Ocean Thermal Energy Conversion (OTEC) Workshop
Assessing Potential Physical, Chemical and Biological Impacts and Risks
A Primer

Ocean thermal energy conversion (OTEC), the concept of extracting energy from the ocean by utilizing the temperature differential between the surface and deep oceanic waters, was first proposed by the nineteenth century French scientist Jacques-Arsène d'Arsonval in 1881. It was another Frenchman, Georges Claude, who made the first attempts to put the concept into practice in the first half of the twentieth century. Between 1928 and 1930 Claude built the first OTEC electrical generating facility at Matanza Bay, Cuba. The facility only operated for 11 days generating sufficient power to light forty 500 watt bulbs during a demonstration; however backers were not sufficiently impressed to finance a proposed 25 megawatt plant (Chiles, 2009). In 1934, using mostly his own money, Claude made his second attempt at a commercial scale OTEC facility. This one was a plant ship for the production of ice off the coast of Brazil. Before the cold water pipe could be completed a storm sank it and the project had to be cancelled due to lack of funds.

Jumping ahead to the 1970's and the Arab oil embargo; oil prices soared as did interest in alternative energy sources, including OTEC. In 1979 a project called Mini-OTEC, operating off of a US Navy barge, successfully generated 50 kilowatts of electricity in waters off Hawaii and a Japan sponsored 100 kilowatt land-based plant was operated on the island nation of Nauru and a 40 megawatt plant was proposed at Kahe Point, Hawai'i. Oil prices dropped followed by interest and federal funding in alternative energy sources. In the intervening years no OTEC facility of any size was constructed but limited research into design of such a facility continued. Back in the 70's and 80's the push for alternative energy sources was largely based on the direct cost of generating electricity, e.g., the cost of a barrel of oil. Today the renewed interest in alternative energy, particularly renewable energy resources is fueled not only by the direct cost of oil but also the indirect costs of utilizing oil and coal as energy sources. These indirect costs include relying on foreign fuel suppliers and pollution emissions, particularly CO_2.

With this renewed interest in renewable energy resources work has been revived on developing a demonstration/pilot facility large enough (5-10 MW) that data obtained from its operation could be reasonably scaled up to a commercial size facility (100 MW or greater). The most likely location, within U. S. territory, for both the first demonstration/pilot facility and the first commercial facility is in Hawai'i. Therefore, this workshop will focus on the potential impacts of 5-10 MW and 100 MW facilities operating in Hawaiian waters, however, keeping in mind that any licensing regulations ultimately written will have to take into account conditions at other sites throughout the United States and its territories.

There are two major design options for an OTEC electrical generating facility: an open-cycle system where flash evaporated surface seawater is used to drive the turbines and is then cooled and condensed by deep seawater; and a closed cycle system where the turbines are driven by a working fluid (currently ammonia is the most likely) heated to gas by warm surface seawater and then cooled and condensed by cold deep seawater. Either type of OTEC facility can be installed in any one of three basic locations: on land, on an off-shore moored floating platform, and on a ship. The only key engineering requirement for the location of such a facility is the accessibility of warm surface water and cold deep water with a temperature differential of at least 20º C.

The major potential for environmental impact which is unique to OTEC results from the large volumes of water required to operate such a facility. It is estimated that from 3-5 m^3/sec of warm surface water and a roughly equivalent amount of cold deep water are required for each megawatt of power generated (Myers *et al*., 1986). This translates to 300-500 m^3/sec for a 100 MW plant, or 26-43 million m^3/day of just warm water. To put this into perspective a 2200 MW coastal nuclear power plant operating at full capacity uses 111 m^3/sec (9.6 million m^3/day) (Ferry−Graham, *et al*., 2008) of cooling water approximately one sixth of the minimum total predicted water requirements for a 100 MW OTEC plant (Table 1). It has been stated that a 400 MW OTEC plant would require the equivalent of 20% of the average annual flow of the Mississippi River. From an environmental perspective the major difference between the open-cycle and closed-cycle OTEC operating systems is that the freshwater produced by evaporating the warm seawater in an open-cycle system could be used as a by-product resulting in a lower volume of warm water discharge with an elevated salinity. Secondarily, the open-cycle system would not pose a potential risk from leakage or spillage of a toxic working fluid.

Table 1. Warm water intake volumes for various sized OTEC facilities with the Natural Energy Laboratory of Hawai'i (NELHA) and San Onofre Nuclear Power Plant as references.

Facility	Million Gal/day	Gal/min	Ft^3/Sec	m^3/sec	m^3/min	Million m^3/day
NELHA 40 in CW	19	13,400	30	0.8	51	0.07
NELHA 55 in CW	39	27,000	60	1.7	102	0.15
5MW plant min	342	237,750	530	15.0	900	1.30
5MW plant max	571	396,250	883	25.0	1,500	2.16
100MW plant min	6,847	4,755,000	10,593	300.0	18,000	25.92
100MW plant max	11,412	7,925,000	17,655	500.0	30,000	43.20
400MW plant min	27,389	19,020,000	42,373	1,200.0	72,000	103.68
400MW plant max	45,648	31,700,000	70,621	2,000.0	120,000	172.80
San Onofre Nuclear Power Plant	2,580	1,791,667	3,991	113.0	6,782	9.77

The closed-cycle system is currently considered the most likely design for the first OTEC facilities, therefore, the discussions at this workshop will focus on the potential environmental impacts of a closed cycle system with either a 5 MW or 100 MW generating capacity. Approximations of key operational and critical parameters of concern for a demo or commercial OTEC facility in Hawaiian waters are listed below; more precise descriptions of these parameters would be dependent on a specific facility design.

- Type
  - Floating platform
  - Anchoring system, to be determined
  - End product: Electricity to be transmitted to shore via cable

- Location
  - 3-4 miles offshore (depending on depth contours and temperature profile

- Warm water intake
    - Depth approximately 20 meters
    - Temperature 25º C
    - Volume
        - 5 MW - ~25 m^3/sec
        - 100 MW - ~500 m^3/sec
    - Antifouling treatment: Probably intermittent chlorination

- Cold water intake
    - Depth approximately 800 - 1000 meters
    - Temperature 5º C
    - Diameter
        - 5MW – ~2-4 m
        - 100 MW – ~10 m
    - Volume
        - 5 MW - ~25 m^3/sec
        - 100 MW - ~500 m^3/sec
    - Antifouling treatment: None

- Discharge water
    - Combined warm and cold water discharge, or
    - Separate warm and cold water discharge.
    - Discharge depth – to be determined.

The **potential** impacts to biological communities resulting from the construction and operation of a closed-cycle OTEC facility, roughly broken down by component/stressor, include but are not limited to the following:

- Warm water intake
    - Entrainment
        - Phytoplankton and zooplankton (including microzooplankton, meroplankton, icthyoplankton and possibly some macrozooplankton) and possibly some small vertebrate fish would be entrained in the warm water intake where they would be subjected to mechanical stresses from the intake pumps, periodic chemical stresses from the application of anti-fouling biocide and a mild temperature stress produced by a temperature reduction of 2-3º C unless a combined discharge is used then the temperature reduction would be approximately 10º C.
            - Quantity taken in is a function of the water volume taken in and screen mesh size.
            - Percent survival unknown.
    - Impingement

        - Macrozooplankton including cnidarians and small fish would be impinged on the debris screens of the intake structure(s).
            - Size and quantity of the impinged organisms is dependent on the screen mesh size, the volume of water taken in and the velocity of the water intake.
            - Percent survival will be dependent on the screen design and could be as low as zero.
            - Could sea turtle hatchlings be impinged?

- Cold water intake
    - Entrainment
        - Mesopelagic microzooplankton would be entrained; whether this would include any meroplankton or icthyoplankton is unclear. Entrained organisms would be subject to extreme pressure changes on the order of 100 atmospheres, mechanical stress from the intake pumps and a slight temperature stress of a few degrees centigrade.
            - Quantity taken in is a function of the water volume taken in and screen mesh size.
            - Percent survival is expected to be zero due mainly to the pressure changes.
    - Impingement
        - Macrozooplankton and small fish would be impinged on the debris screens of the intake structure(s). Since the debris screens for the cold water intake would be located near the top of the cold water intake pipe (CWP) impinged organisms would be subjected to extreme pressure changes on the order of 100 atmospheres.
            - Size and quantity of the impinged organisms is dependent on the screen mesh size, the volume of water taken in and the velocity of the water intake.
            - Percent survival is expected to be zero due mainly to the pressure changes.
    - Other impacts
        - Could larger fish or marine mammals enter into the CWP and potentially be killed?

- Discharge water
    - Individual warm and cold water discharges
        - Warm water discharge will most likely be at a depth below the warm water intake to insure no interference with the intake. It will contain erosion and corrosion products from the facility components, biocide from anti-fouling treatment, and possibly some working fluid which has leaked out during normal operations (spills will be treated separately). It will also include the living or dead entrained organisms.
            - Potential toxic effects from erosion and corrosion products, biocide and working fluid both singly and in combination.
            - Surviving entrained organisms may be carried to an unsuitable depth and thus die.

      - Dead organisms in the discharge plume may act as fish food, attracting fish to the vicinity of the plume.
      - Planktonic organisms which are in the area of the discharge plume may be entrained in the plume (referred to as secondary entrainment) thus being exposed to toxins.
      - Potential for biomagnification of toxins thus impacting higher trophic level organisms.
    - Cold water discharge may be deeper than the warm water discharge or in some proposed designs be above the warm water. It will contain erosion and corrosion products from the facility components, possibly some working fluid which has leaked out during normal operations, and the remains of entrained organisms. It should not contain any biocide, but it will contain dissolved gasses and nutrients from the deep. Its temperature, salinity and density will be different from the surrounding water into which it is discharged and will thus sink below the discharge point with sinking rate to a large extent dependent on the discharge location with respect to the warm water discharge.
      - Potential toxic effects from erosion and corrosion products and working fluid both singly and in combination.
      - Nutrients in the discharge may enhance primary productivity or cause toxic algal blooms. If rapid sinking occurs it may nullify any potential impact.
      - Concern has been expressed over dissolved gases in the discharge with respect to atmospheric release of green-house gases, but again this is dependent on the rate of sinking which is dependent on the discharge location, particularly with respect to the warm water discharge.
      - The higher dissolved CO_2 in the discharge may change the pH in the local receiving water inhibiting the shell production of foramnifera and veliger larvae. If rapid sinking occurs it may nullify any potential impact.
      - Dead organisms in the discharge plume may act as fish food, attracting fish to the vicinity of the plume.
      - Planktonic organisms which are in the area of the discharge plume may be subject to secondary entrainment in the plume thus being exposed to toxins and carried to depths which are unsuitable to their survival.
      - Potential for biomagnification of toxins thus impacting higher trophic level organisms.
  - Combined discharge
    - A combined discharge would consist of water with an average temperature difference of approximately 10º C from both the warm water intake (10º C cooler) and the cold water intake (10º C warmer) with density and salinity also being an average of the two intake water masses. This water would sink to a depth of comparable density. It will contain erosion and corrosion products from the facility components, biocide from anti-fouling treatment, and possibly some working fluid which has leaked out during normal operations. It will also include the living or dead entrained organisms.

        - Potential toxic effects from erosion and corrosion products, biocide and working fluid both singly and in combination.
        - Nutrients in the discharge may enhance primary productivity or cause toxic algal blooms, depending on depth of discharge and sinking rate.
        - Concern has been expressed over dissolved gases in the discharge with respect to atmospheric release of green-house gases, but again any release would be dependent on discharge depth and sinking rate.
        - The higher dissolved CO_2 in the discharge may change the pH in the local receiving water inhibiting the shell production of foramnifera and veliger larvae. Rapid sinking may nullify any potential impact.
        - Surviving entrained organisms and secondarily entrained organisms may be carried to unsuitable depths for their survival.
        - Dead organisms in the discharge plume may act as fish food, attracting fish to the vicinity of the plume.
        - Potential for biomagnification of toxins thus impacting higher trophic level organisms.

- Chemical Effects
    - As previously mentioned the discharge water will contain corroisonal and erosional products, biocide from the heat exchangers, and possibly leaked working fluid. In addition the platform will release biocides from the antifouling paint and there is always the potential of a working fluid or biocide spill. These contaminants may act singularly or in combination on exposed biota.
        - Direct toxicity to exposed organisms.
        - Biomagnification of toxins with toxicity to higher trophic level organisms including humans.

- Construction and Physical Presence of Facility
    - Construction impacts at the site will depend on exactly how much of the construction will be done on-site. The platform will likely be built at a shore based facility and towed to the site; the cold water pipe may be constructed elsewhere and towed to the site or constructed/manufactured on-site.
        - Placement of anchors and transmission cable would disrupt/destroy benthic communities.
        - Construction activities could disrupt movements of marine mammals and reptiles in the area.
        - Could marine organisms be trapped, due to disorientation, in the cold water pipe as it is constructed/manufactured on site?
    - Physical Presence
        - Platform would most likely act as a fish attraction device (FAD).
            - Could increase the number of impinged and entrained organism.
            - Could change local migratory patterns of marine organism.
        - Lights at night would act as a bird attractant.

        - Anchor and transmission cables may pose a risk of entanglement to marine mammals.
        - Anchors may change local bottom habitat type from soft to hard and thus change the local benthic community composition.
        - Cold water pipe?

- Acoustical and Electromagnetic Field (EMF)
    - Noise from plant operation will be principally from the water pumps and the generators. Additional noise would be generated by the actual movement of the water through the system and out the discharge.
        - Possible impact on marine mammal echolocation and communication.
    - EMF generation would occur around the transmission cable. In most if not all situations high power underwater transmission cables run entirely along the bottom or are even buried in the sediments; the transmission cable from a floating OTEC facility will be partially suspended in the water column (from the platform to the bottom).
        - Interference with marine organisms that use electric fields for prey detection (e.g., sharks) or magnetic fields for navigation.

As stated above, these are **potential** impacts, and they may not be the sole **potential** impacts of the construction and operation of an OTEC facility. Hopefully by the end of this workshop we will have an idea of how to determine the real impacts.

Past Evaluations

Prior to the passage of OTECA the U. S. Department of Energy produced an environment assessment for an OTEC test platform (DOE, 1979b). Since little data existed on the potential impacts of the proposed platform they developed a list of the type of data needed to evaluate the impact of the test platform. This list includes necessary baseline data, monitoring data during operations and post operational data requirements (see attachment 1).

OTECA was enacted August 3, 1980; in July 1981 NOAA issued the Final Environmental Impact Statement (EIS) for Commercial Ocean Thermal Energy Conversion (OTEC) Licensing (NOAA, 1981). This document addressed all three siting locations for OTEC facilities: land based, offshore moored platform and open-water ship. It goes on to state "Evaluation of potential environmental impacts associated with commercial OTEC development is presently a matter of speculation . . ." Several other reports are cited which have made preliminary assessments of the potential environmental effects associated with OTEC plants: DOE OTEC Environmental Development Plan (DOE, 1979a), the DOE. Environmental Assessment for OTEC (DOE, 1979b) which was supplemented for OTEC-l (Sinay-Friedman, 1979), a DOE draft of the OTEC Programmatic EA (Sands, 1980), a site- and design-specific EA which was prepared for the proposed second deployment of Mini-QTEC (Donat et a1., 1980), and a generic EA for the 40-MWe OTEC Pilot Plant Program (Sullivan et al., 1980).

Based on the available data at the time NOAA classified the potential environmental effects of OTEC into three categories: major effects, minor effects and potential effects from accidents (Table 2). In addition to determining potential impacts of an OTEC facility they also recommended possible mitigation measures as well as research needs (see attachment 2).

Table 2 OTEC effects categories from NOAA's final EIS (NOAA, 1981).

Catergory	Stressor	Effect
Major Effects:	Platform presence	Biota attraction
	Withdrawal of surface and deep ocean waters	Organism entrainment and impingement
	Discharge of waters	Nutrient redistribution resulting in increased productivity
	Biocide release	Organism toxic response
Minor Effects:	Protective hull-coating release	Concentration of trace metals in organism tissues
	Power cycle erosion and corrosion	Effect of trace constituent release
	Implantation of coldwater pipe and transmission cable	Habitat destruction and turbidity during dredging
	Low-frequency sound production	Interference with marine life
	Discharge of surfactants	Organism toxic response
	Open-cycle plant operation	Alteration of oxygen and salt concentrations in downstream waters
Potential Effects from Accidents:	Potential working fluid release from spills and leaks	Organism toxic response
	Potential oil releases	Organism toxic response

In 1986 NOAA's National Marine Fisheries Service published a report entitled "The Potential Impact of Ocean Thermal Energy Conversion (OTEC) on Fisheries" (Myers *et al*., 1986). This report benefited from some of the research proposed by the 1981 EIS and was able to generate some actual numbers for biomass loses due to entrainment and impingement. However, the report goes on to state that these numbers are still speculative; for example the warm water intake entrainment and impingement numbers were based on average biomass concentrations derived from various reports for both Hawaii and Puerto Rico, however, if the facility acts as a fish attractant the concentration of organisms subject to entrainment and impingement could be significantly higher. The report concluded that "the potential risk to fisheries of OTEC operations is not judged to be so great as to not proceed with the early development of OTEC. Due to the lack of a suitable precedent, however, there will remain some level of uncertainty regarding these initial conclusions until a pilot plant operation can be monitored for some period of time. In the meantime, further research on fisheries should be undertaken to assure an acceptable level of risk regarding the larger commercial OTEC deployments."

For more detailed information on these past evaluations of OTEC it is recommended that the NMFS report (Myers *et al*., 1986) be consulted, since unlike the EA (DOE, 1979) and EIS (NOAA, 1981) cited above, which are both a few hundred pages long, the NMFS report is less than 40 pages including references.

References

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ATTACHMENTS

ATTACHMENT 1

ENVIRONMENTAL ASSESSMENT
Ocean Thermal Energy Conversion (OTEC) Program
Preoperational Ocean Test Platform
Volume 1 of 2
U.S. Department of Energy DOE/EA-0062
1979
(pages 4-29 to 4-33)

Baseline Data

Biological

- Phytoplankton and zooplankton should be identified and species quantified.
- Food chain interactions should be determined.
- Microbiology assays should be determined (qualitative and quantitative).
- Biomass/productivity rates with chlorophyll-a and C^{14} should be estimated.
- Impingeable and entrainable organisms in the water column should be identified.
- Micronekton and nekton density rates through the study sites.

Chemical (support to the above include):

- Particulate and dissolved organic carbon
- Dissolved micronutrients (ammonia, nitrate, nitrite, ortho-phosphate, silicates).
- Total nitrogen
- Residual chlorine and chlorine derivatives
- Carbonate equilibrium (alkalinity, pH).
- Trace metals (titanium, aluminum, copper, lead, etc
- Water column profiles of dissolved oxygen, salinity and temperature.

Physical

- Temporal/spatial current patterns
- Wave height and direction and frequency of occurrence
- Vertical density structure
- Transmissivity.
- Deep scattering layer.
- Mixed layer depth.
- Dye dispersion studies.

On-Site Monitoring

Biological

- Impingeable and entrainable organisms in the vicinity of the intakes (including fish)
- Limited biological sampling for phytoplankton and zooplankton to determine percent mortality
- Micronekton and nekton density around the platform
- In situ bioassay with phyto- and zooplankton

Chemical

- Micronutrients (ammonia, nitrate, nitrite, orthophosphate, silicates, total nitrogen).
- Particulate and dissolved organic carbon
- Temperature, salinity, alkalinity, dissolved oxygen and pH profiles
- Transparency (transmissivity).
- Residual chlorine and chlorine derivatives (monochloramine and dichloramine)
- Water samples should be taken from the water in the cold and warm water pipes, and outfall, and various points in the water column

Physical

- Wave height and period.
- Transmissivity.
- Current speed and direction.
- Radiation.
- Deep scattering layer.

Meteorological

- Air temperature.
- Barometric pressure.
- Wind speed and direction.
- Radiation •
- Humidity •

Post Operation Site Survey

- Same parameters as baseline

ATTACHMENT 2
Final Environmental Impact Statement for Commercial Ocean Thermal Energy Conversion (OTEC) Licensing
NOAA Office of Ocean Minerals and Energy
1981
(Pages 4-40 to 4-41)

TABLE 4-8. POTENTIALLY ADVERSE ENVIRONMENTAL IMPACTS AND MITIGATING MEASURES

Issue	Community Affected					Mitigating Measures (Ranked by Effectiveness)	Research Needs
	Plankton	Nekton	Benthos	Threatened and Endangered Species	Man's Activities		
Biota Attraction and Avoidance	Increased number of organisms due to attraction to lights.	Increased number organisms due to attraction to structure and lights.	Colonization of exposed structures.	Possible avoidance of area due to human presence and noise.	Increased fishing. Loss of desired faunal diversity.	Site away from breeding and nursery grounds. Reduce lights and noise to minimum needed for safe operation. Reduce attraction surfaces	Site evaluation studies to determine ecological sensitivity of areas. Determine biota attraction and avoidance to different platform configurations and lighting systems.
Organism Entrainment	Reduction in population size.	Reduction in population size due to mortality of eggs and larvae. Potential reduction in food resources.	Reduction in population size due to mortality of planktonic larval stages.	Possible reduction in food resources.	Potential decrease in fishery resources.	Site intakes away from ecologically sensitive areas. Site intakes at depths that will entrain the least number of organisms. Reduction in through- plant shear forces.	Site evaluation studies to determine ecological' sensitivity of area. Determine vertical distribution of local populations. Entrainment mortality studies that determine plant induced mortality
Organism Impingement	None.	Reduction in population size due to mortality of juveniles and adults.	None.	None.	Potential reduction in fishery resources.	Use velocity caps to achieve horizontal flow fields. Use fish return system. Site intakes at depths that will impinge the least number of organisms. Reduce intake velocities.	Site evaluation studies to determine ecological sensitivity of area, and size, structure, and vertical distribution of fish populations. Impingement mortality prevention studies
Biocide Release	Reduction in population size.	Decreased metabolic activity and plume avoidance by adults. Reduction in population size due to mortality of eggs and larvae.	Reduction in population size due to mortality of planktonic larval stages. Chronic or acute effects on adults.	Possible avoidance of plume. Possible reduction of food resource.	Potential reduction of fishery resources. Decreased aesthetics.	Discharge below photic zone. Use alternate methods for biofouling control. Rapid dilution through use of diffusers. Site specific biocide release schedule and concentration. Site discharges away from ecologically sensitive areas.	Site evaluation studies to determine ecological sensitivity of area Acute and chronic toxicity and bioassay studies on representative organisms.
Nutrient Redistribution	Increased productivity.	Potentially increased food resource.	Potentially increased food resource.	Potentially increased food resource.	Potential increase in fishery resource. Potentially decreased aesthetics.	Discharge into photic zone. Discharge below photic zone.	Determine discharge plume stabilization depth and downstream mixing rate so that physical models can be calibrated.
Sea-Surface Temperature Alterations	None.	None.	None.	None.	Potential climatic alterations.	Discharge below the thermocline.	Monitor temperature density profiles from OTEC discharges to calibrate predictions.