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Ocean Energy, Challenge for Structural Engineers

Energie des océans, défi pour les ingénieurs

Energie der Ozeane, eine Herausforderung für Ingenieure

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SUMMARY
Ocean energy systems do encounter a new wave of interest because of their environmental advantages. They are interesting for civil engineeres because of the multitude of physical actions encountered, like tides, temperature differences, waves and current. As sizes for commercial units are necessarily large, structural challenges are there to realize such options. The paper explains this with examples.

RÉSUMÉ
La production d'énergie a partir des océans attire a nouveau l'attention par son avantage considérable pour l'environnement. Les ingénieurs sont attirés par la complexité des actions diverses comme les courants de marée, les différences de température, les mouvements ondulatoires. Les dimensions d'un système sur une base commerciale sont tellement larges et compliquées que l'utilisation de l'énergie des océans est un défi permanent pour les ingénieurs. L'article est illustré par des exemples

ZUSAMMENFASSUNG
Energiesysteme der Ozeane gewinnen aufgrund ihrer ökologischen Vorteile an Bedeutung. Für Bauingenieure sind sie hinsichtlich ihrer Vielzahl an physikalischen Wirkungen, wie Tide, Temperaturdifferenzen, Wellen und Strömung, von Interesse. Zudem verlangt eine wirtschaftliche Nutzung derart grosse Baueinheiten, dass ihre Realisierung auch konstruktiv eine Herausforderung darstellt. Der Artikel erläutert dies anhand von Beispielen.

1. OCEAN ENERGY SYSTEMS; HISTORY AND IMPORTANCE

Ocean Energy Systems are referred to as those ways of generating energy, using the potential energy being stored in the oceans. This energy has the characteristic that it is constantly renewed by the sun and its atmospheric effects. Ocean Energy can, therefore, be recovered for commercial use by retrieving it from temperature differences over the depths, or by using waves, swell, tide and tidal currents for energy generation.
Within most systems, three stages of development can be distinguished.
It is first the period that a certain system or physical principle was discovered and developed for demonstration or just publication in interested circles. Most of the present day developments are of older origin, but have new shapes because of new materials, equipment and actual requirements.
A second period of investigations and test, simultaneously now for all systems, started in the late seventies. The increasing prices on the worldmarket for hydrocarbons and instantaneous scarcities of supply, activated the raising of funds in many countries for research and development in ocean energy systems. The schedules raised in the USA, the UK and Japan, were followed by many countries, including countries like India and Indonesia. Most of these activities, however, decreased in volume and attention when the oil price dropped again in the beginning of the 80's. Funds for R&D were reduced and demonstration plants were stopped and cancelled, except for a few.
The present interest for Ocean Energy Systems is born by their potential environment friendly characteristics. This became important after the world became conscious of real long term threats from thermal energy plants in the late 80's. This effect was increased by the uncertain future of safe nuclear energy after the Tsjernobyl disaster in 1986. New schemes for renewable energy were started around the world. A clear example of that is the UK scheme within the so called "Non fossil fuel act", committing the government to install a certain amount of non fossil fuel power generation before the year 2000 and challenging free enterprise in the UK to propose ideas and schemes for actual realization and exploitation of such sources.
The approach within this third wave of interest for Ocean Energy Systems has not only different aims because it emphasizes environmental aspects. Because of the environmental approach, functional requirements regarding economy have changed into considering the increase of the effectiveness of conventional systems by using ocean energy systems complementary. This means that consideration of Ocean Energy Systems does not necessarily have to rule out all other systems at a certain location. They only have to contribute there, where they are effective in conjunction with other systems. For instance, an OTEC (Ocean Thermal Energy Conversion) Plant does not have to generate the energy for a complete island society, but may just be effective to provide cold water into the condensator of an air conditioning plant from a hotel and offices of that society.
The near future will offer many opportunities to explore such cases.

2. CHARACTERISTICS OF OCEAN ENERGY SYSTEMS

Ocean Energy Systems distinguish themselves from conventional thermal plants by the use of low temperature differences, low pressure heads and low velocities. This is generally true for OTEC (Ocean Thermal Energy Conversion), tidal power plants, wave generation units and PAC (Pump Accumulator Conversion).
As a consequence of these relatively low driving forces, the total flow has to be substantially larger. This makes Ocean Energy Systems quite attractive for civil engineers as the percentage of civil engineering works in a specific plant is far higher than for conventional units. This fact leads to a few other conclusions being encountered in several recent projects being under consideration.

- Ocean Energy Systems usually gain in efficiency by enlarging the scale. This can for instance be achieved by increasing flow and pressure. In case of a tidal power plant this means a careful selection of the site regarding the magnitude of the tide and the area of the reservoir. In case of a pump accumulation plant, it concerns the total height and the content and consequentially the diameter of the reservoir.
- Ocean Energy Systems are usually complementary to existing energy systems. They further have side effects for the infrastructure. Such is for instance the case for a tidal power plant, offering a new fixed crossing across a basin as well. The consequence of this is, that such works require very careful strategy and planning with complex procedures with many more people involved.
- Ocean Energy Systems are unique projects, as they are custom made for specific geographical circumstances, such as bottom conditions, waterdepth, wave and current climate and other hydrological characteristics. This means that they require more time for planning and design than conventional plants.
- Because of their scale, they have usually a spectacular influence on the environment. This is not necessarily a negative one, but it requires anyhow a careful approach. In practice realization is more difficult.
- Because of the larger content of civil engineering structures in Ocean Energy System, the approach towards the mechanical and electrical components should be quite different, in order to achieve more effective results. Close joint development in between civil and mechanical engineers as in the time of the great Victorian engineers is required. Apart from that it can be stated that a large potential to improve such systems is present in mechanical components. These are objects like cheap heat exchangers from new and less costly materials and low pressure head turbines.

Last but not least it should be noticed, that the knowledge and experience required for the coastal and offshore aspects of Ocean Energy projects is in its presence limited to only a few countries in the world, where ideal conditions for such plants are in waters belonging to other countries. This makes Ocean Energy Systems to an ideal field of international cooperation in between civil and structural engineers.

3. SYSTEMS AND POTENTIAL OF OCEAN ENERGY

3.1 OTEC

The most imaginative and possible largest volume of ocean energy is thermal. The oceans act as an enormous heat buffer for a large portion of solar radiation that falls on the earth. About one quarter of the total of 1.7×10^{17} Watts of solar energy reaching the earth's atmosphere is absorbed by the seawater. Heating of the upper layers, leads to surface temperatures of 25°C and higher in tropical areas. When this surface water is used in combination with the cold water from the depth, being 4°C or slightly higher, an Ocean Thermal Energy Conversion plant can be made.
Many configurations are possible to achieve this "reversed refrigerator" principle, where a temperature difference generates energy, in stead of energy generating a temperature difference. The most common appearance is the so called closed cycle. In this case, illustrated in Fig.1, cold water is pumped up and used in a condenser to condense a closed cycle of ammonia. The ammonia

liquid is pumped to an evaporator where hot surface water evaporates the liquid into ammonia vapour. Before the ammonia vapour is condensed again, a turbine is placed in the circuit, driving a generator.

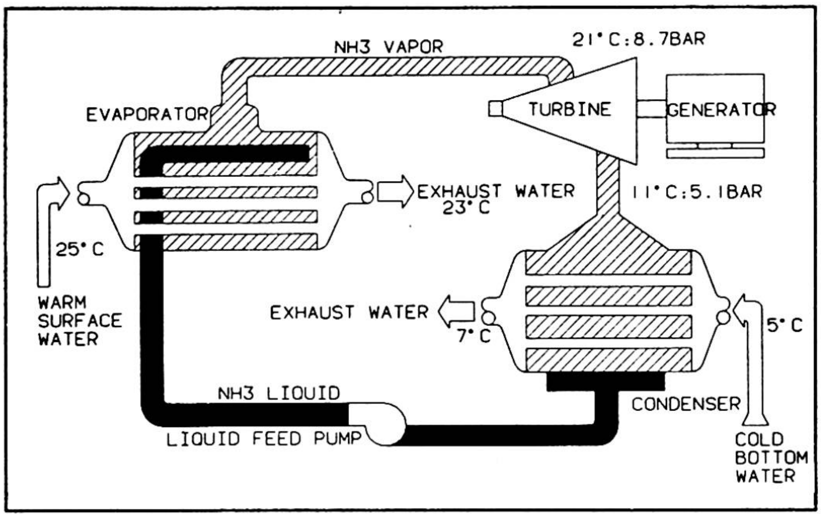

Fig.1 Scheme of closed cycle OTEC plant

The advantage of the OTEC system in comparison with for instance wave and tidal energy generation is that the temperature difference is continuous present. The disadvantage, however, is the large flow required for a commercial system. Estimating the efficiency for an OTEC plant on 1,2% with a temperature difference of 20°C, the production of 1 MW net will require flows through the station at a rate of 5 m^3/sec for both warm and cold water. Such a station, running with a flow of 1 m/sec, would already require a diameter of 2.5 m for the cold water pipe

Looking into the near future option for OTEC, it is most likely, that land based plants will be realized on a commercial basis.

This means, that at a possible location, where the surface temperature is sufficiently high, the coast should drop over a relative small distance, say 1-2000 m to depths of over 800 m where water of sufficiently low temperature can be found. Such locations are present at many coasts in areas with sufficiently high seawater temperatures being shown in Fig.2.

Such is the case for instance at the Indonesian island of Bali and on some Caribbean islands, like Curacao.

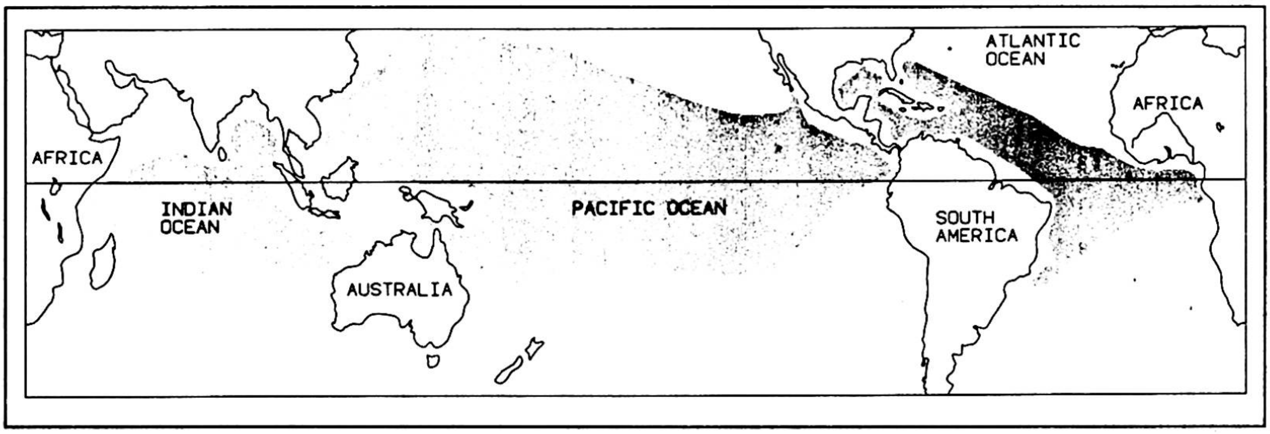

Fig.2 Areas in the world with OTEC potential.

The land based option saves the requirement of an exposed offshore vessel to support the electricity generation equipment as well as an exposed electricity cable through the Ocean towards the shore. These advantages will make a land based option ideal for small commercial applications, such as being proposed for Curaçao, where the costs for the airconditioning of a hotel can be reduced by figures like 70% and a pay back time on the investment of only 3 years.
The principle of OTEC dates back to 1881 when the French scientist Jacques d'Arsonval put the idea forward as an application of the Rankine cycle. His pupil Georges Claude built the first generating station round 1930 at Matanzas Bay on Cuba. The station produced 22 kW of power for only two weeks before the cold water pipe was destroyed in a hurricane. Some other experiments were conducted, most failing again on the deployment of the cold waterpipe, until more frequent research and experiments were conducted from the mid seventies onwards.
Test plants were actually planned on many locations, including India, Indonesia and Abidjan, but only a few have actually been built. These are in offshore Hawaii and offshore the Japanese island of Naru. Many new experiments, research and development exercises and planned installations are under way.

3.2 Tidal energy

Although the principle of tidal energy is much more common to civil engineering practice as it compares with usual hydroplants, only two have been built and a few are being planned.
The absence of continuity in electricity generation due to the tide cycles and the required large scale of the principle may be the reasons for the absence of more units.
The French constructed the first tidal power plant in between 1961 and 1966 in the river La Rance in the province of Brittany.
The installed power is 320 MW and 550 GWH of electricity is produced annually. Seven percent of this output is due to so called pump accumulation. This means that during certain periods, when tides are favourite, but electricity consumption is low, energy from continuous operating electricity plants, like today the nuclear units, is used to increase the waterlevel in the reservoir in order to store more energy than the tide only would do, for consumption during hours of peak consumption. The La Rance reservoir has an area of 15 km^2.
One other tidal powerplant is operating at the Northern coast line of the Soviet Union.
Many other interesting locations on earth, with the required high level of tidal range and reservoir area are being studied. Amongst them are the Canadian Bay of Fundy, the Gulf of Kutch in the Indian state of Gujarat and the British Mersey Barrage in the river Mersey.
The influence a tidal barrier has on the environment around the reservoir is substantial. Currents and water tables change, ship traffic will at least encounter more sluices and the influence on the ecology is present. It is interesting to see, that in case of the Mersey Barrage project in the UK, being inspired by the "Non Fossil Fuel Obligation" integral cost are being evaluated. This takes into account the profit by less exhaust of 1.75 million tons of CO_2, no exhaust of sulfur and nitrogen-oxides, no remaining slags, a better quality of the water and an improved protection against high water.
In certain areas of the world tides are not significant because of their tidal range, but rather because of the current induced in a certain narrow sea strait. This is for instance the case in the area of the Channel islands in between France and the UK, In the Menai Straits and at Chindsudo of the coast of South Korea. Currents of up to 7 m/sec are characteristic for these locations. It is a challenge for mechanical and civil engineers to design reliable devices for the direct conversion of kinetic energy into electricity. Such devices are only of experimental character yet. When developed they could also

serve as energy generators on small scale in fast streaming rivers on land where no possibility exists for the creation of a water head by a dam.

3.3 Wave energy

Wave energy devices have been designed, tested and deployed as an experiment in a wide variety of shapes, mechanisms and capacities.
The reason for this may well be the low level of investment to obtain a demonstration plant, compared to OTEC and tidal devices. Nevertheless there is also much critic on wave energy devices. Some designers state that it is anyhow more efficient to obtain energy directly from the driving force of the waves, the wind, instead of recovering it from the waves. This may be quite feasible offshore. Consequently we see quite some areas in the world where on the beach, or close offshore windmill parks have been put into operation.
Regarding the wave energy projects, small scale test projects have been established, according a variety of physical principles. Devices where floaters are moving in the waves and introduce forces and consequentially forced movements relative to foundations in the seabed are considered as relative expensive, vulnerable to mechanical damage and delicate in maintenance.
Devices that transfer the wave movement into compression and decompression of air, that on its turn moves a turbine above sea level are more attractive regarding costs, possible mechanical damage and maintenance. A most interesting experimental unit has been deployed offshore the Tamil Nadu coast in south east India. Prof Raju from the Indian Institute of Technology in Madras reports on this feature in the Special session R2 on Offshore fixed and floating structures of this conference. A special feature in this project is the anticipation of using these units for breakwaters for new harbours in the area. In this way a substantial part of the costs of these units, i.e. the cost of the caissons and the installation of those, would not charge the investment in energy production. Figure 3 shows a cross section of this installation.

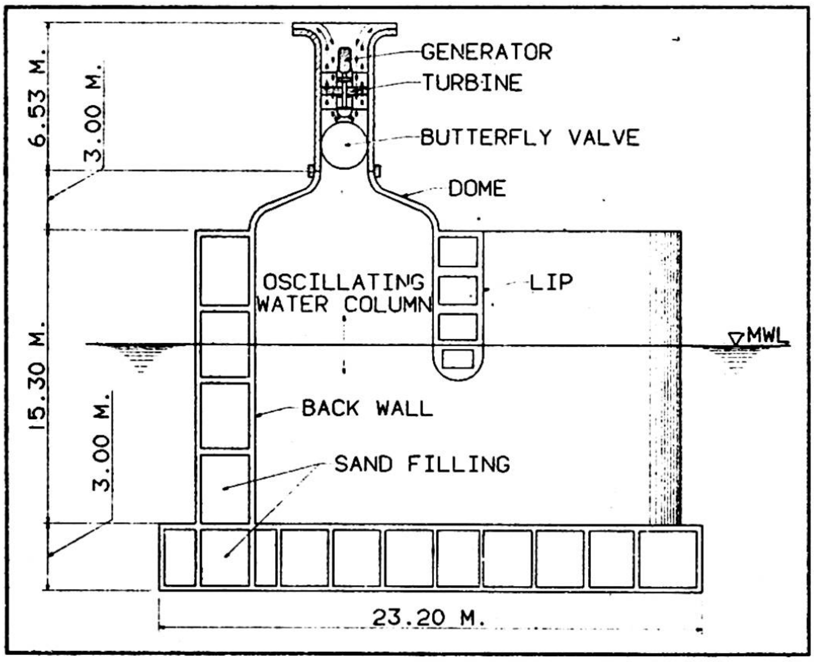

Fig.3 Experimental wave energy generator offshore Tamil Nadu

It may be true, that according these lines of cost sharing other wave energy projects may become feasible.
Wave energy projects have an other disadvantage. Waves are not permanent

present in many locations and vary in time. For this reason the number of locations are limited to those where a permanent ocean swell provides long waves with a high energy content. For such locations other mechanisms of energy generation are possibly feasible.
An artificial atoll is one of those options tested. Chapter 4 of this paper explains on an example.
An other option is tested in Norway. Long ocean waves are guided into a natural or artificial funnel. The wave height does increase by the funnel action. At the end of the funnel a dam is built. The waves, running into the funnel overtop the dam and feed a reservoir with a top level well above the medium sea level. In between the reservoir and the sea a channel with built in low head turbines are provided to generate electricity. This system is tested in Norway and may be deployed in Indonesia shortly.

3.4 Pump Accumulation Conversion

Already under tidal power generation PAC was mentioned. Although PAC is not strictly related to Ocean Energy Systems, it should be mentioned here, as quite some effort is being spent on studies for the development of pump accumulation basins in coastal areas.
The aim of such units, where energy is buffeted by the conversion of kinetic energy in the form of electricity, into potential energy, by increasing the water level of a basin, is appreciated in different ways. See figure 4 for the basic principle.

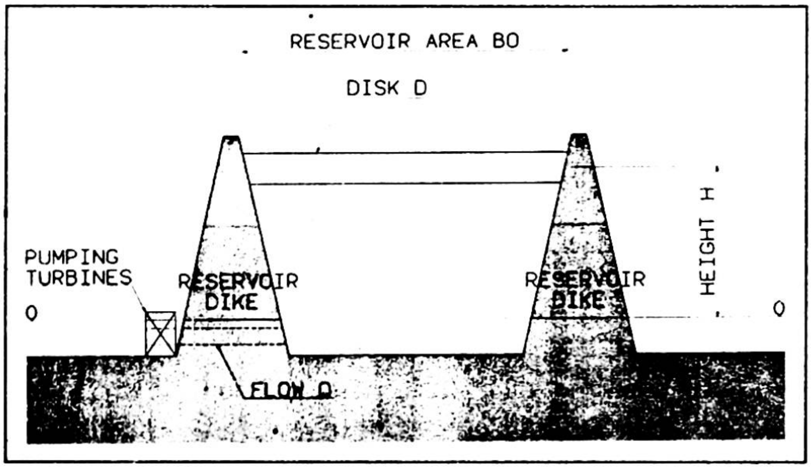

Fig.4 Principle of a PAC plant

In general it is a system to store energy from continuous sources, like nuclear power plants, for use during peak hours in energy consumption. But not just this approach is valid for the justification in the investment of PAC units. As conventional plants, like coal fired thermal units require an increasing investment, because of the necessary provisions for cleaning of exhaust gasses and deposit of slags, it may be more effective to run them on their full capacity and save the not instantaneous required energy in PAC units. Studies in The Netherlands have shown that benefit - cost ratio's are a function of net energy content and guaranteed output. This is demonstrated in an example in figure 5 for a location offshore The Netherlands.

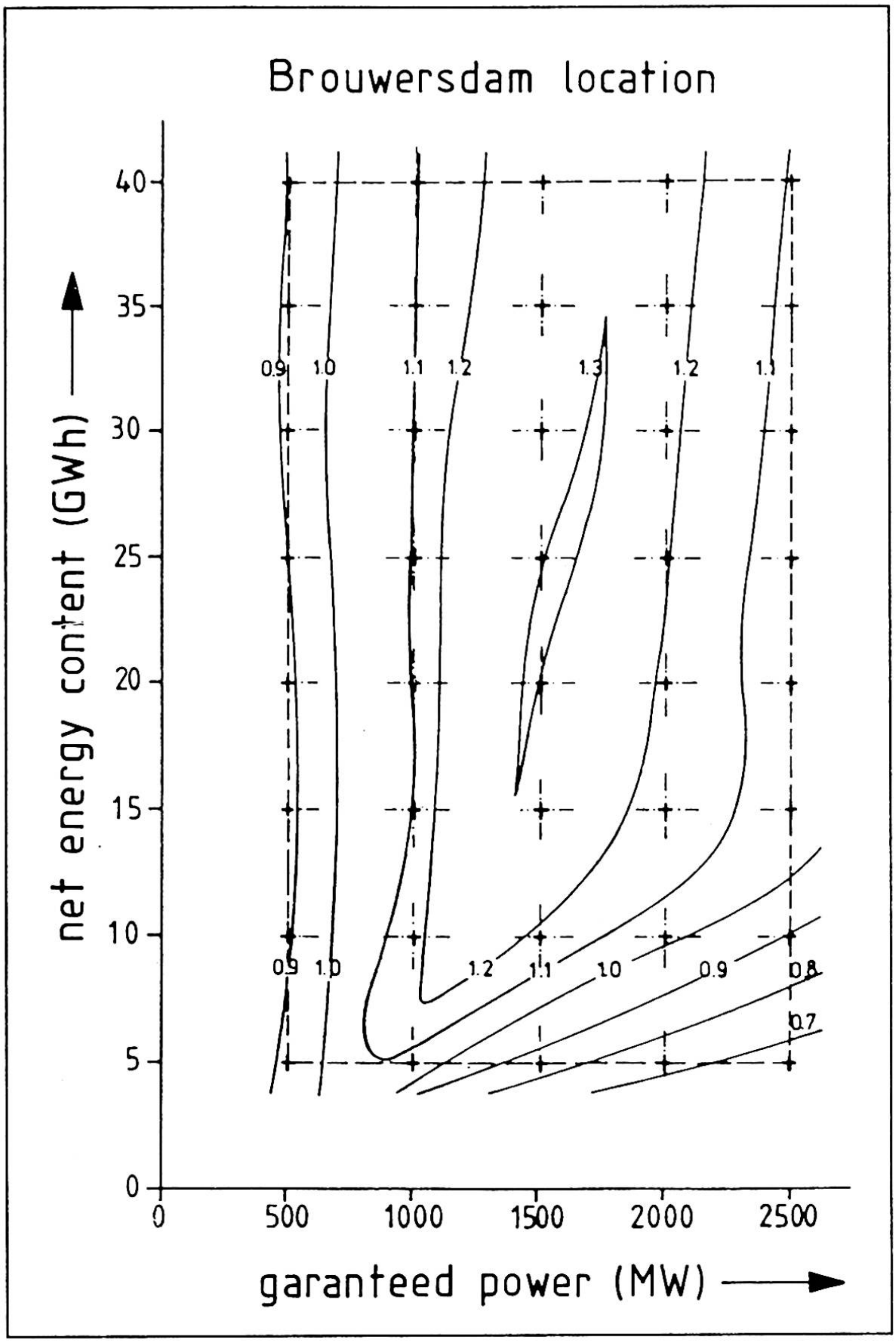

Fig.5 Lines of equal cost benefit ratio for an available pumping capacity of 2700 MW

Pump accumulation conversion systems have been constructed in many places in the world, usually there where natural conditions were favourite and civil engineering works on dams could be reduced to a minimum. Table 1 shows the main characteristics of some of those plants, indicating already, that the height of waterhead has to be considerable.
In case of the recent Dutch investigations mentioned, where no natural geographical gradients can be used and the entire plant has to be constructed offshore, 70 m. high dams with a 2700 MW capacity proved to be most effective.

Location			height (m)	power (MW)
0	Plate Taille	- Belgium	47	135
0	Gabriel y Galan	- Spain	59	110
0	Torrao	- Portugal	52	74
0	Hiwassee	- Tennessee, USA	63	76
0	Ludington	- Michigan, USA	100	1842
0	Smith Mountain	- Virginia, USA	58	108
0	Jocassee	- South Carolina, USA	102	200
0	Midono	- Japan	72	245
0	Mazegawa	- Japan	100	288

Table 1. Examples of pump turbine plants

4. OCEAN ENERGY; CHALLENGES AND PROBLEMS

From the examples given in chapter 3 it is clear that Ocean Energy Systems are quite attractive in many ways. Apart from a promising option for environment friendly and consequentially effective energy, such systems represent a challenge for structural engineers.
Those interested in new shapes, new materials and new ways of construction, have a completely new field with many possibilities. Some examples of creative ideas are presented here.
The cold water pipe for a 400 MW capacity floating OTEC plant has been the subject of several constructability studies. A most interesting new idea, showing new shapes, new materials and new construction methods in just one concept was developed as shown in figure 6. The pipe has to be 30 m. diameter, with a length of 1000 m. to be deployed offshore on location.

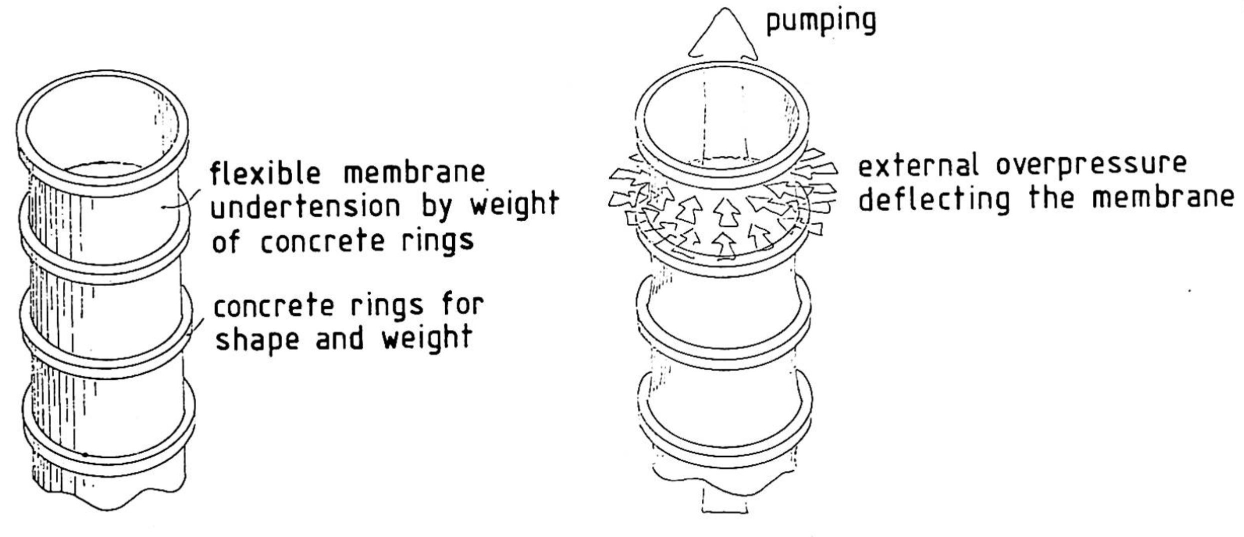

Fig.6 Flexible OTEC cold water pipe

The idea of this design is a composition of high strength fibre being kept in cylindrical shape by the weight and form of concrete stiffening rings. It is clear that such a system can be deployed sequentially, far more easy than a stiff construction, through the well of a floating body.
Another idea mentioned was the artificial dam atoll. Here long waves are used

to generate power by focusing the waves on an atoll type floating construction. Fig.7 shows the principles of a way of constructing such a unit.

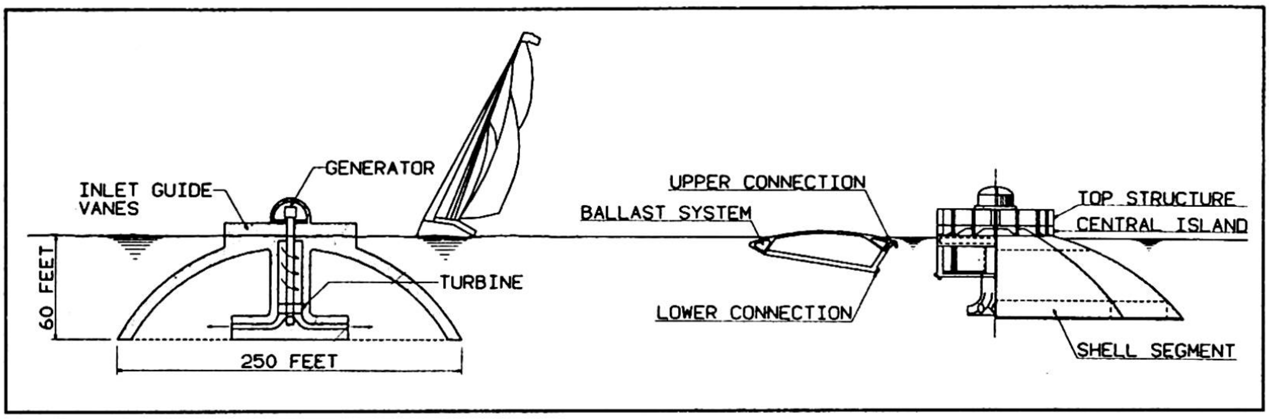

Fig.7 Dam atoll in place and under construction

It may be clear from these two examples that ocean energy systems have a challenge for the imagination of creative engineers. Other systems like the energy storage schemes, require dams on soft soil of magnitudes never encountered in the engineering history. Wave energy systems do invite for linking different functions of marine structures. Tidal energy systems require major civil engineering works that have to be completed in a relatively small time frame to allow for economic feasibility.

For structural engineers focused on analyses and modelling, rather than on creating shapes and systems, ocean energy systems have promising work in hand. What to think of flexible cold water pipes of substantial length and mass, being embedded in a floating structure, subject to waves and current. What to analyze about 80 m. high dams on soft soil for pump accumulation conversion systems. The emphasis of the day, analysis, is served with a wide variety of challenges focused on ocean energy systems.

Both challenging features, design and analyses, require an attention that is embedded in an environment of consciousness about engineering, environment and society. This involves a rather complex way of dealing with the problems.

This means that an engineering approach towards ocean energy systems requires design methodology and a scientific background for solving environmental engineering. Both requirements are presently badly represented in our structural engineering practise.

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