into mechanical energy as power output at the shaft.

1.2 Project Objective

Research and Development of Turbo-Machinery Technology for Capacity Utilization of 25 Kilo-Watts of Hydro-Electric Power Potential present in the stream of the River Kunhar adjacent to Fairy Land Hotel and Resort at Malakandi, Balakot, in Northern Pakistan.

1.3 Project Methodology

The methodology followed during the course of this project to resolve the problem statement, find a solution to it and to achieve the project objective is specified in the chart below.



The literature review conducted in order to follow and complete this project methodology has been discussed in the next section.

CHAPTER 2: LITERATURE REVIEW

In the sub-field of turbines of rotating turbo machinery, various classifications exist to characterize the different types of turbines that produces shaft power from the movement of fluids. One primary classification is upon the basis of the primary-moving force – the impulse force, or the reaction force.

Hence, there are two types of turbines:

1 Impulse Turbines

2 Reaction Turbines

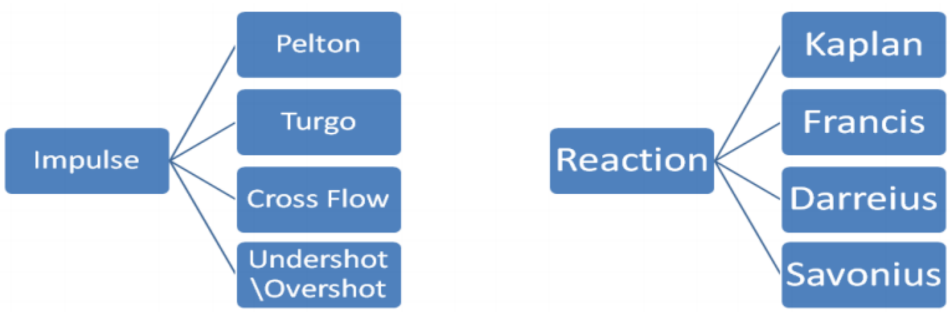


Figure 2.1

In our case, an assessment on a Low-Head, High-Flow rate Turbine, called the 'Kaplan Turbine' will be carried out, since the case study conducted with regards to this project, and as mentioned on the subsequent pages of this report, necessitates the use of this type of a turbine. As is evident from the figure [1]:

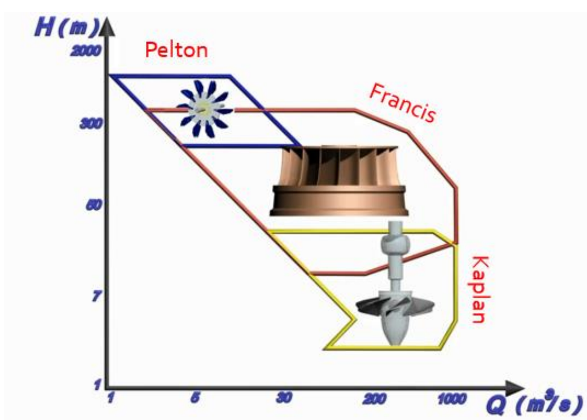


Figure 2.2 – Kaplan Turbine Suited For Low-Head High-Flow Applications

A Kaplan Turbine is a reaction-type turbine, in which the fluid enters the turbine section in an axial direction, and also leaves it axially. The upper section of the turbine is responsible for converting the radial inflow of fluid to and axial direction, and it does this with the help pf guide vanes, stay vanes, and curved profile that varies with the change in diameter of the turbine with respect to the axial direction.

With regards to this Final Year Project, a variable turbine test rig has also been constructed in addition to the development of the turbine in order to demonstrate the fundamentals of the aforementioned turbo-machinery technology, and to allow further relevant experimentation to be conducted on the turbine system.

The case study, which was conducted as an integral part of this project, has been discussed in detail in the next section of this report.

CHAPTER 3: CASE STUDY

A team of engineers from the School of Mechanical and Manufacturing Engineering at the National University of Sciences and Technology, Islamabad assessed the feasibility of developing hydro-energy projects at the Kunhar River Basin within the Kaghan Valley in the Northern Areas of Pakistan. The study included an opportunity assessment, technical research and an investigation into legislative, planning and environmental constraints.

The team also provided the client with advice on technology options and scale, based upon the resource feasibility. An overview of the financial viability of project development was also covered in the study.

Case Study Brief

- Assessment of a site located on the Kunhar River Basin for Hydel Energy Potential
- Realization of more than 25 Kilo-Watt of Hydel Power Capacity
- Financial Feasibility Evaluation of almost Rupees 2 Million (Rupees 20 Lakh)
- Development of Project Schematics
- Development of a Variable Kaplan Turbine Test Rig for Technology Demonstration

3.1 Site Assessment

Figure 3.1 – Fairy Land Hotel and Resort

Location: Fairy Land Hotel & Resort
Malakandi Region
Balakot, Kaghan Valley, Pakistan

Latitude/Longitude: 34.66109, 73.496785

Aerial and Ground Views of Site

Figure 3.2 – Aerial View of Fairy Land Hotel and Resort, on the Kunhar River Basin

Figure 3.3 - Ground Views of 4 different paths assessed on site for Penstock Construction

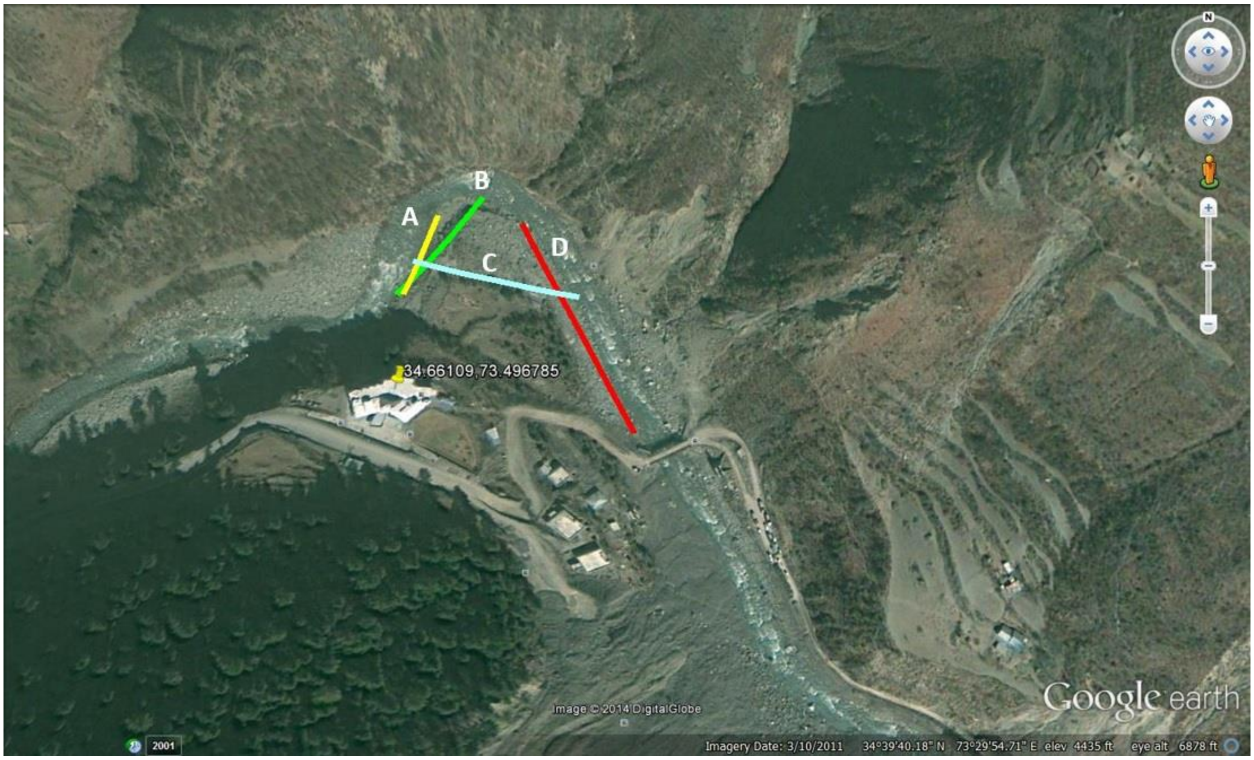


Figure 3.4 – Aerial View of Penstock (Water Channel) Path Layout

Site Data:

Path	**Penstock Length (ft.)**	**Head (ft.)**
A	200	4
B	300	6
C	400	10
D	550	10

Table 3.1

Slope:
For 100 feet length of penstock, slope varies by 2 feet.

River Velocity:
Stream velocity was measured to be in the range 1.8 m/s – 2.2 m/s at site-adjacent stream points.

Project Schematic [1]

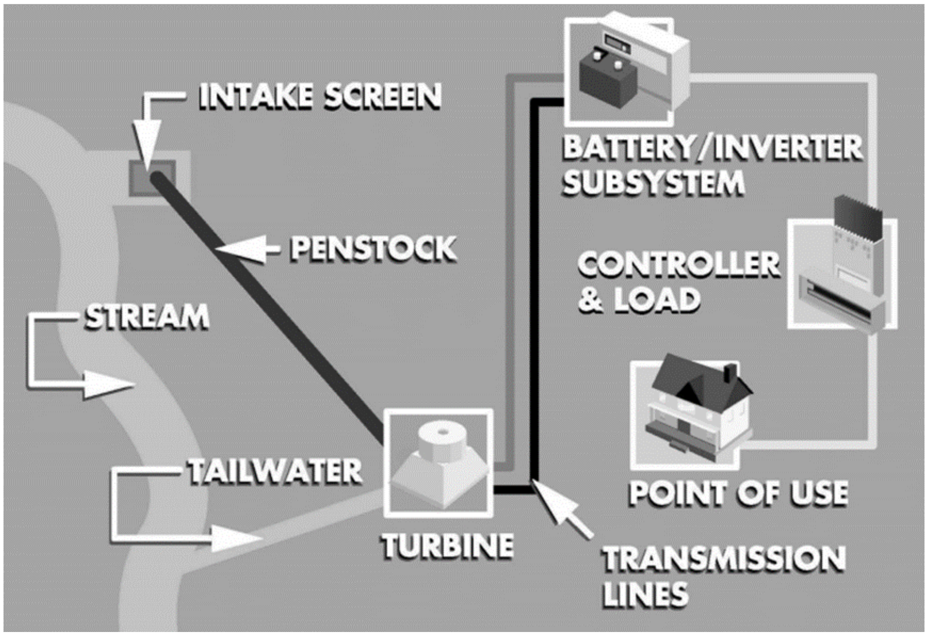
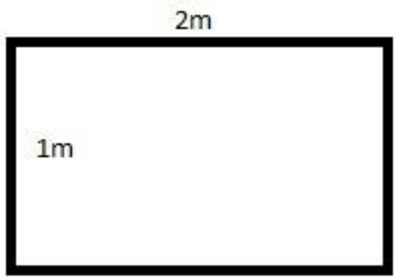


Figure 3.5 – Project Schematic

Site B has a potential to generate up to 31 KW of Hydel Power, based upon the following Open-Channel Flow Parameters. A closed channel flow approach does not yield these results.

Rectangular Cross-Section, 2m x 1m
(2 *meters wide by 1 meter deep)*



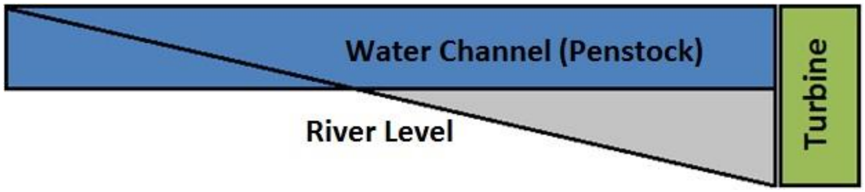


Figure 3.6 – Channel Design

3.2 Feasibility Evaluation

Closed-Channel

Rs. 250 per foot for 12-Inch Dia Pipe (Based on survey), yields:

Site	Penstock Length (ft.)	Head (ft.)	Closed Channel Cost (Rs.)
A	200	4	50,000 + W
B	300	6	75,000 + X
C	400	10+	100,000 + Y
D	550	10+	137,500 + Z

Note: Variables W, X, Y & Z represent the excavation cost for their respective sites.

Figure 3.7 – Closed Channel Cost Estimation

Open-Channel

(Based on Brick-Volume)

Site	Penstock Length (ft.)	Items Required	Open Channel Cost (Rs.)
A	200	20,000 Bricks (Rs. 1,00,000) 4240 Kg Cement (Rs. 42,500) 800 Kg Lime (Rs. 16,000) 15 Cubic-Meters Sand (Rs. 10,000)	1,68,500 + W
B	300	30,000 Bricks (Rs. 1,50,000) 6360 Kg Cement (Rs. 63,600) 1200 Kg Lime (Rs. 24,000) 19.2 Cubic-Meters Sand (Rs. 15,000)	2,52,000 + X
C	400	40,000 Bricks (Rs. 2,00,000) 8480 Kg Cement (Rs. 84,800) 1600 Kg Lime (Rs. 32,000) 25.6 Cubic-Meters Sand (Rs. 20,000)	3,36,800 + Y
D	550	55,000 Bricks (Rs. 2,75,000) 11660 Kg Cement (Rs. 1,16,600) 2200 Kg Lime (Rs. 44,000) 35.2 Cubic-Meters Sand (Rs. 25,000)	4,60,600 + Z

Figure 3.8 – Open Channel Cost Estimation

Cost Estimation per Watt of Energy

Site	*Head (m)*	*Open Channel*	*Closed Channel*
A	4	Rs. 10 / W	Rs. 40 / W
B	6	Rs. 10 / W	Rs. 40 / W

Table 3.2

Sites C and D were eliminated based on factors of higher excavation costs and lower net head availability.

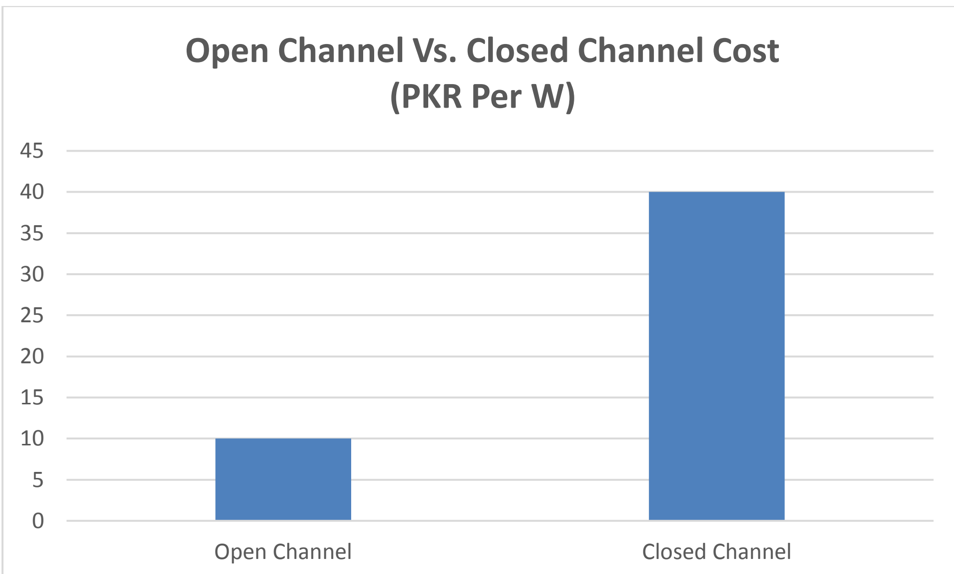


Figure 3.9 – Cost Comparison Open Channel and Closed Channel

Hence, an Open-Channel Approach is the most financially feasible option for Penstock Construction.

A detailed set of calculations is presented in Appendix A.

Total Cost Estimation

(Based On Market Survey Analysis)

Project Breakdown	***Cost (PKR)***
Civil Works	PKR 0.7 Million
Logistics	PKR 0.2 Million
Turbine Manufacture	PKR 0.5 Million
Electrical System	PKR 0.6 Million
Total Cost	PKR 2.0 Million

Table 3.3

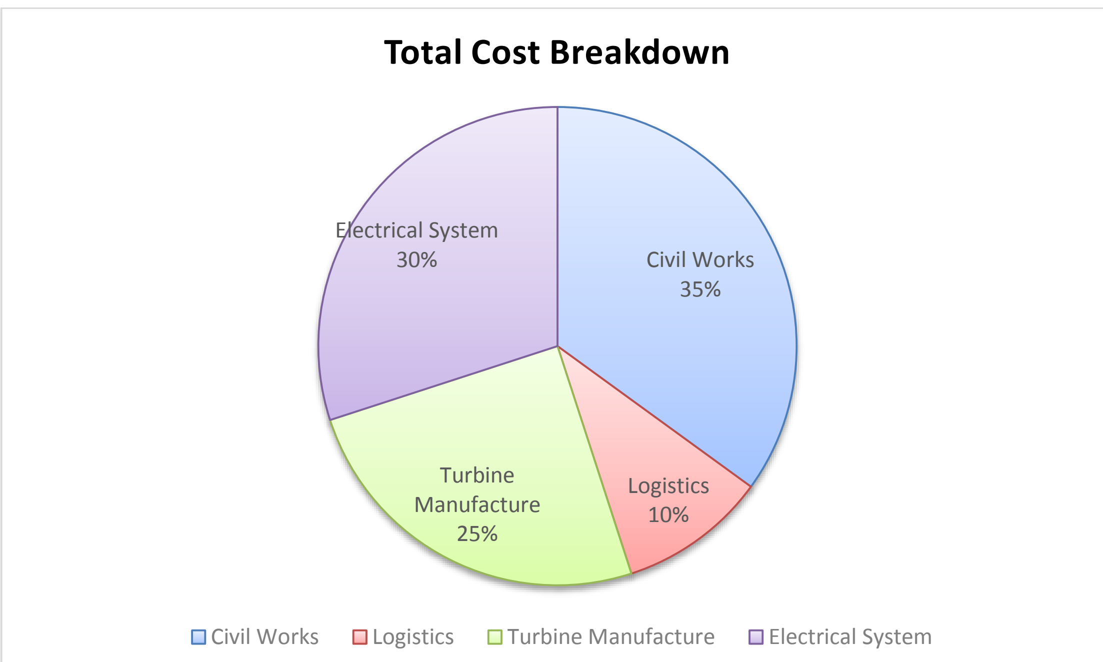


Figure 3.10 – Total Cost Breakdown

3.3 Recommendations

- For a test demonstration with maximum Power Output Capacity less than 10 KW, Sites A and B are recommended, with a Closed-Channel Approach.

- Site C has the best capacity to yield greater power with minimum penstock length; however it is not recommended due to extremely large excavation costs which may be incurred. Taking the factor of high excavation costs into consideration, Site C should be avoided for both Open or Closed channel cases, despite fulfilling the ideal requirements for turbine penstock construction.

- If the Civil Works' Assessment Team can provide valid arguments in favor of Site C, and if the funds available for the complete budget towards the project are sufficient enough, then Site C provides the most ideal conditions for turbine and penstock locations.

- Site D has a profile with a fairly straight and linear layout, but it yields very low change in head with respect to increase in unit length of the penstock. Furthermore, excavation may involve the removal of, or drilling into pre-existing river embankments. This can prove to be a technical challenge and legal jurisdiction to proceed working on the site may be required. As such, the cost vs. benefits ratio for Site D is very high, and therefore it is to be avoided.

- If the Civil Works' Team can observe a solution for construction of an Open-Channel at Site D without affecting the pre-existing river embankments, then it should be preferred over Site C, since the excavation costs for Site D are minimal with respect to those of Site C.

CHAPTER 4: NUMERICAL AND ANALYTICAL METHODOLOGIES

A numerical procedure was followed as described in reference 1 to determine the fundamental parameters of the design of the runner of a Kaplan Turbine. An analytical methodology was then followed to select the best efficiency airfoil section for the Kaplan Turbine blades.

4.1 Numerical Methodology

Step-Wise Procedure [2]

Step 1: Determine Available Parameters for Power Required

$$P = \rho g H Q n$$

Where,

P = Power (Watt)
ρ = Density of Water (1000 kg/m^3)
g = Acceleration Due To Gravity (9.81 m/s^2)
H = Gross Head (Meter)
Q = Flowrate (m^3/s)
n = Efficiency of the System

By defining P = 25 KW, with n = 70 % and H = 1.8 m as measured on the site,

We achieve Q = 2.02$\frac{m^3}{s^2}$.

Step 2: Calculate Specific Speed

The different types of water turbines can be classified by their specific speed. Different definitions of the specific speed exist which can be found in the technical literature. The specific speed is a dimensionless parameter and characterizes the hydraulic properties of a turbine in terms of speed and discharge capacity; it is based on similitude rules.

The specific speed is defined as:

$$N_{s} = \frac{n\sqrt{Q}}{(gH)^{\frac{3}{4}}}$$

Where,

N_{s} is specific speed (Unitless)

n is pump rotational speed (radians per second)

Q is flowrate (m^3/s) at the point of best efficiency

H is total head (m) per stage at the point of best efficiency

g is acceleration due to gravity (m/s^2)

Due to statistical studies of schemes, F.Schweiger and J. Gregory established the following correlation between the specific speed and the net head for Kaplan turbines:

$$N = \frac{2.294}{H^{0.486}}$$

Since the rotational speed is unknown, the specific speed has to be calculated with this formula. Inserting the site parameters into the above equation, we get a specific speed of N = 2.05.

Comparing the results with pre-established Specific Speed parameters for Turbo-Machines yields the range of an axial flow type machine:

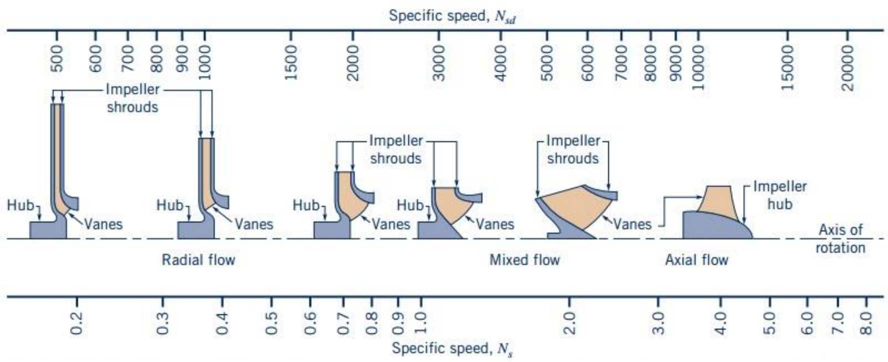


Figure 4.1 Variation in specific speed at maximum efficiency with type of pump [3]

Furthermore, it also helps to ensure that the type of turbine suitable for this application, under the given conditions of Low-Head and High Flow-rate, is an axial flow Kaplan turbine, as it is evident from the following figures.

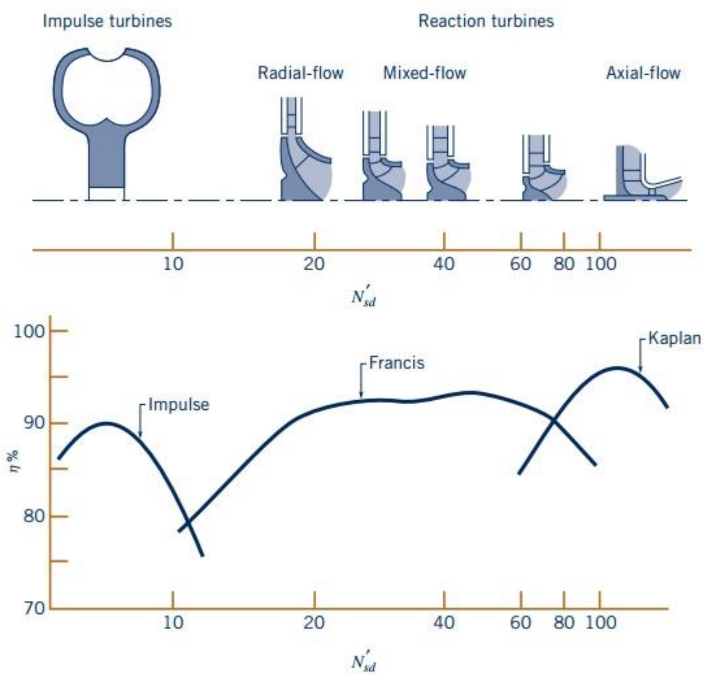


Figure 4.2 Typical Turbine Cross-Sections and Maximum Efficiencies as a Function of Specific Speed [3]

Based on the above assessment, the following ranges are evident for necessitating the usage of different turbine types under different conditions:

Specific Speed Range	Type Of Turbo Machine
0 – 0.8	Radial Flow Impulse Turbine (E.G. Pelton Wheel)
0.8 – 1.8	Mixed Flow Turbine (E.G. Francis Wheel)
1.8 – 3.0	Axial Flow Reaction Turbine (Kaplan Wheel)

Table 4.1 [2]

This tells us that a Reaction-Type Kaplan Turbine is most suited for the case, according to the site conditions.

Step 3: Determine Rotational Speed of the Turbine

From backwards substitution in the following equation, we solve for n:

$$Ns = \frac{n\sqrt{Q}}{(gH)^{\frac{3}{4}}}$$

Where,

n is the Turbine Rotational Speed, in Revolutions Per Second (RPS).

From here, we determine the value of n to be 9.5 RPS,
Or also represented as 570 RPM (Revolutions Per Minute).

Step 4: Determine Runaway Speed

The Runaway Speed is the maximum speed which the turbine can theoretically attain and it is achieved during load rejection, when the turbine is run under no load conditions. Depending on the regulation of the Kaplan turbine, the following guidelines can be used to determine the Runaway Speed:

Turbine Type	**Runaway Speed n_{max}/n**
Single Regulated Kaplan Turbine	2.0 – 2.6
Double Regulated Kaplan Turbine	2.8 – 3.2

Table 4.2 [2]

For this system, (Non-Regulated Kaplan Turbine), n_{max}/n is assumed to be equal to 2.0. Which gives a Runaway Speed of 19.0 revolutions per second (RPS), equivalent to 1141 RPM.

Step 5: Determine Diameter for the Runner Section

The runner diameter D_e can be calculated by the following equation:

$$D_{\mathrm{e}} = 84.5 * (0.79 + 1.602 * n) * \frac{\sqrt{H_{\mathrm{net}}}}{60 * n}$$

This gives a Runner Diameter of D_e = 0.70 m (For the Actual Turbine to be Installed On-Site).

Step 6: Determine Diameter for the Hub Section

The hub diameter D_i can be calculated with the following equation:

$$D_{\mathrm{i}} = \left(0.25 + \frac{0.0951}{n_{qe}}\right) * D_{\mathrm{e}}$$

Where,

D_i = Hub Diameter

n_{qe} = Specific Speed

D_e = Runner Diameter

According to the above calculated values, D_i = 0.207 m.

Hence,

For The Actual Site,

Runner Diameter = 0.70 Meters (70 Centimeters)

And

Hub Diameter = 0.207 Meters (20.7 Centimeters)

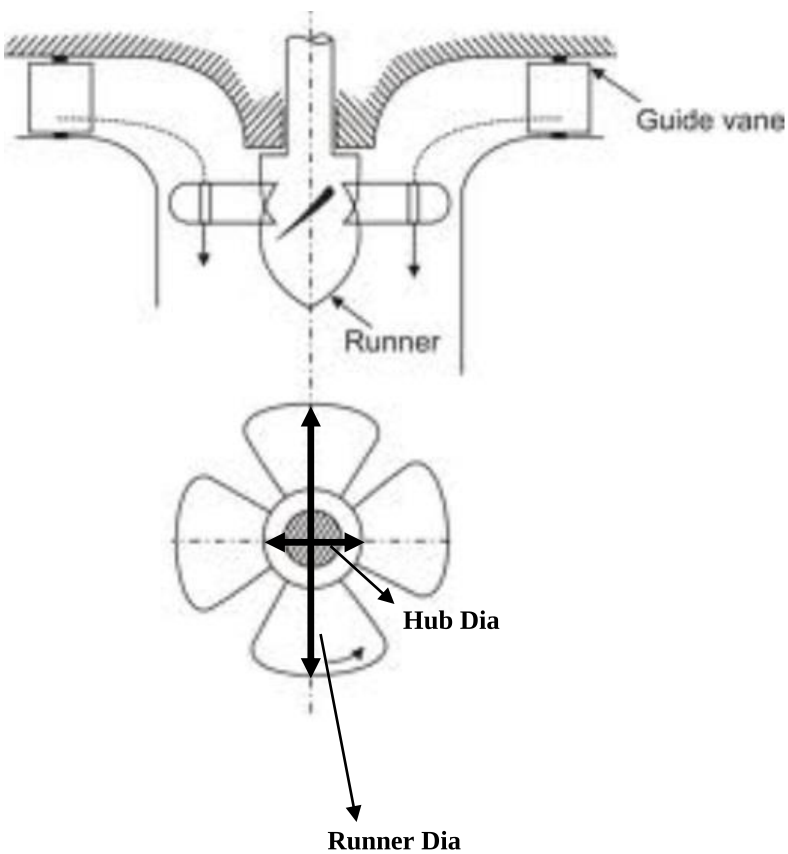


Figure 4.3 – Runner Section

Table 4.3 - Reference Table

Table 4.3 was completed by using the above equations. This table allows the reader to get an overview of the main characteristics of a Kaplan turbine under different head and discharge circumstances.

D_e [m]	0.71	0.75	0.78	0.81	0.84	0.87	0.90	0.93	0.95	0.98	1.01	
D_i [m]	0.22	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.29	0.30	0.31	**H_n**
P [kW]	50	55	60	65	70	75	80	85	90	95	100	
Q [m^3/s]	2.55	2.81	3.06	3.32	3.57	3.83	4.09	4.34	4.60	4.85	5.11	2
n [s^{-1}]	9.56	9.11	8.72	8.38	8.08	7.80	7.55	7.33	7.12	6.93	6.76	
n_{max} [s^{-1}]	28.67	27.33	26.17	25.14	24.23	23.41	22.66	21.99	21.37	20.80	20.27	
P [kW]	66	73	80	86	93	99	106	113	119	126	133	
Q [m^3/s]	2.71	2.98	3.25	3.52	3.79	4.06	4.34	4.61	4.88	5.15	5.42	2.5
n [s^{-1}]	9.84	9.38	8.98	8.63	8.32	8.03	7.78	7.55	7.33	7.14	6.96	
n_{max} [s^{-1}]	29.52	28.14	26.95	25.89	24.95	24.10	23.34	22.64	22.00	21.41	20.87	
P [kW]	83	92	100	108	117	125	133	142	150	158	167	
Q [m^3/s]	2.83	3.12	3.40	3.68	3.97	4.25	4.54	4.82	5.10	5.39	5.67	3
n [s^{-1}]	10.09	9.62	9.21	8.85	8.53	8.24	7.98	7.74	7.52	7.32	7.14	
n_{max} [s^{-1}]	30.28	28.87	27.64	26.56	25.59	24.73	23.94	23.23	22.57	21.97	21.41	
P [kW]	101	111	121	131	141	151	161	171	181	191	201	
Q [m^3/s]	2.94	3.23	3.53	3.82	4.11	4.41	4.70	4.99	5.29	5.58	5.88	3.5
n [s^{-1}]	10.33	9.85	9.43	9.06	8.73	8.43	8.16	7.92	7.70	7.49	7.30	
n_{max} [s^{-1}]	30.98	29.54	28.28	27.17	26.18	25.30	24.49	23.76	23.09	22.48	21.91	
P [kW]	118	130	142	154	166	178	190	201	213	225	237	
Q [m^3/s]	3.02	3.33	3.63	3.93	4.23	4.54	4.84	5.14	5.44	5.75	6.05	4
n [s^{-1}]	10.54	10.05	9.62	9.25	8.91	8.61	8.33	8.09	7.86	7.65	7.45	
n_{max} [s^{-1}]	31.63	30.16	28.87	27.74	26.73	25.82	25.00	24.26	23.57	22.95	22.36	
P [kW]	137	150	164	177	191	205	218	232	246	259	273	
Q [m^3/s]	3.10	3.41	3.72	4.03	4.34	4.65	4.96	5.27	5.58	5.89	6.20	4.5
n [s^{-1}]	10.74	10.24	9.81	9.42	9.08	8.77	8.49	8.24	8.01	7.80	7.60	
n_{max} [s^{-1}]	32.23	30.73	29.43	28.27	27.24	26.32	25.48	24.72	24.03	23.39	22.79	
P [kW]	155	170	186	201	217	232	248	263	279	294	310	
Q [m^3/s]	3.16	3.48	3.80	4.11	4.43	4.74	5.06	5.38	5.69	6.01	6.33	5
n [s^{-1}]	10.94	10.43	9.98	9.59	9.24	8.93	8.64	8.39	8.15	7.93	7.73	
n_{max} [s^{-1}]	32.81	31.28	29.95	28.77	27.73	26.79	25.93	25.16	24.45	23.80	23.20	
P [kW]	173	191	208	225	243	260	277	295	312	329	347	
Q [m^3/s]	3.22	3.54	3.86	4.18	4.51	4.83	5.15	5.47	5.79	6.12	6.44	5.5
n [s^{-1}]	11.12	10.60	10.15	9.75	9.39	9.08	8.79	8.53	8.29	8.06	7.86	
n_{max} [s^{-1}]	33.35	31.80	30.44	29.25	28.18	27.23	26.36	25.58	24.86	24.19	23.58	
P [kW]	192	211	230	250	269	288	307	326	346	365	384	
Q [m^3/s]	3.27	3.60	3.92	4.25	4.58	4.90	5.23	5.56	5.88	6.21	6.54	6
n [s^{-1}]	11.29	10.76	10.30	9.90	9.54	9.22	8.92	8.66	8.41	8.19	7.98	
n_{max} [s^{-1}]	33.86	32.29	30.91	29.70	28.62	27.65	26.77	25.97	25.24	24.57	23.95	

Step 7: Similitude Analysis for Scaling-Down of the Model

From Chapter 12, Fundamentals of Fluid Mechanics, 7th Edition, Munson & Young [3],

Pump Scaling Laws:

$$C_{\mathrm{H}} = \frac{gh_{\mathrm{a}}}{w^2 D^2}$$

$$C_{\mathrm{Q}} = \frac{Q}{wD^3}$$

$$C_{\mathrm{P}} = \frac{W_{\mathrm{Shaft}}}{\rho w^3 D^5}$$

$$C_{\mathrm{P}} = \frac{\rho Q g h_{\mathrm{a}}}{W_{\mathrm{Shaft}}}$$

Where,

C_H = Head Rise Coefficient

C_Q = Flow Coefficient

C_P = Power Coefficient

η = Efficiency of the Pump or Turbine

These four equations provide the desired similarity relationships among a family of geometrically similar pumps. If two pumps from the family are operated at the same value of flow coefficient, then:

(Pump Scaling Laws) [3]

$$\left(\frac{Q}{wD^3}\right)_1 = \left(\frac{Q}{wD^3}\right)_2$$

$$\left(\frac{gh_a}{w^2D^2}\right)_1 = \left(\frac{gh_a}{w^2D^2}\right)_2$$

$$\left(\frac{W_{Shaft}}{\rho w^3D^5}\right)_1 = \left(\frac{W_{Shaft}}{\rho w^3D^5}\right)_2$$

$$\eta_1 = \eta_2$$

Where the subscripts 1 and 2 refer to any two pumps from the family of geometrically similar pumps.

Pump scaling laws relate geometrically similar pumps. With these so-called pump scaling laws it is possible to experimentally determine the performance characteristics of one pump in the laboratory and then use these data to predict the corresponding characteristics for other pumps within the family under different operating conditions.

After adding a restriction of Flow-rate for the scaled-down model, we use the special pump scaling laws.

Assumptions:

$W_1 = W_2$ (Same Rotational Speeds)
$H_{a1} = H_{a2}$ (Same Net Head Available)
$\eta_1 = \eta_2$ (Same Efficiencies)

Special Pump Scaling Laws

$$\frac{Q_1}{Q_2} = \frac{{D_1}^3}{{D_2}^3}$$

$$\frac{h_{a1}}{h_{a2}} = \frac{{D_1}^2}{{D_2}^2}$$

$$\frac{W_{\text{Shaft1}}}{W_{\text{Shaft2}}} = \frac{{D_1}^5}{{D_2}^5}$$

Using the above equations for a Flow rate of 80 Liters per Minute gives

De = 2.4 Inches and Di = 1.7 Inches.

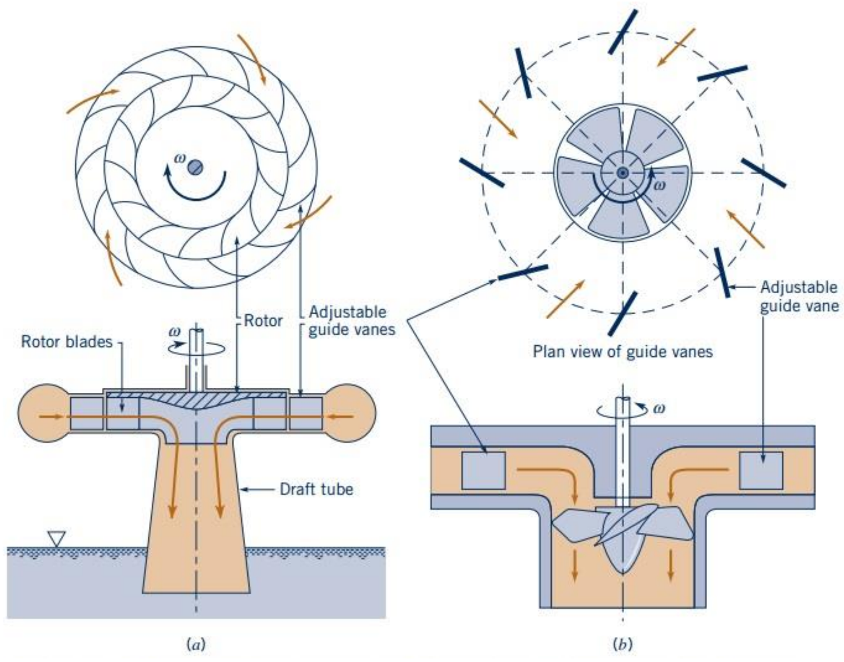


Figure 4.4 – a- Francis Turbine, b – Kaplan Turbine [3]

Additional Notes

For a given pump operating at a given flow coefficient, the flow varies directly with speed, the head varies as the speed squared, and the power varies as the speed cubed.

Also, for a family of geometrically similar pumps operating at a given speed and the same flow coefficient, the flow varies as the diameter cubed, the head varies as the diameter squared, and the power varies as the diameter raised to the fifth power. These scaling relationships are based on the condition that, as the impeller diameter is changed, all other important geometric variables are properly scaled to maintain geometric similarity. This type of geometric scaling is not always possible due to practical difficulties associated with manufacturing the pumps. It is common practice for manufacturers to put impellers of different diameters in the same pump casing.

The effects of viscosity and surface roughness have been neglected in the foregoing similarity relationships. However, it has been found that as the pump size decreases, these effects more significantly influence efficiency because of smaller clearances and blade size.

In general, it is to be expected that the similarity laws will not be very accurate if tests on a model pump with water are used to predict the performance of a prototype pump with a highly viscous fluid, such as oil, because at the much smaller Reynolds number associated with the oil flow, the fluid physics involved is different from the higher Reynolds number flow associated with water.

Hence,
If the test model is too small in size geometrically as compared to the actual full-scale prototype, the test model will be subject to:

1. Greater Turbulence Effects
2. Smaller Clearances
3. Reduced Blade Size
4. Higher Inefficiencies

4.2 Analytical Methodology

An analysis was conducted on different NACA-based airfoil sections in order to arrive at the best airfoil section that could yield the best possible efficiency for the turbine based on site conditions.

A brief summary of the different NACA airfoil series is listed in the table below [4].

Family	Advantages	Disadvantages	Applications
4-Digit	1. Good stall characteristics 2. Small center of pressure movement across large speed range 3. Roughness has little effect	1. Low maximum lift coefficient 2. Relatively high drag 3. High pitching moment	1. General aviation 2. Horizontal tails ***Symmetrical:*** 3. Supersonic jets 4. Helicopter blades 5. Shrouds 6. Missile/rocket fins
5-Digit	1. Higher maximum lift coefficient 2. Low pitching moment 3. Roughness has little effect	1. Poor stall behavior 2. Relatively high drag	1. General aviation 2. Piston-powered bombers, transports 3. Commuters 4. Business jets
16-Series	1. Avoids low pressure peaks 2. Low drag at high speed	1. Relatively low lift	1. Aircraft propellers 2. Ship propellers
6-Series	1. High maximum lift coefficient 2. Very low drag over a small range of operating conditions 3. Optimized for high speed	1. High drag outside of the optimum range of operating conditions 2. High pitching moment 3. Poor stall behavior 4. Very susceptible to roughness	1. Piston-powered fighters 2. Business jets 3. Jet trainers 4. Supersonic jets
7-Series	1. Very low drag over a small range of operating conditions 2. Low pitching moment	1. Reduced maximum lift coefficient 2. High drag outside of the optimum range of operating conditions 3. Poor stall behavior 4. Very susceptible to roughness	Seldom used
8-Series	Unknown	Unknown	Very seldom used

Table 4.4 [4]

It was apparent that the NACA 16-Series Set of airfoils was the most suited to propeller blade applications, and was the basis of further study.

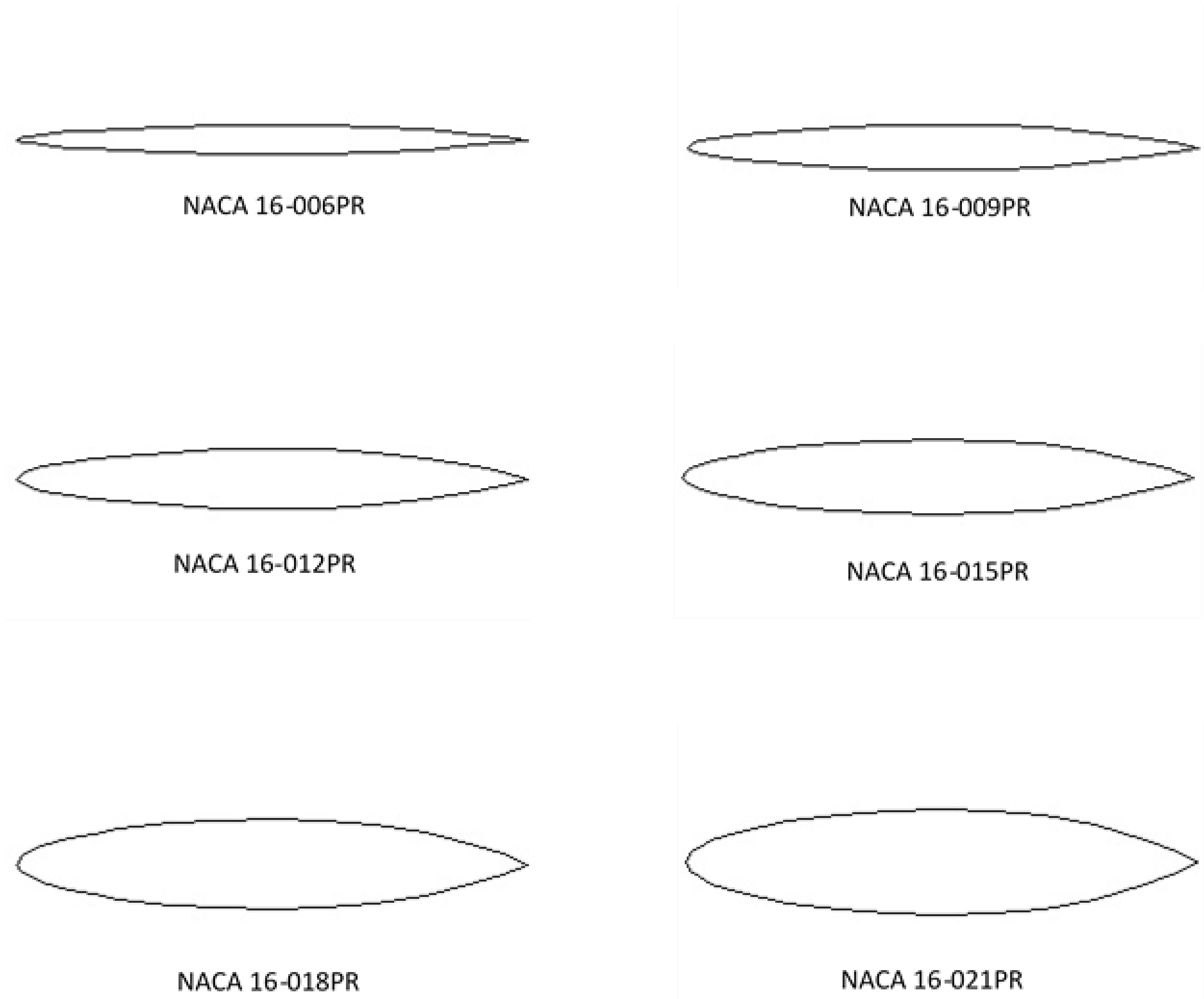


Figure 4.5 – NACA 16 Series Airfoils [10]

Airfoil Assessment

Airfoil Assessment conducted using the Profili Version 2 Toolbox based on the XFOIL Code developed by Mark Drela at MIT.

Program Background & History

XFOIL is an interactive program for the design and analysis of subsonic isolated airfoils. Given the coordinates specifying the shape of a 2D airfoil, Reynolds and Mach numbers, XFOIL can calculate the pressure distribution on the airfoil and hence lift and drag characteristics. The program also allows inverse design - it will vary an airfoil shape to achieve the desired parameters. It is released under the GNU GPL.

Graphs [5]**:**

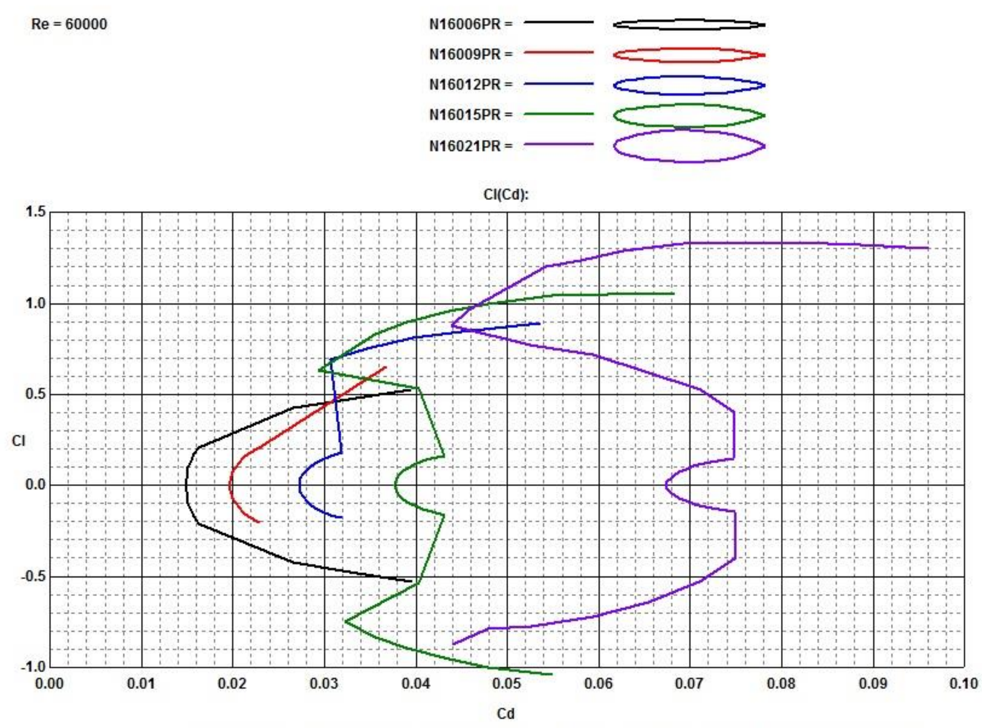


Figure 4.6 - CL vs. CD

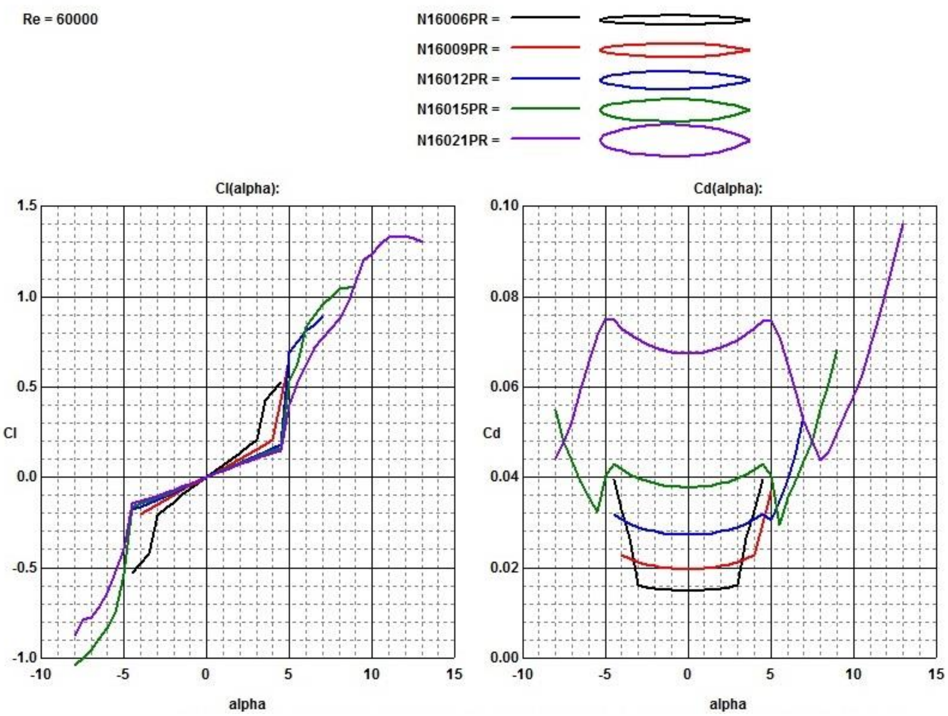


Figure 4.7 CL vs. Alpha and CD vs. Alpha

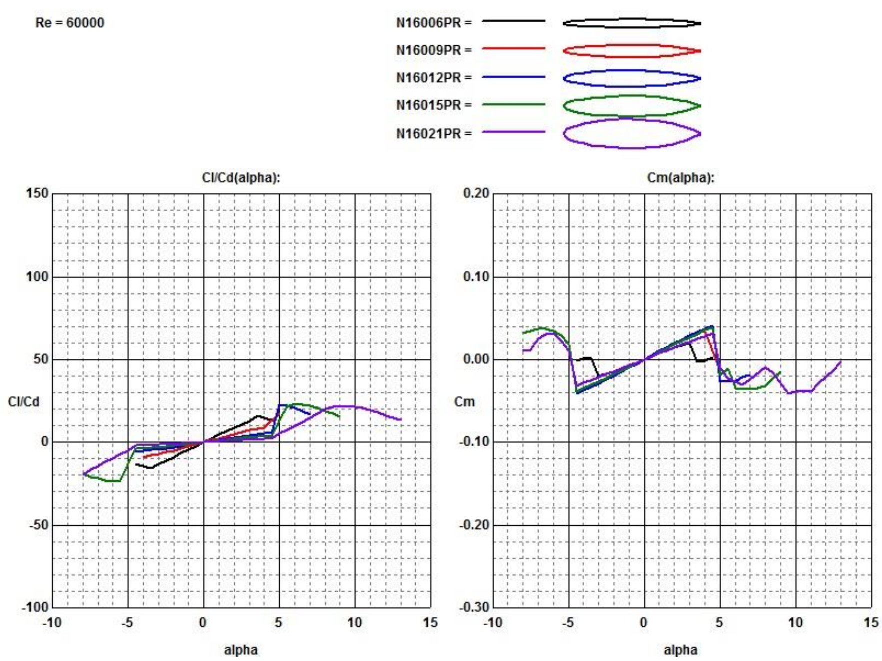


Figure 4.8 - CL/CD vs. Alpha and CM vs. Alpha

Airfoil	*Stall Angle (Degrees)*	*Stall Behavior*	*CL/CD (Ideal)*	*Thickness*
NACA 16-006PR	4.5	Not Smooth	14.10	6%
NACA 16-009PR	5.0	Not Smooth	16.80	9%
NACA 16-012PR	7.0	Relatively Smooth	23.30	12%
NACA 16-015PR	9.0	Relatively Smooth	22.50	15%
NACA 16-0018PR	5.0	Relatively Smooth	15.00	18%
NACA 16-021PR	13.0	Relatively Smooth	21.42	21%

Table 4.5 - Airfoil Characteristics [8]

Selection Criteria

While it is true that in most cases, almost any airfoil will make a turbine rotate, or make an airplane fly, it is true to say that almost anything that is selected will work. However, if one is looking for a certain criteria to be met, then the selection becomes more complex [7].

- One needs an airfoil with very high lift at low Reynolds numbers if the stall speed is most important selection criteria [11].
- If maximum L/D is important at some speed, then one needs to find an airfoil that will give the maximum L/D and lowest pitching moment for the design speed (Reynolds number) [9].
- If pitching moment is important, then one needs to select an airfoil with low moments or at least moments that are within the abilities of the tail surface to balance (in the case of aircraft wings) [8].
- If an airfoil with minimum drag at the design speed is required, then maximum speed is important, regardless of the L/D ratio [8].

Upon consideration of design requirements, the selection criteria is set as follows, based on order of priority:

- High CL/CD (Lift to Drag Ratio) – Maximum Priority for Best Efficiency
- Low Thickness (To Avoid Boundary Layer Separation)
- Reasonable Stall Characteristics (This can be managed by adjusting the Blade Pitch)
- Low Pitching Moment (Can be countered by using even number of blades)
- Degree of Manufacturability – Minimum Priority (CNC or Rapid-Prototyping to be used)

Airfoil Selected: NACA 16-012PR

CAD Models

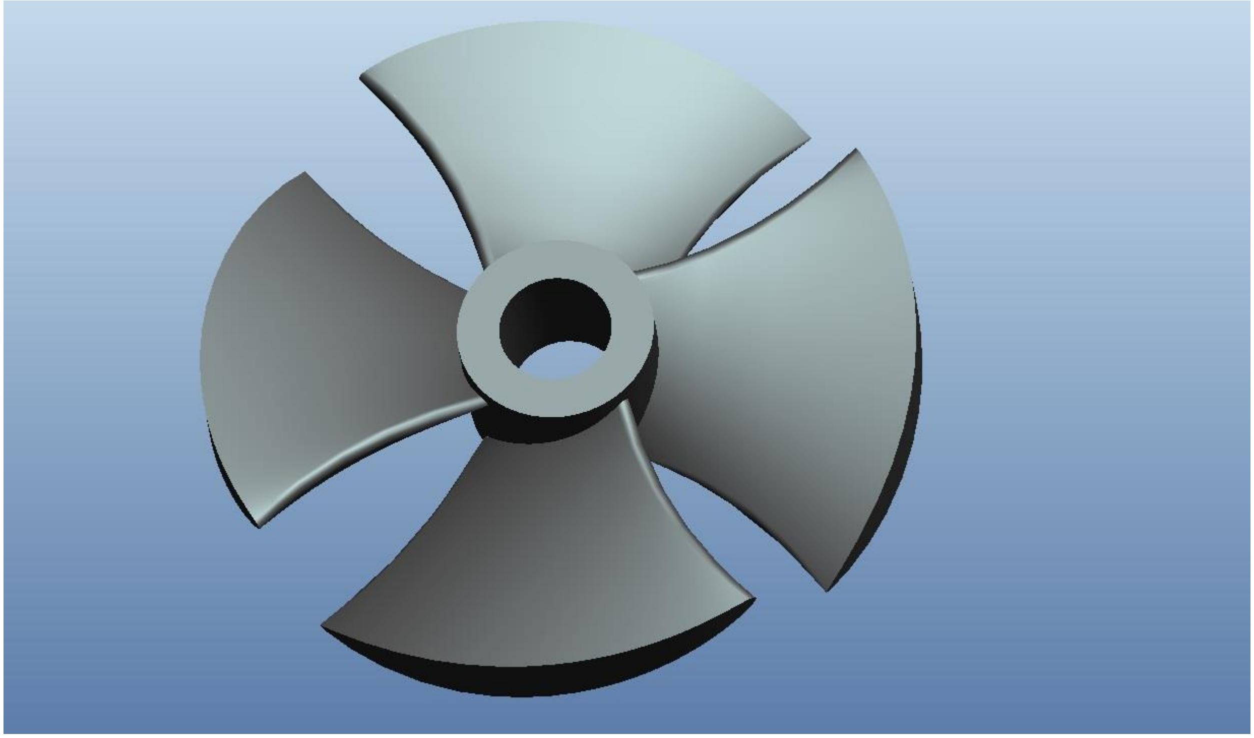


Figure 4.9 – Runner Isometric View

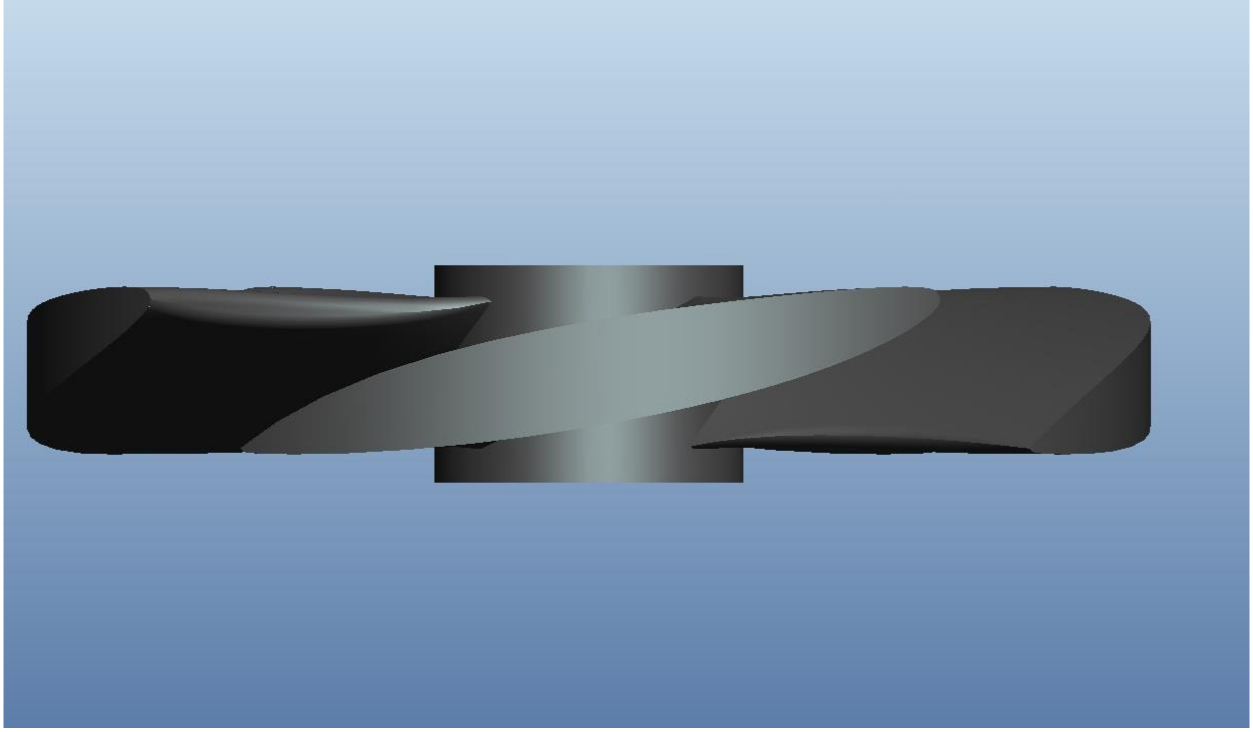


Figure 4.10 – Runner Non-Isometric View 1

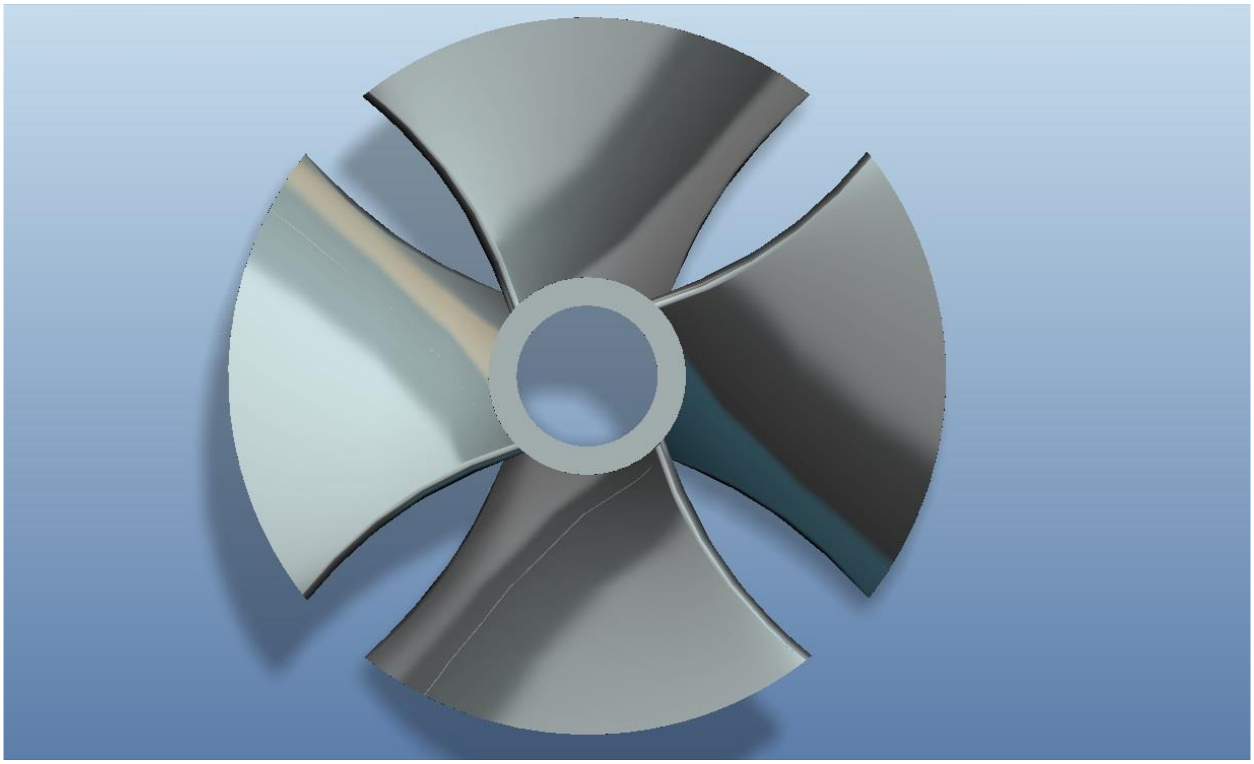


Figure 4.11 – Runner Non-Isometric View 2

Figure 4.12 - Assembly

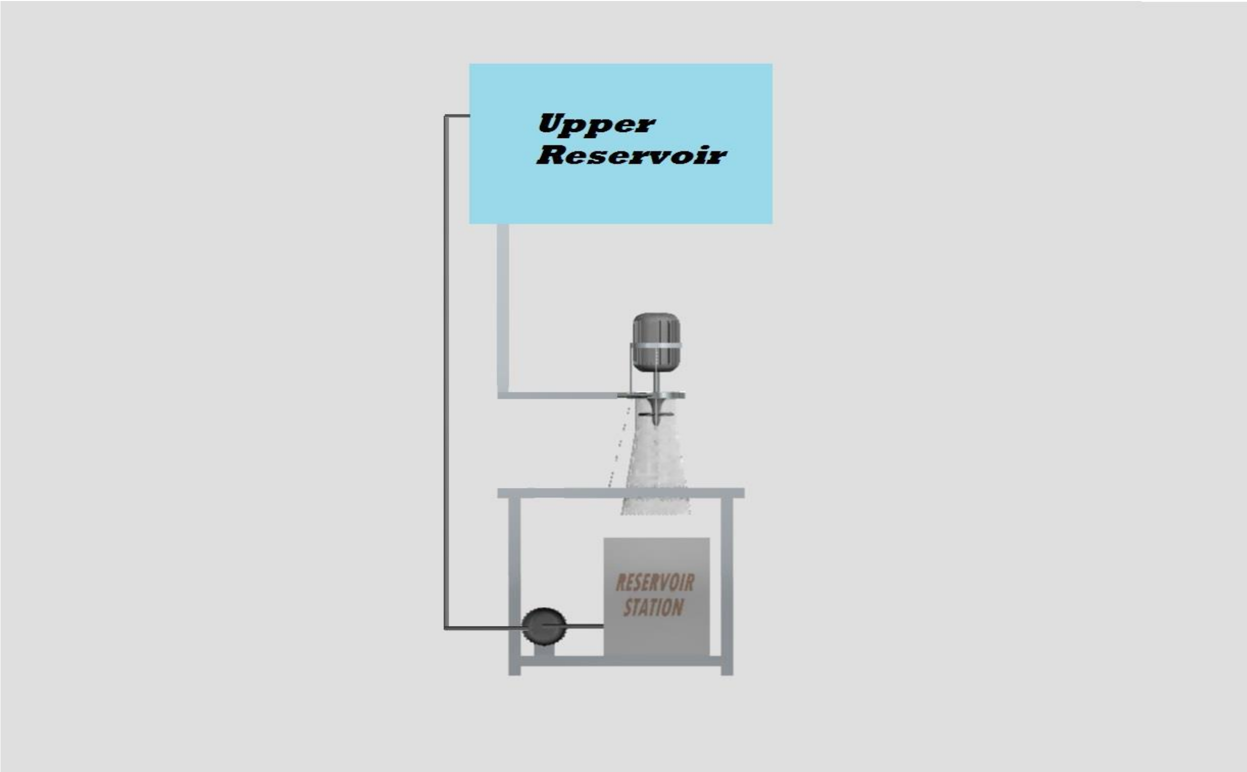


Figure 4.13 - Test Rig Design 1 with Upper Reservoir [6]

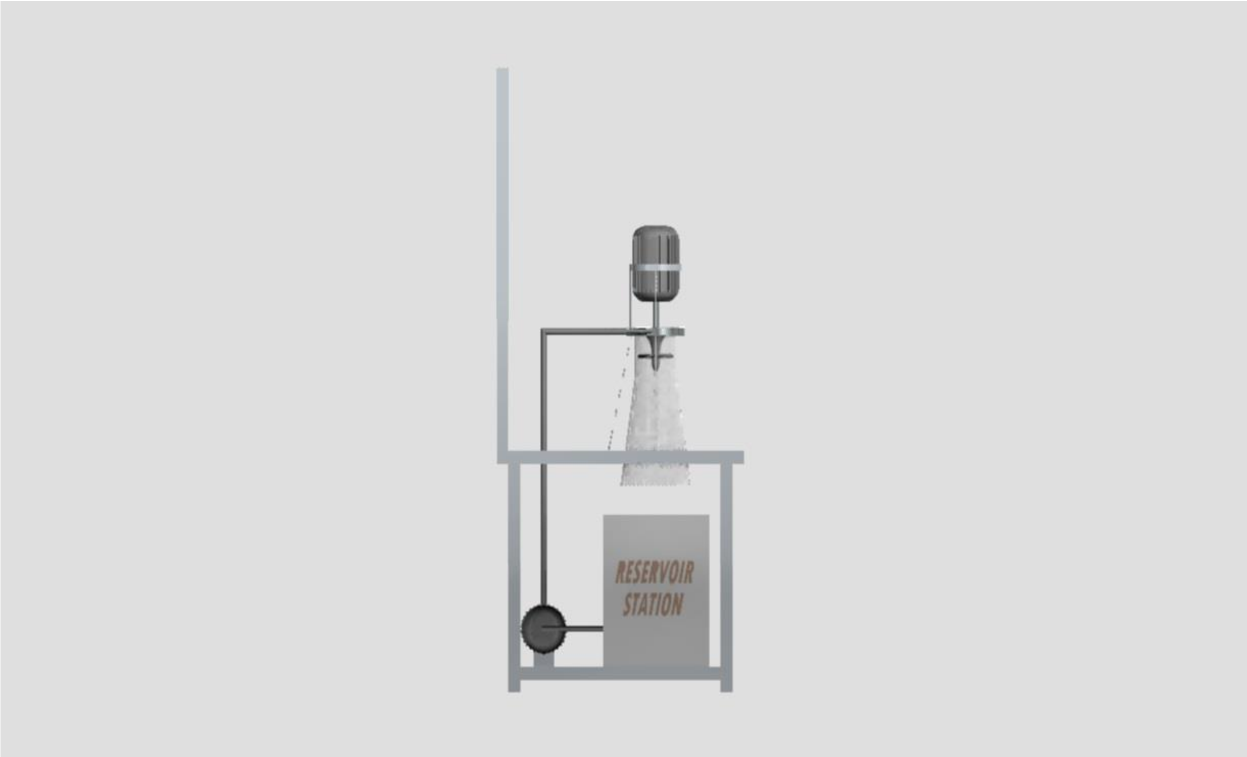


Figure 4.14 – Test Rig Design 2 with Pump [6]

CHAPTER 5: RESULTS AND RECOMMENDATIONS

The results of the analyses conducted during the course of this project have been divided into two sections, the first deals with the results obtained from experimentation on the Variable Turbine Test Rig, while the second deals with the results and recommendations presented in the case study.

5.1 Results - Variable Test Rig

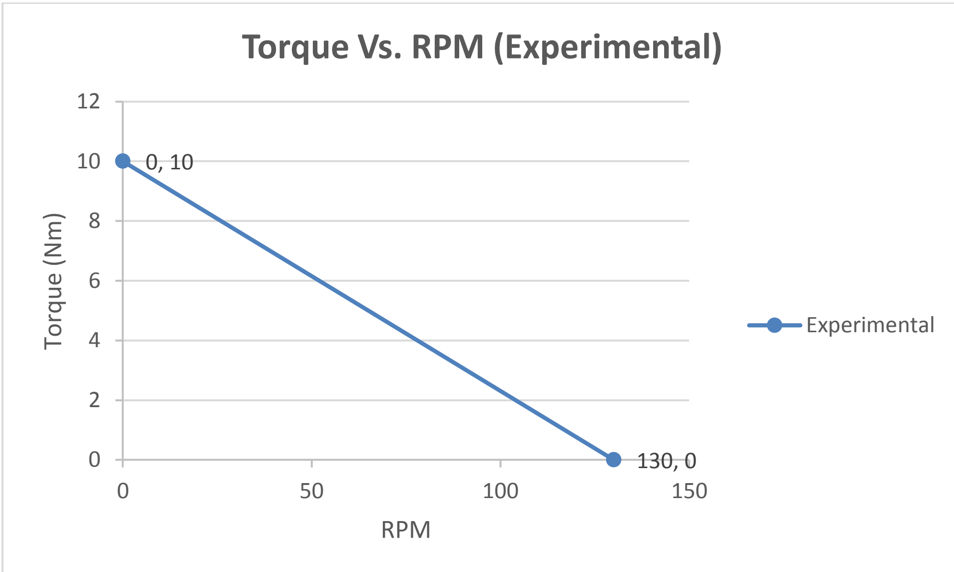


Figure 5.1 – Torque vs. RPM (Experimental)

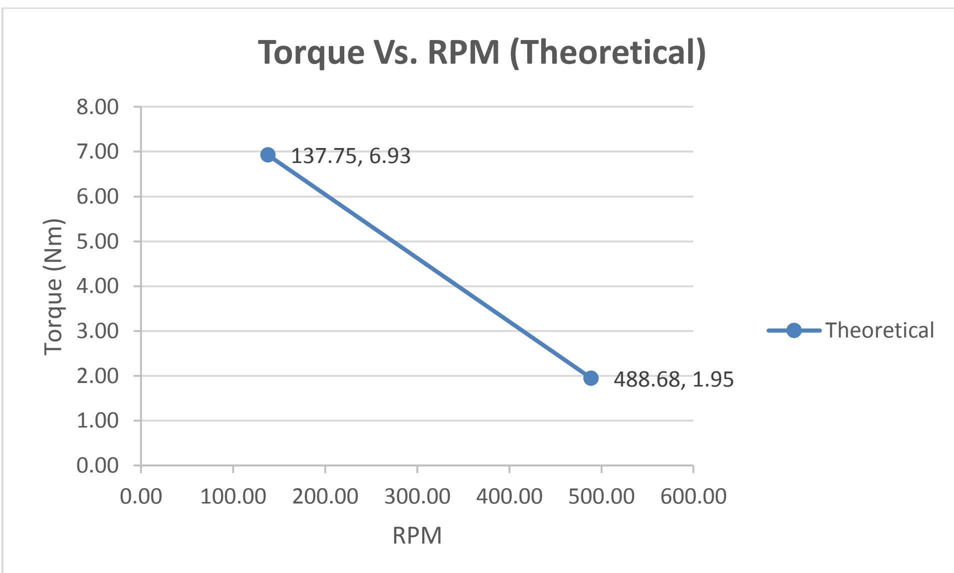


Figure 5.2 – Torque vs. RPM (Theoretical)

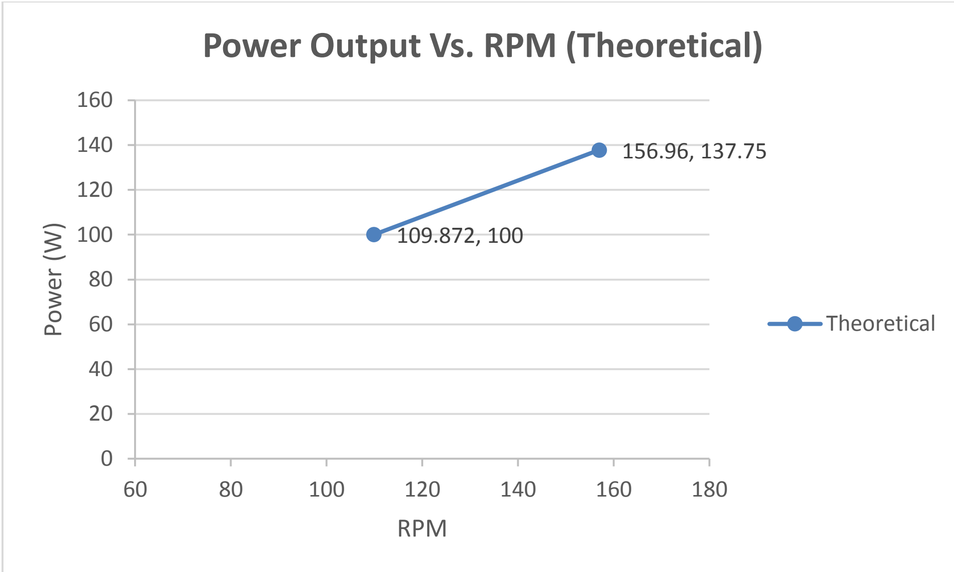


Figure 5.3 – Power vs. RPM (Theoretical)

A graph of Power against RPM for experimental values could not be obtained due to limitations on the availability of a smaller electrical generator/alternator size. The large alternator used had a capacity of 1 KW output power, which was much higher than the power of 100W – 150W which was being supplied to the turbine in the form of Hydraulic Energy. Also, an initial starting torque of 10Nm is assumed to start up the alternator in Figure 5.1, based on its tested specifications.

5.2 Results – Case Study

Based on the findings of the case study, it can be said that the site assessed has the potential to produce 25 KW of hydro-electric power, which should be adequate to address the energy needs of Fairy Land Hotel and Resort.

A total investment of PKR 2 Million is required in order to utilize this aforementioned capacity. Out of the four different possible Penstock Paths assessed at the site, Path B seems to be the most financially feasible and viable option. The breakdown of this cost has already been discussed in Section 3.2 of this report.

Project completion time is subject to the availability of funds, negotiation between all involved parties, approval of governmental bodies and the compatibility of the project with any legislation and other environmental constraints and requirements in place.

Once the performance characteristics of the Scaled-Down Model were obtained, they were dimensionally scaled-up again in order to obtain the parameters of the Actual, On-Site Turbine.

Model	***Runner Diameter (cm)***	***Head (m)***	***Discharge (m^3/s)***	***RPM***	***Power***	***Efficiency***
Scaled-Down	17.78	2	0.009	130	123.606 W	70%
Actual	100.00	2	2.020	570	24.180 KW	70%

Table 5.1 – Design Parameters of Scaled-Down and Actual Turbine Models

Predicted Performance of Actual Site Turbine based on Scaled-Up Calculations and Experimental Values obtained from the Variable Turbine Test Rig is as follows:

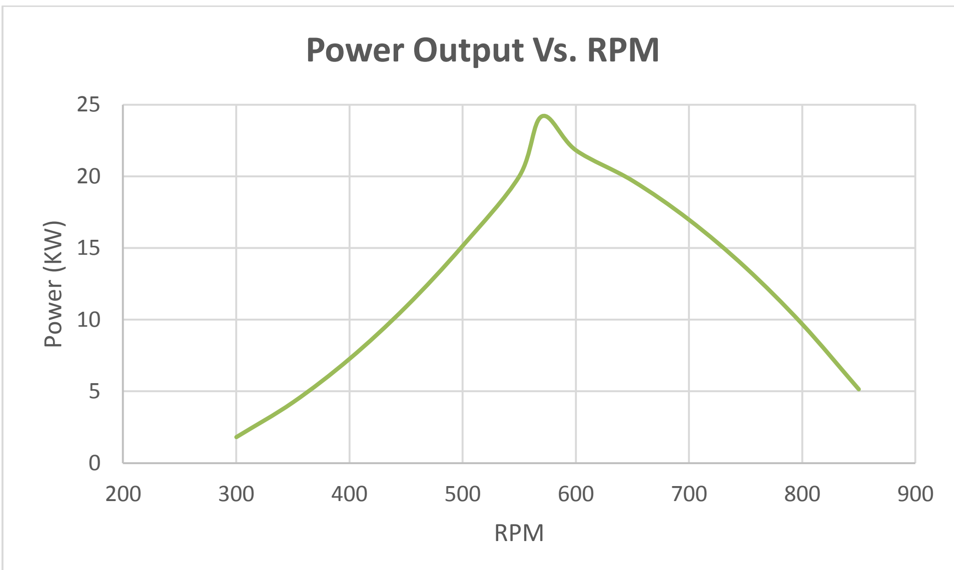


Figure 5.4 – Power vs. RPM with Variation in Efficiency for Actual, On-Site Turbine

In this model, it has been assumed that the Efficiency of the System drops by 10% for a change of every 50 RPM from Design Conditions. The Design Rotational Speed of the Actual, On-Site Turbine is 570 RPM. The Design Efficiency of the Turbine, which is also assumed to be the Maximum Efficiency, is 70%. This drops by 10% for every 50 units of change from the Design RPM of 570 RPM. For further details on calculated values, refer to Appendix D.

5.3 Recommendations

With respect to the Hydel Power Potential in Pakistan, a major portion of the overall capacity is unused, and small Micro-Hydro Projects like these in addition to larger Mega Projects can help alleviate the energy crisis of Pakistan and also pave the way for future research in the field of turbine design.

Turbine efficiency greatly depends upon the design of its blades. It is recommended that in addition to the airfoils already assessed, other NACA and non-NACA Series airfoils should also be checked for the best possible operating parameters like Lift-Drag Ratios and Stall Characteristics, as this can help improve the efficiency of the turbine design.

Instrumentation is an important aspect of all experimental apparatus, and was one of the constraints encountered in the course of this project. Instrumentation that can help with the measurement of various quantities such as the flow-rate, pressure drop, turbine rotational speed (RPM), and especially torque produced can greatly help improve the accuracy of the results of the experimentation.

Instrumentation can also be done in order to measure the amount of cavitation that occurs in the turbine as a result of pressure drops during operation. This can help research new materials and composite materials that can potentially drastically increase the life and reliability of the turbine.

The guide-vanes/stay-vanes section of the Kaplan Turbine was briefly assessed during the course of his project. Guide Vane design theory is rather expansive in nature, and needs to be considered in detail in order to obtain the best efficiency of operation during variable flow-rates.

Lastly, turbines in general are most suited for operation at the exact location for which they were designed, otherwise their efficiencies can drop. In order to mass produce turbines in this context, they need to be featured with variable pitch-angle blades, and also variable guide-vanes in a double-regulated configuration, so that they can be adjusted for best performances and efficiencies on different sites.

APPENDIX A
COST ESTIMATION PER WATT

Close Channel flow:

H = 1.22m (4ft)

Q = 0.146 m^3/s

Cost of 1309 W = Rs. 50000

Cost of 1 W = Rs. 38 (approx. Rs.40)

Open channel flow:

Cost of 17,950 W = Rs.1, 75,000

Cost of 1 W = Rs. 9.75 (approx. Rs.10)

Close Channel flow:

H = 1.8288m (6ft)

Q = 0.146 m^3/s

Cost of 1965 W = Rs.75, 000

Cost of 1 W = Rs. 38.1 (approx. Rs.40)

Open channel flow:

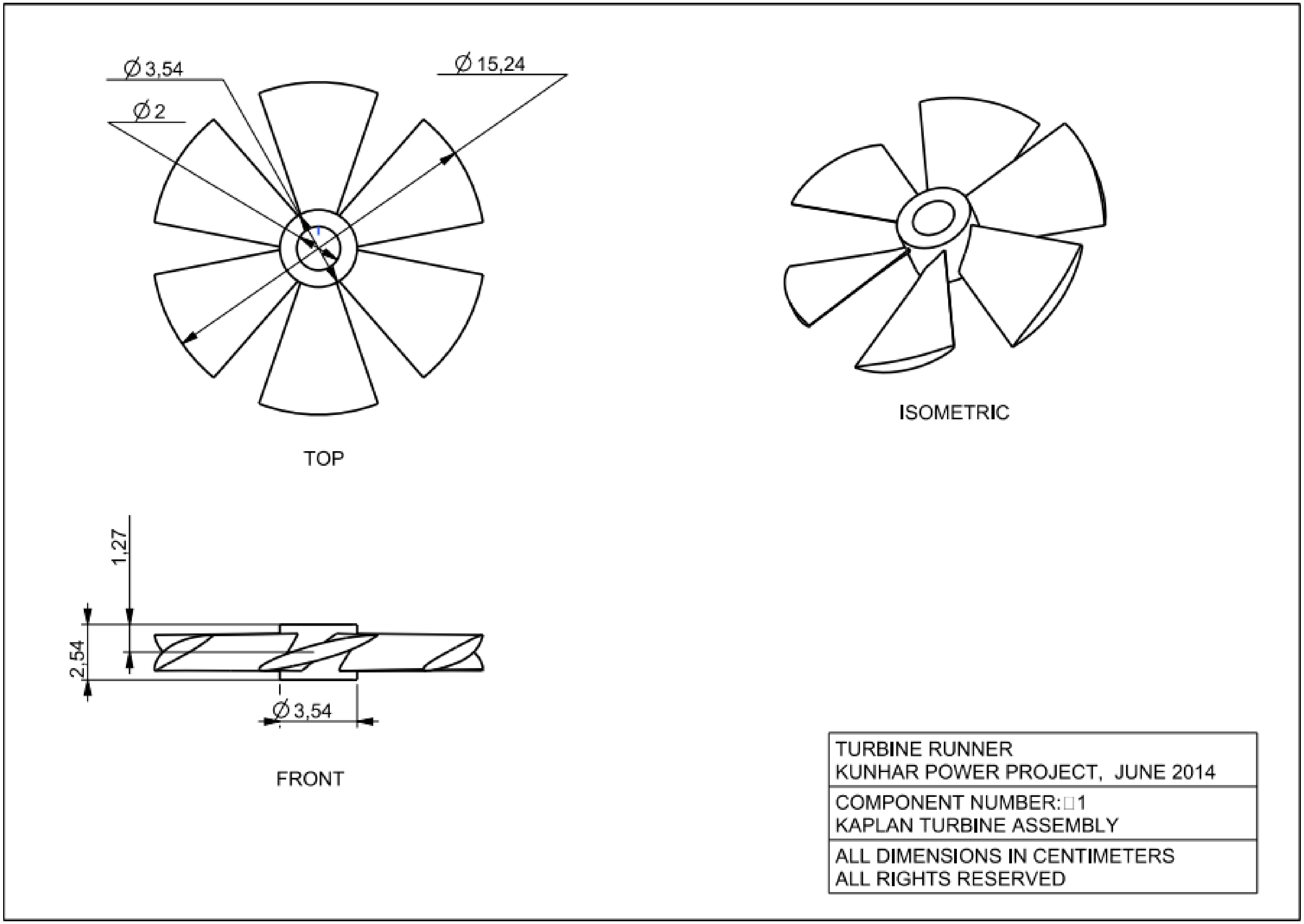
Cost of 26,900 W = Rs. 2, 50,000

Cost of 1 W = Rs.9.3 (approx. Rs.10)

Note: This cost excludes Transportation cost, Excavation cost & Labor cost.

APPENDIX B

ENGINEERING DRAWINGS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FRONT
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TURBINE RUNNER
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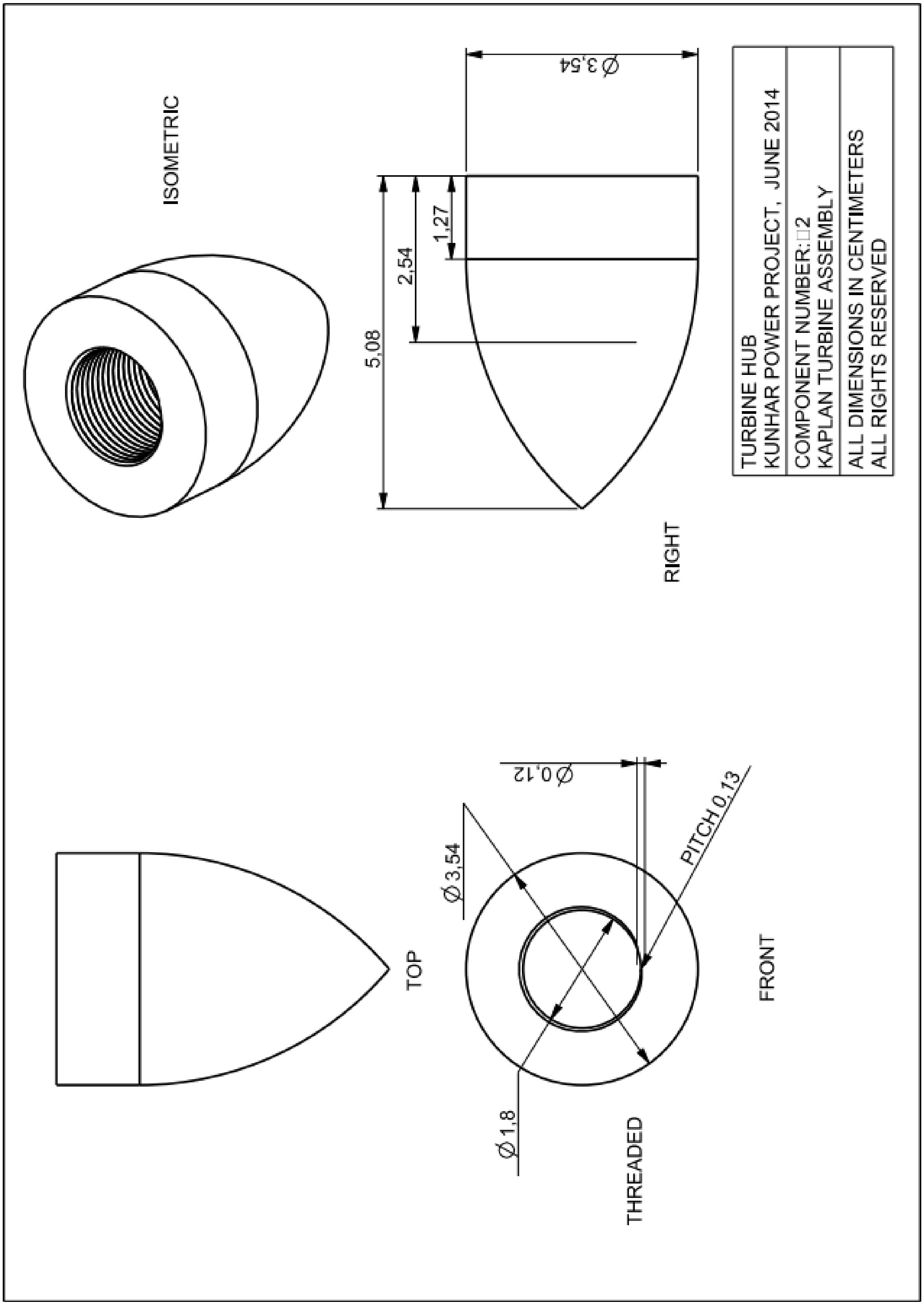
KAPLAN TURBINE ASSEMBLY
ALL DIMENSIONS IN CENTIMETERS
ALL RIGHTS RESERVED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TURBINE HUB
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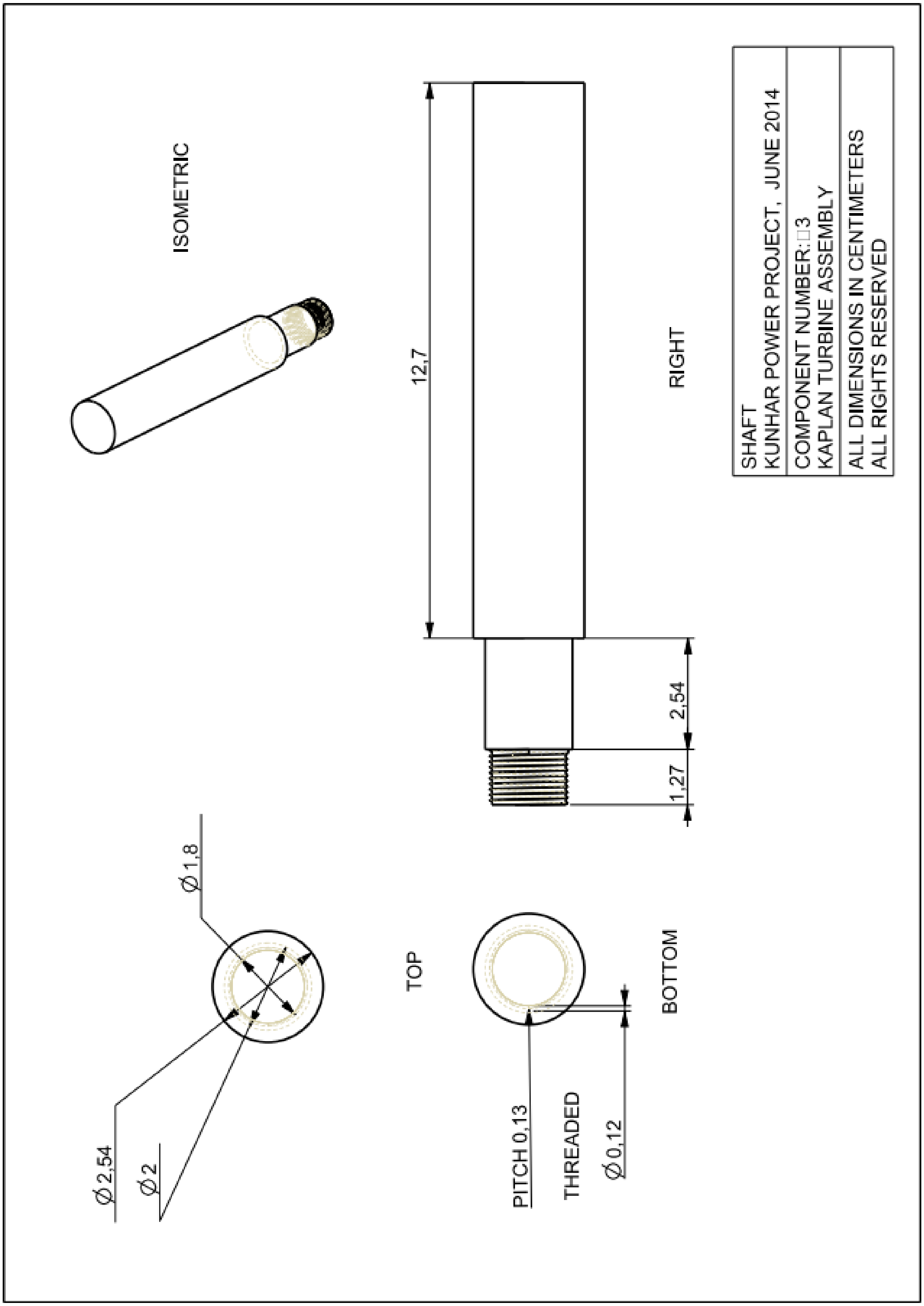
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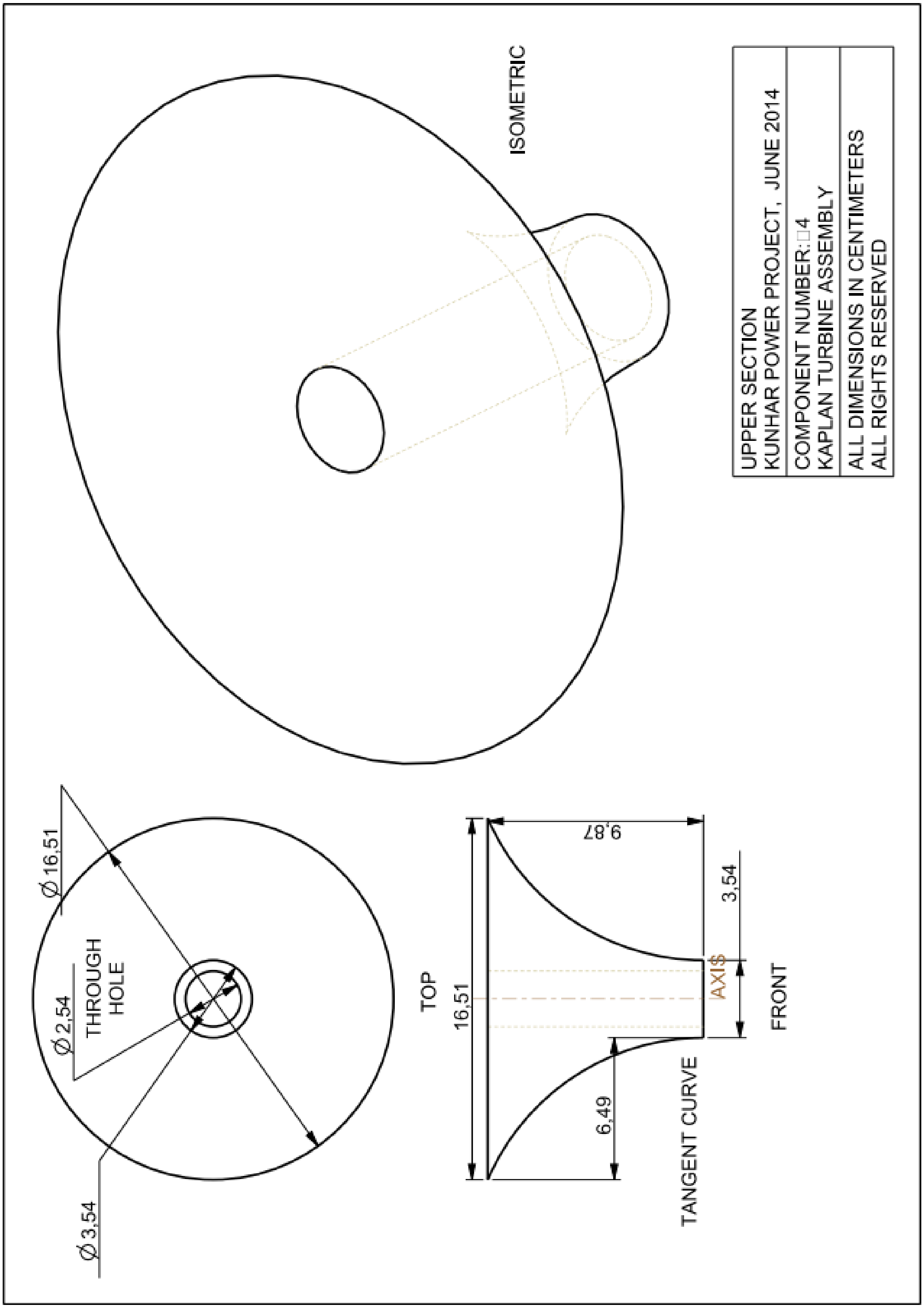
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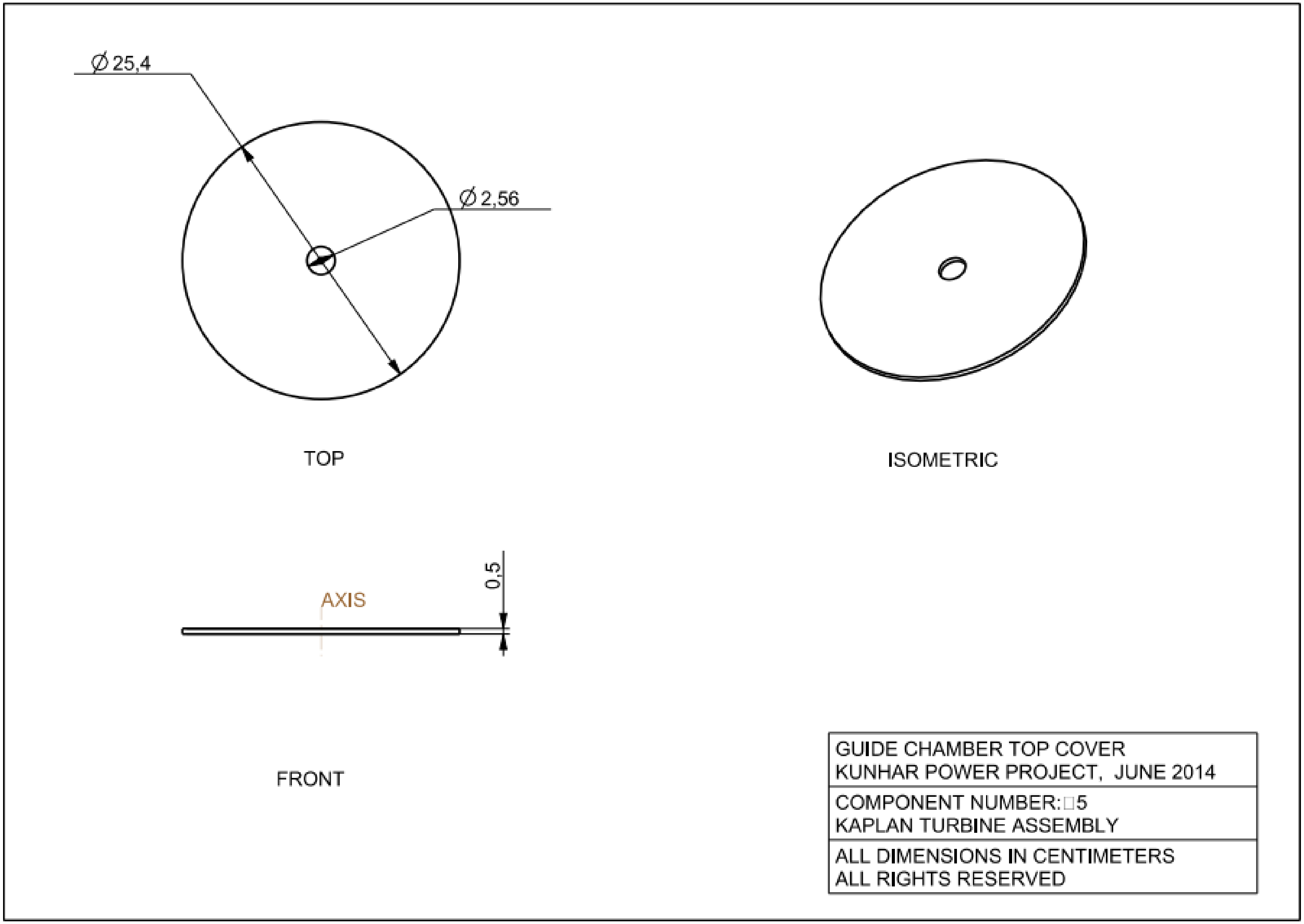
TANGENT CURVE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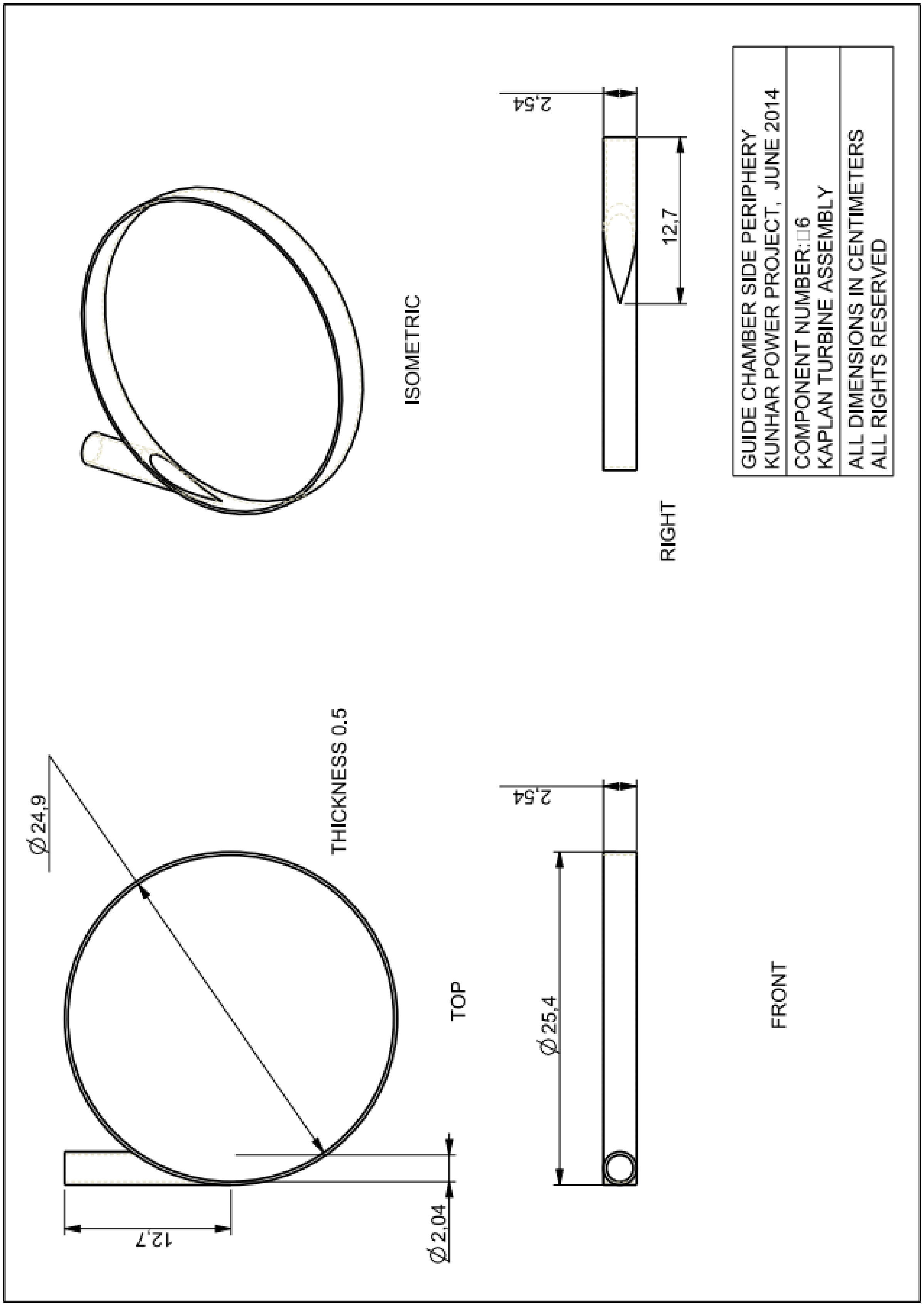
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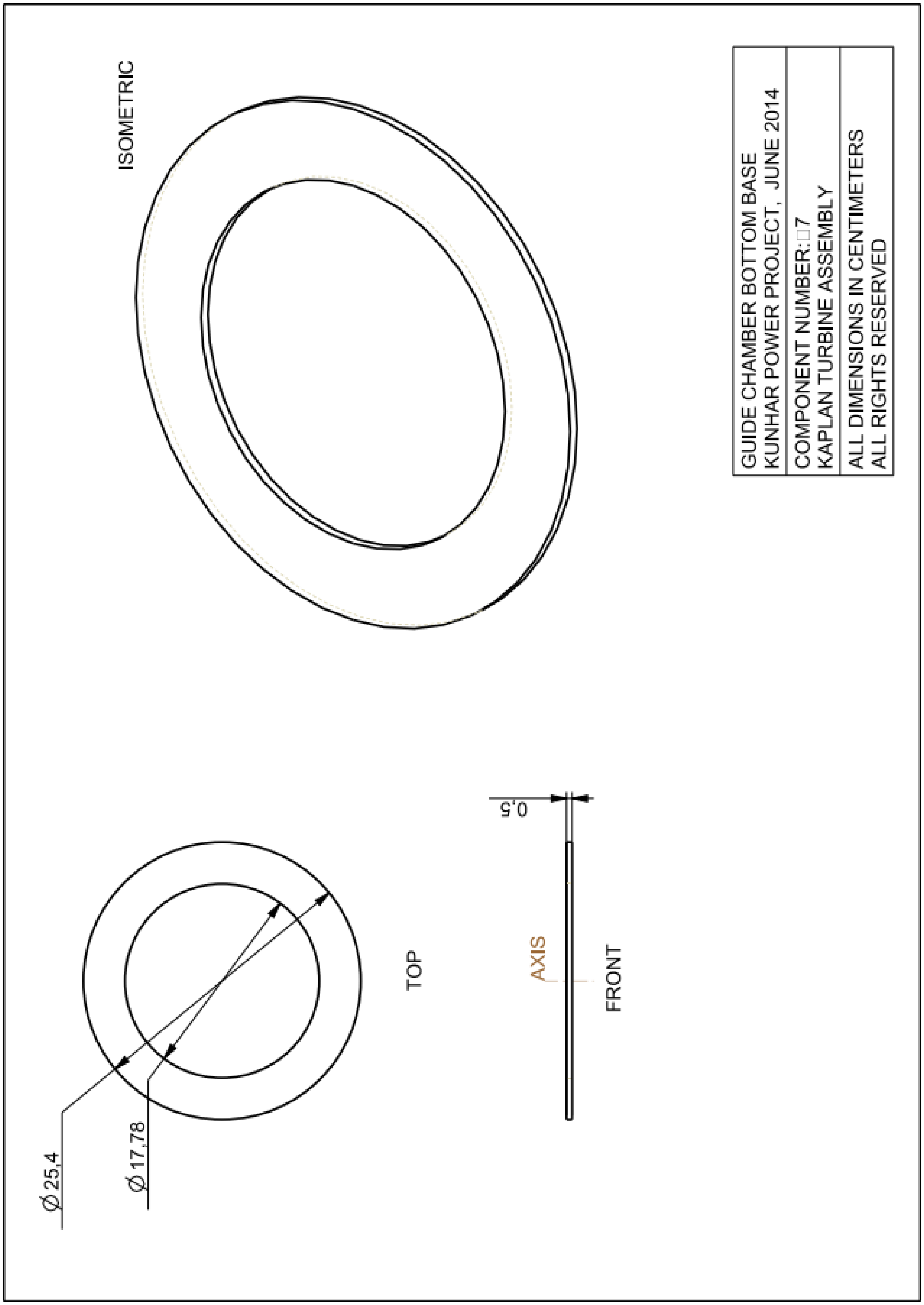
ISOMETRIC
Ø 25,4
Ø 17,78
TOP
AXIS
FRONT
0,5
GUIDE CHAMBER BOTTOM BASE
KUNHAR POWER PROJECT, JUNE 2014
COMPONENT NUMBER:□7
KAPLAN TURBINE ASSEMBLY
ALL DIMENSIONS IN CENTIMETERS
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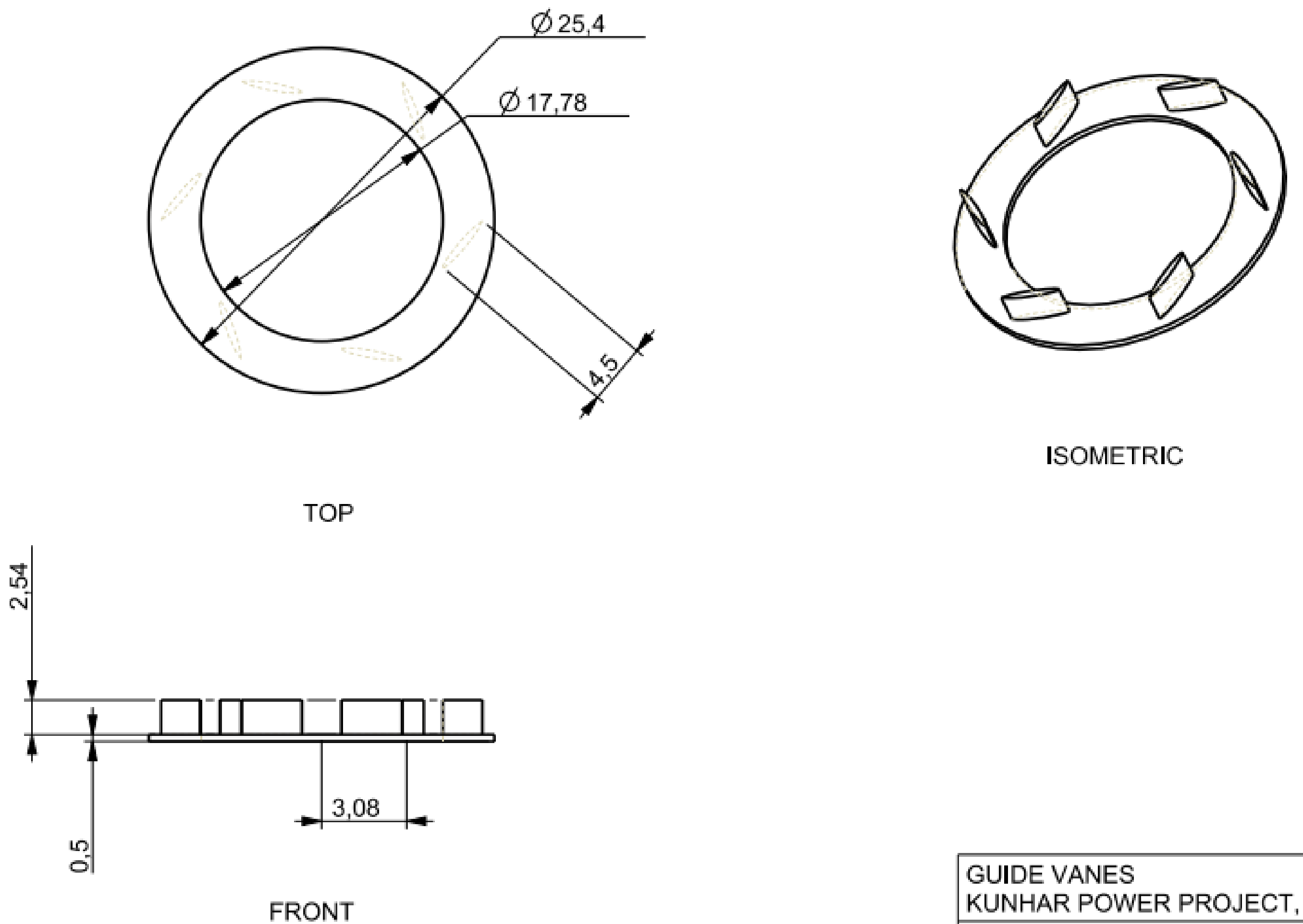
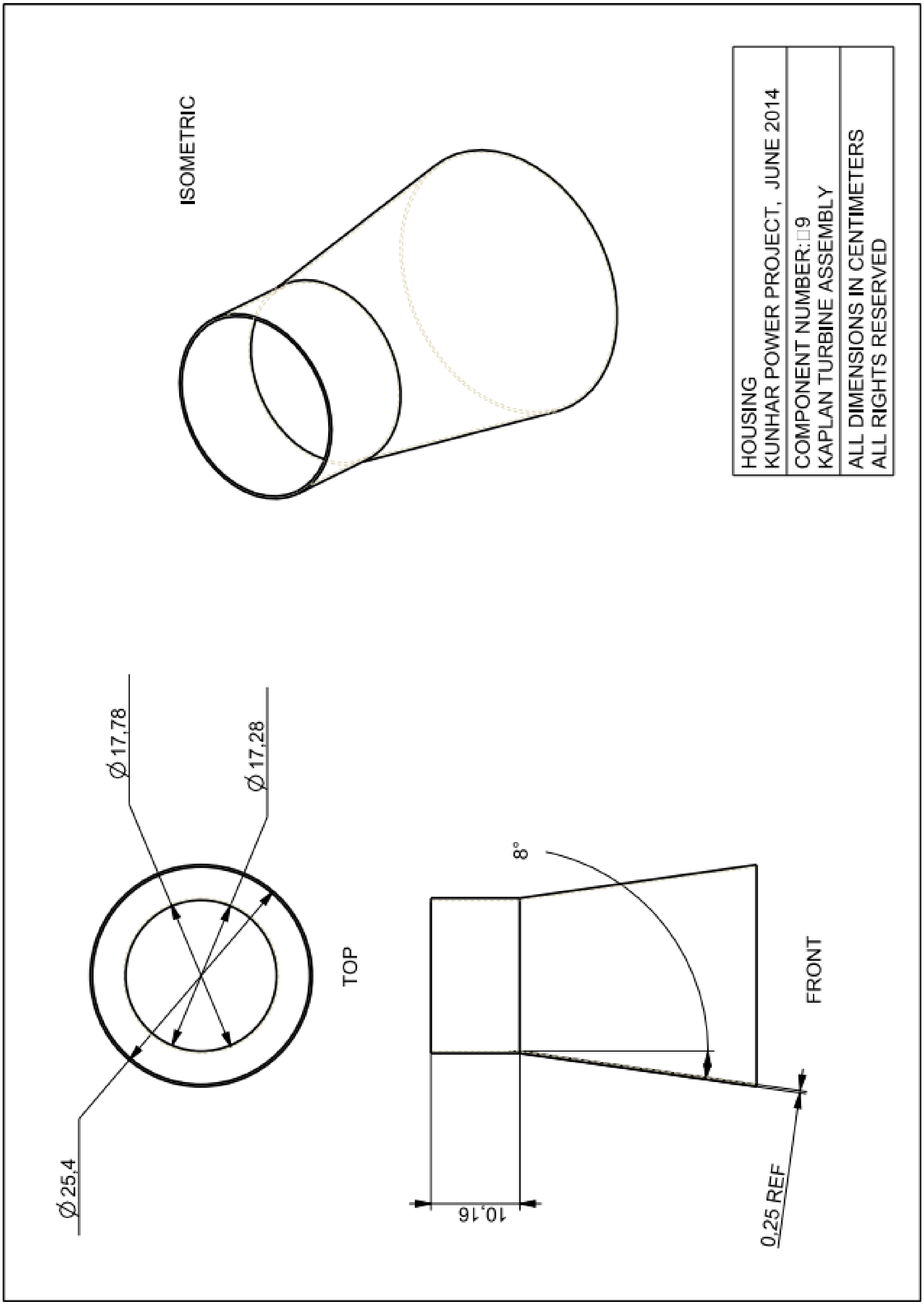
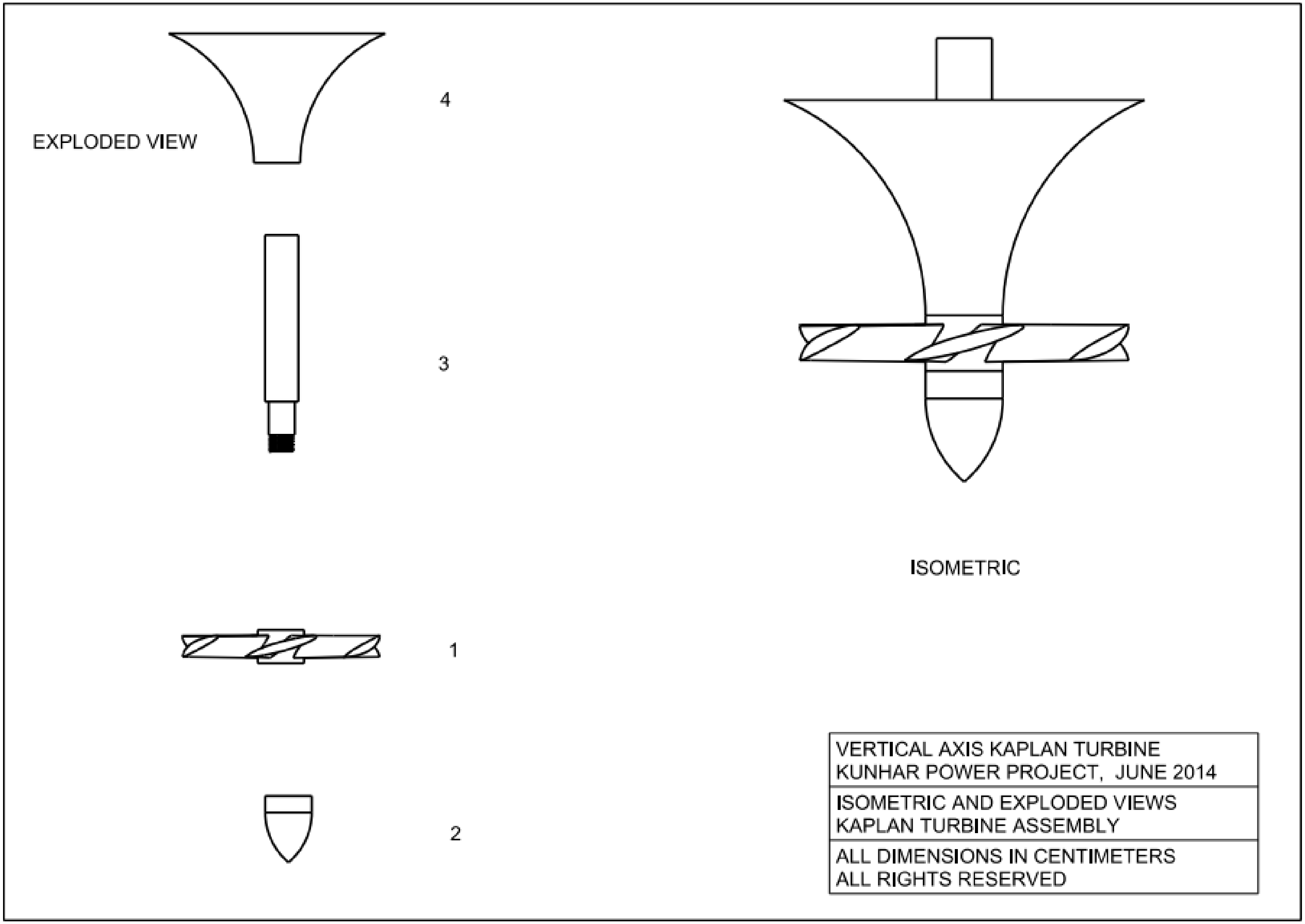
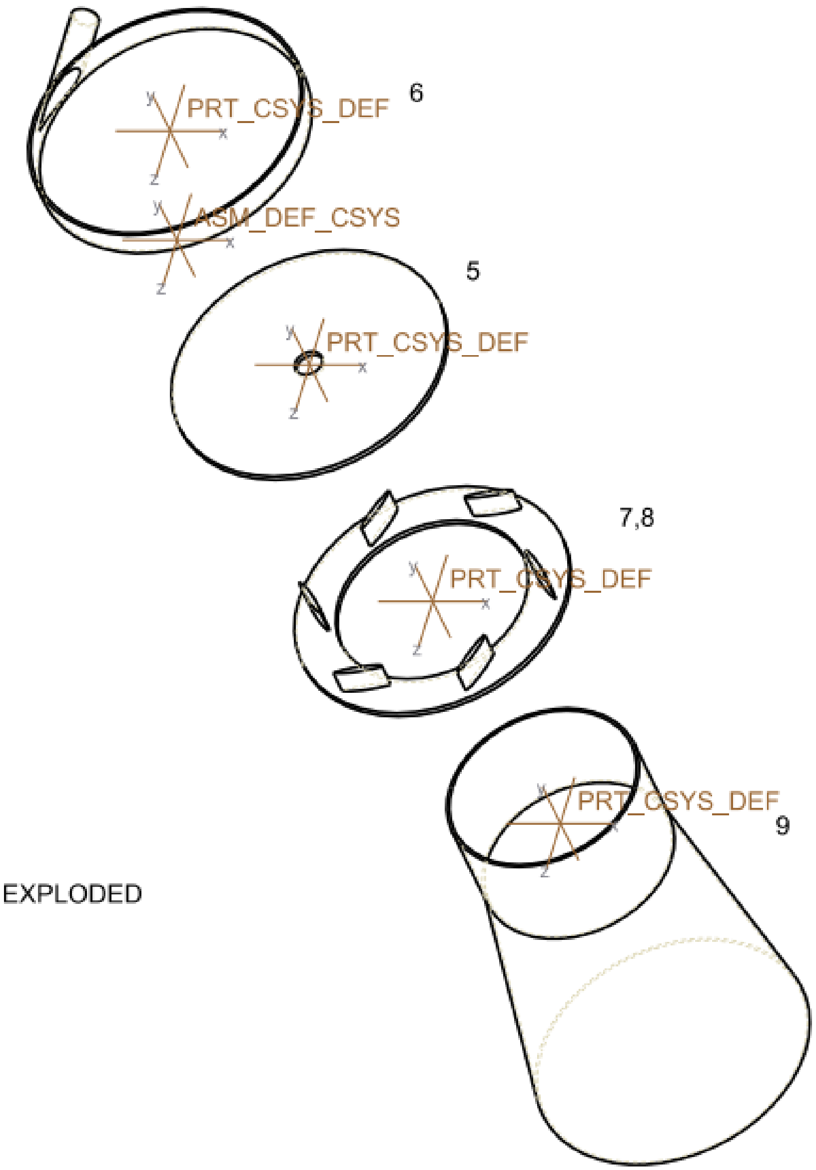


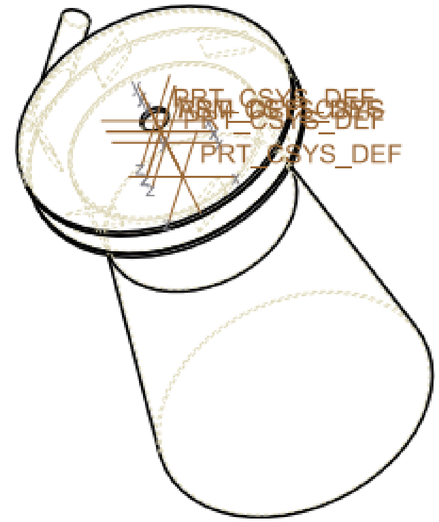
GUIDE VANES KUNHAR POWER PROJECT, JUNE 2014
COMPONENT NUMBER:□8 KAPLAN TURBINE ASSEMBLY
ALL DIMENSIONS IN CENTIMETERS


ISOMETRIC
Ø17,78
Ø17,28
Ø25,4
TOP
8°
FRONT
10,16
0,25 REF
HOUSING
KUNHAR POWER PROJECT, JUNE 2014
COMPONENT NUMBER:□9
KAPLAN TURBINE ASSEMBLY
ALL DIMENSIONS IN CENTIMETERS
ALL RIGHTS RESERVED


EXPLODED VIEW
4
3
1
2
ISOMETRIC
VERTICAL AXIS KAPLAN TURBINE
KUNHAR POWER PROJECT, JUNE 2014
ISOMETRIC AND EXPLODED VIEWS
KAPLAN TURBINE ASSEMBLY
ALL DIMENSIONS IN CENTIMETERS
ALL RIGHTS RESERVED

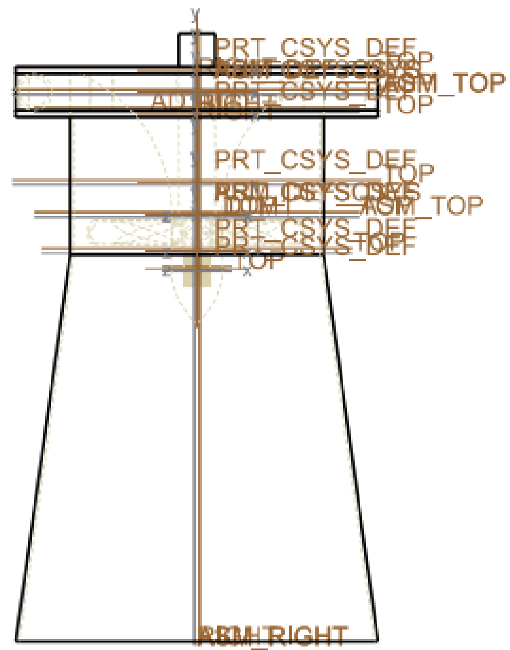


EXPLODED



ISOMETRIC

GUIDE CHAMBER & TURBINE HOUSING KUNHAR POWER PROJECT, JUNE 2014
ISOMETRIC AND EXPLODED VIEWS KAPLAN TURBINE ASSEMBLY
ALL DIMENSIONS IN CENTIMETERS ALL RIGHTS RESERVED



INDEX	PART NAME	QUANTITY
1	RUNNER	1, 6-BLADED
2	HUB	1
3	SHAFT	1
4	UPPER SECTION	1
5	GUIDE CHAMBER TOP COVER	1
6	GUIDE CHAMBER SIDE	1
7	GUIDE CHAMBER BOTTOM BASE	1
8	VANES	6
9	HOUSING	1

FINAL YEAR PROJECT
BILL OF MATERIALS
ALL RIGHTS RESERVED

APPENDIX C

MANUFACTURING IMAGES

All manufacturing processes except for the construction of the draft-tube section and the guide-vanes circular cutting and the manufacture of bearing bushes was done at the Manufacturing Resource Centre (MRC) at NUST.

Casting

Bench-Fitting

Machining Operations, etc.

APPENDIX D

DESIGN PARAMETERS OF SCALED-DOWN AND SCALED-UP MODELS

Design Parameters of the Scaled-Down Model used in the Variable Turbine Test Rig and the Actual, On-Site Turbine, based on Theoretical Calculations are presented below. They were obtained using Pump-Scaling Laws mentioned in Reference 3.

Model	*Runner Diameter (cm)*	*Head (m)*	*Discharge (m^3/s)*	*RPM*	*Power*	*Efficiency*
Scaled-Down	17.78	2	0.009	130	123.606 W	70%
Actual	100.00	2	2.020	570	24.180 KW	70%

Power Output (KW) of the Actual, On-Site Turbine With Respect To RPM and Efficiency.

Power Output With Respect To RPM And Efficiency										
RPM	**Efficiency**									
	10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
	Power Output									
50	0.30	0.61	0.91	1.21	1.52	1.82	2.12	2.42	2.73	3.03
100	0.61	1.21	1.82	2.42	3.03	3.64	4.24	4.85	5.45	6.06
150	0.91	1.82	2.73	3.64	4.55	5.45	6.36	7.27	8.18	9.09
200	1.21	2.42	3.64	4.85	6.06	7.27	8.48	9.70	10.91	12.12
250	1.52	3.03	4.55	6.06	7.58	9.09	10.61	12.12	13.64	15.15
300	1.82	3.64	5.45	7.27	9.09	10.91	12.73	14.54	16.36	18.18
350	2.12	4.24	6.36	8.48	10.61	12.73	14.85	16.97	19.09	21.21
400	2.42	4.85	7.27	9.70	12.12	14.54	16.97	19.39	21.82	24.24
450	2.73	5.45	8.18	10.91	13.64	16.36	19.09	21.82	24.54	27.27
500	3.03	6.06	9.09	12.12	15.15	18.18	21.21	24.24	27.27	30.30
550	3.33	6.67	10.00	13.33	16.67	20.00	23.33	26.66	30.00	33.33
570	3.45	6.91	10.36	13.82	17.27	20.73	24.18	27.63	31.09	34.54
600	3.64	7.27	10.91	14.54	18.18	21.82	25.45	29.09	32.72	36.36
650	3.94	7.88	11.82	15.76	19.70	23.63	27.57	31.51	35.45	39.39
700	4.24	8.48	12.73	16.97	21.21	25.45	29.69	33.94	38.18	42.42
750	4.55	9.09	13.64	18.18	22.73	27.27	31.82	36.36	40.91	45.45
800	4.85	9.70	14.54	19.39	24.24	29.09	33.94	38.78	43.63	48.48
850	5.15	10.30	15.45	20.60	25.76	30.91	36.06	41.21	46.36	51.51
900	5.45	10.91	16.36	21.82	27.27	32.72	38.18	43.63	49.09	54.54
950	5.76	11.51	17.27	23.03	28.79	34.54	40.30	46.06	51.81	57.57
1000	6.06	12.12	18.18	24.24	30.30	36.36	42.42	48.48	54.54	60.60
1050	6.36	12.73	19.09	25.45	31.82	38.18	44.54	50.90	57.27	63.63
1100	6.67	13.33	20.00	26.66	33.33	40.00	46.66	53.33	59.99	66.66
1150	6.97	13.94	20.91	27.88	34.85	41.81	48.78	55.75	62.72	69.69
1200	7.27	14.54	21.82	29.09	36.36	43.63	50.90	58.18	65.45	72.72

Values from this table have been taken to plot the graph in Figure 5.4. It is based on Theory of Turbine Characteristic Curves given in Reference 12.

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