

# Ocean Thermal Energy Conversion

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**Ocean Thermal Energy Conversion (OTEC) is a process that employs the natural temperature difference between the surface and the depths of the ocean. First introduced in 1881, OTEC has been described as an effective and renewable energy source. OTEC systems must be designed with regard to potential efficiency issues. These issues should be properly researched in order to design OTEC systems that are effective. OTEC plants can be a feasible source of cost effective renewable energy in tropical coastal regions that have high shipping costs for fuels and foods.**

## I. Introduction

Covering over 70% of the planet's area, the Earth's oceans could potentially be utilized as a source of virtually inexhaustible renewable energy. Ocean Thermal Energy Conversion (OTEC) is a method that employs naturally occurring temperature differences between warm surface water and colder deep seawater (Thomas, 1993). To be effective a minimum temperature difference between the ocean surface layers is 20°C. These temperature gradients exist primarily in specific tropical regions near the equator (Takahashi and Trenka, 1996).

Originally proposed by French Engineer Jacques Arsene d'Arsonval in 1881, OTEC is not a new technology. Since then many advancements have been made in the development of this technology. The three most common OTEC systems are: open-cycle, closed-cycle and hybrid cycle, all requiring a working fluid, condenser and evaporator within the system. These three systems all employ the thermodynamics of a working heat exchanger and use the temperature differences naturally occurring in the ocean as the driving force.

Concerns with efficiency losses due to biofouling, system power requirements and heat exchanging systems have led to exploration through case studies and analysis. While OTEC systems have been studied since 1881 there have been few full-scale implementations. There are still, however, a number of studies being conducted, especially in Japan, regarding the implementation of this renewable large scale technology.

## II. History

The first known Ocean Thermal Energy Conversion (OTEC) system was proposed by a French Engineer Jacques Arsene d'Arsonval, in 1881 (Takahashi and Trenka, 1996). Recognizing the tropical oceans as a potential source of energy, through the natural temperature differences between the ocean's surface water and deep water,

D'Arsonval built a closed-cycle OTEC system, with ammonia as the working fluid, that powered an engine (Takahashi and Trenka, 1996). Ammonia was chosen as the best fluid available to accommodate the pressure differences between the two temperatures of water assuming that the temperature of the boiler was 30°C and the condenser was 15°C (Avery and Wu, 1994). The pressure differences in the OTEC system design was one of the challenges D'Arsonval had to overcome. Ammonia was selected because it had such a low boiling point allowing it to become vaporized by the small temperature gradients when pressurized by the pumps in the system. In similar cycles where the Rankine cycle is followed there is usually a higher pressure gradient in which to generate energy i.e. combustion driven engines. In the case of OTEC the temperature gradients are maximum 22°C therefore a working fluid that was able to change phases with such a small gradient was chosen. This proposed technology was never tested by d'Arsonval himself.

A student of d'Arsonval named George Claude soon took on the challenge of properly designing and building a working OTEC system. Claude, however, took a different approach to the design. He stated that corrosion and biofouling of the heat exchanger in an OTEC system would be a problem in the closed-cycle design. Claude suggested using the warm seawater itself as the working fluid in an open-cycle, now better known as the Claude cycle (Avery and Wu, 1994). Claude next sought to prove his open-cycle theory at

Ougree-Marhaye in Belgium by creating an engine fueled by water temperature differences. Using the 30°C cooling water from a steel plant as the source for warm water for the boiler (evaporator) and 10 °C water from the Meuse River as the condensing fluid, Claude successfully demonstrated the feasibility of the open-cycle concept (Avery and WU, 1994). This water from the steel plant was the cooling water sprayed on the steel during fabrication in order to prevent flaws in the steel when still malleable.

In 1930 George Claude designed and built a fully operational closed loop system OTEC power station in Matanzas Bay in Northern Cuba (Takahashi and Trenka, 1996). This power station generated 22 kilowatts (kW), but had a negative energy balance, consuming more power than it produced.

Later Claude perused the construction of a floating power plant aboard a cargo ship anchored off the coast of Brazil (Takahashi and Trenka, 1996). Unfortunately before the plant could be completed the coldwater pipes required for the OTEC plant were destroyed by the ocean's powerful waves.

OTEC systems were not investigated again on a serious scale until 1956 when a team of French scientists and engineers designed a 3 megawatt (MW) power plant. This design project had to be abandoned due to the expenses associated with the components of the OTEC system (Takahashi and Trenka, 1996). In 1962 Hilbert Anderson and his son James H. Anderson, Jr. began full scale design analysis of OTEC systems. Soon after, in 1970, they were joined by William E. Heronemus from the University of Massachusetts along with Clarence Zener of Carnegie-Mellon University (Committee on Alternative Energy Sources, 1975). Their research was funded by the National Science Foundation through a grant awarded in 1972 to the University of Massachusetts in order to allow for a complete study of the technical and economic feasibility of the OTEC process. Another grant soon followed awarded again by the National Science Foundation in 1973 to the Carnegie-Mellon University to further investigate other elements of OTEC systems (Committee on Alternative Energy Sources, 1975). Unfortunately their efforts were wasted as the energy board paid little attention to their published findings assuming that coal and nuclear power would supply the future energy requirements.

OTEC study in Japan began in 1974 with the launch of the Sunshine Project by the Japanese government. The primary focus of this project was to research and develop Ocean Thermal Energy Conversion systems. In 1977, Saga University successfully constructed an OTEC plant known as Shiranui 3, which managed to produce 1 kW of energy. Experiments were carried out in 1978 in order to test the performance of the condenser and evaporator in both shell and tube type heat exchangers. In the following year, a plate type heat exchanger was also tested using a different type of Freon as the working fluid (Uehara et al., 2005).

In 1980, a 50 kW offshore OTEC plant was constructed and tested by Saga University. The following year, Tokyo Electric Co. successfully experimented with an OTEC system in the Republic of Nauru, generating up to 120 kW of electricity (Xenysis, 2007). In 1981 a new method for using the temperature differences in the ocean to produce power was proposed. This was known as the Kalina cycle after its inventor Dr. Kalina. Up until 1981 the primary focus of study had been on the well-known Rankine cycle. The Kalina cycle was able to use a mixture of ammonia and water to operate, which gave it an advantage over the Rankine cycle that requires a pure substance (such as ammonia) (Uehara et al., 2005). In 1982, Kyushu Electric Co. also of Japan succeeded in constructing a 50 kW OTEC plant. This plant was based on a closed loop cycle that utilized the waste heat from a diesel generator.

It was not until 1985 that Saga University managed to construct a larger version of their experimental OTEC system, capable of producing 75 kW. In order to move the technology forward and attempt to attain economically feasible power, a group of 25 of Japan's top companies spanning a variety of fields (engineering, manufacturing, ship building, power generation) were brought together in 1988 to form an organization to study OTEC (Xenesys, 2007). This same year Hamuo Uehara and his team managed to optimize a hybrid cycle that combines the energy production of OTEC with the desalination of seawater to bolster the efficiency of ocean thermal energy.

Deep ocean water (DOW) systems were first studied by the Science & Technology Agency of Japan, which began in 1989. In 1994 Saga University designed and constructed a 4.5 kW plant for the purpose of testing a newly invented Uehara cycle, also named after its inventor Haruo Uehara. This cycle included absorption and extraction processes that allow this system to outperform the Kalina cycle by 1-2% (Uehara et al., 2005). In 1997 Saga University and the National Institute of Ocean Technology, India (NIOT) signed a technical agreement for a 1 MW floating OTEC plant designed by NIOT, which was then constructed in 2001. The Uehara cycle was selected for this design in order to maximize efficiency. The Institute of Ocean Energy at Saga University was founded in 2003. Upon the experimental success of the 1 MW plant, a 25-50 MW system is planned (Xenesys, 2007).

### III. OTEC Systems

The extraction of the potential energy available within the ocean is dependent upon the efficiency of the thermal system employed, including pumps, condensers and heat exchangers (Afring and Taylor, 1979).

#### A. Closed-Cycle

The closed-cycle OTEC power plant was the first OTEC cycle proposed by D'Arsonval in 1881. This cycle uses a working fluid with a low-boiling point, usually propane or ammonia, in a closed flow path (Takahashi and Trenka, 1996). The working fluid is pumped into the evaporator where it is vaporized and in turn moves a turbine.

Closed-cycle plants operate on a Rankine cycle. The first stage of this cycle is referred to as isentropic expansion, which occurs in the steam turbine. Isobaric heat rejection in the condenser follows. This stage the water vapor becomes a liquid and therefore the entropy is decreased. The next stage is the isentropic compression in the pump (Takahashi and Trenka, 1996). During this step, the temperature increases due to the higher pressure. The boiler then supplies isobaric heat causing the working fluid to vaporize.

In an OTEC system the warm sea water would be pumped into the evaporator where the liquid ammonia would be pressurized. This pressure causes the ammonia to boil or become vapor. This works due to the ideal gas law that states that the temperature is directly proportional to the pressure; therefore if the pressure increases in a system, the temperature does too. The vapor ammonia then expands by traveling through a turbine. This turns the turbine making electricity. The ammonia vapor pressure at the outlet of the turbine is 7°C higher than the cold seawater temperature. The cold seawater is therefore brought up from the depths where heat exchange occurs and ammonia vapor is changed back into a liquid. The liquid ammonia is then pressurized by a pump started the cycle once more (Thomas, 1993).

Rankine cycles, in theory, are able to produce non-zero net power due to the fact that less energy is required to increase the pressure of a liquid than is able to be recovered when the same fluid expands as a vapor. It is for this reason that phase changes are essential when producing energy this way.

The advantages of using a closed-cycle system are that it is more compact than an open-cycle system and can be designed to produce the same amount of power. The closed-cycle can also be designed using already existing turbo machinery and heat exchanger designs.

#### B. Open Cycle

The open-cycle OTEC power plant, first proposed by Claude, uses the actual sea water as the driving fluid for the heat exchanger. It works by pumping the warm seawater into a low pressure (vacuum) evaporator chamber where the water boils. The evaporator chamber vacuum is maintained through a series of valves and careful maintenance to avoid atmospheric leakages. The vapor then drives a low pressure turbine to create electricity. Finally, the vapor is then cooled using deep seawater (Thomas, 1993).

The open-cycle system differs from the closed-cycle because instead of using ammonia or a specific low boiling point working fluid, it uses warm sea water as the working fluid. Overall the Claude cycle is similar to the Rankine cycle however it has several important differences. The first major difference is that it uses complex heat and mass transfer processes to flash evaporate the warm water in a pressurized system. It also is not essential that the effluent at the end stage matches the warm water heat becomes the working fluid in stage one. That is where the open – cycle concept comes into play.

The first stage of the open-cycle pumps the warm seawater into a pressurized called the evaporator. It is here where the water is introduced into the chamber through spray spouts. This maximizes the warm water surface area, allowing the water to have increased exposure to the reduced pressure. This causes the water droplets to boil and become vapor. This vapor, as in the closed-cycle, moves the turbine to produce electricity. The next stage in this cycle is the heat transfer to the cold seawater thermal sink, this stage is important for condensing the warm seawater. The final stage is the compression of the condensate back to atmospheric pressure. The water is then discharged.

Because the warm seawater is flash evaporated, it becomes desalinated and becomes pure fresh water. This is a major advantage to this type of system as it can provide fresh water to communities who are in shortage. Another major advantage is the fact that the working fluid is not a potential threat to the environment. However there are several disadvantages to this type of system. The first one being that the system must be carefully sealed to prevent leakage into the system of atmospheric air. This would be detrimental to the system as it relies completely on the pressure gradient to flash evaporate the warm

seawater. The second disadvantage is that the volume of working fluid required is much larger than that of the closed-cycle as the actual usable steam produced is about 0.5% of the warm seawater used. The final disadvantage is due to the gasses that are naturally present in the seawater. Although this type of system is beneficial for removing the salt from the pure water, the system also removes the gasses that are dissolved into the water including carbon dioxide and nitrogen gas. These gases do not recondense when introduced to the cold seawater and therefore become trapped in the system. This greatly reduces efficiency (Takahashi and Trenka, 1996).

### C. Hybrid Cycle

The Hybrid-cycle is one that has yet to be tested but uses principles from both the closed and open-cycle OTEC systems to obtain maximum efficiency. The Hybrid cycle uses both seawater and another working fluid, usually designed using ammonia (Takahashi and Trenka, 1996). The fresh water is initially flashed into steam, similar to the closed-cycle; this occurs in a vacuum vessel. In the same vessel the ammonia is evaporated through heat exchange with the warm water. The ammonia is then physically mixed with the warm seawater in a two-phase, two-substance mixture. The evaporated ammonia is then separated from the steam/water and re-condensed and re-introduced into the closed loop cycle. The phase change of the water/ammonia vapor turns a turbine producing energy (Thomas, 1993).

## IV. Biofouling

When designing OTEC systems it is important to identify potential causes of reduced heat exchanger efficiency. One concern is the potential effect of biofouling within the cold and warm sea water pipes. Biofouling is the unwanted accumulation of algae, microorganisms, marine animals and plants on the surfaces of pipes and heat exchangers. The possibility that biofouling of the heat exchangers would quickly degrade OTEC performance was raised as a serious potential problem with OTEC (Avery and Wu, 1994). Biofouling is thought to be a limiting factor in the implementation of OTEC systems. Afring and Taylor (1979) conducted a study from mid-July to the end of September 1977, on a large barge located 13 km north of Christiansted, St. Croix, set out to determine the relationship between heat exchanger efficiency and biofouling. Table 1 gives the conditions of the experiment that sought to reproduce the conditions of an actual OTEC power plant.

After ten weeks of exposure to the open-ocean conditions of a typical OTEC heat exchanger system, the pipes were assayed for overall accumulation of biological material on the inner surfaces using plate counts (Afring and Taylor, 1979). It was observed that bacterial populations were 107 cells/ cm<sup>2</sup>. The densities of other components were 10-27 µg/ cm<sup>2</sup> for organic carbon, 1.5-3.0 µg/cm<sup>2</sup> for organic nitrogen, 4-28 ng/ cm<sup>2</sup> for adenosine 5'-triphosphate, 3.8-7.0 µg/ cm<sup>2</sup> for carbohydrates and 0.2-0.8 ng/ cm<sup>2</sup> for chlorophyll (Afring and Taylor, 1979). It was concluded in this particular project that the actual extent of the biofouling within an OTEC heat exchanger was found to be extremely low and that after 10 weeks of study the layer of biofouling was less than 1µm thick (Afring and Taylor, 1979).

Although this particular investigation concluded that there was no reason to believe biofouling would disrupt OTEC heat exchanger units, other similar investigations found otherwise. In the early 1978 the U.S. Department of Energy funded a program to investigate the relationship between biofouling in an OTEC heat exchanger and overall performance efficiencies. Three different locations were selected: Hawaii, the Gulf of Mexico and Puerto Rico (Avert and Wu, 1994). These studies concluded that biofouling would become a threat if not treated after 6 weeks of full operation. Biofouling treatment options were also investigated, including both chemical and physical methods to treat the OTEC systems. These efforts discovered that the injection of 70 ppb of chlorine for one hour each day effectively prevents the development of a biological film (Avert and Wu, 1994). In July of 1986 further investigations of heat exchanger test samples exposed to seawater to a 70 ppb chlorine treatment for one hour a day for more than 1000 days showed no significant reduction in heat transfer due to biofouling (Avert and Wu, 1994). These concentrations of chlorine would not be harmful to the aquatic environment as they are 5% of the amount the U.S. Environmental Protection Act allows to be released (Avert and Wu, 1994). Other treatment options including brushing and ultra sonic radiation were found to be effective, but were not as appealing as an easily designed chemical treatment option (Avert and Wu, 1994). Biofouling can also be reduced by zinc plating within the HWP (Thomas, 1993).

Although all the studies agreed that the threat of biofouling decreasing efficiency was initially overestimated (Avert and Wu, 1994), biofouling has still been concluded to be a potential problem that can be solved with proper design selection and safe chemical treatment.

**Table 1. Parameters of OTEC biofouling study, St. Croix (Afring and Taylor, 1979)**

Parameter	Parameter Value
Depth of cold water pipe	20 m within surface mixed layer
Pipe Material	Aluminum
Dimensions of pipes	2.6 m long by 2.54 cm inner diameter
Flow Velocities	0.9 – 1.8 m/s
Temperature of seawater entering exchanger units	27.8 – 28.6 °C
Duration of Experiments	10 Weeks

## V. Effect of Non-Condensable Gases on the Heat Transfer Performance in a Condenser of an Open Cycle OTEC Power Station

Open cycle – ocean thermal energy conversion systems (OC-OTEC) use warm surface seawater and convert it to steam via an evaporator in order to move a turbine to create electricity (Amano and Tanaka, 2006). The exhaust from the turbine is then condensed using cold seawater drawn from depths where the temperature is more than 20°C cooler than the surface water (Amano and Tanaka, 2006). These OC-OTEC systems are usually placed several meters above sea level so water discharge from the low-pressure system to the atmosphere is accomplished using gravity (Amano and Tanaka, 2006). However the seawater required for the system has to be pumped into the system and therefore the pump power must be high enough to overcome the pipe resistance (Amano and Tanaka, 2006). It is during this pumping of the seawater into the system that high volumes of dissolved, non-condensable gasses are introduced into the OC-OTEC system.

### A. Dissolved, non-condensable gasses in the condenser

Because the surface water of the ocean contains such a high concentration of non-condensable gas it has been identified as being in a practically saturated solution. OC-OTEC systems depend on this warm surface water to move a turbine, therefore the presence of non-condensable gasses in the condensers of these OTEC systems has become a major problem (Amano and Tanaka, 2006). It is very important to research and design efficient methods for the exhausting of this non-condensable gases originating in the warm surface water, for setting acceptable concentration limits, for estimating the net output of OC-OTEC, and for the design of evaporators and condensers (Amano and Tanaka, 2006). These high efficient power generation systems should also be combined with fresh water recovery units along with cold water recovery systems for air conditioning, cooling and aquaculture.

### B. OC-OTEC Non-Condensable Gas Investigation

In order to identify the relationship between efficiency OC-OTEC power units and non-condensable gases, a small-sized experimental condenser was developed by Masatsugu Amano and Tadayoski Tanaka. A series of experiments were performed by investigating the mass balance when non-condensable gasses accumulated inside the condenser in steady state (Amano and Tanaka, 2006).

Three major conclusions were obtained from their extensive testing. The first conclusion was that the main factor in the influence of the non-condensable gas condensation efficiency was not dependent on the total concentration of the gas in the entire condenser rather the concentration of non-condensable gas located near the surface of the condenser (Amano and Tanaka, 2006). The second conclusion was that the non-condensable gas concentration located at the surface of the condenser depended on the inflowing gas concentration. Therefore, higher efficiency could be achieved by reducing the concentration of non-condensable gas before it enters the evaporator (Amano and Tanaka, 2006). The final conclusion was that the temperature of the warm water must be increased for better operation of the heat exchanger. This could be achieved by having a higher flow rate of surface seawater into the evaporator, thus increasing the heat of vaporization (Amano and Tanaka, 2006). If this was implemented, it would mean that very large evaporators and condensers would be required.

## **VI. Other Uses For OTEC Technology**

OTEC systems are not just limited to just producing electricity and because of the unique design of these power stations are potentially available to tackle other ventures in combination with electricity to offset some of the expenses associates with OTEC.

### **A. Fresh water production**

Desalination is just one of the effective potential products that could be produced via OTEC technology. Fresh water can be produced in open-cycle OTEC plants when the warm water is vaporized to turn the low pressure turbine. Once the electricity is produced the water vapor is condensed to make fresh water (Takahashi and Trenka, 1996). This water has been found to be purer then water offered by most communities as well it is estimated that 1 MW plant could produce 55 kg of water per second. This rate of fresh water could supply a small coastal community with approximately 4000 m<sup>3</sup>/day of fresh water (Takahashi and Trenka, 1996). This water can also be used for irrigation to improve the quality and quantity of food on coastal regions especially where access to fresh water is scarce.

### **B. Air conditioning and Refrigeration**

Once cold water pipes are installed for an OTEC power plant the cold water being pumped to the surface can be used for other projects other then to provide the working fluid for the condenser. One of these uses is air conditioning and refrigeration. Cold water can be used to circulate through space heat exchangers or can be used to cool the working fluid within heat exchangers (Takahashi and Trenka, 1996). This technology can be applied for hotel and home air conditioning as well as for refrigeration schemes.

### **C. Aquaculture and Mariculture**

Another possibility for taking advantage of OTEC plants is the use of the water pipes to harvest marine plants and animals for the purpose of food. This proposition is still under investigation however it is proposed that seawater life including salmon, abalone, American lobster, flat fish, sea urchin and edible seaweeds could be harvested for ingestion using the cold water pipes that would be readily available from the OTEC power plants (Takahashi and Trenka, 1996).

Mariculture is another possibility that is currently being researched that would take advantage of the cold deep ocean water being transferred to the oceans surface. This water contains phytoplankton and other biological nutrients that serve as a catalyst for fish and other aquatic populations (Takahashi and Trenka, 1996). This water could serve to increase native fish populations through the recycling of trace nutrients that would not be otherwise available.

### **D. Coldwater Agriculture**

Because the coastal areas suitable for OTEC are in tropic regions there is a potential to increase the overall food diversity within an area using the cold water originating from the deep ocean. It has been proposed that burying a network of coldwater pipes underground the temperature of the ground would be ideal for spring type crops like strawberries and other plants restricted to cooler climates (Takahashi and Trenka, 1996). This would not only supply the costal populations with an increased variety of food but reduce the cost of transport of cooler climate foods that would otherwise have to be shipped.

## **VII. Environmental Impacts**

Overall proposed OTEC technologies have many potential benefits to the environment. OTEC is a source of clean, renewable energy and harnesses the seawater for electricity generation which is an abundant and is almost unlimited. The use of OTEC also ensures that a reliable able and constant power output would be supplied as it is not depended on certain climate conditions or fossil fuels. OTEC does not discharge any CO<sub>2</sub> and due to the deep water mixing with the upper layers of the ocean actually helps to grow phytoplankton, algae and coral which may lead to an increase on CO<sub>2</sub> fixation.

Environmental concerns associated with OTEC systems have been brought up. One major concern is with the closed-loop and hybrid systems that depend on a low boiling point working fluid (ammonia or chlorine) to facilitate in heat exchange (Takahashi and Trenka, 1996). These potentially harmful substances could leak into the ocean if the pipes were ever damaged. Another problem would be the habitat disruption in the ocean due to the installation of the pipes (Takahashi and Trenka, 1996). Although

OTEC does present potential issues that may be negative to the environment, with proper designing, research and care the negative impacts can be reduced or avoided.

### **VIII. Conclusion**

Ocean thermal energy conversion is a potential source of renewable energy that creates no emissions. The main advantages of OTEC is that the method is fuel free, has a low environmental impact, can supply pure water for both drinking and agriculture, can supply refrigeration and cooling and can provide a coastal community with reliable energy. The disadvantages include high capital cost, potential for hostile ocean environment during construction and use and an overall lack of familiarity with OTEC technology (Thomas, 1993). There have been several analyses of the feasibility of full-scale implementation of OTEC. While some of these investigations are contradictory to each other, research with actual mini OTEC plants is proving that OTEC systems will one day become a feasible, efficient and renewable source of energy.

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