OCEAN THERMAL ENERGY CONVERSION AT SBM

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ABSTRACT

Progress in Ocean Thermal Energy Conversion (OTEC) has come in fits and starts as societies gained and then lost interest in Renewable Energy. OTEC gained significant political and industrial support after the oil price shocks of the 1970's, but then after funding evaporated in the mid 1980's, work had to be carried on by a smaller group of determined individuals and companies.

This paper presents an overview of internal R&D that SBM has carried out on OTEC during 2011 and 2012. OTEC systems have important similarities to our core Floating Production Storage and Offloading (FPSO) business and we have been working to understand possible future applications for OTEC in both the Power and Energy Industries. Some of these new applications for OTEC suggest alternative pathways for implementing the pilot plant that is needed to produce a clear multi-year operational record of a scalable OTEC power block.

In our 2012 OTEC R&D, we have worked to develop a Cold Water Pipe (CWP) design for a 10 MW plant that can be manufactured, transported, installed, and operated with available technology. Analysis of the 4-meter diameter fiberglass reinforced plastic CWP shows manageable stress and angle response to the environment. The CWP system includes a sealed gimbal device at the interface of the ship and CWP. This specialized ship - CWP interface device must be developed to enable the operation of a ship in OTEC service, just as another specialized interface device - the high-pressure fluid swivel - had to be developed to enable operation of a weathervaning ship in FPSO service.

1. INTRODUCTION

The notion of using naturally occurring temperature differences between the warm surface waters of tropical seas and cold water at depth was first proposed in 1870. Since that time, Ocean Thermal Energy Conversion (OTEC) has drawn attention and investment from organizations large and small. Early work in OTEC was led by pioneers like Georges Claude who attempted small OTEC plants in Cuba and Brazil in the 1930's. After the first energy crisis in the early 1970's, OTEC began to attract substantial R&D funding from organizations such as US Navy, General Electric, Lockheed, Westinghouse, Global Marine, Tokyo Electric, and Toshiba. The OTEC Act of 1980 was enacted to regulate and encourage development of ocean thermal resources in the United States.

As illustrated in Figure 1, OTEC is a Rankine Cycle that uses warm surface water from to evaporate the working fluid and then uses cold sea water from depth to condense the working fluid for pumping. Despite OTEC's conceptual simplicity, the small temperature differences in an OTEC plant require handling large volumes of warm and cold seawater. The cold sea water is transported from 1000 m water depth through a large diameter Cold Water Pipe (CWP) that is subject to environmental loads. The small temperature differences also require large heat exchangers (Figure 2) that are exposed to the corrosive and bio-fouling impact of seawater (Ref1).

There is no doubt that an OTEC plant can produce net electric power from the ocean. In 1979, the 18 KWe (net electric power) floating mini-OTEC plant shown in Figure 3 demonstrated that OTEC can produce net electric power from the naturally occurring temperature differences in the ocean. However, this and subsequent demonstrations have been at such small scale that they do not provide enough scalable technical and cost information to guide the design or predict the cost of larger OTEC plants for commercial applications.

The US Navy is now promoting renewable energy for strategic reasons. In 2009-2011, the Naval Facilities Command (NAVFAC) funded a group led by Lockheed Martin to develop OTEC pilot plant designs. These designs are in the public domain and are based on the use of semisubmersible and spar type platforms to support OTEC facilities (Ref 2). There are no known current plans for building this OTEC pilot plant. Moreover, no investor has yet appeared who will fund a commercial scale OTEC plant without a clear multi-year demonstration of successful operation and maintenance of a scalable OTEC plant.

Notwithstanding these challenges, SBM has several reasons for investigating OTEC as a business opportunity.

- Relevant deep water technology and infrastructure has developed in the offshore petroleum industry that can solve the CWP problem.
- Several of the core technical and business competencies of SBM are relevant to OTEC.
- There are emerging opportunities for premium power from smaller OTEC plants in both the petroleum and power industries that are remote from efficient central power stations.

2. OTEC PLANT SHIP

SBM began internal OTEC studies in 2011 based on an OTEC plant design by Luis Vega (Ref 3). Based on Vega's OTEC process design, we prepared data sheets for major equipment and worked with selected vendors to obtain indicative drawings and weight information. Vendor drawings were used to develop overall general arrangement drawings on a specific vessel, in this case a LASH vessel, SS Cape Florida. Based on Cape Florida converted to 5 MW OTEC service with High Density Polyethylene Pipe for the CWP, we conducted preliminary analyses of vessel motion, mooring system, and CWP. We used our Tender Management System cost spreadsheets to consolidate preliminary cost data for total installed cost for: (a) 5 MW Cape Florida Conversion and (b) additional cost sensitivity studies for larger OTEC plants.

We continued internal R&D in 2012 that focused on development on a larger diameter CWP as well as OTEC facility layouts for "study vessels" including Container ship (M/V Colombo Express) and VLCC (M/V Christina Cap). Vessel relative sizes are shown in Figure 4. Based on equipment arrangement and derivative weight reports, we estimated vessel motions with computer program MOSES for the three vessels. These vessel motions entered the analysis of the CWP as displacement controlled loading. By outlining the conversion of three types of vessels to OTEC service, we have gained some insight into problems and opportunities associated with converting these different types of vessels.

The CWP system supplies a continuous stream of cold water from 1000 m depth to the OTEC facility. The CWP is a passive system and allows cold water pumps and heat exchangers to be located in the ship for operation and maintenance. In this design, the OTEC plant ship is permanently moored and the CWP always remains suspended from the ship. When weather deteriorates beyond the defined 25-year storm, it is possible to prevent fatigue or mechanical damage by partially abandoning the CWP. This is done by disconnecting the structural connector and lowering the CWP on its pull-in wire to a position several meters below the ship until weather conditions improve.

2.1. Cold Water Pipe System

The CWP design is based on the Fiberglass Reinforced Plastic (FRP) sandwich design shown in Figure 5 (Ref 3). Similar material was the subject of the 1983 Sea Test sponsored by the US Department of Energy (Ref 4).

General Arrangement for the CWP System is given in Figure 6. The 80 ft. segment length is consistent with hook height of an installation vessel like the Normand Installer. As shown on the right hand side of Figure 6, each CWP segment is equipped with concentric ring connectors, similar to marine drilling riser connectors. These connectors enable the CWP to be run or retrieved in a reasonable weather window.

Manufacture and transportation of 4 m FRP CWP Segments is not a technical limitation. For example, 10m Diameter FRP can be fabricated on construction sites of Coal Fired Power Plants as exhaust stack liner. Figure 7 shows an example of an FRP sea water pipe made on the U.S. Gulf Coast for shipment to the Middle East. Our base case load out scheme is shown in Figure 8.

The installation of the 4 m diameter CWP was shown to be feasible through a detailed set of installation sequence drawings based on the dimensions and capabilities of SBM's Normand Installer (NI). Two selected installation scenes are given to illustrate the installation method. The selected installation scenes show running the CWP through the NI moon pool (Figure 9) and then transferring the complete CWP string for structural connection at the bottom of the cold water sump (Figure 10).

2.2. CWP Design and Analysis

This section presents a summary of design and analysis work done for the CWP system. Our dynamic analysis of the CWP System has shown that it is feasible to operate a 4 m diameter CWP system comprised of 80-ft long segments of Fiberglass Reinforced Plastic (FRP) pipe.

2.2.1. Design Premise

We used environmental data from the NAVFAC study (Ref 2) for a Hawaiian location together with supplemental information from Vega (Ref 3). These storms cases comprise several selected combinations of wind, wave, and current that could coexist simultaneously and would have to be withstood by the CWP system. The NAVFAC study also contained definition of sea states in sufficient detail to support preliminary fatigue analysis of our CWP system.

2.2.2. CWP Components

The main CWP system components are: CWP segments, sealed gimbal, and cold water sump.

CWP Segments

The 80 ft. long CWP segments shown on right-hand side of Figure 6 enable vertical installation of the CWP with a construction vessel such as the Normand Installer. This is similar to vertical installation of tendons except for the much larger diameter of the CWP. The length of the CWP segments and the number of connectors depends on the available installation crane hook height.

CWP segments are joined with steel concentric ring connectors similar to those used for Marine Drilling Risers. These connectors enable the fast make-up times required to run the CWP in an acceptable weather window. Enlarging these connector diameters for CWP service is not so much a technical challenge as it is a matter of cost, given that there are 80+ connectors in the CWP system. An 80 ft mandrel for manufacturing FRP segments would allow the number of connectors to be cut in half.

For the present vertical CWP installation, the CWP segments would be completely outfitted before transporting to the installation site. Connector halves would be secured to the end of the CWP segments and VIV/VIM suppression fairings would be attached to segments near the top of the CWP.

Sealed Gimbal

The sealed gimbal device accommodates the force and relative motion at the interface between the ship and CWP. It is a proprietary mechanical engineering solution to an important interface problem, and in some ways analogous to the fluid swivel solution at the riser-vessel interface in an FPSO. The Sealed Gimbal functions include: (a) supporting the weight of the suspended CWP system; (b) allowing the CWP to gimbal freely at quasi- static and dynamic angles of +- 20 degrees with respect to the vessel; (c) providing a seal between the cold water in the sump and the warm ambient sea water around the ship; and (d) allows the CWP to be suspended when the ship is approached by extreme events that could cause accelerated fatigue damage to the CWP.

This sealed gimbal is installed atop the CWP prior to transferring the completed CWP to the plant ship.

Cold Water Sump

This sump provides sufficient submergence for cold water pump suction inlets to have the minimum required Net Positive Suction Head for the cold water pumps. If these pump inlets do not have sufficient submergence, they will cavitate and fail to deliver the required rate of cold water to OTEC condensers.

2.2.3. CWP Analysis

Our analyses included:

- Extreme analysis
- Wave fatigue analysis
- Vortex Induced Vibration(VIV) analysis
- Clashing analysis
- Collapse analysis
- Weathervaning analysis
- Hang-off analysis

The CWP global dynamic analyses were performed using time domain FEA approach. FLEXCOM 3D, a commercial software widely used in offshore industry, was employed in the analyses. VIV were also analyzed using SHEAR 7.This paper only discusses the results of our extreme analysis. A more detailed discussion of our 2012 CWP design and analysis work will be given in a separate technical paper.

Extreme Analysis

Figures 11 and 12 summarize maximum CWP stress and maximum CWP gimbal angle in response to defined Hawaiian storm cases. These figures illustrate the different CWP response when the CWP is suspended from Cape Florida (LASH Vessel); Colombo Express (Container ship); and Christina Cap (VLCC).

The gimbal can accommodate a 20 degree angle. The FRP strength capacity is 30 ksi. Adopting offshore riser/pipe design criteria, the allowable stress of FRP can be 100% of material strength for survival loading and 67% of material strength for operating conditions.

In general, stresses and angles are below much less than allowable for all cases, except for maximum angle for 100-year storm with Cape Florida. Note that it would be is possible to disconnect and hang-off the CWP as the 100-year event approaches the ship.

Main Conclusions from Analysis

CWP pipe global dynamic behavior is mainly driven by its attachment to the moving OTEC vessel. The CWP is suspended near the CG of the vessel to minimize the coupling effect from roll motion excitation in the wave zone.

CWP global performance is directly related to excitation modes and curvature. It is observed that several modes are likely to be resonant under the wave loadings and some low modes are being VIV locked-in for the proposed 4m diameter pipe. Damping does play an important role in preventing excessive vibration amplitudes, especially for low mode resonance. Further research on VIV design of the large diameter CWP pipe and the damping evaluation of FRP composite should be conducted.

The global analysis results show that CWP is strong enough to survive all the extreme storms, with the estimated strain well below 1%. It appears that the major concern for CWP global design is storm fatigue damage especially during 100yr cyclone conditions. The CWP pipe segment connectors designed with higher SCF will experience high damage, and may exceed 10% of total damage allowable. Further data analysis shows that a few cycles of the highest strain amplitude during the storm caused the majority of the damage. More fatigue test for CWP needs to be performed to collect more strain-cycles (S-N) data for OTEC application, especially for high strain range fatigue test. To manage fatigue damage to CWP system, it is possible to disconnect CWP from vessel and partially hang-off pipe below wave zone ahead of the predicated cyclone event. Composite pipe failure mechanisms are more complicated than steels. In addition to the traditional S-N fatigue estimation approach, a fracture mechanics based analysis is recommended.

The OTEC plant would not be operating at the defined 25-year storm level due to high pressure differential on the sealed gimbal. This pressure differential arises from the friction losses up the CWP plus large pressure pulses from passing storm waves. At the 25-year storm level, the Cold Water Sump would be in communication with the ambient warm seawater and OTEC operations would cease. The CWP could be partially abandoned at onset of the 25-year storm level to further reduce fatigue damage to the CWP.

3. COMPARISON TO FPSO BUSINESS

SBM Offshore has designed, built, and operated semi-submersible units for drilling and production service. Notwithstanding their good motion characteristics, we believe that a ship shape provides important operational advantages for an OTEC facility. The reliable long-term operation of the mechanical and electrical equipment requires that it be accessible for many operating and maintenance tasks, both planned and unplanned. This access is especially important for advanced or derivative equipment operating under new conditions, such as an OTEC pilot operation.

3.1. FPSO Evolution

The FPSO evolved beginning in the 1970's to enable the economic production of offshore oil reserves that were remote from oil markets. The FPSO integrates the functions of oil production and transportation into a single floating facility.

In an FPSO, subsea wells flow up to oil and gas processing facilities installed on the deck of a tanker, and the resulting stabilized crude oil is stored as cargo. In the early days of this technology, a key enabling technology was the fluid swivel that allowed the tanker to weathervane while providing continuous high pressure flow paths from subsea wells to topside facilities.

Shell and SBM evolved practical FPSO designs starting with the Castellon FPSO in 1977 that combined a single pass fluid swivel with a Single Anchor Leg mooring system in 117-meter water depth. The Castellon FPSO was followed by increasingly capable FPSO's such as Petrobras Garoupa (1979) and the Amoco Cadlao (1981). Not only did the Cadlao FPSO include an advanced 4-pass fluid swivel, it marked the beginning of SBM's entry into the FPSO leasing business. SBM now owns and operates a fleet of 20+ FPSO's around the world.

SBM provides FPSO units to the industry on a supply or lease basis. The total installed cost of an FPSO depends on specifics, but is frequently over 600 million USD, with some projects substantially larger. The design and construction of an FPSO requires integration of large sub-systems including tanker and marine systems; processing facilities; power generation; accommodations; oil storage and offloading; mooring systems; and risers. SBM's management, engineering, and operational disciplines work together to integrate these sub-systems on each FPSO project. Operational experience feeds back to create better designs and project execution machinery.

3.2. Competencies Transferrable to OTEC

Several of SBM's technical and business competencies are transferrable to constructing and operating OTEC plant ships. Moreover, relevant deep water drilling and production technology contains the ingredients for solving the long-standing Cold Water Pipe challenge. Figure 13 shows a typical FPSO and illustrates adjacent technology that is applicable to OTEC.

3.2.1. System Integration

OTEC requires the integration of pumps, heat exchangers, and turbine generators with the utilities and supporting systems required for a fully operational unit. Although the OTEC process facilities are different from the oil and gas processing facilities on an FPSO, both involve heat exchangers, pressure vessels, pumps, turbine generators, and utilities. Although OTEC heat exchangers and Cold Water Pipe are larger than those found on our FPSOs or Mobile Offshore Drilling Units, the complexity of FPSO facilities integration is (at least) comparable to an OTEC plant ship. The power generation capacity installed on third generation FPSO's can exceed 200 MW, more than envisioned on OTEC plants. Although the particulars of OTEC equipment are different than FPSO, the engineering and management skills for their integration into an operational unit are similar.

3.2.2. Hull Conversion

Most of SBM's FPSO projects are based on procurement and conversion of existing vessels. We believe that OTEC plant ships could also be cost-effectively based on converted vessels. Converting vessels, rather than new-building, would help to make OTEC cost and schedule more predictable.

3.2.3. Deep Water Mooring

Although the first FPSO's were in shallow water, the Energy Business has moved to deep water. We are presently executing an FPSO project in 3,000 meters water depth in the Gulf of Mexico. We have also designed and constructed Mobile Offshore Drilling Units and installation vessels that are equipped with dynamic positioning systems. OTEC station keeping systems for 1,000 meters water depth are well within the industry's capability.

3.2.4. Deep Water Risers

FPSO's are equipped with riser systems that conduct high pressure well streams to the ship. Some FPSOs support more than 40 high pressure flow line risers. In some environments, the ship must be allowed to weathervane, and this vessel-riser-mooring interface required the evolution of high-pressure fluid swivels to accommodate the earthbound flow lines. The Cold Water Pipe required for OTEC is much larger than any flow line, but is not as hazardous as the high-pressure petroleum contained in the many flow lines supported by an FPSO. Like the FPSO, the vessel-riser-mooring interface on OTEC requires specialized sealed gimbal devices to accommodate relative motion, forces, and operational activities.

3.2.5. Installation

As the turnkey business for FPSO's evolved, SBM found it necessary to own and operate specialized installation vessels. SBM owns two deep water installation vessels, including the Normand Installer which was assumed in our base case installation scenarios.

3.2.6. Lease/Operate

SBM entered the lease/operate business in 1981 with the Cadlao project. We presently own a fleet of about 20 units around the world that are built and operated to SBM standards. SBM employees operate these units and are supported by mobile teams of SBM specialists. Experience derived from owning and operating this fleet gives useful insights that are fed back into design, construction, and logistical support activities. This perspective is relevant to the work of configuring an OTEC unit for long term operation.

3.2.7. Purchase Power Agreements

Although some of our FPSO's have more than 200 MW of power installed, we do not have experience with commercial Purchase Power Agreements and the responsibilities of providing power to third parties that is subject to curtailment and other operating conditions familiar to Power Generators. This would require strategic hires or alignments at a later stage to manage these risks.

4. THE PILOT PLANT PROBLEM

During the late 1970's, OTEC was proven technically feasible and enjoyed industry and governmental support. Then an unfortunate series of events occurred: (1) petroleum prices crashed, (2) Renewable Energy topics lost financial and political support, and (3) a scalable OTEC pilot plant was not built. A scalable OTEC demonstration pilot plant would have to be large enough to provide relevant technical and cost guidance. Conventional wisdom suggests that a 2.5 MW OTEC power block is scalable because it can be multiplied and integrated to produce commercially relevant amounts of power. No investor has yet appeared who will fund a commercial scale OTEC plant without a clear multi-year demonstration of successful operation and maintenance of a scalable OTEC Power Block.

One important reason that OTEC has not been commercialized is that a stand-alone OTEC pilot plant (i.e., vessel, mooring system, facilities) of at least 2.5 MW has been too expensive for 100% funding by government(s). The likelihood of 100% funding of an OTEC pilot plant by the US federal government is low, especially "post-Solyndra". On a practical level, to realize an OTEC pilot plant, it will be necessary to find an application in the Power or Energy Business that produces attractive economics.

5. OTEC APPLICATIONS

This section outlines three possible business opportunities for OTEC technology.

5.1. Remote Micro-Grids

Remote military bases and island economies typically do not have indigenous supplies of fossil fuel to generate electricity. The price of electricity on these smaller micro-grids is doubly sensitive to the price of diesel or coal because fuel is consumed to transport fuel to small and less efficient power stations that generate relatively high cost power. OTEC is relevant to these applications because unlike other renewable sources, it can generate electricity 24*7.

5.2. Co-location with FPSO

If an FPSO is equipped to deliver gas to market, then electrification of waste heat could increase gas sales revenue by reducing fuel gas consumption. The trend toward larger power generation capacity installed on FPSOs increases the availability of waste heat. Third Generation FPSO's have more than 200 MW shaft power installed and would have more than 400 MW of waste heat rejected, most at high temperatures. An OTEC power block module could be installed on the VLCC during the conversion program. The simplified plan view in Figure 14 shows the relatively compact footprint of a 2.5 MW power block. Since waste heat from gas turbines is available at high temperatures, efficiencies are improved, and it may be possible to increase net output even in colder environments and shallower water.

Pre-requisites for this opportunity are: (1) not all waste heat is allocated as process heat and (2) the FPSO station-keeping system would not interfere with a Cold Water Pipe (CWP). For example, a spread mooring, CAM mooring or Dynamic Positioning System would enable a full length CWP. A turret mooring system would require a shorter CWP to avoid CWP interference with the mooring lines.

5.3. Power for Remote Subsea Wells

Shell chaired a 2012 OTC session on "Local Power Generation for Offshore Developments" and presented two technical papers (Refs 5 and 6) Total also presented a paper describing a concept that used renewables to power satellite subsea wells and provide for storage and injection of chemicals into long flow lines (Ref 7).

Some operators have conducted conceptual studies for developing means to power subsea pumps/compressors in or near subsea wells that are offset from existing host platforms by distances of from 50 to 200 km. Alternatives considered included a 5-10 MW OTEC plant, diesel power buoy, and long subsea power umbilical. There are distance limits for AC power umbilical and large fixed costs for the high voltage DC schemes associated with cross country bulk power transport.

Figure 15 shows a flow a conceptual flow assurance platform that would increase the reserves connected to a given FPSO and enable flow line operation and maintenance. This application capitalizes on OTEC's ability to generate continuous power at a remote location to reduce or eliminate costs associated with power umbilical, control umbilical, deep water mooring system, and fuel for dynamic positioning. The only physical connection to the host platform is the flow line which does not board the OTEC vessel. The OTEC vessel is linked to the nearby subsea well by power umbilical, control umbilical, and a service line(s) for delivering pigs, chemicals, and start-up heat to the flow line.

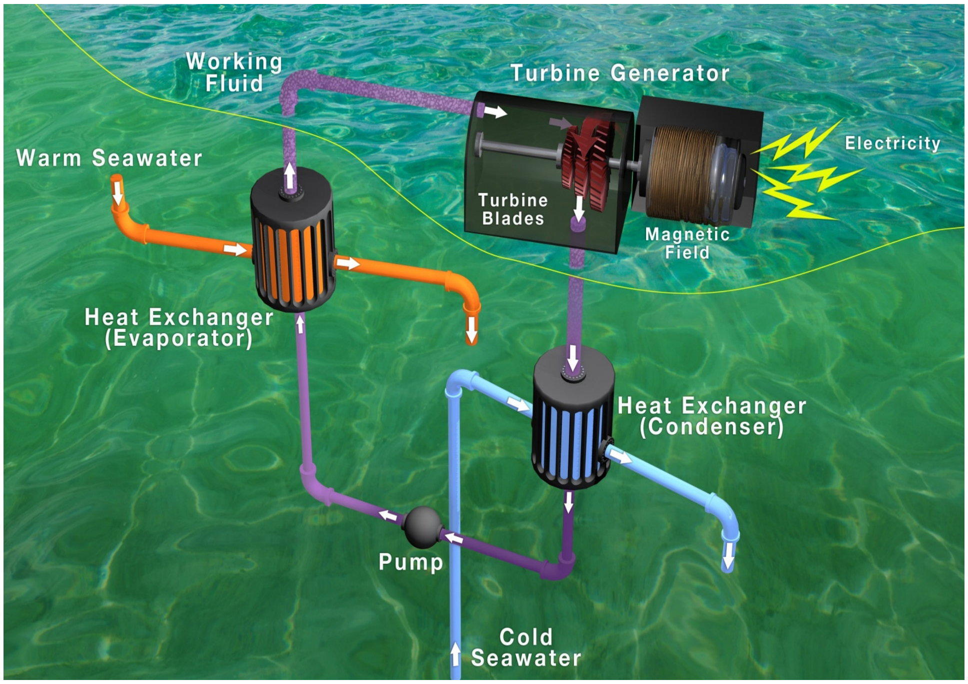


Figure 1. OTEC Power Cycle

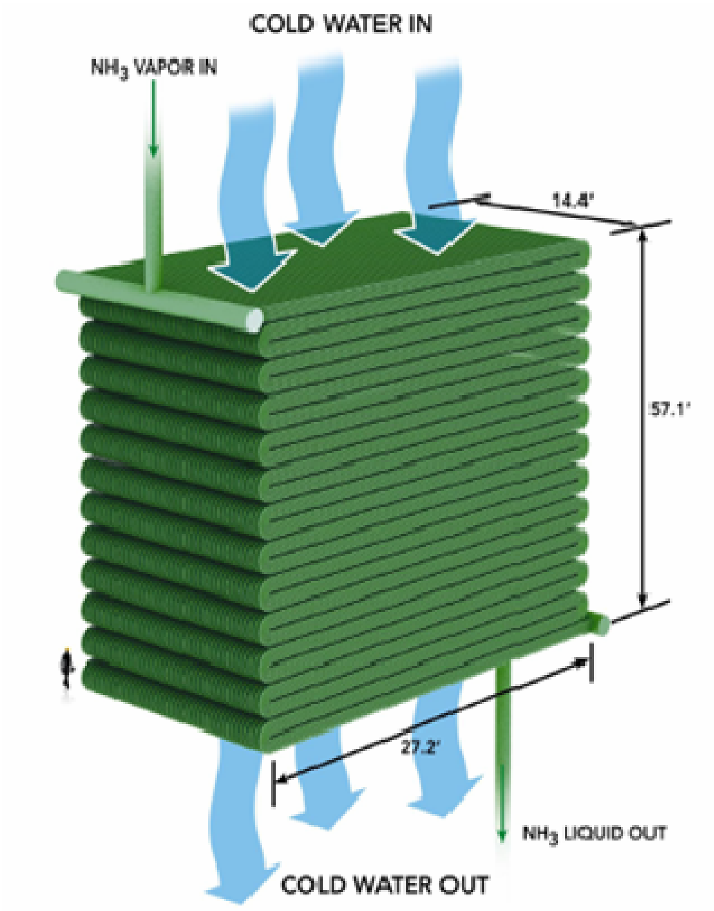


Figure 2. Condenser for 2.5 MWe OTEC Plant

Figure 3. Mini – OTEC Offshore Hawaii, 1979

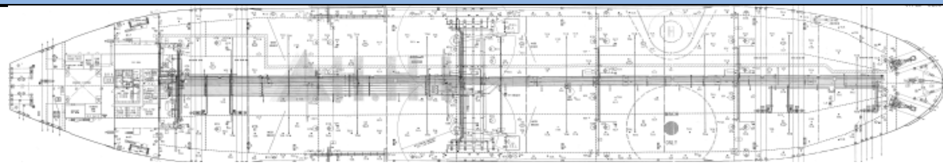
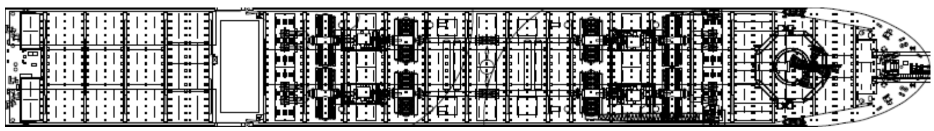
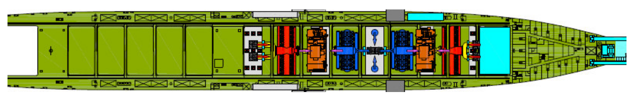
Project	Plan View of the Main Deck	Dim	Meter	Feet
Christina Double Hull VLCC		LOA	340.50	*1,117*
		B @WL	58	*190*
		D @ CL	31	*102*
		T max	22.72	*75*
Colombo Express Post Panamax Container Ship		LOA	335	*1,101*
		B @WL	42.94	*141*
		D @ CL	26.89	*88*
		T max	14.63	*48*
Cape Florida LASH		LOA	250	*820*
		B @WL	30.48	*100*
		D @ CL	13.41	*44*
		T max	10.97	*36*

Figure 4. Vessel Size Comparision

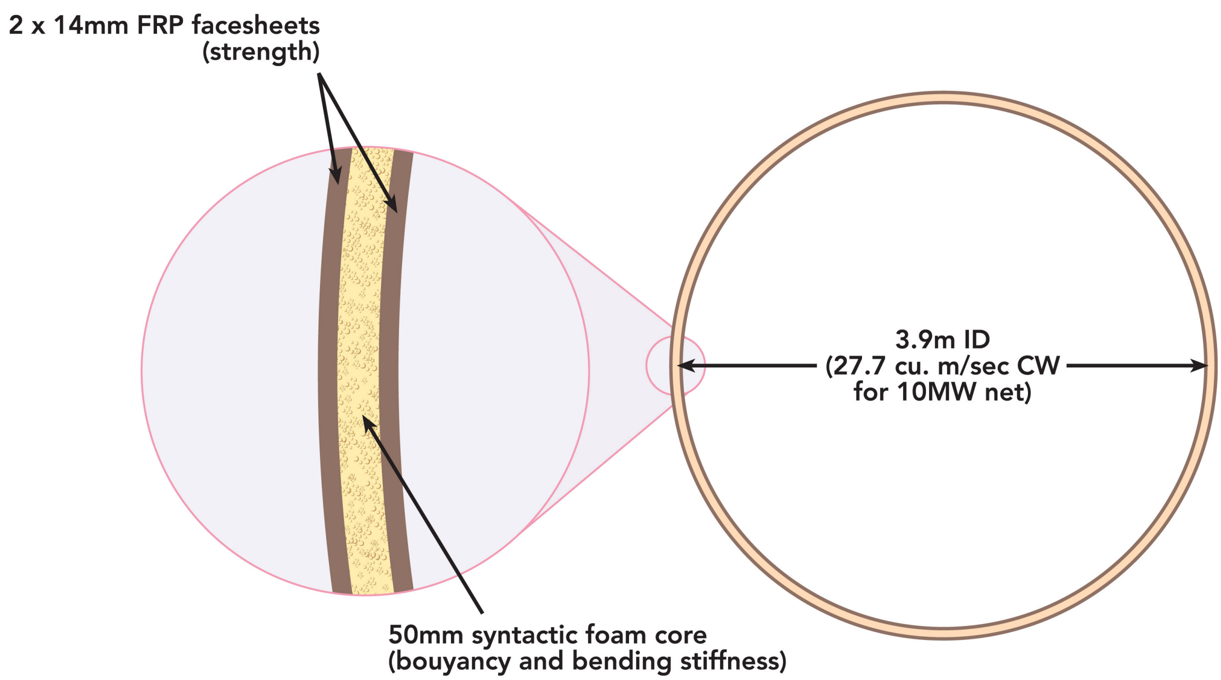


Figure 5. CWP Cross-Section

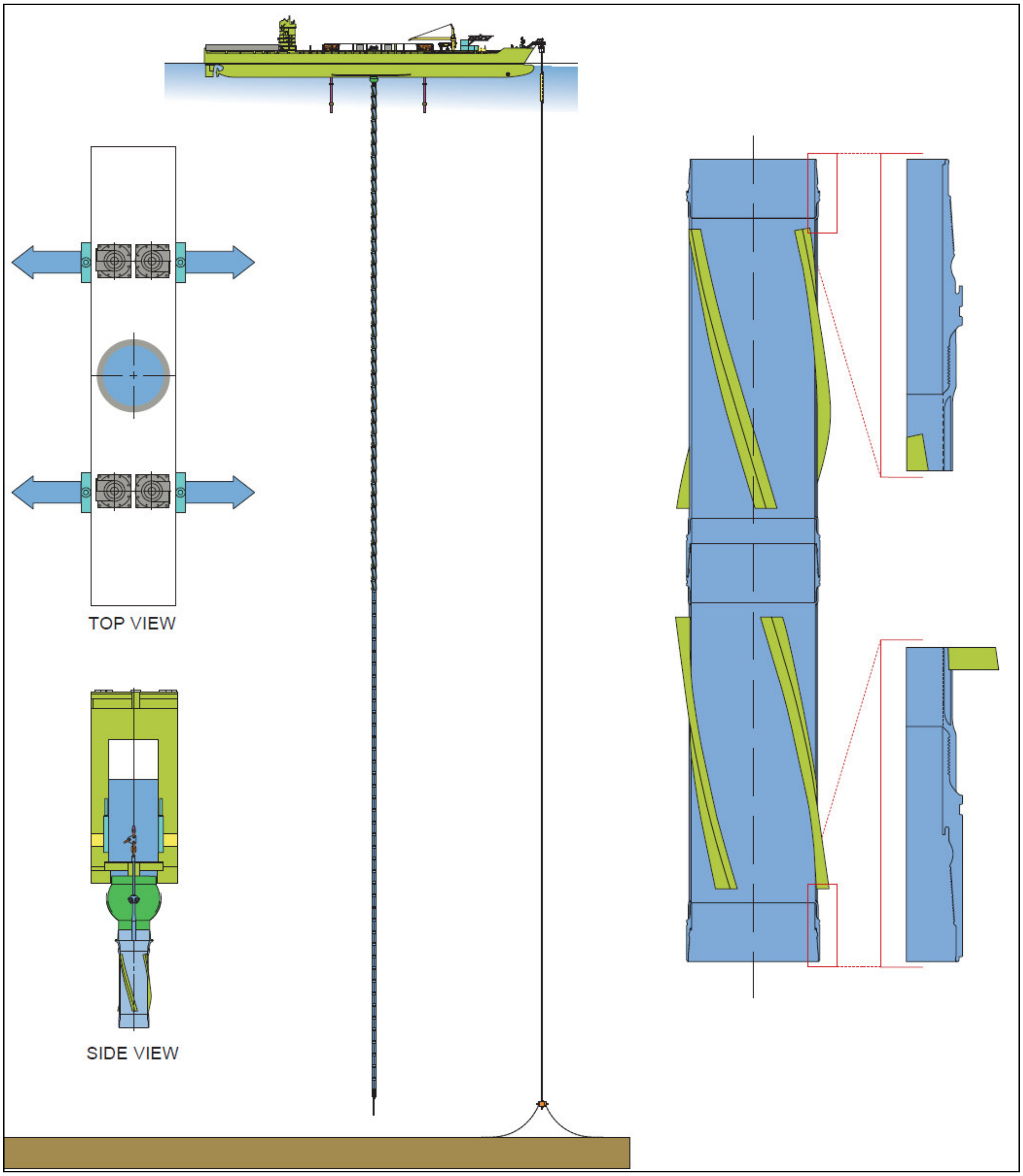


Figure 6. General Arrangement of CWP System

Figure 7. Example Large Diameter Fiberglass Reinforced Plastic Pipe

Figure 8. Load Out of 4 m Diameter CWP Segments

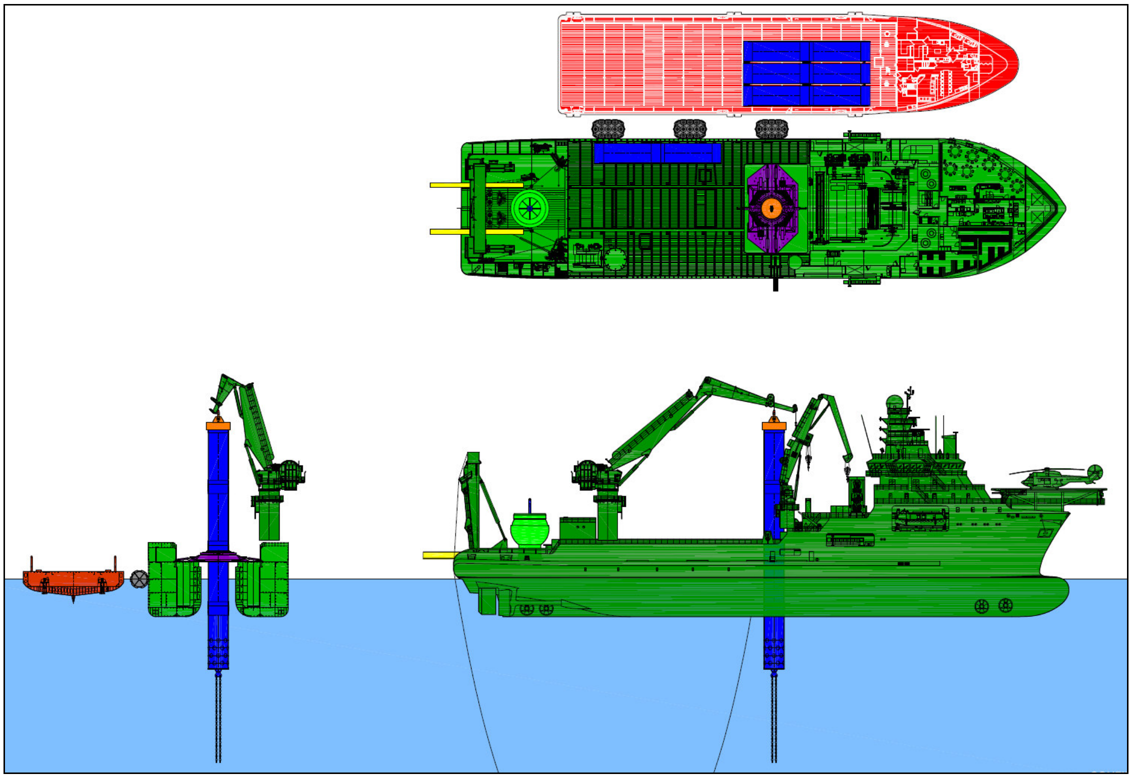


Figure 9. Running the CWP from Normand Installer

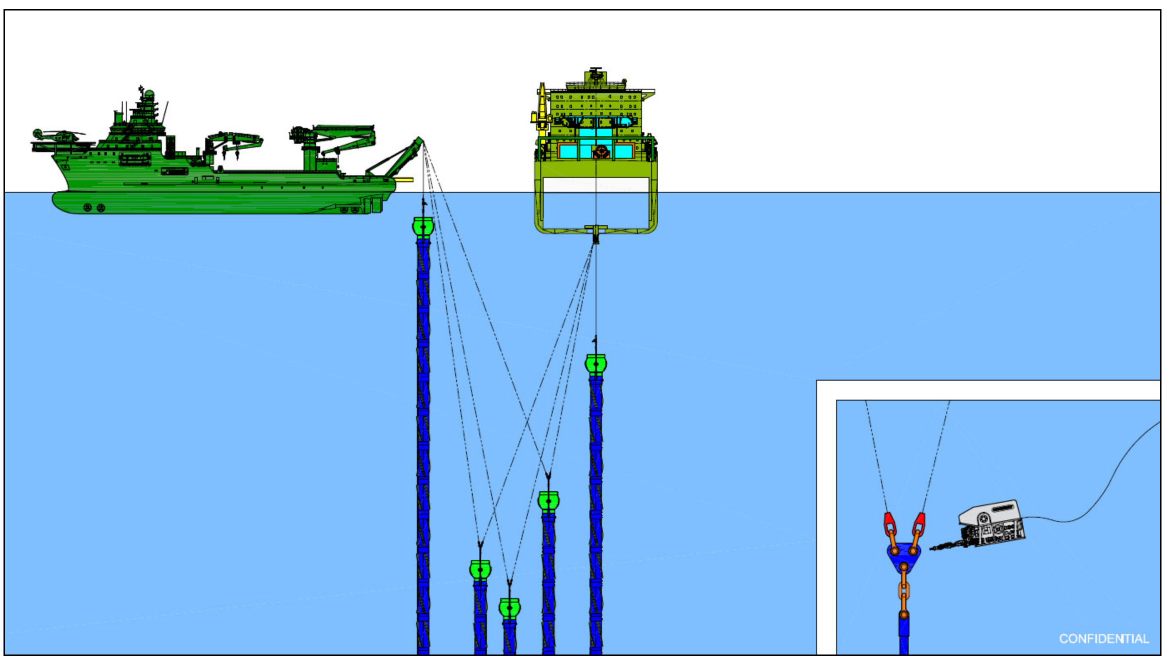


Figure 10. Transferring the CWP from Normand Installer to Plant Ship

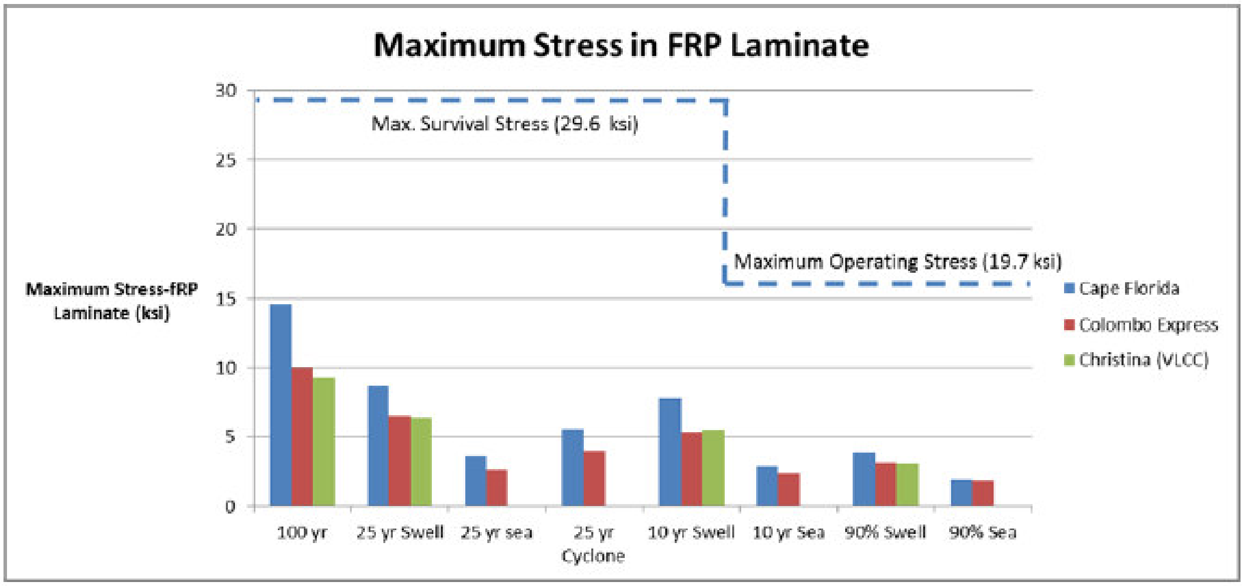


Figure 11. Maximum Stress in CWP

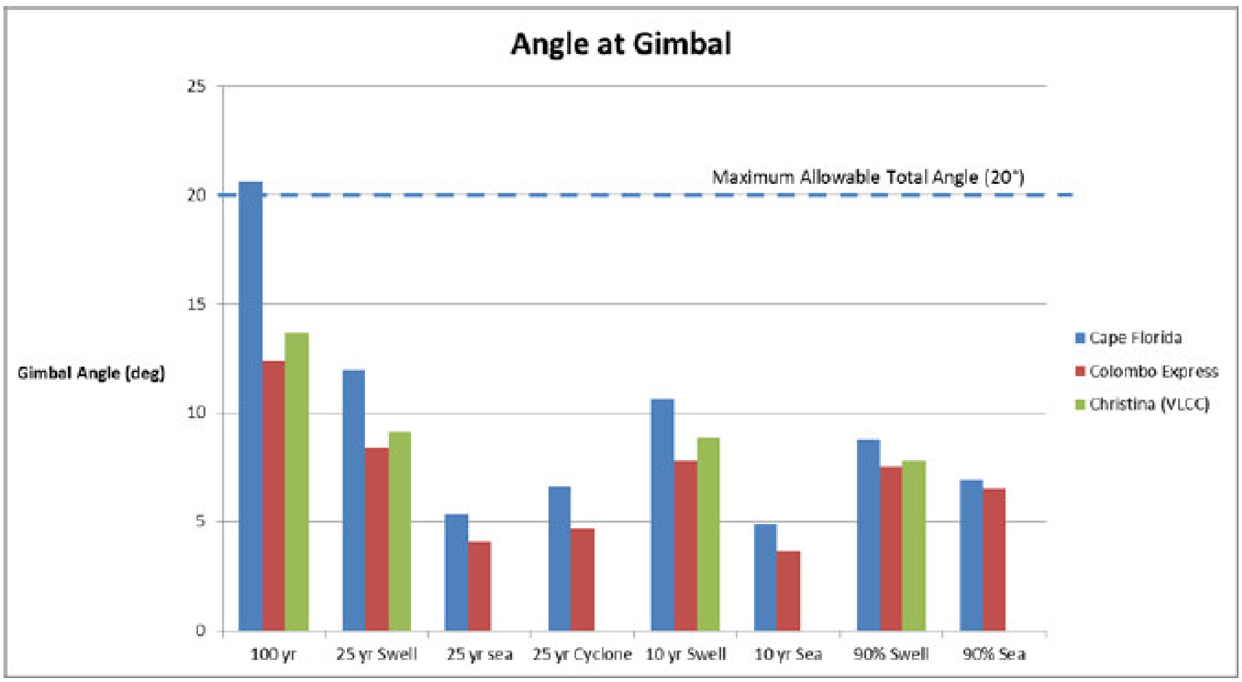


Figure 12. Maximum CWP-Vessel Angle

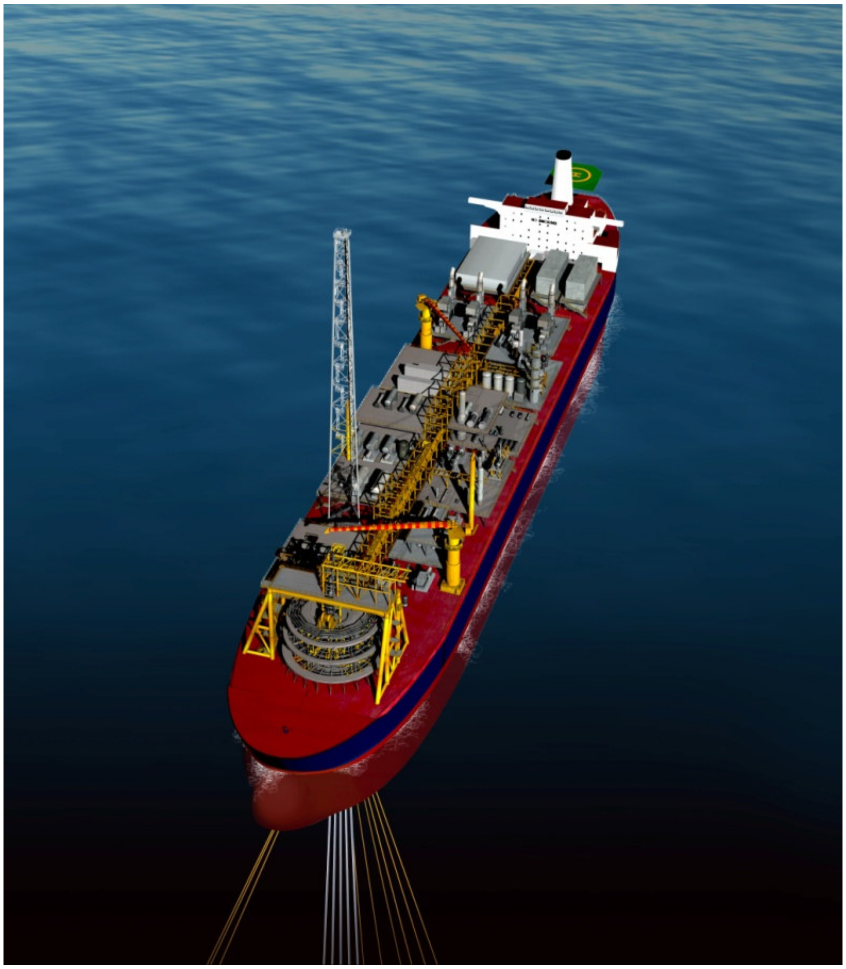


Figure 13. FPSO Sub-systems

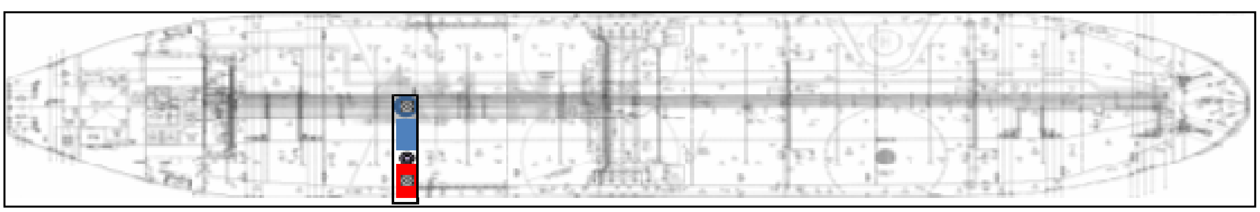


Figure 14. Example Footprint of 2.5 MW Power Block on VLCC Christina

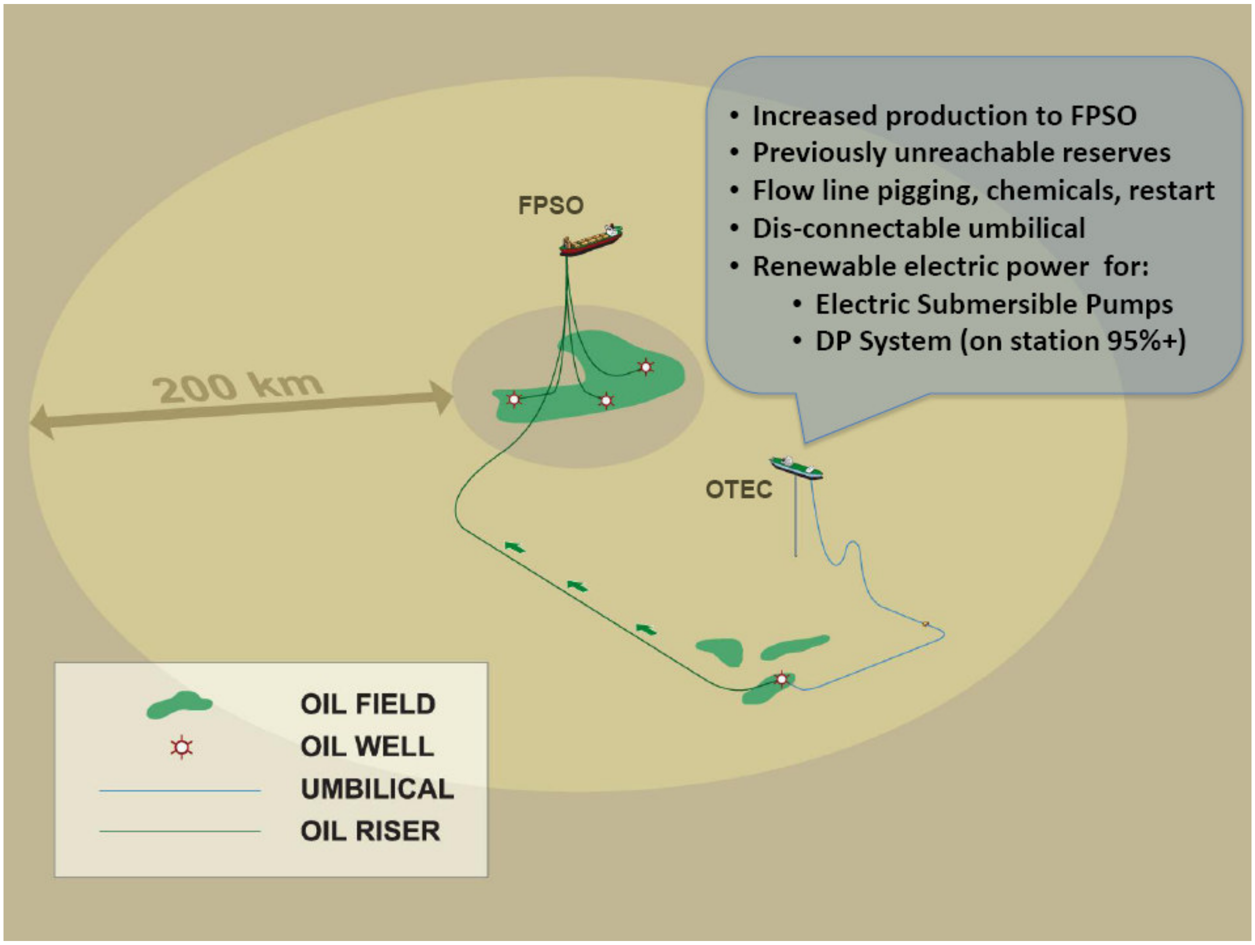


Figure 15. Production of Previously Unreachable Reserves

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