ALTERNATIVE ELECTRICAL ENERGY SOURCES
FOR MAINE

W.J. Jones   M. Ruane

Appendix J
OCEAN AND RIVERINE CURRENT ENERGY CONVERSION

J. Mays

Prepared for the Central Maine Power Company.

This appendix is one of thirteen volumes; the remaining volumes are as follows: A. Conversion of Biomass; B. Conservation; C. Geothermal Energy Conversion; E. Ocean Thermal Energy Conversion; E. Fuel Cells; F. Solar Energy Conversion; G. Conversion of Solid Wastes; H. Storage of Energy; I. Wave Energy Conversion; K. Wind Energy Conversion, and L. Environmental Impacts.

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Appendix A   Conversion of Biomass - C. Glaser, M. Ruane

Appendix B   Conservation - P. Carpenter, W.J. Jones, S. Raskin, R. Tabors

Appendix C   Geothermal Energy Conversion - A. Waterflow

Appendix D   Ocean Thermal Energy Conversion - M. Ruane

Appendix E   Fuel Cells - W.J. Jones

Appendix F   Solar Energy Conversion - S. Finger, J. Geary, W.J. Jones

Appendix G   Conversion of Solid Wastes - M. Ruane

Appendix H   Storage of Energy - M. Ruane

Appendix I   Wave Energy Conversion - J. Mays

Appendix J   Ocean and Riverine Current Energy Conversion - J. Mays

Appendix K   Wind Energy Conversion - T. Labuszewski

Appendix L   Environmental Impacts - J. Gruhl

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Ms. Alice Sanderson patiently weathered out many drafts and prepared the final document.

Preface

The Energy Laboratory of the Mass. Inst. of Tech. was retained by
the Central Maine Power Company to evaluate several technologies
as possible alternatives to the construction of Sears Island #1
(a 600 MWe coal fired generating plant scheduled for startup in
1986). This is an appendix to Report MIT-EL 77-010 which presents
the results of the study for one of the technologies.

The assessments were made for the Central Maine Power Company on
the basis that a technology should be:

1) an alternative to a base-load electric
power generation facility. Base-load is
defined as ability to furnish up to a rated
capacity output for 6570 hrs. per year.

2) not restricted to a single plant. It
may be several plants within the state of
Maine. The combined output, when viewed
in isolation, must be a separate, "stand-
alone", source of power.

3) available to deliver energy by 1985.

APPENDIX J

OCEAN AND RIVERINE CURRENT ENERGY CONVERSION

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

1.1 Ocean Currents:

Ocean currents off the Maine coast due to non-tidal effects are very slight. There is a large, counter-clockwise eddy in the Gulf of Maine formed by a meander off of the Gulf Stream called the slope water current. The behavior of this eddy is seasonal. (TRIGOM, 1974)

winter-spring	0.04 - 0.16 knots
late spring	0.29 - 0.34
July-August	0.20
autumn	0.20 - 0.25

Thus, the ocean current in the Gulf of Maine has an approximate rate of 0.2 knots resulting in a power density of 0.57 watts/m^2, which is negligible.

As a rule, most ocean currents are too weak to be considered as power sources with the exception of such intense, near-shore streams as the Florida current where the mean speed is 2.2 knots, resulting in a power density of 0.75 KW/m^2. It has been calculated that the total power in the Florida current is on the order of 25,000 MW. (Somers and Shoup, 1974).

1.2 Riverine Currents:

There are, however, riverine currents that are driven by rain water runoff and by tidal forcing. In this Appendix, we shall not consider tidal power as the phrase is conventionally used. We shall look at the resource potential of quickly flowing rivers and develop a means for analyzing tidal streams that may have application as power sources.

The literature on tidal energy is voluminous. Some of it is applicable to riverine and tidal stream power extraction. Charlier (1969a, 1969b, 1970), Gray and Gashus (1972), and Wilson (1973) may be consulted. Of more direct relevance is the work of Heronemus (1974) and other contributors to the MacArthur Workshop on Energy from the Florida Current, Feb. 27 - Mar. 1, 1974, hosted by the National Oceanic and Atmospheric Administration (NOAA) - Atlantic Oceanographical and Meteorological Laboratories.

Tidal mills, machines that extract power from the tidal streams, were quite prevalent in previous centuries. Areas that enjoyed significant tidal ranges usually had large tidal streams.

> Early records indicate that tide mills were being worked along the Atlantic coast of Europe, notably in Great Britain, France, and Spain by the 11th century. One such installation in the Deben Estuary, in Great Britain, was mentioned as early as 1170 in the records of the Parish of Woodbridge. This is believed to be still in operation. Tidal energy was widely used in coastal areas where the tides attained a sufficient range to the middle of the 19th century. Part of the water supply of London in 1824 was provided by 20 ft. diameter waterwheels installed in 1580 under the arches of the London Bridge. A tidal power installation for pumping sewage was still in use in Hamburg in 1880. Other installations have been reported throughout this era in Russia, North America, and Italy. Some of the old structures were of impressive size. A tide mill in Rhode Island built in the 18th century used 20-ton wheels 11 ft. in diameter and 26 ft. in width.

(Gray and Gashus, 1970)

Heronemus (1974) further delineates tidal mills as to whether they are fixed or floating. We shall consider only floating tidal mills because the fixed tidal mills usually require extensive construction of coffer dams entailing great expense and ecological impact, not to mention impairment of navigation and other traditional uses of a river.

2.0 TECHNICAL FACTORS

2.1 Fluid Power

The power in a flux of fluid is equal to the mass flow rate times the energy per unit area.

$$\text{Power} = \rho A v \times \frac{v^2}{2} = \rho \frac{A v^3}{2} \tag{1.1}$$

where

ρ = fluid density

A = area of section

v = velocity of flow.

Note that the power is proportional to the cube of the fluid speed. The analysis that follows is applicable to windmills as well as water mills, the appropriate density being used. In this context, efficiency will be defined as the power actually extracted by a device of area A divided by the available fluid power, equation (1.1).

2.2 Power Extraction

There are a number of devices that have been used to take power out of a fluid stream; some use drag force entirely while others utilize lift force as well. A screw propeller uses lift, while a paddle wheel uses drag. Turbines, of which there are many kinds, may use a combination of lift and drag forces for their operation. The water velocities measured in tidal rivers produce a head which is quite small. Head is defined as the pressure difference that causes the fluid to flow in the first place and can be calculated by

$$\text{head (meters)} = \frac{1}{2} v^2/g \tag{1.2}$$

where

g = gravitational acceleration = 9.8m/sec^2.

The size of the head will determine the device. Hydro-electric power plants use turbines that are rated for large heads on the order of hundreds of meters. A head of 0.12 meters is associated with a current of 3 knots.

We shall consider three types of devices for the extraction of power: the undershot paddle wheel, the screw turbine, and the Savonius motor.

2.2.1 Paddle wheel

The simplified theory of the paddle wheel provided in Technical Note A shows that the maximum theoretical efficiency is 33%. We shall consider a paddle wheel supported on a moored raft such that the lower half of the wheel is in the free stream of the current. The tip speed of the paddle cannot exceed the current velocity. Two important parameters characterizing the output of rotational energy extractors are (i) tip speed ratio = tip speed/current velocity, and (ii) torque. Typically, high-torque devices have slow tip speeds and are large, massive devices such as the old-fashioned water wheels. The energy output is used directly as mechanical work such as pumping water or grinding. Electric generators, on the other hand, are usually designed as high-speed devices for better efficiency and lower cost. The paddle wheel with the inherent limitations of low tip speed and low efficiency does not seem a suitable candidate except for ease in construction.

2.2.2 Screw turbine

The screw turbine is equivalent to the windmill. Windmills that are used for mechanical work have relatively low tip speeds, high torque, and high solidity (which is the proportion of cross-
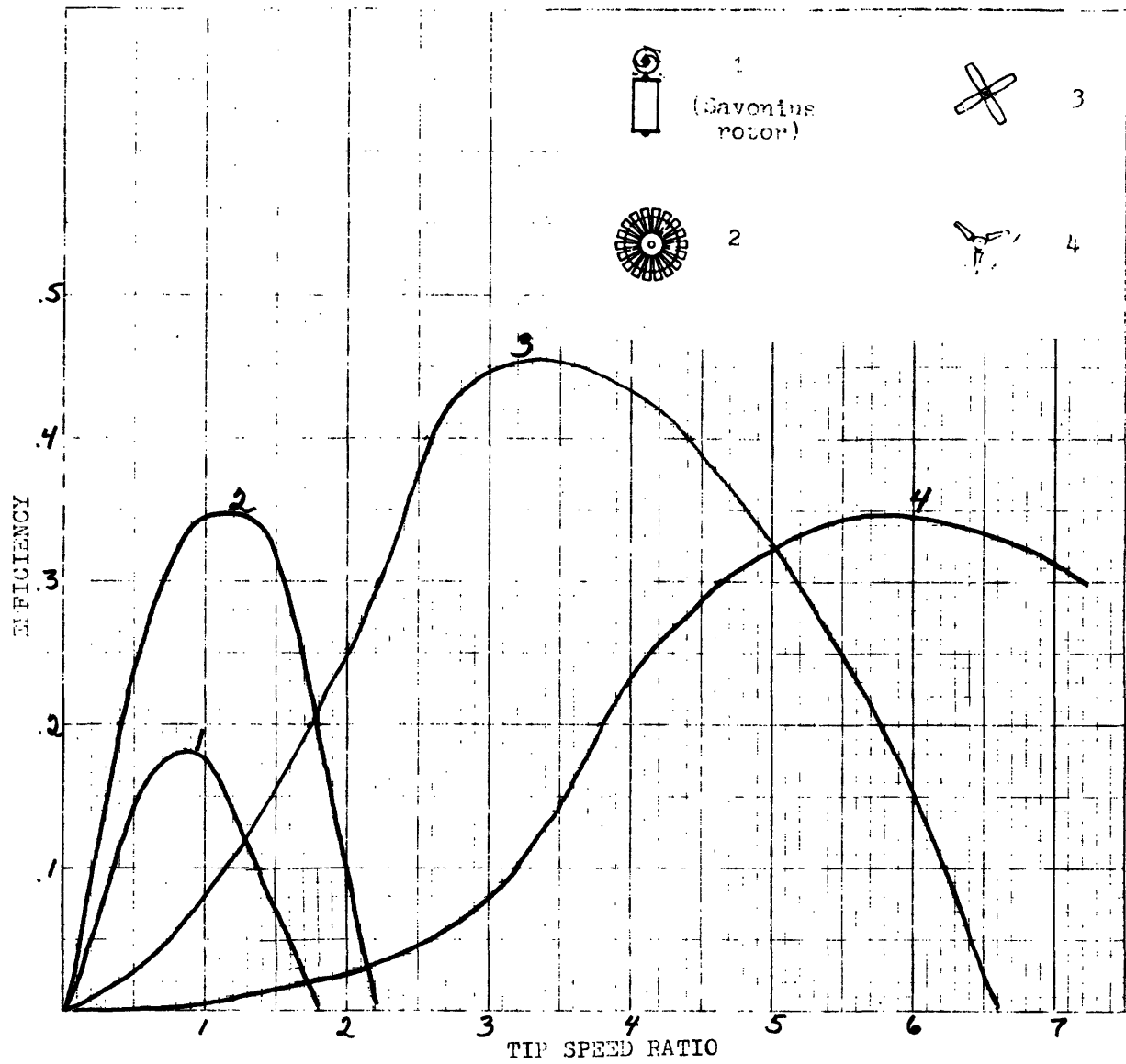
sectional area taken up by blades). See curve 2 on Figure 2.1. If high rpm and efficiency are wanted, then very few blades, perhaps only two or three, are used with a resulting low solidity. Curves 3 and 4 in Figure 2.1 display this feature.

The maximum power that can be extracted from a screw turbine is given in Technical Note B as 59% of the total power of the current. In addition to that, we expect other types of hydro-dynamic losses as well due to interference with the hub, induced drag, and so on. The greatest efficiency in Figure 2.1 is around 45% with a tip speed ratio of 3.5 for a four-bladed screw. By changing the number and the design of the blade, the tip speed ratio can be increased up to 6.0 with a corresponding loss in output to 35%. It is important to recognize that efficiency is not the most important element in power extraction since we are presumably not paying anything for the energy we are extracting. We are paying for the conversion system so it is necessary to match total power out as a function of cost to get the most economically efficient machine.

What allows the screw turbine to achieve tip speeds in excess of the current velocity is the fact that they use the phenomenon of lift to provide their drive much in the same way that an airplane is able to fly. The relative speed of the fluid, provided by the sum of the current and the peripheral velocity of the blades, acts at an _angle_ _of_ _attack_ on the blade or foil in such a way as to provide a strong force perpendicular to the resultant velocity. The lift provides the torque necessary to allow the blades to go faster until an equilibrium is reached between the torque of the generator and the torque of the turbine. Elaborate turbines are provided with automatic pitch control that always keep the angle of the blade at the optimum angle of attack for best power out as the fluid speed changes. Figures 2.2, 2.3, and 2.4 illustrate several screw turbine designs that have been proposed for the extraction of energy from the Florida current. (Heronemus, 1974).

2.2.3 Savonius Rotor

The S-shaped rotor, invented by a Finnish engineer, evolved from the paddle wheel design. Figure 2.5 shows how a paddle wheel with semi-circular blades can be modified to fit entirely in a current. The mechanism of motion is primarily the difference in drag between the concave and convex sides of the rotor. Savonius took this idea and displaced the halves in such a way that the flow is redirected, producing a greater exchange of momentum, Figure 2.6. Several series of tests on different versions of the Savonius rotor have been conducted. Savonius (1931) reported efficiencies of 31% as seen in Figure 2.7. Tests conducted at New York University (1945) found peak efficiencies of

Efficiency vs Tip Speed Ratio for Different Wind Turbines

Figure 2.1

U MASS OCEAN ENGINEERING

A PROPOSED SINGLE DISC UNDERWATER WINDMILL
RATED 7.5 MW IN 7 FPS CURRENT VELOCITY
SIX BLADES. 250 FT. SWEPT DIAMETER
CAPABLE OF CONSTRUCTION & TOWING AS
A 255 FT. LENGTH x 30 FT. BEAM x 25 FT. DRAFT HULL

ONCOMING
OCEAN
CURRENT

W.L. IN 9 FPS CURRENT

W.L. IN 7 FPS CURRENT

365 FT. WORKING HEIGHT

255 FT. CONSTR. & TOWING LENGTH

TETHER

250 FT. DIAMETER

FIG. 3-8
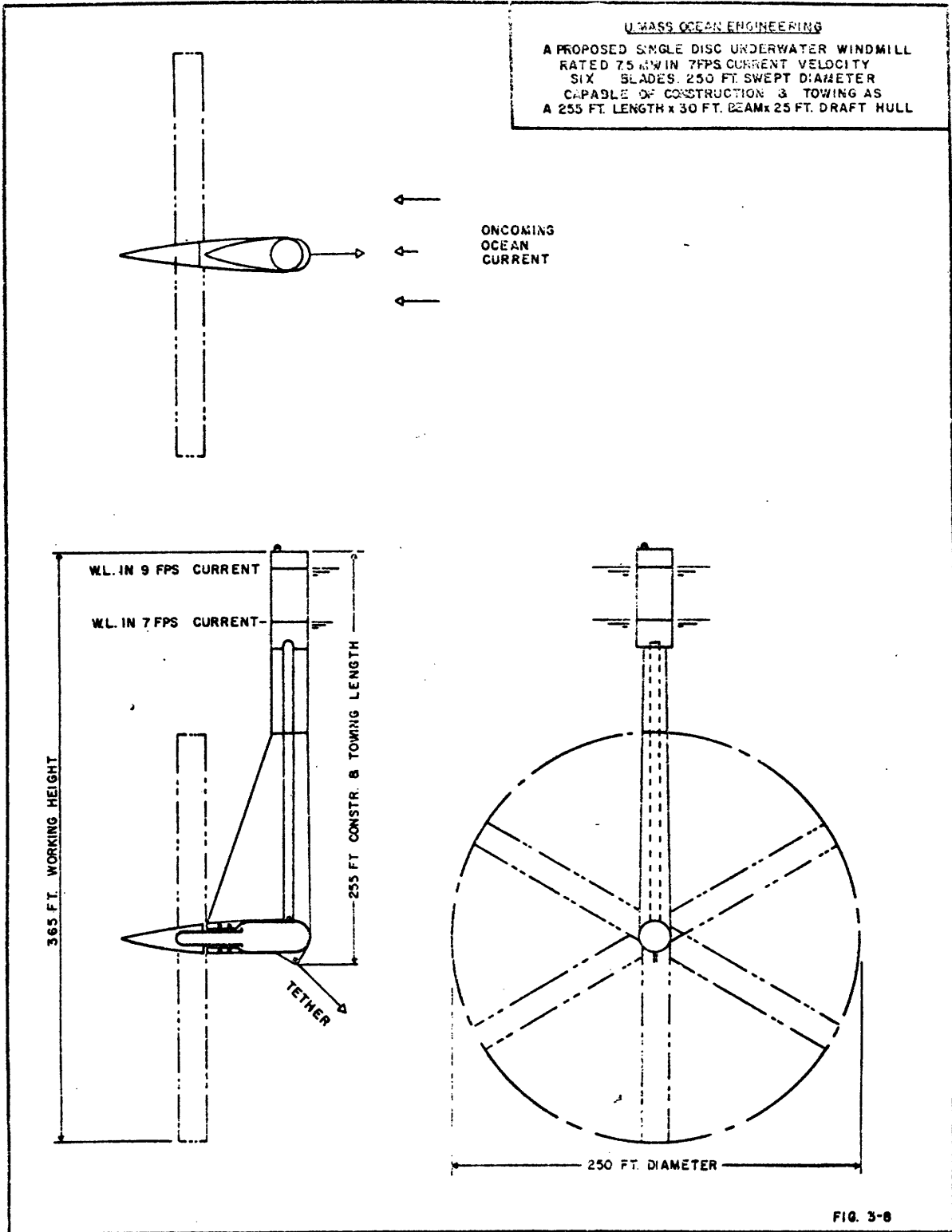
Proposed Florida Current Energy Extraction Device

Figure 2.2

Source: University of Massachusetts
         Department of Ocean Engineering

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U-MASS. OCEAN ENGINEERING

A PROPOSED FOUR DISC AXIAL FLOW WATER TURBINE RATED 24MW IN 7 FPS CURRENT. TWELVE BLADES PER DISC. HINGING OF STRUCTURE TO REDUCE CONSTRUCTION BEAM TO 220' IS POSSIBLE.
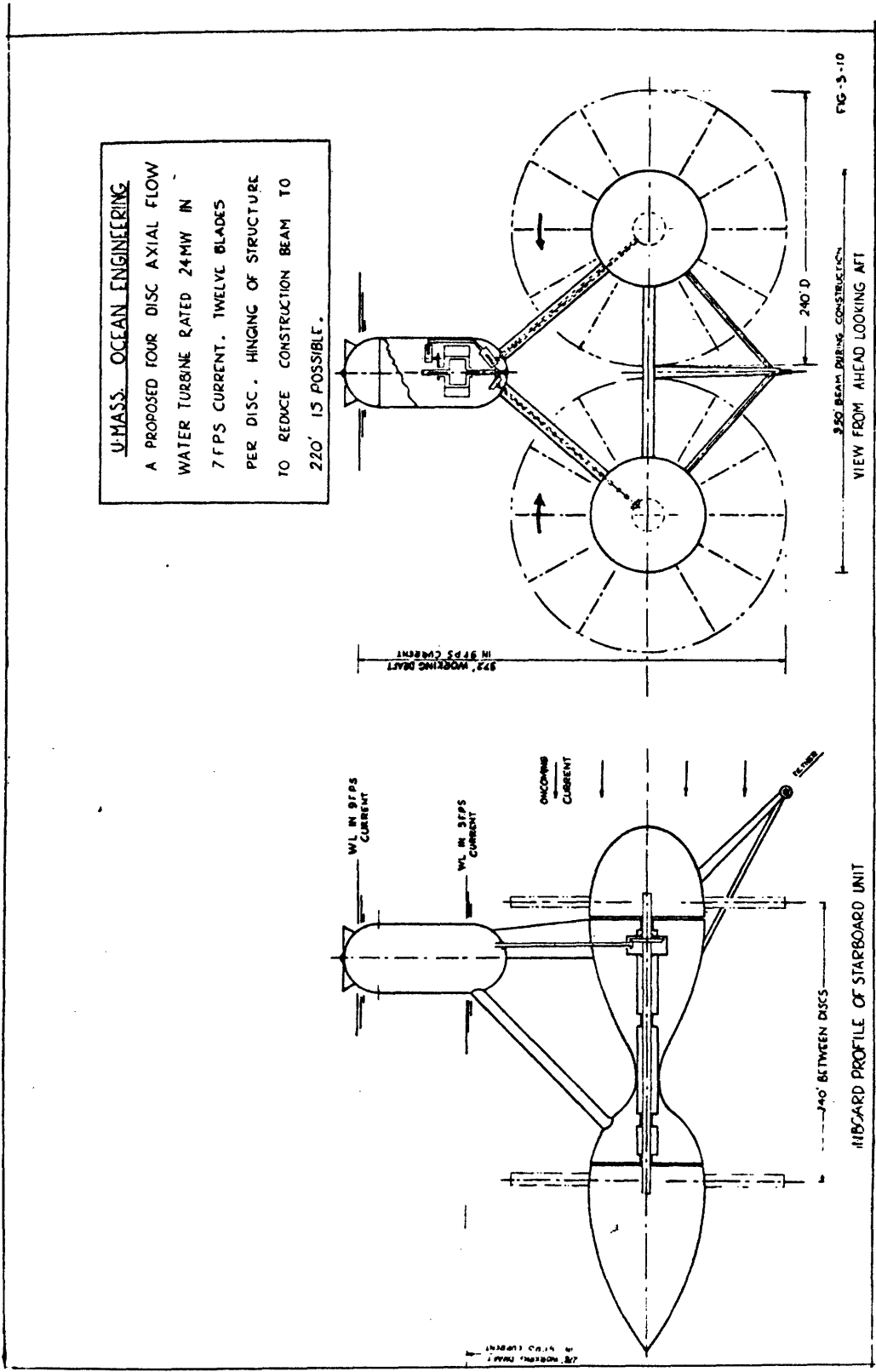
Proposed Florida Current Energy Extraction Device

Figure 2.3

Source: University of Massachusetts
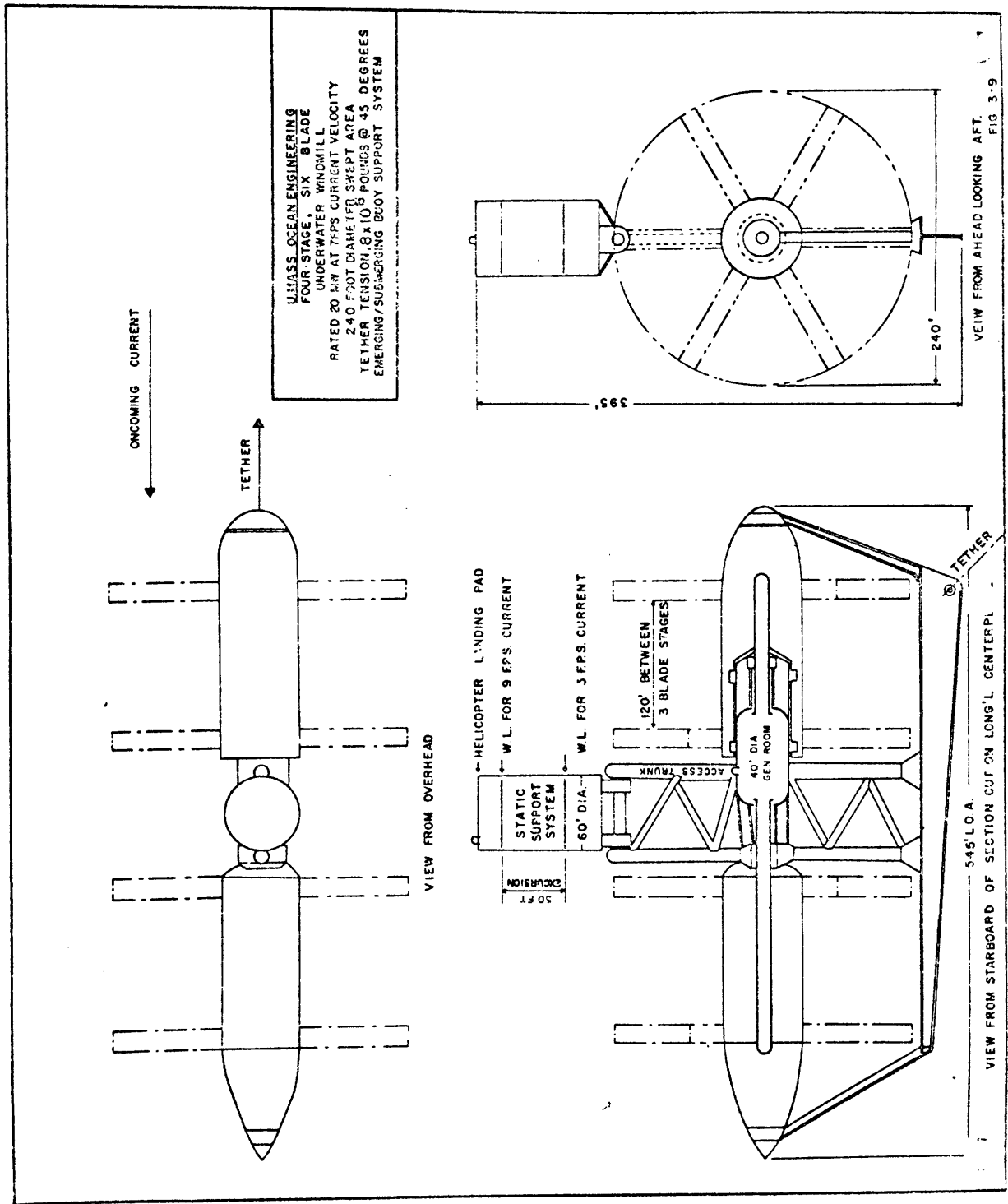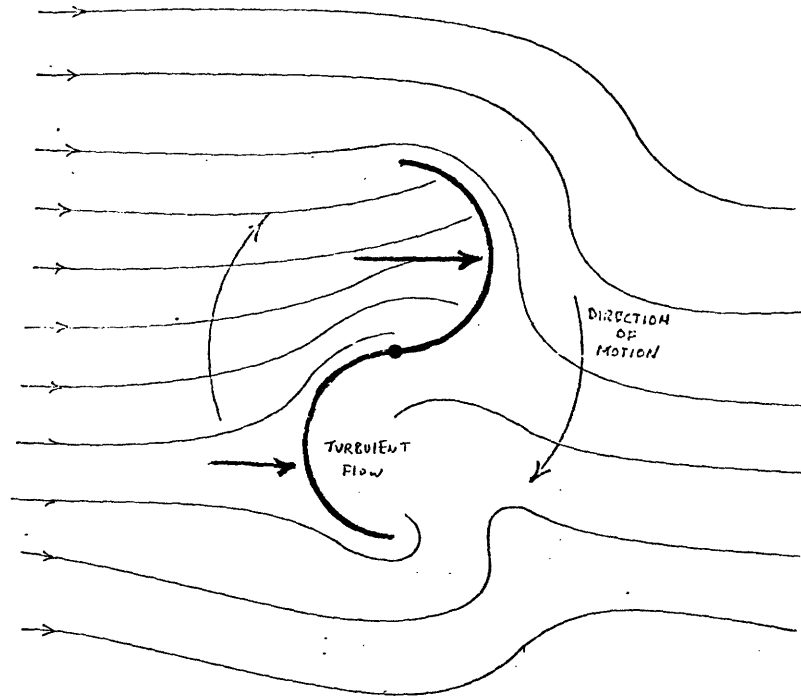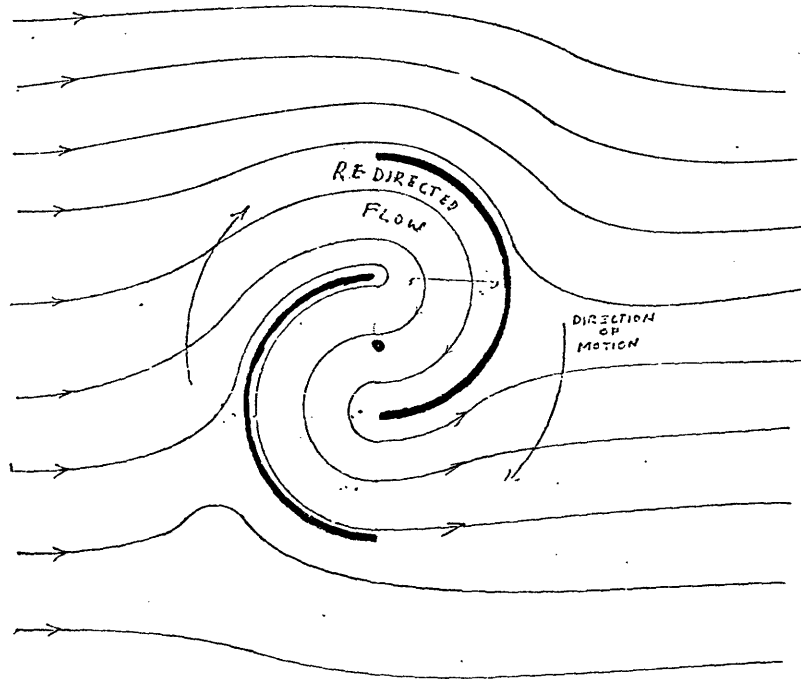Ocean Engineering

J-6

Proposed Florida Current Energy Extraction Device

Figure 2.4

Source: University of Massachusetts
Ocean Engineering

Modified Paddle Wheel Design
Figure 2.5

Savonius Rotor Design
Figure 2.6

28%. Curve 1 in Figure 2.1 shows the performance of one version of Savonius rotor. There is a complicated relationship between the rotational motion of the device and the current that allows some lift to be produced and hence a tip speed ratio of greater than 1.0.

A consideration that has not been mentioned is the torque produced when the device is just beginning to turn. If its starting torque is low, it may not be able to turn the generator until an appreciable velocity is built up. Because we are dealing with low speeds anyway this is an important consideration. Good efficiency would be worth little if a large amount of running time were lost due to poor starting torque. The "American" style multi-bladed windmill rotor, for example, gained wide popularity due to its good starting torque in spite of marginal efficiency. Figure 2.7 indicates that there is very little difference in performance between a Savonius rotor and a 12-vane steel windmill rotor. The Savonius rotor would probably be far cheaper to construct. Heronemus (1974) advocates the Savonius rotor for tidal river use, Figure 2.8. For completeness, Figure 2.9 shows a design of Heronemus' using a cascade of Savonius rotors for service in the Florida current.

2.3 Other Mechnical Considerations

The tidal influence causes a periodic reversal of flow. The implications will be discussed in greater detail in the next section, but suffice it to say that the units have to be reversible to produce power throughout the cycle. Thus, the designs for the Florida current are not really suitable for the Maine coast. A screw turbine would have to have sufficient pitch control for this purpose or the whole configuration could be moored at one point allowing it to "weather cock" as the current changed direction. This approach presents problems to river traffic, not to mention mooring.

Whether we use a screw turbine or a version of the Savonius rotor depends on a complete study of the site, engineering difficulties, and costs. It is not clear which would be more suitable; the efficiencies of the multi-bladed screw turbine and the Savonius rotor are comparable, about 30%, while the efficiency of a well-designed screw turbine of low solidity might be as high as 45%. There is no practical experience on which to base a choice.

So far, we have discussed only the device that extracts the power from the current. Mechanical power at a given torque and rpm then has to be converted to electricity which must be synchronized with the rest of the utility power system. Conversion to electricity can be done with fairly standard generator components. Synchronization can be done mechanically (before the generator) or electrically (after the generator) to produce 60 Hz A.C. power. In the mechnical case, turbine controls and gearing systems are used to maintain synchronous speed. Efficiency is lost by such operation. In the electrical case, expensive elaborate electronic switchgear is needed to convert generated power at varying frequencies to 60 Hz power. In either case, the generator and its linkage will have a minimum and maximum operating condition described by its nominal rated power. There will also be a cut-off speed below which the generator will not extract power. Similarly, above its rated power, it will be saturated and steps must be taken not to exceed this capacity.

A screw turbine would probably have its drive linkage and generator located wholly within the hub. A Savonius rotor like that illustrated in Figure 2.8 would have its generator on the raft where it would be accessible. Power transmission would be by underwater cable to the shore.

There will not be the problem of excessive fluid speeds and gust loadings as with windmills, but the conjunction of problems caused by a hydraulic, mechanical and electrical system subject to wind, waves, and current while partially floating and partially immersed in salt water will require considerable design effort. Technologically, there are not great gaps in knowledge. A timetable for development would depend upon the effort expended. It would not seem unreasonable to expect a working demonstration device along the lines described within three years, given sufficient funding.

Curves taken from wind tunnel
tests (Savonius,1931)

1- 12 blade steel windmill
2- Savonius rotor
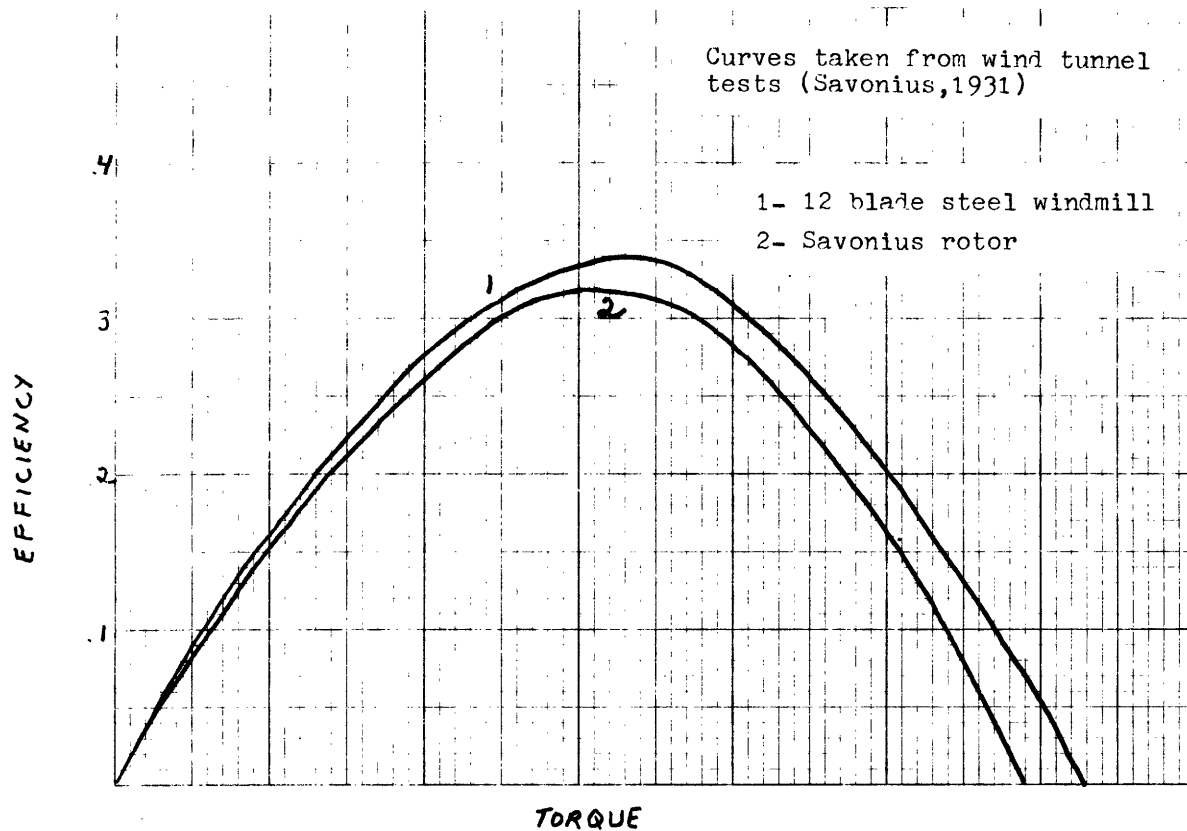
Efficiency vs Torque for Savonius Rotor and Windmill

Figure 2.7

**A PROPOSED ROTOR TYPE FLOATING
ANCHORED KINETIC ENERGY
MACHINE FOR EXTRACTING ENERGY
FROM TIDAL RIVER CURRENTS**

Figure 2.8

VIEW LOOKING DOWN
FROM OVERHEAD

U.MASS OCEAN ENGINEERING
A PROPOSED SAVONIUS ROTOR TYPE
UNDERWATER POWER STATION
RATED 14 KW AT 7 F.P.S. CURRENT VELOCITY
STATIC SUPPORT USING THREE
VARIABLE DRAFT SPAR BUOYS
— HINGED GIRDER CONCEPT —

ONCOMING
CURRENT

PARTIAL VIEW FROM AHEAD
LOOKING AFT

WATERLINE IN
9 F.P.S. CURRENT

WATERLINE IN
5 F.P.S. CURRENT

TETHER
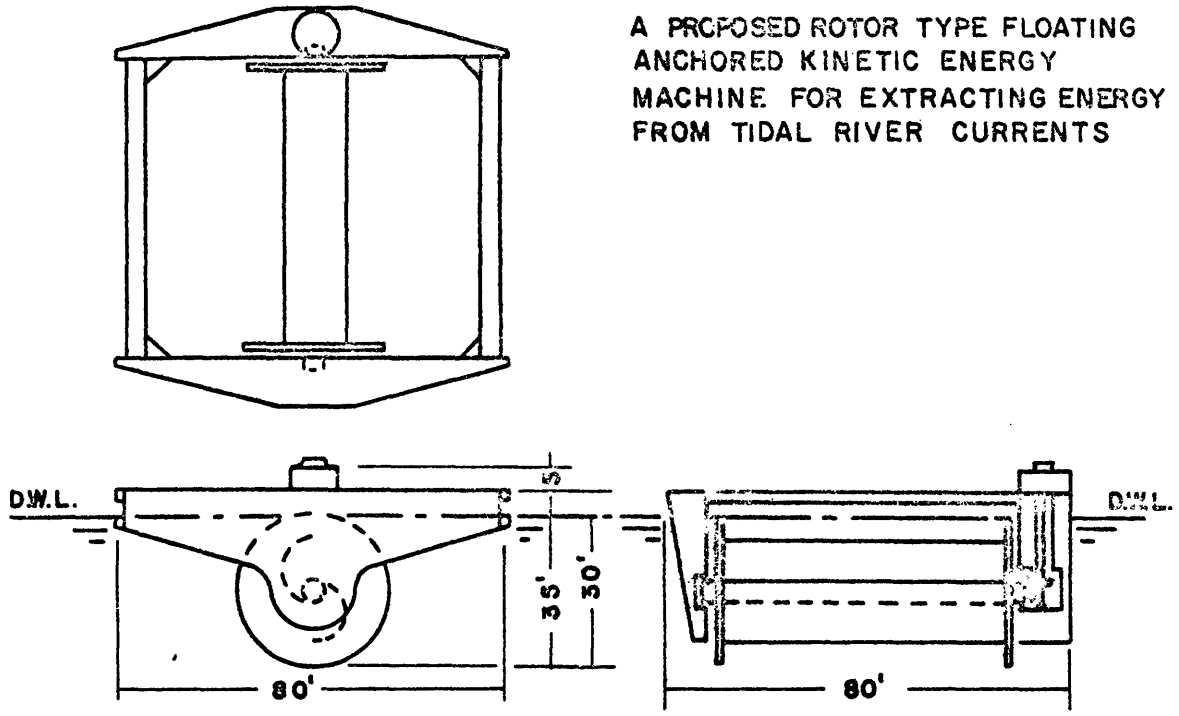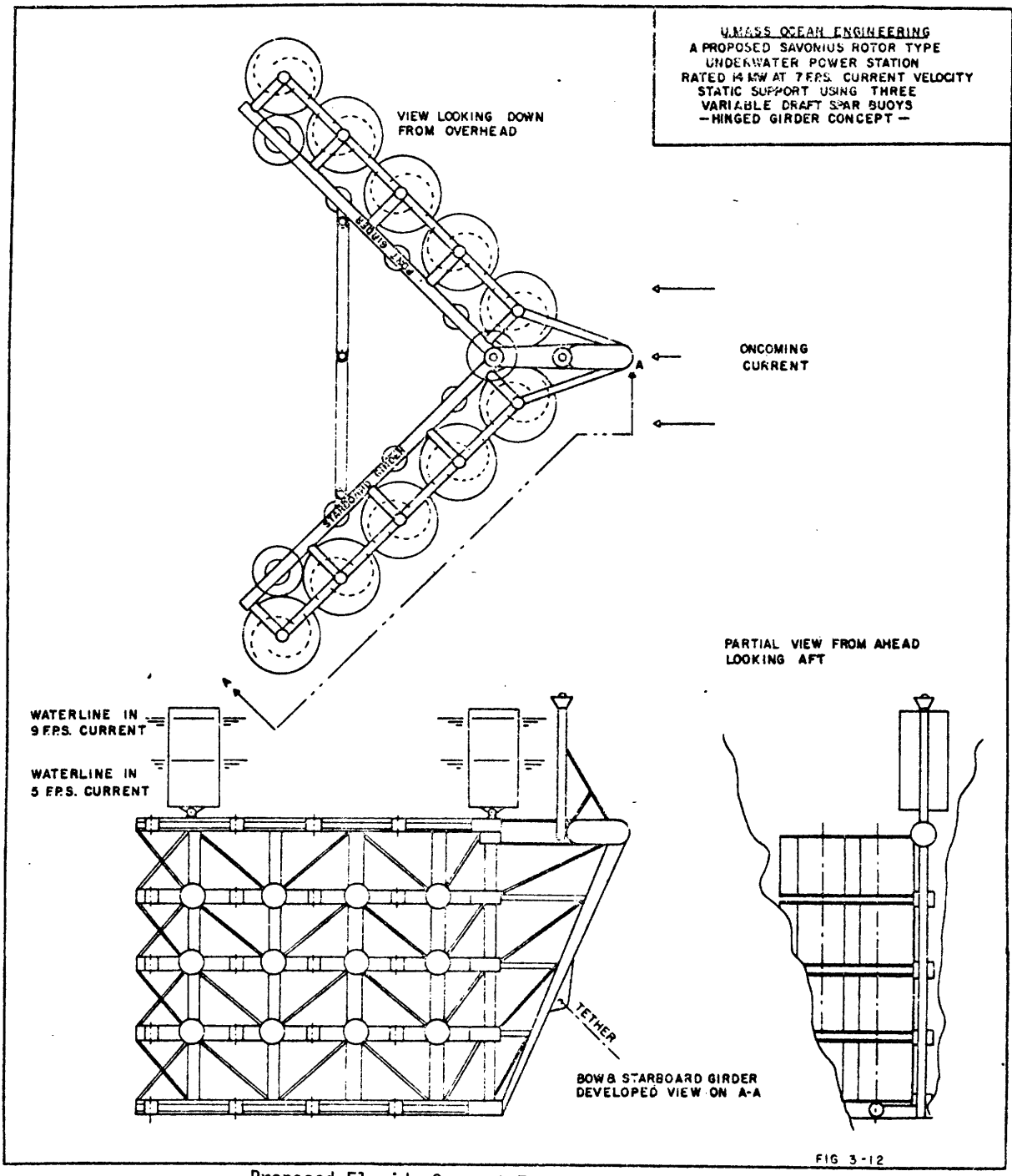
BOW & STARBOARD GIRDER
DEVELOPED VIEW ON A-A

FIG 3-12

Proposed Florida Current Energy Extraction Device
Figure 2.9

Source: University of Massachusetts
Ocean Engineering

J-12

3.0 APPLICABILITY TO MAINE

Maine has a number of tidal rivers that could be candidates for current extraction. Implicit throughout this presentation is that present uses of the river be maintained and that environmental effects due to current loss and tidal range diminution from power extraction be carefully considered to provide maximum social benefit. An inventory of the power extractable from all the tidal rivers in Maine has not been made at this time. The case has to be presented in detail for each river. A narrow channel in a river will produce larger currents, thus increasing the power considerably. Environmental impact of current power is very site-specific. What we shall do is to look at one site each on the Kennebec and the Piscataqua. These "sites" were chosen only because current flow information on them is readily accessible and that it is supposed that they are representative of other sites insofar as power available is concerned, see Table 3.1.

Heronemus (1974) did an analysis based on the current at different locations on the Piscataqua for a random selection of days throughout the year. The available energy is deduced by integrating the power over time subject to a power cut-off below a given current speed. We assume simplistically that the current speed varies like a sine curve whose amplitude is the maximum current and at a period equal to 12 hours and 40 minutes, the semi-diurnal tidal period:

$$v = a \sin \frac{2\pi t}{T} \tag{3.1}$$

where

$$\pi = 3.1416$$
$$a = \text{amplitude (max current)}$$
$$T = 12 \text{ hr } 40 \text{ min}$$

Technical Note C deduces a formula for the energy per cross-sectional area averaged over one month:

$$E_{month} = 5223(a_f^3 + a_e^3) \text{ KWH/m}^2 \tag{3.2}$$

$$a_f = \text{max flood current in knots}$$
$$a_e = \text{max ebb current in knots}$$

The current tables give the amplitudes for the Piscataqua at the Nobles Island station as:

$$a_f = 4.4k \quad a_e = 3.6k$$
$$E_{month} = 689. \text{ kwh/month x m}^2$$

$$P_{eff} = .96 \text{ KW/m}^2 \text{ (average over a month)}$$

$$P_{rated} = 6.02 \text{ KW/m}^2 \text{ rated power (maximum power)}$$

On the Kennebec, south of Doubling Point,

$$a_f = 2.2k \quad a_e = 1.7k$$
$$E_{month} = 81.3 \text{ KWH/month x m}^2$$

$$P_{eff} = .11 \text{ KW/m}^2 \text{ (average over a month)}$$

$$P_{rated} = .75 \text{KW/m}^2 \text{ (maximum power)}$$

TABLE 2.—CURRENT DIFFERENCES AND OTHER CONSTANTS

No.	PLACE	POSITION		TIME DIF- FERENCES		VELOCITY RATIOS		MAXIMUM CURRENTS			
								Flood		Ebb	
		Lat.	Long.	Slack water	Maxi- mum current	Maxi- mum flood	Maxi- mum ebb	Direc- tion (true)	Aver- age veloc- ity	Direc- tion (true)	Aver- age veloc- ity
		° ′	° ′	h. m.	h. m.			deg.	knots	deg.	knots

	MAINE COAST *Time meridian, 75°W.*										
85	Eastport, Friar Roads---------------	44 54	66 59	0 00	0 00	1.2	1.2	210	3.0	040	3.0
90	Western Passage, off Kendall Head-----	44 56	67 00	+0 20	+0 25	1.4	1.3	320	3.2	140	3.1
95	Western Passage, off Frost Ledge------	44 58	67 02	+0 10	+0 10	0.9	0.7	330	2.1	150	1.7
100	Pond Point, 7.6 miles SSE. of---------	44 20	67 30	(¹)	-0 10	0.2	0.5	015	0.5	215	1.2
105	Moosabec Reach, east end-------------	44 32	67 34	-3 00	-3 25	0.4	0.4	110	1.0	260	1.0
110	Moosabec Reach, west end-------------	44 31	67 39	-1 50	-1 45	0.4	0.5	090	1.0	255	1.2
115	Bar Harbor, 1.2 miles east of---------	44 23	68 10	(²)	+0 40	0.1	0.3	330	0.2	150	0.7
120	Casco Passage, E. end, Blue Hill Bay--	44 12	68 28	-1 25	-1 50	0.3	0.3	085	0.7	285	0.7
125	Hat Island, SE. of, Jericho Bay-------	44 08	68 30	-0 55	-1 00	0.4	0.5	320	0.9	125	1.3
			on PORTSMOUTH HBR. ENT., p.10								
130	Isle Au Haut, 0.8 mi. E. of Richs Pt--	44 05	68 35	-2 10	-1 45	1.2	0.8	335	1.4	140	1.5
135	West Penobscot Bay, off Monroe I------	44 05	69 00	-1 45	-1 20	0.2	0.3	005	0.3	160	0.6
140	Muscongus Sound---------------------	43 56	69 27	Current too weak and variable to be predicted.							
145	Damariscotta River, off Cavis Point---	43 53	69 35	-1 05	-1 00	0.5	0.6	350	0.6	215	1.0
150	Sheepscot River, off Barter Island----	43 54	69 41	-1 00	-0 50	0.7	0.6	005	0.8	200	1.1
155	Lowe Pt., NE. of, Sasanoa River-------	43 51	69 43	-0 45	-0 10	1.4	1.0	325	1.7	150	1.8
160	Lower Hell Gate, Knubble Bay³--------	43 53	69 44	-0 35	+0 20	2.5	1.9	290	3.0	155	3.5
165	Upper Hell Gate, Sasanoa River-------	43 54	69 46	(⁴)	(⁴)	0.8	0.5	305	1.0	140	0.8
	KENNEBEC RIVER										
170	Hunniwell Point, northeast of--------	43 45	69 47	+0 05	+0 20	2.0	1.6	330	2.4	150	2.9
175	Bald Head, 0.3 mile southwest of------	43 48	69 48	+0 10	+0 25	1.3	1.3	320	1.6	155	2.3
180	Bluff Head, west of------------------	43 51	69 48	+0 30	+0 40	1.9	1.9	015	2.3	185	3.4
185	Fiddler Ledge, north of--------------	43 53	69 48	+0 35	+1 00	1.6	1.4	265	1.9	115	2.6
190	Doubling Point, south of-------------	43 53	69 48	+0 25	+0 50	2.2	1.7	300	2.6	125	3.0
195	Lincoln Ledge, east of---------------	43 54	69 49	+0 30	+0 40	1.6	1.6	000	1.9	175	2.8
200	Bath, 0.2 mile south of bridge⁶-------	43 55	69 48	⁵+0 35	+0 55	0.8	0.8	005	1.0	175	1.5
	PISCATAQUA RIVER and TRIBUTARIES										
355	NW. of Nobles Island (RR. bridge)-----	43 05	70 46	+0 35	+0 35	1.3	0.5	050	1.6	200	0.9
360	Nobles Island, north of--------------	43 06	70 46	+0 30	+0 30	3.0	2.4	305	3.6	140	4.4
365	Frankfort Island, south of-----------	43 07	70 45	+0 30	+0 30	2.2	1.6	310	2.6	130	2.9
370	Little Bay entrance, Dover Point------	43 07	70 50	+0 35	+0 35	3.2	2.3	270	3.8	095	4.2
375	Furber Strait-----------------------	43 05	70 52	+0 40	+0 40	1.7	1.2	185	2.0	010	2.1

PORTSMOUTH HARBOR ENTRANCE (OFF WOOD I.), N.H., 1977

F-FLOOD, DIR. 355° TRUE   E-EBB, DIR. 195° TRUE

JANUARY

DAY	SLACK WATER TIME H.M.	MAXIMUM CURRENT TIME H.M.	VEL. KNOTS	DAY	SLACK WATER TIME H.M.	MAXIMUM CURRENT TIME H.M.	VEL. KNOTS
1 SA	0343 0942 1631 2204	0532 1230 1801	0.9F 1.6E 0.6F	6 TH	0102 0723 1307 2003	0337 0927 1603 2157	1.7E 1.4F 2.1E 1.2F
2 SU	0430 1028 1718 2253	0036 0621 1315 1853	1.4E 1.0F 1.7E 0.7F	7 F	0141 0805 1341 2043	0420 1010 1645 2240	1.8E 1.4F 2.2E 1.3F
3 M	0516 1112 1802 2339	0122 0710 1357 1940	1.5E 1.1F 1.8E 0.8F	8 SA	0219 0848 1414 2123	0507 1058 1729 2327	1.8E 1.4F 2.2E 1.4F
4 TU	0559 1153 1844	0210 0757 1439 2027	1.6E 1.2F 1.9E 1.0F	9 SU	0258 0934 1449 2205	0552 1143 1815	1.9E 1.4F 2.2E
5 W	0022 0642 1231 1924	0254 0842 1521 2111	1.6E 1.3F 2.0E 1.1F	10 M	0340 1023 1529 2251	0012 0639 1232 1903	1.5F 1.9E 1.4F 2.1E

Current Tables for Selected Maine Sites

Table 3.1

These values are somewhat understated due to the nature of the averaging process. The values given in the current tables for a_f and a_e are averages of the maximum flood and ebbing currents. The cube of the average maximum current is less than the average of the cubes of the maximum current. We estimate this factor may cause actual energies to be 1.5 to 3.0 times larger than values calculated from Table 3.1. Extraction efficiencies are on the order of 10%-20% and conversion efficiencies to electricity are on the order of 85%. Total efficiencies would therefore be between 8% and 17%. To correct for the manner in which the data in Table 3.1 were averaged, we will use a value of 0.24 for our effective efficiency (efficiency x data conversion factor):

$$E_{Piscataqua} = 689 \frac{KWH}{mo \cdot m^2} \times 12 \text{ mo} \times 300 \text{ m}^2 \times .24$$

$$= 595.3 \text{ MWH/year}$$

$$E_{Kennebec} = 8.13 \frac{KWH}{mo \cdot m^2} \times 12 \text{ mo} \times 300 \text{ m}^2 \times .24$$

$$= 70.2 \text{ MWH/year}.$$

If we assume, for comparison's sake, an annual average capability (the average power level which would produce the same energy) based on 6000 hrs/yr operation, Piscataqua would be rated at 99 KW and Kennebec at 12 KW. Because of tidal periodicities the units would have to be rated at much higher power levels but would operate much shorter periods of time (Technical Note C). A point to be made here is that a large premium is gained by even a slight increase in current speed. Cost will depend on the size and complexity of the structure. It would certainly appear to be useful to consider methods of concentrating the current by special channels or ducts in such a way as not to change the overall flow characteristics or traditional usage of the river. Since the cost of ducts or channeling may increase the costs far less quickly than the increase in power out, considerable economies may be achieved by proper system design.

Clearly, these power and energy levels do not offer a viable alternative to conventional base-loaded generation. In addition to being quantitatively inadequate, significant amounts of power are available only every three hours with the device on line about 70% of the time (Technical Note C), and would be qualitatively different from the constant output of base-loaded generation. Storage could be used to level the tidal variations, but the best use would probably be in a fuel saver mode. In this mode the energy from tidal current units would be used to replace energy which would otherwise be generated by fossil fuels. This mode requires the least sophisticated control equipment and operating strategy and always is economically attractive since the operating costs of a unit of energy from an existing tidal current device will always be less than the operating costs for a unit of energy from fuels. Since the energy, barring failure of equipment, would be available on a predictable basis each day, fossil fuel-powered generation could be backed down when tidal current energy was being produced.

4.0 ECONOMICS

As there is no modern design experience with current power generators, capital cost data have been taken directly from estimates by the Kaman Corporation (1976) for a wind turbo-generator.

peak rated power	cost of drive system	cost of elec. system	total cost	cost per kw	1986 $/kw*
500kw	$ 64,800	$ 43,800	$108,600	$217	$326
1500kw	$ 181,000	$ 78,000	$259,000	$173	$258

Assuming a unit of 300 m^2, our sites on the Piscataqua and the Kennebec have rated powers of 1806 and 226 kw respectively. These imply power system costs of $466,000 for Piscataqua and $73,700 for Kennebec. Recall these refer to only one device whose cross-sectional area normal to the flow is 300 m^2. Costs are in 1986 dollars, and do not include moorings, foundations, site access, environmental monitoring, or interest costs during construction.

Transmission cost estimates (Somers and Shoupp, 1974), when applied to a river tidal turbine, would probably contribute only about $18/kw as the transmission distance to shore is negligible; losses are small and repair is easy. Transmission costs to the grid depend on the site.

*Assumes simple escalation @ 5% per year.

Table 4.1

Estimated Current Device Costs

COSTS: (1986 dollars)	"Piscataqua" $1000	"Kennebec" $1000
rotor	$ 325.7	$ 43.9
generator	140.0	29.6
transmission to shore	32.4	4.1
(1) Subtotal	$ 498.1	$ 77.6
operation and maintenance @ 6% of (1) per year	29.9	4.7
levelized annual capital charges for (1) at 18%	89.7	14.0
Total annual costs	119.6	18.7
electrical energy per year	595.3 MWH/year	70.2 MWH/year
ENERGY COST (1986 dollars)	201 mills/KWH	266 mills/KWH

5.0 ENVIRONMENTAL IMPACTS

The use of either a Savonius rotor or a multibladed turbine will probably have similar effects on the environment. The turbine will have higher tip speeds thus posing some possibility of danger to fish.

The moored structure will not add to the esthetics of the river but to the extent that moored ships degrade the view, the insult will be minimal.

The siting should obviously be done to minimize the impact upon the environment and traditional uses of the site such as navigation, fishing, pleasure boating, etc. Some rivers like the Kennebec have quite a lot of ice which would pose a problem.

The greatest direct threat stems from the fact that as energy is absorbed the current is diminished. In Technical Note B it is derived that optimum extraction would diminish the local current by one third. However, the whole river is not going to be tapped, just some fraction. Obviously the more devices that are emplaced, the more the flow will be retarded.

An important element of an environmental statement for a proposed site would be just how the river flow would be affected and hence the ecosystem the river supports.

6.0   CONCLUSION

Ocean currents off the Maine coast are too weak to be considered as a power source, however, tidal forced river currents do offer power densities on the order of 1 - 5 KW per square meter of intercepted current. The power output varies as the cube of the current velocity and depends primarily on the tidal cycle. Consideration of current power on a base-loaded mode is not likely due to the periodicity and small power density. Generation of power in a fuel-saver mode may be considered if the estimated energy cost of 201 mills/KWH (1986 dollars) becomes competitive.

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ENERGY EXTRACTION FROM DRAG-ASSOCIATED DEVICES

When a stationary surface is placed in a fluid moving perpendicularly to the surface with velocity U and density ρ, the force on the surface is given by

$$F = C_d \rho \frac{1}{2} A U^2 = \frac{1}{2} \rho C_d A U^2$$

A = area of surface

C_d = coefficient of drag　　　　　　　　　　　　　　　　(A.1)

C_d depends primarily on the shape of the surface. If the surface is moving with a velocity v which is less than U, then the relative velocity of the fluid with respect to the surface is $(v - U)$. The force on the surface is then

$$F = C_d \rho \frac{1}{2} A (v - U)^2 \qquad\qquad (A.2)$$

and the power absorbed by the moving surface is given by

$$P = C_d \frac{1}{2}\rho A (v - U)^2 v \qquad\qquad (A.3)$$

The velocity of the surface which will result in the maximum power absorbed can be found by taking the derivative of (A.3) with respect to v:

$$\frac{d}{dv}\left[\frac{1}{2}\rho C_d A (U^2 v - 2Uv^2 + v^3)\right] = \frac{1}{2}C_d \rho A (U^2 - 4Uv + 3v^2) \qquad (A.4)$$

Setting this equal to zero, we get

$$(U - 3v)(U - v) = 0. \qquad\qquad (A.5)$$

The maximum power is absorbed when $v = \frac{U}{3}$ or when the surface is moving down stream at one-third of the current speed. When the surface is moving at this velocity, the power absorbed is

$$P = \frac{1}{2}C_d \rho A (U - v)^2 v = \frac{1}{2}C_d \rho A (U - v)^2 \frac{U}{3} \qquad (A.6)$$

$$= \frac{1}{3} \text{ of the power available to the moving surface.}$$

So the maximum efficiency of extraction for a drag device is 33%.

ENERGY EXTRACTION FROM LIFT-ASSOCIATED DEVICES (from Sheets, 1974)

The recovery of energy from fluid motion such as from water by means of water wheels, or from air by means of windmills, has been in use for a long time. Over the years, the configuration of the impeller wheels has changed. The basic problem consists in that the fluid velocity in the energy recovery cannot be reduced to zero, as this would stop the fluid motion. It is quite evident that too high a flow restriction by the energy-recovering device would simply cause the flow to by-pass the energy recovery device. One can postulate the question, "How much can the velocity of the fluid flow be reduced for optimum energy recovery and simultaneously without harming the environment?"

The following analysis solves this problem for the ideal case of an unshrouded propeller (Fig. B.1) which is treated as an infinitely think disk. For this analysis, the following nomenclature is used:

p_0 - undistributed pressure

v - inflow velocity

$v - q$ - exit velocity

a - cross-sectional area of the actuator disk

p' - pressure in front of the actuator disk

p'' - pressure behind the actuator disk

q - velocity removed from the fluid by the disk.

In the immediate vicinity of the disk by continuity:

$$av_u = av_d = av' \tag{B.1}$$

Hence, the velocity in front of (V_u) and behind (V_d) the disk is the same. Employing Bernoulli's Theorem along the streamline 1 - 2 gives:

$$p_0 + \frac{1}{2}\rho v^2 = p' + \frac{1}{2}\rho v'^2 \tag{B.2}$$

and along 3 - 4 gives:

$$p_0 + \frac{1}{2}\rho(v - q)^2 = p'' + \frac{1}{2}\rho v'^2. \tag{B.3}$$

By subtraction we get the drop of pressure $\Delta p = p' - p''$

$$p' - p'' = \Delta p = p_0 + \frac{1}{2}\rho \; v^2 - p_0 - \frac{1}{2}\rho \; (v - q)^2$$

$$\Delta p = \frac{1}{2}\rho \; v^2 - \frac{1}{2}\rho \; (v^2 - 2qv + q^2)$$

$$= \frac{1}{2}\rho \; q(\; 2v - q)$$

$$\Delta p = \rho q(v - q/2) \tag{B.4}$$

Then the thrust imparted to the actuator disk by the fluid is

$$T_d = a \; \Delta p = \rho \; aq(v - q/2) \tag{B.5}$$

or the thrust imparted to the fluid by the disk is

Applying the momentum theorem to Figure 1:

No contribution from pressure integral

ρ av' - quantity of fluid moving through the control volume

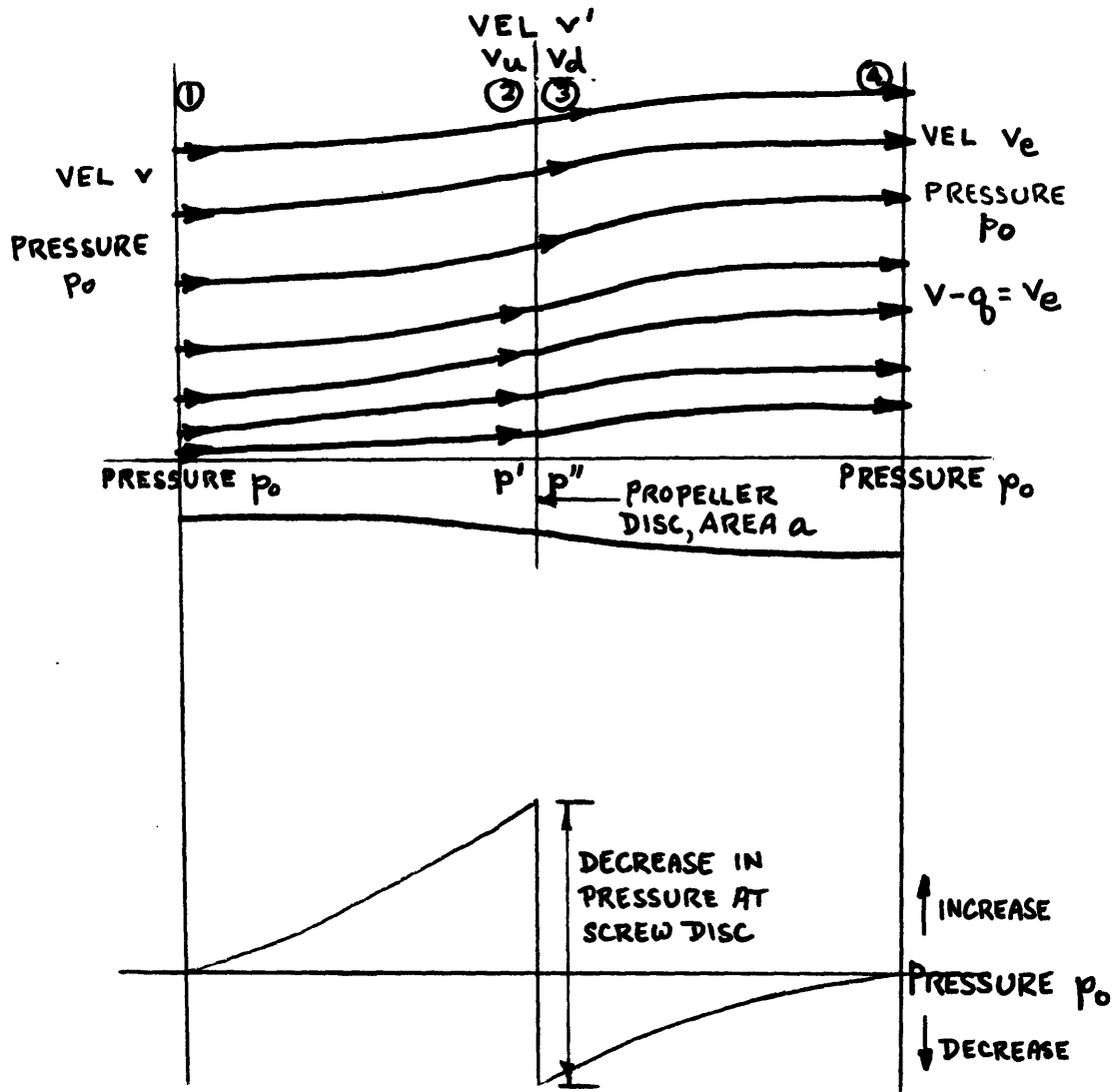ρ av' v = T + ρ av' (v-q)

Hence

T = ρ av'q

VEL v'
V_u | V_d
② | ③
①   ④

VEL V_e

VEL v   PRESSURE
                               P_o
PRESSURE
P_o V-q = V_e

PRESSURE P_o P' P'' PROPELLER   PRESSURE P_o
                             DISC, AREA a

DECREASE IN
PRESSURE AT
SCREW DISC   ↑ INCREASE

                              PRESSURE P_o
                              ↓ DECREASE

Fig. 1 Changes in pressure and velocity of propeller disk, momentum theory.

Figure B.1

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$$T_f = -T_d = \rho aq \, (-v + q/2)$$

Applying the momentum theorem to Figure B.1:

No contribution from pressure integral

$\rho \, av'$ - quantity of fluid flowing through the control volume

$$\rho \, av' \, v = T_d + \rho \, av' \, (v - q)$$

(B.7)

Hence

$$T_d = \rho \, av' \, q.$$

(B.8)

Comparing equations (B.5) and (B.8) gives:

$$v' = v - q/2$$

(B.9)

Available work is: where r = radius (effective) of propeller

$$E = \pi r^2 \, v' \, \Delta p$$
$$= \pi r^2 \, \rho \, q(v - q/2)^2$$

(B.10)

This obtains a maximum value when

$$q = \frac{2v}{3}.$$

(B.11)

Substituting gives:

$$E_{max} = \pi r^2 \, \rho \, \frac{2v}{3} \, (v - \frac{2v}{6})^2$$
$$= \pi r^2 \, \rho \, \frac{2v}{3} \, (\frac{2v}{3})^2$$

$$E_{max} = \frac{8}{27} \, \pi r^2 \, \rho \, v^3.$$

(B.12)

The maximum energy obtainable from the free stream is:

E_{total} = mass flow rate x energy/unit mass $E_{total} = \rho \pi r^2 v \times \frac{1}{2} v^2$

$$E_{total} = \frac{1}{2} \pi r^2 \, \rho \, v^3$$

(B.13)

Therefore, the maximum theoretical efficiency is:

$$\eta_{th} = \frac{E_{max}}{E_{total}} = \frac{\frac{8}{27} r^2 v^3}{\frac{1}{2} r^2 v^3} = \frac{16}{27}$$

$$\eta_{th} = .5926$$

$$v_e = v - q = v - \frac{2}{3} v = \frac{1}{3} v$$

(B.14)

The above analysis indicates that there is indeed an optimum discharge velocity, v_e, which equals one-third of the incoming velocity, v, for the ideal case. It also indicates that the maximum energy recovery for this ideal case equals 59.3% of the incoming kinetic energy. This case considers only a single open propeller turbine unit. It is also clear that the surrounding fluid motion and its field of forces will accelerate the discharge fluid, v_e, to bring it back to a uniform value with the surrounding fluid flow. The above analysis is, therefore, only correct for a single unit, and it assumes that the amount of flow acting on the energy recovery device is relatively small compared to the surrounding flow.

If more than one unit for energy recovery is needed, the arrangement in clusters will be justified only if the flow through these units is small compared to the total fluid. In order to reduce effects on the environment, it may be preferable to arrange multiple units with space between each other so that the flow has an opportunity to adjust itself in as short a time and as short a distance as possible.

ENERGY AVAILABLE IN A TIDAL CURRENT WITH A POWER CUTOFF

Given a current varying like [Figure C.1]

$$v = a \sin \frac{2\pi t}{T} \qquad (C.1)$$

a = amplitude

T = period = 12h 40 min

$$P = \frac{1}{2} \rho v^3$$

and

$$E = \frac{1}{2} \rho a^3 \int_0^{t/2} \sin^3(\frac{2\pi t}{T}) \, dt \qquad (C.2)$$

is the energy/area in one half period. Now introduce a cutoff power which we shall arbitrarily define as being .1 of the rated power where the rated power will be given by the maximum power:

$$\text{rated power} = \frac{1}{2} \rho a^3,$$

The cutoff power reflects the fact that below a certain current speed the turbo-generator will be operating well off design and its conversion efficiency is effectively zero. There are more sophisticated ways of modeling this behavior. Referring to the tidal current tables (Table C.1) we see that the ebb and flood rarely have the same magnitude. Thus we shall integrate over the respective half-cycles and take their sum.

Because the power varies as the cube of the velocity, current variations will cause significant power output variations. We are most interested in the river currents which are primarily tidal driven, so the frequency of variation will vary with the tidal frequencies, e.g., semi-diurnal, diurnal, lunar-fortnightly. Actual current spectra that are used to compile the current tables need to be consulted for accurate power predictions.

Despite the crudeness, we should get an order of magnitude estimate for the power out.

$$v_f = a_f \sin\omega t$$

$$\omega = \frac{2\pi}{T} \qquad (C.3a)$$

$$v_e = a_e \sin\omega t \qquad (C.3b)$$

where we have ignored the obvious phase difference between ebb and flood.

$$P_c = .1 \, P_{max} = .1 \, (\frac{1}{2} \rho a_f^3), \text{ if } a_f > a_e \qquad (C.4)$$

Then the cutoff velocity is
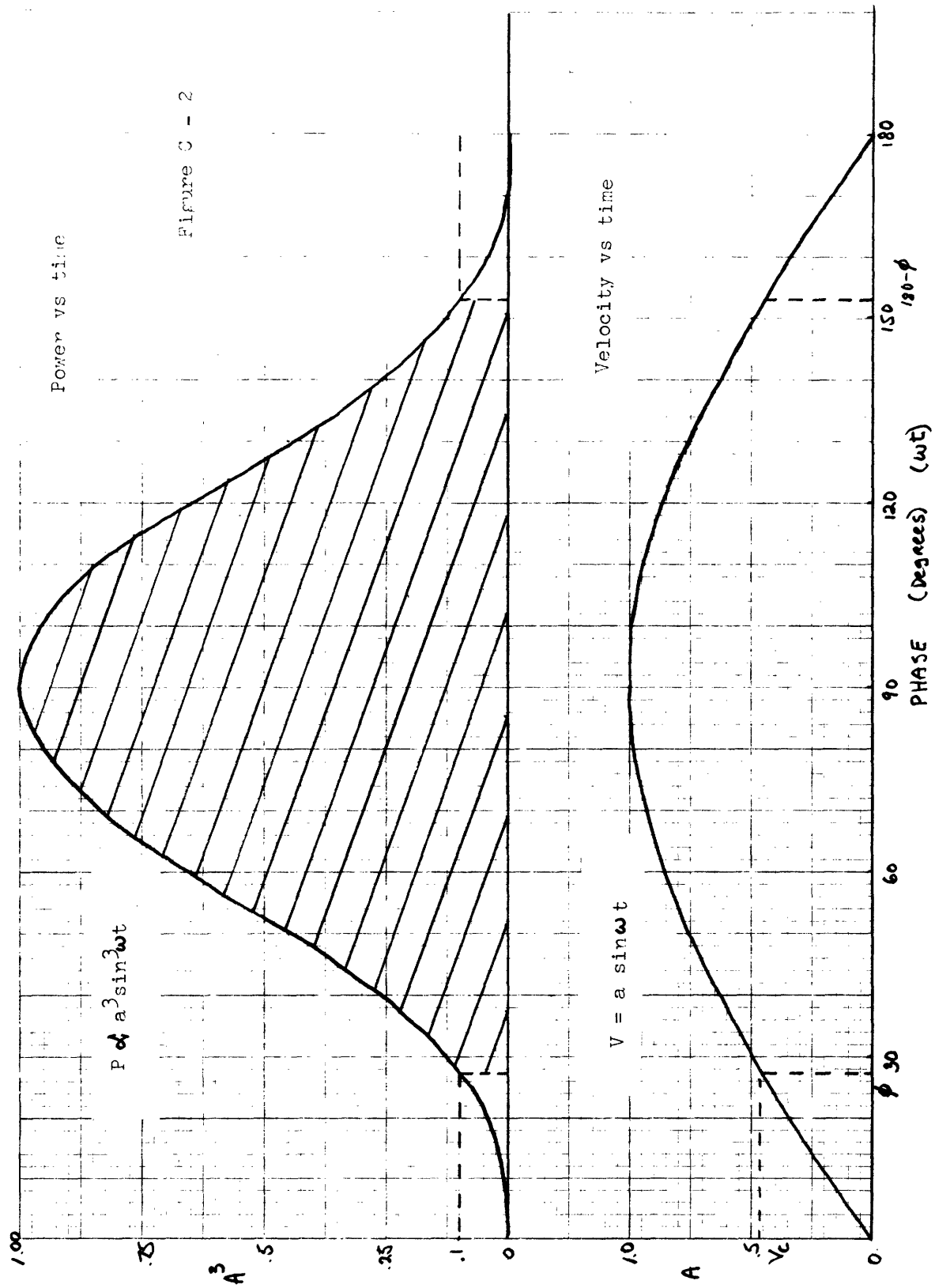
$$v_c = (.1 \, a_f^3)^{1/3} = .46 \, a_f \qquad (C.5)$$

Figure 3.1 Characteristics of a Tidal Current

Figure C.1

Because of the third power behavior, we get no power from the converter until the current has reached almost half of its maximum. Refer to Figure C.2.

When the current has reached v_v the the device comes on line and all the power in the current can be extracted. The shaded area in Figure C.2 represents available energy per half cycle.

$$E_f = \frac{1}{2} \rho a_f^3 \int_{\phi}^{\pi-\phi} \sin^3(\omega t)\, dt \tag{C.7a}$$

$$E_e = \frac{1}{2} \rho a_e^3 \int_{\phi}^{\pi-\phi} \sin^3(\omega t)\, dt \tag{C.7b}$$

$$\int_{T_1}^{T_2} \sin^3 \omega t\, dt = \left. \frac{-3\cos\omega t}{4\omega} + \frac{\cos 3\omega t}{12\omega} \right|_{T_1}^{T_2}$$

where $T_2 = \pi - \phi$, $T_1 = \phi = \sin^{-1}(v_c/a) = \sin^{-1}(.46) = .478$. $\tag{C.8}$

Evaluating, we get $\dfrac{1.309}{\omega}$ as the value of the integral.

If we had no cutoff this value would be 1.5 so we lose $(1.5 - 1.309/1.5) = 13\%$ of the energy due to cutoff at 10% of the rated power. Furthermore we can see that the current necessary is about half (.478) max current, and

$$\frac{2\phi}{\pi} = .30$$

implying that the device will not be extracting any power about 30% of the time.

$$E_f = \frac{1}{2} \rho a_f^3 \frac{1.309}{\omega} \tag{C.9a}$$

$$E_e = \frac{1}{2} \rho a_e^3 \frac{1.309}{\omega} \tag{C.9b}$$

Over the period of one month there are 28 flood half-cycles and 28 ebb half-cycles.

$$E_{month} = 29 \times \frac{1}{2} \times \rho \times 1/\omega \times 1.309 \times (a_f^3 + a_e^3) = 5223\,(a_f^3 + a_e^3)\ kwh \tag{C.10}$$

where

$$\rho = 1035\ kg/m^3\ \text{for salt water}$$

$$\omega = \frac{2\pi}{T} = .469\ \text{radians/hour}$$

a_f, a_e are given in knots (1 knot $\doteq$ 5.5 m/sec).