ALTERNATIVE ELECTRICAL ENERGY SOURCES FOR MAINE

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Appendix I
WAVE ENERGY CONVERSION

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Prepared for the Central Maine Power Company.

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

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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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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 I

WAVE ENERGY CONVERSION

LIST OF TABLES

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1.0 INTRODUCTION

The efficient conversion of the power of ocean waves into electricity is theoretically possible. Present experimental and theoretical research indicate that up to 90% of the power of waves can be extracted under certain conditions. When ancillary conversion processes are considered for the ensemble of all waves throughout the year the total conversion efficiency is around 35%.

Very little is known about the wave climate of the Maine coast -- at least to the degree of accuracy that is necessary for power predictions. Two types of sites are considered: a near shore, "coastal Maine" site that is representative of the waves outside the surf zone but within a few hundred meters of the shore and an "offshore Maine" site that purports to describe the wave climate about 50 kilometers off the coast where the waves are longer and higher.

The levels of uncertainty in the modeling to follow are quite high for several reasons:

(1) the wave data are very sparse and broad inferences have to be made on existing unrefined information

(2) present designs are not finalized and there is no experience with the technology, and

(3) the R&D of such novel machines is linked to the cost of competitive fuel sources and the apparent prospects for achieving an economically viable power technology.

It would be reasonable to expect the power estimates are correct within a factor of two. The uncertainty in the costs is much greater, say, within a factor of three. Development of this technology is a function almost entirely of the effort committed. It is likely that the British will have a pilot wave generation plant capable of power output of around 10MW within two to four years.

As with wind technology, a major problem lies in integrating this unsteady and unpredictable energy source into the grid. The investment decisions will have to call on strategies different from those which have been used in the past with technologies for which output and investment were predictable but where operating costs were not. These alternative devices have a zero fuel cost but high capital cost and an output which is ever-changing and unpredictable.

2.0 TECHNICAL DESCRIPTION

Ocean Waves are generated by winds blowing over the ocean surface. At any one point in time and space on the ocean the waves present are the result of (1) winds presently pumping energy into the wave feld, (2) waves generated locally from past disturbances, and (3) waves that have propagated from other regions of the ocean (swell).

The readers is encouraged to consult (Van Dorn, 1974) as a primer for understanding the physics of ocean waves and wave spectra. Figure 2.1 illustrates some terms that will be important.

The next section will attempt a wave climate assessment for a site representative of the Maine coast and a site offshore. First, however, we shall examine how a device can be designed to extract power from the waves.

2.1 Bodies in Waves

Floating bodies in waves can be considered through two phenomena happening simultaneously: (1) the reflection or diffraction of waves as around a fixed unmoving body and (2) the waves generated by the motion of the body on the otherwise still free surface. (Van Dorn, 1974) discusses the waves, forces and motions associated with fixed and floating bodies.

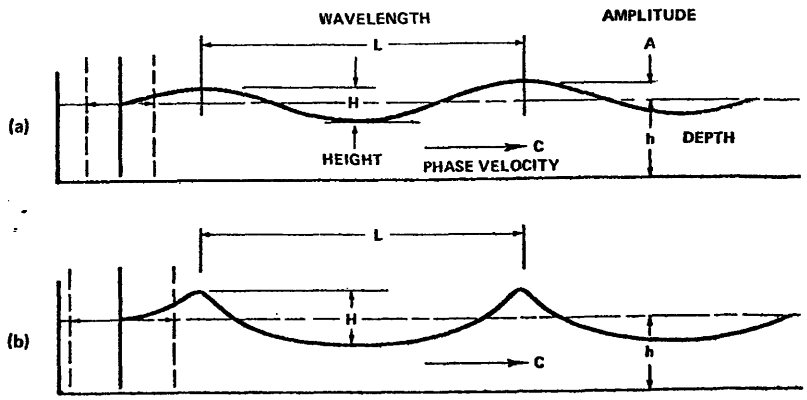


Figure 2.1 Characteristics of a Wave

Figure 2.1.: (a) Periodic, progressive surface waves of low amplitude resemble a moving sine curve, symmetric about the equilibrium water level. (b) Higher period waves are no longer sinusoidal, nor symmetric; their crests are peaked, and extend higher above the equilibrium level than the long, smooth, troughs which fall below it.

One helpful way to consider the floating body problem is to assume that the force exerted on the body by the incident wave causes the body to move. The moving body in turn generates is own waves.

2.2 Interactions of Structures and Waves

2.2.1 Fixed Bodies

When waves impinge on a body that is attached to the bottom such as an offshore platform or a pier, the waves will diffract around the body in a complicated pattern which is the result of the reflection of the incident wave against the body. If the body is designed such that it does not extend continuously to the bottom below the free surface, then it is possible for some of the wave energy to leak underneath the structure. This is true since the energy in the waves is not just localized at the surface but is exponentially distributed from the surface down to the bottom. A rule of thumb is that at a depth of approximately one-half wavelength the wave effect becomes negligible.

Consider the two-dimensional case of a fixed cylinder as in Figure 2.2. What happens to the wave and the cylinder? The incident wave of wave height H_i is partially reflected by the cylinder while the rest of the energy in the wave is transmitted underneath the cylinder to the other side where it can manifest itself as a wave again and continue on its way. By conservation of energy, the amount of energy in the incident wave, $\frac{1}{2}\rho g(H_I/2)^2$, must be equal to the sum of the energy in the transmitted wave, $\frac{1}{2}\rho g(H_T/2)^2$, and the reflected wave, $\frac{1}{2}\rho g(H_r/2)^2$.. Furthermore, this interaction at the body will cause a force to be exerted on the body. We know from our own experience when we wade in the surf that the forces of the waves can be considerable and that the waves can easily knock us off our feet. An important distinction to be noted, however, is that we have been assuming that these waves are not breaking waves which is the situation we experience at the beach quite often. When waves break, the wave loses much, if not all, of its energy in the resulting turbulence.

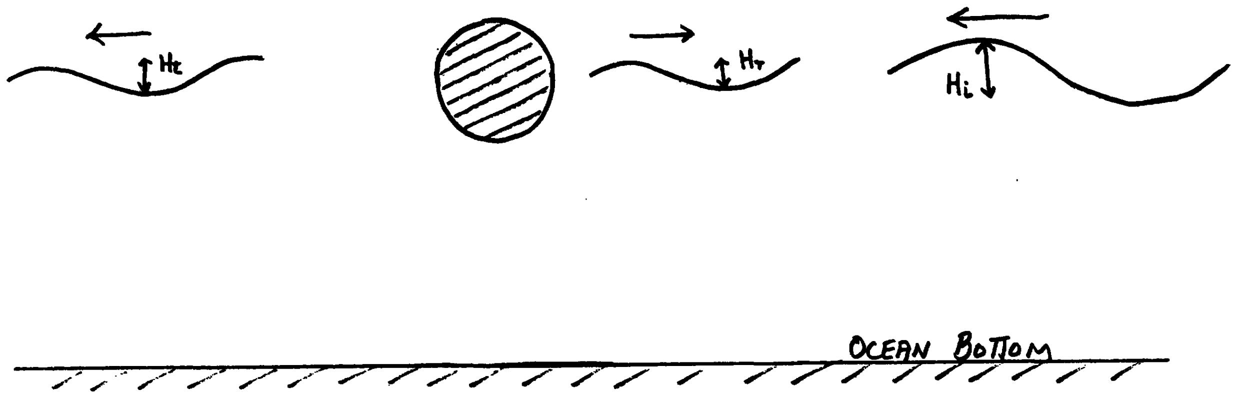


Figure 2.2

Side view of a fixed or floating body in waves showing incident, reflected and transmitted waves.

If we now add another dimension so that instead of a cylinder we have a sphere-like object that we can imagine to be fixed somehow to the bottom. For the purpose of discussion the method of attachment is immaterial. We expect qualitatively the same behavior as in the 2-D case. However, we may anticipate some differences in the reflection, i.e., <u>diffraction</u> of the waves around the sides. The diffracted wave appears as a complicated pattern of interfering waves. As in the 2-D case, we expect some of the wave energy to escape to the other side under the sphere.

2.2.2. Floating Bodies

Consider the same 2-D cylinder as above except now assume that it is freely floating. In the nomenclature of naval architecture, let us define the motions as heave, sway, and roll, corresponding to vertical, horizontal, and rotational motions as depicted in Figure 2.3. If we push the cylinder up and down we expect to create waves that will spread out from either side. We expect similar behavior if we cause it to sway by pushing it from side to side. If the object is a perfect circular cylinder then we do not expect any disturbance in the water to be caused by rolling. However, if we generalize the 2-D shape to a box similar to the cross-section of a rowboat and we rock the boat then here we would expect to create waves. Thus, by causing the body to move in different motions we expect a combination of waves as a result.

Going to three dimensions we are allowed three additional types of motions. In addition to heave, sway, and roll, the modes of surge, yaw, and pitch are also admissible.

If we combined the above "forced motion" problem that results in the radiation of waves with the "fixed body" problem that only considered the diffraction of waves, then we have a picture of the problem of floating bodies in waves.

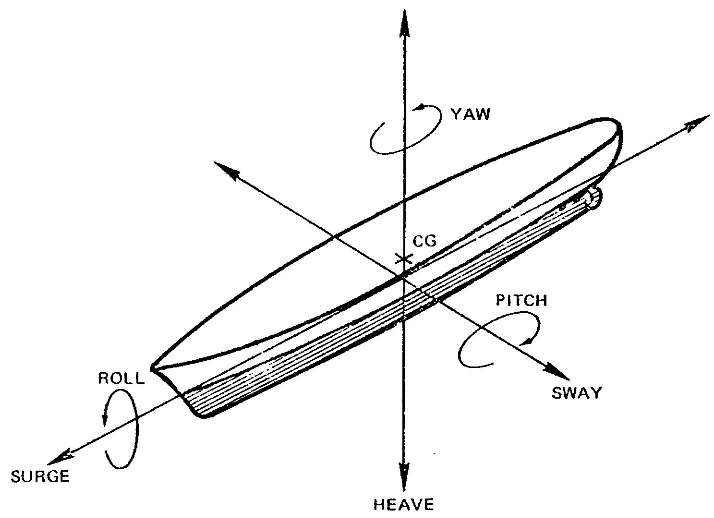


Figure 2.3 Kinds of Motion of a Floating Body

2.3 Power in Ocean Waves

If we sum all the potential energy in a wave of length L, due to a displacement away from the still water level, and sum all the kinetic energy in a wave due to both horizontal and vertical water particle motions, and then add them together we will get an expression for the total energy in an ocean wave in joules per unit width (meter) of wave front.

$$E = \frac{1}{2}\rho g(H/2)^2 \text{ joules/m} \qquad (2.1)$$

g = acceleration of gravity = 9.8 m/sec^2
ρ = density of water = 1000 kg/m^3
L = wave length (m)
H = wave height (m)
T = wave period (seconds)

To get the energy flux or power as averaged over a wave period, we multiply the energy E by the speed of propagation of the energy, the group velocity V_g,

$$V_g = \frac{L}{2T} \text{ for deep water.} \qquad (2.2)$$

In deep water, there is a connection between the wave period T and the wave length L called the dispersion relationship such that

$$L = gT^2/(2\pi). \qquad \pi = 3.1416 \qquad (2.3)$$

Then we can say,

$$\text{Power} = E \cdot V_g = \frac{1}{2} \rho g (H/2)^2 \; (1/2T) \cong H^2 T \text{ kw/m.} \tag{2.4}$$

The last result is a close approximation and is handy to use when estimating wave power. In doing calculations, more accurate formulas are used that take into account water depth and wave steepness. Useful references are (Newman, 1977) and (Kinsman, 1965).

With equation (2.4) we are able to calculate the power in waves given their wave height H and period T. One major difficulty lies in the scarcity of reliable wave spectra for these calculations. Table 2.1 illustrates the power in KW per unit meter of wave crest for various wave heights and periods.

2.4 Wave Power Absorbers

When a floating body is displaced either above or below the water surface there is a restoring force that tends to bring it back to its original equilibrium position, resulting in potential energy of displacement. The motion of the body is associated with its kinetic energy.

If we can convert this mechanical energy somehow, then we can effectively extract energy from the wave system. This is the basic principle of wave energy extractors. Internal mechanical energy converters may consist of pumps, flywheels, compressors, turbines, and generators in various configurations.

We shall adopt a convention regarding the type of energy or power we are dealing with. KWw, KWa, and KWe refer to power in the waves, power absorbed from the waves, and power converted into electricity, respectively.

Over the years there have been hundreds of proposals to harness the power of ocean waves. (Slotta, 1976) offers a catalog of those devices whose principles of operation seem the most promising. (Isaacs, 1976) outlines in a readable fashion some of the proposed modes of operation of some of the devices under study including the Scripps wave pump. (Panicker, 1976) is a useful reference as well.

(Richards, 1976) gives an adequate review of the buoy-shaped wave activated turbine generators that have been advocated. The designs of Masuda, McCormick, Isaacs, Kayser (Figures 2.4 and 2.5), Budal and Falnes (Figure 2.6) all fall into this category. In these devices, the heave motion of a cylindrical buoy is used to provide a pressure head by hydraulic or pneumatic methods which then drives a turbine generator. The Japanese Maritime Safety Agency has been using Masuda units of 70 and 120 watts as navigational and weather buoys for over ten years. Masuda has also proposed a floating, octohedral shaped buoy (Figure 2.4) of outside diameter of 120 m which is expected to produce 3 to 6 MWe in high seas off Japan.

(Woolley and Platts, 1975) have proposed a wave contouring raft (Figure 2.5) at whose joints would be hydraulic pumps operating on the differential motions of the linked rafts. Experiments have been undertaken by Wavepower, Ltd. of Southampton, England. The individual rafts would be built at a length corresponding to one quarter of the wave length of the waves that, on the average, contribute the greatest amount of energy. The rafts would be somewhat wider than their dimension in the direction of the advancing wave.

The appeal of the cylindrical buoys is the fact that they are able to extract energy from the wave system that is in excess of their diameters and are not sensitive to wave direction. Recall that the power or energy flux in an ocean wave goes like H^2T KWw/m of wave front. Because of the interaction of the diffracted and radiated waves, the body can extract an amount of power greater than that intercepted by the diameter of the body. In fact, an array of these devices, if provided

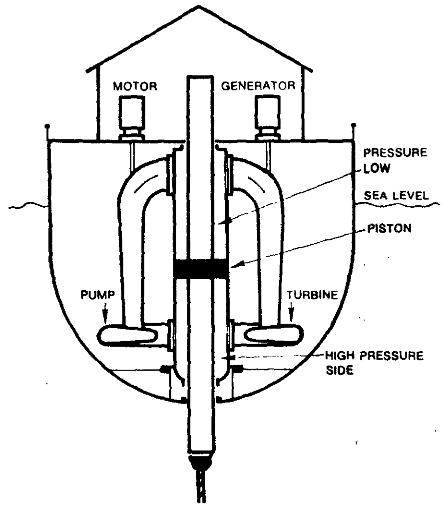
Table 2.1

Wave Power KW/M

Period (in sec.)

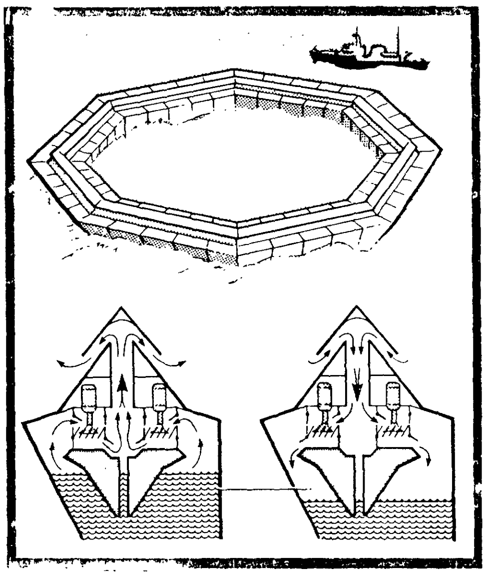
Height (in m.) H_s	5.0	6.8	7.4	8.1	8.7	9.3	10.0	10.6	11.3	11.9
1.4	6.47	6.96	7.62	8.28	8.93	9.59	10.25	10.91	11.56	12.22
1.7	8.58	9.24	10.11	10.98	11.85	12.72	13.59	14.47	15.34	16.21
2.1	13.70	14.74	16.13	17.53	18.92	20.31	21.70	23.09	24.48	25.88
2.5	20.01	21.53	23.56	25.60	27.63	29.66	31.69	33.73	35.76	37.79
3.0	27.51	29.60	32.40	35.19	37.99	40.78	43.58	46.37	49.16	51.96
3.4	36.20	38.96	42.64	46.31	49.99	53.67	57.34	61.02	64.70	68.38
3.9	46.08	49.59	54.28	58.96	63.64	68.32	73.00	77.53	82.36	87.04
4.3	57.16	61.51	67.32	73.12	78.93	84.74	90.54	96.35	102.16	107.96
4.7	69.42	74.71	81.76	88.82	95.87	102.92	109.97	117.03	124.08	131.13
5.2	82.88	89.19	97.61	106.03	114.45	122.87	131.29	139.71	148.13	156.55
5.6	97.53	104.96	114.87	124.77	134.68	144.59	154.50	164.41	174.31	184.22
6.1	113.37	122.01	133.52	145.04	156.56	168.07	179.59	191.11	202.62	214.14
6.5	130.40	140.34	153.58	166.83	180.08	193.32	206.57	219.32	233.06	246.31
6.9	148.62	159.95	175.04	190.14	205.24	220.34	235.44	250.54	265.63	280.73
7.4	168.04	180.84	197.91	214.98	232.05	249.12	266.19	283.26	300.33	317.40
7.8	188.64	203.02	222.18	241.34	260.51	279.67	298.83	318.00	337.16	356.32
8.3	210.44	226.47	247.85	269.23	290.61	311.98	333.36	354.74	376.12	397.50
8.7	233.43	251.21	274.93	293.64	322.35	346.07	369.78	393.49	417.21	440.92
9.1	257.61	277.23	303.40	329.57	355.74	381.91	408.09	434.25	460.42	486.59
9.6	282.98	304.54	333.29	362.03	390.78	419.53	448.27	477.[illegible]	505.[illegible]	534.51
10.9	366.24	394.14	431.35	468.55	505.76	542.96	580.17	617.38	654.58	691.79

100 200 300 400 500 600



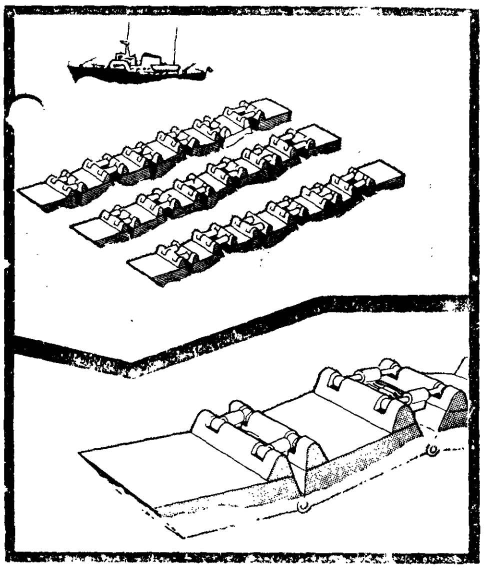
Falnes Buoy Shaped Wave Activated Turbine

Figure 2.4



Air Pressure Ring Buoy

Figure 2.5



Wave Contouring Raft

Figure 2.6

with the proper devices to control their motions with respect to one another and the incident waves, can act like an antenna where relatively few elements are needed to absorb the energy. (Budal, 1977) reports that an array of bodies spaced a wavelength apart capable of coordinated operation in two modes (heave and roll for example) may extract 100% of the incident wave energy. For an 8-second wave, these buoys can be located as far apart as 330 ft.

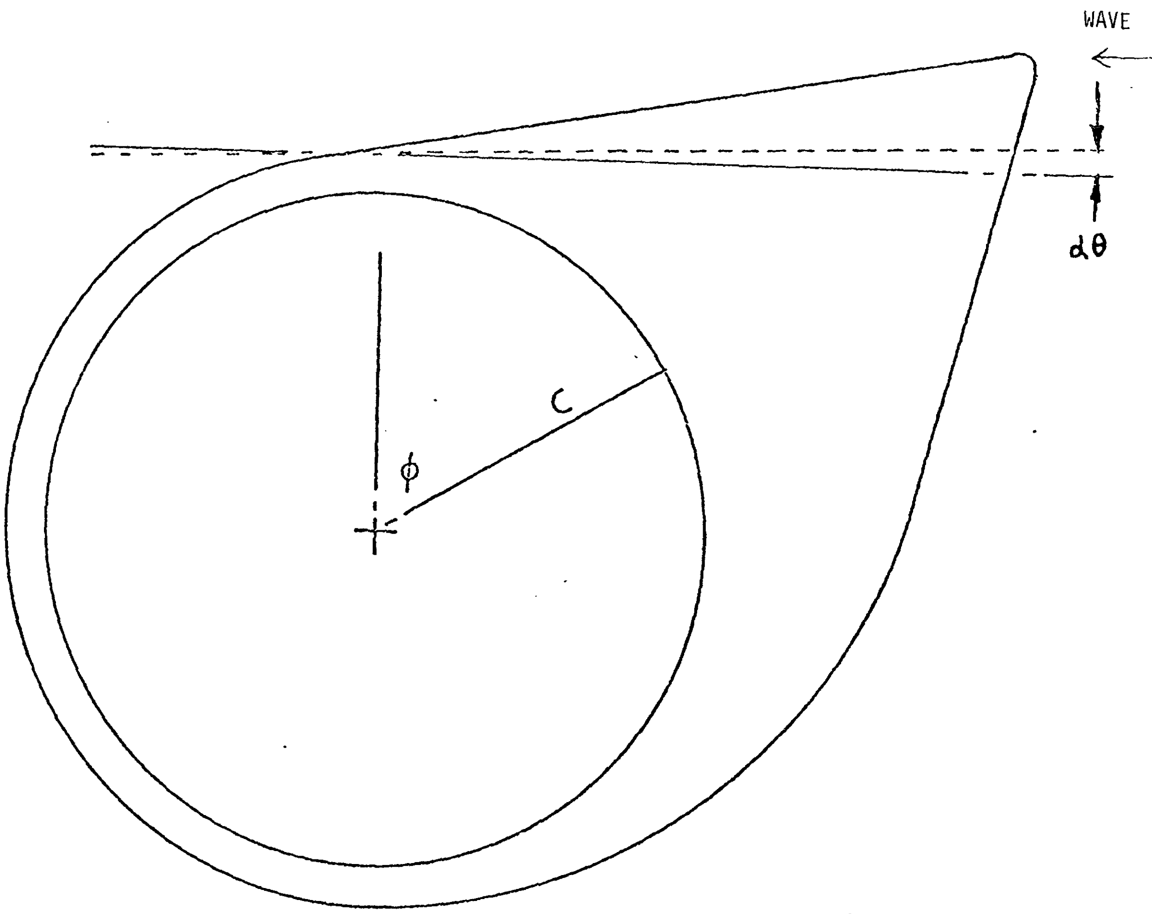
The device that presently enjoys the greatest amount of research effort is the Salter cam. We shall use this converter for the bulk of our analysis. Figures 2.7 and 2.8 show the Salter cam or "nodding duck" which rolls about a fixed inner cylinder activated by an incoming wave. Power is taken off through the differential rotation between the cylinder and the cam. We note that the shape of the cam is such that we expect a large interaction with the incident wave but that we also do not expect a wave generated on the leeward side of the device caused by roll alone because of its cylindrical backside.

This cam acts like a damped harmonic oscillator in that it exhibits a resonant behavior at certain wavelengths. We shall digress slightly to describe the dynamics of a damped pendulum consisting of a mass at the end or distributed along the length of a rod (body of the cam), a restoring force due to gravity (hydrostatic force on the cam) and a damping force in opposition to the direction of motion caused by the viscosity of the medium (internal energy absorber of the cam). When displaced away from a position of rest we expect the pendulum (cam) to oscillate for a few cycles until its motion has been thoroughly damped. If, however, we applied a force in a periodic manner, like pushing a child on a swing, then we expect the pendulum (cam) to oscillate at this driven period. The amplitude of motion would depend not only on how hard we pushed by also on the natural period of the device which is determined by gravity and cam geometry. Such devices exhibit resonant behavior when the period of forcing approaches the natural period.

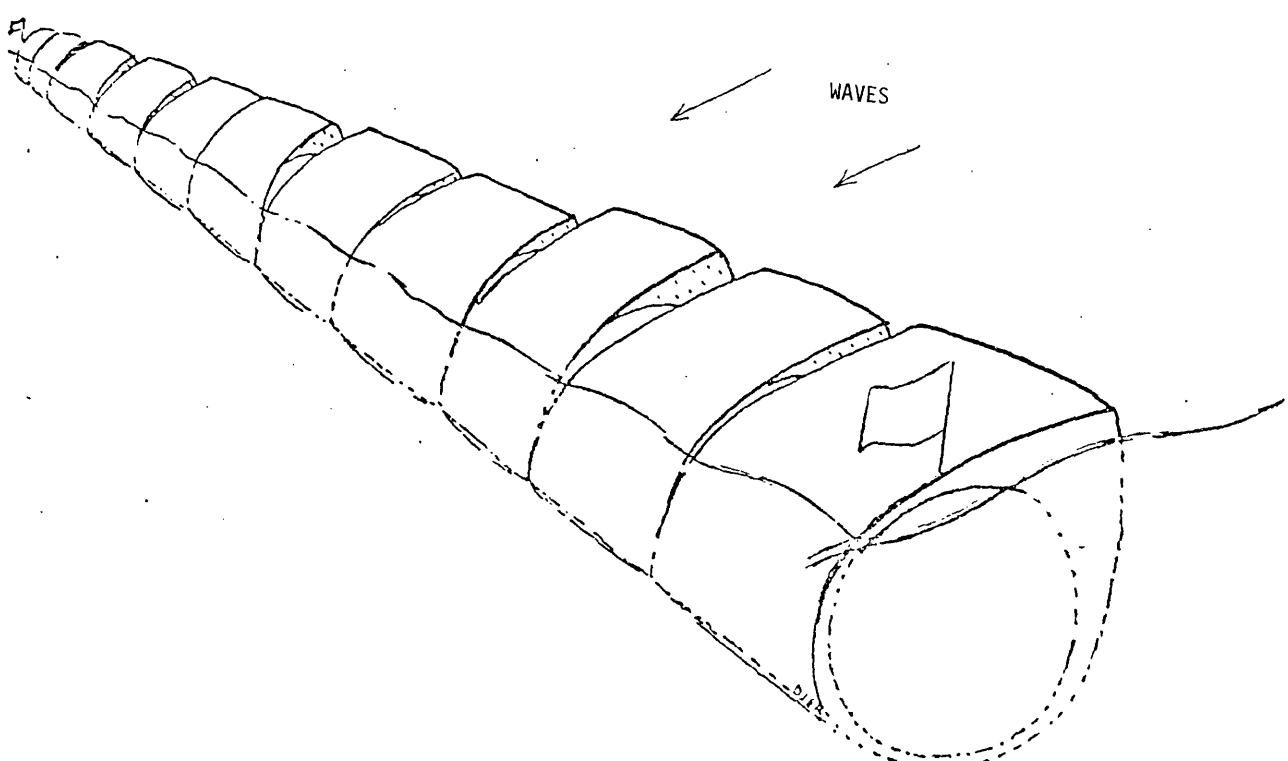
In the case of the cam, the physics is somewhat more complicated that this analogy indicates, but the basic behavior is similar. The important point is that the cam responds with large amplitude oscillations at a certain wave period. The ability of the cam to extract energy depends on the amplitude and period of oscillation. The curve (Figure 2.9) shows the hydrodynamic efficiency of a cam, defined as the ratio of the energy extracted from the wave to energy of the wave as a function of period of the wave. This curves shows that at a period of .67 seconds the hydrodynamical efficiency to be around 90%. We note that this curve is taken from experiments on a 10 cm diameter cam in a laboratory wave tank. We also note the highly efficient response of greater than 80% extractive efficiency over a range of periods from .45 to .85 seconds corresponding to a 2:1 bandwidth in period. A larger diameter cam would be resonant at a longer priod. In fact, on the horizontal axis we see superposed a scale of L/D which is wavelength/cam diameter. So that at an L/D of 6.9 we expect to have 90% wave power extraction. As an example, for a device of 12 meters diameter, the optimum wavelength would be around 80 meters.

It is clear, however, that we do not have any say in the heights and periods of the incoming incident waves. We must accept what nature presents. The wave spectrum of a specific site as deduced from accurate observations allows us to expect in a statistical sense how the waves will be distributed. The following section will make some assumptions on Maine wave spectra and apply that to a design.

If we take a wave spectrum such as is shown in Figure 2.10 and multiply that curve, point by point, by the efficiency curve of Figure 2.1, we can produce a curve of wave power extraction as a function of wave period. The wave energy that is not extracted is the difference between the incident wave spectrum and the extracted power spectrum and represents energy that is somehow dif-



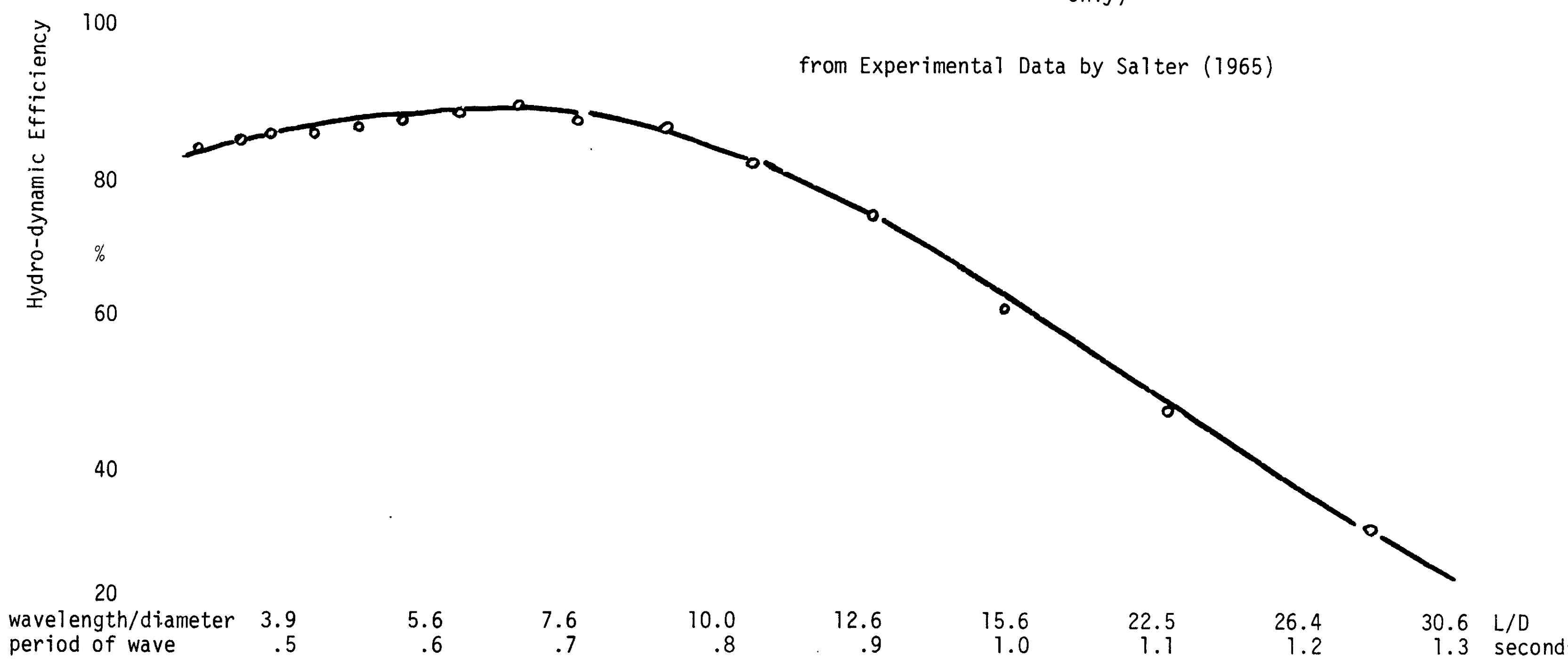
Side View - Salter Cam
Figure 2.7



Salter Cam Assembly
Figure 2.8

Figure 2.9
Wave Absorption Efficiency vs Wave Period
(hydro-dynamic efficiency of a cam)
(10 cm diameter model free to roll
only)

from Experimental Data by Salter (1965)



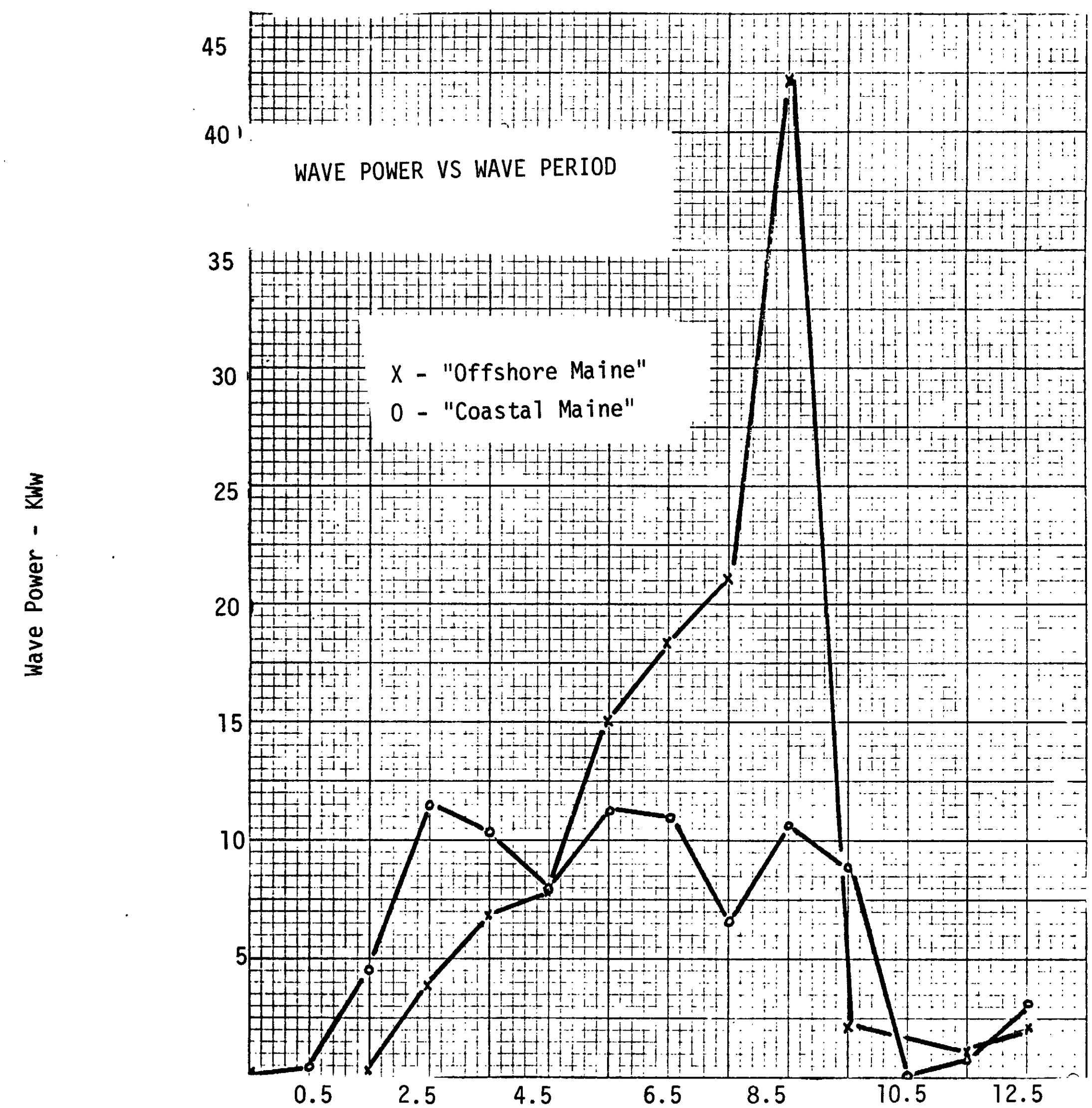

WAVE POWER VS WAVE PERIOD
X - "Offshore Maine"
O - "Coastal Maine"
Wave Power - KWw
45
40
35
30
25
20
15
10
5
0.5
2.5
4.5
6.5
8.5
10.5
12.5

Figure 2.10

fracted either by transmission beneath the cam or reflected back in the opposite direction of the incident wave. Recall that we are now considering the whole spectrum of wave heights and period and that we anticipate to occur in a statistical sense over a specific duration of time like a month or a year.

These wave power extractors thus filter out waves of certain periods and allow waves of other periods to pass. So, in addition to collecting energy, we have a device that behaves as a breakwater at some periods, providing a secondary benefit for some sites.

We have discussed only the hydrodynamics of the cam, subject to certain simplifications such as the fact that we have not examined the contribution or degradation of the device due to heaving and swaying motions. This is an area of current research. By redistributing ballast in the cam, say by pumping water between inboard and outboard tanks, we can also shift the resonant period of the device. Furthermore, we can vary the rate of power extraction to give us the best overall power response for a specific wave field.

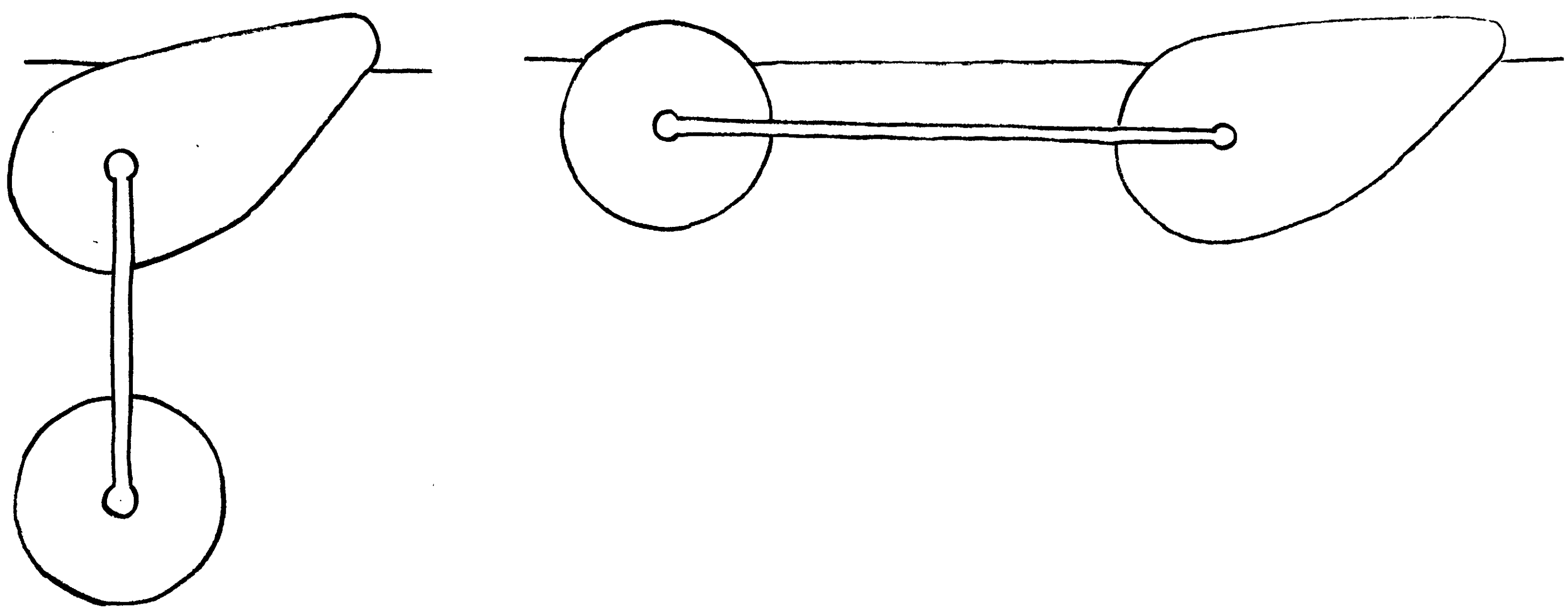
In operation, the cams are envisaged by their inventor to be strung like beads on a string (Salter, 1974, 1976-1); whereby this "string" or common spine will provide a stable frame of reference in roll against which the power is taken off. The cams run on rollers which are the bodies of commercially available rotary pumps. High-pressure oil drives hydraulic swash-plate motors coupled to electric generators. Electrical transmission is by undersea cables.

There are other ideas current for providing a stable platform for the Salter cam, two of which are sketched in Figure 2.11. It is also clear that hydrodynamical efficiency of 90% does not indicate electrical conversion at that rate as other conversion losses have to be considered. These losses will not be conclusively identified until the first demonstration units are tested.

2.5 Wave Power Systems

Much of the following discussion is based on work by (Dingwell, 1977). The modeling will assume a power converter that is characterized by a <u>power rating</u>. We will assume that when the power delivered to the conversion system is less than one-tenth of the power rating, there is <u>no</u> conversion at all and that the conversion efficiency increases linearly from 0 to 75% when the power delivered to the conversion is between one-tenth and one times the power rating. When the available power is greater than the power rating, the device is saturated and the device will produce power equal to .75 times the power rating (see Figure 2.12). This conversion efficiency is applied after the hydrodynamic efficiency curve has been multiplied by the power spectrum.

With the model developed so far we can determine the power output of a cam, or an array of cams end on, as a function of the incident wave spectrum, diameter of the cam and power rating of the conversion system. So far we have not addressed the problem of energy storage. It is clear that there are a number of different and important time scales associated with waves. From season to season we expect wave characteristics to vary as demonstrated in the next section. Furthermore, from day to day, within a given season, we anticipate large variations depending on storm activity, local winds, etc. We would expect, for example, that in the trade wind belt, the wave climate would be relatively constant throughout the year due to the prevalence of waves generated by the reliable trades. However, in New England where the weather could not be more irregular, we expect large variations in wave energy from day to day if not from hour to hour.



Ideas for Providing a Stable Platform for a Salter Cam Using Auxiliary Cylinders
Figure 2.11

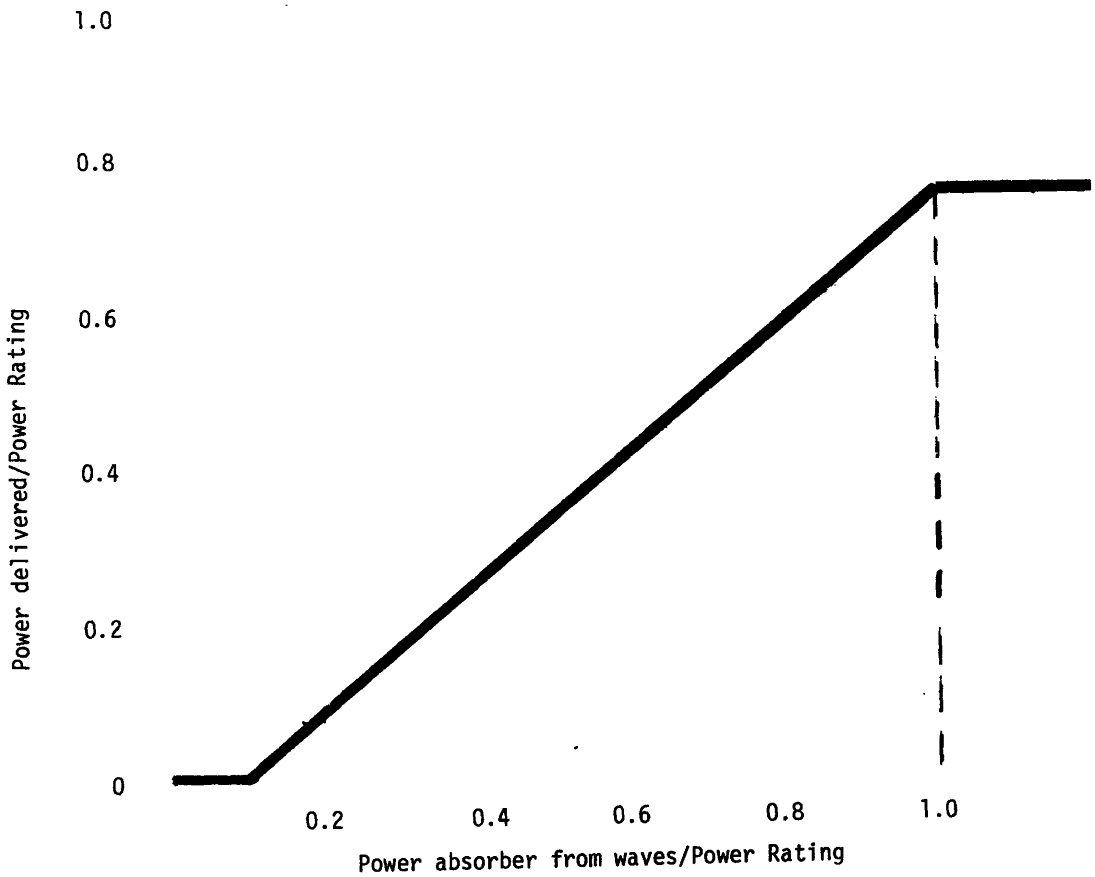


Figure 2.12 Effect of Power Rating on Power Delivered

Clearly this type of variation cannot be tolerated in a system that is designed to provide base-load power. The supply problem is similar to that of windmills and solar collectors wherein the incident energy may be highly stochastic or random in nature. The variability can be smoothed by storing this energy, making it available when the demand exceeds the on-line supply.

Short-term storage will increase the expense considerably. The nature of the supply is fundamental to the economics and will also have a significant impact on the designs of the total system. Section 4 will discuss this issue at greater length. Technologically it is possible to store energy by means of compressed air, for example, that can filter out the higher frequency fluctuations in wave power supply; this principle can be extended to, say, pumped storage systems for longer-term supply smoothing. The greater the proportion of power supply required from such a source to a region, the greater the premium placed on its constancy. Other types of storage proposed such as hydrogen production apply here as well.

For wave power systems working in a fully integrated electrical grid where supply is available from many different sources and types of generating equipment, the variability in wave supply can be treated much in the same way that the variability in demand is treated and analyzed. Presumably the total capacity would have to be available from conventional non-stochastic methods. However, when on line these devices would stand in for peaking devices whose fuel costs generally are quite high. We might remark that often there may be a strong correlation between bad weather causing increased demand and good wave energy supply.

2.6 Other Factors

Several technical factors that have not been examined very carefully are associated with the stable platform that provides a reference frame around which the can can rotate, mooring, heavy weather, and others.

A stable reference is absolutely essential. However, its design depends on a number of factors dealing with the interactions of roll with heave and surge, and the size, and hence cost, of the structural member that may have to sustain considerably bending moments if the cam is to be connected to a reference body. The type of mooring depends on the expected wave forces, local currents, depth, and bottom topography and geology.

Currents may not only modify the wave field which can be predicted, but also can present large forces which mooring designs would have to take into account.

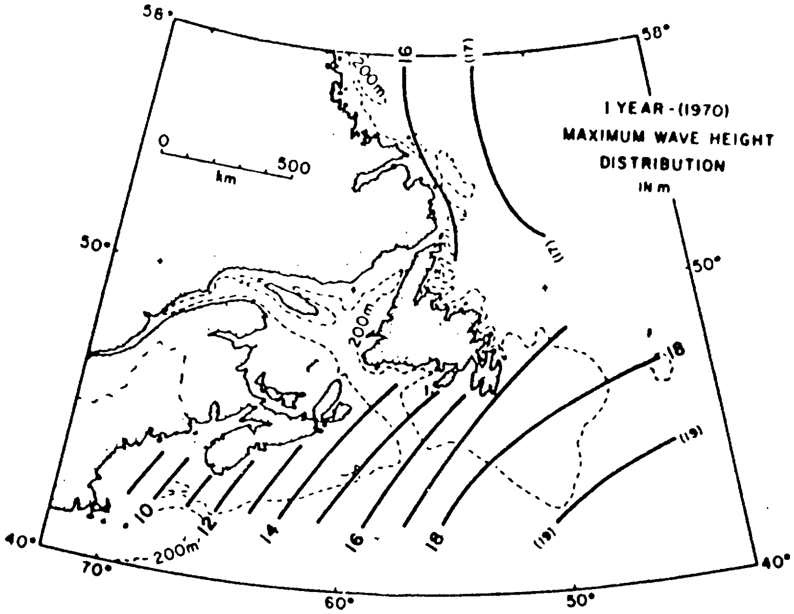
Figure 2.13 (TRIGOM, 1974) indicates that within the Gulf of Maine we can expect to see wave heights of 9 meters at least once a year and wave heights of 16 meters at least every century. To design the system to only just survive a wave height of 9 meters would be foolish underdesign, while the cost of a system to survive the 100-year storm may make it totally infeasible. What should be the proper design survivability criteria? These and similar questions are inextricably linked with the economics of the system. It may be that a tactic can be developed whereby the cam will flood itself when high seas are expected as in a hurricane and hence find some protection from breaking waves and large forces associated with the free surface. If, however, we are looking for the benefit of the system as a breakwater then this strategy is counterproductive.

Research at present is proceeding both in the theoretical and experimental areas. The British government has earmarked 2.5 million dollars for research on wave power devices including the Salter cam "aimed at establishing the feasibility of the large-scale extraction of power from sea waves, and generating information which will enable the cost of further development to be estimated."

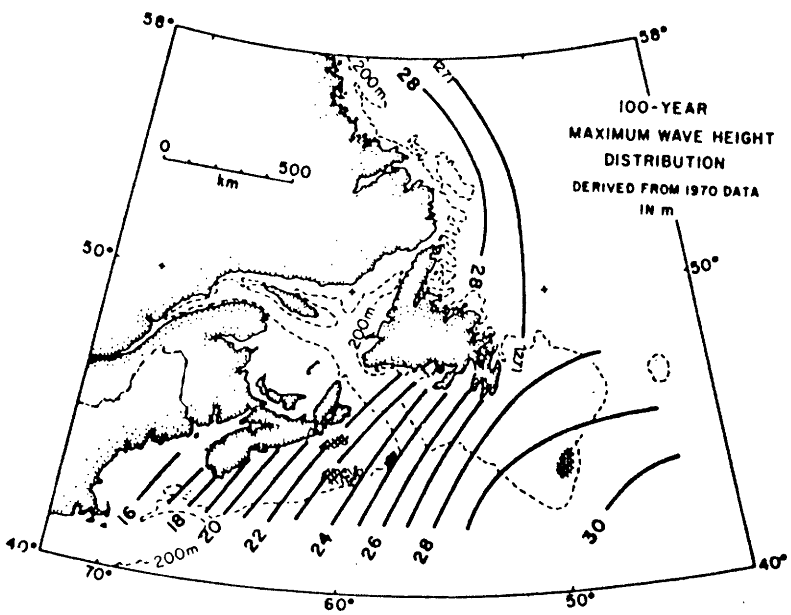
ERDA convened a workshop last spring on Wave and Salinity Gradient Energy Conversion. The report of this workshop (ERDA, 1976) probably contains the best up-to-date information on wave power climatology and technology. A number of the original papers and patents have been included in this report.

With a few minor exceptions, wave power has not been demonstrated as a power source. Clearly, the development of large-scale wave power conversion devices calls for a considerable amount of further research. The British have a pilot plant in the design phase at present. Unfortunately, that work is proprietary. Department of Commerce/Sea Grant funding for MIT has initiated some theoretical and experimental studies to verify and extend Salter's published work.

It certainly appears that there are no overwhelming technological barriers to the development of these converters. The technology available is sufficient but the design experience for this particular application is non-existent. It is believed that a pilot plant of capacity 10 MW may be feasible within two to four years if the present British wave power development is held.



I YEAR - (1970)
MAXIMUM WAVE HEIGHT
DISTRIBUTION
IN m
0
500
km
200m
58°
50°
40°
70°
60°
50°



100-YEAR
MAXIMUM WAVE HEIGHT
DISTRIBUTION
DERIVED FROM 1970 DATA
IN m
0
500
km
200m
58°
50°
40°
70°
60°
50°

Figure 2.13

3.0 APPLICABILITY TO MAINE

Wave Data: One of the major difficulties in attempting this technological assessment for the Maine coast lies in the dearth of reliable wave data. As far as can be determined to date there have been no comprehensive documented wave surveys taken. Coast Guard lighthouse keepers have been estimating wave heights and periods at least for the last several years, but the reduction of this data, which is stored on computer tape at the Naval Weather Service Detachment in Asheville, N.C. has not yet been undertaken. Some experts believe this type of crude data gathering has only marginal value. However, in the absence of any other data, it might prove informative.

3.1 "Coastal Maine"

The site closest to Maine where instrumented wave measuring devices have been used over an annual period is at Nauset Beach on Cape Cod. The data were analyzed by the Coastal Engineering Research Center (CERC) at Fort Belvoir, Va. (Dingwell, 1977) and (Thompson, 1974). The analyzed wave data consist of the number of occurrences of waves observed at discrete periods and heights. Data were missing for the months of March, April, May, and June. It was assumed, somewhat conservatively in the wave energy sense, that the average over the lost months would be comparable to the average over the rest of the year.

We shall take the Nauset Beach data as representative of the coastal wave environment in Maine. Recalling that waves approaching the coast are affected by local wind conditions, refraction due to bottom topography, and masking and diffraction from the presence of land masses and islands, we see that this is an arbitrary assumption. It is only justifiable due to the absence of better data.

3.2 "Offshore Maine"

The Climatic Study of the Near Coastal Zone of the East Coast of the United States provides wave height frequencies of occurrence for the different months of the year for one degree grids off the coast. These collated ship observations were combined with the Nauset wave height and wave period observations by "forcing" the Nauset wave heights to conform to the Climatic Study's wave heights yet preserving Nauset's wave period distribution. There is no theoretical justification for this combination but in order to get an order of magnitude grasp of wave power, it was performed. The grid used is shown in Figure 3.1. The Nauset data are labeled "Coastal Maine" and the Climatic Center-modified Nauset data labeled "Offshore Maine." These labels do not purport to physically represent any one location or region.

Ship data (Hogben and Lumb, 1967) for an area off the coast of New England and the Canadian Maritimes show the wave power distribution, Figure 3.2. For this region, the average power over the year is 38 KWw/m. Estimates of 91 KWw/m are given by (Mollison, Buneman and Salter, 1976) for an ocean site several hundred kilometers west of Ireland.

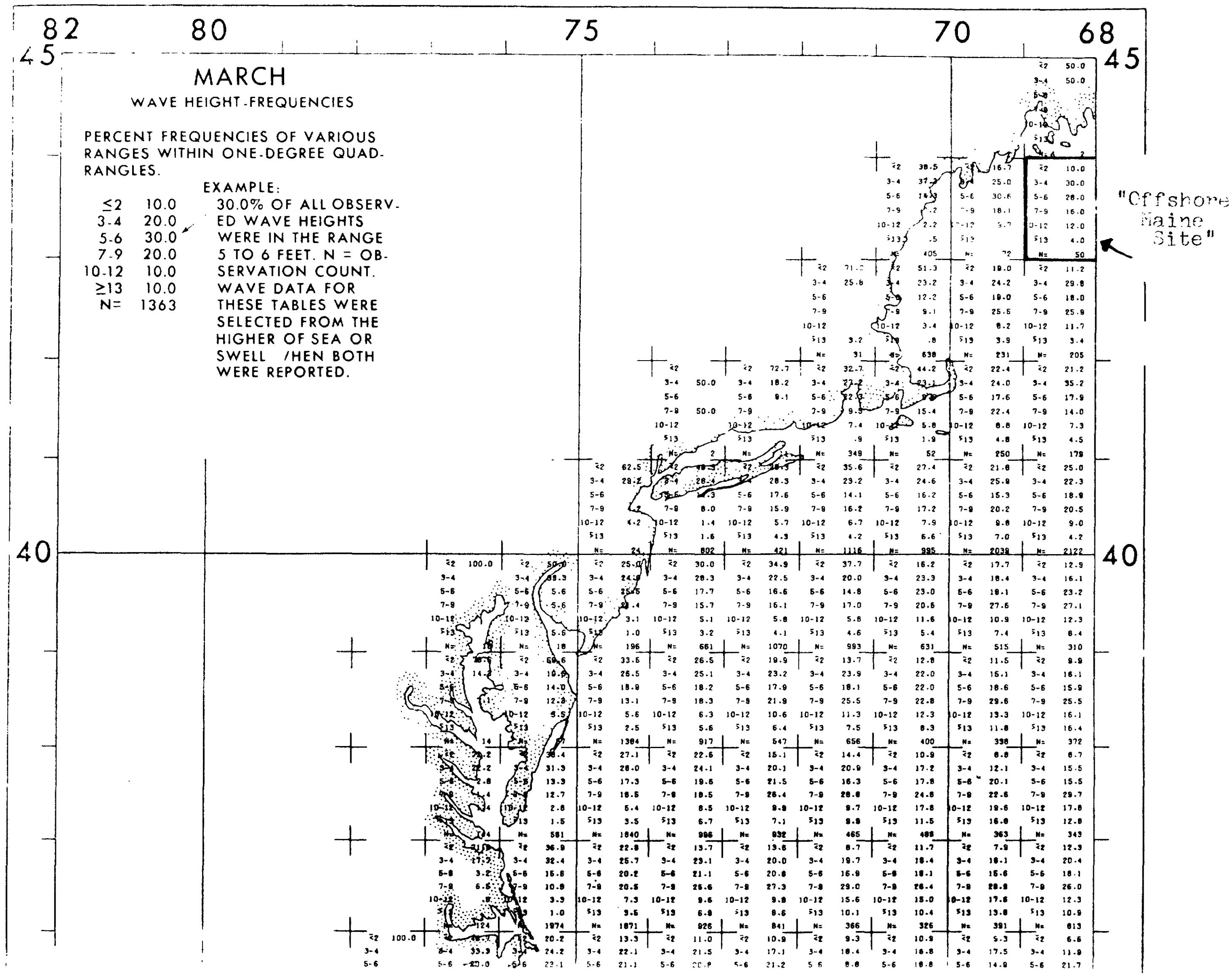

82
80
75
70
68
45
40
MARCH
WAVE HEIGHT-FREQUENCIES
PERCENT FREQUENCIES OF VARIOUS RANGES WITHIN ONE-DEGREE QUADRANGLES.
EXAMPLE:
≤2 10.0
3-4 20.0
5-6 30.0
7-9 20.0
10-12 10.0
≥13 10.0
N= 1363
30.0% OF ALL OBSERVED WAVE HEIGHTS WERE IN THE RANGE 5 TO 6 FEET. N = OBSERVATION COUNT.
WAVE DATA FOR THESE TABLES WERE SELECTED FROM THE HIGHER OF SEA OR SWELL WHEN BOTH WERE REPORTED.
"Offshore Maine Site"

Figure 3.1

Expectation Power Values During All Year New England and Maritimes
(in Watts/Meter)

Height (in M.) H_s	Period (In sec.) 5.0	6.8	7.4	8.1	8.7	9.3	10.0	10.5	11.3	11.9	SubT
1.4	175.59	2.52	3.61	2.08	0.50	0.27	0.29	0.30	10.31	5.79	201.25
1.7	570.0[illegible]	53.05	14.65	8.57	2.64	0.71	0.76	1.21	1.28	61.43	724.38
2.1	[illegible]07.51	627.3[illegible]	130.74	49.82	21.03	7.92	4.84	2.57	3.41	40.39	2545.60
2.5	1233.0[illegible]	187[illegible]	636.[illegible]	194.73	66.99	23.97	4.42	2.82	1.00	6.32	4047.30
3.0	49[illegible]	1893.29	1252.[illegible]	381.49	104.80	38.64	8.50	5.17	0.0	1.45	4183.82
3.4	266.31	1432.95	1502.[illegible]5	671.10	220.10	68.79	12.78	11.90	3.61	0.0	4240.52
3.9	137.41	884.4[illegible]	1476.17	796.82	329.85	91.38	24.41	8.66	0.0	0.0	3749.20
4.3	122.64	771.65	1279.37	968.08	373.92	141.6[illegible]	37.85	10.74	2.85	6.02	3564.83
4.7	71.58	472.61	947.86	351.42	368.68	140.54	76.62	9.78	0.0	0.0	2939.09
5.2	76.22	469.77	973.83	862.81	478.42	198.32	[illegible]5.13	31.15	0.0	0.0	3175.64
5.6	8.15	78.97	227.27	173.85	56.30	40.29	4.31	0.0	4.86	0.0	594.00
6.1	15.80	95.20	178.60	210.17	117.7[illegible]	42.15	20.02	10.65	0.0	5.97	696.35
6.5	29.07	160.34	436.54	446.30	245.89	86.20	34.54	6.13	0.0	0.0	1445.01
6.9	33.13	151.54	419.50	466.28	297.41	135.09	52.49	0.0	0.0	0.0	1555.44
7.4	9.37	50.39	215.09	233.64	181.06	41.65	29.67	0.0	0.0	0.0	760.08
7.8	5.26	84.86	278.61	282.47	188.75	10[illegible].11	24.98	0.0	0.0	0.0	974.04
8.3	5.86	50.49	227.92	217.57	242.95	26.08	27.87	0.0	0.0	22.15	820.90
8.7	0.0	35.00	160.89	149.80	179.66	57.86	20.61	0.0	0.0	0.0	603.82
9.1	0.0	30.90	84.55	101.03	148.70	42.57	60.23	0.0	0.0	0.0	475.98
9.6	23.66	33.95	1[illegible]9.60	282.48	185.13	128.6[illegible]	49.97	39.88	14.[illegible]	14.90	921.25
10.9	0.0	10.98	24.04	0.0	14.0[illegible]	0.0	0.0	0.0	0.0	0.0	49.12
SBTOT	4889.74	9277.17	10669.34	7250.50	3824.71	1411.33	599.26	140.96	41.41	164.40	38258.31 watts/m

Average power for periods and heights over one year

Figure 3.2

Table 3.1

Wave Power Throughout the Year

Month	"Coastal Maine"	"Offshore Maine"
January	3.05 KWw/ft	12.4 KWw/ft
February	1.39	7.0
March	no data	no data
April	no data	no data
May	no data	no data
June	no data	no data
July	.83	4.5
August	1.24	3.8
September	2.13	7.7
October	2.18	15.1
November	2.32	13.6
December	3.34	30.3
Monthly average	2.06 KWw/ft	11.8 KWw/ft
Standard deviation	.87	8.57

Source: Derived from (Dingwell, 1977) and (Thompson, 1974).

Because the wave power increases with the square of the wave height, the power can increase very rapidly. Note that almost one-third of the wave power offshore occurred in December. To harvest that energy requires a large device with a large power rating implying inefficient conversion for much of the rest of the year.

3.3 CAVEAT

It must be borne in mind that these numbers are used only as order of magnitude estimates for the wave power climate. The actual wave energy will be very site specific. It is possible that near shore, the available wave energy may vary by a considerable amount within a very short distance. Site location is critical and depends on a number of factors: wave spectra, wave directions, wave power availability over the year, bottom topography, bottom depth, and distance from the grid connection, to name a few.

3.4 Wave Directions

The Salter Cam we have been considering is a two-dimensional device, that is, it responds preferentially to waves whose wave crests are parallel to its axis. Waves from other directions will be utilized but to a lesser extent. The amount of performance degradation due to nonalignment is a topic of current research. If the body axis is fixed and cannot be re-oriented, then its original alignment must be coordinated with the direction of the greatest extractable energy. Figure 3.3 shows the directions of wave energy as a function of frequency of occurrence and wave height. It would appear that the axis of the device operating in these wave conditions would be oriented roughly north-south to capture the large easterly energy. The source of this figure (TRIGOM, 1974) claims this is for wave measurements taken 50 miles south of Mt. Desert. The inference is that, because of the masking of all waves from the southwest through to the northeast, the station was most likely on a land mass such as Matinicus or Mt. Desert Rock. We use this figure then for illustrative purposes only, to demonstrate that the directional spectra are another important element in the analysis.

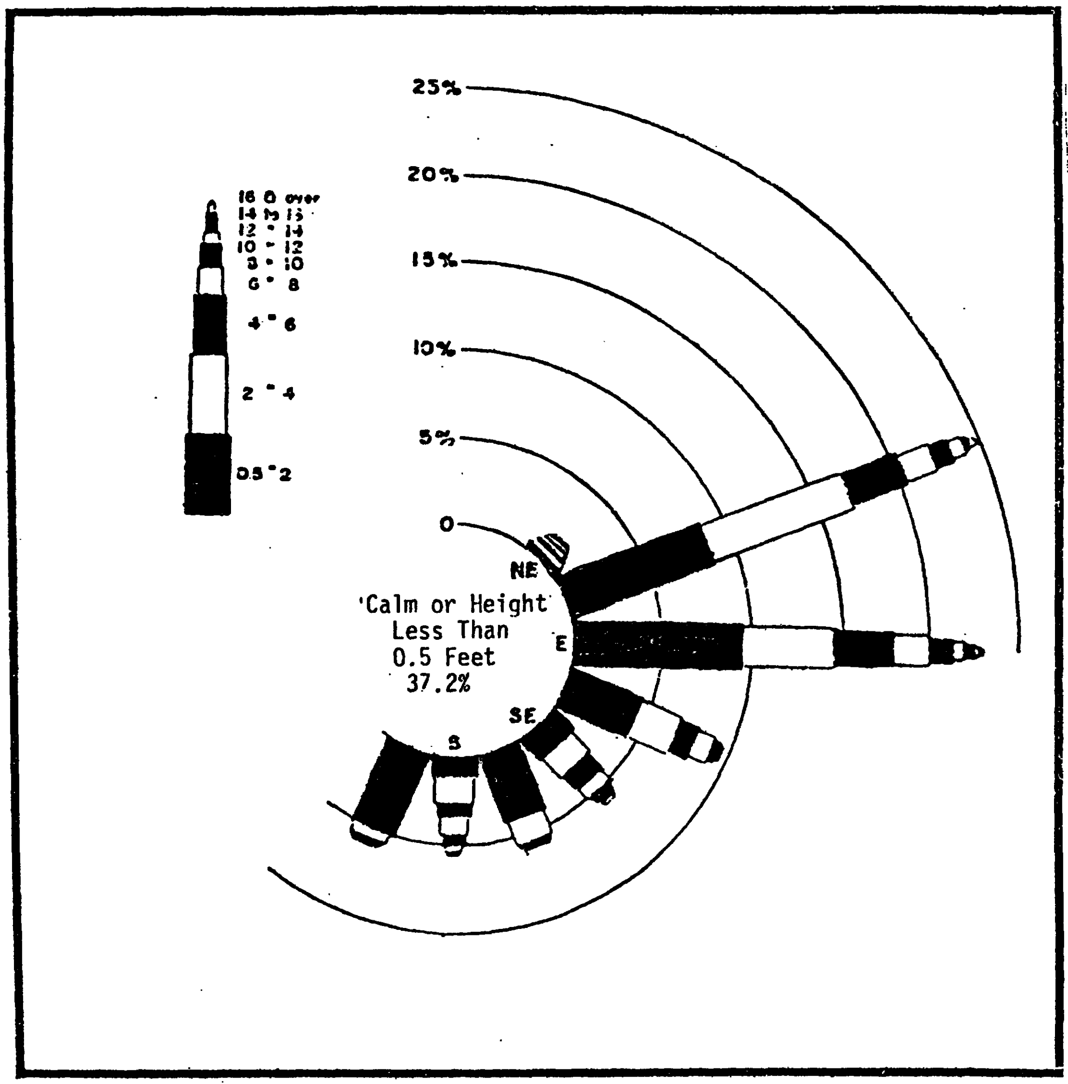


Figure 3.3 Frequency of Occurrence by Wave Height and Direction

The further offshore the cam is to be moored the less effect refraction will have in aligning the waves and the greater the expanse of water over which winds can create local waves which might affect alignment.

3.5 Wave Power Availability

To give some idea of the electrical output as a function of time, the Nauset ("Coastal Maine") results are presented in Figures 3.4a and 3.4b for different power ratings. We note that the amount of electrical power that can be generated varies considerably from day to day. The standard deviation curve reflects the amount of variability within the course of a day.

The top curve in each plot is the average daily power (1) and the lower curve (2) the standard deviation over a day; four periods of measurement per day provide the data. Notice the change of scale in the ordinate between two different power ratings. The higher rated system has an average daily power of zero for 4 or 5 of the 30 days, but the lower rated system is never idle.

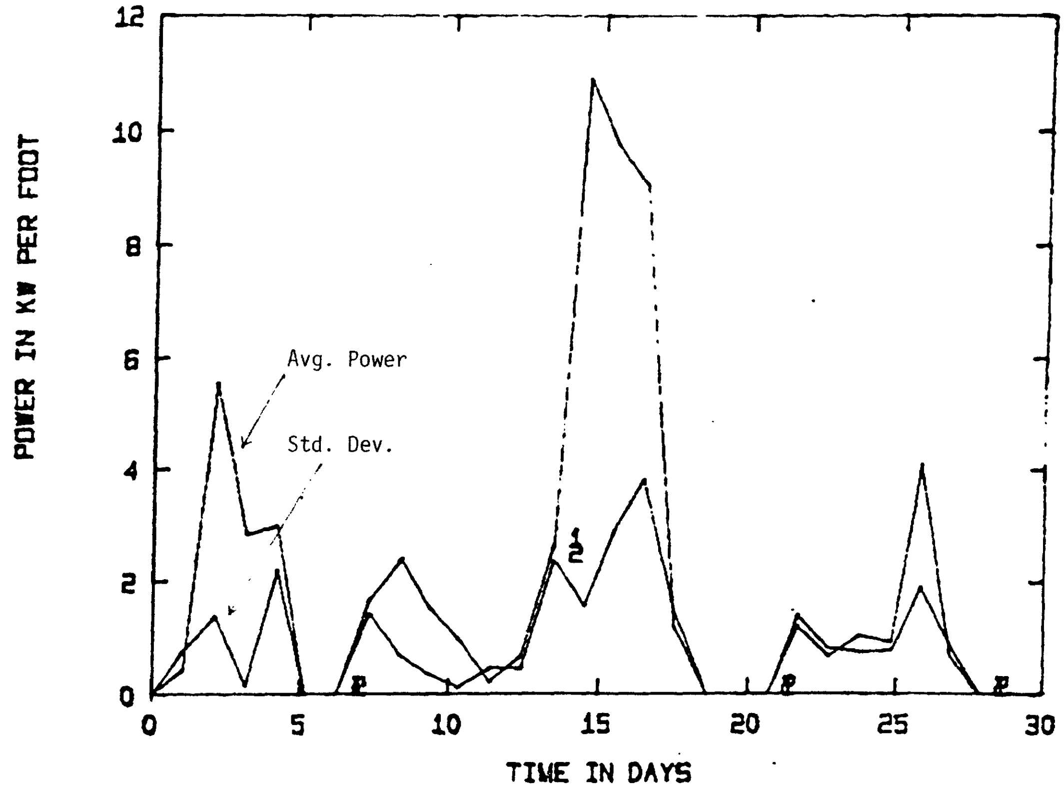


FIGURE 3.4a

Average Daily Power and Standard Deviation of Power Over a Day for Thirty Day Period at Nauset Beach; D = 34 Feet, POWRAT = 14 KW/ft

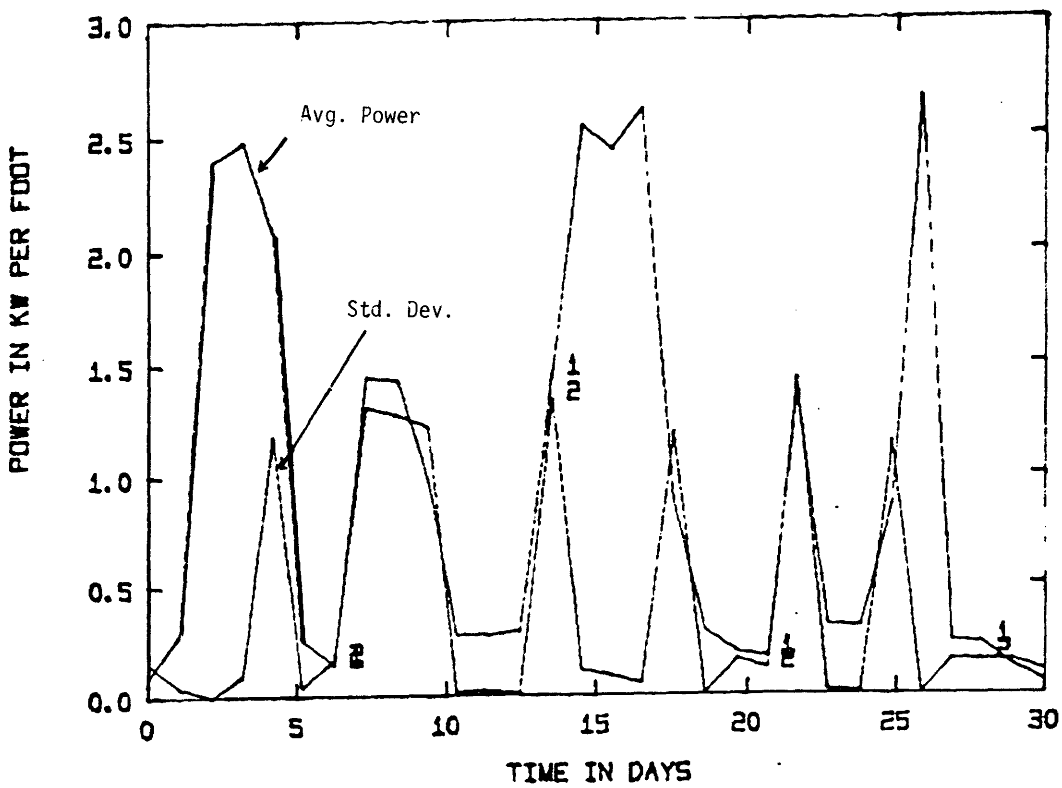


FIGURE 3.4b

Average Daily Power and Standard Deviation of Power Over a Day for Thirty Day Period at Nauset Beach; D = 34 Feet, POWRAT = 3 KW/ft.

4.0 WAVE POWER ECONOMICS

Because of the uncertainty in the designs themselves and the lack of any experience at all with these types of systems, the following numbers, too, must be regarded as indicators only. The precision which the computer attributes to costs is clearly illustory, but the effect of the assumptions on the output is helpful. The model described below is mostly from (Dingwell, 1977).

> "Costs for a device which as yet exists only conceptually must be very approximate, but even at this stage the relevant cost functions used in the computer model may be improved as the design becomes more specific. As they exist, the estimates are somewhat optimistic in that costs for such items as mooring and deployment, connections between cams, leasing of the sea surface, obtaining a license to operate, and establishing aids to navigation have been omitted."

Licensing, operating and maintenance and financing costs during construction have been omitted also.

4.1 Hull

The cost of the hull of a cam can be estimated using methods for estimating shipyard costs of ship hulls. An estimate was made for a cam 30 feet in diameter and 500 feet long. A simple structural analysis suggests plating of 1/4 inch will be sufficient. Frames of T beams welded to the plating with a six-foot spacing are constructed from 1/2 inch plating with a width of 8 inches and flange 8 inches. The labor necessary for a six-foot section was estimated at 76 man-hours, the weight of steel at 4.6 tons for a 6-foot section. Using a labor wage of $5.25 and overhead costs of 60% and plant amortization of 20%, the cost of a man-hour was estimated at $9.50, and $400/ton used as the cost of steel. Within a reasonable range of cam diameters the cost will roughly follow the weight in this way:

Cost of hull/ft = 14 x Diameter

The use of auxiliary cylinders as in Figure 2.9 as a frame of reference was considered in the calculations, thus doubling the hull cost.

4.2 Conversion System

Estimates for the conversion system were taken from a study (Kaman, 1976) on wind-generated electricity. The costs, including maintenance and personnel, provide the following expression for conversion costs. Power rating is a design parameter measuring unit size.

Cost of generator = 256 x power rating if power rating < 1 KWw/ft
= 131 x power rating if power rating > 1 KWw/ft

4.3 Transmission Cost

$400/KWe is assumed for underwater electrical transmission for a distance of 50 km (Somers and Snoupp, 1974). This figure was used in the offshore case. For the coastal case a much lower figure of $15/KWe was chosen.

4.4 Final Costs

A levelized carrying charge of 18% is used to determine the annual cost and the cost per kilowatt hour of electricity. Escalation at a simple rate of 5%/year until 1986 is assumed for the sake of discussion.

$$\text{Total cost/KWHe} = \frac{(\text{cost hull} + \text{cost generator} + \text{transmission cost}) \times .18}{\text{Total Energy Delivered}}$$

4.5 The Model

The computer program takes the total energy available at a site over the year at specific wave periods and heights. It then determines a range of cam diameters that would appear to best collect the available energy. At each cam diameter within this range, the program determines the optimum size of converter by selecting the power rating for that size cam that produces the energy at the least cost. Tables 4.1a and 4.1b and Figure 4.1 show these results for both the "coastal Maine" and "offshore Maine" sites.

We note a minimum cost (subject to the assumptions above) of around 55 mills/KWHe for the coastal station producing an average of .5KWe/ft. of cam and around 24 mills/KWHe for an average of 4 KWe/ft for the offshore case. Recall that the missing components of these systems may increase costs by a factor of 3 or more.

Table 4.1a

"Coastal Maine" Site

[Optimum design size of power ratings to achieve minimum cost of system per KWHe as a function of cam diameter (1986 dllars - 18% levelized carrying charge)].

Cam Diameter (feet)	Cost/ft $/ft	Power Rating KWw/ft	Average Power KWe/ft	Energy Cost* mills/KWHe
8	770	1	.138	116.3
10	1078	2	.304	74.0
12	1182	2	.395	62.3
14	1286	2	.459	58.4
16	1398	2	.525	55.3
18	1519	2	.533	59.3
20	1650	2	.552	62.3
22	1798	2	.564	66.5
24	2161	3	.677	66.5
26	2341	3	.677	72.0
28	2531	3	.661	79.8
30	2702	3	.672	83.8

*may be low by factor of 3 due to uncertain cost projections and unreliability of data.

Table 4.1b

"Offshore Maine" Site

[Optimum design size of power ratings to achieve minimum cost of system per KWHe as a function of cam diameter (1986 dollars - 18% levelized carrying charge)]

Cam Diameter (feet)	Cost/ft $/ft	Power Rating KWw/ft	Average Power KWe/ft	Energy Cost * Mills/KWHe
8	2144	2	.655	68.3
10	223	2	1.183	39.2
12	3133	3	2.047	31.9
15	3237	3	2.443	27.7
17	3349	3	2.798	25.0
20	3471	3	2.857	25.4
23	3602	3	2.980	25.1
26	4546	4	3.511	27.0
29	4691	5	4.073	24.5
33	5140	5	4.073	25.0
37	5059	5	3.949	26.8
41	5231	5	4.013	27.3
46	5424	5	3.858	29.3
51	5658	5	3.585	30.5
56	5887	5	3.929	31.1

*may be low by factor of 3 due to uncertain cost projections and unreliability of data.

More accurate estimates cannot be made until a given site is chosen, the wave spectra collected, and firmer engineering models drawn up. Other factors that will bear are the economics of variable and unpredictable power supply and the economic premiums that may accrue to the converters used as a breakwater.

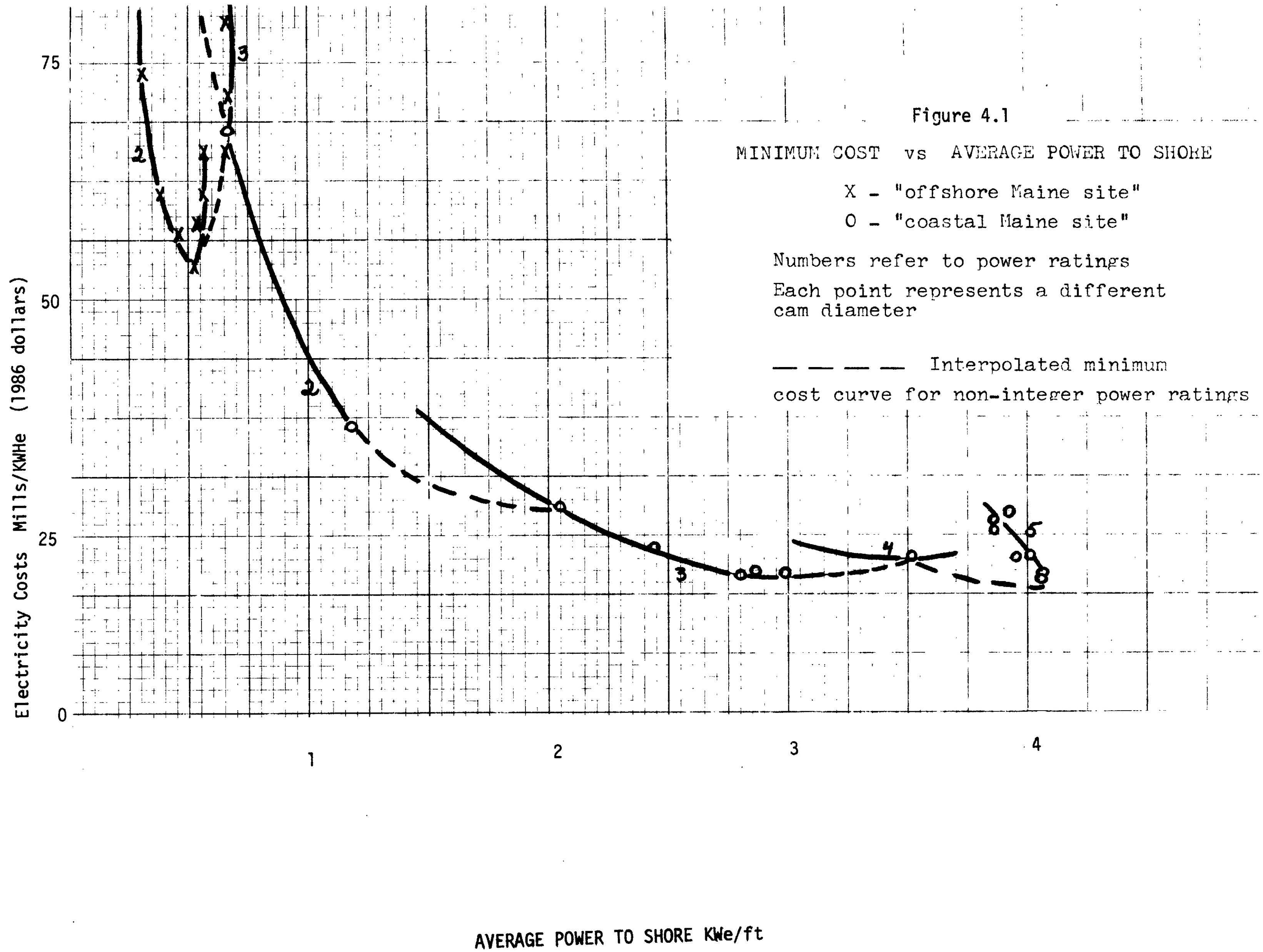


Figure 4.1
MINIMUM COST vs AVERAGE POWER TO SHORE
X - "offshore Maine site"
O - "coastal Maine site"
Numbers refer to power ratings
Each point represents a different cam diameter
Interpolated minimum cost curve for non-integer power ratings
Electricity Costs Mills/KWHe (1986 dollars)
75
50
25
0
1
2
3
4
AVERAGE POWER TO SHORE KWe/ft

5.0 ENVIRONMENTAL IMPACTS

A preliminary analysis tends to indicate that wave power conversion differs considerably from conventional power sources with respect to environmental impact (Salter, Jeffrey and Taylor, 1976), Ziegler, Hyer and Wass (1976) state:

> "we have not been able to identify adverse impacts of the environment associated with wave power plants in any of the environmental categories discussed (water temperature, salinity, fresh water demand, flora and fauna)."

5.1 Pollutants

5.1.1 Antifouling

It is very likely that some kind of antifouling coating will be applied to impede growth of marine organisms. In Maine the temperature of the wate slows barnacle and algal growth considerably but it is likely that a copper base or some similar base toxic coating would be used for antifouling. This antifouling coating could leach into the water.

5.1.2 Hydraulic System

If a hydraulic system is used to provide energy conversion, then the potential for spillage of the hydraulic fluid has to be considered.

5.2 Size

Assuming a bus bar output of between 1 and 4 KWe per foot of lineal extent, a device would have to be between 300 and 1200 hundred feet long to power Vinalhaven and between 25 and 100 nautical miles long to provide the equivalent of 600 MW. One thing is clear: that at the energy densities we have deduced above there is no escaping a large array whether it is a string of Salter cams or a field of buoys heaving up and down. The placement would have to avoid shipping channels and not interfere with fishing operations.

5.3 Breakwater

The social and economic benefits of using the device as a breakwater will have to be assessed. It may represent a positive environmental effect. The artificial breakwater can provide refuge for merchant and fishing craft or protect an offshore deep water harbor allowing large tankers to off-load without having to come into ports whose harbors may only be able to accommodate relatively shallow draft vessels anyway.

On the other hand, the modification to the flow and flushing of estuaries and harbors is unknown.

5.4 Experience with Artificial Reefs

There are indications that fish are more plentiful in the vicinity of artifical reefs. So, too, one might expect a similar phenomenon to take place.

5.5 Erosion Due to Waves

Near the shore it is not clear what effects the placement of an array would have on the aggradation of sand due to waves. It does seem clear that some areas that are particularly vulnerable to wave erosion could be protected by power extractors. However, the mechanism of waves and currents on sand transport is not trivial and would need careful study for any site.

6.0 CONCLUSION

Wave power has not yet been demonstrated as a viable large-scale power source. A number of devices have been suggested as capable of extracting energy from ocean waves; some have offered experimental and theoretical proof of very high conversion efficiencies.

Modeling, based on the Salter cam wave power extractor and hypothetical wave data for two types of Maine locations, [a "coastal" site and an "offshore site"] indicates average wave power delivered on shore as electricity to be 0.5KW and 4 KW respectively per lineal foot of converted broadside to the waves. The onshore delivered energy costs for each site are estimated at 55 mills/KWH and 24 mills/KWH respectively (1986 dollars).

The uncertainty in the wave data, technology, and costs at this time would indicate that power estimates are correct within a factor of two while energy cost estimates may be low by a factor of three.

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