

## Effects of Heated Effluent on Hermatypic Corals at Kahe Point, Oahu<sup>1</sup>

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**ABSTRACT:** The effect of thermal enrichment on hermatypic corals was investigated at Kahe Point, Oahu, Hawaii. The reef off the Kahe Power Plant was surveyed before and after an increase in thermal discharge that accompanied plant expansion. Abundances of dead and damaged corals correlated strongly with proximity to plant discharge and with levels of thermal enrichment. Nearly all corals in water 4° to 5° C above ambient were dead. In areas characterized by temperature increases from 2° to 4° C, the corals lost zooxanthellar pigment and suffered high mortality rates. Damage to the corals was most severe in late summer, and coincided with annual ambient temperature maxima. During the winter months the surviving corals slowly regained zooxanthellar pigment, but there was high mortality of corals during the recovery period. When generating capacity of the plant was increased from 270 to 360 megawatts, the area of dead and damaged corals increased from 0.38 hectare (0.94 acre) to 0.71 hectare (1.76 acre).

STUDIES of thermal tolerance among the hermatypic corals have been limited to laboratory investigations involving short-term exposure to lethal temperatures (Mayer 1917, 1918; Mayor 1924; Edmondson 1928; Yonge and Nicholls 1931). The primary purpose of the present study was to evaluate the effects of heated discharges on hermatypic corals through field observations, with particular emphasis on the sub-lethal long-term effects occurring in areas of marginal thermal stress. The approach employed was a survey of the coral fauna at Kahe Point, Oahu, before and after an increase in thermal discharge from a power plant operating at this location.

### STUDY SITE DESCRIPTION

The Kahe Point Power Plant of the Hawaiian Electric Company (HECO) is an oil-fired steam electric generating station located on the west coast of the island of Oahu near Kahe Point (lat. 22°22' N, long. 158°08' W). Cooling water for the plant is withdrawn from the ocean at the intake basin located approximately 300 m to the north of Kahe Point and is returned to the sea at an outfall located on a small beach some 200 m to the south (Fig. 1). During November 1971, three 90-megawatt generating units were in operation (K1, K2, K3), drawing a total of approximately 14 m<sup>3</sup>/sec (230,000 gallons per minute) of seawater for cooling purposes and discharging this water at approximately 5° to 6° C over intake temperature. Average ambient (natural) water temperatures for this area range from a low of approximately 24° C in March to a high of 27° C in early September. During periods of southerly winds, heated effluent is blown north along the coast and into the intake, producing abnormally high discharge temperatures. Long-term weather records available from

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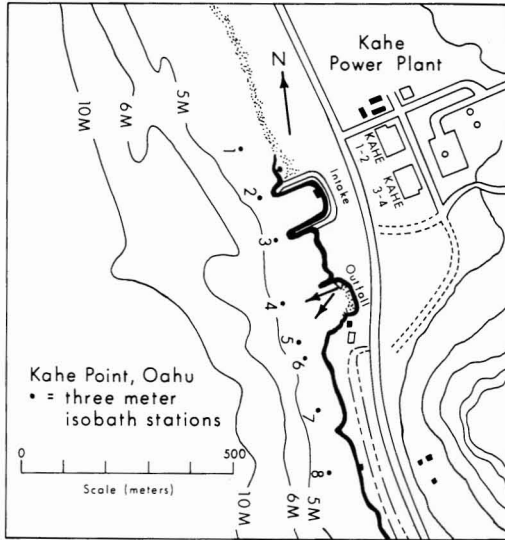


FIG. 1. Map of Kahe Point area showing bathymetric stations.

the National Climatic Center indicate that southerly winds in this region are rare (frequency of occurrence less than 9 percent) and generally occur during the winter months. Kahe Unit 4 (K4) began full operation on 25 July 1972. This unit is of the same capacity as K1–K3 and increased the waste heat discharge rate by over 30 percent.

Waters receiving thermal effluent from this plant are unrestricted from circulation with the open ocean. The ocean floor in the area immediately off the plant is an ancient reef platform that slopes moderately away from the shoreline, reaching the 10 m isobath at a distance of from 200 to 300 m from shore. The bottom in this area consists of areas where modern reef corals have built structures on the old reef platform, interspersed with sand flats and sand channels. In general, the reefs of this area, and in particular those coral reefs south of Kahe Point, are considered to be among the richest in Hawaii. Of the corals, the most prevalent species are *Pocillopora meandrina* var. *nobilis* Dana and *Porites lobata* Dana.

Kahe Point and the sea cliffs to the south are formed by an uplifted limestone bench which rises approximately 5 meters above the ocean surface. The area to the north consists of calcareous sand beaches. Close

inshore to the beach, sand movement and breaking waves prevent coral development. Outside of this shallow surf zone is an area of greater topographical relief where corals grow on the higher elevations, and sand fills the pockets and channels between. Apparently, in areas relatively close to shore and near the bases of reef outcrops conditions periodically become unfavorable to coral development, as evidenced by numerous dead *Pocillopora meandrina* skeletons. These corals probably were killed by burial under shifting sand or by turbidity created during unusual conditions of high surf (Chamberlain, unpublished report, 1971, "Marine environmental impact analysis, Kahe Power Plant," submitted by B-K Dynamics, Inc., Rockville, Maryland, to Hawaiian Electric Co.).

During preliminary surveys we noticed that corals in the area under the immediate influence of the power plant outfall showed a pattern atypical of this coastline. All corals within 120 m of the outfall had been completely eliminated, and only their dead skeletons remained. This dead zone was quite unlike other areas along the coastline where the recognizable dead heads of *P. meandrina* were found interspersed among living specimens of the same and other species. Coral destruction off the outfall was complete and not localized in channels and nearshore regions. The dead zone graded into a zone where surviving corals had lost their pigmentation. Farther from the outfall the zone of colorless and dead heads graded into an area where living corals appeared normal. The striking differences that we observed led us to undertake a more detailed study of this region.

#### METHODS

Four distinct classes of coral condition were recognized: dead, bleached, pale, and normal. The dead class applied only to the branching coral *P. meandrina*, because the dead skeletons of other species found here were difficult to distinguish from the substrate. The "bleached" category included only specimens with tissue that had lost

most of its zooxanthellar pigment, becoming colorless as a result. Bleached corals take on the pure white coloration of their skeletal material. The term "pale" was applied to corals that had lost a great deal of symbiont pigment, but still retained enough zooxanthellae to give them a definite translucent brownish to deep amber coloration. The "normal" category was reserved for corals that displayed the opaque yellow-greens and browns characteristic of healthy coral. The bleached, pale, and normal classes graded into one another, but for the most part could be readily differentiated.

Temperature, salinity, and oxygen profiles were determined on 19 November 1971 (1300 hours) at eight stations running parallel to the shoreline at approximately the 3-meter isobath and at the outfall. Oxygen measurements were made with a Yellow Springs Instrument Co. model 54 oxygen meter and temperature-salinity measurements with an Industrial Products RS5-3 induction salinometer. Plume current velocities were measured with a Tsurumi-Seiki-Kosakusho model 313 current meter secured at various distances from the outfall structure. Plume surface velocities were also measured by timing floats across known distances. Water temperatures throughout the Kahe area were measured at various times throughout the November 1971 to November 1972 time interval by swimmers diving with a hand held mercury thermometer calibrated in  $0.1^{\circ}$  C units. On 17 November 1972, Peabody-Ryan model F-8 thermographs were set at two points along the outfall transect and at one point on the control transect during normal trade wind weather (winds NE, 8 to 10 knots). Complete intake and discharge temperature records were supplied by HECO. These included intake temperatures for each unit taken at 2-hour intervals, as well as a daily outfall temperature measured at time of peak electrical generation. The intake temperature varied diurnally by  $1^{\circ}$  to  $2^{\circ}$  C, generally with a maximum at 1500 hours. Daily peak discharge temperature and 1500-hour intake temperature were plotted for the period of the survey (November 1971 through November 1972 inclusive).

We mapped the area using information from various sources (U.S. Geological Survey Map N2115, Towill Aerial Photographs Nos. 4484-2 and 4125-3, HECO engineering drawings, and from information that we collected in the field by direct measurement along the shoreline and by sextant sightings between fixed landmarks). At the northern edge of the damaged zone, the seaward and shoreward limits of the pale-bleached corals were established by direct measure along transect lines. At the southern edge, we determined these limits by direct measure along the shoreline of Kahe Point. In addition, we secured buoys along the boundaries of the damaged areas and made sightings of the buoys with a sextant from fixed shore points. Sighting coordinates were then transferred to the map, establishing the inner and outer boundaries of these zones and enabling an areal estimate of the damaged zone to be made.

In November of 1971 we selected a site along the discharge plume where complicating effects of wave action, irregular bathymetry, and sedimentation appeared to be minimal. A permanent transect line was established by driving marked iron stakes into the reef. The transect began 100 m from the outfall, at the nearshore termination of hard substrate, and extended 57 m across the zones of dead, pale, and bleached corals and into the area of normal corals (Fig. 2). A  $1 \text{ m}^2$  frame, subdivided with wire into 100 square subsections, was used to estimate coral coverage for each species and condition. The 57 quadrats along the transect were measured in this manner.

In November of 1972 the permanent transect was again measured and a parallel control transect was run approximately 80 m north of the outfall transect. The control transect was laid out over a section of reef that lies outside of the direct influence of the thermal discharge. Although a heated surface layer was present, bottom temperatures approximated ambient (Figs. 3 and 4). The control transect was selected so as to duplicate conditions along the outfall transect with respect to substrate type, depth, distance from shore, and distance from the sand channel. The control transect was dis-

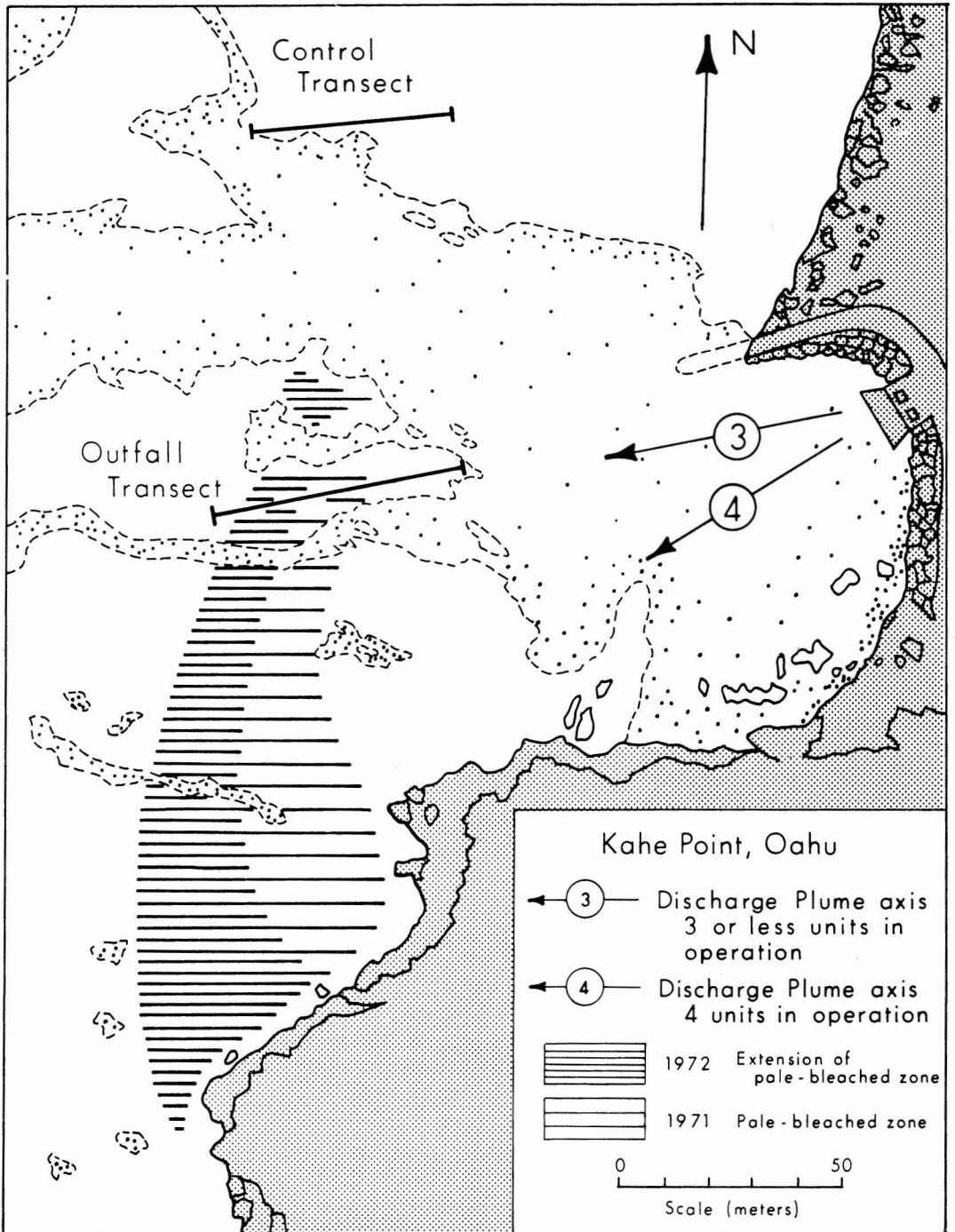


FIG. 2. Detailed map of area off outfall showing locations of permanent outfall transect, control transect, areas of damaged corals for 1971 and 1972, and directions of plume axis with three units and four units in operation.

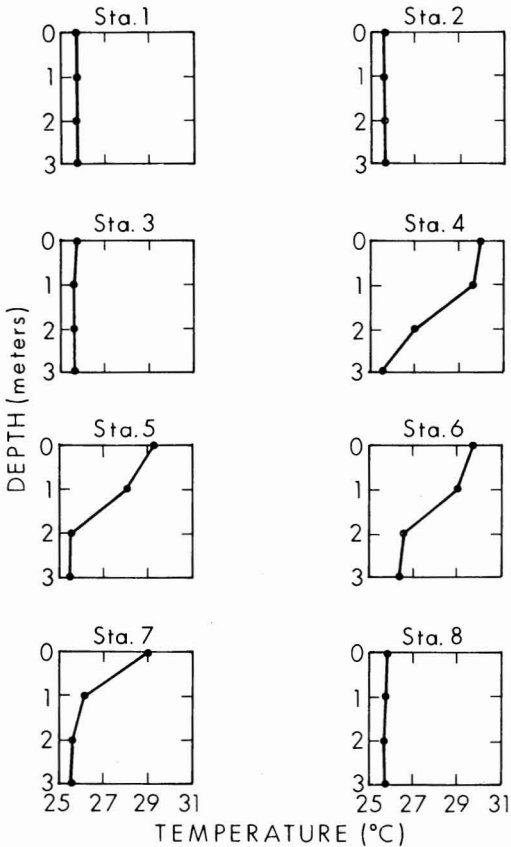


FIG. 3. Temperature profiles for the 3-m isobath stations taken at approximately 1300 hours on 19 November 1971 under trade wind conditions.

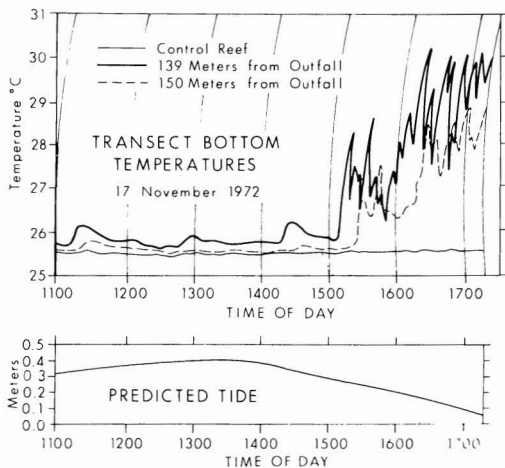


FIG. 4. Thermal environment at two locations along permanent transect and on control reef, as related to state of tide and time of day for 17 November 1972.

continued at a distance of 147 m from shore, at the termination of hard substrate.

During the November 1972 survey, 15 specimens of bleached *Pocillopora meandrina* were tagged with numbered plastic tags. In addition, replicate normal *P. meandrina* heads were removed from the zone immediately outside of the region of pale coral and transplanted to one location in the zone of normal corals (control) and to two locations in the damaged zone (at 116 m and 137 m from outfall).

Photosynthetic pigment concentrations corresponding to bleached, pale, and normal conditions of *Pocillopora meandrina*, *Porites lobata*, and *Montipora verrucosa* (Lamarck) were measured. Discs of 7 mm diameter and 5 to 10 mm thickness were removed from the upper surfaces of *Porites lobata* and *Montipora verrucosa* with a cork borer. These contained all of the coral tissue and its associated symbionts from 0.33 cm<sup>2</sup> of coral surface, along with a plug of underlying skeletal material. The extreme hardness of *Pocillopora meandrina* skeleton precluded use of this method, so branches of this species of approximately 40 g were substituted.

Immediately after removal, the discs were placed in test tubes containing 0.5 ml of distilled water and frozen in Dry Ice. The *P. meandrina* branches were placed in plastic bags and frozen, all samples being kept in darkness so as to prevent photooxidation of pigments.

In the laboratory, extraction of the pigments was accomplished by adding 4.5 ml of 100-percent acetone to the test tubes containing the frozen cores, shaking the contents vigorously, then storing them in a refrigerator for 24 hours. The frozen *P. meandrina* branches were placed in glass containers containing 100 ml of 90-percent acetone, and the same procedure was followed. At the end of the 24-hour extraction period, the samples were reshaken, centrifuged, and the light extinction of the supernatant measured in a 1 cm cell at wavelengths from 750 to 320 nm, with a Beckman DB-G grating spectrophotometer with continuous recorder.

Concentrations of chlorophylls a, b, and c

in mg and of total plant carotenoids in MSPU (one MSPU approximates one mg) were determined by using the formulae of Parsons and Strickland (in Strickland and Parsons 1968). Because the symbiotic zooxanthellae of corals contain no chlorophyll b, its presence in a sample was assumed to originate from the filamentous algae that penetrate the coral skeleton below the level of living coral tissue. The very low chlorophyll b concentrations suggest that cores were shallow enough to avoid most of the filamentous algae layer. Corrections for nonzooxanthellar chlorophylls a and c were calculated from measured values of chlorophyll b (Strickland and Parsons 1968) and subtracted from total chlorophylls a and c.

## RESULTS

### *Thermal Environment*

Temperature profiles for 19 November 1971 (Fig. 3) show the influence of thermal discharge on the thermal structure of the region. A more detailed analysis of this structure is in Chamberlain (unpublished, 1971, B-K Dynamics report) and Sea-Test (unpublished report, 1972, "Physical studies of Kahe," submitted to Hawaiian Electric Co.).

At the discharge point, the velocity of the jet was measured at 3 m/sec with a temperature exceeding ambient by 5° to 6° C. After leaving the outfall, the heated effluent entrained small amounts of slightly cooler water and sand from the beach shallows as it moved seaward, scouring a channel from 1 to 1.5 m in depth. At a distance of from 30 to 50 m from the outfall, the velocity diminished to about 1 m/sec, and the temperature ranged from ambient +4° to +5° C. At 50 m from the outfall at the end of the outfall jetty, the plume entrained large volumes of cooler water from the north, producing eddies of warm and cool water which ranged in temperature from ambient +1° C to ambient +5° C. The formation of these eddies, combined with variations in current velocities due to surf beat, produced an environment

characterized by rapid fluctuations in temperature. These fluctuations were of reduced intensity along the bottom, but even there temperatures routinely changed by as much as 2° C within several seconds. At a distance of about 80 to 100 m from the outfall, the velocity diminished and the effluent spread over the surface, producing thermal stratification. The heated layer was generally between 1 to 2 m in thickness; organisms living below this depth were not visibly influenced by its effects.

After K4 became operational, the direction of the plume axis shifted to the south, and the area enclosed by each elevated isotherm increased (Fig. 2). What originally had been a scoured channel west of the outfall became filled with sand, as was an area that was formerly a region of dead coral heads.

Results of the analysis of power plant temperature records are shown in Fig. 5. Long-term mean open ocean temperatures for the area off Oahu are presented as an approximation of normal ambient temperature.

Results of the *in situ* thermograph study are presented in Fig. 4. Ambient benthic temperature conditions (25.5° C) were measured on the control reef. Thermograph tracings for the outfall transect show a slight enrichment before 1500 hours that increases greatly with ebbing tide. As the level of the tide decreased, the heated surface layer began to make contact with the bottom. The area of dead and damaged coral at 139 m from the outfall showed a maximum enrichment of +3° to +4° C, while the outer termination of the zone of pale and bleached coral (150 m from outfall) showed temperatures of 2° to 3° C over ambient.

### *Coral Pigment*

Replicate absorption curves for pigment extracts from normal, pale, and bleached conditions of *Montipora verrucosa* are shown in Fig. 6. Substantial reductions of total curve areas and of peak heights with bleaching occur at all wave lengths except in the 330-nm region. The pattern shown in the figure also typifies absorption curves for

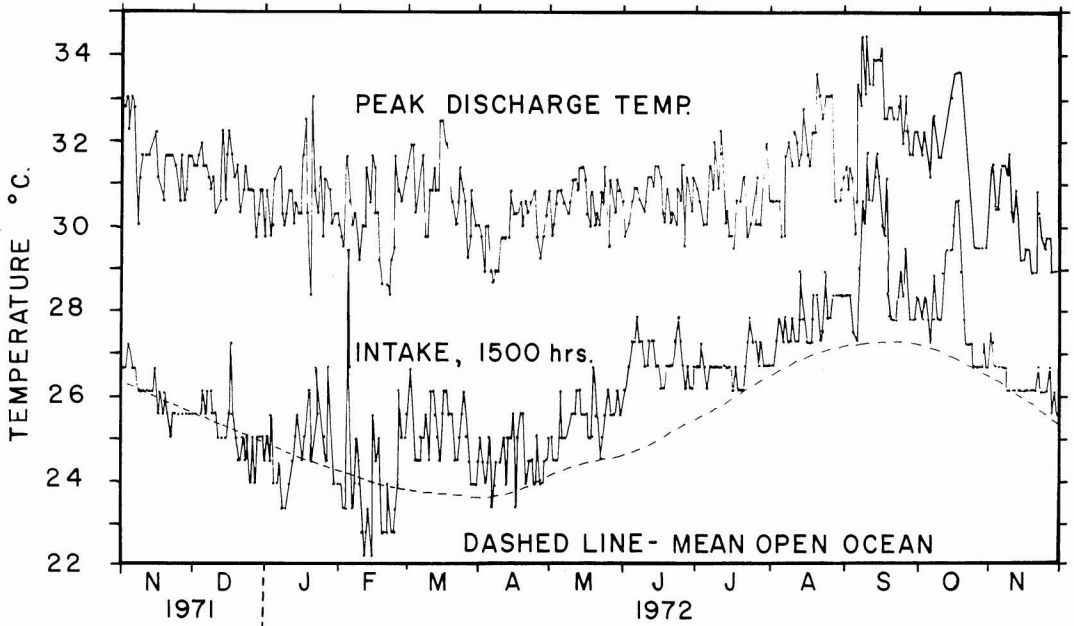


FIG. 5. Daily Kahe outfall temperature measured at time of electrical generation peak and intake temperature at 1500 hours plotted for November 1971 to November 1972.

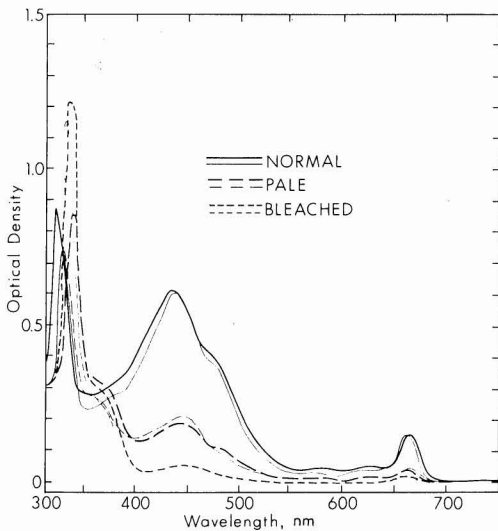


FIG. 6. Absorption spectra for replicate acetone extracts of bleached, pale, and normal specimens of *Montipora verrucosa*.

*Porites lobata* and *Pocillopora meandrina*. Principal absorption peaks occur at 665, 430, and  $330 \pm 10$  nm, with smaller peaks at 630 and 480 nm. The peaks can be compared

to absorption maxima of known photosynthetic pigments (Jeffrey and Haxo 1968, Bogarad 1962). The 665 nm peak corresponds to chlorophyll a concentration; 630 nm to chlorophyll c; 480 nm to plant carotenoids; and the 330 nm peak to an unidentified, colorless compound suggested to be an ultra violet (UV), light-absorbing substance (Shibata 1969, Kawaguti 1969).

Concentrations of the photosynthetic pigments corresponding to various degrees of pigment loss for the three coral species are listed in Table 1. Order of magnitude differences between pigment concentrations of normally colored versus bleached corals were found for all three species. Small amounts of chlorophyll a and plant carotenoid were extracted from bleached specimens, suggesting that a few zooxanthellae are still retained by visibly colorless corals. However, bleached *Porites lobata* specimens sampled nearest the outfall contained no chlorophyll a or c and little carotenoid, indicating that these specimens contained virtually no zooxanthellae. These corals were taken from an area where no other species but *Leptastrea purpurea* Dana

TABLE 1  
 PIGMENT CONCENTRATIONS\* AND 330 NM PEAK HEIGHTS  
 CORRESPONDING TO VARIOUS DEGREES OF CORAL BLEACHING.

SPECIES	COLORATION	CHLOROPHYLL A	CHLOROPHYLL C	TOTAL CHLOROPHYLL	C/A	PLANT CAROTENOIDS	OPTICAL DENSITY AT 320-335 NM
<i>Pocillopora meandrina</i>	bleached	0	0	0	0	0.45	1.99
	"	3.42	0	3.42	0	3.30	1.60
	normal	118	85.4	204	.72	219	3.08
<i>Montipora verrucosa</i>	"	135	81.8	217	.61	234	2.86
	bleached	2.22	0	2.22	0	6.0	1.33
	"	2.55	0	2.55	0	3.9	1.22
	"	1.54	0	1.54	0	3.0	1.19
	pale	4.95	5.61	10.6	1.14	13.5	.71
	"	7.09	2.88	10.0	.41	15.0	.86
	normal	17.7	11.0	28.7	.62	52.5	.86
<i>Porites lobata</i>	"	17.9	9.1	27.0	.51	51.0	.74
	bleached:						
	closest	0	0	0	0	1.95	.80
	specimen	0	0	0	0	2.55	.77
	to outfall	0	0	0	0	2.70	.82
	bleached:						
	specimen from	1.35	0	1.35	0	5.25	1.47
	center of	0.17	0	0.17	0	2.55	1.13
	bleached						
	zone	0.76	0	0.76	0	3.90	1.30
	pale	1.07	3.94	5.01	3.7	18.0	1.56
"	2.81	2.47	5.28	.88	28.5	1.69	
normal	37.0	27.8	64.8	.75	81.0	1.54	
"	28.2	25.2	53.4	.89	67.5	1.75	

\*Concentrations in  $\mu\text{g}/\text{cm}^2$  for *Montipora* and *Porites*, in  $\mu\text{g}/40$  g skeletal weight for *Pocillopora*.

were still living, and the *Porites lobata* specimens were probably living near their upper thermal tolerance limits.

The 330 nm absorption peak showed no consistent decrease with bleaching. In fact, bleached *Montipora verrucosa* showed an increase in 330 nm absorption over pale or normally colored specimens, but this pattern did not hold for the other two species. The absorption peak at 330 nm, therefore, may be associated with coral tissue rather than algal symbionts.

During the winter months, total recovery of coral pigment appeared to accompany decreasing water temperature, although casual observations suggested that coral mortality was high during the recovery period. By 29 February 1972 no pale or bleached corals could be found in the Kahe

Point area, but a few specimens of normally pigmented coral were observed in areas where only pale and bleached specimens occurred the previous fall. During a period of observation in late February, kona (southerly) wind conditions produced intense recirculation of heated effluent. Ambient water temperature at this time was 23° C, intake water temperature was 27° C, and discharge temperature 32° C (ambient +9° C). However, temperatures among the innermost living corals along the discharge plume ranged from 26° to 27° C, the same thermal enrichment value (ambient +4° C) normally encountered during trade wind conditions. These data suggest that benthic thermal enrichment along our coral transect might not have been increased significantly during periods of recirculation.



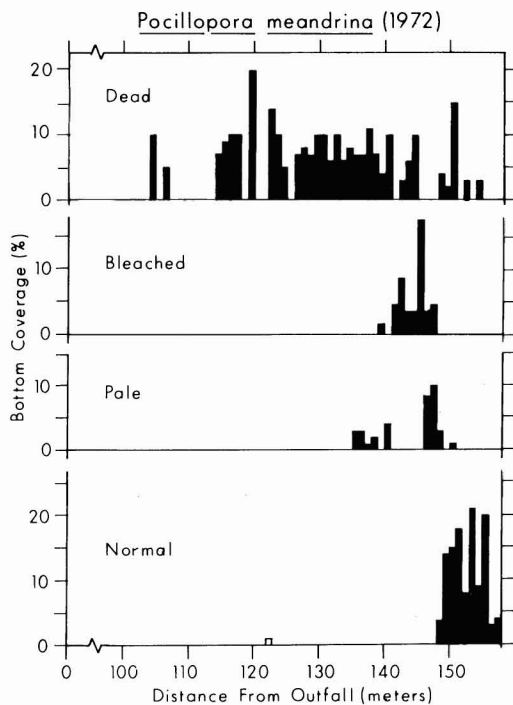
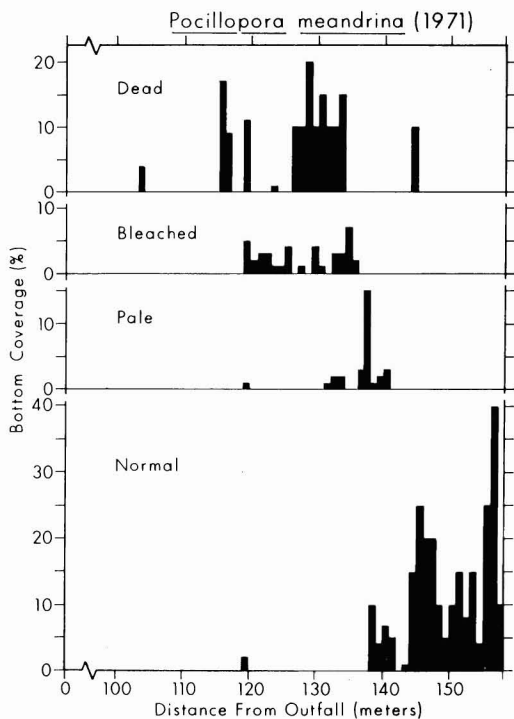


FIG. 7. Percent coverage by various conditions of the coral *Pocillopora meandrina* along outfall transect on 26 November 1971 and 17 November 1972.

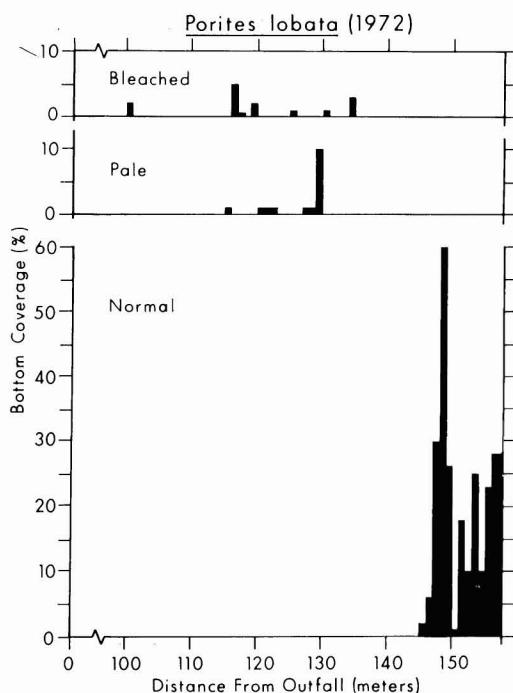
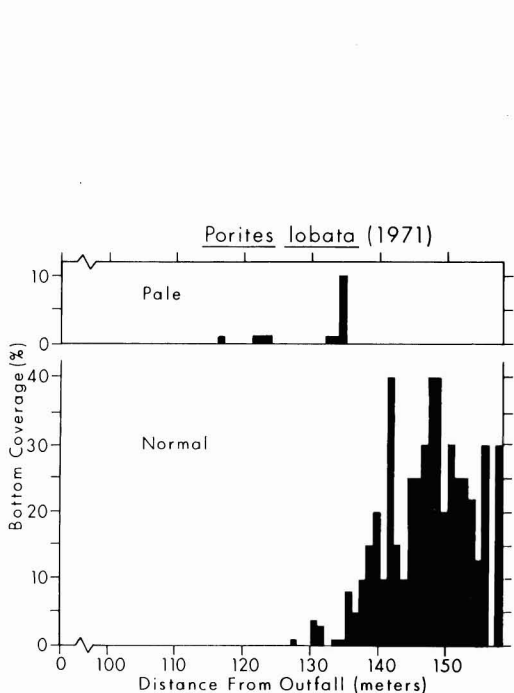


FIG. 8. Percent coverage by various conditions of the coral *Porites lobata* along outfall transect on 26 November 1971 and 17 November 1972.

*Transect*

Results of the 1971 outfall transect are presented in Figs. 7-9. Virtually all dead coral occurred within 135 m from the outfall. Normally pigmented corals ranged from 130 m to beyond the transect's seaward termination. Bleached and pale corals formed a band of transition between the dead and normal zones. The clear demarcation between living and dead zones, the bleached transition zone, and the general reduction in coral coverage approaching the outfall indicated a detrimental influence of the outfall plume on these organisms.

Figs. 7 and 8 present data in detail for the two major species. The data for *Pocillopora meandrina* indicate a gradation seaward from dead through bleached and pale heads to normal coloration. Pale *Porites lobata* heads were found well into the *Pocillopora*

*meandrina* dead zone, which indicates greater resistance to thermal stress by the former species. In the 1971 transect, some pale *Montipora verrucosa* was found well into the zone where other species appeared normal. Loss of pigment in this species is often related to factors such as high light intensity as well as to increased temperature (Coles 1973). This species occurs naturally in pale condition in shallow areas of Kaneohe Bay, Oahu.

The same pattern of damage observed in November 1971 was again observed in November 1972 but by then had become far more extensive. Most of the pale and bleached heads encountered in 1971 had died, and the area of normal corals outside of the 1971 zone of damage had become pale or bleached. *Pocillopora meandrina*, with its readily recognizable dead skeleton, enabled a comparison of all conditions of this

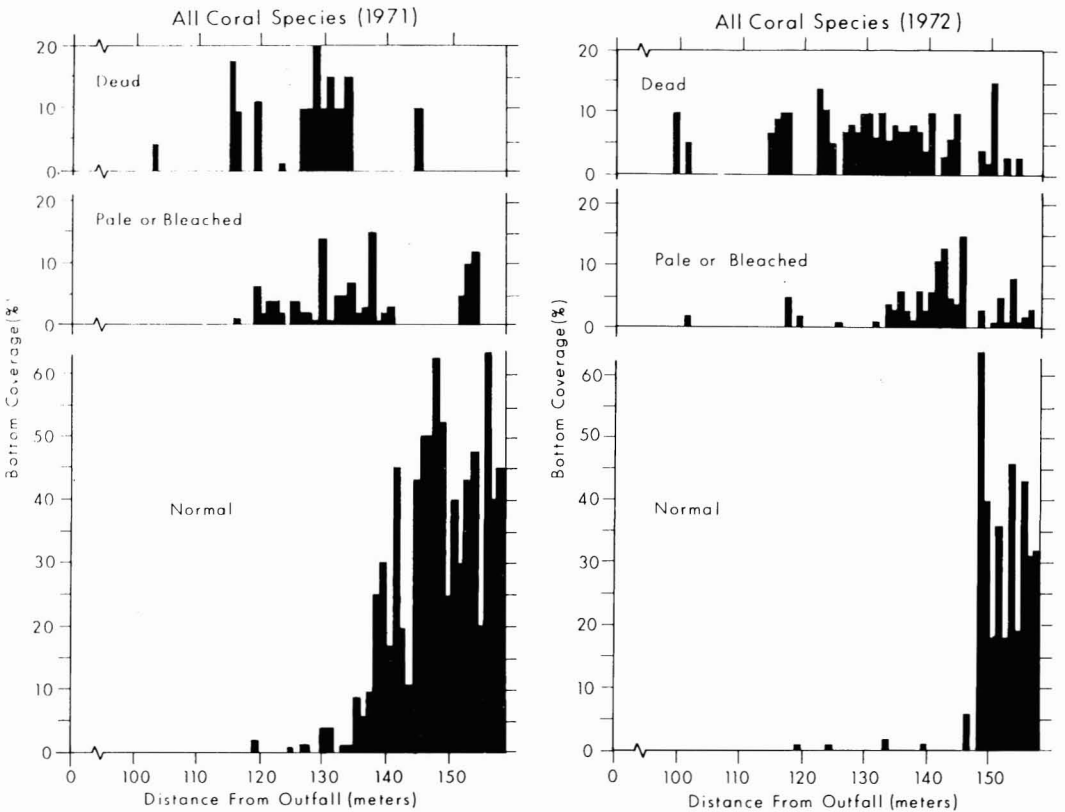


FIG. 9. Percent coverage for all coral species encountered along outfall transect on 26 November 1971 and 17 November 1972.

species along the transect between 1971 and 1972. These data are summarized in Table 2. The increase in dead, bleached, and pale coverage was matched by a corresponding decrease in normal coral coverage.

TABLE 2  
CHANGES IN COVERAGE (DECIMETER<sup>2</sup>) OF  
*Pocillopora meandrina*  
ENCOUNTERED ALONG TRANSECT

CONDITION	COVERAGE (DECIMETER <sup>2</sup> )		% CHANGE BETWEEN SURVEYS
	1971	1972	
Normal	251	117	-53.4
Pale	30	35	+16.7
Bleached	40	51	+28.8
Dead	157	264	+68.1
	478	467	

An analysis of the transect data was conducted, but, because an estimation of coral coverage on the transects involved use of a proportion (% of 1 m<sup>2</sup>) and because coverage frequently was less than 30 percent, it was necessary to employ the arcsin transformation before applying parametric statistical methods (Sokal and Rohlf 1969). A *t*-test of differences between abundances of living coral per m<sup>2</sup> quadrat in 1971 and abundances in the same quadrats in 1972 shows that a highly significant decrease in living coral coverage occurred along the transect between 116 and 157 m from the outfall ( $p < .0005$ , paired comparisons). By the same analysis, dead *P. meandrina* heads showed a highly significant increase ( $p < .0005$ ). Total living coral encountered along the transect decreased by 44 percent during the year. The weighted mean distance, defined as (abundance X distance) / abundance, of all bleached and pale corals encountered in the transect was 134 m in 1971 and increased to 142 m from the outfall in 1972. These data indicate that the center of damage along the transect shifted outward by approximately 8 m during the 1-year time interval. Damage was minimal in the area of the outfall transect since the addition of K4 caused the direction of the

plume axis to shift farther to the south. The center of damage along the new plume axis shifted outward an estimated 30 to 40 m between the two sampling dates.

The results of the control transect (Fig. 10) indicate that good coral coverage can exist under conditions that appeared to be similar to the outfall transect in every respect except in the degree of thermal stress. Living coral coverage along the control transect was not significantly correlated with distance from shore ( $r = 0.19$ ). Along the outfall transect, total live coral coverage (normal, pale, and bleached conditions) showed a high correlation with increasing distance from the outfall ( $r = 0.78, p < .001$ ). Most of the corals encountered in the outfall transect were dead or damaged (pale or bleached condition), whereas those encountered on the control transect were normal. A *t*-test of difference between the *z*-transformed correlation coefficients indicated significance at the  $p < .001$  level.

#### Areal Estimate of Damage

The total area of pale and bleached corals before and after the beginning of operation of K4 (26 November 1971 vs. 15 November 1972) is shown in Fig. 2. The area of damaged corals (pale and bleached condition) covered an area of approximately 0.23 hectare (0.57 acre) in 1971. An area of dead coral heads covering approximately 0.15 hectare (0.37 acre) existed inside this zone. By November 1972 an additional 0.33 hectare (0.82 acre) was pale or bleached, while most of the pale and bleached area observed in 1971 became a zone of dead coral. The dead coral zone of 1971 was largely buried by sand.

#### Transplants

Of the 15 bleached *P. meandrina* heads tagged during November 1972, only one survived in early February 1973 and it was in a bleached condition. One of the two heads that had been transplanted into the dead zone (116 m from the outfall) was dead in February 1973 and the other was pale. The two heads transplanted to the bleached zone

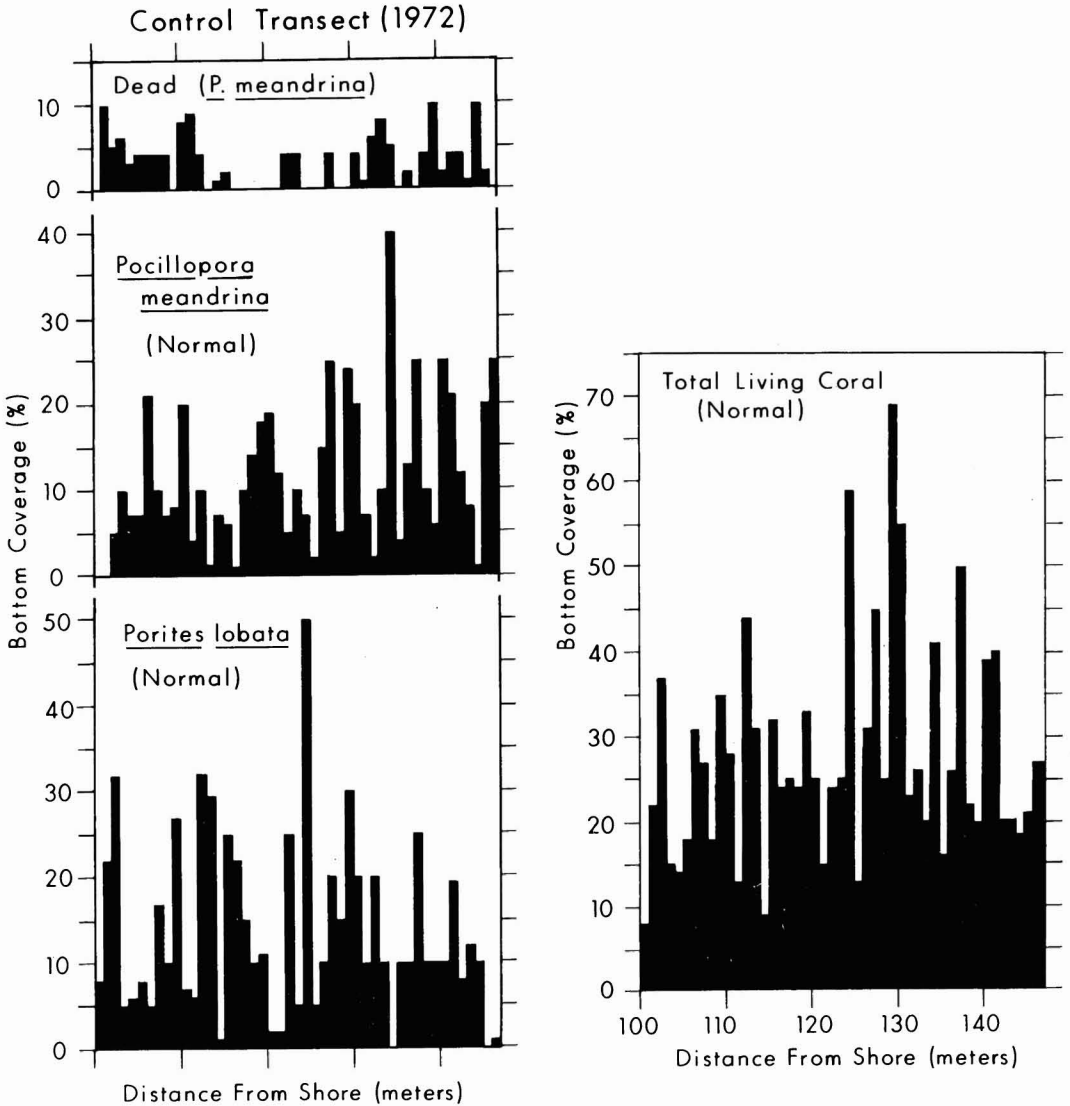


FIG. 10. Percent coverage of corals encountered along control transect on 24 November 1972.

(137 m from the outfall) were paled, while the pair in the control transect remained alive and normally pigmented.

DISCUSSION

The pattern of coral destruction is clearly related to discharges of heated effluent from the Kahe Point Power Plant. Percent abundance of dead, bleached, and pale corals

encountered in the transect is correlated with outfall discharge and increased discharge resulted in increased damage.

Condition of corals off the outfall reflected the complex thermal conditions created by wave action and irregular bottom relief. Often a coral head growing on top of a rock pinnacle was visibly damaged by thermal stress, while its neighbor, located on the side of the outcrop at a slightly greater

depth, was not damaged because it was living below the heated surface layer. As previously shown, fluctuation in the benthic thermal environment resulted from the rising and the falling of tides. Downward mixing of effluent by surf further complicated the thermal environment in some regions. In addition, slight shifts in the direction of the heated plume were induced by changes in wind direction, wind velocity, state of tide, surf conditions, direction of offshore currents, and presumably many other factors (Chamberlain, unpublished, 1971, B-K Dynamics report; and Sea-Test, unpublished report, 1972).

Of the coral species encountered in the Kahe Point region, *Leptastrea purpurea* Dana appeared to be the most tolerant of elevated temperatures. Normal specimens of this species were occasionally found in areas where all other corals had been completely eliminated by thermal stress. The innermost zone off the outfall was characterized by dead coral heads, a few small colonies of normal *L. purpurea*, and a thermal environment of 4° to 5° C over ambient. This zone graded through an area where a few highly bleached specimens of *Porites lobata* survived. Apparently *Porites evermanni* Vaughan, a closely related but uncommon species, is better able to withstand thermal stress because a few normal specimens measuring 10 to 20 cm in diameter were found associated with the bleached *P. lobata* heads. In addition, a few specimens of pale to normal *Montipora patula* Verrill and *Porites compressa* Dana were found, although they appeared to be in poor condition.

Seaward, another zone characterized by a higher coverage of surviving corals and by ambient temperatures of +3° to +4° C was identified. Corals consisted of dead and highly bleached *Pocillopora meandrina*, bleached *Montipora verrucosa*, pale to bleached *Porites lobata*, normal *P. evermanni*, pale to normal *P. compressa*, and normal *Leptastrea purpurea*.

An outermost zone of marginal thermal influence approximating the benthic ambient +2° to +3° C isotherm was identified, characterized by bleached to pale

*Pocillopora meandrina* and *Montipora verrucosa*, with other species appearing normal in pigmentation. This zone grades into an area of visibly unaffected corals at the ambient +1° to +2° C benthic isotherm including some *Montipora flabellata* Studer and *Pavona varians* Verrill, corals which were not encountered within the stressed zone. The general distribution of these two species at Kahe suggests that they normally did not occur close to shore. Therefore, their exclusion from the area of thermal influence may not be the result of thermal stress, but may be more strongly influenced by other factors such as turbidity.

Effects of heated effluent on coral have been noted in Biscayne Bay, Florida, in an area receiving discharge from the Turkey Point Power Plant (L. Lee Purkerson, personal communication). Observations made in the summer of 1970 showed all *Solenastrea hyades* coral colonies to have been eliminated within the area directly effected by thermal discharge. In areas of marginal influence, about half of the colonies were found dead, with the remainder being noticeably damaged. *Siderastrea siderea*, a hardy estuarine coral, was able to reestablish itself within the zone of maximum thermal effects during the winter and spring months but was killed during the following summer. In zones of marginal influence, *S. siderea* heads were pale and appeared to be susceptible to overgrowth by algae and encrustation by other life forms.

The increase of nearly 100 percent in an area of total dead and bleached corals (0.38 hectare to 0.71 hectare) between 1971 and 1972 at first seems unusually large when compared to the 30-percent increase in heated discharge. In the simplest case, one would expect a linear increase in affected area with an increase in thermal discharge. However, Norman Buske, who has investigated the dynamics of the Kahe discharge, predicted the more extensive effect (personal communication, December 1971). He attributes the increased damage to the design of the outfall structure. The outfall tunnel was constructed with a sharp bend just before the discharge point. At discharges of less than 14 m<sup>3</sup>/sec (three units operating)

the effluent is directed seaward along the outfall jetty, while above this value (four units operating) it is deflected to the south. With the addition of K4, the plume direction is unstable and can swing north and south, affecting a much wider area than would normally be the case. Furthermore, when the plume shifts to the south, it moves into a turbulent area created by waves striking against Kahe Point and is mixed vertically downward to depths as great as 3 meters. Normally it would be expected to stratify at the 1 to 1.5 meter depth and would not strongly influence the corals growing below this level. HECO has stabilized plume direction by maintaining full volume discharge at all times, but occasionally units will have to be taken off the line for maintenance.

Another factor which may have contributed to the increased coral damage was the period of unusually high discharge temperatures which occurred in September and October of 1972 (see Fig. 5). However, because the plume was directed to the north during recirculation and because cooling and mixing with ambient water are greatly enhanced by the high winds, it is possible that benthic temperatures in the damaged area were not increased over those encountered in the survey.

On 5 October 1972, John McCain and James Peck of HECO (personal communication) marked off a 10 m square section of the reef along our transect at a distance of 139 to 149 m from the outfall, with our transect line as the south edge. A total of 66 bleached *Pocillopora meandrina* heads located within the square were tagged. A gradual decline in the number of heads was observed in the following months. By 14 December 1972 only six living heads remained, and these had lost nearly half of the original tissue area. These results and the results of our tagging and transplants indicate that equilibrium had not yet been established at the time of our second survey and that coral destruction continued to occur, even though ambient water temperature was decreasing during this period. It also demonstrates the importance of long-term sublethal effects and brings into question the practice of using short-term tolerance limits

to predict environmental damage. Exposure to increased levels of thermal loading did not appear to kill the corals outright but gradually weakened and eliminated them over a period of time.

We expect that damage to the coral reef at Kahe Point will continue even without further increases in thermal discharge. Most of the bleached and pale corals probably will continue to be eliminated with time. A similar situation has been reported from Biscayne Bay, Florida (Roessler and Zieman 1969). Although thermal discharge from the Turkey Point Power Plant remained constant during the period from September 1968 to September 1969, damage to the shallow water *Thalassia* (turtle grass) community increased. In September 1968, an area of 12 to 14 hectares (30 to 35 acres) off the outfall was devoid of all vegetation except blue-green algae. Surrounding this was an area of approximately 20 to 24 hectares (50 to 60 acres) where all macroalgae had been eliminated and the *Thalassia* heavily damaged. By September 1969 the barren area had increased to about 20 hectares (50 acres) and the surrounding damaged areas to 38 to 39 hectares (70 to 75 acres).

Although the obvious environmental parameter being altered in the Kahe discharge is temperature, changes in other factors must also be considered. Measurements made by ourselves and others (Chamberlain, unpublished, 1971, B-K Dynamics report; Sea-Test, unpublished report, 1972; and John McCain, personal communication) indicate that salinity and oxygen saturation are not appreciably altered in the area of the discharge. Toxic substances are not added to the cooling water of this plant. Contamination of the discharge water caused by corrosion of metallic surfaces within the power plant is probably insignificant. On 28 July 1972 samples of water were taken at eight locations along the coastline at Kahe, including the intake and outfall. Analyses for 31 of the most important elements and ions (including Cu, Zn, Al, Ni, Pb, Cr, Fe, Co, and Cd) revealed no detectable differences (Stearns-Roger Inc., unpublished report, 1973, "Environmental assessment Kahe

Generating Stations units 5 and 6," submitted to Hawaiian Electric Co.). The substrate along the transect did not change during the survey, although the inner portions of the 1971 dead coral zone became covered with sand when K4 became operational.

Increased turbidity resulted from the discharge of heated effluent and coincided with degree of thermal stress, necessitating an analysis of the relative importance of these two components in producing the damage. Johannes (unpublished) observed the shallow water reef community off Kahe Point for a period of 1 year when it was continuously being subjected to extremely turbid water created by beach excavations during the construction of the plant. During this period, corals continued to flourish, probably because water movement (wave action and currents) prevented corals from being coated with fine material. This observation is in agreement with the conclusions of Marshall and Orr (1931), who studied the effects of sedimentation on corals of the Great Barrier Reef. Our observations led us to conclude that turbidity was the less important of the two factors in the destruction of corals at Kahe. During the winter of 1971–1972 we observed a complete recovery of pigment in corals that had survived the high temperatures of the previous summer; they again became bleached in the summer of 1972 and recovered in the winter. We attribute these phenomena to temperature, because turbidity appeared to remain unchanged. Such annual loss of zooxanthellar pigment in response to naturally produced high summer temperatures has also been reported by Shinn (1966). Furthermore, we were able to locate an area in the field where the two effects could be separated.

Near Kahe Point, the bottom relief is high, with rock outcrops extending from the bottom into the heated surface layer. Turbidity created by wave action on the sandy bottom is greatest near the bases of the outcrops, whereas thermal stress is greatest near the surface. Corals growing at or near the tops of the outcrops experience high thermal stress and low turbidity, whereas corals growing near the base experience low thermal stress and high turbidity. Corals

found near the tops of these outcrops were dead or obviously damaged by the heated effluent (pale or bleached condition), whereas corals growing at slightly greater depths (excluding corals at the very base that may die when buried by sand) appeared normal. Therefore, we conclude that at Kahe Point temperature was the principal factor in determining the observed pattern of damage.

The association between corals and their intracellular algal symbionts appears to be easily disrupted, and as such provides a valuable indicator of thermal stress. The release of symbiotic zooxanthellae by corals and the consequent loss of photosynthetic pigment as a response to physical stress has been observed by other investigators (Yonge and Nicholls 1931, Goreau 1964, Shinn 1966, and Wells et al. 1973), but has not been quantitatively measured.

Our determinations of photosynthetic pigment concentrations per cm<sup>2</sup> for normal *Porites* and *Montipora* are in agreement with values reported by Margalef (1959) for various Caribbean corals and Maragos (1972) for Pacific species. Our chlorophyll a estimates for normal *Porites lobata* average about four times those of Roos (1967) for *Porites asteroides* sampled at Curacao. Pigment extractions appeared to be complete, as the coral plugs were colorless at the end of the 24-hour extraction period. However, Maragos (1972) has since found that crushing the coral before extraction increases the accuracy of the method. The precision of replicates and large differences between pigment concentrations corresponding to bleaching states clearly demonstrate a strong photosynthetic pigment in gradient corals along the transect. The pigment gradient ranged from values that are equivalent to those obtained by other investigators to virtually no measurable chlorophyll in the highly stressed corals.

Absorption in the 330 nm UV region has been suggested to be of adaptive significance to corals (Margalef 1959, Kawaguti 1969, and Shibata 1969). The increase in the absorption in this region by bleached *Montipora verrucosa* (Table 1) might be interpreted as reflecting an increase in UV

TABLE 3

CORALS RANKED ACCORDING TO DATA FROM EDMONDSON (1928: TABLE 5)

CORAL SPECIES	TIME ELAPSED (HOURS)					
	3	5	8	10	18	24
<i>Leptastrea purpurea</i>	A	A	A	A	A	A
<i>Porites compressa</i>	A	A	D			
<i>Porites lobata</i>	A	A	D			
<i>Montipora patula</i>	A	A	D			
<i>Montipora verrucosa</i>	A	D				
<i>Pocillopora meandrina</i>	D					

NOTE: Survival time of Hawaiian corals after they were raised to 32° C at a rate of 2° C per hour and were maintained at that level for 24 hours. D, specimen dead; A, alive at the end of the specified period.

absorption material in response to loss of photosynthetic pigment. However, *M. verrucosa* is the only one of the three species demonstrating this. The UV peak may merely be a manifestation of the amount of coral tissue remaining on the skeleton, as suggested by the decrease in 330 nm absorption by *Porites lobata* taken nearest the out-fall.

With the elimination of the zooxanthellae and their associated pigments, other pigments in the coral tissue were unmasked, resulting in some heads (mostly *Pocillopora meandrina*) taking on pastel hues of yellow, pink, violet, and occasionally green. This observation supports the results of other workers (Kawaguti 1937, 1944, 1969; Shibata 1969) who found evidence that certain coral pigments are found outside of the zooxanthellae.

Mayer (1917) observed that the ability of a coral species to resist high temperatures is conversely related to the metabolic rate (oxygen consumption). *Pocillopora*, the coral most sensitive to thermal stress at Kahe Point, also has the highest metabolic rate (Franzisket 1964). *Porites lobata* has an intermediate metabolic rate, whereas large polyp corals such as *Leptastrea purpurea* are known to have lower metabolic rates (Mayer 1917, Mayor 1924, Franzisket 1964). This generalization was originally based on short-term laboratory results, but it also appears to hold under field conditions.

Tables 3 and 4 compare resistance of corals to acute temperature rise as reported by Ed-

TABLE 4

CORALS RANKED IN ORDER OF RESISTANCE TO THERMAL STRESS AS DETERMINED FROM OBSERVATIONS AT KAHE POINT, OAHU, HAWAII

Strongly Resistant:	<i>Leptastrea purpurea</i> Dana (synonym: <i>Favia hawaiiensis</i> ) <i>Porites compressa</i> Dana <i>Porites lobata</i> Dana <i>Montipora patula</i> Verrill <i>Montipora verrucosa</i> (Lamarck)
Least Resistant:	<i>Pocillopora meandrina</i> var. <i>nobilis</i> Dana

mondson (1928), with our evaluation of the relative resistance to temperature stress of corals at Kahe based on observed bleaching and mortality. Both approaches show the same resistance patterns among the common species. This agreement further substantiates the argument that thermal stress is the principal factor involved in producing the observed coral mortality.

The absolute temperature level, rather than degree of enrichment over seasonal ambient levels, appears to be the critical factor, as indicated by recovery of the corals during the winter months in areas where thermal enrichment levels were as high as those of the previous summer. Our observations at Kahe indicate a lethal temperature of 31° to 32° C for most Hawaiian species of coral, which is also in agreement with Edmondson's (1928) results. Prolonged exposure to temperatures of 30° to 31° C appears eventually to pale, bleach, and kill



most of the common coral species encountered at Kahe. Temperatures approaching 30° C probably are sublethal and may, if prolonged, lead to the destruction of the more sensitive coral species. These observations are in agreement with results of laboratory studies conducted by us in which the same paling and bleaching effects observed at Kahe were also produced under laboratory conditions (Coles 1973, and Jokiel et al., unpublished).

A question remains as to the relative importance of absolute high levels of temperature vs. stress imposed by rapid temperature fluctuations (thermal shock). Rapid temperature fluctuations occurred throughout the year but acute coral damage was observed only during periods of maximum ambient temperatures. Temperature fluctuations may be more important when the temperature approaches the tolerance limits.

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