The Navy's Ocean Thermal Energy Conversion Program

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Abstract--The Navy views Ocean Thermal Energy Conversion (OTEC) technology as a potentially viable means to reduce dependence on fossil fuel and associated release of greenhouse emissions at Navy bases located in tropical areas, including Naval Support Facility Diego Garcia and facilities in Hawaii and Guam. The Naval Facilities Engineering Command (NAVFAC) OTEC Program is structured to advance commercialization and promote future development of OTEC technology for Navy applications.

While OTEC has a relatively long history of development and demonstration testing, it is only recently that critical technologies have matured to the level needed for commercially viable OTEC facilities. These key technologies include offshore platforms, deep water anchors and moorings, heat exchangers, cold water pipe configurations and fabrication techniques.

The Navy's long term objective for OTEC is the development and commercialization of OTEC technology to permit purchase of power and water from a privately developed OTEC facility at cost effective rates. Advancing OTEC technology to a commercially viable level is expected to require several significant interim steps. At present, both industry and the federal government (Department of the Navy and Department of Energy) are engaged in the development, testing and demonstration of OTEC subsystems to validate critical component designs. These projects include DOE-funded cold water pipe fabrication apparatus validation; NAVFAC supported Congressionally-funded heat exchanger development and testing; NAVFAC supported, ARRA funded OTEC Critical Component and Pilot Plant design, and Office of Naval Research (ONR) funded efforts to assess OTEC feasibility and perform seafloor surveys at potential Navy OTEC locations. An efficient and well defined path to OTEC commercialization is needed to complement and align these ongoing efforts. To that end, the Navy is developing an OTEC commercialization roadmap to visualize, support, and implement the developmental steps needed to reach the final long-term objectives.

The time frame for meeting all program objectives may be years away. However, with support from the Navy, other Government agencies and industry, the time required to reach the objective of OTEC commercialization could be significantly reduced if a structured program and roadmap is used to guide government and industry toward OTEC commercialization.

Therefore, the Navy’s near term objective is to support technical efforts that reduce overall system developmental risks with respect to critical components and subsystems.
This paper discusses the Navy OTEC program, its role in meeting Navy renewable energy objectives, and future steps needed to reach commercialization.

Background

The operating principles of Ocean Thermal Energy Conversion (OTEC) are well known, dating back to the original concept proposed by Jacques-Arsène d’Arsonval in 1881. There are numerous descriptions of OTEC system concepts, including [1] and [2]. A summary of the history of OTEC is presented in [2]. OTEC extracts solar energy through a heat engine operating across the temperature difference between warm surface water and cold deep water. In the tropics, surface waters are above 80°F, but at ocean depths of about 1,000 meters, water temperatures are just above freezing everywhere in the ocean. This situation provides a 40 to 50°F temperature differential that can be used to extract energy from the surface waters and generate base load electricity.

With this low temperature differential, the Carnot efficiencies of OTEC are very low; for a system operating between 85°F and 35°F the maximum theoretical efficiency is only 9.2% and real efficiencies will be less. Regardless, since the “fuel” is free, the challenge is to build commercial scale plants at a capital expense that yields competitive costs of electricity. There are a number of different concepts for the heat engine, including low temperature difference Sterling cycle engines and direct use of water vapor derived from the surface waters that is condensed with the cold water. Most concepts incorporate a Rankine cycle using a low boiling point working fluid.

While the OTEC resource is well-known, previous attempts to develop a viable and practical OTEC electrical-generation system have suffered from a variety of economic and technological challenges, including cost efficient heat exchangers and survivable cold water pipes.

Navy OTEC Program

The Navy’s support for emerging renewable and alternative energy sources is crucial to reducing Navy and Marine Corps dependence on fossil fuel, reducing “carbon footprint” with respect to climate change, and developing energy independence for Navy, Marine Corps, and selected other coastal facilities around the world. Recent Navy initiatives are supporting a range of efforts to assess, develop, and pursue ocean renewable energy demonstration projects at those Naval and Marine Corps bases that are situated in geographical areas favorable to site-specific renewable energy technologies. The Navy, therefore, is in a unique position to further the opportunities to produce clean power from the ocean, a renewable, predictable, and reliable resource.

The system level technical requirements for an OTEC plant can be stated simply as providing a desired number of kilowatt-hours to a specified location at a desired availability for a stated period of time. The fundamental characteristic of the ocean thermal resource is the relatively small temperature difference. The technology challenge for a viable, practical OTEC facility is the development of efficient systems required to convert that thermal resource into usable electric power. The Navy OTEC Program has been structured to address the most important technology areas, the Cold Water Pipe (CWP), heat exchangers (HX) and system engineering and design for an OTEC plant. The ocean environment drives technology challenges from three different perspectives: (1) mechanical/electrical operation in a corrosive and biologically active medium; (2) survival in adverse weather and ocean environments; and (3) minimization of impact to the environment. When one has addressed the detailed approach for each of these challenges, one still needs to integrate all of the pieces to make the whole system work. These technologies are not beyond today’s state-of-the-art. Advances over the decades offer approaches that can be exploited for viable OTEC solutions.

Serious Navy interest and participation in OTEC projects began in 2003 with an ONR-funded Small Business Innovative Research (SBIR) project for an initial feasibility study for utilization of OTEC technology at military (and especially Navy) installations. A contract was awarded in February 2003 to Ocean Engineering and Energy Systems (OCEES) International, Inc., with a Final Report submitted in March, 2004 [1]. Phase II of this SBIR was awarded to OCEES in late 2004 with Final Report in late 2005 [2]. The objective of Phase II was to provide preliminary design information for the most attractive Navy site, Diego Garcia. In December, 2004, the Navy awarded Makai Ocean Engineering, Inc, a phase I SBIR to investigate the “Integration and Optimization of Hydrogen Production with Ocean Thermal Energy Conversion Technology in Offshore Floating Platforms” postulating a future time when fossil fuels might become scarce, OTEC could provide a commercial source of hydrogen as an energy resource. The phase II effort started in June 2006 and culminated in a Final Report in October, 2007. More recently, the Navy awarded Makai a contract, which was completed in October 2009, to “determine whether OTEC is technically feasible for Guam and whether it can provide electrical power and byproducts of water and air conditioning to meet DoD future needs on Guam”.
Navy OTEC Projects

Current Navy and Navy-related OTEC projects include the following significant efforts, with the funding sources indicated:

- Assessment of potential Navy OTEC sites in Hawaii (ONR)
- Preliminary design, including system engineering, for a 5-10MW OTEC pilot plant (NAVFAC)
- Development and demonstration of the apparatus for in-situ coldwater pipe fabrication and handling (DoE)
- Development of anchor technology for OTEC plants on steep slopes typical of tropical islands, and in particular for the Hawaii pilot plant (LMCo internal)
- Design and demonstration of heat exchanger modules for the pilot plant (NAVFAC)
- Preparation of a commercialization plan to take the results of the pilot plant design and operational experience to the design of a nominal 100mW commercial plant (NAVFAC)

Taken together, these projects address key technical challenges in developing an eventual commercial OTEC plant.

Site Assessment

The Naval Facilities Engineering Service Center (NFESC) has been funded by ONR to conduct an evaluation of sites in proximity to Navy facilities in the Hawaiian Operational Area to provide assessments of offshore renewable energy resources of interest to the U.S. Navy. There are numerous potential OTEC sites off the coast of the Hawaiian island chain, including: Kahe Point, Oahu; Keahole Point, Hawaii; Pacific Missile Range Facility (PMRF), Kauai; Pearl Harbor, Oahu; and Marine Corps Base Hawaii-Kaneohe (MCBH-K), Oahu. The first two sites, Kahe Point and Keahole Point, were studied extensively during the late 1970’s and 1980’s as locations for early OTEC experiments and shore or artificial island based pilot OTEC plants. The last three potential OTEC sites have not been investigated in detail for suitability for potential utilization by the Navy. Sound & Sea Technology, Inc., (SST) prepared detailed Desktop Studies (DTSs) of all three candidate Hawaiian OTEC sites [4]. Subsequently, SST conducted an initial survey of a specific OTEC site off the southwest coast of Oahu [2]. The locations of the three sites are shown in Fig. 1 and the bathymetry for the candidate Oahu site is shown in Fig. 2. The results of Desktop Studies of these sites and survey data [5] to provide a site assessment for a prospective Navy offshore OTEC system will reduce OTEC technology developmental risks and accelerate follow-on efforts associated with future technology insertion. This project will result in identifying suitable offshore OTEC locations and cable routes for Navy OTEC technology insertion in the Hawaiian OPAREA.
Pilot Plant Preliminary Design

A major element of the NAVFAC program is to facilitate technology commercialization to obtain electric/potable water/SWAC utilities from mature OTEC systems at long-term cost effective rates and to reduce OTEC system developmental risks and shorten path to full commercialization. One task developed the interface between the cold water pipe (CWP) and the platform. The Lockheed Martin (LM) Industry Team separately developed a composite CWP design fabricated on-site, at-sea to eliminate the risk of deploying the long CWP from shore. For perspective, a 10 MW capacity CWP has a diameter of 4 meters and a length of 1,000 meters, whereas a 100 MW CWP has a diameter of 10 meters. The CWP design is based on the ability to mold sections of pipe, lowering the assembly as each section cures. The NAVFAC task developed the hardware to hold the pipe during fabrication and to lower the assembly in preparation for the next molding step. Fig. 3 is a depiction of the gripper hardware. This task included development of hardware to terminate the pipe to the platform.

The second major task matured the design for a pilot plant. A pilot plant is needed to enable OTEC commercialization. The biggest barrier to deploying OTEC is the substantial upfront capital investment. To attract commercial financing, data on the cost, construction schedule, performance, and time to profitability are needed, but those data cannot be generated in the absence of a pilot OTEC plant. To gather this evidence and lay the foundation for commercial financing, it is considered necessary to build and operate a megawatt scale pilot OTEC plant, and for the resulting cost and performance data made public. This NAVFAC task matured the design for this pilot plant based on top level requirements to site this plant in Hawaii and operate it for a test phase of two years. After to the test phase, it is expected the plant will be upgraded to provide commercial power for another twenty years. Fig. 4 is a depiction of the pilot plant incorporating a semi-submersible configuration with one 5 MW power module.
Cold Water Pipe Development

An OTEC CWP provides the path by which deep cold ocean water is channeled to the condenser heat exchangers mounted on the floating platform. The CWP must provide a cost effective path with minimal friction loss and the ability to survive platform motions over a twenty to thirty year life. The LM Industry Team is building and validating the apparatus to build a composite based CWP design with funding provided in part by the Department of Energy. The composite design is based on molding sections of CWP and, as each section cures, lowering the pipe into the water until the entire 1,000 meters of pipe is complete. The baseline design calls for molding about 40 feet of pipe for each step. The apparatus required for this process includes the area to assemble core sections of the pipe section, lowering the core into a molding chamber to infuse resin over the core, curing the resin, and lowering the pipe assembly to repeat the process until the entire length is fabricated. The apparatus for this process is shown in Fig. 5. The ability to mold 40 foot sections of pipe requires an apparatus of considerable size.

Future trade studies will be conducted to assess the optimal molding step length considering the size of manufacturing apparatus hardware and fabrication time.

Anchor Technology for Steep Slopes

OTEC plants require placement at locations and water depths that provide the required thermal difference between warm surface waters and cold deep waters for efficient operation. The most favorable locations are frequently near tropical islands or atolls of volcanic origin. These locations generally have steep slopes, irregular bathymetry and uncertain sediment thicknesses. These sites present interesting challenges to meet wind, wave, and extreme event criteria. Fig. 6 shows a notional mooring system configuration for an OTEC Pilot Plant off the southwest coast of Oahu. The challenges for the anchor and mooring systems designers concern the different depths at desirable anchor locations, the bottom slopes, the locations of the areas with sediment and the availability of suitable vessels for installation of the anchors and mooring system for potential anchor candidates. These conditions require creative approaches to the design of the anchor and mooring system and can result in a different anchor solution at each anchor location. One size or type of anchor for all anchor locations is not necessarily the best solution. A companion paper discusses the anchoring challenges for OTEC facilities [6].

![Fig. 5 Cold Water Pipe Fabrication Apparatus](image1)

![Fig. 6 OTEC Pilot Plant Mooring System](image2)
Heat Exchanger Development

Heat exchangers comprise the highest cost driver for large OTEC systems. Therefore, reductions in heat exchanger costs are critical to successful commercialization of OTEC power plants for the Navy and subsequently for civilian markets. The OTEC heat exchanger technology challenge is the ability to provide a cost-effective design that maximizes heat transfer while minimizing pressure losses, corrosion, bio-fouling, weight, and volume. OTEC plants need to move about 500 gallons per second per MW through each evaporator and condenser heat exchanger subsystems. A key to successful heat exchanger development is the ability to test candidate designs at large scales to validate performance data. Large scale heat exchanger performance testing will be available at the Natural Energy Laboratory Hawaii Authority (NELHA) facility on Kona, Hawaii at Keahole Point, where a land-based Ocean Thermal Energy Conversion (OTEC) Heat Exchanger Performance Test Facility is being developed by Makai Ocean Engineering, Inc under Navy and State of Hawaii funding. The facility is expected to complete fabrication and installation by the end of summer 2010 and become operational in the fall of 2010.

Shown in Fig. 7, this facility is intended to replicate operational environmental conditions that OTEC heat exchangers would experience in sea-based deployments. NELHA is the only facility in the world that has access to both cold deep seawater (DSW) at depths up to 900 m, and warm surface seawater (SSW), that has a narrow variable temperature range in the same environment as expected for the OTEC Pilot Plant. These unique conditions at the facility provide the ability to test OTEC heat exchanger evaporator and condenser performance with both warm SSW and cold DSW. The facility will also utilize automated data acquisition and high-quality instrumentation for all relevant parameters to maximize the accuracy of the heat transfer measurements.

Commercialization Development

There are no operating OTEC systems anywhere in the world today. Many renewable energy systems such as wind generators, solar photovoltaic systems and even many wave energy systems can be built efficiently on a fairly small scale of a few tens of kilowatts. This enables these systems to be fabricated and tested through multiple iterations before committing to large commercial facilities. These systems are just starting to enter commercial scale phase of development. Wind and solar technologies are entering the commercial scale installations. The marine renewable energy technologies, (wave, tidal, and current) are not presently at commercial scales. Some systems have been iterated through prototype and are seeking investment to cross the “valley of death” to commercial scale projects.

However, OTEC systems are very difficult to build in small scale and need to be relatively large scale to become economically competitive. Thus, the 10 MW Navy Pilot Plant planned by the LM Industry Team is intended mainly as a technical, cost and schedule risk reduction step to enhance confidence with the anticipated concerns of the investment community, as well as all the other stakeholders. The first 100 MW commercial OTEC plant may well be commercially viable even though future cost reductions and production efficiencies could favorably reduce the capital cost of these plants. A few small companies claim to have OTEC system designs ready for production, but the team has been unable to verify that documentation exist with sufficient detail to enable a shipyard or offshore platform builder to even bid on a system. The reality is that OTEC requires high capital costs because the thermal resource is of low energy density relative to traditional fossil and nuclear fuels. Therefore, economic OTEC plants will be large and have high capital costs.

The objectives of the Ocean Thermal Energy Conversion (OTEC) Commercialization Plan are to:

- Define a realistic commercialization path
- Establish system cost targets
- Establish a Development and Permitting baseline
- Establish a total project execution schedule
- Estimate a realistic funding profile
- Establish and communicate the commercialization strategy amongst all stakeholders.
A depiction of the commercialization approach is provided in Fig. 8. Design work, large scale component and subsystem testing, and other risk mitigation activities are necessary to provide confident estimates of system performance and costs. The pilot plant will validate performance and cost estimates and provide means to verify environmental assessments and operation and maintenance requirements. Completion of the first two efforts will provide the evidence for the finance communities to invest in commercial projects. Dates for actual completion of the three major steps shown on the figure are nominal and will be a function of funding, which is neither authorized nor appropriated as of this date.

OTEC’s Role in Meeting Navy Energy Goals

The Department of Defense (DoD) is pursuing aggressive energy policies, including energy independence and security, on-site generation and consumption, and reduced dependence on purchased power. Mandates include:

- **2007/2010 NDAA (10 USC 2911e):** Produce or procure 25% of all DoD energy from renewable energy by 2025;
- **EPACT 2005:** Renewable energy – 3% by 2007, 5% by 2010, 7.5% 2013 and beyond;
- **EISA 2007 & EO 13423:** Energy efficiency, energy intensity, biofuels, etc.; and
- **EO 13514:** Carbon / Green House Gases

The Navy is subject to these same directives, Executive Orders and goals for reduction of fossil fuel usage, increased use of renewable energy sources, and improvements in energy efficiency. These have led to development of a long-term plan for Navy support to renewable ocean energy in general, and OTEC in particular. Recently, the Secretary of Navy has announced even more aggressive goals, which are summarized here:

- **Energy Efficient Acquisition:** Evaluation of energy factors will be mandatory when awarding contracts for systems and buildings;
- **Sail the “Great Green Fleet”:** DON will demonstrate a Green Strike Group in local operations by 2012 and sail it by 2016;
- **Reduce Non-Tactical Petroleum Use:** By 2015, DON will reduce petroleum use in the commercial fleet by 50%;
- **Increase Alternative Energy Ashore:** By 2020, at least 50% of shore-based energy requirements will come from alternative sources; 50% of DON installations will be net-zero; and
- **Increase Alternative Energy Use DON-Wide:** By 2020, 50% of total DON energy consumption will come from alternative sources

The ability to meet these aggressive goals requires application of renewable energy sources that can provide replacements to the existing fossil-fueled base load generation. OTEC can provide such base load capability for bases in tropical waters.

The initial implementation for OTEC power generation will be for those applications where the ocean thermal resource is close enough to shore for an undersea cable to transmit generated electricity to the local grid. For the Navy, the most attractive initial applications include three sites in Hawaii, Guam, Diego Garcia, Kwajalein, and Ascension Island. As the OTEC industry matures, it is expected that larger OTEC plants can “graze” in tropical waters and use the generated electricity to produce energy.
carriers that can be shipped to Navy bases for utilization in power plants. As algal bio-fuel development efforts mature, it is not unreasonable to expect these open ocean power plants can produce synthetic fuels to replace today’s petroleum based transportation fuels.

The aggressive DoD and Navy renewable energy goals mean the Navy is incentivized to help develop new energy resources. A very significant benefit of this activity is to foster OTEC commercialization that will benefit the civilian sector, not only with a new, renewable, base-load energy resource, but also with the attendant industry and jobs that will be created to design, build, install, operate, and maintain this fleet of power plants.

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