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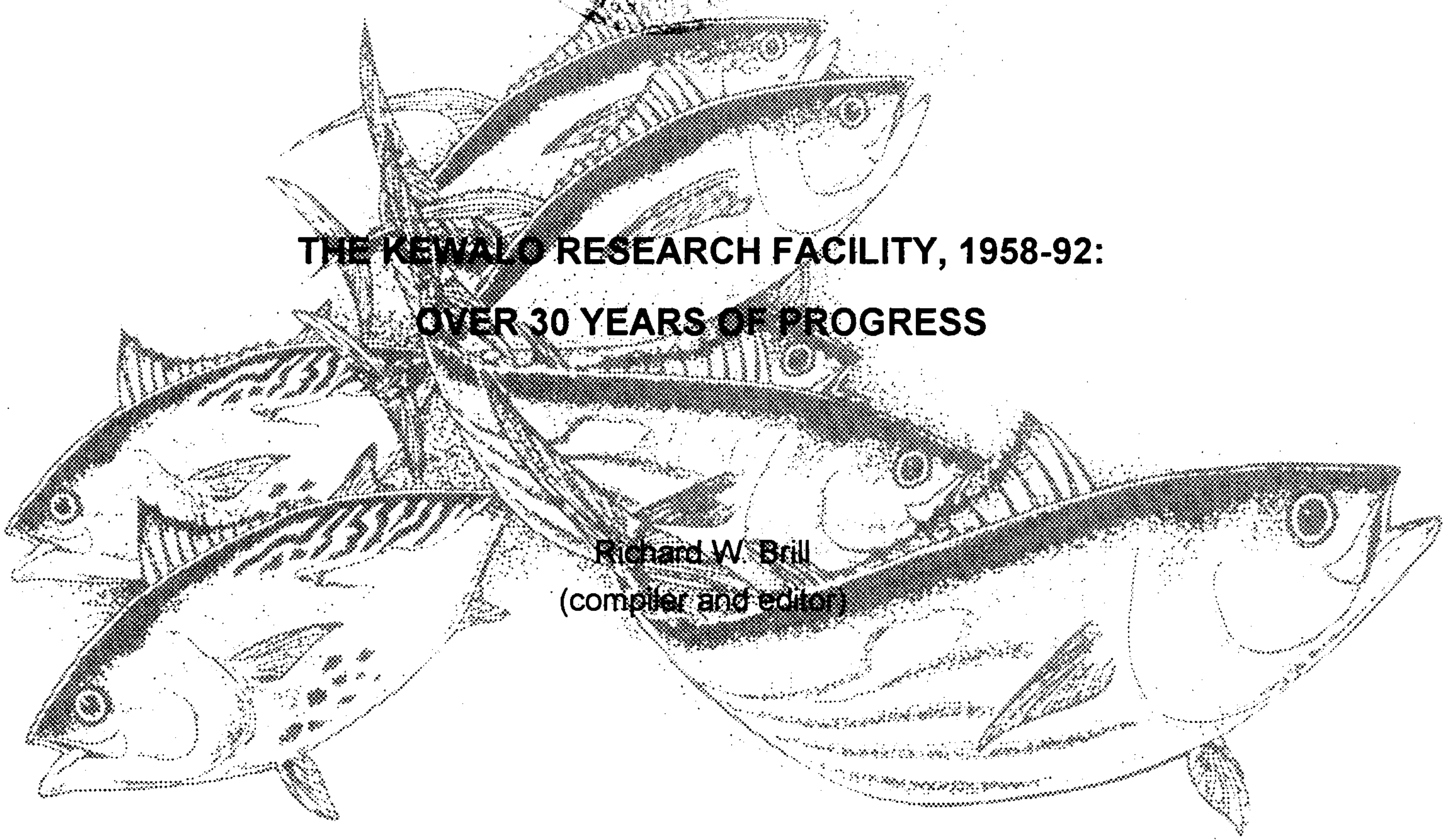

THE KEWALO RESEARCH FACILITY, 1958-92: OVER 30 YEARS OF PROGRESS

Richard W. Brill
(compiler and editor)

NOAA-TM-NMFS-SWFSC-171

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Southwest Fisheries Science Center

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THE KEWALO RESEARCH FACILITY

Kewalo can be translated from the Hawaiian as "the place of wailing." Historical descriptions of the area called Kewalo on the island of Oahu give meaning to the translation. In ancient times, this section of land contained a spring which was used as a place for human sacrifices. Here *kauwa* (outcasts) were first drowned before being taken to the *Heiau of Kanelaau* (temple) on the slopes of Punchbowl Crater for burning in the *imu ahi* (fire oven). Kewalo Basin, as part of the modern city of Honolulu, is of course no longer used for such purposes. Today it is the home of many commercial and recreational fishing boats, tour boats, a fresh fish auction house, and other marine-related enterprises. Kewalo Basin is also the site of the Honolulu Laboratory's **Kewalo Research Facility**.

The area occupied by the Kewalo Research Facility was once a shallow, submerged coral reef. In 1945, the U.S. Navy dredged a small harbor, which became known as Kewalo Basin and was later turned over to the Territory of Hawaii. The harbor was subsequently enlarged, and artificial and sanitary fill was dumped on the adjacent coral reef to create protective land areas. In July 1958, the Honolulu Laboratory of the National Marine Fisheries Service, then a part of the U.S. Fish and Wildlife Service, negotiated a lease to the grounds and building on the spit of artificial land created at the southeast entrance of Kewalo Basin and established the Kewalo Research Facility.

An aerial view of the Kewalo Research Facility in Honolulu, Hawaii.

The facility has a low profile and goes unnoticed by the many tourists, surfers, and fishermen that frequent the area. But within the 0.4 hectare (0.98 acre) area is a unique research laboratory. The main building houses offices, laboratories tailored for various research activities, a machine shop, and storage areas. A saltwater well on the adjoining grounds has the capacity to produce high-quality, coral-filtered seawater at a rate of over 3,785 liters (1,000 gallons) per hour. The seawater is pumped to aerators to be oxygenated and then distributed to various tanks, including a series of five 75,706-liter (20,000-gallon) circular pools, a 757,060-liter (200,000-gallon) oceanarium, and specially designed experimental tanks of various sizes.

The Kewalo Research Facility is today, as it has been since its inception, the only research center in the world capable of maintaining live tunas in captivity throughout the year for use in behavioral and physiological research. The uniqueness of this facility and the past 30 years of quality research have engendered it an enviable international reputation. Indeed, its reputation continues to attract established scientists of diverse backgrounds and expertise to this unique laboratory where experiments that require live tunas and other marine animals can be conducted.

In recent years, the role of the Kewalo Research Facility has expanded. It has served the research needs of scientists charged with the responsibility of enhancing the survival of threatened and endangered species, such as the Hawaiian monk seal (*Monachus schauinslandi*) and green sea turtle (*Chelonia mydas*). The Facility now has a fully functional larval culture laboratory which has successfully reared, from eggs, species as diverse as mahimahi (*Coryphaena hippurus*), spiny lobster (*Panulirus marginatus*), and deepwater shrimp (*Heterocarpus* spp.).

RESEARCH ACTIVITIES

The Early Years

Tuna stocks are distributed throughout the world's oceans and form an important economic resource for many countries. The value of worldwide tuna catches is currently estimated at close to $4 billion each year. The United States alone consumes over 600 million pounds of canned tuna per annum, valued at approximately $1 billion. Despite the high economic value of tuna stocks, very little research had been done with live specimens before 1958, because no facility existed to maintain tunas in captivity. Analyses of fisheries data showed correlations between the apparent abundance of tunas and various oceanographic and meteorological conditions, but the mechanisms that determine the horizontal and vertical distributions, migrations, and vulnerability of tunas to specific types of fishing gear were completely unknown. Temperature, oxygen, and salinity all seemed to exert an influence. Predicting the changing abundance and gear vulnerability of the various tuna species that comprise the resource was obviously a major biological problem and impediment to effective management.

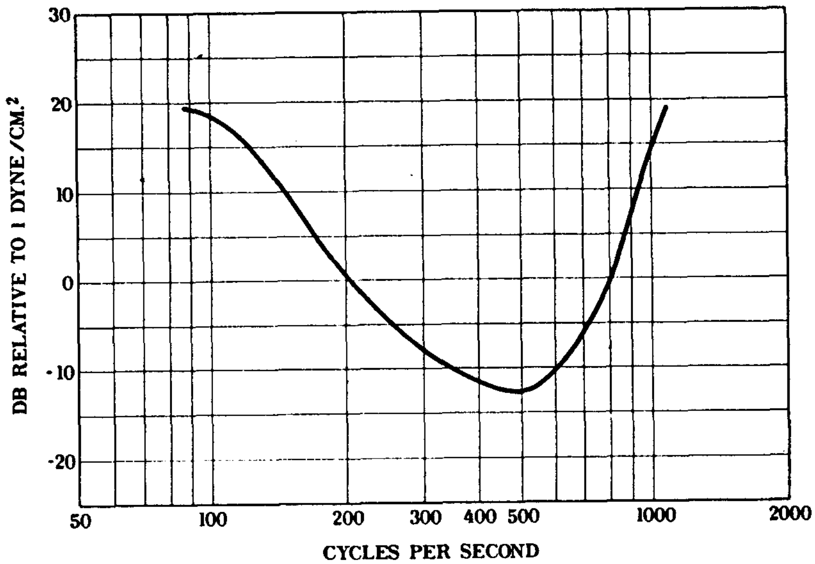
The initial goal of the Kewalo Research Facility was the development of procedures for keeping live tunas in captivity for experimentation. Because this was truly a pioneering effort, early research was aimed at collecting data that would serve as the foundation for future investigations. This early work uncovered several interesting facts about tunas:

- Tunas are heavier than water and must continuously swim to keep from sinking.
- Tunas breathe by simply opening their mouths so that water is forced over their gills as they swim; they sink and suffocate if they stop swimming.
- Basal swimming speeds of tunas are dependent upon the lifting area of fins and the density of the fish and are not a function of either respiratory requirements or the search for food.
- All tunas have the following adaptations for continuous swimming: (1) a high hemoglobin level in the blood to carry sufficient oxygen to maintain continuous muscle activity; (2) a large proportion of the muscle composed of red muscle fibers specialized for continuous activity, as are the muscles of the heart; and (3) a streamlined body shape to reduce hydrodynamic drag.
- Larger species of tunas have evolved two morphological features to reduce the energy required to keep from sinking: (1) pectoral fins became larger to produce more lift; and (2) gas bladders developed to decrease density. [Although gas bladders are very effective in reducing fish density, they limit the vertical movements of tunas. A fast, vertical ascent to the surface can cause large changes in volume and, in extreme cases, burst the gas bladder. Small species of tunas, such as skipjack tuna (*Katsuwonus pelamis*), do not have gas bladders.]

Other early experiments were designed to determine the sensory abilities of tunas--how well they smell, taste, hear, see, and sense changes in water temperature. The rationale for these studies was that a basic understanding of the sensory capabilities of tunas would be useful in designing fishing gear, developing new fishing methods, and locating tunas.

To determine how well tunas can see, studies were conducted on their visual acuity (the ability to see the fine details of objects). Of the three species tested, it was determined that yellowfin tuna (*Thunnus albacares*) can see better than skipjack tuna which, in turn, see better than kawakawa (*Euthynnus affinis*). Further experiments on the optical system of restrained tuna showed that they are color-blind and are most sensitive to blue light.

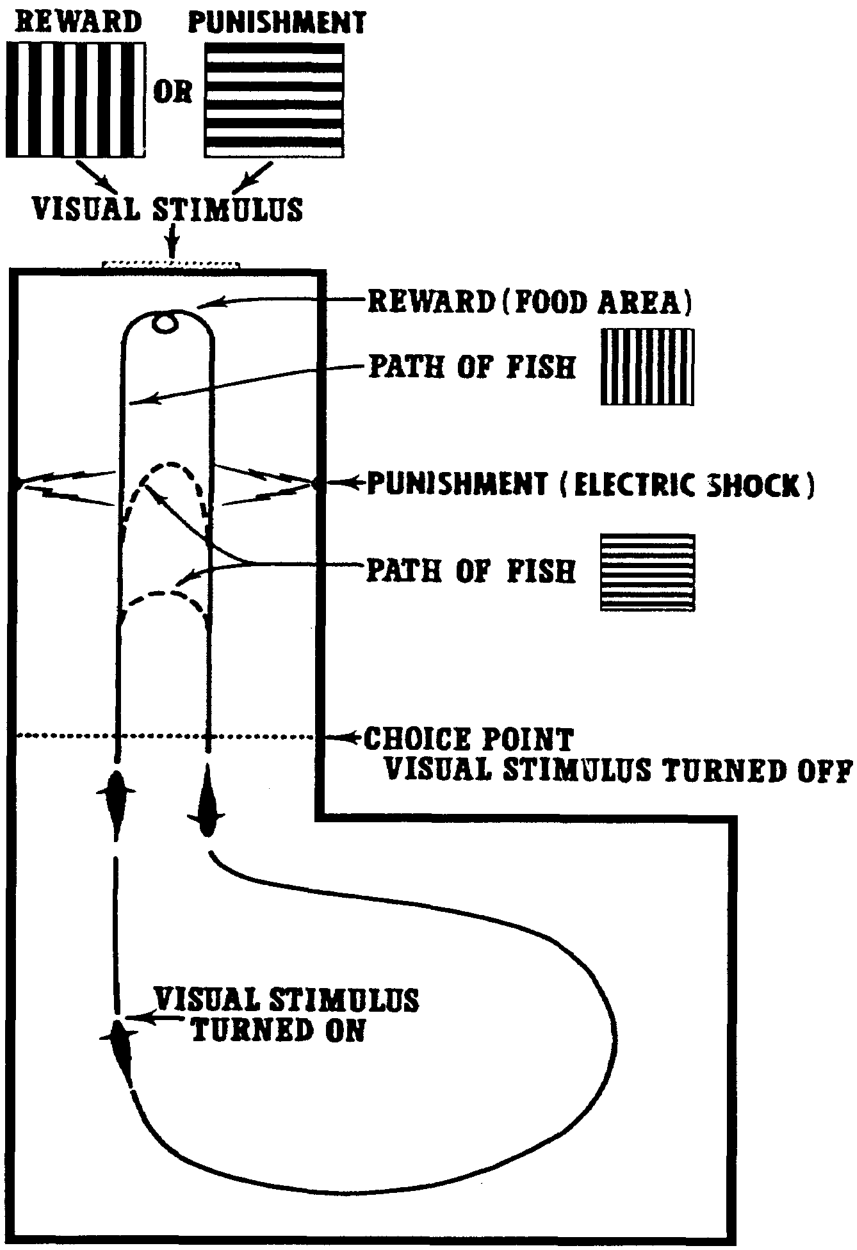
Experiments to define the hearing ability of tunas made it possible to construct a tuna hearing curve--the first ever for a scombrid--and to determine their auditory thresholds (the lowest level of sound that can be heard at a specific frequency). The hearing range of yellowfin tuna is about 200-2,000 hertz (cycles per second), and their hearing is most acute at 500 hertz.



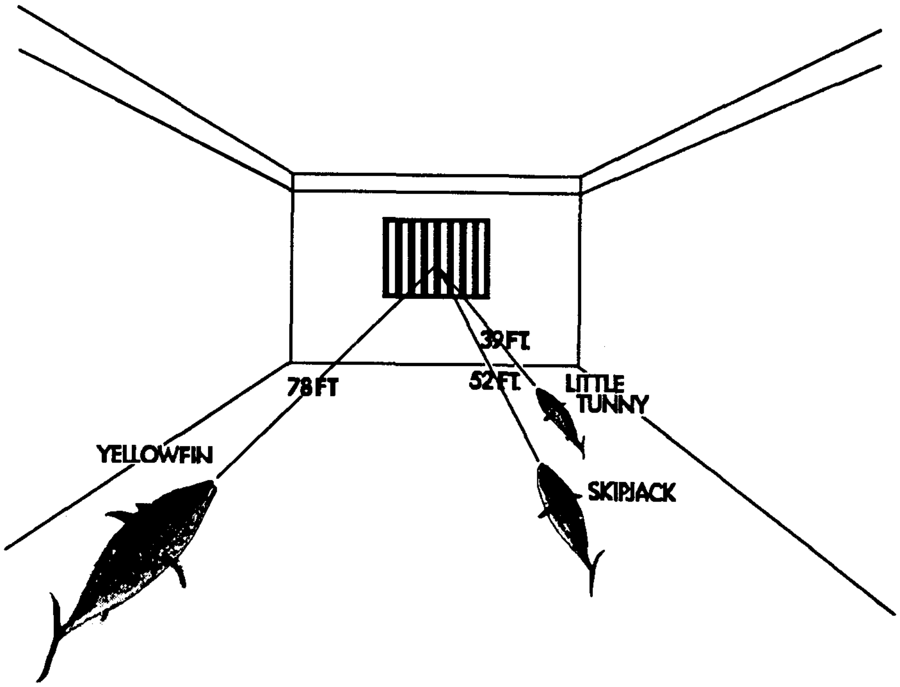
Experiments to determine the hearing ability of tunas were conducted in a pool specially constructed to insulate the fish from outside sounds and electronic interference. The test fish were first trained to recognize a pure "white" sound and then to react to the sound stimulus by swimming through a maze for a reward. The yellowfin tuna best hears sounds that are near 500 Hz, as shown by the dip at that frequency in the hearing curve. Sounds near this frequency (e.g., the sound produced by the swimming of a school of small fish) are common in the ocean.

Experiments at the Kewalo Research Facility also showed that tunas have a highly developed sense of smell. A strong response was elicited from a school of kawakawa when a liter (1.06 quarts) of water in which a small fish (a smelt weighing 10 grams or 0.4 ounce) had been dipped for 10 seconds was introduced to their holding tank. The response was elicited even though the water had been further diluted by its introduction through the inflow seawater system! A study of the morphological structure of the nares (nose) of the tunas revealed that they can "sniff" the water. Each jaw movement of a tuna produces a pumping action that forces water past its nasal rosettes (odor receptors). Observations of fish in captivity showed this pumping action to be continuous.

Two other research projects were designed to determine the ability of tunas to perceive changes in water temperature. One experiment made use of the observation that the heart rate of a restrained tuna slows when the fish is presented with an external stimulus, such as a change in water temperature. In the second experiment, a free-swimming fish was rewarded with food each time it was able to recognize a temperature difference when cooler or warmer water was added to the tank. In restrained fish, a temperature change of 1°C elicited a response. Free-swimming fish were able to do even better; they perceived a temperature difference of as little as 0.1°C.



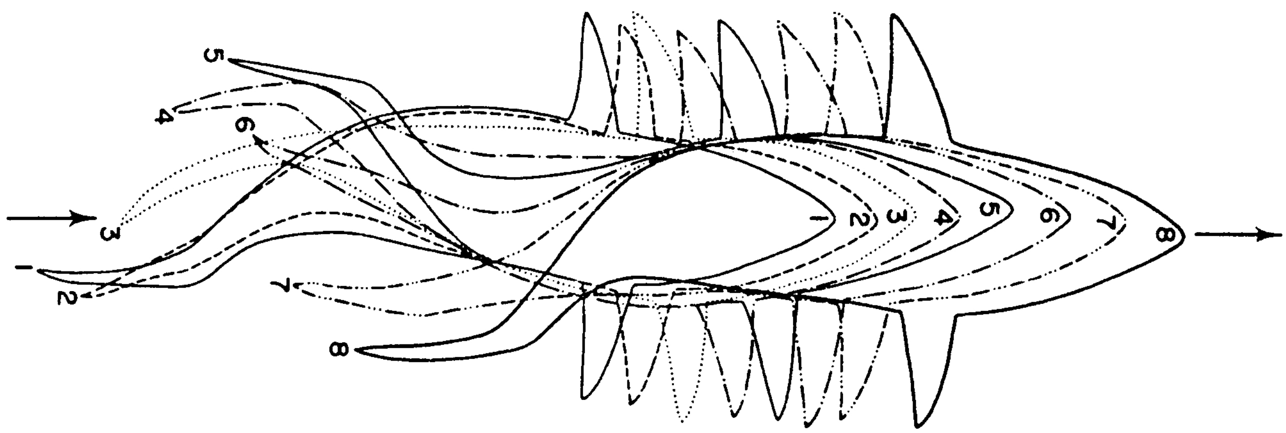
This diagram illustrates the experimental method used to determine the visual acuity of tunas. The method involves training a fish to respond to a visual stimulus (horizontal or vertical stripes), projected on an opal glass plate placed against a tank window. When the stripes are vertical, the fish is trained to swim down the tank to a food-drop area where it is rewarded; when the stripes are horizontal, the fish is trained to turn before reaching the food-drop area and to return to the far end of the tank. If the fish fails to turn, it receives a mild electrical shock.



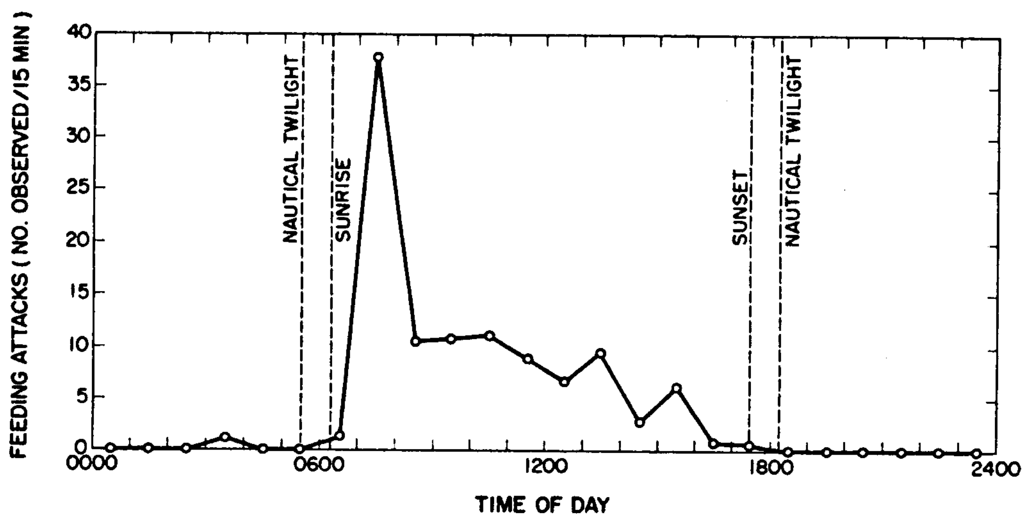
To measure tunas' reactions to various sensory stimuli, an observer must be able to detect the fishes' responses to these stimuli. Tunas can be trained to perform a specific act in response to stimuli if they are rewarded. To measure how well they can see, tunas were trained to respond differently to vertical and horizontal bars, which were projected onto an underwater screen by giving rewards (food) or punishment (electric shock). These experiments showed that at a constant brightness, a yellowfin tuna sees details of an object better than a skipjack tuna which, in turn sees better than a kawakawor a little tunny.

Early work on the feeding and digestion rates showed that tunas can digest a meal several times faster than other fish species. Prey organisms are not homogeneously distributed in the open ocean, but are found in patchy concentrations in space and time. Tunas therefore exist in a "feast or famine" situation and must eat whenever they find food. Knowledge of digestion and feeding rates of fishes adapted to such environments is important for understanding growth and worldwide distribution of tunas and can be of practical value to commercial fishermen.

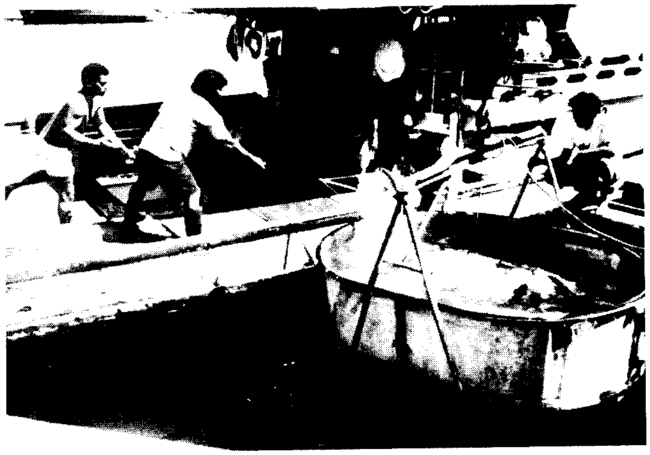
As techniques for capture, transport, and maintenance of tunas improved, the number of live tunas available for experimental purposes increased proportionately. This made it possible to increase the variety of behavioral and physiological studies conducted at the Kewalo Research Facility.



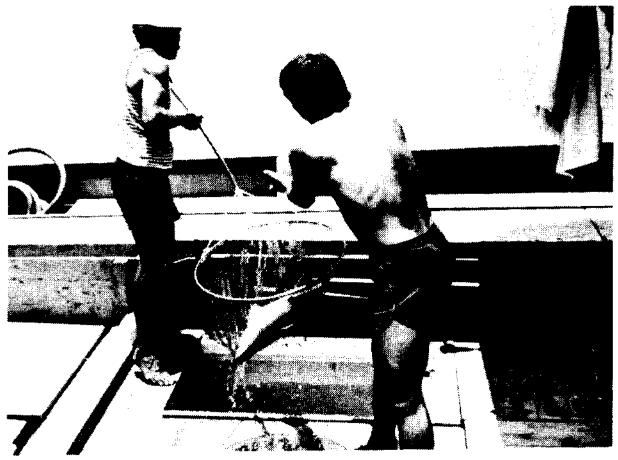
Specialized tanks at the Kewalo Research Facility made it possible to closely observe captive fish and produced the first high-speed movies of swimming kawakawa. The analysis of the film provided intimate details of swimming speed, tail beat rates, body postures and flexures, and how the changing positions of fins and finlets provide drag reduction features. It was determined that the tail provides nearly 100% of the forward thrust and the fish attains burst speeds of twice that of nonscombrid fish. The line drawing shown here was traced from successive cine frames (camera speed, 100 frames per second) for one complete caudal fin beat cycle of a kawakawa. The swimming speed of this fish was 8.2 body lengths per second, which was produced by a tail beat frequency of 14.3 tail beats per second.



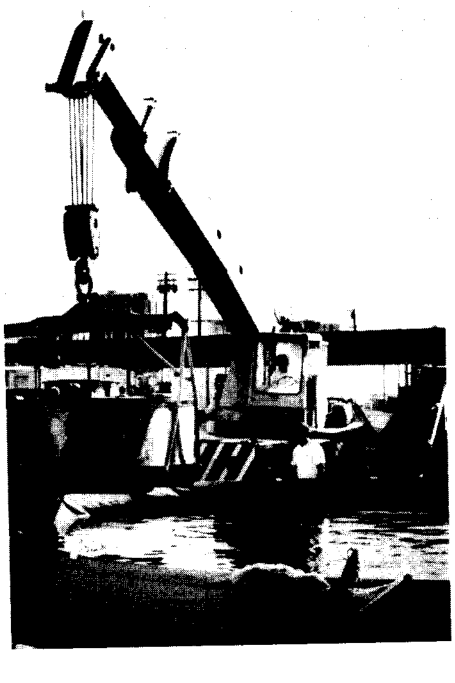
The changes in the feeding activity of kawakawa during a 24-hour period as shown in this graph is typical for all tunas. When tunas in captivity were provided with a constant supply of food, feeding motivation was highest at early morning, followed by a rapid decrease through noon and two smaller peaks at mid-afternoon. They showed no attempts to feed at night. This behavior is consistent with the high consumption and digestion rates which are from two to five times faster than those of other fish. When tunas are fed continuously, an equivalent of 15% of body weight or two times their stomach volume is eaten. The drive to attack prey is dependent on the amount of food in the stomach. Intense feeding always occurs in the morning when the stomach is empty. However, the stomach is not filled to capacity at the first feeding frenzy, and the fish feeds throughout the day. Feeding slows when the stomach is 80% filled.

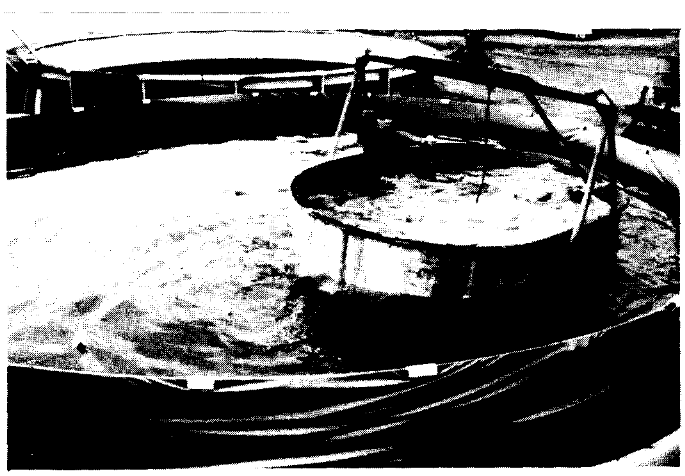


Live tunas are caught with barbless hooks by cooperating commercial pole-and-line fishermen and then dropped into the vessel's bait-holding tanks.

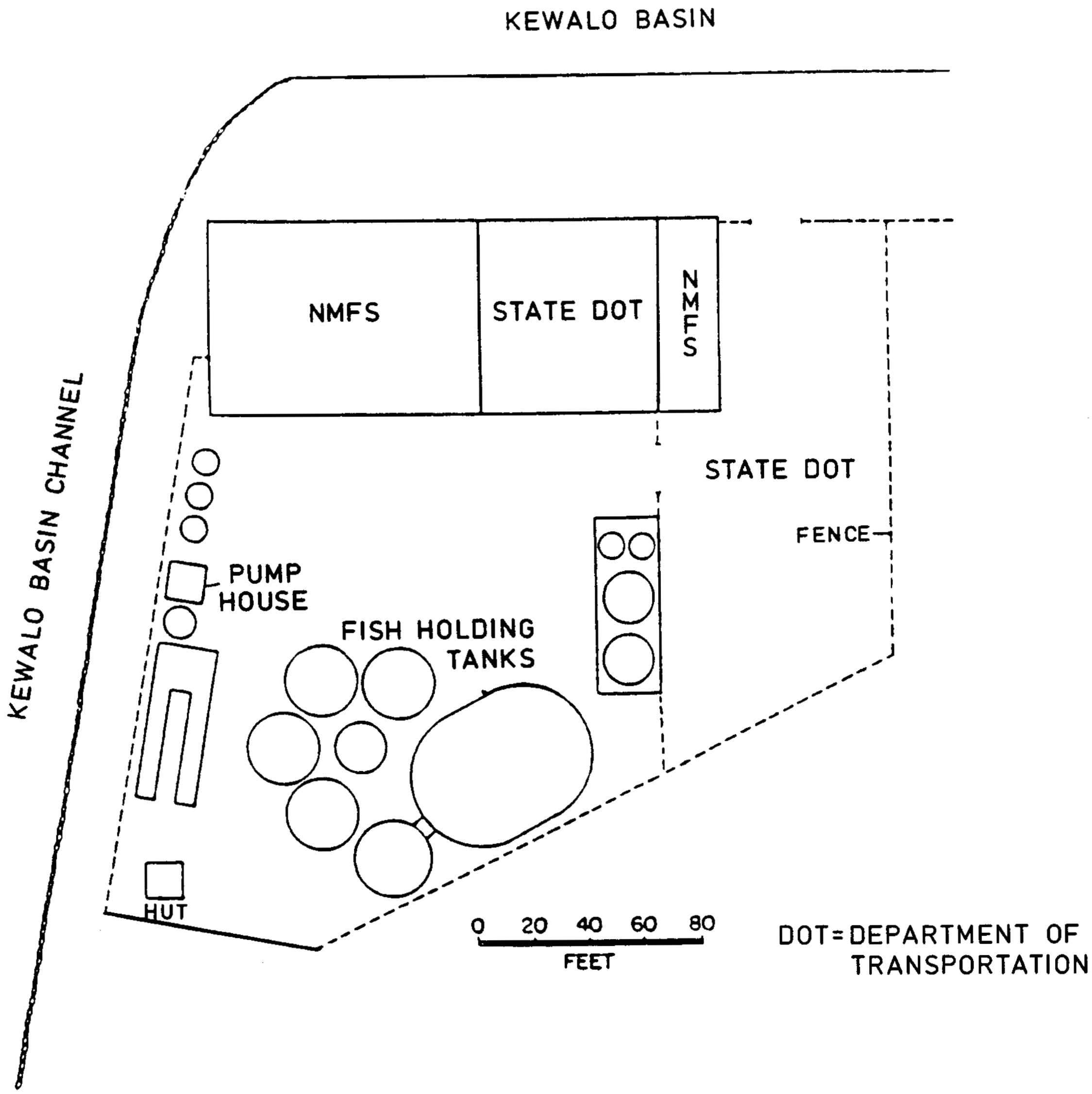


When the vessel returns to Kewalo Basin, the fish are moved to a transfer tank with a chamois-lined dip net.





The transfer tank is then transported by a crane and lowered into a holding tank where the fish can swim freely. This handling technique, which has evolved over the years, minimizes injury to the fish.



The Kewalo Research Facility is able to obtain and maintain tunas in captivity because of several conditions unique to its site. Commercial live-bait tuna fishing boats dock in front of the Facility. Also, because the Facility was built over a filled-in coral reef and Hawaii has a mild climate, the saltwater well is able to provide clean seawater at the appropriate temperature for holding tunas year-round.

The Later Years

Tunas

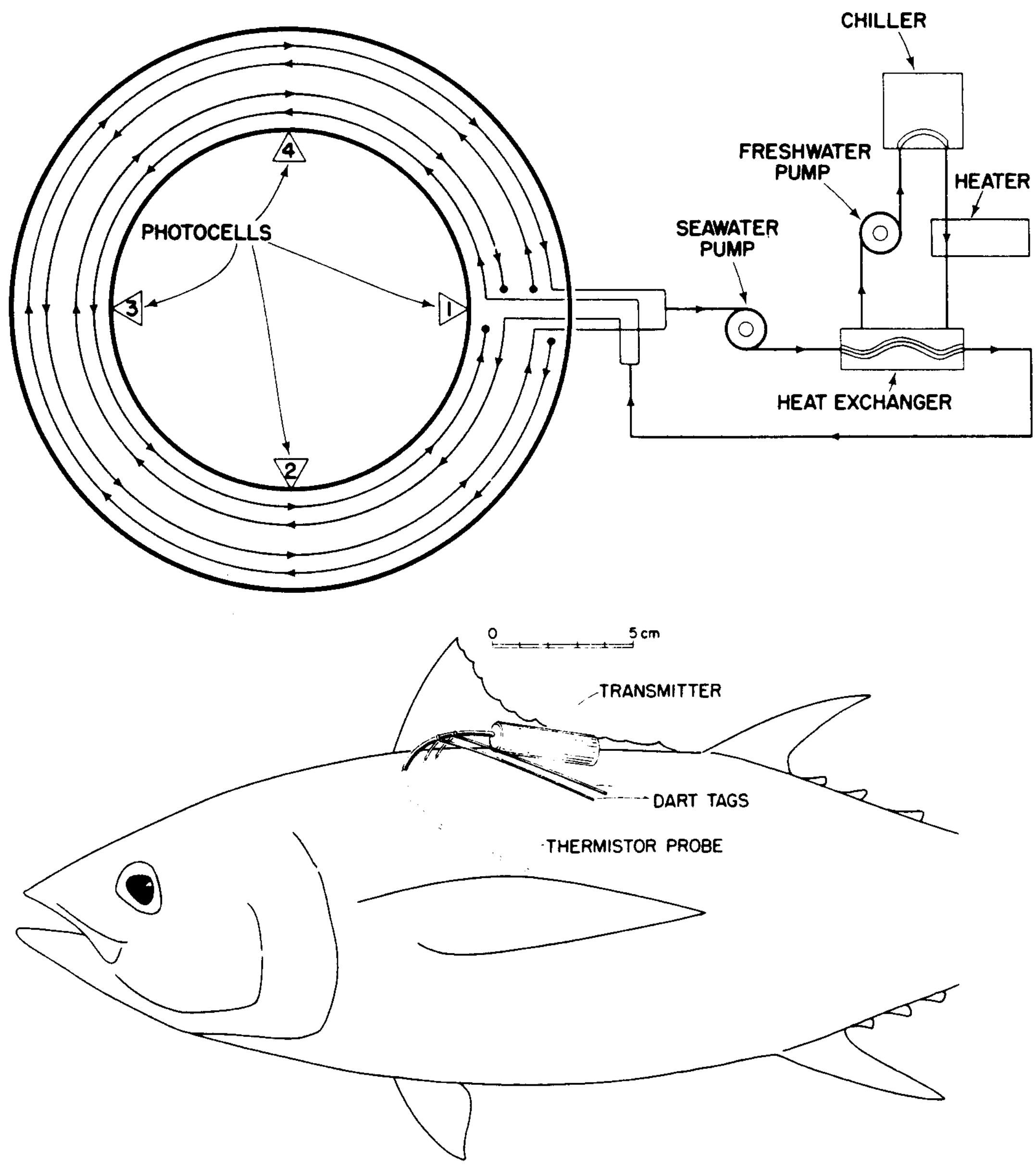
Thermoregulation--Additional studies at the Kewalo Research Facility confirmed that tunas have a remarkable ability to maintain body temperatures higher than the water in which they swim. This ability is attributable to vascular countercurrent heat exchangers that retain the heat produced by metabolic activity within the muscles. In other fishes, metabolic heat is lost to the surrounding water via the gills and body surface. As a predator, the ability to maintain an elevated body temperature probably gives tunas an advantage over other fishes, because it allows them to operate at higher activity levels. Depending on the activity and size of the fish, muscle temperatures of tunas can range from 2° to 21°C above ambient.

The accumulation of knowledge on the effects of temperature on tuna physiology allowed work on more sophisticated experiments, such as those designed to determine whether tunas can physiologically or behaviorally thermoregulate. The first evidence of physiological thermoregulation in tunas was obtained in experiments with yellowfin tuna. Fish, placed in a doughnut-shaped tank, were able to alter their rates of heat loss independently of swimming speed (that is, physiologically thermoregulate) as the water temperature was changed at 12-hour intervals. This ability to physiologically thermoregulate, however, has not yet been demonstrated in all species of tuna.

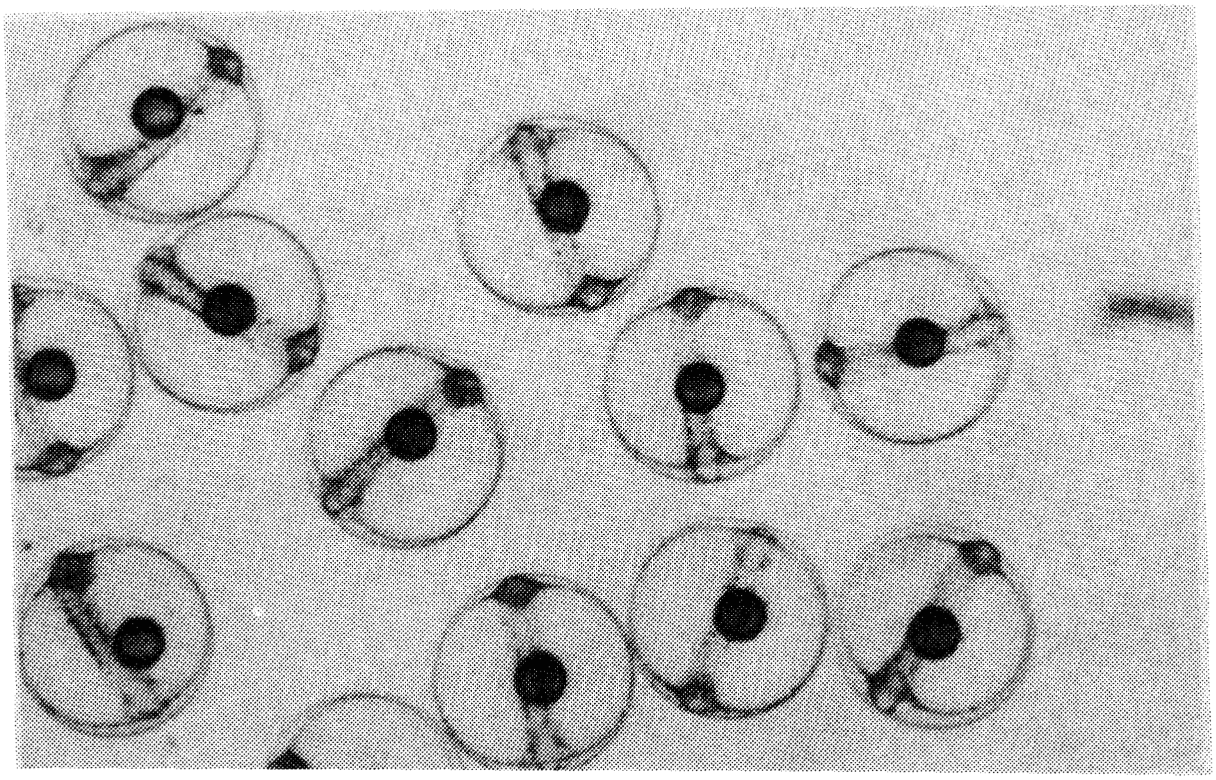
Energetics--Tuna metabolic rates present interesting paradoxes. Tunas have higher energy demands than other fishes, yet they inhabit a very food-poor environment: the tropical oceans. How do tunas obtain energy when they live in a virtual desert? Surprisingly, tunas require more energy to swim at their cruising speed than do other fishes swimming at the same speeds, despite tunas' having a streamlined shape and five swimming fins which can each be withdrawn into a slot or recess leaving the body surface perfectly smooth. Shouldn't tunas be more energy efficient?

The measurement of tuna metabolic rates has a long history at the Kewalo Research Facility. Past projects included measuring standard metabolic rate (metabolic rate at zero activity) and studying the effects of size, temperature, and speed on active metabolic rate. More recent work was designed to reexamine earlier results, which were based on oxygen consumption (respirometry), by directly measuring changes in the energy content (calorimetry) of individual fish.

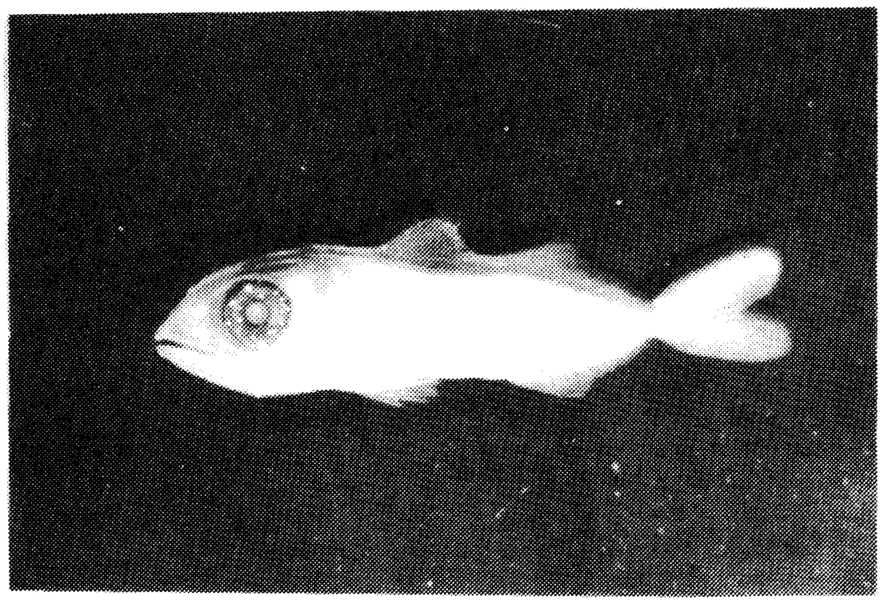
The answer to the paradox of high metabolic rates may come from the advantages they provide with respect to agility and mobility in hunting and capturing prey. Studies indicated tunas become more efficient than other fishes at higher swimming speeds. For tunas, high metabolic rates during low activity appear to be a physiological necessity for greater efficiency at high swimming speeds during feeding or when escaping from predators. The unique ability of tunas to conserve metabolic heat may also make high metabolic rates advantageous by keeping the tunas' swimming muscles warm when they penetrate cold, deep water in pursuit of prey.



Schematic diagram of the annular test tank (doughnut tank) system used to measure the physiological thermoregulatory ability of skipjack and yellowfin tunas. Seawater is delivered to and removed from the swimming channel through countercurrent perforated pipes, so that longitudinal temperature gradients do not develop. A computer continually calculates fish swimming speed based on data coming from the four photocells which monitor fish position in the swimming channel. The fish's deep red muscle temperature is measured by a thermistor probe connected to an ultrasonic transmitter. In this way, muscle temperature could be measured in free-swimming fish. Water temperature is controlled within 0.05°C by a heater and chiller system.



These skipjack tuna eggs are within an hour or two of hatching. The dark spot visible in each egg is an oil globule that provides energy and ensures flotation for the tiny egg, whose actual size is smaller than 1 millimeter in diameter.



This skipjack tuna larva is 26 days old (actual size: 16.72 millimeters long).

Spawning and rearing--The first successful attempts to artificially induce spawning in captive tunas were accomplished at the Kewalo Research Facility. The technique involved a periodic biopsy of kawakawa to determine the developmental stage of the eggs in the ovaries. After the eggs attained a critical size, hormone treatments were administered to induce spawning.

Eventually, because of advances in techniques and knowledge, hormone treatments were no longer used, and during the summer months, skipjack tuna were routinely spawned in the shoreside tanks of the Facility. This enabled researchers to investigate many of the techniques needed to rear larval pelagic fishes.

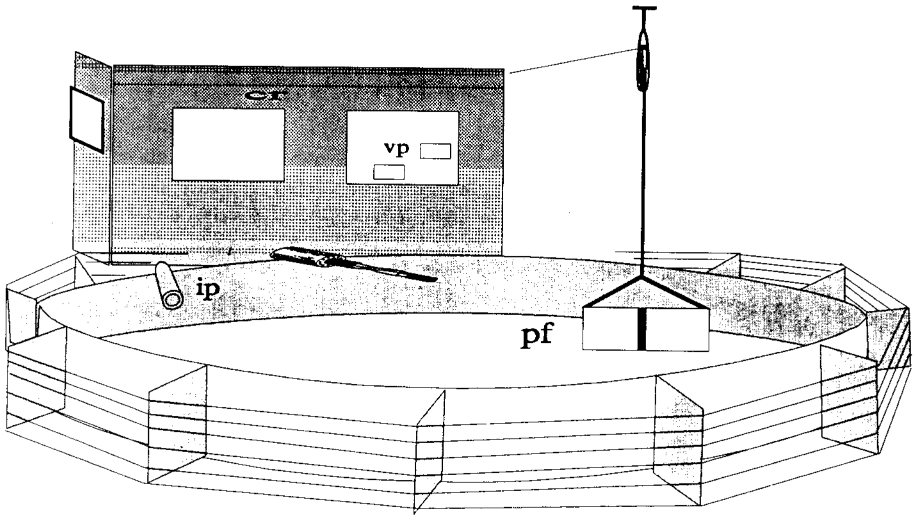
It was discovered that tuna eggs hatch about 24 hours after fertilization, and the yolk sacs of larvae are absorbed in about 2 days. At this critical stage, larval tuna must forage for food. To meet their nutritional requirements, a culture system for phytoplankton, rotifers, and copepods was begun and is continued today. The technology developed to rear larval tuna has opened new fields of research that focus on the previously unobservable, day-to-day development and early life history of pelagic fish.

Building upon the experience gained with tunas, subsequent studies involved spawning and rearing mahimahi (*Coryphaena hippurus*). Besides basic studies on the nutritional requirements, energetics, and growth of larval mahimahi, a series of studies on the species' tolerance to cold shock was also undertaken. These later experiments were designed to help assess the potential impacts of large-scale ocean thermal energy conversion projects, which move massive amounts of deep, cold ocean water to the surface in a process (roughly analogous to a steam turbine) that generates electricity. Although this process produces no air pollutants, unlike fossil-fuel based electricity production, the potential biological impact of the cold water brought to the surface needed to be evaluated. Again, the Kewalo Research Facility with its unique combination of animal holding facilities and laboratories proved an ideal place for the work.

Geomagnetic sensitivity--Tunas are among the most highly migratory fishes. They routinely make transoceanic migrations but also can precisely navigate on a daily basis. An understanding of the mechanism guiding the daily movements and long distance migrations of tunas is therefore central to understanding the biology of these species.

Since migration represents a substantial investment of energy, there has probably been intense evolutionary pressure to develop accurate sensory systems capable of guiding these movements. However, no special abilities useful in navigation had been detected among the tunas' common previously recognized sense systems (vision, smell, taste, etc.). Yet one other possibility existed: Tunas could possess a magnetic compass sense.

After the discovery that yellowfin tuna have up to 10 million crystals of magnetite (a biologically generated magnetic crystal) in the ethmoid bones of the skull and that the fish produce the magnetite under very closely controlled conditions of size, shape, and chemical composition, studies were undertaken to test the ability of yellowfin tuna to discriminate between different magnetic fields. The fish were trained to perform a



This system is for measuring the ability of yellowfin tuna to detect local changes in the Earth's magnetic field. The vertical component of the Earth's magnetic field is altered by passing an electrical current through the coil of wire encircling the tank. The tuna is trained to swim though a rectangular pipe frame (pf) lowered into the tank. The fish's ability to detect the changes is measured by the number of passes through the pipe frame per minute. Correct responses are rewarded by food delivered from an automatic dispenser; incorrect responses are punished by the food reward being withheld. To avoid any possible cues being given by the researcher to the fish, all observations must be made through a one-way glass window in the small hut situated near the tank.

conditioned response (swimming through a hoop) at a consistent rate. They were then tested by being rewarded with food when one magnetic field was present in the tank and punished (food withheld) when the second field was present. If the fish were able to detect the difference between the two magnetic fields, maintaining a high rate of response during positively reinforced trials would maximize food rewards, whereas a low rate of response during negatively reinforced trials would minimize the cost of responding. Thus, discrimination would be measured as a difference in the rates at which the fish swim through the hoop in anticipation of positive or negative reinforcement. These experiments were clearly able to show that yellowfin tuna can learn to use magnetic field information to make appropriate decisions--the first proof tunas possess a magnetic sense which is probably used for navigation.

Related studies showed that a large branch of the anterior, lateral-line nerve ramifies in the area of the ethmoid bones which contain the magnetite crystals. It is therefore possible that a branch of this nerve may be associated with the magnetite crystals and form the magnetoreceptor organ, although this still remains to be determined.

Lobsters

Starting in the late 1970s, the commercial fishery targeting spiny lobster (*Panulirus marginatus*) and slipper lobster (*Scyllarides* spp.) in the Northwestern Hawaiian Islands rapidly expanded. Field research conducted by the Honolulu Laboratory showed that most small (i.e., sublegal) lobsters released after being captured in traps were eaten by fish before reaching the ocean bottom. Escape vents installed in commercial lobster traps were obviously needed to prevent this problem and to retain a viable commercial fishery. But how big and what shape should these escape vents be? Where on the traps should they be located?

Studies were begun at the Kewalo Research Facility where populations of known sizes of lobster were set up in the laboratory's shoreside tanks. Lobster traps with various sizes and shapes of escape vents were added to the tanks, and the sizes of lobsters retained were carefully monitored. Optimal results were obtained using two escape-vented panels with two circular openings of 67 millimeters in diameter. Field trials conducted in the Northwestern Hawaiian Islands using similarly equipped traps confirmed the efficacy of the vents.

As a result of this important laboratory and field research, all commercial lobster traps used in the Northwestern Hawaiian Islands since January 1, 1988, must contain these escape-vented panels.

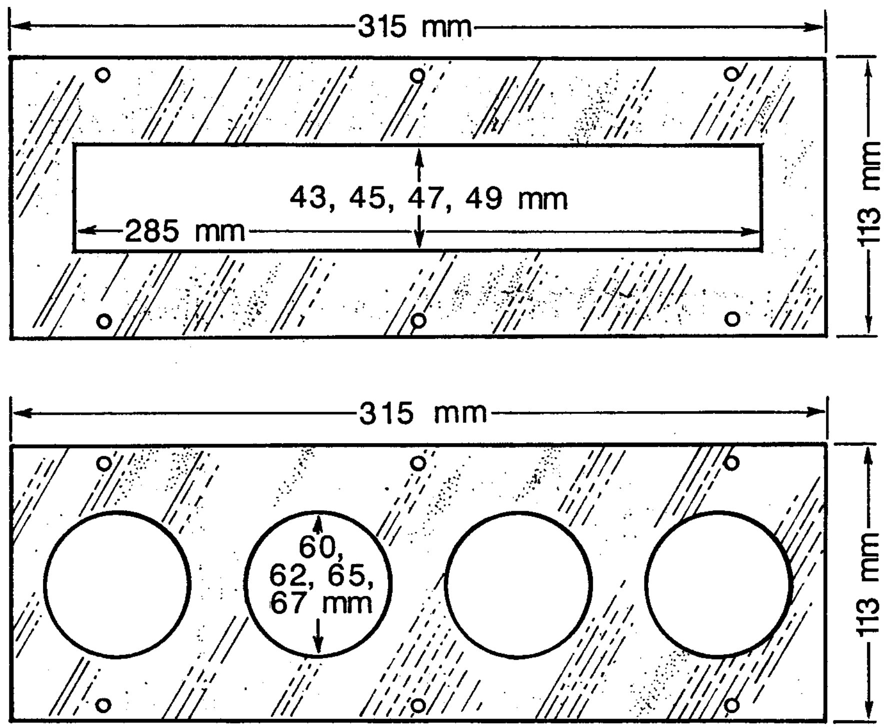
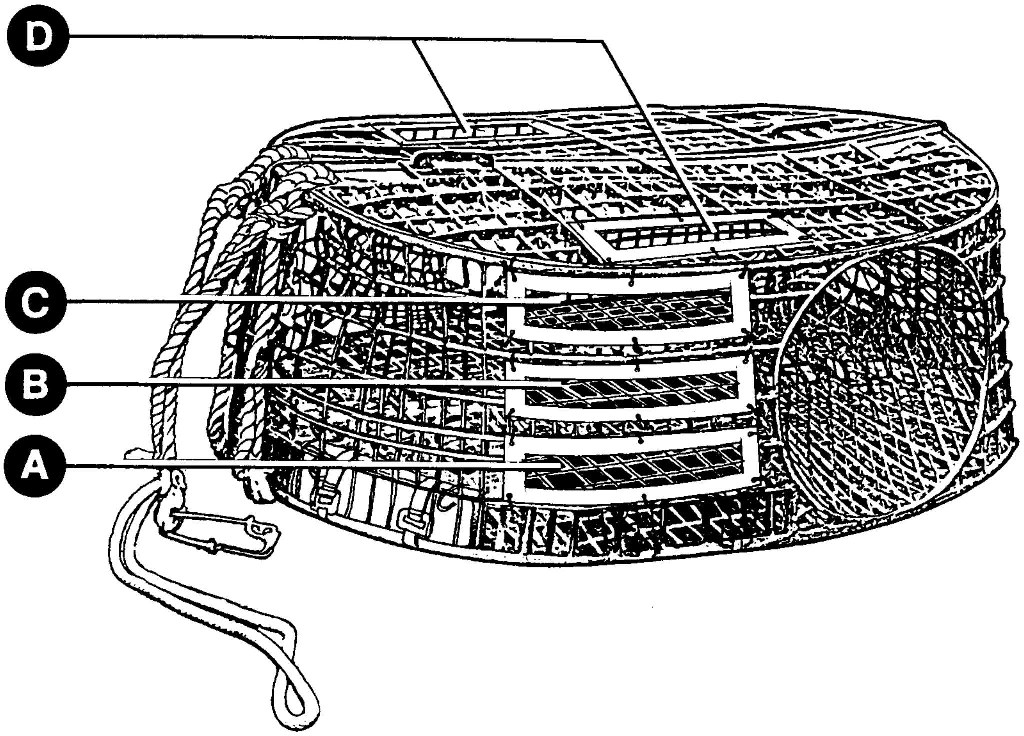


Diagram of escape vents, varying in size and shape, tested at the Kewalo Research Facility.



This diagram depicts a Fathoms Plus shellfish trap, which by 1984 had almost completely replaced the wire mesh trap used by lobster fishermen. This trap has been fitted with several escape vents that Honolulu Laboratory scientists tested to determine the locations which best allow the release of undersized lobsters. This diagram shows the vertical placement of the escape vents tested: (A) 45 millimeters from the bottom, (B) 115 millimeters from the bottom, (C) 195 millimeters from the bottom, and (D) top of trap.

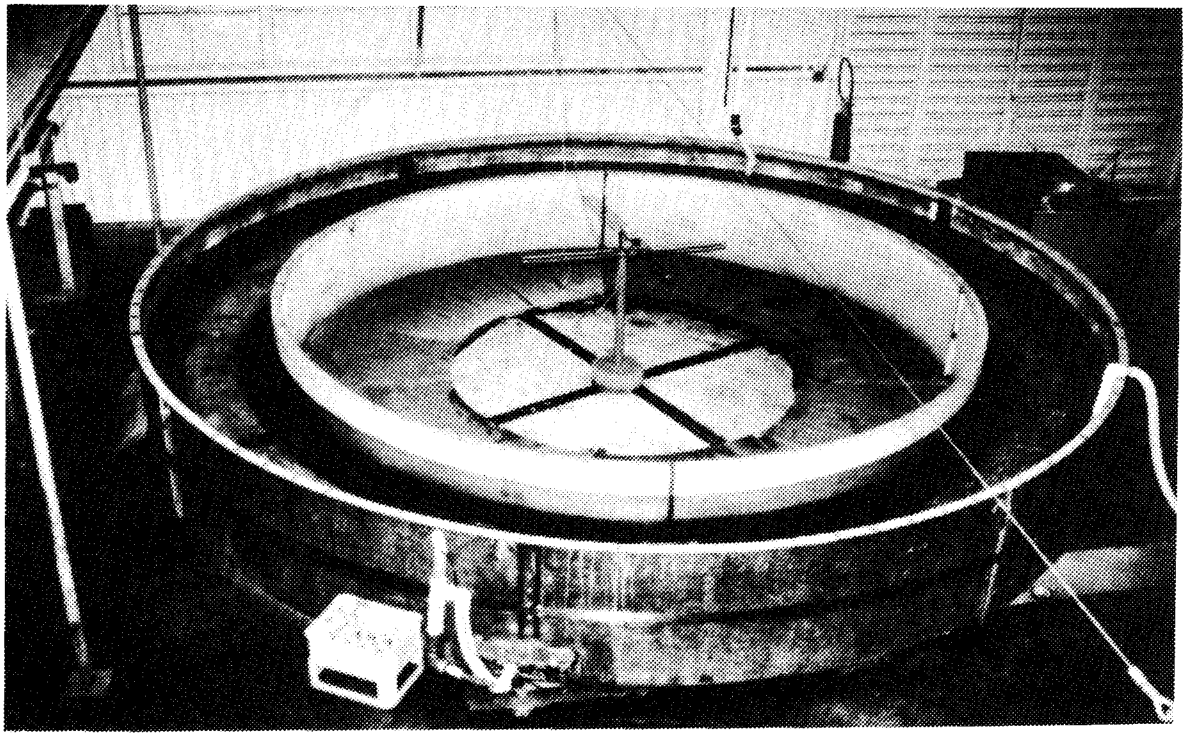
THE KEWALO RESEARCH FACILITY TODAY

Tuna Research

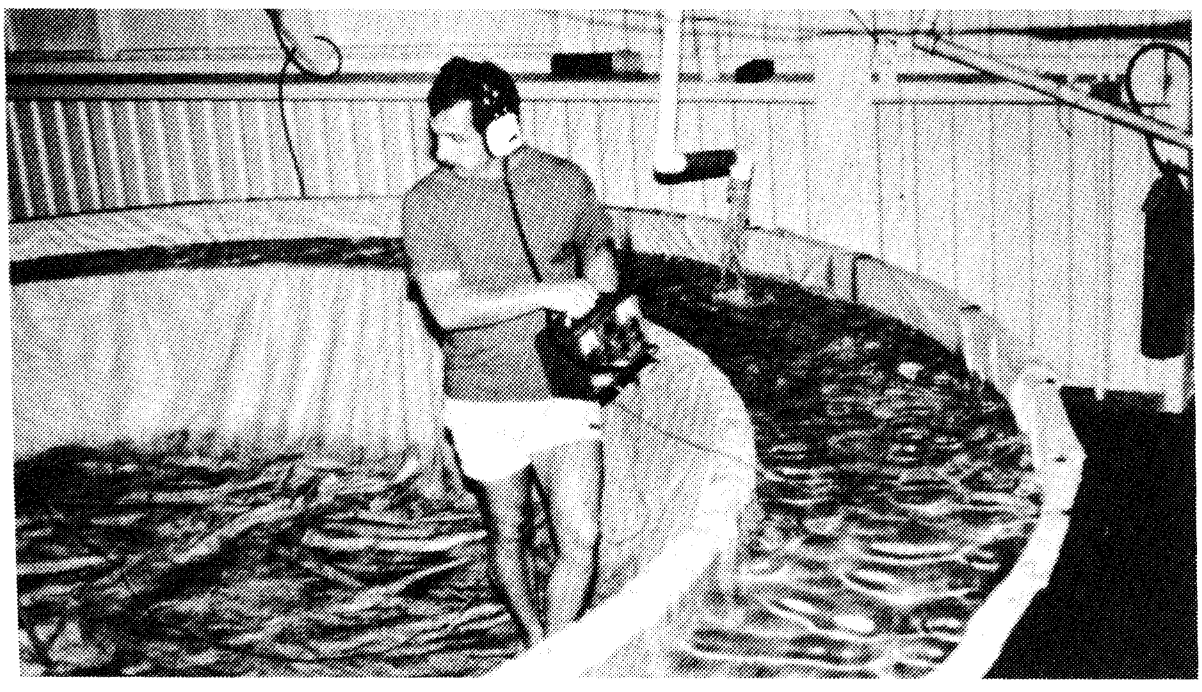
Olfaction

Work conducted 20 years ago at the Kewalo Research Facility established that tunas have an excellent sense of smell, capable of detecting the very dilute odor of their prey. Recent and ongoing research with captive tunas has shown that they can distinguish between odors of different types of prey, and that some prey odors cause stronger search behavior than others, indicating tunas probably use their sense of smell to detect prey before they come within visual range.

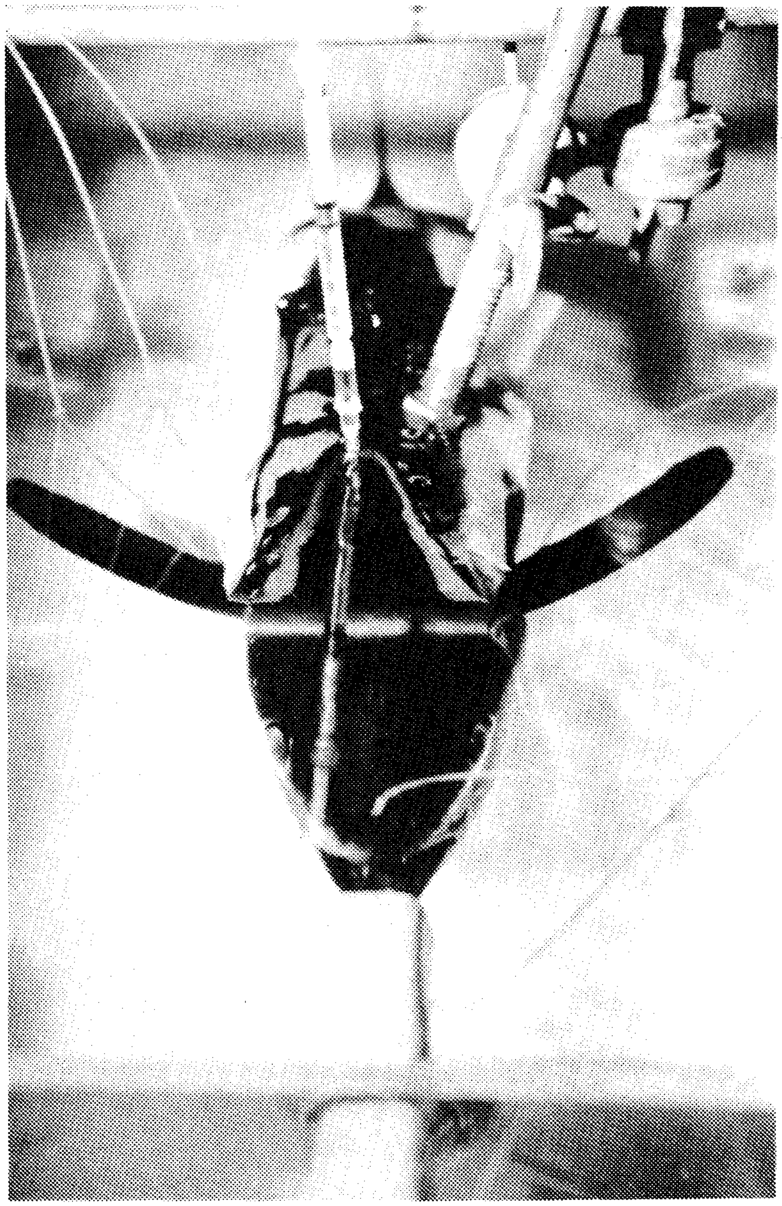
Recent research has been aimed at analyzing the chemical structure of natural prey odors, developing synthetic prey odors, and testing the efficacy of these synthetic prey odors for eliciting a feeding response. Eventually, it may be possible to use natural or synthetic odors to enhance the effectiveness of traditional fishing techniques. If an inexpensive synthetic odor can be formulated, it could be used in the live-bait and the



This "doughnut" tank is used for physiological experiments on swimming tunas. The center section of the tank is dry which allows investigators to follow a fish while carrying physiological (for example, heart rate or cardiac output) monitoring equipment. Data gathered in this manner are used to confirm similar observations made on non-swimming fish in the laboratory.



Much effort at the Kewalo Research Facility has been put forth to determine the habitat requirements of skipjack and yellowfin tunas, especially their temperature and minimum ambient oxygen requirements. Here an investigator is monitoring the cardiac output of a yellowfin tuna by using a Doppler ultrasonic blood flowmeter. The blood flow probe, mounted over the main vessel carrying blood from the heart, is carried by the fish, while the electronic instrumentation needed to quantify blood flow is carried by the investigator. The output of the blood flowmeter is sent to a chart recorder (not shown). The head phones are used to monitor the functioning of the flowmeter.



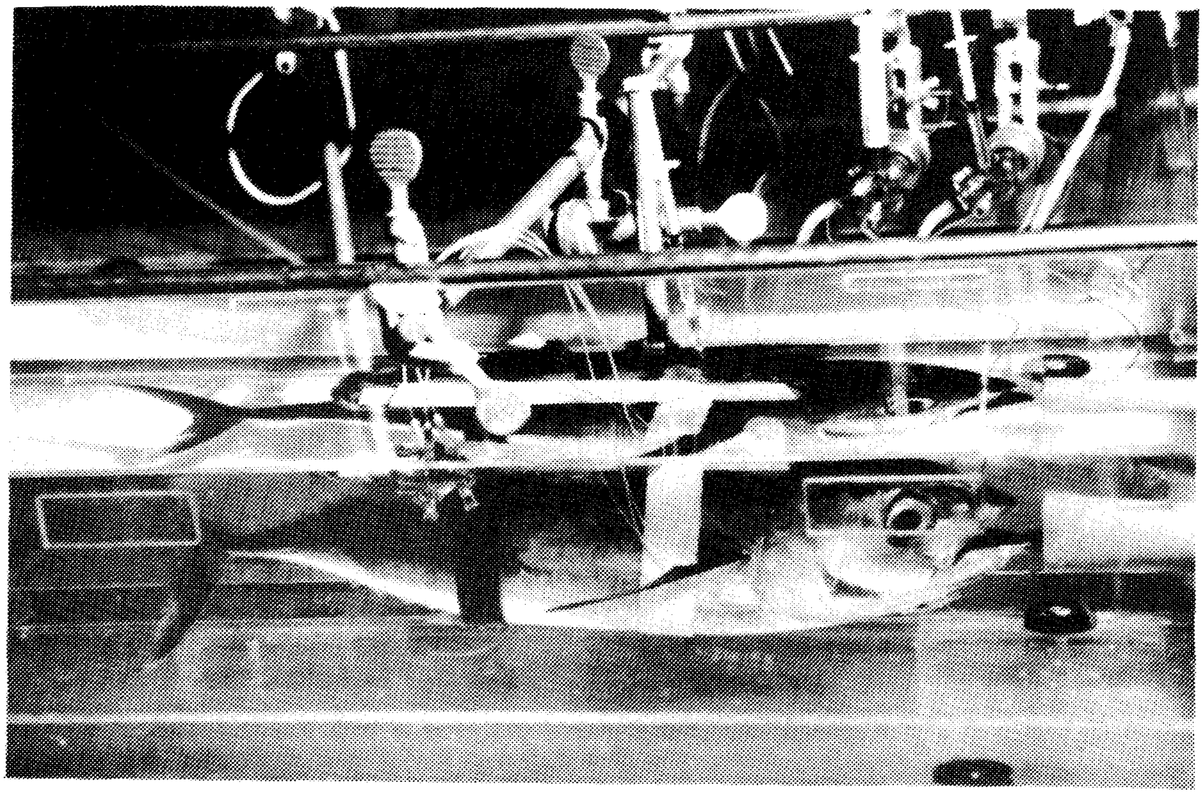
Overhead view (above photo) and side view (right photo) of a live yellowfin tuna being held on the operating table designed specifically to test the physiological responses and tolerances of tunas to changes in environmental conditions. Tunas normally must swim to ventilate their gills; however, in this situation, water is supplied to the fish by the pipe immediately in front of the mouth. With this system, blood pressure, ventilation volume, cardiac output, and other physiological parameters can be simultaneously monitored.

handline tuna fisheries to increase catch success and decrease dependency on expensive natural bait.

Research to Determine Energy and Habitat Requirements of Tunas

Mathematical models of the energetics of tunas enable scientists to better explain and predict abundance and maximum sustainable yields. A large portion of the data collected over the past quarter century at the Kewalo Research Facility has been directed toward acquiring the data necessary for these models. Results to date indicate that the growth rate of skipjack tuna less than 11.8 kilograms (26 pounds) is governed by food consumption, whereas the growth of fish larger than 15.0 kilograms (33 pounds) is limited by the energetic demands of activity. Other models, integrating data from laboratory experiments on tunas with oceanographic information, indicated the distribution of small tunas is most likely dependent on the availability of food, whereas the distribution of larger fish is dependent on environmental conditions, such as temperature and oxygen levels.

To further investigate the physiological abilities and tolerances of tunas to temperature and oxygen conditions, a laboratory specifically designed to conduct physiological experiments on tunas has been developed at the Kewalo Research Facility. The laboratory contains a vibration-free operating table with running seawater and extensive physiological monitoring equipment. The temperature and oxygen levels of the



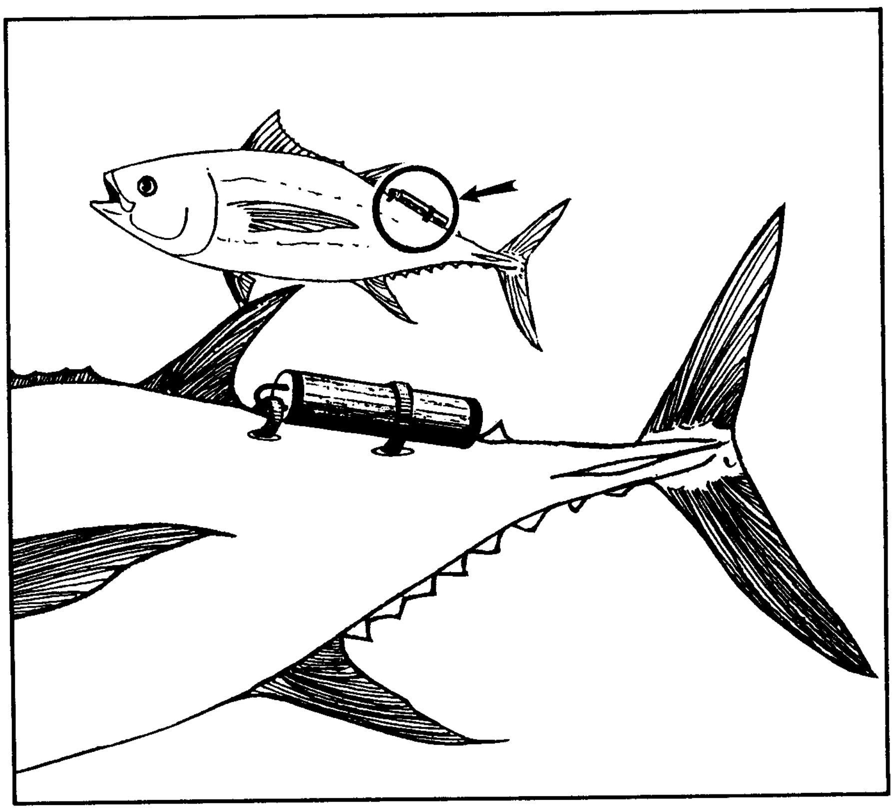
water supplied to the operating table can be closely controlled and monitored. Tunas gently restrained on the table respond normally when subjected to changes in environmental conditions.

Results of recent experiments using this system have shown that tunas are sensitive to even minute reductions in ambient oxygen; they begin making physiological adjustments to reductions in ambient oxygen far smaller than those needed to elicit swimming speed changes. Data have also been obtained on the effects of rapid temperature change on the metabolic rates and blood acid base chemistry of tunas and their truly remarkable ability to recover from strenuous exercise.

Models of the function of the tuna cardiorespiratory system (which removes oxygen from the water passing over the gills) have been recently developed using data obtained in the physiology laboratory. Surprisingly, the results generated by these models imply that the unique anatomy/physiology/biochemistry of tunas has evolved to permit rapid repayment of oxygen debts (i.e., rapid lactate metabolism) rather than high sustained cruising speeds.

Tracking Tuna Movements

The Kewalo Research Facility has at its disposal the *Kaahele 'ale*, a 33-foot research vessel equipped with sophisticated electronic and navigational equipment to track the vertical and horizontal movements of tunas and billfishes carrying ultrasonic transmitters.



This drawing depicts the placement of an ultrasonic transmitter which can be used to track tuna and other animals in the ocean. The transmitter is attached to the fish by two nylon straps that are inserted through the dorsal musculature and pterygiophores associated with the second dorsal fin.

The vessel is an integral part of the facility and is in constant demand to test the results of theoretical and experimental investigations.

Recent tracking work using the *Kaahele 'ale* has determined the short-term horizontal and vertical movements of tunas associated with fish aggregating devices (FADs). Much of the success of the tracking studies is due to the ability to hold tunas in captivity and to test various ultrasonic transmitter attachment methodologies on captive fish. The project is now moving into its second phase, that of simultaneously monitoring tuna movements and physiological parameters such as body temperature and tail beat frequency (i.e., swimming activity). The data collected in these experiments will be incorporated into more sophisticated computer models capable of predicting tuna movements, distribution, and vulnerability to specific types of fishing gear. Again, the ability to test new telemetry devices on fish held at the Kewalo Research Facility is helping to keep the tracking project at the forefront of this area of science.

Burnt Tuna

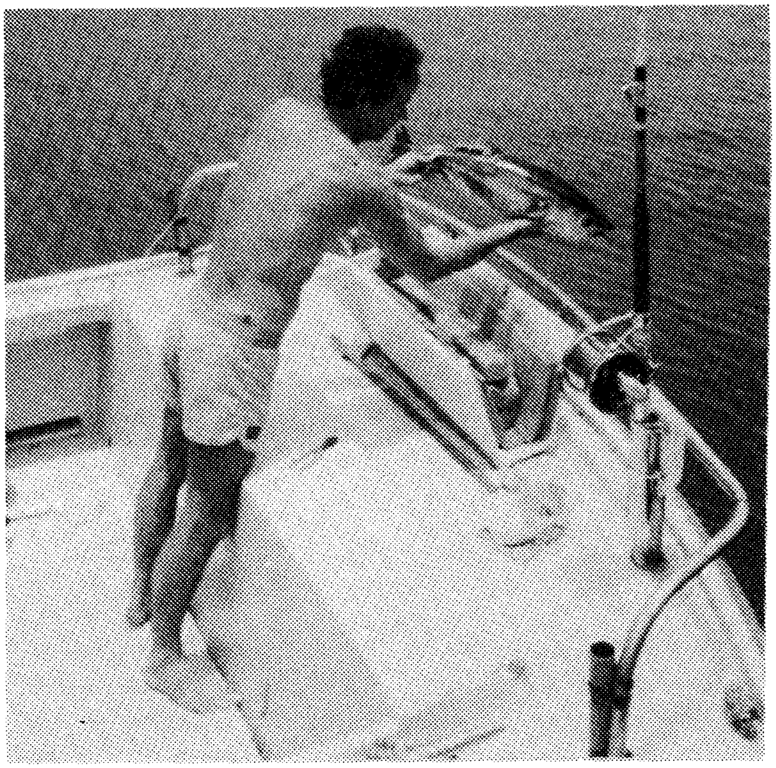
In Hawaii, the handline fishery for large yellowfin tuna and bigeye tuna (*Thunnus obesus*) land fish intended primarily for raw consumption as sashimi. The current value of the fishery is estimated at over $5 million annually. International interest in this type of fishing is growing because of its low initial capital investment, low operating and fixed expenses, strong export markets, and high profitability. Unfortunately, the tuna handline and, primarily, recreational troll fisheries are plagued by a product quality problem known as "burnt tuna" or, in Japanese, as *yake niku* (literally translated as "cooked meat"). When fish are intended for raw consumption, product quality is obviously of utmost importance.

For years, the high muscle temperatures and high muscle acidity created during the landing of large tunas on handlines were hypothesized to be the underlying cause of burnt tuna. However, when samples of burnt tuna muscle were examined at the histological and biochemical level, the observations did not fit the hypothesis. Based on the work of scientists at the Kewalo Research Facility, a new concept was developed: burnt tuna is caused by activation of the proteolytic (protein-destroying) enzyme known as "calcium activated neutral protease" or more commonly as "calpain." Current efforts are directed at proving this hypothesis, developing a thorough understanding of the etiology of burnt tuna, and, more importantly, developing strategies that could be used by fishermen to successfully mitigate this problem.

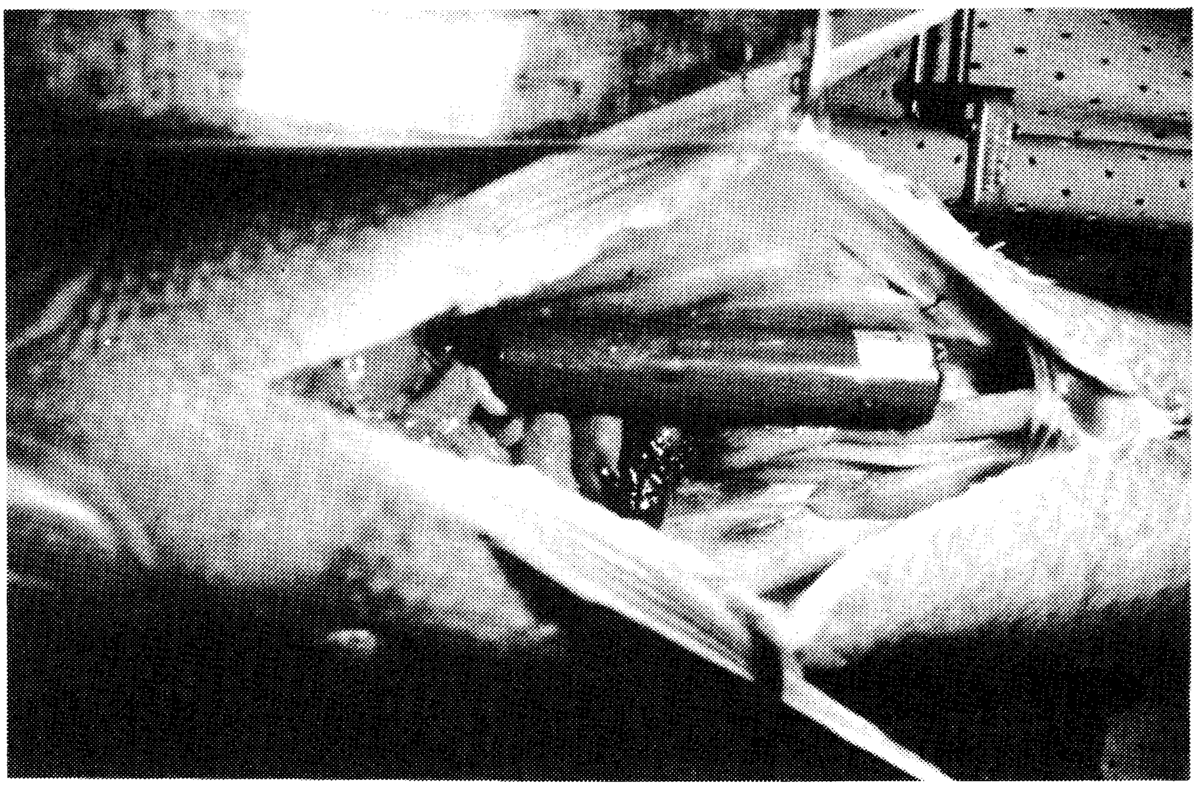
Surprisingly, it also now appears that burnt tuna is not an isolated phenomenon, but rather is biochemically identical to processes occurring in heart muscle during a heart attack and to some forms of human muscular dystrophy. Research begun at the Kewalo Research Facility to answer a specific fishery's product problem may prove to have medical importance!

Spawning and Rearing

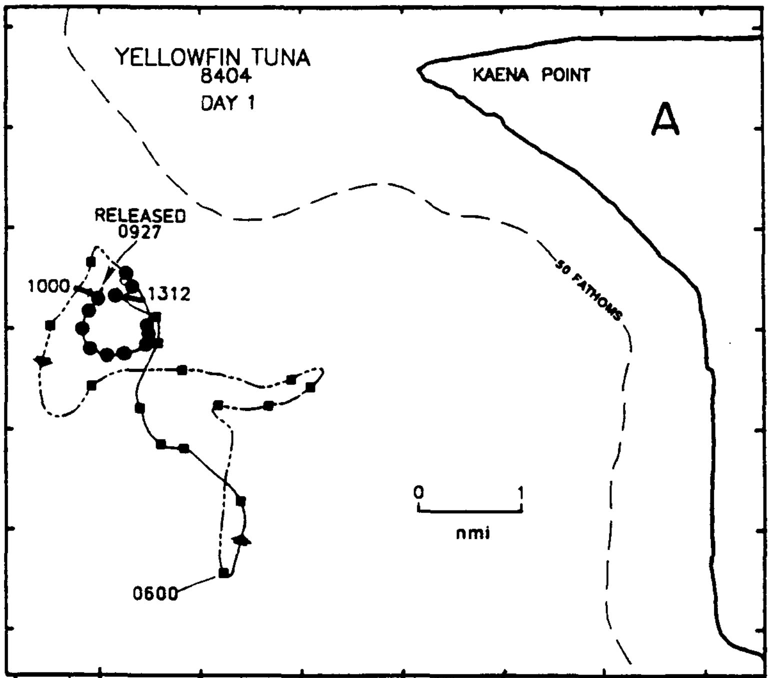
The ability to spawn and rear fishes at the Kewalo Research Facility provides known-age specimens which can be used to validate methods used for estimating the age

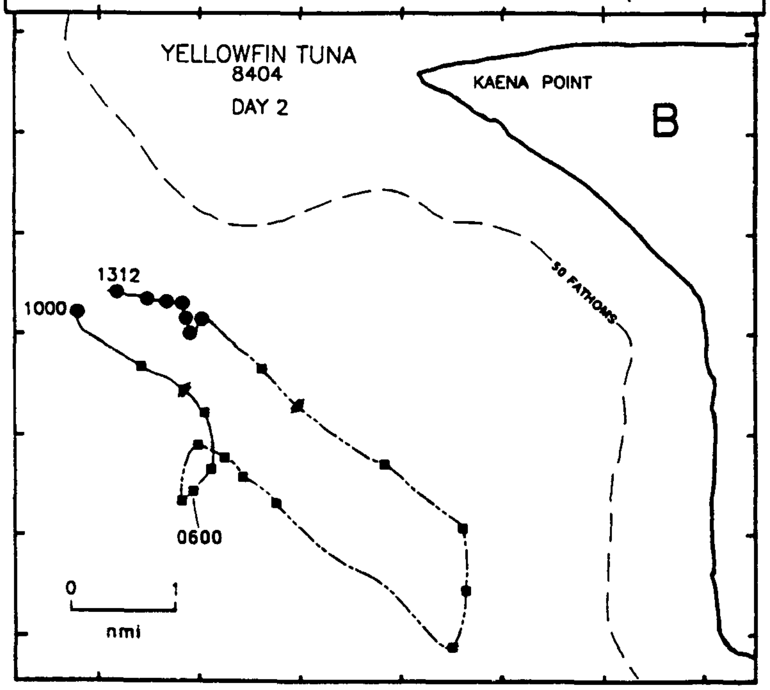


A sonic transmitter is attached to a freshly caught tuna, which is then released so that the fish's swimming depth and direction can be tracked to better understand its horizontal and vertical movement patterns.



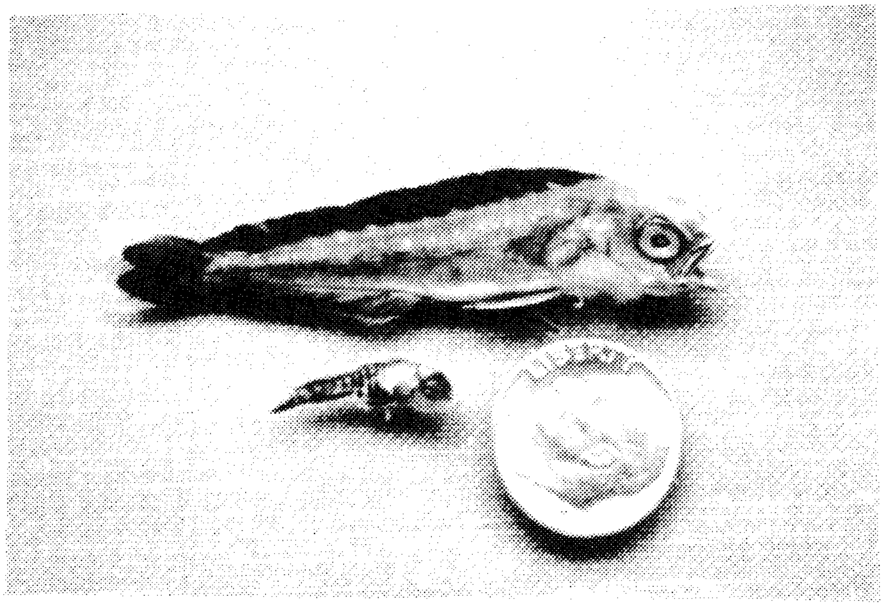
This ultrasonic transmitter is being surgically implanted in the body cavity of an anesthetized opakapaka (*Pristipomoides filamentosus*), so that scientists will eventually be able to track the movements of individuals of this species. The Kewalo Research Facility affords the opportunity to test various transmitter attachment schemes before they are attempted in the field.





The Honolulu Laboratory was one of the pioneers in the use of ultrasonic tags to track tuna in the open ocean. With the use of ultrasonic tags, research has shown that skipjack and yellowfin tunas are temporarily territorial and remain in a given area for some time in Hawaiian waters. They repeatedly return to the same area each morning; this behavior implies that tuna can navigate and have a sense of time.

These figures show a 48-hour track of a yellowfin tuna (No. YF8404) tagged and released at 0927 at a fish aggregating device (FAD) off the island of Oahu. Circles show each hour the fish was near the FAD; squares show each hour the fish was away from the FAD. The solid line equals the daytime movements, the broken line equals nighttime movements. On the first day of tracking (A), the fish remained very close to the FAD which moved in a circular path in the current. The fish departed the FAD after nightfall, and returned at 1312 the following day. On the second day (B), the fish behaved similarly, despite a different pattern of movement by the FAD.

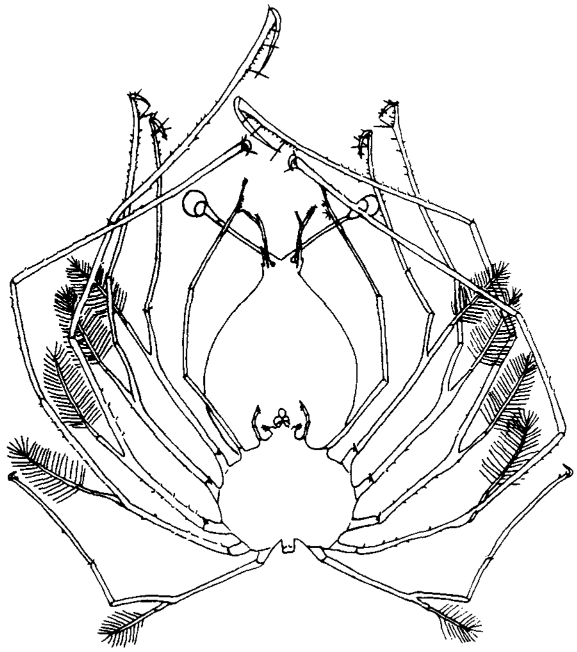


These mahimahi (*Coryphaena hippurus*) were reared from fertilized eggs. The lower individual is about 40 days old, and the upper individual is about 50 days old. When they first hatched, these mahimahi were less than 1 millimeter long (less than the thickness of the dime pictured).

of tropical fishes, especially short-lived (less than one year) species. Such work has been completed for nehu (*Encrasicholina purpurea*), skipjack tuna (*Katsuwonus pelamis*), and mahimahi (*Coryphaena hippurus*).

Most tropical fishes appear to be partial spawners. Only recently, with the discovery of postovulatory follicles, has it become possible to estimate the frequency of spawning. Skipjack tuna and mahimahi observed spawning in tanks have been sampled to determine the deterioration rate of postovulatory follicles which appeared to exist for about only 24 hours after spawning. Thus it is now possible to estimate the spawning frequency of skipjack tuna and mahimahi in the wild.

Recent spawning and rearing studies at the Kewalo Research Facility centered on rearing larval slipper lobster (*Scyllarides haanii*) and deepwater shrimp (*Heterocarpus laevigatus*). Deepwater shrimp, collected at sea, were successfully hatched and the larvae reared for up to 139 days in the laboratory, during which time they went through 37 molts! Similar techniques applied to larval lobster have enabled scientists to rear them in captivity for up to 123 days. The objective of these studies is to provide information useful for identifying the larval lobster and shrimp that often are a large part of specimens caught during plankton sampling. These surprisingly long larval stages also help explain how widespread apparently isolated adult populations can be genetically related. Not the adults, but rather their long-lived planktonic larvae are migrating over long distances. This information also has obvious fishery management implications.



This drawing is of a lobster larva (phyllosome) such as those hatched and reared at the Kewalo Research Facility. Little is known about the early life history of the commercially important lobster species caught near the Hawaiian Islands. Rearing lobster larvae from eggs in captivity allows scientists to (1) identify the larval stages caught in plankton nets in the open ocean, (2) determine how long the larvae of various lobster species remain in the plankton, and therefore (3) calculate how far the larvae could possibly be transported by oceanic currents.

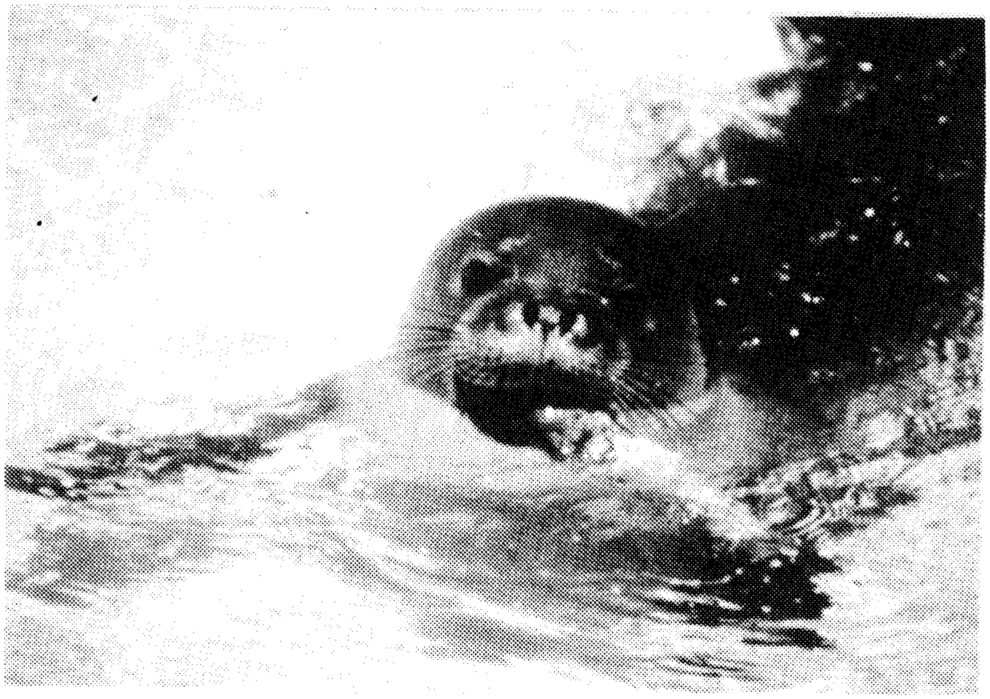
Protected Species

Hawaiian Monk Seals

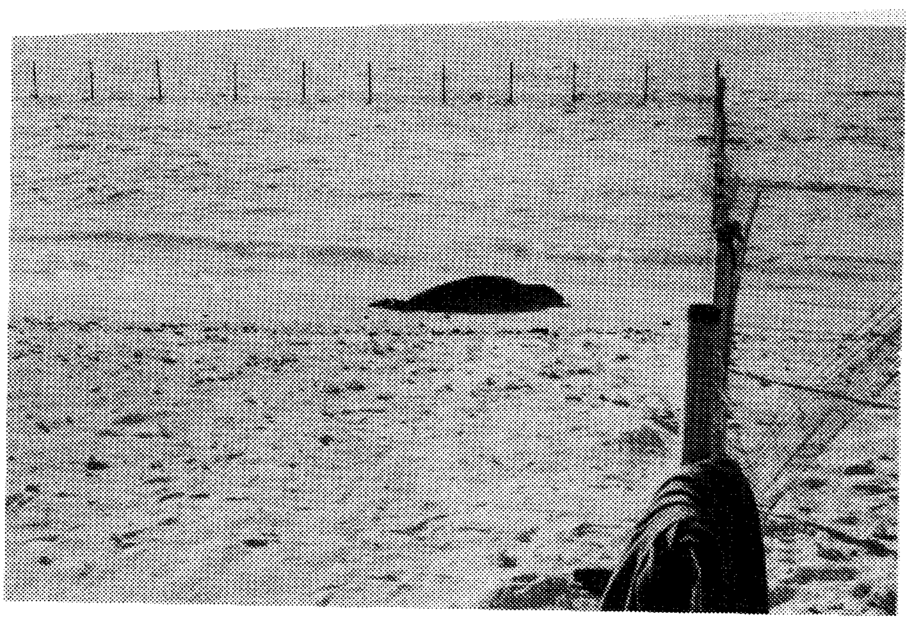
The isolated atolls and beaches of the Northwestern Hawaiian Islands are the primary terrestrial habitat of the Hawaiian monk seal (*Monachus schauinslandi*). This species and its Mediterranean cousin (*M. monachus*) have remained virtually unchanged for 15 million years and are sometimes referred to as living fossils. The Caribbean monk seal (*M. tropicalis*) became extinct in the mid-1950s, the Mediterranean population has fewer than 500 animals, and the Hawaiian monk seal has around 1,500 animals. These are highly endangered animals.

Monk seals, for the most part, lead a pelagic existence and may be at sea for a month or more. They are also able to dive for food up to 400 feet. The seals haul out on deserted beaches and atolls to rest, pup, and nurse their pups. Although docile, monk seals are extremely sensitive to any human disturbance and will leave preferred haul-out areas, sometimes even deserting their pups. Since monk seals are in constant danger from predation by sharks (most adult monk seals carry large shark-caused scars), more time spent in shark-infested waters due to human disturbance means higher mortality rates.

Since the early 1980s, the NMFS Honolulu Laboratory has been sending researchers to the Northwestern Hawaiian Islands to observe, tag, and count monk seals. One project (the Rehabilitation Project) has been transporting sick or abandoned pups to the Kewalo Research Facility and, more recently, to Sea Life Park to be "fattened up" overwinter and then transported to Kure Atoll where the population has been seriously depleted. This



A Hawaiian monk seal catching a bite to eat.



This ocean-beach enclosure at Kure Atoll is used by the Honolulu Laboratory's Head Start and Rehabilitation Projects to protect female Hawaiian monk seal pups and yearlings from attacks by aggressive male seals and sharks until the females are ready to be released into the wild.

project has been successful in bolstering the female seal population at Kure Atoll; already some of the project's seals have become successful breeding members of the expanding Kure population.

Research on monk seals has also been conducted at the Kewalo Research Facility. Studies have included testing techniques to lessen the aggressive behavior of adult male monk seals to reduce the problem of "mob mating" that occurs in certain areas where the male to female sex ratio of adult seals has become abnormally skewed over the years due to high female seal mortality. Studies have also been conducted at the Kewalo Research Facility on the metabolic rate of seals, information important for determining how much undisturbed feeding area adult seals may need.

Hawaiian Sea Turtles

The Kewalo Research Facility provides a badly needed laboratory where research on and rehabilitation of several species of threatened and endangered Hawaiian sea turtles can be conducted. Several successful recoveries of turtles either injured intentionally by spears or unintentionally by boat propellers have been made.

The most common sea turtle around Hawaii is the green turtle (*Chelonia mydas*) or *honu* in Hawaiian. The turtles are primarily vegetarian, eating algae growing on coral reefs.

Hawaiian green sea turtles basking in the sun at French Frigate Shoals in the Northwestern Hawaiian Islands. French Frigate Shoals is a major feeding and nesting area of this turtle species.

The smaller and rare hawksbill turtle (*Eretmochelys imbricata*) or *ea* in Hawaiian is found around the islands of Molokai and Hawaii. Large (up to 1,500-pound) leatherback turtles (*Dermochelys coriacae*) are never found near the islands, but are regularly seen in the open sea where they feed primarily on jellyfish.

Sea turtle populations have been decimated worldwide because of habitat destruction, direct exploitation of adults and eggs for food and other items, illegal poaching, ingestion of plastic debris, and unintended entanglement in fishing gear. In Hawaii, Florida, and elsewhere, another problem has recently cropped up--debilitating, life-threatening tumors which may grow up to 12 inches in diameter on green turtles. The prevalence of this disease is increasing at an alarming rate in a number of Hawaii's green turtle populations. Research on this problem is continuing and involves maintaining turtles in captivity and working cooperatively with scientists from Hawaii and the U.S. mainland, and conducting ultrasonic tracking of healthy and tumor-afflicted turtles.

RELATIONSHIPS WITH THE UNIVERSITY OF HAWAII

The Honolulu Laboratory (through its Kewalo Research Facility and in other ways) maintains a special relationship with the University of Hawaii. There is free dialogue and exchange of information among researchers working at the Kewalo Research Facility and scientists in the University's Departments of Zoology, Physiology, Oceanography, Biochemistry, Nutrition, and Animal Sciences. The Honolulu Laboratory provides part-time employment for University of Hawaii undergraduates and support for master's and doctoral degree candidates by providing laboratory space, experimental tuna, and monetary grants. Laboratory scientists also serve as advisors on graduate student thesis committees.

Numerous graduate students from the University of Hawaii and other universities have earned advanced degrees that involved work at the Kewalo Research Facility:

San Diego State University

Robert Olson

Scripps Institution of Oceanography

Heidi Dewar
Peter Fields

Shizuoka Prefectural Fisheries Experimental Station

Minato Yasui

Simon Fraser University

John Keen

University of Hawaii

Andrew Ayers
C. Scott Baker
Michael Barry
Gordon Bauer
Robert Bourke
Richard Brill
Peter Bushnell
Ron Dunn
Sharon D. Hendrix
Walter N. Ikehara
Barbara A. Kuljis
Christopher Moyes
Elizabeth A. Monckton
Linda M. B. Paul
Anjanette S. Perry
Anthony Sudekum
Michael M. Walker
Cheryl Watson

University of St. Andrews

John Salamonski

University of British Columbia

Les Buck
Michael Guppy
Mark Heieis
Michael Herrick
Tom Petersen
Manabu Shimazu
Jean-Michele Weber
Tim West

University of Miami

Daniel Benetti

University of Wisconsin

Christofer Boggs
Sherry Steffel

LIST OF VISITING INVESTIGATORS

The Kewalo Research Facility has, since its inception, hosted visiting scientists from around the world. Many have come because it is one of the few laboratories in the world that routinely maintains live tunas specifically for behavioral and physiological research. Scientists who have worked at the Kewalo Research Facility include the following:

Aquatic Farms

Dr. Edward D. Scura

Bedford Institute of Oceanography

Dr. Barry S. Muir

Boston University

Dr. Jelle Atema

Canada Center for Inland Waters

Dr. Arthur J. Niimi

Centre National pour l'Exploitation des Oceans

Dr. F. Havard-Duclois

Huntsman Marine Laboratory

Dr. Thomas W. Moon

Indiana University School of Medicine

Dr. Kenneth R. Olson

Institute of Oceanology, Academy of Sciences, Moscow

Dr. Sergei M. Kashin

Inter-American Tropical Tuna Commission

Dr. Gary D. Sharp

John G. Shedd Aquarium

Dr. William P. Braker

Kinki University

Dr. Teruo Harada
Dr. Shigeru Miyashita

Kyoritsu Women's University

Dr. Hiroki Abe

Laboratory of Comparative Biochemistry

Dr. Grant R. Bartlett

Long Island University

Dr. Phyllis H. Cahn

Massey University

Dr. Peter Davie
Dr. Craig Franklin

McMaster University

Dr. Steve Perry

Micronesian Maritime Authority

Michael A. McCoy

Montana State University

Dr. Calvin M. Kaya

Nagoya University

Dr. Hiroshi Niwa
Dr. Tamotsu Tamura

Naval Undersea Center

Dr. A. Earl Murchison

Oceanarium, Inc.

Dr. John H. Prescott

Pacific Gamefish Foundation

Dr. Charles Daxboeck

Resources Systems Institute East-West Center

Dr. John E. Bardach

Rutgers University

Dr. Bryant T. Sather

Scripps Institution of Oceanography

Dr. Jeffrey Graham

Simon Fraser University

Dr. Anthony Farrell
Jeff Johansen
Haruyo Kashihara
Dr. Glen Tibbits

South Pacific Commission

Dr. Robert E. Kearney

State University of New York

Dr. E. E. Suckling

Technion-Israel Institute of Technology

Dr. Daniel Weihs

Texas A&M University

Dr. William H. Neill

University of British Columbia

Dr. Peter Arthur
Dr. Robert Blake
Dr. Brian Emmett
Dr. Christopher French
Dr. Peter W. Hochachka
Dr. C. S. Holling
Dr. William C. Hulbert
Dr. David Jones
Dr. William Milsom

University of Tokyo

Dr. Isao Hanyu

University of Hawaii

Dr. Jean L. Cramer
Dr. E. Gordon Grau
Dr. Kim Holland
Hank Marrow
Dr. Martin D. Rayner
Dr. Terence A. Rogers

University of Guelph

Dr. E. Don Stevens

University of San Diego

Dr. Alan R. Hargens

University of Birmingham, England

Dr. Pat Butler

University of Notre Dame

Dr. F. W. Goetz, Jr.

University of New York

Dr. J. A. Suckling

University of California, Los Angeles

Dr. Malcolm S. Gordon
Dr. Vladimir Walters

University of Toronto

Dr. F. E. J. Fry

University of California, Davis

Dr. Claude M. Nagamine

University of North Carolina

Dr. John M. Miller

University of California, San Diego

Dr. Ted Bullock
Dr. Odile Mathieu-Costello

University of Chicago

Dr. Barbara Block

University of Wisconsin

Dr. James F. Kitchell
Dr. John J. Magnuson
Dr. Warren P. Porter

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Many people over the years have contributed to the ongoing success of the Kewalo Research Facility. I would like to take this opportunity to thank them all and especially recognize the pioneering efforts of Richard Barkley, Andrew Dizon, John Magnuson, John Marr, Eugene Nakamura, Bill Neill, Richard Shomura, Don Stevens, and Albert Tester. If those of us currently associated with the Kewalo Research Facility can reach new heights, it is only because we stand on the accomplishments of the people who went before us.

I also acknowledge the people who contributed to the preparation of this booklet: George Balazs, George Boehlert, Peter Bushnell, Randolph Chang, William Gilmartin, Kim Holland, Tom Kazama, Michael Walker, Cheryl Watson, Leslie Williams, and Howard Yoshida.

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