R.H. CHARLIER and J.R. JUSTUS

OCEAN ENERGIES

ENVIRONMENTAL, ECONOMIC AND TECHNOLOGICAL ASPECTS OF ALTERNATIVE POWER SOURCES

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OCEAN ENERGIES
ENVIRONMENTAL, ECONOMIC AND TECHNOLOGICAL ASPECTS OF ALTERNATIVE POWER SOURCES

Roger H. Charlier
University of Brussels (VUB), B-1050 Brussels, Belgium

and

John R. Justus
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This book is dedicated to Dr. Patricia Simonet Charlier,
Professor Emerita, University of Illinois, Chicago,
and to my children Connie and Jac

Roger H. Charlier

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PREFACE

Do dreams come true? Apparently some do. A library floor could be filled with books, articles and reports pertaining to tapping ocean energy. Yet, only one sizeable project has ever been carried through to completion, though past proposals, appropriately updated, occasionally stir again. In some respects considering tidal power as part of the strategy to reduce reliance on petroleum for electricity generation is somewhat like reinventing the wheel. For hundreds of years small tide mills furnished the mechanical power necessary to operate saw- and floor mills, various shops and even breweries. These mills used tidal current and the rise and fall of tides. As they performed some of the tasks carried out elsewhere by wind mills, the French appropriately dubbed them "moulins à marée" and the Lowlanders "getijenmolens". They dotted coastlines and estuaries from Russia to Spain and were eventually brought to the New World.

De Bélidor perceived in the eighteenth century the potential of such tide utilization in electricity generation. Since then tide harnessing literature has frequently appeared in learned journals, though occasionally an ebb sets in. Tide mills lingered on — with a relic still at work here and there — but like the wind mill, they had become obsolete and were rapidly displaced by newer forms of energy generation. The shortage of fossil fuels at the end of the Second World War brought a revival of interest in tidal energy : not mechanical but electrical power was to be generated, and a Severn River barrage was contemplated but never even got to the stage reached by the defunct Passamaquoddy project in the thirties. Dutch coastal wind mills tapped ocean energy and a short-lived attempt at harnessing ocean water temperatures was made in the Ivory Coast (West Africa); test facilities were built, over the last few years, in Hawaii and on some other Pacific Ocean islands. Salt ponds experiments have been conducted in Israel. An attempt at bioconversion on the California coast should also be mentioned.

Nuclear power soon was thought of as the panacea, while cheap and abundant petroleum displaced coal. Wind mills had to be rescued as landmarks and tide mills were completely forgotten.

Supporters of tidal power nevertheless convinced the Electricité de France to build, twenty years later (1956), a plant on the estuary of the River Rance. It not only proved successful, it prompted the development of the so-called bulb turbine now in use at hydropower plants as well. While ebb-and-flood generation in tidal schemes has been considered by some as not worth the additional cost, and even the installation of bulb turbines has been challenged, all existing and planned tidal power plants include them, though Straflo turbines are being considered.

If large size plants are not numerous, the principal reason is economics. The hurdle exists similarly for all schemes to tap the various ocean energies, not just the tides. They require considerable capital investment and the cost of a generated kilowatt is higher than that of one delivered by conventional or nuclear plants. However, new construction methods, improved technology, the rise in price of petroleum and gas, the respective lifespans of thermal, nuclear, tidal and other plants, are rapidly closing the "economic gap". In fact several recent studies claim that tidal power is already cost competitive while Mini-OTEC made a profit in 1981. Furthermore small schemes, a sort of revival of the tide and wind mills perhaps, could make a significant contribution to the power needs of relatively isolated sites or regions.

Strangely, perhaps, while rather few plants have been built, tidal power technology improves steadily and rapidly, and while every effort was made to update the text up to the time of publication, the author foresaw further fast-paced progress in the areas of construction and turbine development.

In such a *Book of Ocean Energies* the chapter on tidal power summarizes the various aspects of tide harnessing and embodies the ideas expressed at 1985 symposia.

While perhaps, in the near future, the contribution of tidal energy to the overall needs in energy may be increased, several other ocean sources of energy could be tapped. For some, for instance waves, literally hundreds of patents for energy extraction have been taken out. For several, actual pilot plants have been built. I mentioned these other sources of energy some fifteen years ago and have been fascinated by the enthusiasm of researchers in these fields and their sustained optimism in the face of detractors and proponents of nuclear alternative.

Georges Claude remained for decades the champion of utilizing the difference of temperatures of surface and deeper waters to produce electricity. He spent his personal fortune trying to convince investors and governments of the soundness of the system but no real attempt to harness this energy was ever made until the ill-fated undertaking of the Société de l'Energie des Mers near Abidjan. But the idea refused to die and with the "energy crisis" interest in what has become to be known as OTEC plants took an upswing. In the chapter covering this topic, my co-author retraces briefly the early proposals, and then covers comprehensively all schemes suggested thus far. As Mini-OTEC has "turned a profit", it was appropriate to examine in some detail the economics of ocean thermal differences harnessing. Another interesting aspect of the problem triggered by the Mini-OTEC experiment, is the use of ocean temperature differences for small local schemes. While emphasis, within the limited support given by the U.S. Department of Energy to "Ocean Energy", has certainly favored OTEC, there are not sufficient funds, nor is encouragement particularly sanguine. The Japanese, on the other hand, are actively pursuing efforts towards OTEC implementation, which, in fact, are ahead of other nations. One may wonder whether Claude's dream will ever come to fruition on a commercial scale, and, yet, the promise of OTEC is considerable. The chapter provides an exhaustive bibliography, the result of constant updating

efforts, on the part of both authors, during the several years it took to complete this book.

British government support whipped up great expectations for the future of ocean waves energy harnessing and I sincerely believed that the subsequent flurry of papers and books heralded an era of experimental plants. I was very distraught when the announcement came in the spring of 1982 that no further funds would be allocated. That some schemes were abandoned as too costly to implement can be understood, but some devices seem to hold practical, viz. economical promise. Will wave energy remain tapped only for clapping of bells, lighting of buoys and some lighthouses, and to discreetly illuminate a bal musette facility on a California pier? Norwegian researchers developed some attractive alternatives to the conventional projects that envision using the pounding of waves or their lifting capacity and a pilot plant was placed into service. And again, the Japanese launched a first, the Kaimei barge, which has provided reasonably priced electrical power to a coastal community.

Harnessing of ocean winds has been proposed both on land and on natural and artificial islands. Here the technology exists, subject to refinement. In Sweden, encouraging results have been booked; on Puerto Rico, the wind turbine implanted on Culebra Island has provided power less expensive than fossil fuel. True, again, some projects are grandiose, even prohibitively expensive, and some others overlook navigation problems. Yet, ocean winds, particularly on islands, and along some coastlines, could add to the power supply. The recent use of ocean winds as suppletive power for ship propulsion opens vistas which may, in turn, lead to onshore developments of marine wind uses.

Geothermal energy tapping has steadily expanded. While there are considerable geothermal resources offshore, all interest is focused on land, and understandably so because of the substantially larger investment that would be required to tap submarine wells. Nearshore wells could perhaps be drilled in the future; the technology is known from land operations, the experience of drilling at sea has since long been acquired from extracting petroleum and natural gas at sea. As an energy source for small communities, land operations remain far more likely than marine undertakings.

I was awed at the magnitude of the Coriolis Project and remain sceptical about the immediate probability of large scale ocean current energy harnessing. Only once, as far as I could ascertain, was an ocean current used to generate electricity, and that northwest Iceland scheme has been abandoned. Perhaps it is more likely to see run-of-the-river type centrals built that would take advantage of the tidal current. Such generating stations might usefully be considered for small communities or particular industrial plants in industrial and less developed countries alike. My co-author discusses the various schemes and the future of ocean current energy use in the light of the most recent developments and we have put together a comprehensive bibliography on the subject which will be published ulteriorly.

Bioconversion retained my interest as it involves both food and energy production aspects. Ocean farms, pilot installations, that is, have been installed; they met

with untimely ends due to weather conditions and navigational accidents, but it was proven that, on a small scale, marine biomass can contribute to the overall energy picture.

Isaacs, Wicks, and others have studied the possibility of using salinity differences to generate electricity. "Osmotic power" had been put to work in some seawater batteries, more than twenty years ago, but the cost of membranes has put a prohibitive price tag on a kilowatt that would be generated from a major plant. Thought has been given to schemes that would dispense with membranes. Differences in salinity have been put to work in some experimental solar ponds projects, particularly in Israel. The potential of "salt water" power is considerable, and it could add significantly to our pool of needed energy, but in this instance technology requires more than refinement and costs of the delivered kilowatt must be drastically cut.

I was tempted to cover in some detail fossil fuels extraction from the ocean, but since these are conventional non-renewable ocean energy sources discussed in hundreds of highly specialized publications, it appeared redundant to mention it here.

Ocean energy harnessing, whether the source is tides, temperatures difference, waves, winds, or any other, has been and remains controversial; in fact, it has been vocally endorsed, and as loudly opposed. With the cost of conventional and nuclear plants rapidly rising, with serious reservations about the safety of the latter and unanswered questions pertaining to wastes disposal, the ocean energy alternative becomes more attractive and more realistic. While ocean energy may not "displace oil" on its own, its contribution to the world's power needs, may ultimately prove to be far from negligible, and a serious economic help to capital-poor, labor-intensive, distant sites in less developed countries.

ROGER H. CHARLIER

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The authors of the papers presented at the International Symposium on "New Perspectives in Tidal Power" (Darthmouth, Nova Scotia, 1982) joined me in making the volume most comprehensive on the latest in tidal power.

The Electricité de France, Sogreah, Lockheed, Kelco, and so many others have enabled me to illustrate adequately the volume, and so have the U.S. Department of Energy, the Tidal Power Corp. of Canada, and Aerovironment, Inc. Their photographs are identified in the text.

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John R. Justus wrote the chapter on ocean currents, took on the lion's share of the OTEC contribution, substantially contributed to the various "bibliographies" and provided all-around advice.

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Chapter 1

STATE OF THE ART

La mer, la mer toujours recommence!
Le Cimetière Marin, Paul Valéry

INTRODUCTION

Ever since increases in petroleum prices, a frantic search for alternative sources of energy has rekindled an interest in ocean-derived energy. Optimistic prognoses about large untapped oil and gas reserves on continental shelf and slope, possibly even on the seabed, have been made. In addition a re-evaluation of non-conventional energy sources has been conducted in many countries, particularly Great Britain, the United States, Japan, France, West Germany, Australia, Korea, India and Argentina.

In many respects we are somewhat re-inventing the wheel, because some of the proposed alternatives were once tapped, but then fell into disuse as fossil fuels, particularly petroleum, took over. In the search for additional energy we have implemented nuclear power. On land we are taking a close look at solar energy, using ponds or thermal water systems, central receiver systems, or gigantic mirrors, proposing photovoltaic schemes or even satellites. We are thinking of changing over to a hydrogen economy, we have experimented with fuel cells and K-fuel; have squeezed oil out of shales and sands; have used domestic trash and waste wood; have tapped copaibas and euphorbias; have turned grain and cane into alcohol fuels. Even the quaint windmill is being resurrected alongside gigantic-bladed wind turbines capable of generating as much as 60 kW of power.

This chapter will review briefly the state of the art in ocean-derived and related energy sources.

TIDAL ENERGY

Tidal energy was harnessed hundreds of years ago when tide mills dotted coastlines in England, Wales, Brittany, the Lowlands, Spain, Russia, and even the Atlantic coasts of Canada and the United States. Both the vertical rise and fall of the tides, and the ebb and flood of the tidal currents can be put to work. To tap the

tide itself requires a dam across a tidal embayment, basin, or estuary; the water rise and/or fall will drive a generator. Although geographically limited by the magnitude of tidal ranges, progress in the development of low-head turbines and the possibility of using removable plastic barriers instead of dams, may reduce considerably the currently prescribed minimum ranges. Plants have been constructed and are operating in France, the former Soviet Union, and China; plans for implementation of schemes in Korea and Canada could move beyond the planning stages quite soon. An optimistic worldwide potential of 3 million MWe is usually quoted; high capital costs are usually cited as a deterrent, but the continued increases in oil prices and the steady increases in construction costs of conventional and nuclear plants are rapidly closing the "cost" gap.

An alternative to using the tide itself is the utilisation of the flow of the tidal current: diverting a part of that flow into a channel where it turns a wheel.

The number of sites suitable for tidal power plants is limited by several factors. The long dam needed to close off an embayment is expensive to build. A head of less than 5 m (16 ft) is insufficient, unless the new low-head turbines prove successful. A site too distant from its potential market may be undesirable, unless further progress is made on long-distance transmission cables or thought is given to production of a transportable "fuel".

The Rance River and Kislaya plants use bulb turbines — an axial flow turbine of the Kaplan type that is placed in a horizontal hydraulic duct and completely

Fig. 1.1. Seaward view of Rance tidal power station with city and harbor of St. Malo in background.

submerged. Such turbines have been installed in the Rock Island dam on the Columbia River as well. These bulb turbines can function both as a turbine and as a pump; however, recent studies are challenging the economic advantages of bulb turbines and newer plans call for the installation of Straflow turbines (Fig. 1.1).

Environmentally, tidal power plants have had little impact. At the Rance River installation, for instance, except for the relocation of some sand banks and the disappearance of some fish species, which were replaced by other fish species, no impact has been observed after more than 10 years of operation. Currently under construction or active consideration are an 18-MW station in Canada and a 12-MW facility in Maine.

WAVE ENERGY

Wave energy has been tapped for a long time; it has been used to activate buoys, to clap bells aboard ships, to light a pier in California, and to provide electrical power to a Japanese community. Such wave energy can be "captured" in many ways: there are turbines that are activated by waves, or by air columns, while relative-motion devices may also provide power. In 1979 the *Lockheed Corporation* unveiled its dam-atoll, a prototype of which is currently being built; in this system a vortex of spiraling water acts as a flywheel, as the water of the wave spills into the core of a submerged turbine. The structure, capable of producing 1–2 MW, has an 80-m (263 ft) diameter. In the air column system, the water as it rises and falls in a piston-like chamber, drives a generator. Various designs have been developed in many countries. In Norway, for instance, a program focuses on resonant heaving bodies as point absorbers, in Great Britain structures are beam oriented, and in Japan the wave's energy is coupled into a tuned cavity of pressurized air. While as much as 50% of the wave's energy can theoretically be retrieved, only between 5 kW/m to 4 MW/total can be generated (Fig. 1.2).

Floating plants function on the principle that wave motion can be converted into reciprocal motion with vertical floating plates creating a liquid pumping action. The potential is considerable, and the U.K. Central Electricity Generating Board estimated that all of Britain's energy needs could be satisfied by putting wave energy to work. The power potential, per kilometer of beach, of an average wave is usually given as 40 MW. Implementation is thought to be possible by the turn of the century.

All wave-harnessing schemes are expensive to build; all are subject to potential heavy damage and some to being wrecked in case of exceptionally severe storms. Dam-atoll and air column types have mooring problems and are expensive structures; floating plants are also expensive to install. Corrosion constitutes an additional problem, although lessons learned with the French tidal power plant may be put to very good use here. Earlier casts estimates had put a price of $ 2000–3000 per kW of wave-generated electricity [1], but more recent estimates have put the cost at $ 8000–18,000 per kW.

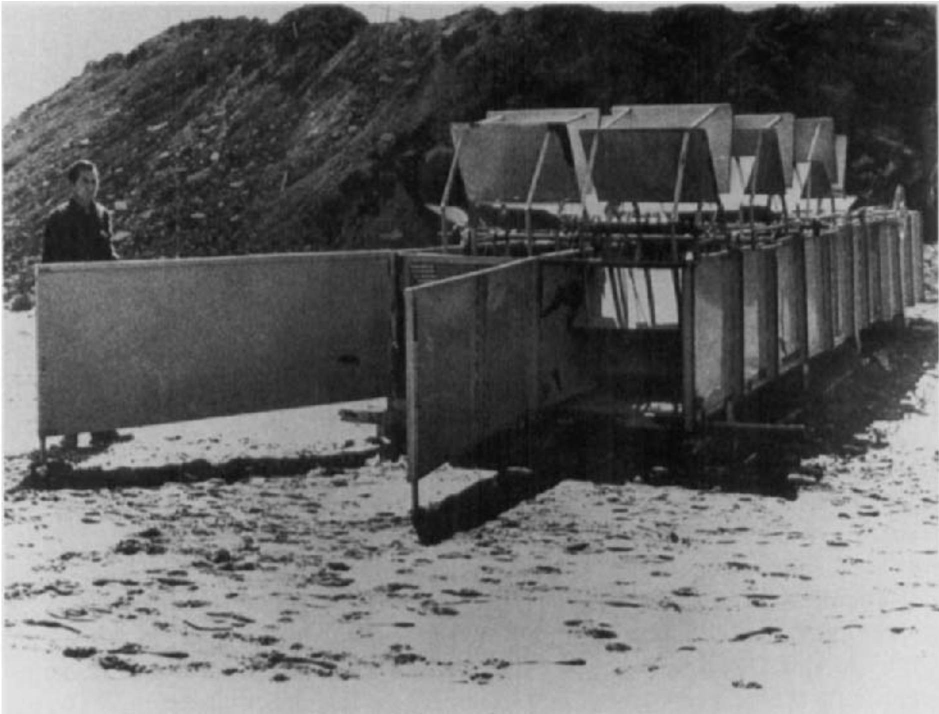


Fig. 1.2. Wave energy absorption machine on California beach.

The major systems currently being refined in addition to Lockheed's dam-atoll include Salter's nodding duck, Cockerell's raft, Masuda's oscillating column, Hydraulic's rectifier, and Isaacs' tail tube buoy. Professor Salters' nodding duck consists of a string of cone-shaped vanes all connected to a single chord or backbone. A rotary pump is driven by the wave-induced bobbing, and powers a generator. Sir Cockerell's contouring raft is made up of three hinged pontoons, which follow the wave's contours. The first pontoon moves freely with each wave and absorbs its initial impact. Consequently, the second pontoon moves less, and the third one is relatively stable. The up and down motion of the three pontoons causes hydraulic jacks, secured on each hinge, to drive fluid into a motor which turns a generator.

Commander Masuda's scheme involves a hollow concrete cylinder with pipes in the top and an air bubble above the waterline. Air is sucked into the pipes or forced out of them as waves fall and rise, thereby driving a turbine. The *Hydraulic Research Station* designed a passive system placed on the seabed: water is led through a channel from a high-level to a low-level reservoir, thereby driving a turbine. Finally, the Isaacs' tail tube buoy is a float with a tail tube about 100–170 m (328–558 ft) long. Successive waves raise the level inside the tube, thereby building up pressure that drives a turbine.

THERMAL ENERGY

Although most ocean energy may be considered as solar energy, the most direct harnessing of ocean solar power is probably through a thalassothermal plant: it has been referred to for some time by the acronym *OTEC*, Ocean Thermal Energy Conversion (Fig. 1.3).

The basic principle is that in some areas of the world deep cold ocean water ascends to relatively shallow depths, while in these same areas the surface waters are quite warm from collected solar heat. OTEC uses this temperature difference to power a turbine and generate electricity. This system has the potential of satisfying

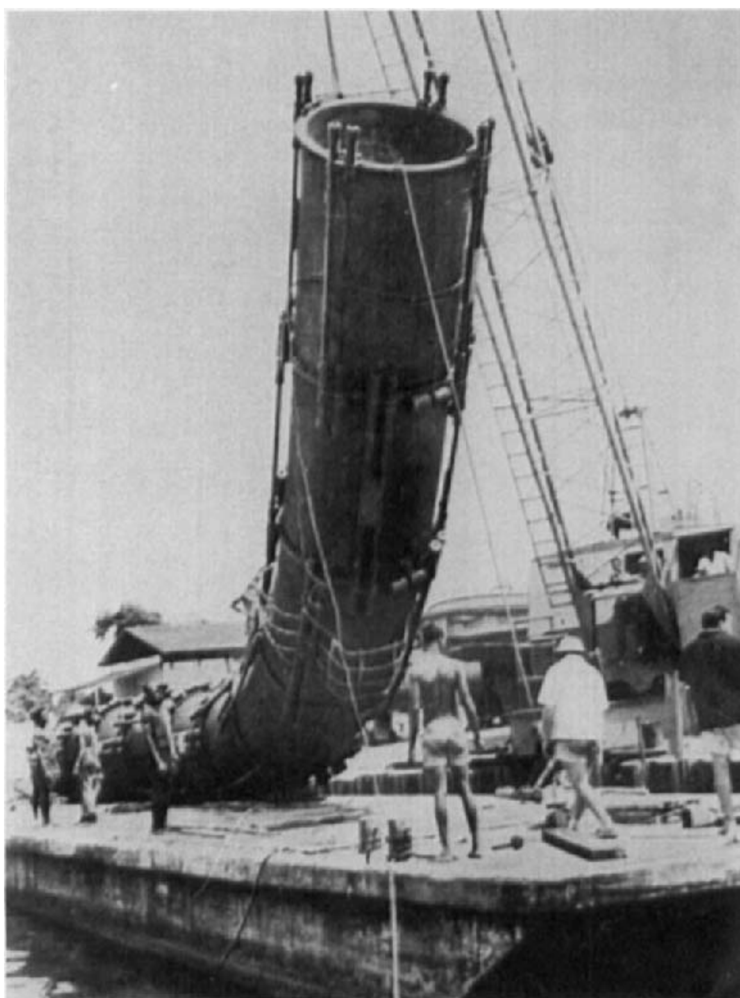
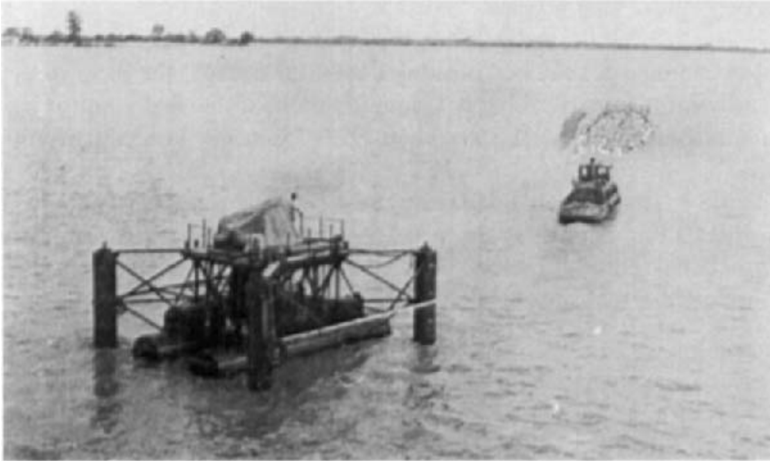


Fig. 1.3. Flexible joint (tube), Abidjan, 1955. Photography "Energie des Mers".



Figs. 1.4. Convoy of floats, 5th December 1955, Abidjan. Photograph "Energie des Mers".

Fig. 1.5. Convoy of floats, 5th December 1955, Abidjan. Photograph "Energie des Mers".

a major share of the U.S. energy needs. The technology exists, and successful experiments were conducted as early as 1928. (Figs. 1.4, 1.5).

A plant was even built in the early 1950s in Abidjan, Ivory Coast, but was eventually abandoned because it could not be operated as economically as conventional power plants and because of repeated failures of the cold water adduction conduit that reached to a 400 m (1312 ft) depth.

Technologies exist for both open-cycle and closed-cycle plants. The open-cycle scheme which is based on the ideas of Arsène d'Arsonval and which was imple-

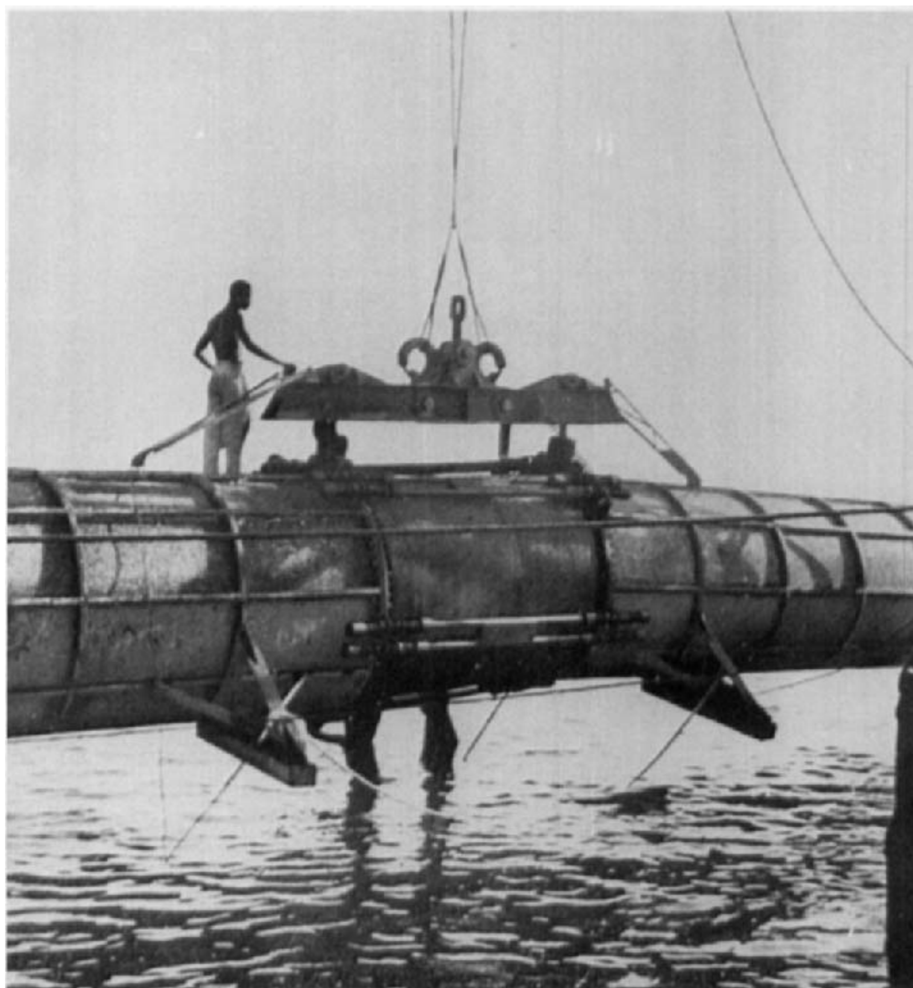


Fig. 1.6. Transportation of a flexible joint (tube), Abidjan. Photo "Energie des Mers".

mented in Belgium, Cuba, and the Ivory Coast, uses low-pressure steam as the working fluid. It has mostly been superseded by the closed-cycle system, in which warm surface vaporizes an intermediate fuel, such as ammonia, propane or Freon; the vapors power a turbine and are subsequently condensed back to liquid by the deep cool waters. The working fluid is then recirculated (Figs. 1.6–1.8).

The basic design includes a floating platform or hull, evaporator, turbogenerator, and condenser, and a 400–1,000 m (1312–2381 ft) long large-diameter cold-water adduction pipe. The Japanese plant currently being used is a barge plant, but some designs include instead a spar-shaped platform. A mini-OTEC plant was launched in 1980 and has performed well. The Lockheed-built facility generates 50 kW