W A V E   A N D   T I D A L   P O W E R   R E V I E W

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DECLARATION BY CANDIDATE

I, Nicolaas Johannes Kok, hereby declare that this thesis is my own work and that it has not been submitted for a degree of another university.

Signed by candidate

SEPTEMBER, 1978

SYNOPSIS

A review of the technology of useful conversion of wave power and tidal power is presented. These two power resources are reviewed separately, but on the same basis : principles of operation, existing devices or plants and research and development.

Promising wave power devices in Britain, the United States and Europe are discussed. If wave power is to be competitive, one of the first requirements may be energy densification. Proposed energy densification schemes include resonance, high pressure water and wave focussing.

Wave focussing is a Norwegian invention, technically feasible, and although more research and development is required, it appears to be more promising than alternative forms of wave power utilisation. According to a preliminary cost analysis, it could be competitive with conventional hydro-electric power.

The large scale exploitation of tidal power has been considered seriously for about half a century; the literature on the topic is voluminous. The main limitations of tidal power are its intermittent nature and the high costs involved in the construction of a plant.

The existing pilot plants at the Rance and Kislaya Guba have respectively proved that tidal power is technically feasible and that construction costs could be reduced. With the rapid increase in the price of fossil fuels, tidal power plants may be realised at the two best sites in the world, the Bay of Fundy and the Severn Estuary.

CONTENTS

INTRODUCTION

Wave power and tidal power are free, everlasting and non-polluting assets.

Waves occur on the sea everywhere, all the time. Wind energy which is interchanged through wide surface areas of the oceans is stored in sea waves as a mechanical oscillation. Compared to tidal energy, sea waves consist of short period oscillations. Also, the utilisation of wave energy need not involve very large natural storage basins, as is the case with the exploitation of tidal energy.

Ocean waves represent a large energy resource. For many years this energy potential has been neglected, but the rising price of fossil fuels, has stimulated interest in the large scale conversion of wave power.

The tide is a resonance phenomenon and appears to be one of nature's most powerful manifestations. Tidal ranges are only of the order of decimetres at certain parts of the world, but as much as 16 metres at one particular area.

Tidal power is controlled by the lunar cycle, while the energy requirements of the community is determined by the solar cycle. The tides offer an abundance of energy, yet remain virtually unharnessed.

In this review, wave power and tidal power are discussed in two separate sections. The review embraces the consideration and discussion of operating principles, existing devices or plants and the development of proposed devices and schemes.

"Living off the land can be compared to a man living off his capital; living off the sea can be compared to a man living off his dividends".

PART ONE

WAVE POWER

CHAPTER 1 - FROM MARINE PROPULSION SCHEMES TO THE 1970's : BRIEF REVIEW

INTRODUCTION

Waves are known for the damage they cause to coastal structures, and are often considered a hindrance. However, the fact that wave power is available on a large scale, in most parts of the world, makes it a valuable energy resource; particularly because it is at its most powerful during the winter, when energy demand is highest and solar energy is at its lowest level.

The power potential of the ocean waves is enormous. Excluding the arctic regions, the coastlines of the five continents amount to 100 000 km. Based on an average nett electric power of 10 kW per metre coastline, Ambli et al (Ref. 1) estimated the total wave power that could be produced as a million MW; this is of the same order as the world's electric energy production in 1973. Panicker (Ref. 2) included the ocean areas as well, and estimated the total potential wave power in the oceans of the world as 90 000 million MW, in October 1975.

Unfortunately, the power of the waves have not been utilised to a large extent. Nevertheless, Salter (Ref. 3) reported that about a hundred proposals for harnessing wave energy had been patented. Panicker (Ref. 2) classified the various devices for harnessing wave energy into the following four groups : "propulsion schemes, buoy power supply devices, offshore power plants and shore-based power stations". The first schemes for extracting wave energy were marine propulsion devices.

MARINE PROPULSION SCHEMES

One of the first propulsion schemes were developed by Herman Linden in Naples, Italy, in 1898. The conversion of wave power to propulsive thrust, to move a boat, was attained through flexible fins, mounted as inclined planes to the horizontal at the bow and stern (Fig. 1.1).

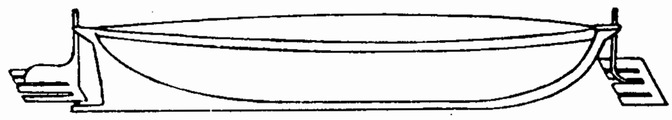


Fig. 1.1. Linden's AUTONAUT with inclined planes for Wave Propulsion (Ref. 2).

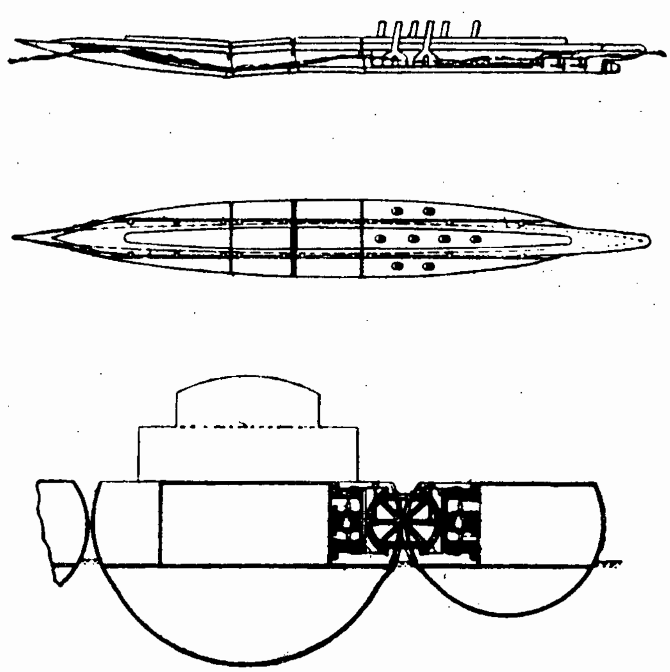


Fig. 1.2. Graham's Automatically Propelled Multiple Hull Vessel (Ref. 2).

Linden's first boat, Autonaut, was 4 metres long. The mounted fins were 500 mm long by 250 mm wide, and they tapered from 200 mm thickness at the front, to 0,03 mm at the back. It has been reported (Ref. 2) that the boat's pitching motion was sufficient to set the fins in motion, resulting in a propulsive forward thrust. Free running speeds up to 1,5 metres per second was obtained by the Autonaut, against wind and sea. Boats of up to 7,5 metres were built by Linden, obtaining speeds of 2 metres per second.

An ambitious scheme was patented by James Graham of New York City in 1902. His multiple-hull vessel has longitudinal and transverse joints. The four longitudinal hull sections were hinged together, permitting undulation with bow-on waves. In the transverse direction, the main hull section was mounted between buoyant pontoons, to which it was hinged; therefore, it was possible to provide a relative movement with transverse waves as well (Fig. 1.2).

The undulations produced in Graham's vessel were converted to power by a series of mechanical components. Rows of pistons, secured by ball joints to one section, moved in cylinders mounted to the adjoining hull sections; this was the case at both deck and bottom levels. The cylinders contained hydraulic oil. The hull's undulatory pitching motion was transferred by the hydraulic pumping action, in the cylinders, to a chain system and from there the power was fed to hydraulic motors. The latter was coupled to the seven propellors which moved the ship.

Another variation of the above marine propulsion schemes was patented by Kalfas of New Hampshire in 1936. A paddle was hinged to the stern of a boat at deck level. The paddle moved up and down relative to the boat, when the latter pitched in a sea wave. This oscillatory motion was converted into a continuous rotary motion by means of a system of gear trains (Fig. 1.3). The rotary motion was utilised to drive a screw propeller.

Isaacs and Schick (Ref. 4) proposed a method whereby flaps fixed to the underside of a craft use the sea water's orbital motion for propulsion (Fig. 1.4). The principle behind their "wave rectifier" is very simple : as a wave travels along, the water particles rotate; similar to a fixed point on a wheel which is rolled forward. The flaps under the craft open as the water particles at the wave crests travel forward. The force of water particles at the wave troughs shut the flaps, thereby evading most

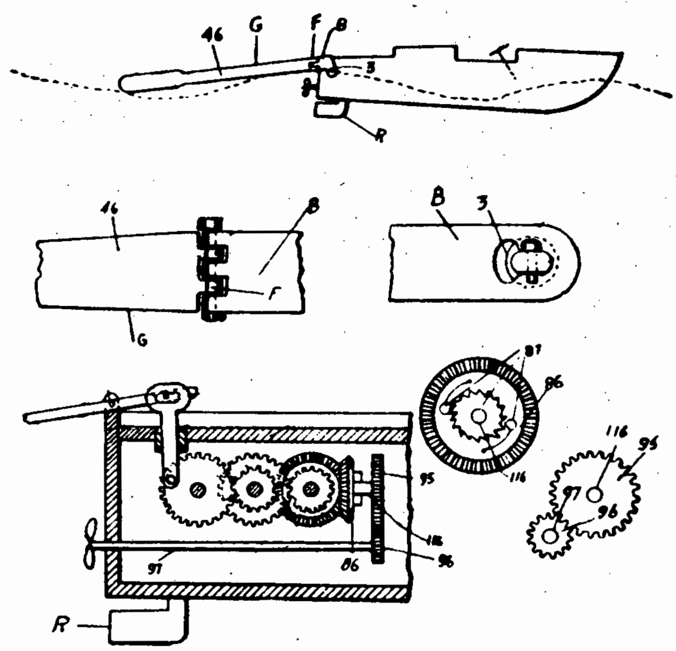
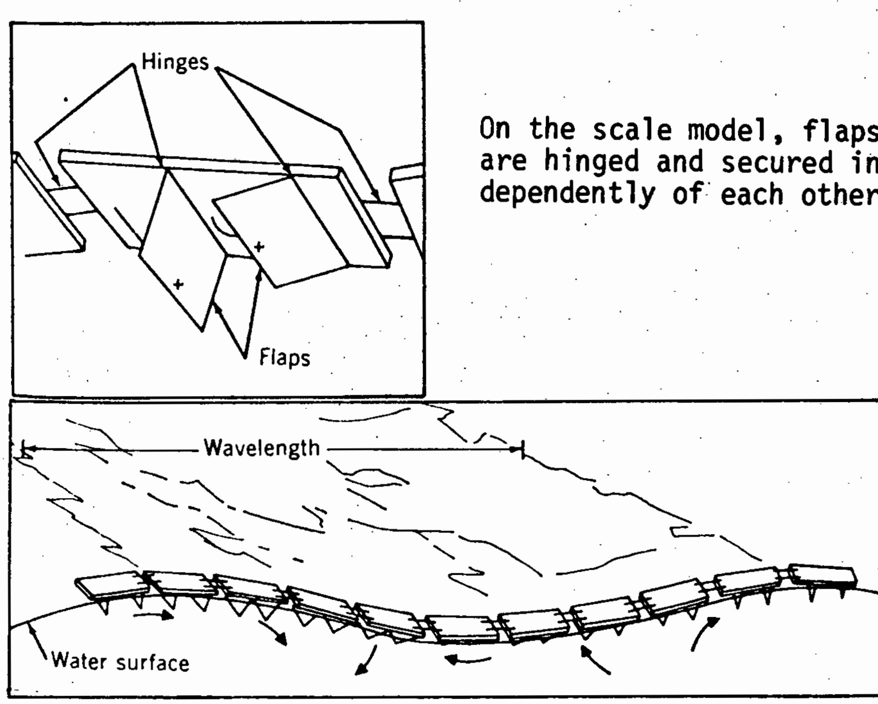


Fig. 1.3. Wave-Propelled Boat of Kalfas with hinged paddles (Ref. 2).



On the scale model, flaps are hinged and secured independently of each other.

Fig. 1.4. Corresponding arrows indicate how water-particle velocities propel barge model in the direction of the wave (to the right). To propel the model in the opposite direction, the flaps instead are constrained to swing to the right (Ref. 4).

of the opposing energy. Due to the forward thrust of waves, the wave rectifier would travel faster with waves than against them. On a 1/12th scale model, 1,7 m long and 100 mm wide, an efficiency of about 60% was achieved, i.e. "a speed of about 60% the orbital velocity of a wave" (Ref. 4).

Although extremely interesting in nature, propulsion schemes have not contributed much towards the tapping of wave energy. As far as the supply of energy to industry and the community is concerned, propulsion schemes are irrelevant!

WAVE POWERED BUOYS

A pneumatic type of wave energy conversion buoy was invented in the early 1960's by Y. Masuda of Japan (Ref. 5). These buoys have been used at sea by the Japanese Maritime Safety Agency since 1965. In 1974 Masuda reported that 300 units were in service (Ref. 6).

The operation of buoys are based on utilising the vertical rise and fall of successive waves : the up and down motion activates a water or an air operated turbine.

The Japanese buoys fall into two classes of generators : the one is used for light buoys and the other for fixed structures such as observation towers and lighthouses – but both based on the same principle of operation.

Experiments and model testing by Masuda on various types of buoys date back to 1947 (Ref. 6). Although the output of the Masuda buoys, and other proposals, is of the order of kilowatts, intensive research work in this field is under way to extract wave energy to a much larger extent. Wave powered buoys are discussed in more detail in the next chapter.

OFFSHORE POWER PLANTS

A large number of different offshore wave power systems have been proposed since the 1950's, particularly during the last decade.

According to Panicker (Ref. 2), Valembois (in 1956) discussed the possibility of extracting wave energy by means of resonators. A simple example of this idea is an open vertical pipe immersed in water and excited at its natural frequency by waves; this resonant effect results in the water level in the tube rising to higher values every cycle. Wave power amplication, as a result of resonance, have been accomplished by well-tuned buoys; thus the maximum power was generated.

A stationary pneumatic wave energy converter has been proposed by McCormick (Ref. 5). He claims that this device would overcome the low efficiency of wave buoys in long waves. The probable power of a 6 m diameter unit in 1 metre waves, was estimated as 25 kW.

At the end of 1973 Salter (Ref. 7) proposed a specially contoured rocking device. Results indicated that as much as 80% efficiency could be obtained. In 1974 the British Government discussed the possibility that wave power could be an economic source of energy for the country. Subsequently it was decided to allocate large sums of money for wave power research.

In 1972 Sir Christopher Cockerell, inventor of the hovercraft, became interested in wave energy (Ref. 8). Early in 1974 the Wavepower Limited was formed to develop the "contouring raft" device.

The Russell rectifier, based on hydraulic principles, was proposed by the director of the Hydraulics Research Station at Wallingford, Robert Russell (Ref. 9).

The three British devices are generally considered as very promising and are discussed in more detail in the next chapter.

SHORE-BASED POWER STATIONS

In 1956 Dhaille discussed the technique and profitability of amplifying waves by means of converging wave channels (Ref. 2). He began experimental work in 1944 and found that up to 50% efficiency could be achieved.

The proposed scheme consists of a series of converging channels which opened offshore, leading the water to a storage basin. From the basin power is generated by conventional hydraulic turbines.

Charlier (Ref. 10) stated that "converging wave channels, seem to provide the highest output of any scheme proposed to recover wave energy". However, Dhaille's scheme was considered economically uninviting at the time due to the relatively low cost of alternative energy sources. Wave focussing, by means of refraction and converging wave channels, are discussed in greater depth in Chapter 4.

CHAPTER 2 - FOUR PROMISING WAVE POWER DEVICES FOR BRITAIN

INTRODUCTION

The countries seriously involved with the practical consideration of wave power, are Britain, Japan, Norway and the United States. It appears as if Britain has taken the lead in wave power research (Refs. 9, 11 and 12). Since its first decision in 1974, the British Government has recently set aside a further 2,9 million * pounds, for wave power research and development. The country's expenditure on wave power now stands at 5,4 million pounds (Ref. 13).

It has been estimated that a dozen wave power stations, each 80 km long, along Britain's coastline could provide half of the country's present energy needs (Ref. 9). Analysis of wave data indicates that the amount of available wave power varies between 40 and 70 kW per metre wave frontage around the British coasts. Most of the energy is offered off the coast of north-western Scotland (Ref. 11).

The British research programme, controlled by a Harwell team, involves a feasibility study of four devices : the Salter duck, contouring rafts, the oscillating water column, and the Russell rectifier. The oscillating water column is a Japanese concept; all the others are British designs.

The four devices are generally regarded as promising, and are discussed in more depth below.

OSCILLATING WATER COLUMN (MASUDA'S CONCEPT)

Wave powered buoys, operating on the oscillating water column concept, have been in use in many parts of the world for more than a decade. As this device is the only existing one of the four proposed systems above, it is discussed first.

* 1 pound = ± R1,70

Masuda's existing buoys :

The original Masuda device, was a "wave-actuated pendulum generating buoy" (Ref. 2). The rolling action of the buoy in waves was utilised. The roll was accentuated by fixing objects of large and small inertia respectively on either side of the buoy; the submersed weight of the two objects were the same. The generator was driven by a large gear, within the buoy, coupled to a small gear; the power output was only about 3 watts. It was found that the large roll the buoy made was a shortcoming, and a different system was developed. The new system's principle was similar to that of the whistle buoy.

The whistle buoy has a pipe through its centre. As the buoy makes an up and down motion in waves, the water level in the pipe changes, resulting in the compression of the air above the water surface within the pipe. The compressed air then sounds a whistle. In the wave-activated turbine generators (WATG) the whistle is replaced by an air turbine, coupled to an electric generator. When the buoy and the water in the pipe are in resonance with the waves, the maximum power is generated (Ref. 2). According to Richards (Ref. 6), the output of Masuda's fairway and weather buoys is 70 W. These units, with spare parts, were priced at 1 200 US * dollars each in 1971.

A 120 W WATG was installed in a lighthouse, on an island, at the entrance of Tokio Bay, in 1967. A larger wave-activated generator, of 500 W, was demonstrated in 1970 and plans for a kilowatt unit have been reported (Ref. 6).

Evaluation of Masuda's buoy :

Richards (Ref. 6) reported on tests done on a commercial Japanese WATG, installed in a buoy, by Colburn and Motherway periodically for about a year. The resonant frequency of the buoy in water was found to be 2,6 seconds. The water in the WATG centre-tube had a resonant frequency of 4,7 seconds. Poor correlation between power generation and wave heights was also reported. Colburn and Motherway noticed biofouling inside the centre tube. Although no salt build-up was noted on the turbine blades during the overall testing period, they mentioned that this had been a problem in the Japanese WATG units in use over a long period of time.

* 1 US dollar = ± R0,80; in 1971

McCormick (Refs. 2, 5 and 6) theoretically analysed the power output of the Masuda buoys. His theoretical results compared favourably, both in magnitude and nature, with Masuda's experimental and prototype data. McCormick (Ref. 2), showed that generating power was not a maximum at the natural heaving period (see above), but at the resonant period of the buoy and water column system! McCormick further reported that the optimum configuration of the Masuda buoy was one with a "large buoy mass and a wide and short centre pipe" (Ref. 2).

McCormick et al (Refs. 5 and 14) reported that a theoretical analysis of a stationary pneumatic wave energy converter showed that the power converted by the device, is proportional to the cube of the wave height. Their work is discussed in more detail in Chapter 3.

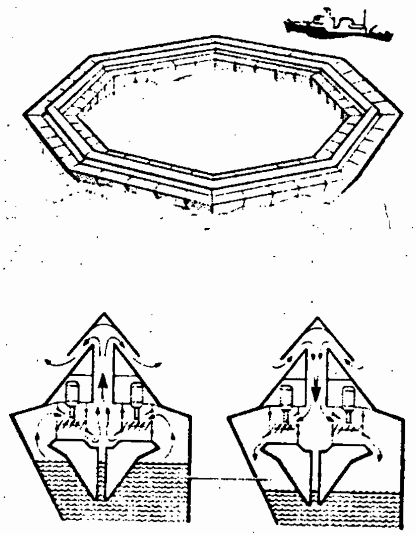
Further proposals by Masuda :

Masuda proposed a floating, octahedral-shaped ring buoy, about 120 m long, to utilise waves off the coast of Japan (Refs. 6 and 12). The ring buoy is illustrated in Fig. 2.1.

According to Richards (Ref. 6), experimental work and model tests which led to this design, began in the 1940's. The dimensions of the buoy are as follows : 120 m outside diameter, 70 m inside diameter, 25 m wide and 4 m deep. The nett weight is estimated to be between 1 500 and 3 000 metric tonnes. The ring buoy is to contain about 20 000 tons of water. The oscillation period of the buoy should be approximately 50 seconds, according to Masuda (Ref. 6).

The principle of operation of the ring buoy is similar to that of the WATG buoys. A "pump room", of 4 000 m^2 area, will be open at the bottom : in cross section the buoy resembles an inverted can. The up and down action of the waves compresses the air above the water surface, inside the buoy. The compressed air operates a turbine, which drives a generator. In high seas the electrical output is estimated between 3 and 6 MW.

It is planned (Ref. 6) to construct the components for the ring buoy in a shipyard, with the assembly undertaken at sea; no problems are envisaged with the component construction. The total construction costs are estimated to be two million US dollars. The Japanese estimate the cost of



The air pressure ring buoy: wave action forces air through orifices in an inverted box. The air operates flaps used for converting energy to a more convenient form

Fig. 2.1 Masuda ring buoy (Ref. 12)

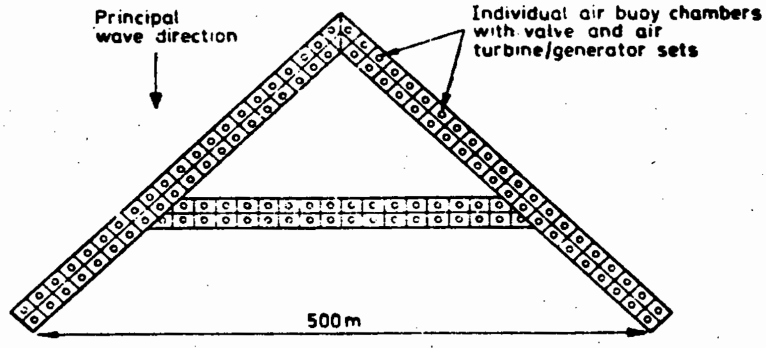


Fig. 2.2 Plan view of a multi-chamber Masuda buoy (Ref. 15)

electricity generation to be approximately 2 cents per kWh, which is 8% less than present methods of production (Refs. 6 and 12).

According to Richards (Ref. 6), Masuda also developed a model of a triangular-shaped, three-legged platform type WATG system. The model was tank-tested, and a feasibility study on a 100 kW unit estimated the cost of electricity generated at about 20 cents per kWh. A prototype of the system is illustrated in Fig. 2.2.

British research :

Very little has been reported on the research and development done in Britain on the oscillating water column concept.

The research programme, regarding the four "promising" devices, embraces a study of the energy transfer of each system as well as problems common to all systems; these include analysis of wave data, wave loading effects on the structures, anchoring and mooring problems and power generation and transmission (Ref. 12). All the devices will also be subjected to tank testing, using models at 1/100th scale.

Some of the advantages of the Masuda "can" is that it can absorb energy from the rear as well as the front, and that it only needs to rotate in one direction against a load. For two of the other three devices under investigation in Britain, a reciprocating motion must be considered (Ref. 15).

THE SALTER "DUCK"

The Salter Duck has had more publicity in Britain than the other proposed systems. This is possibly due to the fact that until Salter proposed his rocking wave power device at the end of 1973, very little was done on wave power in Britain (Ref. 7).

The high efficiencies of over 80%, with respect to energy conversion, obtained at the early stages with the Salter vane, apparently convinced the energy authorities that further detailed investigation into tapping the energy of the ocean waves was justified. During 1974 the University of Edinburgh, where Salter developed his duck, was the first body to receive a government grant (65 000 pounds) for further research (Ref. 9).

In preliminary work, Salter collected data of scatter diagrams to determine significant wave heights, particularly in the North Atlantic. With the help of oceanographers and using well known power formulae, the average power over a whole year was found to be 77 kW per metre of wave frontage. Most of this energy was due to waves having periods from 9 to 12 seconds (Refs. 3 and 7).

Formulating the design problem :

Salter's basic problem was to find a mechanism which would be able to convert dispersed, random, alternating forces (such as waves) into direct force. Such a mechanism had to be robust enough to withstand the worst conditions.

Further, although anchored, the mechanism had to float freely at sea, without rigid connections to the sea bed. Regions of stress had to be avoided, and the extraction of power had to be as smooth as possible.

The use of moving parts in the mechanism was unavoidable. Salter decided on rotating elements, with the mating surfaces protected from the sea. As it would be difficult to "accumulate" the generated power from a number of small units moving independently, it was planned to have a common framework for them.

Salter arrived at the conclusion that the conventional bobbing up and down devices, tradionally considered, are less efficient than mechanisms utilising the to and fro movement (Refs. 3 and 16). He performed tests with a simple vertical vane, pivoted about a horizontal axis, and found an energy conversion efficiency of about 40%; about 25% of the available energy was transmitted further, while roughly 20% was reflected back to the source. It was evident that a more efficient device would be one which "did not displace water astern" and was such that "the amount of water displaced at any depth corresponded to the amplitudes of water movements at that depth" (Ref. 3).

The Salter design :

Salter proposed a specially contoured rocking device to extract wave power. The Salter cam is illustrated in Fig. 2.3.

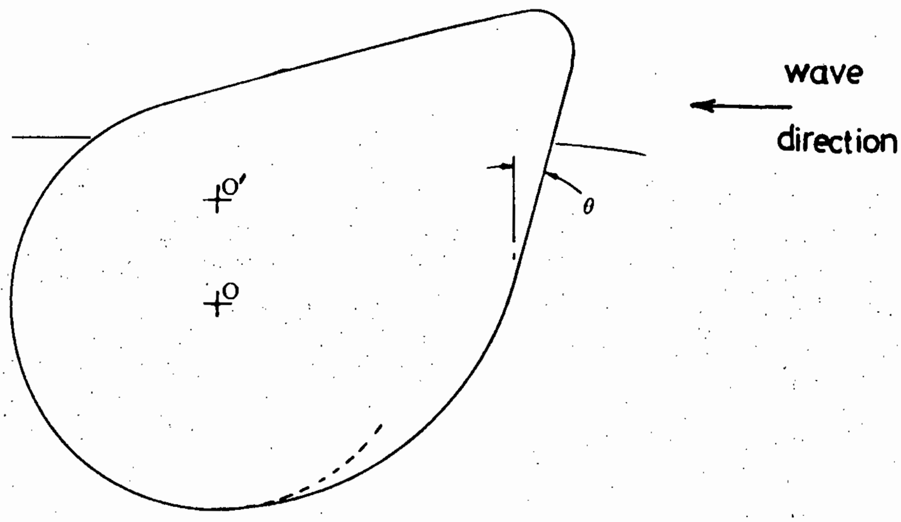


Fig. 2.3 The Salter Cam (Ref. 3)

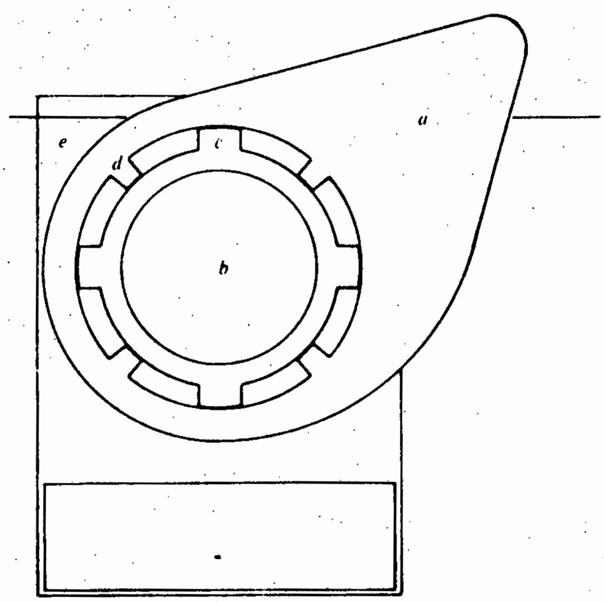


Fig. 2.4 A vertical section through vane and spline pump. *a*, vane; *b*, a hollow cylindrical member; *c*, paraxial ridges; *d*, inward facing ridges on the vane; *e*, vertical fin between this vane and the next. (Ref. 3)

The vane rotates about centre 0 and is directed to oncoming waves from the right. The stern of the vane is a half cylinder with centre at 0. From the bottom point (see intersection of dotted and solid lines), the shape grows into a surface, which is another cylinder, with centre at 0'. The shape continues until it makes an angle θ, to the vertical. From this point it is tangential to the latter circular arc and is continued above the surface of the sea.

In Salter's first model the point 0' was one half radius above centre 0, and angle θ was 15^{o}. The energy conversion efficiency obtained with wavelengths of about eight times the diameter of the model, was over 80%.

When the vane moves, the water behind it is not displaced. In front of the vane, the displacement rises from zero at the base to close to that of an oncoming wave. Salter was therefore satisfied that the shape met the design requirements. The motion of the vane is best described as 'nodding' – by nodding about its axis the duck will hopefully produce useful work!

According to Salter (Ref. 3), the random rotations of a vane will, in full scale equipment at sea, produce unidirectional pulses of water flow through a special pump (Fig. 2.4) : the vane rotates about a horizontal cylinder along which splines incorporating non-return valves are located; the relative motion between the vane and the cylinder causes pulses of water to be pumped through the valves, and along the inside of the cylinder splines. The pumped water is directed to a water turbine, which drives a generator.

A common backbone for a number of vanes is to be provided by the cylindrical member. Salter is of the opinion that a stable reference, against which waves act, can be supplied by a structure of vanes 0,5 to 1 km long. A short structure would develop little force between the vanes and the cylindrical backbone, due to its pitching and heaving action; an increase in length would make the structure more steady. The structure is stabilised by a ballast weight of concrete. A drawback to using great lengths is the development of stress.

Tests on the Salter duck :

In two-dimensional tank tests and using plane monochromatic waves, Salter registered an energy extraction of 90%, of the incident energy (Ref. 15).

For laboratory tests, the duck was coupled to a dynamometer, originally made of two moving coils in a magnetic field, which allowed it to do work.

Towards the end of 1974, the Central Electricity Generating Board (CEGB) conducted tests in Edinburgh with one of the early Salter models : a vane 10 cm in diameter and 30 cm wide, and damped by an electronically controlled load. These tests also indicated a peak extraction efficiency of approximately 90%; but the efficiency dropped fairly rapidly at frequencies on either side of the peak value. If scaled to the Atlantic, this duck would have to be about 40 m in diameter; according to Glendining and Count (Ref.15), this diameter could be reduced by increasing the system inertia.

Tests performed with two 2,4 m long by 0,5 m wide ducks, in the National Physical Laboratory wave tank during 1975 produced interesting results. Scaled to the Atlantic, it was found that a duck of 18 m diameter would have a peak "sea" efficiency of about 45%; only plane waves were used. However, Salter obtained higher "sea" efficiencies, around 67%, with broader bandwidths of wave periods. Experiments done by Swift-hook et al (Ref.17) showed that good power conversion efficiencies, of more than 50%, can be obtained over a 2 : 1 bandwidth of wave periods, i.e. 14 to 7 seconds, which is the range of wave periods found in the ocean waves of the Atlantic.

Trials on 1 m diameter Salter ducks were undertaken on Loch Ness in July 1977 (Ref. 18). The object with these tests, on the 1/15 scale model, was to yield more realistic evaluations under sea-like conditions.

<u>Details of Salter duck at sea</u> :

It is envisaged that prototype Salter ducks will eventually form free-floating concrete and steel breakwater structures, each about 1 km long and submerged to a depth of 10 to 20 m. Each structure would contain 20 to 40 vanes, and is estimated to generate 50 MW (Ref. 6).

The area 10 km west of the Hebrides is considered a promising location for the first installation. According to Salter (Ref. 3), the installations could be self propelled. He also pointed out that the storage of wave power will be necessary as "wave power comes at times not necessarily convenient to the user". However, the electrolytic production of hydrogen from sea water looks promising as a means of 'storing wave energy'.

According to the Central Policy Review Staff (Refs. 15 and 19), the cost of the Salter system may be of the order of 420 pounds per kW; the electricity thus generated would be about 2,5 times more expensive than the generating cost by nuclear fission.

WAVE CONTOURING RAFTS

The wave contouring rafts are a brainchild of Sir Christopher Cockerell. Wavepower Limited, established in 1974, aims to develop a wavepower device which is simple, cheap and made up of relatively small mass-produced units, installed in sections.

Investigations led to a chain of floats, which are hinged together, and are known as wave contouring rafts or Cockerell pontoons.

Principle of operation and tank testing :

The wave contouring raft design (Fig. 2.5) consists of a series of hinged rafts with hydraulic motors/pumps between each raft. As waves travel down the chain of floats, the pumps on the hinges absorb power from the relative rotation of adjacent floats (Refs. 6, 8 and 12).

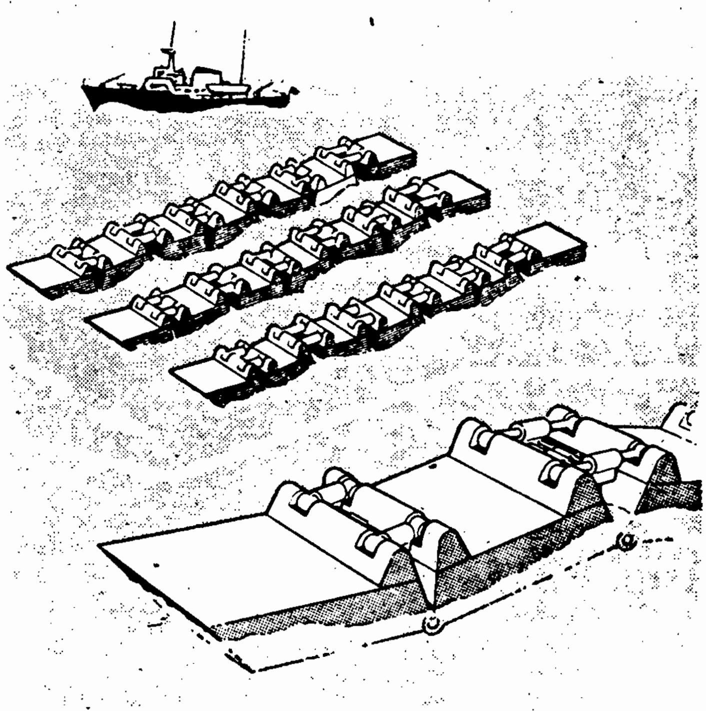


Fig. 2.5 **Contouring rafts** (Ref. 9)

Tank testing on various simple float systems has been conducted by British Hovercraft Corporation, for Wavepower Limited. These tests indicate efficiencies of the same order as Salter's nodding duck. However, Wavepower Limited is more concerned about a comparative assessment of cost efficiences (Ref. 8).

Details of prototype at sea :

It is interesting, that in terms of scale, the size of a raft relates to the smaller waves which it experiences rather than the largest.

When longer than about a quarter of a wavelength, floats would lose efficiency rapidly. To correspond to conditions in the Atlantic, floats would have to be 10 m long; the shortest waves in the Atlantic have a period of 5 second and a quarter of their wavelength is equal to 14 m. Similarly, it was found that the width of floats is related to the minimum wave width rather than the maximum. It is envisaged that the width of rafts may be from 20 m to 40 m. Although the large ocean waves contain an abundance of energy, most of the power is contributed by the smaller waves continuously throughout the year; the optimum wave contouring raft design would therefore not take advantage of the full power supply of the very large waves (Ref. 8).

Wavepower Limited has established the principle of floats, hinges and pumps of reasonable size. They believe that all the parts of their device are within technological capabilities; even at a full ocean scale. According to Wavepower, the "floats could be developed quickly". Due to the fact that all the components could be mass-produced, the cost of this device may become very competitive in comparison to other wave energy systems. It is also envisaged that all parts will be accessible from above for maintenance : any float can then be removed and replaced by a temporary piece bridging the gap. No excessive loads will be carried by the floats. The company believes that their device has as much promise as any other system currently under discussion.

Cost of Wave generating rafts? :

According to the Central Electricity Generating Board of Britain, the construction of a 1 000 MW generating raft may involve the equivalent amount of work required to build 60 half-million-tonne supertankers (Refs. 15 and 20). This analogy of the CEGB, suggested that the likely cost of energy from the waves may be from 400 to 800 pounds per kW, compared with the 200 to 300 pounds per kW produced from thermal sources.

RUSSELL RECTIFIER

The Russell rectifier was proposed by Robert Russell, director of the Hydraulics Research Station (HRS) at Wallingford. The rectifier is a structure for changing wave energy into a form which is such that it can be utilised by low-head turbines. A configuration of the device is illustrated in Fig. 2.6.

General description and principle of operation :

The device consists of a series of box-like compartments, each projecting up through the sea surface; the system is arranged along a line which is perpendicular to the wave direction (Refs. 12 and 21). Alternate compartments are high-level reservoirs while the intervening ones are low-level reservoirs. The high-level reservoirs are interconnected; so are the low-level reservoirs.

The reservoirs are separated from the sea by a number of vertically arranged non-return flaps. The flap valves in front of the high-level reservoirs pass sea water inwards and those in front of the low-level reservoirs pass it only outwards. When there is a pressure difference in the appropriate direction, the flaps open automatically; at other times they are closed. It is therefore possible for waves to drive sea water into the high level reservoirs and abstract it from the low-level reservoirs.

Sea water accumulating in the high-level reservoir system is used to drive low-head turbines, which allow it to pass into the low-level reservoir system and from there back to the sea. If the water is not

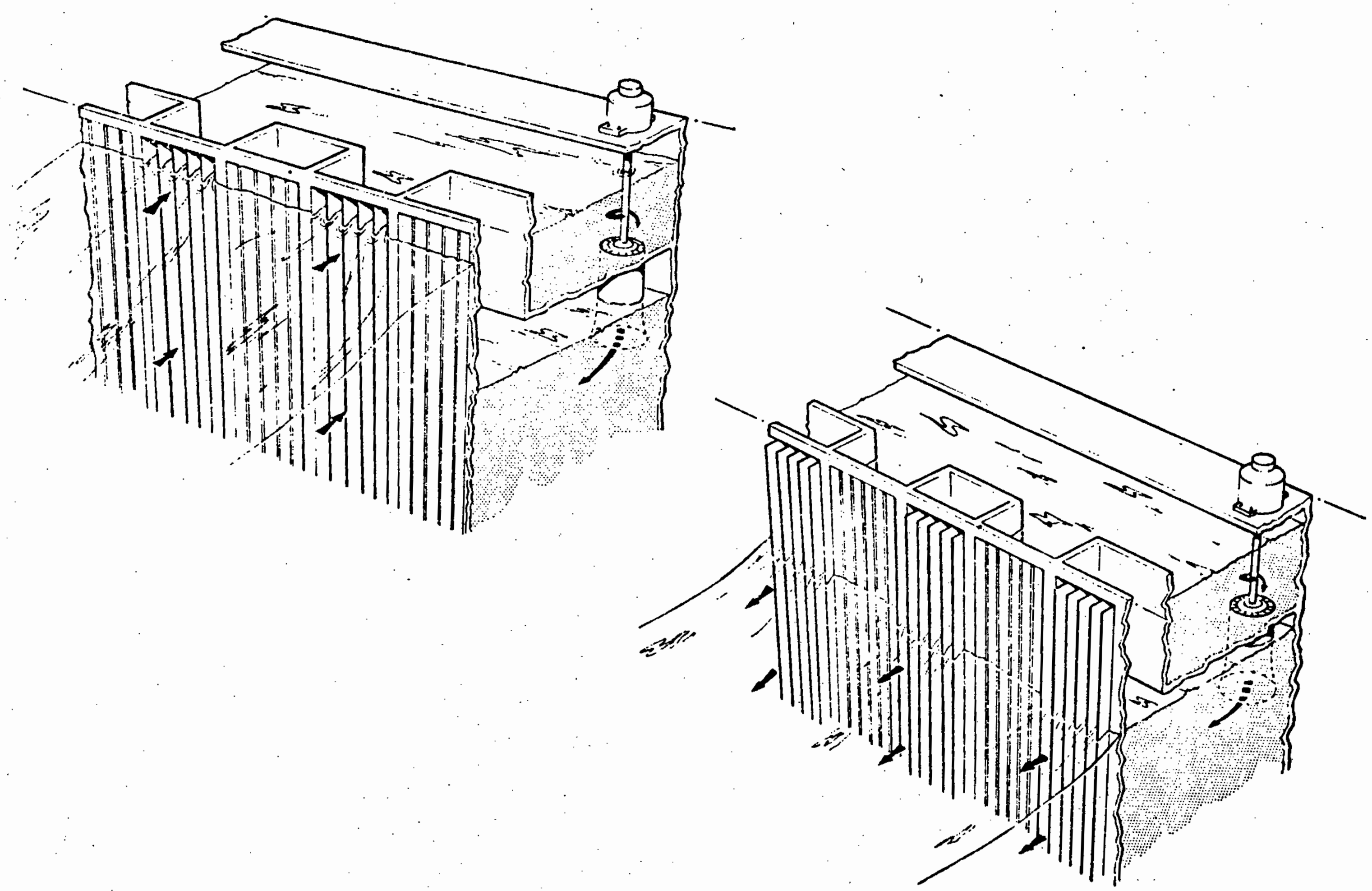


Fig. 2.6 Russell Rectifier (Ref. 21)

used for the generation of power, the levels attained will be those of the wave crest and the wave trough respectively. Excessive volumes of sea water are expected to pass through the low-head turbines. A radical approach to the design of low-head turbines may therefore become necessary; positive displacement paddle-wheels are among the possible configurations being considered. The National Engineering Laboratory is collaborating with the HRS on the aspect of alternative turbines for the Russell rectifier (Ref. 21).

The HRS is currently engaged in measuring the efficiency of a model device and the magnitude of the hydraulic forces imposed under various wave conditions. Because the flap valves to the high-level reservoirs must be capable of twisting, so as to be open at the top while being closed at the bottom, the model constructed at the HRS had to provide this facility : the flaps are made of 0,05 mm Beryllium copper strip, and the hinge constructed of flexible rubber.

Possible dimensions at sea :

The overall dimensions of the Russell rectifier will be determined by its location at sea.

When located out of sight of land, in deep water, a ship-like structure is envisaged. Its cross-section may be similar to that of a supertanker, but only much longer. If, on the other hand, the structure were sited closer inshore, at say 5 km in water of 30 m depth, it could possibly consist of concrete caissons resting on the sea-bed (Ref. 21).

The research and development on the HRS/Russell rectifier is still in an early stage; far too early to consider the possible advantages and disadvantages of the scheme.

DISCUSSION

Of all the systems considered in this chapter, only the Salter duck would not be able to extract energy from the rear; the Russell rectifier could be designed with flap valves, directed to the oncoming waves, on either side. This limitation of the Salter vane is due to its asymmetric shape.

Glendining and Count (Ref. 15) have suggested that "wave power devices should be designed and constructed as cheap expendable units which can easily be replaced and salvaged". Wavepower Limited has based the development of the Cockerell pontoons on this philosophy. A further requirement for units is reliability : the effect on the security of the whole system in the event of storm damage or collision at sea, cannot be overlooked.

One of the main attractions of wave power is the fact that it is non-polluting. However, other environmental impacts will have to be taken into account : visual impact, possible modification to sea bed patterns, obstruction to navigation and the possible damage to coastal installations.

The visual impact of wave power devices may only be important for structures sited relatively close to the shore. The more promising devices are all intended for deep water extraction of power, more than 10 km off the coast. Even although these structures may be very large, they will not be visible from land; the inshore terminal of the transmission link is likely to have a much greater visual impact.

Large water power devices may, in acting as breakwater structures, cause modification to sea bed patterns : creation of sand bars, reduction of littoral drift, etc. Since the optimum design of devices will not be aimed at extracting much energy from storm waves, the sea bed effects will probably be reduced by the resulting transmitted waves.

According to Glendining and Count (Ref. 15), there need to be no concern about the ecological effects of large devices at sea. They believe that giant structures may even attract marine life, in which case the resulting biofouling will be much more severe on the performance and maintenance of devices.

Large structures at sea will most definitely cause an obstruction to navigation; and the consequences of accidental damage, both to ships with their crews and generating devices, may not be neglected. Should a device break free of its moorings, it could cause excessive damage to coastal installations, such as harbours and fixed platforms. The two environmental impact areas mentioned here, require careful study before the installation of any device at sea could be considered.

Wave power cannot be regarded as firm power; but its seasonal variation in supply corresponds to the demand variation on the CEGB system (Ref. 15). The daily and weekly variations of wave power could be 'smoothed' by standby generating capacity, or the energy could be stored for industrial applications (Ref. 8). Processes suggested are the manufacturing of aluminium, extraction of hydrogen or minerals and desalination of sea water; and the CEGB has apparently looked into the possibility of extracting uranium from sea water. Hydrogen could be used as an energy source, or in the production of ammonia for fertiliser, which is relevant to the UK regarding the export market as large areas of the world are experiencing a shortage of fertiliser.

It was mentioned earlier that the CEGB suggested a likely cost band between 400 and 800 pounds per kW for the more promising wave power devices; a more meaningful cost estimate is not possible at present as the development of wave power is still in an early stage.

Lewis Roberts, chairman of the Harwell team which controls the research and development of wave power in the UK, estimates that if all goes well, Britain should have a 10 MW prototype in the sea by 1986; a full scale power station, capable of producing 1 000 MW, is not envisaged before 1996 (Refs. 9 and 11).

CONCLUSIONS

Wave power is a safe, permanent and non-polluting resource. Britain is particularly well suited to the exploitation of wave power : a wave power device, about 1 000 km long, could supply half of the country's present energy needs. Wave power provides a seasonal peak in the winter, when the electricity demand is also at a peak.

It is difficult to decide which of the British devices would give the best performance for the extraction of wave power on a large scale. The Salter duck appears to be very efficient, according to model studies; however, very little research has been done on the other three devices. Several years of intensive study is necessary to confirm the prospects of wave power exploitation with the four'promising'devices – the only existing devices, wave powered buoys, have so far only been capable of generating electricity in the kilowatt range.

The environmental impacts of a large wave generating structure at sea need to be investigated. However, one of the main problems with the British wave power devices will be the storage of excess energy; this aspect requires careful attention in the overall planning of a device. The cost of the British wave power plants do not appear to be competitive with alternative sources of electrical generation. The inflation in fuel costs may change this situation, but a device which is technically and economically feasible is first required.

CHAPTER 3 - DEVELOPMENT OF WAVE POWER DEVICES IN OTHER COUNTRIES

INTRODUCTION

Large areas of the world are short of energy. Unlike the limited availability of natural reserves of fossil fuels to most countries, waves occur on the sea everywhere.

Some proposals of wave energy devices developed in the United States, Germany and Norway are discussed in this chapter.

UNITED STATES

In the United States the energy authorities mainly restrict their support of ocean energy, to means of harnessing the temperature difference between surface waters and cooler layers of water below the surface (Ref. 9).

The most promising wave energy areas around the US, are off its west coast. Unfortunately, all the decisions are taken in Washington on the east coast; due to the geographical separation, wave energy proponents have failed to obtain financial support for wave energy projects on a grand scale. Nevertheless, interesting studies on wave power have been reported by bodies such as the US Naval Academy (by McCormick and others), and the Scripps Institution of Oceanography.

Pneumatic wave energy converter :

The US Coast Guard experienced difficulty in providing their navigation aids, such as buoys and light stations, with continuous power. The WATG, invented by Masuda, is used to supply power to several buoys. McCormick investigated the possibility of increasing the efficiency of pneumatic wave energy converters.

McCormick theoretically analysed the performance of a stationary pneumatic wave energy converter (Ref. 5). He found that this type of device should be most effective in the waves, as it does not "ride with the waves". The device could also be adjusted for purposes of efficiency in any wave spectrum encountered, by changing the length of the centre pipe. McCormick estimated that this device would probably produce 25 kW for a 6 m diameter unit in 1 metre waves.

McCormick et al (Ref. 14), performed an experimental study on a scale model, of a wave energy conversion buoy, in the wave tank at the US Naval Academy. The purpose with the investigation was to study the influence of internal water column length on the converted kinetic energy of a wave. They found that the air velocity (available to an air turbine) resulting from the heaving of the buoy and the wave motion, is proportional to wave height. Since power is proportional to the cube of the velocity, it is then also proportional to the cube of the wave height; this was theoretically predicted by McCormick (Ref. 5). It was further found that the increasing of the centre pipe length, resulted in an additional fluid mass being excited. There is also an optimum length of the pipe at which the maximum power will be produced; this point is near the resonant period of the buoy and the water column.

The work at the US Naval Academy is aimed at designing a system using four pneumatic WATG units. A maximum output of only 20 kW is envisaged and no cost analysis is available.

Scripps wave power generator :

A wave power generator has been developed at the Scripps Institution of Oceanography (Refs. 2 and 6). The principle of operation of the device is illustrated in Fig. 3.1.

The slack-tethered device consists of a vertical pipe containing a one-way flapper valve and a free-heaving buoy at the surface. As the device descends into a wave trough, the water flows up the pipe past the valve. When the device ascends a wave crest, the water is prevented from flowing down. As the device changes direction of motion, the water in the pipe is forced upward by inertia carrying it higher than the wave height. Subsequent cycles raise the water into a reservoir until a pressure suitable for power generation is reached.

Sea trials with a device having a 200 mm diameter pipe, 60 m long, have been reported (Ref. 6). The power output obtained was not very optimistic : only 60 W at "nonoptional design conditions". However, it is expected that a generator with a 5 m diameter pipe, 100 m long, would have an output of 300 kW in waves of 2,5 m significant wave height (Ref. 2); a converted capital cost of 360 US dollars (R310) per kW, for a device of this size, have been indicated by a cost analysis (Ref. 6).

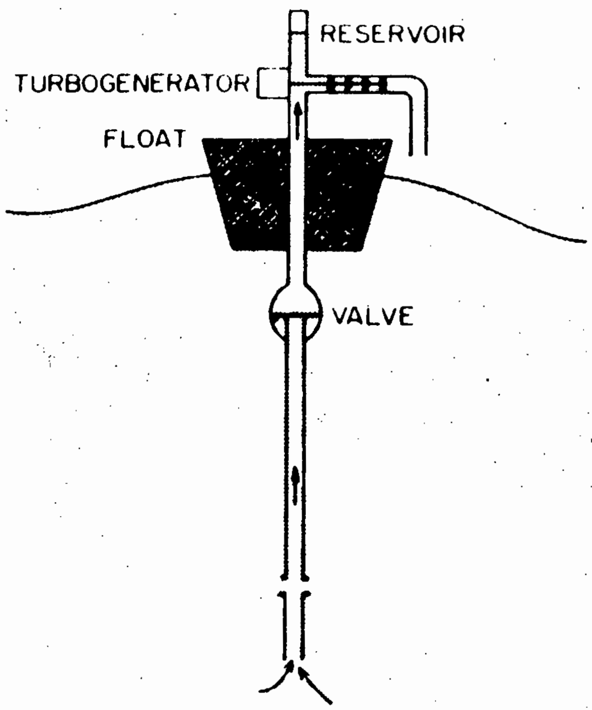


Fig. 3.1 Principle of Operation of Scripps Wave Power Generator (Ref. 2).

GERMANY

A mechanical system for the conversion of wave power into a high pressure water source, has been proposed in Germany by H. Kayser (Refs. 2 and 22). The system could possibly be used for floating power plants, in the kilowatt range, and for larger stationary power plants, in the megawatt range.

Kayser's method and its application to buoys :

Kayser's method involves the reduction of a large volume of low pressure water into a small volume of correspondingly high pressure water, which could be stored in hydraulic accumulators or cliff top reservoirs. From there electric power is generated using standard Francis or Pelton turbines. The pressure and volume transformation is achieved using a system of two pistons. The larger of the two pistons is moved up and down inside the submerged generator, by the periodic wave pressure. The pressure is amplified by the square of the ratio of the piston diameters.

Fig. 3.2 shows the construction of a 1 kW floating wave power generator, of 1 m diameter. In this unit the air or gas pressure above the main piston acts as a spring, to counterbalance the static water pressure beneath the piston (Ref. 22). Water entering the unit through the grate, due to wave motion, moves the main piston upwards. This motion drives the small pump piston : high pressure water is generated and is conducted through a valve and pipe into the hydraulic accumulator at the top. The hydraulic accumulator accomodates a further piston and a gas cushion. A part of the high pressure water volume is immediately fed to the Pelton turbine nozzle; excess water supply is stored in the turbine tail chamber. In wave troughs the gas pressure above the main piston pushes the pistons back to their original positions; water is also sucked, through a valve, from the storage tank. However, the turbine runs continuously until the water in the hydraulic accumulator is run down. The fact that the turbine can run continuously, increases its efficiency. According to Panicker (Ref. 2), the heave of the piston serves as a stabilising factor for floating power generators, as they should not be allowed to follow the motion of the water surface. Another damping method is to increase the mass of the tank.

Kayser has designed a prototype wave generator, capable of powering a navigation buoy, of 1 m diameter with an electric output of 500 W (Refs. 2 and 22).

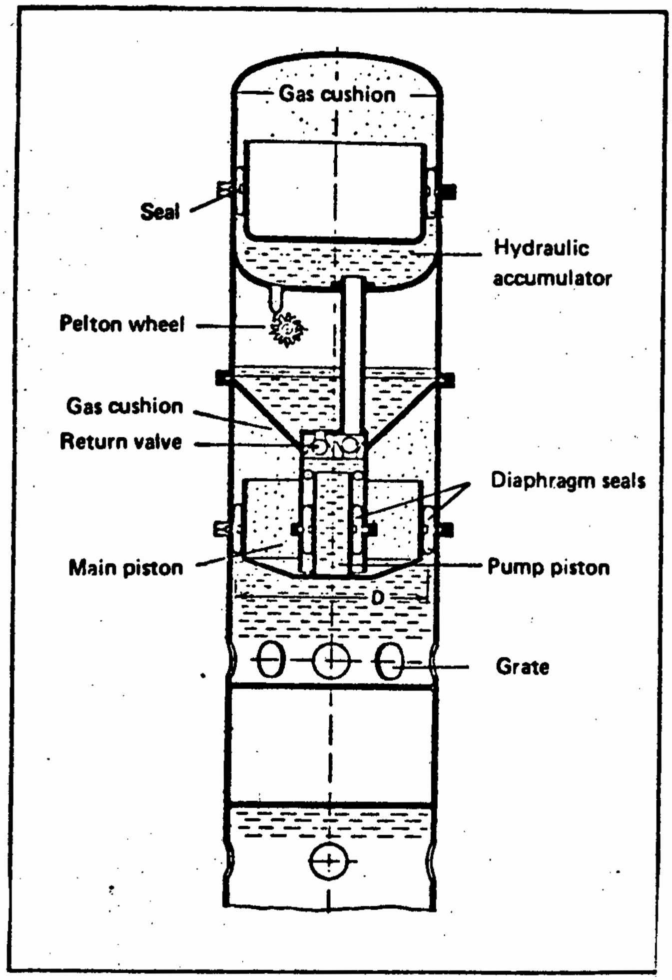


Fig. 3.2 General arrangement of 1 kW wave powered generator (Ref. 22)

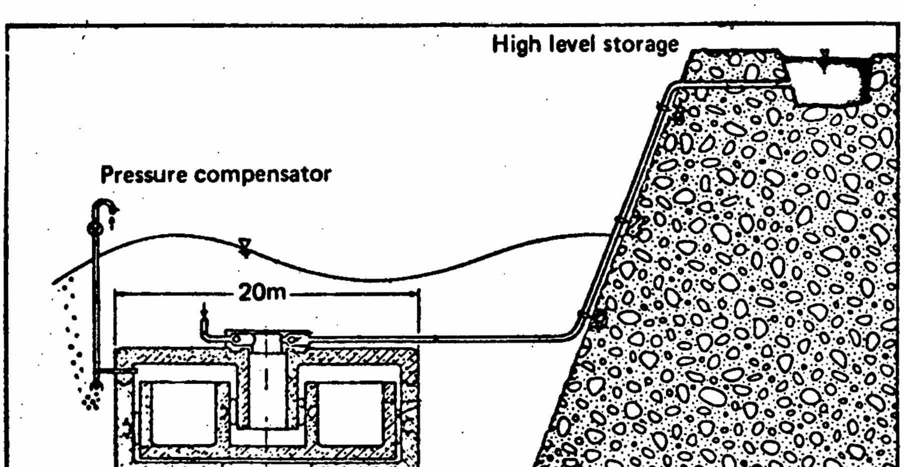


Fig. 3.3 Scheme for 1 MW shore based generator, suggested by Kayser (Ref. 22)

Shore-based power plants :

The same generating concept can be used on a much larger scale for shore-based power plants. Kayser described such a scheme for a generator of 20 m diameter and 1 MW output (Fig. 3.3). In this case the hydraulic accumulator is replaced by an elevated basin on the shore, which is used for intermediate storage of the high pressure water. The tidal influence must be compensated for in this system.

A small compressor could be used to pump air into the cylinder, above the main piston. The correct compensating pressure would be maintained by a simple free ending pipe; therefore the pressure inside the generator would always be equal to the surrounding water pressure. In order to compensate for only the long period pressure changes, the connecting pipe should be of small diameter.

The shore-based Kayser wave generator appears to be promising, but more research and development is required to confirm such prospects.

NORWAY

About half of the consumed energy in Norway is electric power. More than 99% of this energy is produced by hydro-electric power stations, which require large reservoirs particularly in the winter when the consumption of energy is large and the tributary of water is small. Wave observations have indicated that the wave energy incident on the Norwegian coast is large compared to the country's energy consumption (Ref. 1).

Norway is currently engaged in fairly large scale research aimed at tapping the wave energy along her coasts. Investigations regarding a resonant point absorber of wave energy are discussed below, while the densification of wave energy by means of wave focussing is described in chapter 4.

A resonant point absorber :

Budal and Falnes (Ref. 23) call a wave generating system a'point absorber' when its horizontal extent is much smaller than one wavelength. On the other hand, they consider a 'linear absorber' to be a system which is straight and a few wavelengths long, such as Salter ducks mounted on a framework at sea.

The optimisation of a floating point absorber was investigated by Budal and Falnes (Ref. 24). Their object was to obtain a more efficient power converting device, which was smaller and cheaper to construct than other floating devices, such as the Masuda buoy and the Salter duck.

For optimum power generation it is necessary that the resonant frequency of the point absorber is 'tuned' to the frequency of the wave (Refs. 23 and 24).

Example of a resonant point absorbing system :

Resonant wave absorbing systems having horizontal or vertical oscillating movements can be constructed (Ref. 23); an example of the latter type is given here.

Consider the cylindrical, vertically oscillating tank shown in Fig. 3.4. The tank A is kept in a semi-submerged equilibrium position by wire S. The wire, which passes around the circumference of the axis of the flywheel F, is stretched by the buoyancy of an empty tank B. When the tank A moves up and down in the sea due to wave motion, the wire S transmits the heaving force to the flywheel F and the tank B. By adjusting the inertia movement of the flywheel, the resonant frequency of the system is tuned to the characteristic frequency of the wave; the flywheel is placed in housing D on the bottom of the sea (Refs. 23 and 24). An electric generator connected to the flywheel extracts energy from the system.

At resonance the motion of the system is amplified with respect to the motion of the incoming wave. According to Budal and Falnes (Refs. 23 and 24), a resonant point absorber is analogous to the operation of the antenna of a radio receiver. Similar to an antenna, the tuned oscillating tank has an absorption length larger than its diameter; this was theoretically verified by Budal and Falnes (Ref. 24). Another example of a resonant wave absorbing unit is shown in Fig. 3.5.

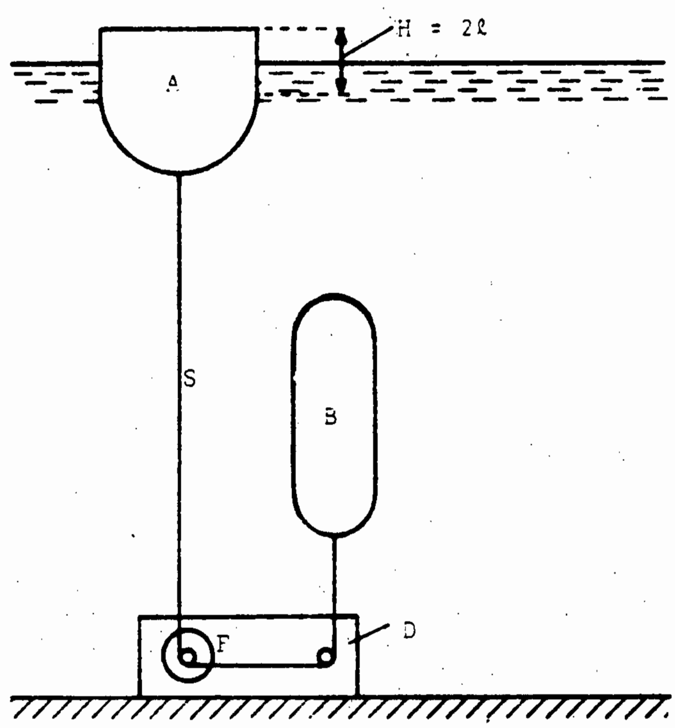
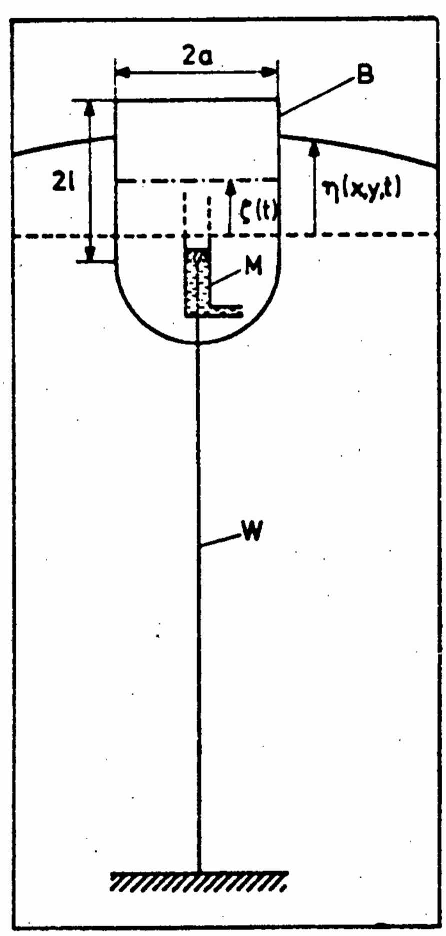


Fig. 3.4 Example of resonant point absorber (Ref. 24).



The floating buoy B is cylindrical with hemispherical bottom. The undisturbed sea level is indicated by the dotted line and the water line of the buoy by the dash-dotted line.

The vertical displacement $\zeta(t)$ of the buoy may be freely controlled within the interval $-\ell<\zeta(t)<\ell$ by means of the hydraulic machinery M; $\eta(x,y,t)$ is the instantaneous elevation of the sea.

Fig. 3.5 Unit of wave power station (Ref. 1).

Large scale power station :

An analysis showed that a tuned tank (such as A in Fig. 3.4), 10 m high (H) and 16 m in diameter, will produce about 10^7 kWh per year, or 1 MW output; i.e. considering sea-like conditions as experienced in the North Atlantic.

A large scale power station may have to consist of say 100 point absorbers, placed in a line at intervals of 100 m to cover a coastline of 10 km. The tanks would then operate practically independently of each other and absorb at least 20% of the average wave power incident on the 10 km coastline; shorter intervals may increase the percentage energy absorption, but could result in reduced power absorption per tank due to interaction between adjacent point absorbers (Ref. 24). However, during 1977 Budal (Ref. 25) using linear theory, analised the effect a system of interacting bodies has on the absorption of wave power, and found that the interaction may raise the absorbed power per body by a substantial factor.

Budal showed that a "linear row of spaced objects, each of which heaves and rolls, may absorb 100% of the wave power incident on its entire length" — even although the diameter of the bodies may be much smaller than their spacing (Ref. 25). When operating in only one mode (heave or roll), it was found that the system may absorb 50% of the incident wave power. The phenomenon is due to the radiated waves and the incident wave which interfere such that the flux of the energy in the ocean is directed to the bodies. The conditions described here are not always possible in practice, as fluctuations in the peak frequency of waves occur throughout the year; these and other factors have to be taken into account when estimating the power absorption.

According to Budal and Falnes (Ref. 23), no technological problems are envisaged in the construction of a large scale power station of resonant point absorbers. The system should be sited fairly close to the coast, to permit the direct connection to the main power network (Refs. 1 and 25); for an offshore system the cost of transmission cables could have a significant effect on the economic feasibility of the scheme. Ambli et al (Ref. 1) believe that the cost of each of the 1 MW units described above, should not exceed 4 million Norwegian crowns (N.kr), i.e. R 670 000; a rate of R670 or 390 pounds per kW. Maintenance and repair costs are estimated to be small compared to the capital costs.

According to Ambli et al (Ref. 1), they are currently designing a full scale resonant wave absorbing system; unfortunately no details are available.

CONCLUSIONS

The devices suggested by wave power proponents in the United States, Germany and Norway represent interesting concepts; unfortunately no sea trials have been reported, except with the Scripps wave generator which was not very satisfactory.

The McCormick buoy, Scripps generator and the Kayser buoy would only be capable of generating power in the kilowatt range, which rule them out for energy production on a commercial scale. The Kayser shore based power plant and the Norwegian resonant point abosrbes, fall in the megawatt category.

Maintenance and repair cost could be high for the Kayser shore based system, while it might be very small for resonant wave generators, due to its simple arrangement. It therefore appears as if the Norwegian resonant point absorber, is the most promising of the different devices considered in this section; but, as indicated before, practical testing under sea-like conditions is essential. However, it may be recognised that the power absorption for the latter system could drop drastically when the wave condition changes from the one on which the adjustable flywheel is tuned.

A very important aspect is accentuated by the various devices being developed by the three countries concerned : wave energy densification is a requirement before the conversion to electrical power!

CHAPTER 4 - WAVE FOCUSSING

INTRODUCTION

The amplification of wave height by means of converging channels was first investigated by French engineers. It was reported (Ref. 2) that Remenieras "analysed the increase in the height of a translatory wave moving along a converging canal", with the purpose of utilisation by low head machines. During the 1940's, Dhaille investigated the technique and profitability of converging wave channels, he found that a low head wave power plant, based on converging wave channels was technically feasible (Ref. 2).

Converging channels :

Dhaille's scheme consists of a battery of converging channels which open offshore to lead amplified waves, through valves, into a storage basin. From the storage basin a regular energy supply to hydraulic turbines, located behind the basin, is possible. Preliminary studies, at two points on the Algerian coast, yielded encouraging results and led to laboratory studies in 1944. Although the model, of a series of converging channels, indicated that the conversion efficiency of wave energy was greatly influenced by wave characteristics, up to 50% effiency was achieved.

Later, detailed studies on larger models were conducted to ascertain the effect of various parameters, such as wave length, wave height and the tides. Encouraging results were obtained but the variation of the tides presented a problem. A detailed cost analysis done by Dhaille in the 1950's on a plant proposed for Casablanca in Morocco, showed that, although technically feasible, his scheme was economically not competitive with other methods of energy production (Ref. 2).

Wave focussing by refraction :

In 1974, Von Arx (Ref. 26) proposed the densification of wave energy by means of refraction, along coastlines abutting broad continental shelves. He suggested an artificial "lens", a number of wavelengths long, which could focus waves towards a "horn". From the "horn", further amplification might achieve a head of some tens of metres, such that the water fills an elevated storage basin; from the storage basin conventional hydro-electric power generation is possible.

However, theoretical studies regarding wave focussing had already commenced in 1971, at the Central Institute for Industrial Research (SI) in Oslo, Norway; the research and development of wave focussing in Norway are discussed below (Ref. 27).

NORWEGIAN POWER GENERATION BASED ON FOCUSSED WAVES

Wave data measurements indicated that the swells of the North Atlantic, directed towards the coasts of Europe, contain an average wave energy of between 20 and 80 kW per metre wave frontage. Norway is currently developing a new method to harness this enormous energy resource — wave focussing!

It has been estimated (Ref. 27) that the cost of constructing and running a Norwegian 'wave focussed' power plant, would compare favourably with conventional methods of energy production; in fact, a cost analysis has indicated a cost of about half the cost involved in producing energy by corresponding hydro-electric schemes.

In contrast to other proposals for utilising wave power, the Norwegian method involves the concentration of wave energy, before converting it into electric power. Most of the available wave energy over a coastline of several kilometres is concentrated within an area of less than 500 m in length. The wave height in this area may be 15 - 30 m. The waves would then enter a large funnel-shaped chute and be forced up to a reservoir, which may be located as much as 100 m above sea level. This tapping method would blend well with the Norwegian coastline. A model of a power plant based on focussed waves is shown in Fig. 4.1. A conventional hydro-electric plant at sea level would then be powered by water flowing down from the reservoir (Ref. 27).

The waves are concentrated by means of refraction, caused by an artificial "lens".

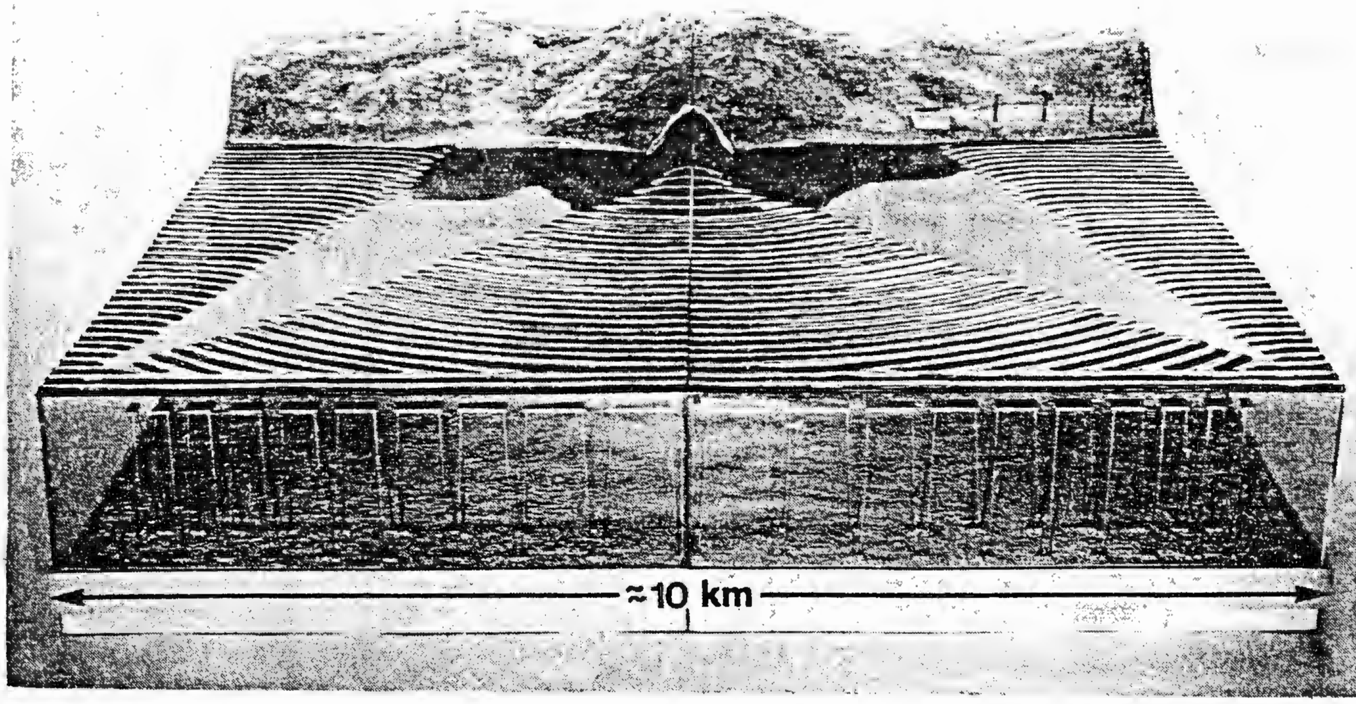


Fig. 4.1 Model of a power plant based on focussed ocean swells (the vertical scale is 5 times the horizontal) (Ref. 27).

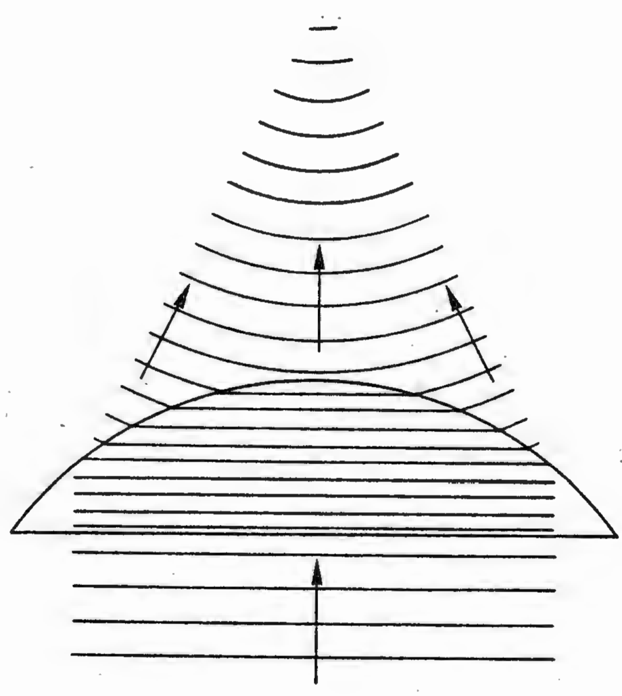


Fig. 4.2 Wave focussing by an optical lens (Ref. 27).

THE FOCUSSING OF WATER WAVES

In explaining the focussing of water waves, it may be useful first to consider how an optical lens refracts light waves.

A plane wave incident on an optical lens, pass through the lens and is transformed into a spherical wave which is converged towards the focal point of the lens. An optical lens consists of glass, which has a higher optical density than air. When travelling through glass, from air, light waves are therefore slowed down. A converging lens is thicker at its centre than at its edges; a wave front passing through the lens centre, will therefore be retarded relatively more than the wave front at the edges (Fig. 4.2). This greater retardation at the lens centre results in plane waves being transformed to converging spherical waves.

Water waves and light waves are similar in nature, concerning reflection, refraction, interference etc. It is therefore evident that a "water lens" should also possess properties analogous to an optical lens, and (i) transform a parallel incident wave such that it emerges as a wave with circular crests, converging towards some focal point; (ii) retard some parts of a wave front relative to other parts of the same wave front.

A water lens :

The wavelength and the velocity of water waves increase with depth. A possible "water lens" would therefore be a structure consisting of a number of plates, placed horizontally and moored to the sea bed at different depths. The wave retardation will then vary according to the size of the plates and the mooring depth. A typical depth of 30 m below the water surface have been indicated, based on preliminary investigations (Ref. 27). A water lens, moored to the sea bed, is shown in Fig. 4.3.

A water lens should also meet a number of other requirements, in addition to its basic focussing property : (i) it should cause as little reflection as possible, of the energy of incident waves; (ii) it should work efficiently even although a relatively large change in the main wave direction might occur, from one period to another (i.e. from one storm to another); (iii) it should also work efficiently over a certain angular spread of wave directions and frequencies, around the main direction and the main frequency respectively, to cater for as wide a wave spectrum as possible. These requirements have to be considered carefully by the designer of a water lens.

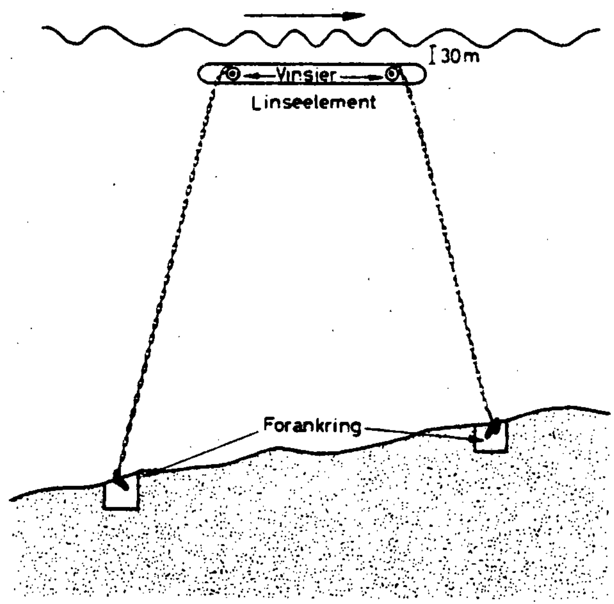


Fig. 4.3 Water lens moored to the sea bed (Ref. 27)

Linear wave theory is appropriate if the amplitude of incoming waves are relatively small; if so, any incident ocean wave may be analised as being a superposition of plane waves travelling in various directions, with various frequencies. It would be ideal if the incident wave consisted of only one plane wave – a spread in wave directions and frequencies, reduces the efficiency of a water lens. To find out how efficient the water lens will be the average spread in direction and frequency of the swells, at the proposed location of the lens, must be measured.

Once the wave characteristics are available, the lens designer can proceed with his task. Differential equations of water waves, with appropriate boundary conditions, are at the disposal of the designer, to determine the shape of the lens which should give the optimum efficiency.

If the lens is to be made out of submerged plates, some aspects regarding the relative size of the lens elements in practice, need to be considered. When passing over the plates, the wavelength of a sea wave is reduced and it is slowed down. If the plates are triangular-shaped in plan, the waves will change their direction as shown in Fig. 4.4. A lens, consisting of a large number of triangular-shaped elements and similar to the lens shown in Fig. 4.2, could be realised in practice. However, such a structure would be enormous and unmanageable in practice.

A better solution would be to split the lens into elements such as indicated in Fig. 4.5. The waves are now broken up and again united to form spherical waves. The lens elements need not be arranged along a line, but may be placed within a particular area depending on the local conditions (Ref. 27).

RESEARCH AND DEVELOPMENT

Towards the end of 1976 methods, developed at the Central Institute for Industrial Research in Norway, indicated that wave focussing could be technically feasible in practice. The tapping of the wave energy at the focal point of a water lens have also been investigated; an adjustable model of a funnel-shaped chute (Fig. 4.6) have been built for this purpose.

The following laboratory results have so far been achieved (Ref. 27) :

(i) more than 90% of the energy contained in an incoming wave can be focussed towards an area of relatively small size;

(ii) more than 80% of the wave energy concentrated at the focal point, can be converted to potential energy in the water reservoir.

An amount of N.kr 900 000 (R150 000)was set aside by the Norwegian government for practical testing during 1977, in a river and a harbour laboratory.

Research programme :

The Norwegian research programme for 1978/79 was influenced by the most likely problems anticipated in the construction of a proposed pilot plant, based on wave focussing.

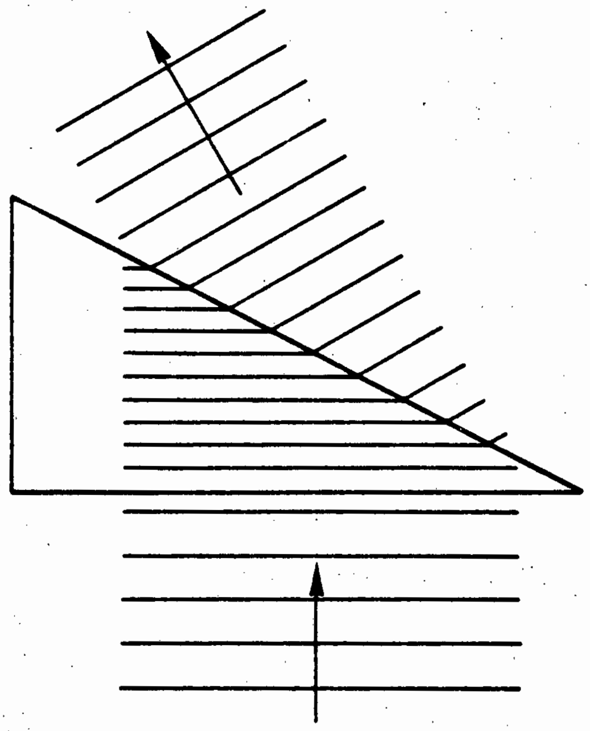


Fig. 4.4 Triangular-shaped lens (Ref. 27)

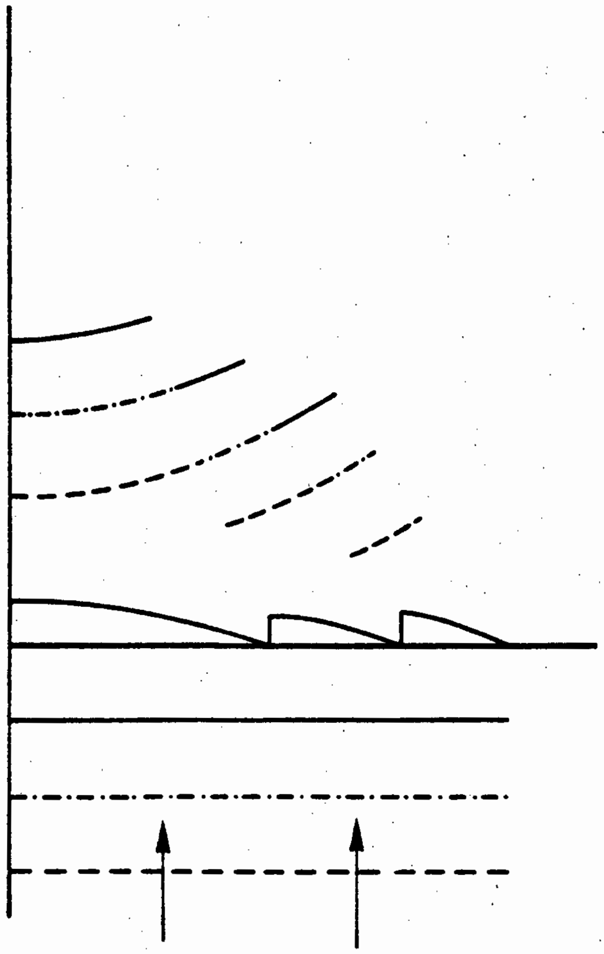


Fig. 4.5 Elements of a water lens, in practice (Ref. 27)

Technical difficulties might be experienced with the building and mooring of the water lens system, as well as the construction of the funnel-shaped chute; the financial implications of such a plant also need to be investigated. A further aspect which may raise objections is the drastical drop in efficiency of the lens system, due to the variation in height, direction and frequency of the waves.

The research programme, involving scale model studies under realistic conditions, comprises the following :

(i) the design of a lens to be used for experimental purposes;

(ii) experimental investigations conducted on the lens and a funnel-shaped chute;

(iii) construction and mooring of a full scale pilot plant, including a cost analysis.

For the experimental investigations, waves having realistic angles of incidence characteristic of conditions along the Norwegian coast, will be generated; initially by using one wave generating machine, but eventually with at least three wave machines.

A pilot plant, having minimum dimensions of 100 m by 150 m, is envisaged with one or more reservoirs (Ref. 27).

The Norwegian Government has budgeted for an expenditure of 7 M.kr (R1,1 million) in 1978 and 10 M.kr (R1,6 million) in 1979, on focussed wave research.

DISCUSSION

The realisation of a full scale wave focussing plant is very important for the Norwegian industry. The extent of the construction of a full scale project may be compared with the construction of a Condeep platform, for oil drilling in the North Sea; more employment opportunities in the industry may therefore become available. The interest of industry in the utilisation of this form of power, is stressed by the fact that research and development has gained financial support from a number of companies in Norway (Ref. 27).

A preliminary cost analysis (Ref. 27) has indicated that the realisation of a wave focussing plant could be economically feasible. As starting point it was assumed that the incident wave energy is 500 MW per 10 km coastline (50 kW per metre). A further assumption was that the whole plant, using a lens system 10 km long, has an efficiency of 60%. The total cost of the plant was estimated at 1 500 M.kr (R240 million), i.e. R480 or 280 pounds per kW installed; 20% of the total cost was allowed for the lens system and a further 13% for the mooring facilities. The production per year, over 8 000 hours, was calculated to be approximately 2,4 TWh; this represents a capital investment of about 0,6 kr (10 cents or 6 pence) per kWh produced.

A "pessimistic" survey of costs was also conducted : assumptions made were an incident wave energy of 200 MW per 10 km coastline; an efficiency of only 40%; and a lens system three times more expensive than that for the previous preliminary analysis. The total cost was now estimated at 2 400 M.kr (R390 million); R 1 300 or 760 pounds per kW installed. The values assumed and the cost estimated reflect an annual production of 1,3 TWh and a capital investment of 30 cents or 18 pence per kWh produced.

According to the SI report (Ref. 27), the cost of conventional hydro-electric power amounts to 24 - 32 cents per kWh. The economic lifetime of wave focussing plants is comparable to hydro-electric schemes. Keeping this fact and the "pessimistic" survey above in mind, the prospects for the realisation of wave focussing plants appear to be very promising.

However, one also need to compare wave focussing plants to other proposed wave power devices. At sea the wave focussing system would have no visual impact as the lens is submerged and not visible at all. The funnel-shaped chute at the shore, could be blended with the coastline and if not possible, it could become a major tourist attraction. As far as the modification of sea bed patterns are concerned, the lens system may cause similar effects as those due to the huge British structures envisaged at sea.

An area where serious objection could be raised to most of the other types of schemes, is the obstruction to navigation. No problems are envisaged in this field with a wave focussing plant. Like the British and most other devices, the mooring of lens elements may present a problem. However, the maintenance and repair costs of the lens elements may be small compared to that of the British devices.

It has already been mentioned that according to a preliminary cost analysis, focussed wave power compares favourably to conventional hydro-electric power. Although very little information regarding costs, are available for most of the other devices, it appears that focussed wave power may not only be cheaper than other forms of wave power utilisation, but also economically feasible.

CONCLUSIONS

It was concluded in chapter 3 that wave energy densification is a requirement, before power conversion should be considered. Wave focussing meets this requirement; energy concentration by a lens system and further wave height amplification using a funnel-shaped chute.

With the lens system moored some distance offshore, it is not likely that wave focussing will be significantly affected by tidal changes. However, the efficiency of wave focussing plants may be rapidly reduced by the variation of height, direction and frequency of waves. More intensive research is required to find the lens system of optimum shape, to minimise this effect; the Norwegian wave power research programme includes this aspect.

According to experimental studies (Ref. 27) wave focussing is technically feasible. Laboratory results have yielded power conversion efficiencies of as high as 80%. Successful experiments have been performed at the Harbour Laboratory in Trondheim during 1977. Further experiments, with lens and chute, are to take place in a lake near Oslo, during 1978.

A preliminary cost analysis has indicated that focussed wave power is competitive with conventional hydro-electric power. At this early stage in the development of wave power research, it appears as if focussed wave power may be cheaper than most alternative forms of wave power utilisation: in comparison to other promising wave power devices, the maintenance and repair cost would be low and no transmission cables are necessary at sea. The estimated cost of a resonant point absorbing system (buoys arranged in a row) is R700 per kW, against R480 (60% efficiency) and R1 300 (40% efficiency and "pessimistic") per kW for a wave focussing plant. Theoretically, resonant point absorbers are regarded as promising, but no testing in practice have been reported.

The environmental impacts of wave focussing plants would probably be less significant than that caused by any other proposed wave power device.

Norway is fortunate to have a coastline into which a wave focussing plant could be blended. Wave focussing is a Norwegian invention; this puts the Norwegian industry in a favourable position with respect to foreign countries.

The Norwegian research on wave focussing has been very successful. If all goes well, a power plant utilising wave focussing will be realised on the Norwegian coast within the next 15 years.

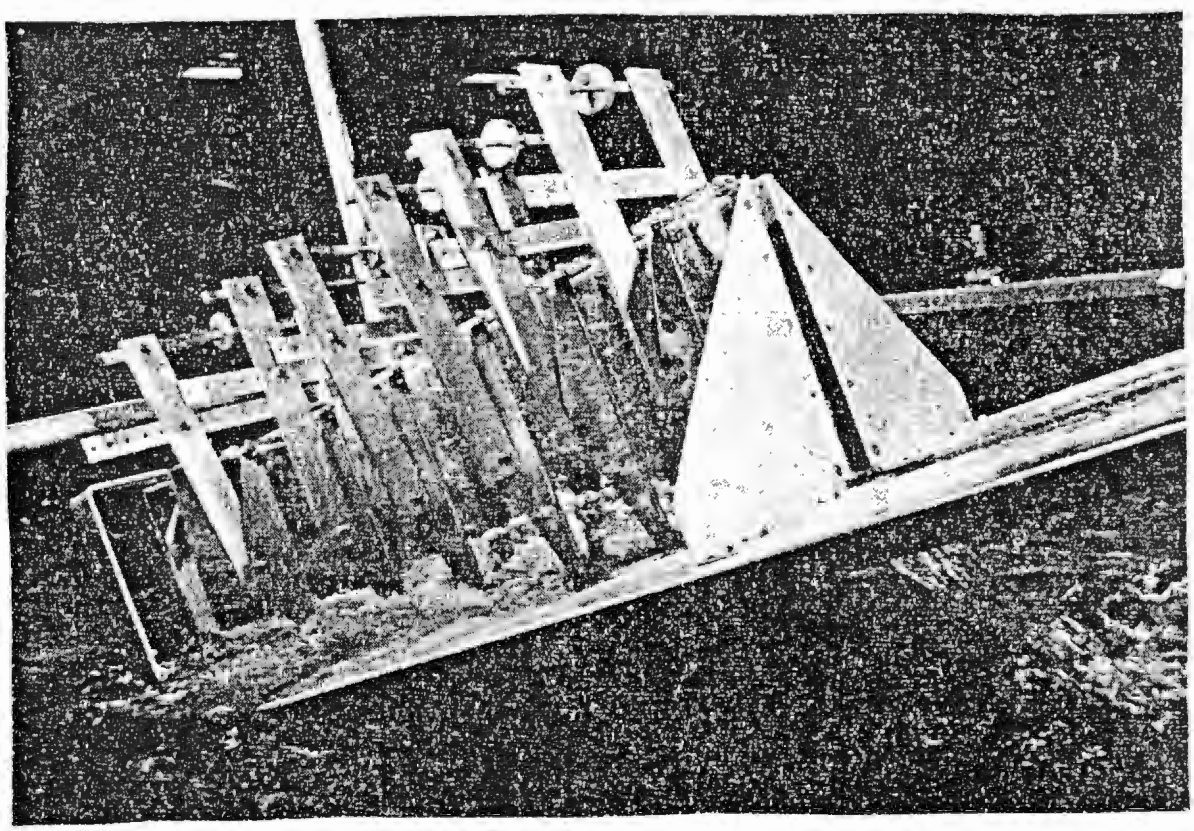


Fig. 4.6 Adjustable model of a funnel-shaped chute. The waves that enter from the left side are pressed up by the shape of the chute and spill out at the top as can be seen at the right side. (Ref. 27)

PART TWO

TIDAL POWER

THE RANCE TIDAL POWER PLANT

(by courtesy of BP South Africa)

CHAPTER 5 - TIDAL POWER THROUGH THE CENTURIES : HISTORICAL SKETCH

INTRODUCTION

For many centuries the vast oceans and seas which cover 71 percent of the earth's surface have been considered as a source of energy. The ancient Greeks attempted to use the tides to their advantage in the Euripus, a narrow channel between Boeotia and the isle of Euboea (Charlier, Ref.28).

Before the phenomenon of tides had been explained many tidal mills existed on the shores of France, Spain and Britain. Bernshtein (Ref.29) reported that most of these mills were constructued during the 11th century.

Some tidal mills depended exclusively upon the tide while others were partly powered by fresh water streams. However, the principle of operation were the same in all cases; even similar to that at the basis of the huge schemes proposed for certain parts of the world. This principle involves a retaining basin, a dam, sluice gates : the basin fills as the tide flows in.

TIDAL MILLS

The earliest reference to tidal mills appears in the "Domesday Book" which mentions such a mill in Dover harbour in 1066. Mills built in 1135 and 1170 respectively were those of Bromley-by-Bow, in the London region, and of Woolbridge, in Suffolk, on the Deben estuary. These were still in use during World War II (Charlier, Ref.28).

The famous London Bridge over the Thames River was equipped with tidal mills for pumping water in 1580. In 1824 London's water supply was still partly due to these enormous water wheels of 6m in diameter (Lawton, Ref.30). In Hamburg a tidal installation was still in use for pumping sewage in 1880.

Tidal mills functioned in Zuid-Holland and Zeeland in 1200. Dutch colonists built tidal mills near New York in the early 17th century. The first tidal mill in the United States had been built in Salem, Massachusetts, in 1635. Slade's Mill, with a capacity of 50 horsepower, was built in 1734 at Chelsea, Massachusetts, to grind spices.

In the Rance River, in France, fourteen tidal mills existed furnishing the Breton millers with energy once per tide. In England and Wales twenty-three mills were still in existence by 1940, of which ten were still in use (Charlier, Ref.28).

The East Greenwich mill, located approximately halfway between Blackwall Turmel and Woolwich (London region), in 1826 utilised both the ebb and flood tides and could therefore be regarded as a precursor of the double effect Rance tidal power plant, which was commissioned in 1966. According to Charlier (Ref.28) the mill's wheel revolved in a wooden frame which rose and fell with the tide. The change in direction of wheel motion was obtained by a system of cogs engaging bevels at both ends of two upright shafts, together with a level action.

Why did tidal mills disappear from the scene? According to Lawton (Ref.30) early tidal mills were designed to extract a relatively small proportion of energy, about 30 to 100 kW, used at the site and therefore virtually disappeared at the advent of the electric motor and long-distance power transmission towards the end of the 19th century. However, the French attributed the disappearance of tidal power generation to power economics. Power generation on an industrial scale were mainly utilising energy provided by fossil fuels and the hydro-electric possibilities of rivers — resulting in a decline in the price of energy at the turn of the century. The small tidal mills just could not meet this fall in price!

TIDAL CURRENTS

According to Lawton (Ref.30) records indicate that between 1856 and 1939 some 280 patents dealing with the utilisation of tidal energy were registered. Although most of the early patents were taken out in France, Charlier (Ref.28) reported that a German, Pein, published plans for a tidal power plant in the North Sea, in 1912; unfortunately Pein's plant was never built.

The designers of the first tidal installations did not need to concentrate high outputs into single units as energy was only required at the site and not some distance away. They therefore mainly utilised the kinetic energy of the tides (tidal current). Bernshtein (Ref.29) indicated that the energy generated by using the tidal current only is negligible - roughly 7,35 kW per m^2 current cross-section for a maximum current velocity of 2,5 m/sec.

Remenieras and Smagghe reported in 1956 that they had designed "a unit which uses a screw propeller to exploit tidal current" (Bernshtein, Ref.29). The unit operates on the same principle as wind turbines, except that a "1 - 2 m/sec sea current provides the same power as a 9,3 - 18,6 m/sec wind", with the same size propellers. The Chinese developed a simpler unit, suitable for small power plants and in 1958 had already built 17 installations in the Kwangtung Province alone.

More recently, Richards (Ref. 6) reported that Heronemus et al, have reviewed several types of water turbines capable of utilising low velocity currents. The tapping of the kinetic energy of the Florida Current, east of Miami, was mentioned. Heronemus et al also proposed using Savonius-rotor type machines about 6 m in diameter and extending 18 m across fast-flowing river streams. They believed that these machines would generate considerable electricity without the equipment cutting off river traffic. However, the contribution of energy from tidal currents is small and do not warrant any further discussion.

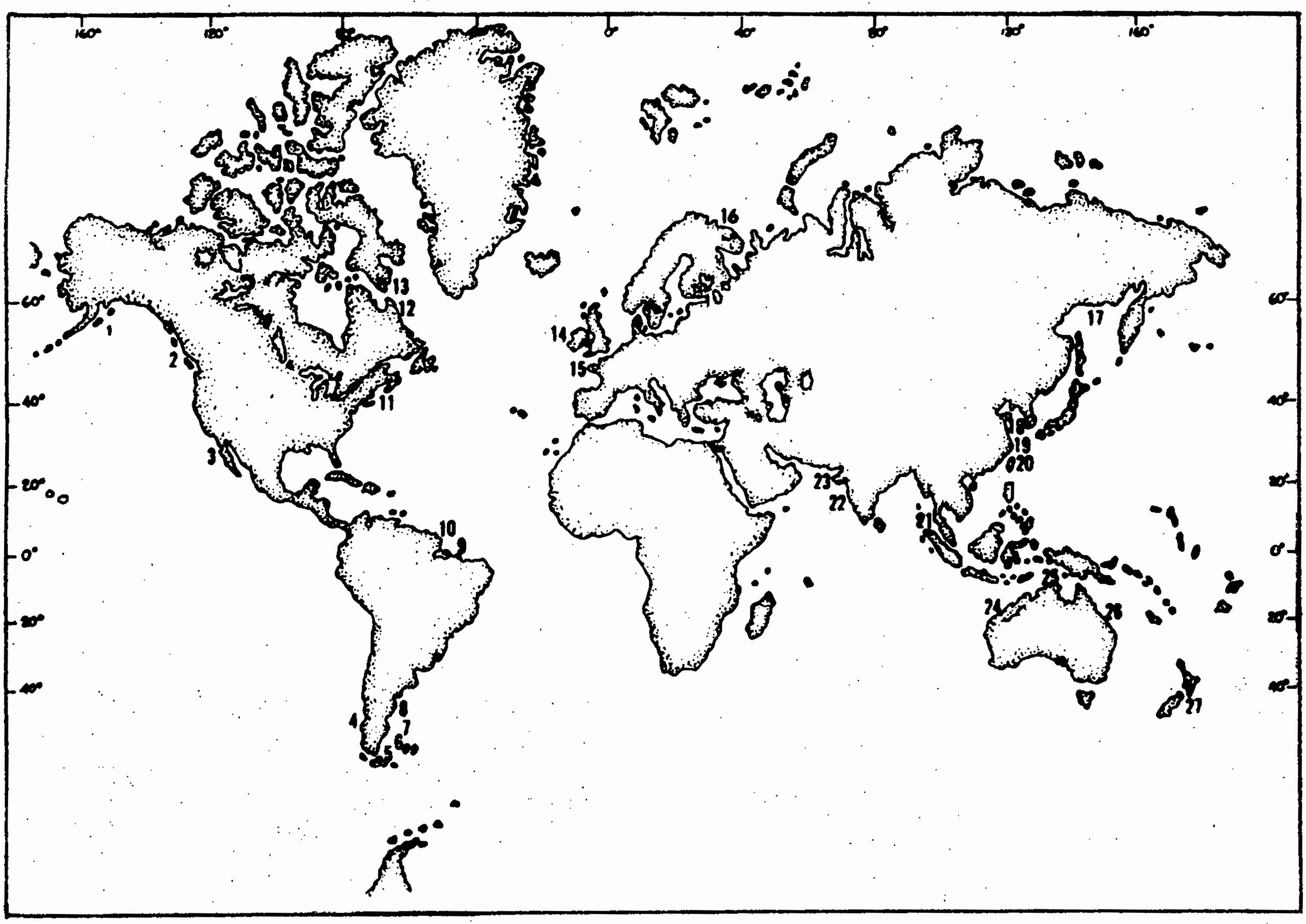
SITES FOR MAJOR TIDAL POWER PLANTS

Wilson (Ref.31) has estimated that the total output of tidal power sites capable of being practically developed is of the order of 350 TWh (terra = 10^{12}) per annum.

Major tidal power plant sites considered over the years are those in France, the Soviet Union, Great Britain, Canada, the United States, Argentine and Australia. Fig.5.1(Charlier, Ref.28) on the next page gives an overall picture of these and other sites.

FIG. 5.1 MAJOR TIDAL POWER PLANT SITES

(FROM CHARLIER, REF. 28)



1. Cook Inlet
2. British Columbia
3. Baja California
4. Chonos Archip
5. Magellan Straits
6. Gallegos/Sta.Cruz
7. San Jorge Gulf
8. San Jose Gulf
9. Maranhao
10. Araguaia
11. Fundy/Quoddy
12. Ungava Bay
13. Frobisher Bay
14. Severn/Solway
15. Rance
16. Mezen et al Kislaya
17. Okhotsk Sea
18. Seoul River
19. Shanghai
20. Amoy
21. Rangoon
22. Cambay Bay
23. Cutch Gulf
24. Kimberleys
25. Darwin
26. Broad Sound
27. Manukau

The Rance River plant in France is the only large capacity tidal power plant now in operation. It was put on line in 1966 at a cost of about 100 million dollars and produces 240 MW of electricity. An experimental plant was constructed on the coast of the Barents Sea and came into operation at the end of 1968. Soviet designers are considering the construction of large facilities to tap the energy of the tides in the White Sea and the Sea of Okhotsk. The Americans actually started construction in 1935 of a plant in Passamaquoddy Bay. The United States allocated 45 million dollars for the development, but work was stopped after 7 million dollars had been spent. (R1 = ± 1,30 dollars, in 1975)

Studies show that sites where the natural tidal range is less than 5 m are unlikely to be capable of economic development of tidal power plants. High tidal ranges are the product of particular hydraulic and topographical circumstances and are confined to relatively shallow coastal estuaries and gulfs. Fig.5.2(Wilson, Ref.31) indicates regions where relatively high tidal ranges are experienced.

Over the years various techniques for the effective and optimum operation of tidal power plant have been proposed. Some of these proposals are outlined in the next chapter.

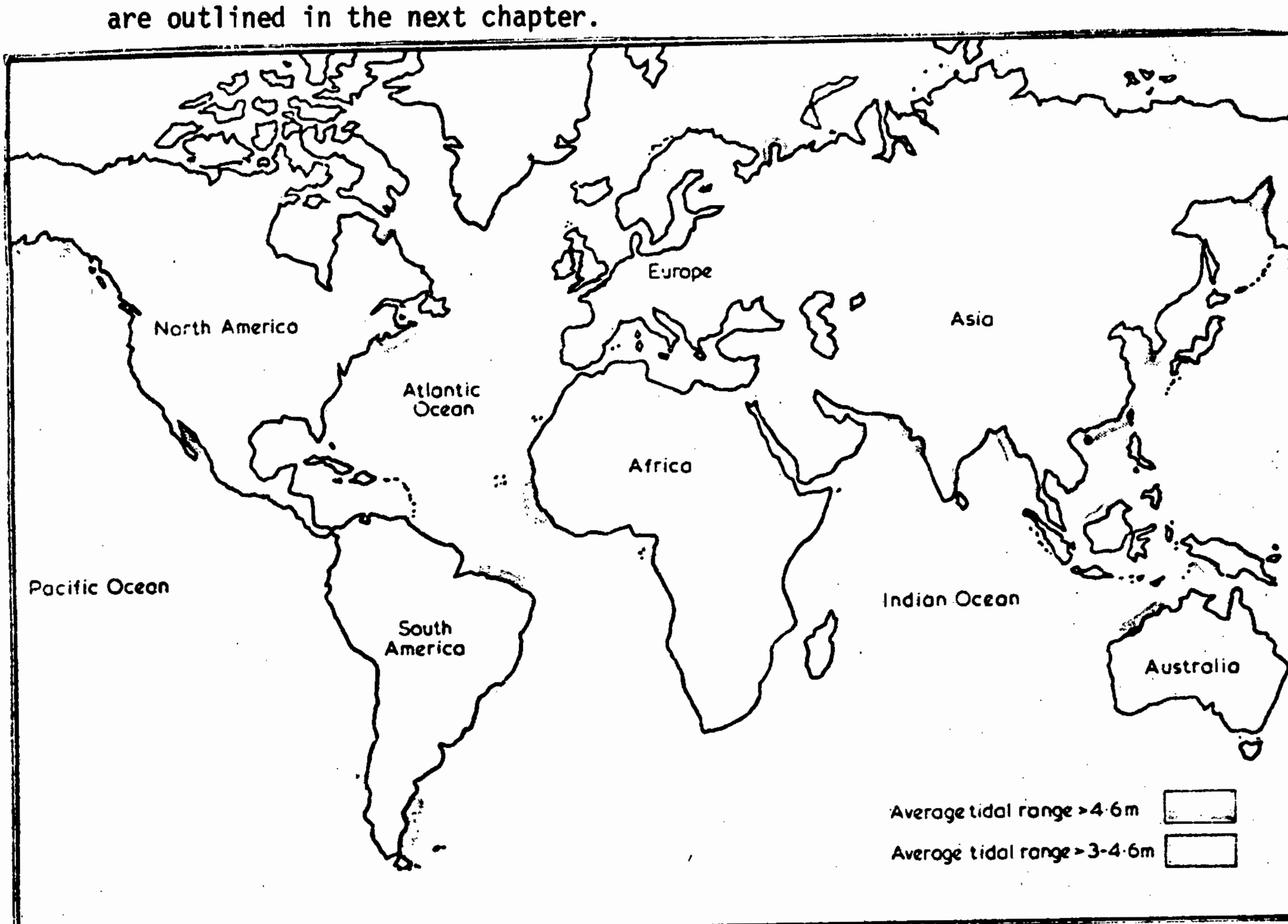


Fig. 5.2 World sites for tidal development, showing tidal ranges (Ref. 31)

CHAPTER 6 - PRINCIPLES OF OPERATION

INTRODUCTION

The tides, entirely predictable many years in advance, follows the lunar cycle and hence gradually moves out of and then back into phase with the solar cycle. Tidal energy may be obtained from this oscillatory flow of water in the filling and emptying of enclosed coastal basins.

Some of the characteristics of tides and random factors that exert influence may be listed as follows (Shaw, Ref.[32]) :

(i) tidal period of approximately 12,4 hours,

(ii) cycles of variation of tidal range occur over approximately two and four weeks,

(iii) tidal variations may only vaguely resemble a sine wave,

(iv) amplification of tidal curves is largely controlled by estuarial geometry,

(v) atmospheric, barometric and river discharge conditions may modify the basic wave motion.

Tidal power plants consist of three basic elements : the power house or setting for the generating units; the sluiceways with their gates for the filling or emptying of the controlled basins; and the dykes. The latter, usually rockfill, constitutes the closures between power house and sluiceways and between either and the abutments of the development. The basin must be filled from the sea or emptied to the sea as required by the operating regime of the power plant so that production can be co-ordinated with the load curve of the power network with which it is interconnected. The technique of timing and quick and reliable operation of the sluiceways is essential (Ailleret, Ref.[33] and Shaw, Refs.[34] and [35]).

POWER FORMULAE

Consider a dam built in a bay or estuary separating a basin from the sea. Suitable generating sets, which operate in both directions, make it possible to use the water to produce electrical energy during ebb and flood tides. Power formulae applicable to emptying, filling and pumping are given below (from Gibrat, Ref. 36 and Charlier, Ref. 28).

Let us assume

H = tidal height

$S(z)$ = area of basin at elevation z

γ = unit weight of sea water

E_p = energy to pump

$-B$ = a point below normal low water

$+C$ = a point above normal high water

V_p = volume pumped

If S(z) is the pool area at elevation z, the energy generated by emptying a section dz is γ S(z) zdz (see Fig. 6.1).

Then (only tidal potential energy considered),

Energy produced per cycle, during emptying of basin (Fig. 6.1)

$$E_e = \int_{z=o}^{H} \gamma \, S(z) \, zdz \qquad (1)$$

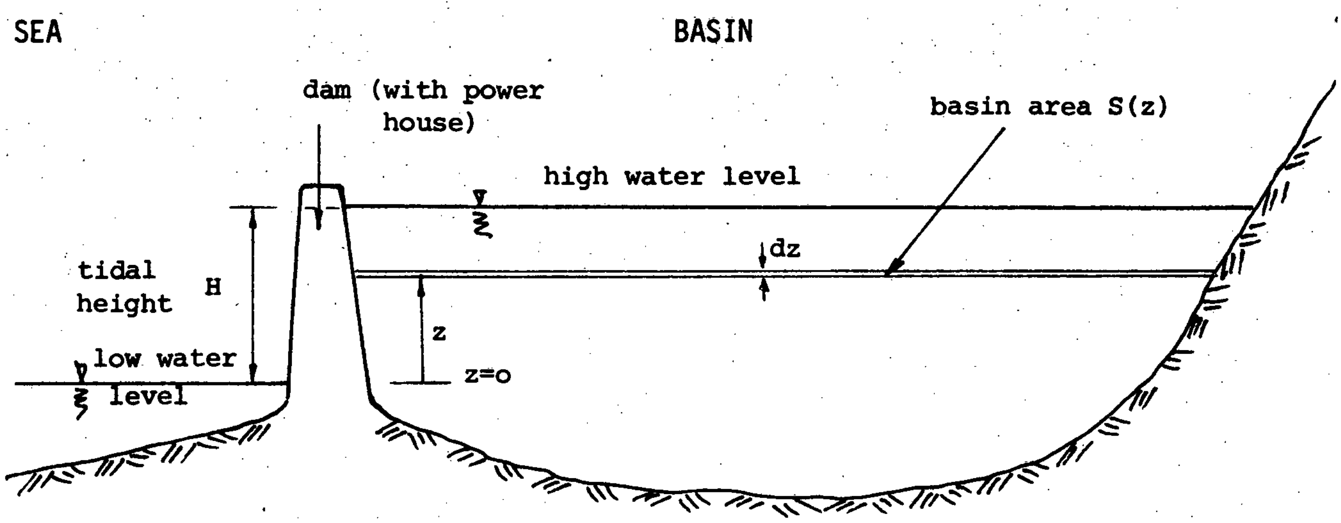
Energy produced per cycle, during filling of basin (Fig. 6.2)

$$E_f = \int_{z=o}^{H} \gamma \, S(z) \, (H-z)dz \qquad (2)$$

Therefore, total energy per cycle with double working

$$E_c = E_e + E_f = \gamma H \int_{z=o}^{H} S(z)dz \qquad (3)$$

Volume of basin, $V_b = \int_{z=o}^{H} S(z)dz,$ (4)

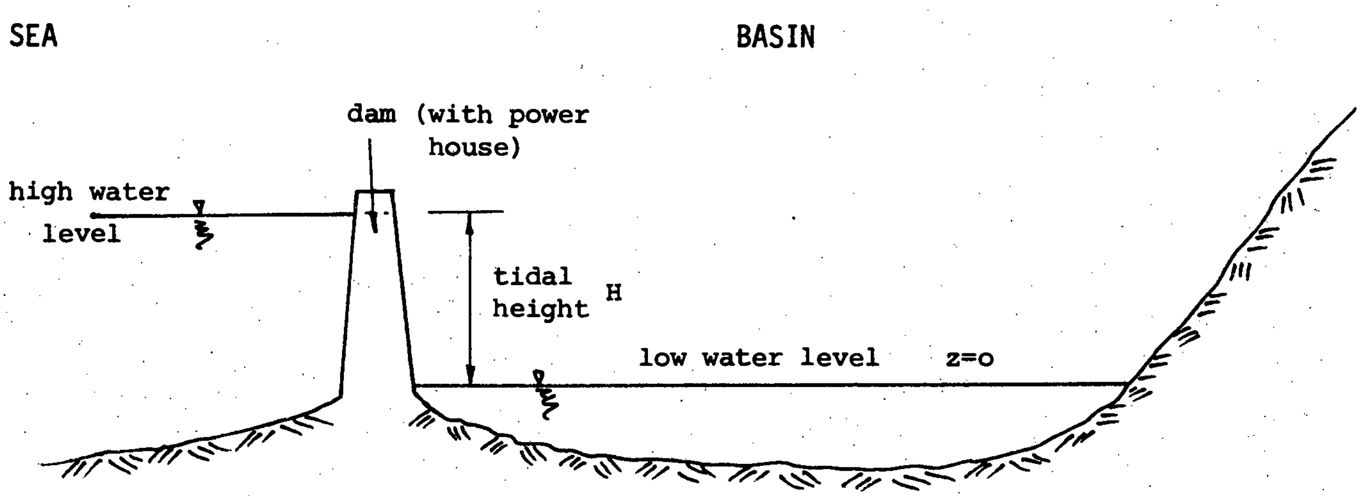


Volume of element dz = $S(z)\,dz$

Effective head = z (assuming no change in sea level and emptying at the turn of the tide)

∴ Energy generated by emptying a section dz = $\gamma\, S(z)\, z\,dz$

FIG. 6.1 EMPTYING OF BASIN



As the basin fills, its level z rises;
therefore effective head = $H-Z$ (assuming filling at the turn of the tide)

∴ Energy generated by filling a section dz = $\gamma\, S(z)\,(H-Z)\,dz$

FIG. 6.2 FILLING OF BASIN

and energy produced to complete tidal cycle,

$$E_c = \gamma H V_b \tag{5}$$

Gibrat (Ref. 36) referred to this quantity as the "natural" energy of the basin for a tide H. As early as 1942, the French had shown by scale-model testing how to exceed this value (Gibrat, Ref. 36) :

> "At high tide (level H), the gates are suddenly opened without using the energy as the water passes through, a wave is propagated up the estuary and, increasing in amplitude, is reflected at the other end. The gates are closed at the moment when the wave returns and when the direction of flow at the dam is about to change. Finally the water surface settles down to a level higher than H. We attained 1,5H on a scale model without any difficulty."

Gibrat showed that the inclusion of pumping in a tidal power plant with single basin and using a double working cycle, could increase the "natural"energy. He considered four phases :

(i) At the end of a cycle (basin emptied to low-tide level and the gates closed), the basin level is lowered to -B by pumping, by using energy

$$E_{p_1} = \int_{z=o}^{-B} \gamma S(z)\, z dz \tag{6}$$

(ii) As the tide rises, the basin is filled by flood tide producing energy

$$E_{f_1} = \int_{z=-B}^{H} \gamma S(z) \quad (H-z) dz \tag{7}$$

(iii) At the turn of the tide, water is pumped from the sea to the basin raising the basin level to C. The energy used is

$$E_{p_2} = \int_{z=H}^{+C} \gamma S(z) \quad (z-H) dz \tag{8}$$

(iv) At low tide the basin is emptied from C to zero producing energy

$$E_{e_1} = \int_{z=o}^{+c} \gamma\, S(z)\, zdz \qquad (9)$$

Nett energy production for complete tidal cycle

$$E_c = E_{f_1} + E_{e_1} - E_{p_1} - E_{p_2}$$

$$= \gamma H \int_{z=-B}^{c} S(z)dz \qquad (10)$$

$$= \gamma H(V_b + V_{p_1} + V_{p_2}) \text{ from relationship (4)} \qquad (11)$$

Therefore, the gain in energy

$$E_{gain} = E_{c_{(11)}} - E_{c_{(5)}} = \gamma H(V_{p_1} + V_{p_2})$$

The inclusion of pumping in a double working cycle thus appears to be an advantage and is only restricted by the plant limitations, due to the energy gained depending only on the total volume pumped and the tidal height.

Swales and Wilson (Ref. 37) described a method for the energy and economic optimisation of tidal power generation with the aid of a computer. The method is explained in relation to ebb-generation schemes, but could be applied to other forms of generating cycles, where pumping is not required. They concluded that their analysis provided an accurate and rapid method of selecting the equipment required for minimum energy costs.

VARIOUS TECHNIQUES FOR HARNESSING TIDAL POWER

The literature on various schemes proposed for the harnessing of tidal energy is voluminous. Bernshtein (Ref. 29) has given a full account of the schemes proposed before 1960. Other useful sources of information are due to Shaw et al (Refs. 38 and 39), Shaw (Ref. 32), Wilson(Refs.31 and 40), Wilson and Severn (Ref. 41) and Varzeliotis (Ref. 42).

Wilson (Ref. 31) summarised six types of tidal power systems :

(1) single pool ebb-flow generation using simple fixed-blade turbines;
(2) single pool ebb- and flood-flow generation using variable-pitch turbines;
(3) single pool ebb- and flood-flow generation using complex turbines and incorporating pumped storage – the Rance system;
(4) double pool, in which the turbines are located between the two pools, one of which is intermittently filled by the flood tide and the other intermittently drained by the ebb tide;
(5) double pool with pumping from off-peak system power;
(6) tide-boosted pumped storage.

The water level variation and power distribution curves of the first five types are illustrated in Fig. 6.3. However, each one of the six schemes is discussed in greater detail below.

(1) SINGLE POOL EBB-FLOW SCHEME

Physically, this is the most straightforward scheme. The turbines may be simple fixed-blade machines due to generation in one direction only, resulting in simpler thrust bearings.

Due to its simplicity, this scheme is the most convenient standard for comparison among tidal power systems. The pool is filled at high tide and discharged after an interval through turbines generating electricity. For the most energy, theoretically available, to be generated, the pool should be emptied to nearly low water level at low tide and almost completely filled at the next high tide. To achieve such rapid discharge implies very large turbine installations as well as very large sluice capacity.

Wilson and Severn (Ref. 41) investigated possibilities of exploiting only that part of the total potential which could be developed relatively cheaply. Their considerations are graphically illustrated in Fig. 6.4. The continuous line represents an idealised regime, while the broken line depicts a more practical possibility. In the latter situation, generation may last approximately six hours always occurring during the same part of the cycle. They estimated that roughly half the energy, theoretically available, would be extracted. Also, navigation in the pool would not be adversely affected as the water levels were artificially maintained.

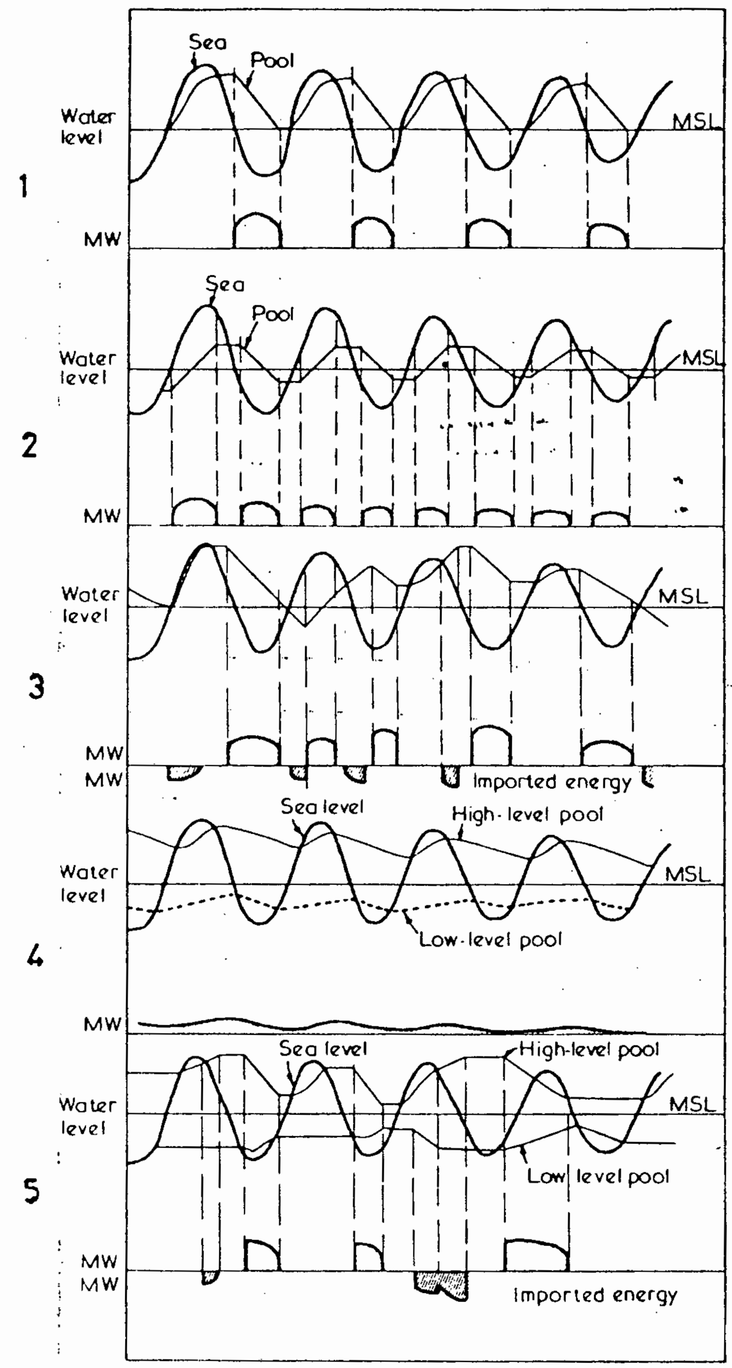


Fig. 6.3 Tidal scheme operating possibilities (Ref. 31)

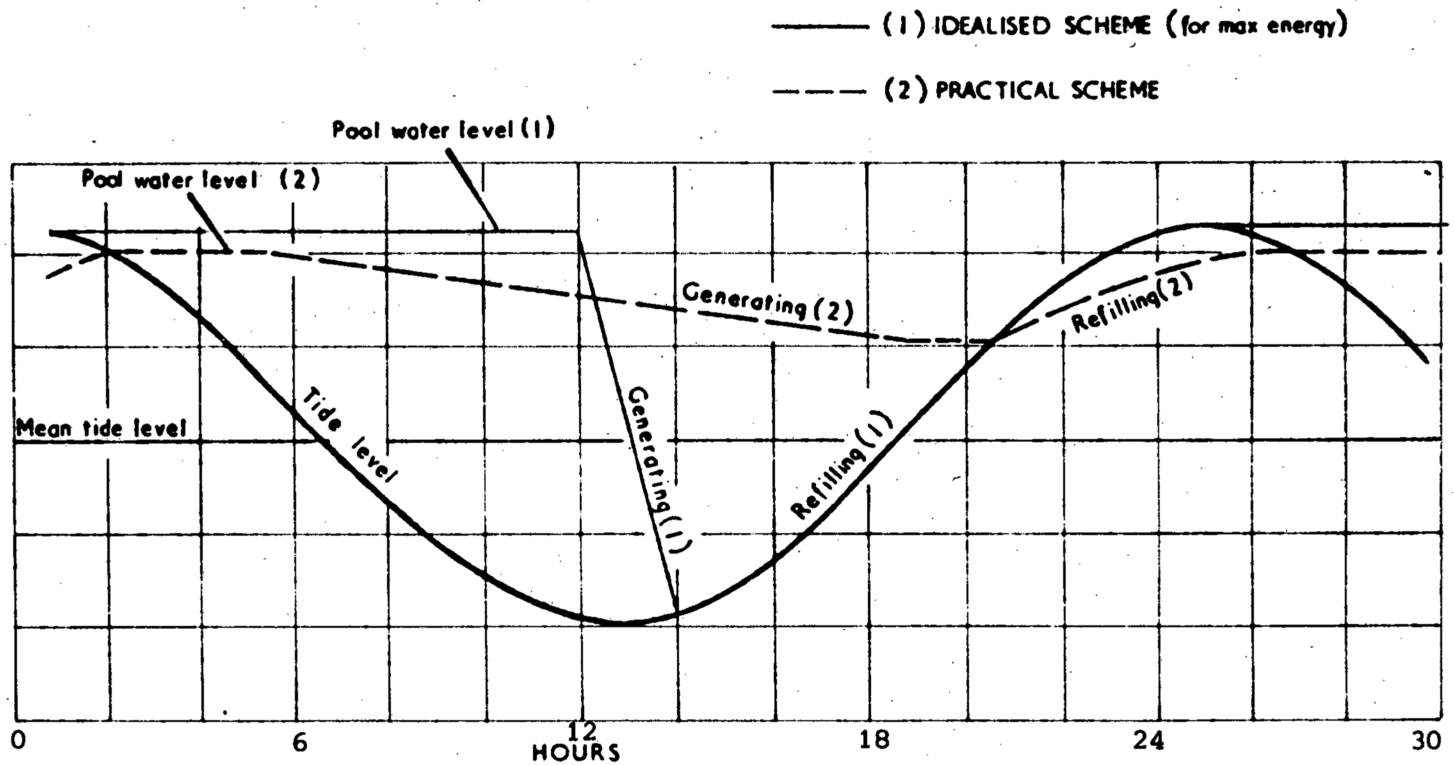


FIG. 6.4. Single pool one-way system (Ref. 41)

With generation in the opposite direction, i.e. with flood-flow, the main difference lies in the timing of the generating periods. These periods will occur about six hours earlier or later compared to ebb-flow generation. However, the useful basin area will be less : the sea level cannot be controlled as was done with the basin level! Less power will be available and navigation inside the pool may become impractical.

The energy is generated intermittently and at times when it may or may not be required. The amounts of energy generated varies between spring and neap tides by a ratio of up to 3 : 1 (Wilson, Ref.40). It is evident that storage of the electrical energy is necessary.

Wilson and Severn suggested that the electrical interconnection of two equivalent, neighbouring one-way systems, one generating during ebb-tide and the other during flood-tide, might offer some prospect of continuously available power - of course, under unusually favourable circumstances.

(2) SINGLE POOL TWO-WAY SCHEME

In this system energy is generated when the reservoir is both filling and emptying; all the energy being generated by the same power house. Generation in both directions is achieved by reversible-flow tubular turbines. Both the existing two tidal power plants, La Rance and Kislaya Guba, are equipped with reversible-flow bulb turbines.

The energy which is available in this scheme is greater than for the single-pool one-way system. The turbines are larger and there are more of them, as a much larger volume of water is discharged in each direction, in every cycle, than in method 1. Also, the turbines thrust bearings are more complex due to the reversible-flow action.

Generation periods need to be curtailed to provide enough time for emptying or refilling of the reservoir, for the subsequent generation phase with the reverse flow. This results in sluice discharge and possibly free discharge through the turbines, as well as a lower average head compared to the one-way system. Refilling or emptying will also be less complete than in the first scheme. The continuous line in Fig.6.5 (Wilson and Severn, Ref.41) represents a typical operating regime for this scheme.

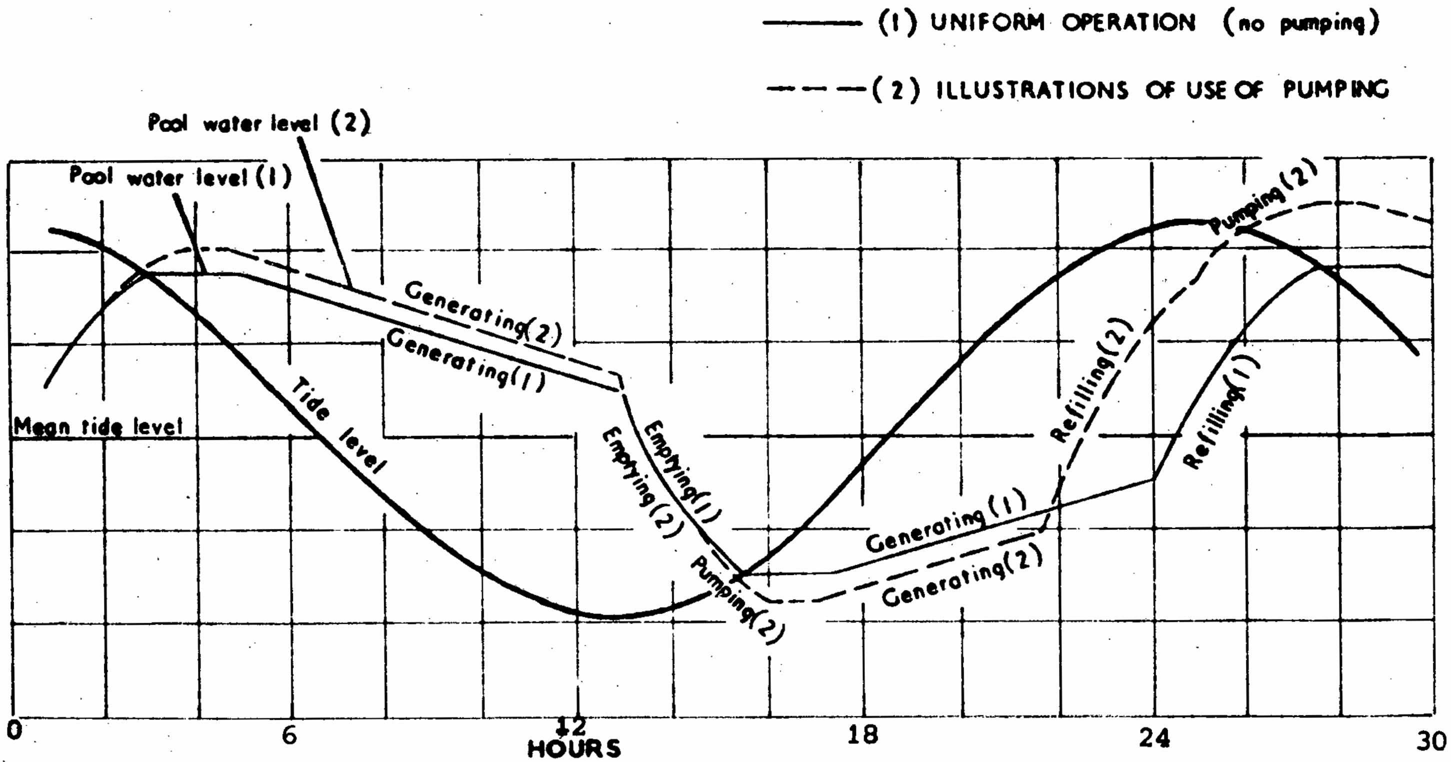


FIG. 6.5. SINGLE POOL TWO-WAY SYSTEM (REF. 41)

This scheme involves higher cost due to it requiring more and larger machines, but 20% more energy may be generated (Ref. 40). The higher cost might be justified due to the fact that a two-way system may possibly be more conveniently absorbed in the interconnected electrical supply system.

(3) SINGLE POOL TWO-WAY SCHEMES, INCORPORATING PUMPED-STORAGE

This is the principle on which the Rance tidal power plant operates. Reversible-flow turbo-generators are used as motor-pumps as well. The reservoir is used for pumped-storage by either pumping the sea in at high water, or by pumping from the reservoir at low water. The off-peak network energy, utilised for pumping, provides a greater working head during generation periods.

Generation is in either direction. The machines are very complex and expensive. Also, the pumping efficiency is low. Generation at peak-periods is confined to approximately four hours. Some firm power could be guaranteed, if requested, in advance. However, this is only obtained by sacrificing some of the available tidal energy.

Earlier in this chapter, under "Power formulae", it was proved mathematically that the added facility of pumping results in a gain compared to ordinary two-way generation. The broken line in Fig.6.5 shows how pumping is incorporated into a two-way system to increase the energy output.

A very important aspect of pumping is that the next generation period can be controlled, by pumping an hour or more before the demand peak. Departure from the optimum times for maximum energy production reduces the energy output but results in making the energy produced available at times when it is in demand and most valuable.

The Rance scheme has fully utilised the facility of pumping and has in fact increased its nett production since it was commissioned in 1966 (Refs. 31 and 43). Fig. 6.6 illustrates the adaptability of this scheme : electrical energy may be produced at any required time!

(4) DOUBLE POOL (DE COEUR TYPE) SCHEME

According to Shaw et al (Ref. 38) "one of the main objections to tidal power developed by single-basin techniques is that its availability is dictated by the cycle of the tides rather than by the consumer".

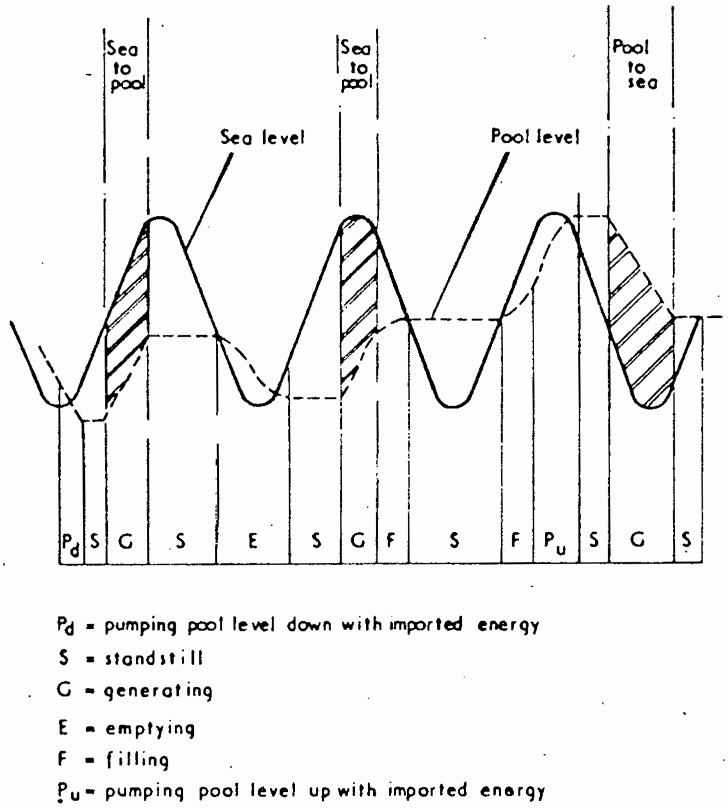


Fig. 6.6 Single pool two-way scheme, incorporating pumped storage (Ref. 41)

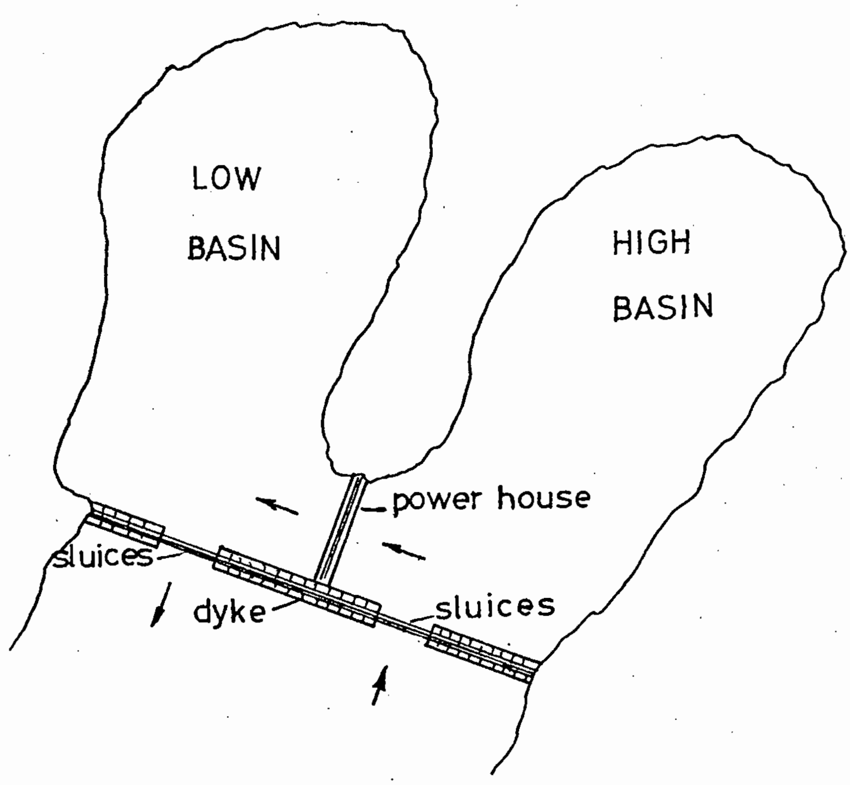


Fig. 6.7 Double pool (De Coeur) scheme

With two basins of approximately equal area, this shortcoming is reduced : the power house is located in the separating dam and operates under the head between the upper and lower basins – see Fig. 6.7 . The upper pool is intermittently filled by flood tides and the lower pool intermittently drained by low tides.

The operating regime of the double pool system is illustrated in Fig.6.8. Two options are illustrated :

(1) the continuous line represents continuous generation.
(2) the broken line represents intermittent generation.

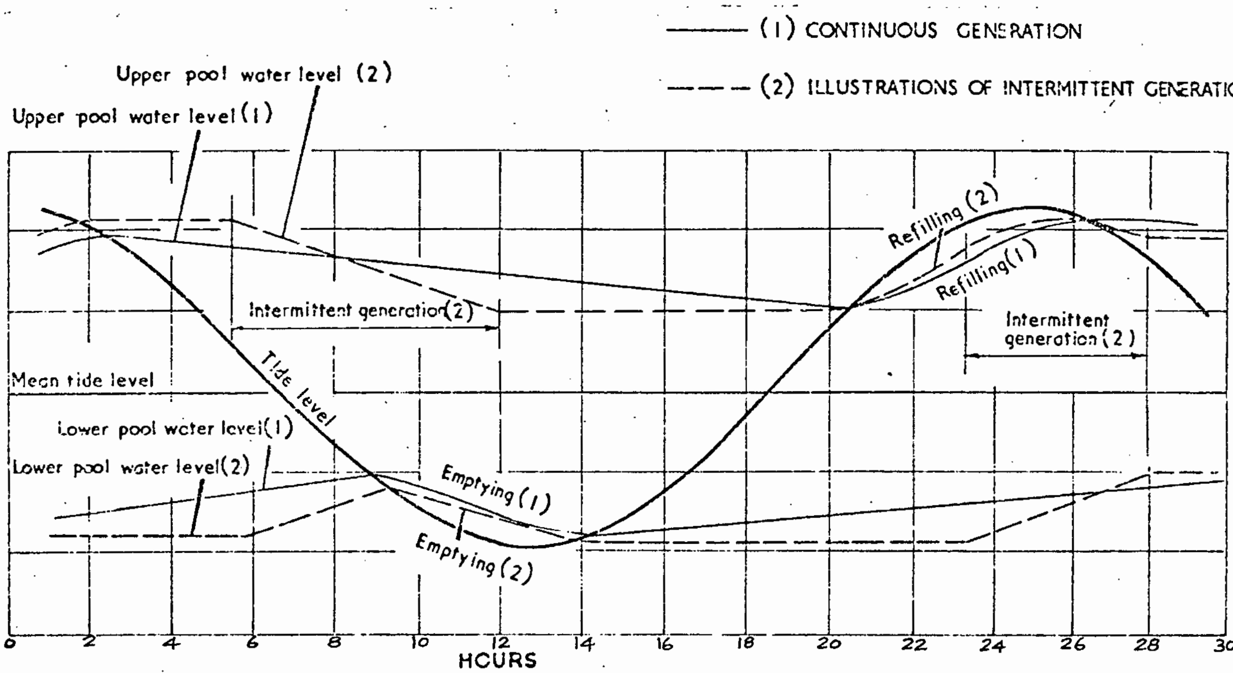


Fig. 6.8 Double pool (De Coeur) scheme (Ref. 41)

Continuous energy generation is obtained at the price of low efficiency : about half the available tidal energy is sacrificed (Ref. 31). Also, the firm power output is only 25% of maximum and the total energy generated is much reduced, compared to the single pool systems (Ref. 40).

In the double pool system the average head is lowered which increases the turbine costs. The scheme requires two sets of sluices and a longer barrage than the single basin systems, and may therefore be more expensive.

Numerous other two or three pool systems have been proposed over the years; some involving turbines between the sea and alternative pools, with dams and sluices for the switching of flows. These schemes are complex and costly and may result in extra head losses due to the difficulty in timing the generation periods.

(5) DOUBLE POOL WITH PUMPED STORAGE

Apart from their many disadvantages, double pool schemes are well suited for pumped storage. For a double pool scheme of the De Coeur type, two alternatives are available : (i) pumps located in the two sea/pool barrages; (ii) pumps in the pool/pool barrage, separately or as reversible pump-turbines (Ref. 31).

For the first alternative off-peak system power can be used when available either to pump the upper pool up or the lower pool down. An energy gain is possible, provided the pumping head to or from the sea is less than the pool to pool generating head.

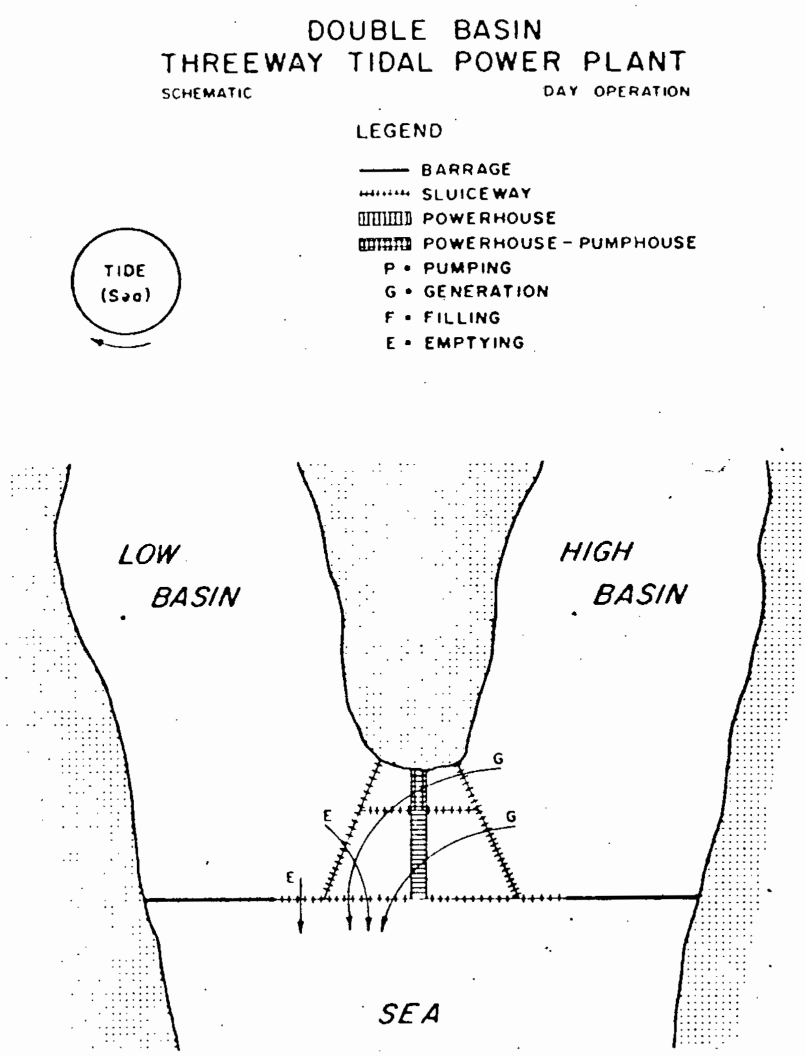
Varzeliotis (Ref. 42) suggested a refinement to the first alternative by introducing more sluiceways; such that the central complex is enclosed by gated waterpassages. Two of the seven operating regimes of Varzeliotis scheme are illustrated in Fig. 6.9. The scheme utilises most of the available head and produces continuous power output.

In the second alternative off-peak system power can still be used for pumping in any non-generating period but with no prospect of energy gain. The first alternative is more expensive but also more flexible, due to pump capacity being independent of generating capacity.

(6) TIDE-BOOSTED PUMPED STORAGE SCHEME

This system consists of two pools, not necessarily of the same surface area, with pump-turbines sited between the sea and the smaller pool (see Fig. 6.10 Sluices are located in the main barrage and between pools A and B (Ref. 41).

The smaller basin B is regulated up or down; this ensures a difference in levels between it and the sea at a forecast time of peak demand. The level of basin B can be raised or lowered by pumping between it and the sea, according to the expected tidal levels and the power demand; off-peak energy is used for pumping. With proper timing of pumping and generating, there may be a gain in nett energy production.



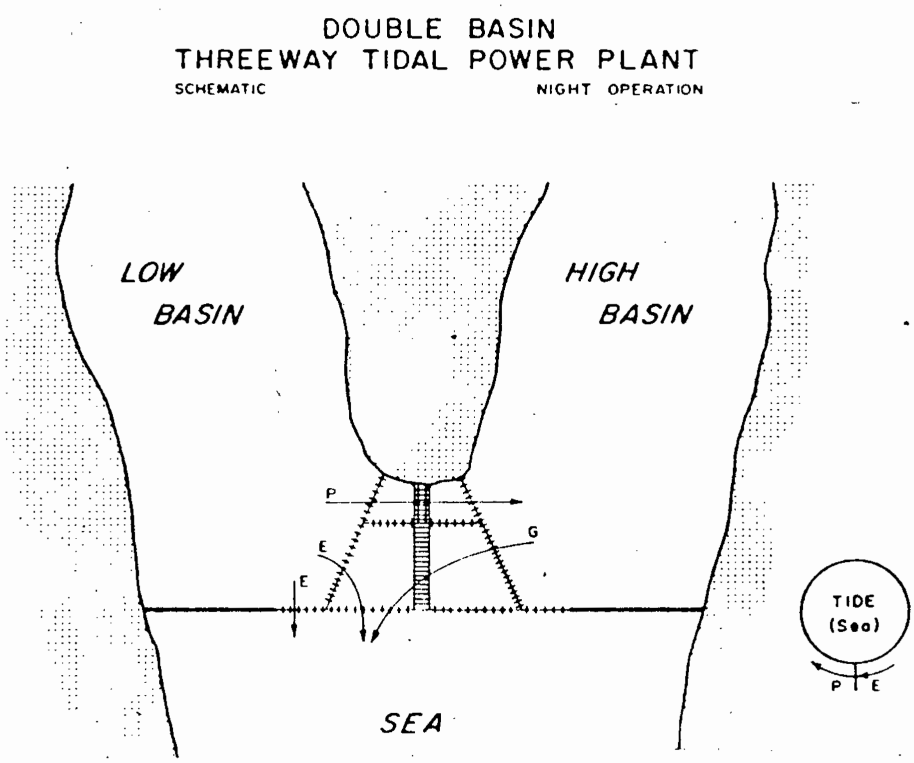


Fig. 6.9 Examples of operating regimes, suggested by Varzeliotis (Ref.42)

The system could be made a more attractive proposition by using the main barrage as a roadway to link the two banks of an estuary.

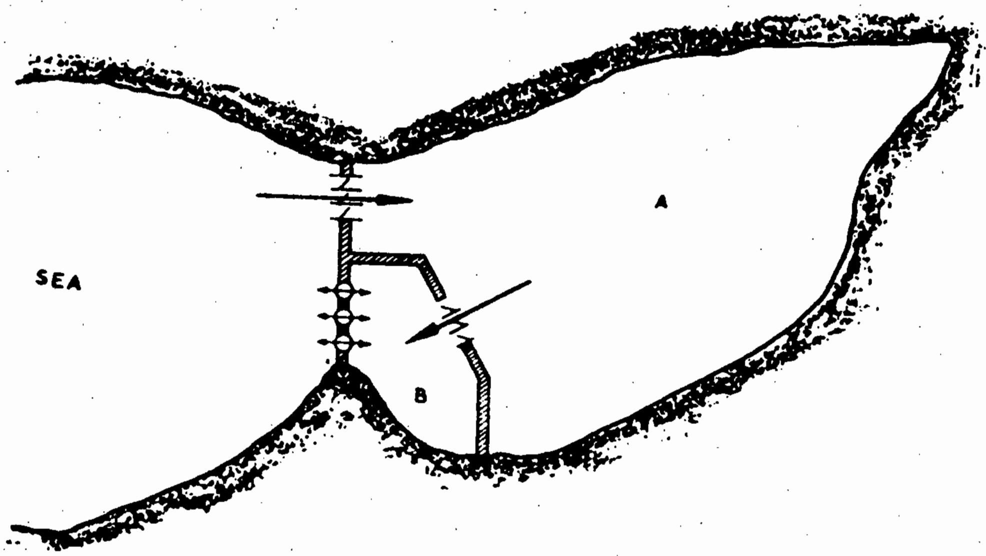


Fig. 6.10 Layout for tide-assisted pump storage plant. (Barrage built for other main purpose.) (Ref. 41).

OTHER SCHEMES : EXTERNAL PUMPED STORAGE

Sorensen (Ref. 44) believes that "tidal power plants by themselves, have little chance of being economical as part of large utility systems. Tidal power pumped storage can have multi-purpose benefits, be a positive energy producer, and be an essential element in an integrated generating center".

Shaw and Thorpe (Ref. 39) found it possible to design a combined pumped storage and tidal power plant which provides both a steady contribution to the generating system at peak demand periods, as well as assisting in balancing the day and night demand on other plant. The system they proposed is similar to the tide boosted pumped storage scheme above, with either generation between the pools or between the sea and the main basin.

Sorensen (Ref. 44) proposed the combination of tidal power with underground pumped-storage and nuclear plants. He investigated the possibility of this combination with regard to tidal power development in the Minas Basin, Nova Scotia, and found that the existing conditions there appeared to be very favourable.

COMPARISON OF VARIOUS TIDAL POWER SYSTEMS

Wilson and Severn (Ref. 41) did a cost analysis of single pool and double pool schemes regarding the three main components : barrages, power house and sluices. The dominant elements in cost distribution are the power house, in all the single pool systems, and the barrages, in multiple pool systems.

The small energy production of the multiple pool systems rules them out, unless the cost of barrages in a particular case is exceptionally low. The disadvantage of the varying or intermittent generation of single pool systems, can only be compensated for by means of interconnected pumped storage!

According to Wilson and Severn (Ref. 41) the choice for future development is likely to be between single pool ebb-flow schemes with external pumped storage and single pool two-way schemes (similar to La Rance), with or without external pumped storage. They favour the first alternative due to its relatively cheap tidal machinery, the fact that all available energy may be extracted and that the external pumped storage plant may at all times act as reserve capacity.

In conclusion, it is evident that a tidal power plant cannot satisfactorily be designed independently : it must be tailored to suit the rest of the particular system in which it is to work, so that system costs may be minimised.

CHAPTER 7 - EXISTING TIDAL POWER PLANTS

INTRODUCTION

Modern tidal power became a reality on 26th November 1966 when General de Gaulle formally opened the barrage and power station on the river Rance in Brittany, France.

The Rance tidal power plant is located between the old walled city of Saint Malo and Dinard (see Fig. 7.1). The Rance's installed capacity of 240 MW may be modest compared to current thermal and nuclear power stations, but it has been functioning without problems producing substantial amounts of pollution-free energy. The station is linked with France's national electric grid.

The only other existing tidal power plant was built by the Soviet Union in Kislaya Bay. Kislaya Guba is a small 400 kW tidal power plant built for experimental purposes and involving minimal expenditures. The basic concept entailed the use of prefabricated units built under factory conditions, floated and towed to site and sunk onto prepared foundations.

Both these tidal power plants are discussed in more depth below.

THE RANCE TIDAL POWER PLANT

The Rance tidal power plant was designed in 1959 and construction started in 1961. The cost of the project was roughly 530 million francs, i.e. 100 million dollars or 48 million* pounds, at 1959 prices (Ref. 46).

The cost of the project is considered rather high but it is difficult to assess the benefit of the convenient 14 metre wide two-lane motorway which shortens the distance between Dinard and Saint Malo by 35 km. In 1976 the motorway took up to 500 000 motor vehicles per month across the river.

* 1 pound = R2,00 in 1959

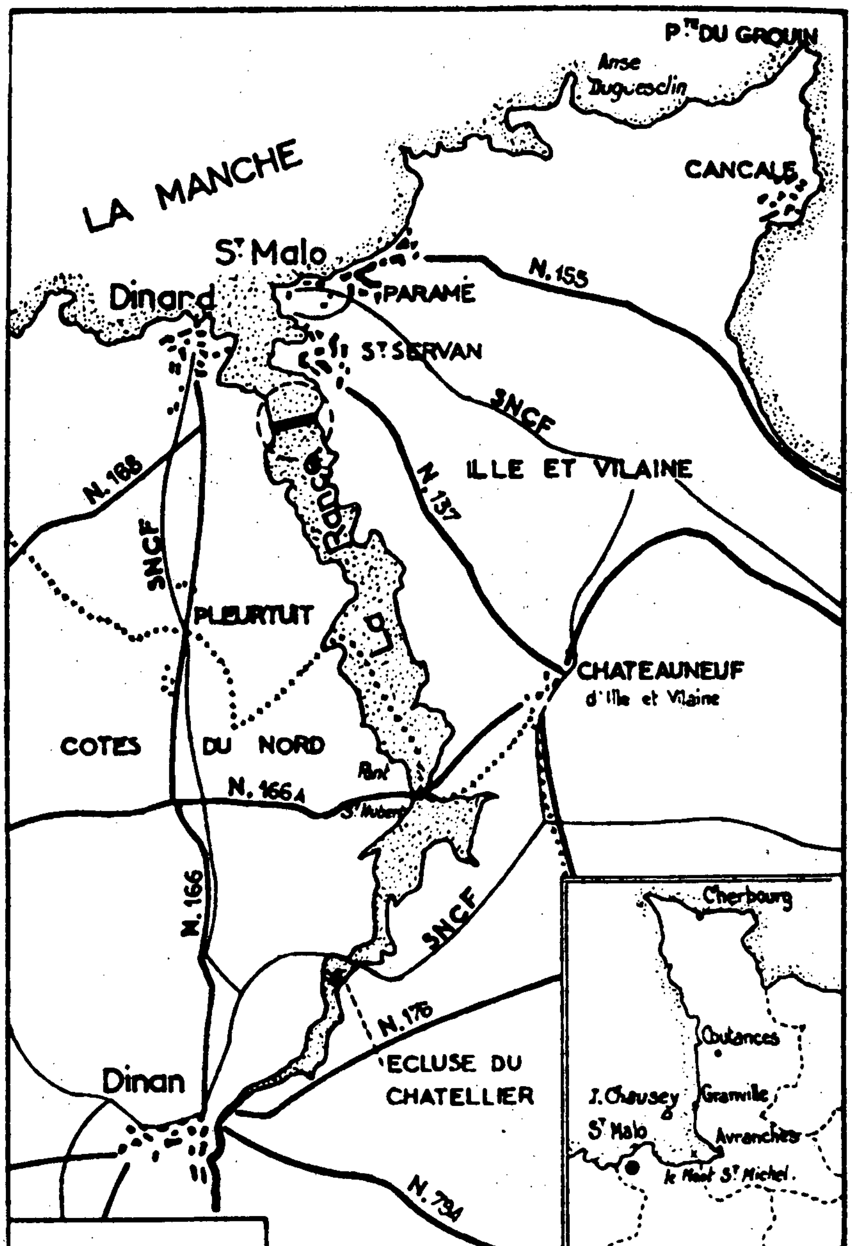


Fig. 7.1 Map of the Rance estuary (Ref. 45).

The following aspects of the plant will now be discussed : general description, planning and development, generating units, construction phases and the control system.

General Description :

To a large extent, the Rance scheme owes its success to a favourable site : the average tidal range is 8,2 m and at peak spring tide it reaches 13,5 m; the Rance estuary provides an area of 22 km^2 of water which can be cut off by a relatively short barrage, 750 m long. Also, the peak flow of the Rance is about 18 000 m^{3}per second (Refs. 30 and 46).

The station has a capacity to displace 718 million m^3 of water. The dimensions of the power plant is 390 metres long by 53 metres wide and with twenty-four generating units, each of 10 MW, has an available nett production of 544 GWh per year. The output of the plant has steadily increased since 1966 (Ref. 31) and in 1976 it was around 560 GWh per year (Ref. 46).

The Rance plant operates on the single pool two-way principle, combined with pumping. The elements of the plant, see Fig. 7.2, are the navigational lock (with two drawbridges) and access building, the power house with its 24 reversible pump-turbines, an inactive dyke (constituting closure) and six sluice gates. As mentioned before, a 14 metre wide roadway on top of the barrage is a fringe benefit of the plant and also completes the picture.

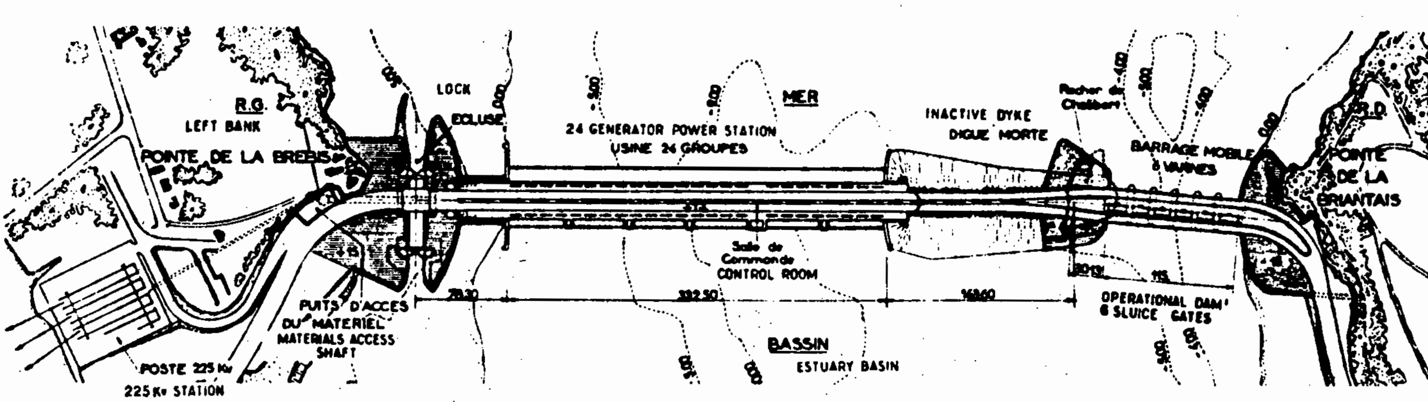


Fig. 7.2 Plane section of the installation (Ref. 47).

A section through the power house is shown in Fig. 7.3. The sketch indicates the relative position of the generating units. The maximum elevation of the water in the pool is 13,5 metres.

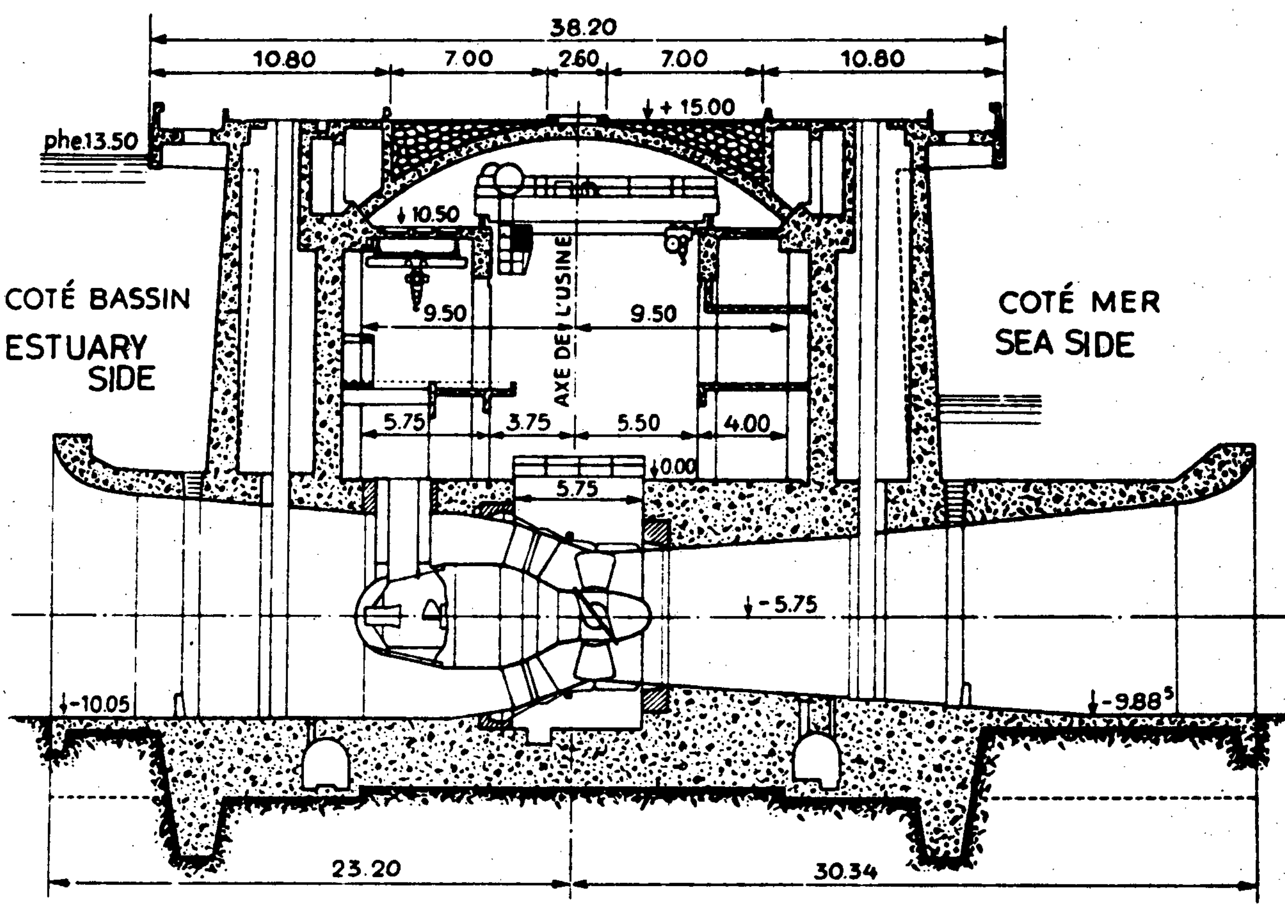


Fig. 7.3 Cross section of a machinery bay (Ref. 47).

Planning and Development :

Robert Gibrat may be considered the "builder" of the Rance tidal power plant (Ref. 28). Gibrats' theoretical research marked a decisive turning point in convincing the French that the tides should be harnessed.

Research and development for the scheme extended over almost 15 years before work began. Scale models played a great part in the development of tidal energy for the Rance. The first model of the Rance was built in Grenoble in 1944, at horizontal and vertical scales of 1/500 and 1/80 respectively (Ref. 36).

The Rance scheme was constructed in dry surroundings, in enclosures sealed off by cofferdams. Olivier-Martin et al (Ref. 45) reported that preliminary studies regarding the major cut-off operations of the Rance river were undertaken. The cut-off and the phasing of the construction operations were studied using a scale model installed in the premises of the National Hydraulic Laboratory at St. Servan, near the port of St. Malo. The model was built at a scale of 1 : 150 without distortion.

The behaviour of the model, regarding external forces, was monitored by means of an analogue computer. The model functioned extremely satisfactorily : the measurements never differed by more than 10% from the anticipated values (Ref. 48).

Research into the erosion of the foundation and the action of the current on the caissons and cells (constituting the cofferdams) in construction was also undertaken in detail (Ref. 45). For this purpose 1 : 40 scale watercourse tests were performed in 1958 at Chatou, based on the hydraulic data developed from the 1 : 150 model.

Since November 1959 an unused lock, in the harbour of St. Malo, was used for tests on a reversible pump-turbine of 9 MW capacity. The lock separates the sea from the Vauban Basin, of 65 ha surface area. Bernshtein (Ref. 29) regards the St. Malo installation as the first tidal power plant in the world. It was equipped with a special control panel and numerous instruments, and was connected to the general power system. The unit operated at a point where the maximum tidal range is 13,5 metres.

Until it shut down in June 1964, the St. Malo unit was tested under very severe conditions, involving numerous generating and pumping operations as well as many change-overs from one type of operation to another. Despite these conditions, the unit proved itself perfectly reliable and showed great operational flexibility (Ref. 49).

The Rance tidal power plant undoubtedly owes much of its success to the research and development done for the scheme over more than a decade : the end product was an ingenious final design!

Generating Units :

Bulb turbines were installed in the Rance plant. A bulb set resembles a small submarine and contains an alternator and a Kaplan turbine. The turbine is totally immersed and the generator is on the axis of the machine.

Twenty-four of these units, rated at 10 MW each and with a blade diameter of 5,35 m were provided for the Rance plant (Refs. 28 , 46 and 49). The turbine rating speed is 94 r.p.m., with a starter drive speed of 380 r.p.m. The most important feature of the bulb turbine is that it functions as a turbine and as a pump, and regulates flow in both directions : tide to reservoir, and reservoir to tide.

The turbines have restricted access for servicing. At the Rance the whole unit can be lifted out of its tunnel housing on to the higher level floor of the machine hall using a large travelling crane. The Rance sets need a head of about 2 metres to start useful operation and reaches reasonable efficiency at a head of 4 to 5 metres.

One of the problems anticipated at the Rance, that of blade corrosion, has not materialised. Corrosion control investigations were made at submerged, intertidal and atmospheric test sites on the shore and in the estuary. A wide variety of coatings were assessed and in the end an elaborate cathodic protection system was decided on (Ref. 49). The total current used for the cathodic protection of the 24 machines amounts to 10 kW. During construction rubber tape was put on surfaces susceptible to damage.

On the whole, the design of the bulb turbines proved to be quite satisfactory for the Rance plant.

Construction Phases :

Construction of the Rance commenced in 1961 and required the removal of 1,5 million m^3 of water and the drying up of about 10 ha of the estuary (Refs. 28 and 50).

The whole tidal power plant was built in the dry, inside three protective sets of weirs which were later dismantled - see Fig. 7.4.

The first phase involved the building of a protective wall on the left river bank to construct the lock, and a wall on the right hand bank, reaching to Chalibert island, for the construction of the sluices.

Phase two involved the construction of the main cofferdam. The cofferdam consisted of prefabricated concrete caissons alternating with cells. The caissons were towed to the site and sunk into position. The northern section, on the seaward side of the plant, was first constructed so that the Rance river could be barred. Once this section was completed (in March 1963), the lock and the sluices were put into use. The water level was kept at 8,5 metres in the estuary, permitting normal navigation. In the meantime the southern weir was progressively constructed and completed towards the end of 1963.

The last phase was the dewatering of the central enclosure, the removal of about 230 000 m^3 of rock and the construction of the power house and the 'inactive' dyke (Fig. 7.4). Dismantling of the cofferdams then started and the first generating sets were commissioned in 1966. The construction phases showed the correctness of the indications gathered on the scale model.

Extensive research had been made into the properties which the concrete had to possess to withstand the action of sea-water as effectively as possible. Mauboussin and Soulas (Ref. 50) have summarised the particulars of the concrete constituents, the concreting procedure and site control. The concrete structure has not been seriously affected since construction and only minimal water seepage has occurred.

Erosion of the foundation rock close to one of the water passages on the pool side, caused some concern in 1970. Eighty m^3 of concrete was pumped in together with concrete blocks - apparently this solved the problem (Ref. 31).

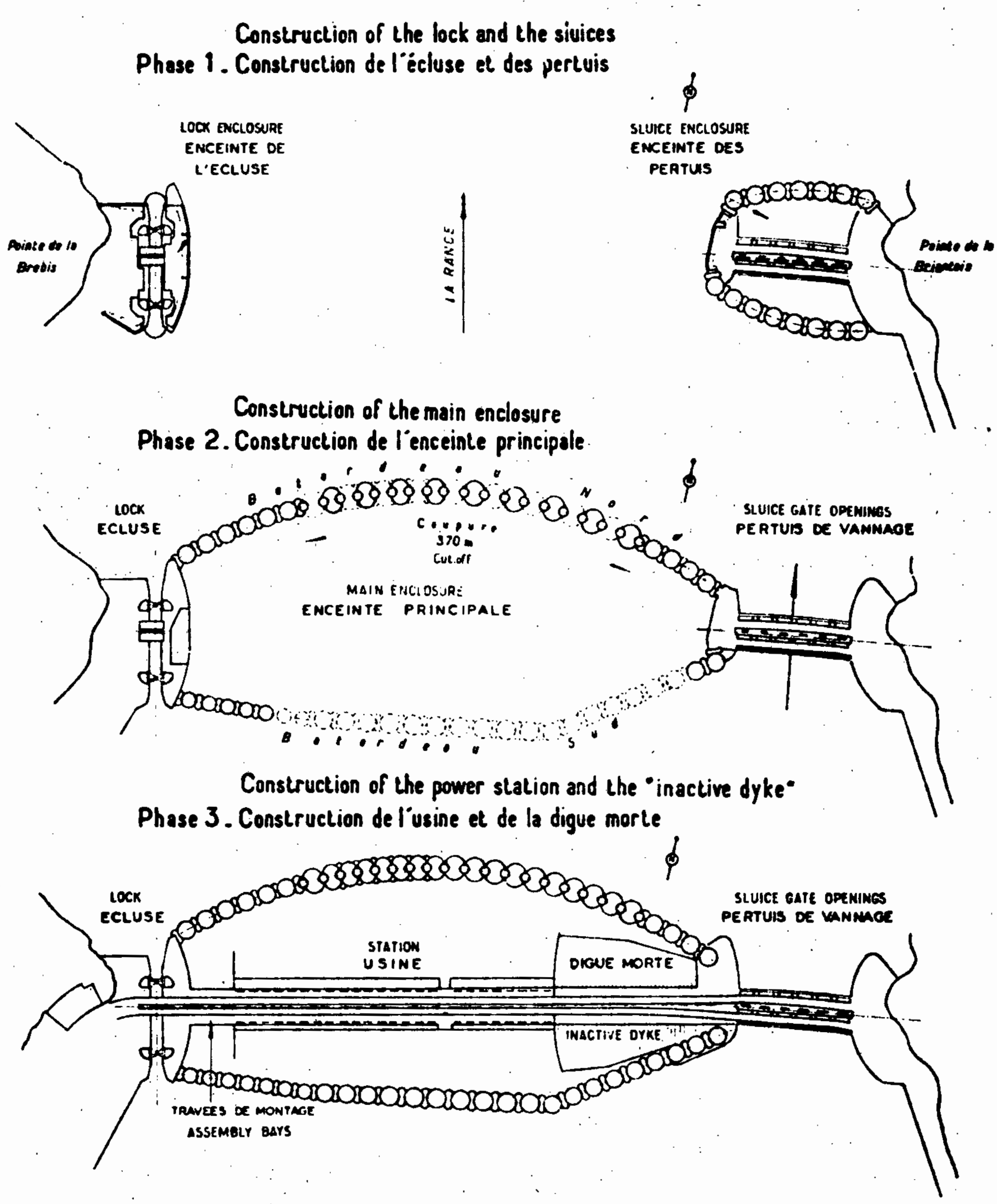


Fig. 7.4 Construction phases (Ref. 50)

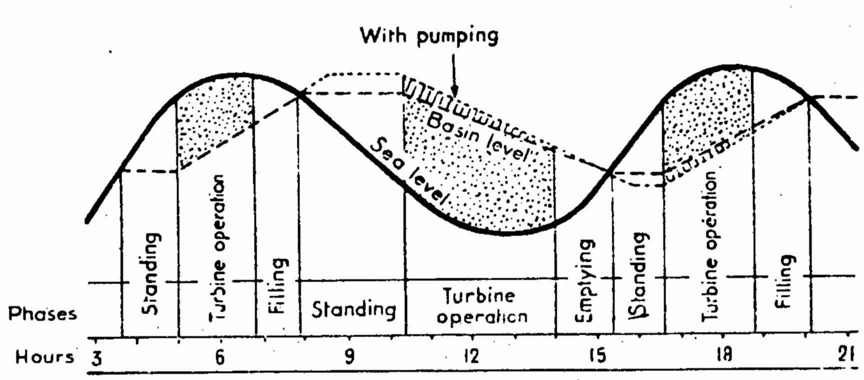
In general, the barrage has so far only required normal maintenance and this situation is expected to continue in future.

The Control System :

The control system of the Rance tidal power plant is another important factor contributing to its success. The system is computer controlled and the local control room is linked to Electricité de France's main regional control centre at Nantes (Ref. 46).

The system can be programmed either to give the lowest effective cost per unit (which is normally chosen), or to optimise the total number of units generated within a tidal cycle. A measure of the power produced at any instant can also be given. An important facility of the system is that off-peak power can be used to drive the generators as pumps; this speeds up the change-over between turbining operations in opposite directions, and more important : the pumping results in a nett energy gain!

A typical operating regime of the pump-turbines is illustrated in Fig. 7.5.



Typical operating regime of the pump-turbines at La Rance. Note the additional head that can be gained by pumping, an option sometimes taken at off-peak times.

Fig. 7.5 (Ref. 46)

The opening of the six large sluice gates is also computer controlled. This is done when the head is too small for an effective generating operation.

The computer print-outs give a series of data at ten minute intervals throughout a day. The data includes water levels, the head, the number of machines operating and in which direction, power being generated and the total cummulative nett energy generated on the day concerned.

The designers and builders of the Rance scheme had access only to slow computers. Fortunately, however, more sophisticated and high speed computers could be utilised to control the energy production satisfactorily.

KISLAYA GUBA EXPERIMENTAL TIDAL POWER PLANT

The Kislaya Guba plant is the only other tidal power station of note. It is located on the Barents Sea, some 60 km north of Murmansk, and was commissioned in 1968. The site is not far from an electric power system and as such did not call for large expenditure on the construction of transmission lines.

The object of building a pilot plant at Kislaya Bay was to examine the feasibility of building and operating a tidal power plant in the severe conditions of the Arctic : temperatures down to -35^{o}C for up to 200 days of the year! (Refs. 51 and 52).

General Description :

Kislaya Bay is a small deep basin with an area of one km^2, connected to the sea by a narrow estuary about 50 m in width. The tide is relatively low and varies from 1,3 to 3,9 m, which is less than at other portions of the Murmansk and Mezen coasts (Ref. 53).

The dimensions of the tidal station building are 36 m x 18,3 m x 15 m high. This concrete box, a prefabricated caisson, contains two turbine conduits, for two bulb turbines. The only installed turbine is similar to the Rance machines, except that coupling is not directly to the generator but via a planetary gear which raises the speed from 72 to 600 r.p.m. The output of the generator is 400 kW, or 1,2 GWh per year, and the blade diameter is 3,3 m (Refs. 31 and 54).

Although Kislaya Guba may be regarded as a very small station, it has contributed considerably to the development of tidal power in future, due to its peculiar method of construction : the float-in-place method. This method is discussed below.

Planning and Construction :

The cost of the Rance plant was about 2500 francs per kW, approximately three times a conventional hydro-electric station. However, the Russians maintain that their float-in-place method is far cheaper.

According to Bernshtein (Refs. 53 and 54), an examination of the expenditure pattern of the Rance project revealed that the main cause for the high cost was the cofferdam protection, enabling construction in the dry. Russian research was therefore directed towards the elimination of cofferdams, using floating components : a method based on the construction of underwater tunnels (in the U.S.A., Canada, West Germany, Italy) and dykes (in the Netherlands).

Research on the construction of Kislaya Guba began in 1962. A prepared foundation for the prefabricated plant was planned. Hydraulic investigations of a model of the narrow neck in the Kislaya Bay made it possible to establish the size of foundation layers and the velocity and hydraulic conditions to be experienced.

It was very important to use reliable construction materials for the construction of the power house. Sulphate-resisting cement together with a certain plasticiser was used for the concrete. To reduce the stresses arising from temperature differences (from -1^{o}C down to -35^{o}C), the structure above the water line was covered with a 5 cm layer of thermo-hydraulic insulation of epoxy resin. Protection of the structural and exposed metal parts against corrosion by sea water, was solved by electro-chemical means (Ref. 53).

The power house was assembled on a raft in Murmansk. The total volume of concrete was 1800 m^3, and the weight of the structure was 5200 tons. The structure was towed to the site in 18 hours 20 minutes. The most important part of the whole experiment, the submergence of the power house onto the prepared base, was then successfully undertaken; the alignment of the plant was done with the aid of shore based winches (Fig. 7.6).

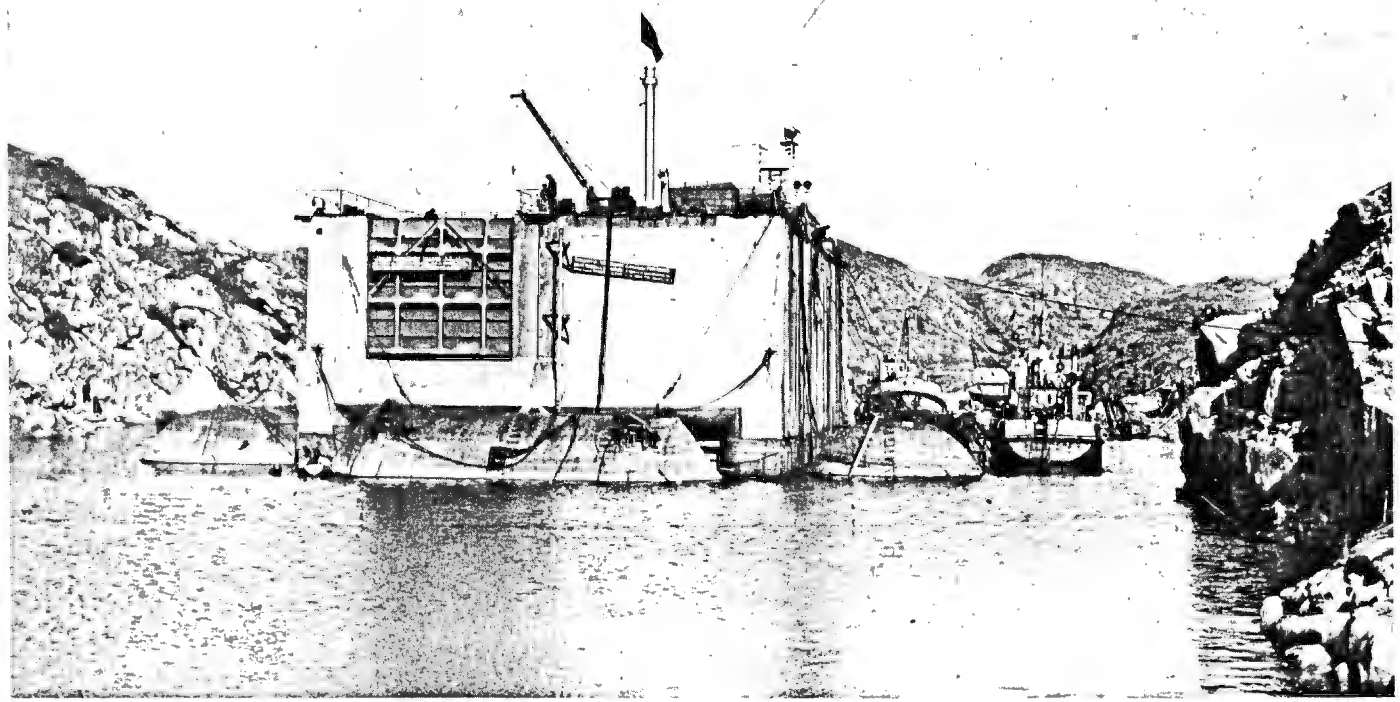


Fig. 7.6 Aligning the Tidal Power Station building before sinking (August 1968) (Ref. 53).

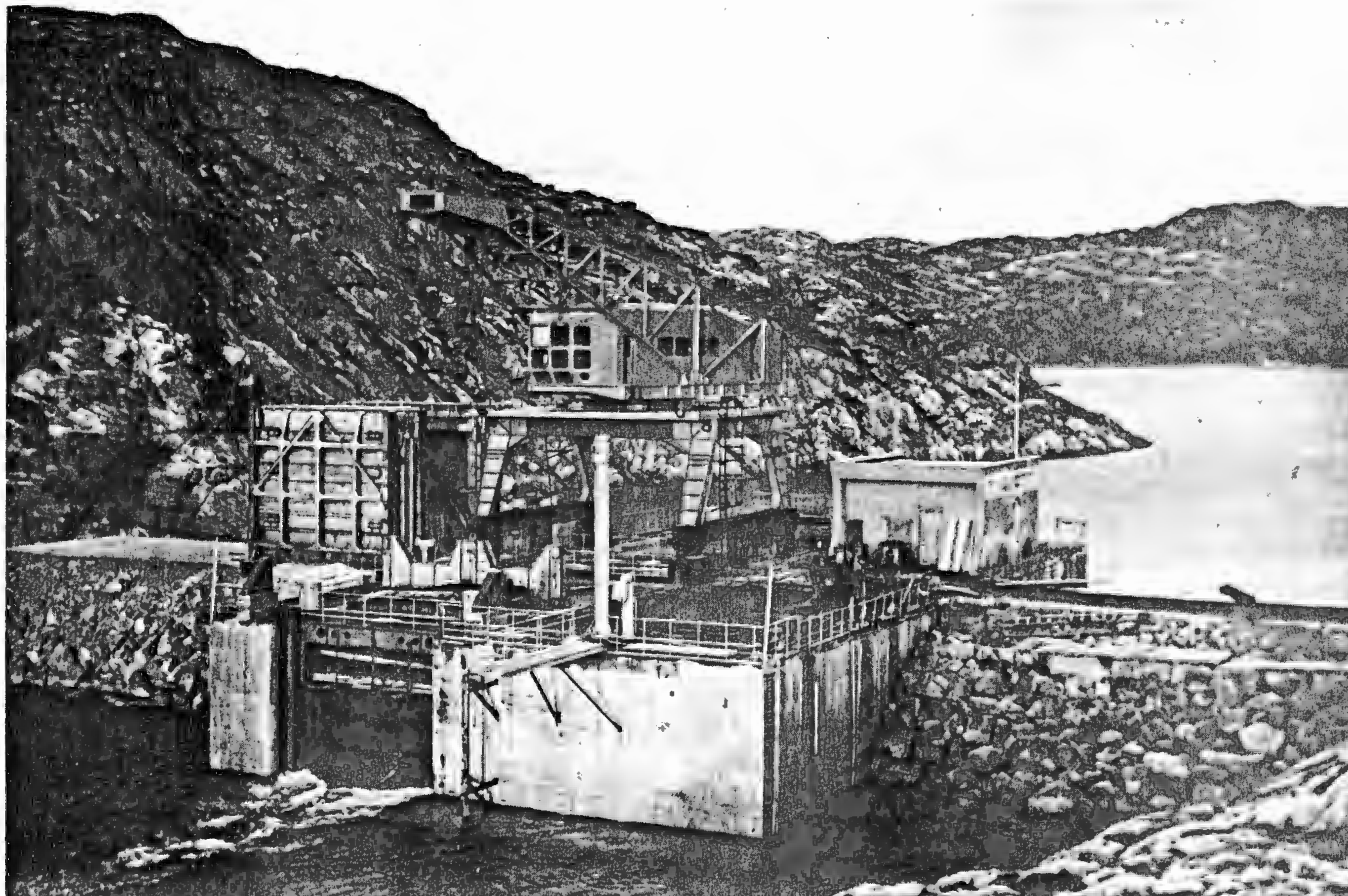


Fig. 7.7 Kislaya Guba tidal power station as completed with the turbines and surface spillway working (October 1969) (Ref. 53).

The bay was then dammed using conventional methods, and the plant was ready for operation during the closing days of 1968.

DISCUSSION AND CONCLUSIONS

The Rance plant was the pilot for the large Chausey Islands' tidal power project, planned for an output of 12 000 MW. However, shortly after the completion of the Rance the French government decided to shelve the Chausey project. Priority was given to the construction of atomic plants over tidal power plants.

According to Bernshtein (Ref. 53) there were two factors contributing to the delaying of the Chausey project : firstly it seemed impossible to include the proposed plant, with weekly power fluctuations from 3 000 to 12 000 MW, into the country's power system, and the second obstacle was the high cost of constructing tidal power plants (the cost of the Rance was 2500* francs per kW).

Further disadvantages of the Rance scheme is pointed out by Wilson (Ref. 40). He compared the four to five hours' continuous generation of the Rance to his proposed scheme for Solway Firth, which is to be capable of sustaining a load peak of eight hours' duration. A further objection to the Rance is that the extreme water levels in the basin is a hindrance to navigation. However, he admits that this hindrance is of no significance.

According to Charlier (Ref. 28) the Rance barrage has done nothing to spoil the surrounding countryside, and that the sheer uniqueness of the project has made it a major tourist attraction : busloads of tourists come to view "the picturesque countryside and the scientific achievement of the dam".

On the technical level, a great deal has been learned about corrosion protection methods. However, the most important fact is that the Rance is functioning very satisfactorily. The success and performance of the Rance scheme will undoubtedly play an important role in the future development of tidal power.

* (R1 = ± 7 francs, in 1966)

The Soviets seem intent on harnessing tidal energy. According to Bernshtein (Ref. 53 and 54) the tidal power potential of the U.S.S.R. amounts to approximately 17% of the world total. Kislaya Guba was built as a pilot plant for the proposed large plants at Mezenskaya (5 000 MW), Tugursk (10 000 MW) and Penzhinsk (35 000 MW).

At Kislaya Guba 500 monitoring and measuring instruments were placed in the building, permitting study of structural forces, temperature effects and plant energy patterns. Indications are that the plant structure has not been adversely affected by the low temperature conditions of the Arctic.

The main characteristic of the Kislaya Guba plant was its float-in-place method of construction : a money-saving and a time-saving method. According to Bernshtein (Ref. 53) this method is being considered for many of the large schemes planned for places elsewhere (Bristol Channel, Solway Firth, Bay of Fundy, Passamaquoddy Bay and San José).

In conclusion, the Rance has demonstrated that tidal power could be integrated into an existing electrical energy network, while Kislaya Guba's contribution to tidal energy development is the float-in-place method.

CHAPTER 8 - OTHER TIDAL POWER DEVELOPMENTS

INTRODUCTION

A large number of sites in the world are considered suitable for the construction of tidal power plants. Charlier (Ref. 10) estimated the figure at about a hundred sites.

Twenty-seven major tidal power plant sites are indicated in Fig. 5.1. Sites experiencing average tidal ranges of 3 to 4,6 metres and more than 4,6 metres, are indicated in Fig. 5.1. If only sites with a mean tidal range of at least 7 metres and within 160 km of electrical demand areas were considered, "only France, England, the Bay of Fundy (in Canada) and the Shanghai region would be worthy of consideration" (Ref. 28).

However, factors such as the basin's characteristics, the quality of the foundation soil underneath the barrage and other geological aspects should also be considered when selecting sites for tidal power projects. Therefore, apart from France, England, Canada and the United States, tidal power developments in the Soviet Union, Australia and the Argentine are also discussed in this chapter.

FRANCE

Since 1921 a number of very large schemes in the Gulf of St. Malo have been proposed (Ref. 29). Electricité de France decided to concentrate on one only : the Chausey Islands project, a single basin variant.

It was planned to construct the Chausey plant over a period of 15 years; to be completed by 1980. The power house would be located in the western dam (Fig. 8.1). The plant would be built in two stages. The first stage would involve construction of the dividing dam and half of the western dam; after completion, this stage would operate as a single basin two-way scheme. The second stage would embrace construction of the northern dam and the remainder of the western dam; at completion another single basin two-way scheme would come into operation.

The Chausey Islands have tides exceeding ten metres. The total basin area at high tide would be 730 km^2. Six hundred 20 MW pump-turbines would be installed in the caissons of the western dam. The capacity would be 12 000 MW at an annual output of 25 TWh (Ref. 29).

Although the planned output of the Chausey plant was to be 50 times more than that of the Rance, Gibrat estimated its cost at only about 20 times more, i.e. at 10 000 million* francs. Unfortunately, as was pointed out earlier, the Chausey scheme was shelved by the French government shortly after the Rance plant was commissioned.

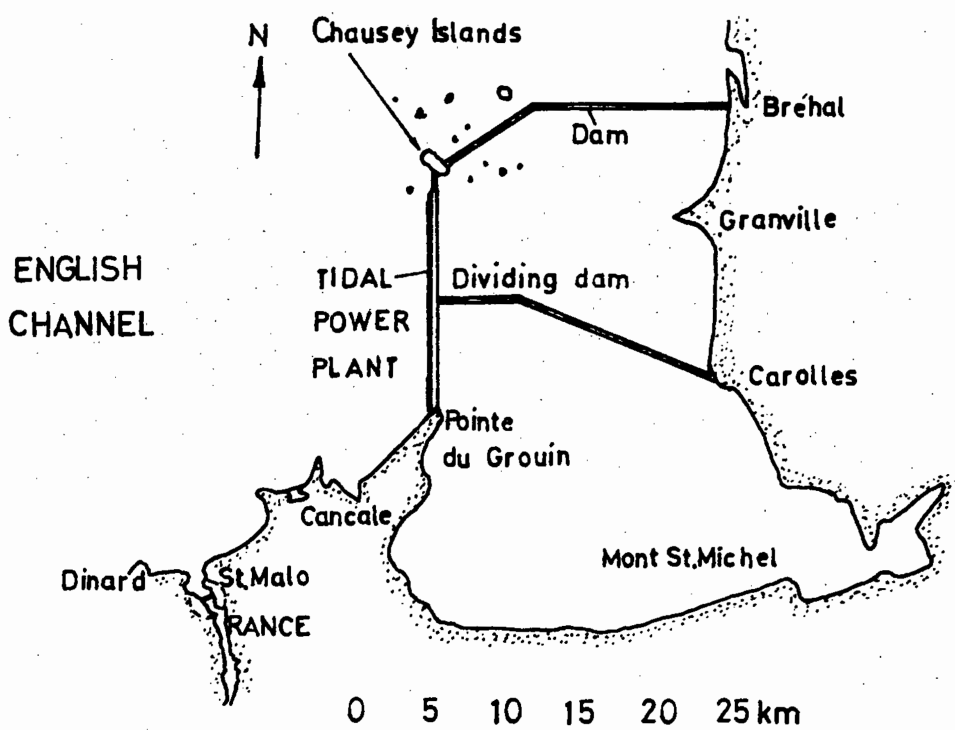


Fig. 8.1 Chausey tidal power plant, 1959 project.

* (R1 = ± 7 francs, in 1966)

SOVIET UNION

The Soviets pride themselves on being the holders of the largest reservoir of power. As indicated in the previous chapter, they seem intent on harnessing tidal power and very large schemes have been proposed for the White Sea (5 000 MW, at Mezenskaya) and the Sea of Okhotsk (10 000 MW, at Tugursk, and 35 000 MW, at Penzhinsk). These projects would result in an annual output of 160 TWh (Refs. 54 and 55).

According to Bernshtein (Ref. 54) the Mezenskaya scheme is currently being designed. A dam of 50 km length and average height of 15,25 m will be built. The tidal range in the Gulf of Mezen varies from 4,6 to 5,8 m and the storage area of the basin will be 860 km^2. The storage capacities of the enormous schemes proposed for the Okhotsk Sea are even larger : 1 140 km^2 and 6 720 km^2, for Tugursk and Penzhinsk respectively (Ref. 54). The tidal ranges in the Okhotsk Sea are also much larger and varies up to 11,6 metres.

The Soviets have yet to solve a number of complicated tasks before these schemes become a reality; amongst these are the difficulty in manufacturing possibly thousands of generating units, and the construction of barrages under exceptionally complicated climatic conditions.

CANADA AND THE UNITED STATES

Large tidal power projects were considered for Passamaquoddy Bay (on the United States – Canada border) and the Bay of Fundy in Canada, (Fig.8.2) since the 1920's.

The Bay of Fundy experiences the strongest tides in the world : up to 16 metres! In the Passamaquoddy region the tide often reaches 15 metres (Ref. 55). At Anchorage, in Alaska, the mean tidal range is 7,7 metres (Ref. 57).

Tidal energy developments in the Fundy/Passamaquoddy region and the Cook Inlet, Alaska, are discussed below.

Passamaquoddy Bay :

Construction commenced in 1935 on the so-called Passamaquoddy tidal power plant, the only United States project. Unfortunately, work came to a standstill in 1936 when the U.S. Congress failed to continue appropriations.

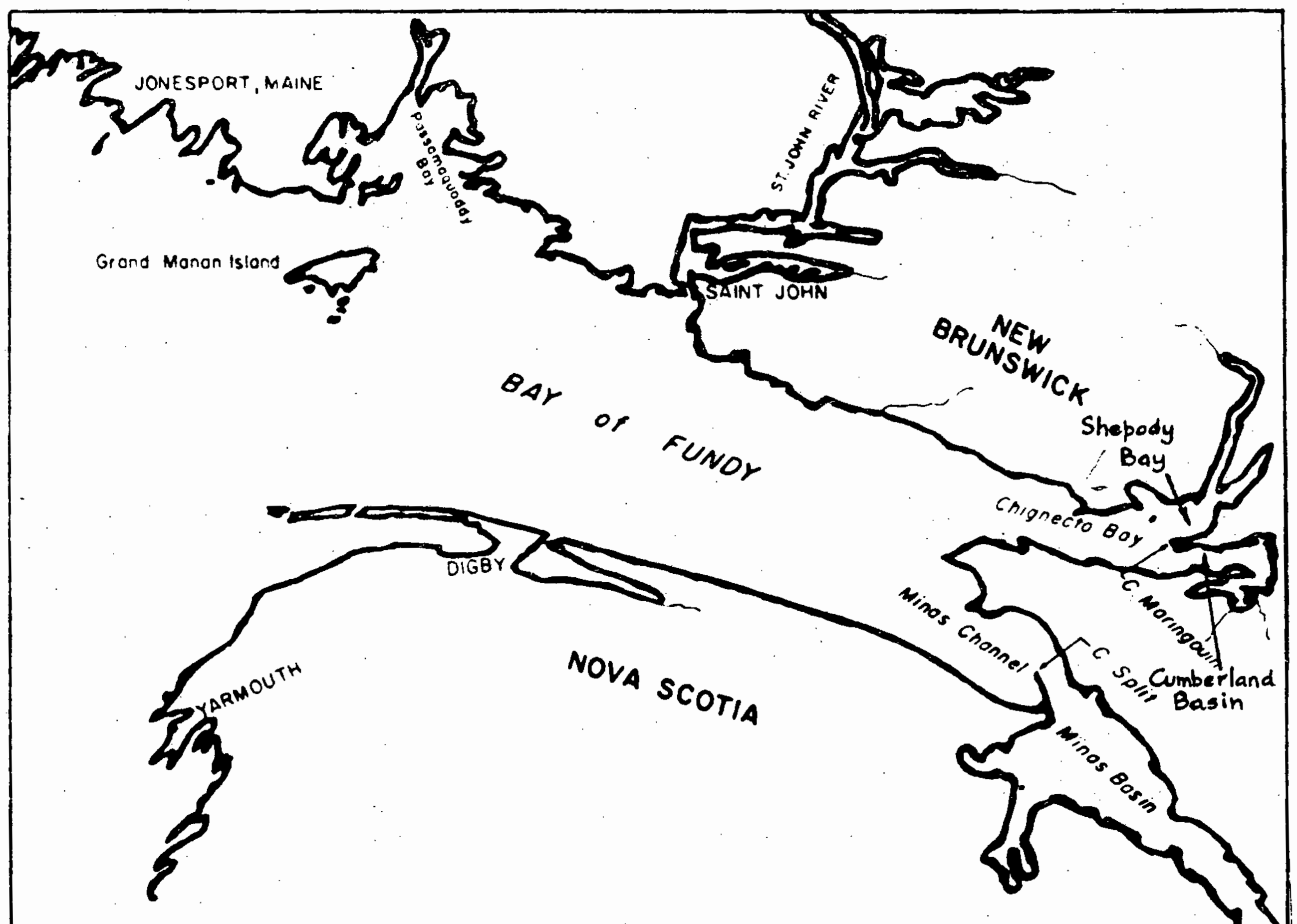


Fig. 8.2 Bay of Fundy region (Ref. 56)

The Passamaquoddy project would involve a double pool scheme, with Passamaquoddy Bay as the high pool and Cobscook Bay as the low pool (Fig. 8.3). The operation of the scheme is as follows : the high pool is filled during the incoming tide while the locks of the low pool are closed. The stored floodwaters are then released through the power house to produce electricity and to drain into the low pool and then back into the sea (Ref. 28). This scheme was regarded as more flexible than a single pool system in that the storage water could be used to generate power at the most appropriate times. Power generation would vary from 65 to 345 MW.

A further proposal was made in 1963 but turned down for economic reasons. This plan included a double pool tidal plant together with adjoining hydro-electric and conventional power generating facilities capable of producing 1 250 MW of electrical power.

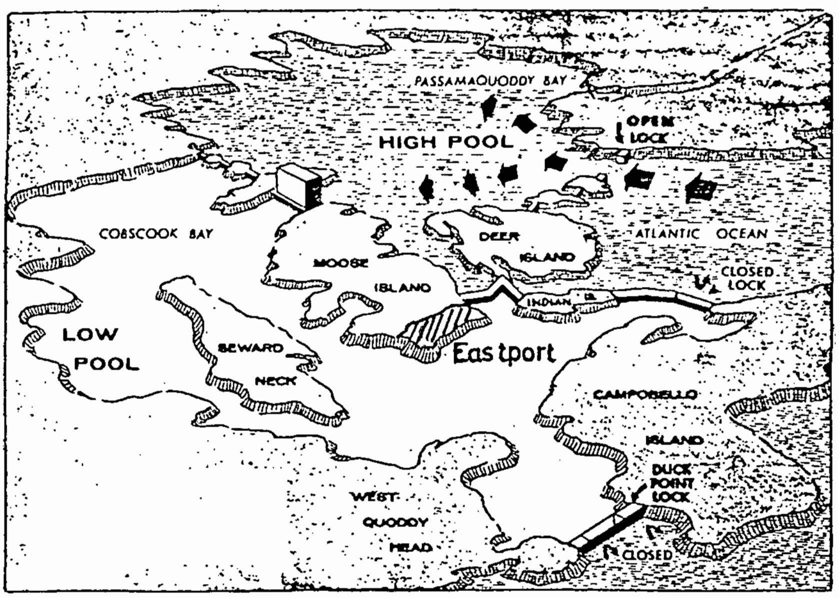
According to Griffin (Ref. 55) the proposed U.S. energy program for the 1970's and beyond makes no mention of tidal power. However, a Boston firm announced in 1976 (Refs. 46 and 58) that they were carrying out a feasibility study for a tidal power scheme at Eastport (Fig. 8.3), Maine, on the United States – New Brunswick border.

Bay of Fundy :

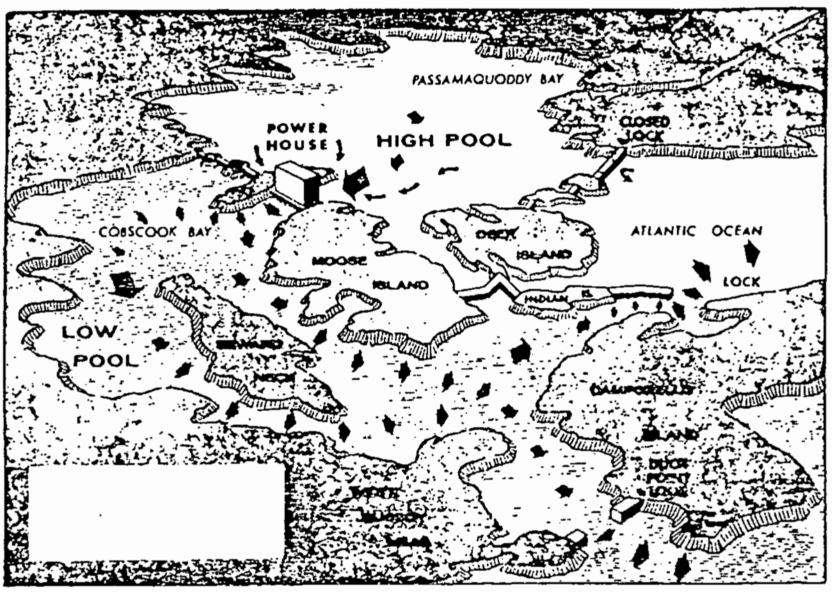
Tidal power development in the Bay of Fundy is currently being considered by a joint federal-provincial board (Ref. 46).

At the head of the Minas Basin, at the north easterly end of the Bay of Fundy, the maximum tidal range is up to 16 metres. In Chignecto Bay, at the northerly end, the tidal range is 14 m but, at the southerly end, in St. Mary's Bay, the range is only about 7 m (Ref. 30).

Lawton (Ref. 30) reported on investigations for tidal development in Shepody Bay, the Cumberland Basin (both at the head of Chignecto Bay) and the Minas Basin; of the 23 potential sites examined, these three sites showed the best possibilities for economic development.



(a)



(b)

Fig. 8.3 The proposed plan for a two basin tidal power project in Passamaquoddy Bay; (a) the flow of incoming tides fills the upper basin high pool. The lower basin locks are closed to keep out the flood tide and (b) stored flood tidewaters are released through the power house into the low pool and back into the sea. (Ref. 55)

According to a very recent report (Ref.59, May 1978) detailed evaluations showed that only the Cumberland Basin (1058 MW) and the Cobequid Bay (3800 MW), in the Minas Basin, could be developed economically. The total projected capital requirements to develop the Cumberland site, assuming commissioning in 1990, would be 3 120 million* dollars (Refs.59 and 60), including allowances for inflation and interest during construction. A tidal power project in Cobequid Bay would cost three times more.

Investigations of different operating modes confirmed that a single pool one-way scheme, with generation on the ebb-tide, would be the least expensive per kWh of energy generated. Also, the "float-in-place" method of construction is estimated to be less costly than construction in situ (Ref. 59).

Lawton (Ref. 61), in reference to the Bay of Fundy, pointed out that although tidal power developments were capital intensive, their economic life has been estimated at 75 years. Alternative generation sources such as fossil-fuel-fired and nuclear thermal power plants are thought to function economically for no longer than 30 years. Inflation in fuel costs might become of considerable significance during the course of 75 years, and would tend to improve the economic position of tidal power, as tidal power plants have no fuel costs.

"A detailed investigation and definitive design and a detailed specification of a single basin for tidal power" in the Cumberland Basin has been recommended (Ref. 59). The Canadian Government has already indicated that it would provide half of the 33 million dollars required for such an investigation.

Alaska :

The extra-ordinary tidal range (mean range of 7,7 m) in the Cook Inlet (Fig. 8.4) was recorded in 1798 by Captain James Cook. Since then there has been speculation about the possibility of harnessing tidal energy in Alaska.

Alaska is a remote and sparsely populated state. Its electrical load is small, resulting in an elementary network system. The inlets become full of drift ice in winter, large proportions of silt are in suspension and earth movements may be expected regularly, due to the region being active geologically (Ref. 57).

* 1 dollar = ± R0,87

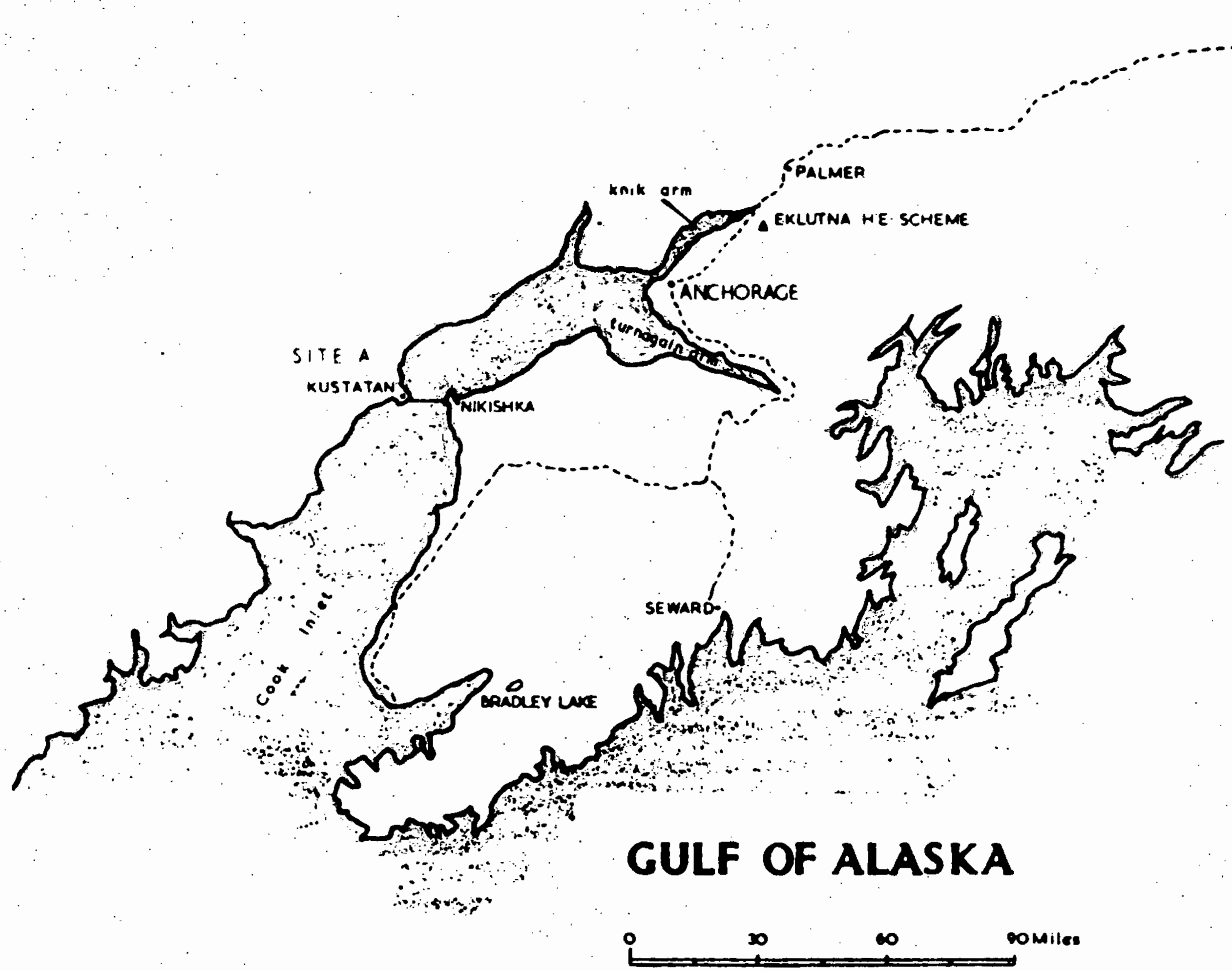


Fig. 8.4 Map of the Cook Inlet, Alaska (Ref. 57)

According to Wilson and Swales (Ref. 57) the two Arms at the northern end of Cook Inlet, Knik and Turnagain, could be developed to provide tidal power of 6 and 12,5 TWh per year respectively.

The partial development of Knik Arm would result in the following benefits :

(i) provide 750 GWh of completely firm power per year after integration with an Eklutna pumped storage scheme,

(ii) provide a permanent road/rail/cable/pipeline crossing of Knik Arm near Anchorage leading to development of the western side of the Arm,

(iii) provide the port of Anchorage with permanent deep water, reduced currents and probably greatly reduced ice hazard in winter (Ref. 57).

Large natural gas and oil fields have been discovered in the area; fuel costs for thermal generation are therefore low. The costs of tidal energy would have to be competitive before construction could be justified!

BRITISH SCHEMES

The United Kingdom, particularly the Severn estuary, experiences the second strongest tides in the world : up to 14 metres!

Two sites in Britain, one in the Solway Firth in Scotland and the other in the Severn Estuary in Wales, are discussed below .

Solway Firth :

The Solway Firth is a wide, shallow inlet of the Irish sea bordering the coasts of Scotland and England (Fig. 8.5). Wilson (Ref. 40) proposed a tidal power scheme in the Solway Firth with power output varying between 400 and 1600 MW.

Wilson's feasibility study (Ref. 40) of this tidal power project resulted in interesting conclusions :

(i) the generation of large quantities of energy is technically feasible,

(ii) the energy production could be integrated with other electricity supply sources,

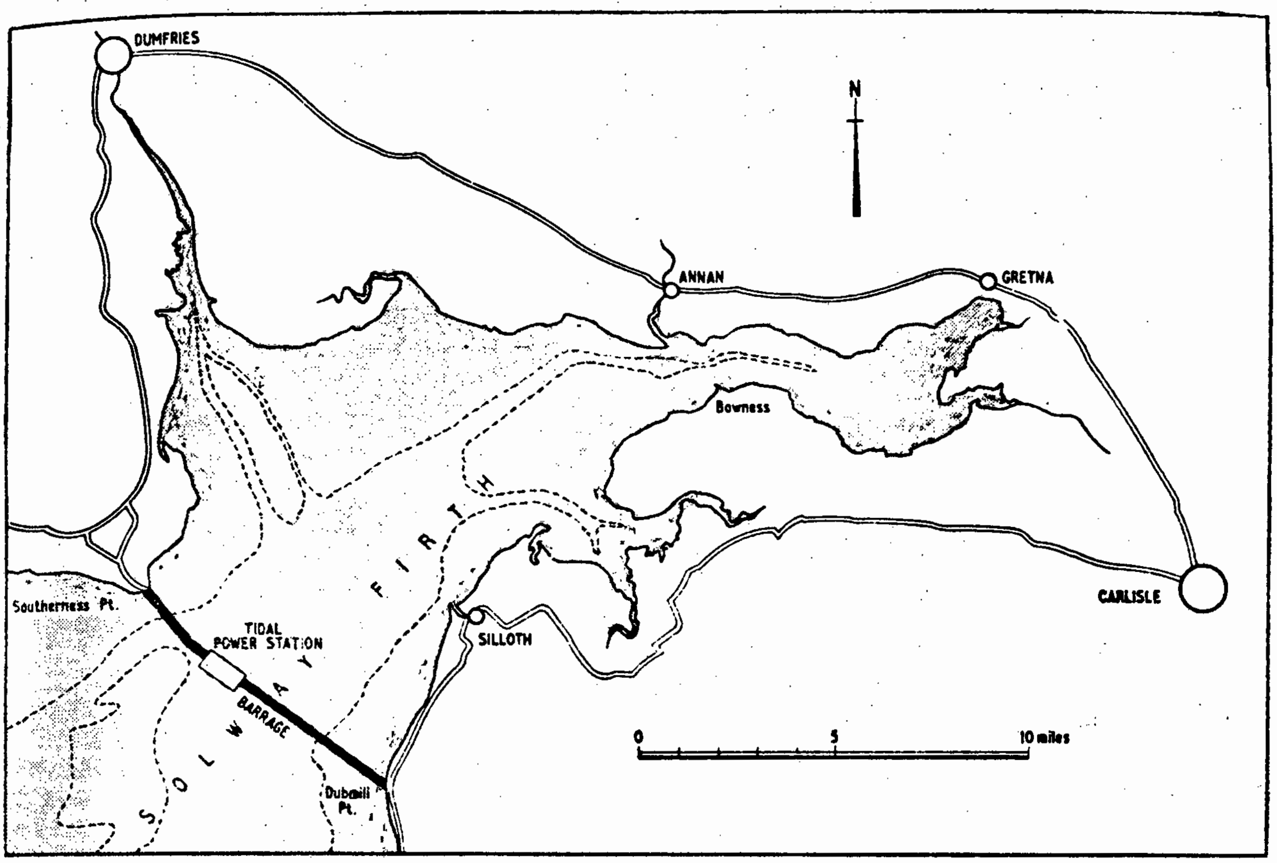


Fig. 8.5 Proposed Solway Firth tidal power barrage (Ref. 40).

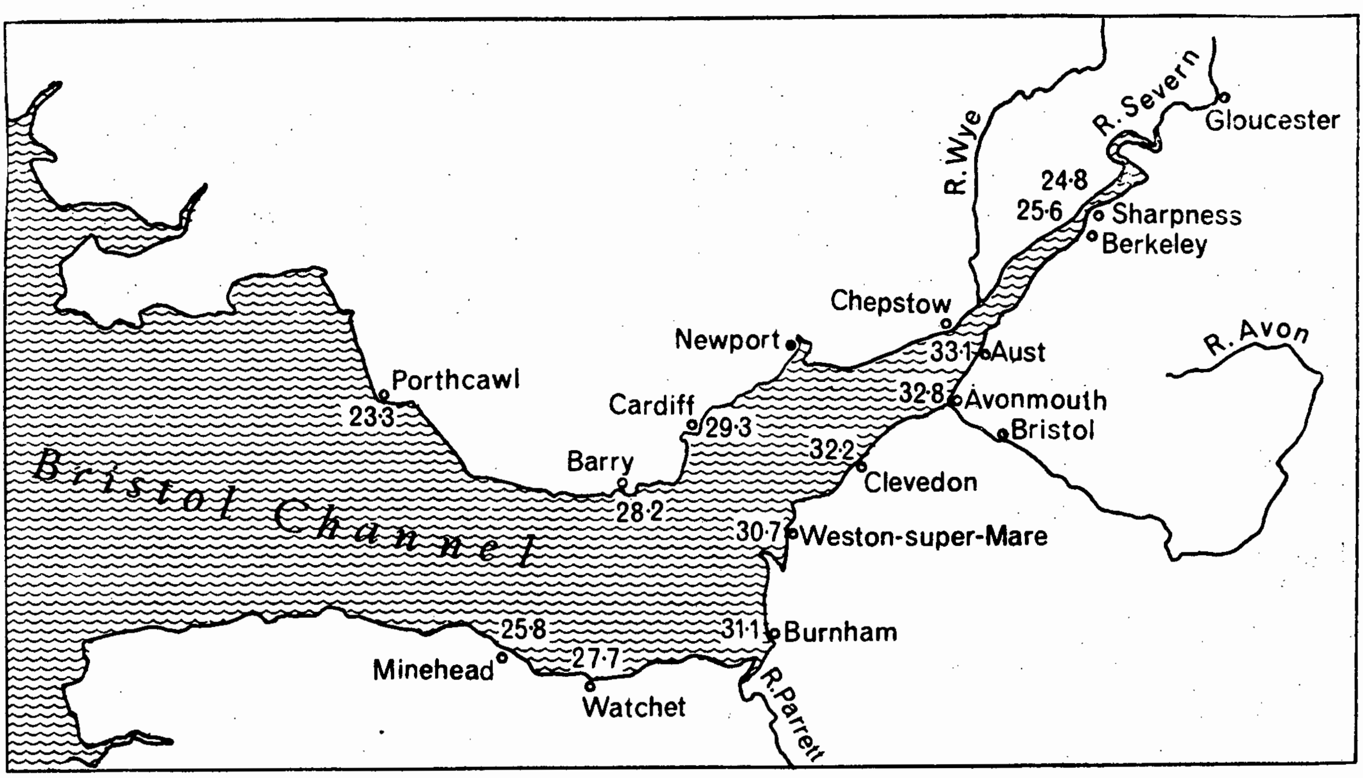


Fig. 8.6 Average tidal ranges (in ft.) in the Severn Estuary (Ref. 38).

(iii) the overall annual cost of a scheme integrated with pumped-storage appears to be lower than pumped-storage only in conjunction with conventional plant,

(iv) a tidal power barrage would improve navigation into the estuary ports and could result in an important road link between the Scottish and English counties opposite the Firth.

However, the outstanding site for the utilization of tidal energy in Britain is the Severn Estuary; understandably, the proposal for the Solway Firth was therefore allowed to fall into oblivion.

Severn Estuary :

The Severn Estuary provides an estimated two-thirds of Britain's exploitable tidal energy (Ref. 62). According to Wilson (Ref. 31) a Severn Estuary scheme could be designed to produce between 8 and 14 TWh annually at a competitive cost. A fringe benefit of such a development would be a second road crossing of the estuary, which may anyway be necessary by 1985.

The idea of barring the Severn was first suggested seriously as long ago as 1924. Since then until the early 1970's, virtually every proposal was turned down by the British government due to the high construction cost involved. However, the main proponents of the two past decades, Wilson (Refs. 20 , 31 and 43) and Shaw (Refs. 34 , 35 , 38 , 39 , 63 , 64 , and 65) never gave up!

In 1976 the British Department of Energy commissioned the Hydraulics Research Station at Wallingford to examine the influence of proposed barrage schemes on tidal levels and currents in the Bristol Channel (Ref. 66) Schemes tested were (i) a single barrage, generating on ebb-tide only, proposed by Wilson in 1968, and (ii) two double-basin schemes, proposed by Shaw and the Central Electricity Generating Board (CEGB) respectively (Fig. 8.7). The main barrage of the double-basin schemes would partly share the line of Wilson's scheme. Model simulation was in good agreement with published tidal data. The tests indicated that tidal levels were not significantly affected. However, a full-scale feasibility study was yet to be done!

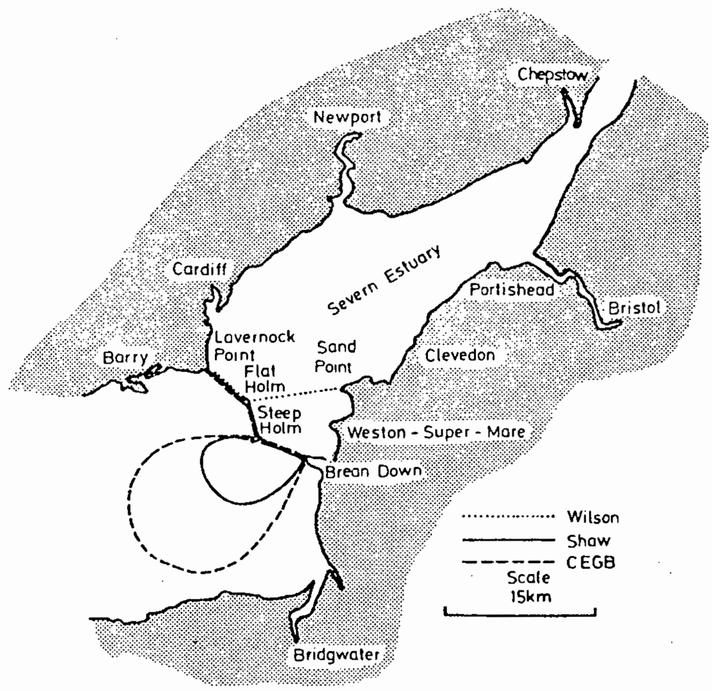


Fig. 8.7 Location map of the schemes tested (Ref. 66)

Shaw (Ref. 67) indicates early in 1977 that "approximately 1,2 million *pounds a day will be lost in energy costs, until the Severn Tidal scheme is implemented". The many disputes and Select Committees' discussions over the years (Ref. 68) had a happy ending in September 1977 : the Government decided to set aside 1,5 million pounds for research needed on the Severn Barrage, ranging from studies of conceptual studies to construction methods (Refs. 13 and 69).

The means for investigation and design of a scheme in the Severn Estuary are available as never before (Ref 58). A large number of schemes have been proposed and each needs to be examined in depth before a final decision can be made (Ref. 69). Most of the proponents appear to be adamant that the only method of construction for the power house is to be the float-in-place one (Refs. 31 and 69).

Much uncertainty prevails about the output and cost of a future Severn tidal plant. If a multiple-basin scheme was chosen, it could take some 15 - 20 years to complete, costing 3 000 to 4 000 million pounds based on a unit cost rate of 900 pounds per kW installed (Refs. 65 and 69). Shaw (Ref. 65) pointed out that although (at this unit cost rate) a tidal power plant of 4 500 MW is energy-wise equivalent to a 2 000 MW thermal plant, it does not require fuel as the tidal energy is either directly sup-

* 1 pound = ± R1,70

plied or stored until required.

An integrated estuary pumped storage project offers worthwhile economic and operational advantages over a pure tidal power development; apart from acting as a pumped-storage centre and generating electricity, the output could be re-timed and smoothed out (Ref. 63). Shaw (Ref. 65) suggested further that, as a cost compensation, the full investment of a tidal plant could be spread out such that energy is first produced before say 40 per cent is spent; with output increasing as the work proceeds.

Finally, a Severn tidal plant appears to be inevitable. The British Government has already indicated that "expenditure will increase substantially if results justify going on to the development stage" (Ref. 69).

ARGENTINE

Investigations for the development of tidal power at five sites in the Argentine were already undertaken in 1928. The San Josê project has retained the main support over the years, and is briefly discussed below.

The San Josê Gulf (Fig. 8.8) has a strait to the ocean which is 7 km wide, a basin area of 2 000 km^2 and its tidal range varies from 3,5 to 7,8 m (Refs. 29 and 70). Natural conditions made a single pool two-way scheme necessary. An output of 7 000 MW is envisaged. Fentzloff (Ref. 70) proposed a float-in-place method for the most economic construction of the barrage.

According to Bernshtein (Ref. 29) the building of a second tidal power plant in the New Gulf, adjacent to the Gulf of San Josê, would produce a further 11 400 MW. The width of the strait connecting the New Gulf with the ocean is 15 km. The Gulf's basin area is 3 400 km^2, and a single basin two-way scheme was envisaged.

The digging of a canal, only 8 kilometres long, cutting the isthmus and connecting the Gulfs of San Josê and New, appears quite feasible; the power house, with a capacity of 600 MW, would be located in the canal between the two Gulfs. Jeffs (Ref. 51) has pointed out that this proposal would have the disadvantage of not being capable of continuous

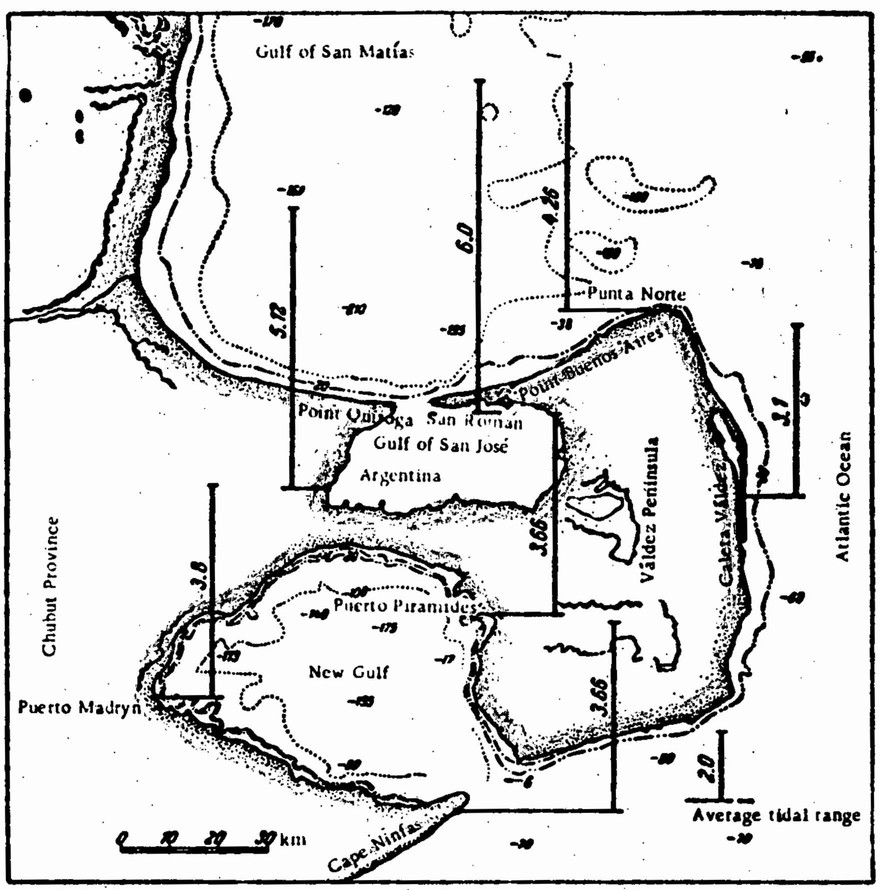


Fig. 8.8 Plan of the Gulfs of San José and New (Ref. 29).

generation; interconnection with another power source is the only solution.

After 50 years there is still no indication when the Argentine will develop its tidal power potential. This is possibly due to the fact that the country relies heavily on its hydro-electric resources and oil production commenced in the 1960's (Ref. 29).

AUSTRALIA

The Kimberley region in the north-west of Western Australia contributes mainly to Australia's potentially exploitable tidal energy. The many inlets, with narrow entrances suitable for damming, in this area experiences tidal ranges between 9 and 12 metres (Refs. 71 and 72).

Intensive surveys of the Secure Bay and Walcott inlets, in the Kimberley area, have been conducted since 1963. Of the many sites examined, these two sites appear to be the most suited for tidal power development. Unfortunately, the Kimberley region is remote and sparsely populated; hence, no market for the electricity that could be produced. Long distance transmission expenses added to the already extreme capital costs involved in tidal power development, would prove an enormous barrier.

The investigations, by the consultants Sogreah of France, incorporated a pumped-storage system to achieve re-timing. Further, a firm output of 170 MW with a 570 MW peak generating capacity was envisaged for Secure Bay, the most favourable of the two Kimberley sites. Capital cost of the proposed scheme has been estimated at 400 million Australian dollars (1974 prices) and to earn an 8½% return, electricity would have to be sold at 39 cents per kWh. To reduce civil engineering costs, closure was to be achieved by caissons manufactured at Perth, towed to Secure Bay and sunk onto a prepared rock platform. According to Scott (Ref. 72) the next obvious target, to reduce capital costs, is the turbine generators which account for about half the total capital cost. (1 Austr.dollar = ± R1).

The exploitation of tidal power in the Kimberley region would lead to the development of heavy industry such as steel, copper, aluminium, lead etc. in North-west Australia. The Australian government has undertaken to continue its investigation for tidal power generation, as Western Australia has a shortage of black coal deposits and crude oil reserves.

INDIA

Studies carried out by Wilson indicated that there is a large tidal power potential in the Gulfs of Kutch and Gambay in Grujarat (Ref.73).

The mean tidal ranges are 5 to 7 metres. Wilson suggested various schemes with outputs ranging from 586 to 7364 MW, at an energy generating cost of 40 to 14* paise per kWh respectively (at 10% interest rate). The dams for these schemes would be up to 34 km long.

The proposed schemes would involve large civil works and huge capital outlays. It was therefore recommended that the Wilson proposals be shelved and studies into the economic viability of medium sized developments in the Gulf of Kutch be undertaken.

ADVANTAGES AND DISADVANTAGES OF TIDAL POWER PLANTS

The main advantage of a tidal power plant is its steadiness; it is more reliable than most alternative forms of generation. This is due to the predictability of the tides, even years in advance, and the many small generating units comprising the plant. "Several small generating units need less reserve equipment than one larger unit of equivalent total capacity" (Ref. 61).

Tidal energy is a free, everlasting and a non-polluting asset. Fossil-fuel-fired power plants can cause environmental pollution as follows : by emission of gaseous effluents; by the exhaust of particulate matter to the atmosphere; and by increasing sea or river temperatures as a result of the discharged cooling water. The problem of pollution is receiving closer scrutiny from the community than ever before.

Tidal power plants could be used as an important road link between the opposite banks of an estuary, as in France; further, they could result in the improvement of navigation to estuary ports, such as in the Severn Estuary. Tidal barrages could also play an important role in attracting tourists.

* (1 SA cent = 7 paise)

The economic lifetime of tidal power plants are estimated at approximately 75 years, compared to about 30 years for thermal and nuclear power plants. Tidal plants cannot be affected by drought, flood, ice jam or silting. Minor maintenance is required, involving only nominal running costs.

Why not more tidal power plants? According to Charlier (Ref. 28) the answer is economics! The construction of a tidal power plant involves extremely high capital costs. However, the civil engineering costs could be reduced considerably by utilizing the float-in-place method which was successfully demonstrated by the USSR at Kislaya Guba. Casacci (Ref. 74) of Société Neyrpic in France, claims that they have developed bulb-turbine units of 53 MW unit capacity, and suggests ways in which the overall economics of future tidal plants could be improved.

Another major disadvantage of a tidal power plant is its intermittent nature and the considerable variation of power production. Unfortunately, the tides are controlled by the moon while energy demand is determined by the sun! The French have demonstrated that this problem can be solved by using two-way pump-turbines at the Rance tidal power plant. With a multiple basin scheme the variations could also be smoothed out and the output re-timed; this happens to be one of the proposals for the Severn Estuary.

The smallness of the heads of water under which the turbines must operate is another disadvantage of tidal power plants. Low heads require large and expensive generating sets. Fortunately, continuous research is being undertaken to develop better and less expensive machinery.

The high cost of transmission lines in the case of remotely located sites such as the Kimberley region in Australia, adds to the already huge capital investment of a tidal power plant. Any power development has a tremendous economic advantage if it is located close to an electricity demand centre.

DISCUSSION AND CONCLUSIONS

The price of fossil fuels have increased rapidly over the past five years. It has been reported that the generation of electricity at the Rance tidal power plant in France "is now cheaper than that produced by nuclear plant" (Ref. 65). The general rule of comparing the ratio "cost per kW of installed capacity" should therefore not generally be quoted for tidal power; the price of fuel should also be reflected in any comparison.

Wilson (Ref. 31) cautions that the development of large-scale tidal power necessitates :

(i) the availability of large interconnected electrical transmission networks to utilise the output;

(ii) developing engineering methods to build and handle large floating concrete caissons and sink them onto prepared underwater foundations and

(iii) developing low-cost electro-mechanical machinery of high hydraulic efficiency, capable of sea-water operation over long time periods with minimum maintenance.

The first requirement is met for many possible sites, notably the British sites at the Solway Firth and the Bristol Channel. The second is fulfilled by the concrete caissons built and successfully sunk in the North Sea. The third requirement for cheap, low-head turbo-generators has not yet been achieved. As pointed out in the previous section, research is being undertaken to develop better and cheaper machinery.

The two existing tidal power plants, Rance and Kislaya Guba, have contributed considerably to the advancement of tidal power. A great deal has been learned at the Rance about corrosion protection methods and the re-timing of tidal power output to produce firm power and suit demand peaks. The float-in-place construction method utilized at Kislaya Guba, will play a major role in future tidal power developments.

Environmentally, the building of the Rance plant has lead to improved conditions along the shores of the pool : the high levels occur more frequently and can be held for three or four hours. Since the construction of the dam, navigation has improved such that the number of movements through the lock has doubled in the five years prior to 1974. As mentioned before, the Rance has become a major tourist attraction.

It is hard to believe that the Rance will remain the world's only major tidal power station. The development of tidal power in the Severn Estuary and the Cumberland Basin (in the Bay of Fundy) is technically feasible. The exploitation of tidal power at Passamaquoddy Bay should have been settled 30 years ago. Charlier (Ref. 28) believes that had the Passamaquoddy and British plants "been constructed, it would have paid for itself a long time ago".

The inflation in fuel costs has stimulated the development of tidal power. The author believes that tidal power plants could be realised in the Severn Estuary and the Cumberland Basin within the next two decades!

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Prof. F.A. Kilner	for his guidance and stimulating suggestions, which made the investigation a constructive, rewarding and very enjoyable exercise.
Jacqueline and the children	for tolerating me while working on the script, with the request not to be disturbed.
Mrs. Val Hamilton	for the rapid typing of the script.

APPENDIX

EXAMINATIONS WRITTEN TO COMPLETE THE REQUIREMENTS OF THE DEGREE

Examination		Year Passed	Credit Rating
CE 506	Properties of Concrete	June 1976	4
CE 519	Steel Structures	Nov. 1976	3
CE 511	Hydraulic Transportation of Solids in Pipelines	Feb. 1977	5
CE 522	Aquatic Chemistry	June 1977	7½
CE 525	Coastal Hydraulics	July 1977	5
CE 528	Advanced Aquatic Chemistry	Dec. 1977	5
CE 513	Waste Water Treatment	July 1978	7½
Thesis	"Wave and Tidal Power Review"	Sept. 1978	10
		TOTAL	47

No. of credits required 40

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION: JUNE 1976

COURSE CE 506 - PROPERTIES OF CONCRETE

Time allowed: 3 hours 5th June, 1976

Part A consists of fifteen multiple-choice questions. Each question is followed by five suggested answers; select the one which is best in each case and circle one of (a), (b), (c), (d) or (e) for each question. This portion of the examination paper must NOT be removed from the Examination Room and must be handed in for marking.
Part B consists of five questions. Answer all questions.

PART A - Multiple-Choice Section (All questions of equal value)

Question A1: In controlling the quality of concrete produced for a project, a test is needed which:

(a) gives the true strength of the material;

(b) gives, for variations in testing procedures, the least variation in results;

(c) gives the true strength of the specimen;

(d) gives a clearly defined stress pattern;

(e) is easy to carry out.

Question A2: In design of concrete mixes according to CP 110 Concrete Structures Code, the target strength chosen is directly related to:

(a) the design strength f_{cu};

(b) the design strength f_{cu} plus 1,65 times the standard deviation 'σ'.

(c) the design strength f_{cu} plus the standard deviation 'σ';

(d) the design strength f_{cu} plus the coefficient of variation 'v';

(e) the design strength f_{cu} plus 1,65 times the coefficient of variation 'v'.

Question A3: The most important aspect of sampling from a pre-mixed concrete truck is to:

(a) protect the sample from wind and sun;

(b) obtain a representative sample in order to carry out further tests;

(c) ensure that the concrete is properly mixed;

(d) check the workability and slump;

(e) obtain a sufficient quantity of concrete to carry out further tests.

/Question A4: ....

Question A4: For a water/cement ratio of 0,6 by weight the use of rounded river gravel in place of crushed aggregate of cubic shape and rough texture will:

(a) show little difference in compressive strength but increase flexural strength;

(b) increase compressive strength by about 10% and also increase flexural strength;

(c) decrease compressive strength by about 10% but increase flexural strength;

(d) increase compressive strength slightly but lower flexural strength;

(e) decrease slightly, both compressive and flexural strengths.

Question A5: The Unit Water Method of Mix Design, described in lectures, suggests that the grading of the combined aggregate be made finer than the recommended grading when:

(a) the maximum aggregate size is larger;

(b) the maximum aggregate size is smaller;

(c) the coarse aggregate is crushed material;

(d) the cement content is higher;

(e) the cement content is lower.

Question A6: An increase in the proportion of aggregate material in the sieve range 2,00 mm to 9,5 mm (No. 8 to 3/8") will tend to:

(a) make the concrete harsh and liable to honeycomb;

(b) make the finishability of the concrete better;

(c) improve the economy of the mix;

(d) increase the amount of water required;

(e) reduce the amount of water required.

Question A7: The addition of an air entraining agent to a concrete mix usually leads to:

(a) a more economical mix;

(b) a stronger concrete;

(c) a decrease in the required sand percentage;

(d) a decrease in cement content;

(e) a denser concrete because of improved workability.

/Question A8: .....

Question A8: In the Unit Water Method of Mix Design, described in lectures, the estimated water content for a particular slump is fixed by:

(a) the maximum size of the aggregate;

(b) the grading of the aggregate;

(c) the shape of the aggregate;

(d) (a) and (b) above;

(e) (a) and (c) above.

Question A9: Capillary water in hydrated cement paste is:

(a) water held in areas of restricted adsorption of the gel structure;

(b) water occupying space beyond the range of surface forces of the solid phase of the gel structure.

(c) water existing in cavities and channels up to 100 times greater than the size of gel pores;

(d) both (b) and (c) above;

(e) water chemically combined such that it is part of the solid matter in the hardened paste.

Question A10: Plastic shrinkage of concrete is caused by:

(a) removal of capillary and gel pore water;

(b) the absorbtion of mixing water by porous or dry aggregates;

(c) sedimentation and settling of solids in the concrete mix;

(d) bleeding of free water to the top surface of the concrete where it is often lost by evaporation or drainage;

(e) all of (b), (c) and (d) above.

Question A11: The secant elastic modulus of concrete is increased by:

(a) increased water:cement ratio and increased paste content;

(b) constant water:cement ratio and increased paste content;

(c) increased water:cement ratio and decreased water content;

(d) constant water:cement ratio and air entrainment;

(e) decreased water:cement ratio and decreased paste content;

Question A13: Decreasing the water/cement ratio influences the ultrasonic pulse velocity because:

(a) poor compaction leads to voids;

(b) a decrease in the density causes the pulse velocity to increase;

(c) an increase in strength (due to a lowering of the water cement ratio) causes the pulse velocity to increase;

(d) an increase in the density causes the pulse velocity to increase;

(e) an excess of paste causes the pulse velocity to decrease.

/Question A14: ....

Question A14: Rapid Hardening Portland cement can be manufactured by:

(a) more finely grinding the Portland cement;

(b) changing the ratio of $C_2S:C_3S$;

(c) intergrinding some high alumina cement with the Portland cement;

(d) both (a) and (b) above;

(e) all of (a), (b) and (c) above.

Question A15: Excessive bleeding of concrete can be corrected by:

(a) adding more cement;

(b) adding crusher dust or other fine material;

(c) by air entrainment;

(d) both of (a) and (b) above;

(e) all of (a), (b) and (c) above

[Total 20 marks]

PART B

Question B1:

(a) A laboratory trial mix of concrete with 30 kg of water, 50 kg of cement, 130 kg of sand and 180 kg of stone gave a 28-day strength which was too low, a slump of 110 mm and real mortar excess of 8%. It is decided that a reduction in water/cement ratio to 0,56 will probably correct the strength requirement. What mix would you suggest for a second trial to give a slump of 60 mm and a real mortar excess of 2% given that the densities of the water, cement, sand and stone are 1000, 3150, 2600 and 2750 kg/m^3 respectively.

(b) The compressive strength of the second trial mix after 28 days' storage at 18°C is 33 MPa. Using Plowman's method, determine how long it would take to reach the same strength at 25°C. What will be the compressive strength after 3 days at 25°C?

[20 marks]

Question B2:

Consider an average structural grade concrete made with 20 mm river gravel aggregate (irregular gravel), normal Portland cement, water/cement ratio (by weight) 0,60 aggregate/cement ratio 6,0, and slump of 75 mm.

(i) Calculate the effect on strength of adding water so as to increase the slump to 150 mm.

(ii) How does this strength change compare with that expected to result from changing from gravel to crushed coarse aggregate but maintaining the aggregate/cement ratio at 6,0 and slump at 75 mm?

(iii) If a graded river gravel with maximum size 80 mm was used in place of the 20 mm gravel, comment on the expected water demand, water/cement ratio and resulting compressive strength of the concrete.

Clearly state the assumptions made in each case.

[15 marks]

Question B3:

(i) Explain briefly how the progressive hydration of cement may lead to self-desiccation of concrete.

(ii) Calculate the gel/space ratio for a concrete with a water/cement ratio of 0,60 at an age of 14 days at which time 60 per cent of the cement had hydrated. Comment on the expected compressive strength corresponding to this gel/space ratio.

(iii) 100 g of cement and 20 g of water are placed in one sealed container and 100 g of cement and 60 g of water are placed in another sealed container. Calculate in both instances the maximum degree of hydration possible, the volume of gel formed, the weight of chemically combined water and the weight of free water in the capillary pores.

[20 marks]

/Question B4: ....

Question B4: "When concrete specimens are loaded axially in compression they always fail in tension". Briefly discuss this statement and go on to discuss the effect of specimen size and shape, and also the effectiveness of capping materials on the apparent ultimate compressive strength of concrete test specimens.

[10 marks]

Question B5: A considerable number of different types of test procedures have been devised to measure "workability" of concrete. Discuss the reasons for the multiplicity of methods used. List ways in which the workability of concrete can be increased without increasing the water content.

[20 marks]

UNIVERSITY OF CAPE TOWN

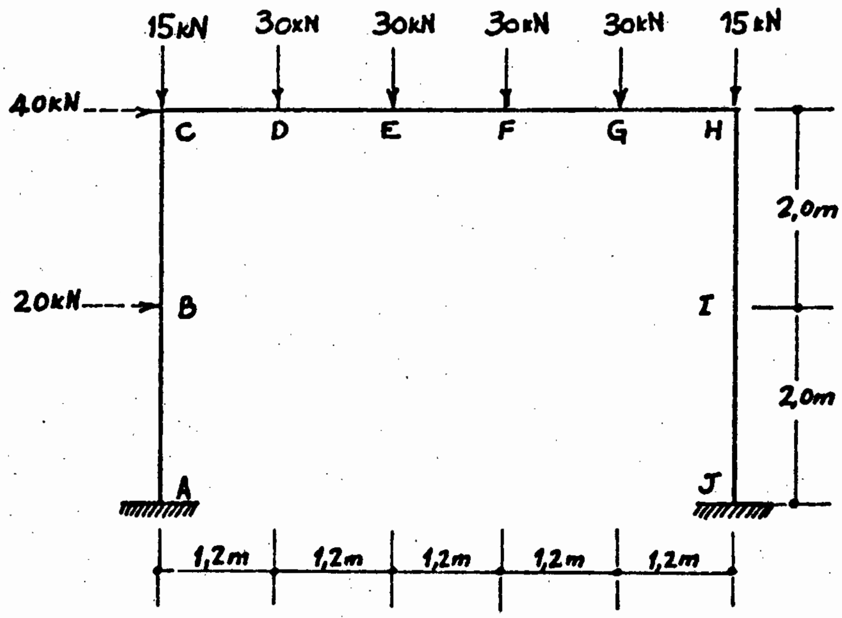
DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION: 13th NOVEMBER, 1976

CE 519 - STEEL STRUCTURES

Time allowed: 3 hours

1.



The rectangular frame shown above is to be designed by plastic methods. The loads shown are working loads: the vertical loads represent dead plus superimposed loads and the horizontal loads represent wind loads. The wind loads may act from left to right (at B and C as shown) or from right to left (at H and I).

1. Use limit analysis to determine the least value of M_p for which the frame can equilibrate all factored load combinations using the following assumptions:

(a) the frame is designed with a uniform section,

(b) the load factor for dead plus superimposed load alone is 1,75, and for dead plus superimposed load plus wind load 1,4.

Draw the bending moment and shear force diagrams, and determine the axial loads in the members, for the collapse conditions.

[40 marks]

2. Using the Abridged Version of the Handbook on Hot Rolled Structural Steel Sections, and the Design Recommendations issued, select an appropriate parallel flange I-section for this design. The yield stress is to be taken as 250 MPa.

Choose your section/sections with respect to the collapse bending moments, shear forces and axial loads. Consider

(a) whether the section or sections chosen is/are compact,

(b) whether shear stiffeners are required,

(c) lateral stability and the points at which lateral bracing is required,

(d) in-plane buckling.

[35 marks]

3. The moments computed from an elastic analysis with uniform E.I. over the entire frame are given below. Tension on the inside of the frame is taken as positive.

Section	Moment due to vertical loads only (kNm)	Moment due to wind only acting from left to right (kNm)
A	+ 27,00	- 70,91
B	- 13,50	+ 1,93
C	- 54,00	+ 34,77
D	+ 18,00	+ 20,36
E	+ 54,00	+ 5,95
F	+ 54,00	- 8,45
G	+ 18,00	- 22,86
H	- 54,00	- 37,27
I	- 13,50	+ 9,95
J	+ 27,00	+ 57,16

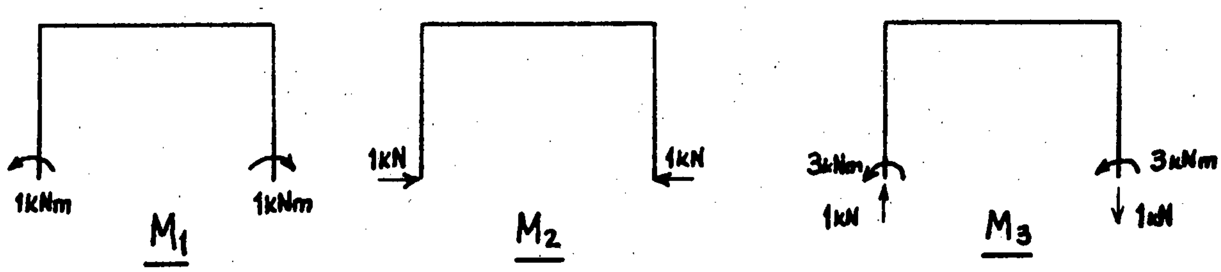
Assume for simplicity that the dead and superimposed load together may or may not act. The wind may act from left to right or from right to left.

For the M_p value calculated in part (a), determine the load factor against failure by alternating plastic deformation at any section.

Do you consider this result to be significant in determining member sizes?

[10 marks]

4.



Using the three independent self-stress systems associated with the force systems shown above, write down the compatibility equations for the structure analysed in 1. above at the point of collapse. Assume plastic hinge rotations at each of the hinges in the mechanism.

You may take the following values for the integrals below:

$$\int M_1 \frac{M}{EI} \, ds = -0{,}0076 \text{ kNm}$$

4. (Continued)

$$\int M_2 \frac{M}{EI} ds = - 0,0491 \text{ kNm}$$

$$\int M_3 \frac{M}{EI} ds = + 0,0240 \text{ kNm}$$

M is the collapse bending moment diagram, and moments causing tension on the inside are positive. The integrals extend over the whole structure.

Hence determine which is the last hinge to form.

[15 marks]

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION: FEBRUARY, 1977

COURSE CE 511 - SEDIMENT TRANSPORTATION

Note: This is an 'open book' examination. Scripts are to be collected at 5.30 p.m. on Thursday, 24th February 1977 and returned by 9.00 a.m. on Monday, 28th February, 1977. The attached affidavit is to be signed by each student on receipt of the examination script.

Answer ALL questions

1. One criterion for determining whether suspensions will be settling or non-settling is a particle Reynolds number of 2,0. For sand of relative density $S_s = 2,65$, indicate into which category "average" particles of sand, of mean particle diameter 38, 100, 250, 1000 and 2000 μm at concentrations of 0, 10, 20 and 30%, will fall. Tabulate your results and show how they can be presented graphically. Hence determine for each of the four concentrations, the particle size which designates the boundary between settling and non-settling suspensions.

   (a) Compare the above results with those obtained by two other methods.

   (b) Repeat the above procedure for coal of sphericity 0,7 and relative density as given by Fig. 3.11.

   (c) Repeat the above procedure for iron ore assuming spherical particles and a relative density of 4,0. In this case include particles of size d = 2,5 mm. Assume $\nu = 1,14\ mm^2/s$

2. Carry out a feasibility study for transporting 10 million metric tonnes (1 metric tonne = 10^3 kg) of iron ore of relative density 4,0, a distance of 600 km in a horizontal pipeline with a load factor of 95%.

   Assume the pipe roughness is constant at k = 0,06 mm and the kinematic viscosity of water is $\nu = 1,14\ mm^2/s$.

   In order to carry out the feasibility study, consider five alternative proposals.

   (i) Assume that the ore is crushed to an average particle size of d = 2,5 mm and the mean drag coefficient can be taken as $C_D = 0,44$.

      (a) Which flow regime would you consider as being feasible for transportation of this material and why?

      (b) Assume that the delivered volumetric concentration is $C_{vd} = 20\%$. Determine the limit deposit velocity according to Durand and show that the pipe diameter required to operate at the minimum energy loss is approximately 300 mm.

      (c) What is the total power required per km? Compute this value as the average obtained by four methods.

      (d) Compare the pipe diameter obtained above with that obtained by another method for determining the value of the limit deposit velocity.

/(ii) .....

2. (Continued)

(ii) In order to transport the material in the pseudo homogeneous regime at the same rate and volumetric concentration in a 300 mm diameter pipe it is possible to grind the material finer.

(a) Determine the drag coefficient of the finer material if it is just transported as a pseudo homogeneous mixture at the same rate (i.e. same mixture velocity).

(b) What is the mean particle size of this finer material ? Assume that the analysis for spherical particles applies. Compare this result with the results obtained in (i)(c) above.

(c) What is the total power requirement in this case?

(iii) The finer material can also be transported at a lower mean mixture velocity as a heterogeneous suspension in the 300 mm diameter pipe.

(a) What is the power requirement in this case? Assume that the heterogeneous mixture is transported at the minimum deposit velocity as determined from the Durand equation with the coefficient F_L = 0,95. Note that the delivered volumetric concentration will be greater than 20% in this case.

(iv) The material is ground further to give a non-Newtonian suspension at 20% volumetric concentration.

(a) What would the average size of particle have to be in this case?

(b) The rheological properties as determined by means of a capillary tube viscometer, 3 mm in diameter and 3 m long, are as follows:-

Mass Flow (g/s)	0,848	1,69	2,54	4,24	8,48
Pressure Drop (kN/m^2)	4,0	7,2	10,8	16,8	36,0

Determine the power requirement for the same flow rate as in schemes (i) and (ii)

(v) Consider a pipe diameter of 500 mm with the average roughness size of 0,06 mm and for the same mixture flow rate and material concentration as in scheme (iv), determine the power requirement.

Summarise the power requirements, in tabular form, for the five schemes considered above and comment briefly on the feasibility of scheme (v) as compared with the other schemes.

3. Coal of size d_{50} = 225 µm was tested in pipeline test loops of 100 mm and 200 mm diameters at a concentration by weight of C_W = 53%. The relative density of the coal is 1,5 and the kinematic viscosity of water ν = 1,14 mm^2/s. The following test results were obtained at V_m = 1,75 m/s:-

D(mm)	100	200
i_m	0,0457	0,0224

/The pipes ....

3. (Continued)

The pipes were found to be hydraulically smooth.

Determine the head loss in a 300 mm diameter pipe at a mean mixture velocity of 1,75 m/s. Use three different methods of scaling and compare them.

4. Calculate the mixture head loss in units of clear fluid (water) for the coal described above, assuming a heterogeneous flow regime in a pseudo homogeneous mixture (i.e. the method of Wasp et al) in a 300 mm diameter pipe. Compare with the Durand equation.

Assume that the Weltman Green equation $\mu = (\mu_o + A)\, e^{\beta v_r}$ applies

with $\mu_o = 1{,}14 \times 10^{-3}$ kg/ms

$A = 0{,}000064$ kg/ms

$\beta = 4{,}29.$

Ignore the effect of hindered settling of the particles.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION   JUNE 1977

COURSE CE 522   AQUATIC CHEMISTRY

Answer ALL questions

The examination script must be returned to the Department of Civil Engineering by 5.00 p.m. on Monday, 27 June 1977.

Please sign the following undertaking when handing in your script.

I confirm that the work in the script is my own and that I have not consulted any person in completing the examination.

. . . . DATE   . . . . SIGNATURE

Question 1

In the Table below results from two sets of jar test experiments are presented, each for a different water sample. The coagulant used for each set of experiments was aluminium sulphate. Results are in terms of arbitrary units. Identify the type of water in each case discussing fully your reasoning and stating clearly the type of coagulation mechanism you assume to be likely in each case.

Dosage mg ℓ^{-1}	pH 5	pH 6	pH 7	pH 9
20	10,4	7,2	2,8	9,2
40	7,8	3,8	1,2	7,0
60	7,6	2,4	1,0	6,0
80	6,8	2,0	1,0	5,8

Dosage mg ℓ^{-1}	pH 5	pH 6	pH 7	pH 8
50	0,36	0,1	0,35	0,4
70	0,08	0,05	0,2	0,3
90	0,03	0,04	0,075	0,23
110	0,025	0,04	0,03	0,18

Question 2

Batch flocculation experiments were conducted on a water. Values for the general flocculation and breakup constants were found to be $K_A = 3{,}2.10^{-4}$ and $K_B = 5{,}1.10^{-7}$ sec respectively. A plant is to be designed for this water with a design flow of 10 Mℓ d^{-1}. As a result of the coagulation and flocculation experiments optimal removal efficiency is obtained using aluminium sulphate at a dosage of 50 mg ℓ^{-1} (as alum) at a pH of 6,0 (lime needs to be added) followed by 5 ppm floccotan. The design turbidity values of the raw and final waters are 50 and 2 JTU respectively.

Question 3

(a) Briefly outline the reasons why the parameters alkalinity and acidity have attained importance in water chemistry.

(b) Analyses of a water gives pH 9,2 and HCO_3^- Alk = $3{,}16.10^{-4}$ moles/ℓ. Estimate values for C_T and the remaining forms of alkalinity and acidity using the inter-relationships between the mass parameters ($pK_1 = 6{,}35$ and $pK_2 = 10{,}33$)

(c) Analyses of a water gives Alkalinity 120, Ca 24 (both in ppm expressed as $CaCO_3$) and pH 8,6 ($\mu = 0{,}01$ and temperature = 20°C) This water is titrated with a strong acid in three ways:

i) gentle stirring so that no CO_2 exchange occurs with the atmosphere,

ii) finely ground $CaCO_3$ is added to the water prior to the titration. The titration is then executed slowly with gentle stirring so that the water remains saturated with respect to $CaCO_3$ but no CO_2 exchange occurs with the atmosphere,

iii) same as in (ii) above except that the water is stirred vigorously so the CO_2 equilibrium with atmosphere is maintained at all times. Plot pH titration curves for each of these three systems. Briefly compare these curves giving special reference to the mechanisms of pH buffering. From your discussion draw analogies to the pH stability (or instability) of natural water systems.

Question 4

Analysis of a water from the Western Cape gives Alkalinity 2 ppm, Ca 6 ppm (both expressed in ppm as $CaCO_3$) and pH 6,0 (μ = 0,001 and temperature 20°C). It is desired to stabilize the water using $Ca(OH)_2$ and CO_2 to one of the following conditions:

i) pH 9,0 and SI + 0,2
ii) pH 9,7 and SI + 0,2
iii) pH 7,4 and SI + 0,2 (assume final μ = 0,01)

Critically compare these three proposals.

Question 5

Analyses of a water gives Ca 340, Mg 60 and Alkalinity 260 (all in ppm expressed as $CaCO_3$), pH 6,9, μ = 0,015 and temperature 20°C

i) Estimate lime and Na_2CO_3 dosages to soften the water to Ca 120 and Mg 20 (both in ppm expressed as $CaCO_3$)
ii) Estimate CO_2 requirements to stabilize the water and sketch the plant layout
iii) A source of ground water is available: pH 6,0, Alk 32 ppm, Ca 100 ppm (both expressed as $CaCO_3$), μ = 0,01 and temperature 20°C.

How should the ground water and softened water be blended to give a final stabilized water without using CO_2 gas.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

M.Sc. IN CIVIL ENGINEERING

UNIVERSITY EXAMINATION : JULY 1977

CE 525 : Coastal Hydraulics

All Questions may be attempted — Time : 3 hours

Constants

Sea water density = 1025 kg/m^3
Sea water weight = 10 kN/m^3

1. A beach site has an average underwater slope of 1 in 50, and the beach material is a coarse quartz sand of relative density 2,65 and average size 1,35 mm, the shoreline being essentially straight.

Two conditions of wave attack are being considered :-

(A) swell of 10 second period with a deep water wave height of 1,6 m approaching the beach with wave crests parallel to the shore line.

(B) as in (A) above, but with a deep water wave incidence of 35^o, (angle between wave crest and contour)

For case (A) make the following calculations :-

(a) the wave length and wave celerity in deep water.
(b) the water depth at which the wave begins to be affected by the presence of the sea bed.
(c) the wavelength, celerity and height for water depths at 10 m intervals between d=80 m and d=10 m, and at 1 m intervals between d= 10 m and d=1 m.
(d) the water depth in which the wave breaks, the breaker type, and the wave height at breaking. Ignore the effect of wave set up or down.
(e) the deep water energy flow.
(f) the wave height and energy flow in a water depth of 1 m.
(g) the water depth in which the sand is on the point of moving.
(h) the water depth in the which the sand is in motion but has no net drift.

For case (B) make the following calculations :-

(i) the water depths in which the angle of incidence becomes 30°, 20° 10° and 5°, and the wave heights at these depths.

(j) the water depth and wave height under breaking conditions. (assume the depth at breaking is 80 per cent of the value obtained for parallel waves)

(k) the thrust on the mass of water in the surf zone, per metre length along the shore.(N)

(l) an estimate of the bulk sand volume flow rate in m^3/s in the alongshore direction.

2. A cylindrical pipe is laid on the sea bed across a harbour entrance in 10 m of water, the pipe diameter being 0,3 m, and the axis of the pipe is parallel to the local wave crests. If the local wave length is 50 m, estimate the wave period, and find the peak magnitudes of the velocity and acceleration force components per metre length of pipe. Estimate the peak resultant force in the inshore direction, and the timing of this in relation to the passage of the wave crest. The wave height is 2 m, take $C_D = 1,2$ and $C_M = 2,16$

3. (a) A steady wind of speed 15 m/s blows over a fetch for a period of 8 hours, producing a significant wave height of 1,8 m at the downwind end of the fetch. Estimate the fetch length in km and the wave period. Check whether the wind duration is sufficient for this condition to be stable and also check whether this is the fully arisen sea for this wind speed.

(b) In a zero damage design calculation for the armour protection of a rubble mound breakwater, 3 tonne and 5 tonne dolosse are specified for the trunk and head respectively, the slope of the breakwater face being $\cot\theta = 2$. Estimate the block masses and block heights if tetrapods had been used in the same design. If the design wave height was 3 m, and a storm causes damage of the order 20-30 per cent to the tetrapod scheme, estimate the storm wave height.(concrete density = 2245 kg/m^3)

(c) An incoming swell has crests parallel to a straight beach with a deep water wave height of 2 m. Estimate the horizontal force (per metre along the beach) acting on the beach inside the refraction zone, due to the dynamic action of the waves.

(d) In an area where the sea bed is horizontal, and the water depth is 3 m, a wave has a period of 7 s, a wavelength of 38 m, and a wave height of 1,5 m. Estimate the drift velocity at bed level, and indicate the direction. Compare this velocity with the maximum orbital velocity at the same level, and indicate the influence on bed drift of a strong onshore wind.

(e) A storm at sea generates waves with a period range of 8 to 16 seconds. The resulting swell travels towards a harbour 500 km away. Estimate the time interval between the arrival of the shortest and longest waves, assuming deep water throughout.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

NOTE: This is an 'open book' examination. Scripts are to be collected after 9.00 a.m. on Friday, 9th December 1977 and returned before 5.00 p.m. on Monday, 12th December 1977. The attached affidavit is to be signed by each student on receipt of the examination script.

Answer ALL questions

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION : DECEMBER, 1977

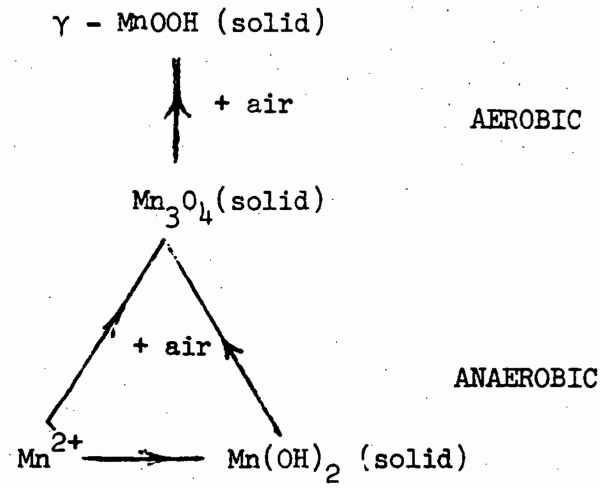
COURSE CE 528: ADVANCED AQUATIC CHEMISTRY

- - - - - - - - -

1. (a) Set out a table of analogy between weak acid reactions and redox reactions in water.

b) Water has a pH of 9,0 and contains a total $SO_4^{=}$ - HS^- species concentration of 10^{-4} moles/litre. Construct a diagram showing the dependence of species concentrations on redox potential (either E_h or pe). Superimpose in this diagram lines representing the partial pressures of hydrogen and oxygen.

(c) A pathway of reactions for precipitation of manganese minerals in aerobic and anaerobic environments is illustrated below:



Construct a pH-redox potential diagram (either as E_h or pe) showing the fields of stability for the various forms of manganese. What minimum partial pressure of O_2 is required to precipitate γ - MnOOH? Assume $[Mn^{2+}] = 10^{-6}$ moles/ℓ; temperature = 25°C.

(d) How could the addition of chlorine affect removal of manganese?

2. (a) Biologically mediated nitrification of NH_4^+ and NH_3 (aqueous) to NO_2^- and NO_3^- may occur in many aqueous systems. Indicate graphically the chemical conditions favouring nitrification in a pH-redox potential (either E_h or pe) diagram.

(b) Superimpose on the diagram constructed in (a) above the conditions favouring denitrification of NO_3^- and NO_2^- to N_2 gas.

Assume a partial pressure of nitrogen = 1 atmosphere and the concentration of NO_3^- or NO_2^- equal to 10^{-6} moles/ℓ.

(c) Determine the partial pressure of nitrogen required such that NO_3^- would be preferentially reduced to NO_2^- or NH_4^+ (or NH_3) in (b) above.

(d) Based on the graphical work above, sketch a plant layout to effect nitrification and denitrification in wastewater treatment.

3. Analysis of a highly saline water gives:

$[Na^+]_T = 0{,}47$; $[Ca^{++}]_T = 0{,}0105$; $[Mg^{++}]_T = 0{,}054$;

$[SO_4]_T = 0{,}028$ (all in moles/ℓ); HCO_3^- Alk = 10^{-4} moles/ℓ

pH = 8,70; μ = 0,7 and temperature = 25°C:

3. (i) Determine the apparent dissociation constants K_1'' and K_2'' for the carbonate system.

pK' values for Equil. Constants at 25°C				
	(H^+)	Ca^{++}	Mg^{++}	Na^+
HCO_3^-	6,06	0,74	0,64	-0,56
$CO_3^=$	9,76	1,84	2,26	0,55
$SO_4^=$	-	0,85	1,00	-0,1
OH^-	13,69	0,78	2,06	-

(ii) Plot a log [total species] - pH diagram for the system. Using only graphical procedures plot in the lines for the concentrations of the free species $[HCO_3^-]$ and $[CO_3^=]$.

(iii) Sketch a pH buffer capacity diagram for the system.

(iv) Discuss how the occurrence of ion-pairing affects $H_2CO_3^*$ Alkalinity measurement.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION - JULY 1978

CE 513 - WASTEWATER TREATMENT

To be collected after 09h00 on 28th July 1978 and returned before 17h00 on 31st July 1978. The attached affidavit to be signed by the student on receipt of the examination script.

ANSWER ALL QUESTIONS

QUESTION 1

An activated sludge plant is to be built for a town with a population of about 20 000 people. The data listed in the table below is available as representative of the flow and load conditions to be expected at the main sewer outfall of the town. At present the process is to be operated on the completely mixed principle including nitrification. The wastewater is well buffered and has a pH of about 7,2. As the wastewater principally is of domestic origin, assume a specific growth rate of nitrosomonas (μ_{nm}) of 0,50 per day.

RAW SEWAGE

TIME	FLOW (Mℓ/d)	COD (mgCOD/ℓ)	TKN (mgN/ℓ)
0600	1,10	248	30,2
0800	2,35	213	24,9
1000	4,60	412	55,1
1200	5,85	567	60,5
1400	5,70	625	54,9
1600	5,00	620	54,9
1800	4,50	576	51,8
2000	4,25	536	45,3
2200	3,95	480	42,8
2400	3,80	442	42,3
0200	3,40	389	35,8
0400	2,00	323	31,1
0600	1,10	248	30,2

a) Assuming steady state conditions :

i) Design the plant for summer conditions (20°C) at a sludge age of 15 days and an MLVSS concentration of 4000 mgVSS/ℓ.

ii) Check your design for winter conditions (12°C).

iii) Make a comparison, in tabular form, of the average effluent quality, oxygen demand and sludge concentration during summer and winter months.

iv) Estimate the minimum factor of safety with respect to nitrification.

b) Estimate from the influent loading variations given in the Table, the peak and minimum total oxygen requirements during summer and winter.

c) Assume that instead of a single reactor, three reactors of equal volume are built. Describe qualitatively with the aid of sketches, how the process variables such as oxygen demand, nitrate, TKN, filtered COD and MLVSS concentrations vary over the day through the plant at 20°C.

QUESTION 2

The waste sludge of the above plant is to be thickened by flotation to 4%, prior to aerobic digestion. Design the flotation system, presenting your final design in the form of sketches to scale on graph paper.

QUESTION 3

Design an aerobic digestor for the thickened sludge on the basis that the digested sludge may not be discharged to the drying beds unless the active fraction is less than 25%. The design may be based on steady state conditions at 20°C. Nitrification must be included in your design.

QUESTION 4

As an alternative scheme to that given in Questions 1,2 and 3 above, investigate a design of an activated sludge process at 20°C, operating at a very long sludge age, so that thickened waste sludge (also by flotation) may be directly discharged to the drying beds (i.e. active fraction of the sludge less than 25%) without the use of aerobic digestion. Do not design the flotation system.

a) Assuming steady state conditions, determine ;

i) the required sludge age; and

ii) the reactor volume given that X_v is also 4 000 mgVSS/ℓ.

b)

i) Compare the oxygen and volume requirements of the two schemes (exclude the flotation plant in the comparison as both schemes require this unit process).

ii) Which of the two schemes is the better in terms of phosphorus removal ? Discuss with the aid of calculations.

c) Write down briefly your conclusions on the comparison of the two schemes.

QUESTION 5 ...../3

QUESTION 5

For an activated sludge plant, determine the average total power requirements of the aeration of the mixed liquor, for the following conditions. The volume of the aeration basin is 1,65 Mℓ and the average total oxygen demand is 48 mgO/ℓ/hr. Assuming that mechanical aerators are to be used with an oxygen transfer rate of 2,44 KgO/Kwh under standard conditions, what power, measured at the shaft, needs to be supplied for the following conditions?

At the proposed site :

Atmospheric pressure = 725 mm Hg ;

Temperature = 21°C ; an oxygen concentration in the reactor of 3 MgO/ℓ, (to ensure nitrification) is to be maintained.

The α and β values for the mixed liquor are estimated to be 0,8 and 0,9 respectively.

QUESTION 6

A cannery has an effluent flow of about 1 500 m^3/d during the main canning season. The daily averaged BOD is approximately 700 mg/d; phosphorus and nitrogen concentrations are negligible. The cannery operates at peak production for about 4 months of the year during the summer when the flow and BOD given above are applicable. For the rest of the year the load and flow are less. An aerated lagoon system has been proposed to treat the waste stream. It is essential that the effluent from the system must have volatile solids and BOD concentrations as low as possible, but no settling rank or maturation pond system following the treatment works are envisaged.

With the objective of satisfying the conditions above, design and compare the following two solutions :

i) A single lagoon with a retention time of 10 days;

ii) A system of two lagoons in series, the first having a retention time of 2,5 days; the second a retention time of 7,5 days.

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20 DEC 1978