The Coal-Waste Artificial Reef Program (C-WARP): A New Resource Potential for Fishing Reef Construction

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Introduction

Artificial reefs undoubtedly work: They form a settlement base for biological colonization and growth, and their crevices and surfaces provide cover and habitat for many organisms including fishes, crabs, and lobsters. They have proven success in attracting marine life, and in enhancing the local marine environment to improve recreational fishing significantly.

Artificial reefs are popular with sport fishermen; angler's clubs and civic groups have been active in reef construction, frequently with cooperation from local and state agencies.

While it is well known that reefs provide benefits to recreational fishing, they also provide more direct economic benefits. A recent study by the South Carolina Division of Marine Resources indicated that recreational fishing on the South Carolina artificial reefs in 1977 accounted for local expenditures of about \$5 million in the coastal communities, although through "multiplier effects" the total expenditures within the State were estimated at about \$10 million. Reef building may therefore be a desirable activity for marine habitat improvement, which provides tangible biological, recreational, and economic benefits to local communities.

ABSTRACT— The feasibility of using solid blocks of waste material from coal-fired power plants for underwater construction, including building artificial fishing reefs, is being tested. On 12 September 1980, a 500-ton demonstration reef, consisting of 15,000 solid blocks of stabilized fly ash and flue-gas desulfurization (scrubber) sludge from coal-burning power stations, was constructed in the Atlantic Ocean off Long Island, N.Y. Biological settlement and epifaunal colonization are already well established. Fishes inhabit the reef at high population densities, and crabs and lobsters have begun to immigrate. Laboratory and sea experiments over the past 5 years suggest that stabilized coal waste blocks may be environmentally acceptable in the ocean.

Unfortunately, funding for reef construction is currently an important obstacle. Although materials for reef construction are frequently donated, the costs are high for labor and for hiring cranes and barges to place the materials in the ocean. Because the benefits from a reef are distributed widely in the community no single group may wish to fund the project. At the same time there is taxpayer resistance to spending public funds for privately enjoyed recreational activities. In recent years the lack of adequate funds has prohibited new reef building in important candidate areas such as the New York Bight, which are subject to intense sport fishing and would benefit from habitat improvement (Jensen, 1975).

A potentially important new resource for the construction of fishing reefs may be provided from by-products of coal combustion, as electricity generating stations increasingly convert from burning oil to coal (Woodhead et al., 1981). The waste materials from coal combustion, produced in large volumes daily, consist of a flue-gas desulfurization (FGD) sludge and fly ash, both of which require disposal. For power plants near the coast, marine disposal might be an option, but uncontrolled dumping of untreated scrubber sludge or fly ash in the sea would have deleterious environmental effects. However, industry has developed a system to treat these wastes with additives and enable cementitious reactions to occur. The mix becomes a stable material that can be formed into blocks and cured to hard solids. The stabilization reactions which take place during hard block formation are very similar to pozzolanic reactions which occur in curing of concrete.

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We are assessing the feasibility of using such stabilized, solid blocks of coal combustion by-products as potential construction material for artificial fishing reef building. If the blocks prove suitable and have no adverse effects on the marine environment, the major expense of reef construction—handling and transportation — may be encumbered in the waste disposal costs.

Early Studies

The coal-waste artificial reef program (C-WARP) began in 1976 with various laboratory studies of the interactions of test blocks made from coal waste materials in seawater systems. Special attention was given to the leaching of major chemical components and of heavy metals from the blocks (Seligman and Duedall, 1979). Bioassays of seawater elutriates were made with cultures of a sensitive marine diatom, *Thalassiosira pseudonana,* to determine whether there were any toxic effects. Assay methods recommended by the U.S. Environmental Protection Agency and the U.S. Army Corps of Engineers were followed. Significant leaching of potentially toxic elements did not occur and inhibitory effects on plant growth and photosynthesis were not observed in the elutriates. Physical tests showed that the blocks did not bread down in seawater but remained solid, dense, and strong.

Following the positive results of the laboratory investigations, small-scale field investigations were conducted during 1977-78 and 1978-79 with arrays of blocks of stabilized materials set out on the bottom of a shallow embayment of Long Island Sound. The results of these early series of field investigations also suggested that the coal combustion waste materials, when stabilized into solid blocks, are acceptable in the marine environment (Roethel et al., 1980). We saw no adverse environmental effects. The physical integrity of the blocks was maintained over exposure periods of 1 and 2 years at sea and some increases in block strength during exposure were measured. The materials were found to provide suitable substrates for biological colonization and overgrowth by encrusting marine organisms which are characteristic of artificial reefs. Fishes became associated with these early arrays of test blocks — toadfish, *Opsanus tau,* soon spawned and attached their eggs to the block surfaces, some fish species fed upon the encrusting epifaunal growths, and others took up residence in the nooks and crannies between blocks.

Blocks and Reef Building

The next phase of the C-WARP was to build a demonstration, pilot-scale reef of waste blocks in the Atlantic Ocean. The program required that the demonstration reef would be studied for 3 years by a multidisciplinary team of oceanographers, fishery biologists, and engineers to provide data to assess its biological, physical, and chemical interactions with the marine environment.

Our initial laboratory and field studies had been mainly made on stabilized wastes formed into small numbers of cubic-foot blocks which were individually mixed and formed by hand. For the demonstration reef, which required thousands of blocks, such laborious, slow fabrication methods were unacceptable as well as expensive and new methods had to be adopted. In collaboration with the Besser Company[1], Alpena, Mich., we developed techniques to process power plant wastes with the machines and equipment used by the concrete industry. The new techniques were successfully transferred to a commercial concrete block factory and 500 tons of power plant FGD scrubber sludge and fly ash were used to manufacture large numbers of solid blocks of the stabilized materials, 20 × 20 × 40 cm (8 × 8 × 16 inches). The blocks were formed out of two coal waste mixes from different sources, having fly ash to scrubber sludge ratios of 4:1 and 1:1, respectively. Concrete blocks of the same size were used for controls.

The 500 tons of factory fabricated blocks were cured in kilns to achieve compressive strengths of about 500 psi, which allowed stacking for transport. They were trucked to a terminal on the Hudson River estuary and loaded on a barge fitted with bottom opening doors (Fig. 1). On 12 September 1980 the barge released the blocks at the project site (Fig. 2, 3) to build the Atlantic demonstration reef consisting of more than 15,000 blocks of stabilized coal waste.

Our field studies on this demonstration reef and its interactions with the ocean are in their second year and prospects for utilizing coal waste materials as a resource for reef construction continue to look promising. We are also making comparisons between the populations of colonizing invertebrates and of fishes on our reef, and the populations that we find on the long established Fire Island artificial reef system, described by Jensen (1975), which is nearby.

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

Study Area Description

The demonstration coal waste block reef is located south of Long Island, N.Y., at long. 72°13′W, lat. 40°35.8′N; 5.8 miles ESE of Fire Island Inlet. The 15,000 blocks lie on a sandy seabed at 20 m depth, and form one continuous structure approximately 77 m (250 feet) long, 14-18 m (45-70 feet) wide, and 1 to 2 m (3-6 feet) high. The seabed sediments in the vicinity consist generally of medium to coarse light brown quartz sand with grains from 0.1 to 2 mm diameter; there are also overlying patches of dark gray mud up to 1 cm thick scattered in the area. The macrobenthic infauna has been sampled frequently and is characteristic of the general inshore region of the New York Bight.

Repeated oceanographic surveys have been made at and near the project site to characterize the physical and chemical properties of the water column, nutrient concentrations, suspended particulates, current speed and direction, etc. Sea temperatures range from maxima in August of 23°C at the surface and about 14°C at the bottom, falling to a winter minimum of 0°-1°C in February, when the water column is completely mixed. Salinities are typical of the coastal seas and range from 30 to 34‰, although periodic low salinity inputs from Great South Bay are not uncommon. Close to the seabed, turbidity is relatively high, sighting distances often being only 1 or 2 m and after storms may be reduced to zero visibility. The results of the initial oceanographic surveys of the site have been published (Woodhead and Duedall, 1979) and further surveys have been completed to describe the seasonal cycles of oceanographic change.

Physical and Chemical Results

Long-term laboratory experiments have confirmed several trends in the physical effects of seawater immersion on test blocks. Block densities were found to increase throughout continued exposure to seawater. Block strengths also showed increases after immersion. Such extended nondestructive studies were made possible by the use of ultrasonic test procedures developed by engineers in the program. Positive cor-

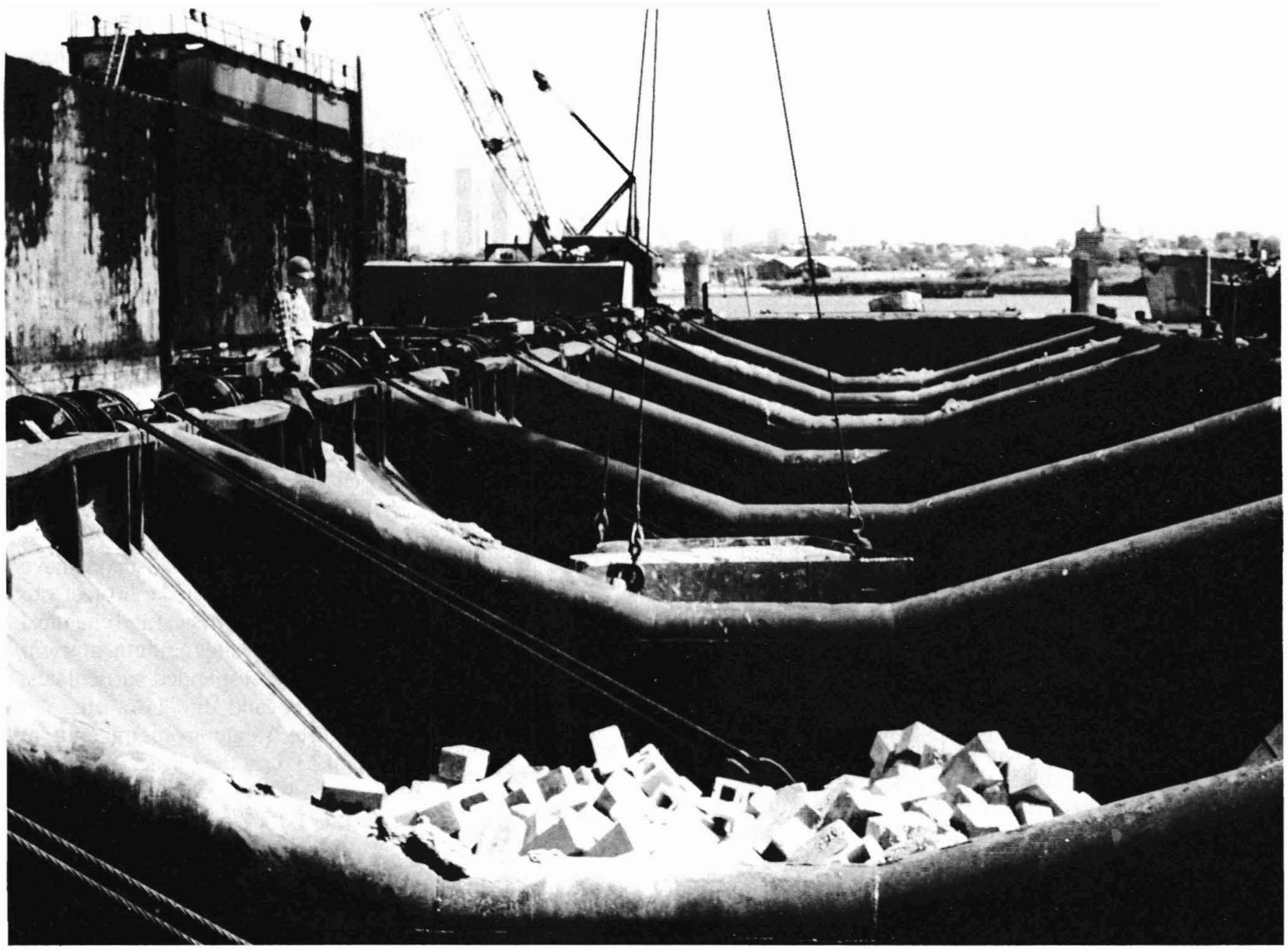

Figure 1.—Loading "pocket" barge with eight compartments fitted with bottom opening doors.

Figure 2.—Barge filled with 15,000 blocks being maneuvered for release at project site.

Figure 3.—Blocks on sea bed. Bottom water at site characteristically contains particulates and mucous strings.

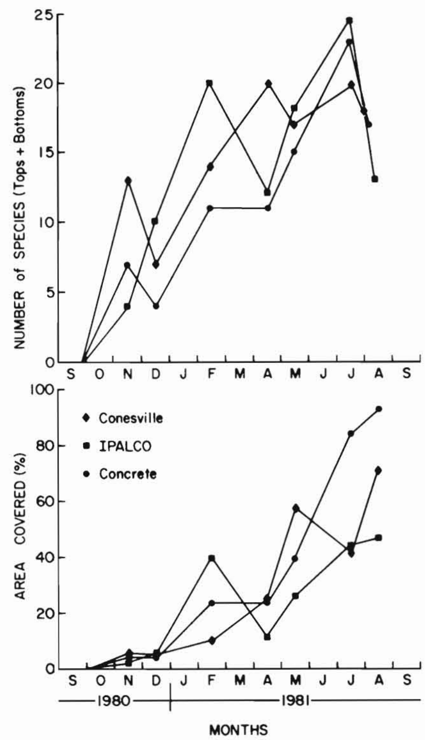

Figure 4.—Progress of epifaunal colonization on reef blocks. Top, number of colonizing species; bottom, area covered.

relations were developed between the velocity of sound transmitted through the blocks and compressive strength. The ultrasonic method is now used by divers at sea for nondestructive, repetitive testing of reef blocks in situ.

A variety of coal wastes which were screened were analyzed by a number of different techniques for elemental composition and mineralogy. The changes which occur with curing and during prolonged exposure in the sea are now being studied. Long term leaching experiments in seawater yielded leaching rates for major block components, such as calcium and sulfate. These data have been used to construct a model for the diffusion with time of major components from the blocks into seawater (Duedall et al., 1982). Such a model may be important in estimating the life of the blocks in the ocean, based on the rates of loss of major components which we measure in blocks which we periodically bring back from the reef.

Epifaunal Colonization

Biological settlement and colonization on the reef blocks have taken place continuously since the reef was first established. Test blocks have been removed from the site every 4-6 weeks for laboratory analysis, and a steady increase in the biological cover of block surfaces was recorded. Due to low light penetration at the site, plants did not settle and grow but overgrowth by animals on the top surfaces of the blocks after 1 year in the sea was 51 percent and 41 percent of the surface area on the 4:1 and 1:1 waste blocks, respectively. Colonization on bottom surfaces was rather more dense (probably because the bottoms had protection from sedimentation), the equivalent percent cover being 75, 70, and 45, respectively (Fig. 4). Generally the degree of settlement on the concrete and on the 4:1 waste were similar during the first year, but settlement on the 1:1 coal waste was slower or less successful. Concrete surfaces were harder than either coal waste and the immediate surficial layer of the 1:1 mix in particular was soft or slick. This probably influenced surface selection by some epibenthic larvae and may also have effected the long-term adhesion of organisms with upright, branching growth forms, such as hydroids and bryozoans.

The community of epifaunal organisms growing on the blocks after a year's exposure at sea was diverse; the predominant organisms were stalked ciliates, polychaete worms, mussels, barnacles, and feathery growths of hydroids and bryozoans. In August 1981, 16 different species were found on concrete blocks compared with 19 and 13 species on the 4:1 and 1:1 mix experimental blocks. In the following month, September, after completion of 1 year in the sea, there was a small reduction in the number of species recorded on the coal waste mixes to 14 and 10 species, respectively, compared with 16 on the concrete controls. The communities on all blocks had similar species composition although the percentage representation of some species changed significantly with block type. In particular, quite marked differences were found consistently over most of the year for the polychaete tube worm, *Polydora socialis*, which occurred commonly on the blocks of coal waste but was only sparsely represented or absent from concrete. *Polydora* was able to bore superficially into the outer layer of the coal waste to build tubes, but not into the concrete, which may account for its success in becoming established on the coal waste blocks.

Epifaunal colonization and overgrowth of the blocks had been more rapid in the early field experiments made in a shallow embayment of Long Island Sound, with good light penetration. Marine plants grew profusely on these shallow blocks and within less than a year epifaunal development on the different types of blocks had converged so that the communities were not distinguishable (Roethel et al., 1980). The differences which we have found at the Atlantic project site, particularly the lower rate of colonization, may be attributed to the low levels of light penetration. Plants do not grow and the energy inputs to the fauna are probably less allowing only slow growth and community development.

Toxic Potentials

These waste materials contain very small amounts of potentially harmful elements such as cadmium, arsenic, lead, mercury, and selenium. Released into the environment, these components of combustion wastes might be expected to exert toxic effects. However, initial laboratory bioassays made on seawater elutriates from finely powdered block material failed to demonstrate inhibitory effects on the growth and photosynthesis of a marine diatom, nor were the survival and normal development of sensitive eggs and larvae of winter flounder, *Pseudopleuronectes americanus*, affected (Woodhead and Duedall, 1979).

Bioaccumulation of heavy metals through marine foodwebs is an important environmental concern and organisms exposed to these wastes for long periods have therefore been analyzed for uptake of heavy metals. A series of repeated collections of epifaunal biomass from the blocks in an embayment of Long Island Sound was made on five occasions over 2 years. Analyses of acid digests of the biomass collections for copper, chromium, zinc, nickel, lead, cadmium, mercury, and selenium showed no evidence of elevated levels in the colonizing biomass growing upon coal waste blocks, compared with that which was collected at the same time from concrete block controls (Roethel et al., 1980).

Suspension feeding organisms which filter particulates from large volumes of surrounding seawater would be especially vulnerable to releases of block components. Tests for trace element uptake were made by holding actively feeding blue mussels, *Mytilus edulis*, for 3 weeks in aquaria with different sediment loadings of finely powdered coal wastes, which were kept in suspension by slow agitation. The mussels were fed on phytoplankton and ingested the particulates with their food; particulates were subsequently found in their fecal pellets having passed through the gut. Microanalyses of digests of the soft tissues of experimental mussels for trace elements showed significant elevations of tissue iron concentrations, which are not toxic. But no increases were found in zinc, lead, nickel, manganese, or cadmium. As this study continues, more elements such as arsenic and mercury are being included. But on the basis of the initial results, it does not appear that filter feeders had accumulated toxic elements from the ingestion of coal waste particulates.

Habitation by Fish

Divers reported that fishes had already begun to move into the nooks and cran-

Figure 5.—Cunner and blackfish at Fire Island Reef.

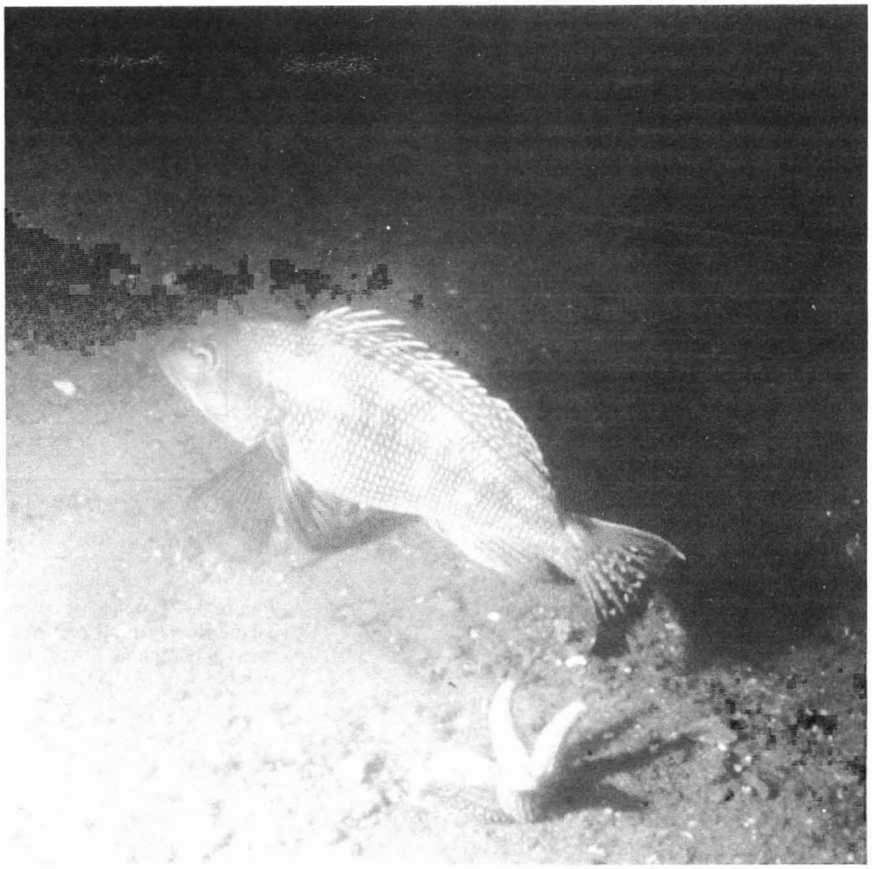

Figure 6. – Black sea bass occur in numbers from June to October.

nies of the new reef by the time of the first scuba survey, 5 weeks after placement on the seabed. Cunner, *Tautogolabrus adspersus*, were the initial inhabitants and remained the most numerous fishes throughout the first year of surveys. It was also the most abundant species on nearby Fire Island Reef (Fig. 5). Other species found at the reef during the first year's surveys were black sea bass, *Centropristis striata;* blackfish, *Tautoga onitis;* conger eel, *Conger oceanicus;* winter flounder; summer flounder, *Paralicthys dentatus;* ocean pout, *Macrozoarces americanus;* sea raven, *Hemitripterus americanus;* and longhorn sculpin, *Myoxocephalus octodecemspinosus* (Fig. 6). Adult rock crabs, *Cancer irroratus*, were early migrants to the reef and toward the end of the first year during summer, juvenile lobsters, *Homarus americanus*, 10-25 cm in total length, began to appear in increasing numbers.

A census of the fish populations taking up habitation on the new reef was made by regularly setting out fish traps in standard arrays, both on the new reef of waste blocks and also on an outlying section of the old Fire Island Reef nearby. The traps are rectangular, made from vinyl-coated 14 gauge wire and measure 90 × 60 × 30 cm, and they have a single netting funnel about 60 cm long. The "soak" time is 2 days, two strings of traps being fished on the waste reef, with two additional strings fished on Fire Island Reef at the same time. (Fig. 7).

A storm wrecked much of the trapping gear the first time it was fished after placing the reef, but after replacement, the gear subsequently worked well, being

Figure 7. – Shooting a string of fish traps over the stern of SUNY research vessel *Onrust*.

fished throughout 1981. Average catches of fish showed increases from March through summer (Fig. 8), with cunner usually forming about 90 percent of the trap catch. Larger male fish were predominant among the early colonizers, but by summer small juveniles had recruited to the reef in numbers. Average catches on the Fire Island Reef were about twice as large but followed the same seasonal cycle of change and had a similar species composition.

The total area being fished at Fire Island Reef is not yet established but it is larger than the area of the new reef of blocks, which may account for the larger catches made. The catching efficiency of traps is influenced by temperature and the low catches made in spring 1981 (when temperature was low) in both situations probably do not reflect the density of fish on the reefs when compared with summer catches at higher temperatures.

Fish caught in the traps are in excellent condition and several hundred have been tagged with both plastic "spaghetti" tags and with Petersen buttons to provide information on the residence at the site by different species and on their seasonal movements. Perhaps more importantly, recaptures of tagged fish have been used to make first estimates of the size of fish populations at the reef.

Due to their abundance, the best available population estimate in the first year is for the cunner. Using all the recapture information from a sequence of tagged fish releases in 1981, two methods were used to calculate population size from the release-recapture experiments: Schnabel's method and modified Schnabel (Ricker, 1975). The two estimates of the numbers of adult cunner on the reef were 3,735 and 3,856 fish. The area of the waste reef is approximately 1,230 m^2 and the mean density of adult cunner on the reef in the first year was therefore about 3 fish per m^2. That density is already as high as Stone's (1978) estimates for adult cunner on rough bottoms in the New York Bight.

The reliability of these estimates will be reassessed in 1982. Population assessments will be extended to other fishes which have been tagged: Black sea bass, ocean pout, conger eel, and blackfish. The black sea bass in particular have shown quite high tag returns — almost all coming from sport fishermen. Further growth and development of the epifaunal communities on the reef blocks are anticipated in 1982. We hope to determine the extent to which this occurs and whether epifaunal changes are matched by changes in the composition and size of fish populations inhabiting the new reef.

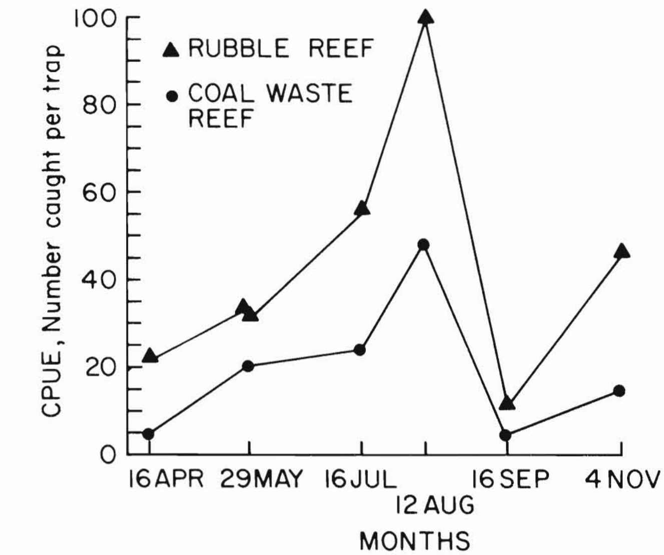

Figure 8.—Catches of cunner (cpue) at new reef and at Fire Island Reef ('rubble reef'). Note that low catches in September were accompanied by highly turbid conditions which reduce catch.

Conclusions

Since 1976, the C-WARP has made a wide variety of studies of the reactions of coal waste materials with seawater systems, both on small scale in the laboratory and, more significantly, at sites in the open sea. Our diverse data derived from these investigations of the physical, chemical, and biological interactions of different stabilized coal waste mixes in marine systems have so far all suggested that in the form of solid blocks, the material is compatible with the marine environment.

During some longer exposures, where blocks have been in the sea from 1 to 4 years, physical integrity has been maintained and material strength increased. Leaching of major components into seawater decreased exponentially with time and trace elements appeared to remain absorbed in the blocks. Different measures of biological acceptability have indicated that the stabilized material is not toxic to organisms in the sea. The study should continue for 3 years before assessments are made but already it appears that the cured blocks are suitable for biological colonization and overgrowth by epifauna, and that fish are resident in the reef.

Zawacki (1969) has made the point: "The use of waste materials . . . to construct artificial reefs may help solve some of the disposal problems of large cities while providing excellent fishing for the ever-increasing angling public." While agreeing, Jensen (1975) cited the need for caution and a systematic approach, to temper the zeal for building new reefs with due regard for regulatory requirements and accepted environmental safeguards.

The stabilization of coal waste into cured blocks for disposal may provide just such an example. If our extended program of testing and oceanographic monitoring continues to find the blocks to be without adverse effects in the sea, an acceptable alternative may have been found to problems of disposal of coal combustion wastes from power plants. That solution would also carry benefits for the marine recreational fishing community through reef construction and marine habitat improvement.

Acknowledgments

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