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SERI/TP-634-1195
(PREPRINT)

CONF-810808--8

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OCEAN ENERGY - WAVES, CURRENT, AND TIDES

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MAY 1981

PRESENTED AT ENERGY IN THE
MAN-BUILT ENVIRONMENT
URBAN PLANNING AND
DEVELOPMENT DIVISION SPECIALTY
CONFERENCE
3-5 AUGUST 1981
VAIL, COLORADO

PREPARED UNDER TASK NO. 1115.00

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A Division of Midwest Research Institute
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Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

OCEAN ENERGY-WAVES, CURRENTS, AND TIDES

by

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Abstract

An overview is presented on the mechanical forms of ocean energy; i.e., waves, currents, and tides. Following an introductory section on wave mechanics, we consider each of the three forms of ocean energy under the headings of the resource, device types for energy extraction, and prognosis for practical implementation.

A. Waves

A.1 Wave Mechanics

A complex phenomenon, ocean waves are generated by atmospheric winds acting over large areas for a long time. To gain an appreciation for waves, let us consider some relationships for an ideal wave in deep water; i.e., one of sinusoidal shape, small amplitude, monochromatic frequency, and straight wave fronts. Such a progressive wave, as opposed to a standing wave, advances at a speed C:

$$C = L/T \quad ,$$

where L is the wavelength and T is the period. Furthermore, the speed of the wave is related to wavelength:

$$C^2 = gL/2\pi \quad ,$$

where g is gravity acceleration. Combining these relationships, we see that

$$L = gT^2/2\pi$$

$$\text{and } C = gT/2\pi \quad .$$

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A typical ocean wave has a period of approximately 10 s, which corresponds to a wavelength of 156 m and to a wave speed of 15.6 m/s. Note that for this simple case the water particles move in circular orbits while only the wave advances.

A refinement accounting for finite water depth h yields a wave speed of $C^2 = (g/K) \tan h(Kh)$, where K is the wave number $2\pi/L$. "Deep" typically requires the water depth to be greater than half of a wavelength. An example of this reduction in wave speed in shallow water is the observed refraction of oblique waves approaching a beach so that they arrive almost parallel to the beach.

Another important measure of the simple wave is the power it transports per unit crest length past a fixed location. This measure, in turn, describes the maximum power available from a linear (two-dimensional) wave-energy extraction device. We can show the wave energy to be one-half potential energy and one-half kinetic energy, expressing the total power per unit crest as:

$$P = \rho \frac{g^2 H^2 T}{32\pi} ,$$

where H is the peak-to-trough wave height. For a 3-m wave of 10-s period, this equation results in 86 kW/m. The energy distribution and particle motion decline sharply with distance below the ocean surface; e.g., over 95% of the energy is present in the first quarter of the wavelength below the sea.

When a device extracts energy from a wave, a force occurs as a result of simple momentum principles. If 100% of the energy in a wave is absorbed by a device, the resulting force per unit length of wave crest is

$$F = \rho g H^2/16 \quad .$$

The previously considered 3-m wave yields a value of 5500 N/m.

Real waves are a mixture of heights, periods, wavelengths, and direction. Thus, it is not surprising that one uses statistical approaches to describe them. One such widely used approach is the wave spectrum, which is the distribution of the wave energy by frequency. Wave spectra can be evaluated from a record of wave height versus time through the process of Fourier transformation. One well-proven theoretical spectrum is the Pierson-Moskowitz spectrum, applicable to a fully developed sea (waves no longer growing) (see Figure 1).

A.2 The Wave Resource

It has been estimated that the total wave energy delivered to the coastlines of the world is comparable to the global power consumption. The distribution of this energy varies strongly with season as well as location. Favored locations are those on the eastern boundaries of large ocean bodies because of the prevailing westerly winds.

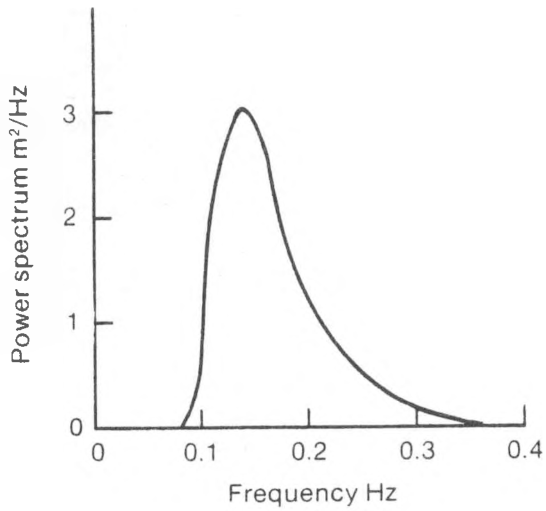


Figure 1. Pierson-Moskowitz Spectrum for a Wind Speed of 10 m/s

Figure 2 displays some typical distribution estimates around the United States. By comparison, the wave resource off the west coast of Scotland is very strong (up to 100 kW/m).

An average resource varies from around 10 to 90 kW at favorable locations, while the peak storm values might reach 1 MW/m. This represents a major obstacle. We must develop a device that is economically feasible in an average wave environment of approximately 30 kW/m, but can also withstand wave forces corresponding to the peak waves.

Another indicator of the wave resource is available energy flux per unit area. If we consider a location where the average power is 30 kW/m, and a linear device that is 20 m deep, we arrive at a power density of 1.5 kW/m^2. By comparison, a favorable wind speed of 15 mph yields a maximum power density of 0.18 kW/m^2. Additionally, it may be possible to intensify the waves through refraction and diffraction processes, as we will briefly discuss later.

A.3 Leading Wave Device Types

Inventing wave energy extraction devices has been a popular pastime through the ages, as reflected by the large number of patents. However, during the past six or seven years of renewed interest in wave energy, a few extraction concepts and devices have come to the forefront. We judge these devices against the following criteria:

- Energy conversion efficiency
- Mooring forces
- Durability and ability to survive in an ocean environment
- Wave direction and frequency sensitivity.

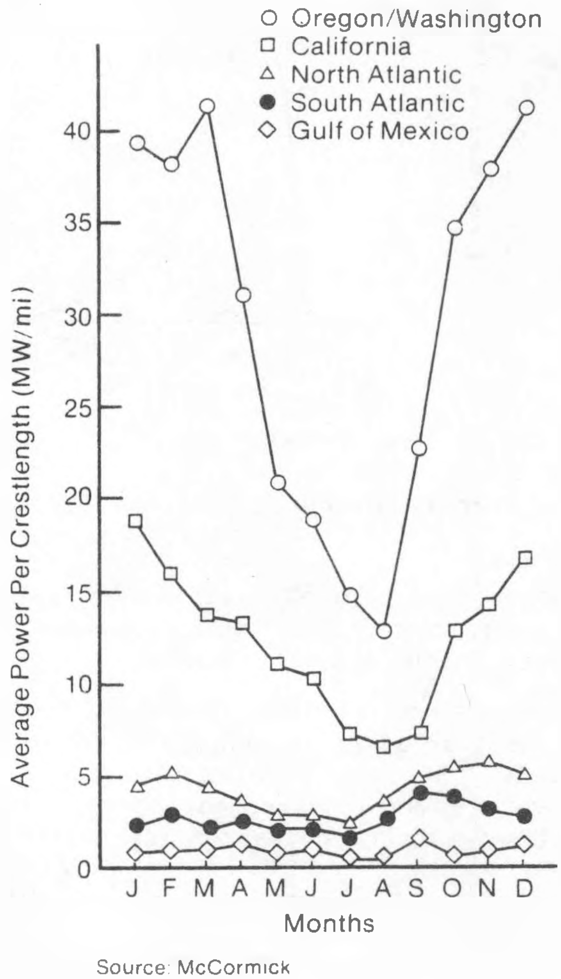
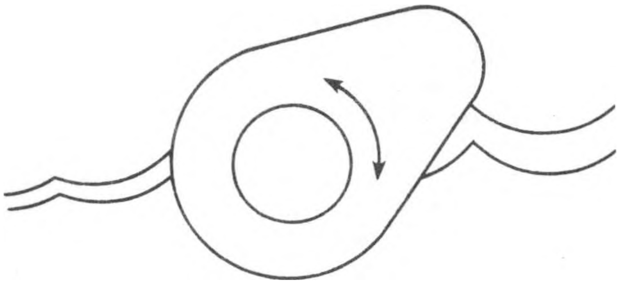


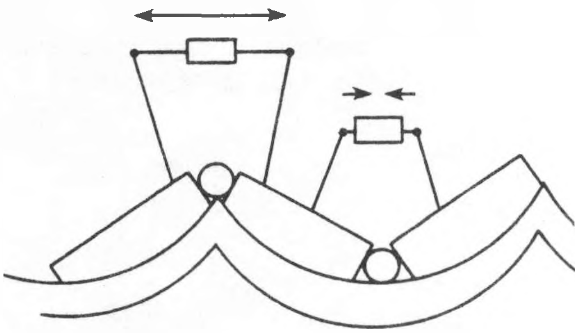
Figure 2. Available Wave Power for Various Regions of the United States

However, we must especially consider the cost of the delivered product (electricity) over the expected lifetime.

The most active country in the development of wave energy devices is the United Kingdom. Their scientists have developed theoretical analyses, laboratory experiments, limited sea tests on reduced scale models, and systems economic studies. Funding has been about $\$6 \times 10^6$/yr for the past three to four years. Leading device candidates from the United Kingdom development program include:

Duck--This device is in the shape of a stubby hydrofoil section that oscillates about a reference axis with a motion matching the orbital motion of the water in the waves approaching its "beak." No new waves are produced astern because of the cylindrical shape on the back side, thereby leading to a high energy capture efficiency.





Rafts--A segmented floating surface yields relative motion between the various segments (rafts). This motion can be converted to useful energy by a system of hydraulic pumps and motors.

Pneumatic Cavity Resonator--A passing wave causes a water column to resonate in a tuned air cavity, and the pressure variations produced are used to cause an oscillating air flow that drives a pneumatic turbine.

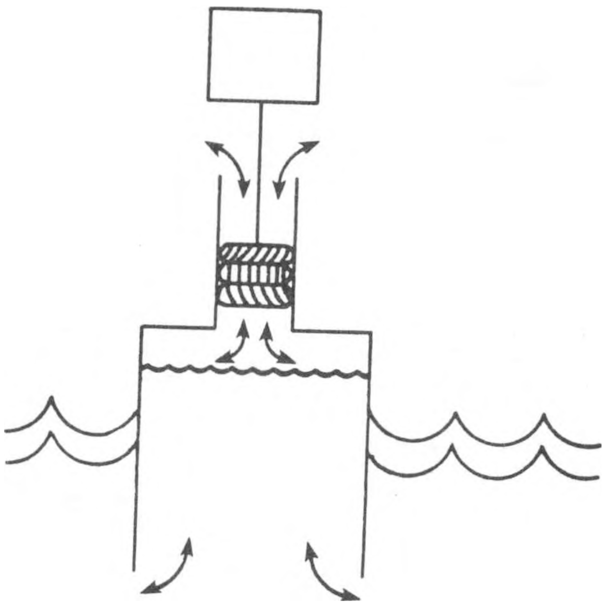


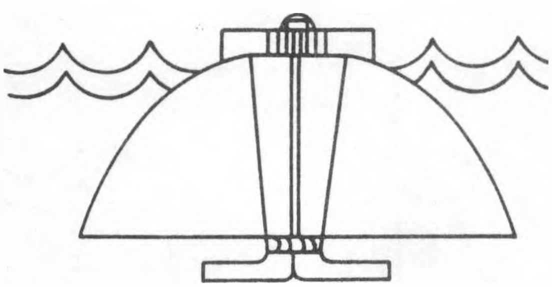
Figure 3. Candidate Wave Energy Extraction Devices

The Japanese have developed practical small-scale point absorbers (buoys with vertical axes). Several hundred units of 70- to 120-W capacity have been in service for more than a decade as power sources for navigational buoys and lighthouses. Additionally, the Japanese initiated the international effort known as the Kaimei project, involving the United Kingdom, United States, Canada, Ireland, and Japan. Several air turbines were placed over chambers of about 50 m^2 in planform area, open at the bottom to the sea and positioned along the length of the 80-m long, barge-like vessel Kaimei. Placed in the Sea of Japan for several months, its various systems functioned generally without fail, although the power production was much less than anticipated. Engineers currently suggest that the low power production resulted from nonoptimum hydrodynamic design of the Kaimei for the particular sea environment. Interestingly, the Kaimei was moored head-sea (into the predominate approaching waves) to reduce mooring forces.

The U.S. wave program, coordinated by Solar Energy Research Institute (SERI) for the U.S. Department of Energy (DOE), with its annual budget of about $1 x 10^6/yr, has been designed to complement the more mature international programs. The focal points of the U.S. program are:

- The Dam-Atoll device
- Counter-rotating air turbine
- Systems and resource study
- Analytical studies of hydrodynamic performance
- Kaimei participation
- Innovative device solicitation
- International liaison.

The Dam-Atoll device (see Figure 4), is based on wave refraction and the resulting intensification of power. A qualitative 1/100th scale model test has occurred, and currently analytical studies are being directed to optimize a design for a quantitative 1/50th scale test.



Refracted Wave Energy Device--An artificial atoll is used to cause incoming waves to focus, by refraction, toward the center of the atoll. The energy collected from the focused waves is converted into a vortex flow in a standpipe at the central core of the device. The vortex flow drives a hydraulic turbine/generator located at its base.

Figure 4. Dam-Atoll Device

The counter-rotating air turbine is novel in design and allows for operation in bidirectional airflow, which occurs on the Kaimei or on a pneumatic cavity resonator, without employing flow rectification valves (with their inherent losses). The turbine has a design output of 125 kW_e and is nearing the steady-state test phase. Eventual deployment will probably be in conjunction with a fixed, optimized single resonant air chamber or as part of an improved, Kaimei-type structure. Application of this turbine together with an optimized air chamber holds the promise for considerable wave focusing through a process that is similar to that in a well-designed radio antenna.

A.4 Wave Power Prognosis

Most agree that waves can be tapped to produce useful energy, primarily electrical, and that any of several devices might be employed. However, the salient consideration is economic. The British are perhaps the most advanced in addressing this question through a systematic, regularly up-dated evaluation procedure. Their initial exercise for a 2000-MW reference design yielded installed costs of upwards from $850/kW and electrical energy costs of 600-1000 mils/kWh. Improvements in device performance have resulted in more optimistic cost projections.

Since no outstanding choice of an optimum wave energy device has emerged and no thoroughly documented evidence is available on high performance from large or full-scale devices, development work and analytical studies continue. Eventually, these combined international efforts might yield a wave device and system that is competitive in cost and risk with the ever-increasing cost of conventional energy systems. A factor that could favorably influence the competitive position of wave energy systems is their potential use as breakwaters.

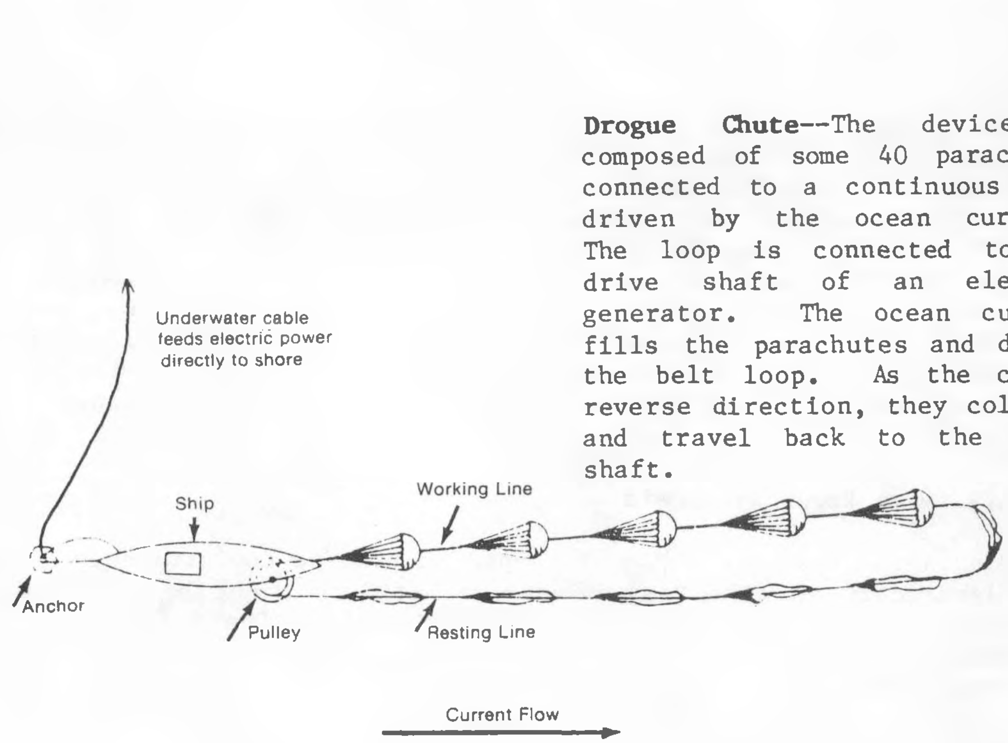
B. Ocean Currents

B.1 Ocean Current Resource

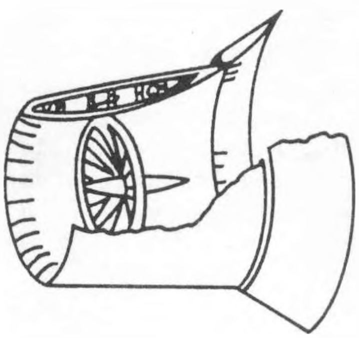
The resource represented by ocean currents is estimated as 100,000 MW globally, with perhaps 50% of that contained in concentrated sites such as the Gulf Stream. In general, the swiftest ocean currents are in equatorial regions and along western ocean boundaries. Detailed information on the worldwide distribution of ocean current energy is not extensive. The most complete survey of ocean current velocity data for the Florida Straits shows magnitudes of 1.0 to 1.8 m/s. These figures correspond to a potential energy flux from 0.5 kW/m^2 to 2.9 kW/m^2.

B.2 Ocean Current Devices

The Department of Energy through SERI is supporting the development of two ocean current devices, as shown in Figure 5.



Drogue Chute--The device is composed of some 40 parachutes connected to a continuous loop driven by the ocean current. The loop is connected to the drive shaft of an electric generator. The ocean current fills the parachutes and drives the belt loop. As the chutes reverse direction, they collapse and travel back to the drive shaft.



Axial Flow Turbine--An axial flow turbine configuration is used to convert the ocean current's kinetic energy into mechanical energy. This particular device has two counter-rotating rotors with catenary supported blades mounted within a stationary housing that serve as an augmenting duct. Mechanical energy is converted to electrical energy using generators connected to a friction drive power takeoff at the rotor's rim.

Figure 5. Ocean Current Energy Devices

As suggested by the brief description in Figure 5, the axial flow turbine (named the Coriolis device) is a high technology development project. Initial designs called for an exit diameter of 171 m and an average power output of 83 MW per unit when placed in the Gulf Stream 30 km east of Miami. An array of these units was forecast to yield 10,000 MW of average annual power. The present phase of development features the following tasks:

- Refinements in the hydrodynamic design of the high augmentation duct and counter-rotating turbine rotors.
- Definition of the rim-drive system.
- System engineering and economic studies leading to minimum project costs.
- Development of scale and preliminary design for a test unit.

Current results of these studies have suggested an optimum diameter of approximately 30 m. Also, a factor favoring the Coriolis-type device is that it is immersed below the level of intense storm activity. Furthermore, all properly placed ocean current devices rely on a steadier source than wave or wind devices.

The drogue chute device has received limited development support through DOE. Tests have been performed on a device with 5-ft diameter parachutes, towed at an inland lake. No quantitative evaluation of this reduced scale test are available, nor have any detailed systems or economic studies been performed regarding an optimized full-scale device.

Finally, scientists are also investigating the use of the electrically conducting ocean current to drive a magnetohydrodynamics (MHD) device. This development has been limited to laboratory work and preliminary design studies for a small-scale ocean device.

B.3 Ocean Current Power Prognosis

Devices to extract useful power from ocean currents are less developed than those devices to extract wave or tidal power. Their potential appears to exist, but only further development of ocean current devices and systems and clarification of competitive energy sources will reveal how economically feasible they are.

C. Tides

C.1 Ocean Tide Resource

Tidal waves are longer period waves generated by the interaction between the earth and moon. Near-shore areas with a great tidal range and potential for tidal power development are widely distributed and include the coasts of Alaska and British Columbia, the Gulf of California, the Bay of Biscay, the Central Indian Ocean, and the coasts of eastern Maine and Canada. Worldwide tidal power has been estimated at 2.7×10^6 MW, but only 30,000 MW is considered feasible for conversion to electricity. A mean tidal range of more than 5 m is considered necessary for an economically feasible operation.

Numerous ideas have been considered for the extraction of tidal energy, but impoundment of ocean water in a river estuary or bay with narrow inlet is the only method that has been practically employed or that is being substantially developed. The design and placement of a tidal power facility is complicated by the fact that the observed tidal fluctuations may be, in part, a resonant phenomena, which would be significantly damped by the extraction of a large portion of the tidal energy.

C.2 Existing Tidal Power Systems

The most noteworthy installations are in the French Rance River estuary and at Kislaya Bay in the Soviet Union. The French broke ground for the 240-MW plant in 1960 and completed construction in 1967. They report mean tides of 8.5 m, and the 10-MW, 5.35-m diameter turbines generate power on both ebb and flood flow. Net output has reached 500 GWh/yr, and the total cost of the operation in 1975 compared favorably with peaking power being obtained from conventional hydroelectric plants.

C.3 Tidal Power Prognosis

The successful operation of the Rance River project, together with the commitment of considerable amounts of money by several countries to develop additional tidal power projects, indicates most strongly a viable future for tidal power.

The South Korean government is spending \$2 to \$3 x 10^6 to develop plans for a 450-MW inner basin plant and an 810-MW outer basin plant at Asan Bay. The French are performing a feasibility study on a giant two-pool tidal power station (6,000 to 12,000 MW) at Chausey in the Bay of Mont St. Michel. Canada has initiated a \$33 x 10^6 study of tidal power, looking at three main sites--Shepody Bay and the Cumberland and Minas Basins.

The Department of Energy has awarded funds for the initial study of a concept that would use a high-strength plastic dam rather than the conventionally employed rigid structure. Projected cost savings would allow feasible operations at tide levels as low as 2 m. Power extraction would be by piston-type air motors, operating off compressed air.

D. Conclusions

The quest for extracting economical energy from the mechanical resource of the ocean continues. Tidal power has already produced useful energy on a limited scale. Wave energy is being vigorously pursued, especially by the United Kingdom and Japan, and to a lesser extent by the United States and other countries. The United States appears to lead in investigating the extraction of energy from ocean currents, but this technology is the least developed of the three.

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