POTENTIAL ENVIRONMENTAL IMPACTS OF CLOSED-CYCLE OCEAN THERMAL ENERGY CONVERSION

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Ocean Thermal Energy Conversion (OTEC) uses the temperature difference between warm surface water in the tropical ocean and the cooler water at depth to generate power. Energy extraction efficiencies are low, 2 to 4 percent (Dugger et al. 1981), relative to conventional steam generation plants, necessitating large flows of ocean water (the fuel in an OTEC system): about 10 m^3/sec/MW (DOE 1979a). Two OTEC operating cycles, closed-cycle and open-cycle, are currently under development in the United States. In an earlier paper we addressed the environmental concerns associated with open-cycle OTEC operating in conjunction with several secondary uses (Quinby-Hunt et al. 1986). This paper addresses the environmental concerns associated with closed-cycle OTEC, examining, in particular, OTEC impacts in the coastal zone.

Closed-cycle operations use warm surface water to evaporate a working fluid which passes through a turbine to generate power. The working fluid is then condensed by cold, deep water and recycled. In open-cycle operations, the working fluid is surface water which is separated into steam and brine under partial vacuum. The steam, after passing through a turbine, is condensed using cold ocean water.

Although several configurations for OTEC plants have been considered, near-shore, bottom-resting, and shore-based plants currently are being more actively pursued in the US program due to increased technical and safety risks associated with floating and far offshore configurations (Lewis 1983). The federal environmental documents that addressed the environmental effects of closed-cycle OTEC (DOE 1979a; 1979b; 1980; 1981) focused on free-floating plants. Concerns associated with closed-cycle generation on shore-based or bottom-resting plants have been addressed only in two site/design specific documents (OTC/MSG 1985; MSG 1985).

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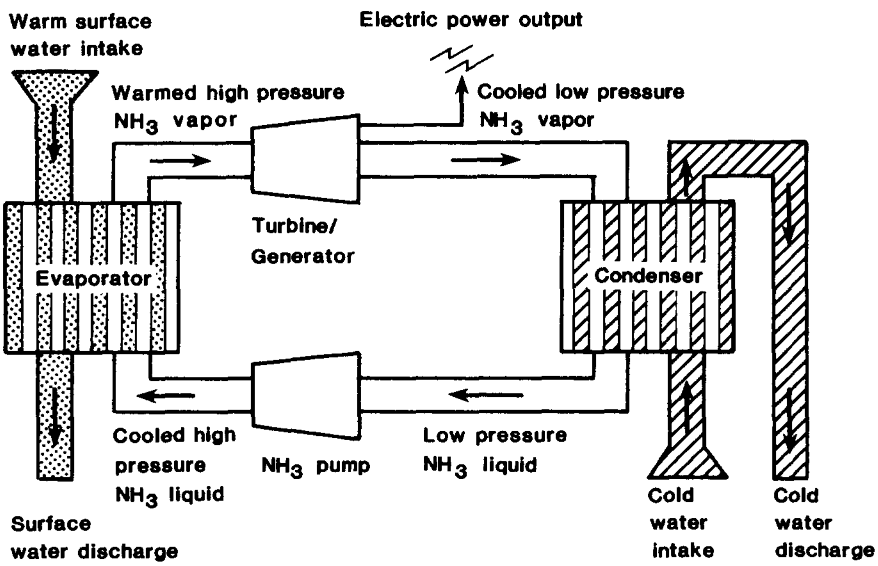
Closed-Cycle OTEC

Closed-cycle systems are based on transfer of heat from surface waters to a working fluid contained within a closed power loop (Figure 1). The working fluid is pressurized and then vaporized by heat from surface water. The vapor drives one or more Rankine-cycle turbines, producing mechanical power which generators convert to electricity. The expanded low-pressure working fluid is condensed by cold seawater from the deep ocean. Condensed working fluid is repressurized and recycled through the system. The working fluid is recycled; both warm and cold seawaters are discharged back into the ocean after a single pass through heat exchangers. Ammonia commonly has been proposed as a working fluid, although freon and other similar gases could be used.

In order to have effective heat transfer, it is necessary to protect the heat exchangers from biofouling. Chlorine, a chemical antifoulant, commonly has been used, as have various mechanical means (Lewis 1981). Depending upon the type of heat exchanger, both chemical and mechanical means could be used (OTC/MSG 1985).

Several different effluents could result from closed-cycle operations: a warm-water stream, a cold-water stream, or a stream of mixed cold and warm water (Figure 2, Table 1), as well as atmospheric releases. The liquid streams either can be discharged directly, or used for other purposes and then discharged. Current research programs suggest that at least part of the sea water discharges could be used for mariculture (HTDC 1985) or solar ponds (SPOTEC) (McCord

FIGURE 1. Schematic of Closed-Cycle OTEC (adapted from DOE 1979a).



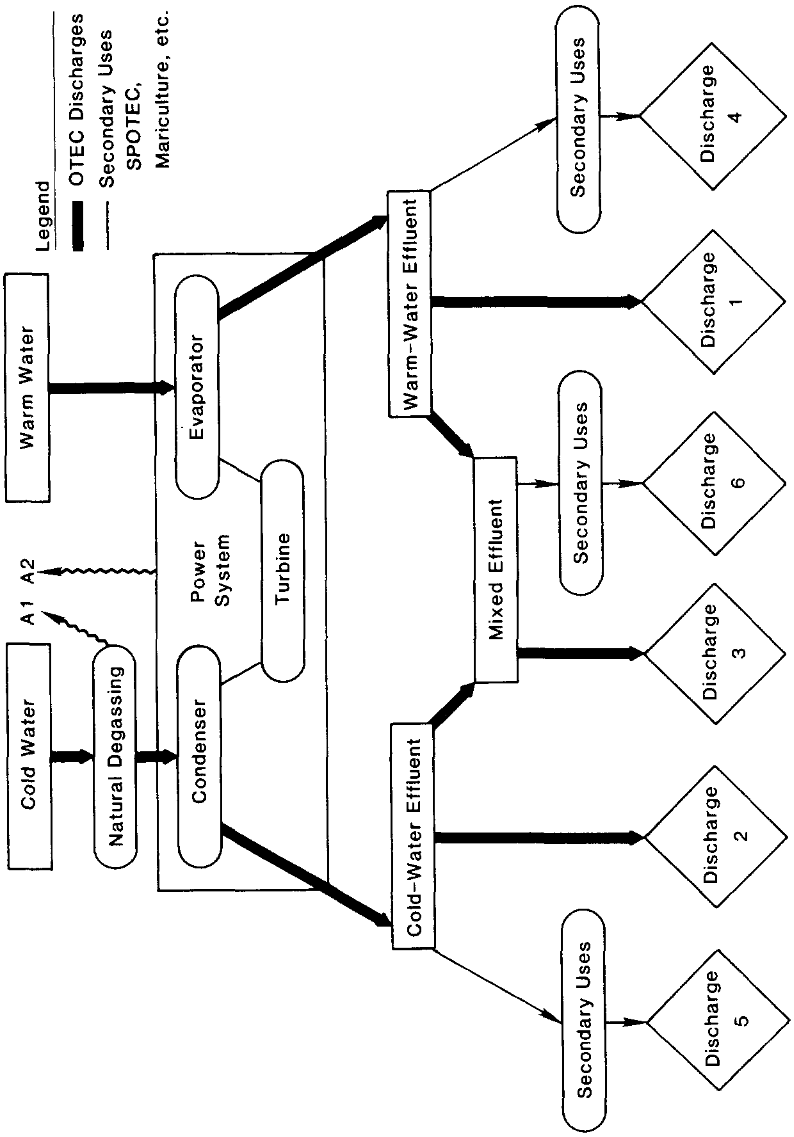


FIGURE 2. Flow Paths for Closed-Cycle OTEC.

TABLE 1. Discharges associated with various closed-cycle OTEC paths. (See Figure 2 for schematic showing discharges and emissions.)

Emissions A1	Co_2, O_2, N_2, trace gases Volatile trace metals
Emission A2	Working fluid plus gases found in A1
Discharge #1 Warm-water Effluent	Ambient surface water plus biocide Working fluid Trace metals
Discharge #2 Cold-water Effluent	Low temperature Low dissolved O_2 Low salinity (potentially) High nutrients Enhanced levels some trace metals or other constituents
Discharge #3 Mixed Effluent	Lower temperature Lower dissolved O_2 Lower salinity (possible) Enhanced trace metals or other constituents Biocides
Discharge #4, #5, #6 Secondary Uses	Discharges #1, #2, #3 plus Contributions from SPOTEC, mariculture, etc.

et al. 1983). The streams and potential impacts associated with such secondary uses are discussed elsewhere (Quinby-Hunt et al. 1986). Available discharge options are displayed in Figure 2; heavy lines indicate the pure, that is, energy production only, OTEC option.

Paths to the Environment

The nature of the releases to the marine environment depends on the heat exchanger, working fluid, and biofouling control agents used. The significance of the impacts associated with discharges will depend also on the location of the discharge both vertically in the water column and its proximity to shore. The character of atmospheric releases also will depend on whether the effluents are discharged separately or combined.

Carbon dioxide, oxygen, nitrogen, other atmospheric trace gases, and volatile trace metals will be released naturally from the cold-water stream when it reaches lower pressures and higher temperatures (Table 1, Emission A1) as it is brought to the surface. The power system routinely will release some quantity of working fluid during operations (Table 1, Emission A2).

Marine discharges will depend on the working fluid, biocides, depth of intake, discharge configuration chosen, and any secondary uses. Effluents associated with secondary uses have been discussed elsewhere (Quinby-Hunt et al. 1986). Two possible "pure OTEC" configurations must be considered: separate discharges of warm and cold water, and a combined or mixed effluent discharge. The mixed effluent discharge has been proposed most often (OTC/MSC 1985; Sinay-Friedman 1979).

Potential Impacts of Closed-Cycle OTEC

Many possible impacts of closed-cycle OTEC can be conceived. The following have been identified as potentially significant:

- atmospheric release of working fluid or biocide;
- impacts to threatened, endangered, or endemic terrestrial or marine species;
- biota attraction;
- entrainment and impingement of nearshore organisms or ecologically and commercially important species;
- redistribution of oceanic constituents;
- secondary entrainment;
- toxic effects of biocide and working fluids in the effluent;
- socioeconomic impacts; and
- risks of credible accidents.

The significance of the above concerns may increase with proximity to shore. In addition, several concerns are associated primarily with plants located nearshore or onshore. These include:

- degradation of air quality during construction, deployment, and operation;
- atmospheric impacts of artificial upwelling;
- terrestrial habitat destruction;
- impacts of land or well discharge on groundwater systems;
- impacts on historical or archeological sites;
- aesthetic effects;
- impacts of dredging, site preparation, and construction on the marine environment;
- ciguatera outbreaks; and
- impacts on coastal wave conditions, sediment transport, and currents.

Atmospheric and Climatic Issues

Atmospheric emissions from a closed-cycle OTEC facility will be minor except during construction or in the case of accidental working fluid or biocide releases. Routine working fluid and biocide releases are expected. Artificial upwelling may cause local fogs. Worst case estimates (see below) indicate that it is improbable that local atmospheric climates would be affected significantly due to the effects of cooling of surface waters by plant effluent and release of carbon dioxide (CO_2) and other trace gases.

Impacts of Construction and Deployment

Air quality may be degraded by dust and exhaust fumes generated during grading of roads, blasting, trenching, or other construction activities. By their nature, construction-related emissions are temporary. During plant operation, movement of service and maintenance vehicles may increase total exhaust emissions. If the prevailing winds are offshore, air emissions from construction and operation will affect only the plant area. However, where winds are onshore, a larger area may be affected.

Working Fluid and Biocide Releases

Large amounts of working fluid or biocides may be stored at or near the plant site. Working fluid systems may develop leaks due to wear corrosion, aging, malfunction, maintenance operations, or accidents. Large releases could be caused by sabotage, ship collisions, or catastrophic events, such as earthquakes or storms of greater magnitude than those used in defining standards for construction. Biocides by their nature are toxic. Extreme care in storage and handling is necessary, as spills or leaks could occur at any time during use. Although Ocean Thermal Corporation suggested storing large quantities of chlorine at the proposed OTEC plant at Kahe Point, Oahu (OTC/MSG 1985), chlorine can be generated *in situ,* eliminating the risk of storing such a hazardous material.

If occupational health and safety regulations are followed, working fluid and biocide (most probably ammonia and chlorine) emissions from a plant should be too low to detect outside the plant sites (OTC/MSG 1985). A major release of working fluid or biocide would be hazardous to plant workers and potentially to the populace in surrounding areas depending on their proximity. Both ammonia and chlorine can damage the eyes, skin, and mucous membranes, and can inhibit respiration (Sax 1979). Should an accident occur with either system, the risks are similar to those for other industrial applications involving these chemicals. Ammonia is used as a fertilizer and in ice skating rink refrigeration systems. Chlorine is used in municipal water treatment plants and as an antifoulant in steam electric power generation systems (EPA 1974).

If large volumes of both working fluid and biocide are stored at the plant site, then the hazards associated with a simultaneous release of both need to be considered. Serious problems could result if both the ammonia and chlorine systems ruptured simultaneously. The reaction of ammonia with chlorine in air can result in the formation of highly toxic or explosive chemicals (Sax 1979; NFPA 1975). The probability of such an occurrence is low, particularly if US Coast Guard (46 CFR 106) and other applicable regulations are followed.

Impacts of Artificial Upwelling on Local Atmospheric Conditions

As with open-cycle systems (Quinby-Hunt et al. 1986), under certain conditions (ie, use of cold water for open mariculture operations or open trench discharge), large volumes of cold seawater in direct contact with warm, saturated air potentially could cause local fogs. If the plant is located near resorts or other areas where good visibility is desirable (airports, rocky or hazardous coast lines), mitigation measures should be devised.

Sea-Surface Temperatures

The possibility that cold water discharged from an OTEC plant would alter sea-surface temperatures has caused concern. Climatic alterations may result from small (on the order of degrees C) sea-surface temperature changes over large ocean areas (Barnett 1978; White and Haney 1978). Release of warm surface water would have no significant impact on surface water temperatures, nor would release of cold, deep water released at depth. The outfall from an OTEC facility should be designed to minimize injection into the surface mixed layer, although Bathen (1975) calculated that there would be no significant effect on surface temperature of a discharge from an 100-MW OTEC plant into shallow water (20 m).

Release of Carbon Dioxide and Other Gases

Gas solubility in sea water decreases with increasing temperature (Weiss 1970). Thus, cold, deep water allowed to come to equilibrium with warm, surface water would release CO_2 and other gases when the cold deep water is brought to the surface. Outgassing of CO_2 occurs naturally in tropical waters (Keeling 1968). Mercury released during natural upwelling is detectable (Fitzgerald et al. 1984). Outgassing from OTEC-cycled water may alter local rates of outgassing, but as the gases are eventually redissolved into seawater at higher latitudes and colder temperatures, the total volume of gas in the atmosphere is changed little (OTC/MSG 1985). On the other hand, when fossil fuels are burned, the CO_2 produced is "new," formed by combining carbon from ancient geologic sinks with atmospheric oxygen during combustion.

Some concern has been expressed (NRC 1983b; EPA 1983a) regarding possible climate effects due to increased CO_2 in the atmosphere—the greenhouse effect (Brewer 1978). OTEC plants bring water containing CO_2 at levels greater than saturation to the surface. As the dynamics of CO_2 release are determined by a complex set of environmental conditions and chemical reactions, only a worst-case order of magnitude (at best), estimate of CO_2 release by OTEC operations (OTC/MSG 1985; MSG 1985) is discussed here.

At an OTEC facility, CO_2 may be released to the atmosphere (Table 1, Figure 2). Residence time and pressure shifts are insufficient to allow significant gas evolution from the cold-water reservoir, a confined space through which water passes rapidly (Morse 1984). After discharge, CO_2 or other gas concentrations in the effluent would approach equilibrium with gases at that point of discharge, as a worst case, in the mixed layer. The maximum CO_2 that could evolve due to OTEC operations is the difference between the CO_2 in deep and surface waters. For example, the CO_2 concentration in surface water is approximately 2.0 mmole/kg seawater (Takahashi et al. 1970). Water from 700 m contains approximately 2.4 mmole CO_2/kg (Takahashi et al. 1970). Therefore, the maximum CO_2 released would be 0.4 mmole/kg, or 0.018 g/kg. If a 40-MW OTEC plant pumps 90 m^3/sec (7.8×10^9 kg/day) of deep water to the surface, approximately 1.4×10^5 kg of CO_2 could be released each day if all excess CO_2 was outgassed (OTC/MSG 1985).

A typical 40-MW oil-fired power plant emits about 9×10^5 kg "new" CO_2 per day (DOE 1981), more than six times the maximum amount of CO_2 that might be released by OTEC plant operation. If an OTEC plant displaced 40 MW of power from an oil-fired plant, CO_2 emissions would decrease by at least a factor of six (OTC/MSG 1985). Release of CO_2 from an OTEC plant is not expected to affect local or regional climate significantly, particularly when compared with the consequences of conventional combustion to produce power.

Trace gases and volatile trace elements, such as mercury, will be released from OTEC discharge water in proportion to their solubility in sea water and rate of formation *in situ* in biological processes (Quinby-Hunt et al. 1986). As in open-cycle systems, the quantity of mercury and other volatile metals released and the impact of such releases should be assessed.

Terrestrial Issues

The effects of OTEC construction and operation on the terrestrial environment include: habitat destruction, impacts on threatened, endangered, and endemic species, impacts of a land or well discharge on groundwater, aesthetic and socioeconomic issues, and impacts on archeological and historical sites. Construction could also elevate noise levels, reduce recreational facilities and disrupt traffic flow patterns. These disturbances will diminish after construction is completed.

All of these impacts are potentially significant. As with open-cycle systems (Quinby-Hunt et al. 1986), the extent of impact of excavation and construction on the local habitat depends on the specific site and design. The structures associated with OTEC must be acceptable to the local community aesthetically.

Construction of a shore-based OTEC plant will necessitate clearing vegetation, potentially driving birds and animals out of the area to find new habitats, and thereby exerting pressure on nearby ecological communities (Brewer et al. 1979). Although the effects of this migration from a small area are likely to be small, construction that disturbs habitats of threatened, endangered, or endemic species should be avoided (MSG 1985).

Any discharge (#1–#6, Figure 2) on land, to trenches, or to wells may change the character of local groundwater by increasing levels of salinity, nutrients, trace elements and so on. For example, the character of anchialine ponds located near the Natural Energy Laboratory of Hawaii may change due to mariculture discharges (HTDC 1985). If the groundwater is an important water source or is a unique natural resource, alteration of the water characteristics may be of concern (Barsamian 1985).

Marine Issues

OTEC construction, deployment and operation will perturb the marine environment. The activities that may affect the environment significantly include:

- Construction: burial, siltation, removal of fauna, release of pollutants and nutrients from dredged materials, turbidity, and destruction of habitat;
- Presence: biota attraction, wave diffraction, sediment transport, current impedance, and navigational hazard;
- Withdrawal: organism impingement or entrainment, redistribution of oceanic properties, sand loss, and bottom scour; and
- Discharge: redistribution of ocean properties and biota; alteration of species composition, bottom scour, release of biocide, working fluid, and trace constituents, secondary entrainment, and resource degradation.

The major effect of these impacts will be on the biota.

Indigenous marine organisms at most potential OTEC sites are adapted to a relatively stable, predictable habitat and may be more vulnerable to environmental stress than organisms adapted to unstable, unpredictable environments (Slobodkin and Sanders 1969; Fisher 1977). Thus OTEC construction and operation may affect such an environment more significantly than activities in more variable or already affected areas.

An OTEC plant will alter the local marine environment, perturbing the natural population of marine organisms found there. In order to determine whether perturbations will affect the standing populations significantly, the magnitude of the effect on the population dynamics of the community must be estimated. If the perturbation is sufficient, it may threaten the survival of certain populations. An impact is considered significant if the reproductive success of a population or its size is altered significantly (Sinay-Friedman 1979; OTC/MSG 1985).

Population groups most vulnerable to OTEC-induced effects are identified based on comparisons of induced versus natural mortalities, geographic extent of impact region versus natural habitat, and initial versus final species composition. Where potentially significant impacts are identified, prediction of standing stock perturbations must be made. The affected communities must be described, including a qualitative and quantitative description of the species in the community. Species characteristics and composition may be obtained from literature review, at-sea surveys, and laboratory experiments. Population dynamic models also should be used to determine impacts (OTC/MSG 1985).

Construction Impacts

Dredging, blasting, and backfilling will elevate levels of noise, turbidity, and siltation (MSG 1985). Some benthos will be affected by trenching or permanently covering. Shock waves due to blasting could cause mortalities. Impacts are not expected to be significant because blasting usually is short term, although the presence (throughout the year or seasonally) of threatened, endangered, or endemic species must be considered.

The extent of impacts from increased turbidity and siltation depends on the interaction of the settling velocity of the dredged material, determined by the grain-size distribution and composition, with the ambient flow regime determined by waves and currents, and the duration and extent of site preparation activities. Siltation and impacts from light attenuation will affect organisms on reefs more severely than those on sandy bottoms. Sandy bottoms shift continuously and sometimes severely due to wave action. The benthic community in sandy bottoms, therefore, is adapted to deposition and erosion of sediment and tends to repopulate disturbed areas quickly (Harrison 1985). Organisms that need light are a minor part of the sandy-bottom community. Coral reef communities are vulnerable to siltation, increased turbidity, and light attenuation. Although corals cannot relocate readily, they may remove newly settled particles by ciliation and production of mucus (Bak 1978) and may survive if the insult is removed (Dollar and Grigg 1981). In areas where coral coverage is high, and communities of corals are considered to be unique natural resources or of economic value, impacts might be significant (OTC/MSG 1985).

The effect of organic material, nutrients, or toxic substances released from sediments disturbed during construction need to be evaluated by studies of porewater chemistry in sediment samples (OTC/MSG 1985). In localized wellsorted sand bodies, porewater generally reflects ambient bottom water chemistry and thus needs not be studied. The composition of porewater in more poorly sorted sediments may diverge from that in bottom water (Berner 1980). This change is caused by diagenetic and biological reactions between the trapped porewater, organic matter, and clay minerals of low porosity and permeability where exchange with bottom waters is restricted.

Ciguatera poisoning occasionally is associated with construction in tropical coastal waters, particularly where new surfaces are exposed by dredging (Parsons Hawaii 1981). Outbreaks are temporary. Potentially serious, ciguatera poisoning is caused by ingestion of fish tainted with a paralytic neurotoxin (Parsons Hawaii 1981). The toxin apparently is released by a common tropical marine dinoflagellate, *Gambierdiscus toxicus* (Yasumoto et al. 1977). Fish may become tainted when the toxin is released during blooms of *G. toxicus*. The mechanism causing the blooms is too poorly known to predict the likelihood of an outbreak due to plant construction activities (Yasumoto et al. 1984).

Impacts on Coastal Processes due to Presence of OTEC Structures

OTEC structures will affect coastal processes such as near-shore wave conditions, sediment transport, and currents. These effects depend on local bathymetry, shoreline configuration, and sediment type.

Impacts of Biota Attraction

OTEC structures act as an artificial reef, providing a new habitat for sessile and motile invertebrates, benthic algae, and fish (OTC/MSG 1985). The structure provides shelter and food for reef-dwelling organisms, and may become a point of orientation for transient fishes. Attraction of organisms from surrounding waters and increased local production will increase standing stocks of nekton and benthic organisms (Stone et al. 1979). The extent of the fish community that could develop around an OTEC plant might be estimated from artificial habitat studies. Because fish congregated at an OTEC structure will attract fishermen, regulation to determine access, ensure safety, and prevent overfishing may become necessary. At OTEC-1, fishermen worked an area from the platform itself to over 1 km away from the platform with great success (OTC/MSG 1985).

Lights on an OTEC facility may attract or repel organisms, including zooplankton and fish (Seki 1983). Attraction to lights has been used by night fishermen to catch fish such as the opelu (*Decapterus marcellus*) and akule (*Selar crumenophthalmus*) in the Hawaiian Islands (Brock 1983b; Seki 1983).

Impacts of Water Withdrawal on Coastal Processes

Water intakes differ in design and location. Depending on local conditions, removal of the warm, nearshore water may modify local coastal circulation and net transport of sediments by vertical displacement of large volumes of water in the coastal region. Changes in coastal circulation could increase the mortality rates of coastal marine populations. Site-specific and design-specific coastal circulation modeling is needed to estimate the magnitude of this effect.

Impacts of Impingement and Entrainment

Impingement and entrainment occur at both the warm-water and cold-water intakes. Organisms impinged by an OTEC plant are caught on the screens protecting the intakes. In general, impingement is fatal to the organism. An entrained organism is drawn into and passes through the plant. Entrained organisms may be exposed to biocides, physical abuse (acceleration, impaction, shear forces, and abrasion), and temperature and pressure shock (OTC/MSG 1985). Entrained organisms may also be exposed to working fluid and trace constituents (trace metals and oil or grease). Intakes should be designed to limit the inlet flow velocity to minimize entrainment and impingement. If inlet-induced flow velocities do not exceed average ambient tidal current amplitudes, they should not enhance local sediment transport (Hove et al. 1982). The inlets need to be tailored hydrodynamically so that withdrawal does not result in turbulence or recirculation zones in the immediate vicinity of the plant.

Losses of passively floating plankton due to impingement and entrainment can be estimated using flow rates and organism concentrations. Micronekton losses can be estimated by including factors for intake avoidance and biota attraction by the OTEC facility. Estimating biomass losses of adult fish, whose behavior and ability to avoid the intake complicate the problem, is more difficult and may have to rely on comparisons with similar structures in the vicinity. To illustrate the assessment of impacts from impingement and entrainment, the methods of estimating biomass loss for the OTEC Pilot Plant at Kahe Point are outlined below (from OTC/MSG 1985).

The size and location of the region of impact must be determined. The region of impact is the region in which the species of interest has an unacceptable probability of being entrained or impinged by the plant. For plankton, the boundary is determined by the ambient and induced flow fields. Determination of the region effecting nekton and benthos is more difficult.

The efficiency of capture of species at the site must be estimated (OTC/MSG 1985). Capture efficiency is an estimate of the probability that an individual will be either impinged or entrained at the intake or secondarily entrained at the discharge. Capture efficiency depends on behavior in the presence of currents, visual perception, and swimming speed.

For the Kahe Point assessment, the capture efficiency was assumed to be zero if all individuals avoided capture. The efficiency is one if all individuals at the intake cannot escape capture. Phytoplankton capture efficiency was assumed to be one; for zooplankton or micronekton capture efficiency depends on the size, mobility, and avoidance behavior of the species in question. As such information is incomplete for most species, it was assumed to be one for zooplankton, phytoplankton, and micronekton.

Rates of plant-induced mortality should be compared with natural rates of mortality. Population dynamics models indicate that, to a first approximation, effects of induced mortality on standing stocks are proportional to the ratio of induced mortality to natural mortality (OTC/MSG 1985).

The size of the region of impact should be compared to the size and location of a species habitat. If the region of impact is a small fraction of a species habitat, induced mortality within the region of impact will not increase greatly the mean mortality within the species habitat, and perturbation to the population dynamics of the species will be minimal. If the habitat of the species falls entirely within the region of impact, then induced mortality is more likely to increase mean mortality significantly and to reduce the population standing stock.

To estimate losses from the micronekton and plankton communities, the latter including holoplankton (permanent members, such as phytoplankton and zooplankton) and meroplankton (temporary members, such as eggs and larvae of fish or benthos), the region of impact is estimated and the degree of perturbation of populations found within this region is assessed. The warm-water intake region is defined as the region where any parcel of water or free-floating organism has less than a 1 percent probability of entering the intake (Sinay-Friedman 1979; DOE 1979b; DOE 1981; OTC/MSG 1985). Near shore, the average water depth could be used as the thickness of the region; further offshore, the depth of the mixed-layer applies. Determination of the 1 percent limit requires consideration of currents, net wind drift, and turbulent dispersion. The region of impact for the cold-water intake is determined by the combined effects of the volume flow rate at the intake and ambient advection and dispersion. Probability of capture within this region increases with proximity to the intake.

Many, if not all, organisms impinged or entrained by the intake waters may be damaged or killed. Although experiments suggest that mortality rates for phytoplankton and zooplankton entrained by the warm-water intake may be less than 100 percent, in fact, only a fraction of the phytoplankton crops from the surface may be killed by entrainment (Bienfang and Johnson 1980). The avoidance capability of micronekton may reduce the percentage killed in the warm-water system to below 100 percent. Prudence suggests that for the purpose of assessment, 100 percent capture and 100 percent mortality upon capture should be assumed unless further evidence exists to the contrary.

Biomass losses of phytoplankton and micronekton is approximated by:

$$\begin{array}{c}\text{Biomass}\\\text{Loss Rate}\end{array} = \begin{array}{c}\text{Intake}\\\text{Volume}\\\text{Flow Rate}\end{array} \times \begin{array}{c}\text{Natural}\\\text{Standing}\\\text{Stock}\\\text{Concentration}\end{array} \times \begin{array}{c}\text{Concentration}\\\text{Factor}\\\text{Due to OTEC}\\\text{Presence}\end{array} \times \begin{array}{c}\text{Efficiency}\\\text{of}\\\text{Capture}\end{array}$$

The volume flow rate is the rate of warm-water or cold-water intake. Capture efficiency is as discussed above. The natural standing shock is the population concentration which can vary with depth and horizontal extent of the source waters. For the Pilot Plant assessment, mean standing stocks of phytoplankton, microzooplankton, and macrozooplankton were used (OTC/MSG 1985). The concentration factor is a measure of the congregation in the vicinity of the OTEC plant. For the Pilot Plant assessment, the concentration factor was assumed to be one for holoplankton. Because zooplankton and micronekton may be attracted to lights or substrates, the concentration factor for these groups must be assumed to be >1. The concentration factor also may be >1 for some ichthyoplankton, the early life stages of fish, as adults attracted to the OTEC structure may increase local spawning.

For predicting losses of ichthyoplankton and micronekton biomass at the warm-water intake at Kahe Point, a concentration factor was estimated from locally observed fish populations by dividing the wet weight of fish observed on natural reefs (0.045 kg/m^2) by that observed over sandy-bottom habitats (0.004 kg/m^2). This approximation grossly simplifies attraction mechanisms. As OTEC plants are constructed, actual measurements of attraction will provide a more reliable data base for estimating the magnitude of attraction. Subsequent declines in population size depend on the relative increases in larval mortality caused by plant operation and the extent to which recruitment comes from breeding within the region of impact.

Standing stocks of organisms at the depth of the cold-water intake are largely small vertebrates and invertebrate micronekton with relatively sparse macronekton stocks. Many micronekton found at the depth of the cold-water pipe feed near the surface at night and migrate to depth during the day; they are part of the deep scattering layer (Maynard et al. 1975).

To estimate micronekton loss at the Kahe Point Pilot Plant cold-water intake, reported standing stocks were used (Maynard et al. 1975). Their efficiency of capture is assumed to be one, as the behavior of mesopelagic micronekton is not well understood (Clarke 1980; 1982). Because some micronekton found at the depth of the cold-water intake are delicate, 100 percent mortality of impinged and entrained biomass is expected. Estimated daily losses of micronekton biomass by entrainment were 32 kg wet weight/day and an additional 5 kg wet weight/day of mesopelagic gelatinous zooplankton.

The region of impact for the warm-water intake of the Pilot Plant is about 1 km^3. If the plant withdraws about 1 percent of this volume each day, and if the plankton are randomly distributed within this region of impact, 1 percent will be lost daily by entrainment over the 4-day residence time of a water parcel in the impact region. Daily natural mortality rates for phytoplankton and zooplankton are highly variable and species and site-dependent (Parsons et al. 1977). If zooplankton are attracted to the plant (Seki 1983), zooplankton mortalities could increase significantly. In the Kahe Point example, predicted OTEC-induced mortality rates increased moderately over natural rates of mortality (OTC/MSG 1985). Plankton losses within the region of impact would be replenished by surrounding unperturbed water.

Planktonic losses due to impingement or entrainment at the warm-water intake probably would not cause detectable declines or variations in composition of ocean plankton communities because continuous recruitment should replace losses if the region of impact is a small fraction of the total planktonic habitat. Potential impacts may vary with site: the habitats of coastal and some ocean species may be limited, whereas other oceanic species occupy vast habitats (McGowan 1974).

OTEC-induced mortality of ichthyoplankton may affect local fish populations significantly. In the Kahe Point example, significant rates of biomass loss were expected (OTC/MSG 1985). If benthic organism and fish populations within the region of impact are based upon the recruitment of planktonic larvae produced within the region of impact, then population decreases within the region can be expected. The decline in population size depends upon the extent of increased larval mortality due to plant operation and the extent of recruitment from breeding within the region of impact. Natural rates of mortality of eggs and larval stages are large and variable so that induced mortality has a less predictable effect on rates of recruitment. Site-specific studies are necessary in determining ichthyoplankton losses (OTC/MSG 1985).

OTEC-induced mortality of mesopelagic micronekton due to cold-water withdrawal at Hawaiian OTEC sites is not expected to be significant because of their large habitats. In the Pacific, for example, some species may be restricted to the Northeast Central Pacific water mass, but many are more broadly distributed (Clarke 1983; Barnett 1983; Menzies et al. 1973). Reports indicate that about half the Hawaiian species also occur in the equatorial water mass to the south and are thus warm-water cosmopolitan (Hartmann and Clarke 1975). Other OTEC sites may be habitats for threatened, endangered, or endemic species.

Without more information about standing stocks and behavior of the mesopelagic benthos and nekton, assessment of impacts to these communities is difficult. Because of difficulties in sampling, little is known about benthic fauna and benthic nekton living at depths typical of an OTEC cold-water resource (Menzies et al. 1973; Clarke 1972).

Adult stages of fish may not experience high rates of mortality if intake speeds allow adult fishes to avoid the intake. Estimation of adult fish losses at the warm-water intake is complicated by lack of data on fish intake avoidance behavior (ie, capture efficiency) and population density changes due to attraction (the concentration factor). Therefore, for the Pilot Plant assessment, impingement rates observed in the cooling waters at a nearby steam electric power generation plant, the Hawaiian Electric Company (HECO) plant at Kahe Point (Coles et al. 1982), were used to estimate losses of fish biomass:

$$\begin{array}{l}\text{OTEC}\\ \text{Fish}\\ \text{Biomass}\end{array} = \begin{array}{l}\text{HECO}\\ \text{Fish}\\ \text{Biomass}\end{array} \times \frac{\text{OTEC Flow Rate}}{\text{HECO Flow Rate}} \times \frac{\text{OTEC Reef Size}}{\text{HECO Reef Size}}$$

The region of impact for adult fish and benthos is difficult to define because the probability that an individual will be entrained depends on its natural behavior and swimming strength and speed.

The induced mortality to fish or benthos may not affect significantly the reproductive success of most species because of the large size of their natural habitat, which is generally significantly larger than the region of impact. As an example, the roughly 100 species of fishes recorded in the coastal water off Kahe Point (Coles et al. 1982) are distributed as a "relatively continuous element along this (western Oahu) coastline and are related to the diverse coral communities" (Brock 1983a). The pelagic species recorded have even larger habitats. The few studies of the macroinvertebrates suggest that they are widely distributed (Maynard et al. 1975). Impacts to threatened, endangered, or endemic species at a site could be serious.

Impacts of Discharge

Organisms entrained in the discharge plume (secondary entrainment) will experience similar physical abuse and exposure to biocides, working fluid, and trace constituents released by the plant, but with less intensity than that experienced by organisms drawn through the plant. In addition, depending on discharge configuration, secondarily entrained organisms could be exposed to lower levels of dissolved oxygen (DO), and enhanced levels of nutrients and trace constituents than ambient at the point of discharge. Impacts and their potential significance depend on the depth of discharge and the equilibrium depth of the plume as well as the distance from point of discharge.

Discharge depth, exit velocity, height off bottom, and exit-pipe geometry and orientation (relative to the bottom) affect the effluent trajectory, mixing rate, and effluent equilibrium depth. For the Pilot Plant the amount of water secondarily entrained was estimated to be two to three times the initial volume discharged. Organisms entrained in Pilot Plant discharge waters would be exposed to plume concentrations for a short period of time (about two minutes along the plume centerline, based on the plume trajectories calculated in the assessment, OTC/MSG 1985).

A shallow discharge near shore may allow the effluent plume to have greater contact with benthic biota, as well as biota attracted to the plant or pipes. If the depth of discharge is in the mixed layer[1] or the euphotic zone, then impacts may occur in that zone, potentially affecting larger numbers and masses of biota than if the discharge were at greater depth. For discharge depths below the mixed layer, that is, in the pycnocline, the possibility that the discharge will enter the mixed layer decreases as the discharge depth increases. Therefore, the discharge ideally should be below the average depth of the mixed layer and the euphotic zone. Due to economic factors, the discharge depth will be as shallow as possible, but deep enough to prevent recirculation and degradation of the thermal resource and remain environmentally acceptable.

Based on a discharge at the average depth of the mixed layer, if the discharge is only warm-water effluent (Discharge #1, Table 1, Figure 2), organisms will be exposed to enhanced levels of working fluid, biocide and its by-products and trace metals. Relative to ambient, a cold-water effluent (Discharge #2, Table 1, Figure 2) will have lower temperature, and low levels of DO and salinity. Nutrient levels will be enhanced, as will concentrations of certain elements. A mixed effluent will have lower temperatures, low DO and salinity, as well as enhanced levels of biocides (and their by-products), working fluid, trace constituents, and nutrients. Of specific concern are the effects of artificial upwelling, the toxic effects of biocides and their by-products, the possible elevation of trace elements within the food web, and the potential disruption of fishing industries. There is a possibility of sediment scour. A rock mat at the point of discharge can mitigate scouring but would increase mixing.

In the near field (the region between the discharge depth and the equilibrium depth), the discharge will entrain and mix with several times its own volume of ambient water, and will displace the entrained water and plankton as much as 100 m below the initial discharge depth. The entrained plankton will be subjected to thermal shock for a mixed discharge (Discharge #3, Table 1), a sudden change from about 26° C to 16° C, and even greater for an unmixed cold-water discharge (Discharge #2) and turbulent shear. If the discharge is unmixed cold-water (Discharge #2), biota may also be exposed briefly to very low concentrations of DO and high concentrations of nutrients and trace elements. Biota entrained in an unmixed warm-water discharge (Discharge #1, Figure 2) would be subjected to enhanced levels of certain trace constituents and biocide (probably chlorine and its by-products and possibly abrasives). Biota entrained in a mixed-effluent discharge (#3) would be subjected to lower than ambient temperatures and DO, enhanced levels of nutrients and some trace elements, and biocides and their by-products.

Specific mortalities of secondarily entrained organisms in the near field cannot be estimated without detailed analyses. Entrained organisms will experience much less intense thermal, chemical, and mechanical shocks for shorter periods of time than those ingested into the plant. Therefore, less than 100 percent mortality can be expected in the near field, and the total numbers of plankton killed by entrainment in the plume are expected to be less than those killed by intake into the plant.

Far-field Impacts

The far field is the region in which the plume has lost its momentum and disperses passively in the ambient current field of the equilibrium depth. In the far field, at equilibrium depth, temperature and salinity will be about the same as ambient. Concentrations of some constituents may differ significantly between the plume and ambient waters: concentrations of biocide and nutrients will be higher and oxygen lower than ambient. Table 2 gives predicted concentrations of chlorine,

TABLE 2. Predicted concentrations of chlorine, DO, nitrate and cadmium in the far-field discharge associated with an OTEC Plant proposed for construction at Kahe Point, Oahu, Hawaii. The model did not consider chlorine by-product formation.

	Chlorine (mg/L)				
	OTEC-1	Pilot Plant	Oxygen (mL/L)	Nitrate (μM)	Cd[a] (ng/L)
Ambient at equilibrium depth	0	0	5	0	0.3
Original effluent	0.2[b]	0.07	3	20	60
Far-field maximum	0.04	0.014	4.6	4	12
End of impact region	0.002	0.0007	5	0.2	0.6

[a]Cd concentrations approximated from Bruland (1980).
[b]This value was chosen because 0.2 mg/L was the maximum concentration of chlorine release permitted by the NPDES (National Pollutant Discharge Elimination System) permit for OTEC-1.

DO, nitrate, and cadmium in the ambient waters at equilibrium depth, in the mixed effluent, in the plume at the beginning of the far field, and at the end of the impact region, 25 km downstream, where concentrations are by definition 1 percent of those in the original effluent. The model did not consider decay or uptake of these species.

Based on the above assumptions for the Pilot Plant, elevated levels of nutrients and chlorine toxic to some organisms will remain in the near part of the impact region. Similarly, if metal ions drawn from the depths or released in the plant reach appreciable levels in the original effluent, some bioaccumulation may occur in the far-field impact region. The minimum value of dissolved oxygen in the impact region is below the normal ambient value. Oxygen levels will remain near saturation throughout the region, and no adverse impacts are expected.

Impacts of Artificial Upwelling

Elevated levels of nutrients may enhance productivity within the region of impact and potentially could alter species composition. An increase in phytoplankton stock might result from the enhanced nutrients in the equilibrium plume. Based on the Pilot Plant example, the residence time of phytoplankton within the far-field region is about 6 days, a time that is likely to be sufficient for enhanced crop growth (OTC/MSG 1985). The doubling time for biomass of phytoplankton in well-lit waters is approximately 1 to 5 days (Eppley et al. 1973). At the Pilot Plant phytoplankton may be exposed to nitrate concentrations above 0.2 μM for 6 days, long enough for some of the nitrate in the plume to be converted to phytoplankton biomass before it is diluted to insignificant levels.

Higher productivity of netplankton (phytoplankton >20 μm) relative to nannoplankton (phytoplankton <20 μm) is associated with natural upwelling systems (Malone 1971). Netplankton productivity increases during periods of upwelling.

As discharges (#2 and #3) from an OTEC plant may be considered artificial upwelling, in areas where upwelling is not a natural phenomenon, species composition may change. Such a perturbation may affect the food chain at the OTEC site.

Biocide Release

Biocides used to prevent biofouling and their by-products may be discharged to the ocean. Chlorine (Cl_2) has been the most commonly used biocide in OTEC operations (OTC/MSG 1985). OTEC-1 used 0.2 mg/L Cl_2 for 2 hours daily; Ocean Thermal Corporation proposed to use 0.07 mg/L Cl_2 for 1 hour daily (OTC/MSG 1985). The EPA allows a maximum Cl_2 discharge of 0.5 mg/L and an average of 0.2 mg/L for 2 hours daily for steam electric power generation facility cooling waters (EPA 1974). Nonetheless, the EPA recommends a maximum Cl_2 concentration of 0.013 mg/L and an average concentration of 0.0074 mg/L to protect saltwater aquatic life and its uses (EPA 1983b). As Table 2 shows, if the initial dose of Cl_2 is 0.2 mg/L, concentrations of Cl_2 and its by-products toxic to non-target organisms may remain in both the near and far field.

Chlorine is a biocide; some of its by-products are also toxic. Figure 3 illustrates the major reaction paths of Cl_2 in seawater. Few studies have quantified the toxicity of Cl_2 and its by-products to subtropical and tropical saltwater species; however, low concentrations are associated with acute toxicity for species found in more temperate waters (ie, juvenile Coho salmon, 0.03 mg/L, [EPA 1983b]). Further studies investigating the toxicity of Cl_2 and its by-products to sensitive tropical and subtropical species at potential OTEC sites are necessary to assure that the biota are protected.

If biocides are to be stored in large quantities at OTEC sites, the impact of their catastrophic loss must be considered. Such a release to the ocean would result in formation of a toxic cloud. Chlorine can be generated *in situ;* therefore storage of large quantities of chlorine is not recommended.

Working-Fluid Leaks

Working fluid (ammonia (NH_3) has most commonly been proposed) could enter the water streams via perforations or cracks in the heat exchangers caused by mechanical stress and corrosion. The effects of an NH_3 leak depend on the magnitude and rate of release. Small leaks and routine discharges could stimulate primary productivity downcurrent. Locally, pH increases may cause precipitation of $CaCO_3$ and $Mg(OH)_2$, increasing local turbidity (Schrieber et al. 1979).

Routine losses of low concentrations may not constitute a significant environmental hazard. Toxic effects are associated primarily with non-ionized NH_3, the limit of minimum risk is 10 μg/L (0.59 μM) of non-ionized NH_3 for seawater (NAS 1973). In seawater which has a pH of 8 and a temperature of 25° C, about

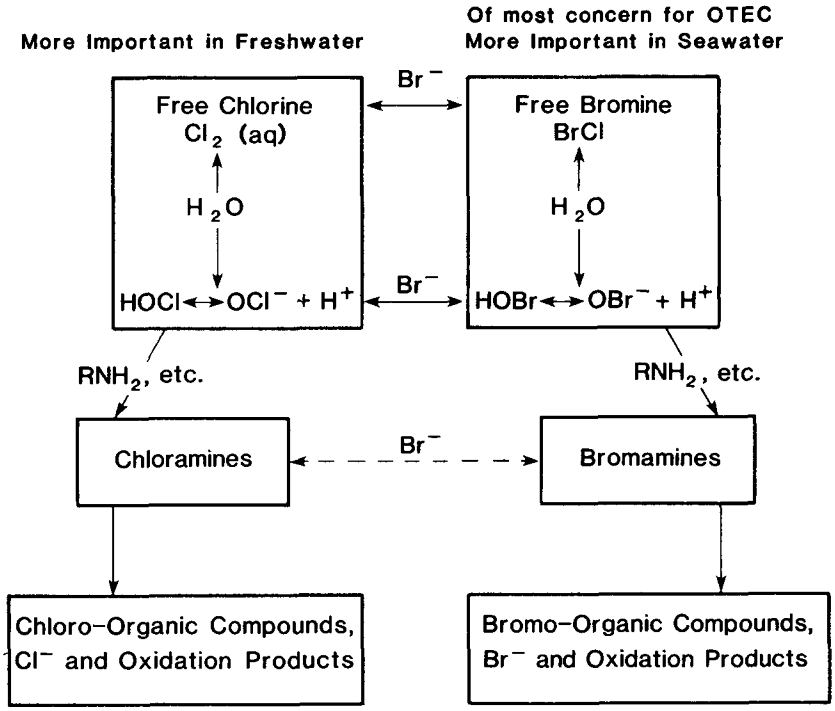


FIGURE 3. Major reaction paths of chlorine in freshwater and seawater (Sugam and Helz, 1980, as adapted by Hall *et al.*, 1981).

5 percent of the total NH_3 is non-ionized ammonia. At the Pilot Plant site, for example, approximately 1.4 μg/L (0.08 μM) non-ionized NH_3 would be discharged in the mixed-effluent, which is below the limit of minimum risk, although significantly greater than the ambient concentration of non-ionized NH_3. Therefore, this level of routine NH_3 loss should not result in toxic concentrations. At the proposed Kahe Point Pilot Plant, a leak would have to be on the order of 3200 kg/day of total NH_3 to reach the limit of minimum risk (OTC/MSG 1985).

A major release could result in the release of a concentrated plume of working fluid, which may be toxic. Working-fluid spills within a plant could be double-contained, with the equipment compartment providing the first barrier and the outer seawall/foundation serving as the second. As a first approximation, site-specific dispersion calculations of a catastrophic NH_3 spill of Kahe Point predict the formation of a toxic cloud, with maximum dimensions of 1250 m radius and 15 m depth 36 hours after release. More than 56 hours would be required for the plume to be diluted to non-toxic concentrations (OTC/MSG 1985).

Trace Constituents

Metallic structural elements (eg, heat exchangers, pump impellers, metallic piping) corroded or eroded by seawater will add trace elements to the effluent. These releases are of concern because trace elements can be toxic, sublethal, or bioavailable to marine organisms (DOE 1979a). In addition, trace constituents in deep waters whose concentrations increase with depth (ie, Cd, see Table 2) will be introduced into surface layers (Quinby-Hunt and Turekian 1983).

It is difficult to predict whether metals released from a plant will affect local biota. Trace elements differ in their toxicity and resistance to corrosion. Few studies have been conducted of tropical and subtropical species. Furthermore, trace metals released by the plant will be quickly diluted with great volumes of water passing through the plant. Those redistributed from depth will be diluted by the warm-water stream and by waters secondarily entrained. However, the sheer size of the plant circulation system suggests that the aggregate of trace constituents released from the plant or redistributed from natural sources could have long-term significance for some organisms.

Metal release will be greatest at start-up when metal filings accumulated in the seawater systems during construction and corrosion products formed in water standing in the system will be released to the receiving waters (OTC/MSG 1985). The heat exchangers are the greatest potential source of trace elements because their large surfaces are in continuous contact with the seawater streams. The pumps and piping in the plant will be comparatively minor sources of corrosion products. However, their composition may include alloys and materials bearing potentially toxic metals such as chromium, copper, and lead.

Information on speciation and toxicity of trace constituents should be developed to permit assessment of the effects of trace element release from OTEC plants (OTC/MSG 1985). Baseline concentrations of trace elements in waters off the plant site must be determined. Corrosion and toxicity of metals in tropical marine environments need to be surveyed. Elements of particular concern include copper, aluminum, zinc, tin, chromium, cobalt, nickel, cadmium, manganese, lead, and titanium (DOE 1980b). Trace element releases should be predicted and the resulting concentration field defined. The potential impacts on existing metal levels must be assessed: toxic concentrations are not expected, but long-term bioaccumulation is possible. The potential of bioaccumulation could be investigated by monitoring the trace element concentrations of an indicator species trapped in an effluent discharge bay as in the Mussel Watch Program (Goldberg 1975; Farrington et al. 1983).

Oil and Grease

The release of trace amounts of petroleum hydrocarbons from a plant also is possible. Site-specific baseline concentrations of oil and grease need to be determined. OTEC plants not mounted on an ocean-going vessel have no need for large quantities of fuel oil, although diesel fuel might be stored in limited amounts. Precautions must be taken to reduce both the likelihood and impact of oil spills.

Endangered Species

The impact of OTEC operations on endangered species must be evaluated for each site. Major resting or breeding sites should be avoided. A plant's discharge will probably have minimal effect on transients. Navigational mechanisms of whales should not be disrupted by noise emanating from a plant and outfall because machine and flow noises emitted by a plant peak at low frequency and fall below ambient noise levels within one nautical mile of the plant (OTC/MSG 1985). Green sea turtles or other endangered marine mammal species may be attracted to the warm-water intake; however, they probably can avoid impingement if intake velocities are low.

Socioeconomic Issues

Residents will be affected by changes due to construction and operation of an OTEC plant. There may be significant short-term (2 to 3 years) effects on the population in communities near the construction and assembly sites during construction. The construction and assembly of a plant will provide building, construction, and utility installation jobs to local contractors and laborers. Construction may disrupt traffic patterns or recreation, and the facility will change the appearance of the locality. Tourists may visit the OTEC plant. People may be concerned about possible impacts on fishing, surfing, and other ocean activities. An OTEC facility should be designed with input from the local community to be aesthetically acceptable.

Fishing and Recreation

Commercial and recreational fishing may be affected by OTEC plant construction and operation. Fish will be attracted to the plant, potentially increasing fishing in the area. Enhanced productivity due to redistribution of nutrients may improve fishing. However, the losses of inshore fish eggs and larvae, as well as juvenile fish, due to impingement and entrainment and to the discharge of biocides may reduce fish populations. The net effect of OTEC operation on aquatic life will depend on the balance achieved between these two effects.

Local recreational areas may also be affected, and the impact must be addressed. Surfing conditions may be altered, beach conditions changed, and so on. Through adequate planning and coordination with the local community, recreational assets near an OTEC site may be enhanced.

Aesthetics

OTEC plants located nearshore will affect the aesthetics at the site. Visual impacts during construction and operation should be minimized. Off-site fabrication of pipes and foundation structures can reduce the need for local construction and storage sites, and avoid the stockpiling of visible, unassembled structures. Visual impacts can be mitigated by using berms or vegetation to conceal hard edges, grouping structures together to blur their definition, and using inconspicuous colors with low reflectance that blend with the background. Facility lighting can be minimized and beams can be directed to minimize impacts (Parsons Hawaii 1981). Studies of a plant's visual impact can determine ways to integrate the plant into the locale. Because aesthetics are highly subjective, the local community should have an opportunity to review and comment on plant appearance.

Risk of Credible Accidents

Accidents potentially could occur to construction and operating personnel and the public in the immediate vicinity of the plant during construction, deployment,[2] and operation of OTEC plants. During construction and deployment, potential accidents are those typical of large oceanic excavation or construction projects coupled with those encountered on land. Risks during operation include those associated with OTEC power systems and those associated with the ocean elements.

Key risks to the public involve people using the area near the plant for recreational activities such as fishing and surfing. An OTEC plant presents a navigational hazard and must meet appropriate regulations.

Construction and Deployment Phase Risks

Risks of potential accidents during construction and deployment increase with increasing water depth, bottom slope instability, at-sea construction time, and experimental nature of the tasks involved (MSG 1985). There should be no credible risk for those outside the immediate area of operations. With proper care, only construction and deployment personnel should be at risk.

Site preparation requires heavy sea-going equipment, such as cranes, barges, and tugs (MSG 1985). Deployment requires the use of many lines under tension. Site preparation may include dredging, blasting, drilling, and excavation on land, in the surf zone, and potentially to great depth at sea. All are potentially dangerous to workers. At-sea operations involving many vessels are hazardous: lines snap and vessels collide. Lines may snap under operational conditions. Such an accident at the Natural Energy Laboratory of Hawaii during deployment of the cold-water pipe resulted in loss of life. A pipe was lost during an attempted deployment of Ke-ahole Point, Hawaii, in late 1983 (Searle et al. 1984).

Site preparation and deployment may require many days at sea. During this time, changes in weather and sea state may result in hazardous conditions (MSG 1985). Operations at sea are risky even with calm seas; with heavy seas or inclement weather, the risk is magnified, therefore appropriate precautions must be taken. An analysis of the effects of environmental conditions on operations should be conducted as the load exerted by oceanic forces may be considerable. Before deployment, atmospheric and oceanic conditions should be assessed (using various techniques including real-time monitoring) to assure that conditions are sufficiently calm at the site for a safe operation. For a test deployment of a 1.2 m pipe on a steep slope, the site was monitored just prior to deployment to evaluate the possibility of an eddy event (Lewis et al., 1985).

For some construction and deployment operations of OTEC facilities, there are no comparable off-shore industry activities (MSG 1985). Joining sections of such large sections of pipe under the slope and depth conditions common to OTEC sites is not a standard oil-field technology nor is the deployment of deep-water segments on steep slopes. Drilling and grouting piles down a steep slope requires extension of state-of-the-art drilling technology. Coupling techniques and foundation placement are highly experimental procedures based on off-shore practices. If a procedure is not routinely executed, the element of risk increases; few, if any, safety regulations have been developed and there has been little experience in avoiding risk.

The use of divers necessitates particular caution. A dive safety manual must be prepared, approved, and implemented prior to the diving activities (29 CFR 1910.420).

Risks During Operation

Risks are assessed in the context that the plant is situated and must be operated in an oceanic environment (OTC/MSG 1985). Major risks associated with the OTEC power system involve the working fluid or biocide (discussed above under Atmospheric Impacts and Marine Impacts). Other risks associated with the OTEC power system are the safety issues associated with steam electric power generation plants: electrical hazards, rotating machinery, use of compressed gases, heavy material-handling equipment, and shop and maintenance hazards. Because the OTEC power plant operates as a low-temperature, low-pressure Rankine cycle, it poses less hazard to operating personnel and to the local population than conventional fossil-fuel plants.

Potential risks of accident include the following (OTC/MSG 1985).

- Utility connections (telephone, sewer, etc.), pipelines, or power transmission cables running along a trestle or on the bottom may be a risk to those on the trestle or in the water nearby.

- OTEC structures are a potential hazard to navigation presenting potential risk to ship, plant, or small boat activities.
- Inspection and maintenance of the pipes and structures require operations at sea with the inherent risk involved in any such operation.
- High winds and waves or extreme events could endanger personnel or public on the structures, or could endanger the structures.
- Sabotage could endanger plant and personnel.

OTEC structures may fall under US Coast Guard jurisdiction and OSHA regulations and control (OTC/MSG 1985). Proper warning devices and precautionary measures must be incorporated in the design for general operational and public safety. Plant operations involving the ocean systems, primarily inspection, maintenance, and logistic support, are similar to offshore platform operations. A plant designed to rest on the sea floor and connected to shore by a trestle simplifies these operations significantly, reducing the risks normally associated with operations on floating or moored platforms at sea.

Summary

Closed-cycle OTEC can be designed to be a relatively benign technology when compared with conventional energy production methods. However, a number of potentially significant environmental concerns have been identified above. These include impacts of:

- atmospheric or marine working fluid, biocide or trace constituent releases;
- air and water quality degradation during construction, deployment, and site preparation;
- artificial upwelling;
- destruction of terrestrial habitats;
- discharges on land or into wells;
- biota attraction;
- impingement and entrainment (primary or secondary);
- redistribution of oceanic constituents;
- alteration of coastal wave conditions, sediment transport, or currents;
- social, economic, or aesthetic changes;
- ciguatera outbreaks; and
- credible accidents.

It is essential that all potentially significant concerns be examined and assessed for each site and design to assure that OTEC is an environmentally benign and safe alternative to conventional power generation.

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Notes

1. The mixed layer is the near-surface layer of the ocean that is well mixed by wind and waves. Temperature, salinity, and density are roughly homogenous within this zone. The euphotic zone is the layer of the ocean in which there is sufficient light for photosynthesis. Most biota live within the euphotic zone. In the tropics the depth of the biomass maximum usually is fairly deep in the euphotic zone and often within the mixed layer.
2. When the term *construction and deployment* is used, the discussion is intended to refer to pipe or facility construction, site preparation, pipe deployment, assembly, towout, and connection.

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