Environmental assessment for ocean thermal energy conversion in Hawaii

Available data and a protocol for baseline monitoring

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Abstract— **The need to increase renewable energy supply in the United States has prompted ocean thermal energy conversion (OTEC) technology to be re-considered for use in Hawaii. As with any new development, a thorough environmental impact assessment is needed before the technology can begin field trials. A previous Final Environmental Impact Statement (EIS) from 1981 is available, but needs to be brought up to current oceanographic and engineering standards. There has been much research done on the oceanography of Hawaii since the original EIS, and this report highlights some of the most important contributions in terms of OTEC development as well as existing gaps in knowledge. A protocol for environmental baseline monitoring is proposed, focusing on a set of ten chemical oceanographic parameters relevant to OTEC and addressing gaps in knowledge of the ecology and oceanography of the area chosen for OTEC development.**

Keywords- Ocean thermal energy conversion, OTEC, renewable energy, Hawaii, environment, oceanography

I. INTRODUCTION

Ocean thermal energy conversion (OTEC) is a promising renewable energy technology which exploits the thermal gradient between warm, surface seawater and deep, cold seawater to generate electricity [1]. During the operation of an OTEC plant, seawater intake pipes will draw warm water from 20m depth and cold water from 1000m. After moving through the heat exchange system, the two water masses will be mixed and discharged at 60m or deeper, to be determined based on environmental impact analysis. Hawaii is a prime location for OTEC because of its large thermal gradient and steep bathymetry, allowing relatively easy access to deep water [2]. The lee of the island is particularly steep, so new OTEC plants would preferentially be constructed there to minimize costs. A pilot plant is planned to be constructed several kilometers south of Barber's Point, Oahu, and a commercial scale plant may eventually be located off of Kahe Point, Oahu.

Every new energy technology has unique challenges in terms of environmental impact, social acceptability, or engineering. OTEC is unique in its redistribution of relatively large water masses in the ocean. For a 5MW pilot plant which requires $25m^3/s$ in both cold and warm water flow, the daily flow is over 2 million cubic meters of water [3]. The commercial scale flow volume would be $500m^3/s$ for each pipe. Both water types will be mixed in the plant and discharged in the upper 120m of the ocean, which is an unprecedented environmental modification and must be rigorously evaluated. Another compelling impact is the entrainment of organisms in the intake pipes with high mortality [4].

One step in moving OTEC technology forward to an operating pilot plant, and eventually commercial scale plants, is a thorough environmental impact assessment. There has been much discussion of the potential environmental impacts of operation of the plants, from the original Environmental Impact Statement (EIS) in 1981 [2] to a recent Coastal Response Research Center conference held June 2010 in Honolulu, HI. The CRRC meeting generated many requests for baseline environmental research before installing OTEC, including such important points as nutrient concentrations and variability, variability in primary production, and densities of larval fish and other plankton which may be entrained in the system [3]. The oceanography of leeward Oahu is well-researched, but there is a lack of coherence among projects, published studies, and ongoing research that would be useful to include in an updated EIS. A review of the available oceanographic and OTEC-related data, including unpublished data and technical reports, shows that many of these questions have been addressed in the past. In the interest of moving OTEC technologies forward, we recommend using these existing data sets as baseline environmental information for OTEC, and propose a one year, directed baseline monitoring program to efficiently address gaps in knowledge.

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II. PHYSICAL CHARACTERIZATION OF THE OTEC SITE

Many aspects of the physical oceanography of Oahu have been characterized and published in the literature, and the data spans from the 1960s to present. Understanding the physical characteristics and flow regime is critical background information for modelers tasked with determining the behavior of an OTEC discharge plume. Plume modeling was carried out by Planning Solutions LLC and Makai Engineering.. The trajectory of the plume is of primary importance because of the redistribution of water associated with OTEC operation [2].

The OTEC plume will have different physical and chemical parameters than the surrounding ocean water where it is discharged. The plume outflow will be cooler than ambient water, and its higher density will cause the plume to sink to an equilibrium depth [5, 6]. Additionally, the chemical characteristics of water at 1000m are significantly different from surface water [7]. Elevated nutrient levels can fuel phytoplankton blooms if the plume reaches equilibrium in the photic zone, and the increase primary production could subsequently alter food web dynamics [8]. Ensuring that the nutrient-rich plume remains below the most biologically productive depths is essential to minimizing the environmental impact of OTEC operation. Additionally, many animals are sensitive to changes in temperature, salinity, or pH e.g. [9, 10], and the plume will locally alter these parameters. Therefore, it is crucial to monitor oceanographic parameters for both surrounding seawater and the plume, to quantify natural variability, and to predict the far-field behavior of the plume based on existing knowledge of circulation on leeward Oahu.

A. Physical Oceanography: General Circulation

The Hawaiian Islands are an archipelago of tall volcanic islands. Northeast trade winds are funneled through the narrow channels between the islands, which creates a wind stress pattern driving the Hawaiian Lee Countercurrent (HLCC) [11, 12]. When the winds are forced through the channels, it can cause cyclonic mesoscale eddies to form. These eddies can cause upwelling, lead to increased primary production, and entrain plankton and larvae. They move in a westerly direction and eventually dissipate, leaving entrained organisms in a new location.

On a smaller scale, the circulation around Oahu is also primarily driven by trade wind activity. Focusing on the leeward coast, early experiments showed that trade winds created more alongshore geostrophic flow to the northwest, while Kona (southwesterly) winds created a more convoluted flow pattern with a small gyre forming on the southwest corner of the island [13].This general flow pattern has been confirmed and studied in more depth more recently. High-frequency radar observations have provided detailed knowledge of surface circulation [14]. Additionally, the Kaena ridge generates tidal baroclinic energy flux which propagates as internal waves [12]. The model generated by [12] reveals two regions along the Waianae coast: a shallow coastal area with strong alongshore flows and a deeper region with vertical shearing and weaker mean flows. This report concludes that the dominant circulation patterns are forced by the HLCC, generation of baroclinic tides at Kaena Ridge, and by diurnal and semi-diurnal tides which drive the alongshore direction of currents.

The speed of ocean currents will also have an effect on the trajectory of the plume [6]. Currents were measured in 1981 on a series of four cruises off Kahe Point, Oahu [15]. Based on the observations from these cruises, most current speeds in the upper ocean fall between 10 and 20 cm/s in a non-Gaussian distribution skewed right. The Hawaii Mapping Research Group recently deployed an ADCP mooring at the Barber's point OTEC site for several months in summer of 2010, measuring currents from 0 to 1000m in the water column. The results corroborate older measurements by [15].

B. OTEC Plume Models

Plume models have been developed specifically for Hawaii to predict an OTEC plume's trajectory given the known physical oceanographic conditions. The models focus on determining the terminal depth of the plume, nutrient concentrations, and in one modeling effort, the effects of various current speeds on the plume [5, 6].

In the preliminary model designed by Planning Solutions, LLC., discharge depths of 50m and 100m were used [5]. The model found that the differences between a mixed discharge and a cold discharge were insignificant, so only performed simulations with mixed discharges on the 50m discharge. The plume sinks to its deepest depth rapidly, and then rebounds to oscillate around an equilibrium depth. The 50 m mixed discharge plume was detectable in the model at 76-144m at the end of the simulation. Nitrate concentrations were quickly diluted from about 16umol/kg at the point source to 2-4μmol/kg within about 30 horizontal meters, with the highest concentrations in the center of the plume. Given a cold-water 100m discharge, the plume was detectable between 134-182m at the end of the simulation. Nitrate concentrations were diluted from 16umol/kg to 2-4 μmol/kg within 40 horizontal meters of the point source [5].

Makai Engineering ran simulations using a 70m mixed discharge, and found terminal depths of about 120-180m with typical current speeds of 10-20cm [6, 15]. The terminal nitrate concentrations were modeled between 2.5 and 4.5 μmol/kg, with some data points as high as 6μmol/kg. This modeling effort also focused on the effects of current speed, and found that faster currents of about 50cm/s produced shallower, more diluted plume signatures than typical Oahu currents of 10cm/s [6].

C. *Gaps in Knowledge*

A model has not yet been run using the optimized design specifications developed by Luis Vega. The plume from this 10MW design has a lesser proportion of cold water than do the two modeled plumes, and therefore will be slightly warmer and slightly less concentrated in nitrate than the models. The higher temperature will cause the plume to reach terminal depth higher in the water column, and the slightly lower concentration of nitrate (about 13.3 µmol/kg, versus 16-18µmol/kg) will cause faster dilution. Given the previous modeling results, one would predict that this 60m discharge would still settle around 100m depth, but it is important to run the simulations with the final engineering parameters when available. The depth of the discharge pipe is still under some debate, as concerns about biological impacts are yet to be resolved. These modeling results along with time-series oceanographic data can help to design the effluent pipe to minimize environmental impact.

III. BASELINE OCEANOGRAPHIC CONDITIONS

As with any assessment of environmental change, it is ideal to have an understanding of the ecology of the region before an impact occurs, and a control site with which to compare observations after the system is affected. Baseline observations should be designed to capture seasonal variability in ecosystem conditions, and keep in mind decadal scale oscillations and other large-scale fluctuations.

A. *The Hawaii Ocean Time Series*

One tool available to OTEC environmental researchers is the Hawaii Ocean Time Series (HOTS), a multi-decadal project run by the Microbial Oceanography laboratory at the University of Hawaii [7]. Lead scientists on the project are Dr. Dave Karl and Dr. Matt Church. Researchers track temperature, salinity, nutrients, primary production, and other oceanographic parameters at designated sites. The primary site of research is Station ALOHA, located about 100km north of the island of Oahu, and the secondary Station Kahe is located just a mile from the proposed location of the commercial OTEC facility, making it a valuable baseline data set for OTEC. An analysis comparing the two sites found that there are significant differences in mixed-layer depth and seasonal variability, and slight differences in nutrient concentrations, so data from Station Kahe should be used where available [16].

We have identified a set of key parameters to monitor at the OTEC sites. These parameters include nitrate, phosphate, silicate, and chlorophyll a; temperature, salinity, and oxygen; pH, dissolved inorganic carbon, and alkalinity. They have been chosen to capture basic oceanographic parameters, nutrient levels, primary productivity, and the carbonate cycle. These parameters are all routine oceanographic measurements and have at least several years of data available from HOTS Station Kahe [7].

Data from the HOTS online open-access database has been extracted in bins relevant to OTEC. Data was divided seasonally, with spring being March, April, and May. The mean and standard deviation for nitrate + nitrite is displayed in Fig. 1 as an example, and the full dataset is available online at http://hinmrec.hnei.hawaii.edu/otec-references/. Depth bins were chosen as follows:

- 0-50m: Source water for the warm intake pipe.

- 50-75m: Shallow option for the discharge pipe
- 100-150m: Equilibrium depth of a shallow discharge plume; deeper option for discharge pipe.
- 150-200m: Equilibrium of a deep discharge plume
- 800-1000m: Source water for the cold water intake pipe.

One point of note is that the modeled terminal concentration of up to 4µmol/kg nitrate [5, 6] are outside normal variability in water <150m. A concentration of 4µmol/kg nitrate is significantly different from the ambient conditions (greater than two standard deviations from the mean, $p<0.05$) and could lead to greater productivity in the region if light levels permit. Currently, Makai Engineering is conducting a modeling effort examining the phytoplankton dynamics that could be influenced by an OTEC plume settling at these depths [17].

B. *Gaps in Knowledge*

The HOTS database provides valuable background data for OTEC environmental monitoring, but there are some gaps. Notably, nutrients in the upper 50m have been measured only sporadically, and nutrients in water >50m depth were only measured from 1989-2001 [7]. For OTEC environmental assessment, establishing a current baseline for nutrient levels should be a priority, since it is unavailable through the Station Kahe database.

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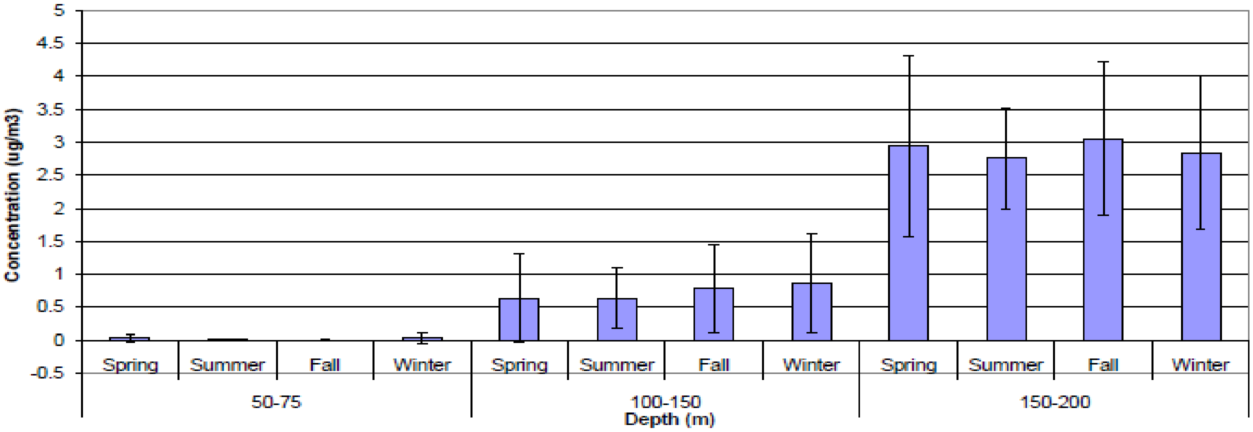

Figure 1. Concentration of nitrate + nitrite at Station Kahe. This data was extracted from the online Hawaii Ocean Time Series database. The scale of natural variability from 50-200m is represented based on data points from 1989-2001. Error bars represent one standard deviation.

IV. BIOLOGICAL OCEANOGRAPHY

The operation of OTEC will impact organisms inhabiting or moving through the area to an unknown degree. Scientists have identified a list of potential biological impacts, including nutrient redistribution, entrainment and impingement, organism attraction or avoidance, and biocide release, among others [3]. To understand OTEC's ecological impact, long-term monitoring protocols are necessary to track primary productivity, animal abundance and density, habitat use, and entrainment rates.

As with any offshore operation, the plant is likely to attract fish and seabirds, noise may interfere with animal communication, and lubricants or anti-biofouling chemicals may enter the ocean. Specifically concerning OTEC, the redistribution of millions of cubic meters of water per day will change stratification, salinity, oxygen, and nutrient levels near the site. Some organisms base their behavior on certain temperature or salinity gradients, e.g. [10], while others may be affected by increased nutrient levels [18]. Additionally, plankton and small nekton will be entrained in the water flow in both the shallow and deep intake pipes, and will likely suffer high mortality rates due to rapid temperature and pressure changes [4]. Organisms could be impinged against screens on the shallow water intakes if their burst swimming capacity does not overcome the current generated by the pipe [2, 3].

A. Primary Productivity

Of these, one of most prominent environmental concerns for OTEC development is the potential for upwelled nutrients to fertilize surface waters and cause a phytoplankton bloom. To assess if OTEC causes primary production, we first must understand natural variability. Most of the variability in chlorophyll occurs below 44m in Hawaiian waters [19], which is evident in the contour plot generated from the HOTS interface (Fig. 2). If high chlorophyll levels are observed for prolonged periods above the normal range of variability, OTEC upwelling may be the cause.

To avoid significantly fertilizing surface waters, it is crucial that the plume settle beneath the mixed layer, where wind could bring plume nutrients to the upper photic zone though mixing. Average mixed layer depth at HOTS Station Kahe is 42.4m, much shallower than the settling depth of an effluent plume; however, mixed layers have been recorded at greater than 90m on several occasions. Experts recommend that the effluent pipe be placed below the 1% light level, which generally ranges from 90m to 115m based on measurements at Station ALOHA [20, 7]. This places the equilibrium of the plume far below maximum mixed layer depths, and at a light level where photosynthesis is less efficient. With shallower discharge pipes, models predict equilibrium depths around 90m and greater, but plankton may still be able to uptake nutrients from the sinking plume higher in the water column [20]. Given the uncertainties, a conservative 120m discharge pipe is preferred by oceanographers at this time.

Conversely, the colder temperature of the plume may inhibit phytoplankton growth where the plume is still in the euphotic zone. A six day lag time was observed for phytoplankton growth in 50% "deep water" from a test OTEC at Kona, Hawaii [21]. The long lag time for growth coupled with sinking flux, colder temperature, and phytoplankton entrainment may reduce the potential for functional biomass increase of phytoplankton due to OTEC. Monitoring the primary productivity at the pilot plant will help address this question.

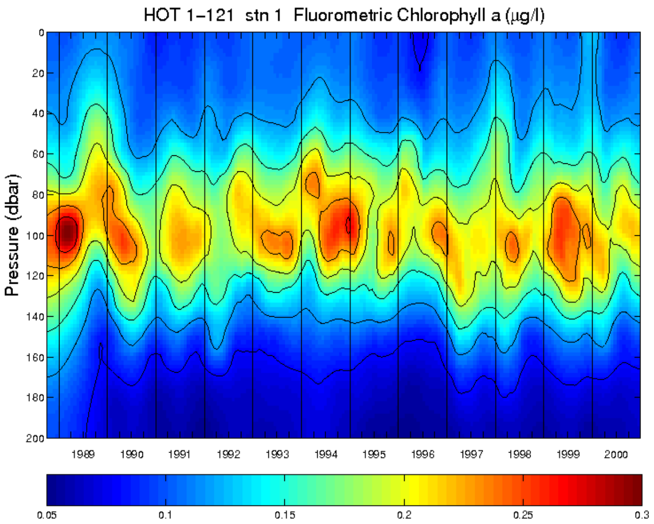

Figure 2. Time series contour plot of chlorophyll a at station Kahe, 1989-2000. Red indicates higher concentrations. Figure extracted from the Hawaii Ocean Time Series online database, [7].

B. *Entrainment and Impingement*

Beyond productivity and nutrients, which have been monitored consistently through HOTS, most knowledge of Oahu's biological oceanography comes from individual studies. Therefore, it is patchy and limited in scope, but there is a good deal of useful work that can be used to design an efficient baseline monitoring strategy. Studies based on net tows, acoustic backscatter, and data from the NELHA facility on the Big Island are a readily available starting point.

Lethal entrainment of organisms in the intake pipes is one of the most direct impacts OTEC can have on the environment. Small nekton may also be impinged on the intake screen, if their swimming capacity is less than the approach velocity of the water [4]. Estimates of organism density and depths of occurrence are necessary to estimate the impact of OTEC entrainment or impingement on a population. Studies investigating the plankton community at discrete depths, rather than net tows which integrate across the water column, are relatively rare, but one thorough study of larval fish does exist and is a valuable resource for OTEC environmental assessment [22]. A small selection of other plankton has been characterized with respect to depth and onshore-offshore distribution, including heteropod mollusks [23] and nemerteans [24].

An example from Boehlert and Mundy's larval fish database is a study of scombrid larvae [10]. The researchers used MOCNESS (multiple opening-closing net and environmental sensing system) to sample larvae at 8 depth bins, both during the day and at night. Multiple species and genera of tuna were characterized by their relationship with depth, temperature, and salinity. At the location of an offshore OTEC plant, most tuna larvae are found in 10-20m depth water, putting them at high risk for entrainment in the warm water intake at 20m [10]. Conversely, the larvae of other species such as billfish are found primarily in the neuston, where they are unlikely to be entrained [25].

Deeper-dwelling organisms are also be subject to entrainment in the cold water pipes. Because an intake screen cannot be cleaned at depth, the mouth of the intake pipe will be open, allowing entrainment of larger organisms [3]. Some entrainment monitoring has been carried out at an operational cold water pipe at Natural Energy Laboratory of Hawaii Authority (NELHA) in Kona. For example, a high school group sampled the deep water sump for 2 months and identified macro-organisms which had been entrained at 1000m (Table 1) [26]. Data from this site is an ideal way to predict the biomass and types of organisms which may be entrained at 1000m depth. Baseline studies of the deep water habitat should ideally include more formal monitoring of entrainment at the NELHA site.

Nekton which may be impinged on the warm-water intake screens are difficult to sample at discrete depths due to their ability to evade the MOCNESS device, but integrated net tows are fairly effective for studying micronekton distributions. In March 2011, micronekton was sampled with a Tucker trawl along the Waianae coast of Oahu. Sampling ranged from 0-2000m depth. The results showed expected diurnal patterns reflecting diel vertical migrations [27], with gonostomatids, myctophids, and sergestid and caridean shrimp undertaking large vertical migrations related to time of day. While this method cannot determine which specific organisms are more likely to be entrained or impinged, it does add to the understanding of the ecosystem and how animals move in the water column.

Acoustic backscatter techniques can also identify micronekton and larger organisms subject to impingement on intake screens, and this method was used to study the spatial ecology of the Hawaiian mesopelagic boundary community [28]. The mesopelagic boundary community is diel migratory community that is an important foraging base for spinner dolphins and large predatory fish, but fortunately the behavior of the community is likely to prevent a high rate of entrainment or impingement from occurring. Daytime residence depths are around 400-700m, and nighttime depths, ranging from 0-400m, are farther inshore than the proposed OTEC facilities [29].

Larger organisms may also interact with OTEC plants, since floating objects in the ocean act as fish aggregating devices. In Hawaii, it is likely that tuna, dolphinfish, and other large pelagic animals will be attracted to the plant e.g. [30]. Large organisms are unlikely to be impinged due to their swimming capacity, and the intake pipe will be designed to have as low an approach velocity as possible to minimize impingement [3]. Medium to large fish, marine mammals, turtles, and monk seals will easily manage the current flow of

TABLE I. ENTAINMENT IN NELHA COLD WATER PIPE: 2 MONTHS. DATA COURTSEY OF [26].

NELHA Cold water pipe entrainment	Organism	#
Fish	Gonostomatidae fish	10
	Rattail Ventrifossa	4
	Pufferfish	2
	Unkown Fish	2
	Anglerfish	1
	Cut Throat Eel	1
	Oilfish	1
Crustaceans	Acanthephyra	43
	Lobster larvae	7
	Other Shrimp	4
	Unknown crustacean	2
Cnidarians	Chili Pepper Jellyfish	15
	Anenome	8
	Satellite Jellyfish	4
	Unknown Jellyfish	3
Other invertebrates	Ctenophores	12
	Radiolarian	3
	Deep sea cucumber	1
	Unidentified slug	1
	Egg sac	1

about 0.15m/s. Additionally, the vibration of the deep water pipe will create a signal that may be detectable by marine mammals and fish, and acoustic monitoring of the site is necessary to be sure that the frequency emitted does not cause a large disturbance for marine mammal communication and navigation [3].

C. *Gaps in Knowledge*

To accurately predict the biomass that will move through the OTEC pipes each day, discrete-depth sampling covering a broader range of taxa is needed. The number of larvae of a given species that will be entrained each day can be calculated, but knowledge of species-specific life history and recruitment is often unavailable, and therefore the effect on the breeding population is unknown [4]. Additionally, ecology of the deep slope ecosystem at the intake depth of 1000 meters remains poorly understood; particularly, densities of organisms are unknown, as is the likelihood of entrainment based on swimming capabilities and habitat use. Acoustic monitoring should be conducted before and during operation of the plant to look for signals which would disturb animal communication and navigation.

V. A PROPOSED PROTOCOL FOR BASELINE ENVIRONMENTAL ASSESSMENT

Physical modeling of the OTEC plume has been accomplished, and the models should be run with the most up-to-date engineering specifications when they are finalized. The available chemical and biological baseline data has been assembled, and while there is generally a good understanding of the Hawaiian ecosystem, studies directed specifically at OTEC will facilitate a thorough environmental impact statement and allow researchers to more accurately predict impacts on the ecosystem. Here, a protocol is proposed for creating a more complete environmental baseline.

- *Measure the oceanographic parameters identified in this report at relevant locations.* These include the Barber's point proposed site, Kahe Point proposed site, and sites about 5km down-current of these (where the plume will be directed in accordance with Makai Engineering model output). At minimum, nutrients (nitrate, phosphate, and silicate) should be measured at least seasonally at each depth bin as defined above, since HOTS will continue doing other measurements at Station Kahe. The methodology should be identical to the HOTS program so that data is comparable. All methods are openly available in the metadata of the HOTS project, http://hahana.soest.hawaii.edu/hot/methods/results.html

- *Use MOCNESS to sample plankton at discrete depth bins at the OTEC sites.* At a minimum this sampling should consider depths near 20m and 1000m and near the depth of the discharge pipe (60m or 100m, depending on design). Ideally, this should replicate the MOCNESS sampling carried out in the 1980s and 1990s by NOAA, which involves tows at 0-0.7m, 0.7-20m, 20-40m, 40-60m, and so on [22]. This sampling should be done quarterly to capture seasonal shifts and to look for any notable divergence from results published in [22]. Both day and night sampling should be conducted. The total wet weight of carbon should be ascertained and converted into a mass per day of carbon entrained by OTEC. As necessary, fish larvae can be identified and added to the NOAA database created in 1996.

- *Conduct consistent monitoring of entrainment from the cold water pipe at the NELHA facility.*

- *Deploy an acoustic monitoring device to quantify baseline noise levels.*

- *Consider the use of acoustic backscatter technology to determine relative abundance of larger nekton at the warm water intake depth.* This may help identify the presence of nekton in the size category that may be subject to impingement, given an approach flow rate is about 0.15 m/s [3].

After baseline monitoring is complete and the first OTEC pilot plant is installed, ongoing monitoring will allow researchers to ascertain the scale of environmental impacts. It will also allow engineers to make adjustments based on these impacts, as necessary, for the design of a commercial scale plant. The operational environmental monitoring should include at least the following:

- Continue to measure oceanographic parameters at sites that are near the plume outflows (about 100m) and in the far-field (5km or more). If the plume signature cannot be detected by normal Niskin bottle sampling, autonomous gliders could be used to search for the plume signature.
- Sample water moving through the system for entrained organisms and compare to estimates based on MOCNESS data.
- Continue monitoring noise levels and determine if the vibrations produced may disrupt animal behavior.
- Monitor nekton abundance near the site, using backscatter techniques or fishing.
- Record the organisms impinged and frequency of impingement, and calculate biomass per day that is impinged.

VI. CONCLUSION

Leeward Oahu is a well-researched area of the ocean. While there are indeed gaps in critical data needed to write a complete EIS for OTEC, there are large, relevant databases available which are unpublished or simply require user manipulation, e.g. [3] and [7], and many other studies exist which enhance the understanding of this ecosystem. These studies may not have been intended for OTEC environmental assessment, but they encompass much of the work which was proposed at the CRRC conference in June 2010. In the interest of moving forward with OTEC on Oahu, and given the proximity of many of these studies to proposed OTEC locations, we recommend that these datasets be treated as baseline data for OTEC environmental assessment. The gaps in data, such as in plankton depth distribution outside of ichthyoplankton and the lack of nutrient data in the past decade, could be remedied with one year of directed baseline monitoring. By using these existing datasets to move forward with the pilot OTEC plant, researchers can begin studying the effects of an offshore OTEC facility in operation, rather than only by modeling. Given thorough, rigorous monitoring of the pilot plant, scientists and engineers can work together to ensure that commercial scale plants have a minimal environmental impact in Hawaii and elsewhere.

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