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Tidal Turbine Design Research Document

Introduction

Many designs have been proposed for turbine devices that will harness the power of fast moving tidal streams, such as those found in the confined entrances of coastal inlets. This paper examines some of the general design considerations, highlights some of the most common design themes, and presents information and recommendations made by various engineers and researchers.

Design Considerations

There are many factors to consider when designing a tidal turbine, many of which are not directly related to the mechanics of designing the components. A summary of some areas of concern:

- Environmental Issues
    - Will marine life such as fish be at risk of injury or death from the blades?
    - How will the turbine and associated electrical cable affect the seabed and sediment?
    - Will contaminants be introduced into to area, such as leaking oils or other chemicals?
    - Will the flow be obstructed enough to alter the local tidal behavior, perhaps changing the height of the tides or the current velocity, possibly changing the local ecosystem?
- Transportation and Commerce Issues
    - Will the turbines interfere with shipping lanes?
    - Will the turbines interfere with fishing grounds or nearby aquaculture?
    - Will local recreational activities be affected?

Once the impact on the surrounding area has been taken into account, the design parameters for the actual turbine can be considered. This becomes a complex optimization problem [1] between cost and power generation. Though of course, the decisions made here will relate back to the environmental, transportation, and commerce issues presented earlier, making the whole process an evolving “guess and check.” In short, an analysis of the cost, performance, and impacts of different combinations of components is estimated and the optimal configuration is selected.

When considering the costs, some of the main areas to consider are:

- Materials
- Fabrication
- Installation
- Study / Testing
- Maintenance
- Recovery Time

The maintenance costs are a very important factor since they are ongoing and though hopefully predictable, not necessarily. Time that repairs are being made is time that the turbines are not generating power, and that is certainly not desirable. Some things to reduce loss of money due to maintenance are:

- Ease of access to components
- Autonomous and preventative maintenance
- Monitoring systems

Of the many physical turbine components that need to be designed, the major ones to consider are:

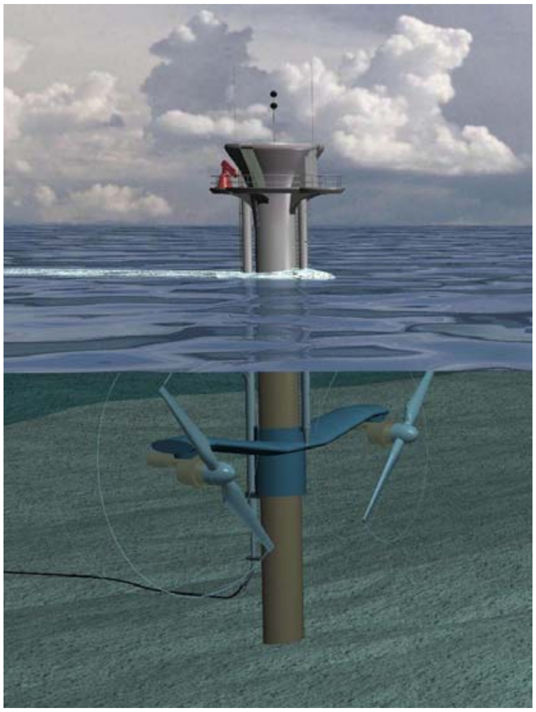
- Foundation/Installation
- Tower/Frame
- Rotor/Blades
- Transmission system
- Power conversion/transport system

For a more detailed list of design considerations, see the Design Matrix in the appendix.

Proposed Designs

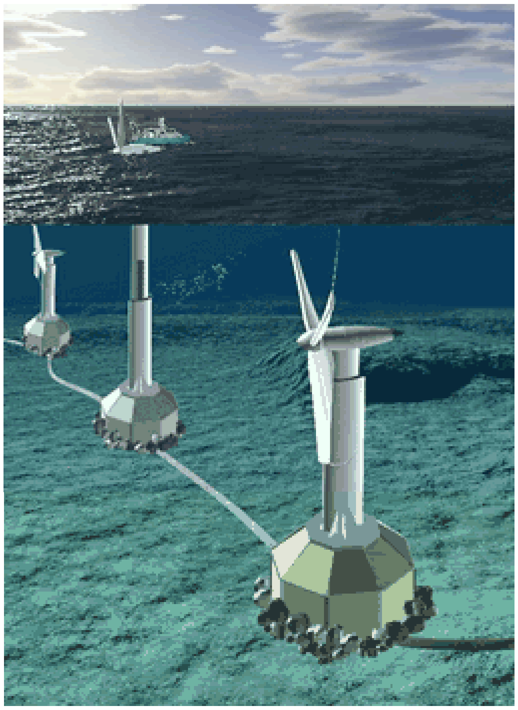
Part of the difficulty in designing an effective and efficient tidal current turbine is that many of the factors affecting the design are site specific; meaning what works in one place will not work quite as well in another. Perhaps the seabed is rock at one possible site and muddy at another, making the choice of how to secure the turbine in place not one that can be answered universally. Difficulties such as this have given rise to many ideas, so if each of the currently proposed designs is broken down into its major parts, it is easier to see what each approach offers.

One of the biggest divides in design would probably be the horizontal axis vs. the vertical axis turbine. Some examples of horizontal axis turbines can be seen in Figures 1 and 2 below, while Figures 3a and 4 show two views of a vertical axis turbine or Darrieus rotor. Figure 3b shows a helical vertical axis turbine.



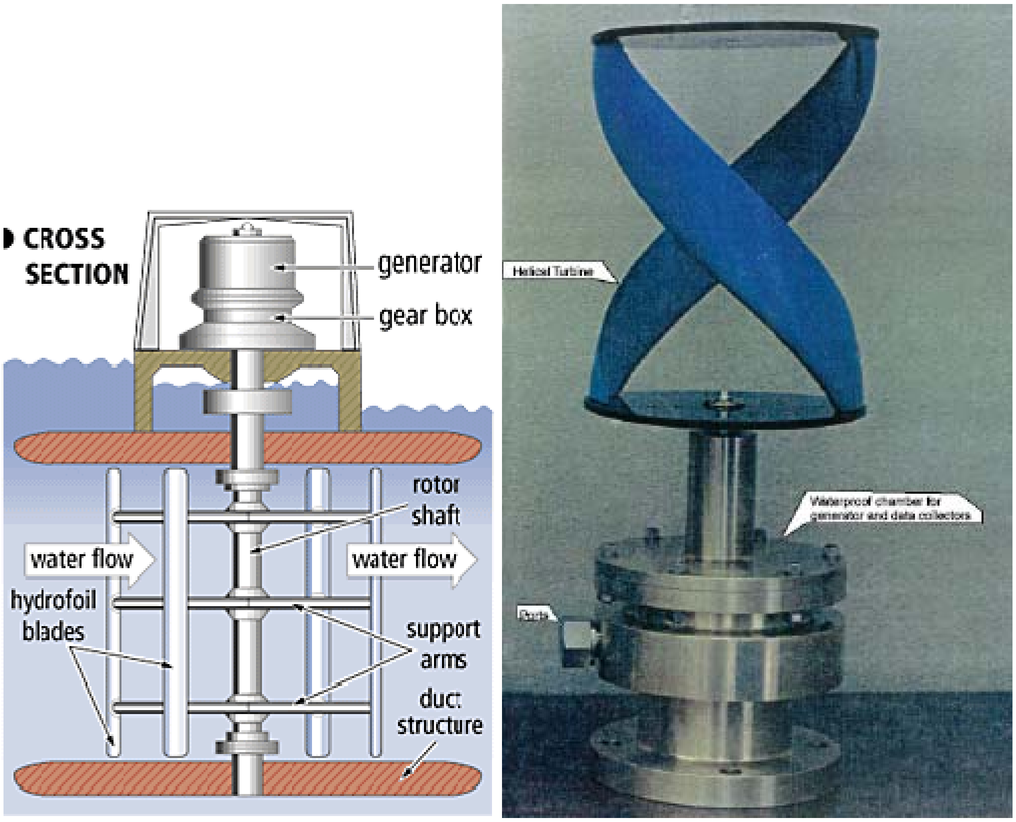
Source: Marine Current Turbines Ltd., “Artists impression of MCT Segen pile-mounted twin rotor tidal turbine,” accessed Sept. 2007, http://www.marineturbines.com/technical.htm

Figure 1. Horizontal axis, pile-mounted tower, exposed, risible, multi rotor turbine



Source: Swanturbines, accessed Sept. 2007, http://www.swanturbines.co.uk/technology.htm

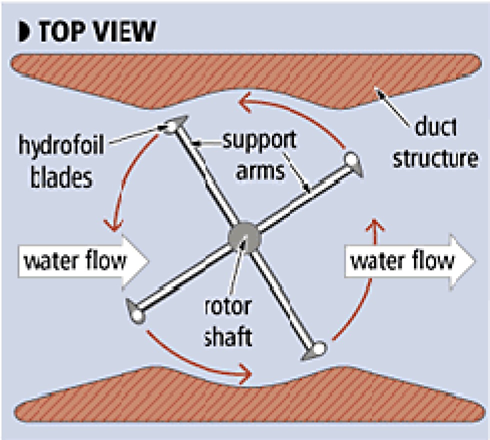
Figure 2. Horizontal axis, gravity base tower, submerged, risible, single rotor turbine



a. **b.**

Source-a: Blue Energy International, accessed Sept. 2007, http://www.bluenergy.com/technology.html
Source-b: Gorlov A. M., 2001, “Tidal Energy,” Academic Press, Northeastern University, Boston, MA, USA

Figure 3. a. Cross section of a Darrieusvertical axis turbine
b. Helical vertical axis turbine



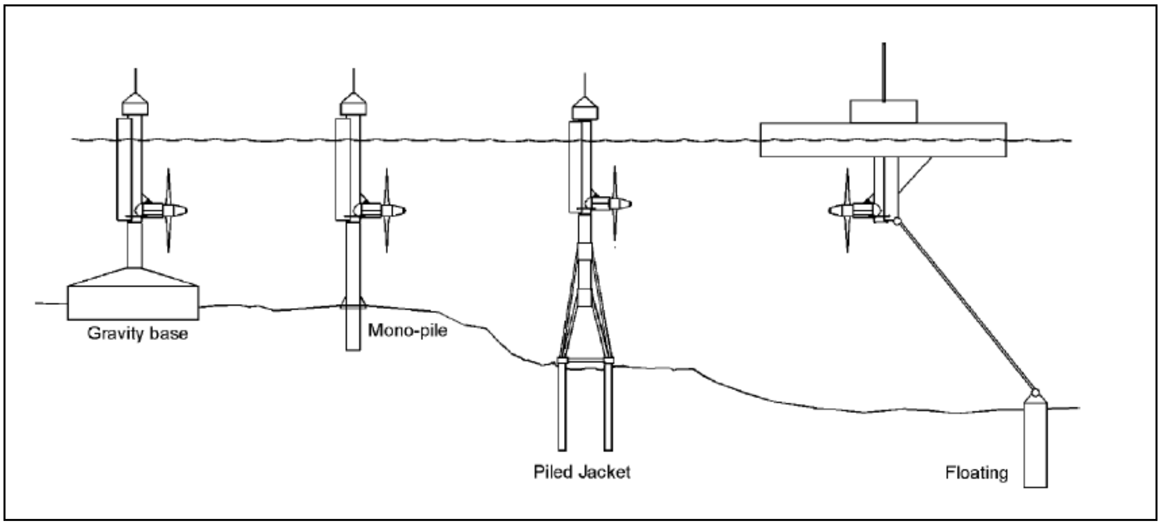
Source: Blue Energy International, accessed Sept. 2007, http://www.bluenergy.com/technology.html

Figure 4. Top view of a Darrieus vertical axis turbine

Some of the characteristics of horizontal and vertical axis turbines [2]:

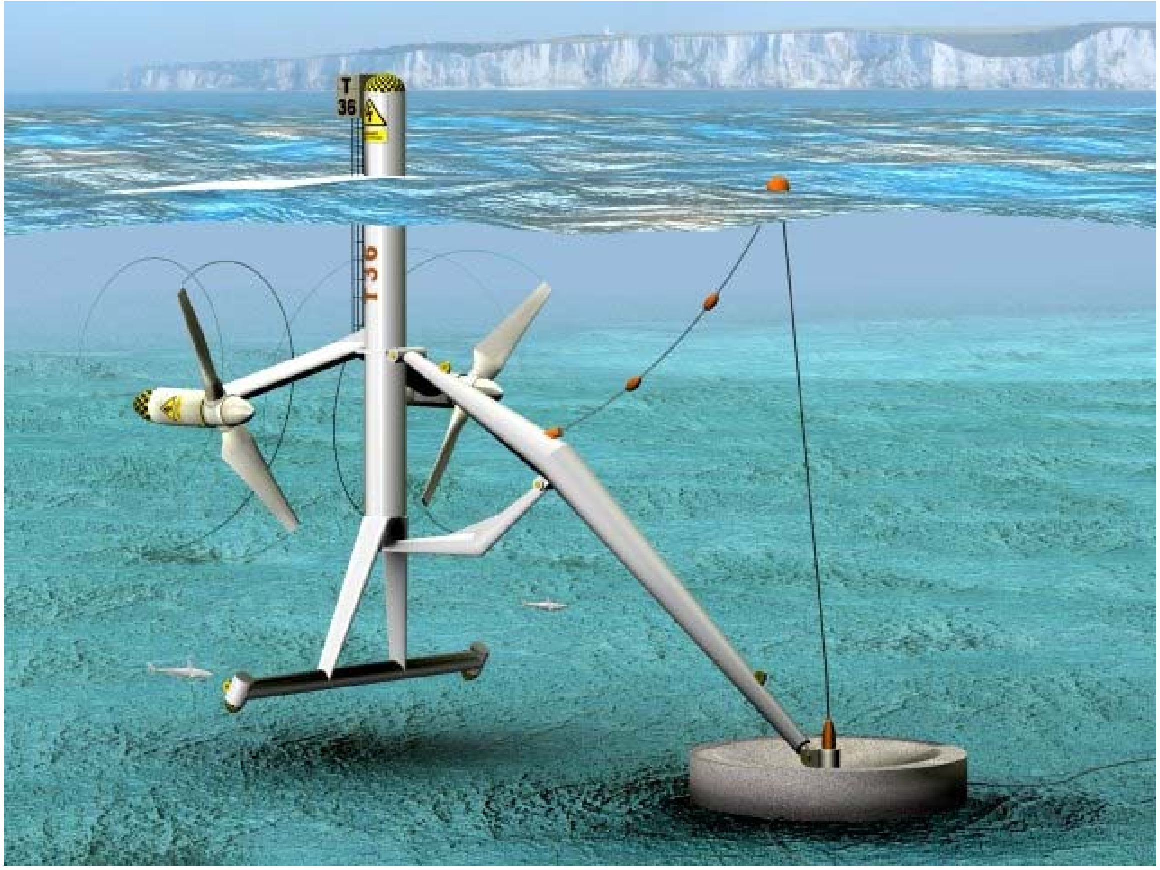
- Horizontal
    - Drive train must be at rotor level or a right angle energy transmission mechanism is needed (restrictive)
    - Less rotor structure per unit of swept area (less cost)
    - Generally self-starting
    - Can be easily stopped in an emergency by turning the rotors out of the flow direction
    - Less sensitivity to cavitation
- Vertical (Darrieus)
    - Shaft power taken out perpendicular to the flow, allowing the drive train to be in the seabed or on a surface vessel (advantageous)
    - More rotor structure per unit of swept area (more cost)
    - Generally not self-starting
    - Difficult to stop in an emergency since it cannot be turned out of the flow
    - Efficiency reliant on a good surface finish to maintain a high lift:drag ratio
    - Greater sensitivity to cavitation
    - Four or fewer blades – major cyclic lateral forces develop

Another important difference is how the turbine is supported and installed. Most standard designs involve a tower that is somehow secured to the seabed, though others have the turbine suspended from a floating platform of some kind (Figure 5). Finally, there are also some more unique designs that involve some form of submersible or semi-submersible turbines (Figure 6).



Source: Fraenkel P.L., 2002, "Power from Marine Currents," Proc Instn Mech Engrs, Vol 216, Part A.

Figure 5. Turbine installation methods



Source: TidalStream, accessed Sept. 2007, http://www.teleos.co.uk/turbines.htm

Figure 6. SST, Semi-Submersible Turbine

Some characteristics of each installation method:

- Tower [2]
    - Pile-mounted – Mono-pile/Piled Jacket
        - Feasible in shallow to intermediate depths
        - Works with a rocky/solid seabed
        - Pile-mounting experience in other industries has made this option attractive
    - Gravity Base
        - Only feasible for shallow water
        - Works well if there is no solid material to drill into
- Floating Platform [2]
        - Essential in deep water
        - Installation and removal would be quick and inexpensive
        - Mooring and anchoring technically difficult
- Submersible [2], [3]
        - Requires anchoring hinge and/or cables, which can be unstable
        - May be able to orient itself to the current as it changes direction

A key factor for shipping lanes could be whether or not the turbine is completely submerged or if it has components above water. Once again, Figures 1 and 2 demonstrate the two possibilities. Whether or not the turbine is risible plays a major role here in terms of maintenance. Either way, turbines that can rise for maintenance are more convenient.

- Partially Exposed
  - May be convenient to have some systems above the water for monitoring and maintenance
  - May pose a greater barrier to shipping lanes
- Completely Submerged
  - May pose maintenance difficulties, especially if the turbine cannot be raised
  - May restrict surface shipping less, though this depends on how far the rotor tip is from the surface

Figures 1 and 2 demonstrate possible designs for multi or single rotor turbines.

- Single Rotor
  - Simpler, fewer components that could break down
  - Tower behind the rotor affects flow
- Multiple Rotors
  - More complicated mechanical transmission
  - Less material behind each rotor affecting the flow
  - Can serve as a stabilizer for submersible turbines by balancing forces [3]

Of course, decisions about the specifics of each of these major components then have to be made. For example, how many blades should the rotor or rotors have, or what should the tower be made out of and so on. Once the overall structure concept has been chosen, these details are something for the design team to figure out.

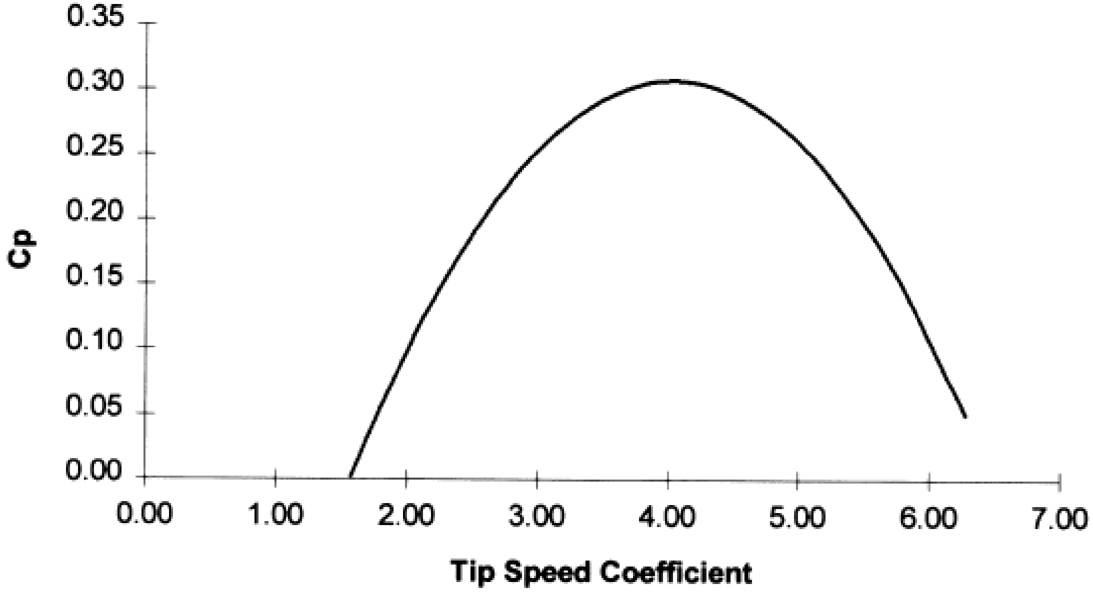
Relevant Information and Recommendations

Contained in various research publications concerning tidal energy and turbines is data and other information which is helpful to know when designing a turbine. This section summarizes some of that useful information.

- Theoretical maximum power from tidal current
  - $P = \frac{1}{2}\rho A V^3$ [2]
- Realistic power from tidal current
  - $P = ½\, C_P\, \rho\, A\, V^3$, where C_p is called the power coefficient and represents the percentage of power that can be extracted from the stream taking into

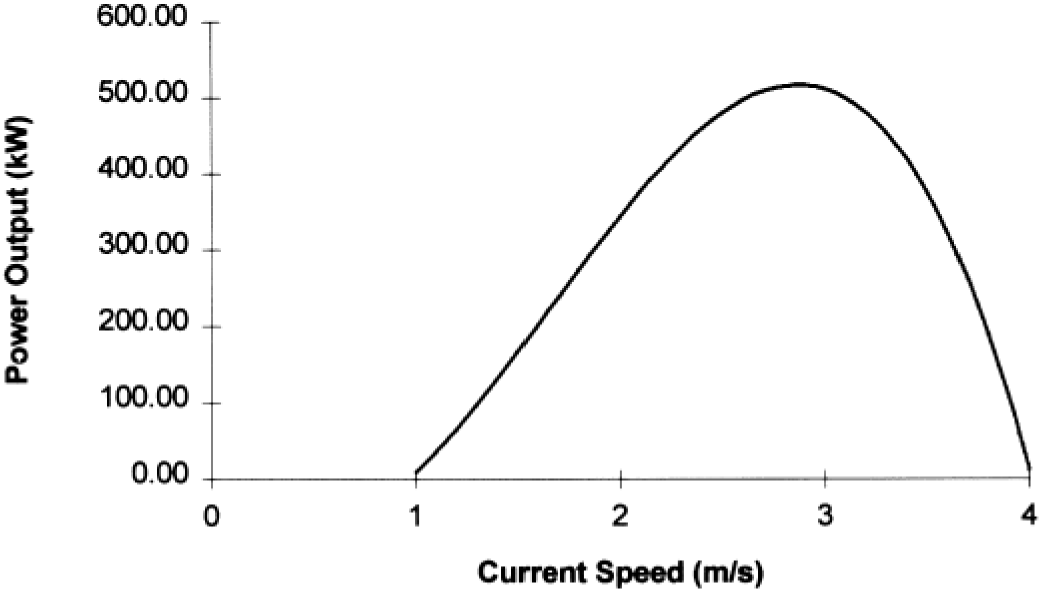
account losses due to Betz' law. A value of 0.3 is typical for a machine with low mechanical losses [4]

- C_p has a maximum theoretical value of 0.6, but is generally determined as a function of the ratio between the speed of the turbine tip and the flow speed (the tip speed ratio, λ). An example curve is shown in Figure 7. The curve depends on the blade form and the number of blades. Since most proposed designs operate at a constant rotational speed, flow speed and power output can then be related. Figure 8 shows such a curve for a 20m diameter turbine rotating every 10 seconds. The curve changes to Figure 9 if the period is changed to 12 seconds [1]



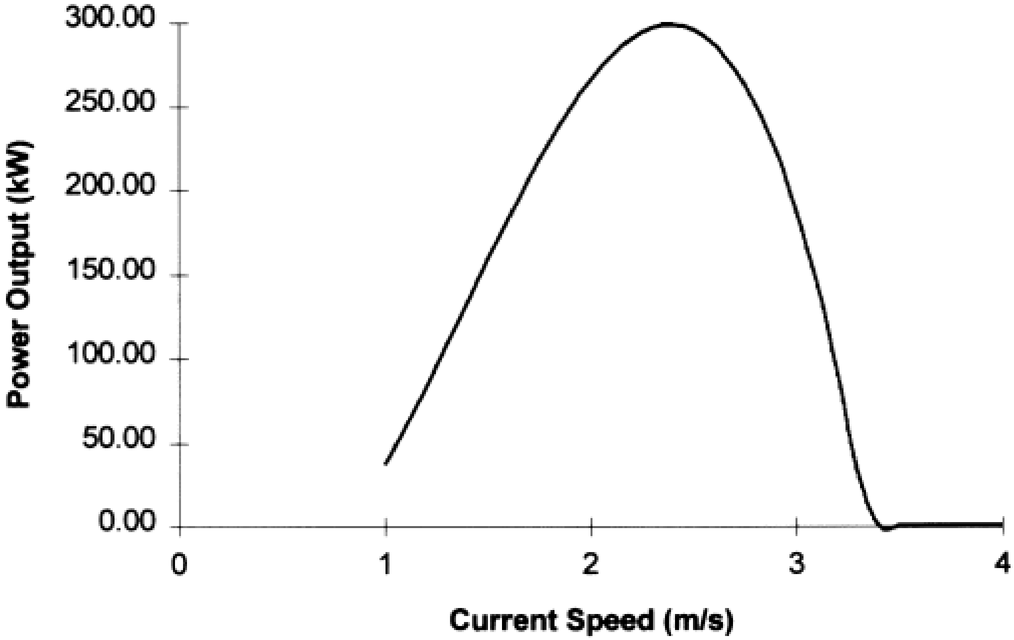
Source: Bryden, I. G., Naik S., Fraenkel P., and Bullen C. R., 1998, "Matching Tidal Current Plants to Local Flow Conditions," Elsevier Science Ltd., Vol 23, No. 9, pp. 699-709

Figure 7. Power coefficient as a function of tip speed ratio for a four-bladed turbine



Source: Bryden, I. G., Naik S., Fraenkel P., and Bullen C. R., 1998, "Matching Tidal Current Plants to Local Flow Conditions," Elsevier Science Ltd., Vol 23, No. 9, pp. 699-709

Figure 8. Power output as a function of current speed: 20m turbine, 10 sec period using Figure 7 information



Source: Bryden, I. G., Naik S., Fraenkel P., and Bullen C. R., 1998, "Matching Tidal Current Plants to Local Flow Conditions," Elsevier Science Ltd., Vol 23, No. 9, pp. 699-709

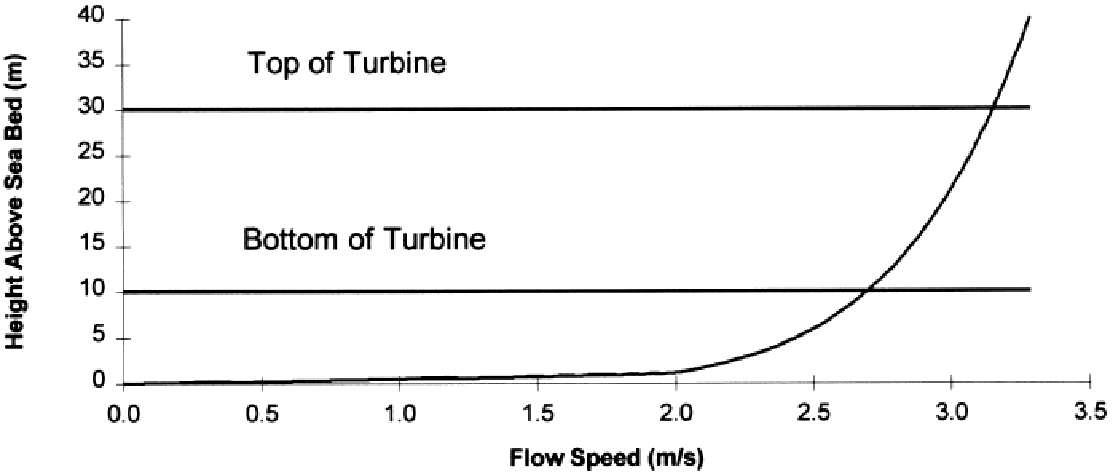
Figure 9. Power output as a function of current speed: 20m turbine, 12 sec period using Figure 7 information

- Current velocity as a function of time (relates to tidal cycles)
    - $V = \left[K_0 + K_1 \cos\left(\frac{2\pi t}{T_1}\right)\right] \cos\left(\frac{2\pi t}{T_0}\right)$, where K_0 and K_1 are constants determined by the mean spring peak and the ratio between the mean spring peak and the mean neap currents, T_1 is the spring neap period (353 h) and T_0 is the diurnal tidal period (12.4h) [2]
    - $U_x(t) = A + [B + C\cos(2\pi t/T_1)]\cos(2\pi t/T_0)$, $U_y(t) = F + [D + E\cos(2\pi t/T_1)]\sin(2\pi t/T_0)$, and $|U(t)| = \sqrt{U_x^2(t) + U_y^2(t)}$. where A, F are related to residual current speeds, B,C,D, and E are amplitude terms and the T's are the same as above [1]
- Vertical velocity profile
    - $V_{(Z)} = \left(\frac{Z}{0.32h}\right)^{1/7} V_{(\text{mean})}, \quad \text{for } 0 < Z < 0.5H$ and $V_{(Z)} = 1.07V_{(\text{mean})}, \quad \text{for } 0.5H < Z < H$ [2]
    - $U(z) = 0.93 \times (z/0.32h)^{\frac{1}{7}} U_{\text{peak}},$ Figure 10 shows a possible vertical velocity profile [1]
- Estimation of average current speed over swept area
    - $\bar{u} = \frac{4}{\pi D^2} \int_{-(D/2)}^{+(D/2)} \cos\left[\sin^{-1}\left(\frac{2y}{D}\right)\right] u(y + z_0)\,\mathrm{d}y$ where z_0 is the hub height [5]
- Maximum axial thrust
    - $T_{MAX} = ½\, C_t\, \rho\, A\, V^2_{MAX}$, where C_t is the thrust coefficient (≈0.9)
- Rotor size for given depth
    - Bryden suggests that the top of the rotor needs to be at lowest astronomic tide (LAT) minus 1.5m for the lowest negative storm surge, minus 2.5m for the trough of a 5m wave, and minus 5m more to minimize the potential damage from shipping and waves. Also, the bottom tip of the blades should not go below 25% of the water depth at LAT from the seabed. Without shipping the restrictions can be relaxed. An alternative estimation is that the turbine diameter should be 50% of the water depth with the hub at the mid-water point. Table 1 provides some estimates [1]
    - Figure 10 shows an example turbine size for a given depth along with a vertical velocity profile, which demonstrates how having the turbine close to the seabed is not useful [1]

Table 1. Influence of water depth on maximum permitted turbine size.

Water depth	Rotor diameter (assuming no shipping (exclusion)	Rotor diameter (assuming shipping exclusion)
< 20 m		10 m
20–25 m	5 m	120 m
25–40 m	10 m	20 m
> 40 m	20 m	20 m

Source: Bryden, I. G., Naik S., Fraenkel P., and Bullen C. R., 1998, “Matching Tidal Current Plants to Local Flow Conditions,” Elsevier Science Ltd., Vol 23, No. 9, pp. 699-709

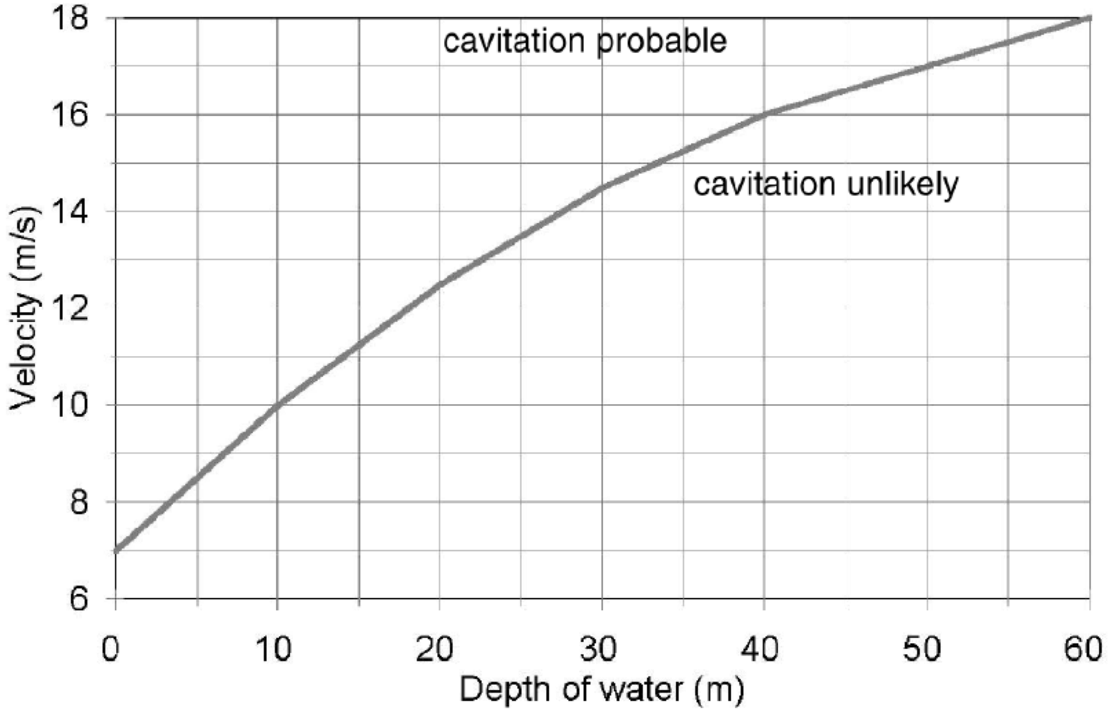


Source: Bryden, I. G., Naik S., Fraenkel P., and Bullen C. R., 1998, “Matching Tidal Current Plants to Local Flow Conditions,” Elsevier Science Ltd., Vol 23, No. 9, pp. 699-709

Figure 10. Vertical velocity profile with suggested turbine size and placement

- Cavitation
    - **Cavitation** is a general term used to describe the behavior of voids or bubbles in a liquid. . . Inertial cavitation is the process where a void or bubble in a liquid rapidly collapses, producing a shock wave. Such cavitation often occurs in pumps, propellers, impellers, and in the vascular tissues of plants. . . Cavitation is, in many cases, an undesirable occurrence. In devices such as propellers and pumps, cavitation causes a great deal of noise, damage to components, vibrations, and a loss of efficiency.When the cavitation bubbles collapse, they force liquid energy to very small volumes. Thereby, they create spots of high temperature and emit shock waves which are the source of noise. The noise created by cavitation is a particular problem for military submarines, as it increases the chances of being detected by the enemy. Although the collapse of cavities is a relatively low energy event, it is highly localized and can even erode metals such as steel. The pitting caused by the collapse of cavities produces great wear on components and can dramatically shorten a propeller or pump's lifetime. [6]
    - Figure 11 shows when cavitation is likely to become an issue [2]

- $$K_f = \frac{P_{abs} - P_V}{\rho V^2 / 2}$$ where K_f is a dimensionless term known as the cavitation number. As K_f increases, cavitation is less likely to occur. Clearly, K_f is a function of pressure and velocity. K_i, the Inception Parameter is a measure of conditions at which cavitation will start to occur, so cavitation begins when $K_f < K_i$. K_i is currently best estimated by modeling in wind or water tunnels [4]



Source: Fraenkel P.L., 2002, "Power from Marine Currents," Proc Instn Mech Engrs, Vol 216, Part A.

Figure 11. Graph showing when cavitation may become a problem as a function of water depth and the rotor blade tip velocity

- Cost Analysis
  - Bryden demonstrates a cost analysis of a particular design, and that can be used a reference when trying to determine the optimal design [1]

Conclusions

The tidal current turbine industry is still very young, making hard facts about design and testing difficult to find, however, the design considerations, proposed design features, and relevant information presented in this paper should help to summarize what is available, and to focus efforts to design an appropriate and high quality turbine device.

References

[1] Bryden, I. G., Naik S., Fraenkel P., and Bullen C. R., 1998, “Matching Tidal Current Plants to Local Flow Conditions,” Elsevier Science Ltd., Vol 23, No. 9, pp. 699-709.

[2] Fraenkel P.L., 2002, “Power from Marine Currents,” Proc Instn Mech Engrs, Vol 216, Part A.

[3] TidalStream, accessed Sept. 2007, http://www.teleos.co.uk/turbines.htm.

[4] Bahaj A. S. and Myers L. E., 2002, “Fundamentals Applicable to the Utilization of Marine Tidal Current Turbines for Energy Production,” Elsevier Science Ltd., WREC 2002.

[5] Bryden, I. G., Couch S. J., Owen A., and Melville G., 2007, “Tidal Current Resource Assessment,” Proc. IMechE Vol. 221, Part A.

[6] Wikipedia contributors, 'Cavitation', *Wikipedia, The Free Encyclopedia,* 1 October 2007, 17:15 UTC, <http://en.wikipedia.org/w/index.php?title=Cavitation&oldid=161597789> [accessed 10 October 2007]

Appendix

DESIGN MATRIX

ADVERSE EFFECTS:

	IMPORTANCE	DESIGN 1	DESIGN 2	DESIGN 3
A. Environmental Impact:				
1. Seabed Erosion				
2. Sediment				
3. Power Transportation				
4. Material Corrosion				
5. Flow Obstruction				
6. Chemical Pollution				
7. Wildlife/Marine Animal				
8. Thermodynamic Changes				
B. Transportation/Commerce:				
1. Commercial Transportation				
I. Draft Depth Interference				
II. Current Fluctuations				
III. Shipping Lane/Channel Changes				
2. Commercial Fishing				
I. Changing Fishing Grounds				
II. Tangling/Loss Fishing Equipment				
III. Aquamarine Farming				
3. Recreation				
I. Sailboats				
C. Cultural:				
1. Appearance				
2. Boating/Recreation				
D. Political:				
1. Environment				
2. Cultural				
3. Transportation				
4. Economics				

5. International Relations				
6. Alternative Energy				
7. Less Foreign Dependence				
FEASIBILITY:				
A. Cost:				
1. Materials				
2. Design				
3. Fabrication				
4. Installation				
5. Maintenance				
6. Study/Testing				
7. Recovery Time				
B. Maintenance:				
1. Access to Component				
2. Autonomus/Preventitive Maintenance				
3. Monitoring Systems				
B. Efficiency:				
1. Adverse Effects vs. Power Generation				
2. Cost Recovery Time				
3. Ease of Access				
PHYSICAL DESIGN:				
A. Foundation:				
1. Drilled Bedrock Tower				
2. Suspended from Bedrock				
B. Tower/Frame:				
1. Strength				
2. Perpendicular to Flow				
3. Hydro/Fluid Dynamics				
4. Weight/Size of Material				
5. Durability				
6. Height/Depth in Water				

C. Propeller/Turbine:				
1. Weight/Dimensions				
2. Hub				
3. Material				
D. Blades:				
1. Number of Blades				
2. Pitch(Adjustable??)				
3. Material				
4. Type/Axis				
5. Size/Dimensions				
6. Profile				
E. Power Generation:				
1. Output Type				
2. Type of Generator				
3. Conversion to Grid				
4. Transportation medium				
F. Drive/Mechanical Transmission:				
1. Bearings				
2. Dual Turbine Gearing				
3. Containment/Seals				
4. Breaker/Trip				
5. Speed Variation				
6. Size/Durability				