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TECHNIQUES FOR ASSESSING THE IMPACT OF OCEAN THERMAL ENERGY CONVERSION (OTEC) OPERATIONS ON FISHERIES

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I. INTRODUCTION

The environmental effects of a commercial ocean thermal energy conversion (OTEC) facility, which may process roughly 13.8 x $10^6 m^3$ of water per day (for a 40 MW plant), will impact the marine ecosystem and possibly extend to the marine fisheries. The final environmental impact statement (EIS) prepared by the National Oceanic and Atmospheric Administration (NOAA) for commercial OTEC licensing indicated that the majority of the environmental effects center on the marine ecosystem because it is the source of evaporating and condensing waters and the recipient of the plant's effluent ([U.S.] NOAA 1981). The EIS further categorized these effects as being major (those potentially causing significant long-term environmental impact), minor (those causing insignificant long- or short-term environmental changes), and potential (short-term impacts occurring only during accidents). The major effects included attraction or avoidance of organisms to the structure, impingement on, and entrainment of, organisms due to the withdrawal of water at the cold and warm water intakes, lethal or sublethal effects of biocide releases and thermal alterations, and nutrient redistribution from the discharge plume. These concerns are also potentially those which would affect the fisheries to the greatest degree (Matsumoto 1983).

Assessment of the impact of OTEC facilities upon marine fisheries will depend on simulation models which provide the basis for bringing the results of preoperational data and environmental impact studies into perspective. The goal of these models is to minimize the environmental effects in the design of OTEC plants.

This report describes the techniques in obtaining the types of information required to develop predictive models for assessing the impact upon fisheries by the major concerns resulting from OTEC operations.

II. ASSESSMENT TECHNIQUES FOR FACTORS THAT MAY AFFECT FISHERIES

A. Impingement

Previous studies on environmental impacts of OTEC operations have labeled impingement as a major concern. Impingement occurs when certain nektonic and large planktonic organisms with limited avoidance capabilities are pulled and trapped against the intake screens due to the force of the water being drawn into the plant during normal operation. Sullivan and Sands (1980) classified impingement as not only an environmental issue but also as an economic concern to plant operations because of maintenance costs of cleaning the intake screen and plant downtime.

1. Organisms affected

The organisms most likely to be impinged in estimated screen mesh size of 0.95 to 1.3 cm (Sands 1980) are the micronekton, namely small epipelagic and mesopelagic fishes, macroplanktonic crustaceans, cephalopods, and other gelatinous invertebrates. Assuming 100% mortality of impinged organisms, the environmental concerns focus upon the potential reduction in the local populations and populations of the impinged forms downstream of the plant. In addition, the impingement of micronekton may indirectly affect nektonic species through food chain interactions ([U.S.] NOAA 1981).

Regarding the proposed OTEC plant at Kahe Point, Hawaii, Matsumoto (1983) reviewed past research results on the distribution and behavior of commercial pelagic fishes and concluded that there should be no immediate effect on the fisheries due to impingement at either the warm water or cold water intakes (with intake velocity = 0.25-0.30 m/sec) since the adults of the commercially important species should not be affected. Matsumoto, however, expected impingement of juveniles and larval forms of some commercially important inshore species which inhabit offshore surface waters near the warm water intake.

2. Assessment techniques

The available data and literature are insufficient to fully evaluate the direct and indirect effects of impingement on commercially important species. Assessment of impingement effects on fisheries begins with the determination of species and abundance of organisms subject to impingement. Because micronekton are highly susceptible to impingement, catches by midwater trawls could provide clues to species and numbers likely to be impinged; however, trawls are typically fished at 1.5 to 2.0 m/sec, speeds which are about five to seven times the intake velocity of an OTEC facility. Therefore, the number and species of organisms captured in a trawl will be greater than those actually entrained since the avoidance capabilities of the organisms relative to the OTEC intakes are greater than they are to a trawl.

Although several different trawls have been used in the past to sample midwater fishes (Matsumoto 1961; King and Iversen 1962; Higgins 1970; Clarke 1973; Maynard et al. 1975), the most success in capturing micronekton has been achieved by the 10-ft Isaacs-Kidd midwater trawl (IKMT) and the anchovy No. 2 Cobb pelagic trawl (CT).

The IKMT (the more commonly used trawl of the two) was originally designed by Devereux and Winsett (1953). Although the net has remained the same with respect to design dimensions and mesh sizes, slight modifications have been made, usually to the cod end to serve the various needs of the collectors. In a study designed to collect juvenile tunas, King and Iversen (1962) used a cod end with 12.7 mm (1/2 inch) mesh and made of No. 207 nylon lined with coarse silk grit gauze or fine meshed nylon netting. In a general assessment of mesopelagic micronekton, Maynard et al. (1975) used a 1.0 m diameter plankton net of 0.333 mm Nitex[1] mesh for the cod end as did Clarke (1973).

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[1]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

Although the IKMT is preferred as a quantitative sampling tool over the CT, Matsumoto (1961) and Higgins (1970) found that the ability of a larger trawl to catch juvenile forms of commercial species such as tuna was much greater than that of the 10-ft IKMT.

Both Matsumoto (1961) and Higgins (1970) modified large pelagic nekton nets to sample the micronekton. Matsumoto (1961) modified the British Columbia midwater trawl (BCMT) (Barraclough and Johnson 1956) with a cod end of 6.4 mm (1/4 inch) mesh, whereas Higgins (1970) used the BCMT as well as a modified CT, which was two-thirds the size of the original Cobb trawl (McNeely et al. 1965). The CT is used in present assessment studies of the mesopelagic fauna by the Southwest Fisheries Center Honolulu Laboratory (HL). The modified CT has a headrope and footrope 30.9 m long, a mouth opening of 96 m^2, and a cod end which has an outer portion of 38-mm stretched mesh 24-thread (210-denier) nylon netting, and an inner liner of 6.3-mm stretched mesh, 6-thread (210-denier) nylon netting.

Sampling can be conducted using horizontal tows at the desired depths, oblique tows, or step oblique tows. A horizontal tow is made by simply lowering the trawl to the desired depth and towing horizontally for a predetermined time subject to the needs of the collectors. To attain the desired depths, time-depth recorders (TDR) can be used to determine depth independent of wire angle; however, if not available, estimation of the amount of cable required to reach the desired depth can be calculated before the tow. Such calculations of trawl depth are based on measurements of wire angle and wire out as described by Hida and King (1955). On oblique tows, the trawl is lowered to the desired depths and hauled through the water column or is towed from the surface to the desired depth and back to the surface. The step oblique tow involves lowering the trawl to the desired depth and towing it horizontally, then progressively raising it to the next desired depth and continuing the haul to the surface. Matsumoto (1961) found that this method resulted in a higher percentage of hauls containing juvenile tunas (57% versus 25% as compared with horizontal tows). No comparisons were made with oblique tows.

Other acceptable sampling gear for micronektonic organisms include some of the multiple net samplers, such as the multiple opening-closing net and environmental sensing system (MOCNESS) (Wiebe et al. 1976), the Bedford Institute of Oceanography net and environmental sampling system (BIONESS) (Sameoto et al. 1980), and the rectangular midwater trawl (RMT) series (Baker et al. 1973). With these types of gear, discrete vertical samples can be obtained. Such discrete depth information collected on a diel basis would be beneficial to an assessment study.

B. Entrainment

1. Vital communities affected

In entrainment, organisms small enough to pass through the intake screens are drawn into the system and exposed to sudden temperature and pressure changes as well as mechanical damage. For a proposed OTEC plant with estimated screen mesh size of 0.95 to 1.3 cm, marine organisms smaller than 3 to 4 cm long, including phytoplankton, microplankton, zooplankton, ichthyoplankton and micronekton, will be entrained (Sands 1980). Sands predicted 100% mortality for organisms entrained by an open-cycle plant or at the cold water intake of a closed-cycle plant due to the inner plant stresses. Although percent mortality for entrained organisms at the warm water intake of a closed-cycle plant was not determined, Sands anticipated a significantly higher entrainment rate at the warm than at the cold water intake. Any significant impact due to entrainment will probably be a result of the mortality of organisms entrained at the warm water intake.

Matsumoto (1983) suggested that ichthyoplankton would be the major fisheries-related organisms affected directly by entrainment (in particular at the proposed Kahe Point site). More specifically, the larvae of tunas and billfishes and the pelagic larval forms of snappers, groupers, and jacks represent the greatest concern. Matsumoto (1983) also suggested that although eggs would be entrained, tuna eggs are buoyant and would be found above the intakes at or near the surface. Studies on various commercial bottom fish species conducted at the HL indicate that eggs of these species are also buoyant. Therefore, as concluded by Matsumoto (1983), the amount of eggs entrained may be small and impact important commercial fisheries little, if any.

2. Assessment techniques

Without an existing operational facility to monitor, assessment techniques are truly limited. Baseline information will be required and obtainable before plant construction. Predictive models generated from available biological data will supply a relative assessment of the potential effects of the resultant environmental stresses and ecological perturbations. The models should reflect not only the information regarding mortality (lethal) effects but should also consider the sublethal effects (Rosenthal and Alderdice 1976).

The assessment of distribution and abundance of ichthyoplankton which will provide baseline data, involves sampling methods similar to those employed by King and Demond (1953), Matsumoto (1958), Strasburg (1960), Nakamura and Matsumoto (1967), and Miller (1979) in their studies on tuna larvae or the discrete depth sampling methods described by Clarke (1969), Wiebe et al. (1976), and Sameoto et al. (1980). Most of the tuna larvae were collected in 1-m, fine mesh plankton nets equipped with a flowmeter to estimate the water strained. A detailed description of the gear can be found in King and Demond (1953). The tows, either oblique or surface hauls, lasted from 15 to 60 minutes; most were about 30 minutes.

The meter ring nets, however, have their disadvantages. Obstructions at the mouth of the net during a tow from the bridles are believed to increase the potential for avoidance of the net by organisms. Newer designs, including many of the multiple net samplers, have adopted versions of the rectangular net described in Tucker (1951). The design eliminates any obstruction in front of the net mouth when fishing.

Meter ring nets were also inadequate for the needs of researchers desiring discrete depth collections since contamination from organisms captured during the ascent or descent of the net was inevitable. Several variations of opening and closing nets were thus developed. Among these is the opening-closing Tucker trawl (Clarke 1969) based on the rectangular net design by Tucker (1951).

The trawl consists in part of a series of horizontal bars of which the top and bottom bars are fixed. The bars between the fixed set slide along wires attached to the top and bottom bars to open and close the nets at desired depths. The opening and closing triggering mechanisms can be controlled with acoustic and telemetering equipment or mechanical messengers. The net was designed to fish with the mouth at 45° from the vertical, forming a square to the front and sampling an area of 8 m^2.

The MOCNESS is similar in principle to the Tucker trawl but carries nine rectangular nets (1 x 1.4 m). It is further equipped with environmental sensors to measure conductivity, temperature, and depth. Sensors to monitor water flow, net angle (from the vertical), and the opening and closing of the nets are also included (Wiebe et al. 1976).

The BIONESS adds one modification to the MOCNESS and Tucker net arrangement. Rather than having nets and their closing bars stacked vertically, making the front profile much larger than the mouth opening of a single net of the sampler, the nets and closing bars are arranged horizontally in the BIONESS. This eliminates the highly visible structures of the frame and makes the front view inconspicuous and streamlined for smoother water passage. Sensors for temperature, conductivity, depth, illumination, and water flow, among others, are part of the BIONESS sampling system.

Other gear used in assessing the abundance and species composition of ichthyoplankton are neuston and bongo nets. These were utilized by Hirota (1977) in his study of zooplankton at the Deep Ocean Mining Environmental Study area. Bongo nets are also available in opening-closing versions to take discrete depth samples.

3. Inner plant mortality

Entrained organisms are expected to be subjected to considerable stress including sudden thermal and pressure changes, exposure to antifouling biocides (probably chlorine), and mechanical damage resulting from abrasion and collision with structures. Using data from cooling water intakes of coastal power plants, Marcy (1975) found mortalities of fish eggs and young passing through power plants to be between 39 and 100%; the vast majority was near 100%. As indicated by Hoss and Peters (1983), research on environmental effects of coastal marine power plant operations have provided general information for use in initial evaluation of potential OTEC environmental problems. A study on the cooling water system of a Connecticut nuclear power plant indicated that of the near 100% mortality of nine species of young fish, 80% of the mortality was due to mechanical damage, 20% was due to thermal shock, and no measurable mortality due to presence of biocide (Marcy 1973).

a. Thermal effects on entrained organisms

Although many studies have been conducted on temperature effects on fish larvae and eggs, none are based on tropical species such as those that may be found at OTEC sites in low latitude regions. Therefore. once the major species affected by entrainment at an OTEC facility are established, temperature tolerances for those species must be determined to obtain estimates of mortality attributable to sudden temperature changes.

Two of the methods for determining lethal temperature for ectothermic animals have been described by Hutchison (1976) and Talmage and Opresko (1981). Hutchison's method measures resistance times of fish that were previously acclimated to a wide range of temperatures in the laboratory. These measurements are made for various constant test temperatures. In this method, the organisms are abruptly exposed to test temperatures and the resulting measurements are subjected to statistical treatment for determination of lethal temperatures. A median tolerance limit (TL_{50}), which indicates the temperature at which 50% of the fish survive for a designated period of time, is then calculated. This lethal threshold is the upper (and similarly the lower) incipient lethal temperature. From this, one can determine the ultimate incipient lethal temperature of the species.

The other method to determine lethal temperatures called the "critical thermal maximum (or minimum)" (CTM) (Fry 1971; Hutchison 1976; Talmage and Opresko 1981), is the temperature at which the animal dies or becomes visibly incapacitated while exposed to a constant rate of change. The procedure allows deep body temperature to follow the test temperatures without a significant time lag. The rate is usually 1°C every few minutes.

b. Effects due to pressure changes

Entrained organisms will also be subjected to rapid changes in hydrostatic pressure. Hoss and Blaxter (1981) subjected larval herring to different series of pressure changes to simulate passage at a coastal power plant's cooling water intake. The study involved acclimation and rapid pressure increases followed by rapid decompression. Subsequent mortality and behavior were observed. Such studies should be conducted for the commercial tropical species that would be potentially affected.

c. Effects due to biocides

In a commercial OTEC plant, the biocide most likely to be used will be chlorine, which will be routinely released into the heat exchangers to control biofouling. Numerous studies have been conducted on power plant chlorination and its effects upon estuarine and marine systems; these have been summarized in Hall et al. (1981). In a study on mortality of entrained fishes, none of the mortality could be attributed to the presence of chlorine (Marcy 1973). When considering combined stresses, however, Hoss et al. (1975) suggested a synergistic interaction between chlorine and temperatures above ambient. This was based on the findings of an increased sensitivity of the test species to chlorine with the elevated temperature.

Studies on chlorine toxicity on marine animals of direct application to OTEC plants were conducted by Venkataramiah et al. (1981a, 1981b). They utilized bioassays to define sublethal, incipient lethal, and lethal concentration ranges of chlorine, the 96-hour lethal concentration for 50% mortality (LC_{50}), and the lethal time for 50% mortality (LT_{50}) for each of the test species (mullet, _Mugil cephalus_, and sargassum shrimp, _Latreutes focorum_). They also studied the effect of size on the test species' LC_{50} and LT_{50}. The sublethal concentration range was defined as the narrowest range in which none of the organisms, subjected to subsequently narrower concentration ranges, died due to toxicity. The incipient lethal concentration range was defined as the range in which some of the animals (but not all) died, and lethal concentration range as that in which they all died. Continuous flow-through seawater systems were used for the bioassays.

Similar studies should be conducted on the commercial species (such as tuna larvae) that are subject to entrainment to provide estimates of inner plant mortality due to biocide presence.

d. Effects due to mechanical damage

The mortality due to mechanical damage represents deaths of organisms from abrasions and collisions resulting from turbulence and pressure changes in passage through the system. Marcy (1975) concluded that mechanical damage was the highest single cause of entrainment mortality based on numerous power plant studies.

The assessment of the effects due to mechanical damage at a proposed OTEC facility, however, is a difficult one. Past studies at coastal power plants have had the benefit of monitoring cooling water intakes, so a direct count of dead versus live organisms after passage through the plant was available. Such data will not be available for an OTEC preconstruction assessment.

One experimental method that provided conservative estimates of mortality due to mechanical stress for a given entrained fish species was described by Morgan et al. (1973). Their experiments on white perch and striped bass measured the mortality caused by the shear fields that are created by water movement over the surface of fish eggs and larvae. Shear fields were defined as the variation in water velocity with respect to time, expressed as units of force per unit area (dynes/cm^2).

4. Entrainment effects on supportive food chains

One aspect of entrainment that also must be addressed is the effect entrainment will have on supporting food chains of recreationally and commercially important fishes. Feeding studies have been conducted for many of Hawaii's commercial fish species that are apt to be affected, namely the pelagic tunas (Reintjes and King 1953; King and Ikehara 1956; Iversen 1962; Alverson 1963; Waldron and King 1963) and mahimahi (Palko et al. 1982).

The procedures for food studies of fishes in general are similar. A review of food study methods and their application is described in Hyslop (1980). In food studies conducted at HL, stomach contents are sorted into identifiable groups and measurements of prey volume (water displacement method), prey length (if possible), and sometimes prey weight are taken. The numbers of prey items are also recorded. Identification methods of the forage items include the use of vertebral counts and morphology, scales, and otoliths for fishes, beaks and pins for cephalopods, and exoskeletal remains for crustaceans. To determine the importance of the forage items to the predator, numerical, volumetric, and frequency of occurrence systems of analyses and methods have been used to express the results. Pinkas et al. (1971) incorporated these three traditional methods of stomach analysis in the development of an index of relative importance (IRI). The IRI provided insight to the rankings of forage items within the diet.

To estimate the forage organisms that would be entrained involves trawling targeted at micronekton (King and Iversen 1962; Blackburn and Laurs 1972), a procedure similar to that described earlier under impingement effects.

It does not appear that food chains of the commercial demersal fishes such as snappers and groupers will be directly affected by entrainment mortality. Bottom fish food studies in Hawaii have revealed that they fed predominantly on benthic organisms (Humphreys in press; Seki in press a, in press b). Water column prey items, when taken, were generally large and would possess enough swimming strength to avoid entrainment. Since the benthos gets energy from the pelagic environment, however, there may be indirect effects through the lower trophic levels.

C. Biota attraction

1. Open-ocean plant ships

Assessing the potential OTEC impact upon fisheries due to biota attraction requires two approaches, that is, attraction due to an open-ocean plant ship and that resulting from facilities constructed on or near the shoreline. The attraction properties of an open-ocean plant ship appears analogous to those of organisms collecting around flotsam and fish aggregating devices (FAD's). Facilities near the shoreline in which pipes and foundations are placed in shallow water or onshore will act as artificial reefs (Seki 1983).

Gooding and Magnuson (1967) and Matsumoto et al. (1981) studied attraction of animals to artificial open-ocean structures. To describe faunal abundance and diversity, especially of the smaller juvenile forms, direct observations were the most useful. Observations were either made by divers or from an observation chamber of a raft. To monitor the commercial species attracted to FAD's, Matsumoto et al. (1981) also conducted trolling, recorded sightings of bird flocks and fish schools, and scanned for subsurface fish schools utilizing hydroacoustics. Fish catch data from commercial tuna pole-and-line boats visiting the monitored FAD's were also used to assess the effectiveness of the structures as attractants.

Fish catch data from trolling operations and from commercial boat data will provide catch per unit effort (CPUE) which is one of the most commonly used techniques for environmental monitoring. The CPUE is defined as the catch divided by the effort exerted to obtain that catch. The catch will generally be measured in numbers or weight. The effort per unit time can be in terms of tows, hauls, fishing trips, number of vessels, or number of anglers. The major disadvantage to using this method, primarily when using commercial catch data, is the difference in gear and effort which makes analysis difficult. However, CPUE from trolling operations and commercial catch data is probably the most effective method of monitoring migratory species at a specific locality.

2. Nearshore facilities

Nearshore OTEC facilities, especially the proposed tower design, will also require evaluation of the attraction of offshore migratory commercial species. In addition, artificial reef effects created by the structure's presence must also be assessed. This involves possibly using bottom drift fishing (bottom handline) and trapping to assess the impacts on the commercial demersal species.

Studies on inshore artificial reefs have generally utilized fish transects to inventory species composition and estimate density. Briefly, this method involves the laying down of a premeasured transect line along which fish species on both sides of the line are identified and counted (Brock 1954). Other methods that will supplement the transect data in determining species composition are hook and line, throw net, and spearing.

Various species of tunas, squids, and carangids are the major commercial marine animals that are caught by the use of night lights and various types of fishing gear including handlines, dip nets, pole and line, and jigging machines. In a recent 5-year survey of the fishery resources in the Northwestern Hawaiian Islands conducted by the HL, night-light fishing was among the methods used in assessing species composition and density of the resources. The light (a 1,500-W bulb) was initially submerged to 21.3 m (the maximum amount of wire out). After about an hour, the light was raised and eventually dimmed to concentrate the organisms, facilitating observation and capture. The raising and dimming of the lights drew organisms farther down in the water column closer to the surface.

III. SUMMARY

The assessment of the impact of OTEC facilities on fisheries without an existing operational plant will have to rely on the use of models based upon available biological data. This report describes some of the techniques in obtaining the types of information required for the model development. With regards to fisheries, the effects due to organism impingement, entrainment, and attraction have been identified as the major areas of concern.

The organisms most likely to be affected by impingement at the intakes would be the micronekton. The use of midwater trawls such as the IKMT, the CT, or the RMT series (for discrete depth sampling) could provide clues to the species and numbers of organisms likely to be impinged.

Multiple net samplers such as the MOCNESS, the BIONESS, and the Tucker trawl will sample the entrainable marine organisms smaller than 3 to 4 cm in length. For ichthyoplankton, using these multiple nets allow sequential discrete depth sampling, which is most important. In past studies meter ring nets, bongo nets, and neuston nets have also been used to sample ichthyoplankton.

The organisms entrained will be subjected to the stresses of inner plant mortality. These include sudden thermal and pressure changes, exposure to antifouling biocides (probably chlorine), and mechanical damage resulting from abrasion and collision with structures. Knowledge of sublethal and lethal limits when exposed to the stresses for the potentially affected species is needed, especially for tropical species.

Assessment of the attraction effects on fisheries involves addressing environments created by open-ocean and nearshore facilities. Direct observations (by divers or subsurface chambers), catch results from trolling operations, and commercial catch data have been used to monitor open-ocean localities. Abundance and diversity of commercial demersal species settling on artificial reefs created by nearshore facilities can be obtained by catch data from bottom handlining and trapping. Fauna that have taken residence on inshore artificial reefs have generally been assessed by using direct observations on line transects and catches from throw nets, spearing, and hook and lines.

Organisms attracted to night lights can be captured with various types of fishing gear including handlines, dip nets, pole and lines, and jigging machines.

These are some of the methods that have been used to sample in either analogous situations or potentially impacted areas produced by the presence and operations of a commercial OTEC facility. Information obtained from such sampling and experimental methodologies can be used in developing predictive models which in turn can be applied to plant design strategy to minimize the environmental effects.

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