The Use of Designed and Prefabricated Artificial Reefs in the United States

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Introduction

Artificial reefs have been used to promote fisheries development in both Japan and the United States for at least 200 years. Taiwan and Australia have more recently begun to construct reefs. Although artificial reefs have been built in other countries, the major reef development activities have occurred in these four countries. Japan has a large, well-funded national artificial reef development program. Taiwan had a nationally funded reef research program for several years; reef construction by regional and private groups is now in progress. Neither the United States nor Australia have national reef programs.

Rocks and logs, or scrap materials such as ships, tires, and construction rubble, were used in most of the early U.S. reef-building efforts. Solid waste disposal has been a secondary motive in many American projects, particularly those using tires.

Many of these projects using available or scrap materials proved to be very effective. In Japan and Taiwan, such reefs were used extensively to improve commercial fisheries and aquaculture. In the United States and Australia they are still used to promote recreational fisheries.

However, research conducted in Japan and Taiwan has shown that even though scrap materials and rock can function effectively as artificial reefs when properly handled and sited, appropriate sites for the deployment of these materials are limited. Furthermore, the shapes, size, and long-term physical stability and biological productivity afforded by such materials are less than ideal. Transportation and handling costs, which constitute the major expenditures in the construction of this type of reef, have increased significantly in recent years and the long-term cost effectiveness of such projects has been reduced.

As a result of this situation and an increasing amount of information on optimum design criteria, prefabricated artificial reef units began to be developed in Japan during the early 1950's. Most of this first generation of designed reefs were made from reinforced concrete and were either cubes (Fig. 1) or rectangular boxes with sides of about 1-2 m, hollow interiors, and "windows" on each side, or cylinders of similar dimensions and properties. The larger cubes and boxes, which generally had bigger "windows" and more open space, were often piled in two or three layers to create high profile reefs, while the cylinders and the smaller, less open cubes and boxes were generally not placed in layers. These concrete units proved to be quite effective. In 1954, designed concrete units were designated as the only type of component to be used in government-subsidized regional reef construction projects.

In both Japan and Taiwan, coordinated programs to improve coastal fisheries production have recently been undertaken in response to declines in fisheries production due to the 200-mile extended jurisdiction statutes, increases in fuel prices, and the deleterious effects of coastal development and pollution. Large-scale designed units prefabricated from a number of materials have been used to expand the artificial reef programs in both countries.

The new generation of artificial reef units developed in Japan is manufactured in a wide variety of shapes, sizes, and materials. An assortment of new midwater and floating fish attractors has also been developed and introduced. These new units can be used in a wide range of site conditions not suitable for earlier designs. Many are quite large and are deployed as single units to build very large-scale fish banks. Results of preliminary studies have indicated that in some cases these new units are more

ABSTRACT—Designed and prefabricated artificial reefs have been used with great success to promote fisheries development in Japan and Taiwan, and have been tested on several occasions in the United States. Although efforts in the early 1960's to test Japanese-style reefs in California, New York, and Florida met with problems due to lack of experience with that type of reef, those units which were properly placed proved effective in attracting fish. Pumice concrete shelters designed for lobsters were tested in Rhode Island in the 1970's and were shown to increase significantly the abundance of resident lobsters in areas previously devoid of shelter. The Japanese have recently developed a new generation of large-scale, advanced-technology artificial reefs. To introduce this technology in the United States, Japanese FRP (fiberglass reinforced plastic) reefs have been installed off Florida as part of a demonstration/research project funded by the National Marine Fisheries Service. Their cost-effectiveness will be evaluated by comparing them with concrete culvert reefs.

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cost-effective over the long term than the earlier scrap material or designed units.

Although most artificial reefs in the United States are still built from scrap materials, the availability of some of these (such as liberty ships) has decreased and the cost of transporting, handling, and preparing others has increased in recent years. "White goods" (appliances) and car bodies are no longer considered suitable for reefs because of their high preparation costs and short life expectancy in the water. Both the cost-effectiveness and long-term stability of tire reefs have come into question. Hanni and Mathews (1977) indicated that it is cheaper in Pinellas County, Fla., to dispose of tires in a landfill than to dispose of them at sea by using them for reefs. Problems with tire reefs breaking apart and ending up on tourist beaches or in fishermen's nets have caused several states (i.e., Florida and California) to no longer support the use of tires as an artificial reef material.

Because of the current interest in the United States in installing artificial reefs and the decreasing availability and cost-effectiveness of scrap materials for construction, it is useful to review the past and potential role of designed, prefabricated reefs in American coastal waters.

Figure 1.—Japanese concrete cube reef units (sides = 2 m) being built in Chiba Prefecture, Japan.

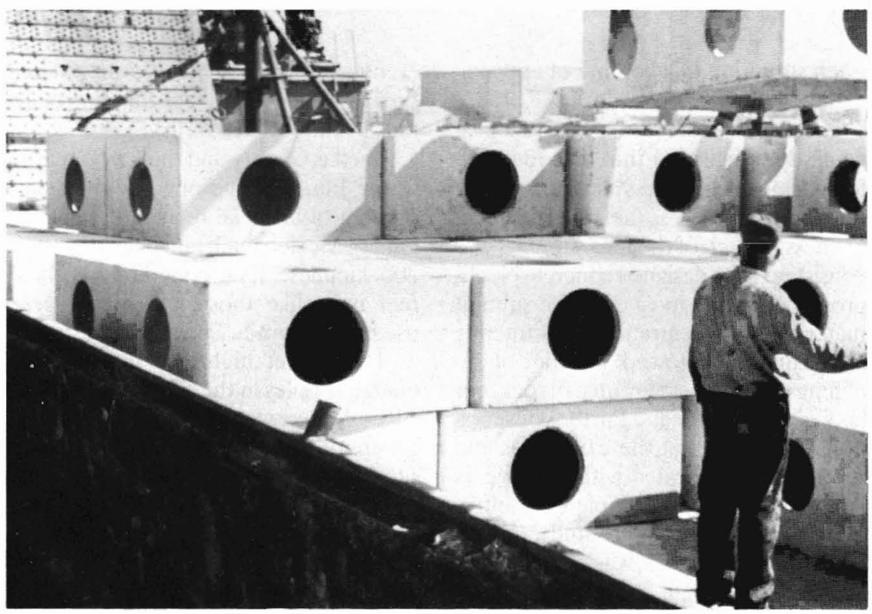

Figure 2.—Japanese-style concrete blocks used in California in the early 1960's. (Photo courtesy of the California Department of Fish and Game.)

Japanese-Style Concrete Reefs

Based on the development of the first reefs designed in Japan during the early 1950's, several states began testing similar structures during the early 1960's. This effort began in California and included Florida and New York. These studies are of interest since the results suggested some of the problems as well as the potential advantages of using such structures.

Early preliminary work by the California Department of Fish and Game (Carlisle et al., 1964) demonstrated that artificial reefs could add productive habitat for recreational fishing.

Further studies, initiated in 1960, compared four types of reef materials in order to determine which would be most suitable for future construction projects in California. Three reefs were built in about 18 m of water on sandy barren ocean bottoms off Malibu, Santa Monica, and Hermosa Beach. Each reef consisted of four subunits composed of the materials under consideration: Streetcars (1/subunit), automobile bodies (14/subunit), designed concrete block shelters(44/subunit) (Fig. 2), and quarry rock (about 333 tons/subunit).

Figure 3.—Concrete units adapted from Japanese-style units prior to placement off Long Island, N.Y., during 1964-65. (Photo courtesy of the New York State Department of Environmental Conservation.)

Each subunit had a volume of approximately 409 m^3.

Extensive observations for several years demonstrated that although differences in effectiveness occurred among the three reef sites, the relative effectiveness of each of the four subunits was consistent. The designed concrete blocks proved to be the most effective subunit material for concentrating and attracting fish. This was followed, in order of declining effectiveness, by quarry rock, car bodies, and streetcars. Further observations indicated that the car bodies and streetcars deteriorated within 3-4 years and became almost completely ineffective. At the time of this study (1963), however, quarry rock was considerably less expensive than the concrete units and was determined to be the most cost-effective material for reef construction in California (Duffy, 1974).

During the late 1960's and early 1970's, a number of tire reefs were constructed in California (Dewees and Gotshall, 1974; Duffy, 1974). Although tires proved to be more durable than car bodies or streetcars and cheaper than quarry rock, problems with binding, puncturing, ballasting, and siting led to eventual dispersal of the reefs and caused tires to be banned as reef-building materials in California (Carlisle[1]).

Pinellas County and the City of Clearwater, Fla., which pioneered the development of artificial reefs in the eastern Gulf of Mexico, built and placed in 1965, 200 Japanese-style concrete "pill box" reef units like those which had been used in California. Each box measured 8 × 4 × 3 feet high and had 18-inch diameter holes in the sides and top. The City of Clearwater placed 75 units in groups of 3-6 on a 2,600 × 500-yard reef site. The remaining 125 units were placed by the county off Indian Rocks Beach.

Due to lack of experience with this type of reef component, inadequate planning, and insufficient control during placement, many of the units ended up scattered over an area believed to cover a half-mile of bottom. Only about 20 of the units remained in the intended area. The rest were so scattered that they cannot be located by fishermen and thus are effectively lost.

[1]Carlisle, J. G. 1980. California Department of Fish and Game, Long Beach. Pers. commun.

A number of concrete units of a design adapted from the Japanese-style units used in California and Florida were placed off southern Long Island, N.Y., during 1964-65. A local contractor used a modified septic tank mold to fabricate the units (Fig. 3).

While available information on this project is incomplete, several problems are known to have made it a failure. The design modifications resulted in apparently extensive damage to the units during handling and placement on the barge used to tow them to the deployment site. Because of further problems resulting from poor weather and lack of proper planning, the location of the placement area was not recorded. The units remain unlocated and unevaluated.

As this brief review indicates, the major problems encountered in attempts to use Japanese-style concrete units in the United States arose from improper design, handling, siting, and placement. (It should be noted, however, that similar problems due to similar causes were not unknown in Japan when designed concrete units were first put into use.) Except in California, where considerable experience in building large-scale reefs had been developed, some or all of the units were lost due to improper placement. Attempts in New York to adapt existing septic tank molds for fabrication of the reef units resulted in structural degradation and losses during handling even prior to actual placement.

In California, where the units were placed relatively properly, they proved to be the most effective form of reef unit; they were 18 percent more effective than quarry rock. Despite the placement problems in Florida, the 20 units which were not lost have been observed by divers for more than 17 years and continue to provide very effective habitat for grouper, sheepshead, and a variety of other species. A recent dive on this reef in December 1981 indicated that these units are completely intact, stable, and very productive (Fig. 4).

Although 20 years ago the California Department of Fish and Game suggested that, at least for the term of their study, quarry rock was more cost-effective than the otherwise more effective concrete units, cost differences may not be such a significant factor today, especially over a long-term period. This is particularly true in light of the recent advances in reef design, siting, and placement techniques which have been made in Japan and confirmed in Taiwan.

In 1963 the cost of 1,000 tons of quarry rock delivered in place in Santa Monica Bay cost $6,000 ($6/ton). A similar volume of concrete units cost $11,000 at that time. A recent project in California which involved the placement of eight rock-pile reefs off San Onofre cost about $250,000 (10,000 tons at $25/ton), more than four times the 1963 cost. Although the new Japanese-designed reefs may still be somewhat more expensive per unit volume than rock, they may also be more effective on a long-term basis. Furthermore, volumetric comparisons may not be valid for measuring effectiveness.

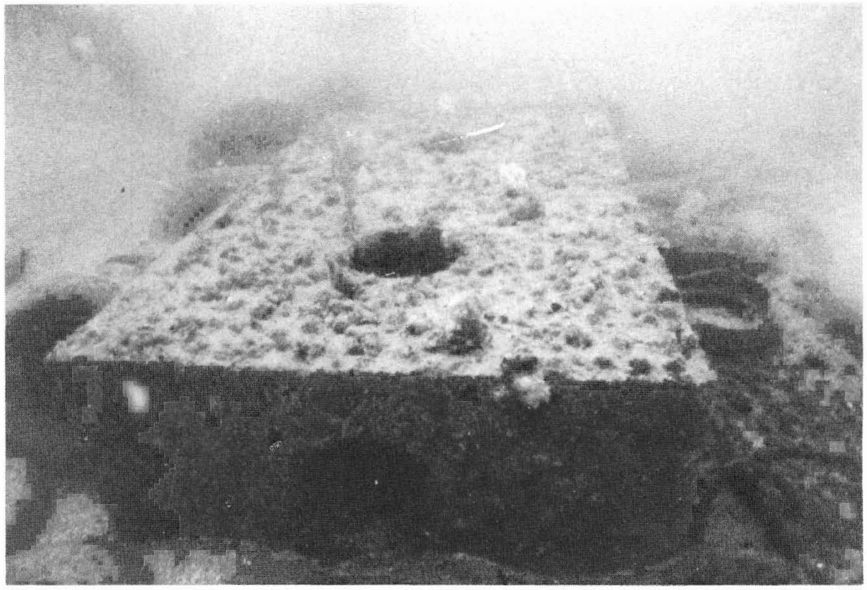

Figure 4.—Japanese-style "pill box" reef placed off Clearwater, Fla., in 1965 and photographed in 1981.

Lobster Reefs

Designed artificial shelters have also been used to promote or expand fishing areas for commercially important invertebrates and seaweeds. Although most of this work has been done in east Asia, several studies have been conducted in the United States with the northern lobster, *Homarus americanus.*

A number of researchers (Briggs and Zawacki, 1974; Scarratt, 1973; Stewart, 1970) have suggested that in some areas shelter is a limiting factor in the distribution and abundance of nearshore lobsters. The addition of shelter in areas previously devoid of cover or substrate suitable for burrowing has been shown to increase the abundance of resident lobsters. Observations have also indicated that extensive growth of encrusting organisms on artificial substrates serves as a source of food for the lobsters (Sheehy, 1976; Alfiere, 1975; Weiss, 1970).

Several types of designed artificial shelters for lobsters were fabricated from pumice concrete as part of a series of studies begun in Rhode Island during 1971. Preliminary studies with a single chamber unit (Fig. 5A) were conducted at several shallow sites off Point Judith, R.I., to determine if the carrying capacity for lobster in sand bottom areas could be increased.

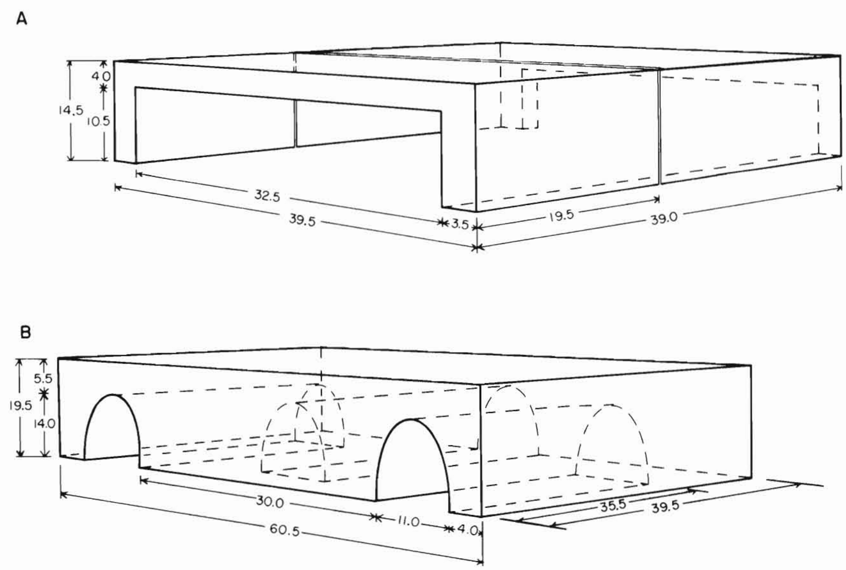

Figure 5.—Artificial shelters fabricated from pumice concrete in Rhode Island: A = single-chamber (2-piece) unit and B = triple-chamber unit.

Results indicated that the addition of lobster shelters significantly increased resident lobster populations (Fig. 6). Observed lobster abundances were equal to or greater than those observed on good natural grounds. In addition, results indicated that shelter spacing had a significant effect on occupancy by lobsters

Figure 6.—Lobster occupying two-piece single-chamber shelter. Extensive mussel growth on the shelter surface.

Figure 7.—Juvenile lobsters and crabs, *Cancer borealus*, found in triple-chamber unit being examined by diver.

and that shelter orientation, with respect to predominant wave and current directions, affected the stability of the shelters on the bottom. Interactions between lobster size and shelter spacing intervals were also suggested (Sheehy, 1976).

Two-piece shelters used in the initial study proved to be unstable during severe wave conditions and current velocities. Shelter loss was due both to subsidence resulting from scour and to overturning and separation of sections by wave action. Shelter orientation had some influence on the rate of loss; however, the design was considered unsuitable for all but experimental purposes (Sheehy, 1976).

A second pilot study which compared single- and triple-chamber shelter units affording approximately the same available shelter volume (Fig. 5B) demonstrated that triple-chamber units had greater overall use and supported larger populations due to the compartmentalization. During this study, all benthic life stages of the lobster were observed on and within the reefs. Significant seasonal variations in both lobster and other populations (Fig. 7) occupying the reefs were also observed (Sheehy, 1976).

Although triple-chamber shelters were more stable due to increased weight and bottom surface area, they proved more difficult for divers to handle and space. Both laboratory and field studies were conducted by Jones (1974) to develop a more stable design and a basic computer simulation program to evaluate these units under various combinations of substrate and oceanographic conditions. This information, as well as fabrication costs and logistic considerations, was used to design a new and smaller single-chamber unit (Fig. 8, 9) to conduct larger scale controlled tests at six sites in Rhode Island.

Each of these six reefs (Fig. 10) was monitored bimonthly by divers for a year. The three most stable reefs were monitored for a second year as part of a tagging program. During each survey, divers carefully monitored the position, size, sex, molt condition, and claw number and size of each lobster (Fig. 11). Multidimensional contingency table analysis was used to examine the interaction of variables in the lobster abundance and distribution within the reef (Sheehy, 1977).

Results from this study confirmed and expanded on the prior studies by again demonstrating that the addition of artificial shelters in areas devoid of natural shelter or substrate suitable for burrowing can significantly increase the abundance of lobsters. However, the results also confirmed earlier statements by Scarratt (1973) and others that suitable sites for lobster reefs are limited. A careful examination of all relevant site factors, particularly maximum wave and current conditions, substrate, and available food resources, should be made prior to future construction.

Unit artificial shelters may offer a viable alternative to the use of natural rock or scrap material in the construction of large-scale reefs for lobsters. Although such designed shelters can be used to create new habitat for lobster, a careful analysis of all cost factors should be made before commercial scale reefs are constructed. If some of the legal restraints to "extensive aquaculture" are removed, additional uses for such reefs may soon develop.

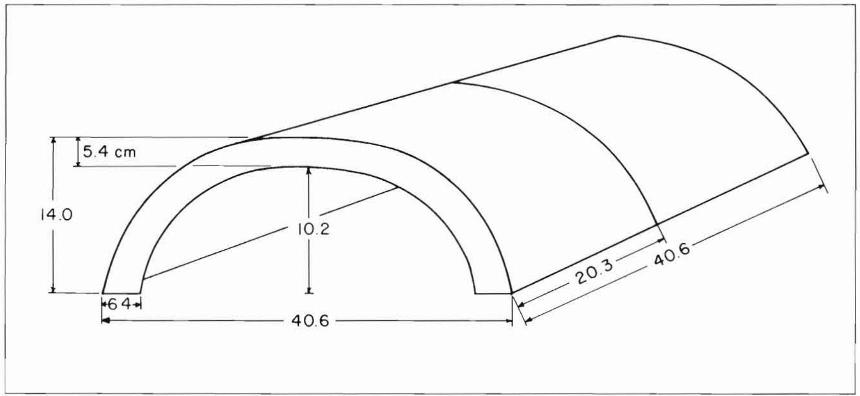

Figure 8.—Smaller single-chamber unit fabricated from pumice concrete (dimensions in centimeters).

Figure 9.—A lobster occupies a smaller single-chamber unit with extensive macroalgae growth on shelter surface.

Japanese Fiberglass Reinforced Plastic (FRP) Reefs in Florida

The new artificial reef technology developed in Japan and Taiwan has been described (Sheehy, 1979, 1981; Chang[2]). These large-scale structures represent a new generation of artificial reefs which are designed, prefabricated, and installed to promote commercial fisheries, to rehabilitate areas adversely impacted by human activities such as pollution and coastal development, and to serve as part of extensive aquacultural projects (Sheehy and Vik, 1981). They are the result of considerable research and development. To receive approval for use in projects funded by the Japanese government, reefs must meet certain standards for strength and stability and must be judged to have a minimum useful life span (without structural degradation) of 30 years when properly built, handled, and sited.

Aquabio, Inc.[3], a marine research and development group, has recently initiated a project to introduce this new Japanese technology in the United States and

[2]Chang, K.-H. 1981. Taiwan's artificial reef research program. Presented at the Mid-Atlantic Artificial Reef Conference, Atlantic City, N.J. Institute of Zoology, Academia Sinica, Taipei, Taiwan.

[3]Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

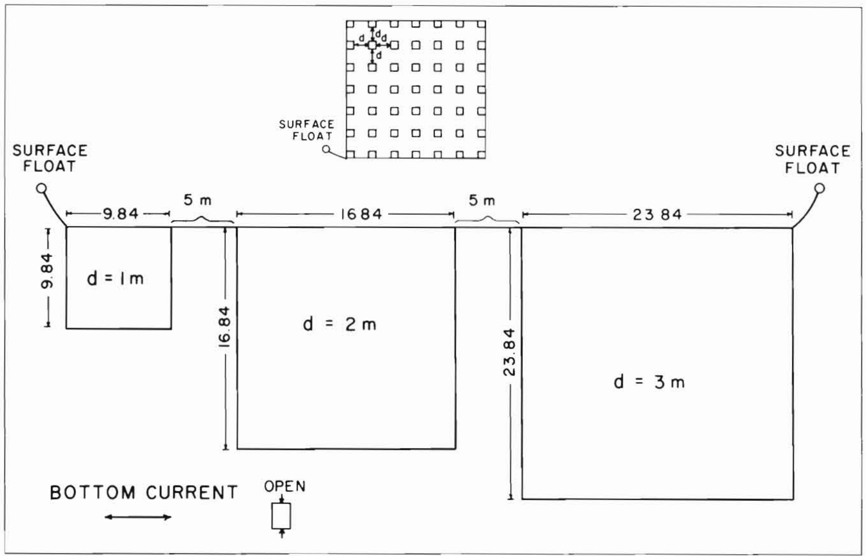

Figure 10.—Placement configuration of individual reefs (spacing intervals in meters). Inset: Expanded view of an individual matrix; "d" is the intershelter distance.

determine which aspects have the most potential for application in American fisheries development. An important part of this project, funded principally by the National Marine Fisheries Service (NMFS), involves a demonstration and evaluation of Japanese artificial reefs in U.S. coastal waters.

To determine which types of reefs have the most potential for immediate use in the United States and would therefore be most appropriate for the demonstration, the stability, strength, life expectancy, and biological effectiveness of a number of manufactured reef units commercially available in Japan were evaluated. Design flexibility and costs associated with construction, transportation, and placement were also considered.

FRP units, manufactured by Asahi Chemical Industry Co., Ltd., were selected as most suitable for small-scale testing and evaluation off the Florida coast. The reef components were readily shipable from Japan, capable of being assembled with relatively unskilled labor and minimal equipment, and could be placed without the use of large cranes and barges. In addition, these units could be built in a variety of configurations, and this could be designed for fish, shellfish, and macroalgae.

Reef components and materials manufactured in Japan were sent by container ship to the United States, erected, and placed off Panama City and Jacksonville,

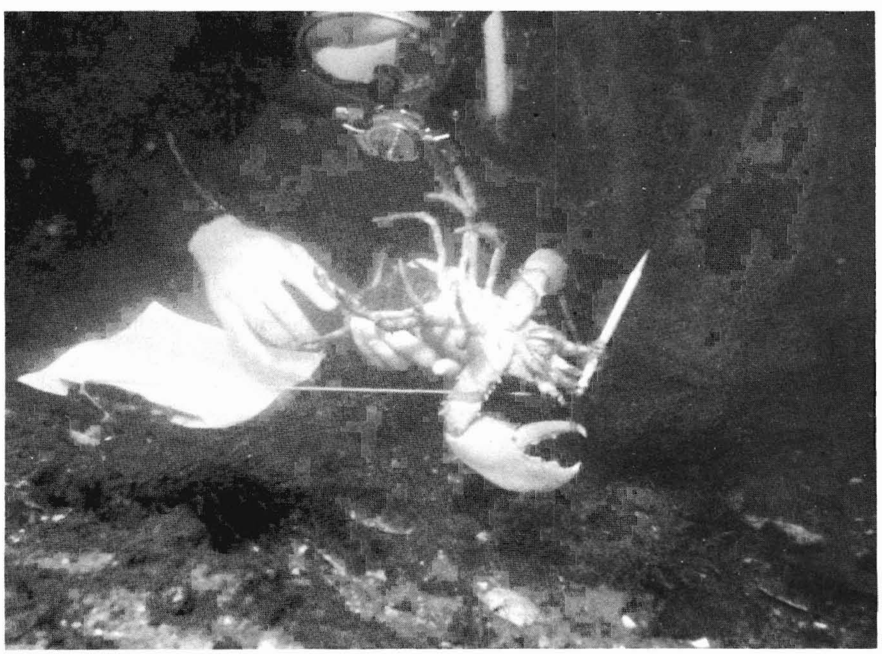

Figure 11.—Diver examining egg-bearing female lobster while monitoring reef.

Fla., during August and September 1981. Reef components, essential materials, and engineering services were donated by Asahi. The reef units were built and placed by students, graduates, and staff from the Panama City and Jacksonville Marine Institutes with technical supervision by Asahi and Aquabio. Some financial and administrative support to assist with construction of the Japanese units and a concrete culvert reef placed at each site for comparative purposes were provided by the Florida Department of Natural Resources. Assistance with selection of specific sites was provided by the Jacksonville Offshore Sport Fishing Club and the Marine Institutes.

As previously noted, many of the problems encountered in the earlier use of Japanese-style reefs in the United States were due to improper design, siting, handling, and placement. To gain the full benefits of using Japanese reefs in this demonstration project, Aquabio made every effort to ensure that the units were built exactly according to the manufacturer's directions, were handled properly to avoid damage, and were placed correctly and accurately on predesignated, carefully selected sites. This conservative approach, along with the diligent work of the Marine Institute students, graduates, and staff, resulted in the proper placement of undamaged units at the specified permitted sites.

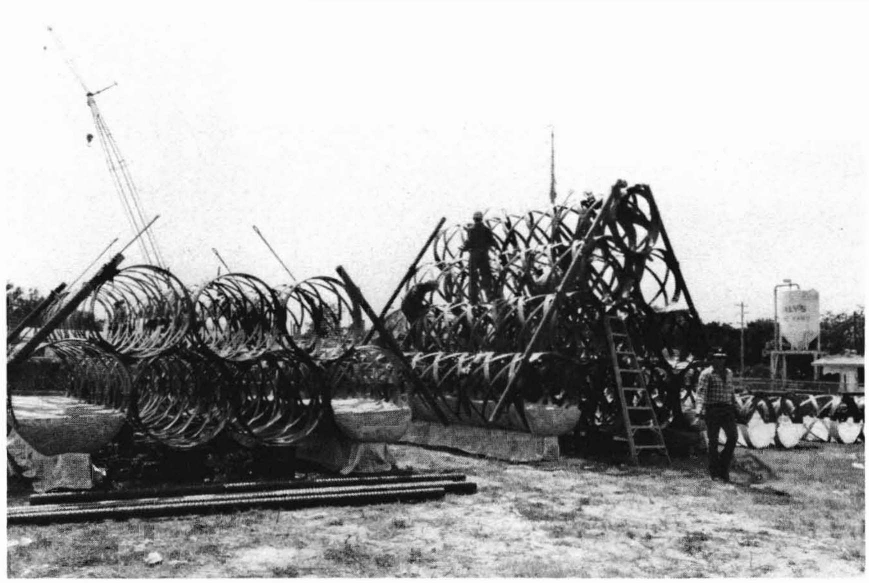

Figure 12.—Three types of FRP units built in Jacksonville, Fla. Concrete ballast has been placed in lower cylinders of largest unit.

Jacksonville and Panama City were chosen as sites for this project for a variety of oceanographic and logistic reasons, as well as criteria recommended by the manufacturer. Both represent fairly typical substrate types and water depths for reef construction along both coasts of Florida. Jacksonville is relatively typical of areas along the southeast Atlantic coast in terms of slope and bottom type. Panama City, while not really typical of the entire Gulf area, is representative of the northwest coast of Florida and is an area which has potential need for further reef development. Panama City also provides relatively reliable visibility for detailed underwater observations. A maximum depth limit of 80 feet was set in order to provide sufficient no-decompression bottom time for divers to conduct surveys and recover sample plates and instruments.

Sites were also screened to ensure long-term reef stability. Prior to selection, available oceanographic data and estimates of significant and maximum wave heights and periods and maximum current velocities were collected along with substrate data. Using stability calculation equations developed in Japan, the stability of various reef unit configurations was evaluated. Since these units have been extensively tested in Japan under a variety of conditions, field data confirming these calculations was available.

Both Jacksonville and Panama City have had artificial reef programs for some time and a number of other reefs of different types are available for comparative purposes. The Jacksonville Offshore Sport Fishing Club has built reefs off Jacksonville for over 20 years and has collected considerable information on species caught in the reefs and their seasonal variation. Likewise, the Panama City Marine Institute has built a variety of reefs off Panama City; recent field studies on these reefs conducted by researchers from Texas A&M University will provide useful comparative information.

The specific sites selected in both areas had flat, coarse sand bottoms devoid of any natural relief. Preplacement surveys conducted at each site indicated a relatively low abundance of fish. Adjacent areas with similar bottom characteristics were selected as control sites for future surveys.

The reef components and materials arrived through the port of Savannah, Ga., and were trucked to staging areas in Panama City and Jacksonville. The principal components were cylinders 5 m long and between 1.0 and 1.2 m in diameter fabricated from strips of FRP (Fig. 12). The slight variations in the diameters of the cylinders permitted the components to be nested during shipping to reduce space requirements. Additional structural components, such as guard bars and anchor piles, were made from heavy-wall FRP pipe sections.

Although the FRP reefs are not difficult to build, proper supervision and quality control are essential in all aspects of the building and placement. The erection process took about 2½ days at each site, with several slight delays due to material variations, equipment adjustments, and rain. The work crew consisted of five students or graduates and two supervisors.

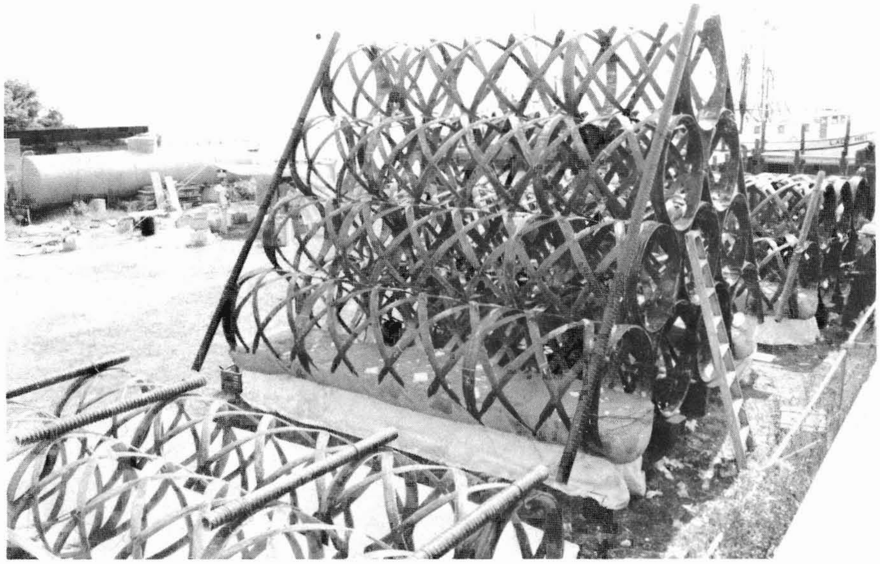

Figure 13.—The 10- and 7-cylinder units during construction in Jacksonville, Fla.

Figure 14.—Workers fiberglassing all connecting points.

After being unpacked, the units were sized, placed in position on stands, and fastened together with heavy wire (Fig. 13). FRP guard bars, designed to add structural support and reduce damage from towed fishing gear, and steel lifting eyes used for hoisting the units into the water were also wired into place. All connections were then fiberglassed with impregnated twisted roving wound on a hand machine designed for this purpose (Fig. 14).

Fabric bags used for casting the concrete ballast were also temporarily attached with steel wire to the appropriate number of bottom cylinders. The number to be ballasted and the amount of ballast per cylinder are adjusted to site-specific oceanographic conditions. Anchor piles, used to prevent the reef unit from slipping on the sea bottom, were placed through the fabric bags; specially fabricated reinforcing rod frames and connecting rods and pieces were then placed in the ballast cylinders. Quick setting, early-strength concrete was poured, smoothed, and permitted to harden.

Airbags designed to fit into the lower cylinders were inserted. The reusable airbags permit these units to be floated and towed to the placement site, thus eliminating the need for a barge or floating crane required by all other large-scale Japanese reef units. Nylon covers, FRP sheeting, and linoleum were placed around the airbags to reduce abrasion by the concrete and FRP strips. The bags were then inflated, inspected for leaks, and secured in place (Fig. 15).

Tow bridles and lines were attached to both units and a crane equipped with a special spreader bar was used to pick up the units and place them into the water. The units were temporarily secured at dockside while lines were rearranged and the tow line was secured to the tow vessel. A vessel of about 5 tons is generally sufficient to tow the units in tandem; however, a small tug was used in Panama City and a large charter boat was used in Jacksonville for safety and to carry additional observers.

The units were towed (Fig. 16) to the permitted site where temporary buoys had been placed earlier. On site, the two units were detached and maneuvered into position by a small outboard vessel. The stern of each unit was anchored and the unit was oriented by the outboard. The airbags were vented, causing the reefs to sink (Fig. 17). Dive teams recovered the lines and inspected the units. The airbags and nylon liners were recovered by the tow vessel.

No damage from impact on the bottom or other causes was observed at either site. Units rested on the bottom and were supported by the anchor piles, with about 5-12 cm between the bottom of the cylinders and the seabed.

A 10-cylinder unit and a smaller unit (9-cylinder unit in Panama City and a 7-cylinder unit in Jacksonville) were placed at each site. This variation was planned as part of a long-term stability test to determine if theoretical calculations concerning stability in "worst case" conditions such as a hurricane were correct.

As part of the project, Aquabio is currently conducting a 1-year research program at both sites funded by an NMFS grant. This program includes surveys of benthic, encrusting, and fish populations, as well as primary productivity and oceanographic studies. The research effort will evaluate the Japanese FRP reefs, the concrete culvert reefs of approximately equal volume constructed at each site, and control areas in terms of fish abundance and distribution, and benthic and encrusting community development (Fig. 18). At the end of the monitoring period, a cost-effectiveness comparison between the FRP and the culvert reefs will be made.

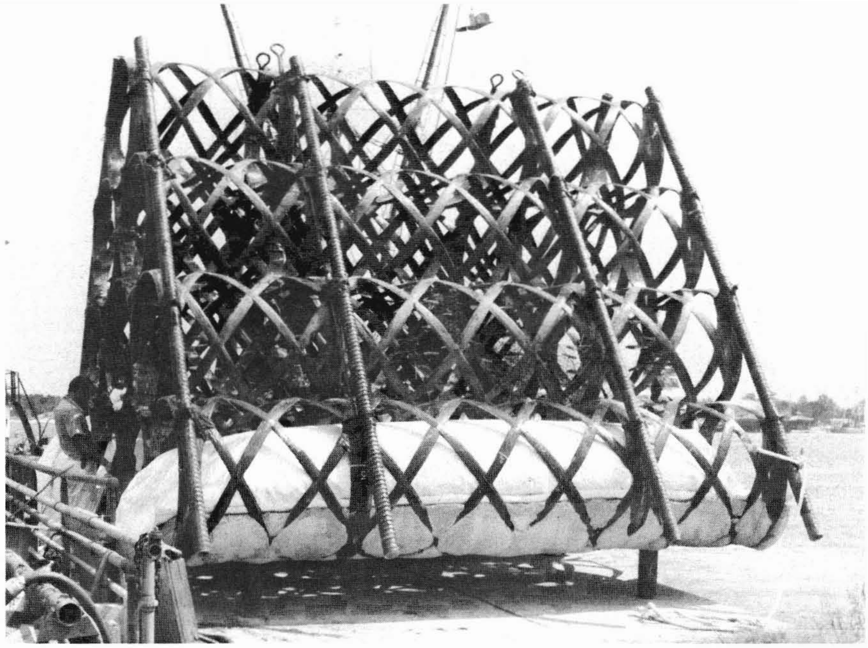

Figure 15.—Reef unit on dock. Airbags are being checked and inflated. The unit is standing on anchor piles.

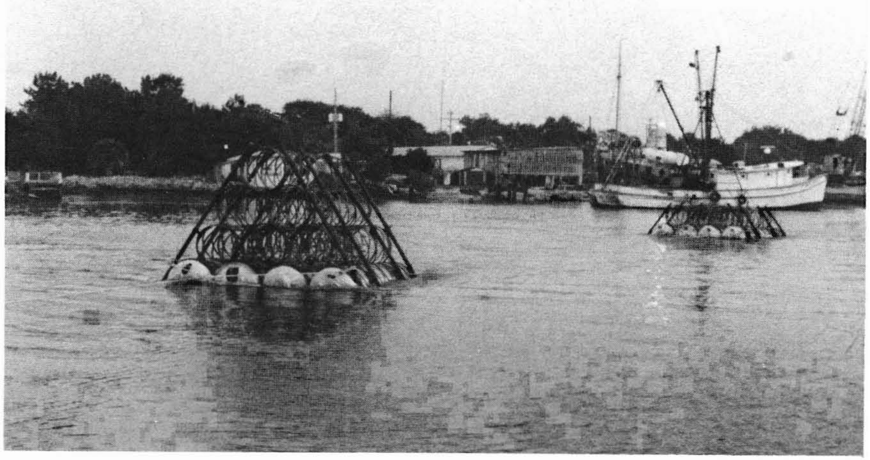

Figure 16.—Reef units being towed to site off Jacksonville, Fla.

Potential Uses for Designed Reefs in the United States

Designed and prefabricated reefs offer a means of improving and managing coastal marine areas. The design flexibility permits the construction of stable, durable units which can be directed at specific species or even life stages. This flexibility and relative permanence make such reefs particularly suited for enhancing heavily used recreational fishing areas, increasing the production of commercial fisheries, serving as part of compensation/mitigation projects, and developing extensive aquaculture programs.

Although construction of artificial reefs to promote recreational fishing has a long history in the United States (Stone, 1972), very few reefs have been used extensively for commercial fishing, with the exception of those used by charter boat fisherman. It is possible, however, that commercial use may become more common in the future. Many U.S. commercial fisheries could benefit from the application of advanced artificial reef technology. Japan, the premier fishing

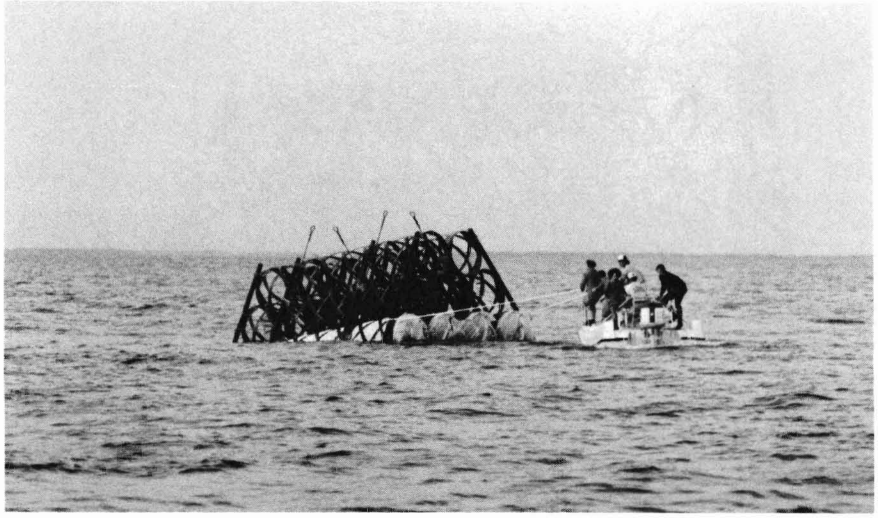

Figure 17.—Reef unit being sunk on site off Jacksonville, Fla.

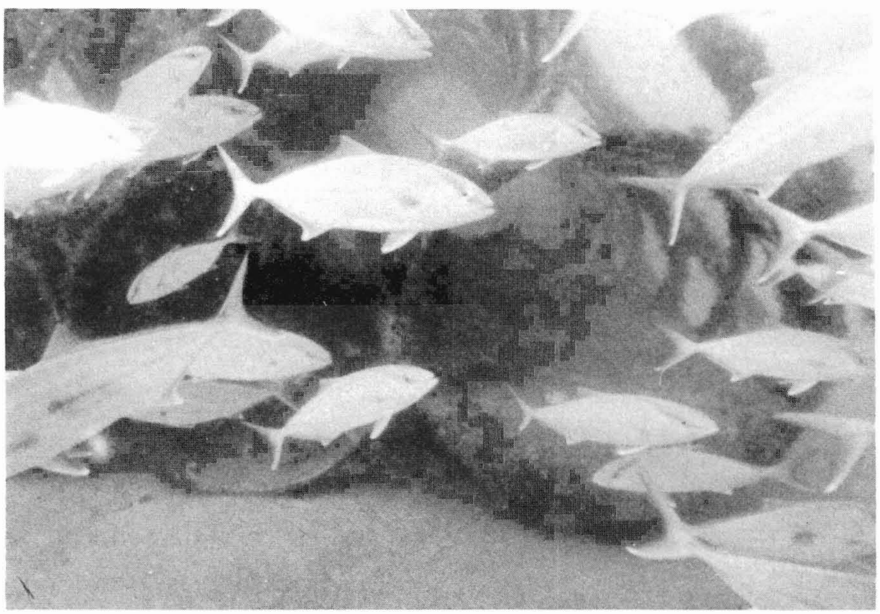

Figure 18.—FRP reef off Panama City, Fla., photographed during the November survey.

nation, has relied on designed units for almost 30 years.

The use of reefs as a means of compensation or mitigation for various coastal development projects has been common in Japan for some time but is relatively recent in the United States. The potential of this application has been shown by recent efforts in California described by Grove (1982). Other coastal and estuarine areas subjected to some form of environmental or fishery loss may find that artificial reefs can contribute to comprehensive mitigation or compensation programs or plans. Many such projects are in high energy coastal or restricted estuarine environments where dredging, filling for land reclamation, power plant effluents, and other disturbances can have significant impacts. It is important that stable, aesthetically acceptable, effective, and relatively permanent structures be used in such compensation or mitigation projects since they should last as long as the impact for which they are compensating or mitigating. Many of these areas are subject to heavy recreational fishing; since suitable available space is limited to multiple uses and physical or biological restraints, it is essential that the most effective type of unit be used.

Artificial reefs have been used quite successfully to improve coastal aquaculture in both Japan and Taiwan. This use has been particularly effective with some of the mobile invertebrates and macroalgae species. Designed reefs are also used as nursery and spawning areas for fish. Some of these reefs are used to augment natural nursery areas or in conjunction with stocking programs. The only real marine culture reefs which have been used commercially in the United States are oyster reefs; however, there is significant potential for a variety of both marine and anadromous fish as well as invertebrates such as the abalone and lobster (*Homarus*), and macroalgae such as *Macrocystis*.

Although there are differences between east Asian and North American fisheries, the advances resulting from the extensive research and development in Japan and Taiwan can be modified for application in the United States. The design and site selection criteria developed for prefabricated units can also be applied to scrap material reefs to help improve their effectiveness and stability. This criteria could be especially valuable to the continued use of tires, concrete rubble, ships, and the expanded use of surplus oil and gas production rigs (Sheehy, 1982).

As the Japanese have demonstrated, the habitat improvement techniques made possible by designed and fabricated artificial reefs have enormous potential for expanding coastal resources and rehabilitating areas adversely impacted by human activities. The possible applications of this advanced reef technology in the United States should continue to be investigated.

Acknowledgments

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