Chapter 6

DEVELOPMENT AND USES OF FACILITIES FOR STUDYING TUNA BEHAVIOR

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I. INTRODUCTION

Tunas are pelagic fishes of several genera† belonging to the family Scombridae. They are fished commercially and recreationally in the temperate and tropical seas of the world. Sizes of adult tunas range from less than a kilogram (e.g., *Auxis rochei*) to over 400 kg (e.g., *Thunnus thynnus*).

Accumulation of knowledge on the behavior of tunas was slow and haphazard before the 1950s, but has accelerated since then. In 1951, the HL (Bureau of Commercial Fisheries Biological Laboratory in Honolulu, Hawaii), known then as the Pacific Oceanic Fishery Investigations, contracted with researchers at the University of Hawaii to undertake studies of the behavioral responses of tunas to assorted stimuli. These experiments required the establishment of tunas in captivity. This feat was successfully accomplished for the first time in 1951. In the following years, techniques and methods for capturing and maintaining tunas in captivity were improved, and tanks were constructed especially for studying tuna behavior. In the mid-1950s, development of facilities to observe tunas underwater at sea was started. Significant advances in studies of tuna behavior have been made owing to observations and experiments made at sea and ashore with these facilities.

Reviews of tuna behavior have been made by several authors. Tester

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† Species of the following genera have been included as tunas in this paper: *Thunnus*, *Euthynnus*, *Katsuwonus*, *Auxis*, and *Sarda*.

(1959) summarized the studies he and his colleagues conducted from 1951 through 1956 on the responses of tunas to stimuli. Magnuson (1963) reviewed the literature on tuna behavior and physiology. Behavioral studies that were being conducted at HL were described by Magnuson (1964*b*). A popularized account of the work at HL was given by Manar (1965). Nakamura (1969*a*) has summarized observations on tuna behavior made at sea.

The purpose of this chapter is to present a history of the development of the techniques and facilities for studying tuna behavior, a statement of the problems and questions that prompted their development, and an account of the uses to which they were put. Most of the facilities and methods were developed at HL.

II. OBSERVATIONS AND RESEARCH AT SEA

Observations of tuna behavior at sea before 1957 were made only when opportunity afforded, usually from the deck of a boat—particularly boats used in fishing for tunas by pole and line. In this method, tunas are attracted to the boat by throwing overboard live bait, which is kept aboard in bait-wells. The tunas are then caught with pole and line (Yoshida, 1966). Various aspects of feeding, schooling, swimming, reactions to stimuli, behavior in relation to environmental features, and associations with other organisms and objects have been learned by observing from the decks of boats (Nakamura, 1969*a*).

The need to learn more about tuna behavior by observing tunas in their own environment became more and more apparent to biologists at HL in the early 1950s. Answers to such questions as the effectiveness of various species of bait, the possibility of controlling tuna behavior by manipulating fishing conditions, reactions elicited in tunas by actions of the bait, the efficacy of gear, the necessity for live bait, were difficult to obtain without going below the sea surface to observe.

The first attempt to observe tunas underwater during fishing was made in 1957. A steel ladder was lowered and secured to the side of HL's research ship *Charles H. Gilbert*. An observer descended, so that his head was about 0.5 m below the surface. He wore a regulator with an air hose attached to a cylinder of compressed air on the deck of the ship. He faced aft and observed tunas which had been attracted to the stern of the ship with live bait. This method had some notable disadvantages: the ship's speed had to be greatly reduced, observations could be made only in calm water, the observer had a difficult time keeping his purchase on the ladder and on his face mask and mouthpiece against the current, and the observer's view was often obstructed by bubbles (Strasburg and Yuen, 1960*b*). Subsequently, a protective shield was built aroung the ladder, providing sufficient freedom to photograph.

Despite the shield, the ladder was unsatisfactory. The mouthpiece and regulator were bothersome, and communication with the ship's personnel was crude, to say the least (prearrangements were made to signal changes of events by pounding on the ship's hull). Use of this ladder did convince us, however, that observing tuna behavior underwater was feasible. Plans were therefore developed for a structure that would permit the observer to remain in air but still be below the sea surface and that would permit voice communication.

A retractable overside caisson (Fig. 1) was built in 1958 (Strasburg

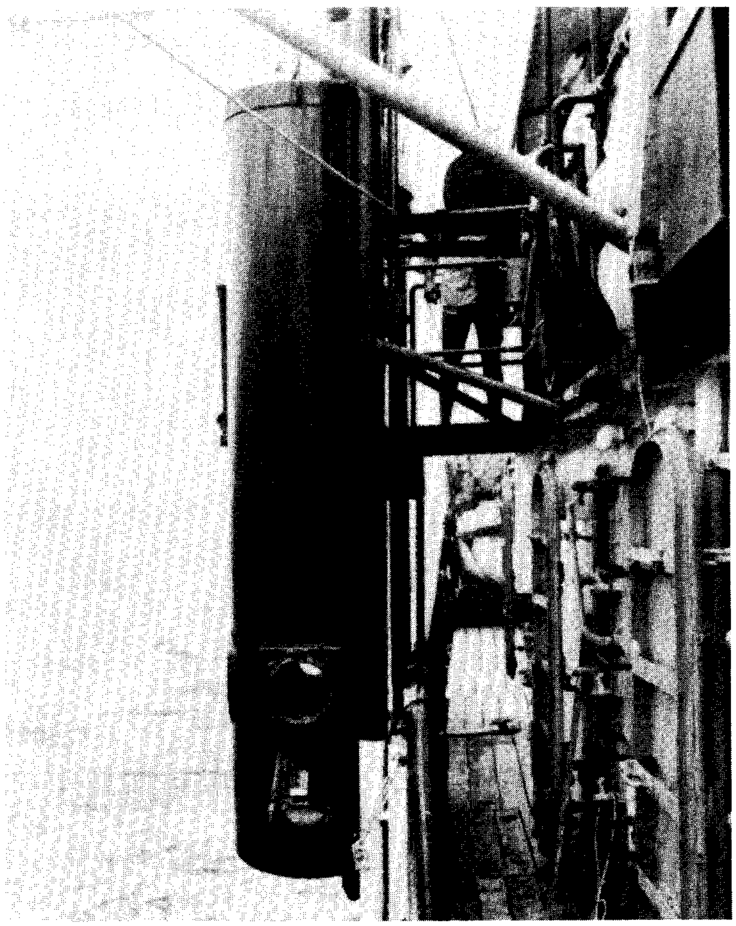

Fig. 1. The retractable caisson.

and Yuen, 1960*b*). The caisson was a tube about 3.5 m long. It was large enough to permit one person to observe and photograph through ports about 1–1.5 m below the surface of the sea. When not in use, the caisson was raised out of the water with block and tackle. Later, the tube was extended to prevent water from splashing in over the top, the ports were enlarged to permit a wider field of visibility, and a winch was installed for lowering and raising it.

Use of the caisson was described by Strasburg and Yuen (1960*a*) and Strasburg (1959). They observed the behavior of skipjack tuna (*Katsuwonus pelamis*) under varying fishing conditions, such as when water sprays were turned on and off, when live and dead bait were chummed, when the rate of chumming was altered, when different species of bait were chummed, when body fluids from dead skipjack tuna were poured into the water, and when noise was presented to the tuna. Changes in schooling behavior, feeding behavior, coloration, and abundance were recorded during the experiments.

A serious disadvantage in using the caisson was the poor visibility in

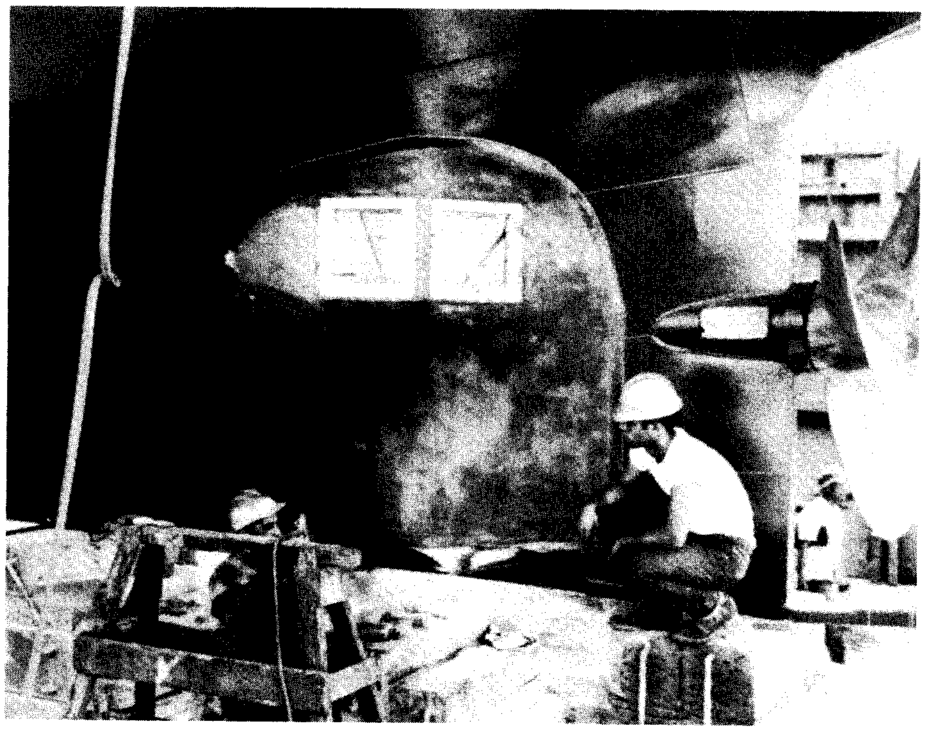

Fig. 2. The stern observation chamber of the *Charles H. Gilbert*.

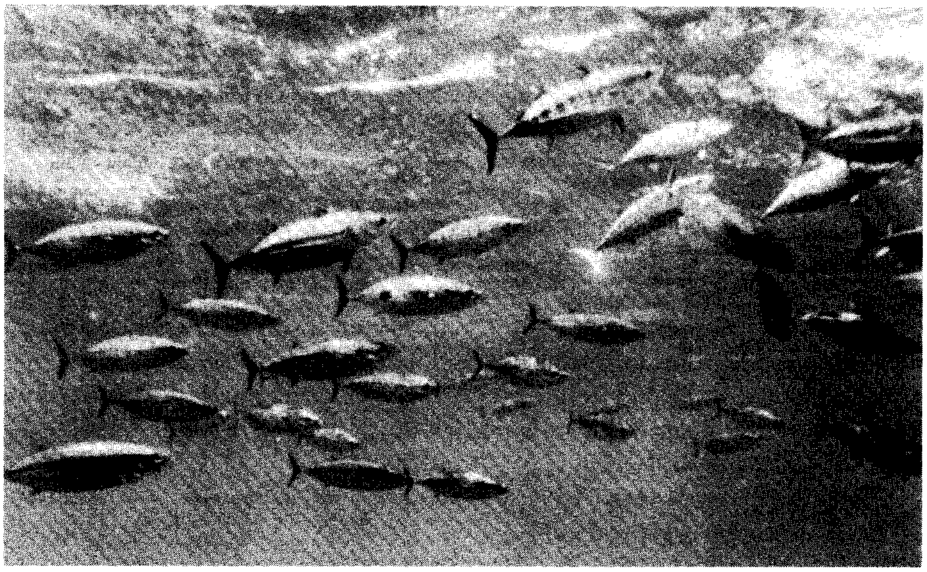

Fig. 3. School of skipjack tuna (*Katsuwonus pelamis*) photographed from stern chamber.

the after direction caused by bubbles in its wake. To overcome this problem, installation of underwater viewing ports in the hull of the *Gilbert* was proposed. The location of these ports as far astern as practicable seemed desirable, since fishing was at the stern.

After problems involving reductions of fuel storage, effect on ship's speed and steerage, turbulence, etc., were considered, an observation chamber was installed in 1959 on the port quarter just forward of the propeller (Fig. 2). Dimensions and details of construction have been provided by Akana *et al.* (1960), Strasburg and Yuen (1960*b*), and Mann (1961).

The stern chamber consists of a streamlined semicylindrical shell. Two ports permit observations from about 2 m below the sea surface directly below one of the fishing racks. Although the chamber can accommodate two persons, only one can observe comfortably in the semicylinder. The entrance is on the after bridge deck. A blower system provides ventilation. Communication is via a sound-powered telephone with headsets. The headsets help to block out much of the noise generated by the ship's machinery. Visibility is excellent and unimpeded by bubbles (Fig. 3).

The stern chamber was used during additional experiments on variation of fishing conditions. Strasburg (1961) noted a relation between diving frequency of schools of skipjack tuna and the presence of certain species of prey in stomachs of fish caught from these schools. Yuen (1969) observed catch rates, rates of attack on bait, and numbers of tunas attracted to the vessel during the experimental fishing. The stern chamber has also been used to study the behavior of different species of bait and the behavior of tunas in response to the behavior of the bait (unpublished).

Schooling behavior, swimming behavior, and coloration of tunas have been observed and recorded from the stern chamber. Banded color phases of skipjack tuna (and also dolphin, *Coryphaena hippurus*) were observed and photographed by Strasburg and Marr (1961). Motion pictures taken from the chamber of yellowfin (*Thunnus albacares*) and skipjack tunas were analyzed to study schooling behavior (Yuen, 1963) and to determine swimming speeds (Yuen, 1966).

Although the stern observation chamber permits excellent observations of tuna behavior during fishing, it does not permit observations of tuna schools ahead of the ship. An observation chamber in the bow of the ship seemed desirable for observing while sailing up to and through schools of tuna or while following them.

A bow chamber (Fig. 4) was installed in the *Gilbert* in 1960 (Akana *et al.*, 1960; Strasburg and Yuen, 1960*b*; Mann, 1961). To do so, the bottom of the bow was reshaped into a bulbous form to provide space for an observer.

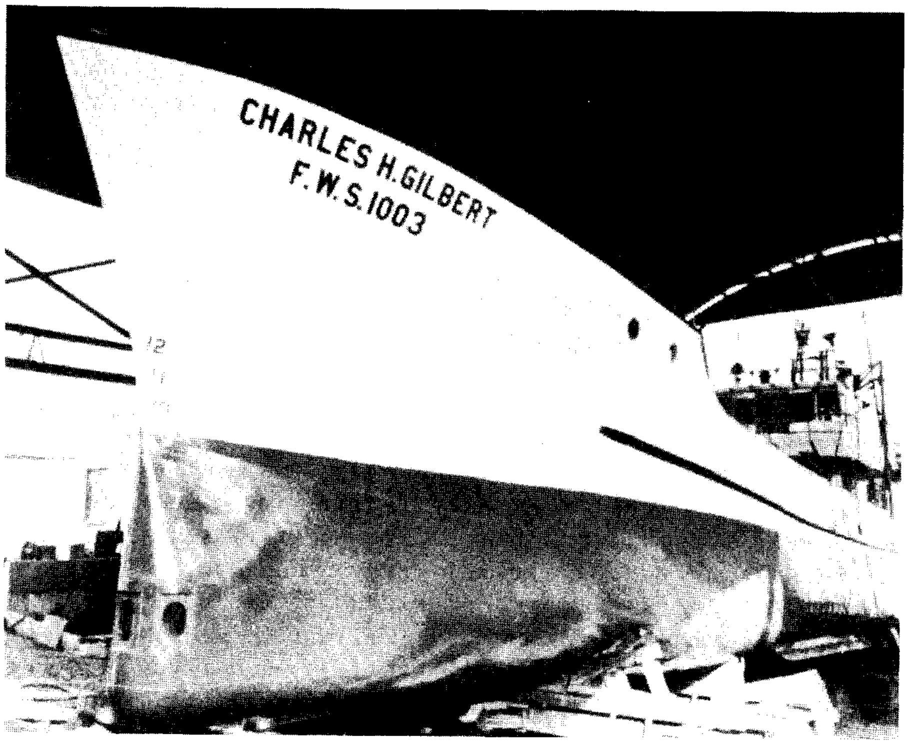

Fig. 4. The bow observation chamber of the *Charles H. Gilbert.*

Three ports were provided for viewing straight ahead and to both sides from about 2 m below the waterline.

The bow chamber comfortably accommodates one observer. Access is from the forecastle. The chamber is ventilated by a forced-draft system. As in the stern chamber, a sound-powered telephone is used for communication.

Soon after the bow chamber was constructed, Yuen (1961) had opportunities to observe and film bow wave riding by porpoise (*Tursiops* sp.). The method of bow wave riding by porpoises was the subject of a controversy among scientists at the time. Yuen settled the matter by describing "the method the (porpoises) themselves seem to consider proper."

The bow chamber has been used to observe the effectiveness of gill nets after skipjack tuna were attracted toward the net with live bait (unpublished). Most of the tuna evaded the net, which was clearly visible from about 20 m. A few skipjack tuna were seen to swim into the net, become gilled, struggle a few seconds, and then succumb.

The ports in both the stern and bow chambers require periodic cleaning, but, in general, visibility in near-surface waters during the day is limited only by water clarity and the endurance and will of the observer. When the ship is heading into moderate to rough seas, the bow chamber often rises above the surface, causing discomfort to all but the most hardy.

Use of the stern and bow chambers in the *Gilbert* does have limitations. Tunas cannot be observed at night, and they cannot be observed at depths greater than about 25 m. Tunas cannot be followed, because their maneuverability is greater than that of the ship. Several methods were considered to overcome these problems.

Underwater television was tested in 1959 (Strasburg and Yuen, 1960*b*). A closed-circuit set was installed on the *Gilbert*. A television camera was set in the stern chamber, and another was suspended in the water. Observations of tuna behavior with television were found to be inferior to observations with the human eye under good light conditions. Under poor light, television provided good observations owing to better contrast. The major difficulty with this method was our inability to shift quickly the field of view. The use of television therefore was abandoned.

In 1959, responses to inquiries sent to manufacturers of submersible vehicles indicated that a submarine for studying various biological and oceanographic problems in addition to tuna behavior appeared practicable. Much thought and effort were put forth in the early 1960s on the uses, on the scientific and operational requirements, and on the design of a research submarine. In 1964, an industrial company was contracted by HL to undertake a feasibility and conceptual-design study. The vessel was required to travel as fast as 20 knots while submerged, remain submerged for as long as 6 weeks, dive as deep as 300 m, and have an operational range of 40,000 km. The specified requirements and design of the research submarine (Fig. 5),

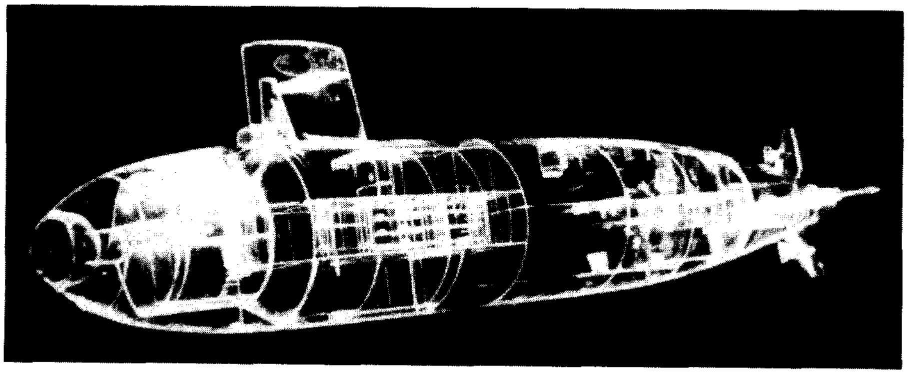

Fig. 5. Plastic model of a proposed nuclear research submarine.

which called for nuclear power, were found to be feasible. One of the great advantages of a submarine is its independence of weather and sea state. Observations are possible in relative comfort while the submarine is submerged despite inclement weather or rough seas. Uses, design, requirements, and facilities of the submarine were presented by Strasburg (1965).

In 1965, HL chartered the *Asherah* (Fig. 6), a submersible about 5 m long, to gain experience in operating and conducting missions with an under water craft. The *Asherah* carried one observer in addition to the pilot. It was operated in the lee of the island of Oahu, Hawaii. Skipjack tuna and kawakawa (*Euthynnus affinis*) were seen on six of the 50 dives with the *Asherah* at depths as great as 152 m (Strasburg, 1966; Strasburg *et al.*, 1968). The tunas were observed preying upon forage fish, but because of the limited speed and maneuverability of the *Asherah* the tunas could not be followed.

A charter of a larger submarine to gain further experience was planned, but owing to insufficient funds the plan was cancelled. Early in 1967, plans for constructing the nuclear research submarine were shelved for the same reason.

Acoustic means of studying tuna behavior at sea were also considered. Acoustic devices could be used to locate and track tunas at night as well as during the day and at depths and distances beyond visual range. Echosounders had been used to study movements and speeds of large, deep-swimming tunas (several species of *Thunnus*) by Nishimura (1963, 1966), but for faster-swimming tunas in waters near the surface conventional sonars which transmit sound impulses at fixed intervals and at fixed frequencies were inadequate for tracking. Such fast-swimming fishes could easily escape detection between transmissions. A sonar that could keep tunas under continuous surveillance was desired.

A CTFM (continuous-transmission, frequency-modulated) sonar (Fig. 7) was installed in HL's research ship *Townsend Cromwell* in 1966. Additional equipment has been installed so that pertinent data can be recorded

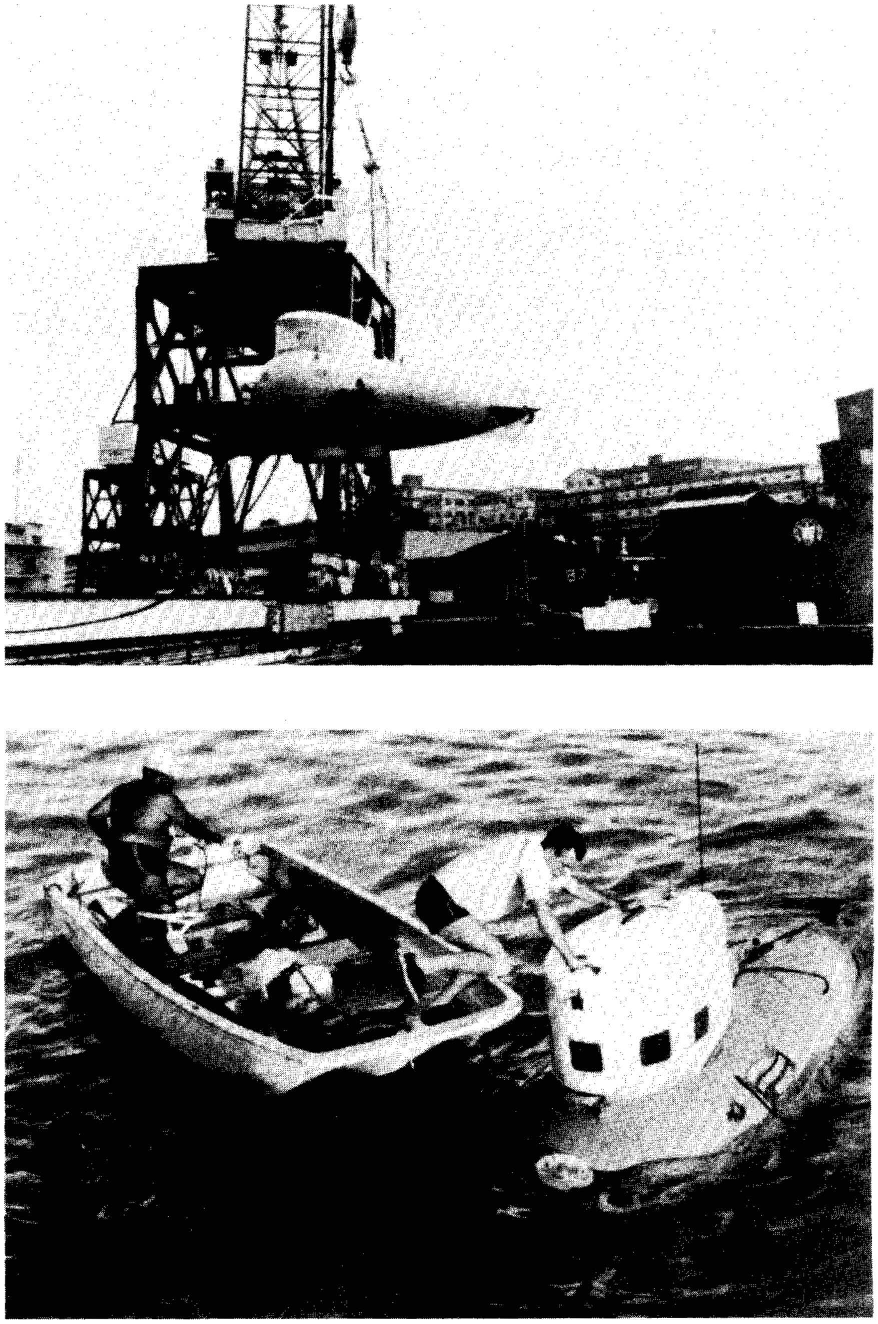

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Fig. 6. The submarine *Asherah*. **(a)** Loading for transport. **(b)** Boarding at sea.

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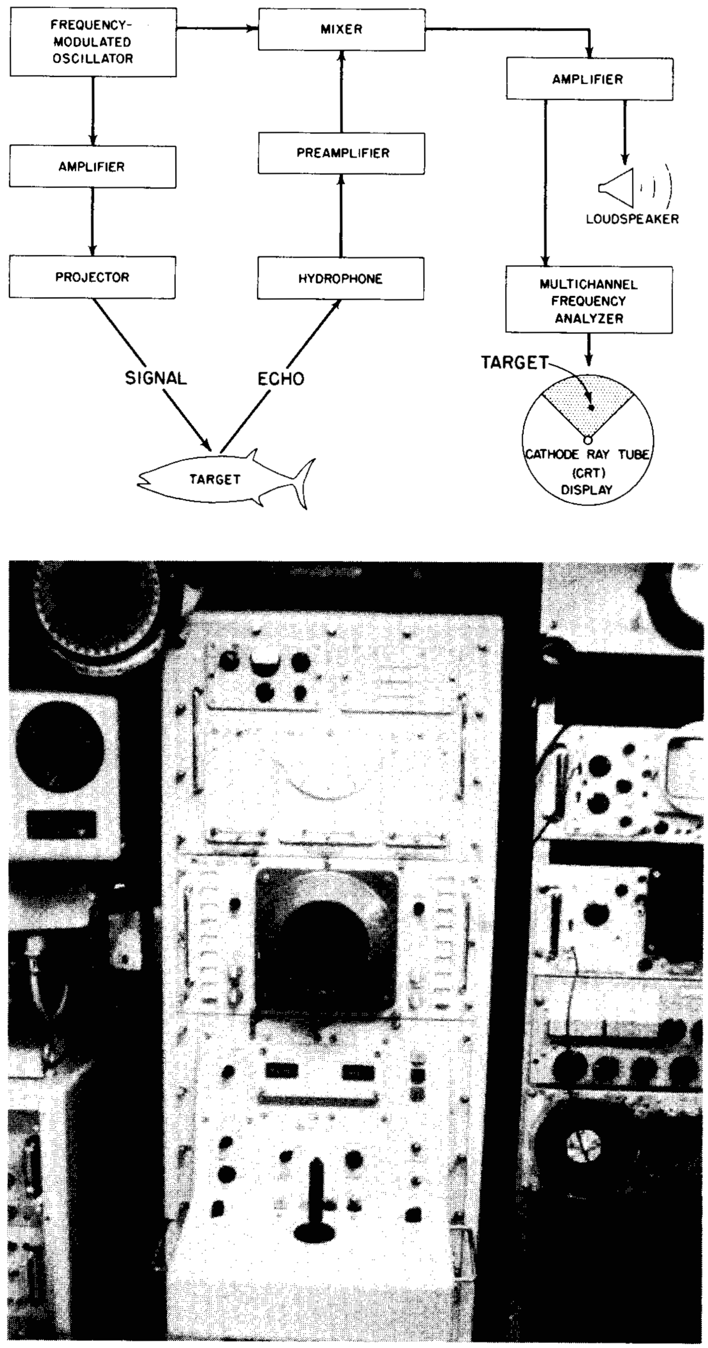


Fig. 7. The CTFM sonar. (a) Block diagram. (b) Control and display panels.

on a 14-channel magnetic tape recorder. The sonar has two operational modes: a search mode with frequencies modulated from 52 to 32 kHz for targets up to 1600 m, and a classify mode with frequencies modulated from 290 to 260 kHz for high resolution at short ranges (100 m). The data from the CTFM sonar are recorded in analog form on magnetic tapes. The tapes are brought ashore, where the data are digitized and then analyzed with the aid of computers. Descriptions of the sonar units and of the operations have been given by Yuen (1967, 1968).

The CTFM sonar, which projects and receives acoustic energy continuously, thereby lessening the possibility of losing a fast-moving target, has been used to observe movements of tuna schools. Diving and swimming behavior of yellowfin and skipjack tunas in relation to their size and to temperatures and depths have been investigated (Yuen, 1968). Schools of skipjack tuna have been followed for many hours continuously while observing their behavior in relation to time and space. These and other studies, including use of ultrasonic tags with the sonar, are in progress.

Hester (1969) attempted to use a CTFM sonar to identify tunas and other species and to determine their sizes by analyzing shifts in frequencies (Doppler shifts) caused by motions of the fishes. The loss of echo strength when fish turned toward or away from the sonar made this method impractical.

Another method used in 1967 for underwater observations was a sea sled towed by the *Gilbert* (Anonymous, 1967). The sea sled was manned by

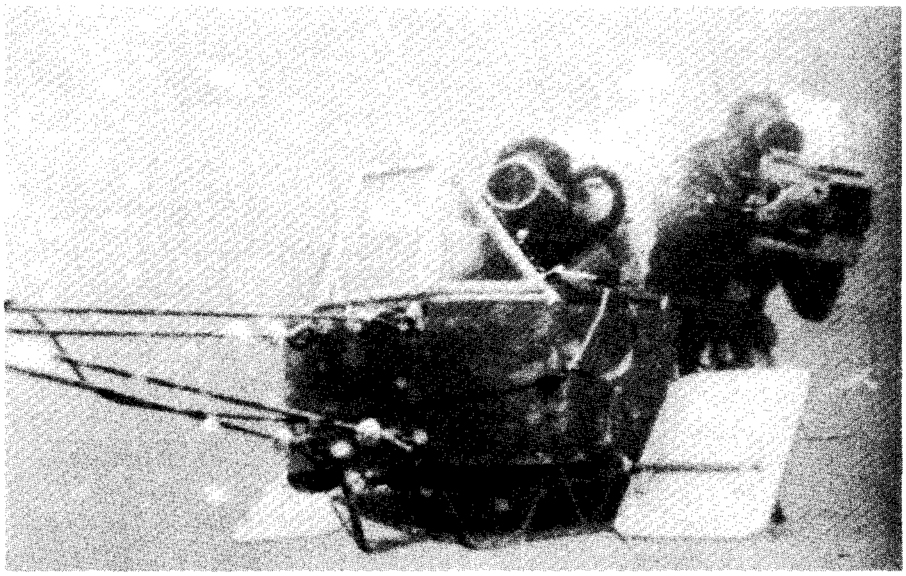


Fig. 8. Photographing from sea sled.

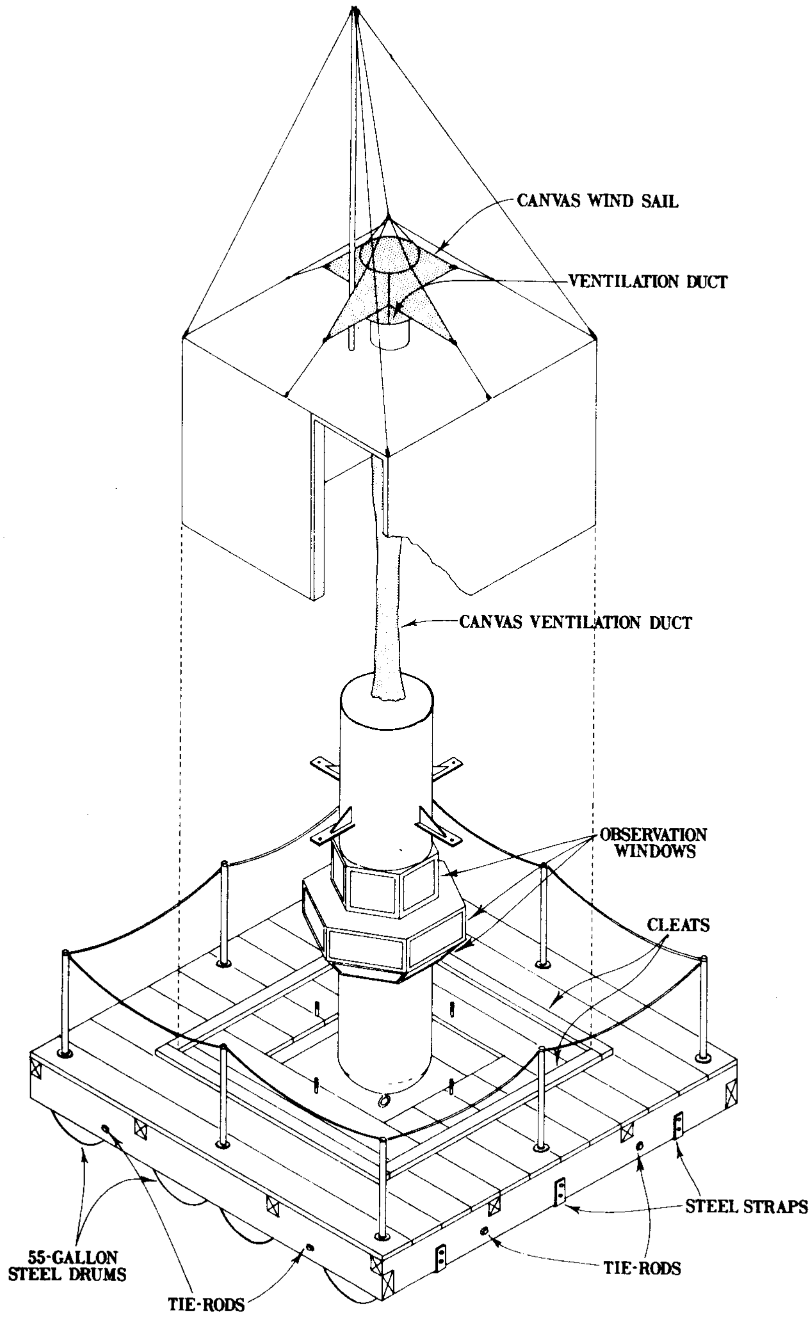


Fig. 9. The raft *Nenue*. (a) Diagram.

two divers equipped with aqualungs (Fig. 8). Communication with the ship was conducted by prearranged signals through a buzzer system. The sled was constructed at the Bureau of Commercial Fisheries Exploratory Fishing and Gear Research Base, Seattle, Washington, by fitting diving planes, windshield, and other equipment to a basket litter.

The behavior of baitfish and the behavior of skipjack tuna preying upon the bait were observed and photographed from the sled, which was towed at about 2 knots at distances up to 50 m behind the ship and as deep as 15 m. The sled proved to be impractical, because by the time it was launched and in operation, the tuna school usually had departed. However, the first underwater observations of courting behavior of skipjack tuna were made (Iversen *et al.*, 1970) before use of the sea sled was discontinued.

During the late 1950s and early 1960s, a number of papers appeared describing parasite-picking and cleaning behavior by fishes and crustaceans in reef communities. Members of HL began to wonder if this phenomenon existed in pelagic environments also. Tunas were often found with ectoparasitic copepods. Which organisms, if any, picked parasites off large

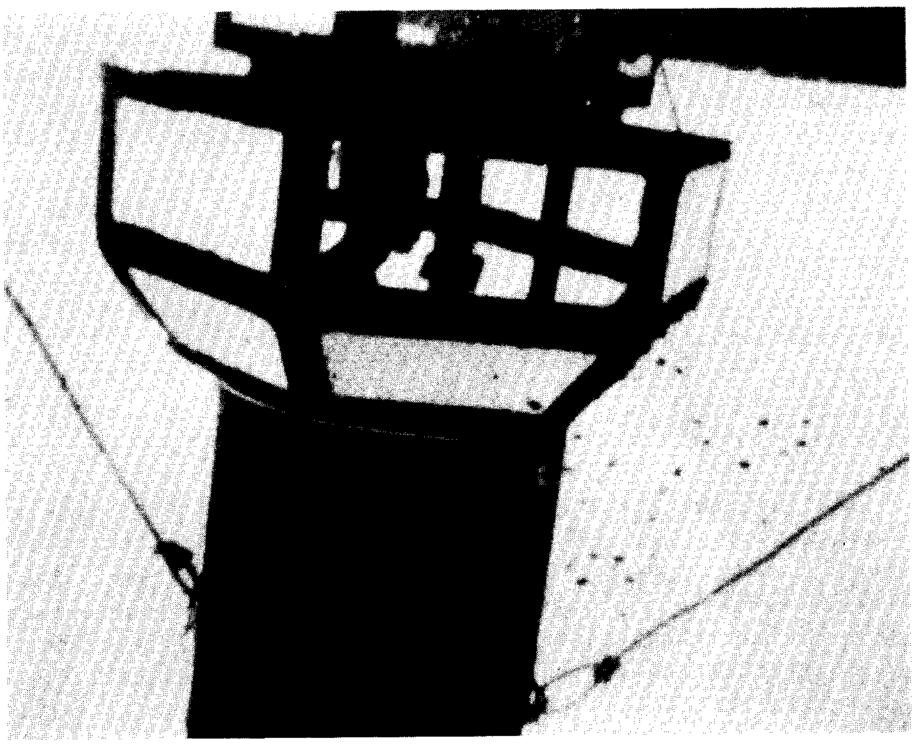


Fig. 9. (b) Observer in cylinder.

pelagic fishes? Tunas were often found in association with drifting objects at sea. These drifting objects almost always had small fishes under them. Could these small fishes act as cleaners for tunas and other pelagic predators?

In an attempt to answer these questions, a raft with observational facilities (Fig. 9) was built in 1962 (Gooding, 1965). The square raft had about 4 m to a side with an aperture in the center through which a steel cylinder was suspended. The cylinder was provided with windows permitting underwater observations in all directions except immediately below. The raft was named *Nenue*, which is the Hawaiian name of *Kyphosus cinerascens*, a fish commonly found under floating objects. The *Nenue* was manned by two persons, who took turns observing in the suspended cylinder. The raft was occupied only during daylight hours. Each evening the observers left the *Nenue* to return to the tending research ship.

The *Nenue* proved to be highly seaworthy, more so than some of the observers. (One observer was removed after 15 min aboard the raft; he had threatened to jump off and swim ashore if he were not taken off.) Many interesting observations and photographs (Fig. 10) were obtained of animals that visited and accumulated under and around the raft. After 13 drifts, 11 in the lee of the island of Hawaii and two south of Hawaii near the Equator, use of the *Nenue* was terminated. Although skipjack and yellowfin tunas were seen, no noteworthy behavior of these tunas was observed (Gooding, 1964; Gooding and Magnuson, 1967). The question concerning cleaning of tunas remains unanswered.

Observations of tunas under floating objects have also been made by Hunter and Mitchell (1967, 1968). They made their observations by diving near floating objects which they found or which they built and placed in the water. Courting behavior and duration of association of black skipjack tuna (*Euthynnus lineatus*) with the floating objects were noted.

III. OBSERVATIONS AND RESEARCH ASHORE

The previously mentioned contract between HL and the University of Hawaii called for determining the reactions of tunas to various chemical, visual, and physical stimuli in the hope that the results might lead to new methods of catching tunas or to improvements in existing methods. To conduct controlled experiments, tunas had to be established and maintained in captivity. Since tunas had never before been held captive for experimental studies, development of methods and techniques for doing so became the first objective.

In 1951, two species of tunas, kawakawa and yellowfin tuna ranging

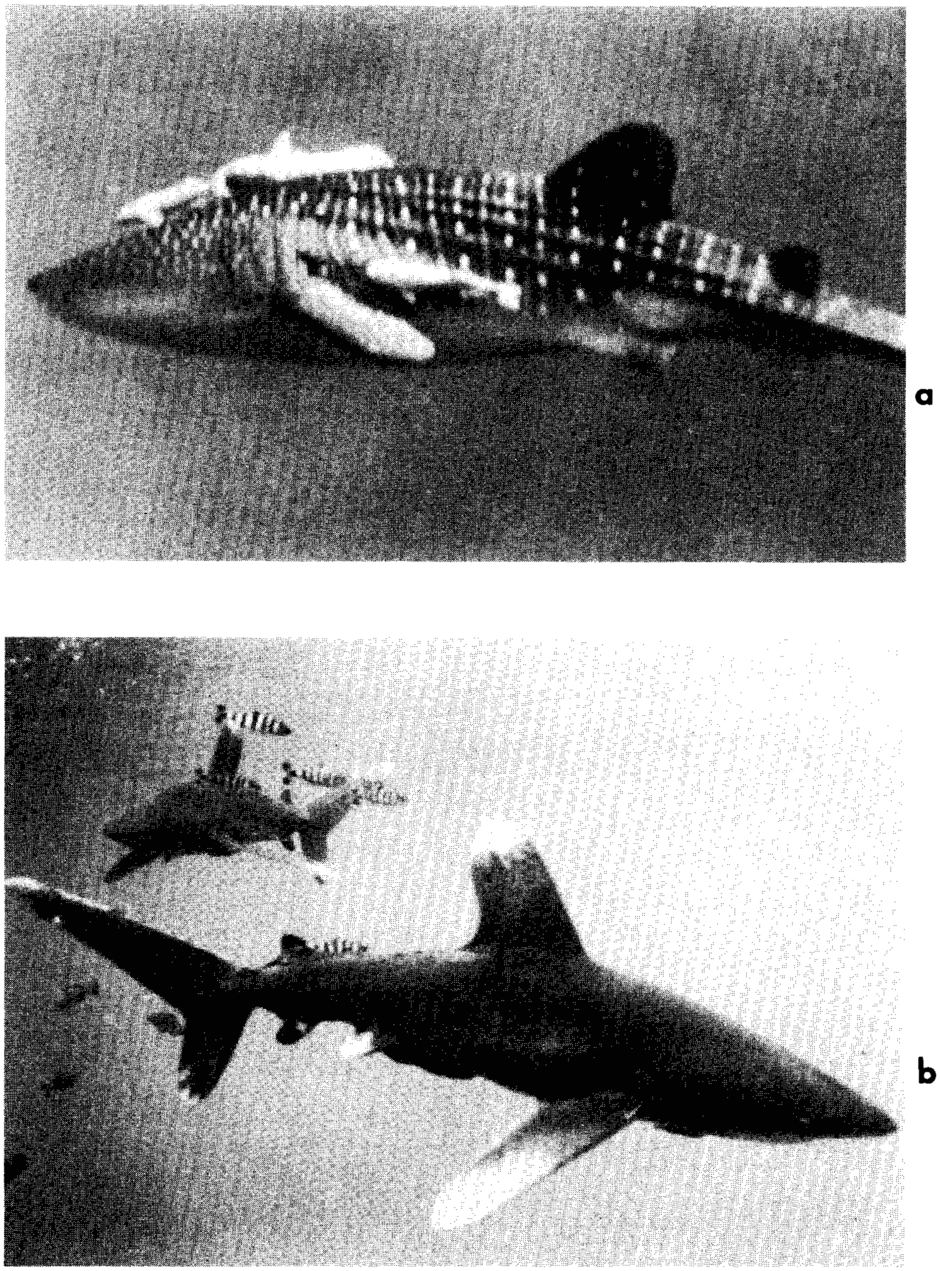
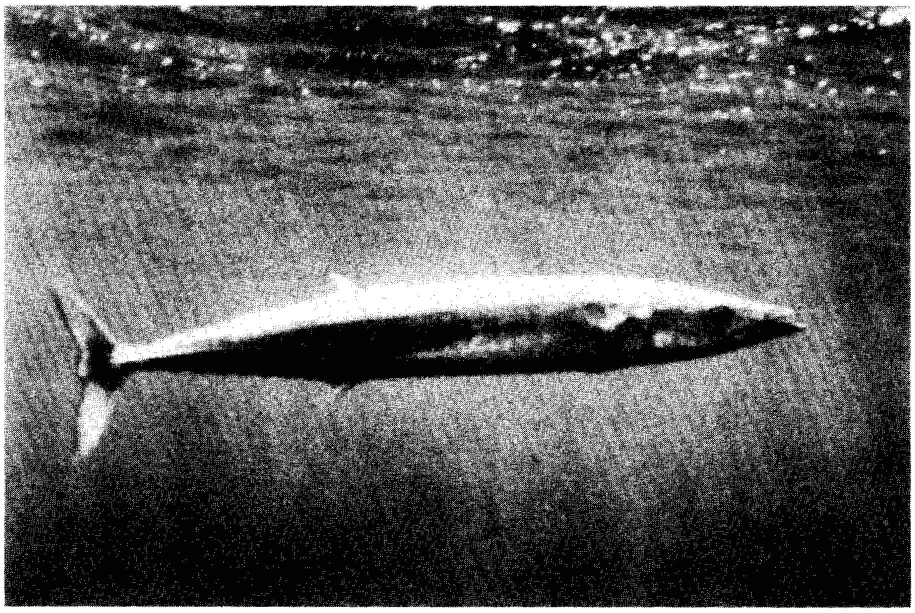


Fig. 10. Fishes seen from observation cylinder of *Nenue*. (**a**) Whale shark (*Rhincodon typus*) with unidentified remora. (**b**) Whitetip shark (*Carcharhinus longimanus*) with pilotfish (*Naucrates ductor*).



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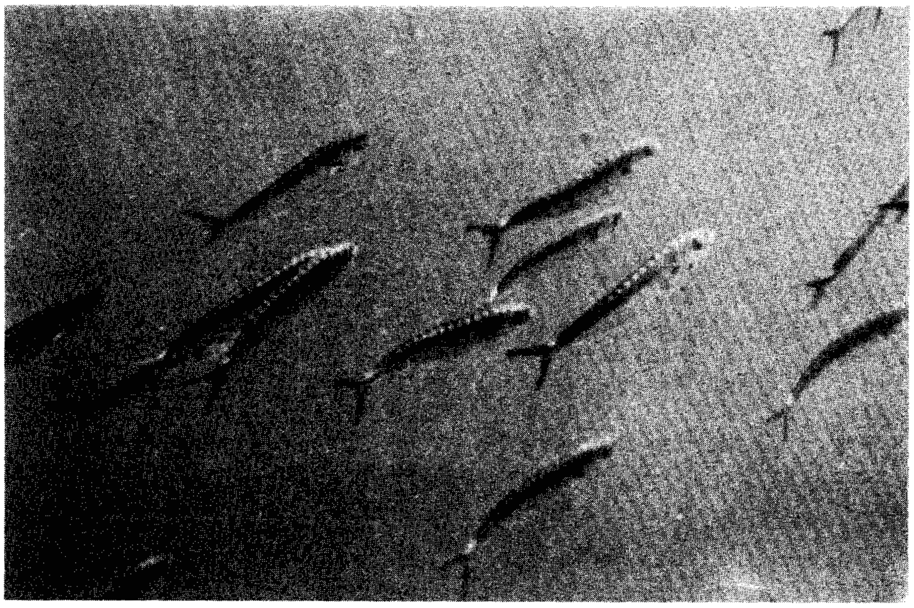

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Fig. 10 (*continued*). (**c**) Wahoo (*Acanthocybium solandri*). (**d**) Juvenile dolphin (*Corpyhaena* sp.).

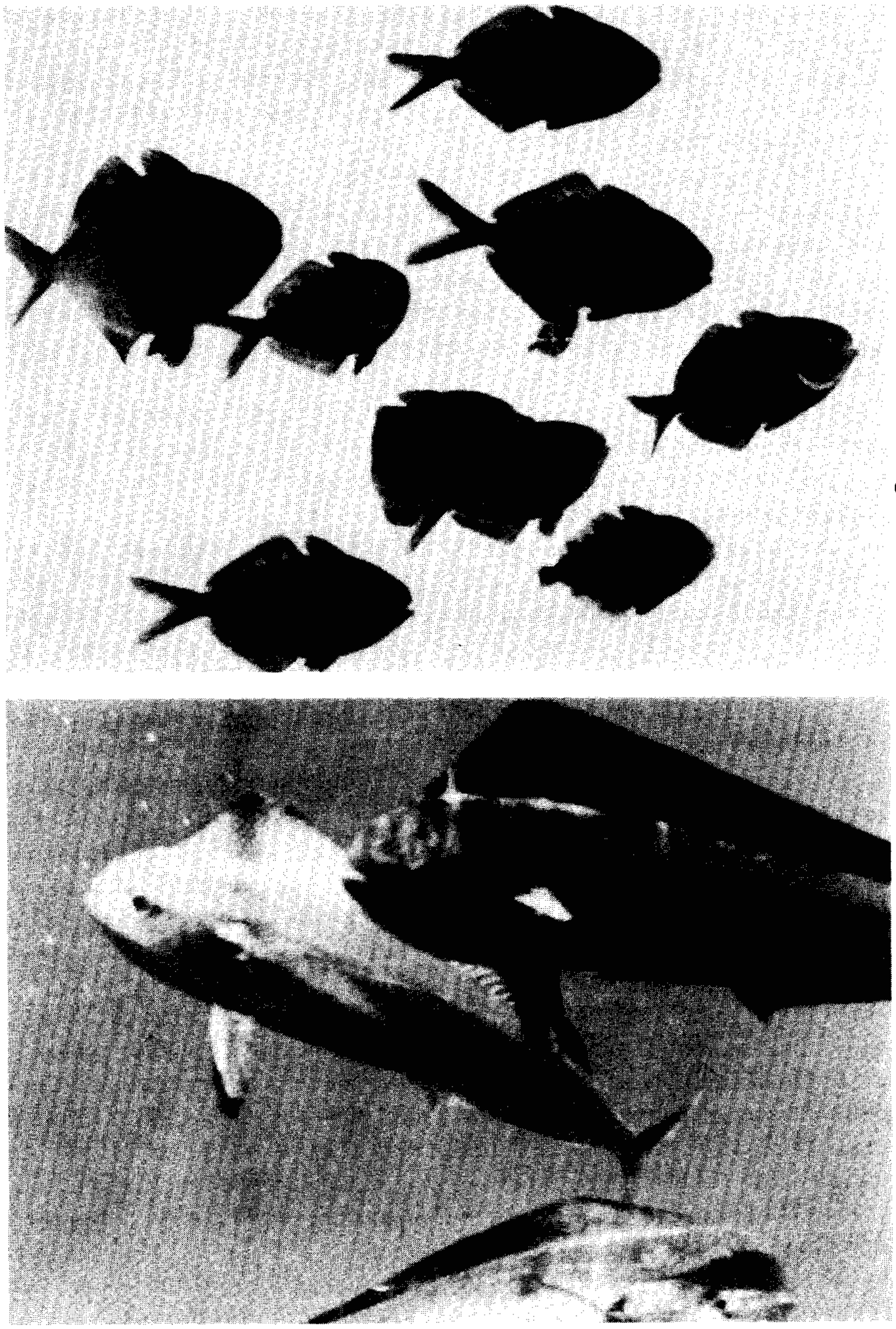

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Fig. 10 (*continued*). (**e**) Freckled driftfish (*Psenes cyanophrys*). (**f**) Adult dolphin (*Coryphaena hippurus*).

from 37 to 58 cm long, were successfully established in a small concrete tank and a large pond after initial failure in a small pond (Tester, 1952). Tunas were caught by surface trolling. They were transported to shore in the baitwell of the boat. A dip net was used to transfer fish from the baitwell to the pond or tank.

The concrete tank was about 11 m long, 3 m wide, and 1.2 m deep. Salt water was supplied by pumping from a channel. Baffles had been used to round the corners, because the tunas tended to swim along the walls of the tank and had difficulty in turning, especially if they were swimming rapidly when they reached a right-angle corner. The baffles eliminated the sharp corners. (The corners in the baitwell of the boat also were rounded with baffles.)

The pond had concrete walls built along a channel dredged out of a coral reef. The length was about 115 m, the width about 21 m. The depth of the pond varied from less than 1 m to about 4 m. Salt water was circulated by tidal currents through screened gates.

Kawakawa survived in the pond for over 2 years. Yellowfin tuna were kept in captivity for shorter periods. Attempts to establish frigate mackerel (*Auxis thazard*) and skipjack tuna in captivity were unsuccessful. Dolphins were also successfully established in captivity. Only the kawakawa and yellowfin tuna were used in experiments (Tester, 1952, 1959).

Responses of kawakawa and yellowfin tuna to visual, auditory, chemical, and electrical stimuli were observed in the pond and tank. Hsiao (1952) studied responses to white and colored lights at various intensities, and to continuous and interrupted white light. Hsiao and Tester (1955) conducted experiments on responses to moving lures of various colors. Some of their experiments were conducted when food extracts were introduced into the water. Experiments on attraction and repelling of tunas by sounds of various frequencies were conducted by Miyake (1952). He also investigated sound production by tunas. Responses to chemical stimuli were studied by Van Weel (1952) and Tester *et al.* (1954, 1955) by use of food extracts, water in which bait had been living, and assorted organic and inorganic chemicals. Tester *et al.* (1954) made ersatz baits by impregnating gelatin and macaroni with extracts of fish and squid, and tested them on both captive and wild tunas. Responses to electrical stimuli were studied briefly by Miyake and Steiger (1957). All of these experiments were summarized by Tester (1959).

In the late 1950s, facilities for holding and observing tunas ashore were developed at HL to complement the facilities developed to observe tunas at sea. A salt water well was dug in 1958 near the waterfront to get clean sea water—salt water which had undergone natural filtration and thus was relatively free of pollutants and marine organisms. Because the water lacked oxygen, an aerator consisting of layers of perforated trays was built (Strasburg, 1964). A circular, plastic-lined swimming pool (Fig. 11) about 7 m in diameter and 1.2 m deep was set up to hold the captive tunas (Nakamura, 1960).

Initial attempts to establish skipjack tuna in the pool failed. The tuna were captured by pole and line after they had been attracted to the ship with live bait. The fish were pulled out of the water, held by the fishermen while being carefully unhooked, and then placed in the baitwell. In port, the tuna were dip-netted, carried to the pool in a net (wet towels and plastic bags containing seawater were also tried), and released. None survived for more than a few hours. To counteract the excited actions exhibited by skipjack tuna, a drug (thorazine) was injected intramuscularly in some immediately after capture to tranquilize them. The additional excitation from handling while the injection was administered probably offset any tranquilizing effect the drug may have had. Again, none survived for longer than a few hours after release in the pool. All of the skipjack tuna incurred contusions, abrasions, loss of mucus, as indicated by discolored areas of the body, and nervous excitation from handling during these procedures. To prevent these effects, a method which eliminated handling was developed in 1959.

An elliptical steel tank 2.4 m long, 1.8 m wide, and 0.6 m deep was built to transport the tunas from sea to shore. When a fish was hooked, the fishermen swung the pole over the tank, quickly lowered the fish into the tank, and slackened the line to permit the fish to shake the barbless

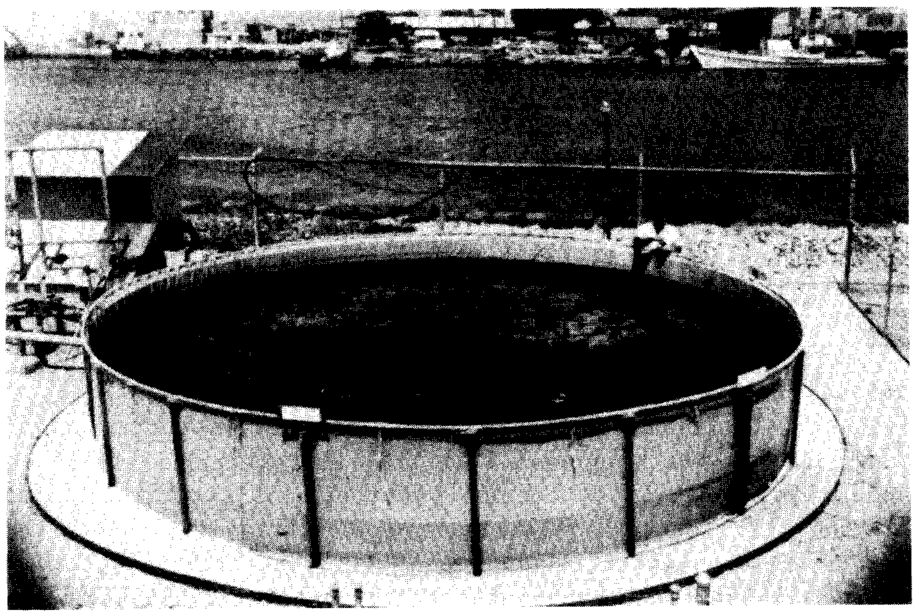


Fig. 11. Circular, plastic-lined swimming pool for holding tunas.

hook out of its mouth. Once inside the tank, which was continuously provided with seawater, the fishes swam along the walls, but since the tank had no corners they were not required to make sharp turns. When the ship returned to shore, the tank was removed with a crane and immersed in the pool, and the fishes were allowed to swim out through a side hatch. Skipjack tuna brought ashore by this method did not have discolored areas, swam less excitedly and more slowly, and were successfully established in captivity. General observations were made on feeding behavior, coloration, swimming and schooling behavior, and recovery from injuries on these captive skipjack tuna (Nakamura, 1962).

After methods and facilities for establishing skipjack tuna and other species in captivity had been developed, additional experimental and observational tanks and pools were built. To determine visual capabilities of tunas, a U-shaped tank 15.9 m long, 4.9 m wide, and 1.2 m deep was built in 1960. The tank (Fig. 12) was enclosed in a Quonset hut to control light. Also, the Quonset hut facilitated observations by preventing rippling of the water surface by winds. Clear glass windows were placed in the ends of the tank. The observer conducted experiments from observation booths placed over the ends of the arms.

Visual acuities of skipjack tuna, kawakawa, and yellowfin tuna were measured in the tank in the Quonset hut. The method involved training tunas to respond differently to horizontal and vertical stripes which were projected onto an opal glass plate at a window in the tank (Nakamura, 1964*a*, 1968 1969*b*).

In 1961, a larger well was dug, and a new modified aerator was constructed (Nakamura, 1964*b*).

Another circular swimming pool was set up in 1962 for conducting experiments on hearing abilities of tunas. The pool was lined with mats made of rubberized pig and horse bristles to provide acoustic insulation. Experiments were conducted from an elevated observation booth built alongside the pool (Fig. 13). Training methods were used again to determine frequencies of sound perceived by yellowfin tuna and kawakawa (Iversen, 1967 1969).

Since the circular swimming pool was found to be most useful for observing tuna behavior, an array of pools was set up in 1962. Six pools were arranged in a ring around an observation tower (Fig. 14). An aerator, which sprayed water through small holes, was built in the center of the observation tower. Water flowed from the aerator into the pools and then out through a drain in the center of each pool. Since seawater from the well was plentiful, recirculation was unnecessary. Windows in the tower permitted views of each tank. Three small huts were constructed, one between each

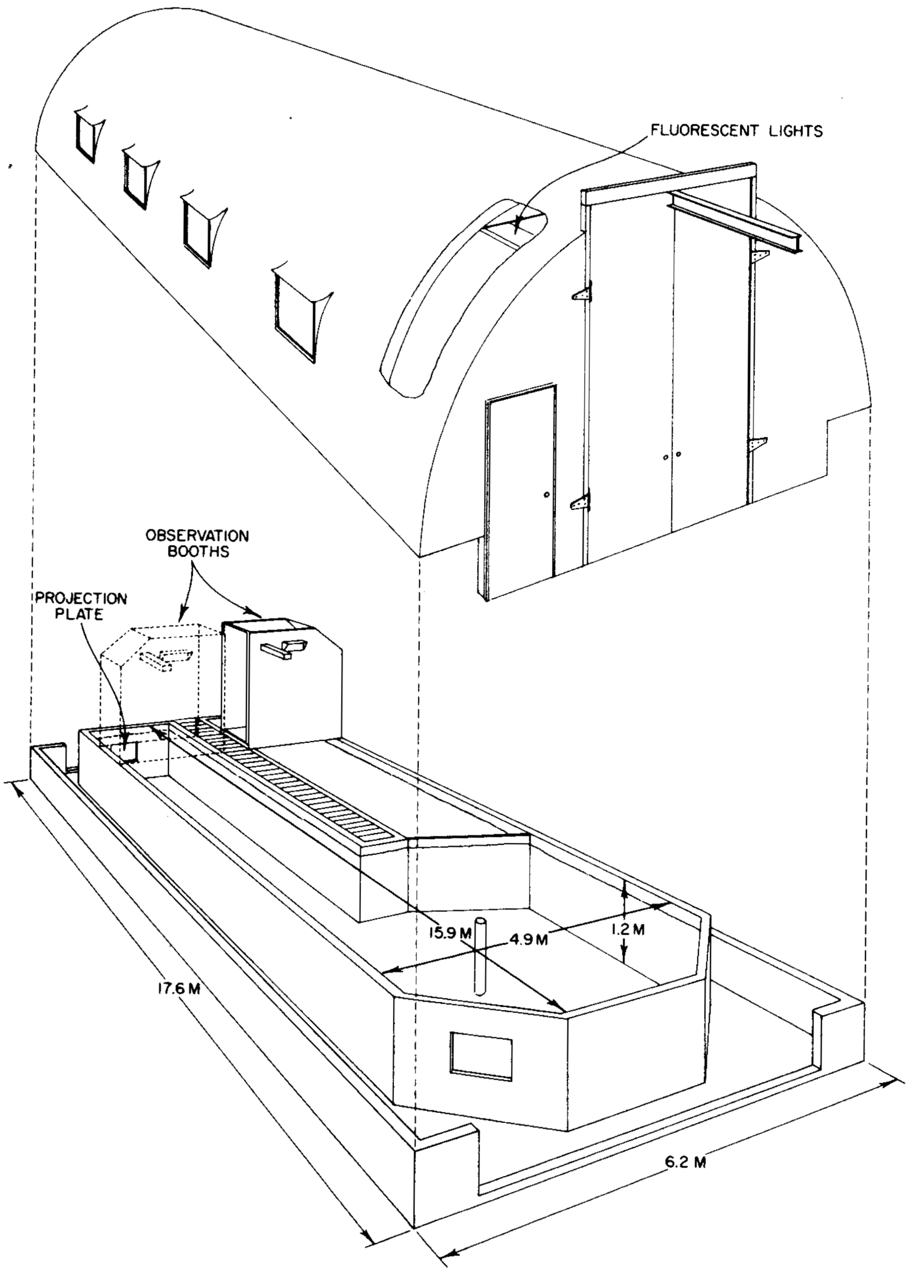


Fig. 12. Diagram of U-shaped tank in Quonset hut.

pair of pools. Windows in the huts permitted observations from below the water surface (Magnuson, 1965).

Awnings were placed over the six-pool complex and the acoustic pool in 1965 to reduce the amount of sunlight entering them. Because a diatom of the genus *Melosira* grew rapidly and profusely in pools open to the sun, the pools had to be cleaned twice a week. After the awnings were placed, the frequency of cleaning was reduced to once every 1 or 2 weeks.

The need to obtain more tunas per trip plus problems concerning the weight and maintenance of the steel transfer tank led to the construction in 1964 of five fiberglass transfer tanks. The new tanks (Fig. 15) were similar to the steel tank in size and design except for removable tops. The fish were released by removing the top and overturning the fiberglass tank in the pool (Nakamura, 1966).

Several species of tunas (Fig. 16) have been kept in our pools at HL. The length of survival has varied with species. Kawakawa have been kept for years, but frigate mackerels (*Auxis thazard* and *A. rochei*) have not survived for longer than a month. Other tunas, such as yellowfin tuna, bigeye tuna (*Thunnus obesus*), and skipjack tuna, have survived for months—generally until they were either sacrificed for experimental reasons, lost owing to accidents, or poached (one of the few people ever to catch tunas by

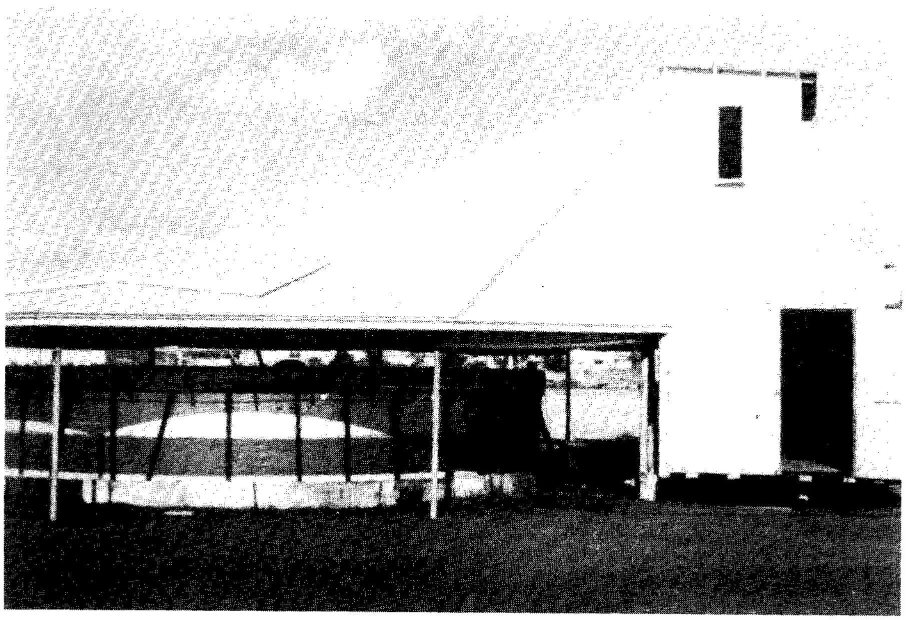


Fig. 13. Pool and observation tower for acoustic experiments.

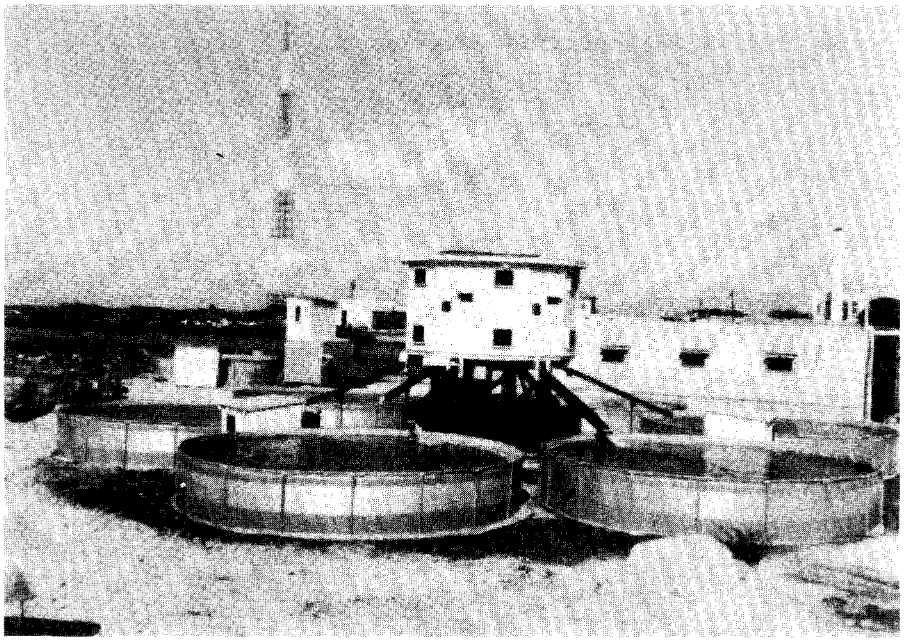


Fig. 14. Array of six swimming pools around an observation tower with small observation huts between each pair of pools.

spearfishing was a youngster who sneaked into our pools in the evenings). Skipjack tuna, however, have not survived longer than 6 months. Other pelagic fishes, such as the dolphin and the rainbow runner (*Elagatis bipinnulatus*), have also been successfully established in our pools.

Small specimens are sought in fishing for tunas to establish in captivity. The size of the transfer tanks and the pools has favored smaller fish. Also, more small tunas can be placed in a transfer tank and in a swimming pool.

Behavior of tunas in HL's pools has been observed visually from the central observation tower, from the small hut adjacent to the pools (Magnuson, 1965), and from the pool's edge. Cine and still photography and other special equipment have been used in experiments conducted in these pools. High-speed cinematography was used by Walters (1966) to investigate the mechanics of feeding by kawakawa. Schooling behavior of kawakawa has been observed by Cahn (1967). Magnuson (1964*a*, 1966*a*,*b*, 1969*b*) has studied swimming behavior of kawakawa in relation to respiration and feeding and to hydrostatic equilibrium, and Magnuson (1970) has analyzed the hydrostatic functions of the appendages of kawakawa. He has also determined digestion rates in skipjack tuna (Magnuson, 1969*a*). Changes in color and in body markings have been noted in several species

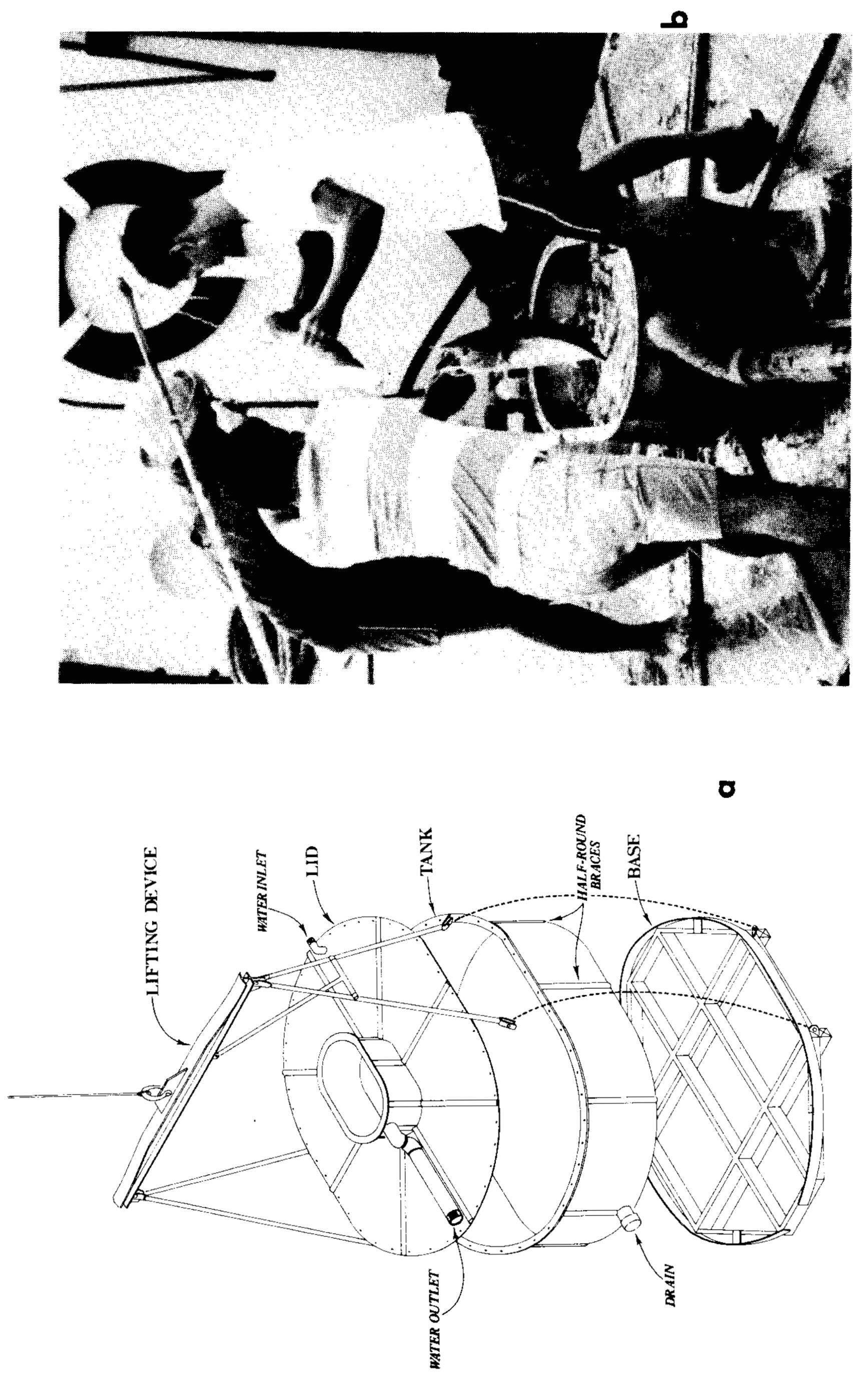
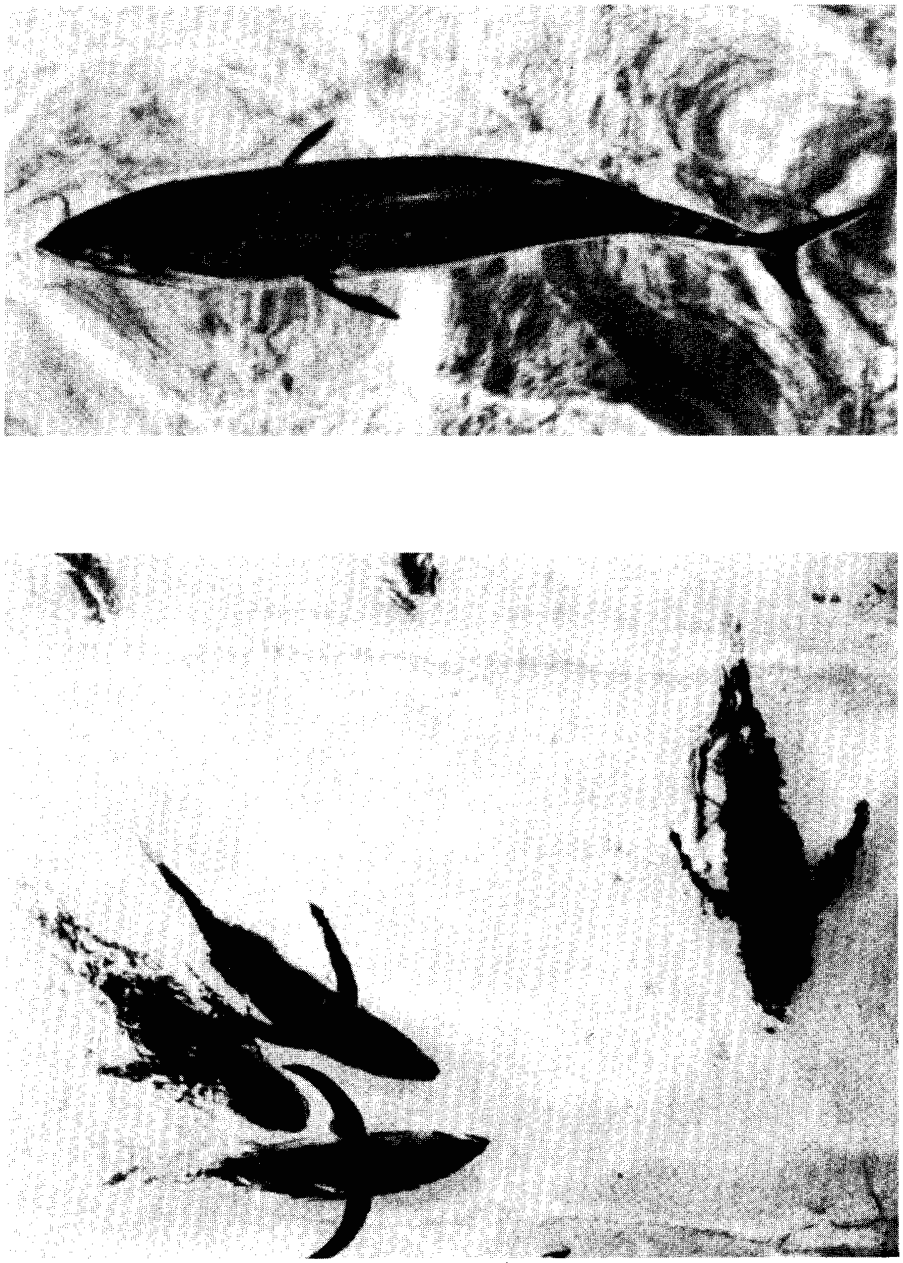


Fig. 15. Fiberglass transfer tank. (a) Diagram. (b) Placing skipjack tuna (*Katsuwonus pelamis*) into transfer tank.



a

b

Fig. 16. Tunas kept in captivity. (**a**) Skipjack tuna (*Katsuwonus pelamis*). (**b**) Bigeye tuna (*Thunnus obesus*).

c
d

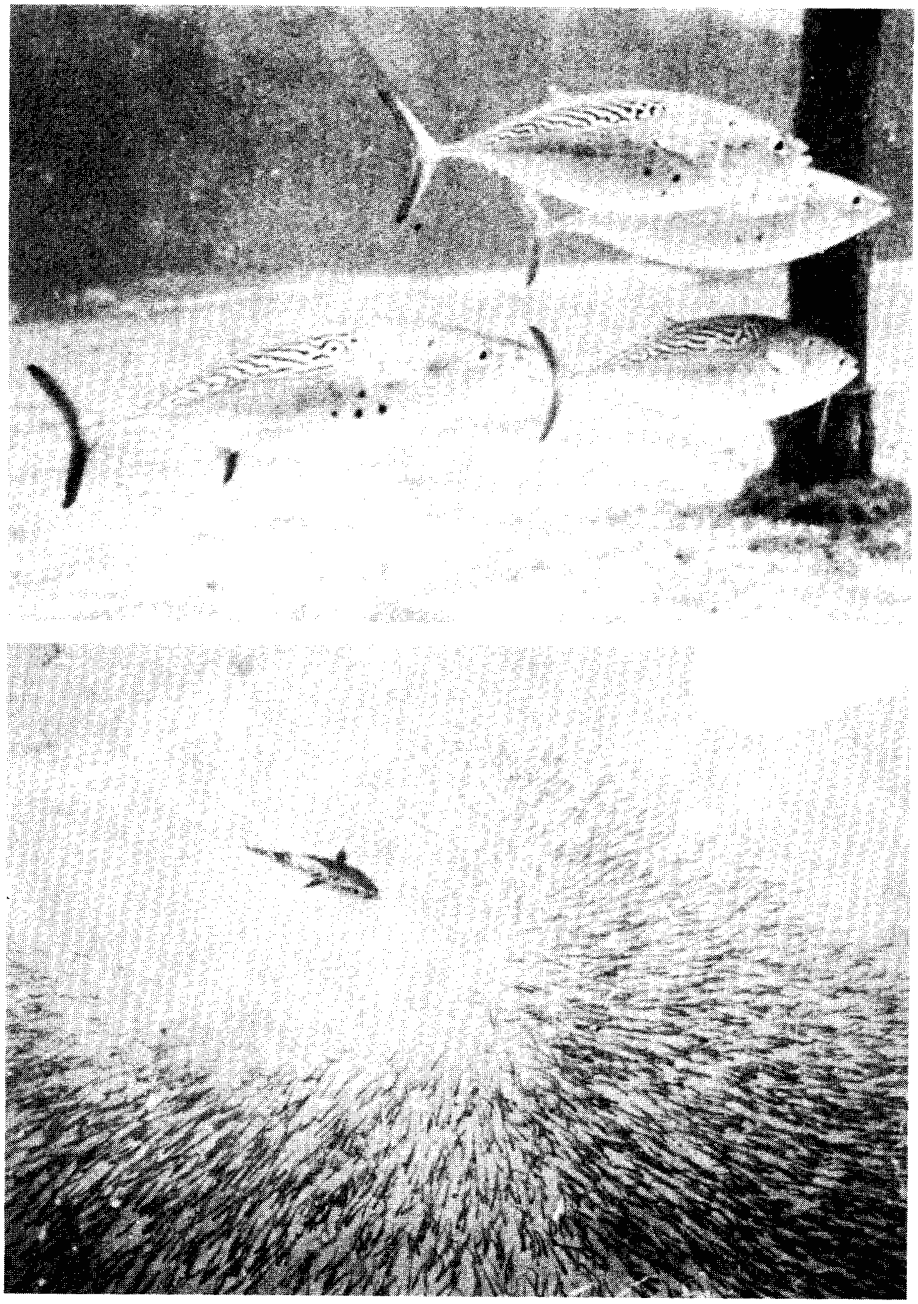


Fig. 16 (*continued*). (**c**) Kawakawa (*Euthynnus affinis*). (**d**) Kawakawa preying upon a school of baitfish (*Stolephorus purpureus*).

of tunas (Nakamura, 1962; Nakamura and Magnuson, 1965) and also in the dolphin (Murchison and Magnuson, 1966). Some preliminary experiments (unpublished) on olfaction and oxygen tolerance in tunas have been conducted in the pools and have indicated sensitivities and awareness by tunas to dilute concentrations of aquatic odors and to changes in oxygen tension.

While the behavior of captive tunas was observed, questions of sensory capabilities arose which led to studies of the morphology and histology of several organs. The ability of tunas to perceive objects thrown to them before the objects hit the water, even when the surface was rippled, led to examination of the gross morphology and retinal histology of the eyes of several species of tunas (Matthews, unpublished work cited by Tester, 1959). The nature of the small openings of the anterior nares and slitlike posterior nares led to studies of the mechanics of water flow and the morphology and histology of the olfactory organ of skipjack tuna (Gooding, 1963). Questions concerning the silvery tongue of skipjack tuna led to histological examination for taste buds, which were found. A layer of guanine crystals was responsible for the silvery appearance of the tongue (unpublished).

The availability of live tunas at HL has permitted several investigators to carry out anatomical and physiological studies requiring live or fresh specimens. Physiology of muscles of skipjack tuna has been investigated by several workers (Chung *et al.*, 1967; Rayner and Keenan, 1967; Sather and Rogers, 1967). Anatomical and electrophysiological studies of the nerve in the trunk lateral line of skipjack tuna have been made by J. Suckling (1967) and E. Suckling (1967). Oxygen consumption in muscles of skipjack and bigeye tunas has been investigated by Gordon (1968).

Many skipjack tuna, after a few days in confinement, develop a condition we have termed "puffy snout" (Fig. 17). Tissues of the snout begin to swell and become edematous. The swelling spreads posteriorly until the fish is unable to close its jaws and the tissues around the eyes swell to give the appearance of sunken eyes. If left in this condition, the fish dies.

Puffy snout is believed to result from stress due to confinement in small tanks or pools. When tunas with puffy snout are placed in larger tanks or pools, the swelling recedes. We have had kawakawa which developed severe cases of puffy snout when kept in an annular raceway less than a meter wide. When these kawakawa were transferred to one of the swimming pools, the swelling disappeared within 2 weeks. Puffy snout develops more frequently in skipjack tuna than in other species, so we believe skipjack tuna are less able to adapt to confinement in space as small as our pools. Some skipjack tuna that were transported to Sea Life Park, Makapuu, Hawaii, and established in a large display tank (21.4 m top diameter, 10.7 m bottom

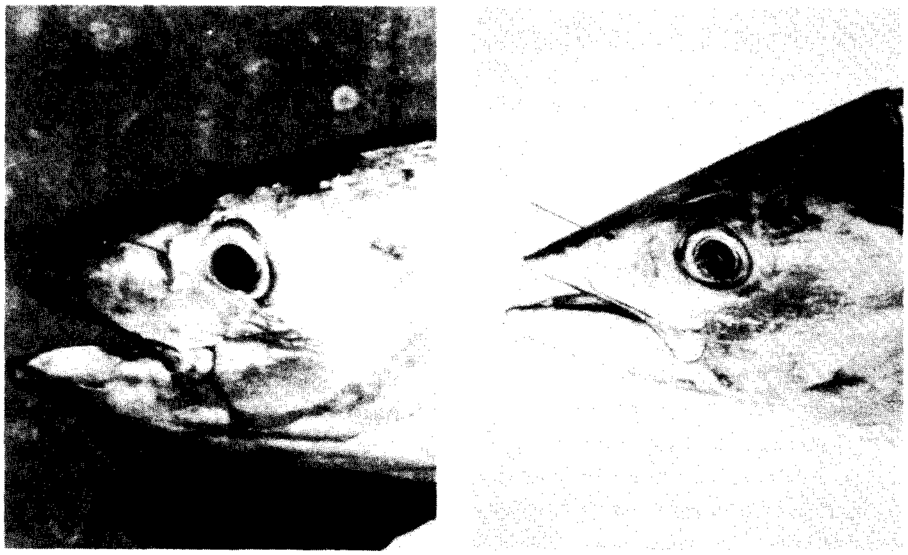


Fig. 17. Head of skipjack tuna (*Katsuwonus pelamis*). (**a**) Skipjack tuna with puffy snout. (**b**) Skipjack tuna with normal snout. Pin is stuck in anterior naris.

diameter, 4.3 m deep) did not develop puffy snout. Yellowfin tuna also have developed this malady (Tester, 1952). So have mackerels kept in small tanks. I have seen puffy snout in Pacific mackerel (*Scomber japonicus*) in an aquarium at Scripps Institution of Oceanography, La Jolla, California, and in Atlantic mackerel (*Scomber scombrus*) in an aquarium at The Plymouth Laboratory, Plymouth, England.

Larger tanks undoubtedly are more favorable for maintaining swift pelagic fishes, such as tunas, in captivity. The largest tank in which tunas have been kept in captivity is the tank for public display of fishes at Marineland of the Pacific, Palos Verdes, California. The tank is about 33 m long, 16.3 m wide, and three stories deep. Pacific bonito (*Sarda chiliensis*) have been maintained in captivity for years. These are the only tuna ever known to spawn in captivity. Courtship, spawning, swimming, feeding, and other activities of this species have been observed in this tank (Magnuson and Prescott, 1966).

In 1965–1966, Inoue *et al.* (1967) attempted to establish tunas in small pools in Japan. A pool, 1.5 m in diameter and 0.6 m deep, was used aboard a vessel at sea. Skipjack tuna died soon after placement in this pool; yellowfin tuna survived for 19 hr. A larger pool, 4 m in diameter and 0.6 m deep, was used ashore. Bonito (*Sarda orientalis*) and kawakawa were kept for over 400 hr. The authors attributed their poor success primarily to insuficient oxygen. In my judgment, the smallness of the pools was also a significant factor.

IV. CONCLUSION

Much has been learned from the use of facilities to observe tuna behavior both at sea and ashore under natural and experimental conditions. Tunas are able to detect dilute concentrations of certain chemicals (Tester *et al.*, 1955; Van Weel, 1952) and to detect sounds of certain frequencies with greatest sensitivity between 300 and 700 Hz (Iversen, 1967, 1969), but vision appears to be the most important sense used in feeding (Hsiao and Tester, 1955; Tester, 1959). Baitfish which are silvery and which are active and which take evasive action when pursued have been observed to elicit greater excitement in tunas, which makes tunas more vulnerable to the pole-and-line fishery; the greater swimming speed and the frequent changes in direction while pursuing the baitfish gives a tuna less time to discriminate between hook and bait. Visual acuity (Nakamura, 1968, 1969*b*) and swimming speed measurements (Walters, 1966; Yuen, 1966) have permitted calculations of distances of visibility of objects and the time tunas have to accept or reject a hook or evade a net (Nakamura, 1969*b*). Color patterns and color changes observed in tunas during their feeding and courtship behavior are probably used as communicating signals between fish and are certainly used by observers as signs that a fish has detected certain stimuli (Nakamura, 1962; Nakamura and Magnuson, 1965). Courtship behavior has been described for three species of tunas (Magnuson and Prescott, 1966; Hunter and Mitchell, 1967; Iversen *et al.*, 1970). Studies on feeding (by skipjack tuna) indicate that indigestible materials pass rapidly ($1\frac{1}{2}$ hr) through the alimentary canal (Nakamura, 1962), that about 15 percent of their body weight is eaten per day, that a full stomach empties in about 12 hr (Magnuson, 1969*a*), and that filter feeding (by kawakawa) is accomplished by swimming over the food rather than sucking it in (Walters, 1966). Studies of schools containing two or more species of tunas have indicated that such schools were formed by separate schools of each species drawn together by a common attractant, such as food (Yuen, 1963). Disruption of schooling orientation occurs during feeding (Nakamura, 1962). The importance of hydrodynamic and hydroacoustic stimuli in augmenting visual stimuli in schooling orientation has been noted (Cahn, 1967). Tunas without gas bladders possess negative buoyancy, and to maintain hydrostatic equilibrium they must swim continuously and use primarily their pectoral fins to obtain hydrodynamic lift (Magnuson, 1969*b*, 1970). These and other results from observations and experiments made with the use of special facilities have significantly advanced our knowledge of tuna behavior. Experience with captive tunas has indicated the ease and rapidity of conditioning them for use in experiments (Iversen, 1967, 1969; Nakamura, 1962, 1968, 1969*b*). However, the results of studies on the responses of captive tunas to various stimuli have had limited value in predicting the responses of wild tunas to the same stimuli in the open sea (Tester, 1959; Tester *et al.*, 1954).

Development of methods and facilities for studying tuna behavior is continuing. Techniques to anesthetize and revive fast-swimming pelagic fishes without injuries are being developed to permit studies requiring operations on these fishes. Larger pools are planned to maintain larger tunas and skipjack tuna in better health. New techniques and facilities for studies both at sea and ashore will continue to increase our research capabilities and will allow continued growth of our knowledge of tuna behavior.

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