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First Generation 50 MW OTEC Plantship for the Production of Electricity and Desalinated Water

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Abstract

Preliminary designs for first generation Ocean Thermal Energy Conversion (OTEC) plants utilizing either closed cycle (CC) or open cycle (OC) concepts are presented. These are based on existing technology and current offshore industry practices. The CC-OTEC plant utilizes pressurized anhydrous ammonia as the working fluid to drive turbine-generators to produce electricity; and, the OC-OTEC plant makes use of low pressure steam generated in flash evaporators to drive steam turbine generators to produce electricity and surface condensers for the production of desalinated water.

Introduction

Given that oil reserves (≈ 1400 billion barrels) can satisfy world-wide demand (> 30 billion barrels/year) for at most another 50 years, it seems sensible to envision marine renewable energy resources as additional alternatives to our oil-based economy. In theory, for example, the ocean thermal resource could be used to generate most of the energy required by humanity (Michaelis, 2002 and Nihous, 2007). We should consider the implementation of OTEC plantships providing electricity, via submarine power cables, to shore stations. This could be followed, in 20 to 30 years, with OTEC factories deployed along equatorial waters producing energy intensive products, like ammonia and hydrogen as the fuels that would support the post-petroleum era.

What is pending, however, are realistic determinations of the costs and the potential global environmental impact of OTEC plants and this can only be accomplished by deploying and subsequently monitoring operations with first generation plants (Vega, 2003).

In the 1990s, it was determined that to be cost competitive OTEC plants larger than about 50 MW were required in the USA market; and, that it was necessary to deploy demonstration plants as a prerequisite to commercialization (Vega, 1992). Unfortunately, development did not proceed beyond an experimental plant sized at about 0.25 MW (Vega, 1995).

A number of configurations ranging from offshore to land based concepts have been proposed. Large and small waterplane platforms have been considered. In general, the former (ship shape) is ideally suited for OTEC applications. Moored offshore configurations transmit electrical power to shore via a submarine power cable. The grazing configuration operates as a self-contained factory ship on which an energy-intensive product is produced (Nihous, 1993). The grazing plantship can cruise around tropical waters essentially decoupled from land.

Conceptual designs for 50 MW OTEC plants utilizing either closed cycle (CC) or open cycle (OC) technology are summarized herein. The CC-OTEC plant utilizes pressurized anhydrous ammonia as the working fluid to drive turbine-generators to produce electricity; and, the OC-OTEC plant makes use of low pressure steam generated in flash evaporators to drive steam turbine generators to produce electricity and surface condensers for the production of desalinated water.

The OTEC platform must interface with both the cold water pipe (CWP) and the deep ocean mooring system. The attachment between the vessel and CWP must provide freedom in at least pitch and roll. Deep Ocean mooring systems or dynamic positioning thrusters developed by the offshore industry can be used for position keeping.

The CC-OTEC plant would require a 198 m long ship-shaped platform with 39 m beam and an operating draft of 16 m resulting in 120,600 tonne (metric ton) displacement. The OC-OTEC plant would be shorter at 176 m but beamer at 90 m resulting in a displacement of 247,400 tonnes. For the concepts considered herein, the products are 430,000 MWh/year for the CC-OTEC; and, 414,400 MWh/year and 118,400 m^3/day for the OC-OTEC.

The seawater subsystems consists of the pumps and the pipes required to supply warm and cold seawater streams to the heat exchangers, and allow for the return of seawater effluents into the ocean. Because of the relatively low thermodynamic efficiency of OTEC, these pipes have to meet unusual specifications: the CWP has to reach depths of about 1,000 m to supply cooling fluid at 4.5˚C (Vega, 1988). The combined needs for large amounts of cold seawater (138.6 m^3/s), and minimal pumping power losses result in a relatively large diameter CWP. The 1,000 m long 8.7 m i.d. fiber-reinforced-plastic (FRP) sandwich construction CWP is attached to a gimbal at midship.

Applicable single point mooring systems, including electrical and fluid swivels, are available from the offshore industry. The Aluminum plate-fin heat exchangers considered for the ammonia cycle can be manufactured in the USA (Panchal, 1990). The electricity is transmitted to shore via a submarine power cable and the desalinated water via a flexible pipe (e.g., hose). Several firms manufacture the submarine power cable required for the OTEC plant (Vega, 1994).

The final design will have to integrate the following:

- platform hull and structures;
- propulsion and positioning;
- land support system;
- seawater pipes and pumps;
- pipe/hull connection;
- deployment and attachment of seawater pipes to the platform;
- the power block consisting of the evaporator, turbine-generator and condenser along with the ammonia system and instrumentation and controls;
- the electrical transmission system consisting of the submarine power cable and the cable/hull connection;
- the desalinated water system consisting of flash evaporator and surface condenser and the transport pipe (hose).

Design Environment

For the purpose of this article a generic site was considered to proceed with concept definition (Table 1). Survival current conditions are from Keahole Pt. on the Big Island of Hawaii and the wave conditions are from offshore Kahe Pt. in Oahu.

Ocean Surface Temperature:	26 °C (Annual average) 24 °C to 28 °C range
Ocean Temperature at 1000 m depth:	4.5 °C (Annual average) 4 °C to 5 °C range
Operational Waves:	3.7 m significant wave height/ 7.5 s period
Survival:	6 m significant wave height/ 9.6 s period 20 m/s wind 1.5 m/s ocean current

Table 1.- Baseline Design Environment.

The design oriented analysis of an OTEC system must consider both survivability design loads and operational/fatigue loads. The first kind are based on extreme environmental phenomena, with a long return period, that might result in ultimate strength failure while the second kind result in fatigue induced failure through normal operations. The meteorological, sea surface, water column and sea floor description required to determine both kinds of loading for each major subsystem are established by considering the design processes.

The operational environment is given by up to 3.7 m significant wave height (7.5 sec period); and, surface currents below 1.5 m/s corresponding to annual occurrences of 96%. The conditions used to determine survivability design loads are given by: 20 m/s winds, 1.5m/s surface currents, 6 m significant wave height (9.6 sec period) head seas, or equivalent. The design wave conditions have an annual exceedence of 0.5%. For environmental conditions exceeding these values, the vessel would release the CWP and the submarine power cable and move away from the storm track. The CWP and power cable attachment sequences are designed to be reversible.

Closed Cycle OTEC

A simplified block diagram of the CC-OTEC power cycle is shown in Figure 1. The plant is housed in a ship–shaped platform with the electricity transmitted to shore via a 13 cm submarine power cable.

Given a surface water temperature range of 24°C to 28°C and a 1,000 m deep ocean water temperature ranging from 4°C to 5°C, the design values were selected as 26°C and 4.5°C (Table 1). Output would be 80 MW at the generator terminals with a corresponding net production of 53.5 MW.

For the temperature range considered, the gross power output varies as a function of surface water temperature by ≈ 8 MW/°C such that for temperatures of 28 °C and 4.5 °C, under the electricity production mode, a gross power output of ≈ 96 MW is sufficient to produce 69.5 MW-net with an in-plant consumption of 26.5 MW.

The facility will employ 2,750 kg/s of anhydrous ammonia as the working fluid with the power extracted through turbine-generators available from several manufacturers. The baseline aluminum plate-fin heat exchangers (evaporator and condenser) are currently available.

The design seawater flow rates are:

- 264.6 m^3/s (270,400 kg/s) of warm water; and,
- 138.6 m^3/s (142,300 kg/s) of cold water.

These flowrates were optimization to maximize net power under baseline conditions.

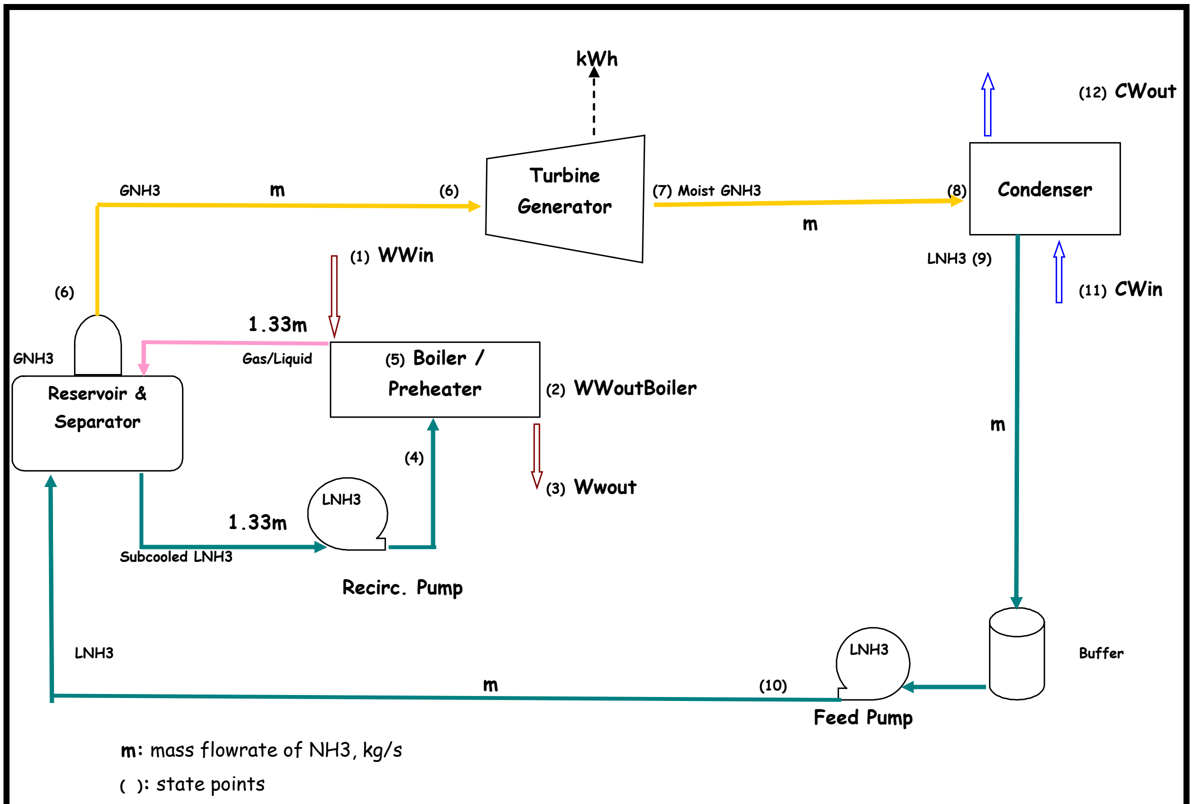
The process depicted in Figure 1 can be further described as follows. Warm seawater is drawn from a sump, with submersible pumps, into the evaporator. The evaporator is designed to withstand extended exposure to seawater and ammonia. Pressurized liquid ammonia is fed into the evaporator through a system of pumps and valves. The evaporator includes a “preheater” to provide liquid ammonia to the "boiler" at the saturation temperature. Energy transferred from the warm seawater evaporates the ammonia and the vapor that is produced rises up through a low-pressure-drop mist eliminator. The mist eliminator is included in the flow path of the wet vapor to separate the liquid ammonia and to ensure minimal carry-over of entrained liquid ammonia into the turbine. The separated liquid ammonia flows by gravity to the recirculation pump shown in Figure 1.

The ammonia vapor exiting the evaporator flows past a series of stop and control valves before expanding through a single-flow axial turbine coupled to a synchronous electrical generator. A short diffuser downstream of the turbine stage is employed to recover some kinetic energy. The exiting vapor passes down into a second heat exchanger (condenser) where it is condensed using cold seawater brought up from a depth of 1,000 m. Several submersible pumps are used to draw the cold water from a sump connected to the CWP.

The pressure of the ammonia condensate is increased and the liquid is transferred to the evaporator by means of a feed pump before beginning the cycle again. The ammonia power system flow loop is connected to an on-site ammonia storage and purification system. The purification system removes any water or solids which may have entered the working fluid.

Ammonia is used extensively in industry, and relevant codes, standards, and practices have been established for the construction and operation of ammonia systems. Temperatures and pressures encountered in the present application fall well within the ranges of practical experience. It is not anticipated that any significant safety risk will be entailed during normal operation of this facility if standard procedures are followed.

A chlorination unit will be included to minimize biofouling of the evaporator passages (Panchal, 1990). It has been determined that biofouling from cold seawater is negligible and that evaporator fouling can be controlled effectively by intermittent chlorination {50-100 parts per billion of chlorine for 1 hr/day}.



m: mass flowrate of NH3, kg/s

( ): state points

Figure 1.- Process Flow Diagram for CC-OTEC (NH3)

Estimates of evaporator and condenser heat transfer coefficients and pressure drops are state-of-the-art. The proposed concept considers compact plate-fin heat exchangers with core dimensions of 6.1 m (L) x 1.0 m (W) x 4.6 m (H). Our estimates indicate that four cores are required for a 4 MW-gross NH_3 evaporator submodule. Four of these submodules are integrated into a 16 MW-gross module such that the overall dimensions, including flanges and ducting, would require a volumetric space of 34 m (L) x 13 m (W) x 16 m (H). These dimensions are also applicable to the 16 MW-gross condenser module.

Turbine-generator (TG) units are available from well established manufacturers with the maximum size available *off-the-shelve* rated at about 16 MW-gross. The overall dimensions of a 16 MW unit, including the lube-oil-skid, are such that the volumetric space required is 12 m (L) x 8 m (W) x 5 m (H).

The volumetric space requirements for the heat exchangers and the turbine generators are summarized in Table 2. These are used as input to the sizing of the plantship.

Unit	**16 MW-gross Assembly Volumetric Space**
***NH_3/Seawater Evaporator** (Plate-Fin)	34 m (L) 13m (W) 16 m (H)
***NH_3 Turbines**	12 m (L) 8m (W) 5 m (H)
***NH_3/Seawater Condenser** (Plate-Fin)	34 m (L) 13m (W) 16 m (H)

Table 2.- Closed Cycle Heat Exchangers and TG: Overall Volumetric Space Requirements (including piping and ducting).

The seawater effluent streams are mixed together and returned to the ocean at a depth of 60 m by means of two 12.3 m inside diameter FRP pipes. This seawater return technique meets the most stringent environmental standards.

Open Cycle OTEC

A simplified block diagram of the OC-OTEC process is shown in Figure 2. The plant is housed in a ship with the electricity transmitted to shore via a 13 cm submarine power cable and the desalinated water via a 110 cm diameter hose pipe.

The process can be described as follows. In a low-pressure vessel the warm seawater is partially flashed into steam (e.g., flash-evaporator). The flash-evaporator units are connected to turbine-generators using the low-pressure steam as the working fluid. Subsequently, the wet steam exhaust enters the surface condensers, where the steam is converted into desalinated (fresh) water by exchanging heat with the cold seawater. The baseline 1.8 MW-gross submodule is depicted in Figure 3.

The heat and mass balance can be described using Figure 2 as reference and is summarized in Table 3. The 270,400 kg/sec of 26 °C surface seawater are drawn into two sumps via 10 m inside-diameter (id) pipes from a depth of approximately 20m. The seawater is sucked into the sumps by submersible pumps that supply the flow into the flash evaporators[1]. Similarly, 146,800 kg/s of 4.5 °C deep seawater are drawn into one sump via an 8.7 m id pipe from a depth of 1,000 m. The surface condensers utilize 142,300 kg/s and in intercoolers, for the vacuum compressors, 4,500 kg/s.

Uprisers take the warm seawater into the evaporators. Predeaeration nozzles remove a portion of non-condensables from the warm water accumulated below the spout plate. The warm seawater flashes through the spouts into the evaporation chamber at a pressure of 2.76 kPa. A small fraction (1,500 kg/s) of supply seawater is flashed into steam and the rest is discharged into the return water sumps at a temperature of 23.3 °C.

Steam from each evaporator enters the turbine at 2.74 kPa and leaves the turbine diffuser system at 1.29 kPa. Each turbine-generator (TG) unit gives a gross output of 1.8 MW for a total of 16.2 MW per module. Each unit comprises a single stage, single flow, condensing, axial flow, reaction turbine coupled to a synchronous generator. Nine axial turbine units would be used per 10 MW-net module. Using this turbine, a so-called ‘telephone’ configuration imposes itself, where evaporator and condenser are well separated, and are only connected through the turbine.

Steam exhausted from the turbine-diffusers (98% quality) enters the surface condenser. Approximately 99% of the steam (1,485 kg/s) is condensed into desalinated water. The remaining vapor along with the non-condensable gases are evacuated by the vacuum compressor system.

During this process, dissolved gases, mainly nitrogen and oxygen, are released from the warm seawater when pressures as low as 2 % of atmospheric pressure are reached. These non-condensable gases must be evacuated continuously by vacuum compressors to prevent accumulation and sustain the required low operating pressures. Non-condensables also adversely affect condensation performance through a blanketing effect at the heat exchanger walls. To reduce the impact released non-condensable gases, a pre-deaeration chamber at about 17 kPa is installed below the flashing chamber, so that about 50% outgassing occurs before steam generation, and at a higher pressure more suitable for compression.

Non-condensables and vapor from the condensers enter the vacuum compressor system through a counter-current direct contact precooler. The precooler receives 4.5 °C cold seawater and ensures that the mixture temperature at the first stage inlet of the compressor system is not more than 5.5 °C and the entire vapor is condensed till its partial pressure becomes equal to the seawater saturation pressure at 5.5 °C. The basic compressor system has four stages with intercoolers in-between. The fourth stage compressor takes the no-condensables from warm water predeaeration in addition to the non-condensables from the third stage. The discharge from the fourth stage is re-injected at 30 kPa into the warm water effluent piping. A fifth stage compressor could also be provided to bypass the re-injection scheme and discharge into the atmosphere. The fifth stage would require $\approx$ 1.6 MW in addition to the 3.6 MW required for the other stages. The first four stages are centrifugal whereas the fifth stage would be positive displacement type. All coolers should be of the direct contact type.

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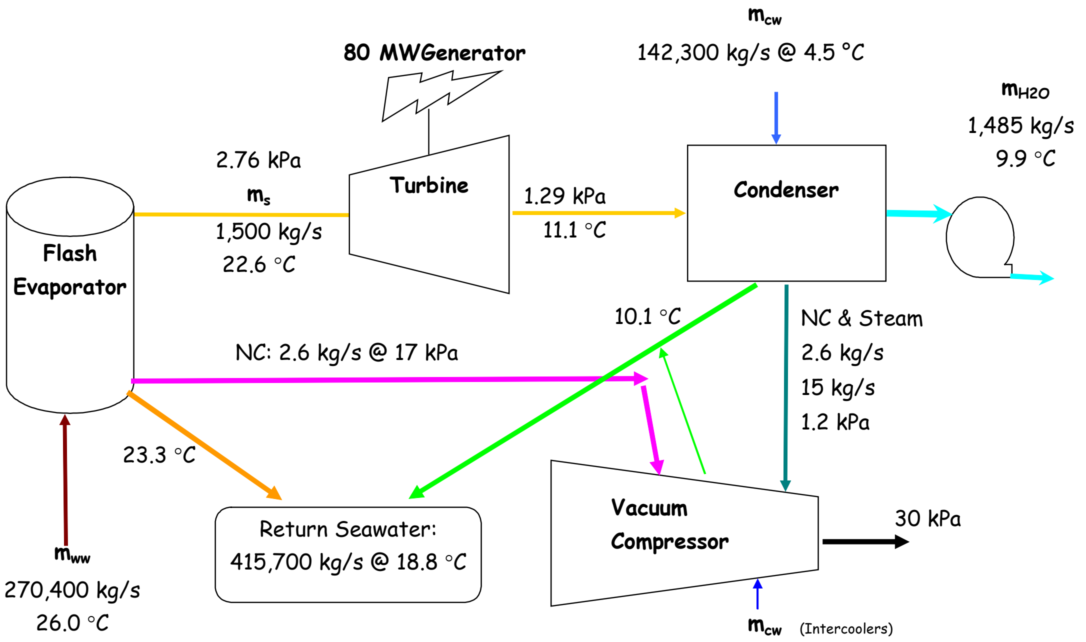
[1] There are a total of forty-five (45) flash evaporators, turbine generators and surface condensers and nine (9) each per module.

The net power from the system, after subtracting seawater pumping, vacuum compressors pumping and desalinated water pumping is approximately 51 MW. The total desalinated water produced is 1485 kg/s. Therefore, with a capacity factor of about 92%, annual outputs ought to be 414,400 MWh and the equivalent of 118,400 m^3/day for electricity and desalinated water respectively. These values are estimated onboard ship and do not account for losses related to transmission to the onshore station.



m_s: mass flowrate of steam

m_{ww}: mass flowrate of warm water discharged from 1st Stage

m_{cw}: mass flowrate of cold water discharged from 1st Stage

m_{H2O}: mass flowrate of condensate (desalinated water)

Figure 2.-Process Flow Diagram for OC-OTEC

SUBSYSTEM	Input	Output	Power Consumption
Flash Evaporator	270,400 kg/s @ 26 °C	Seawater: 268,900 kg/s @ 23.3 °C; Steam: 1,500 kg/s @ 22.6 °C/ 2.76 kPa; Non-Condensables: 2.6 kg/s @ 17 kPa 2.6 kg/s @ 2 kPa	
Turbine-Generator	Steam: 1,500 kg/s @ 22.6 °/ 2.73 kPa	Steam: 1,500 kg/s @ 11.1 °/ 1.29 kPa; 98 % Quality Power: 80 MW	
Surface Condenser	Seawater: 142,300 kg/s @ 4.5 °C; Steam: 1,500 kg/s @ 1.29 kPa NC: 2.6 kg/s	Seawater: 142,300 kg/s @ 10.1 °C; Desalinated Water: 1,485 kg/s @ 9.9 °C; Steam: 15 kg/s NC: 2.6 kg/s	0.45 MW Condensate pumps (desalinated water)
Vacuum Pumps (4 stages) with Seawater Intercoolers	Seawater: 4,500 kg/s @ 4.5 °C (for Intercoolers) NC: 2.6 kg/s @ 17 kPa 2.6 kg/s @ 1.2 kPa Steam: 15 kg/s @ 1.2 kPa	Seawater: 4,500 kg/s NC: 5.2 kg/s @ 30 kPa	3.6 MW

Table 3.- Heat and Mass Balance: OC-OTEC

OC-OTEC condensers operate under very unusual and critical conditions. For example, the volumetric flow rate of steam is relatively large which implies substantial dimensions for the condenser assembly, and a corresponding need for compactness. On the other hand, pressures as low as 1.3 kPa (= 1.3 % of atmospheric pressure) render any steam-side pressure drop extremely undesirable for efficient condensation to take place. Water-side pressure drop should be minimized as well from a net power viewpoint, even though high cold seawater velocities may result in higher heat transfer coefficients. Finally, the potentially negative effects of non-condensable gases upon the steam condensation process complicate the analysis and design task.

The main input parameters are the steam flow rate, the inlet steam pressure, and the cold seawater temperature (Table 3). The concept selected is the compact water channel configuration tested in Hawaii (Vega, 1995). This is basically a brazed aluminum plate-fin configuration similar to the units selected for the closed-cycle ammonia condensers. It is a crossflow arrangement, with cold seawater flowing through horizontal channels in three to four passes, while steam follows a downward vertical path.

The baseline volumetric space requirements for the flash evaporators, turbine-generators, surface condensers and vacuum pumps are summarized in Table 4. These are used as input to the sizing of the plantship.

Unit	**Overall Unit Dimensions (1.8 MW-gross)**	**Unit Input**	**Unit Output**	**Number Units**	**“16 MW” Module Volumetric Space**
Flash Evaporator	9.2 m Diameter 16 m Height	Seawater: 6000 kg/s	Steam: 33.4 kg/s NC*: 0.116 kg/s	3 x3 Matrix (9 total)	28 m (L) 28 m (W) 16 m (H)
Surface Condenser	10 m (L) 10 m (W) 12 m (H)	Seawater: 3000 kg/s	Desalinated Water: 33.0 kg/s	“	30 m (L) 30 m (W) 16 m (H)
Vacuum Pumps with Intercoolers	4 m (L) 1 m (W) 2 m (H)	Steam: 0.4 kg/s NC: 0.116 kg/s (50% at 17 kPa and 50% at 2 kPa) 4.5 °C seawater	NC @ 30 kPa 8 °C Water	“	Included above
Turbine Generator	11 m (L) 7 m (W) 7 m (H)	Steam: 33.4 kg/s NC*: 0.116 kg/s	98% Quality Steam 1.8 MWe-gross	“	11 m (L) 21 m (W) 21 m (H)

Notes:
*NC: Non-Condensable gases; 50% released in pre-deaeration chamber with balance into Surface Condenser
19.36 mg NC per kg-of-Warm-Seawater (Hawaii Experiment)

Table 4.- OC-OTEC Major Components: Global Space Requirements

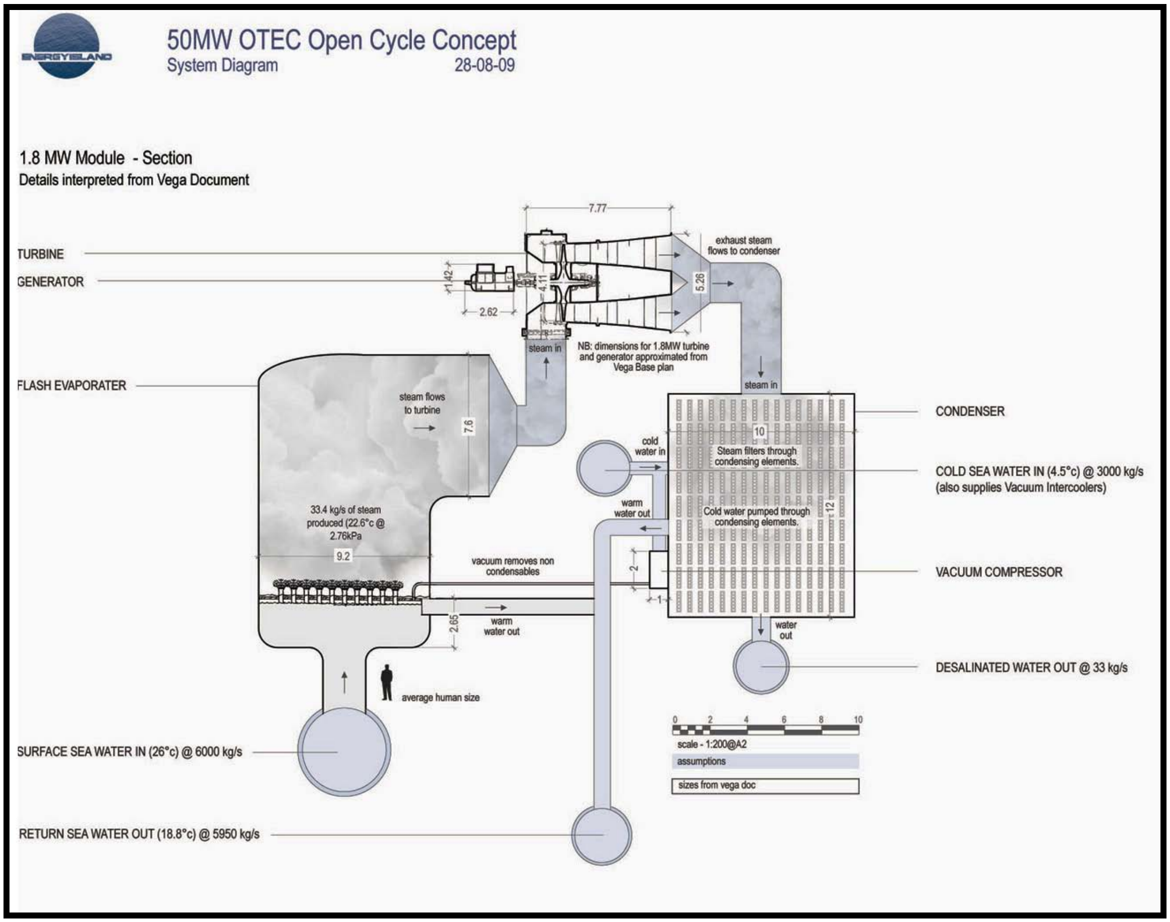


Figure 3.- 1.8 MW-gross OC-OTEC Submodule.

OTEC Plantships

The objectives for the ship-shaped baseline platform (i.e., plantship) are:

- Develop a floating platform of sufficient size, and with adequate structural arrangements to support large OTEC components and sea water piping systems for normal operations as well as for maintenance and repair procedures;
- The platform shall meet international regulatory body requirements for stability and damage subdivision and be reasonably seakindly for the safety and comfort of personnel in severe open sea conditions;
- Locate OTEC components to achieve optimum power production and system efficiency;
- The platform construction shall be cost effective and based on *"state of the art"* tanker construction procedures.

In addition, the mooring, propulsion and position control systems must:

- Maintain platform position within a predetermined watch circle with acceptable loading on the seawater pipes and the power transmission cable while exposed to the operational environment;
- Minimize power consumption;
- Maintain vessel deck motions within allowable values for the operation of power cycle components;
- Provide adequate propulsive power to depart site after CWP detachment, prior to extreme environment occurrence.

The baseline platforms, for the OTEC system considered here, consist of a straight-walled vessels fitted with semi-circular ends. Baseline dimensions for the two systems considered here are summarized in Table 5 and in Figures 4-9.

A 1,000-meter long cold-water pipe will be suspended from the vessel via a double gimbal joint, which effectively decouples the two structures in roll and pitch. The electricity and desalinated water produced will be transmitted to shore via a submarine power cable and a hose-pipe, respectively.

The overall plantship dimensions given in Table 5 provide the space required for the heat exchangers, turbine generators and pumps with associated sumps. The HXs are located below the main deck with the TGs on the main deck. The flash evaporator protrudes above the main deck.

Mode	LBP (m)	Beam (m)	Ops Draft (m)	Height/Depth, (m)	Displacement (tonnes)
CC-OTEC (NH3 TG) **430 GWh/year** **0 m^3/day**	**198**	**39**	**16**	**24**	**120,600**
OC-OTEC (LP Steam TG) **414 GWh/year** **118,400 m^3/day**	**176**	**90**	“	“	**247,400**
100 MW OTEC H_2 Plantship (Nihous, 1993)	250	60	20	28	285,000
“Typical” Double Hull Tanker	180	32.2	11.2	19.2	≈ 63,000
“Typical” Double Hull Container	205 LOA: 217	32.2	10.5	20.3	≈ 68,000
Titanic	259 LOA: 269	28	10.5	19.6	
Nimitz Class (Aircraft Carrier)	LOA: 333	41 (Flight Deck: 77 m)	11		≈ 97,000
Knock Nevis (oil storage tanker)	440 (LOA: 459)	69	24.6		≈ 730,000
Panamax Limits	≤ 294.1 (LOA)	≤ 32.3	≤ 12		

Table 5. - OTEC Plantships Baseline Dimensions (LBP: length-between-perpendiculars); Displacement: LBP x B x D x ρ x Cb; ρ: density seawater 1022 kg/m^3; Cb: block coefficient ≈ 0.95

The CC-OTEC plant could support a population of 500,000 with a per capita daily consumption of 2.3 kWh. This value is representative of the all encompassing per capita consumption in developing countries. In addition, the OC-OTEC system could also supply 240 l/day per capita. Representative per capita water consumption in developing countries is estimated at 160 l/day in the domestic sector and 940 l/day for all sectors (i.e., domestic, industrial and agricultural).

As shown in Table 5, the plantship required for the CC-OTEC system is comparable to typical double-hulled vessels and could be constructed in numerous shipyards throughout the world. The OC-OTEC system, incorporating desalinated water production, requires a vessel that is about three times wider (beam direction) than the standard tanker and container ships and might limit the number of shipyards with appropriate fabrication capabilities.

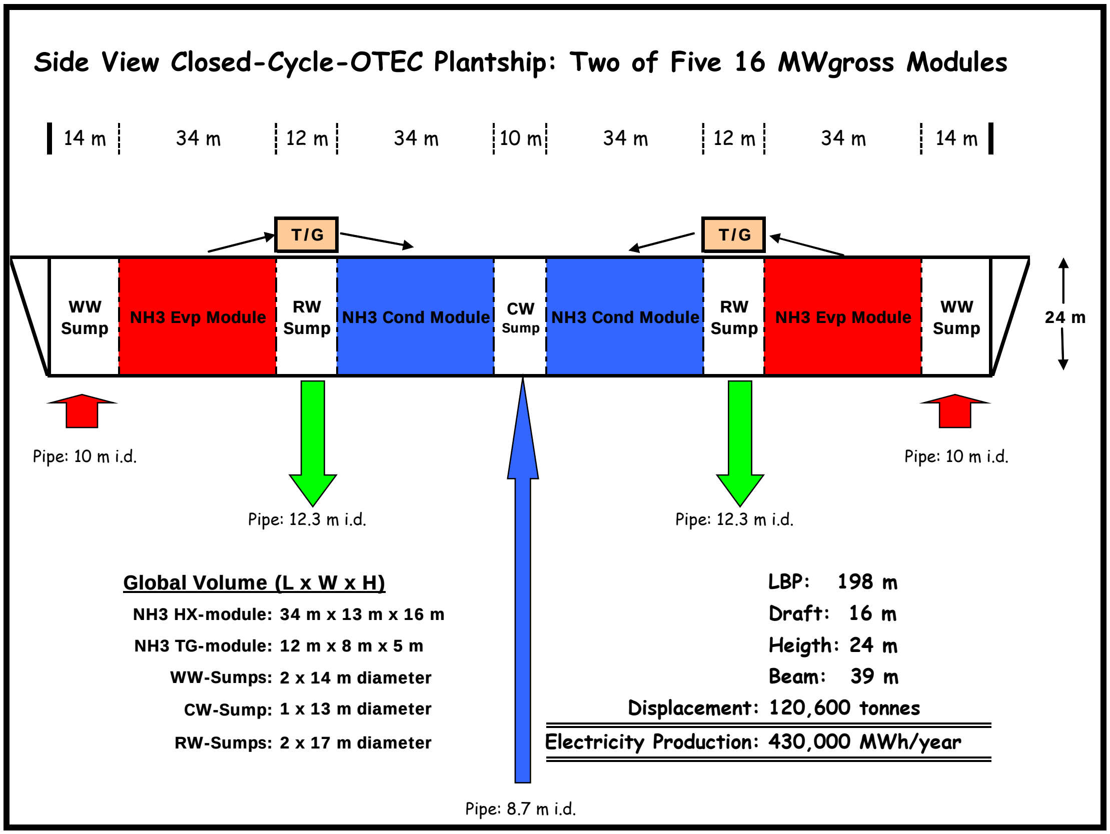


Figure 4.- 50 MW Closed-Cycle-OTEC Plantship: Side View. Broken lines indicate space overlap.

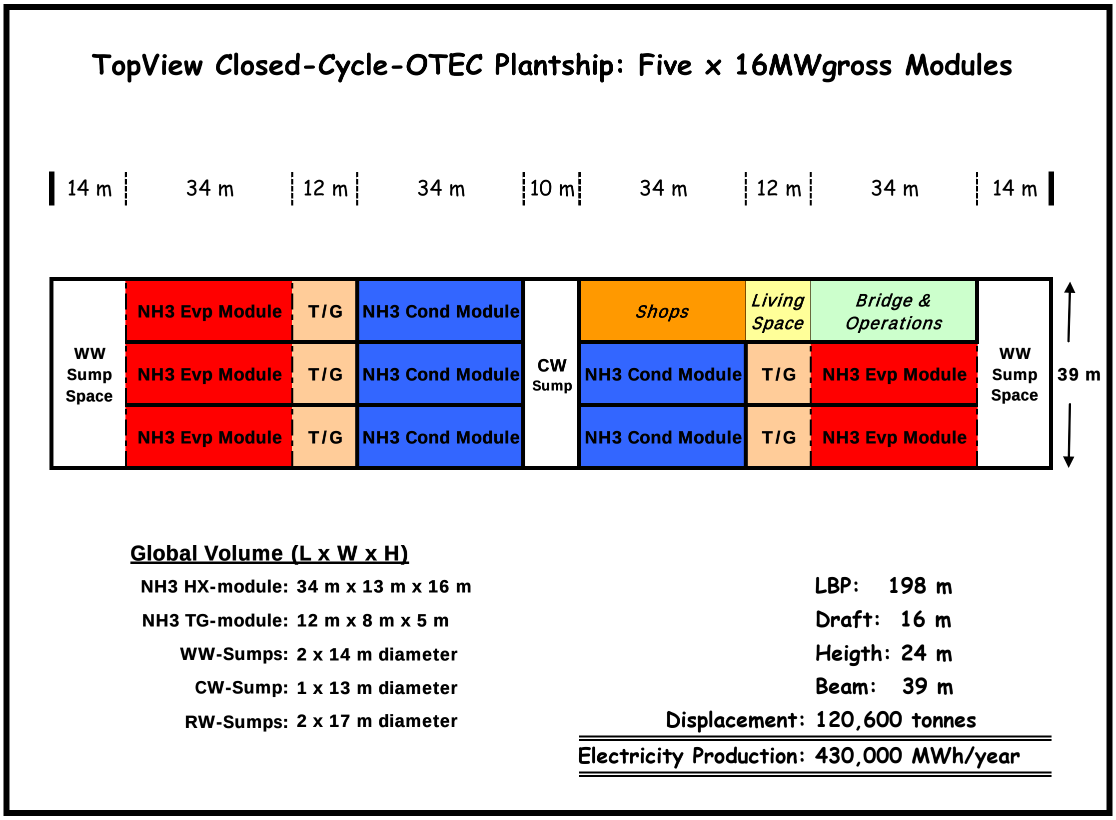
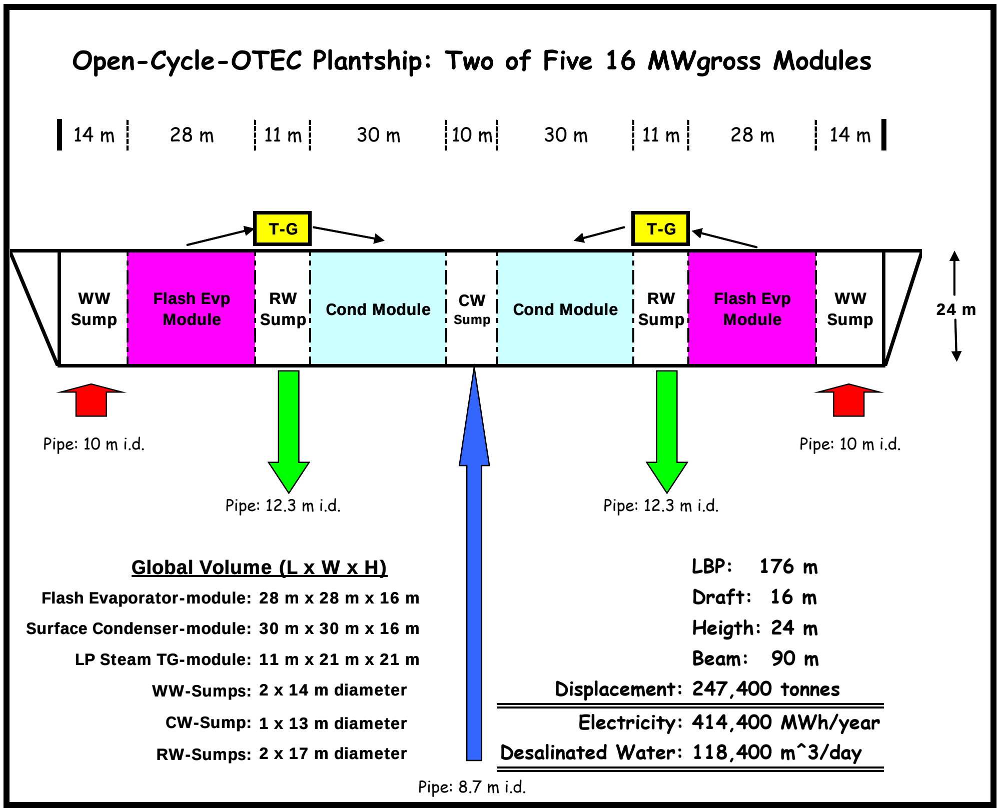


Figure 5.- 50 MW Closed-Cycle-OTEC Plantship: Top View. Broken lines indicate space overlap.

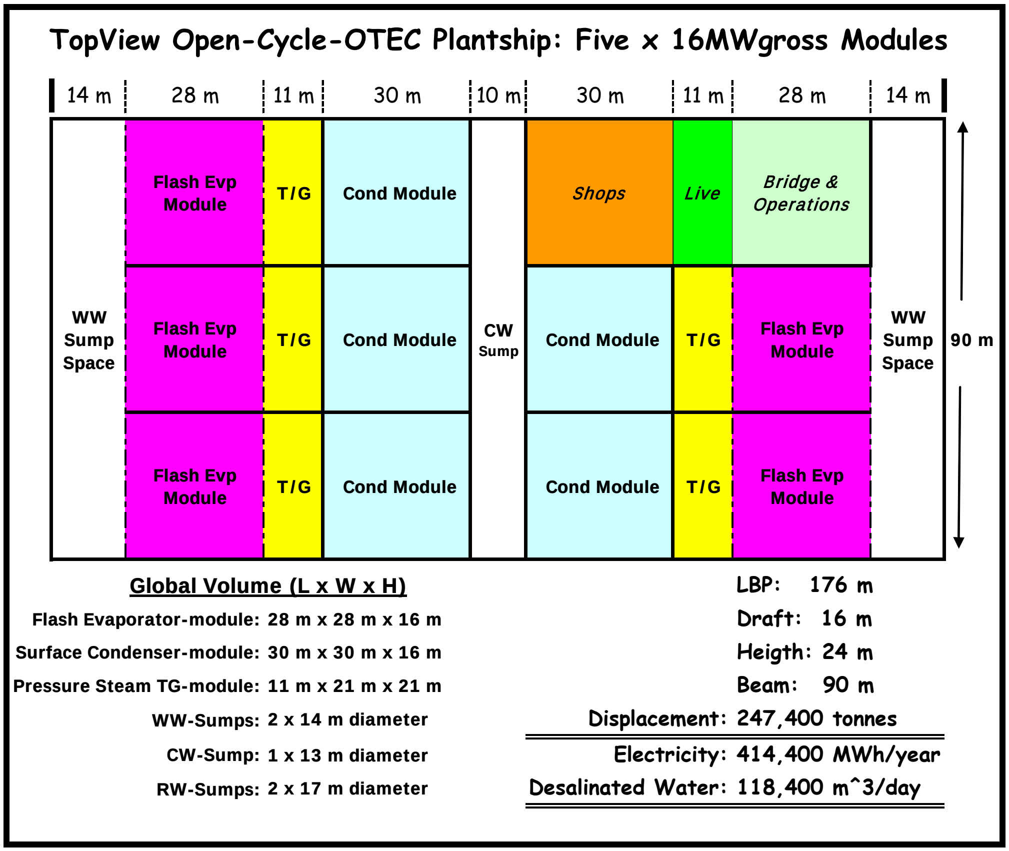


Global Volume (L x W x H)

Flash Evaporator-module: 28 m x 28 m x 16 m
Surface Condenser-module: 30 m x 30 m x 16 m
LP Steam TG-module: 11 m x 21 m x 21 m
WW-Sumps: 2 x 14 m diameter
CW-Sump: 1 x 13 m diameter
RW-Sumps: 2 x 17 m diameter

LBP: 176 m
Draft: 16 m
Heigth: 24 m
Beam: 90 m
Displacement: 247,400 tonnes
Electricity: 414,400 MWh/year
Desalinated Water: 118,400 m^3/day

Figure 6.- 50 MW Open-Cycle-OTEC Plantship: Side View. Broken lines indicate space overlap.



Global Volume (L x W x H)

Flash Evaporator-module: 28 m x 28 m x 16 m
Surface Condenser-module: 30 m x 30 m x 16 m
Pressure Steam TG-module: 11 m x 21 m x 21 m
WW-Sumps: 2 x 14 m diameter
CW-Sump: 1 x 13 m diameter
RW-Sumps: 2 x 17 m diameter

LBP: 176 m
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Displacement: 247,400 tonnes
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Figure 7.- 50 MW Open-Cycle-OTEC Plantship: Top View. Broken lines indicate space overlap.

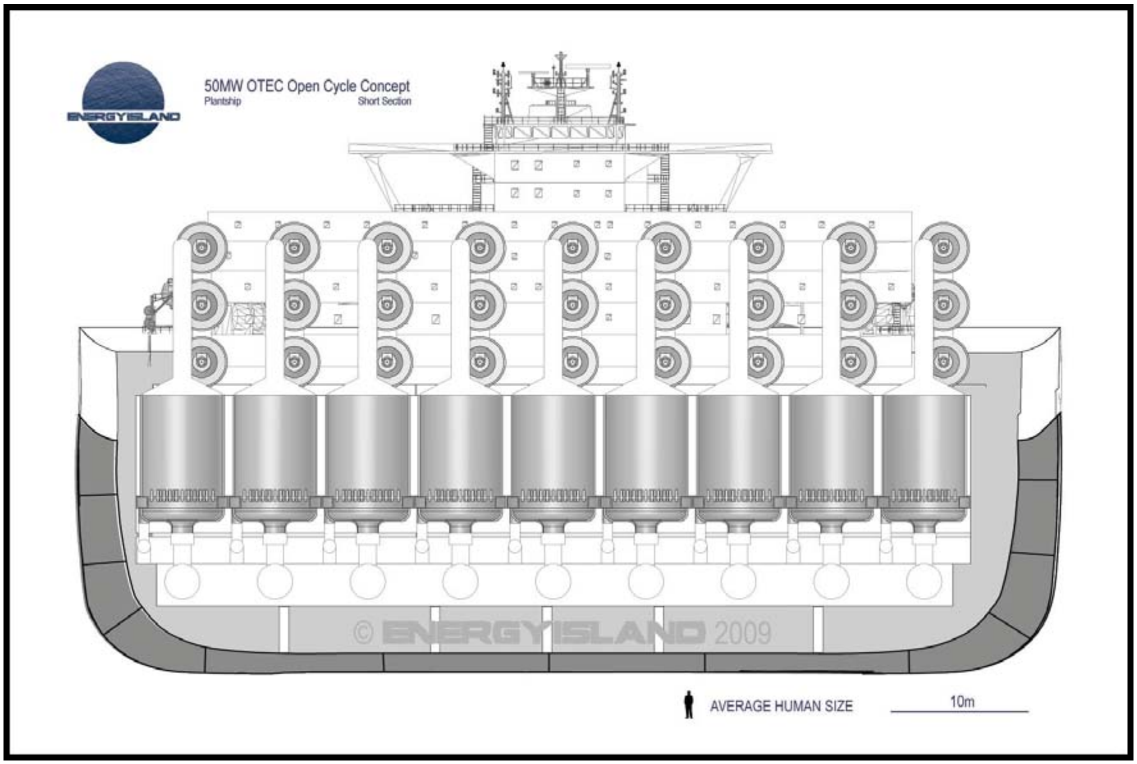

Figure 8.- 50 MW OC-OTEC Plantship Cross Section Drawing showing backend of three out of five nine of forty-five Modules (Flash Evaporators and Turbine Generators shown).

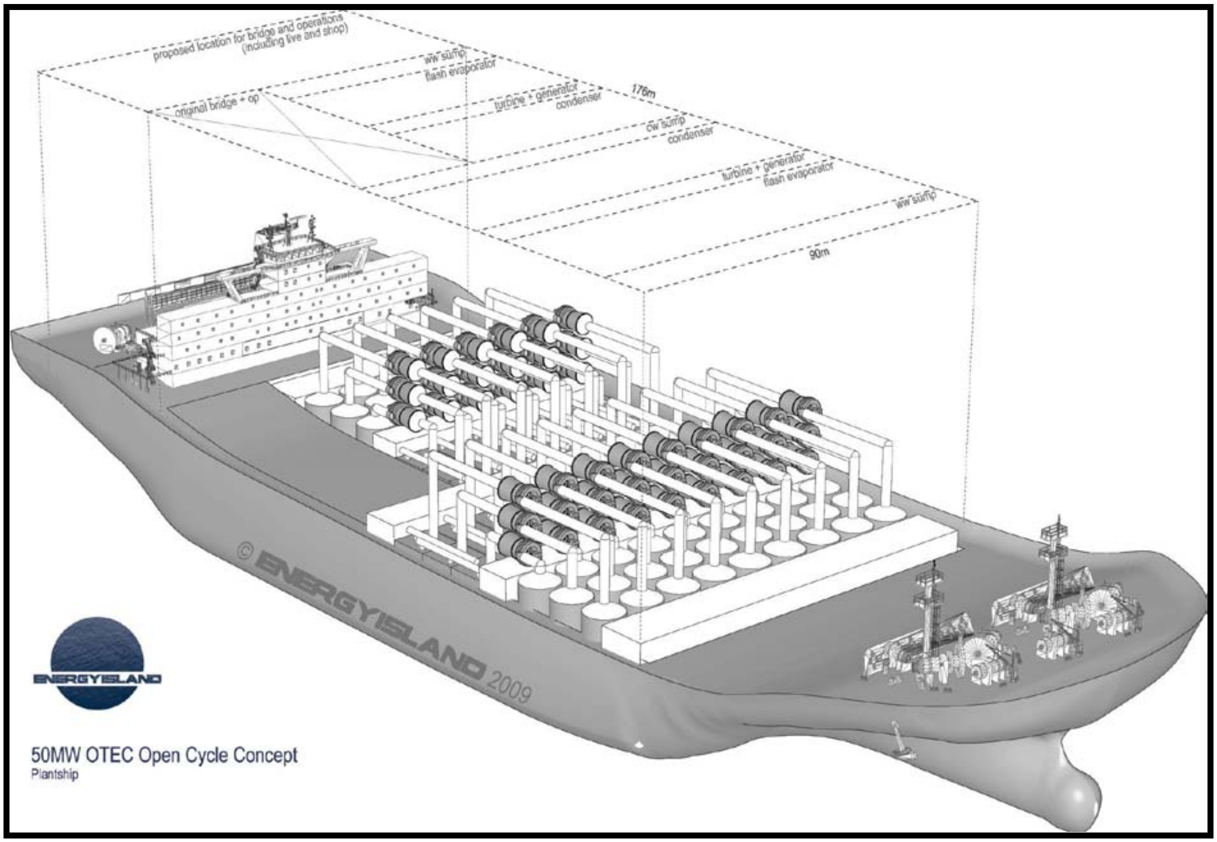

Figure 9.- 50 MW OC-OTEC Planthship Contrast View Drawing.

The conceptual position control system consists of two subsystems: a single point moor to maintain position, within a given watch circle, during OTEC operations and up to the site departure condition; and, four propulsion and position control thrusters to assist in directional positioning (weather vaning) during operations and to provide the propulsive power required to depart the site. The single point mooring subsystem is available from several manufacturers. For the CC-OTEC system four propulsion thrusters are rated at ≈ 2,000 kW each and would be used minimally during operations. The actual schedule for thruster usage would be developed during the final design phase.

The single-point mooring system includes a power cable swivel, and a water hose swivel. The power cable and water hose are linked to the OTEC plant at their respective swivels on the turntable. This system provides a minimal-thruster-power-consumption means of holding the OTEC platform in position. Auxiliary power diesel generators would be available to operate the thrusters during transit and departure, as well as in situ when OTEC power is not available.

OTEC Seawater Components

The OTEC seawater system consists of the pipes and pumps required to supply warm and cold seawater streams to the OTEC heat exchangers and allow for the return of effluents to the ocean. The concept considered for the cold water pipe (CWP) is an 8.7 m i.d. FRP sandwich pipe suspended from the OTEC platform to a depth of 1,000 m. Warm seawater will be drawn in through two 10 m i.d. pipes from a depth of about 20 m. The mixed effluent will be returned through two 12.3 m i.d. FRP pipes at a depth of 60 m. This depth has been selected to minimize the environmental impact.

At the conceptual level we envision five sumps with appropriate distribution piping and pumps. One sump is for the cold water supply and two each for the warm water and mixed effluent return. Each sump has sufficient volume to sustain the head necessary for pumping during start-up and normal operations. The warm and cold water sumps house the submersible pumps envisioned for the baseline system.

Flow	Pipe(s) Inside Diameter	Sump(s) Diameter
Cold Seawater	8.7 m	12.3 m
Warm Seawater	2 x 10 m	2 x 14 m
Return Seawater	2 x 12.3 m	2 x 17 m

The CWP is attached to the platform with a gimbal located on the platform's inner bottom structure. Cold water in the sump is free to flood to the 20 m operating waterline of the platform. The deep-well pumping system located on centerline draws water up through the well and into a manifold that distributes cold water. This pumping system supplies power for the flow of cold water from the pipe inlet to its discharge through the mixed effluent discharge pipe.

The mixed effluent from all of the condensers and evaporators is returned from the mixed effluent sumps through the 40 m long pipe. The mixed effluent pipes are attached to the inner bottom structure of the platform via a spherical heads and inner bottom ring sockets.

Cold Water Pipe

The 8.7 m id CWP structural properties are summarized in Table 6. This design is based on the successful at-sea test of a similar pipe (Vega, 1988). The selected CWP walls consist of a sandwich construction, with two 14 mm thick cross-plied unwoven FRP facesheets separated by a 60 mm syntactic foam layer (thus, the outer diameter of the CWP is 8.9 m). The load bearing FRP provides structural strength, whereas the foam filler allows for the adjustment of wet weight and flexural bending stiffness, as well as for load transmission. The syntactic foam uses glass microspheres and milled fiber to achieve a density of 670 kg/m3 for buoyancy control. The facesheets are helically wound using 450 yield strand interspersed with 20 oz unidirectional roving and a minor amount of chopped strand. The wind angle is 60° for the helical layers. The pipe is wound in a rotating mandrel. A vinylester resin (e.g., Hetron 922)[2] is used.

The strength of the FRP facesheets is almost comparable to that of steel, with a modulus of elasticity E equal to 20,600 MPa (3×10^6 psi). The longitudinal bending stiffness EI is about 19.2×10^{10} N-m^2. Eighty 12.5 m long CWP segments would be fabricated to facilitate land transportation, and butt-connected via splice joints near the launching site (harbor). 150 mm deep FRP ring stiffeners, located every 6 m, would provide enhanced lateral buckling capability, to resist differential (suction) loads across the CWP walls. It is expected that pipe construction would require about 12 to 14 months.

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[2] These are common units used in the USA by FRP pipe fabricators.

Parameter	Value
Inside Diameter	8.7 m
Laminate (facesheet) thickness	14 mm
Core (syntactic foam) thickness	60 mm
Laminate Density	1760 kg/m^3
Outside Diameter	8.9 m
Core Density	670 kg/m^3
Dry (air) Weight	2,460 kg/m
Wet (submerged) Weight	3 kg/m
Flexural Rigidity, EI	19.2 x 10^{10} N-m^2 (46.4 x 10^{10} lb-f^2
Laminate Modulus of Elasticity	20,680 MPa (3 x 10^6 psi)
Core Modulus of Elasticity	2,370 MPa (0.344 x 10^6 psi)

Table 6.- Cold Water Pipe Structural Properties

Several different types of CWP/Hull platform attachment (gimbal) have been proposed. This is required to decouple the pipe from the roll and pitch of the platform and minimize bending moments at their interface. The attachment system must provide a water seal at the cold water sump to insure the quality of the cold water resource. The gimbal should provide ease of attachment of the CWP to the platform at sea. The gimbal system selected is based on the OTEC 1 design tested in Hawaii.

CWP deployment procedures suggested for the various configurations proposed in different suspended CWP designs have been of two generic types: (1) horizontal tow of a full-length pipe with subsequent upending at the deployment site; or (2) vertical deployment, by sections, through the OTEC platform or an adjacent work platform. All designs have proposed transporting the pipe to the deployment site independently of the platform, because combined movement may result in excessive loads and untenable vessel handling problems. The deployment method selected is basically a function of material selection and CWP buoyancy characteristics. In general, configurations which are buoyant or neutrally buoyant (Table 6) will employ the upending technique, while designs that are fabricated from materials that are considerably denser than seawater will utilize the vertical, sectional approach, in which the CWP is actually assembled during the deployment process. A successful deployment scenario must ensure a minimum exposure time at sea, define weather windows clearly and be somewhat reversible. This is especially important for the attachment of the CWP to the barge, since detachment must be allowed before extreme events (e.g., hurricanes).

For the concept considered here, the former procedure applies with the CWP transported awash (filled with water). Towing of the pipeline awash would be acceptable if the confidence of the deployment team in keeping the CWP reasonably well aligned with the dominant wave direction, or in short-term (≈ 48 hour) weather forecasts, is high. Alternatively, submerging the CWP about one diameter deeper would theoretically provide a significant safety factor in reducing bending stresses, through less favorable marine environmental conditions.

The conceptual CWP proposed herein will have to be reevaluated after the specific site in selected. Our experience indicates bending stresses induced by platform motions as the most critical operational loads. Other concerns are fatigue failure and transportation (towing) bending stresses. A shell analysis of the CWP, to quantify hoop stresses and confirm the pipe lateral buckling capability and load evaluation during CWP handling and attachment to the platform is left for the final design.

Submarine Power Cable

A submarine power cable is required to transmit the electricity produced by the 50 MW-net OTEC plant from the floating platform to shore. For the concept summarized in this report, we selected submarine power cables available from several manufacturers as baseline. It is assumed that the plantship would be located approximately 10 km from the shore station. The submarine power cable would have an outside diameter of approximately 13 cm. and it would be attached to the single point mooring system described above.

The cable could be a 3-core AC power cable configuration with an ethylene- propylene rubber (EPR) insulation operating at a voltage of 69 kV. Other types of insulation, which may be competitive for land-based applications, usually require the addition of a watertight metallic sheath in the marine environment. Each copper wire conductor would be approximately 15 mm diameter.

Inspection, Maintenance and Repair (IM&R)

From the perspective of inspection, maintenance and repair (IM&R), three general areas can be identified throughout the OTEC Platform:

- the components on board the plantship, such as heat exchangers, turbine-generators, and pumps;
- the platform hull and appendages;
- the deep water components, such as CWP, submarine power cable, water hose and mooring devices.

On board the plantship, with adequate layout of the OTEC components IM&R requirements should be comparable to those stipulated for onshore power plants.

IM&R tasks are naturally more cumbersome for the platform itself because of the presence of seawater, and of possibly disturbing platform motions during rough weather. Diver intervention and instrumentation/tool deployment from the platform decks should remain relatively easy most of the time. Moreover, the OTEC platform is not fundamentally different from other seagoing structures.

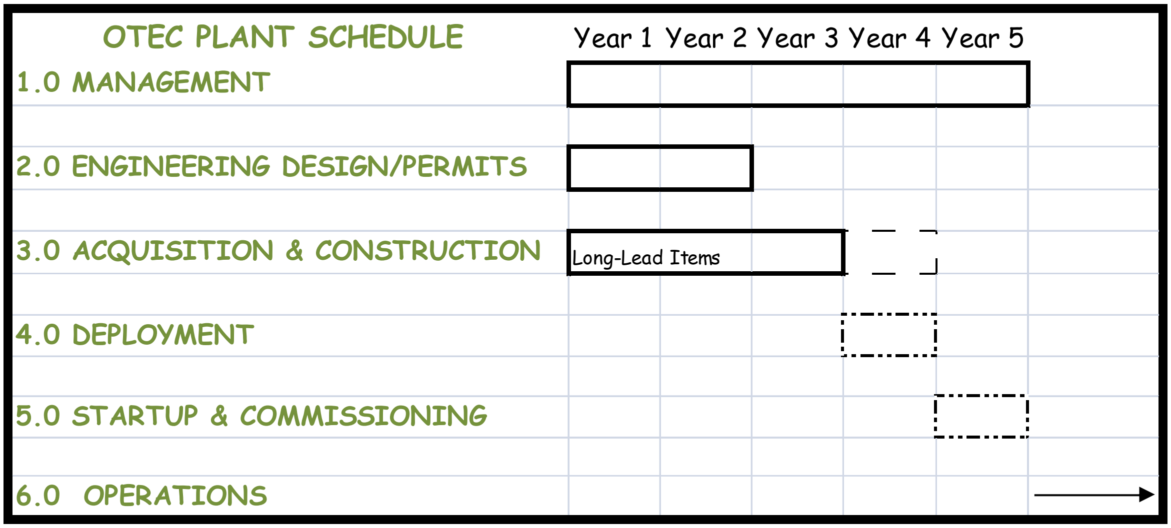
IM&R is challenging for the deep water components of the floating OTEC plant, because the depths at stake place those components out of divers' reach. A failure of the mooring system could break the power cable, although thrusters should provide excess redundancy in positioning the platform if the single-point moor fails.

Strict quality control procedures must be applied at the fabrication, shipping and assembly stages before the structures are finally deployed at sea.

Conclusions

Preliminary designs for a CC-OTEC plantship and an OC-OTEC plantship sized at approximately 50 MW have been documented. The economic analysis based on capital and operational costs applicable in the USA are presented in a separate paper at this conference (OTC-21016).

In discussing OTEC’s potential it is important to remember that implementation of the first commercial plant would take about 5-years after order is placed. This is illustrated in the baseline schedule reproduced below.



OTEC Implementation First Generation Plant: Baseline Schedule

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