A STUDY OF BIOLOGICAL IMPACT CAUSED BY NATURAL AND MAN-INDUCED CHANGES ON A TROPICAL REEF

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INTERIM REPORT

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NOTE

This report constitutes an unofficial pre-printing of our research efforts.

The Guam Power Authority is attempting to correct some of the environmental problems that are referred to herein. Proposals have been solicited from several engineering firms to aid the GPA in this task. We have been approached by a number of these firms requesting data to aid in their design work.

Our present time schedule does not call for official publication of our data through the U. S. Environmental Protection Agency for at least another year or more. We have therefore chosen to pre-print and release our preliminary data in the interest of saving time and the environment. The Guam Power Authority has generously agreed to finance the cost of printing. Verbal authority to release the preliminary data has come from our Project Officer and Director of the Region IX EPA office.

In view of the fact that these data have not been officially accepted and approved by the EPA, that agency should not be held responsible for the contents of this report. However, should any part of the report be used in future publications, the U. S. EPA should be acknowledged for funding the research.

ABSTRACT

A biological study was conducted on a fringing coral reef adjacent to a thermoelectric power plant on Guam, before and after release of plant effluent. The before study showed corals of the reef front, submarine terrace, and seaward slope to be devastated by a recent infestation of the crown-of-thorns starfish, *Acanthaster planci* (L.). The reef margin was found to comprise a rich and diverse coral reef community, presumably spared from *Acanthaster* attack by strong wave surge. The reef flat was found to be a naturally depauperate environment due to frequent exposure at low tide.

Release of plant effluent resulted in an elevation of water temperature on the adjacent reef flat and reef margin. Wave action exposed even the deeper parts of the reef margin to temperatures above ambient as well as other potentially detrimental effluent parameters such as chlorine and heavy metals. Introduction of the effluent has led to destruction of reef margin corals in a zone of 4320 m^2 and damage to a peripheral area including a total of 10,000 m^2. Damage was first observed in December 1971 when plant operations began and was still evident after one year of operation. Effluent was found to stratify beyond the surf zone and no longer served as a threat to benthic organisms.

Coral transect studies have shown an increase in recent coral colonization on the reef front, terrace and slope since the *Acanthaster* infestation. No such recovery is evident in benthic habitats of the reef margin, exposed to effluent.

Preliminary thermal simulation experiments, performed on a series of reef corals in the laboratory, suggest an upper tolerance limit for the corals between 30 and 32°C. These temperatures are not uncommon on the reef margin. Sublethal elevation of temperature was shown to reduce growth rate in some of the coral species.

Recommendations are made to release the effluent in deeper water in order to provide a greater mixing zone and to relieve present stress on the reef margin organisms.

This report was submitted in partial fulfillment of Grant No. 18080 EUK by the University of Guam Marine Laboratory, under the sponsorship of the Environmental Protection Agency. This portion of the work was completed as of June 1973.

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We owe our appreciation to Mr. Paul Jokiel and our other counterparts at the University of Hawaii for sharing their data on a related project.

Plant operations personnel at Tanguisson No. 1 were always open and willing to aid in our work. Cooperation from Guam Power Authority employees Frank Melder, Bill Masters and Donald McCullum was especially appreciated. Our thanks are also due to Mr. P. E. Cavote and Mr. George Pomeroy of GPA management.

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SECTION I

CONCLUSIONS

GENERAL BIOLOGICAL CONDITIONS OF THE TANGUISSON STUDY AREA PRIOR TO RELEASE OF PLANT EFFLUENT

Tanguisson No. 1 is located on an elevated terrace covered with bioclastic material. The plant site is on an old coconut plantation. Attempts were made by the contractor to save most of these trees, but a considerable portion of the previous well-developed strand vegetation was removed well outside the immediate construction site to provide a mobilization area. On the landward side of the plant is a steep limestone cliff with a talus slope at its base. The cliff is about 100 m high and has a good growth of limestone forest vegetation on its sides and slopes. This vegetation has been left basically undisturbed except where power transmission lines and a pipeline pass up the cliff.

Seaward of the power plant site is the first of the series of reef zones studied. The intertidal is the first zone encountered and, in the immediate vicinity of the plant, consists of the remnants of an elevated fossile reef. There are sand beaches along the intertidal to the north and south of the plant.

The reef zone seaward of the intertidal is the reef flat. This is a limestone platform that is mostly flat and pavement-like except for a few scattered holes and channels. The reef flat has a characteristic biota that is mostly dominated by fishes, crustaceans, echinoderms, and benthic algae. Corals are rare on the reef flat and in general, it is a biologically depauperate area due to frequent exposure of much of its surface at low tide. Temperatures on the reef flat are often 2 to 3°C higher than oceanic temperatures when low tides occur in midafternoon.

The next zone is the reef margin and is that portion of the reef where waves break against the reef platform. The area is dissected by numerous surge channels and is the site of a rich and diverse coral fauna. Unlike the remaining zones, this one has not been subjected to intense predation by the coral-feeding starfish, *Acanthaster planci* (L.).

We suspect that heavy wave attack in this area prevents the animal from attaching to corals in order to feed. Temperatures in this zone and those that follow had a range of 27 to 29°C, a mean annual temperature of 27.6°C, and an annual fluctuation of only 3°C.

The reef front is the next zone and in most respects closely resembles the reef margin. The primary exception is that it is a deeper, more steeply sloping zone and not subjected to breaking waves. The lower portion of this zone has been completely devastated by *Acanthaster*.

At the 6 m contour, the reef front flattens out and grades into the first submarine terrace. This area was, until recently, covered by a rich coral community but has now been wiped out by *Acanthaster*. Nearly 100 percent of the former coral community was destroyed.

At about 15 m, the submarine terrace ends and the bottom slopes steeply down to the next submarine terrace at about 32 m. This drop-off is known as the seaward slope and, as in the case of the first submarine terrace, once supported a luxuriant growth of reef corals. Again the area was found to be devastated by the starfish.

The second submarine terrace is basically a flattened shelf covered with sand derived from the nearby seaward slope. Some scattered coral knolls are found here but these too are now mostly devoid of live corals.

THE EFFLUENT AND ITS DISTRIBUTION

Circulating water is pumped through the power plant for condenser cooling. The source of this water is the Philippine Sea. Tanguisson No. 1 uses about 17,000 gpm with one pump on the line, and about 28,000 with two. (One pump is now being used almost exclusively since the time the original manuscript was prepared, personal communication with P. E. Cavote.)

At least four things happen to cooling waters and entrained planktonic organisms as they pass through the plant.

1. Physical agitation at the circulating pumps.

2. Leaching of heavy metal ions, particularly copper, from the piping.

3. Addition of 12.5 lbs. of chlorine per day to control sliming. (Chlorination has been stopped completely since the preparation of the original manuscript, personal communication with P. E. Cavote.)

4. Elevation of temperature.

The outfall site for this effluent is at the intertidal zone. Water enters a stilling well and rises up to the level of the reef flat. Effluent then flows seaward, directly across the reef flat, in a relatively narrow band (10 to 15 m wide). At the reef margin, the effluent encounters breaking waves and is mixed with incoming seawater. This mixing effectively carries effluent to the bottom of the surge channels. The mixing water tends to be carried parallel to the margin and front in a series of zig-zag patterns. The lateral movement is due to prevailing offshore currents, and the zig-zag to wave action. Currents may either run northeast or southwest at Tanguisson. When the effluent is carried to the north, it immediately encounters a rip current that emerges from the intake channel surface. The rip diverts the effluent seaward out over the terrace and away from the reef margin and front. When the effluent is carried to the southwest, it results in a considerable portion of the reef margin and front being washed by effluent. The effluent gradually shifts seaward as it moves south toward Transect C. A second rip current occurs at Transect C that serves to divert the remainder of the effluent seaward.

Once the effluent reaches the submarine terrace, it comes under the influence of the offshore water mass. Except for wave transport during times of heavy seas, effluent entering this water mass is carried either northeast or southwest and away from the study area. Its direction depends upon tide and local climatic and related oceanographic conditions. Effluent moving northerly was not tracked beyond Tanguisson Point. Effluent moving south is usually deflected seaward off of Amantes Point and moves in a westerly direction away from the island. This may be due to a weak convergence zone that would be expected to form opposite the Amantes headland. A recent drift cross study showed a drift that rounded Amantes Point and continued south opposite Tumon Bay. The drift crosses ultimately swung seaward as they approached Ypao Point. Except in the areas immediately adjacent to the plant, we expect all effluent to be carried gradually seaward.

GENERAL BIOLOGICAL IMPACT OF THE EFFLUENT AND PLANT CONSTRUCTION

As the effluent passes clear of the mixing action of the surf zone, thermal stratification occurs. The heated portion of the effluent is confined to the upper 1 to 2 m of the water mass and is no longer a threat to the benthic biota and most of the other organisms in the water column. Heated effluent was not apparent south of Transect C or north of Transect A.

Concern for potential environmental damage is, therefore, limited to the reef flat and reef margin opposite the plant and between Transects A and C. All other zones were found to be outside the limits of the effluent plume.

On the reef flat we found that the few scattered corals that occurred prior to plant operation died in the effluent plume. Fishes that are characteristic of the reef flat (many are territorial species) abandoned the plume area. The same was true for crustaceans and echinoderms. Benthic algae normally present in this area has for the most part disappeared and been replaced by a predominately blue green algae community. This implies that, with regard to the algal community, the area has reverted to an early stage of ecological succession that features the pioneering blue greens. The reef flat is not considered particularly rich in terms of diversity or biomass, and the area affected is confined to the immediate area of the effluent plume. A "normal" reef flat community is found immediately adjacent to the plume.

The most striking effect on the reef that we can attribute to plant effluent, is on the reef margin. A massive die-off of the reef coral community has occurred here. There is a central core of about 4320 m^2 spread along a linear front of about 108 m, where most of the corals have been killed. A peripheral zone lies outside of this area that shows dead, dying, and bleached corals (corals that have extruded their pigmented symbionts). This zone has shown a constant and gradual die off. The coral kill began in December, 1971, when the plant began full scale operation and is still going on today in the peripheral zones. The total area affected is 10,000 m^2 and spreads along 186 m of the reef margin.

The obvious question at this point is, what factor or factors in the effluent are affecting the corals? The first factor mentioned above, agitation, would not be involved with the coral kill but might affect entrained planktonic organisms through mechanical damage. This was not a part of the study and was not pursued except for one significant phenomenon. In this case, large numbers of the juvenile rabbitfish, <u>Siganus spinus</u>, were entrained by the circulating water and killed, possibly by mechanical damage from the pumps. We suspect that many thousands of these animals are killed when they make their seasonal migrations from the pelagic to the inshore environment. Enormous numbers of the juveniles are found in the intake channels of both the Tanguisson and Piti power plants during their migrations in April, May, June, and October.

Copper is known to be toxic to marine organisms. Total copper values in the outfall were at times nearly three times (2.9 ug/l) higher than the values in the intake channel (1.0 ug/l), and nearly 30 times higher than control samples taken one half mile to sea (0.1 ug/l). The values were quite variable and are still below those reported as normal in oceanic water (about 3 to 10 ug/l total copper). We are uncertain at this point as to what role copper might play in the death of the corals. This factor could be multiplied as the plant ages.

Chlorine is another toxic material that may cause the death of reef corals. There are no bioassay data available as to the level of chlorine that is toxic to coral species and we had no way of measuring either free or residual chlorine during the project. We did note on one occasion, when the power plant ran out of chlorine from November 2 to November 20, 1972, that reef flat fish species began recolonizing the reef flat and the stilling well (11 spp). These species seemed unaffected by the turbulence of effluent or the heat. However, when chlorination was started again, the species disappeared immediately.

Waste heat in the effluent is considered to be a very likely source of some, if not most, of the coral damage. We found a mean ΔT of 6.5°C during the first year of plant operation. The range of intake temperature was 26.5 to 28.5 and mean was 27.3°C. Outfall temperature ranges were 32.8 to 34.8 with a mean of 33.8°C. Sampling showed that, except during higher high water tides and heavy seas, there is little reduction in temperature from the stilling well to the reef margin. Wave attack immediately begins to mix the water, and the temperature drops as mixing proceeds. Seawater temperatures fluctuate between 29 and 32°C along the reef margin adjacent to the plant. Data on the elevation of temperatures along the reef margin are incomplete due to the inaccessability of this wave washed zone. We found that we were unable to work in this area except during rare periods of extreme calm. At these times the effluent was stratified and we were not able to measure its effect below about 1 m. Attempts to place in situ temperature recording instruments in this zone usually resulted in damage to the instruments.

In addition to effluent damage, there was some initial damage to the reef from construction activities. A channel was excavated from the reef margin and reef flat zones to provide access for cooling water to plant condensers. The rich coral community at the immediate entrance to the intake channel was obliterated by dynamiting and excavation. This constitutes an area of about 250 m^2. There was little damage done to the reef margin corals either to the left or right of this channel. The remainder of the channel has physically replaced about 1835 m^2 of reef flat environment. In terms of biomass and diversity, the loss is less than the smaller area disturbed along the reef margin.

THERMAL SIMULATION EXPERIMENTS WITH REEF CORALS

It is certain that plant effluent has caused a massive coral kill along the reef front, but it is not so obvious as to what plume parameter or parameters might be involved. Synergistic effects or other factors which we are as yet unaware of might be responsible for the damage.

A laboratory experiment was designed to eliminate all the potential stress parameters on reef corals except temperature. The system was set up at the Marine Laboratory and uses fresh, uncontaminated seawater from the reef margin at Pago Bay. Reef corals are subjected to temperature elevations of +2, +4, and +6°C above ambient. The experimental tanks are heated with immersion heaters and have electronic control devices with built-in ΔT sensor systems. The controls compare experimental tank temperatures with the ambient control tank temperatures($\bar{x}$ = 28°C) and automatically adjust the experimental temperatures to 2 degree increments above the existing ambient temperature. This, in effect, simulates the thermal influence of plant effluent while eliminating the other parameters.

Seven species of reef corals have been tested in the thermal simulator thus far. There was no significant difference in survival between most coral species in the ambient control tanks and those at +2°C above ambient. At +4°C above ambient, all the corals were usually dead within 6 to 14 days. The coralla went through the same stages of death as those at Tanguisson Point. The symbionts were expelled first, leaving the coral polyps bleached white. This stage was usually reached within a few days and was followed by death within the period described above. Coral species in the +6 tanks were usually all dead within 6 days. It would appear that the upper thermal tolerance limit for the majority of the species is between 30 and 32°C. These temperatures are not uncommon at the reef margin near the plant, at least for the small amount of data available from that zone. The apparent slow die off of the corals may be correlated with the mixing of plant effluent with oceanic water. Corals would not receive constant exposure in the peripheral zone of the coral kill due to variability of wave attack in direction and magnitude, tide cycle, and current direction. Corals tested at sublethal temperature elevations showed a general reduction in growth when compared with controls.

Effects of thermal stress on other marine organisms, specifically marine algae and echinoderms, are considered in separate reports in Appendices A to C.

SUMMARY

We feel that there is no doubt that effluent from Tanguisson No. 1 is responsible for the death of the corals along the reef margin as well as their continued dying. Laboratory data indicate that elevated temperature may be the primary but not necessarily the only causal factor.

Evidence gathered from the _Acanthaster_ killed reef front, submarine terrace, and seaward slope zones indicates that corals are now resettling and recolonizing these areas. There is no evidence of coral resettlement in the reef margin area within the influence of effluent. Furthermore, it is apparent that the coralline algae are also being killed by the effluent. These organisms normally cover corals killed by _Acanthaster_ and result in a stabilization of the reef structure that prevents erosion. There is the possibility that the absence of both calcium carbonate secreting corals and coralline algae will result in biogeochemical erosion of the reef platform opposite the power plant.

It seems quite likely that if Tanguisson No. 1 is still killing corals in the peripheral area after one year of operation, then the recently completed Tanguisson No. 2 will increase the kill rate. We are uncertain at this point as to the extent of the additional damage that might be brought about by Tanguisson No. 2. These effects will have to be monitored.

SECTION II

RECOMMENDATIONS

Jokiel and Coles[11] recently completed a study of the Kahe Point power generating facilities in Hawaii. Their results are similar to ours and we feel that they summed up the problem quite well.

> "The use of the marine environment for the disposal of waste heat is an attractive concept in a land-scarce island community. Cooling tower and cooling pond schemes are expensive in terms of terrestrial space. The Pacific Ocean represents a heat sink of incomprehensible proportion. The major problem in using the ocean as a receiving body for the heat lies in getting the waste heat far enough away from the shoreline so that shallow inshore marine communities are not disrupted. Initial dilution with the receiving water mass must be high so as to avoid excessive temperature increases over ambient conditions."

We are in agreement with the logic expressed above and would recommend the following:

1. Abandon the present outfall structure.
2. Build a new outfall line from the two power plants to edge of the submarine slope (a distance of about 250 m and depth of about 10 m).
3. Place a diffuser structure at the end of the line.
4. Use the existing intake channel for the pipe run through the reef flat and reef margin, thus eliminating the need for additional channeling. If channeling is necessary on the submarine terrace, now is the time to do it. Coral recovery is at an early stage and would not be significantly affected if construction is completed soon.

The above action would result in relief of stress on the damaged reef margin zone and we suspect that corals and coralline algae would recolonize the area. Effluent released offshore would rise rapidly to the surface due to the low density of hot water. This would provide a 10 m deep mixing zone and the resultant surface plume would be stratified and well clear of the benthic reef biota.

SECTION III

INTRODUCTION

BACKGROUND

The island of Guam lies at the southern end of the Mariana chain. This far-flung territory of the United States is experiencing the pressures of boomtown growth. Both civilian and military components are contributing to this phenomenon. The island population in 1960 was 67,000 -- it now stands at 85,000 and the rate of growth shows no sign of decreasing in the near future. There is at present a frantic expansion of construction activities on the island to create more homes for the growing population and to provide more industrial, business, military, and tourist facilities which support the expanding economy.

The explosive growth of so many power-consuming entities has, predictably, caught the island woefully short of power-generating facilities. This has led to short term and often shortsighted planning for new generating plants. The net result is that locations for these new facilities are frequently chosen for convenience of the power industry and with little regard for the environment.

In order to meet the expanding power needs of Guam, plans were made to construct generating facilities at Tanguisson Point (Fig. 1). A series of four units were to be constructed on an incremental basis over a period of years to try to keep abreast of the growing power curve. Unit No. 1 was scheduled for completion in early summer 1971.

Each unit was to have a generating capacity of about 26 megawatts. The units were to be oil-fired, steam electric facilities, utilizing sea water for condenser cooling. Cooling water for all units was to be taken from the adjacent waters of the Philippine Sea through an intake channel, 14 m wide and 2 m below mean low water, cut through the reef margin and reef flat. Plans for Unit No. 1 called for two circulating pumps with capacities of about 17,000 gpm each, to carry water to the condensers. Heated effluent was to be released in an outfall channel,

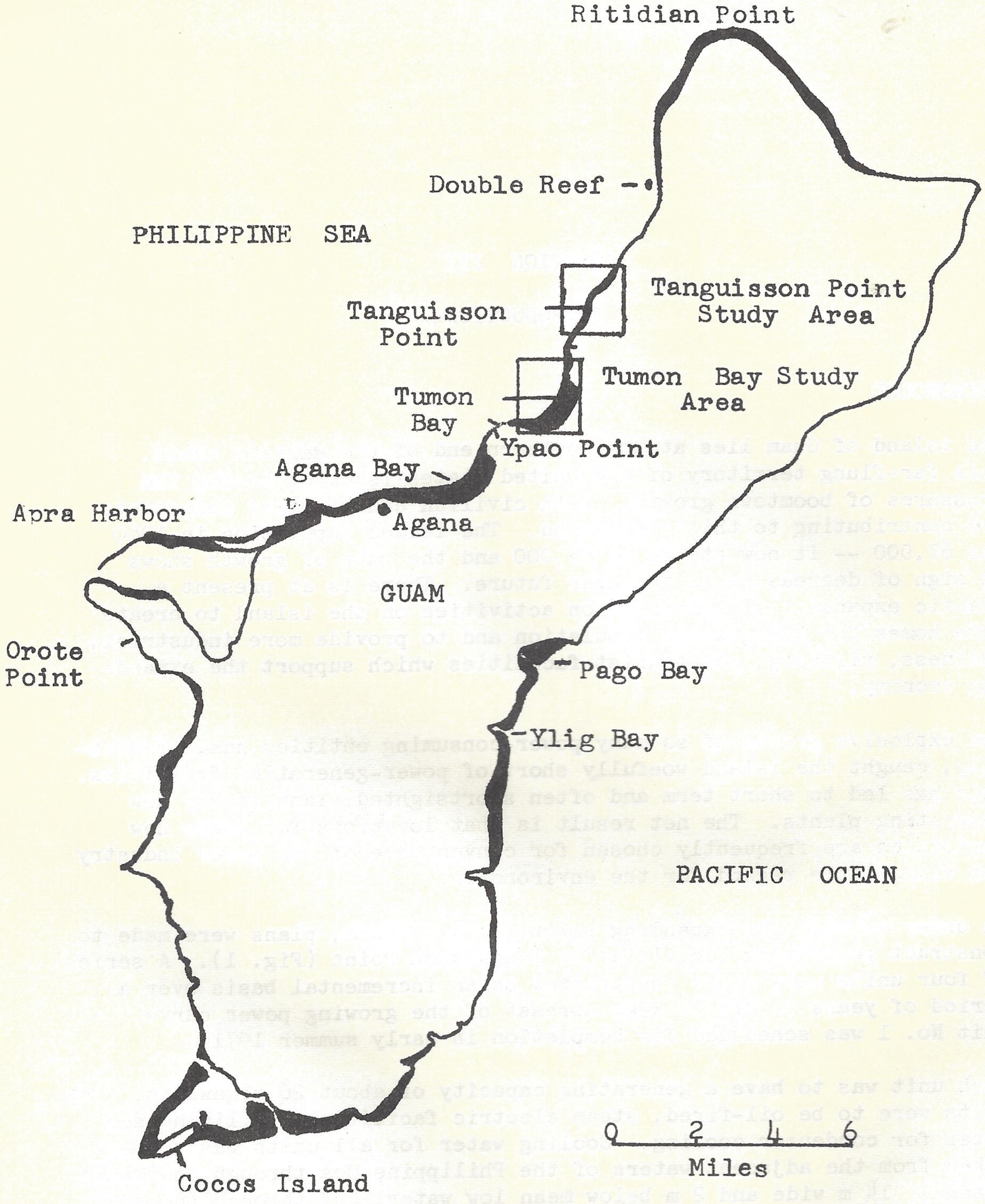

Figure 1. Location map of Guam showing study areas and fringing reef platform. Reef platforms are shaded. Map modified from Emery (1962).

also excavated from the reef flat and reef margin. With one pump on the line a ΔT of 12-14°F was predicted and with two (about 28,000 gpm) 9-11°F (personal communication, Frank Melder). Operational plans called for use of both pumps about 50 percent of the time during peak power times. (At the writing of this report, the Tanguisson system was using only one pump most of the time, personal communication with P. E. Cavote).

At the suggestion of EPA Regional officials, the University of Guam submitted a research proposal to study the effects of Unit No. 1 on the adjacent marine environment. This initial proposal was accepted and the grant awarded on September 13, 1969.

SCOPE OF STUDY

The primary objective of the research was to evaluate (Phase I) the biological condition of a section of coral reef at Tanguisson Point prior to the completion of Unit No. 1 and then to reevaluate the reef (Phase II) after the plant became operational. The second phase would provide a catalog of the induced environmental changes, if any. This objective, in spite of its simplicity, was deemed valuable because it was to be the first such study of thermal impact on a well-developed fringing coral reef.

As a secondary objective, the survey included a study of the effect of the coral feeding crown-of-thorns starfish, *Acanthaster planci* (L.), which had recently invaded Guam. The significance of this study was twofold. First it was necessary to document (Phase I) any existing damage attributed to the starfish and thus avoid possible confusion with effects of thermal effluent that might be "discovered" later. Second, existing starfish damage provided a unique opportunity to study reef recovery following severe damage (Phase II). The starfish, in essence, simulated an environmental catastrophe that might have occurred through some form of pollution.

By a fortuitous circumstance, one of the authors (Randall) had been studying the distribution of reef corals prior to the starfish infestation in Guam. This study was concentrated on the fringing reef opposite Tumon Bay, an area contiguous with the Tanguisson Point study area (Fig. 1). These valuable collections and transect information form a cornerstone for this report because they provide us with a control area comparable with the Tanguisson study area and allow us to make some reasonable approximations of what the Tanguisson reef was like in an undisturbed condition.

Delays in plant construction and the usual difficulties encountered in trying to evaluate an ecosystem as complex as the coral reef resulted in several no cost extensions of the original grant and considerable modification of the specific objectives. The first grant period was from 1 September 1969 to 31 August 1970. Three no cost extensions were necessary and extended the grant period through 30 September 1971. During this period, studies of ecological succession were planned in intake and outfall channels to be excavated adjacent to the plant. Phase II comparisons were to document successional changes between intake and outfall channels once the plant became operational. This objective was not possible because excavation of the outfall channel never materialized. Instead, plans were made to release effluent directly on the reef flat. The intake channel was eventually excavated late in Phase I of the project. The contractor continued to work on intake structures within this channel until after the first grant period expired. During this time, the channel was rarely clear of turbid water and heavy sedimentation. As a result virtually no organisms settled in the channel and the objective had to be deemphasized.

A study of the succession of reef organisms following destruction of the corals by Acanthaster planci was begun on the submarine terrace and seaward slope as planned. After considerable trial and error to establish methods of evaluating the succession of a wide variety of marine organisms including benthic algae, invertebrates, and fishes, we found that the most rewarding and quantifiable data collected lay in the transect study of coral resettlement. The result is that Phase I concentrated on accumulating baseline physical and chemical data and emphasized the coral recovery aspect of succession.

Near the end of Phase I, a continuation proposal was submitted to begin Phase II. The study period was from 1 October 1971 to 30 September 1972. Plant start up had been delayed and was now expected in December 1971. The continuation proposal was accepted, however, in addition to the original Phase II objectives, the Agency asked that heavy metals be monitored and that thermal stress experiments be done in the laboratory. These additional objectives were added without increase to the project budget. The net result of the additional work load and cost was further deemphasis of some of the original proposal objectives and increased emphasis on the coral succession work and the new thermal simulation experiments.

This paper reports on the progress of the work thus far and sets the stage for a possible request for a third year of funding. At this point, the project is in an extension period that will end 30 June 1973. There is a need for rapid dissemination of the results of the study because of the impending completion of a second power generating unit at Tanguisson Point. (At the time of writing, Tanguisson No. 2 was in operation).

SECTION IV

THE STUDY AREA

GENERAL DESCRIPTION OF GUAM

Guam is the largest and most southerly of the fifteen small islands that make up the Mariana group in the western Pacific Ocean. It is 48.3 kilometers in length, and ranges in width from 6.5 kilometers at the narrow central waist to 18.5 kilometers at its widest part. The island has a land area of 549 square kilometers.

The northern half of Guam, that includes the study area, is a limestone plateau bordered on the coasts by steep cliffs that range in elevation from more than 180 m at the north end to less than 60 m at the centrally located, narrow waist. The limestone is porous and no streams are found on the northern plateau. The western and northern coasts are bordered by fringing reefs, whereas the more windward eastern coasts are bordered by cut benches and narrow terraces.

CLIMATE

The following summary of climate and rainfall data is condensed from a report found in Tracey, _et al_[1]. Guam has a warm, humid climate that is mainly determined by its oceanographic setting. The island lies within the belt of westward-moving, warm humid air of the tropics, which is produced between the subtropical anticyclones of the northern and southern hemispheres. Variations in the weather are caused by cyclonic eddies or whorls that form continuously, sweep westward, and dissipate. These disturbances may grow in size to become tropical storms or typhoons. The period from July to November includes the rainy months, January to May is considered the dry season, and June and December are transitional months. The mean annual rainfall on Guam ranges from less than 228.6 cm in the lee of the mountains to more than 279.4 cm in the higher mountain areas. About two thirds of the annual rainfall occurs during the rainy season. Tradewinds predominate during the dry season. Winds usually become light and variable during the wet season, except during storm conditions.

PHYSIOGRAPHIC DESCRIPTIONS

General Comments

The northern limestone plateau, which borders both study areas, is very porous, resulting in a well-developed Ghyben-Herzberg fresh water lens system. Water escapes continually along most sections of the intertidal zones of both Tumon Bay and Tanguisson Point. This fresh water seepage onto the reef flat is particularly noticeable along sandy beaches at low tide, where it forms small rills. Emery[2] measured the fresh water seepage along a 47 m section of Gogna Beach at Tumon Bay and found it to be 42.5 liters per second. Analysis of beach samples from Tanguisson Point by Emery[2] shows that the sediments of this region are nearly 100 percent bioclastic material. This is due to the absence of rivers and streams emptying onto the reef flats of the study areas.

Tanguisson Unit No. 1 is located on an elevated terrace that is covered with beach deposits (Fig. 2). Vegetation around the plant is composed of an old coconut plantation and a well-developed strand vegetation along the beaches. This terrace is backed by steep limestone slopes and a cliff on the landward side. The cliff reaches heights of about 100 m. Both the slopes and cliff support dense limestone forest vegetation. To the south, the terrace narrows down and eventually disappears near Amantes Point (Fig. 1). To the north, the terrace includes the Naval Communications Station (NCS) swimming beach and then continues along the coast up to Hilaan Point where it narrows to a thin strip. Immediately to the west is the first of the reef zones described below.

The reef platform and slopes are divided into several reef divisions after Tracey, _et al_[1]. These divisions are based on various physical parameters such as degree of reef surface exposure at high tides, degree of reef surface submergence at low tides, amount of reef slope, and reef growth and erosional structures.

The biologic parameters have been deliberately omitted from the fringing reef descriptions. This was done because later parts of this report (Section X) describe reef coral distribution by zones in detail, and because future workers investigating reef recovery would experience difficulty in comparing structures and descriptions of former living coral reefs with those that have since been killed by _Acanthaster planci_.

A series of transects were established and are shown on Figure 3. Reef profile and zones for the Tanguisson study area are shown on Figure 4.

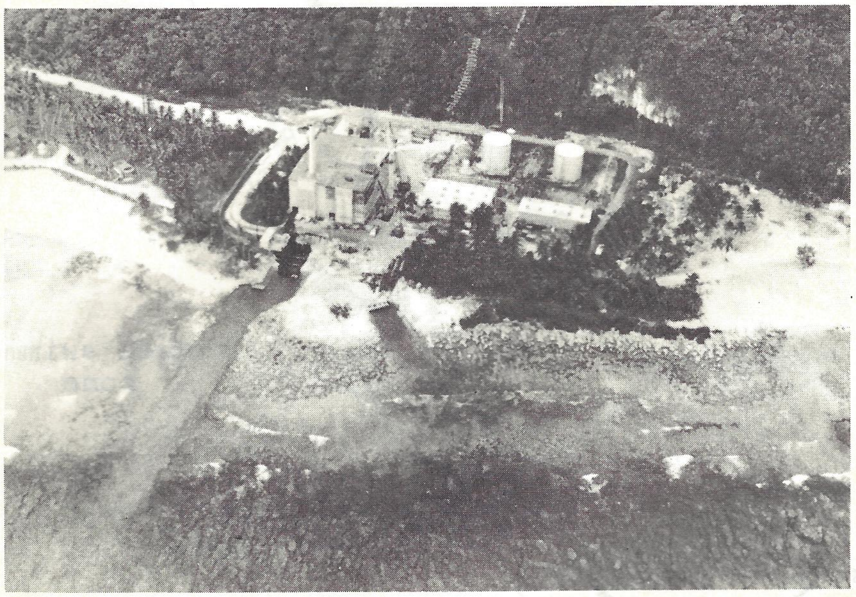

Figure 2. Aerial photograph of Tanguisson No. 1 site. Tanguisson No. 2 is under construction directly adjacent to No. 1.

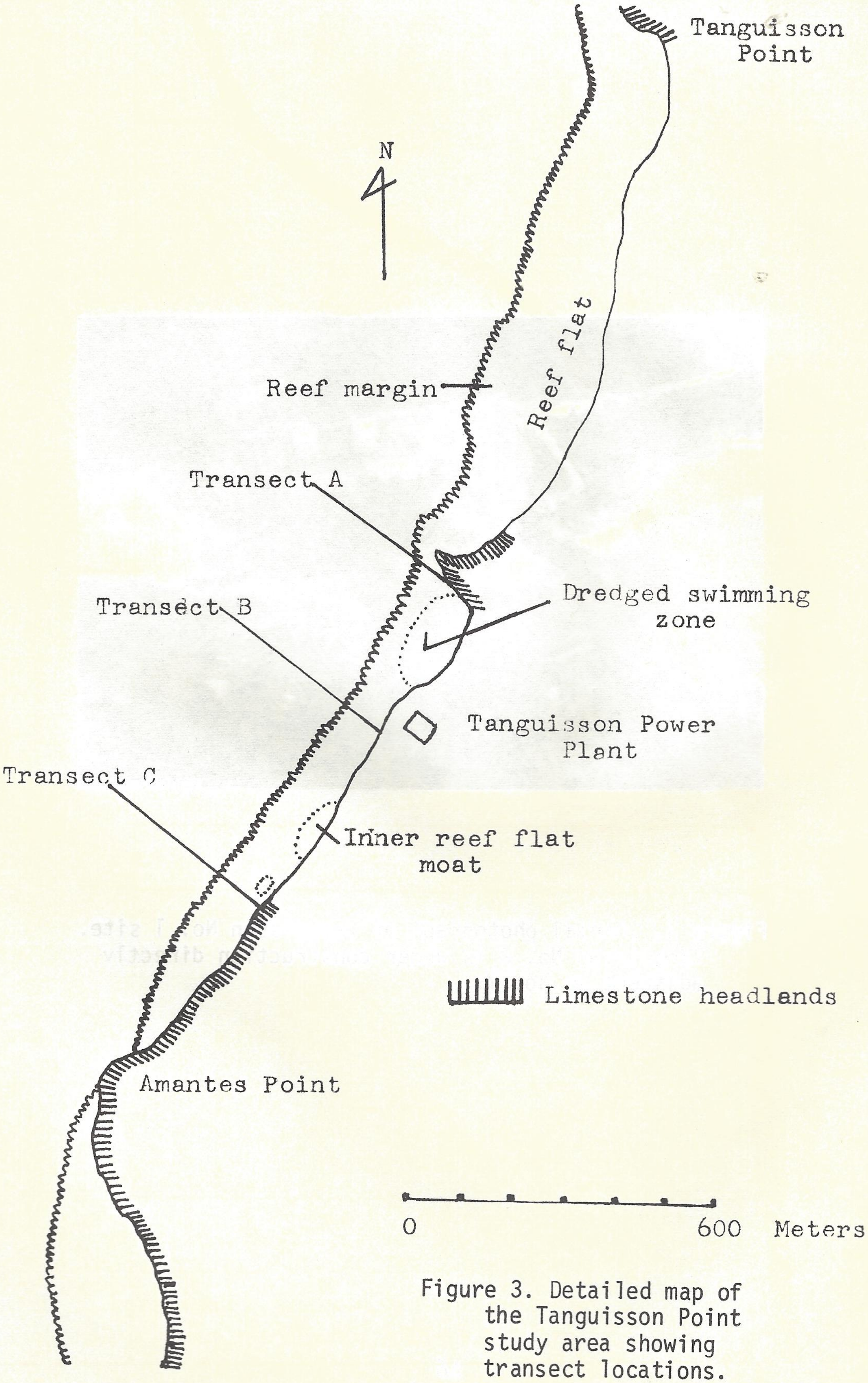

Figure 3. Detailed map of the Tanguisson Point study area showing transect locations.

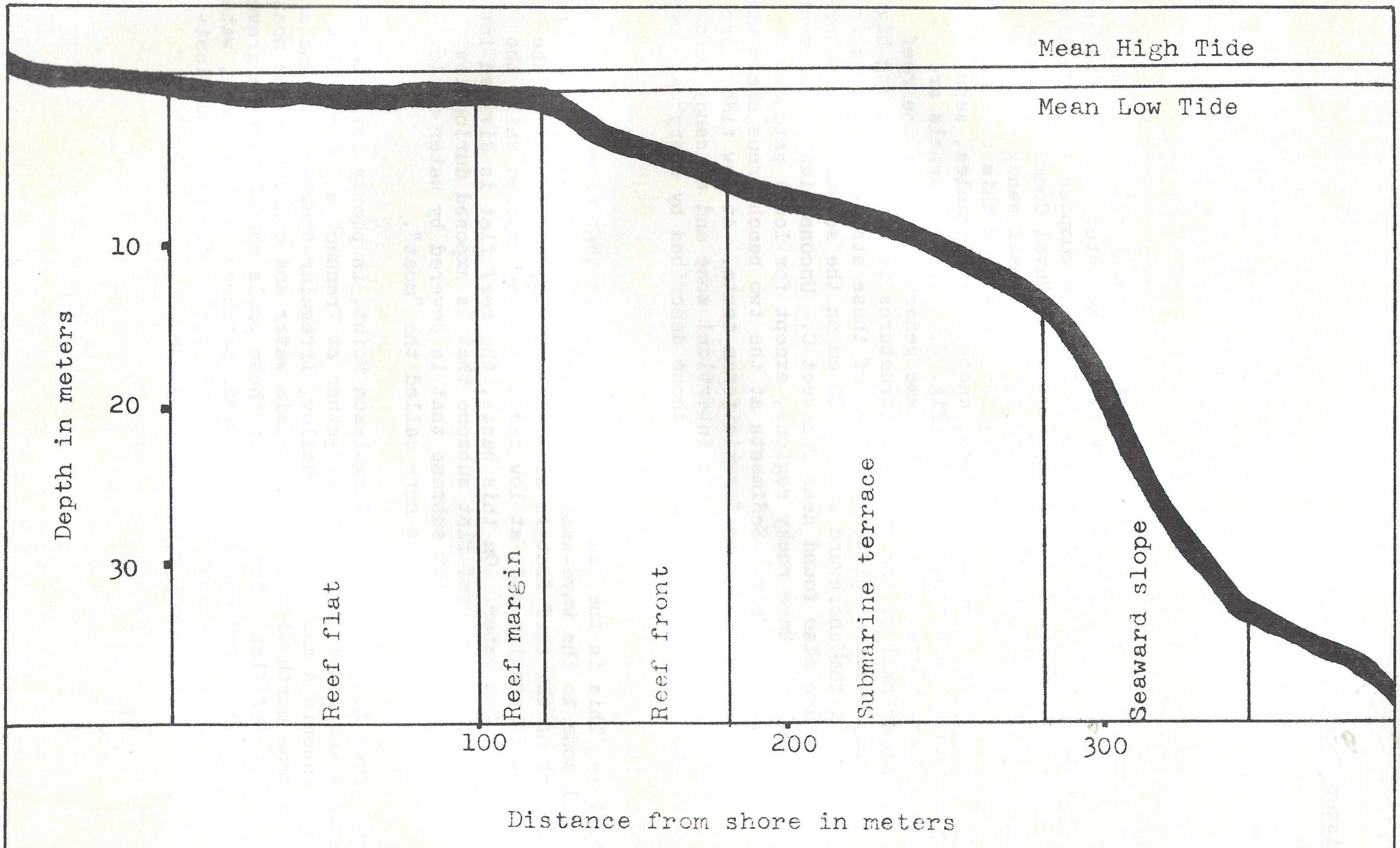

Figure 4. Reef profile at Transect B, Tanguisson Point; vertical exaggeration X5. The flattened region seaward of the seaward slope is the beginning of the second submarine terrace.

Tanguisson Point Fringing Reef

Tanguisson Point study area (Figs. 1-3) is located between Amantes Point and Tanguisson Point. The fringing reef platform along this section of coastline is relatively narrow. It ranges in width from 70 m at Transect A to 110 m at Transect C. The fringing reef has a westerly exposure to the sea.

Intertidal -- This zone is the portion of the beach or shore covered by water at high tide and exposed at low tide. The intertidal zone bordering the transect locations at Tanguisson Point is composed of bare limestone, with the exception of a sandy section at Naval Communication Station (NCS) swimming beach, and several other small sandy sections between Transects B and C (Figs. 2-3). At Transect B this zone is 40 m wide and consists of limestone ridges, knobs, and pinnacles, separated by numerous interconnecting channels (Fig. 2). These channels are relatively flat-floored and about the same general level as the reef flat. The upper half of the emergent structures is exposed during high tide and deeply solution-pitted. Relief of these structures ranges from about a meter at the shoreward side to 20 cm on the seaward side, where the structures are also found near Transect C. Unconsolidated sediments are scarce along the bare rocky regions, except for local patches of course gravel and boulders. Sediments at the two beach areas are mostly sand, largely composed of worm foraminiferan tests. At low tide fresh water can be seen escaping from the intertidal zone and at sandy locations it forms small rills similar to those described by Emery[2] at Gognga Beach.

Reef Flat -- This is the flat limestone platform that extends from the intertidal zone to the wave-washed reef margin (Figs. 2-4). The outer seaward part of the reef flat is slightly elevated in respect to the inner shoreward section and, at low tide, is often exposed while the inner part retains water. On this basis, the reef flat is divided into two subzones--an outer reef flat subzone that is exposed during low tide, and an inner reef flat subzone that is covered by water at low tide. The inner water mass is here called the "moat".

The inner reef flat subzone at Tanguisson Point, is poorly developed at Transects A and C and is absent altogether at Transect B. During low tide at Transects A and C, a few shallow, irregular-shaped pools and a depressed zone north of Transect C retain water and constitute the moat of the inner reef flat. The floors of these pools contain coarse gravel, boulders, and scattered emergent limestone patches. At NCS Beach, water is retained at low tide, but this is partly due to dredging and blasting and does not represent natural conditions.

The outer reef flat subzone is more extensive than the inner reef flat and represents most of the reef platform. At Transect B, where no inner reef flat occurs, the outer reef flat extends from the reef margin to the intertidal zones and is 60 m wide. At Transects A and C, the subzone width is 50 m and 90 m respectively. At low tide, the exposed platform is a flat pavement with very little relief. A few small shallow pools (10 to 50 cm deep) are widely scattered over the surface. Sediments are scarce and accumulate only in the small scattered pools. An algal turf covers most of the surface and contains many foraminifera.

Reef Margin -- This zone is represented by the seaward edge of the reef flat platform that is constantly awash even at low tide (Figs. 2-4). The reef margin at Tanguisson Point is slightly elevated, about 20 cm above the outer reef flat level, and forms a low, poorly-developed algal ridge. The algal ridge development is greatest at Transect B. Observations immediately seaward of Transect B show that the degree of reef front slope is less than at Transects A or C, causing greater surf action and thereby enhancing algal ridge development. The reef margin width is fairly uniform and, at the transect locations, ranges from 20 to 30 m. The seaward edge is very irregular and is cut at right angles by short surge channels 1 to 3 m wide, 2 to 4 m deep, and up to 20 m in length. Some surge channels coalesce and fuse at their upper margin, forming cavernous channels beneath the reef margin platform. Most of the cavernous channels open at intervals along the fusion zone, forming pools and open cracks. In cross section, most surge channels are wider at the bottom than at the upper margin, which may be due partly to growth at the upper regions and abrasion at the base or floor which contains large, rounded boulders. Most boulders, however, do not show evidence of constant movement because most are encrusted with red algae and small coral growths. These boulders are probably moved about only during typhoons and other storms. Surge channels are separated by lobate elevations called buttresses (Fig. 2) that slope seaward toward the reef front zone. The upper surface of a buttress is very irregular, with knobs, pinnacles, and in many places is honeycombed with numerous interconnecting holes.

Reef Front -- The reef front represents the extreme seaward edge of the reef flat platform, where the reef margin abruptly increases in depth and degree of slope (Figs. 2 and 4). This zone is constantly covered with water. The reef front is composed of the seaward sloping extensions of the reef margin buttresses and surge channels. The point where the submarine buttresses and channels terminate marks the seaward boundary of the reef front (Fig. 2). Generally, the 6 m submarine contour coincides with the seaward limit of the reef front. Width of the reef front zone is variable and ranges from 70 m at transect A to 60 m at Transect C. Submarine channels near the reef margin are 2 to 6 m in depth and commonly branch into several secondary channels. These channels are similar in cross section to those described above. Some submarine channels widen into holes 5 to 15 m in diameter, with large boulders covering their floors. Submarine buttresses slope seaward at 10° to 15° and are extremely irregular on the upper surface due to the presence of coral-algal knobs, bosses, and pinnacles. At the seaward half of this zone, these various prominences may have a relief of as great as 2 to 3 m.

Submarine Terrace -- The first submarine terrace represents a noticeable flattened region when compared to the reef front and seaward slope zones (Fig. 4). This zone ranges in width from 40 m at Transect C, to 110 m at Transect B. The shoreward margin of this zone begins at the 6 meter contour but its seaward margin, where the steep seaward slope begins, is located at the 10 to 15 m contour. Relief of the surface features ranges from 1 to 2 m. Occasional coral mounds or pinnacles attain a relief of 3 m. Shallow channels up to a meter in width and depth cut across the surface at some locations. Sediments are found in localized patches in holes, cracks, and in shallow channels. These sediments consist mostly of rounded boulders, coarse sand, and gravel.

Seaward Slope -- At the seaward margin of the Tanguisson Point submarine terrace, the degree of slope abruptly increases and sharply differentiates the seaward slope from the terrace. Width of this zone at the three transect locations averages 70 m. The steep seaward slope flattens into a second submarine terrace at about the 30 to 35 m depth. This second terrace probably corresponds to the 32 m submarine terrace found by Emery[2] at Tumon Bay.

Distinct linear sediment tracks can be traced from the upper part of the slope to the second submarine terrace below. Although depth of sediments was not measured at the second terrace, visual observations made with SCUBA equipment indicate a considerable accumulation at the base of the slope.

A conspicuous feature of the second submarine terrace is the presence of scattered coral knolls. These knolls arise from the sandy terrace floor at a 40 to 45 m depth and have a relief of up to 10 m.

SECTION V

CURRENT PATTERNS

GENERAL COMMENT

Transport of water masses around the island of Guam is similar to that for most islands in the Central Pacific (i.e. Avery, et al[3]). The prevalent northeast tradewinds of the area play a major role in generating the enormous North Equatorial Drift Current that sweeps by the island from east to west. This great current is responsible for much of the energy that transports water along the coasts. According to Emery[2] the north equatorial current splits on the northeast corner of the island and streams around the south end at Cocos Island and around the north at Ritidian Point (Fig. 1). These two streams then sweep along the west coast were they supposedly rejoin off Apra Harbor. As they move along the western coast, the near shore portions of the streams are distorted and forced into complicated eddy systems by prominant headlands and local submarine topography. These currents may also alter their flow because of seasonal changes in strength and direction of the North Equatorial Current. They are further complicated in some areas by tidal currents superimposed on them, often resulting in a temporary reversal of direction with changes in tide (Jones and Randall[4]).

Inshore water movement is generated primarily by tide changes and wave action. These two forces combine to transport water over the reef margin onto fringing reef platforms around the island. This water often forms long shore currents on reef flats, for some distance, and then returns to sea as rip currents via natural low spots and surge channels through the reef margin.

It seemed apparent at the beginning of this study that the Tanguisson water mass could be divided into three parts. First there is the shallow water portion bathing the reef flat and a portion of the reef margin. Second, there is that portion which encompasses the reef front and remainder of the reef margin. The third component includes the submarine terrace and seaward slope. Overlap of the first two parts may occur because of surge activity in the shoaling water that mixes them.

Effluent released on the reef flat would be influenced first by current patterns generated there and then pass into the influence of reef margin and reef front water transport systems. After some mixing because of wave attack in these zones, the remaining effluent would be carried offshore where it would join the currents that dominate the water mass over the terrace and slope.

REEF FLAT AND UPPER MARGIN

Prior to plant startup, a series of reef flat stations were established at the proposed outfall site near Transect B and along the coastline towards both Transects A and C (Fig. 3). Current patterns were investigated by releasing fluorescein dye at these stations. The dye powder was sewn into cloth bags and buoyed. Movement of the dye was timed and plotted on scaled area charts and in some cases recorded with time lapse photography. Wind, wave, and tidal data were recorded. The dye study schedule was set to include both high and low tide stands and to cover ebb and flow.

The same methods were used to study changes in current pattern induced by the release of plant effluent after startup of Tanguisson No. 1. Dye releases were then concentrated at the stilling well of the plant outfall and around the intake channel. Construction of Tanguisson No. 1 was under the jurisdiction of U. S. Navy Public Works and requests were made to the Officer-in-Charge of Construction for current studies that might have been made in the area during the planning stages. Although some offshore and inshore dye studies had been made, little data could be found to indicate the results of the study. One unidentified site plan was located that showed a series of arrows drawn on the reef flat that indicate current direction. These arrows show water flowing from the NCS (Naval Communication Station) swimming lagoon across the proposed intake channel and thence seaward at a point directly adjacent to the power plant.

By the time our project began, the contractor had constructed an earth fill causeway parallel to the proposed intake channel. The causeway was used to excavate material blasted loose from the reef margin and reef flat. When the intake channel was completed the causeway was removed. Presence of the causeway and then the completed channel made it impossible for us to determine current patterns over the Tanguisson reef flat prior to construction. However, we have reason to believe that they were as the Navy chart shows in part and in part as discussed below.

Because the Tanguisson reef flat has a slightly raised seaward margin, there are two natural ways in which seawater may encroach on it. Rising tides periodically cover and uncover it, and water transported by wave action may pour over the margin and spread out over the reef flat. The predominant swell direction on Guam is northeasterly. This swell becomes more northerly as it wraps around Ritidian Point. Swells approach the study area consistantly from the north and north northwest. As the swells begin to "feel bottom" on the submarine terrace they wrap until they basically approach the shore at right angles. Most break along the margin from the northwest. Currents on the reef flat are generated by water on the platform returning seaward. In the study area, there are six major points where this seaward flow occurs (Fig. 5, I-VI). These are usually natural low spots on the reef margin and have one or more large surge channels associated with them. There is a low point in the reef at the north end of the NCS swimming lagoon (I). A smaller channel occurs near the center of the margin bordering the lagoon (II). The recently excavated intake channel provides an artifical escape point through the reef margin (III). Immediately southwest of the intake channel there is an area of deep caverniculous surge channels that cover a broad front opposite the outfall structure and Transect B (IV). This is one of the dominant points for the seaward escape of water from the platform. The natural depression in the margin is 50 m wide and has five to seven major surge channels through it. The fifth and sixth escape points for water on the reef flat are two narrower sectors of reef margin with caverniculous surge channels similar to the above (V-VI). These points are located opposite the sandy beach just north of Transect C.

The following discussion considers the various currents generated on the reef flat prior to plant startup (Fig. 5). During the somewhat rare times of calm seas (little or no swell) flood tides gradually cover the reef flat and there is a net movement of water shoreward with little or no movement seaward. Dye placed in the intertidal in the vicinity of Transect B tended to form an even stain and spread out from the shore by diffusion of the dye particles. It usually took 30 minutes or more for the cloud to reach the reef margin. Ebb tides under similar conditions (calm sea) show a net movement seaward through the six points in the reef described above. This continues until the Tanguisson reef flat is completely uncovered except for a few depressions that retain water even at low tide. Due to the absence of an inner reef flat opposite the power plant, there are few such pools. Large pools occur in the moat that forms south of Transect B and in the NCS swimming lagoon. Dye introduced at Transect B and opposite the outfall showed a positive movement seaward, on ebb tides, through the cavernous surge channels along the adjacent reef margin (IV). It took a dye cloud an average of 20 minutes to reach the reef margin surge channels.

The situation described above changes somewhat if there is a surf breaking on the margin. On a flood tide, wave transport adds to the net shoreward movement. Dye placed in the intertidal opposite Transect B and the outfall, again showed a net movement seaward due primarily to diffusion. This movement was very slow due to resistance caused by translated waves on the reef flat. The dye patterns tended to oscillate back and forth with each wave surge, just maintaining a net seaward movement. The direction of movement is still toward the surge channel sector opposite the plant (Fig. 5, IV). During high surf conditions (3 + m), it often took the dye cloud up to 60 minutes to reach the reef margin. A combination of ebb tide and wave transport resulted in the same oscillatory movements of dye clouds but the net movement to the surge channels at the reef margin was somewhat faster, about 20 to 25 minutes depending upon the magnitude of the surf. There are times, during strong west winds, when some of the dye spreads northeast and enters the intake channel of the plant.

Figure 6 shows conditions that now exist since startup of Tanguisson No. 1. Water that formerly entered the intake channel from the adjacent reef flats still does so but the strong rip current that moved seaward before plant startup has been reduced somewhat because of currents generated in the channel by the power plant's circulating pumps. Except at the surface on the seaward end, there is now a net movement of water in the intake channel toward the plant.

Current patterns opposite the outfall structure have been modified in speed but not direction by plant effluent (Fig. 6). Circulating water is released in a stilling well at the intertidal. The effluent wells up onto the reef flat and moves seaward. During low tides and periods of low surf, there is a well-defined stream of water that flows in a direct line seaward. It takes 10 minutes or less for dye released at the stilling well to reach the margin. Effluent enters the reef margin and pours seaward through surge channels. During low spring tides, the effluent forms cascades off of the reef margin into surge channels. At high tides and periods of high surf, the effluent stream is interrupted at the reef margin by wave transport. At this time, part of the stream occasionally turns south. This water may exit at the second set of surge channels near Transect C (Fig. 5, V & VI). The larger portion of the effluent merges with part of the incoming wave transported water and escapes seaward through surge channels opposite the plant, in a series of pulses between wave crests.

LOWER REEF MARGIN AND FRONT

The lower reef margin and front are essentially transition zones between the reef flat and upper margin water masses and those of the terrace and seaward slope. Dye studies were also used in this area

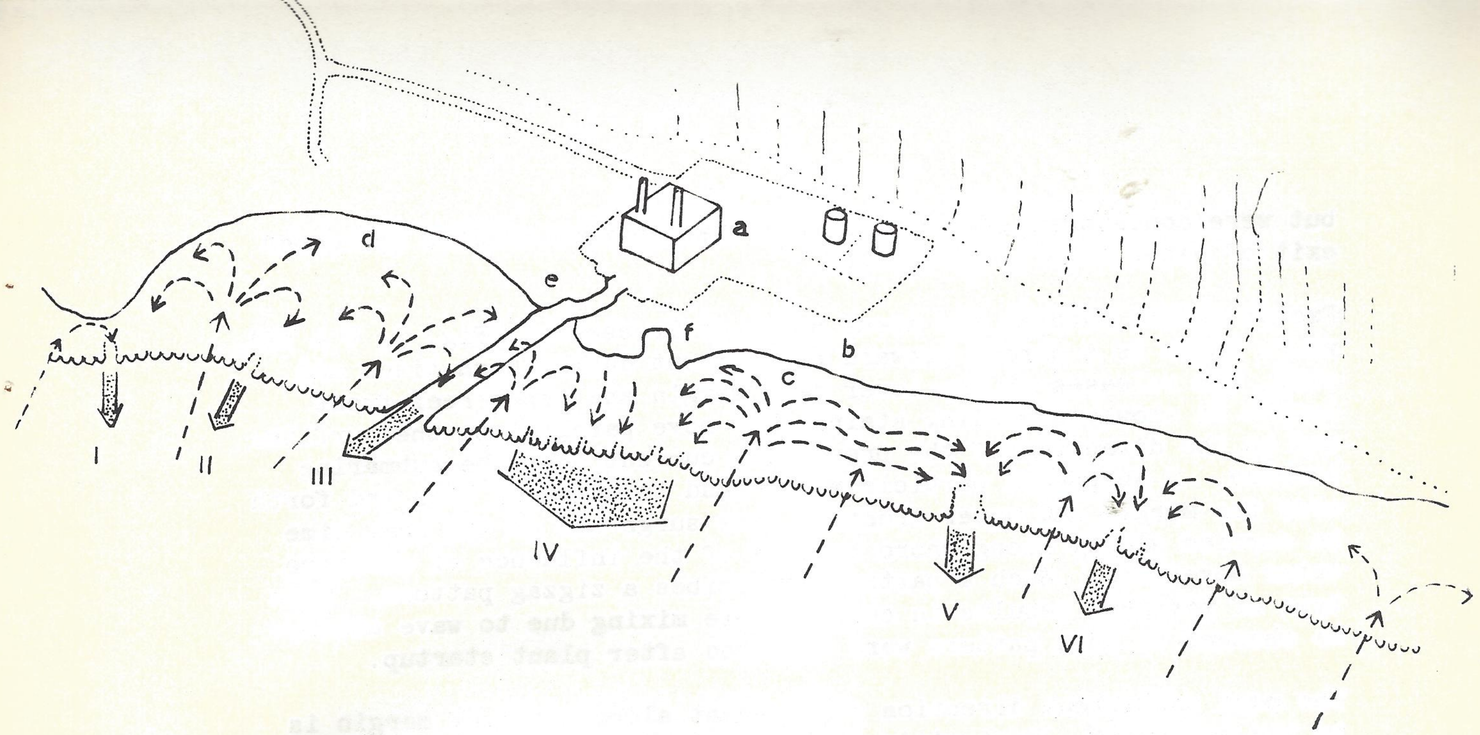

Figure 5. Current patterns on the reef flat prior to release of effluent. The dashed lines show movement of wave transported water onto the reef flat and the subsequent movements of that water along shore. The stippled arrows, labeled with roman numerals, show the major escape points of the reef flat water. (a- power plant, b- shoreline, c- reef flat, d- Naval Communications Station swimming lagoon, e- intake channel, f- outfall site).

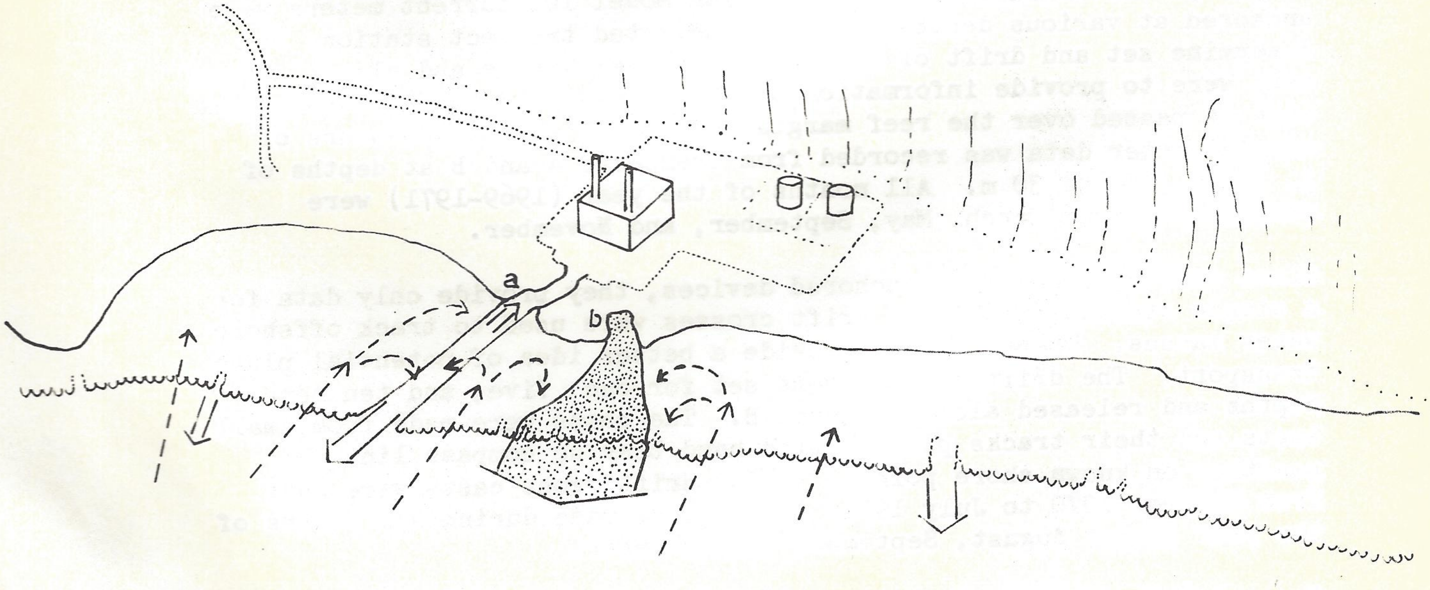

Figure 6. Current patterns on the reef flat after release of effluent. The actual changes are shown at the intake (a), and outfall (b) channels; otherwise, the patterns are the same as figure 5.

but were concentrated where the reef flat current studies indicated exit of water from the reef flat.

Except in the natural low areas north of Transect C (Fig. 5, V & VI), where there is a strong seaward rip current during high tides and surf, dye releases on the lower reef margin and upper reef front result in slowly spreading stains that move parallel to the surfline and in the direction of the prevailing current over the submarine terrace. A suspended particle would tend to be swept back and forth over the margin and upper front by wave surge and at the same time be carried slowly along shore because of the influence of offshore water movements. Such a particle describes a zigzag pattern. This type of movement results in considerable mixing due to wave attack. No changes in this pattern were observed after plant startup.

The most consistent direction of movement along the reef margin is to the southwest. West winds and strong tidal shift may set this water to the northeast on occasion.

SUBMARINE TERRACE AND SEAWARD SLOPE

These areas tend to be dominated by the northwestern branch of the North Equatorial Current that swings around Ritidian Point, and by tidal currents.

A Hydroproducts Model 502 and three TSK Model 101 current meters were anchored at various depths and along selected transect stations to determine set and drift of currents over the terrace and slope. These data were to provide information on the movement of the effluent plume once it passed over the reef margin and front. Over 1600 hours of current meter data was recorded from Transects A and B at depths of 5, 10-14, 23 and 30 m. All months of the year (1969-1971) were monitored except March, May, September, and November.

Since current meters are anchored devices, they provide only data for a single stationary point. Drift crosses were used to track offshore water masses. These devices provide a better idea of potential plume transport. The drift crosses were set for one, five, and ten meter depths and released along Transect B. The casts were made from small boats and their tracks plotted with hand bearing compass lines of position on known shore points. Fifty drift cross casts were made from October 1970 to July 1971. Casts were made during all months of the year except August, September and November.

Our original plan was to rely primarily on <u>in situ</u> current meter data for delineating current patterns opposite the plant site at Tanguisson Point. The Hydroproducts Model 502 meter was borrowed from another project to allow us to begin our work prior to ordering additional meters for the project. The first set was made in December 1969 and additional sets were made in January and February 1970. This meter was unavailable for use from March through May. In April, funding was available and we had located the meters we wanted to purchase for the project. Orders were placed for TSK meters. We were able to use the Hydroproducts meter again from June through August. The TSK meters arrived in September and were prepared for use. These meters were used heavily through the month of October and November. Analysis of the tapes showed considerable variation between the TSK meters and the Hydroproducts meter. Basically the TSK meters showed a bidirectional flow at Tanguisson while the Hydroproducts instrument indicated a unidirectional flow. We feel confident that the bidirectional flow of the three TSK meters is a truer picture than the unidirectional flow indicated by the one Hydroproducts meter. Since there was some question about data gained from <u>in situ</u> meters, we elected to use more drift cross data than originally planned. These data tend to bear out the bidirectional flow shown by the TSK meters.

Seas were rough on Guam through the month of November 1970 but a period of calm appeared again in December. During this time the TSK meters were again set at Tanguisson. Shortly after we made this set, Guam received a series of very high swells generated by a distant North Pacific storm. We were unable to recover the meters during this period. The instruments were recovered the day after the swells subsided and all three were found to be damaged. Spare parts were ordered but did not arrive until May 1971. We attempted to use the Hydroproducts meter in January and February of 1971. Data were again unidirectional and use of this meter was discontinued. The TSK meters were repaired and used again in May 1971 but in late May suffered mechanical failures, this time of unknown causes. Again parts were ordered but the meters remained erratic and their use was discontinued for the remainder of the study. At this point we began working exclusively with drift crosses.

Mean current direction obtained from current meters is plotted in Figures 7 to 11. Data on the upper submarine terrace (5m) nearest to the effluent release point is shown in Figure 7. The basic directions are on a northeast and southwest axis. The numerous small easterly components are the result of wave surge operating very nearly at right angles to the current axis. Figure 8 shows the current directions in the transition zone between the lower terrace (10m) and upper slope (14m). This region shows a dominant southerly component with considerable representation in southwest and southeast quadrants.

These data were taken with the Hydroproducts meter and the north to northeasterly components are less well represented here than in the upper terrace (Fig. 7). Again, the easterly components reflect wave surge against the current meter vanes which are normally set either northerly or southerly with the prevailing currents. Figure 9 shows the resultant directions of current for meters set on the mid to lower slope regions (23m). All measurements at this depth were taken with the TSK meters and the data show equally numerous northwest-northeast to southwest-southeast components. The Hydroproducts meter was set several times at the bottom of the slope (30m) and again showed the odd truncated pattern with very little northerly current evident (Fig. 10). We are uncertain at this point why the Hydroproducts meter is unresponsive to northernly components, but suspect a calibration problem. When the data from all stations are combined and mean directions calculated, the pattern shown on Figure 11 emerges. Here the basic current direction lies from northwest-northeast to southeast-southwest. The most common direction is southerly but may be somewhat biased due to the inclusion of data from the Hydroproducts meter.

The current speed data also showed considerable variation between the two types of meters. The TSK meters showed generally lower velocities than the Hydroproducts meter. TSK readings rarely exceeded 0.3kts., the majority were less than 0.15kts. and included numerous zero readings. The Hydroproducts meter showed a range from 0.1 to 0.8kts. with no zero readings. The majority of the readings were grouped around 0.4kts.

We feel that current direction and possibly velocity is correlated with Guam's semidurnal tides. There are numerous local meterological and hydrographic phenomena that influence the degree of fit of this correlation. Figure 12 shows a relatively close fit of current direction with tide shift. In general, we found that on ebb tides, the current ran to the north or northeast. On flood tides, we encountered a higher frequency of southerly drifts. Some lags or shifts may be seen around the tide turns on Figure 12. Figure 13 shows that on occasion, current direction did not shift with tide for several successive cycles. In the case of Figure 13 the tide ran continuously in a southerly direction. Figure 14 demonstrates the same over-riding of tidal shift but with northerly components dominating. Similar data are reported by Jones and Randall[4].

Drift cross data also suggest that currents in the Tanguisson area move along a basic northeast to southwest axis. Figures 15-17 show direction of drift indicated by 1m, 5m and 10m drift crosses. The occasional strong westerly sets are resultant vectors between

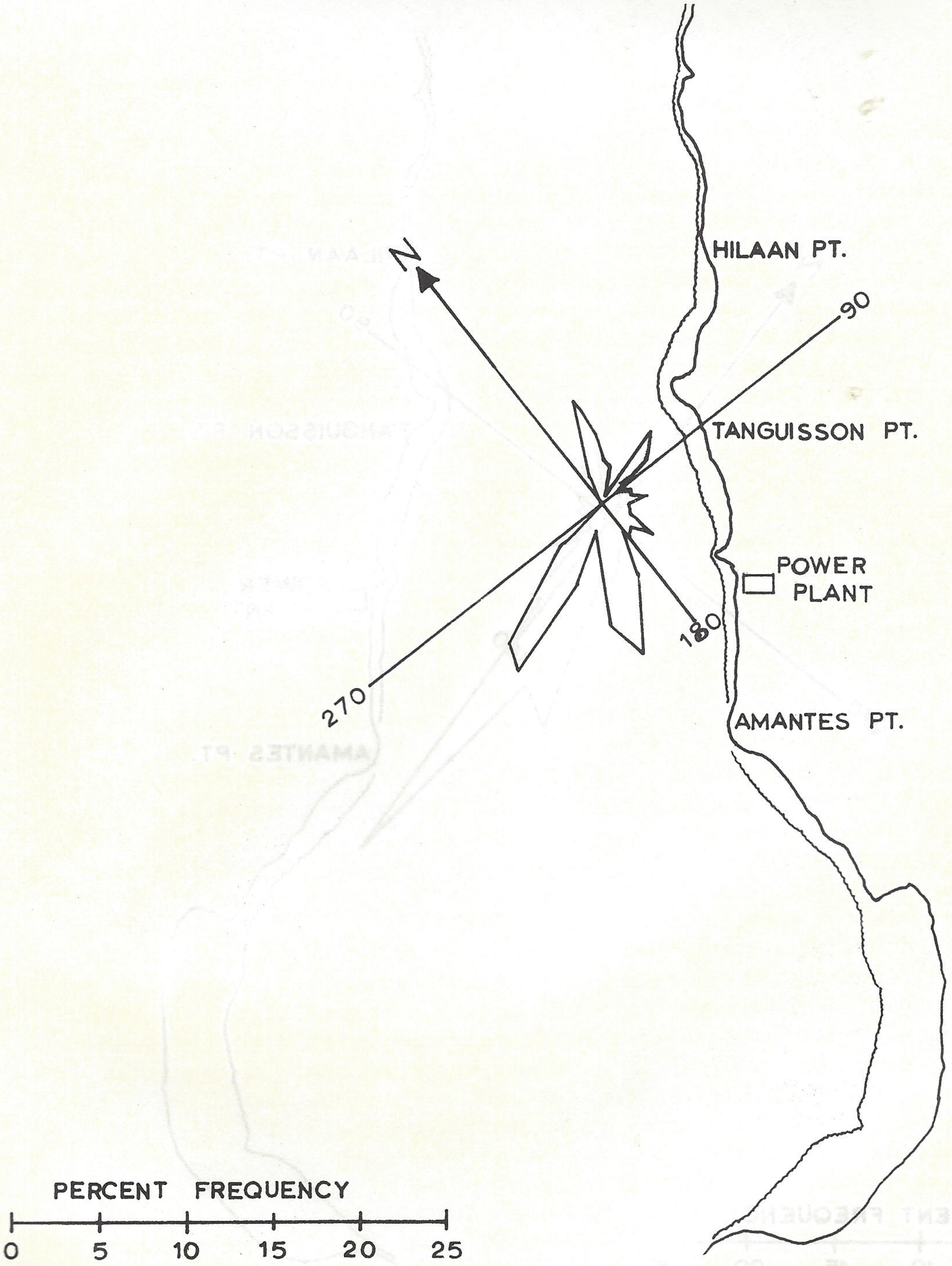

Figure 7. Mean frequency diagram for current direction at 5 m (TSK meter).

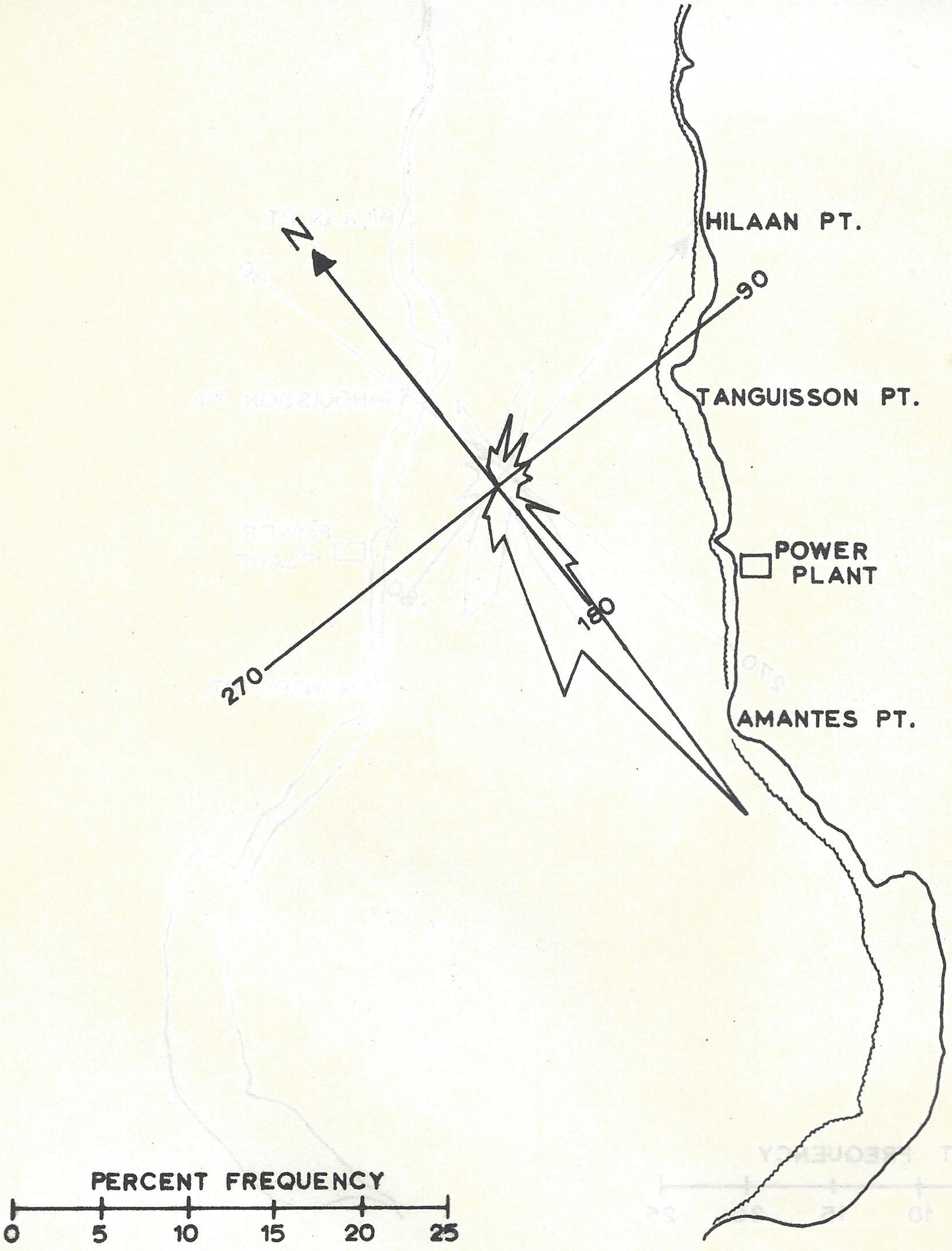

Figure 8. Mean frequency diagram for current direction at 10 to 14 m (Hydroproducts meter).

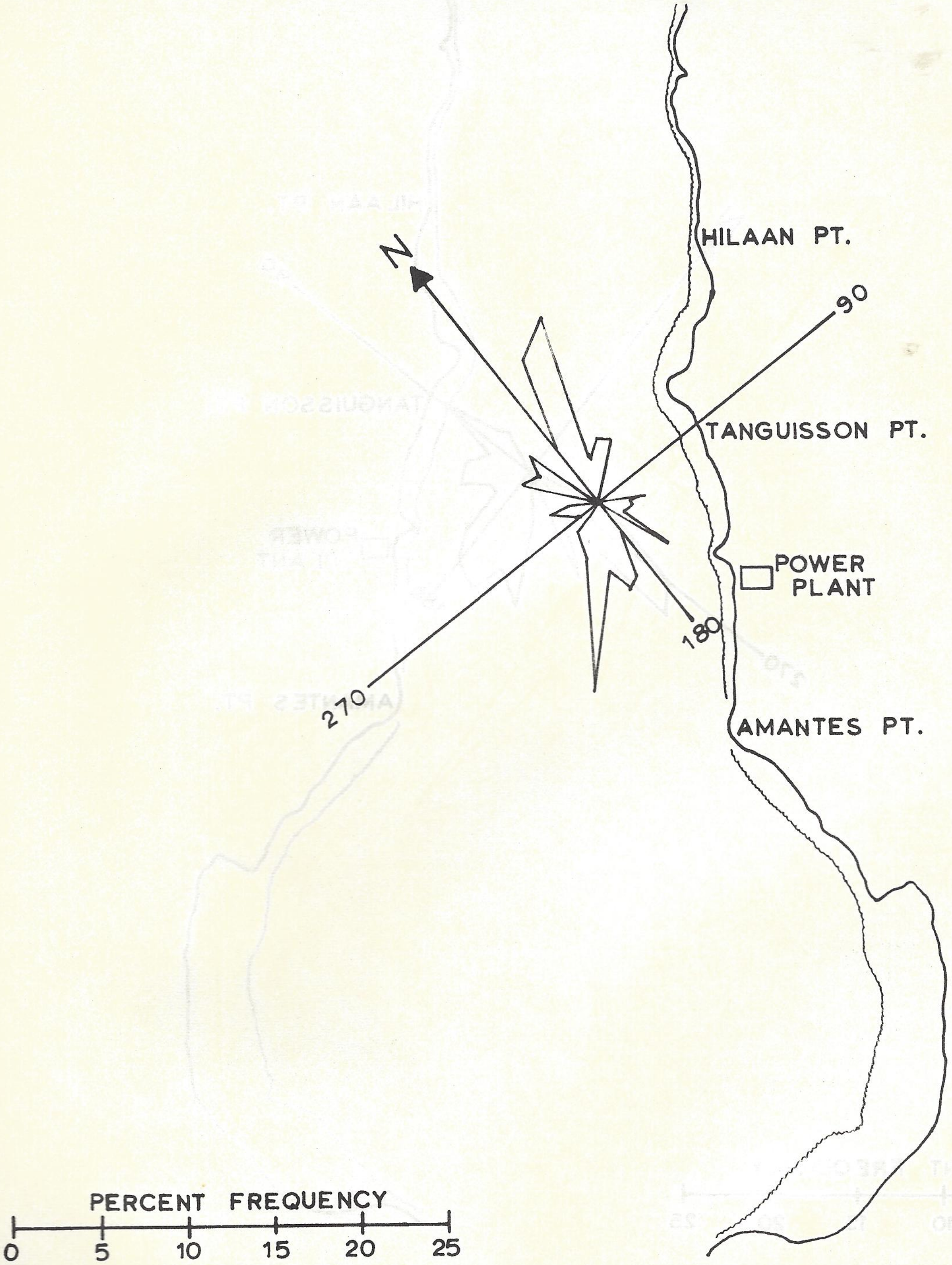

Figure 9. Mean frequency diagram for current direction at 23 m (TSK meter).

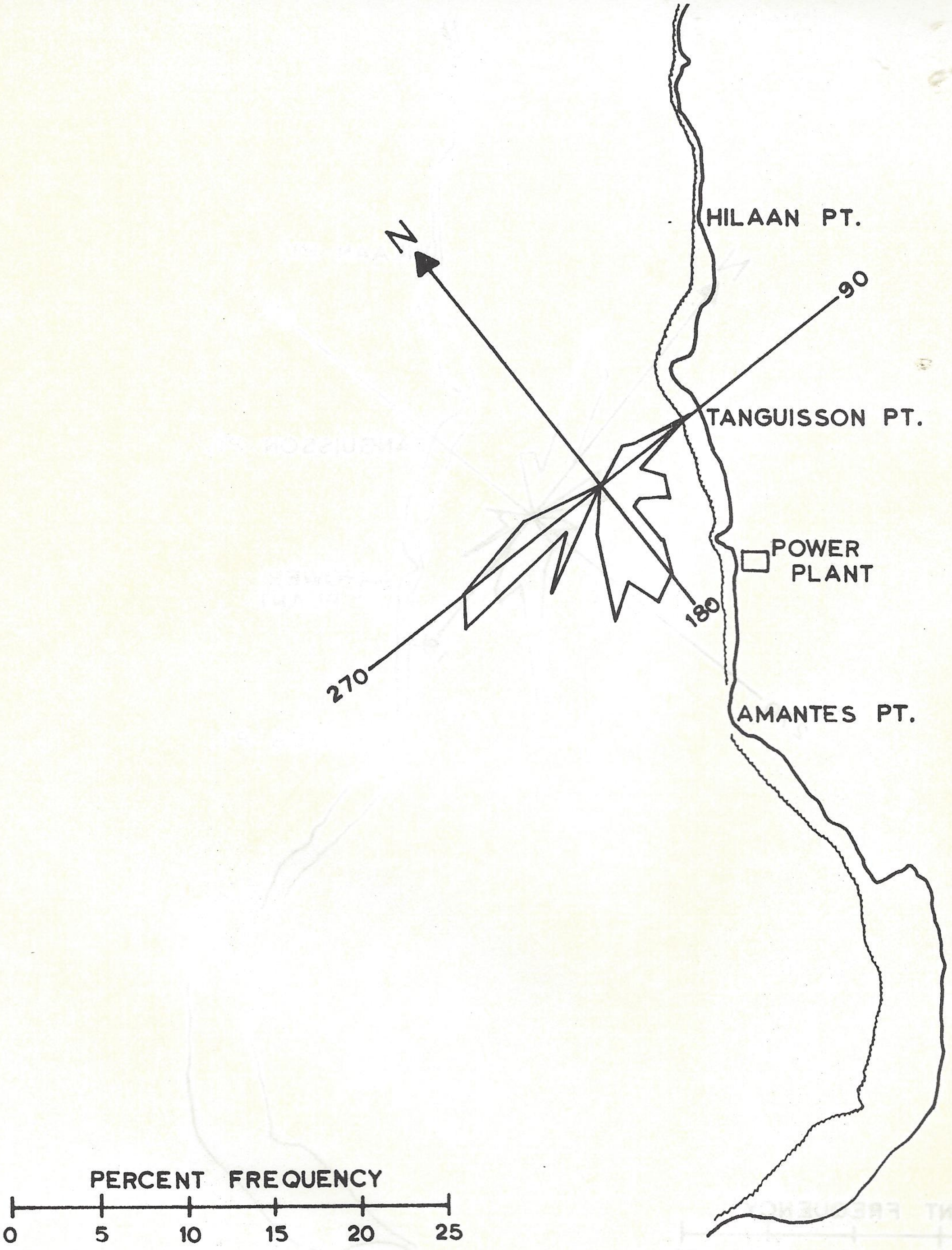

Figure 10. Mean frequency diagram for current direction at 30 m (Hydroproducts meter).

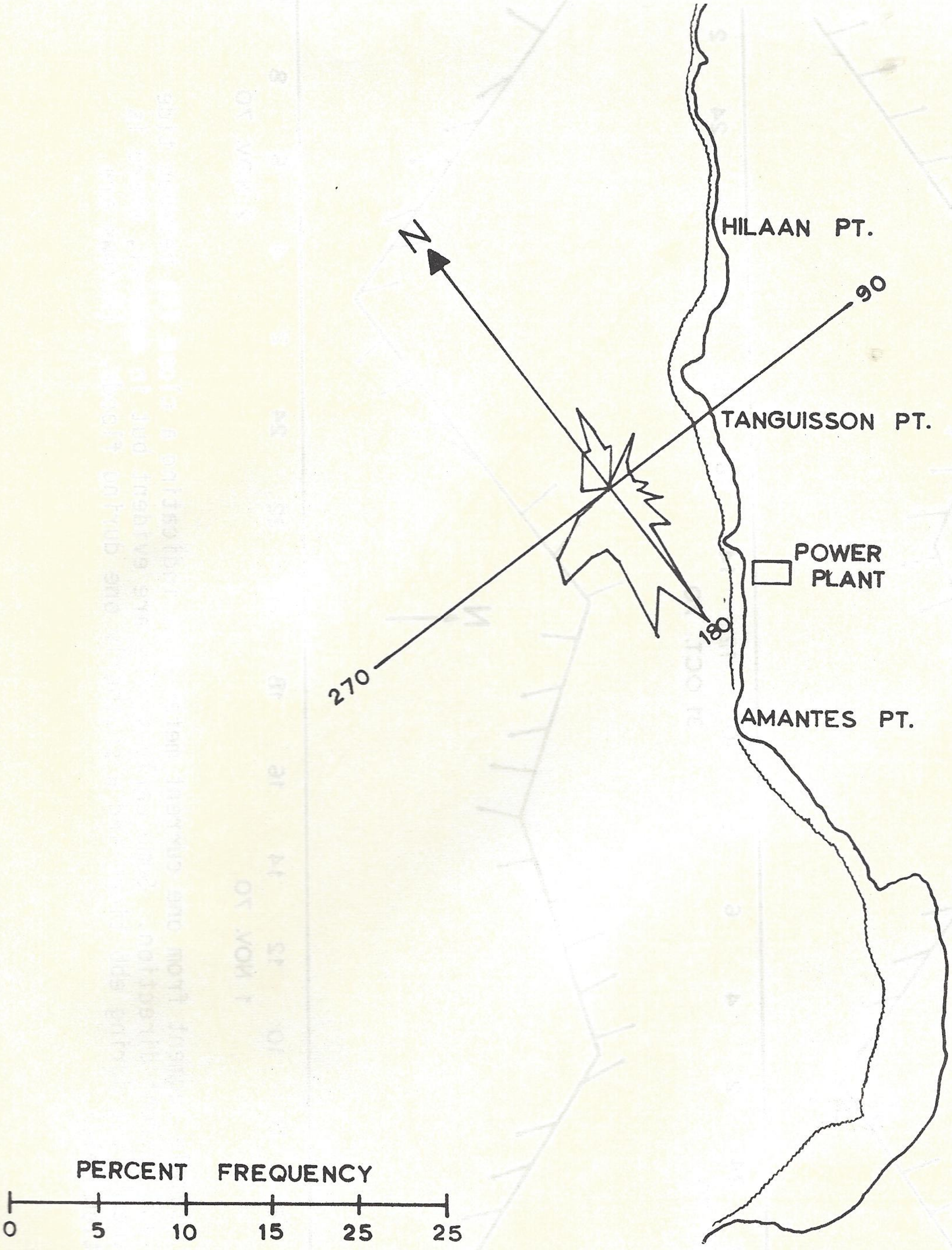

Figure 11. Mean frequency diagram for current direction, all stations combined. The data are biased by the inclusion of the truncated pattern produced by the Hydroproducts meter.

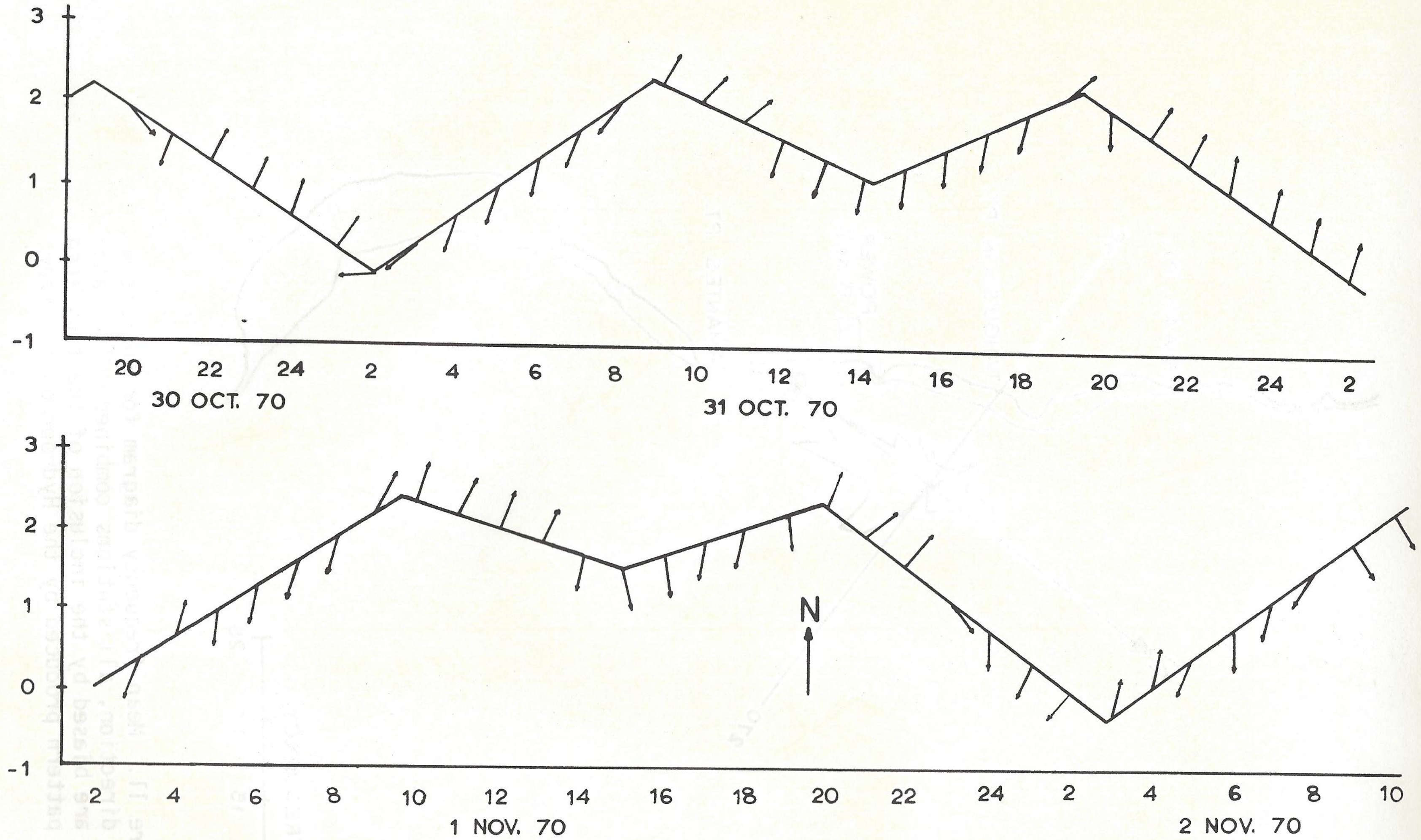

Figure 12. Sample segment from one current meter tape indicating a close fit between tide cycle and current direction. Some early shifts are evident but in general, there is a northerly set during ebb tides and a southerly one during floods. (Arrows are direction only).

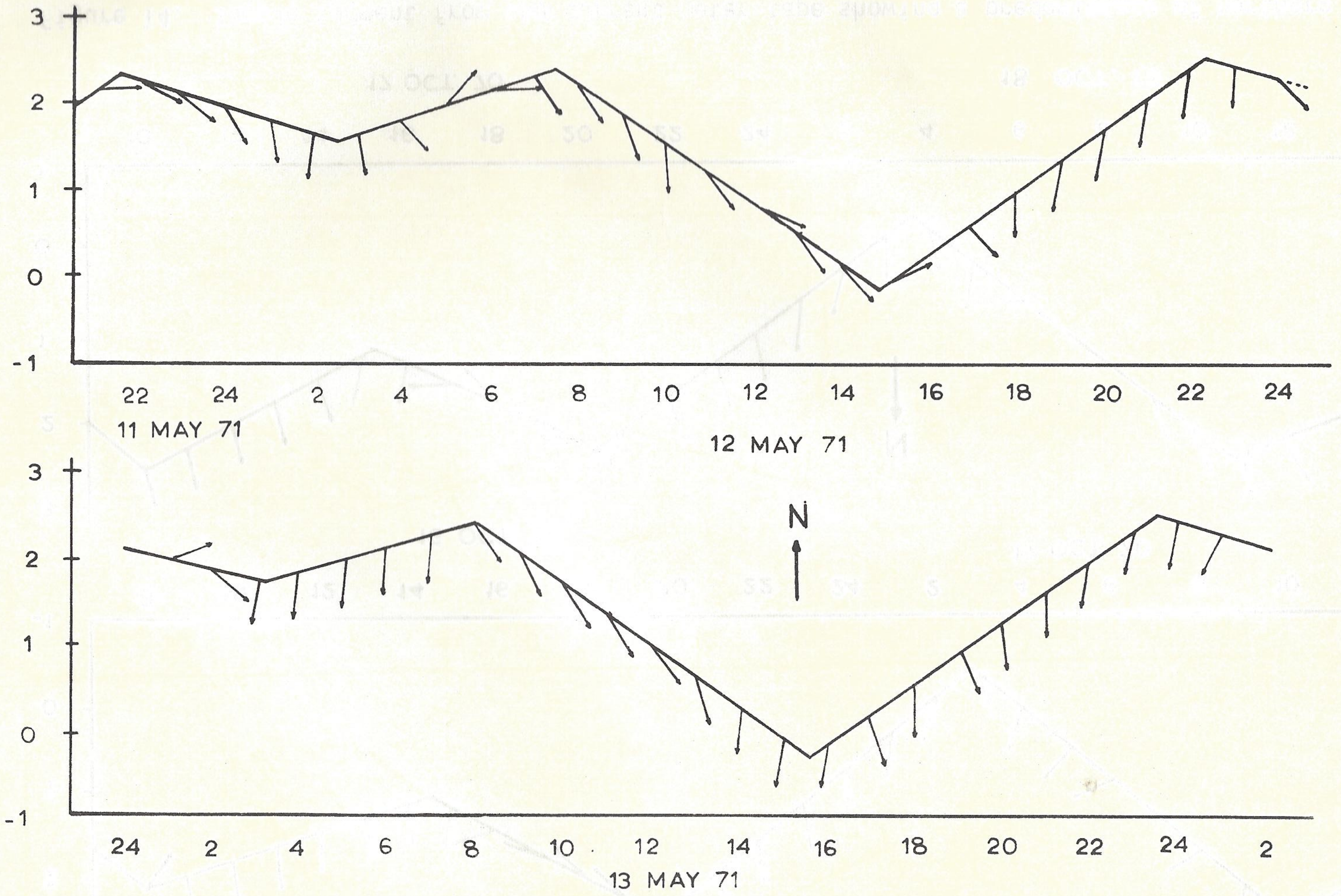

Figure 13. Sample segment from one current meter tape showing a predominance of southerly components with no correlation with tide cycle.

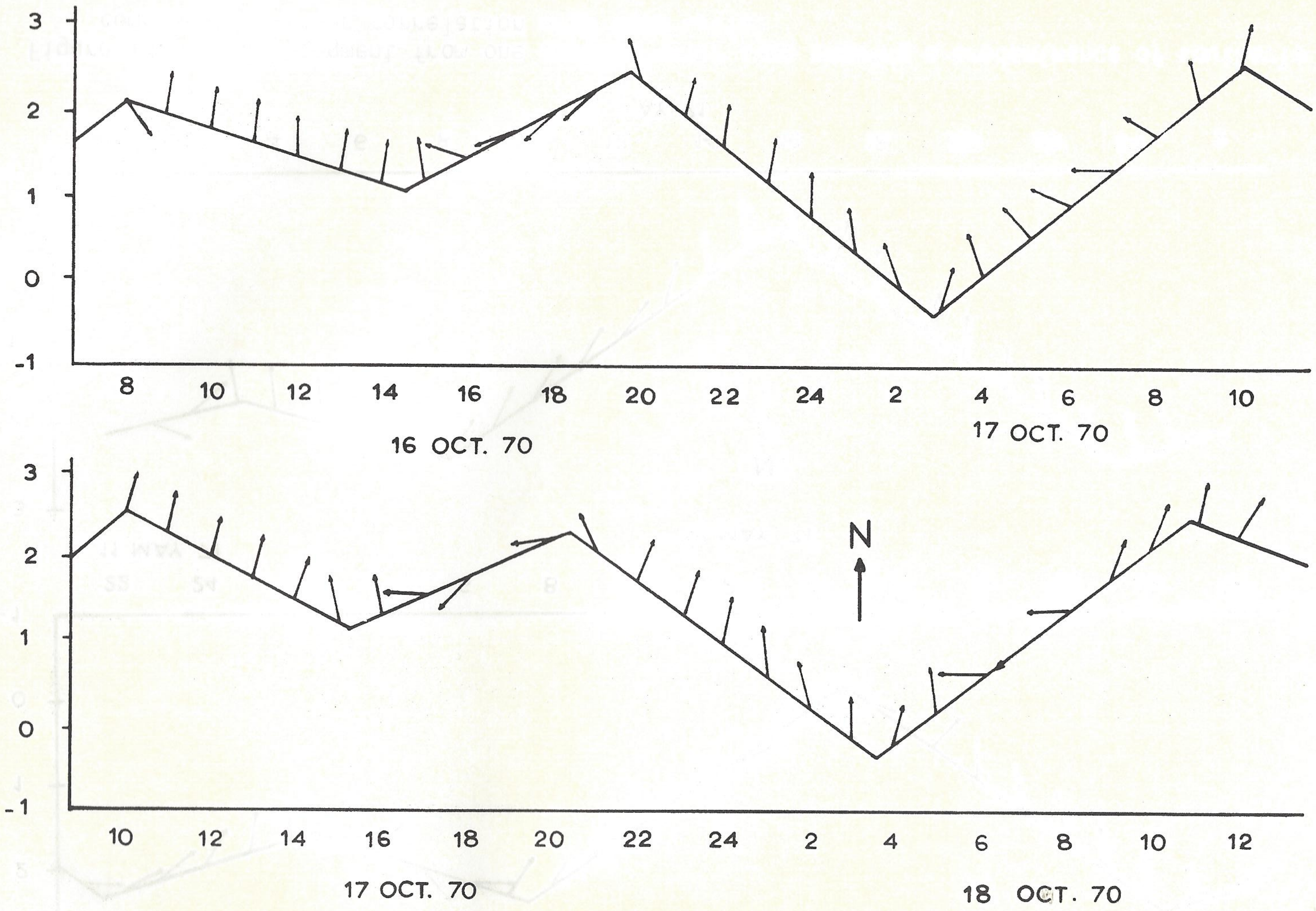

Figure 14. Sample segment from one current meter tape showing a predominance of northern components with no correlation with tide cycle.

the northeast wind and tidal shifts to the north. Due east or west vectors also occur temporarily during times of tide change.

Again there is frequent apparent correlation between tide changes and changes in current direction. But as in the case of current meter data, current shifts may precede or lag behind tidal shifts or fail to change at all.

In general, the drift cross patterns roughly approximate a northerly drift on ebb tides and a southerly one during floods. Drift numbers 16 and 18 (Figs. 15-16) failed to follow the pattern. Both drifts showed definite northerly directions during floods. The two casts were made in July when the rainy season starts on Guam. At this time tradewinds often break down and the strength of the NEC may be reduced. The tide change during the drifts was from a higher low water to a lower high water thus producing a weak flood. Both tide changes were preceded by relatively strong ebbs from a higher high water to a high low. Therefore the northerly flowing currents from the previous ebb may have persisted through the next weak flood.

Drift cross observations indicated a range of current speed from 0.1 to 0.6 kts. with very few zero readings. The mean of the combined drift cross speeds was 0.2kts.

In 1971, the U. S. Navy Oceanographic Office sponsored a series of current measuring stations at Tanguisson Point and nearby Hilaan Point to the north. This study was conducted in two parts, one survey in the "winter" and one in the "summer". The winter measurements were taken in February 1971 (Anon.5). The current meter set off Tanguisson Point showed:

> "....pronounced movement to the northeast and southwest, and observations are evenly distributed in these two directions. Tidal movement shows as a factor when plotted against monitored current, but ocean currents generated by storms at long or short distances from Guam are of greater impact than the tide and generally mask tidal fluctuations."

Dye studies conducted at the same time showed general northwest-northeast and southwest currents that agreed with current meter data.

The Navy's summer survey was conducted from August to September 1971. These data are found in an unpublished report furnished by NAVOCEANO (Anon.6). The report summarized the previous winter data as follows:

Figure 15. One meter drift cross casts. The drift cast numbers are as follow:

1- 10/6/70 Flood to ebb
2- 10/9/70 Flood
3- 12/23/70 Flood to ebb
4- 2/23/71 Ebb to flood
5- 3/4/71 Flood to ebb
6- 3/17/71 Ebb
7- 3/24/71 Ebb to flood
8- 3/31/71 Ebb
9- 4/18/71 Flood to ebb
10- 4/29/71 Flood to ebb
11- 5/6/71 Ebb
12- 5/11/71 Ebb
13- 6/9/71 Ebb
14- 6/17/71 Flood (weak)
15- 6/23/71 Ebb
16- 7/1/71 Flood (weak)
17- 7/9/71 Ebb
18- 7/15/71 Flood (weak)

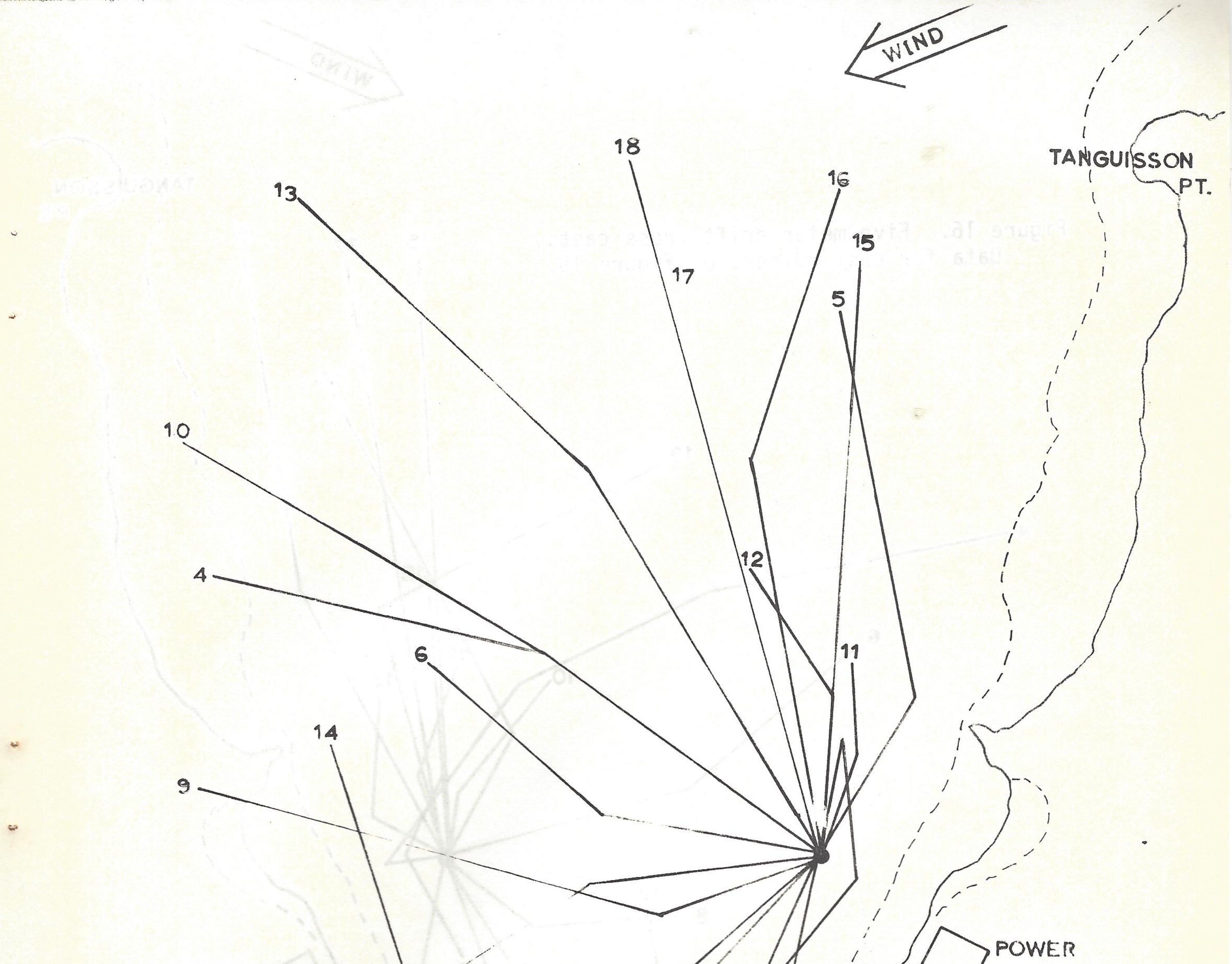
WIND
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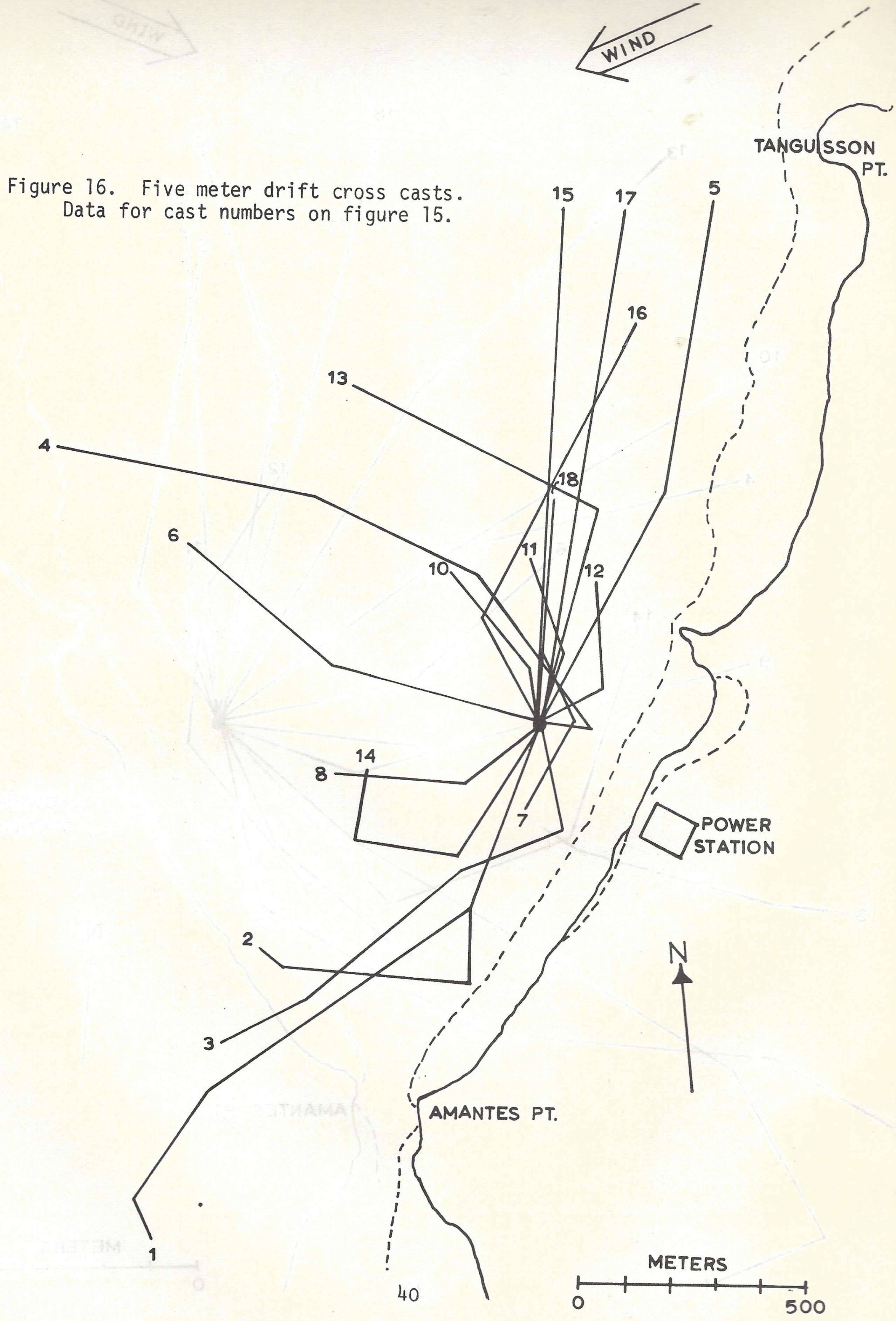
Figure 16. Five meter drift cross casts. Data for cast numbers on figure 15.



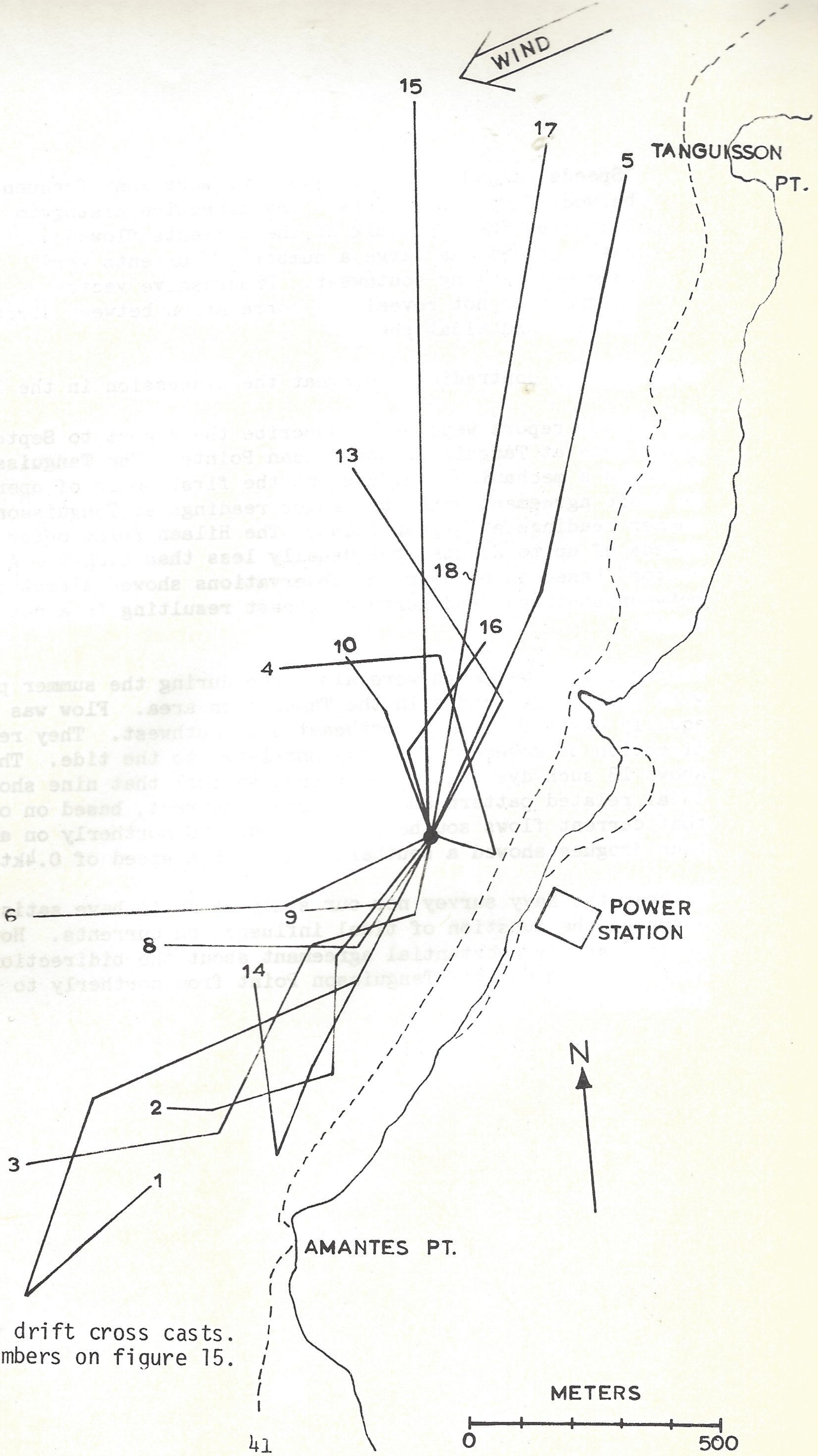


Figure 17. Ten meter drift cross casts.
Data for cast numbers on figure 15.

> "Speeds ranged up to 0.75kts. but were most frequent between 0.05 and 0.25kts. The direction histogram indicates that the bulk of the currents flowed northeast. Almost as large a number of currents were recorded flowing southwest. Progressive vector diagrams do not reveal any correlation between direction of flow and tidal phase."

This summary contradicts somewhat the discussion in the 1971 report.

The summer report went on to describe the August to September current meter sets at Tanguisson and Hilaan Points. The Tanguisson meter suffered a mechanical failure but the first hours of operation were in basic agreement with the winter readings at Tanguisson and the summer readings at Hilaan Point. The Hilaan Point meter showed speeds of up to 0.4kts. but usually less than 0.2kts. A "progressive vector" based on 66 hours of observations showed direction shifts between southwest and north-northeast resulting in a net westerly drift.

Thirty-eight dye casts were also made during the summer period along with four drogue casts in the Tanguisson area. Flow was almost equally divided between northeast and southwest. They reported the direction of movement as being unrelated to the tide. The report shows 13 such dye casts. Of these, we feel that nine show a correct tidal related pattern and four were incorrect, based on our assumption that current flows southerly on floods and northerly on ebbs. All four drogues showed a southerly set with a speed of 0.4kts.

Neither the Navy survey nor our study seems to have satisfactorily answered the question of tidal influence on currents. However, both studies are in substantial agreement about the bidirectional current shifts that occur off Tanguisson Point from northerly to southerly directions.

SECTION VI

TEMPERATURE REGIMES

GENERAL COMMENT

Phase I baseline data were expected to show reasonably consistent oceanic temperatures in the study area. The highest temperatures were expected along the reef flat where, during some months of the year, low tides are coincident with intense solar insolation. These conditions would be temporary and moderated by successive high tides.

Emery[2] reported seawater temperatures for Apra Harbor, Guam between 27.2 and 29.4°C (10 year period). Months with average water temperatures above 28.9°C were July through October.

These data are in reasonable agreement with data collected by the Guam Division of Fish and Wildlife from Tanguisson Point. Division personnel take thermometer readings an average of three mornings per month from the reef margin near Transect A. These data are presented in Figure 18 and are a reasonable approximation of the seasonal temperature regime for oceanic water around Guam. For a 10 year period from 1963 to 1972, the mean water temperature was 27.6°C (Table 1). Extreme ranges were 25.6°C, which occurred only once and 29.4°C, which occurred on two occasions. The maximum range of mean monthly temperatures were 25.9°C, which occurred once (February 1966), and 29.0°C which occurred twice (August 1966 and November 1969). The range of annual means for 10 years was 27.4 to 27.9°C. These data suggest that the oceanic temperatures around Guam commonly fluctuate between 26.0 and 29.0°C (Fig. 18). Oceanic surface temperatures rarely fall below or climb above this 3°C range.

REEF FLAT

Prior to plant startup, recording thermographs were placed along Transect B at stations B-2 and B-8. These stations are 20 and 80 m from the shoreline and adjacent to the outfall structure. This

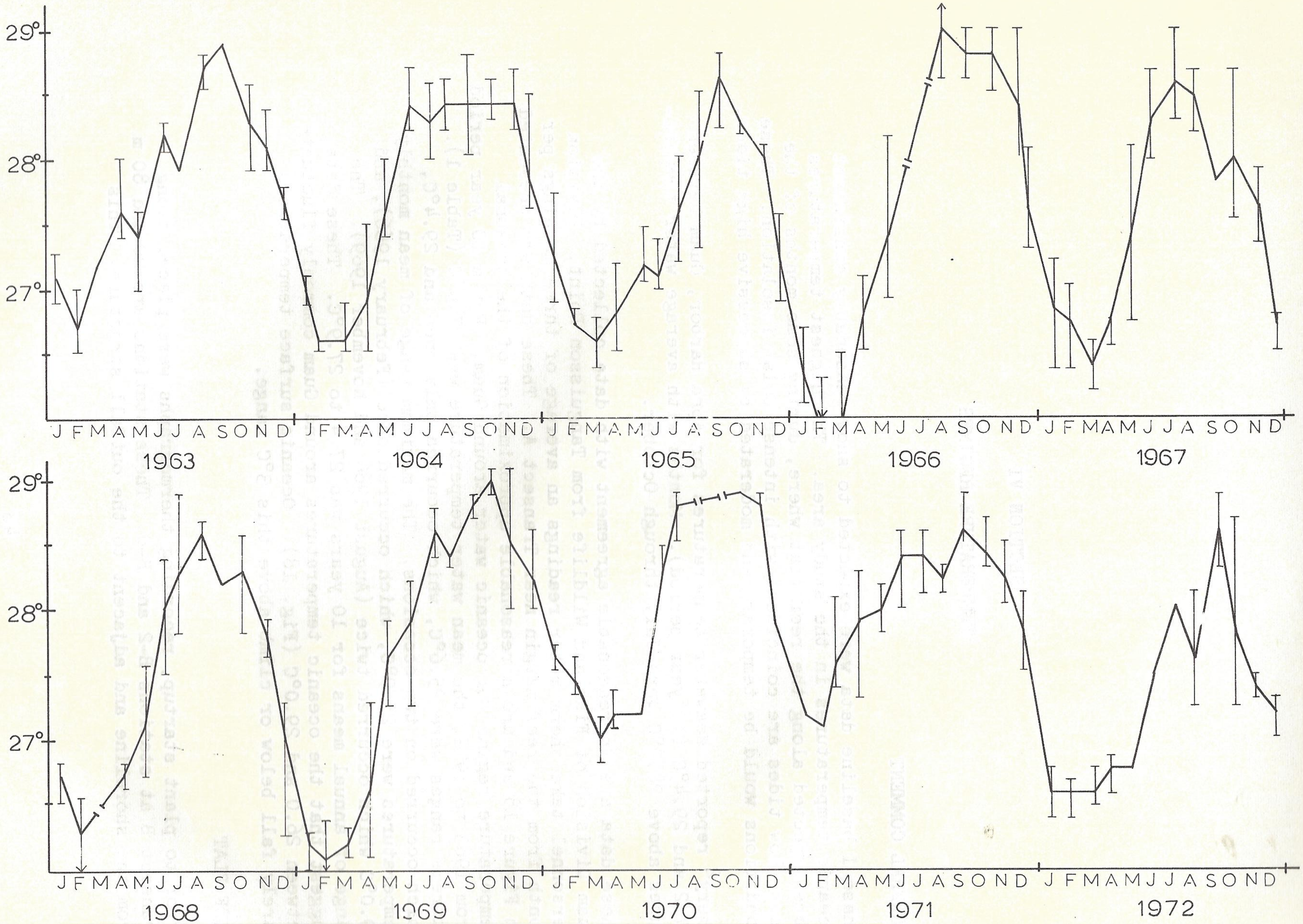


Figure 18. Plot of monthly mean sea surface temperatures for a 10 year period at Tanquisson Point Transect A. Vertical bar represents monthly range of temperatures.

Table 1. Temperature regimes in Tanguisson area (°C).

Time Period	Location	Method	Procedure	Mean of Means for Time Period	Range of Means for Time Period	Extreme Range for Time Period	Remarks
1963-1972 (Fish & Wildlife Data)	Transect A, Reef Margin	Thermometer	3-4 monthly samples (10 years)	27.6	27.4-27.9	25.5-29.4	Mostly wave transported oceanic water little return flow from reef flat.
1972 Jan.-Dec.	Intake channel	Thermocouples, power plant	Daily means, 12 mos.	27.3	26.5-28.5	----	This is primarily oceanic water from the reef margin. There is some mixing with effluent, reef flat, and Ghyben-Herzberg lens water.
1972 Jan.-Dec.	Outfall	Thermocouples	Daily means 12 mos.	33.8	32.8-34.8	----	*Plant in operation.*
1970-1971 May-Sept, Dec, Feb-Mar.	Reef Flat (Station B-8)	Thermograph	Continuous Readings	29.3	28.1-30.9	27.2-33.9	Influenced by solar heating and cool ground water.
1969-1970 (Jones & Randall[4])	Reef Flat Agana Bay	Thermometer	Periodic Readings	29.1	28.5-29.8	28-30.5	
1972, Aug.	Reef Flat	Thermograph	Continuous Readings	33.1	----	28.3-37.8	*Plant in operation.*
1970 April-June, Sept & Dec. Combined	Reef margin	Thermograph	Continuous Readings	29.0	28.2-30.2	27.8-31.1	Consists of oceanic water and reef flat water passing through surge channels.
1972 Sept-Oct	Reef margin	Thermograph	Continuous Readings	29.9	----	28.9-31.1	*Plant in operation.* Instruments damaged by wave attack, reading at least 1°C too low and likely lower.

procedure was repeated after plant startup and thermometer recordings were made on several occasions along the plume axis at 10 m intervals from the stilling well to the reef margin.

After Tanguisson No. 1 began generating power, plant personnel provided valuable temperature readings from Control Room thermocouples. These data included intake and outfall temperatures for January to December 1972 (Fig. 19). Thermometer and thermograph readings were obtained several times from the intake channel and stilling well to varify these data.

Table 1 shows that prior to plant startup, mean monthly reef flat temperatures for the months of May to September 1970 (warm months) and February to March 1971 (cool months) range from 28.1 to 30.9°C. Periodic fluctuations of considerable magnitude were noted on several occasions during low tide periods. The maximum range of these fluctuations was 27.2 to 33.9°C but these times were rare. The former occurred three times and the latter four during the seven month sampling period. The high end of the scale is explained by the coincidence of low tides and high mid-day temperatures. The low end is correlated with low tides and encroachment of ground water escaping along the intertidal from the Ghyben-Herzberg lens. This flow is heaviest after recent rains. Both situations are moderated, as expected, with the next flood tide. The mean reef flat temperature for the entire period was 29.3°C. These data are in agreement with thermometer readings taken from the Agana Bay reef flat in 1969 and 1970 (Jones and Randall[4]). The Agana data show a mean temperature of 29.1°C and a range of 28 to 30.5°C, for the months of January, February, April, May, September, November and December. Hence it would appear that the reef flat temperatures on Guam can, and often do, run two or more degrees higher than mean oceanic temperatures. The reef flat may be subjected to even greater fluctuations at times of low spring tides.

Tanguisson No. 1 began regular power production in January 1972. As pointed out in the Introduction, seawater at ambient temperature is pulled into Tanguisson No. 1 at a rate of 17,000 to 28,000 gpm depending upon the number of circulating pumps on the line. According to engineering criteria, the temperature of this water is expected to be increased by 12 to 14°F with one pump in operation and about 9 to 11°F with two. Two pumps are used about 50 percent of the time, usually during peak power times. (This policy has changed since the writing of this report. One pump is used most of the time.) If we assume that cooling water in the intake channel is primarily oceanic water (range 26-29°C) then we can predict a ΔT at the low end of the range of from 26.0°C to 31.0°C and at the high end an increase from

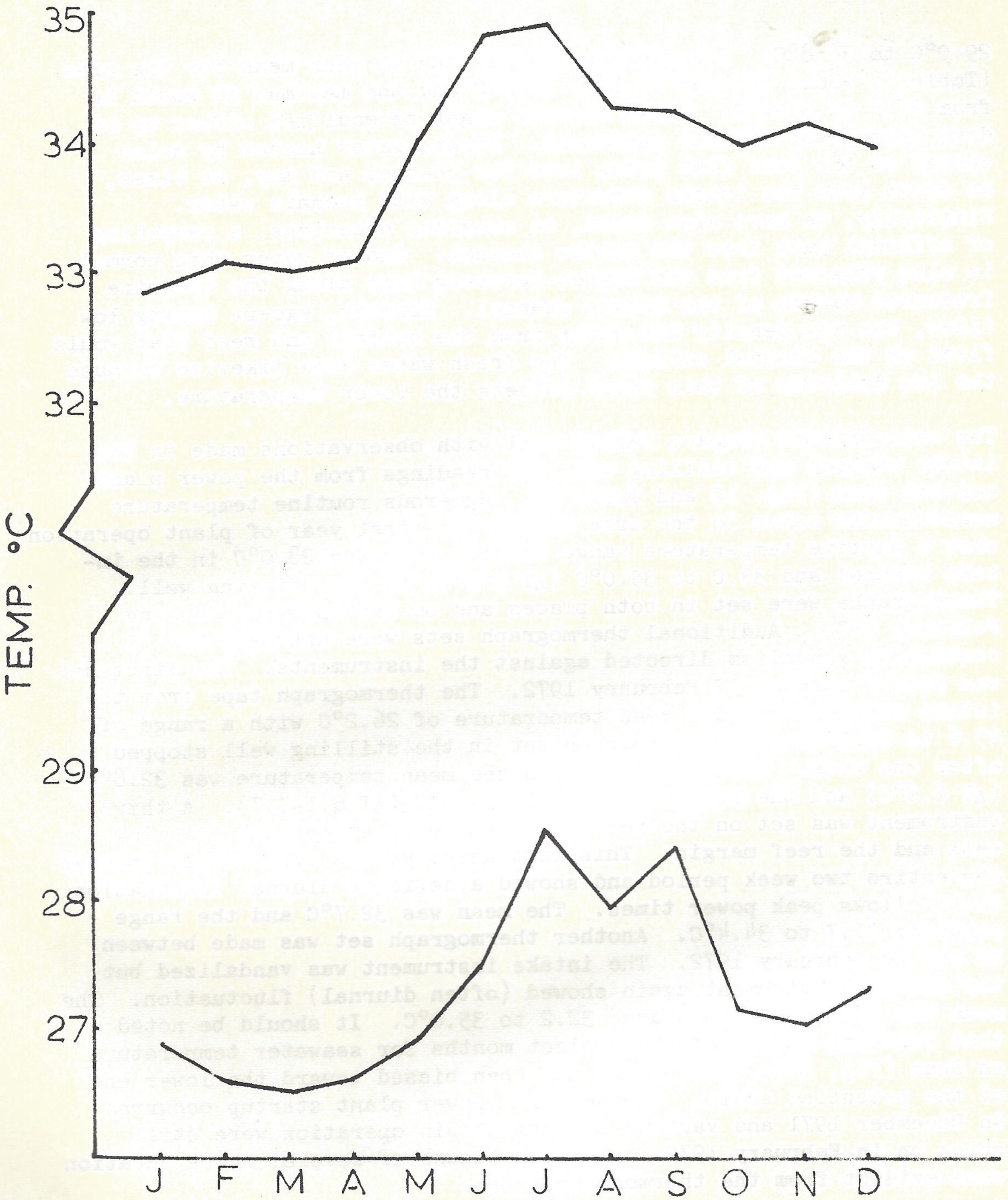


Figure 19. Plot of monthly mean intake and outfall temperatures for the first year (1972) of operation of Tanguisson No. 1.

29.0°C to 36.8°C. The minimum ΔT over the 10 year mean for the area (Table 1) would be from 27.6 to 32.6°C and the maximum ΔT would be from 27.6 to 35.4°C. These figures might be modified either up or down because of several phenomona. First, water heated by solar energy on the reef flat pours into the channel and may, at times, be drawn into the intake structure along with oceanic water. Similarily, we have also noted, on numerous occasions, a recycling of effluent back into the intake channel. Cooler water than normal is also released from the Ghyben-Herzberg lens along the dynamite fractured margin of the intake channel. However, except during low tides, the low density hot water from the outfall and reef flat would float on the channel surface. The fresh water does likewise because the low salinity of this water offsets the lower temperature.

The calculations compare fairly well with observations made in the intake channel and stilling well and readings from the power plant control room (Fig. 19 and Table 1). Numerous routine temperature measurements taken in the area during the first year of plant operation show a daytime temperature range between 26.0 and 28.0°C in the intake channel and 33.0 to 35.0°C (ΔT 5-7°C) at the stilling well. Thermographs were set in both places and on two occasions during February 1972. Additional thermograph sets were not made due to continuous vandalism directed against the instruments. The first set was from 8 through 22 February 1972. The thermograph tape from the intake channel showed a mean temperature of 26.2°C with a range of 25.6 to 26.7°C. The thermograph set in the stilling well stopped after one week. During this period the mean temperature was 32.8°C (ΔT 6.6°C) and the range was 31.7 to 34.4°C (ΔT 6.1-7.7). A third instrument was set on the reef flat half way between the stilling well and the reef margin. This instrument worked effectively through the entire two week period and showed a definite diurnal fluctuation that follows peak power times. The mean was 32.7°C and the range remained 31.7 to 34.4°C. Another thermograph set was made between 22 and 28 February 1972. The intake instrument was vandalized but the outfall instrument again showed (often diurnal) fluctuation. The mean was 32.9°C and the range 32.2 to 35.0°C. It should be noted that February is one of the coolest months for seawater temperature on Guam (Fig. 18). These data are then biased toward the lower end of the potential scale. Furthermore, power plant startup occurred in December 1971 and various adjustments in operation were still going on in February 1972. Plant shutdowns of several hours duration were evident from the thermograph tapes.

Control room temperature recordings for the first year of plant operation are shown in Figure 19. The range of mean monthly temperatures are 26.5 to 28.5°C in the intake and 32.8 to 34.8°C in the outfall (ΔT 6.3). The intake and outfall means for the entire year

1972 are 27.3 and 33.8°C respectively. This results in a mean ΔT of about 6.5°C. Figure 20 presents additional data on one of the cooler months, February, and a series of the warmest months, August to September.

It is apparent then that temperatures several degrees above oceanic surface temperatures may occur naturally on the reef flat. But these conditions are temporary and are relieved during the next flood tide cycle. The power plant, on the other hand, pours a constant volume of heated water across the reef flat adjacent to the plant. This effect is moderated somewhat during times of high tide and a high surf. Such conditions tend to spread the plume front as it approaches the reef margin but at the same time exposes a broader portion of the margin to water temperatures above normal.

Table 1 shows that the normal mean reef flat temperature (29.3°C) tends to run nearly 2°C higher than mean oceanic (27.6°C). The plant effluent mean (33.8°C) is 6.2°C higher than oceanic and 4.5°C higher than the normal reef flat mean. Thermograph recordings at station B-8 in August 1972 show a mean of 33.1°C and a range of 28.3 to 37.8°C (Table 1). The broad fluctuation in range is due to incoming waves that results in surges of cool to warm water. This same station showed a mean of 29.3 and a range of monthly means of 28.1 to 30.9 prior to plant startup (Table 1). The influence of plant effluent on station B-8 is obvious, resulting in a mean environmental ΔT of 3.8°C.

REEF MARGIN AND UPPER FRONT

Recording thermographs were placed at station B-14, directly in the surge channels opposite the power plant. Recordings were made both before and after plant startup. This area is subject to violent wave attack and attempts to use in situ instruments has met with only moderate success. Thermographs were lost or damaged on several occasions and we eventually had to abandon our efforts. Attempts to sample the region with hand held thermometers has rewarded the authors with assorted cuts, bruises and broken thermometers. The subsurface waters of the reef margin can only be sampled during times of calm weather, when wave mixing is at a minimum and surface stratification maximum. Our inability to place in situ temperature recording devices in this area is particularly unfortunate because it is a critical interface between the coral reef community and the effluent.

Surface water temperatures taken by the Division of Fish and Wildlife are from this zone (Fig. 18). These data were taken along an elevated reef section opposite Transect A (Fig. 3) and therefore are a measure of incoming wave transported water. Temperature measurements taken

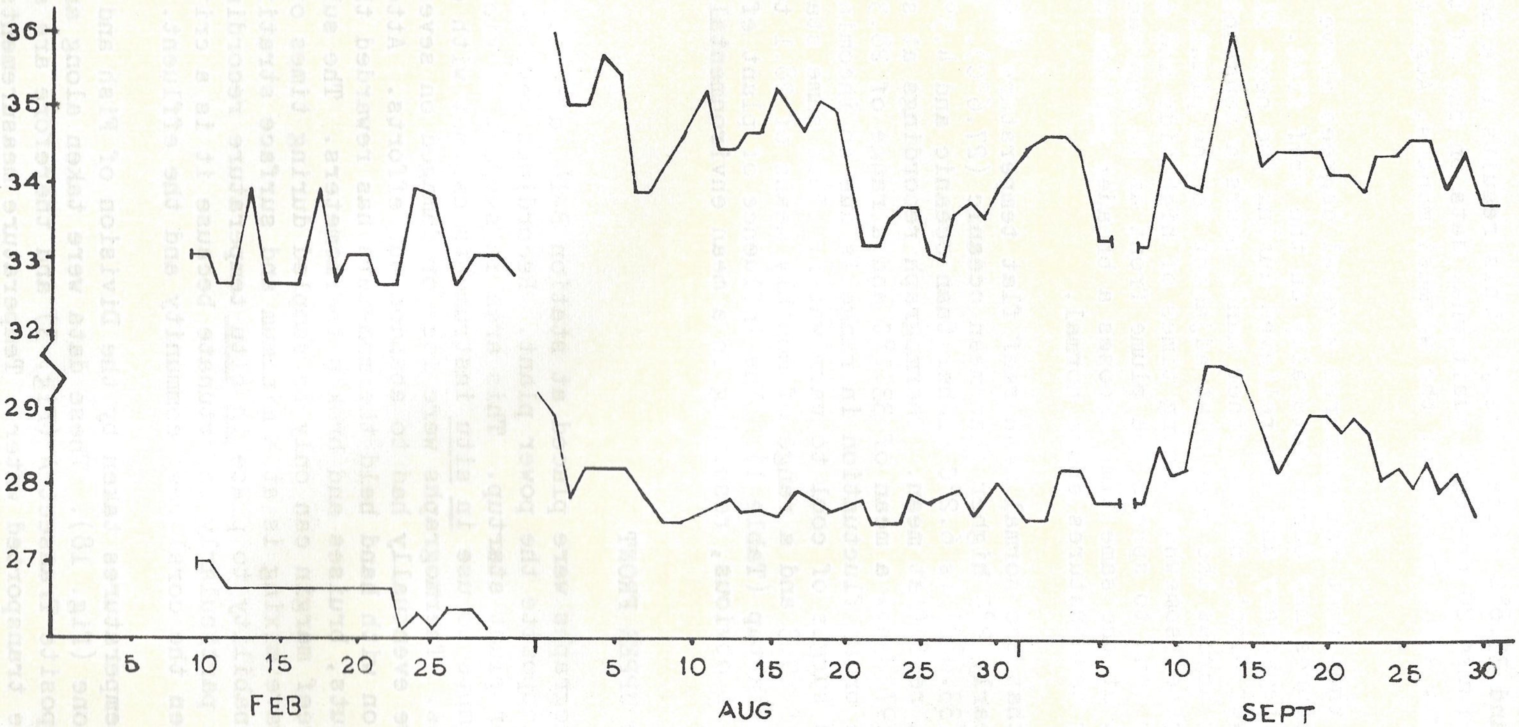


Figure 20. Plot of daily mean intake and outfall temperatures for one cool month, February, and two warm months, August and September, 1972.

by project personnel at and around Transect station B-14 reflect incoming wave transported water and reef flat water escaping through the reef margin surge channels at this point (Fig. 5 IV).

Prior to plant startup, a series of thermograph sets showed a mean temperature of 29.0°C at Station B-14 (Table 1). This is 1.4°C above the oceanic mean recorded at the reef margin near Transect A. The difference, as noted above, is due to reef flat water escaping along Transect B. The range of monthly means was 28 to 30.2°C. Thermograph readings in September and October 1972 showed slightly higher temperatures after plant startup. The mean for this period was 29.9°C and the range 28.9 to 31.1°C. However, the instruments were found to be damaged after recovery and calibration tests showed the thermographs to be reading about 1°C too low at the high end of the scale. These data must then be viewed with some reservation. Mercury in glass thermometer readings at Station B-14 and directly opposite the outfall site were frequently a degree higher than the above mentioned thermograph readings. For example, on October 19, 1972 a series of thermometer readings were taken along Transect B. This particular field trip was part of an investigation of a recent coral kill along the margin. Water temperature in the intake channel was 28.6°C. Water in the stilling well was 33.4°C. At mid reef flat, the temperature was still 33.4°C. These measurements were taken when the sea was relatively calm (1-2' swells) and during a low tide that exposed most of the reef flat. Water was cascading off of the reef flat and into reef margin surge channels. The temperature of the cascading water was 33.2°C. One meter seaward of this point the temperature was 33.1°C. Effluent stratified in the upper 0.5 to 1 m of water between wave sets. During times of breaking swells, alternate flashes of hot and cold water could be felt at the bottom of the surge channels. At the midpoint of the reef margin width, surface water temperatures were 32 to 32.8°C. Temperature did not fall below 30°C along the margin opposite the plant except where fresh water springs emerge at the bottoms of surge channels.

There is a tendency for the low density hot water to stratify as it enters the reef margin. However, a strong swell normally predominates on the reef and results in mixing water into the deepest parts of the surge channels. This is exemplified by a series of vertical profiles made along the margin (in October 1972).

Transect B (Edge of Plume)		(Off Center, Plume Axix)	(Plume Axis)
Surface	29.7	31.2	31.8
1 m	28.6	30.5	31.3
2 m	27.8	29.6	29.4

LOWER FRONT AND TERRACE

Water temperatures in these areas are consistent with those shown in Figure 18. The sheer size of this water mass effectively damps out major diurnal fluctuations of ambient temperature. The limits of the thermal plume was studied by establishing stations at 10 m intervals along temporary transect lines running at right angles to the reef margin. Transect B served as the control transect. Temperature profiles were made at each station.

It soon became obvious that the plant effluent behaves in a relatively consistent manner. Once the effluent passes through the wave-mixed reef margin and enters the quiet waters of the reef front and terrace, the warm water tends to restratify in the upper 1 m of the offshore water mass (Fig. 27). This plume then drifts with the prevailing current either to the northeast or southwest. The preceeding current study shows the net movement to be southerly. The plume is diverted seaward as it meets the seaward flowing rip currents at the surge channels north of Transect C (Figs. 6, V & VI and 21). Water temperatures attenuate rapidly as the effluent moves south and normal ambient oceanic temperatures are evident opposite Transect C. When currents move the plume to the north, it immediately encounters the surface rip coming out of the intake channel (Fig. 6, III and 21). This diverts the plume seaward and there is no indication of elevated temperatures along the reef margin opposite NCS swimming lagoon. The plume tends to spread out along a broad front seaward and temperatures are usually back to normal at Transect A. Maximum recorded seaward extension of the plume is Station B-19 (190 m from shore) where surface temperatures as high as 31.0°C have been recorded.

There is no evidence of hot water below 1 m which suggests that the plume has little or no influence on benthic organisms of either the lower reef front or terrace. An exception to this is the presence of occasional coral growth features with enough relief to raise them to the upper 1 m, but these features are rare (Fig. 27).

It is likely that when Tanguisson No. 2 begins operating, the horizontal limits of the plume will be expanded. There is little likelihood that the vertical limits will change significantly.

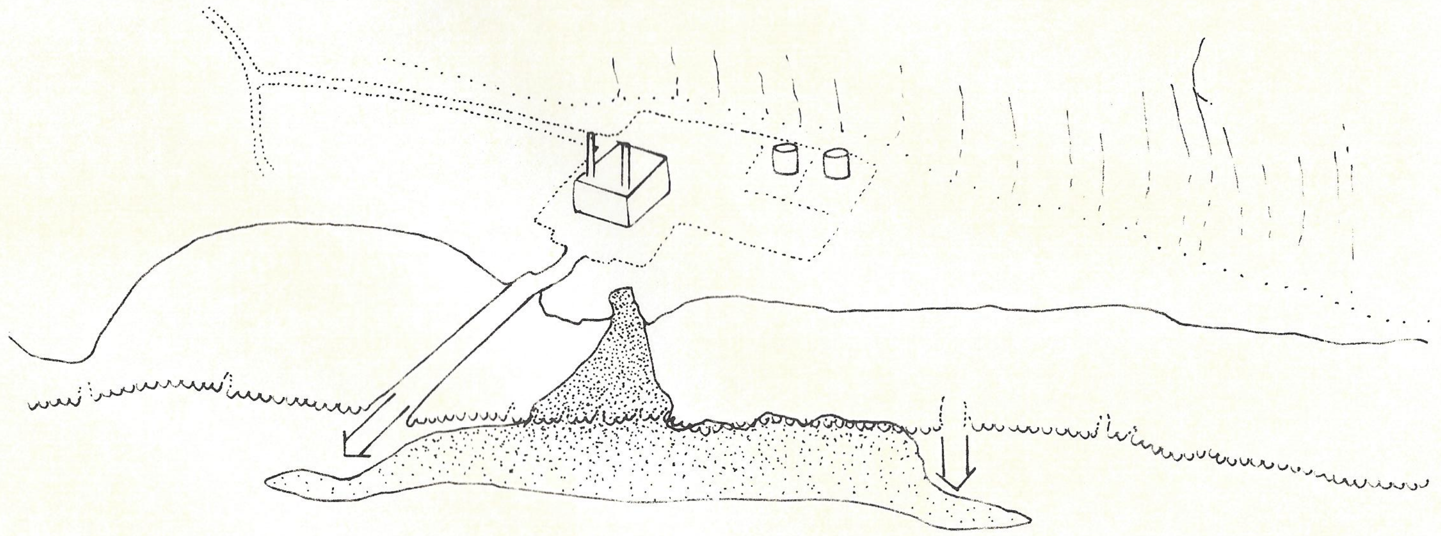


Figure 21. Diagrammatic presentation of the influence of the thermal plume on the reef margin. The rip currents at the intake channel and near Transect C provide partial boundaries to the effluent, diverting it seaward.

SECTION VII

CHEMICAL PARAMETERS

SALINITY

Salinity measurements were taken in the intake channel and stilling well and along Transect B. Samples were collected in bottles and analyzed in the Laboratory with a Hytech Salinometer.

A 9 month (March to November 1969) sample period by the Division of Fish and Wildlife showed that average monthly oceanic surface salinities in the area range from 33.83 to 34.63 with a mean of 34.28°/oo. The only major changes in salinity expected were those of the reef flat environment where ground water escapes from the Ghyben-Herzberg fresh water lens system. The primary intrusion of this water is along the intertidal zone of the reef flat. Salinity is considerably lowered at this point (Table 2). At times, the eggs and larvae of the toad Bufo marinus are found in brackish pools along the intertidal.

Natural freshwater springs are also found beyond the reef platform. Several of these springs are evident in reef margin surge channels. Similar springs have also been encountered at various points on the submarine terrace. The sudden changes of temperature are easily distinguished by divers passing through the rising freshwater. During times of heavy flow, shimmering clouds of low density spring water can be seen rising in the water column. Construction of the intake channel has broken through the limestone cap of the reef flat and freshwater also escapes along the channel margin.

The data in Table 2 show a salinity gradient along Transect B from the intertidal to the reef margin. Salinities as low as 1.84°/oo were recorded near shore. The rate of mixing is dependent upon wind, sea and surf conditions and to a certain extent upon the tidal phase. Periods of calm associated with low tides result in low salinities on the inner reef flat. High tides during calm weather often result in

Table 2. Reef flat salinities (o/oo). Stations are along Transect B at 10 m intervals from the shore.

Date			Station Numbers							
			B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8
14 Sept.	70	Surface	1.84	27.31	29.29	33.01	31.84	33.99	33.79	33.86
		Bottom	1.98	27.81	29.95	32.86	31.84	33.99	33.79	33.86
15 Oct.	70	Surface	2.89	29.14	31.68	32.72	33.64	34.08	34.40	34.50
		Bottom	4.43	29.11	31.65	32.65	33.89	34.09	34.48	34.50
18 Feb.	71	Surface	5.58	31.17	32.82	33.93	34.43	34.44	34.43	34.43
		Bottom	9.28	31.15	32.92	33.93	34.43	34.44	34.43	34.43
25 Feb.	71	Surface	6.24	33.28	33.89	34.42	34.40	34.54	34.56	34.60
		Bottom	17.18	33.32	34.16	34.42	34.40	34.54	34.56	34.60
2 Mar.	71	Surface	24.40	26.56	29.47	34.54	34.49	34.49	34.49	34.49
		Bottom	23.18	27.34	30.49	32.54	34.49	34.49	34.49	34.49
21 April	71	Surface	14.31	22.65	23.11	29.58	29.26	31.93	33.58	34.22
		Bottom	17.20	23.00	23.11	29.58	29.26	31.93	33.58	34.22
Mean			10.76	28.53	30.21	33.02	32.95	33.91	34.22	34.35

a visible lens of fresh water that is carried seaward over the reef margin and onto the surface above the submarine terrace. Table 3 shows that seawater is diluted somewhat in the intake channel. A gradient occurs from the channel surface to the bottom at the intake structure. Salinity changes between the intake and the stilling well are minimal and less than the natural changes that occur on the reef flat.

OXYGEN

There was no evidence to show that dissolved oxygen values varied significantly from intake to outfall. A sample of data taken in November 1972 is given below.

Date	Intake (mg/l)	Outfall (mg/l)
2 Nov. 1972	6.45	6.50
8 Nov. 1972	7.63	7.77
14 Nov. 1972	6.97	6.98
22 Nov. 1972	7.07	7.00

A reduction of percent saturation of 15 to 20% may be expected at higher outfall temperatures but this change in itself would not be of great environmental significance. Dissolved oxygen values of over 7.0 mg/l were higher than expected for oceanic water but were found both in intake and outfall channels. Samples were taken near the surface and may have been influenced by reef flat water.

CHLORINE

Chlorine is used as a desliming and anti-fouling agent to keep the surfaces of the circulating water system clean. The procedure is called shock chlorination. The project did not include an investigation of either free or residual chlorine in plant effluent. However the known toxicity of chlorine makes at least a discussion of its use worthwhile.

The consulting engineers for Tanguisson No. 1 recommended from "past experience" a chlorination dosage of 5 ppm chlorine rate for 20 minutes, three times per day. Maximum design feed rate for the chlorination system is 4000 lbs/per day. The design specifications therefore provided for a capability of about 55.6 lbs of chlorine/per 20 min. treatment period. This would be 166.7 lbs/per day for the three treatments and a total use of about 5000 lbs per month.

At the beginning of plant operations, actual usage was about 70 lbs per day or a little over one ton/per month. In this case 23.3 lbs of

Table 3. Salinity data for intake and effluent (o/oo).

	STATIONS							
Date	Channel Entrance Surface	Channel Entrance Bottom	Intake Surface	Intake Midwater	Intake Bottom	Stilling Well	Mid-Reef Flat	Reef Margin
18 Oct. 72	---	---	33.68	---	33.92	33.92	33.74	33.76
2 Nov. 72	---	---	33.32	---	---	33.76	33.76	33.75
8 Nov. 72	---	---	33.84	33.90	33.93	33.65	33.62	33.63
14 Nov. 72	34.09	34.17	32.73	34.09	34.12	34.76	34.88	34.14
22 Nov. 72	34.06	34.09	30.24	34.12	34.12	33.98	33.99	34.20
Mean	34.08	34.13	32.76	34.04	34.06	34.01	34.00	33.90

chlorine was used over a 20 minute treatment period on each of the three working shifts (personal communication). This produced a theoretical 5 ppm rate ahead of the circulation pumps.

On November 2, 1972, the plant chlorine supply ran out and none was available on the island. It was nearly a month before chlorine was available again. Examination of the water boxes and condenser tubes at this time showed very little sliming or other fouling. Plant management decided to reduce the chlorine treatment to one shot per day using about 23 lbs in 20 minutes or about 700 lbs per month. When no loss in plant efficiency was noted, this was further reduced to 12.5 lbs in 10 minutes or about 400 lbs per month.

The reduction in use of chlorine served not only to reduce potential environmental damage but also cut operational costs.

HEAVY METALS

A special request was made by the Project Officer to monitor copper, cadmium, and nickel in the plant effluent. Water samples were taken on three occasions and shipped to the EPA Water Quality Laboratory at Alameda, California for analyses. The data are presented in Table 4.

There is very little evidence to indicate that large quantities of these metals are escaping from the power plant. Copper is obviously higher in the stilling well than in either the intake or offshore water. However this amount does not exceed that shown by Goldberg[7] for open ocean water (3.0 μg/l) and by Alexander and Corcoran[8] for water in the Florida Straits (10 μg/l. total Cu).

Cadmium was present in amounts usually less than 0.1 μg/l. However cadmium values increased to 0.4 at the mid-terrace station on Transect A on one occasion and went as high as 0.3 and 0.8 μg/l in the open ocean station. This is higher than normal seawater values (Table 4). Contamination might be suspected in these three samples.

Nickel values seemed variable, however, the values near the power plant were often higher than oceanic water.

It is apparent that considerably more sampling would be called for including replicate sampling from each station if we are to obtain an accurate picture of heavy metal distribution. The three samples taken were from within the first four months of plant operation and the content of these metals in the effluent might be low and expected to increase.

Table 4. Heavy metal analyses. The data are arranged as Cu/Cd/Ni and the units are in ug/l.

Date	Intake	Outfall	Reef Margin Transect B	Reef Margin Near Transect C	Mid-Terrace Transect A	Open Ocean 1/2 Mile Seaward
13 Jan. 72 Current Running North	0.8/≤0.1/1.6	2.1/≤0.1/0.6	0.7/≤0.1/1.1	0.6/≤0.1/1.0	0.6/≤0.1/2.9	0.6/0.3/1.0
4 April 72	0.5/≤0.1/0.8	1.1/≤0.1/≤0.5	0.2/≤0.1/1.1	≤0.1/≤0.1/≤0.5	0.3/0.4/≤0.5	0.9/0.8/≤0.5
23 May 72	1.0/≤0.1/≤0.5	2.9/≤0.1/≤0.5	1.2/≤0.1/≤0.5	≤0.1/≤0.1/≤0.5	≤0.1/≤0.1/≤0.5	≤0.1/≤0.1/≤0.5

SECTION VIII

BIOLOGICAL IMPACT OF EFFLUENT

GENERAL COMMENT

It became obvious in the early stages of this work that the thermal plume would have little influence on the benthos after it passed through the surge zone along the reef margin. Once over the reef front and terrace, the effluent was stratified in the upper one to two meters and offered no threat to organisms below these depths. Consequently, biological surveys along the reef front, terrace, and slope concentrated on the effects of the _Acanthaster_ damage and the subsequent recolonization by corals.

The reef flat and reef margin environments were directly impinged upon by the effluent plume and the studies there were concentrated on delineating the effects of the effluent. Biologically, the reef flat was found to be naturally depauperate, while the reef margin was a diverse, rich ecosystem that had remained unaffected by the _Acanthaster_ infestation.

ALGAE

A series of quantitative algal transects were made by Dr. R. T. Tsuda from March to July, 1970. Dr. Tsuda found the algal community in all reef zones to be "typical" for these habitats. The only differences were in the _Acanthaster_ damaged reef front, terrace, and slope. In these areas, algal species composition was virtually identical to undamaged areas but the standing crop of algae was higher, presumably due to the reduction in live coral cover. No changes were noted in qualitative transects run by Dr. Tsuda in the same areas from May through July 1972, over one year after the power plant began to operate.

Considerable change was noted, however, in the reef flat and reef margin zones where there was obvious influence from the thermal plume.

Table 5 lists the change in species composition encountered over the reef flat and upper reef margin in the immediate vicinity of thermal discharge. Thirty-nine species were encountered before plant operation and only 12 afterward, a 60% reduction in the number of species. The blue green algae became the dominant group present. Species of this group are well known for their role as pioneering species. They are among the first algae to appear and often dominate early successional stages on coral reefs. They are, for example, among the first colonizers of coral coralla after the polyps are removed by Acanthaster. As succession proceeds, the species are normally replaced by species from other algal divisions. The blue green species are rarely replaced entirely but are merely reduced in their role as the dominant algal species.

Thus, introduction of effluent from Tanguisson No. 1 effectively reduced the reef flat and upper reef margin algal community to an earlier stage of succession. However unlike natural perturbations, the effects of thermal effluent are persistent as long as the plant remains operational. Hence, normal algal succession following the initial kill and recolonization does not advance but rather holds at the level of the early pioneering species, the blue greens. Exceptions to this are Halimeda opuntia, and Cladophoropsis membranacea, green algae; Dictyota divaricata and Padina tenuis, brown algae; and Amphiroa fragilissima and Polysiphonia scopulorum, of the red algae. These species all seem somewhat resistent to plume effluent; but, Cladophoropsis membranacea seems to thrive there. This species produces a thick mat within the limits of the plume and shows an obviously lower biomass and patchy distribution outside the limits of the plume, during its growing season. Prior to plant operation, Gelidium pusillum was the dominant alga from the intertidal to the reef margin, this species has disappeared in the vicinity of the plume. Figure 22 shows the general distribution of the algal mats opposite the outfall as of December 1972.

Due to heavy sedimentation from continued construction up through November 1972, very few algal species settled in the intake channel. The dominant species were Jania capillacea, Gelidiella acerosa, Amphiroa fragilissima, and Galaxaura marginata of the red algae and Sargassum cristaefolium of the brown. Blue green algae were still present in the channel but were no longer dominant as they had been after the initial channel construction.

FISHES

Considerable effort was expended in developing methods of censusing fishes over the submarine terrace and slope. This work is still preparation and will not be presented at this time. These methods are being developed to allow us to evaluate differences, based on fish community structure, between areas devastated by either Acanthaster

Table 5. Species listing of marine benthic algae present on reef flat and upper reef margin before (March - July, 1970) and after (May - July, 1972) thermal discharge.

SPECIES	BEFORE	AFTER
CYANOPHYTA		
Calothrix confervicola (Roth) Ag.	X	X (abundant)
Entophysalis conferta (Kutz.) Dr. & D.	X	X
Microcoleus lyngbyaceus (Kutz.) Crouan	X	X (abundant)
Schizothrix calcicola (Ag.) Gomont	X	X
Schizothrix mexicana Gomont	X	X
Spirulina subsalsa Gomont	X	X
CHLOROPHYTA		
Boergesenia forbesii (Harv.) Feldmann	X	
Boodlea composita (Harv.) Brand	X	
Bryopsis pennata Lamx.	X	
Caulerpa racemosa (Forssk.) J. Ag.	X	
Caulerpa taxifolia (Vahl) C. Ag.	X	
Chlorodesmis caespitosa J. Ag.	X	
Chlorodesmis fastigiata (C. Ag.) Ducker	X	
Codium geppii O. C. Schmidt	X	
Dictyosphaeria cavernosa (Forssk.) Boerg.	X	
Dictyosphaeria versluysii W. v. Bosse	X	
Enteromorpha intestinalis (L.) Link	X (rare)	
Halimeda opuntia (L.) Lamx.	X	X (abundant)
Valonia fastigiata Harvey	X	
Cladophoropsis membranacea (Ag.) Boerg.	X	X
PHAEOPHYTA		
Dictyota bartayresii Lamx.	X	
Dictyota divaricata Lamx.	X (erect)	X (matted)
Feldmannia indica (Sondar) Womersley & Bailey	X (rare)	
Hydroclathrus clathratus (Ag.) Howe	X	
Padina tenuis Bory	X	X (only vaughiella stage)
Rosenvingea intricata (J. Ag.) Boerg.	X	
Sargassum cristaefolium J. Ag.	X (rare)	
Turbinaria ornata (Turn.) J. Ag.	X	
RHODOPHYTA		
Actinotrichia fragilis (Forssk.) Boerg.	X	
Amphiroa fragilissima (L.) Lamx.	X	X

Table 5. (Continued)

SPECIES	BEFORE	AFTER
RHODOPHYTA (continued)		
Cheilosporum multifidium (Kütz.) Manza	X	
Gelidiella acerosa (Forssk.) Feldmann & Hamel	X	
Gelidium pusillum Setchell	X	
Gracilaria salicornia (Mert.) Grev.	X	
Hypnea pannosa J. Ag.	X	
Jania capillacea Harvey	X	
Laurencia obtusa (Huds.) Lamx.	X	
Mastophora lamourouxii (Decaisne) Harv.	X	
Polysiphonia scopulorum Harvey	X	X
	39	12

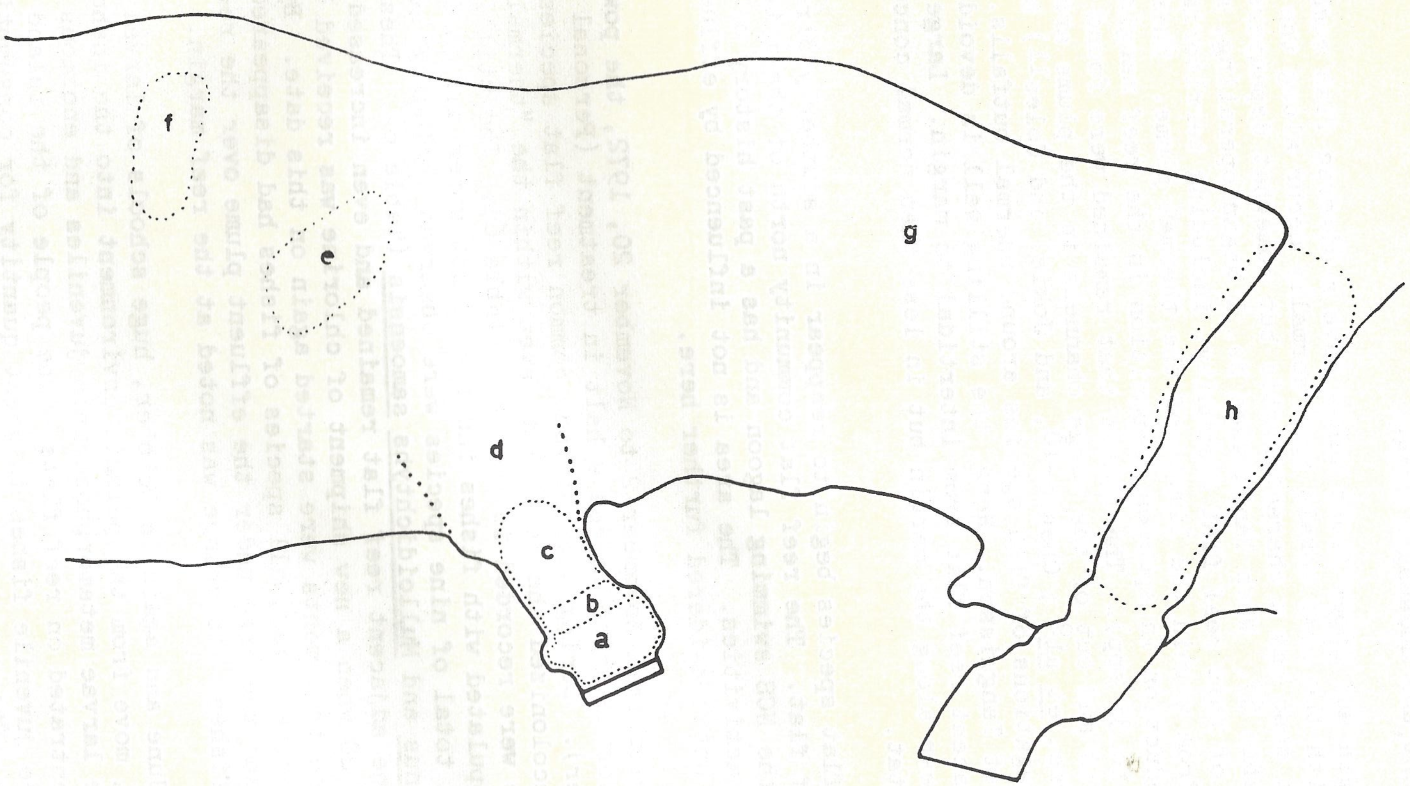


Figure 22. Algal community after thermal discharge. (a- outfall channel and *Microcoleus lyngbyaceus*; b- *Padina tenuis*; c- *Dictyota divaricata* and mats of *Calothrix*, *Microcoleus*, and *Schizothrix*; d- *Cladophoropsis membranacea*; e- *Halimeda opuntia*; f- *Amphiroa fragilissima*; g- *Polysiphonia scopulorum*; h- intake channel; *Jania capillacea*, *Gelidiella acerosa*, *Sargassum cristaefolium*, *Amphiroa fragilissima*, and *Galaxaura marginatus*).

or the effluent, and undamaged areas.

The reef margin and upper front zones have a diverse fish community associated with the live corals that normally occur along the margin. The reef flat zone has a characteristic but somewhat depauperate fish community (Table 6). When Tanguisson No. 1 began operating, all members (33 species) of this reef flat community, including territorial species, disappeared from within the limits of the thermal plume. There was a 44 percent reduction in species composition in the reef margin community (Table 6, 63 to 35 spp). The fishes that remained were found wandering continuously in and out of the surge channels in the plume area. Other workers (Clarke, et al[9] ; Chesher[10], and Jokiel and Coles[11]) have reported aggregations of fish species around thermal outfalls. This is not the case at Tanguisson. Here, the stilling well is devoid of fishes as is the adjacent reef flat from intertidal to margin. Large numbers of fishes appear along the margin but in less than normal concentrations for this habitat.

Typical reef flat species begin to reappear in a southerly direction along the reef flat. The reef flat community north of the intake channel is a part of the NCS swimming lagoon and has a past history of disturbance from dredging activities. The area is not influenced by effluent discharge and is not considered further here.

During the period from November 2 to November 20, 1972, the power plant ran out of chlorine which forced a halt in treatment (Personal Communication, F. Melder). During this period, common reef flat species began to immediately recolonized the reef flat, even within the "thermal effluent". Eleven species were recorded in the area (Table 6). The stilling well also became populated with fishes inspite of hot water and considerable turbulence. A total of nine species were observed including large schools of Siganus spinus and Mulloidichtyhs samoensis (Table 6). These species and those of the adjacent reef flat remained and even increased in numbers until November 20 when a new shipment of chlorine was received by the plant. Chlorine treatments were started again on this date. By the afternoon of the next day, all species of fishes had disappeared from the stilling well and the area under the effluent plume over the reef flat was devoid of fishes. No change was noted at the reef margin.

From April to June and again in October, huge schools of larval mañahac, Siganus spinus, move from the pelagic environment into the inshore waters of Guam. These larvae metamorphose into juveniles and enormous schools are found concentrated on reef flats. The people of the island traditionally harvest the juvenile fishes in great quantity for consumption. During the 1972 mañahac run, large schools of the species were found in the intake channel of Tanguisson No. 1. Near the end of the period when

Table 6. Visual fish counts. Contrast is shown in each zone, before and after the release of plant effluent. In addition, a comparison is made during and after the November 2 to November 20, 1972 period when the power plant was not using chlorine.

		REEF FLAT			STILLING WELL			REEF MARGIN	
SPECIES	Intake Channel	Before Effluent	After Effluent	No Cl^-	With Cl^-	No Cl^-	With Cl^-	Before Effluent	After Effluent
Acanthuridae									
Acanthurus lineatus	0	+	0	+	0	0	0	+	+
A. nigroris	+	0	0	0	0	0	0	+	0
A. nigrofuscus	0	0	0	0	0	+	0	+	+
A. triostegus	+	+	0	+	0	+	0	+	+
A. xanthopterus	0	+	0	0	0	0	0	+	+
A. glaucoparieus	0	0	0	0	0	0	0	+	0
A. olivaceus	0	0	0	0	0	0	0	+	0
A. guttatus	0	0	0	0	0	0	0	0	+
Ctenochaetus striatus	0	0	0	0	0	0	0	0	+
Naso lituratus	0	+	0	0	0	0	0	+	+
N. unicornis	0	0	0	0	0	+	0	0	+
Apogonidae									
Apogon sp.	0	+	0	0	0	0	0	+	0
Balistidae									
Rhinecanthus rectangularis	0	+	0	0	0	0	0	+	+
Balistapus undulatus	0	+	0	0	0	0	0	0	+
Blenniidae									
Entomacrodus sp.	0	0	0	0	0	0	0	+	0
Istiblennius coronatus	0	0	0	0	0	0	0	+	+
I. cyanostigma	0	+	0	+	0	+	0	0	0
Cirripectes variolosus	0	0	0	0	0	0	0	+	0
Runula tapeinosoma	0	0	0	0	0	0	0	+	0
Rhabdoblennius snowi	0	+	0	0	0	0	0	0	0
Praealticus natalis	0	+	0	0	0	0	0	0	0
Salarias fasciatus	0	+	0	0	0	0	0	0	0

Table 6. (Continued)

		REEF FLAT			STILLING WELL			REEF MARGIN	
SPECIES	Intake Channel	Before Effluent	After Effluent	No Cl$^-$	With Cl$^-$	No Cl$^-$	With Cl$^-$	Before Effluent	After Effluent
Canthigasteridae									
Canthigaster janthinopterus	0	0	0	0	0	0	0	+	0
C. amboinensis	0	0	0	0	0	0	0	+	0
C. solandri	0	+	0	0	0	0	0	0	0
C. bennetti	0	+	0	0	0	0	0	0	0
Carangidae									
Caranx sp. 1 (juveniles)	0	+	0	0	0	0	0	0	0
Caranx sp. 2	0	0	0	0	0	0	0	0	0
Chaetodontidae									
Chaetodon auriga	0	+	0	0	0	0	0	+	+
C. citrinellus	0	+	0	0	0	0	0	+	+
C. lunula	0	+	0	+	0	+	0	+	+
C. ornatissimus	0	0	0	0	0	0	0	+	+
C. ephippium	0	0	0	0	0	0	0	+	0
C. punctato-fasciatus	0	0	0	0	0	0	0	+	0
C. falcula	0	0	0	0	0	0	0	+	0
C. unimaculatus	0	0	0	0	0	0	0	+	0
C. quadrimaculatus	0	0	0	0	0	0	0	0	0
Heniochus permutatus	0	0	0	0	0	0	0	0	0
Forcipiger flavissimus	0	0	0	0	0	0	0	+	0
Pomacanthus imperator (juv.)	0	0	0	0	0	0	0	+	0
Cirrhitidae									
Cirrhitus pinnulatus	0	0	0	0	0	0	0	+	+
Paracirrhites forsteri	0	0	0	0	0	0	0	+	0
P. hemisticus	0	0	0	0	0	0	0	0	0
P. arcatus	0	0	0	0	0	0	0	+	0
Neocirrhites armatus	0	0	0	0	0	0	0	+	0
Eleotridae									
Eviota smaragdus	0	+	0	0	0	0	0	0	0
E. zonura	0	+	0	0	0	0	0	0	0
Ptereleotris tricolor	0	0	0	0	0	0	0	+	0

Table 6. (Continued)

		REEF FLAT			STILLING WELL			REEF MARGIN	
SPECIES	Intake Channel	Before Effluent	After Effluent	No Cl⁻	With Cl⁻	No Cl⁻	With Cl⁻	Before Effluent	After Effluent
Fistulariidae									
Fistularia petimba	0	0	0	+	0	0	0	0	0
Gobiidae									
Bathygobius fuscus	0	+	0	0	0	0	0	0	0
Kelloggella cardinalis	0	+	0	0	0	0	0	0	0
Labridae									
Halichoeres hortulanus	0	+	0	0	0	0	0	+	+
H. marginatus	+	0	0	0	0	0	0	+	+
H. margaritaceus	0	+	0	+	0	0	0	+	+
H. trimaculatus	+	+	0	0	0	0	0	0	0
Labrichthys cyanotaenia	0	0	0	0	0	0	0	+	0
Cheilinus fasciatus	0	0	0	0	0	0	0	+	0
Macropharyngodon meleagris	0	0	0	0	0	0	0	0	+
M. pardalis	0	0	0	0	0	0	0	+	0
Stethojulis axillaris	+	+	0	0	0	0	0	+	+
S. linearis	0	0	0	0	0	0	0	+	0
Hemigymnus melapterus	0	0	0	0	0	0	0	0	+
Thalassoma umbrostigma	0	0	0	0	0	0	0	0	+
T. quinguevittata	0	0	0	0	0	0	0	+	+
T. purpureum	0	0	0	0	0	0	0	+	0
T. fuscum	0	0	0	0	0	0	0	+	0
Labroides dimidiatus	0	0	0	0	0	0	0	+	0
Lutjanidae									
Scolopsis cancellatus	0	+	0	0	0	0	0	+	0
Lutjanus monostigmus	+	0	0	0	0	0	0	0	0
Monacanthidae									
Amanses sandwichiensis	0	0	0	0	0	0	0	+	0
Mugilidae									
Chelon vaigiensis	0	+	0	0	0	0	0	0	+

Table 6. (Continued)

SPECIES		REEF FLAT			STILLING WELL			REEF MARGIN	
	Intake Channel	Before Effluent	After Effluent	No Cl^-	With Cl^-	No Cl^-	With Cl^-	Before Effluent	After Effluent
Mullidae									
Parupeneus trifasciatus	0	0	0	0	0	0	0	+	+
P. bifasciatus	0	0	0	0	0	0	0	+	0
Mulloidichthys samoensis	+	0	0	0	0	+	0	0	0
Ostraciontidae									
Ostracion meleagris	0	0	0	0	0	0	0	+	0
Pomacentridae									
Abudefduf dicki	0	0	0	0	0	0	0	+	+
A. imparipinnis	0	0	0	0	0	0	0	+	0
A. amabilis	+	+	0	+	0	0	0	+	+
A. leucopomus	0	+	0	+	0	0	0	+	+
A. biocellatus	0	0	0	0	0	0	0	+	0
A. septemfasciatus	+	+	0	+	0	0	0	+	+
A. sexatilis	0	0	0	0	0	0	0	0	+
A. leucozona	0	+	0	0	0	+	0	0	0
A. glaucus	+	+	0	+	0	+	0	0	0
Pomacentrus albofasciatus	+	+	0	0	0	0	0	+	+
P. jenkinsi	0	0	0	0	0	0	0	+	+
P. vaiuli	0	0	0	0	0	0	0	+	0
Scaridae									
Calotomus spinidens	0	0	0	0	0	0	0	+	0
Scarus sp.	0	0	0	0	0	0	0	+	0
S. sordidus	0	+	0	0	0	0	0	+	0
Serranidae									
Cephalopholis urodelus	0	0	0	0	0	0	0	+	0
Teuthididae									
Siganus spinus	+	0	0	+	0	+	0	+	+
Zanclidae									
Zanclus cornutus	0	0	0	0	0	0	0	+	+
	12	32	0	11	0	9	0	63	35

plant personnel had suspended chlorination treatments, the water boxes of the plant were opened and condenser tubes inspected for possible fouling. Hundreds of specimens of mañahac were found plastered to the interspaces between the condenser tubes and on the floor of the water boxes. It is quite likely that many thousands, of the animals are entrained in the circulating water and killed by either mechanical damage or temperature increase. This high mortality is probably a seasonal phenomenon involving this species primarily. It is doubtful that normal channel inhabitants are drawn into the circulating system. No attempt was made to study the possible destruction of larvae or juveniles of other fish species passing through the plant.

Fishes common in the intake channel are shown in Table 6. Except for transients, most of the species listed are common in channel structures such as this. The intake channel fish community has not yet reached its full potential in terms of succession. This process has been considerably delayed by the fact that intake construction for Tanguisson No. 2 has kept the channel turbid until recently (November 1972).

CORALS

The fringing reefs located along the northwest coast of Guam (Fig. 1) supported a rich and diverse coral community prior to the *Acanthaster planci* infestation of this region (Tracey, *et al*[1] and Randall[12]). Randall[12] describes the reef complex at Tumon Bay in detail. These rich coral zones at Tumon Bay and nearby Tanguisson Point (Fig. 1) became infested with *A. planci* in 1967 and 1968 (Randall[12, 14, 18] and Chesher[15]). Intensive predation left the seaward slope, submarine terrace, and the outer part of the reef front zones with less than 10 percent of the reef surface covered with living corals. The reef margin and inner part of the reef front were not heavily infested by starfish because of wave agitation in these zones and much of the coral community survived. Section X of this report describes the reef complex at Tanguisson Point in detail after the starfish predation of 1967 and 1968.

Prior to plant operations, it was predicted that effluent from Tanguisson No. 1, might kill part of the coral reef community existing on the reef margin and reef front zones (Jones, *et al*[13]). The prediction was based on the fact that the coral reef community, in the above reef zones, has developed in and is adjusted to the small annual temperature changes that occur in this part of the Pacific Ocean. Moreover, thermal stress on reef corals is probably greater when applied continuously, as is the case with power plant effluent, than when applied diurnally from solar insolation or seasonal changes.

Final testing of the Tanguisson No. 1 began in December, 1971 and the plant became fully operational in January, 1972. Effluent was discharged at the outfall site onto the inner part of the reef flat platform (Fig. 23). The movement, and factors affecting the movement of this outfall water toward the reef margin is discussed in the previous section on currents and is shown in Figures 6 and 21.

During the testing period, the first observation of a coral-kill in the outfall region was made (on December 27, 1971). At that time a two-man team was recovering thermographs from the reef margin zone on Transect B and noticed that numerous corals were of a pale or bleached-white color (Fig. 24-26). The results of a survey showed that the zone in which freshly killed corals were found was roughly limited to the region outlined in Figure 23. The boundaries of the coral-kill zone were not sharply defined except for a shoreward section located along the inner reef margin zone where the outfall water first makes contact with living corals (Fig. 23d). In the peripheral zone (Fig. 23f) the corals killed were usually limited to the upper surfaces of submarine buttresses and the upper margins of the surge channels (Fig. 24 and 27). The coral species killed in the peripheral zone were presumably those with less thermal tolerance (Table 7). As the warmer area of the coral-kill zone (Fig. 23e, core zone) was approached, the density of bleached and freshly killed corals increased along with the number of species affected. In the core area the coral-kill was not limited to the upper regions of reef topographic features. It extended downward as well, along the walls of surge channels, submarine channels, and the floors of these two features (Figs. 25 and 27). Although heated outfall water has a tendency to float on the surface of the cooler ambient temperature seawater, data presented in the previous section on temperature indicates that wave and surf action mixes the outfall water at the reef margin and inner part of the reef front zones (Fig. 27). This mixing action extends the vertical range in which corals are killed. Seaward of the surf zone the warmer outfall water becomes stratified and is generally restricted to the upper one meter layer of water. It has little effect on the living corals, since the water depth there is usually greater than one meter, except where the upper parts of coral knobs and knolls extend up into this one meter layer (Fig. 27).

Table 7 was based on observations of the number of bleached corals, and surviving corals from the central core of the coral-kill zone outward to the peripheral region. This table should indicate the relative resistance of species to effluent. Corals of the genera Acropora, Montipora, and Pocillopora were found to be the least tolerant to effluent. The only coral species consistently surviving in the central core zone were Goniastrea retiformis, Psammocora haimeana, Favites abdita, Cyphastrea chalcidicum and a small, cryptic, encrusting Porites species.

Close observation revealed that not all the pale colored or bleached corals were dead. Some were still living, with polyps and tentacles extended.

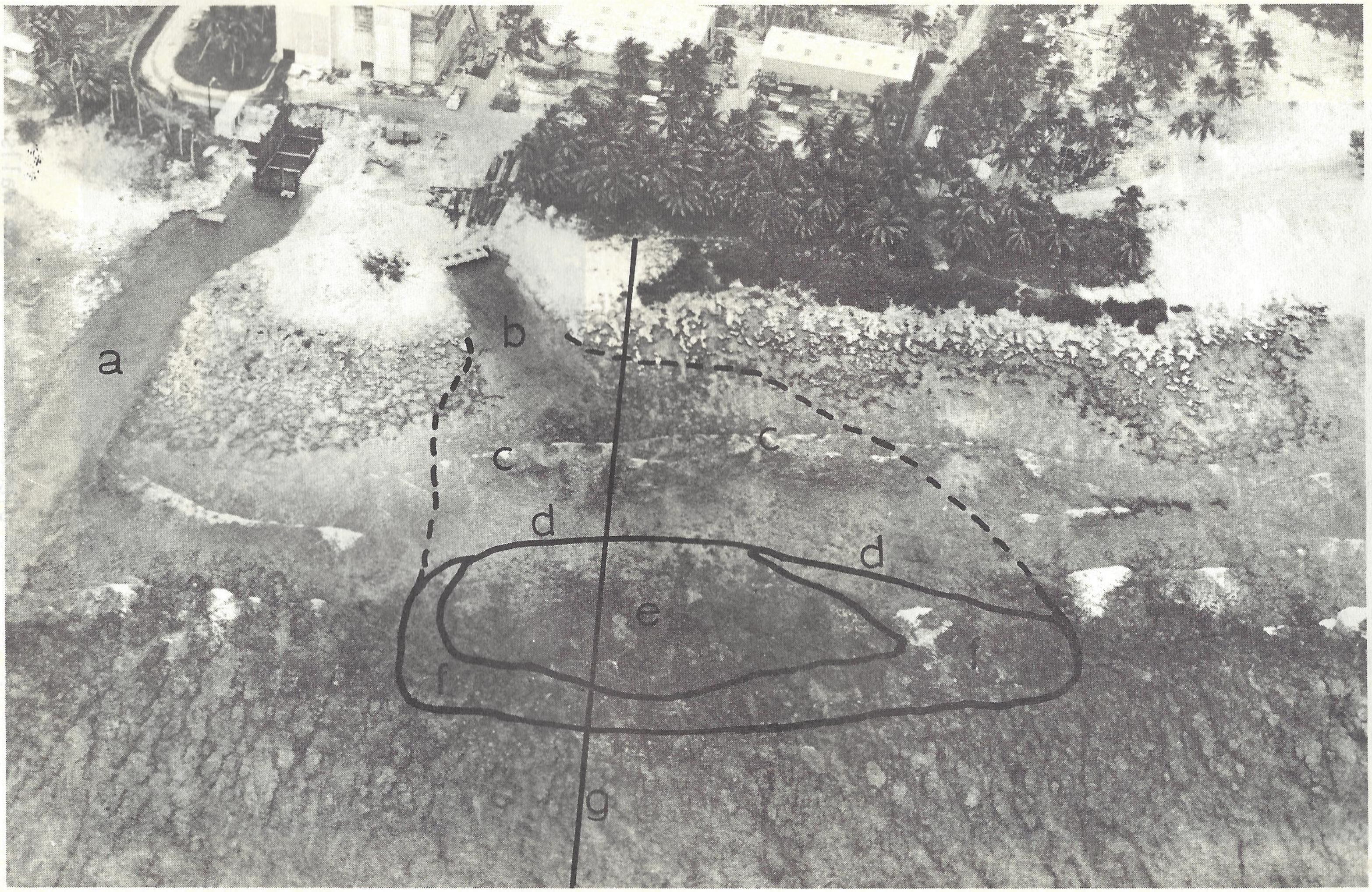


Figure 23. Limits of coral kill as of December, 1972 (a- intake channel, b- outfall channel, c- reef flat zone influenced by effluent, d- contact zone of effluent with living corals, e- core zone of coral kill, f- peripheral zone, g- Transect B).

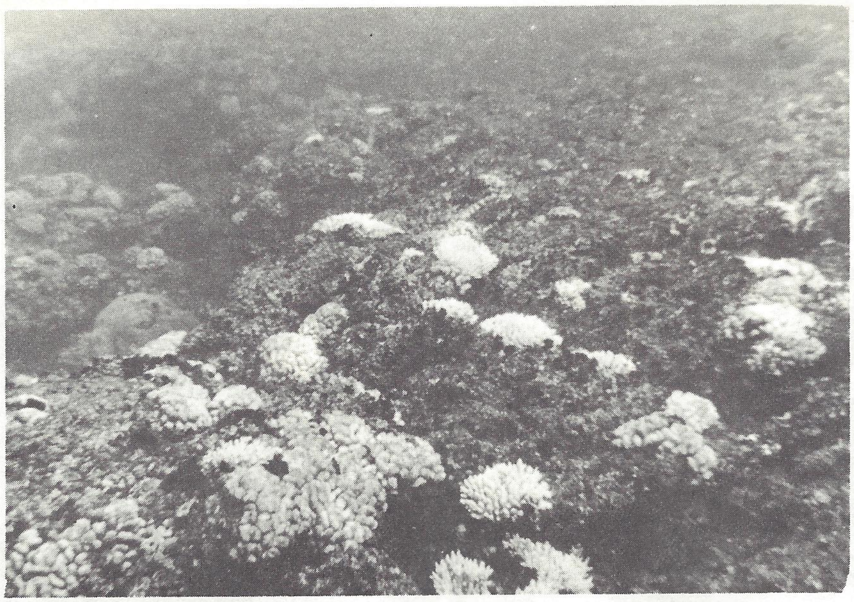


Figure 24. Coral kill on upper surface of a reef margin buttress.

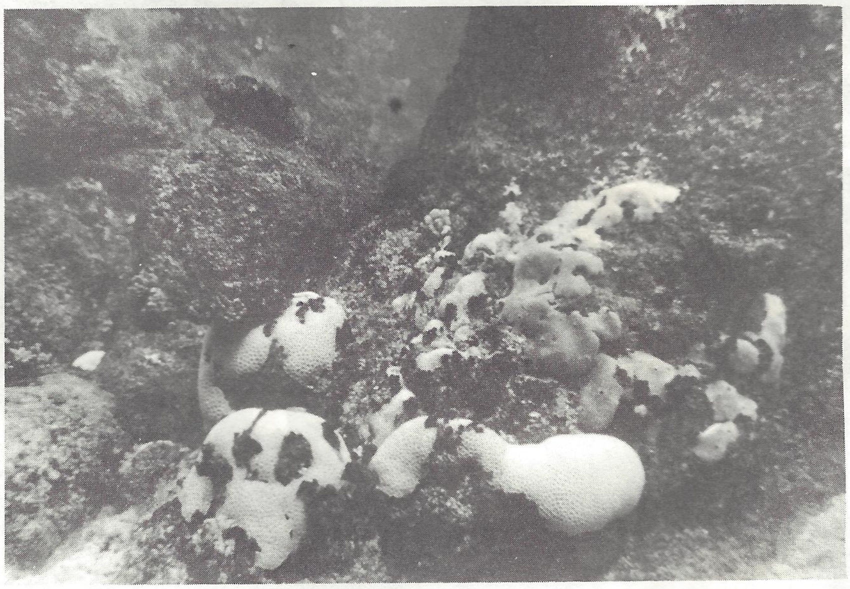


Figure 25. Pale and bleached corals on the walls and floor of a reef margin surge channel.

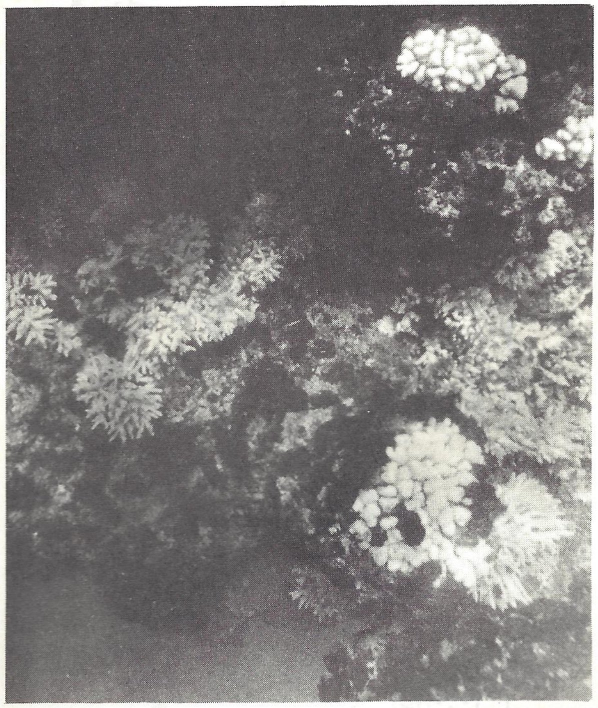


Figure 26. Dead coral and coralline algae surface being recolonized by blue green algae.

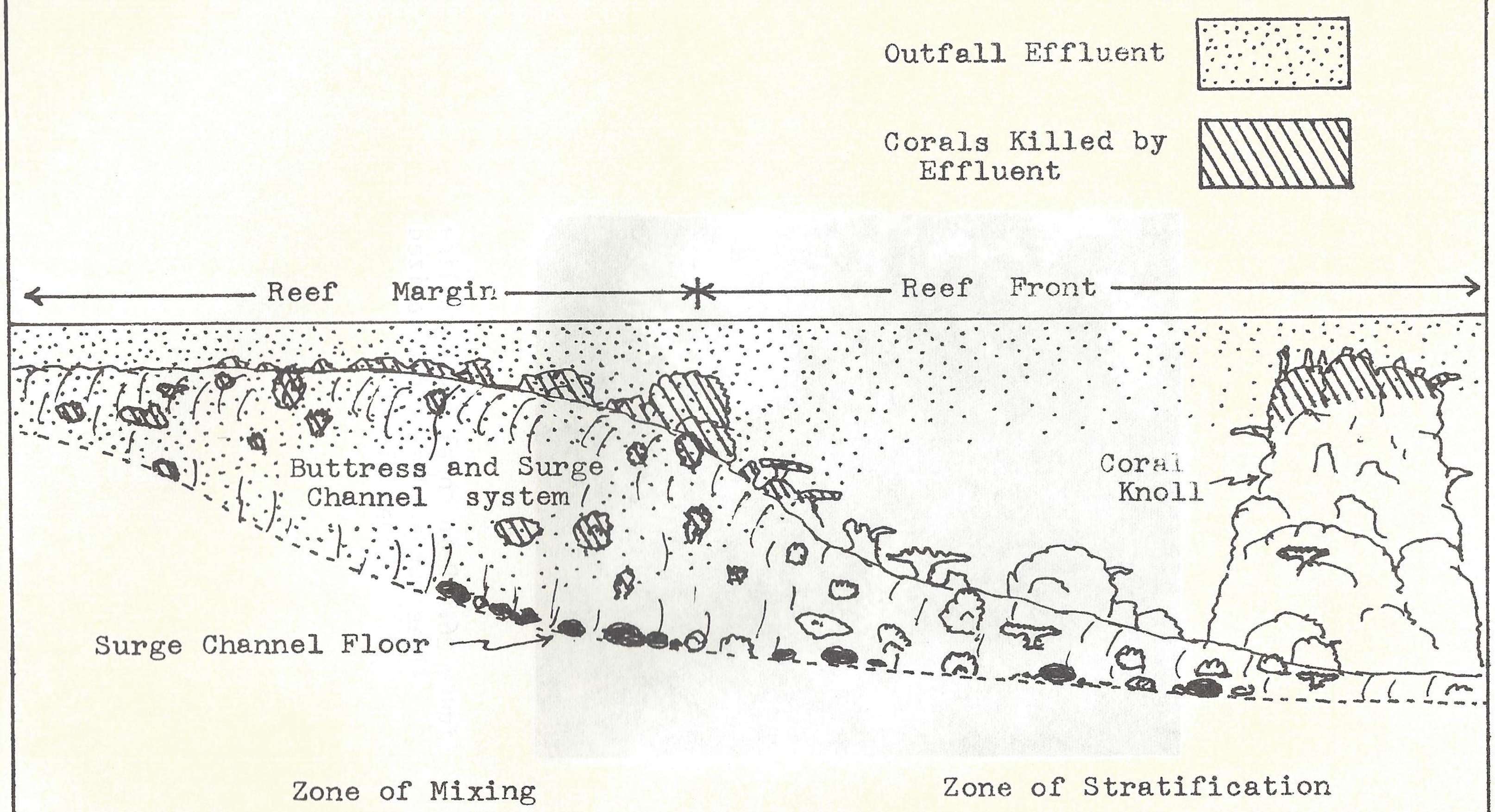


Figure 27. Vertical profile through the reef margin and reef front zones showing mixing and then stratification of the effluent.

Table 7. Relative resistance of corals to the outfall plume at Tanguisson Point. Loss of pigment coloration is used as index.

Name of Coral	Normal	Pale	Bleached	Dead
Stylocoeniella armata		X		
Psammocora nierstraszi	X			
Psammocora (P.) haimeana	X			
Stylophora mordax			X	
Pocillopora eydouxi			X	
Pocillopora meandrina				X
Pocillopora setchelli				X
Pocillopora verrucosa				X
Acropora abrotanoides				X
Acropora corymbosa				X
Acropora humilis			X	
Acropora hystix				X
Acropora murrayensis				X
Acropora nana				X
Acropora nasuta				X
Acropora ocellata				X
Acropora palmerae				X
Acropora smithi				X
Acropora surculosa			X	
Acropora syringodes				X
Acropora valida				X
Acropora wardii				X
Montipora conicula			X	
Montipora elschneri		X		
Montipora foveolata			X	
Montipora hoffmeisteri			X	
Montipora verrilli			X	
Montipora verrucosa				X
Montipora sp. 1				X
Montipora sp. 2			X	
Pavona clavus			X	
Pavona varians			X	
Coscinaraea columna	X			
Porites australiensis		X		
Porites lobulata		X		
Porites lutea		X		
Porites sp. 1	X			
Favia favus		X		
Favia pallida		X		
Favia speciosa		X		
Favia stelligera		X		

Table 7. (Continued)

Name of Coral	Normal	Pale	Bleached	Dead
Favia rotumana		X		
Favites abdita	X			
Favites complanata		X		
Favites favosa		X		
Favites flexuosa	X			
Plesiastrea versipora		X		
Goniastrea retiformis	X			
Goniastrea parvistella		X		
Platygyra rustica			X	
Platygyra sinensis			X	
Leptoria gracilis		X		
Leptoria phrygia		X		
Hydnophora microconos	X			
Leptastrea purpurea		X		
Leptastrea transversa		X		
Cyphastrea chalcidicum	X			
Galaxea hexagonalis		X		
Lobophyllia costata			X	
Acanthastrea echinata	X			
Heliopora coerulea			X	
Millepora dichotoma			X	
Millepora exaesa			X	
Millepora platyphylla			X	
TOTAL SPECIES	10	19	18	17

Others were partly killed with the uppermost bleached part of the corallum dead and the basal-lateral parts bleached and living. Numerous authors have shown that corals under stress begin to expel their zooxanthellae. The loss of this brown colored algal symbiont leaves the coral either a bleached white color, or more commonly, reveals the presence of other pale colored pigments normally masked by the zooexanthellae (Fig. 25). Under continued stress the corals lose more zooexanthellae and pigments, becoming white and colorless (Fig. 25). If stress is uninterrupted, death of polyps and disintegration of the coenosarc follows. This is in basic agreement with observations made on Kahe Pt. generating facility in Hawaii by Jokiel and Coles[11]. Usually, the first organisms to recolonize this new surface are various species of blue-gree algae (Fig. 26).

The reef margin and reef front zones have been monitored since the initiation of field work and the establishment of permanent Transects A, B, and C in 1970 (Fig. 3), to the present. Transect B bisects the main part of the outfall plume, where it crosses the reef flat zone and enters the reef margin and reef front zones (Fig. 23g). Quadrat stations on Transect B were analyzed for percent of living coral covering the reef surface, and species composition just before the coral-kill during April 1970, a second time after the coral-kill in May 1972, and in the reef flat, reef margin, and reef front zones a third time in January 1973. Table 8 summarizes the results of these transect studies by quadrat stations in the region of the coral-kill zone.

Seasonal changes in seawater temperatures, changes in wind and swell direction, and continued stress from the effluent plume has subsequently changed the boundaries of the original coral-kill zone (Fig. 23) to that shown in Figure 28. The initial region effected (peripheral zone) in Figure 23 was 118 meters by 32 meters. The core zone was 80 meters in length and 26 meters in width. The area affected was 3776 m^2, for the entire region, and 2080 m^2 for the core zone. The effected region shown in Figure 28 was drawn from field data collected one year later. The effected region has now increased to a total of 186 meters by 55 meters. The core zone has increased to 108 by 40 meters. The area affected has increased to about 10,000 m^2 overall and 4320 m^2 for the core region. The boundaries of the coral-kill zone have not become stabilized to date.

A check of the outfall region was made in January, 1973. The results of this check revealed that newly killed corals were evident in the peripheral zone. After Tanguisson No. 2 begins operation, routine monitoring of this region should be continued to determine the extreme limits of the coral reef community that is affected by the additional effluent.

Table 8. A comparison of the percentage of living coral covering the reef surface and the number of coral genera and species present at Tanguisson Point. Transect B, 1970 - 1973.

Transect Quadrat Station	Reef Zone	Percent of Cover			Number of Genera and Species		
		1970	1972	1973	1970	1971	1972
8	Reef Flat	0	0	0	0-0	0-0	0-0
9	Reef Flat	0	0	0	0-0	0-0	0-0
10	Reef Flat	1	0	0	2-2	0-0	0-0
11	Reef Margin	1	2	0	7-12	1-1	0-0
12	Reef Margin	56	1	0	10-14	6-10	0-0
13	Reef Front	83	37	4	9-15	8-16	2-4
14	Reef Front	41	38	12	9-18	7-14	2-4
15	Reef Front	64	19	18	8-10	9-12	9-10
16	Reef Front	21	53	49	11-13	10-15	10-16

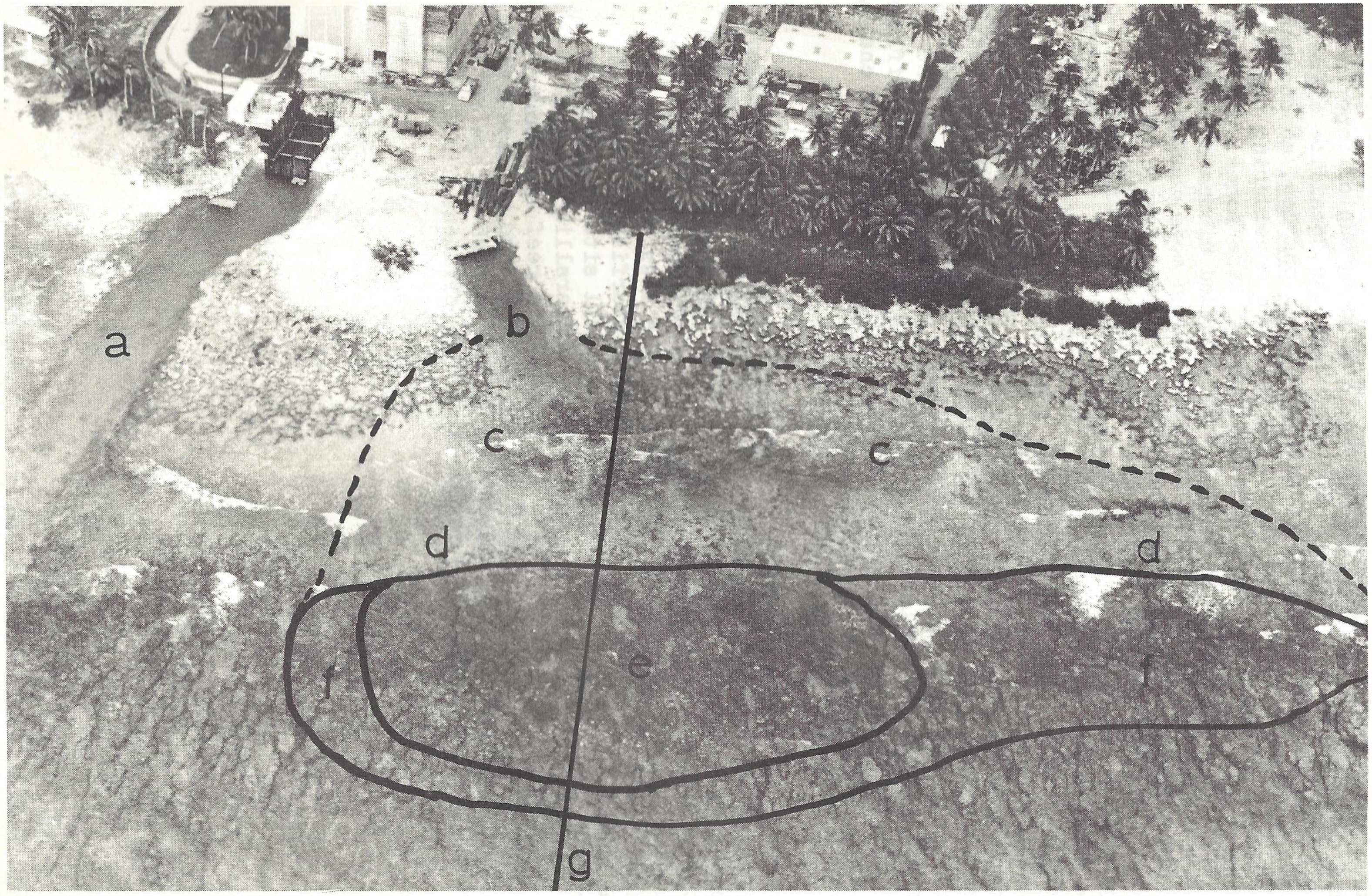


Figure 28. Limits of coral kill as of January, 1973. See figure 23 for legend.

In terms of reef building and maintenance, another group of important organisms affected by the effluent were the crustose coralline algae. In the reef margin and reef front zones *Porolithon onkodes*, an encrusting coralline, covers more reef surface area, when considering the numerous holes, cracks, and cavernous regions of these zones, than any other organisms. *Porolithon gardineri* forms rounded clumps of closely set branches, and in the reef margin zones is often more abundant than corals. *Porolithon gardineri* has about the same degree of tolerance to the effluent as the corals. *Porolithon onkodes* shows slightly greater resistance than *P. gardineri*. The reef surface covered by these two encrusting and ramose corallines in the core zone has been greatly reduced. In the peripheral zone, the *Porolithon* kill is patchy and more or less restricted to the upper parts of surge channels, submarine buttresses and knobs. *Porolithon onkodes* seems to be surviving in the small cracks, holes, and on the basal branches of dead ramose coral colonies. In these cryptic locations the encrusting coralline has a normal pink to red coloration. Under the influence of the effluent, this red pigmentation turns pale and finally, at death, becomes a chalky white color. Blue-green algae are usually the first organisms to recolonize the freshly killed surface (Fig. 26).

Unless another carbonate secreting organism recolonizes this important niche, erosion of the reef margin and inner part of the reef front zone will probably take place. Recent investigations at Tumon Bay (Gognga Transects) revealed that *Acanthaster planci* has killed nearly all the corals in these two reef zones (both zones endure less wave exposure than Tanguisson reefs). This coral kill by the starfish at Tumon Bay is not as serious as that at the Tanguisson outfall site because the dead corals in Tumon were rapidly encrusted with coralline algae, thereby maintaining the structural integrity of the reef framework. In time, the reef margin corals at Tumon Bay will become re-established, but at the outfall site at Tanguisson, there are no such corals or coralline algae recolonizing the region where the effluent has killed them.

SECTION IX

THERMAL SIMULATION EXPERIMENTS

GENERAL COMMENT

As pointed out in the Introduction, a laboratory study on the effects of thermal stress was added to the field work proposed in Phase II. The research was specifically requested to measure the effect of temperature on reef corals, however, the availability of the necessary equipment for thermal simulation allowed for some additional work. One such paper involves the effect of elevated temperature on metabolism of Acanthaster planci. This work was done by a visiting investigator, Dr. Masashi Yamaguchi. The preliminary research is presented in Appendix A and eventually will be published along with additional work now in progress by a graduate student. Grant support also allowed for two, now completed, student research papers, one of which led to a Masters thesis. The latter, also to be submitted for publication soon, was conducted by Masters candidate John H. Rupp and is found in Appendix B. This paper deals with the effects of elevated temperature on the early embryology of some tropical echinoderms. The third contribution, was completed by a recent graduate student, Mr. Tom Hohman, and staff phycologist Dr. R. T. Tsuda. Their work is preliminary and involves a study on the effect of temperature on photosynthesis and respiration in the green alga Caulerpa racemosa (Appendix C).

THERMAL SIMULATION EXPERIMENTS WITH REEF CORALS

A team of University of Hawaii scientists has been working, with support from another EPA grant, to provide information on upper thermal tolerance limits and growth rate of adult coralla and settlement of planulae in Hawaiian corals. Unpublished data provided by one of these scientists, Mr. Paul Jokiel, indicates that the upper thermal limit for the common species of Hawaiian corals (Pocillopora damicornis, Montipora verrucosca, and Fungia scutaria) in approximately 31-32°C. Jokiel noted that these data are in agreement with those from a similar study by Edmondson[16].

The Hawaii group suggested that Hawaiian corals were probably adapted to temperatures at or below 27°C, which is the highest (summer) seawater temperature in the Hawaii study area. They pointed out that other physiological races of the same coral species found in Hawaii exist in the warmer waters of the Indo-Pacific and these races may well have tolerance ranges set higher than those found in Hawaii. The Jokiel team advanced the following hypothesis:

> "...that (coral) communities are adapted to the prevailing temperature of the region, with temperature additions of 2 Celcius degrees above normal summer ambient being clearly damaging and temperature additions of 4 Celcius degrees above normal summer ambient being outright devastating."

The Hawaii group also found that the coral growth optimum fell within the normal ambient range (22-27°C) for the study area, Kaneohe Bay, Oahu.

In the Fall of 1971, the EPA requested that the Guam team aid in testing the above hypothesis. Guam lies within the Indo-Pacific region (Wells[17]) referred to by Jokiel and his colleagues and the island has a mean annual temperature (27.6°C) slightly greater than the maximum for Kaneohe Bay (27°C). The Guam team was also asked to catalog the upper thermal tolerance limits for additional coral species because Guam has a richer coral fauna (∿200 spp.) than Hawaii (∿35 spp.)

In Guam the seawater temperature regime follows the wet and dry season more than the traditional winter and summer months. For example, the coolest water temperatures are found from January to April, which approximates the dry season. The warmest months are June through November, the wet season. Transitional months are usually May (sometimes June) and December. The cool months have a water temperature range of 25.5 to 28.3°C with a mean of 26.8°C, for a 10 year period (Fig. 18). According to the above hypothesis, reef corals on Guam should be adapted to higher temperatures than Hawaiian corals.

The thermal simulation apparatus used by the University of Hawaii group utilized a heat pump and a titanium tube heat exchanger. Temperature of seawater was controlled by mixing heated with ambient temperature seawater. This system worked well but was beyond the budget and support facilities of our project. With the aid of personnel from the EPA National Water Quality Laboratory in Rhode Island, we were able to design a system that utilized commercial immersion heaters and electronic controllers with a built in ΔT system (Fig. 29). The controllers compare experimental tank temperatures with the ambient control tank temperatures (about 28°C) and automatically adjust the experimental temperatures to two degree increments above the existing ambient temperature (Fig. 30).

A

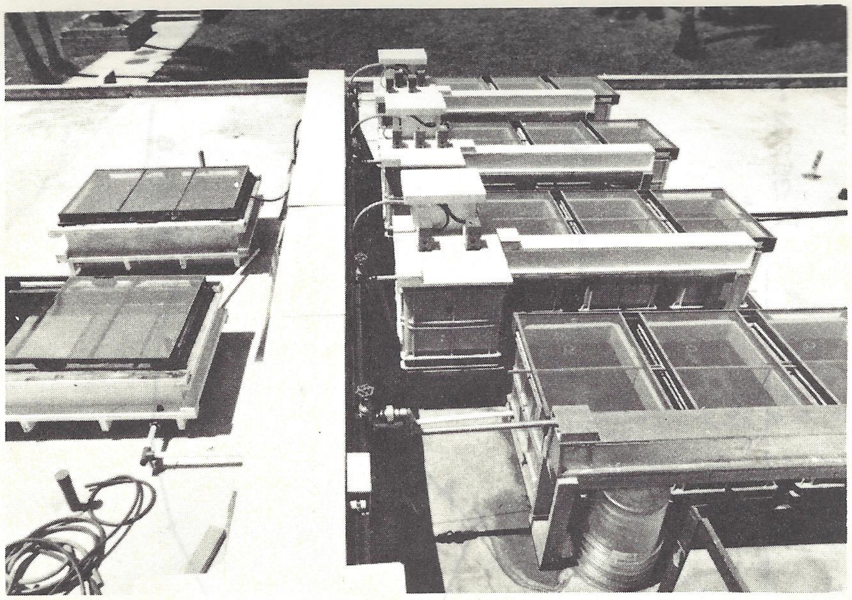


Figure 29. Thermal simulation device. (A- oblique view, B- side view). Figure 28a shows the common seawater feeder trough with valves to provide seawater to acclimation tanks on the left and the experimental system on the right. Control tanks are in the foreground with the +2, +4, and +6 tanks extending into the background. There are three replicate tanks in each temperature series. Tanks with white tops are heater tanks with immersion heaters and control boxes.

B

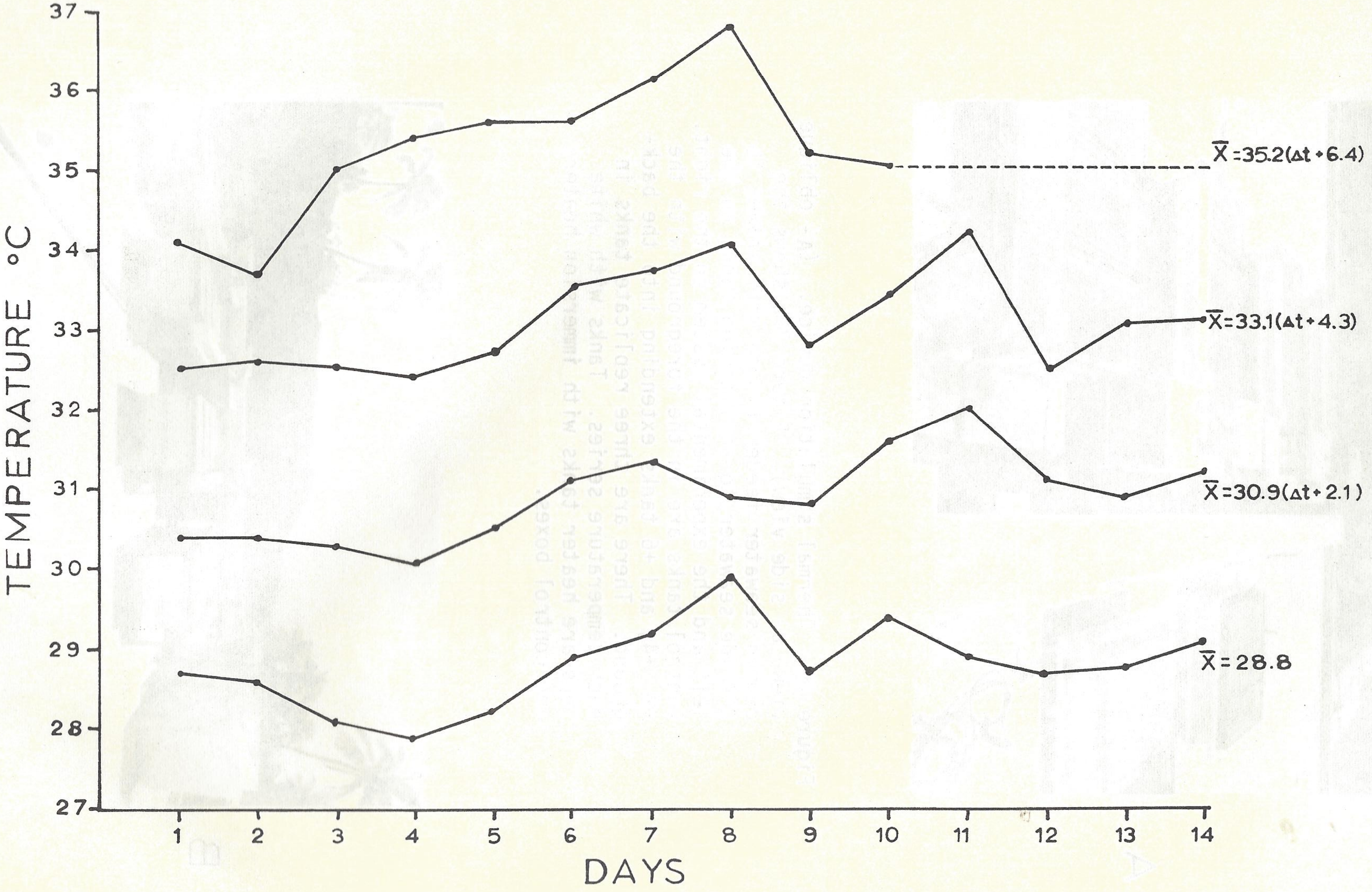


Figure 30. Sample telethermometer readings showing tracking ability of the thermal simulator controls. This two week period occurred during the summer during low tides when reef flat water entered the seawater system and raised the ambient temperature above 28°C.

This results in experimental temperatures of about 30, 32, and 34°C. The Hawaii group used the same two degree increments above ambient in their study but with a normal summer ambient of 27°C (Jokiel, personal communication). The Hawaii experimental temperatures were then 29, 31, and 33°C.

Corals were acclimated for one to two weeks prior to introduction to the simulator (Fig. 31). The corals were placed in pans of fresh seawater and floated in the experimental tanks until they reached the experimental temperature (two to three hours). They were then arranged in rows within the tanks. The tanks were set up in replicates of three for each experimental temperature (Fig. 29). The rows of coral specimens were alternated between tanks to avoid bias in placement. Coralla were placed on inverted specimen jars to avoid bacterial contamination that often occurs when the coralla are in contact with the bottom. It was also necessary to place one layer of plastic screen over each tank to cut down (by about 32%) on the intense sunlight of our Latitude (13°N). Unless this was done, the corals tended to lose their pigments and often died in the shallow tanks. The 12 experimental tanks were 79 by 59 by 50 cm and rigged with stand-pipes to hold the water level at 39 cm (182 liters). Uncontaminated seawater flowed constantly through the system at four liters/minute. A scanning telethermometer with recorder was set to monitor all tanks as well as the ambient control tanks continuously.

The following data are strictly preliminary. The remoteness of Guam's location resulted in considerable delay in setting up the experimental apparatus (three to six month shipping lag). In addition, a series of unusually low late summer spring tides (lowest tides recorded on Guam) exposed the Marine Laboratory's seawater well heads and damaged our pumping system. These low tides also led to encroachment of reef flat water of unusually high temperature into the system. This resulted in our having to terminate the first three 30 day experiments after they were well underway. A more detailed paper will be prepared after we have had an opportunity to gather more data.

Three experiments of 30 days duration each have been completed to date (Figs 32-34). In the first experiment, 48 specimens each of Pocillopora damicornis, Fungia scutaria, and Psammocora contigua were divided up among the experimental tanks. Four specimens of each species were placed in each of the three ambient (control) tanks. The same procedure was followed in the nine treatment tanks for each of the three experimental temperatures. The Pocillopora and Psammocora were taken from warm, shallow reef flat environments. The Fungia were taken from deep water (15 m).

There was no significant difference between the controls and the +2° tanks with Pocillopora and Psammocora (Fig. 32). Seven of the Fungia were dead

Figure 31. Acclimation tank; corals are placed on inverted jars to avoid bacterial contamination that often occurs when they are on the bottom.

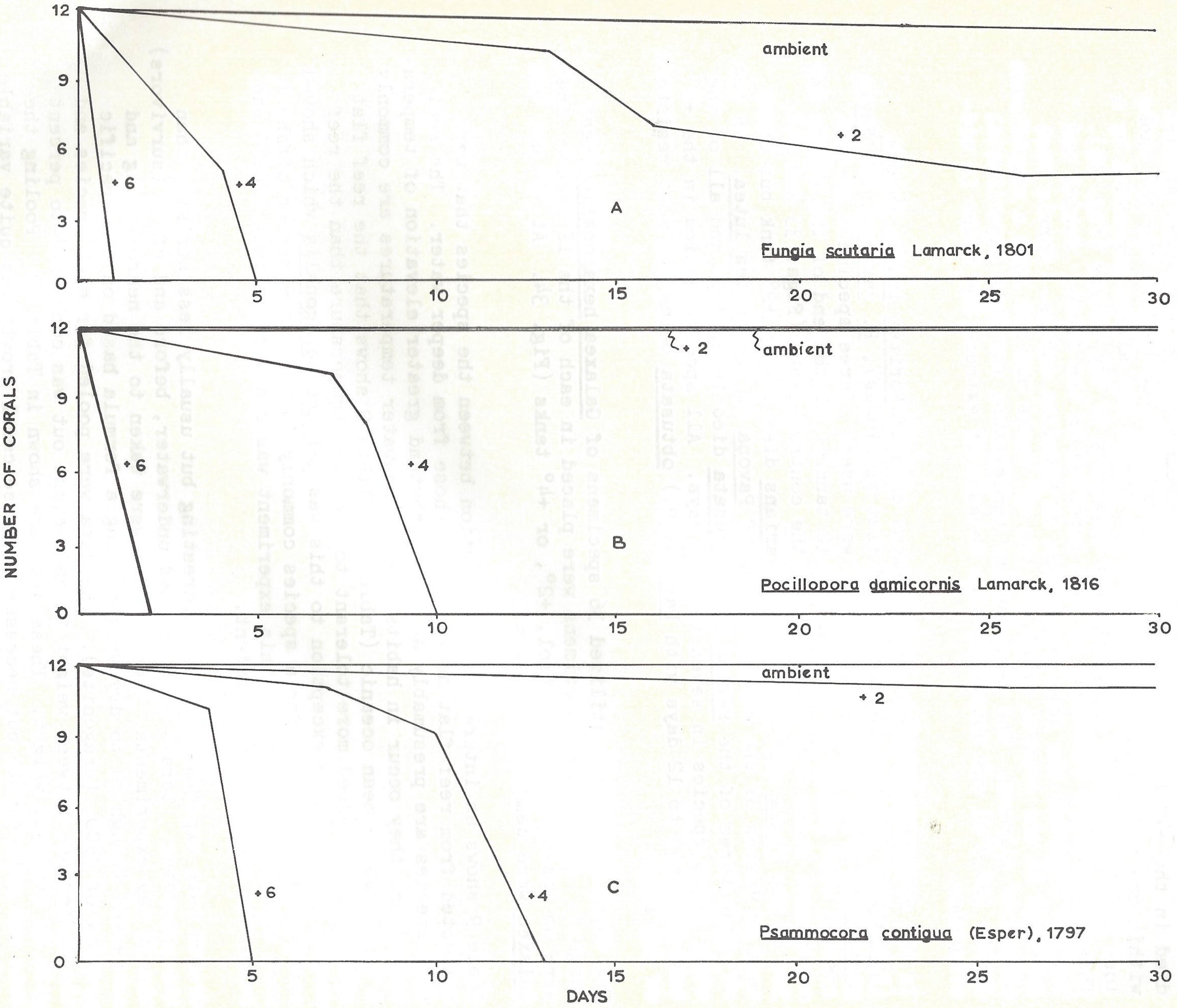


Figure 32. Results of experiment I. (Ambient = 28.8°C)

at the end of the 30 days in the +2° tank. All specimens survived in the control tanks except one specimen of Fungia. All of the coral species died in the +4° tanks within 5 to 13 days and all died in the +6° tanks within one to five days. Death of the corals was always preceeded by a loss in pigment that resulted in a bleaching of the polyps (Fig. 35). This response is identical to that reported in the field. Jokiel and Coles[11] reported the same phenomenon in Hawaiian corals. Corals that survived in the control tanks and the +2° tanks did not lose a significant amount of pigment. The mean ambient temperature for this experimental series (28.8°C) was unusually high because of extreme low tides in mid-afternoon.

In the second experiment, 36 specimens each of Porites lutea, Pavona (Polyastra) obtusata (shallow reef flat specimens), P. varians, and Favia stelligera (reef margin specimens) were used. Three specimens of each species were placed in each of the 12 tanks. At the end of the thirty day experiment there were no losses in the control tanks (Figs. 33 and 34). Two of the Favia and three Pavona varians died in the +2° tank but there were no losses of the other species of Pavona or of Porites lutea. In the +4° tank three of the Pavona (P.) obtusata died in 30 days and all of the other three species in seven to nine days. All specimens died in the +6° tank within 3 to 12 days with Pavona (P.) obtusata being the most resistent of the four.

The third experiment utilized 36 specimens of Galaxea hexagonalis (reef margin). Again three specimens were placed in each of the 12 tanks. There were no losses in the control, +2°, or +4° tanks (Fig. 34. At +5° all the Galaxea were dead in four days.

Table 9 shows an interesting correlation between the species that were collected from reef flat habitats and those from deeper water. The reef flat species are presumably able to withstand greater elevation of temperature since they occur in habitats where seawater temperatures are commonly 2 to 3°C above mean oceanic (Table 1). Table 9 shows that the reef flat species were indeed more tolerant to elevated temperature than the reef margin species. An exception to this was Galaxea haxagonalis which showed unexpected resistance for a species commonly found in the deeper offshore reef community. However, this experiment was run when ambient (26.7) was below the normal summer abmient.

Growth rate experiments were interesting but usually less striking than the preceding. Corals were weighed underwater, before and after (survivors) the 30 day experiments. The weights were taken to the nearest 0.1g and corrected (roughly) to dry weight using a formula based on the specific gravity of $CaCO_3$ (aragonite). The data were pooled for each species and the difference between weight in and weight out was converted to percent gain in skeletal weight. These data are shown in Table 10. Pooling the data was unfortunate but necessary because coral growth was quite variable within sample groups. This occurred because of differences in the ratio of total living tissue area to the total weight of the corallum. The

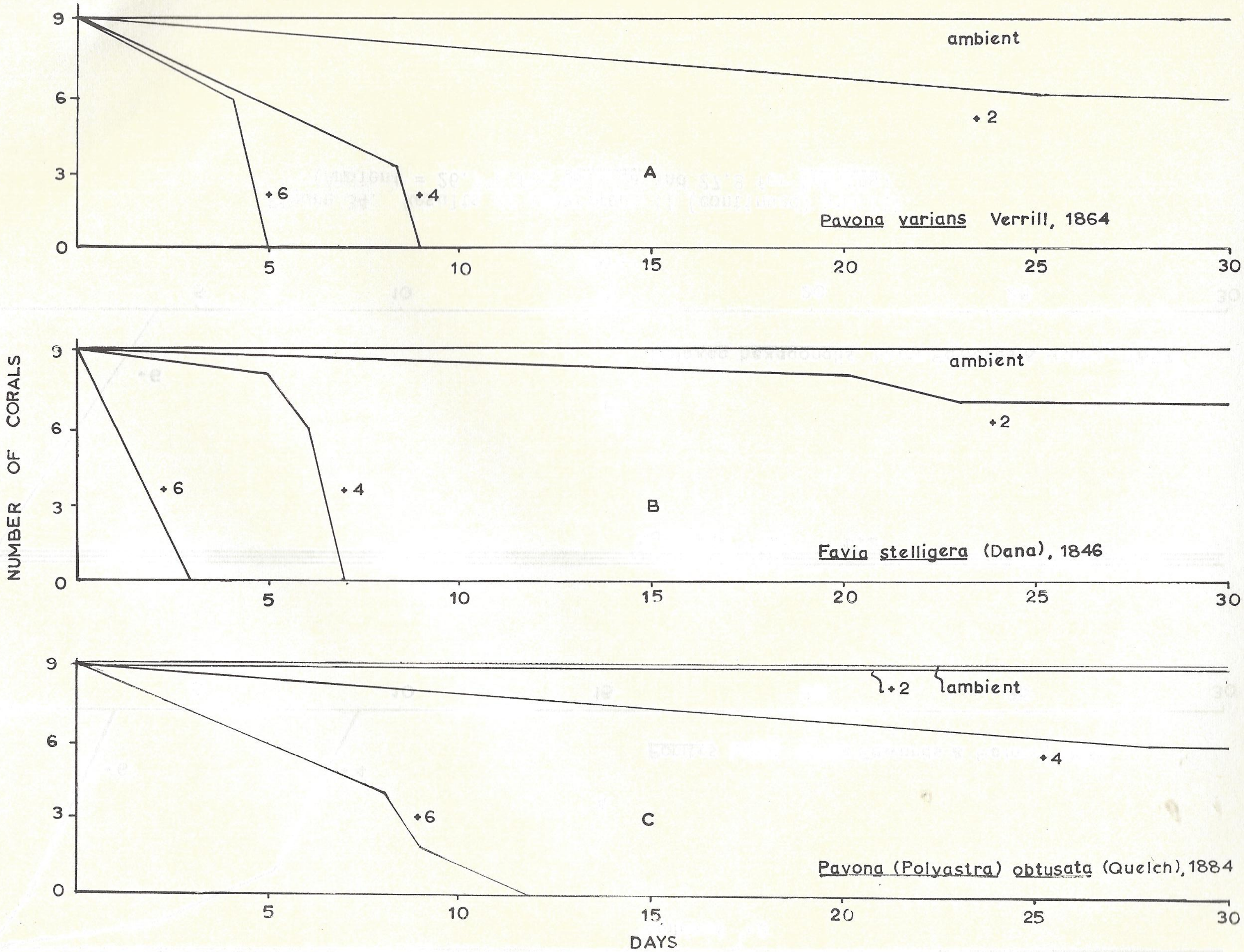


Figure 33. Results of experiment II, with the exception of *Porites lutea.* (Ambient = 27.8°C).

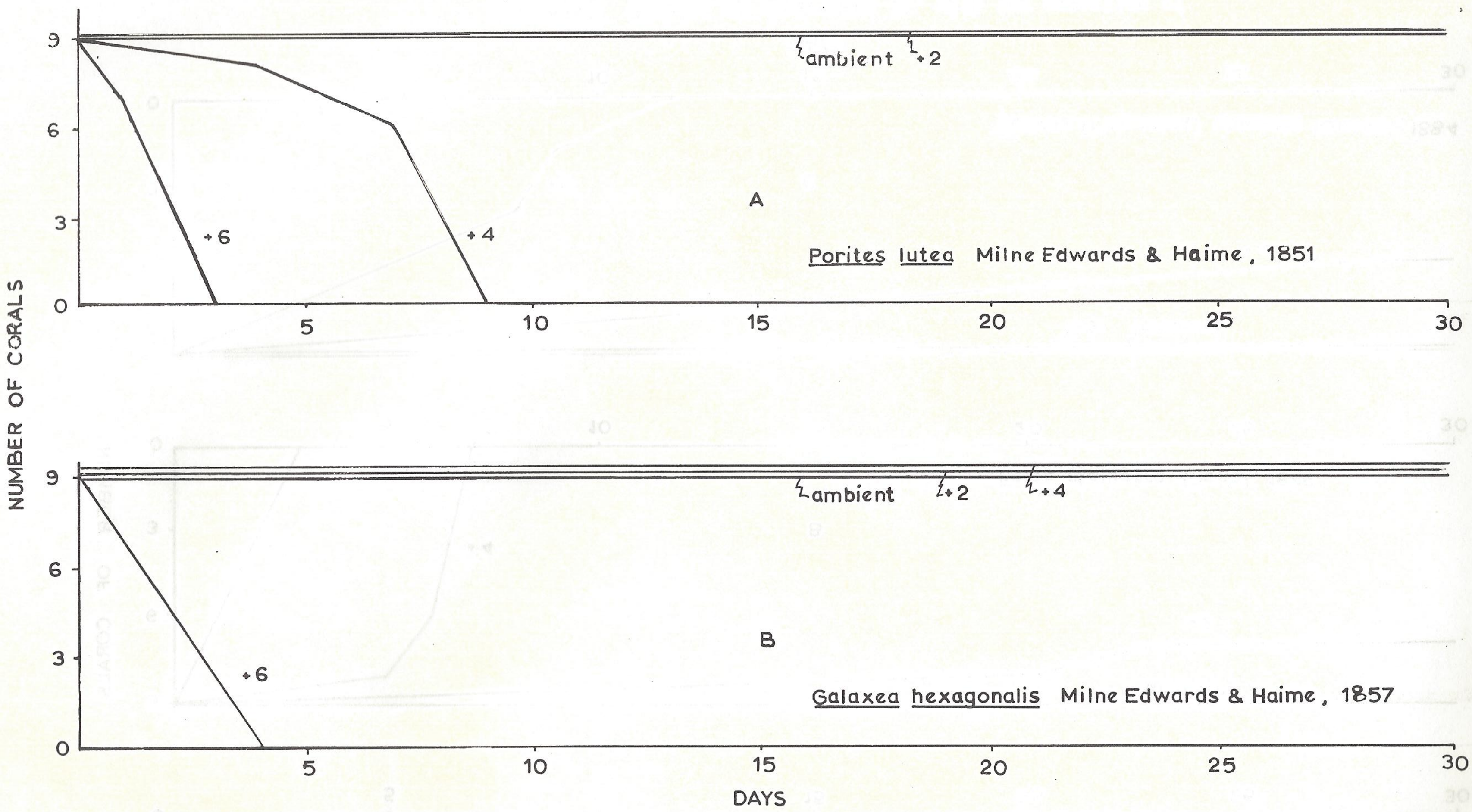


Figure 34. Results of experiment II (continued) and III.
(Ambient = 26.7°C for Galaxea and 27.8 for Porites)

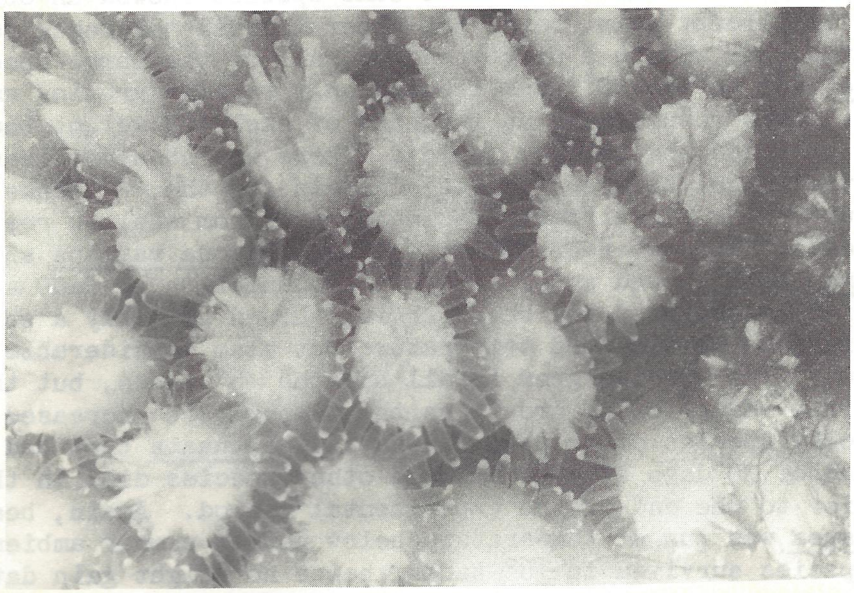


Figure 35. Bleached polyps of Galaxea hexagonalis.

is difficult to control intrasprecifically and extremely difficult interspecifically because of growth form and size differences in the coralla.

Reef flat collected specimens of Pocillopora and Psammocora both showed rather rapid growth rates but definite reductions between controls and those in the +2° tanks (Table 10). There was a slight increase in percent of skeletal weight gain (over the controls) in Pavona (P.) obtusata in the +2° tank which may be normal for this species which is found in shallow reef flat habitats. This would imply that the optimum temperature for growth exceeds offshore oceanic temperatures. In the +4° tank, the same species showed an obvious decrease in percent gain, hence the upper thermal tolerance range may be elevated, but within a narrow range. All of the large specimens of Fungia died in the +2° tank leaving only rapidly growing small colonies. This resulted in an increase of skeletal weight that slightly exceeded the control series. There was no significant change in skeletal weight between Porites controls and the +2° tanks. This is not surprising since these specimens were from shallow reef flat environments. The two reef margin species, Pavona varians and Favia stelligera, both showed a reduction in accumulation of CaCO at +2°C. Galaxea, collected from the reef margin, showed not only a surprisingly high resistance to elevated temperature but also considerable growth (Table 10). The species grew in all but the +6° tanks, but there was a consistent reduction of growth as the temperature increased. This was the only species other than Pavona (P.) obtusata that had survivors at the end of 30 days at +4°, all the other species died in the +4° tanks prior to the end of the experimental period. Again, bear in mind that Galaxea was run at temperature below normal summer ambient. None of the species survived in +6° tanks, hence no weight gain data are available.

A large number of reef flat species were used in the preliminary experiments even though they are uncommon on the Tanguisson reef flat. This was done to provide contrast between the presumably resistant reef flat species and the more thermally sensitive species of the reef margin and deeper habitats. The reef margin species are most likely to be affected by plant effluent.

Our preliminary data do not indicate a difference in temperature tolerance between Guam and Hawaiian corals. We must say, however, that we have only scratched the surface and hope to go far deeper into the problem now that our thermal simulator is operating satisfactorily. Considerably more data are needed before we can make any definite statements with regards to the hypothesis proposed by the Hawaii group. In addition, both teams need an opportunity to meet and compare data and methods. A standardization of techniques is critical if the work is to satisfactorily compare response to thermal stress in these two tropical reef ecosystems.

Table 9. Order of resistance of coral species tested in thermal simulator, and the number of corals that died. The numbers in parentheses indicate the maximum number of days of survival.

Species	Locality	Ambient	+2	+3	+4
Galaxea hexagonalis [n=9]	Reef Margin	0(30)	0(30)	0(30)	9(3)
Pavona (*Polyastra*) *obtusata* [n=9]	Reef Flat	0(30)	0(30)	3(30)	9(12)
Psammocora contigua [n=12]	Reef Flat	0(30)	1(30)	12(13)	12(5)
Pocillopora damicornis [n=12]	Reef Flat	0(30)	0(30)	12(10)	12(2)
Porites lutea [n=9]	Reef Flat	0(30)	0(30)	9(9)	9(2)
Pavona varians [n=9]	Reef Margin	0(30)	3(30)	9(9)	9(5)
Favia stelligera [n=9]	Reef Margin	0(30)	2(30)	9(7)	9(3)
Fungia scutaria [n=12]	Terrace (15m)	1(30)	7(30)	12(5)	12(1)

Table 10. Growth rates of corals at experimental temperatures. Percent gain of skeletal weight is corrected to dry weight. The ( ) show number of corals surviving thirty days.

Exp.	Name of Coral	Temperature Mean (Amb.)	%of Weight Gain			
			Amb.	+2	+4	+6
I	*Pocillopora damicornis* [n=12]	28.8	7.1(12)	4.8(12)	-----	------
	Psammocora contigua [n=12]	28.8	7.1(12)	5.6(11)	-----	------
	Fungia scutaria [n=12]	28.8	0.3(11)	1.0(5)	-----	------
II	*Pavona* (*P.*) *obtusata* [n=9]	27.8	2.0(5)	2.6(6)	1.6(6)	------
	Pavona varians [n=9]	27.8	3.3(9)	2.2(6)	-----	------
	Favia stelligera [n=9]	27.8	2.1(9)	.07(5)	-----	------
	Porites lutea [n=9]	27.8	2.6(9)	2.7(9)	-----	------
III	*Galaxea hexagonalis* [n=9]	26.7	3.2(9)	2.3(9)	1.5(9)	------

SECTION X

EFFECTS OF ACANTHASTER PREDATION ON TANGUISSON CORALS

In February 1967, the coral eating "Crown-of-Thorns" starfish, Acanthaster planci (Linnaeus), was noted (Randall[12, 18]) in above normal population densities along local portions of the relatively sheltered northern half of Tumon Bay (Fig. 1). The infestation spread to Tanguisson Point located 2.4 kilometers north of Tumon Bay, sometime between June 1968, and September 1968. By April 1969, nearly all the starfish had migrated out of the Tanguisson area, leaving over 95 percent of the reef building (hermatypic) corals dead in the area seaward of the reef front zone.

OBJECTIVES

One of the grant objectives was a study of the damage to Tanguisson reefs, attributable to Acanthaster. This was to be completed prior to release of plant effluent in order to avoid confusion between environmental damage that might ultimately result from plant operations and that caused by Acanthaster. Unfortunately the Tanguisson reef was destroyed prior to the start of the research and it was necessary to extrapolate about its pre-Acanthaster conditions from research on the nearby Tumon reef. A thorough study of coral distribution on the Tumon Bay fringing reef was conducted by Randall[12, 18] prior to the infestation of Guam by Acanthaster planci and before the grant research began. The Tumon reef is contiguous with the Tanguisson fringing reef and the two, except for the reef flat zones, were very similar in terms of coral species composition and distribution. Collections and observations were also made at Tanguisson by Randall[12, 18] during his 1966 to 1969 study of Tumon.

The second objective, regarding the Acanthaster damaged zones of the Tanguisson reef, was a study of potential coral recovery following intense predation. This natural catastrophe simulated a possible pollution induced one and basic research on coral recovery and recolonization was done.

INITIAL *ACANTHASTER* DAMAGE (1968-1970)

Previous Work

Little previous work has been done on the fringing reefs of Guam with respect to coral distribution. Most studies are of a geological nature, dealing mainly with various physical parameters of the reef complex.

Some coral collections were made on Guam and Saipan by Cloud[19, 20], during U. S. geological surveys of these two islands. A list of coral genera was compiled from these collections by Wells[17]. Tracey, *et al*[1], conducted several reef traverses in the study area. As far as could be determined, no systematic coral collections were made by Tracey but severl coral genera are listed by reef zones from "Reef Traverse 2, at Tumon Bay." The following genera were reported: from the reef margin-*Acropora*, *Pocillopora*, *Favia*, and *Millepora*; from the reef flat-*Porites* in the outer part, *Acropora*, *Pavona*, and *Pocillopora* in the inner part.

Other work on the reefs of Guam was done by Stearns[21], Cloud[22], and Tayama[23]. Coral distribution was not included in these studies. A study of the marine geology of Guam by Emery[2] includes investigations of submarine slopes, lagoon floors, channels through fringing reefs, beaches, and rocky shores.

Observations on *Acanthaster* were first reported by Chesher[15]. Chesher described *A. planci* population movements, densities, feeding behaviour, relative coral predation rates, control measures, and possible causative factors related to the sudden increase in numbers of starfish in various Indo-Pacific regions. Tsuda[24] described the current status of *A. planci* on Guam with regard to population densities, location of infested reefs, and the extent of the coral damage.

Methods

Three permanent Transects (A, B, and C), were established at Tanguisson Point. Figure 3 shows the location of these transects. Stations were established at 10 m intervals along the transects from the upper intertidal zone to a depth of 30 m on the seaward slope zone. These station locations were permanently marked by placing three to five links of ship anchor chain (4.7 kg per link) at each. Stations were identified by attaching numbered fiberglass cards to the anchor chain links. For ease in locating the transect stations, the numbered cards were suspended approximately 0.5 m above the anchor links by a plastic float (Fig. 36). At each station a reference point was established at the point where the numbered card was attached to the anchor links.

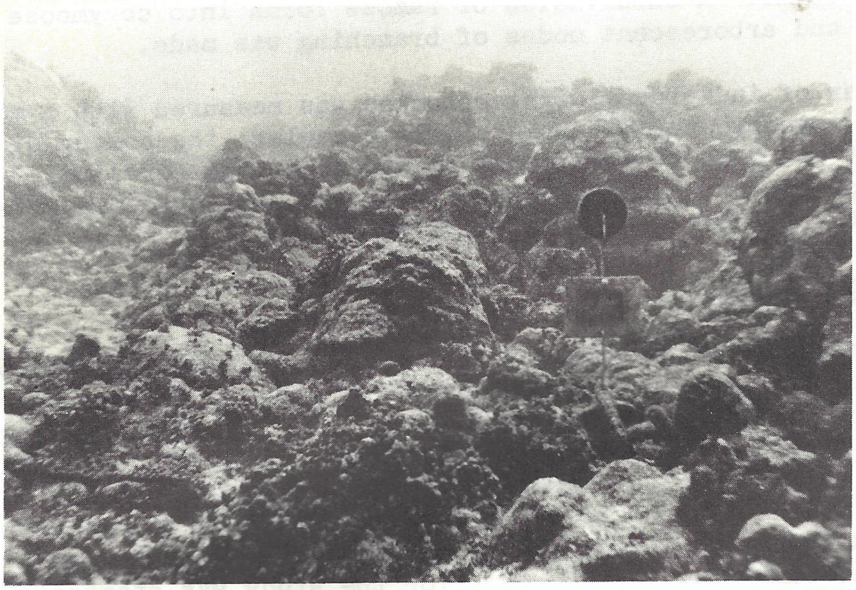


Figure 36. Transect B station showing anchor links and station number suspended by a float. Station 23 is located on the inner part of the submarine terrace. The outer part of the reef front is visible in the background. Ninety percent or more of coral colonies visible have been killed by <u>Acanthaster planci</u> and most are still intact and in position of growth.

two wire grid quadrats, each one meter square, were positioned at the station reference point (Fig. 37). After positioning of the quadrat grids, the following data were recorded from each: (1) the transect station number; (2) the quadrat number; and (3) the specific name, size, and growth form of each living coral found within the confines of the grid. The various coral growth forms differentiated follow those described by Wells[25]. A columnar form was added which differentiates an intermediate mode of development between the massive and ramose forms. A subdivision of ramose forms into corymbose, cespitose, and arborescent modes of branching was made.

The diameter of individual coral colonies was measured with a meter stick with moveable trammel points. If circular, the colony diameter measurement was made at the widest point across the corallum. If the colony shape was not circular, its outline was sketched and several measurements of length and width were recorded.

Distribution of Corals

Coral distribution at Tanguisson Point is based upon data from the three transects, general field observations, and specimen collections. Extensive systematic coral collections were not made at the Tanguisson study region because a similar species composition was collected at Tumon Bay (Randall[12]). The only corals collected at Tanguisson Point were those that could not be identified in the field, those that represented new growth forms, or those that were not previously collected at Tumon Bay. Field work for the study was started at Tanguisson during September 1969, and was continued until July 1970. Table 11 lists the coral species known from the study area.

Table 12 lists the frequency distribution of coral species observed on the transects by reef zones. This table shows that 86 species representing 30 genera occurred on the three transects. Combining this with the number of species shown on Table 11 that did not occur on the transects, the total number of species is raised to 96 representing 33 genera. From the total number of species and genera occurring at Tanguisson Point, 90 species represented by 30 genera are hermatypic, scleractinians and the remaining 5 species representing 3 genera are nonscleractinians. No ahermatypic corals were observed or collected at Tanguisson Point, even though investigations were made to depths of 35 m.

Intertidal (5 to 10 meters wide)-- In most places the intertidal zone is either bare reef-rock, sand, or an irregular raised strip of solution-pitted limestone (Fig. 2).

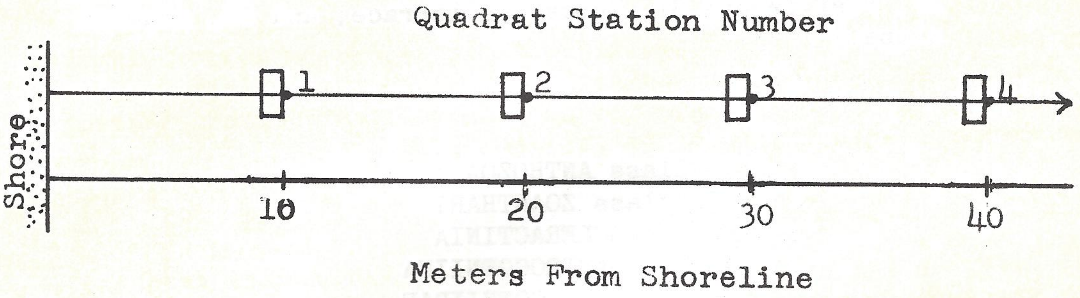


Figure 37. Diagram of the station quadrat transect method used at Tanguiison Point. Two one meter square quadrats are shown positioned at the stations.

Table 11. Checklist of corals that were observed on the transects and collected from Tanguisson Point.

[* indicates that the specimen was collected, # indicates a species observed on the transects, + indicates a species observed in the study area, ++ indicates a species which was identified from dead corals at Tanguisson Point. The locality and reef zone in which the coral was observed or collected (University of Guam catalog number is included if specimen was collected) follows the symbol. The following-reef zone abbreviations are used: IRF, inner reef flat; ORF, outer reef flat; RM, reef margin; RF, reef front; ST, submarine terrace; and SS, seaward slope.]

Class ANTHOZOA
Subclass ZOANTHARIA
Order SCLERACTINIA
Suborder ASTROCOENIINA
Family ASTROCOENIIDAE
Subfamily ASTROCOENIINAE

Genus *Stylocoeniella*
  Stylocoeniella armata (Ehrenberg, 1834)
    *Tanguisson Point - 1555, RF
    #Tanguisson Point - RF, ST, SS

Family THAMNASTERIIDAE

Genus *Psammocora*
  Psammocora exesa Dana, 1846
    #Tanguisson Point - RF
    ++Tanguisson Point - SS
  Psammocora nierstraszi van der Horst, 1921
    #Tanguisson Point - RM, RF, ST

Subgenus *Stephanaria*
  Psammocora (S.) togianensis Umbgrove, 1940
    ++Tanguisson Point - SS

Subgenus *Plesioseris*
  Psammocora (P.) haimeana Milne Edwards and Haime, 1851
    #Tanguisson Point - SS

Table 11. (Continued)

Family POCILLOPORIDAE

Genus Stylophora
- Stylophora mordax (Dana, 1846)
  - #Tanguisson Point - RF, ST

Genus Pocillopora
- Pocillopora brevicornis Lammarck, 1816
  - +Tanguisson Point - RM, RF
- Pocillopora eydouxi Milne Edwards and Haime, 1960
  - #Tanguisson Point - RF
  - +Tanguisson Point - ST
- Pocillopora ligulata Dana, 1846
  - *Tanguisson Point - 1599, 1600, RF
- Pocillopora meandrina Dana, 1846
  - #Tanguisson Point - ORF, RM, RF
- Pocillopora setchelli Hoffmeister, 1929
  - #Tanguisson Point - RM
- Pocillopora verrucosa (Ellis and Solander, 1786)
  - #Tanguisson Point - RM, RF, ST, SS
- Pocillopora sp. 1
  - #Tanguisson Point - ORF, RF, ST

Family ACROPORIDAE

Genus Acropora
- Acropora abrotanoides (Lammarck, 1816)
  - #Tanguisson Point - RF
- Acropora corymbosa (Lammarck, 1816)
  - #Tanguisson Point - RF, ST
- Acropora humilis (Dana, 1846)
  - #Tanguisson Point - RF, SS
- Acropora hystrix (Dana, 1846)
  - *Tanguisson Point - 1550, RF
  - #Tanguisson Point - RM, RF
- Acropora kenti (Brook, 1892)
  - ++Tanguisson Point - RM, RF
- Acropora nana (Studer, 1879)
  - *Tanguisson Point - 1549, RF
  - #Tanguisson Point - RM, RF
- Acropora nasuta (Dana, 1846)
  - #Tanguisson Point - RM, RF
- Acropora ocellata (Klunzinger, 1879)
  - *Tanguisson Point - 1559, 1560, 1561, 1562, RF
- Acropora palifera (Lammarck, 1816)
  - ++Tanguisson Point - SS

Table 11. (Continued)

Acropora palmerae Wells, 1954
  #Tanguisson Point - RM, RF
Acropora rambleri (Bassett Smith, 1890)
  ++Tanguisson Point - SS
Acropora rayneri (Brook, 1892)
  ++Tanguisson Point - RF
Acropora squarrosa (Ehrenberg, 1834)
  *Tanguisson Point - 1553, 1557, RF
Acropora surculosa (Dana, 1846)
  #Tanguisson Point - RF, ST
Acropora syringodes (Brook, 1892)
  *Tanguisson Point - 1551, 1552, 1563, 1564, RF
Acropora valida (Dana, 1846)
  #Tanguisson Point - RF

Genus Astreopora
Astreopora gracilis Bernard, 1896
  #Tanguisson Point - RF, ST
Astreopora myriophthalma (Lammarck, 1816)
  #Tanguisson Point - ST

Genus Montipora
Montipora conicula Wells, 1954
  #Tanguisson Point - RF
Montipora elschneri Vaughan, 1918
  #Tanguisson Point - RF
Montipora foveolata (Dana, 1846)
  #Tanguisson Point - RF, ST
Montipora granulosa Bernard, 1897
  #Tanguisson Point - RF
Montipora hoffmeisteri Wells, 1954
  #Tanguisson Point - RF
Montipora monasteriata (Forskaal, 1775)
  #Tanguisson Point - RF
Montipora tuberculosa (Lammarck, 1816)
  #Tanguisson Point - ST
Montipora verrilli Vaughan, 1907
  #Tanguisson Point - RM, RF, ST, SS
Montipora sp. 1
  #Tanguisson Point - RF, ST, SS
Montipora sp. 2
  #Tanguisson Point - ST
Montipora sp. 3
  #Tanguisson Point - RF, ST
Montipora sp. 4
  #Tanguisson Point - RF
Montipora sp. 5
  #Tanguisson Point - RF, ST

Table 11. (Continued)

Suborder FUNGIINA
Superfamily AGARICIICAE
Family AGARICIIDAE

Genus Pavona
  Pavona clavus (Dana, 1846)
    #Tanguisson Point - RF, ST
  Pavona varians Verrill, 1864
    #Tanguisson Point - RF, ST

Subgenus Pseudocolumnastrea
  Pavona (P.) pollicata Wells, 1954
    #Tanguisson Point - RF

Subgenus Polyastra
  Pavona (P.) sp. 3
    #Tanguisson Point - RF, SS

Genus Leptoseris
  Leptoseris hawaiiensis Vaughan, 1907
    #Tanguisson Point - SS

Genus Pachyseris
  Pachyseris speciosa (Dana, 1846)
    +Tanguisson Point - SS
    ++Tanguisson Point - SS

Family SIDERASTREIDAE

Genus Coscinaraea
  Coscinaraea columna (Dana, 1846)
    #Tanguisson Point - RM
    ++Tanguisson Point - SS
  Cycloseris sp. 1
    *Tanguisson Point - 1568, ST
    #Tanguisson Point - RF, ST

Superfamily PORITICAE
Family PORITIDAE

Genus Goniopora
  Goniopora columna Dana, 1846
    #Tanguisson Point - ST, SS
  Goniopora sp. 1
    ++Tanguisson Point - SS

Genus Porites
  Porites australiensis Vaughan, 1918
    #Tanguisson Point - RF, ST
  Porites lobata Dana, 1846
    #Tanguisson Point, 1846
  Porites lutea Milne Edwards and Haime, 1851
    #Tanguisson Point -RM, RF, ST, SS
  Porites sp. 1
    *Tanguisson Point - 1648, RF
    #Tanguisson Point - RM, RF, SS
  Porites sp. 2
    *Tanguisson Point - 1490, 1491, SS

Subgenus Synaraea
  Porites (S.) convexa Verrill, 1864
    +Tanguisson Point - SS
  Porites (S.) hawaiiensis Vaughan, 1907
    #Tanguisson Point - SS
  Porites (S.) horizontalata Hoffmeister, 1925
    #Tanguisson Point - SS
  Porites (S.) iwayamaensis Eguchi, 1938
    #Tanguisson Point - ST, SS

Genus Alveopora
  Alveopora verrilliana Dana, 1872
    *Tanguisson Point - 1570, ST

Suborder FAVIINA
Superfamily FAVIICAE
Family FAVIIDAE
Subfamily FAVIINAE

Genus Favia
  Favia favus (Forskaal, 1775)
    #Tanguisson Point - RF, ST
  Favia pallida (Dana, 1846)
    #Tanguisson Point - RM, RF, ST, SS
  Favia stelligera (Dana, 1846)
    #Tanguisson Point - RM, RF, ST
  Favia rotumana (Gardiner, 1889)
    #Tanguisson Point - ST

Genus Favites
  Favites complanata (Ehrenberg, 1834)
    *Tanguisson Point - 1601, ST
    #Tanguisson Point - RF, ST, SS
  Favites favosa (Ellis and Solander, 1786)
    #Tanguisson Point - ST

Table 11. (Continued)

Favites flexuosa (Dana, 1846)
#Tanguisson Point - SS

Genus Plesiastrea
Plesiastrea versipora (Lammarck, 1816)
*Tanguisson Point - 1639, RM
#Tanguisson Point - RM, RF
++Tanguisson Point - SS

Genus Goniastrea
Goniastrea parvistella (Dana, 1846)
#Tanguisson Point - RF, ST
Goniastrea pectinata (Ehrenberg, 1831)
#Tanguisson Point - ST, SS
Goniastrea retiformis (Lammarck, 1816)
#Tanguisson Point - RM, RF, ST

Genus Platygyra
Platygyra rustica (Dana, 1846)
#Tanguisson Point - RF, ST
Platygyra sinensis (Milne Edwards and Haime, 1849)
*Tanguisson Point - 1568, RF
#Tanguisson Point - RF, ST

Genus Leptoria
Leptoria gracilis (Dana, 1846)
*Tanguisson Point - 1603, 1647, RF
#Tanguisson Point - RM, RF, ST
Leptoria phrygia (Ellis and Solander, 1786)
+Tanguisson Point - RM, RF, ST

Genus Hydnophora
Hydnophora microconos (Lammarck, 1816)
#Tanguisson Point - RF
++Tanguisson Point - SS

Subfamily MONTASTREINAE

Genus Leptastrea
Leptastrea purpurea (Dana, 1846)
#Tanguisson Point - RF, ST, SS
Leptastrea transversa (Klunzinger, 1879)
*Tanguisson Point - 1571-1, RF
#Tanguisson Point - ST, SS
Leptastrea sp. 1
#Tanguisson Point - RF, SS

Table 11. (Continued)

Genus Cyphastrea
    Cyphastrea serailia (Forskaal, 1775)
        #Tanguisson Point - RF
        ++Tanguisson Point - SS
    Cyphastrea chalcidicum (Forskaal, 1775)
        #Tanguisson Point - RF, SS

Genus Echinopora
    Echinopora lamellosa (Esper, 1787)
        #Tanguisson Point - RF, SS

Genus Diploastrea
    Diploastrea heliopora (Lammarck, 1816)
        +Tanguisson Point - ST, SS

Family OCULINIDAE
Subfamily GALAXEINAE

Genus Galaxea
    Galaxea fascicularis (Linnaeus, 1758)
        #Tanguisson Point - RF, ST, SS

Family MUSSIDAE

Genus Lobophyllia

    Lobophyllia corymbosa (Forskaal, 1775)
        #Tanguisson Point - SS
    Lobophyllia costata (Dana, 1846)
        #Tanguisson Point - RF, ST

Genus Acanthastrea
    Acanthastrea echinata (Dana, 1846)
        *Tanguisson Point - 1645, RF
        #Tanguisson Point - RF, ST

Family PECTINIIDAE

Genus Echinophyllia
    Echinophyllia asper Ellis and Solander, 1786
        #Tanguisson Point - SS

Subclass OCTOCORALLIA
Order COENOTHECALIA
Family HELIOPORIDAE

Genus Heliopora
    Heliopora coerulea (Pallas, 1766)
        #Tanguisson Point - ST

Table 11. (Continued)

Class HYDROZOA
Order MILLEPORINA
Family MILLEPORIDAE

Genus Millepora
  Millepora dichotoma Forskaal, 1775
    #Tanguisson Point - RF
    +Tanguisson Point - ST
  Millepora exaesa Forskaal, 1775
    #Tanguisson Point - RF, ST
  Millepora platyphylla Hemprich and Ehrenberg, 1834
    #Tanguisson Point - RM, RF
    +Tanguisson Point - ST

Order STYLASTERINA
Family STYLASTERIDAE
Subfamily DISTICHOPORINAE

Genus Distochopora
  Distochopora violacea (Pallas, 1776)
    #Tanguisson Point - RM

Table 12. Relative frequency of occurrence and zonal distribution of corals at Tanguisson Point. Relative frequency of occurrence is expressed as a percentage of the total number of colonies found in a transect zone or combination of zones. Data from Transects A, B, and C are combined. The species are listed in order of decreasing frequency when all zones are combined.

Name of Coral	Reef margin		Reef front		Submarine terrace		Seaward slope		All Zones combined	
	No.	Rel. %	No.	Rel. %	No.	Rel. %	No.	Rel. %	No.	Rel. %
Galaxea hexagonalis	---	---	94	15.03	13	4.06	1	.62	108	8.29
Goniastrea retiformis	10	5.52	69	10.92	8	2.50	---	---	87	6.68
Favia stelligera	11	6.08	39	6.17	20	6.25	---	---	70	5.38
Montipora verrilli	12	6.63	31	4.91	10	3.13	12	7.45	65	4.99
Pavona varians	---	---	13	2.06	39	12.19	---	---	52	3.99
Favia pallida	3	1.66	18	2.85	18	5.63	12	7.45	51	3.92
Porites lutea	5	2.76	9	1.42	17	5.31	17	10.56	48	3.69
Pocillopora verrucosa	12	6.63	21	3.32	8	2.50	1	.62	42	3.23
Acropora nana	14	7.73	23	3.64	---	---	---	---	37	2.84
Pocillopora meandrina	15	8.29	15	2.37	---	---	---	---	34	2.61
Acanthastrea echinata	---	---	24	3.80	9	2.81	---	---	33	2.53
Leptoria gracilis	8	4.42	20	3.16	5	1.56	---	---	33	2.53
Leptastrea purpurea	---	---	4	.63	16	5.00	12	7.45	32	2.46
Leptoria phrygia	5	2.76	16	2.53	9	2.81	---	---	30	2.30
Porites sp. 1	14	7.73	10	1.58	---	---	1	.62	29	2.23
Millepora platyphylla	14	7.73	9	1.42	---	---	---	---	23	1.77
Pocillopora setchelli	12	6.63	11	1.74	---	---	---	---	23	1.77
Stylocoeniella armata	---	---	8	1.27	4	1.25	10	6.21	22	1.69
Montipora sp. 1	---	---	6	.95	6	1.88	7	4.35	19	1.46
Galaxea fascicularis	---	---	4	.63	6	1.88	8	4.97	18	1.38
Pavona clavus	---	---	10	1.58	8	2.50	---	---	18	1.38
Acropora hystrix	8	4.42	9	1.42	---	---	---	---	17	1.31
Favites complanata	---	---	6	.95	6	1.88	5	3.11	17	1.31
Goniastrea parvistella	---	---	6	.95	11	3.44	---	---	17	1.31
Leptastrea transversa	---	---	---	---	4	1.25	13	8.07	17	1.31
Plesiastrea versipora	7	3.87	10	1.58	---	---	---	---	17	1.31
Acropora nasuta	10	5.52	6	.95	---	---	---	---	16	1.23
Porites (*Synaraea*) *iwayamaensis*	---	---	---	---	4	1.25	12	7.45	16	1.23

Table 12. (Continued)

Name of Coral	Reef margin		Reef front		Submarine terrace		Seaward slope		All Zones combined	
	No.	Rel. %	No.	Rel. %	No.	Rel. %	No.	Rel. %	No.	Rel. %
Psammocora nierstraszi	3	1.66	10	.58	3	.94	---	---	16	1.23
Millepora exaesa	---	---	5	.79	10	3.13	---	---	15	1.15
Leptastrea sp. 1	---	---	1	.16	---	---	13	8.07	14	1.08
Porites lobata	---	---	4	.63	10	3.13	---	---	14	1.08
Stylophora mordax	---	---	8	1.27	5	1.56	---	---	13	1.00
Acropora murrayensis	8	4.42	4	.63	---	---	---	---	12	.92
Acropora corymbosa	---	---	6	.95	5	1.56	---	---	11	.84
Goniastrea pectinata	---	---	---	---	8	2.50	1	1.86	11	.84
Favia favus	---	---	4	.63	6	1.88	---	---	10	.76
Montipora elschneri	---	---	8	1.27	2	.63	---	---	10	.76
Acropora surculosa	---	---	7	1.11	2	.63	---	---	9	.69
Platygyra rustica	---	---	6	.95	3	.94	---	---	9	.69
Acropora humilis	---	---	5	.79	---	---	3	1.86	8	.61
Montipora foveolata	---	---	4	.63	4	1.25	---	---	8	.61
Montipora sp. 3	---	---	8	1.27	---	---	---	---	8	.61
Platygyra sinensis	---	---	5	.79	3	.94	---	---	8	.61
Porites australiensis	---	---	3	.47	5	1.56	---	---	8	.61
Acropora abrotanoides	---	---	7	1.11	---	---	---	---	7	.54
Pavona (Polyastra) sp. 3	---	---	4	.63	---	---	3	1.86	6	.46
Cyphastrea chalcidicum	---	---	4	.63	---	---	2	1.24	6	.46
Lobophyllia costata	---	---	4	.63	2	.63	---	---	6	.46
Montipora sp.2	---	---	---	---	6	1.88	---	---	6	.46
Acropora palmerae	4	2.21	1	.16	---	---	---	---	5	.38
Distochopora violacea	5	2.76	---	---	---	---	---	---	5	.38
Echinopora lamellosa	---	---	2	.32	---	---	3	1.86	5	.38
Montipora sp. 4	---	---	5	.79	---	---	---	---	5	.38
Montipora sp. 5	---	---	1	.16	4	1.25	---	---	5	.38
Pocillopora sp. 1	---	---	1	.16	4	1.25	---	---	5	.38
Psammocora (Plesioseris) haimeana	---	---	---	---	---	---	5	3.11	5	.38
Astreopora gracilis	---	---	1	.16	3	.94	---	---	4	.31

Table 12. (Continued)

Name of Coral	Reef margin No.	Reef margin Rel. %	Reef front No.	Reef front Rel. %	Submarine terrace No.	Submarine terrace Rel. %	Seaward slope No.	Seaward slope Rel. %	All Zones combined No.	All Zones combined Rel. %
Lobophyllia corymbosa	---	---	---	---	---	---	4	2.48	4	.31
Acropora smithi	---	---	3	.47	---	---	---	---	3	.23
Astreopora myriophthalma	---	---	---	---	3	.94	---	---	3	.23
Cycloseris cyclolites	---	---	---	---	---	---	3	1.86	3	.23
Echinophyllia aspera	---	---	---	---	---	---	3	1.86	3	.23
Coniopora columna	---	---	---	---	1	.31	2	1.24	3	.23
Leptoseris hawaiiensis	---	---	---	---	---	---	3	1.86	3	.23
Montipora conicula	---	---	3	.47	---	---	---	---	3	.23
Montipora monasteriata	---	---	3	.47	---	---	---	---	3	.23
Montipora tuberculosa	---	---	---	---	3	.94	---	---	3	.23
Acropora valida	---	---	2	.32	---	---	---	---	2	.15
Cycloseris sp. 1	---	---	---	---	2	.63	---	---	2	.15
Favia rotumana	---	---	---	---	2	.63	---	---	2	.15
Favites favosa	---	---	---	---	2	.63	---	---	2	.15
Montipora granulosa	---	---	2	.32	---	---	---	---	2	.15
Pocillopora eydouxi	---	---	2	.32	---	---	---	---	2	.15
Psammocora exesa	---	---	2	.32	---	---	---	---	2	.15
Acropora sp. 1	---	---	1	.16	---	---	---	---	1	.07
Coscinaraea columna	1	.53	---	---	---	---	---	---	1	.07
Cyphastrea serailia	---	---	1	.16	---	---	---	---	1	.07
Favites flexuosa	---	---	---	---	---	---	1	.62	1	.07
Heliopora coerulea	---	---	---	---	1	.31	---	---	1	.07
Hydnophora microconos	---	---	1	.16	---	---	---	---	1	.07
Millepora dichotoma	---	---	1	.16	---	---	---	---	1	.07
Montipora hoffmeisteri	---	---	1	.16	---	---	---	---	1	.07
Pavona (Pseudocolumnastraea) pollicata	---	---	1	.16	---	---	---	---	1	.07
Porites (Synaraea) hawaiiensis	---	---	---	---	---	---	1	.62	1	.07
Porites (Synaraea) horizontalata	---	---	---	---	---	---	1	.62	1	.07
Totals	181		632		320		161		1302	
Total species	21		65		45		28		86	
Total genera	12		24		22		19		30	

Reef Flat (70 to 100 meters wide)-- The fringing reef platform along Tanguisson Point is divided into inner and outer reef flat subzones, but the inner reef flat is very poorly developed. At low tide the impounded water or moat, which delineates the inner reef flat subzone, represents a very small percentage of the reef platform and is not contiguous along the entire study region (Fig. 3). The inner reef flat subzone is represented by several small pools (Fig. 3) at Transects A and C. No corals occurred on the transects, but several small colonies of *Porites lutea* were observed in a small pool near Transect C. The outer reef flat subzone is, in most places, a flat limestone pavement with very little relief. Only eight colonies of corals were encountered on the transects. One each of *Pocillopora meandrina* and *Porites lichen* and six of *Acropora nana*. These colonies were found occupying shallow pools near the reef margin zone. Coral observations along other parts of the outer reef flat are similar to those found near the transect regions.

Reef Margin (20 meters wide)-- This zone is awash constantly and represents conditions favorable for coral development. Figures 38 and 39 reflect this change in habitat by abrupt increases in the percentage of reef surface covered by living corals and the number of species and genera per transect station.

The reef margin environment can be divided into three separate habitats: the well-lighted, strongly-agitated water region found on the upper surface of buttresses that separate surge channels; the open surge channels and pools; and the poorly-lighted, cavernous regions of surge channels and pools. On the upper surface of the buttresses (Fig. 40), the most common corals were: *Acropora palmerae*, *Goniastrea retiformis*, *Millepora platyphylla*, *Pocillopora meandrina*, *P. setchelli*, and *P. verrucosa*. In the surge channels and open pools habitats the more common corals encountered were: *Acanthastrea echinata*; *Acropora hystrix*, *A. murrayensis*, *A. nana*, *A. nasuta*, *Favia pallida*, *F. stelligera*; *Favites abdita*, *Goniastrea retiformis*, *Leptoria gracilis*, *L. phrygia*, *Montipora verrilli*, *Millepora platyphylla*, *Plesiastrea versipora*, *Pocillopora verrucosa*, *P. setchelli*, *P. brevicornis*, and *Porites lutea*. Growth forms in the surge channels are mostly encrusting, low flattened massive growths, or cespitose with closely set branches (Fig. 41). In open pools the growth forms are more like the forms encountered on the shoreward half of the submarine terrace. Corals encountered in cavernous regions of surge channels and pools were mostly encrusting forms of *Psammocora nierstraszi*, *Chyphastrea chalcidicum*, *Porites* sp. 1, and an encrusting growth form of *Coscinaraea columna*. Cespitose growth forms are predominant when considering the entire reef margin zone (Table 13).

Corals not encountered on the reef margin quadrat stations, but commonly observed there were: *Acropora abrotanoides*, *A. smithi*, *A. surculosa*;

Hydnophora microconos; *Pavona clavus*, *P*. (*Pseudocolumnastraea*) *pollicata*; and *Stylocoeniella armata*. *Porites* sp. 1 and *Stylocoeniella armata* were found in all three reef margin habitats in small holes, cracks, and on the underside of large spreading coralla.

Eighty-seven percent of the colonies measured in this zone were less than 15 cm in diameter (Table 14). The great number of small coral colonies could be the result of coral recovery following a limited amount of *Acanthaster* predation in this zone during the summer of 1968. Surf conditions are much reduced during Summer months, thus, allowing the starfish to successfully feed in this zone. Observations of corals in the 0-5 cm range reveal that some are newly settled juvenile colonies, whereas many others are small surviving patches of larger colonies.

Reef Front Zone (50 to 70 meters wide)-- Major differences in coral distribution begin to emerge at the reef front zone because of prior *A. planci* activity. The percentage of reef surface covered by living corals is high only for the first one to three quadrat stations immediately seaward of the reef margin zone (Fig. 39). This high percentage of cover at first indicates that starfish predation was absent or at least nearly so along this narrow one to three quadrat band and quite high for the remainder of the zone (Fig. 39). Observations and collections at Tanguisson Point reveal that ramose, cespitose, and corymbose growth forms were previously more abundant. This is indicated by the many dead coralla of these growth forms which have been overgrown by coralline algae and various encrusting *Millepora* and *Montipora* species. Breaking waves and accompanying surge seems to result in selective feeding by *A. planci* on corymbose and cespitose *Acropora* growth forms in this section of the reef front. During the earlier *A. planci* infestation and predation period some starfish were observed feeding in this part of the front zone. Chesher[15] also reported some starfish activity in this zone, but noted that they had difficulty in attaching their tube feet to smooth, rounded coralla. From the above data and observations, it would seem that selective feeding behavior by *A. planci* has changed the distribution of corals in this narrow band of surge and wave-assaulted reef front, but, because of coral resettlement by different species and growth forms, the percentage of corals covering the surface remained nearly the same.

Common corals observed in inner part of the reef front zone were: *Acanthastrea echinata*, *Acropora abrotanoides*, *A. corymbosa*, *A. hystrix*, *A. murrayensis*, *A. nasuta*, *A. surculosa*; *Favis stelligera*; *Galaxea hexagonalis*; *Goniastrea retiformis*; *Leptoria gracilis*; *Millepora platyphylla*; *Montipora verrili*, *Montipora* sp. 1, *Montipora* sp. 2; *Pavona varians*; *Platygyra sinensis*, *Pocillopora verrucosa*; *Porites lutea*; and *Stylophora mordax*.

Seaward of the narrow wave and surge agitated section of the reef front, the percentage of living corals covering the reef surface (Fig. 39) drops rapidly to less than 1 percent for some quadrats near the submarine terrace. The reef front zone at Transect B is shallower than that at Transects A and C. This extends the wave-assaulted section of Transect B farther, thus lessening the degree of starfish infestation seaward and explains the presence of a fairly high percentage of living coral found covering the reef surface for the outer part of the zone (Fig. 39). Observations of dead coralla (Fig. 36) indicate that species composition, colony diameter, and growth forms were very similar to those found living at Tumon Bay (Randall[12]). Even though slightly less relief of topographic growth structures such as coral-algal knobs, bosses, and pinnacles was noted at Tanguisson Point, it is still obvious that reef development was taking place like that at Tumon Bay.

Most living colonies encountered are either small, regenerated parts of larger, older, dead coralla, or small encrusting coralla from new planula settlement. Prior *A. planci* predation did not, in many cases, kill the entire corallum. Some small, inacessible sections of the corallum, especially if of irregular lobate or cuneate growth form, survived the predation. These surviving sections resume growth by growing upward and spreading outward over old dead parts of the parent corallum and appear as small encrusting patches. Most young colonies established from newly settled planulae also appear as small encrustations, even though later growth development may be of ramose or massive form. Corallum diameter is, therefore, small (Table 14) and the number of encrusting growth forms is high (Table 13) because of patchy regeneration and the presence of newly settled corals. Some corals observed to be regenerating from surviving parts of older colonies were: *Cyphastrea serailia*; *Favia stelligera*; *Goniastrea parvistella*, *G. retiformis*; *Leptoria gracilis*; *Lobophyllia corymbosa*, *L. costata*; *Pavona clavus*; *Plesiastrea versipora*; *Porites australiensis* and *P. lutea*. Corals that were developing from newly settled planulae were: *Acropora corymbosa*, *A. humilis*, *A. surculosa*, *Astreopora* sp. 1; *Favia favus*, *F. pallida*; *Favites complanata*; *Leptastrea purpurea*, *Leptastrea* sp. 1; *Millepora platyphylla*; *Montipora foveolata*, *M. granulosa*, *M. verrilli*, *Montipora* sp. 1, *Montipora* sp. 3, *M. conicula*; *Pavona varians*; *Pocillopora* sp. 1 and *Porites lutea*.

Table 12 lists 65 species representing 24 genera for the reef front zone. Adding to this list those species collected but not observed at the transect stations (Table 11), increases the total species for the zone to 69 species representing 24 genera.

Submarine Terrace Zone (40 to 110 meters wide) and Seaward Slope Zone (50 to 70 meters wide) -- The submarine terrace and seaward slope zones were the most heavily infested with *A. planci* during the initial invasion, and as a result nearly all the original coral populations were killed (Figs. 36 and 42). Regeneration of small sections of larger colonies and resettlement of some corals has taken place as described for the reef front, but to a lesser degree, especially on the seaward slope. Eighty-six to 84 percent of the corals were less than 5 cm in diameter (Table 14) and 78 to 81 percent were of encrusting growth form (Table 13). The average percentage of living coral covering the reef surface in these zones (Fig. 39) was less than one. At Transect A, station 25, the highest percentage of coral coverage (4%) was found, caused by a single patchy living colony of *Porites* (*Synaraea*) *horizontalata*. Figure 38 shows a drop in the number of genera and species per transect station from that found in the reef front zones.

For the submarine terrace zone, 45 species represented by 22 genera (Table 12) occurred within the quadrat stations. Specimen collections made in this zone increased the number of species and genera to 47 and 24 respectively. The most common corals encountered on the submarine terrace were: *Favia favus*, *F. pallida*, *F. stelligera*; *Goniastrea parvistella*, *G. pectinata*; *Leptastrea purpurea*; *Leptoria phrygia*; *Millepora exaesa*; *Montipora verrilli*, *Montipora* sp. 1, *Montipora* sp. 3; *Pavona varians*; *Porites lobata* and *P. lutea*.

The total number of species occurring on the seaward slope zone transects was 28 species representing 19 genera (Table 12). If the corals observed in this zone are added to the above, the number is raised to 32 species and 21 genera. This was a considerable reduction when compared to the submarine terrace and was related to less regeneration from older colonies and a reduction in the number of new corals developing from planulae settlement. A considerable number dead coralla of some species were encountered on the seaward slope that were not observed as living species (Table 11). This indicates that not all the original species were regenerating in this zone, nor had resettlement of these species taken place. Some of the dead coralla that could be identified in the field and that were not observed as living on the seaward slope transect stations were: *Acropora rayneri*, *A. rambleri*, *A. kenti*, *A. palifera*; *Coscinaraea columna*; *Cyphastrea serailia*; *Goniopora* sp.; *Hydnophora microconos*; *Pachyseris speciosa*; *Psammocora exesa*, *P.* (*Synaraea*) *togianensis*; *Plesiastrea versipora*, plus some tuberculate *Montipora* species. Common living corals observed on the seaward slope were: *Favia pallida*; *Galaxea fascicularis*; *Leptastrea purpurea*, *L. transversa*,

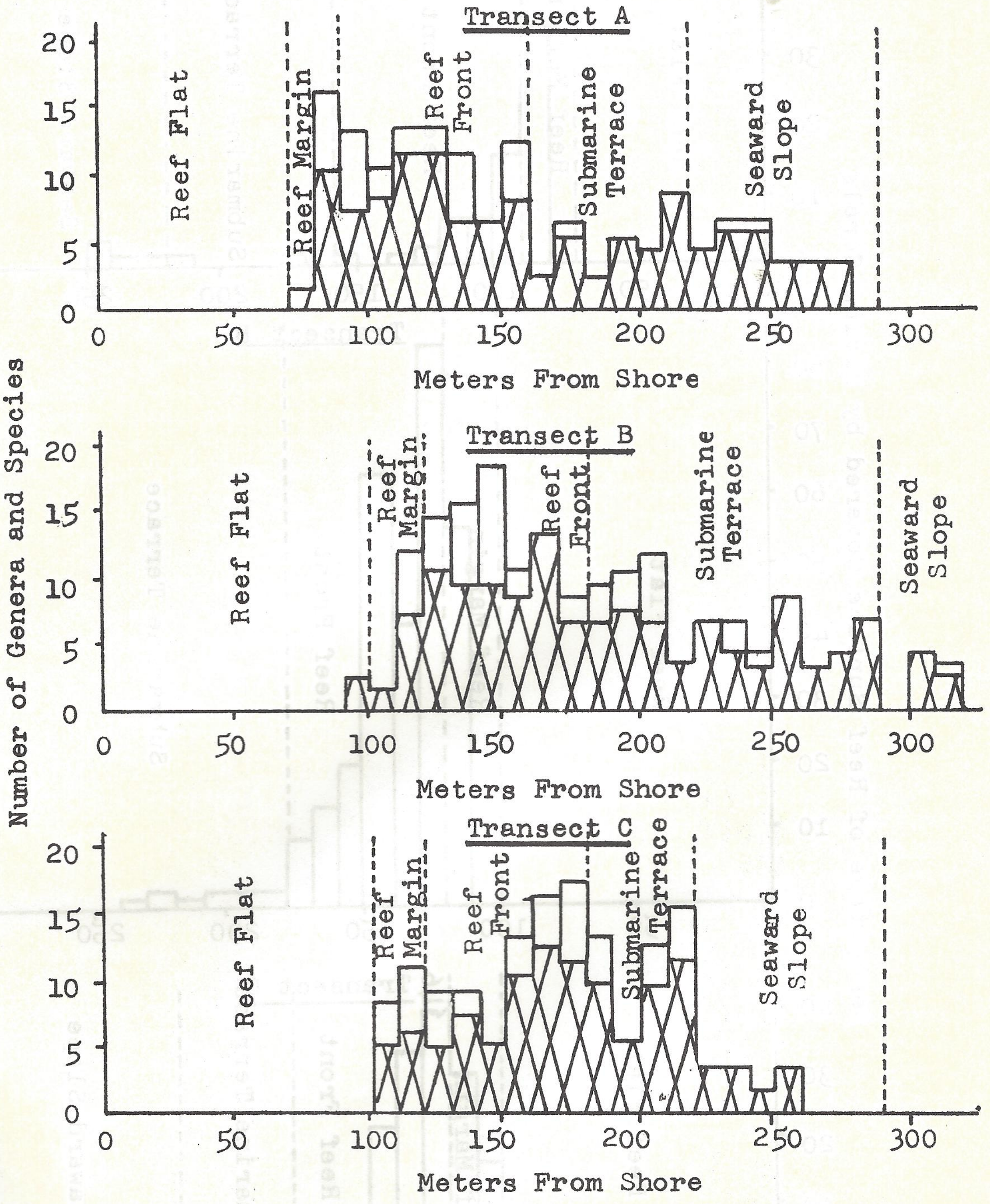


Figure 38. Number of genera and species per transect station at Tanguisson Point, 1970. Cross-hatched area indicates genera and non-hatched area species.

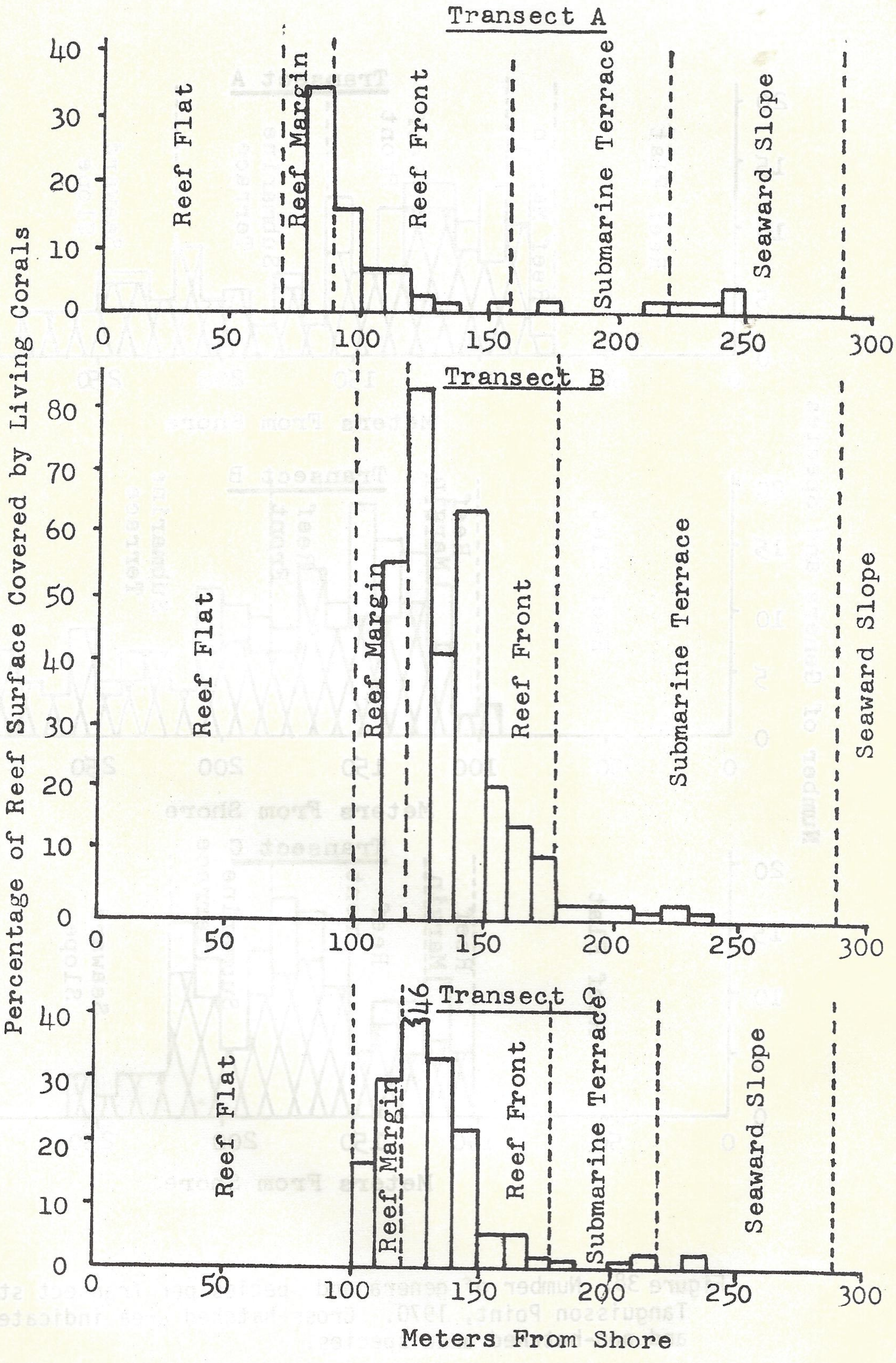


Figure 39. Percentage of reef surface covered by living corals at Tanguisson Point, 1970. Each column represents a transect station.

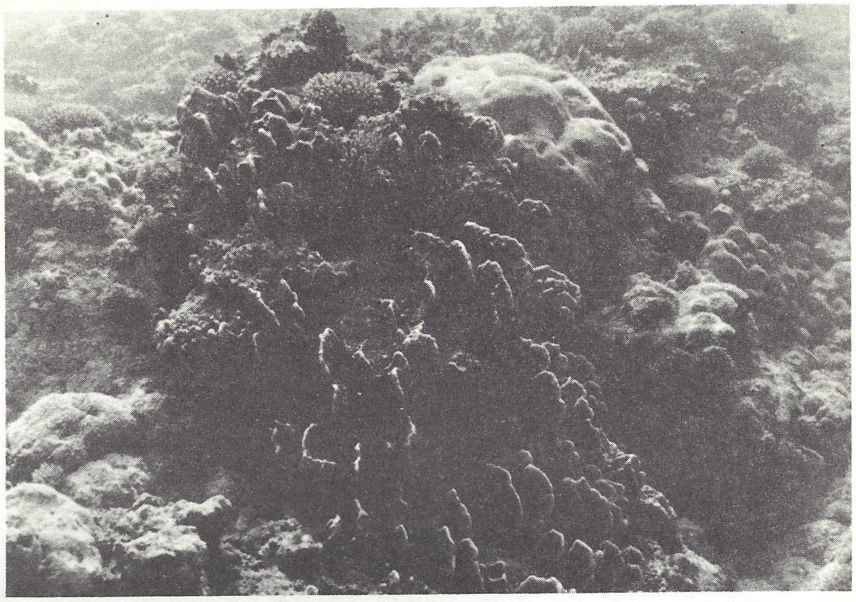


Figure 40. Rich coral growth on the upper surface and side of a reef front buttress at Tanguisson Point. The large colony in the foreground consisting of upright plates is Millepora platyphylla.

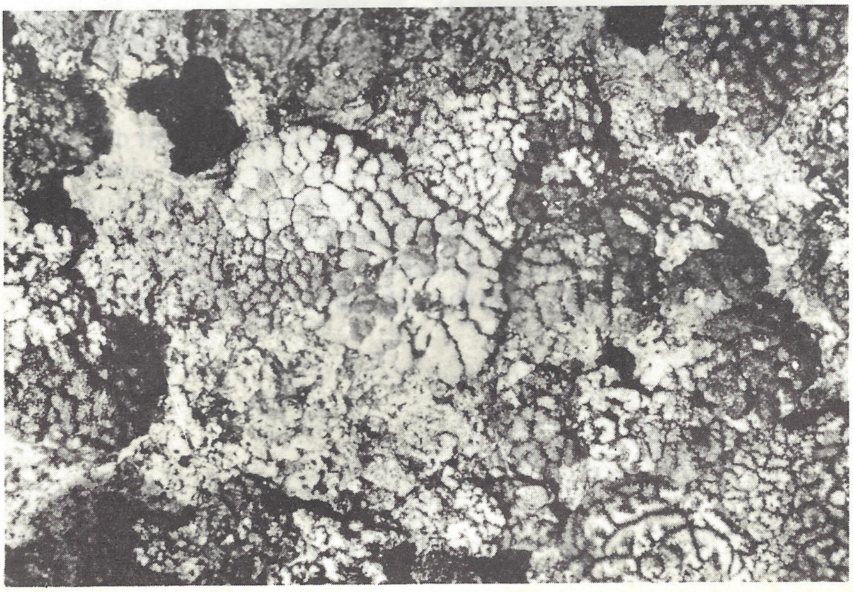


Figure 41. Dense growth of Pocillopora colonies on the floor of a reef margin surge channel.

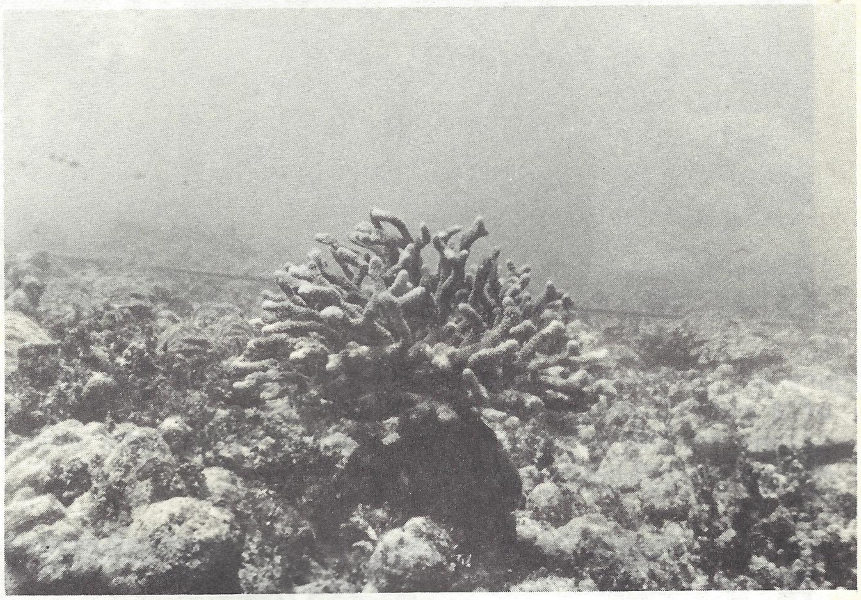


Figure 42. A view looking down the steep seaward slope zone on Transect A. In the foreground, at 24 meter depth, a large colony of Pocillopora eydouxi (1 m dia.) has survived the Acanthaster predation. Note the presence of numerous dead coralla. In 1967 this slope was covered with a rich growth of living corals to depths of more than 50 meters.

Leptastrea sp. 1; Montipora sp. 1, Porites lutea; and Stylocoeniella armata.

Observations of the submarine terrace and seaward slope zones at Tanguisson Point and from other reefs of Guam indicate that some coral species are not usually preyed upon by A. planci (Fig. 42). Some of these corals observed at Tanguisson Point were: Acanthastrea echniata; Diploastrea heliopora; Galaxea fascicularis, G. hexagonalis; Goniopora columna; Heliopora coerulea; Millepora dichotoma, M. exeasa, M. platyphylla; and Pocillopora eydouxi.

Comparison of Coral Reefs at Tumon Bay and Tanguisson Point

Comparisons of physical reef characteristics and coral distribution indicate that the reef margin, reef front, submarine terrace, and seaward slope zones at Tumon Bay and Tanguisson Point were similar (except for slightly less topographic relief at the latter) in reef development before starfish predation took place (Randall[12]). The only zones not comparable at the two locations are the subzones of the reef flat, which were not initially infested with starfish during the population explosion stage. Based on the above assumptions, a comparison can be made of the coral communities between the two study locations.

The following data summarize the number of genera and species, for the major divisions of corals, at Tumon Bay before the Acanthaster infestation and Tanguisson Point after the infestation.

	Tumon Bay (From Randall[12, 18])		Tanguisson Point	
	Genera	Species	Genera	Species
Hermatypic Scleractinians	31	139	30	91
Ahermatypic Scleractinians	2	2	0	0
Non-Scleractinians	3	5	3	5
Total	36	146	33	96

The data above show that the total number of living coral genera surviving the A. planci predation is nearly the same as that found before predation. The only genera not found at Tanguisson Point, after the starfish predation, but that were earlier found at Tumon Bay before the starfish predation were Euphyllia, Paracyathus, and Polycyathus. Of these three

Table 13. Distribution of coral growth forms by reef zones at Tanguisson Point, 1970. Relative frequency of occurrence is expressed as a percentage of the total number of colonies found in a transect zone. Data from Transects A, B, and C are combined.

	Outer reef flat		Reef margin		Reef front		Submarine terrace		Seaward slope		All zones combined	
Growth Form	No. of Corals	Rel. Freq.	No. of Corals	Rel. Freq.	No. of Corals	Rel. Freq.	No. of Corals	Rel. Freq.	No. of Corals	Rel. Freq.	No. of Corals	Rel. Freq.
Massive	0		19	10	128	20	41	13	14	9	202	16
Encrusting	1	12	31	17	376	59	250	78	130	81	788	61
Foliaceous	0		0		0		0		5	3	5	1
Flabellate	0		5	3	7	1	1	1	0		13	1
Corymbose	0		13	7	29	5	0		0		42	3
Cespitose	7	88	112	62	80	13	25	8	8	5	232	18
Arborescent	0		1	1	8	1	0		0		9	1
Phaceloid	0		0		4	1	1	1	2	1	7	1
Columnar	0		0		0		1	1	1	1	2	1
Solitary	0		0		0		1	1	1	1	2	1
TOTALS	8		181		632		320		161		1302	

Table 14. Distribution of coral colony diameter by reef zones at Tanguisson Point, 1970. Relative frequency of occurrence is expressed as a percentage of the total number of colonies found in a transect zone. Data from Transects A, B, and C are combined.

Diameter range in cm	Outer reef flat		Reef margin		Reef front		Submarine terrace		Seaward slope		All zones combined	
	No. of Corals	Rel. Freq.	No. of Corals	Rel. Freq.	No. of Corals	Rel. Freq.	No. of Corals	Rel. Freq.	No. of Corals	Rel. Freq.	No. of Corals	Rel. Freq.
0 - 5	5	63	72	40	314	50	275	86	135	84	801	62
6 - 10	2	25	53	29	200	32	43	13	25	15	323	25
11 - 15	1	12	33	18	59	9	2	1	0		95	7
16 - 20	0		9	5	18	3	0		1	1	28	2
21 - 25	0		5	3	13	2	0		0		18	1
26 - 30	0		4	2	11	2	0		0		15	1
31 - 35	0			0	2	1	0		0		2	1
36 - 40	0			0	6	1	0		0		6	1
41 - 45	0		2	1	5	1	0		0		7	1
46 - up	0		3	2	4	1	0		0		7	1
TOTAL	8		181		632		320		161		1302	

genera, two (Euphyllia and Polycyathus) were more or less restricted to the reef flat and Paracyathus is an ahermatypic coral of little importance in terms of reef building. The high number of genera surviving A. planci predation, even though of low density, may be essential in the recovery of devastated reefs if diversity of seed populations is an important prerequisite.

The number of species found on the Tanguisson reefs after A. planci predation is 34 percent less than at Tumon Bay. The number is reduced to 27 percent if those species that are specific for the reef flat moat, which is well developed only at Tumon Bay, are discounted.

Comparisons of Coral Distribution by Reef Zones -- The number of coral genera and species that were observed or collected from the various reef zones at Tumon Bay and Tanguisson Point are shown in Table 15.

Table 15. Total number of genera and species by reef zones.

	Tumon Bay (From Randall [12])		Tanguisson Point	
Reef Zone	Genera	Species	Genera	Species
Reef margin	14	26	12	21
Reef front	32	98	24	69
Submarine terrace	28	73	24	47
Seaward slope	26	57	21	32

Some A. planci predation occurred in the reef margin zone at Tanguisson, but not to be extent that coral distribution was greatly changed there.

A. planci predation has caused extensive damage in the reef front zone. A 30 percent reduction in the number of species and a 25 percent reduction in the number of genera has occurred in this zone. Coral damage to the reef front zone is not uniformly distributed across it. A comparison of Figure 39 with Table 16 shows that the inner (shoreward) sections of the reef front zones at Tanguisson Point have a near pre-starfish percentage of reef surface covered by living corals, while the outer (seaward) sections show a great reduction.

Table 16, Average percent of coral cover by reef zones.

	Tumon Bay Transects (From Randall[12])	Tanguisson Point Transects
Reef margin	26.4	22.6
Reef front	49.1	20.9
Submarine terrace	59.1	0.9
Seaward slope	50.1	0.5

However, a comparison of Figure 38 with Table 15 shows that the inner (shoreward) part of the reef front has changed in the number of coral species even though the percentage of living coral coverage has not greatly changed. Upon close inspection of this zone, it was found that *A. planci* predation had selectively killed many of the ramose growth forms of corals, especially the acroporoid species. This selective predation resulted in lowering the percentage of reef surface coverage, but subsequent resettlement and regeneration of encrusting coral growth forms has restored the normal percentage of coral cover found there. This section of the reef front is located in a zone of wave agitation where starfish have difficulty in remaining attached to coralla other than ramose forms and, as a result, selective predation occurs. Future assessment of coral damage caused by *A. planci* on the wave-assaulted regions of the reef front zones, and possibly the reef margin as well, must therefore be made with care. It is within this section of the reef front where near optimum coral reef development takes place and probably optimum coral growth rates as well. Many regions on Guam and other parts of the Indo-Pacific possess reefs that have undergone *A. planci* predation in the past several years. Resettlement and regeneration of specific fast growing corals may, by now, have obscured much of the coral damage in the wave assaulted reef zones.

Quantitative transect data for the submarine terrace and seaward slope zones at Tumon Bay were not recorded before *A. planci* predation there, but species diversity and percent of coral coverage studies of these zones were made (Randall[12]). The number of major coral species and genera observed in these zones is shown in Table 15 and the percent of coral coverage in Table 16. Observations of dead coralla found in these zones at Tanguisson Point indicate a similar degree of development to that which was previously found at Tumon Bay (Randall[12]). The number of species found on the submarine terrace and seaward slope at Tanguisson Point is much lower than at

Tumon Bay because of the extensive starfish damage. Table 16 shows that the total reef surface occupied by living corals on the submarine terrace and seaward slope averages less than one percent of surface coverage at Tanguisson, whereas at Tumon Bay the mean percent of coverage for six sample quadrats at each zone was 59.5 and 50.1 respectively. It was in these two zones that A. planci predation was most intense. It was astounding to see such large areas of previously living coral killed in less than a year's time by A. planci.

Comparison of Corallum Size Distribution -- There has been a shift in corallum size in all reef zones where corals were killed by Acanthaster. This shift was less intensive on the reef margin and inner part of the reef front zones. At Tanguisson Point 99 percent of the coralla found in zones of previous starfish predation were less than 10 cm in diameter, whereas at Tumon Bay less than 50 percent were in this size range for the same zones. Reduction in corallum size in regions of starfish predation is due to the small size of newly established coralla and the small size of regenerating parts of older, larger coralla that survived the initial A. planci predation.

CORAL RECOVERY

The purpose of this study is to assess, over a one year period, changes that have occurred in the distribution of reef corals in the Tanguisson area. The first distributional analysis of the reef corals was made during the first six months of 1970 and discussed above. A second analysis was made during the same period in 1971 (Randall[14]). Living corals were found at 59 stations in 1970, and at 65 stations in 1971. In regard to stations with living corals present from 1970 to 1971, there was a gain and a loss of one station each on the outer reef flat zone, a loss of one station on the reef margin zone, and a gain of seven stations on the seaward slope zone. During the 1970 study, 1302 living corals were found within the confines of the quadrat stations and one year later, 1971, the number had risen to 2116. Nearly 82 percent of these new coral colonies have settled in the submarine terrace and seaward slope zones. Settlement of most of the remaining new colonies took place on the outer half of the reef front zone.

Species Comparison

Table 17 lists the coral species composition along with their relative frequency of occurrence on the fringing reef at Tanguisson Point during the 1970 and 1971 study periods and for the Tumon Bay control reef studied in 1968. At the control reef 15 species are more or less restricted to the reef flat zones (Table 17). These restricted species

Table 17. Checklist of corals and their relative frequency of occurrence. Relative frequency for each species is expressed as a percentage of the total number of colonies found on a transect. [# indicates that the species was not found on the transects proper, but was observed in the study area. ( ) indicates a species more or less restricted to the reef flat at Tumon Bay.]

	Tumon Bay control reef	Tanguisson Point 1970	Tanguisson Point 1971
<u>Stylocoeniella</u> <u>armata</u> (Ehrenberg), 1834	.36	1.69	.95
<u>Psammocora</u> <u>contigua</u> (Esper), 1797	(5.03)		
<u>Psammocora</u> <u>exesa</u> Dana, 1846	.03	.15	
<u>Psammocora</u> <u>nierstraszi</u> van der Horst, 1921	.33	1.23	.71
<u>Psammocora</u> <u>profundacella</u> Gardiner, 1898	.33		
<u>Psammocora</u> <u>stellata</u> (Verrill), 1866	(#)		
<u>Psammocora</u> <u>verrilli</u> Vaughan, 1907	#		
<u>Psammocora</u> (<u>S</u>.) <u>togianensis</u> Umbgrove, 1940	.18		
<u>Psammocora</u> (<u>P</u>.) <u>haimeana</u> Milne Edwards & Haime, 1851	.03	.38	.28
<u>Psammocora</u> sp. 1			.10
<u>Stylophora</u> <u>mordax</u> (Dana), 1846	.64	1.00	.43
<u>Seriatopora</u> <u>hystrix</u> (Dana), 1846	.18		.05
<u>Pocillopora</u> <u>brevicornis</u> Lamarck, 1816	.30		
<u>Pocillopora</u> <u>damicornis</u> (Linnaeus), 1758	(5.84)		
<u>Pocillopora</u> <u>danae</u> Verrill, 1864	.12		
<u>Pocillopora</u> <u>elegans</u> Dana, 1846	#		
<u>Pocillopora</u> <u>eydouxi</u> Milne Edwards & Haime, 1960	.64	.15	.24
<u>Pocillopora</u> <u>ligulata</u> Dana, 1846	#	#	.05
<u>Pocillopora</u> <u>meandrina</u> Dana, 1846	.79	2.61	2.98
<u>Pocillopora</u> <u>setchelli</u> Hoffmeister, 1929	1.12	1.77	.71
<u>Pocillopora</u> <u>verrucosa</u> (Ellis & Solander), 1786	4.03	3.23	2.36
<u>Pocillopora</u> sp. 1		.38	.38
<u>Acropora</u> <u>abrotanoides</u> (Lamarck), 1816	.42	.54	.19
<u>Acropora</u> <u>acuminata</u> Verrill, 1864	(5.42)		
<u>Acropora</u> <u>arbuscula</u> (Dana), 1846	(#)		
<u>Acropora</u> <u>aspera</u> (Dana), 1846	(10.69)		
<u>Acropora</u> <u>brueggemanni</u> (Brook), 1893	.18		
<u>Acropora</u> <u>studeri</u> (Brook), 1893	1.18	.84	.33
<u>Acropora</u> <u>cuneata</u> (Dana), 1846	.03		
<u>Acropora</u> <u>diversa</u> (Brook), 1891	#		
<u>Acropora</u> <u>humilis</u> (Dana), 1846	.55	.61	.43
<u>Acropora</u> <u>hystrix</u> (Dana), 1846	.18	1.31	.28
<u>Acropora</u> <u>kenti</u> (Brook), 1892	#	#	.14
<u>Acropora</u> <u>lutkeni</u> Crossland, 1952	#		
<u>Acropora</u> <u>monticulosa</u> (Bruggemann), 1879	#		

Table 17. (Continued)

	Tumon Bay control reef	Tanguisson Point 1970	Tanguisson Point 1971
Acropora murrayensis Vaughan, 1918	.24	.92	.10
Acropora nana (Studer), 1879	2.67	2.84	3.31
Acropora nasuta (Dana), 1846	12.69	1.23	1.75
Acropora nobilis (Dana), 1846	#		
Acropora ocellata (Klunzinger), 1879	.61	#	.05
Acropora palifera (Lamarck), 1816	#		
Acropora palmerce Wells, 1954	.36	.38	.47
Acropora rambleri (Bassett Smith), 1890	#		.10
Acropora rayneri (Brook), 1892	#		
Acropora smithi (Brook), 1893	.55	.23	.24
Acropora squarrosa (Ehrenberg), 1834	#	#	#
Acropora surculosa (Dana), 1846	2.06	.69	.80
Acropora syringodes (Brook), 1892	.30	#	.47
Acropora valida (Dana), 1846	.39	.15	.14
Acropora wardii Verrill, 1901			.10
Acropora sp. 1	.79	.07	.57
Acropora sp. 2	.03		
Acropora sp. 3	#		
Astreopora gracilis Bernard, 1896	.27	.31	.24
Astreopora listeri Bernard, 1896	#		
Astreopora myriophthalma (Lamarck), 1816	.15	.23	.80
Astreopora sp. 1	#		
Montipora acanthella Bernard, 1897	(#)		
Montipora composita Crossland, 1952	#		
Montipora conicula Wells, 1954	.39	.23	.76
Montipora elschneri Vaughan, 1918	.30	.76	.99
Montipora floweri Wells, 1954	#		
Montipora foveolata (Dana), 1846	.39	.61	.10
Montipora granulosa Bernard, 1897		.15	.05
Montipora hoffmeisteri Wells, 1954	.27	.07	.28
Montipora lobulata Bernard, 1897	.09		
Montipora monasteriata (Forskaal), 1775	.27	.23	.33
Montipora patula Verrill, 1869	#		
Montipora planiuscula Dana, 1846	(#)		
Montipora spumosa (Lamarck), 1816	#		
Montipora stilosa (Ehrenberg), 1834	#		
Montipora tuberculosa (Lamarck), 1816	.24	.23	
Montipora verrilli Vaughan, 1907	2.51	4.99	5.39
Montipora verrucosa (Lamarck), 1816	.39		.24
Montipora sp. 1	.75	1.46	2.08
Montipora sp. 2	.09	.46	.24
Montipora sp. 3	.03	.61	1.65
Montipora sp. 4		.38	.71
Montipora sp. 5		.38	.19
Montipora sp. 6			.28
Montipora sp. 7			.05

Table 17. (Continued)

	Tumon Bay control reef	Tanguisson Point 1970	Tanguisson Point 1971
Pavona clavus (Dana), 1846	1.36	1.38	.19
Pavona decussata (Dana), 1846	(.48)		
Pavona divaricata (Lamarck), 1816	(#)		
Pavona frondifera (Lamarck), 1816	(#)		
Pavona varians Verrill, 1864	.91	3.99	3.31
Pavona gardineri van der Horst, 1922	#		.10
Pavona (*P.*) *pollicata* Wells, 1954	.21	.07	.19
Pavona (*P.*) *planulata* (Dana), 1846	.15		.47
Pavona (*P.*) *obtusata* (Quelch), 1884	.03		
Pavona (*P.*) sp. 1	.45		
Pavona (*P.*) sp. 2	#		
Pavona (*P.*) sp. 3		.54	.57
Leptoseris hawaiiensis Vaughan, 1907	.03	.23	.05
Leptoseris incrustans (Quelch), 1886	.03		
Leptoseris mycetoseroides Wells, 1954			.05
Pschyseris speciosa (Dana), 1846	#	#	#
Anomastraea sp. 1			.47
Coscinaraea columna (Dana), 1846	.18	.07	
Cycloseris cyclolites (Lamarck), 1801		.23	
Cycloseris sp. 1		.15	.19
Fungia fungites var. *incisa* Doederlein, 1902	#		
Fungia fungites var. stylifera Doederlein, 1902	.06		
Fungia scutaria Lamarck, 1801	#		.05
Goniopora columna Dana, 1846	#	.23	.19
Goniopora sp. 1	.21		.05
Goniopora sp. 2	.09		.24
Porites annae Crossland, 1952	(.09)		
Porites australiensis Vaughan, 1918	.42	.61	1.51
Porites cocosensis Wells, 1950	(.36)		
Porites compressa Vaughan, 1907	(.18)		
Porites duerdeni Vaughan, 1907	(#)		
Porites lichen Dana, 1846	#		.76
Porites lobata Dana, 1846	1.67	1.08	4.73
Porites lutea Milne Edwards & Haime, 1851	2.60	3.69	2.22
Porites murrayensis Vaughan, 1918	#		
Porites sp. 1	2.79	2.23	.38
Porites sp. 2	.03	#	
Porites (*S.*) *convexa* Verrill, 1864	.42	#	.10
Porites (*S.*) *hawaiiensis* Vaughan, 1907	#	.07	.85
Porites (*S.*) *horizontalata* Hoffmeister, 1925	#	.07	
Porites (*S.*) *iwayamaensis* Eguchi, 1938	1.03	1.23	1.13
Porites (*S.*) sp. 1	#		
Alveopora verrilliana Dana, 1872	.09	#	#

Table 16. (Continued)

	Tumon Bay control reef	Tanguisson Point 1970	Tanguisson Point 1971
Favia favus (Forskaal), 1775	#	.76	.24
Favia pallida (Dana), 1846	.48	3.92	2.08
Favia speciosa (Dana), 1846	.30		2.13
Favia stelligera (Dana), 1846	2.13	5.38	3.64
Favia rotumana (Gardiner), 1889	#	.15	.14
Favites abdita (Ellis & Solander), 1786	.03		
Favites complanata (Ehrenberg), 1834	.67	1.31	2.08
Favites favosa (Ellis & Solander), 1786		.15	.14
Favites flexuosa (Dana), 1846		.07	
Favites virens (Dana), 1846			.24
Oulophyllia crispa (Lamarck), 1816			.05
Plesiastrea versipora (Lamarck), 1816	.39	1.31	.80
Plesiastrea lilli Wells, 1954			.05
Plesiastrea sp. 1	.27		
Goniastrea parvistella (Dana), 1846	.46	1.31	.99
Goniastrea pectinata (Ehrenberg), 1834		.84	1.04
Goniastrea retiformis (Lamarck), 1816	3.48	6.68	7.14
Platygyra rustica (Dana), 1846	.39	.69	.10
Platygyra lamellina (Ehrenberg), 1834			.05
Platygyra sinensia (Milne Edwards & Haime), 1849	.33	.61	1.23
Leptoria gracilis (Dana), 1846	1.36	2.53	1.23
Leptoria phrygia (Ellis & Solander), 1786	.09	2.30	.80
Hydnophora microconos (Lamarck), 1816	.33	.07	.14
Leptastrea bottae (Milne Edwards & Haime), 1849	#		
Leptastrea purpurea (Dana), 1846	2.27	2.46	4.40
Leptastrea transversa (Klunzinger), 1879		1.31	1.65
Leptastrea sp. 1	.21	1.08	3.97
Cyphastrea chalcidicum (Forskaal), 1775			.28
Cyphastrea serailia (Forskaal), 1775	.36	.07	1.13
Cyphastrea sp. 1	.51	.46	
Echinopora lamellosa (Esper), 1787	.09	.38	.10
Diploastrea heliopora (Lamarck), 1816	.09	#	.14
Galaxea fascicularis (Linnaeus), 1758	.24	1.38	.14
Galaxea hexagonalis Milne Edwards & Haime, 1857	2.36	8.29	7.69
Merulina ampliata (Ellis & Solander), 1786			.05
Lobophyllia corymbosa (Forskaal), 1775	.27	.31	.14
Lobophyllia costata (Dana), 1846	.21	.46	.19
Acanthastrea echinata (Dana), 1846	.48	2.53	.71
Echinophyllia asper Ellis & Solander, 1786		.23	.85
Mycedium sp. 1			.14
Paracyathus sp. 1	#		
Polycyathus sp. 1	#		
Euphyllia glabrescens (Chamisso & Eysenhardt), 1821	#		
Heliopora coerulea (Pallas), 1766	.24	.07	.10

Table 17. (Continued)

	Tumon Bay control reef	Tanguisson Point 1970	Tanguisson Point 1971
Millepora dichotoma Forskaal, 1775	.18	.07	#
Millepora exaesa Forskaal, 1775	.88	1.15	1.94
Millepora platyphylla Hemprich & Ehrenberg, 1834	1.12	1.77	1.23
Distochopora violacea (Pallas), 1776	.09	.38	.14
Total species - 172	100%	100%	100%
Total number of colonies	3302	1302	2116

would not be expected to occur at Tanguisson Point because the reef flat zones are poorly developed there and a well defined inner reef flat "moat" is absent.

Table 17 shows, that of a total of 96 species and 33 genera found at Tanguisson Point during 1970, all but nine species and one genus were found again in 1971. There were 23 species and 6 genera of corals new to the Tanguisson transects in 1971. Of these new corals, 12 are also new to the Tumon Bay control reef. At Tanguisson Point, from 1970 to 1971, the relative frequency of occurrence (Table 17) decreased for 43 species, increased for 41 species, and remained unchanged for two species.

For the reef as a whole, Table 18 shows that the total number of genera has increased by five at Tanguisson Point from 1970 to 1971. This increases the total number of genera found at Tanguisson Point in 1971 to 38, which is greater than the total of 36 found at the Tumon Bay control reef prior to the *A. planci* infestation period. The same table, shows an increase of 14 species from 1970 to 1971 at Tanguisson Point, but unlike the number of genera which now surpasses that found at the Tumon Bay control reef, the number of species is still 21 below the 131 found prior to the starfish infestation period.

A zonal analysis (Table 19) shows very little change in the number of genera and species on the inner reef flat, reef margin, and reef front zones. Only small changes should be expected in these zones since there has been comparatively little *Acanthaster* damage to the corals on this part of the reef. Greatest changes have occurred in the submarine terrace and seaward slope zones where *Acanthaster* predation on corals was more intense.

Figures 43 and 44 show the number of genera and species for each transect by stations and reflects more exactly where changes have occurred. Two artifacts are present in Figures 43 and 44. The first is at Transect A on the reef margin zone and the second at Transect B on the reef margin and inner (shoreward) part of the reef front zones. At both of these transect locations a reduction in the number of genera and species has occurred. At Transect A this reduction was caused by a bloom of a blue-green alga, *Anacystis dimidiata* which, in a small localized region, covered nearly 100 percent of the reef surface. Many corals were killed as a result of their living tissues being covered by gelatinous shards of this alga. At Transect B the reduction was caused by the presence of heated effluent from the power plant outfall. Transect B bisects a portion of the outfall plume. Nearly all the corals have been killed on the reef margin and inner (shoreward) part of the reef front zones. Figure 42 graphs, otherwise,

Table 18. Number of genera and species for the major groups of corals found at Tumon Bay and Tanguisson Point,1970-1971. Values enclosed by parentheses indicate the number of coral genera and species found only on the transect stations. Values not enclosed by parentheses indicate the number found on the transect stations plus additional genera and species found by making observations of the reef surface located between Transect A and Transect C.

	Tumon Bay Control Reef (1968)		Tanguisson Point (1970)		Tanguisson Point (1971)	
	Genera	Species	Genera	Species	Genera	Species
Hermatypic Scleractinians	31 (29)	139 (98)	30 (27)	91 (81)	35 (33)	105 (103)
Ahermatypic Scleractinians	2 (0)	2 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Non-Scleractinians	3 (3)	5 (5)	3 (3)	5 (5)	3 (3)	5 (4)
Totals	36 (32)	146 (103)	33 (30)	96 (86)	38 (36)	110 (107)

Table 19. Changes in the number of coral genera and species by reef zones from 1970 to 1971. Values enclosed by parentheses indicate the number of coral genera and species found only on the transect stations. Values not enclosed by parentheses indicate the number found on the transect stations plus additional genera and species found by making observations of the reef surface located between Transect A and Transect C.

Reef Zones	Tanguisson Point 1970 Genera	Tanguisson Point 1970 Species	Tanguisson Point 1971 Genera	Tanguisson Point 1971 Species
Inner reef flat	0 (0)	0 (0)	0 (0)	0 (0)
Outer reef flat	2 (2)	2 (2)	4 (1)	5 (2)
Reef margin	12 (12)	21 (21)	10 (10)	21 (20)
Reef front	24 (24)	70 (65)	21 (21)	68 (67)
Submarine terrace	24 (22)	47 (45)	27 (27)	70 (70)
Seaward slope	21 (19)	32 (28)	30 (30)	61 (61)

Table 20. Changes in the percentage of reef surface covered by living coral by reef zones from 1970 to 1971.

Reef Zone	Transect A 1970	Transect A 1971	Transect B 1970	Transect B 1971	Transect C 1970	Transect C 1971
Outer reef flat	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Inner reef flat	0.0%	0.0%	0.1%	0.0%	0.0%	1.0%
Reef margin	17.5%	0.1%	28.0%	1.5%	22.2%	25.0%
Reef front	5.1%	8.7%	39.0%	32.2%	18.8%	24.8%
Submarine terrace	0.7%	2.7%	1.1%	4.9%	1.0%	4.3%
Seaward slope	0.9%	3.0%	0.2%	1.8%	0.5%	1.6%

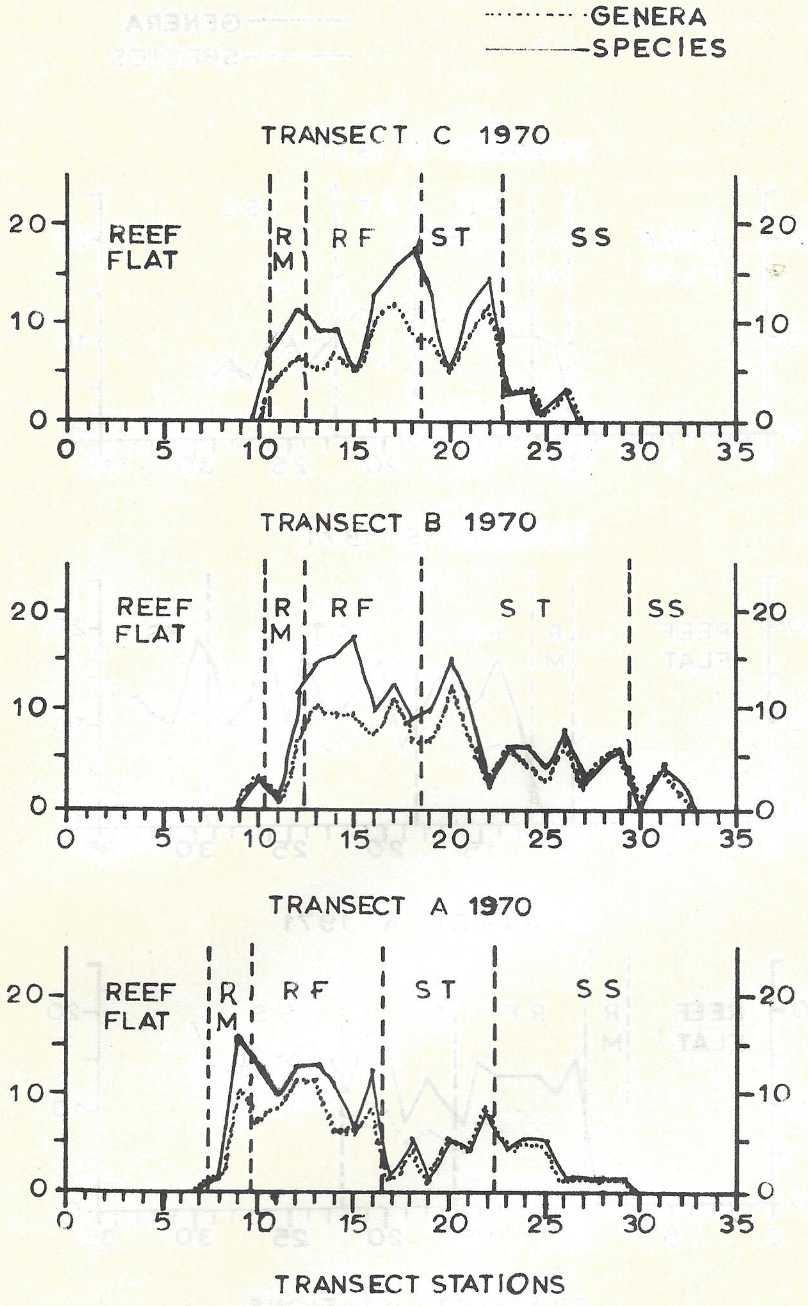


Figure 43. Number of coral genera and species per transect station for 1970.

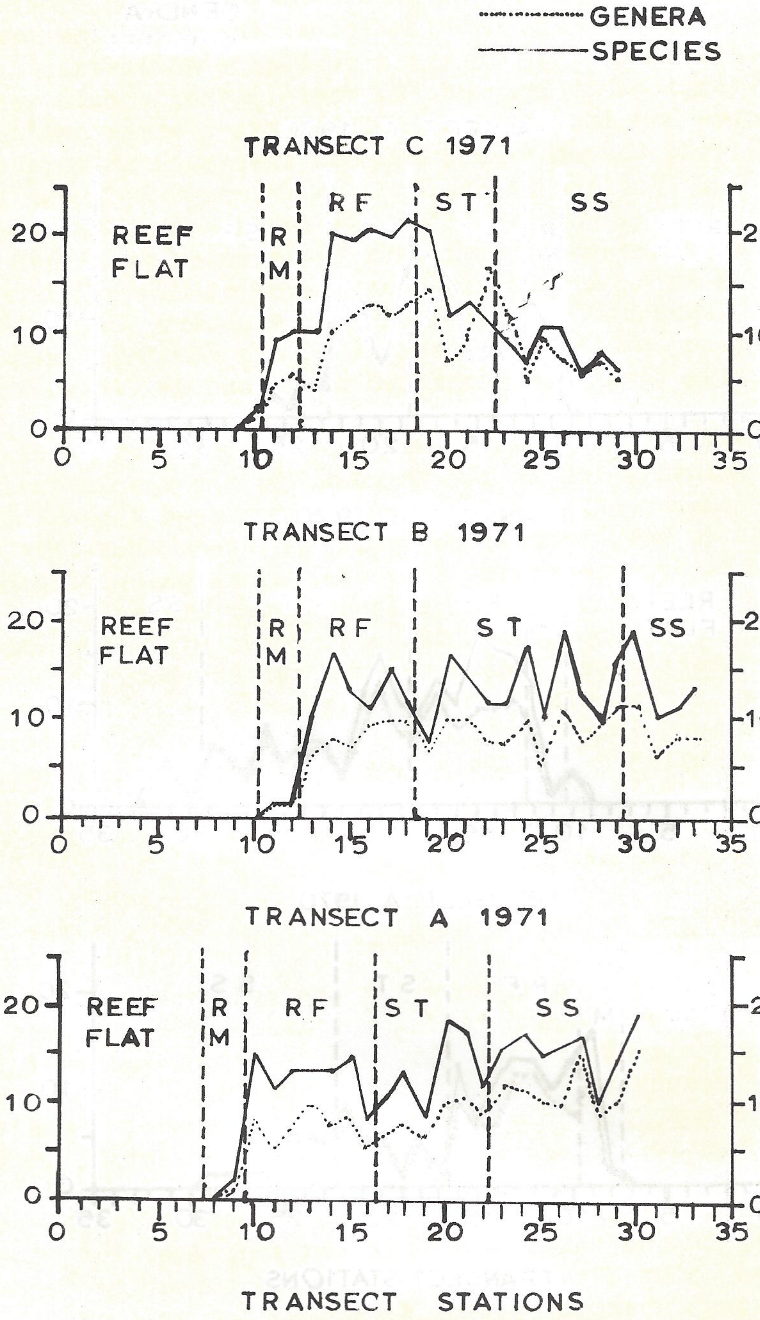


Figure 44. Number of coral genera and species per transect station for 1971.

show that greatest changes in the number of genera and species has taken place on transect stations located on the submarine terrace and seaward slope zones. An analysis of Figure 43 reveals that: 1) for the 23 stations at Transect A, where living corals were found, the generic total has increased at 15, decreased at 6, and remained unchanged at 2; and the species total has increased at 18 and decreased at 5. 2) For the 24 stations at Transect B, where living corals were found, the generic total has increased at 17, decreased at 5, and remained unchanged at 1; and the species total has increased at 18, decreased at 4, and remained unchanged at 2. 3) For the 20 stations at Transect C, where living corals were found, the generic total has increased at 16, decreased at 1, and remained unchanged at 3; and the species total has increased at 19 and decreased at 1.

It appears then, that species diversity is increasing fairly rapidly at Tanguisson Point, which is due in part to the recolonization of not only the former species which commonly occurred there, but also to species that do not normally occur in the area. Possibly the corals new to the area represent a pioneer group which recolonize the reef surface recently killed by *Acanthaster* predation. Porter[26] reported a similar phenomenon on the west coast of Panama where corals were killed by *Acanthaster*. As more reef surface becomes covered with living corals, especially by those species which formerly occupied the region, interspecific competition may well become an important factor which could again restore the pre-*Acanthaster* species composition to the reef. Until competition becomes a limiting factor at Tanguisson Point, species diversity could go beyond the 131 level found previously at Tumon Bay.

Reef Surface Coverage by Living Corals

The percentage of living coral covering the reef surface (Table 20) increased on all transects and reef zones except for the reef margin on Transect A and the other reef flat, reef margin, and reef front on Transect B. Reduction of reef surface coverage in these zones is due again to the *Anacystis dimidiata* bloom on Transect A and the presence of the outfall plume at Transect B. Transect C, located well south of the outfall plume, shows a gain in living coral coverage in all reef zones. Figures 45-47 show the percent of coral coverage for each station on the three transects and indicates that the highest relative gains have taken place in the submarine terrace and seaward slope zones where *A. planci* damage to the reef corals was greatest.

Corallum Size Distribution

Table 21 lists the frequency distribution of corals by diameter for

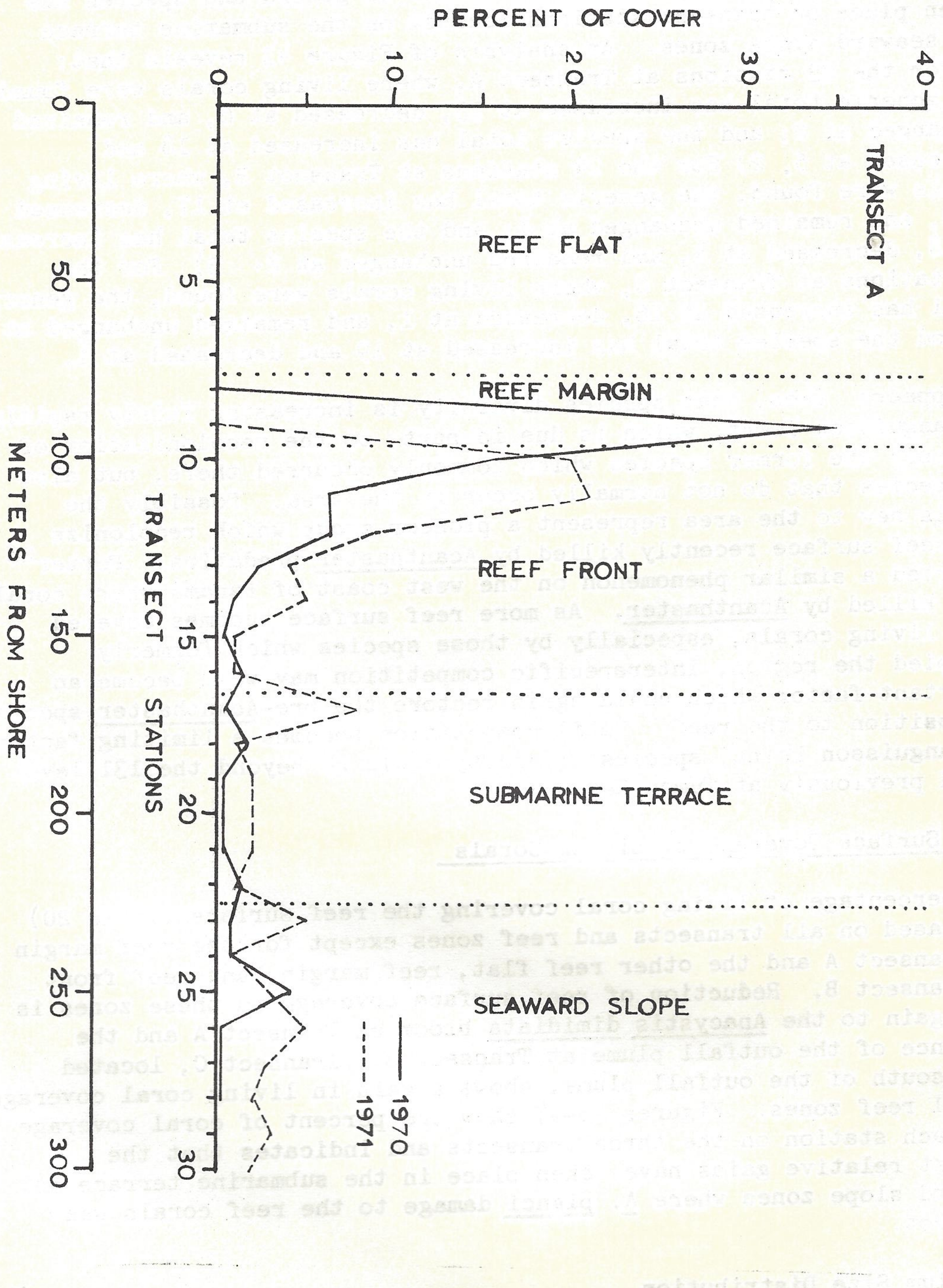


Figure 45. Percentage of reef surface covered by living corals from 1970 to 1971 for Transect A.

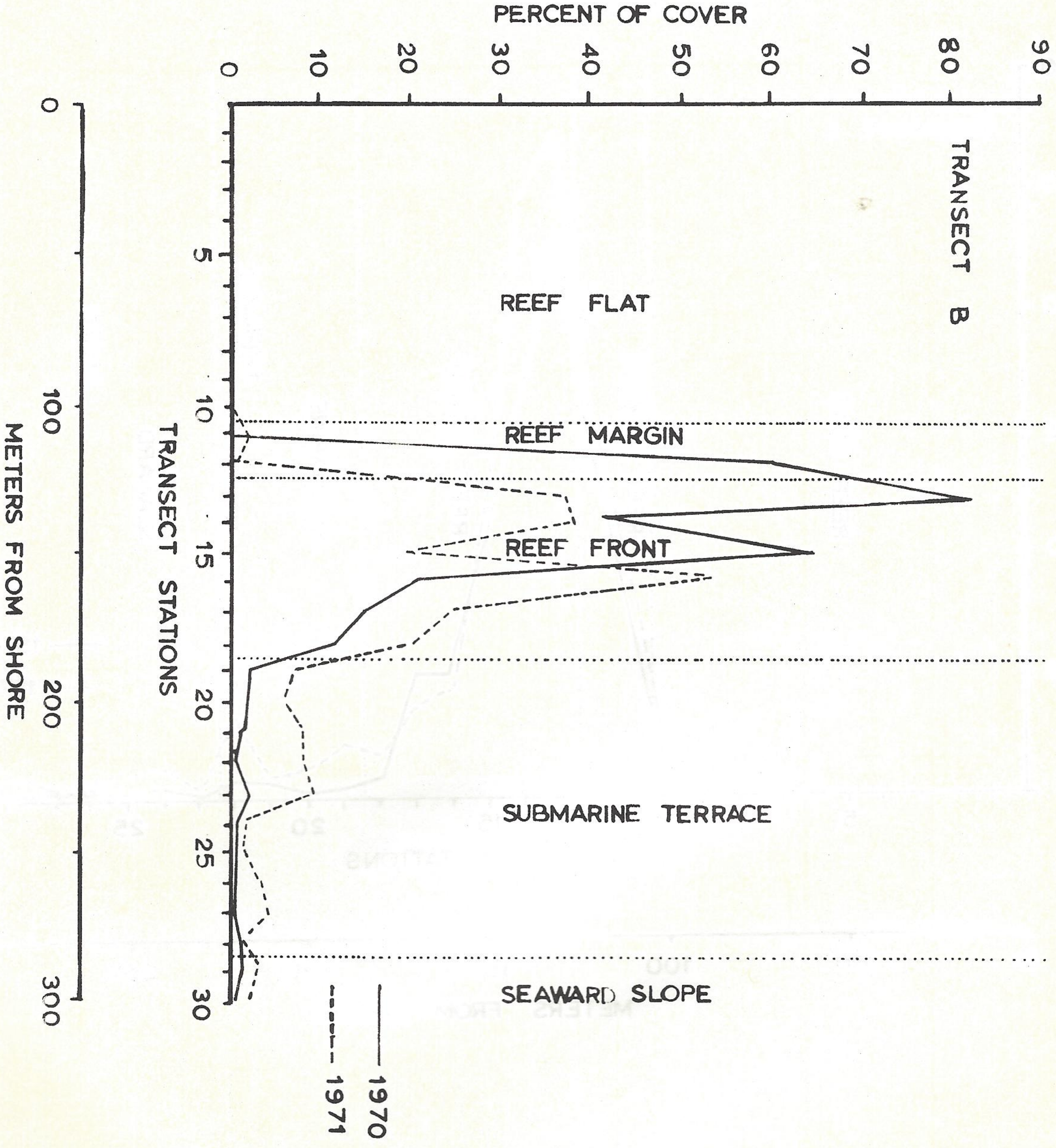


Figure 46. Percentage of reef surface covered by living corals from 1970 to 1971 for Transect B.

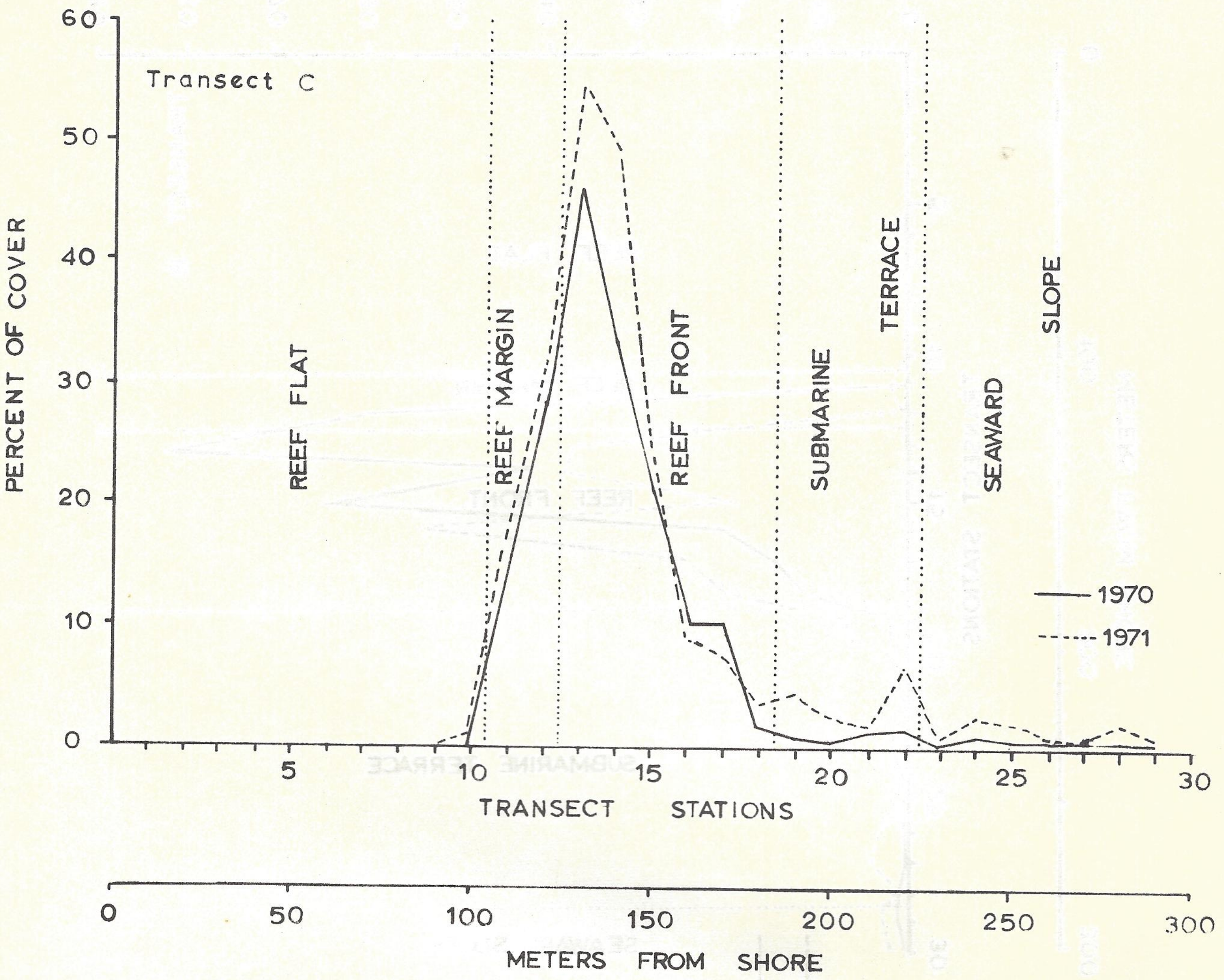


Figure 47. Percentage of reef surface covered by living corals from 1970 to 1971 for Transect C.

Table 21. Distribution of corals by diameter from 1970 to 1971. Data from Transects A, B, and C are combined.

Reef zones	Outer reef flat		Reef margin		Reef front		Submarine terrace		Seaward slope		All zones combined	
Dia. range in cm	1970	1971	1970	1971	1970	1971	1970	1971	1970	1971	1970	1971
0 - 5	5	6	72	31	314	326	275	451	135	428	801	1242
6 - 10	2	1	53	92	200	317	43	146	25	77	323	633
11 - 15	1	1	33	22	59	77	2	29	0	14	95	143
16 - 20	0	0	9	8	18	30	0	3	1	1	28	42
21 - 25	0	0	5	6	13	13	0	2	0	1	18	22
26 - 30	0	0	4	4	11	14	0	1	0	0	15	19
31 - 35	0	0	0	0	2	4	0	0	0	0	2	4
36 - 40	0	0	0	0	6	1	0	0	0	0	6	1
41 - 45	0	0	2	1	5	3	0	0	0	0	7	4
46 - up	0	0	3	2	4	4	0	0	0	0	7	6
Totals	8	8	181	166	632	789	320	632	161	521	1302	2116

each reef zone from 1970 to 1971. The greatest change in size distribution occurred in the 0-5 cm range, where a 55 percent increase took place. This large increase is due mainly to the new settlement and growth of coral planulae on the algal encrusted surface of corals previously killed by A. planci. Even though this large increase took place between 1970 and 1971, 62 percent of the corals were also found in the 0-5 cm range in 1970. Most of the colonies were represented, at that time, by small patches of coralla, surviving from larger colonies, that were not completely killed by A. planci. The second largest increase was in the 6-10 cm range which mostly represents an increase in growth of the surviving coral patches described above, plus some recolonization from planulae settlement from 1969 to 1971. Most of the increase that took place in the 0-5 and 6-10 cm size ranges occurred in the submarine terrace and seaward slope zones where A. planci activity was the greatest. There has been a decrease in the number of the inner half of the reef front zone because of the coral kill due to the algal bloom at Transect A and the outfall plume at Transect B. Most of the larger coralla are found in reef zones which were not subjected to much damage from A. planci.

Corallum Growth Form Distribution

If the observed increase in the total number of new colonies found at the station quadrats are due to recent coral planulae settlement, then a marked increase in the number of encrusting growth forms should be expected, since most newly settled corals go through an encrusting stage early in their development. Table 22 shows an increase from 788 colonies in 1970 to 1468 colonies in 1971 has occurred in the number of encrusting growth forms. Eighty-three percent of the above increase has taken place in the submarine terrace and seaward slope zones. There have been decreases in the number of colonies in the reef margin and reef front zones because of the corals killed by the algal bloom and outfall plume at transcets A and B respectively. Seventeen percent of the increase in encrusting growth forms occurred in the reef front zone. Most of this increase actually took place on the outer part of the reef front zone where there was some A. planci damage. This reef front increase of encrusting forms should coincide with a corresponding increase in the same zone for corallum diameter in the 0-5 cm range, but due to optimum growth conditions found at this zone, these new colonies are mostly distributed in the 6-10 cm size range (Table 21). The reef front zone also shows some gains in the number of corymbose and cespitose growth forms (Table 22) which are attributable to newly colonized corals, but as above, they have apparently passed through their early encrusting growth form because of elevated growth rates in this zone.

Table 22. Distribution of corals by growth forms from 1970 to 1971. Data from Transects A, B, and C are combined.

Reef zones	Outer reef flat		Reef margin		Reef front		Submarine terrace		Seaward slope		All zones combined	
Growth form	1970	1971	1970	1971	1970	1971	1970	1971	1970	1971	1970	1971
Massive	0	0	19	18	128	122	41	44	14	56	202	240
Encrusting	1	1	31	26	376	491	250	533	130	417	788	1468
Foliaceous	0	0	0	0	0	0	0	0	5	8	5	8
Flabellate	0	0	5	7	7	7	1	11	0	0	13	25
Corymbose	0	0	13	24	29	50	0	4	0	2	42	80
Cespitose	7	7	112	91	80	107	5	29	8	20	232	254
Arborescent	0	0	1	0	8	12	0	0	0	2	9	14
Phaceloid	0	0	0	0	4	0	1	6	2	1	7	7
Columnar	0	0	0	0	0	0	1	5	1	10	2	15
Solitary	0	0	0	0	0	0	1	0	1	5	2	5
Totals	8	8	181	166	632	789	320	632	161	521	1302	2116

Summary

1. During 1968 at Tanguisson Point, over 95 per cent of the living reef corals were killed by A. planci in the submarine terrace and seaward slope zones.

2. The number of living coral colonies recorded on the Tanguisson Point transects has increased from 1302 in 1970, to 2116 in 1971. Most of these new colonies have developed in the submarine terrace and seaward slope zones.

3. The total number of coral genera has increased from 30 to 35 on the Tanguisson Point transects and from 33 to 38 when additional genera observed between transects A and C are included.

4. During the study period, the total number of species has increased from 86 to 107 on the Tanguisson Point transects and from 96 to 110 when additional species observed between transects A and C are included. From 1970 to 1971 there were 23 species and 6 genera of corals recorded that were new to the Tanguisson Point transects. Of these new species 12 were also new to the Tumon Bay control reef. Of all the species recorded in 1970, only 9 were not recorded again in 1971.

5. When increases in the number of genera and species are compared by reef zones at Tanguisson Point from 1970 to 1971, there has been little change in the zones where A. planci damage was minimal (except for damage caused by the alga bloom at Transect A and the power plant effluent at Transect B). The most significant increases have occurred on the submarine terrace and seaward slope zones where A. planci infestation and damage to reef corals was greatest.

6. The percentage of reef surface covered by living corals has increased on all reef zones at Tanguisson Point except the reef margin at Transect A (reduction caused by alga bloom) and the inner reef flat, reef margin, and reef front zones at Transect B (reduction caused by power plant outfall). The greatest relative increase in the percentage of reef surface covered by living corals has occurred on the submarine terrace and seaward slope zones.

7. During the study period,increases in coral size has been greatest in the 0-5 cm range and in the 6-10 cm range. Most of these increases have occurred in the submarine terrace and seaward slope zones.

8. During the study period,greatest changes in the distribution of coral growth forms has been an increase of the encrusting types. Most of this increase has occurred in the submarine terrace and seaward slope zones.

Conclusions

The increase in the total number of new coral colonies observed, the increase in species diversity, and the increase in the percentage of reef surface covered by living corals indicate that coral recovery is taking place at Tanguisson. Most of the coral recovery is taking place in those zones where A. planci infestation and the resulting damage was greatest. The increases observed for the percentage of reef surface covered by living corals is due to recolonization by the settlement of planulae and an increase in size of the few surviving patches or colonies of coral that remained after the starfish infestation period.

Based on a pre-Acanthaster value of 60 percent for the living coral surface coverage at the Tumon Bay control reef and an average gain of 3.0 percent coverage for the submarine terrace zone at Tanguisson Point, from 1970 to 1971, it will then take this reef zone about 20 years to attain the same degree of coverage found before A. planci predation. With a 50 percent pre-Acanthaster value for the living coral coverage at the control reef and an average gain of 1.6 percent coverage for the seaward slope zone at Tanguisson Point, from 1970 to 1971, it might take the reef zone, there, about 31 years to attain the same degree of coverage as was found before A. planci predation.

The above recovery rates were determined from one year of data and a simple linear extrapolation based on the control reef values taken in 1967 and 1968. Actual growth rates of organisms seldom express themselves in a linear fashion, especially within an ecosystem as complex as that of a coral reef. The above reef recovery hypotheses are, at best, tenuous and based on gains in reef surface coverage by living corals. For the reef to attain the massive framework development that was once found in this region, it may take a much longer period of time-possibly as much as the 700 years predicted by the late T. F. Goreau[27].

SECTION XI

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SECTION XII

APPENDICES

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[illegible] temperature [illegible]
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APPENDIX A

EFFECT OF TEMPERATURE ON THE METABOLIC ACTIVITY OF THE STARFISH *ACANTHASTER PLANCI* (L.)

by

Masashi Yamaguchi

INTRODUCTION

Although much research has been done on the effects of elevated temperature on temperate marine animals (see reviews by Kinne[1], McWhinnie[2], Vernberg & Vernberg[3]), knowledge of thermal stress on coral reef animals is limited. Mayer[4] conducted thermal experiments on reef-building corals and other invertebrates in Samoa. Cary[5] studied the effects of temperature on the Samoan Alcyonaria. Edmondson[6, 7] recorded behavior of both adult and larvae of Hawaiian corals under conditions of thermal stress. The above papers indicate, as has often been suggested, that many coral reef invertebrates have a fairly narrow upper tolerance range of temperature for their survival and well-being. While there may be a range in which the animals can tolerate thermal stress for short periods, they cannot maintain normal behavior and metabolism indefinitely. Since temperature has a direct effect on the metabolism of every organism, it is important to know how thermal conditions modify metabolic activity and subsequent behavior of coral reef animals.

Acanthaster planci (L.), a coral-predator asteroid, has proven to be an excellent laboratory animal. It is easily maintained under laboratory conditions and can be readily subjected to experimentation under well-defined nutritive and behavioral conditions. This species is a widely distributed and relatively common reef asteroid with populations recorded from the Red Sea and throughout the entire tropical Indo-Pacific region including Hawaii (see review by Vine[8]). Thus it may well represent an important test animal for experimentation on the effect of altered thermal conditions on tropical reef organisms. This report considers the effect of water temperature on the "standard metabolic activity" of the starfish, measured in the laboratory as the rate of oxygen consumption when the test animals are at rest.

MATERIALS AND METHODS

Three laboratory-grown _Acanthaster_ about 15 months old and from the same batch of fertilized eggs were used for the present experiment.

They were about 120 mm in total diameter at the beginning of this series of observations and the weight of each individual specimen was monitored throughout the experimental period from November 19th to December 9th, 1972 (Fig. 1). The animals were weighed in seawater by means of a specific-gravity type balance (Ohaus Dial-O-Gram Balance), to the second decimal point. Wet weight of the starfish determined in the air is highly variable and not reproducible due to permeability of the body to fluids, while the weight in the seawater gives good results. The underwater weight of Acanthaster is approximately one half its dry weight.

Each experimental animal was kept individually in a rectangular plastic holding aquarium about 40 liter in capacity and with a sand-filter bed on the bottom. Seawater in the aquarium was circulated by an air-lift, driven by an air-pump. The chlorinity of seawater in the aquaria was maintained at 19.1 ± 0.1% by adding distilled water to compensate for evaporation. Chlorinity was determined by silver nitrate titration. Water temperature of each aquarium was controlled by an immersion heater connected to a bimetal thermostat and was kept within ± 0.5°C fluctuation at most.

Water temperature of the holding aquaria was set at the experimental level at least 12 hours prior to transfer of the animals into respiration chambers so as to condition them to the experimental temperatures.

The three young Acanthaster were fed exclusively Acropora spp. during the experimental period as this genus of coral is consistantly grazed by the starfish in the laboratory. The starfish showed cyclic feeding activities, feeding on coral at night and remaining quiescent in the daytime. The animals showed locomotive activities when disturbed during weighing and transfer from holding aquaria to respiration chambers. They became quiescent again within an hour inside the chamber and remained so during the observation period of up to seven hours each day. It was possible to take advantage of these cyclic activities in order to determine the at-rest condition of experimental animals for measurement of standard metabolism in the growing young. The need to use well fed animals was indicated by preliminary research which showed a remarkable reduction in rate of oxygen consumption in starved animals.

Rate of oxygen consumption was determined for the temperature range of 25 to 33°C at intervals of two degrees. The experimental animals were raised through most of their coral-eating juvenile life in outdoor aquaria, prior to the experiment, and their thermal environment fluctuated between 25 and 31°C.

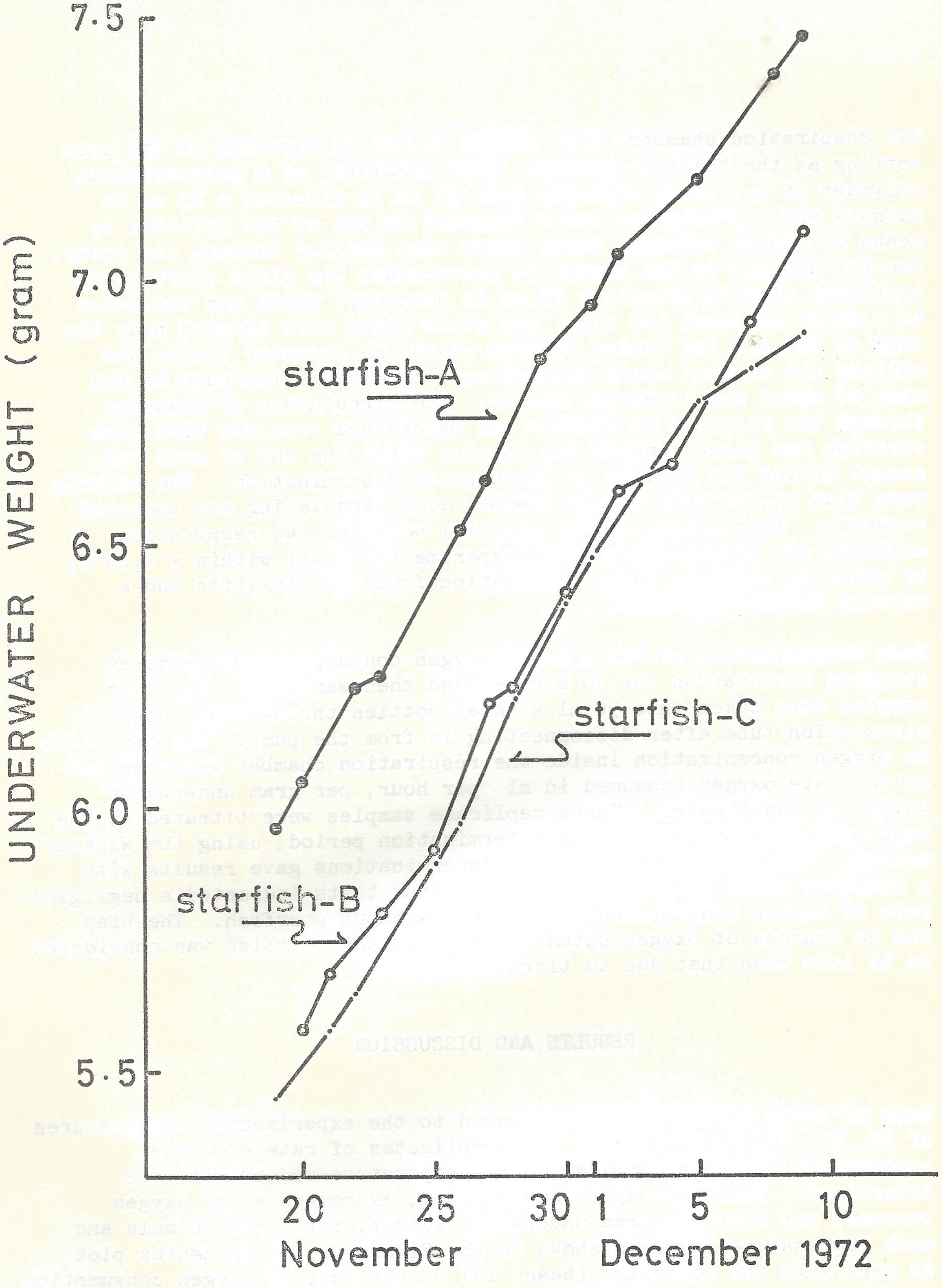

Figure 1. Growth of <u>Acanthaster planci</u> during the experiment, from November 19th to December 9th, 1972. Underwater weight, measured in seawater of about 1.024 in specific gravity, for the three experimental animals is plotted on Y-axis.

Two respiration chambers were placed inside an aquarium of the same setting as the holding aquaria. Each consisted of a polycarbonate cylinder of 4.5 liter capacity (ca. 16 cm in diameter x 23 cm in height) and a plexiglass cover fastened on top of the cylinder by means of rubber tubing. Three holes were drilled through the cover. One was drilled in the center to accommodate the glass shaft of an agitating plastic propeller (5 cm in diameter) which was connected to a motor of about 100 rpm. Two other holes were located near the edge of the lid for tubing through which the seawater inside and outside the chamber could be exchanged by a vibrating pump at the rate of about one liter per minute. The circulation of seawater through the respiration chamber was maintained from the time each starfish was placed inside the chamber until the end of each run, except during the periods of consumption determination. The animals were thus conditioned in the chamber with circulating and agitated seawater. Temperature of the aquarium with the two respiration chambers was controlled at each experimental level within ± 0.05°C, by means of vigorous water circulation from two air-lifts and a mercury thermo-regulator.

Each determination of the rate of oxygen consumption was made by stopping circulation for 30 minutes and then sampling. Seawater samples were taken into 50 ml Winkler bottles through the outgoing circulation tube after disconnecting it from the pump. The reduction in oxygen concentration inside the respiration chamber was computed as the rate oxygen consumed in ml per hour, per gram underwater weight of *Acanthaster*. Three replicate samples were titrated at the beginning and the end of each determination period, using the Winkler method. The means from the three determinations gave results with a relative error of less than 0.5%. Blank tests indicated a negligible rate of oxygen consumption in chambers without starfish. The bias due to sources of oxygen uptake other than the starfish was considered to be less than that due to titration error.

RESULTS AND DISCUSSION

Each of three *Acanthaster* was exposed to the experimental temperatures of 25, 27, 29, 31, and 33°C. Six replicates of rate of oxygen consumption for each combination of temperature and animal were determined. The mean oxygen consumption, expressed as ml oxygen consumed per hour per gram underwater weight, for three animals and each temperature level is shown in the Figure 2. An Arrhenius plot is used with the logarithm (base: 10) of the rate of oxygen consumption on the Y-axis and the reciprocal of absolute temperature (which is

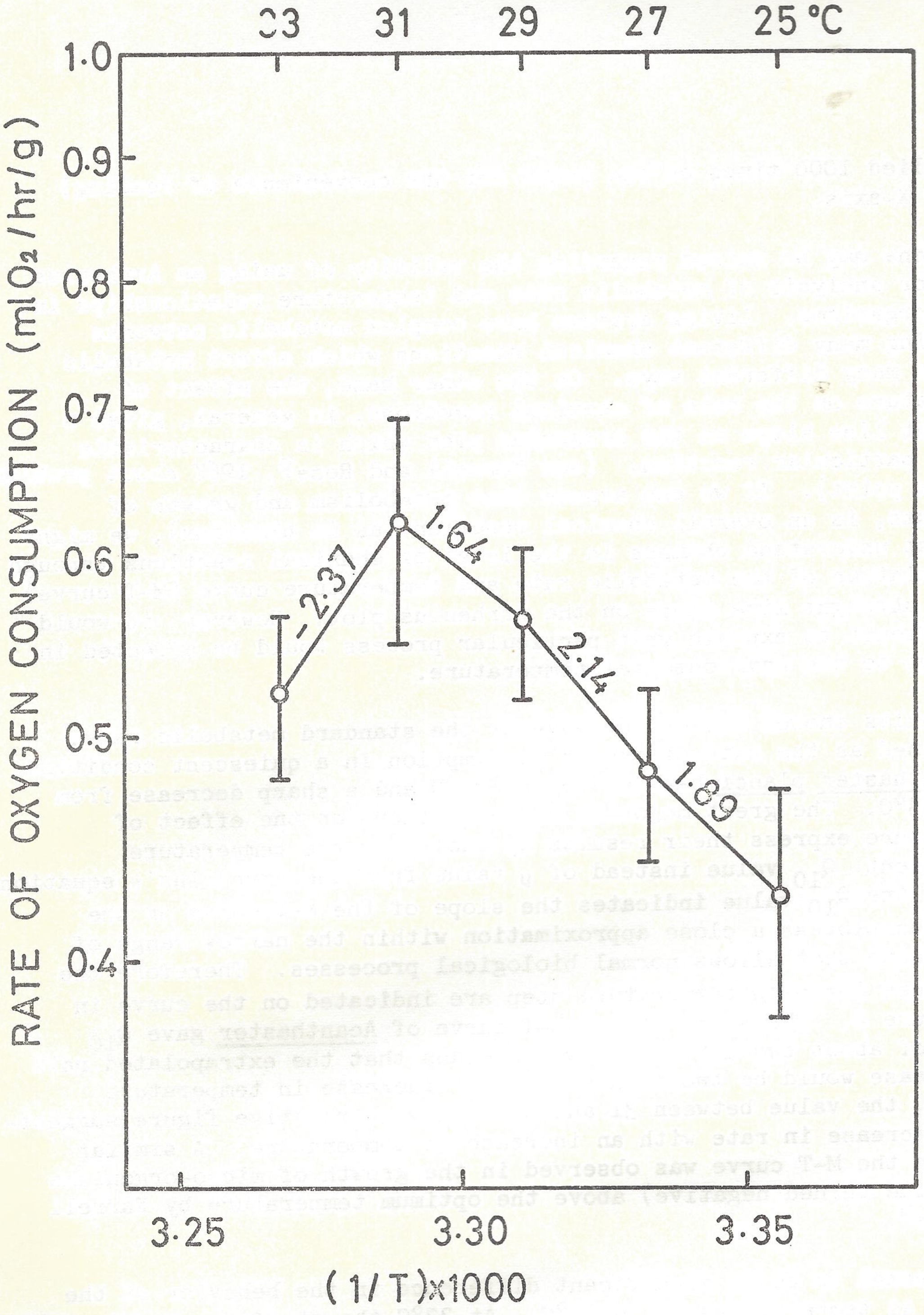

Figure 2. Metabolic rate and Temperature (M-T) curve of Acanthaster. Arrhenius plot of the rate of oxygen consumption of Acanthaster against the water temperature. Y-axis indicates the logarithm of the rate as ml. oxygen consumed per hour, per gram of underwater weight. X-axis indicates the reciprocal of the water temperature in degrees absolute, with an indication of centigrade scale on the top which corresponds to absolute temperature. Mean rate of consumption and one standard deviation to either side is shown. The figures on the slopes indicate Q_{10} value for each slope.

multiplied 1000 times on the scale for the convenience of reading) on the X-axis.

Questions may be raised regarding the validity of using an Arrhenius plot for analysis of metabolic rate and temperature relationships in these organisms. Living systems have complex metabolic networks involving many different chemical reactions which affect metabolic rate in many different ways. On the other hand, the effect of temperature on the rate of chemical reactions, in general, gives a straight line slope on the Arrhenius plot which is characteristic of the particular reaction. (see Farrell and Rose[9], 1967 about problems on this point). If we can assume that metabolism and growth of organisms, is an overall chemical reaction (as in blackbox), we might at least understand changes in the level of chemical reactions through the deviation of the metabolic rate and temperature curve (M-T curve) from a straight line slope on the Arrhenius plot. However, it would be difficult to explain what particular process would be affected in relation to the environmental temperature.

The results showed steady increase of the standard metabolic rate, determined as the rate of oxygen consumption in a quiescent condition in Acanthaster planci between 25 and 31°C and a sharp decrease from 31 to 33°C. The great majority of researchers on the effect of temperature express their results by analyzing the temperature coefficient: Q_{10} value instead of μ value from the Arrhenius's equation. Indeed, the Q_{10} value indicates the slope of the M-T curve on the Arrhenius plot as a close approximation within the narrow range of temperature that allows normal biological processes. Therefore the Q_{10} values for each temperature step are indicated on the curve in the Figure 2. The slope of the M-T curve of Acanthaster gave Q_{10} values of about two up to 31°C which means that the extrapolated rate of increase would be two-fold with a 10° increase in temperature. However, the value between 31 and 33°C shows a negative figure suggesting a decrease in rate with an increase in temperature. A similar trend in the M-T curve was observed in the growth of micro-organisms (Q_{10} value turned negative) above the optimum temperature by Farrell and Rose[9].

There seemed to be no significant difference in the behavior of the animals at temperatures up to 31°C. At 33°C the starfish showed signs of stress that interfered with their normal cyclic feeding activity. When they tried to feed on coral pieces, placed in the holding aquaria on the first or second night, stomach eversion was in-complete and the feeding process was shorter than that under normal conditions. Moreover, the starfish ceased feeding activity altogether after two full days at 33°C in the holding aquaria. At this time all the body surfaces were swollen and the ambulacral grooves which are usually half closed when the starfish is in a quiescent condition at normal temperature, were wide open. When the starfish were kept at a higher temperature (35°C), the body became extremely swollen and tube feed showed a restless expansion and contraction from the gaping ambulacral grooves. Under these conditions it was no longer possible to measure the standard metabolic rate in the starfish and the experiments with temperature above 33°C were terminated.

It is well known that the rate of oxygen consumption in asteroids is controlled not only by temperature but also by a number of endogenous and environmental conditions such as the body size, activity of the animal, nutrition, salinity, pH, and concentration of dissolved oxygen (Farmanfarmaian[10]). An attempt was made to account for the above factors in the present study by either controlling them or monitoring the range of fluctuation. Feeding and activity of the experimental animals was fairly constant except at 33°C when the animal stopped feeding. Body size increased considerably during the observation period (Fig. 1) but the weight increment during this period seemed to alter the rate of oxygen consumption negligibly. Duplicate determinations at the same temperature on the same animal at different sizes produced nearly identical results. The weight increased about 25 to 30% but the increment of diameter was less than 20% during the period. Salinity of seawater in the experimental aquarium was controlled at 34.50 ± 0.10°/oo (chlorinity 19.10 ± 0.05°/oo) and pH varied between 8.0 and 8.1, with a tendency toward inverse correlation with temperature. It is doubtful that either salinity or pH affected the results significantly.

Because the solubility of oxygen in seawater decreases with increase in water temperature, the level of dissolved oxygen in the experimental aquarium and respiration chambers varied significantly with the changes in water temperature as a matter of course. The dissolved oxygen in the respiration chambers and that of theoretical concentration of saturation level are shown in Figure 3. As the theoretical concentration decreased with increase of temperature, the oxygen concentration in the respiration chambers decreased in a similar manner. The saturation level remained at about 90% in the chamber without animal and about 80 to 85% with the animal. The reduction in the latter was due to the limited water circulation between the aquarium and the chamber. <u>Acanthaster</u> would be, presumably, similar to other asteroids in the manner of oxygen consumption, that is the rate is proportional to the concentration of oxygen (Farmanfarmaian[10]). The slope of M-T curve in the Figure 2 might be much steeper than that observed if the determination of oxygen consumption was carried out at a constant level of environmental oxygen concentration at each temperature.

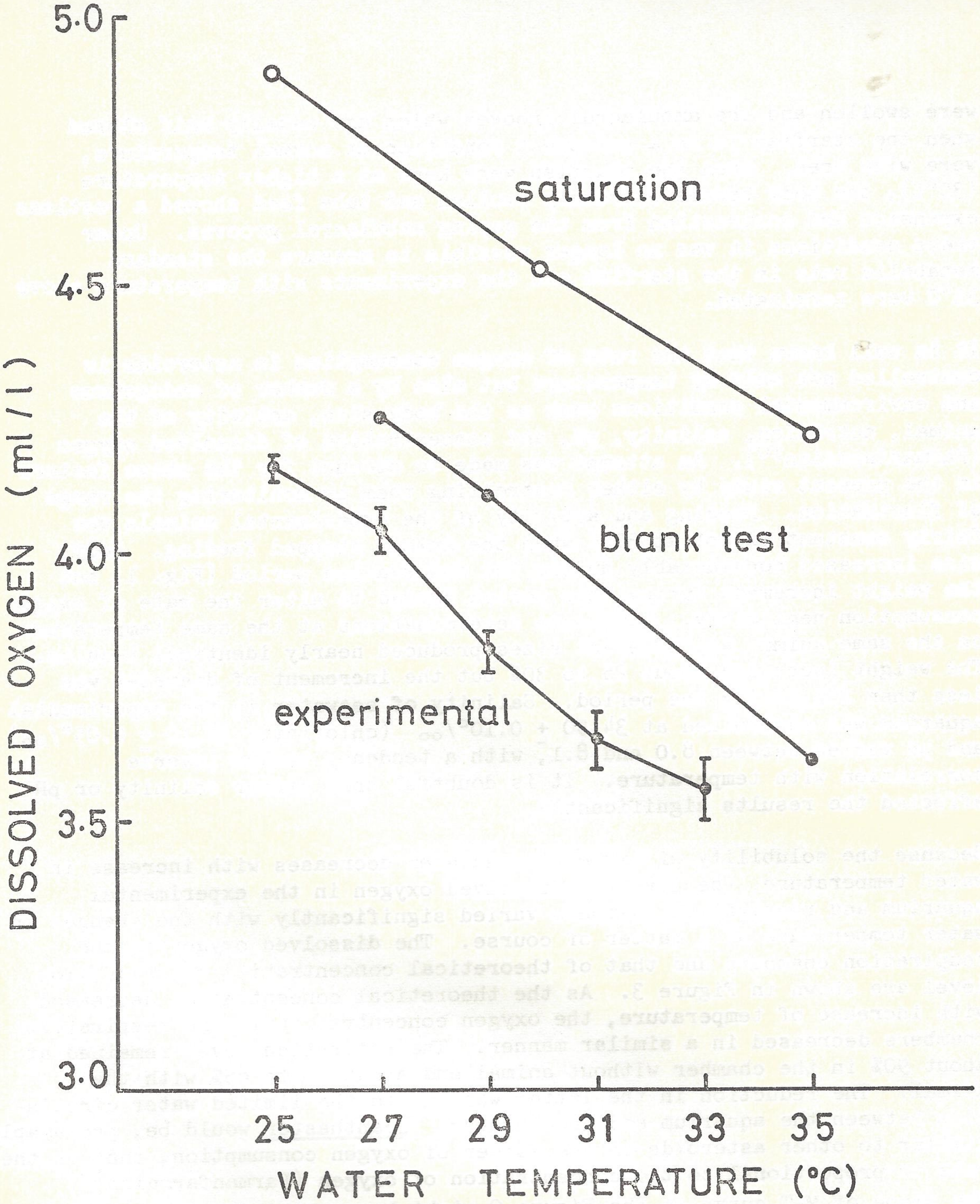

Figure 3. Relationship of water temperature and concentration of dissolved oxygen inside the respiration chambers with animals (mean and one S.D. from initial determinations when the circulation of water stopped) and without animals (blank tests). A theoretical concentration of oxygen saturated in the seawater of 19.1°/₀₀ in chlorinity (after Green[11]) is also shown.

The elevated thermal condition results in the reduction of the environmental oxygen concentration. The increased requirement for oxygen in poikilothermic animals with accelerated metabolism at higher temperature is obviously not favored by this reduction of oxygen tension. The response of Acanthaster to high temperature in the form of swollen body and gaping ambulacral grooves might be an aid in the exchange of dissolved gases. However, the actual rate of oxygen consumption dropped at 33°C compared with that at 31°C.

CONCLUSION

Acanthaster planci represents a typical metabolic-conformer in which the rate of oxygen consumption is controlled by environmental temperature and other factors. The range of temperature in which the starfish could behave normally and maintain normal metabolism seemed to be limited to 31°C. At 33°C, the starfish showed an abnormal behavior, ceased feeding, and its metabolic activity seemed to be disturbed as the slope of M-T curve turned negative. The starfish has no specialized respiratory organ and is not organized to maintain a constant metabolic level over any range of temperature. This character, which is common among most poikilothermic invertebrates, will prove destructive in their well-being if the thermal environment is modified above a certain level, although it may be species specific. Information on this point is very important in evaluating the effects of thermal discharge over coral reefs by the power plants which use seawater as a coolant.

Thermal death in Acanthaster planci was observed prior to the present experiment in three field specimens and two laboratory-grown ones. Those starfish, ranging from 5 cm to 18 cm in total diameter, were kept in aquaria under the same culture conditions described in the present experiments. Water temperature was held between 33 and 34°C for these animals and their behavior and appearence were noted. There seemed no significant differences between the responses of the five animals. The general pattern of their thermal death was as follows:

1. Cease feeding within one or two days.
2. Dorsal spines depressed, body wall swollen, and ambulacral grooves wide open within three to four days.
3. Spines located near arm tips are shed from the body surface, locomotion ceases and degeneration of whole body commences a day later.

The period required for the complete death of the animals was about one week at temperatures between 33 and 34°C.

The incipient thermal death point is near 33°C for _Acanthaster_ although this might be shifted slightly beyond this range by acclimatization. Water temperature around Guam fluctuates between 27 and 30°C outside the reef (oceanic water) but may be several degrees warmer inside the reef margin. Tide pools and small lagoons on the reef-flat often show wild fluctuation in environmental conditions. The temperature range which may stress _Acanthaster_ is found commonly in such areas when spring tides cause extreme low tides in the mid and late afternoon. _Acanthaster_ is uncommon on the reef-flat and may avoid these aras because of stress including high temperature. There is, however, at least one conspicuous reef asteroid, _Linckia_ _laevigata_, which does inhabit the reef-flat habitat avoided by _Acanthaster_. It would be interesting to make a comparative study of the relationship between metabolic activity and temperature for _Linckia_, since resistance to thermal stress in this species may be different from that of _Acanthaster_.

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APPENDIX B

EFFECTS OF TEMPERATURE ON FERTILIZATION AND EARLY CLEAVAGE OF SOME TROPICAL ECHINODERMS WITH EMPHASIS ON ECHINOMETRA MATHAEI (DE BLAINVILLE)

by

John H. Rupp

INTRODUCTION

Benthic marine invertebrates, particularly echinoderms, are sensitive to water temperatures above normal ambient (Farmanfarmaian and Giese[1], Glynn[2]). These temperatures may affect survival and distribution of adults as well as their gametes and larval stages which occur in the plankton.

Although the normal annual temperature fluctuation in oceanic surface waters around Guam is less than 3.0°C (26.5-29.0°C), conditions leading to temperature stress on coral reef organisms do exist, both naturally and man-induced. Temperatures in reef flat pools and lagoon areas are often several degrees above normal oceanic and, during periods of low tide and intense solar radiation, may exceed 36.0°C. Other sources of increased water temperature on tropical reefs are steam generating stations which use seawater for condenser cooling and often discharge the effluent directly onto the reef. Discharge water may reach temperatures as high as 35.0 to 36.0°C.

Because echinoderms constitute a large segment of the fringing reef fauna and would likely be affected by major changes in ambient water temperature, a study was designed to determine: if fertilization success (defined as the formation of the fertilization membrane) at select temperatures above normal is significantly reduced from that at normal ambient temperature; if normal cell cleavage at select temperatures above normal is significantly reduced from that at normal ambient temperature; which is more sensitive to increased temperature, fertilization or early cleavage; and how long gametes and zygotes can be exposed to temperatures above normal, without inhibiting further embryonic development.

The effects of temperature on development of temperate echinoderm species has been studied by numerous workers including Tyler[3], Farmanfarmaian and Giese[1], and Andronikov[4], but there is little information regarding the effects of temperature on the early development of tropical echinoderms. Because so little information is available, this study was conducted in two phases. In the first phase, preliminary information was collected on the effects of temperature on fertilization and early cleavage of tropical echinoderms in general. Species tested in phase one was Acanthaster planci (L.), Culcita novaeguineae Muller and Troschel, and Linckia laevigata (L.) from the class Asteroideae, and Echinometra mathaei (de Blainville) and Diadema savignyi Michelin from the class Echinoideae. Phase one also served to select an experimentally suitable species for more intensive study and to test the experimental apparatus and design.

In phase two, E. mathaei was selected for additional experimentation to answer questions set forth in the objectives.

Phase one was conducted from May to September, 1972, and phase two from September through November, 1972. Experiments were conducted at the University of Guam Marine Laboratory.

MATERIALS AND METHODS

Live specimens of adult asteroids A. planci, C. novaeguineae, and L. laevigata were collected from the fringing reefs of Guam. Adult echinoids D. savignyi and E. mathaei were collected from the intake channels of steam electric generating stations at Tanguisson Point, and Cabras Island, Guam.

Since the spawning periodicity of these animals was unknown, it was often difficult to obtain ripe individuals. Ripe adult males of C. novaeguineae were rarely found between May and September, 1972, and although eggs were easily obtained, sperm were released in sufficient quantity on only two occasions. Ripe adult D. savignyi were found only during late July, 1972.

It was necessary to transport asteroids in individual containers with frequent changes of fresh seawater, because slight increases in water temperature and vibration often caused spawning during transportation and because separate containers prevented individuals which spawned in transit from stimulating spawning in others.

Echinoids were transported in common containers, each carrying three to ten specimens. Handling and transportation did not normally cause spawning of ripe individuals.

In the laboratory, individual adult asteroids were kept in containers (14 X 36 cm dia.) of fresh seawater. Spawning was induced by injecting a solution of 10^{-5} M 1-methyladenine (Kanatani[5]). Three to five ml were injected, depending on the size of the organism. Ova were collected by pipette from the stream of spawning ova and put in a 400 ml beaker of 28.0°C fresh seawater. Once the ova settled, they were rinsed by decanting and refilling the beaker with fresh seawater. To avoid possible negative effects of overcrowding, ova were concentrated to a density less than one layer thick. Asteroid sperm samples were collected by pipette as they were released from the gonopore. These samples were held in clean glass beakers until experiments began.

Adult echinoids held at 28.0°C were removed from the water and induced to spawn by injecting approximately 1 ml of 0.5 M KCl solution (Tyler[6]).

After injection, the animals were rinsed with fresh seawater. Females were inverted over 250 ml beakers of fresh seawater at 28.0°C and the ova collected and concentrated as noted above. Males were inverted over a watch glass and "dry," undiluted sperm (Kobayashi et al[7]) were collected on the surface. Occasionally, "dry" sperm were pipetted directly from the gonopore.

Four temperature baths set to maintain 28.0 (control), 31.0, 34.0, and 36.0, ± 0.2°C, were made from 30 liter aquaria equipped with 100 watt immersion heaters and thermostatic controls (Fig. 1). The aquaria were filled with fresh tap water. To insure uniform temperature throughout, the water was circulated with two air lifts (flow rate 1.4 liters per minute) driven by an air pump. Plexiglass racks, each holding twelve 40 ml glass vials (experimental chambers), were submerged in the temperature baths (Fig. 1).

In each experiment, the control group (28.0°C) was used to establish normality criteria against which comparisons were made. Success of fertilization and early cleavage was determined by microscopic examination and calculated as the percent of ova with fertilization membranes or percent of zygotes showing normal cleavage, of the total within a 2 mm microscope field (magnification 10X). Statistical analyses follow procedures outlined by Sokal and Rohlf[8]. Statistical significance was accepted at $P \leq 0.01$.

RESULTS

Phase I: Survey of Species

Effects of Temperature on Fertilization -- To test the effects of select temperatures above 28.0°C (normal ambient) on fertilization, 3 ml aliquots, containing between 1,000 and 2,000 ova and 1 ml of sperm (ca. 0.05 ml "dry" sperm per 50 ml seawater) were added simultaneously with automatic pipettes to the experimental chambers. Each chamber contained fresh seawater maintained at the four experimental temperatures. After approximately five minutes (two to four minutes was found to be sufficient for fertilization membranes to form in all species tested), 10-15 ml of a three percent formalin solution were added to the chambers to fix activity. Three to five replicate samples were aliquoted by pipette from each experimental chamber within each temperature treatment, and percent success of fertilization was determined.

The results of these experiments are summarized in Table 1 and show that, for all five species tested, a temperature treatment of 31.0°C had no apparent effect on the mean percent of fertilization success when compared to the mean at the control temperature (28.0°C). At

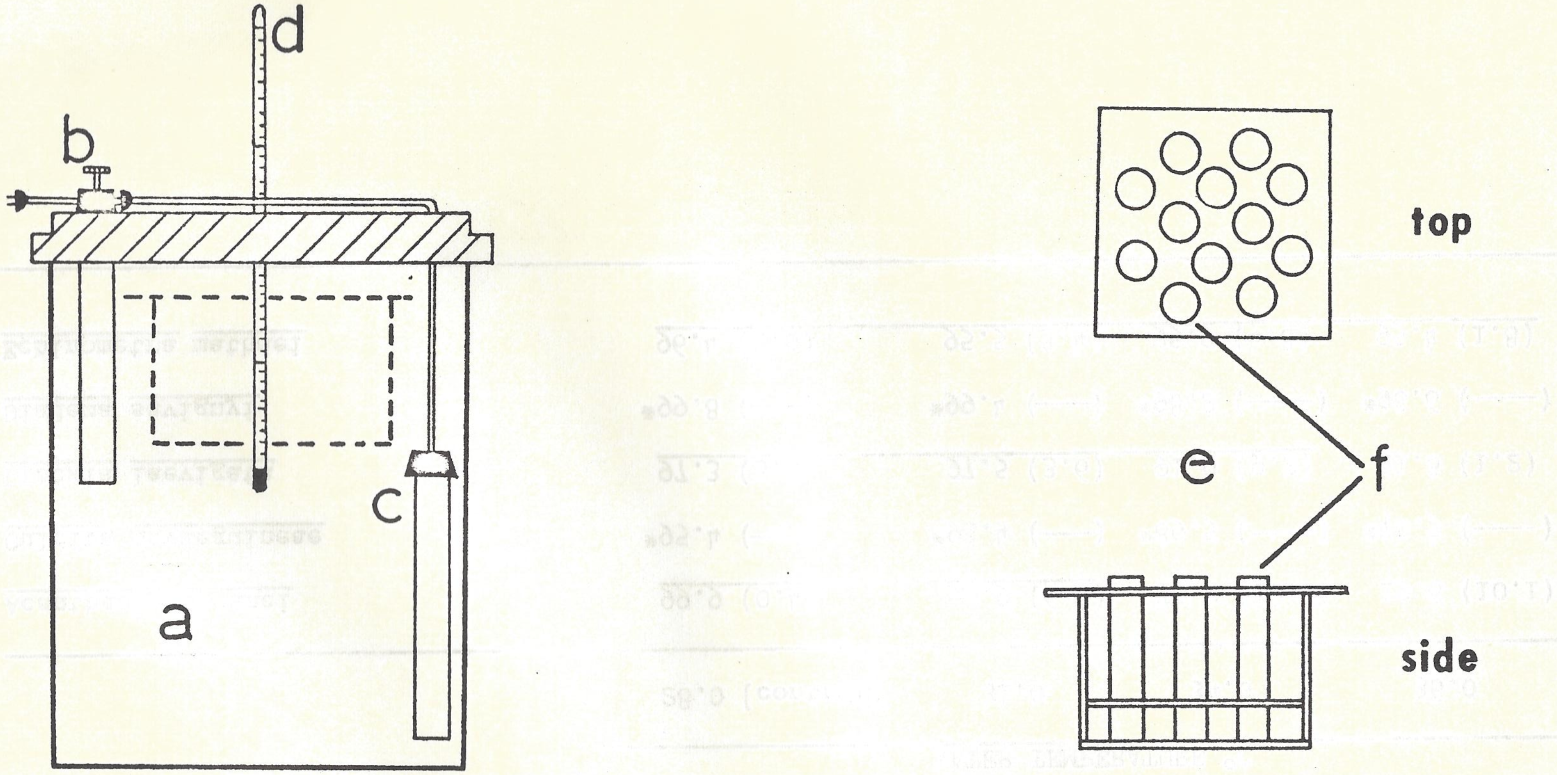

Figure 1. Constant temperature bath. (a) 30 ℓ aquarium, (b) thermostat, (c) 100 watt heater, (d) thermometer, (e) rack for experimental chambers, (f) experimental chambers (40 ml glass vials).

Table 1. The effects of temperature on fertilization success among select echinoderms expressed as the mean percent of ova showing fertilization membranes. Parentheses enclose two standard errors of the mean. n = 3 except, where asterisk appears n = 1. Means statistically homogeneous ($P \leq .01$) with the control mean are underscored by a horizontal line.

	WATER TEMPERATURE °C			
	28.0 [control]	31.0	34.0	36.0
Acanthaster planci	99.9 (0.4)	90.9 (6.8)	70.2 (10.8)	19.8 (10.1)
Culcita novaeguineae	*95.4 (——)	*93.4 (——)	*89.5 (——)	*70.5 (——)
Linckia laevigata	97.3 (3.6)	97.5 (3.6)	91.0 (9.2)	21.8 (1.2)
Diadema savignyi	*99.8 (——)	*99.4 (——)	*98.2 (——)	*98.6 (——)
Echinometra mathaei	96.4 (2.0)	95.5 (3.4)	95.9 (4.8)	95.4 (1.8)

34.0°C a statistically significant effect was noted only for A. planci. At 36.0°C the mean percent of fertilization success in both A. planci and L. laevigata was significantly different from the control. Although the mean percent of fertilization in C. novaeguineae at 36.0°C was 25 percent below the mean at the control temperature, inadequate sample size precluded drawing statistical conclusions. Fertilization success in D. savignyi appeared to be unaffected by temperature treatments, but again, inadequate sample size precluded drawing statistical conclusions. A temperature treatment of 36.0°C showed no statistically significant effect on the mean percent of fertilization success in E. mathaei

Effects of Temperature on Early Cleavage -- To test the effects of select temperatures above normal ambient on development to the four cell stage, fertilization was first induced at normal ambient temperature (28.0°C). After fertilization membranes appeared, within five minutes, 3 ml aliquots containing between 1,000 and 2,000 zygotes were added with automatic pipettes to experimental chambers containing fresh seawater maintained at the experimental temperatures. Development at each temperature was monitored microscopically with samples taken from separate monitoring vials. When fifty percent of the zygotes reached the four cell stage, development was fixed by adding a three percent formalin solution. Three to five replicate samples were obtained by the same procedure outlined for the fertilization experiment. Development to the four cell stage as it proceeded at 28.0°C was accepted as the norm for comparative purposes.

For all five species tested, the effects of 31.0°C on normal four cell development were indistinguishable from the control (Table 2). When comparing the results at the control temperature (28.0°C) with 34.0°C, a statistically significant effect was noted in all species except E. mathaei. At 36.0°C, development to the four cell stage was significantly reduced in all species. The occasional embryo reaching the four cell stage at this temperature was generally deformed and ceased to develop further.

Phase II: Echinometra mathaei

Despite the preliminary findings that E. mathaei was the most thermally resistant of the species tested, it was still considered the best experimental prospect of the group for carrying out the objectives of the study. It would represent the high end of the thermal resistance scale and might act as a general indicator of effects expected on less resistant species. Additionally, the species was readily available and ripe throughout the study period.

Table 2. The effects of temperature on the success of early cleavage in select echinoderms expressed as the percent of zygotes undergoing normal cell cleavage to the four cell stage. Parentheses enclosed two standard errors of the mean. $n = 3$ except, where asterisk appears $n = 2$. Means statistically homogeneous ($P \leq .01$) with the control mean are underscored by a horizontal line.

	WATER TEMPERATURE °C			
	28.0 [control]	31.0	34.0	36.0
Acanthaster planci	97.5 (2.2)	96.6 (3.0)	35.2 (20.4)	0 (0)
Culcita novaeguineae	96.6 (5.6)	97.6 (4.0)	51.1 (10.2)	0.6 (0.2)
Linckia laevigata	97.9 (2.4)	94.0 (3.8)	30.2 (18.0)	0 (0)
Diadema savignyi	*96.6 (0.1)	*95.4 (3.4)	*26.8 (19.8)	*1.2 (1.2)
Echinometra mathaei	98.3 (0.8)	97.1 (2.2)	92.4 (6.4)	5.4 (8.4)

Effects of Temperature on Fertilization and Early Cleavage -- The results of the fertilization experiments are presented in Table 3 and confirm the preliminary observations of phase one. Temperature treatments of 31.0, and 36.0°C had no significant effect on the mean percent of fertilization success when compared to the mean success at the control temperature (28.0°C).

The results of the cleavage experiments also confirm the results of phase one (Table 3). Temperature treatments of 31.0 and 34.0°C had no significant effect on the mean percent of cleavage success when compared to the mean success at the control temperature (28.0°C). At 36.0°C the mean percent cleavage success was significantly different from the control (28.0°C). Only a small percentage of zygotes were found to undergo cleavage at 36.0°C and these became deformed and died after a few hours.

During two of the experiments, development of the zygotes was followed to the pluteus stage (48 hours) under thermal stress. Normal development and swimming activity was observed in approximately 100 percent of those at 31.0 and 34.0°C. As noted above, zygotes at 36.0°C did not survive beyond a few hours.

Effects of Exposing Spermatozoa to 36.0°C -- After establishing that continuous exposure to 36.0°C significantly reduced development to the four cell stage, spermatozoa were tested at this temperature to determine the exposure time required for loss of motility in 100 percent of the cells. Three ml aliquots of spermatozoa, at the same concentration as the fertilization experiments, were added with automatic pipettes to a series of twelve vials of fresh seawater, maintained at 36.0°C. The twelve vials were sampled in rotation every ten minutes until 100 percent of the spermatozoa in a 2 mm microscope field (10X) had lost motility.

At the normal ambient temperature of 28.0°C (control), 100 percent of sperm cells had lost motility after 60 minutes (Fig. 2). At 36.0°C approximately 90 percent of the sperm cells had lost motility after 60 minutes. A few isolated cells remained active after 70 minutes. Eighty minutes was required for loss of motility in 100 percent of the cells. No explanation is readily available for this observation.

Effects of Exposing Unfertilized Ova to 36.0°C -- Unfertilized ova were tested at 36.0°C to determine the exposure time beyond which normal cleavage would be significantly reduced. Three ml aliquots containing between 1,000 and 2,000 ova were added with automatic pipettes to experimental chambers of fresh seawater maintained at 36.0°C. Ova were exposed to 36.0°C for periods ranging from 1 to 6 hours. Following

Table 3. The effects of temperature on the mean percent success of fertilization (A) and early cleavage (B) of _Echinometra mathaei_. Parentheses enclose two standard errors of the mean. Means statistically homogeneous ($P \leq .01$) with the control mean are underscored by a horizontal line.

	WATER TEMPERATURE °C			
	28.0 [control]	31.0	34.0	36.0
A. Percent Fertilized	99.8 (0.2) n = 18	99.5 (0.4) n = 18	99.5 (0.6) n = 18	97.7 (0.4) n = 25
B. Percent Normal Early Cleavage	99.5 (0.6) n = 20	99.4 (0.4) n = 20	98.9 (0.6) n = 20	3.5 (1.0) n = 20

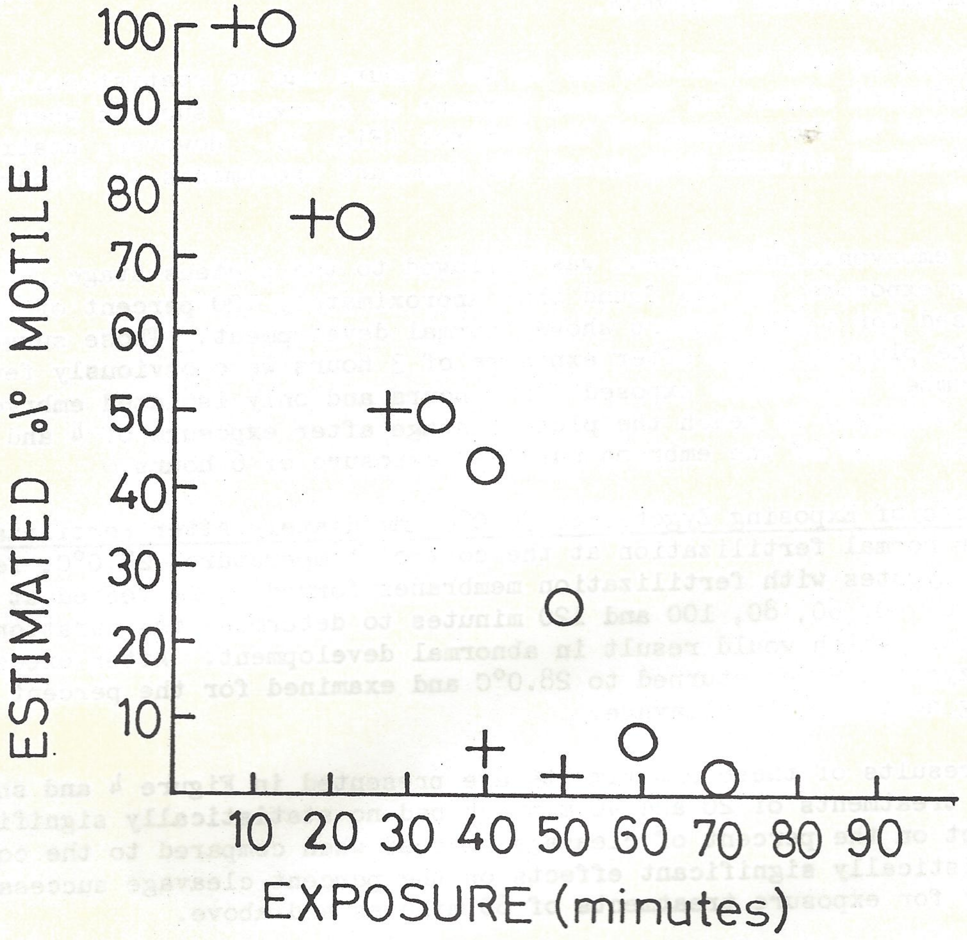

Figure 2. The estimated percent of motile *Echinometra mathaei* spermatozoa as a function of exposure time to 28.0° C (+) and 36.0° C (o).

exposure, each experimental chamber was returned to 28.0°C (control) and the ova fertilized with fresh sperm. After one hour (ca. 55 minutes was normally required for first cleavage at 28.0°C) each experimental chamber was sampled to determine the percent of zygotes displaying normal cleavage.

Exposure of ova to 36.0°C for up to 2 hours had no statistically significant effect on the mean percent of cleavage success when compared to the success of the control (Fig. 3). However, statistically significant effects were noted for exposure treatments of 3 hours and above.

When embryonic development was followed to the pluteus stage, 48 hours after exposure, it was found that approximately 100 percent of those exposed for 1 and 2 hours showed normal development. Those surviving to the pluteus stage after exposure of 3 hours were obviously fewer in number than those exposed for 2 hours and only isolated embryos were observed to reach the pluteus stage after exposure of 4 and 5 hours. None of the embryos survived exposure of 6 hours.

<u>Effects of Exposing Zygotes to 36.0°C Immediately After Fertilization</u> -- After normal fertilization at the control temperature, 28.0°C, fertilized ova (zygotes with fertilization membranes formed) were tested at 36.0°C for 20, 40, 60, 80, 100 and 120 minutes to determine the duration of exposure which would result in abnormal development. After exposure, the zygotes were returned to 28.0°C and examined for the percent undergoing normal early cleavage.

The results of these experiments are presented in Figure 4 and show that treatments of 20 and 40 minutes had no statistically significant effect on the percent of cleavage success when compared to the control. Statistically significant effects on the percent cleavage success were noted for exposure treatments of 60 minutes and above.

When embryos developed to the pluteus stage (48 hours after exposure) it was found that approximately 100 percent of those exposed for 20, 40 and 60 minutes developed normally. However, few zygotes survived to the pluteus stage after exposure of 80 and 100 minutes, and none survived exposure of 120 minutes.

<u>Effects of Exposing Zygotes to 36.0°C at First Cleavage</u> -- Zygotes at the two cell stage were tested at 36.0°C to determine the time required to inhibit normal development. Ova were fertilized and allowed to develop to the two cell stage at the control temperature, 28.0°C. Three ml aliquots containing between 1,000 and 2,000 zygotes, were added with automatic pipettes to the experimental chambers of fresh

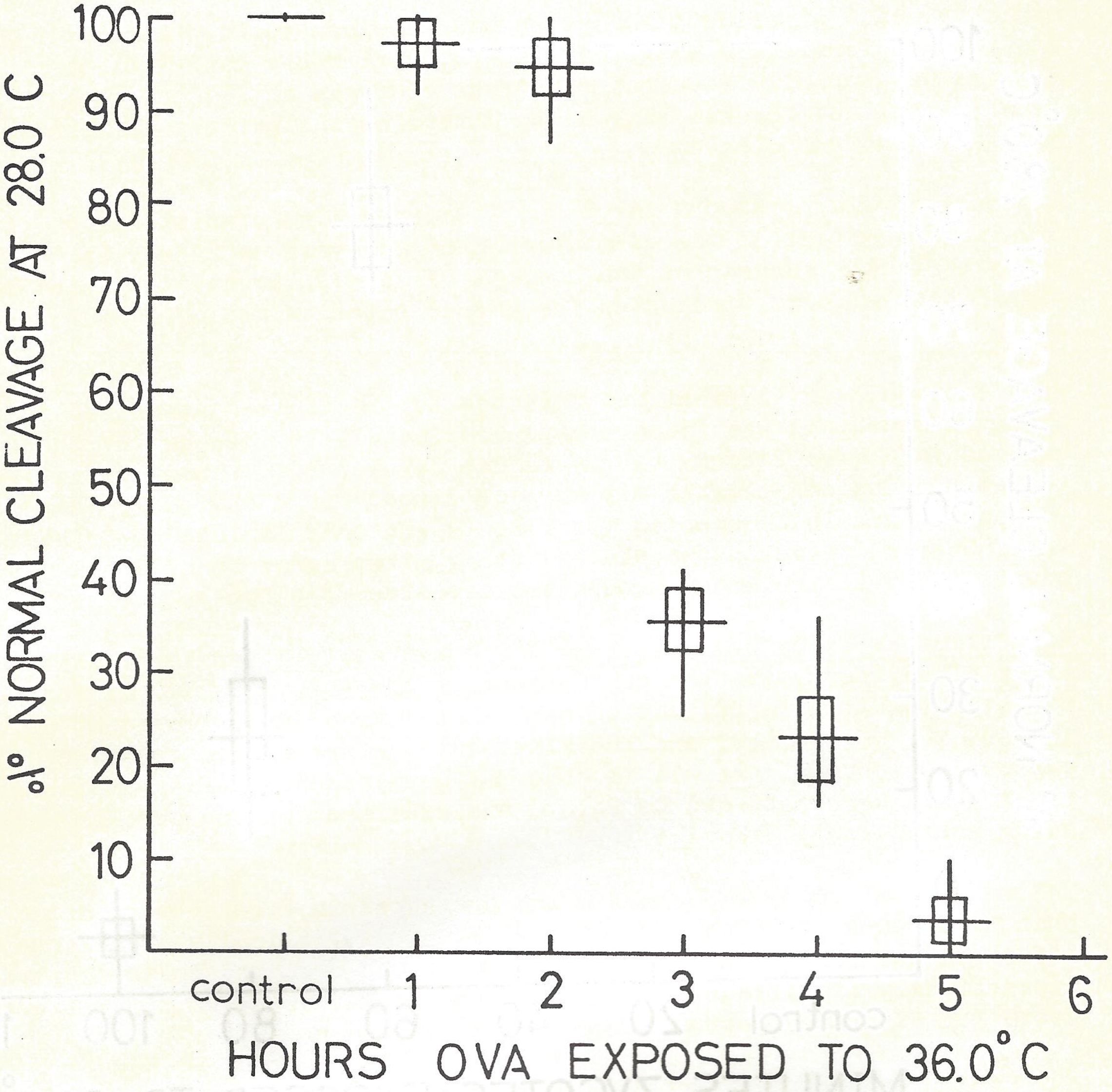

Figure 3. Percent of Echinometra mathaei zygotes undergoing normal early cleavage at 28.0° C, after exposure to 36.0° C for varying times before fertilization. Vertical line represents range; white bar, two standard errors; and the horizontal line, the mean. n = 9

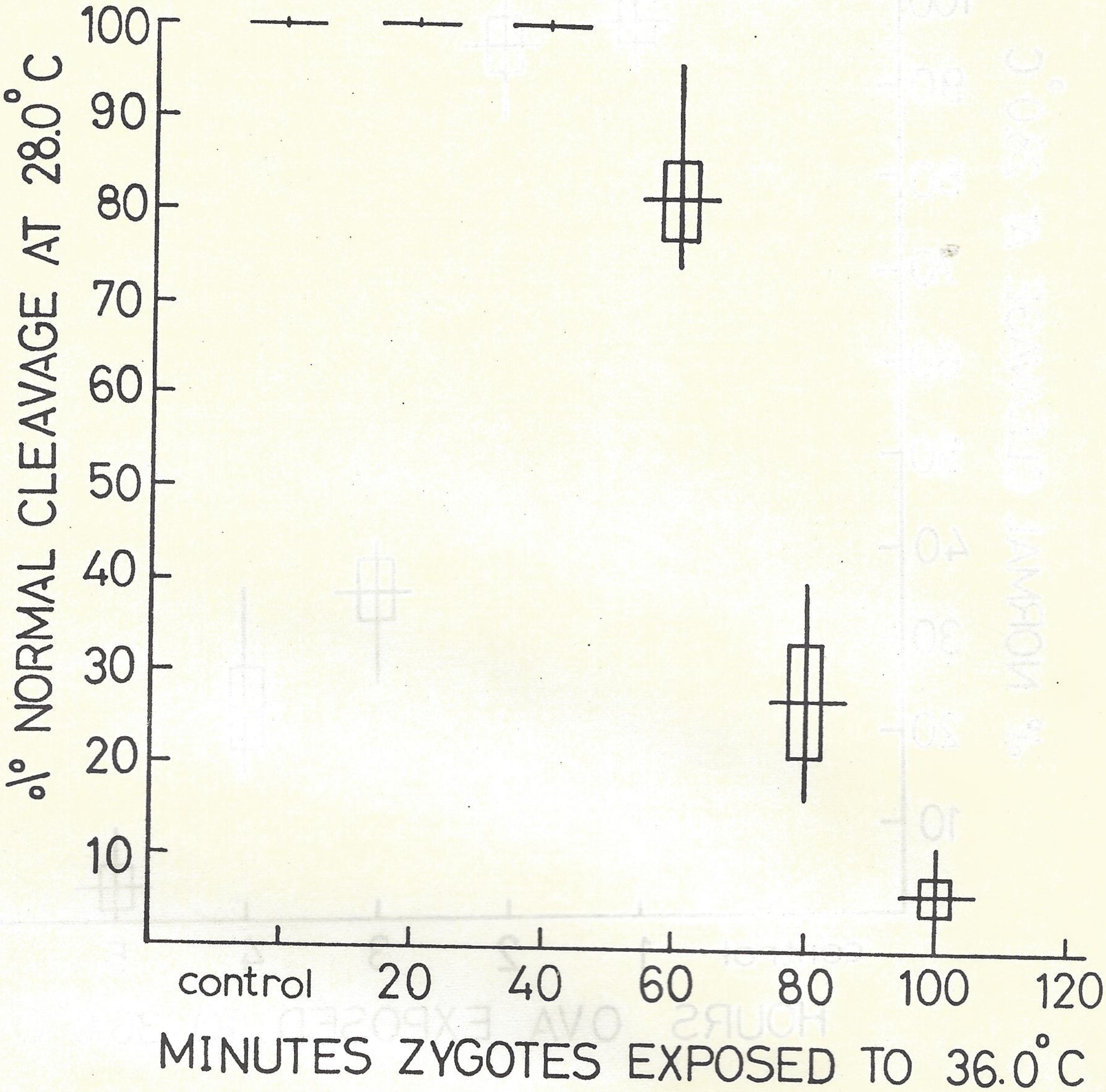

Figure 4. Percent of Echinometra mathaei zygotes undergoing normal early cleavage at 28.0° C, after exposure to 36.0° C for varying times immediately after fertilization. Vertical line represents range; white bar, two standard errors; and the horizontal line, the mean. n = 9

seawater maintained at 36.0°C. Zygotes were exposed for 20, 40, 60, 80, 100, 120 and 140 minutes. After exposure each vial was returned to 28.0°C (control) and after 15 minutes sampled to determine the percent of zygotes displaying normal cleavage.

Exposure treatments of 20 and 40 minutes had no statistically significant effect on the percent of cleavage success when compared to the control (Fig. 5). Statistically significant effects on the percent cleavage success were noted for exposure treatments of 60 minutes and above.

When embryos developed to the pluteus stage (48 hours after exposure) approximately 100 percent of those exposed for 20 and 40 minutes developed normally. However, exposure for 60, 80 and 100 minutes resulted in an obvious reduction of the number surviving and none survived exposure of 120 and 140 minutes.

CONCLUSIONS

Preliminary information from the first phase of this work indicates that fertilization success in A. planci was reduced at 34.0°C, whereas in C. novaeguineae, L. laevigata, D. savignyi and E. mathaei it was unaffected. At 36.0°C, fertilization in C. novaeguineae and L. laevigata appeared to be reduced, but in D. savignyi and E. mathaei it remained unaffected.

Cell cleavage was reduced at 34.0°C in all species except E. mathaei which did not show a reduction in early cleavage until 36.0°C, 8°C above normal. Farmanfarmaian and Giese[1] found similar results with the temperate sea urchin Strongylocentrotus purpuratus. They showed that at 25.0°C, 8°C above ambient range, fertilization membranes developed, but division of the fertilized eggs was abnormal and essentially "nil." Tyler[3] has also shown this to be true at 25.0°C for another temperate urchin from the same locality, Dendraster excentricus.

These preliminary results suggest that early cleavage is more sensitive to increased temperature than fertilization for each species tested except A. planci in which both processes appear to be inhibited at 34.0°C.

Although development is inhibited in E. mathaei by continuous exposure at 36.0°C, it was found that both gametes and zygotes of this species are resistant to this temperature for short periods. Unfertilized ova are able to withstand exposure to 36.0°C for up to two hours, but when exposed for three hours and then fertilized at normal temperature, the percent of zygotes undergoing normal cleavage is significantly reduced.

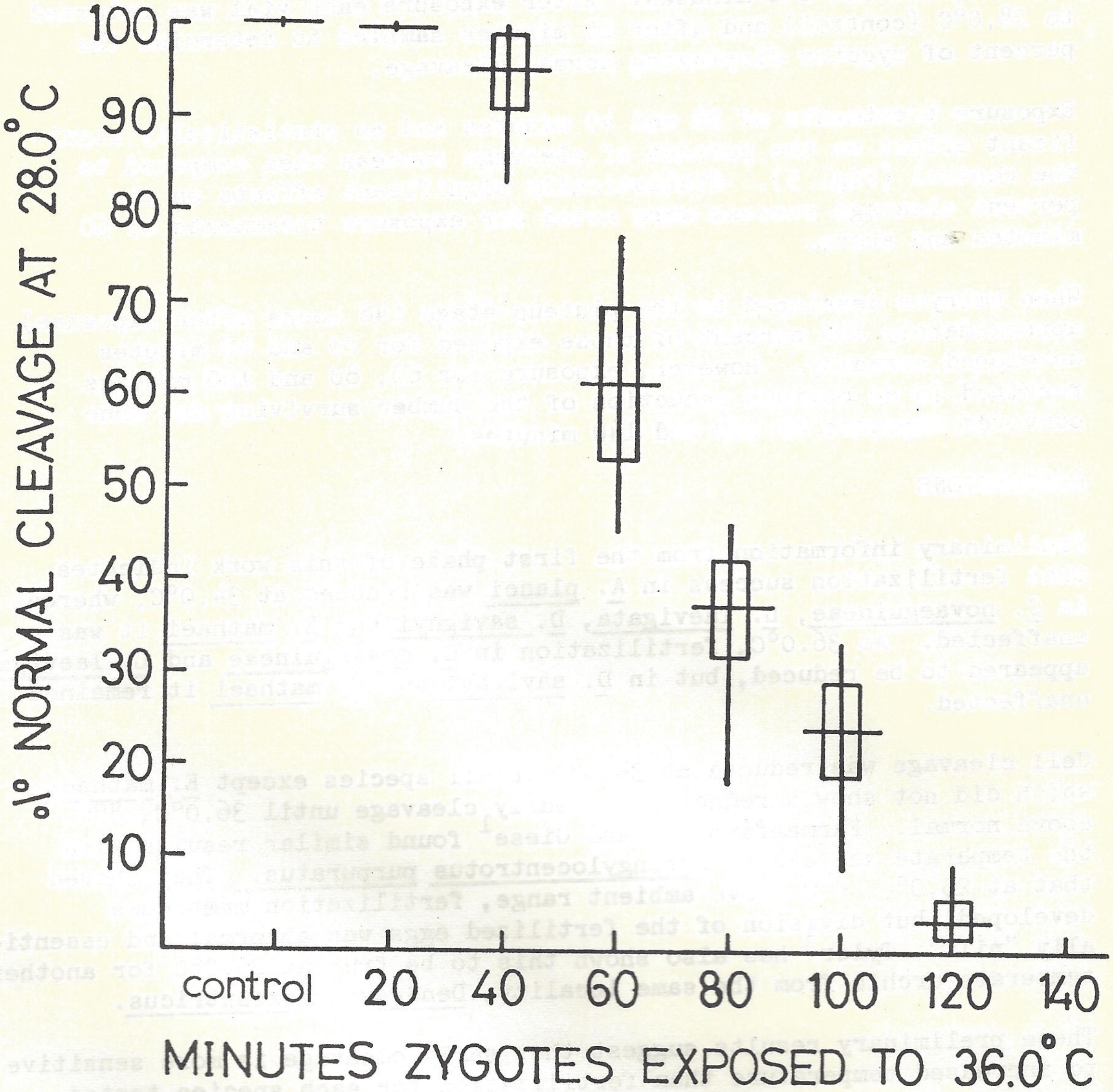

Figure 5. Percent of Echinometra mathaei zygotes undergoing normal early cleavage at 28.0° C, after exposure to 36.0° C for varying times at first cleavage stage. Vertical line represents range; white bar, two standard errors; and the horizontal line, the mean. n = 9

Ova with fertilization membranes and zygotes at first cleavage were unaffected by exposures of 40 minutes or less, but showed a significant reduction in normal cleavage after one hour. The difference in duration of thermal resistance between unfertilized ova and zygotes suggests that activation of the ova by fertilization might render them somewhat less thermally resistant.

In any case, the ability of the early developmental stages of E. mathaei to withstand extreme temperature elevation for at least short exposure periods would presumably have survival value. For example, resistance for short periods might protect ova and zygotes from elevated temperatures brought about by a mid-day low tide, until relieved by the cooling water of the next flood tide. This, of course, would not be the case for reef environments adjacent to power plants. The continuous operation of these facilities would ensure a virtually constant thermal stress on the organisms and would effectively mask the flushing action of the tide cycle.

In summary, these data point to an upper thermal tolerance limit between 34.0°C and 36.0°C for early embryonic development of these species. The exact temperature affecting fertilization and cleavage may vary somewhat in a species specific manner and needs further investigation.

The critical temperatures are probably correlated with the environmental temperature conditions to which each species is exposed. For example, fertilization and cleavage in A. planci, which usually inhabits deeper water with little diurnal temperature variation, appears to be significantly inhibited at 34.0°C, whereas fertilization and cleavage in E. mathaei, which often inhabits shallower water with broad temperature variations, is unaffected at 34.0°C.

The fact that E. mathaei appears to be a thermally resistant species in terms of its early embryonic development may therefore be a factor in its broad distribution on the coral reef.

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APPENDIX C

THERMAL STRESS IN CAULERPA RACEMOSA (FORSSK.) J. AG. AS MEASURED BY THE OXYGEN TECHNIQUE

by

Thomas C. Hohman and Roy T. Tsuda

INTRODUCTION

Numerous studies (see Biebl[1]) have been carried out on thermal tolerance in marine algae. The majority of these studies have focused on temperate algal species, and deal with tolerance limits and the optimum temperatures at which these species can survive. While these reports indicate that the majority of species studied are characteristically found growing within a specific temperature range, and rarely survive temperatures outside of this range, little quantitative data have been presented to demonstrate the metabolic changes of algae within this range.

Recently, Yokohama[2] reported on the photosynthesis-temperature relationship in several marine algae from Shimoda, Japan, which has a seasonal seawater temperature fluctuation between 13° and 24°C. He provides quantitative photosynthetic and respiration values for several algal species at various temperature points within their thermal tolerance range. The results of these experiments agreed favorably with the results expected when an enzyme system is viewed in terms of the "rate of reaction theory." However, the situation on coral reefs is considerably different since the yearly temperature fluctuation is small and the marine algae are already living very close to their upper temperature tolerance in the natural environment (Mayer[3]).

The purpose of this paper is to determine the effects of temperatures within the tolerance range on plant photosynthesis and respiration, and to explore the method of quantifying thermal stress in marine algae by using the net photosynthesis respiration ratio (P/R ratio) as an indicator. At ambient temperature when the light intensity is above saturation level, the P/R ratio is expected to be above 1. Any significant decrease in the P/R ratio at temperatures higher than ambient during the light hours may be interpreted as an indication of metabolic stress. If the P/R ratio is 1, the algae are still capable of surviving. However, if the P/R ratio is less than 1, the algae, although still alive, cannot theoretically survive for any length of time unless heterotrophy is taking place.

MATERIALS AND METHODS

Caulerpa racemosa (Forssk.) J. Ag., a green siphonaceous alga commonly found on reef flats, was chosen as our experimental alga because considerable information has been gathered on its photosynthetic periodicity (Hohman[4]) and its ecological response to different light intensities (Peterson[5]). In addition, this alga is accustomed to periodic exposure at low tides and seems better adapted to tolerate temperature extremes than algae inhabiting the subtidal zone.

In this preliminary study, three experiments were run which differed only in the duration at which the algae were held in their respective temperature baths - experiment 1, 12 hours; experiment 2, 2 hours; and experiment 3,0 hours.

Specimens of Caulerpa racemosa of comparable size and age were collected from the same field population and taken to the laboratory where all visible epiphytes were removed. Five specimens were held in each of the four separate temperature baths which were supplied with fresh flowing seawater and exposed to natural illumination (ca. 10,000 f.c.). The baths differed only in the temperature of the water - bath 1 (ambient temperature of 28 to 29°C), bath 2 (ambient plus 2°C), bath 3 (ambient plus 4°C), and bath 4 (ambient plus 6°C).

One hour before incubation, four light bottles and three dark bottles (435 ml capacity) were filled with previously vacuumed filtered seawater of known oxygen concentration and were placed in each bath to be temperature equilibrated. Vacuum filtered seawater at a pressure of 8 mm of mercury decreased oxygen concentration by 20%.

Algae were then placed into three of the light bottles and two of the dark bottles. The remaining two bottles without algae were used as controls. The algae were incubated for 30 minutes at the same time each day, i.e., 1200 to 1230, to negate differences caused by photosynthetic periodicity. Prior experiments (Hohman[4]) with incubation periods of 15, 30, 45, and 60 minutes showed that a 30-minute incubation was sufficient to observe noticeable changes in oxygen concentration without demonstrating a bottle effect.

At the end of the incubation period, the water was siphoned into 300 ml BOD bottles for oxygen determination and measured using the azide modification of the Winkler technique APHA[6]). Replicate titrations were run and differed by less than 0.5%. Rates of net photosynthesis, respiration, and P/R ratios were calculated for the algae in each bath.

At the completion of the experiments, the algae were place in pre-weighed containers, stored in a drying oven at 105°C for 24 hours, and weighed to the nearest .001 gram. These values were then used to correct differences in the biomass of each alga; thus, final values for net photosynthesis and respiration are expressed as mg O_2 per gram dry weight per hour.

RESULTS AND DISCUSSION

The results of the three experiments (Fig. 1) agree closely. The highest rate in net photosynthesis in each of the experiments occurs at 28° (ambient). At temperatures above 28°C, the photosynthetic rates decrease

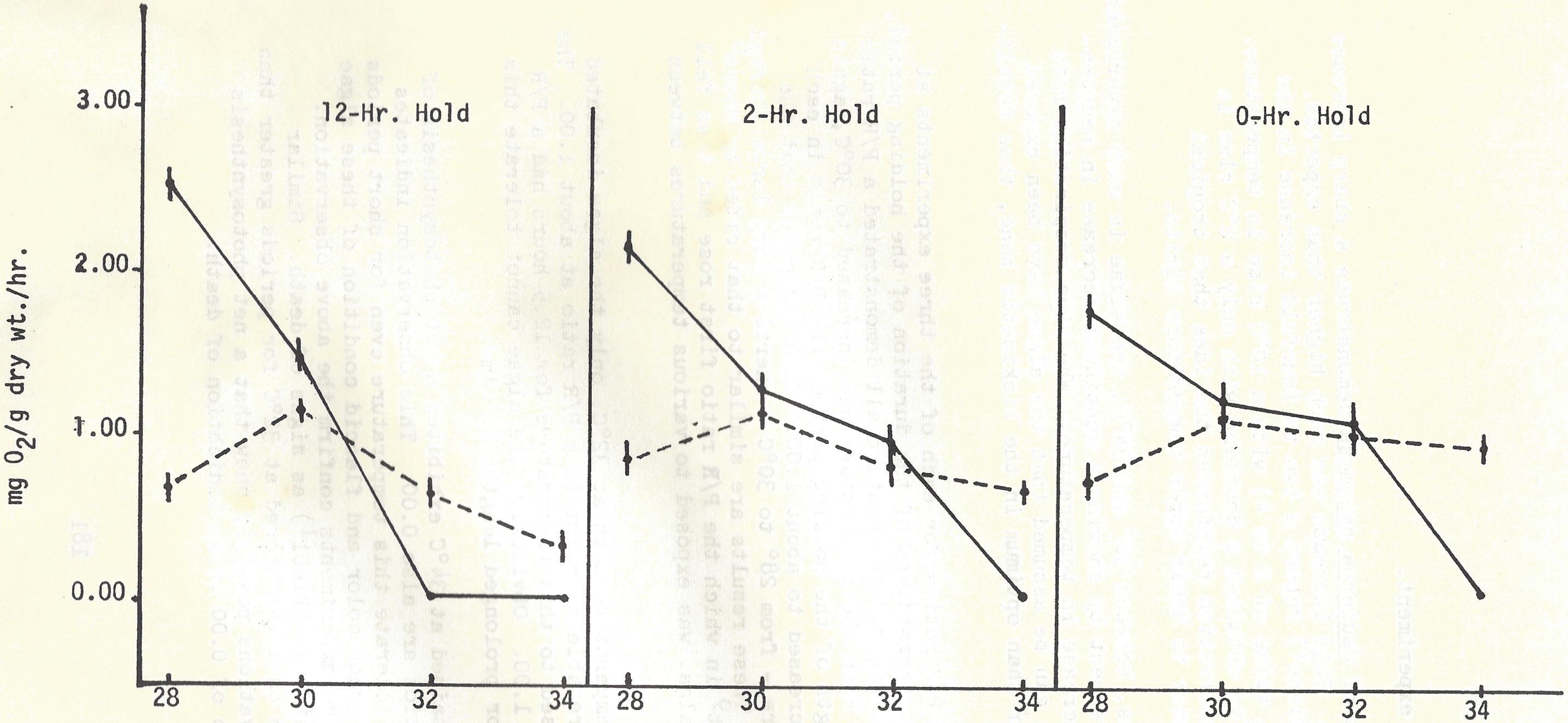

Fig. 1. Net photosynthesis (————) and respiration (--------) values, ±1 S.D. from the mean, at four temperatures.

continuously in each experiment.

The respiration rates of Caulerpa racemosa demonstrate a sharp increase between 28° and 30°C. This increase was much higher than expected. Most investigators (Giese[7]) report a two to fourfold increase in the respiration rate (Q_{10} value of 2 to 4) with a 10°C rise in temperature. In these experiments we obtained a doubling with only a 2°C rise in temperature. This observation reinforces the idea that tropical organisms do live closer to their upper temperature limits.

At higher temperatures, between 30° and 34°C, the algae in each experiment again demonstrate agreement by showing a continual decrease in respiration rates with an increase in temperature. When the respiration rate begins to decline, it can be assumed that the algae have been exposed to temperatures higher than optimum in the biokinetic zone, thus resulting in injury.

Figure 2 presents the P/R ratios for each of the three experiments at the four temperatures. Regardless of the duration of the holding period, the algae incubated at ambient temperature all demonstrated a P/R ratio much greater than 1. When the temperature was increased to 30°C, again regardless of the length of the holding period, the P/R ratio in each of the experiments decreased to about 1.00. This indicates that the 2°C rise in temperature - from 28° to 30°C - exerts a very large thermal stress on the algae. These results are similar to that cited by Moore[8] in a study by Montfort[9] in which the P/R ratio first rose and then fell when Porphyra, a red alga, was exposed to various temperatures between 5° and 21°C.

In the experimental temperature bath at 32°C, only the algae incubated for short duration were able to maintain a P/R ratio at about 1.00. The algae which were exposed to this temperature for 12.5 hours had a P/R ratio much lower than 1.00. Obviously, the algae cannot tolerate this temperature extreme for prolonged lengths of time.

All of the algae maintained at 34°C exhibited a net photosynthesis of 0.00; thus the P/R ratios are also 0.00. This observation indicates that the algae cannot tolerate this temperature even for short periods of time. The lighter green color and flaccid condition of these algae at the completion of the experiments confirm the above observation. These changes are considered (Biebl[1]) as signs of death. Similar observations were made on algae stored at 32°C for periods greater than two hours. The observations possibly show that a net photosynthesis of 0.00 or a P/R ratio of 0.00 is an indication of death.

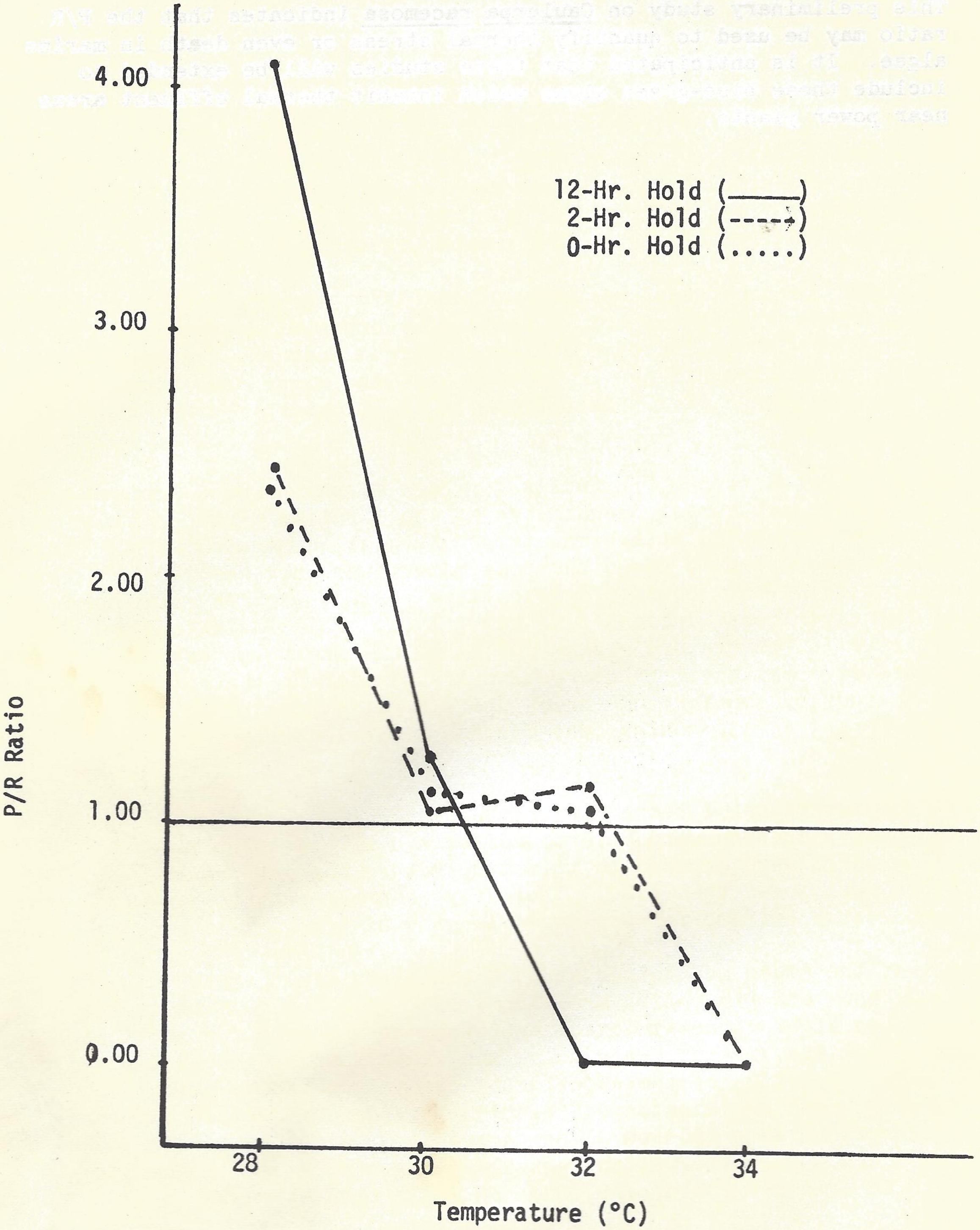

Fig. 2. Net photosynthesis/respiration ratio at four different temperatures obtained in the three experiments.

This preliminary study on <u>Caulerpa racemosa</u> indicates that the P/R ratio may be used to quantify thermal stress or even death in marine algae. It is anticipated that these studies will be extended to include those blue-green algae which inhabit thermal effluent areas near power plants.

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