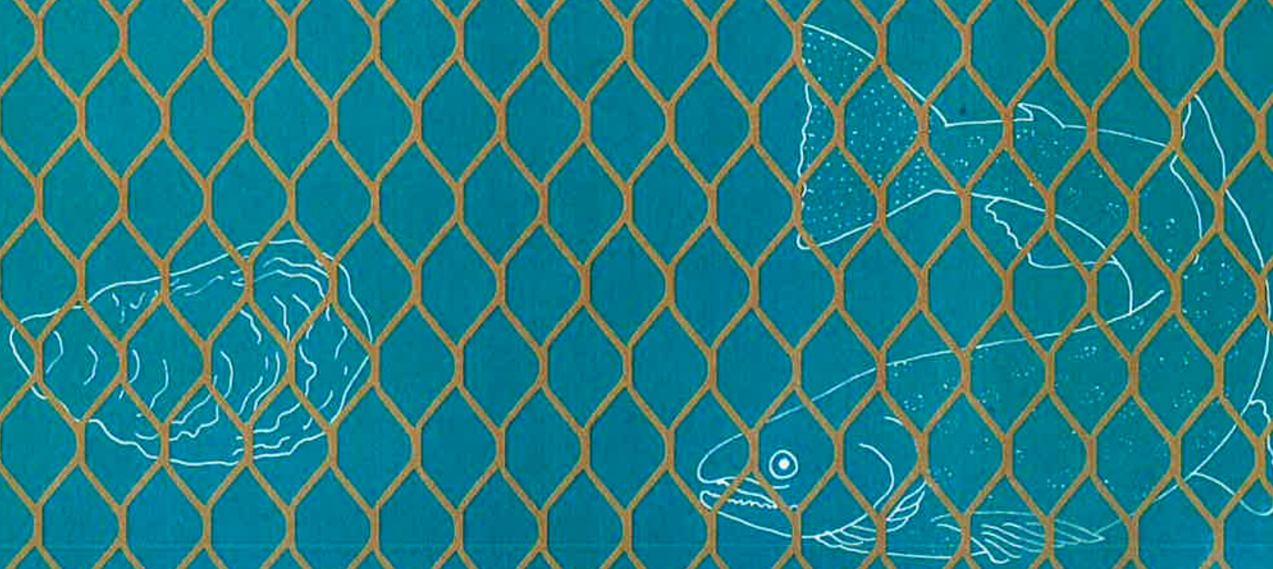
Design Guide

Copper Alloy Mesh in Marine Aquaculture

International Copper Research Association, Inc.



Design Guide

For Use of Copper Alloy Expanded

Metal Mesh in Marine Aquaculture

INCRA Project 268B

July 1984

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ABSTRACT

The International Copper Research Association, Inc. has been involved with exploring the uses of copper alloys in marine aquaculture since 1975. These continuing efforts have resulted in a wide diversity of research, prototype design and construction and commercial test projects in at least a dozen countries and with a variety of end purposes. These uses have included shellfish trays, fish cages, intake screens, and sheathed floats. These efforts have grown and diversified including large numbers of private, university and government organizations on an international basis. There have been many successes resulting in the build up of considerable international interest in the use of copper alloys in marine aquaculture. All this activity has been documented over time in a number of INCRA reports* and papers published in the scientific literature. The purpose of this report is to present in a single document a summary of these diffuse data, the results and conclusions to date and to provide a means of identifying sources for more detailed technical data. In short, a helpful guide to anyone interested in exploring the uses of copper alloys in marine aquacultural applications.

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* Available upon request from INCRA, 708 Third Avenue, New York City, NY 10017, see reference section for report citations.

1.0 INTRODUCTION

International Copper Research Association, Inc. has been actively supporting the beneficial uses of copper in aquaculture since 1975. These efforts are based on the fact that marine biofouling of meshes is often a very serious operational problem, sometimes THE major problem, with high economic impacts through effects on labor, and reduced system performance (Huguenin & Ansuini, 1978; Huguenin & Huguenin, 1982). Biofouling can dramatically reduce necessary water flow, increase head losses, and alter the oxygen content of the water. In addition, much of the conventional aquaculture equipment are very vulnerable to storm damage and forced entry by predators, and often exibit short useful service lives in seawater.

In 1975 a number of promising applications of copper and its alloys in marine aquaculture were identified (Huguenin & Ansuini, 1975). These included the use of copper alloy meshes for both shellfish trays and fish cages. In the same year field tests were started with shellfish trays made from woven copper wire mesh. It soon became clear that this type of mesh alone wasn't structurally adequate and that copper-nickel alloy mesh in expanded metal form had the most potential for practical and economic applications (Huguenin, Hammar & Tucker, 1975). All subsequent research has been with 90-10 Cu-Ni (Alloy CA-706) expanded-metal mesh with a nominal opening size of about 3/8 in. Although, the mesh has come from at least three sources in the U.S. and Europe, it all has had the characteristics shown on Table 1.1 with only small variations. In most applications to date, with a few exceptions, the structural components have been made from a nonconducting synthetic material. Pultruded fiberglass sections have been used for fish cages and several different plastics have been employed in shellfish trays, mostly polyethylene, polypropylene and polystyrene.

The first INCRA prototype fish cage was designed, built and deployed to a commercial Maine fish farm in July 1977 for operational testing. It was comparable in size with the other fish cages on that farm and built of Cu-Ni expanded metal mesh and pultruded fiberglass structurals. The intent was not only to exploit the benefits of Cu-Ni mesh but also to address in the design all the problems, needs and requirements for commercial marine fish farming. The design requirements were derived from a careful evaluation of marine fish farming world wide (Huguenin & Ansuini, 1978). As a consequence, the INCRA prototype is different from more conventional fish cages in a number of ways other than just different materials. It has proven itself, under varied and rigorous service conditions in both the U.S. and Canada, to be incredibly rugged, biofouling resistant, versatile and successful (see Table 1.2 and Section 3). A number of other fish cages in seven countries have been designed and built based on the experiences with the prototype (see section 3). In addition to the fish cage itself, the prototype program successfully demonstrated the concept of using thin 0.01 in. (0.25 mm) 90-10 Cu-Ni sheet to provide long term protection to vulnerable styrofoam float blocks from physical damage and biofouling (see Figure 1.1)(Huguenin & Ansuini, 1977).

Table 1.1 INCRA sponsored research around the world has been with an expanded-metal mesh with the general characteristics, with only small variations, as shown below:

- metal - 90-10 Cu-Ni (alloy CA-706)
- mesh - expanded-metal mesh
- nominal mesh size - 3/8" (1.0 cm)
- gauge - .035" (0.89 mm)
- strand width - .050" (1.27 mm)
- long way dimension(LWD) - .750" (1.9 cm)
- short way dimension(SWD) - .425" (1.1 cm)
- weight - 0.38 lb/sq ft (1.86 Kg/sq m)
- percentage open area - 73% perpendicular
  - 76% @ 20 degrees to perpendicular
- metal hardness ≃ 1/4 to 1/2 hard
- ultimate yield strength ≃ 48,000 psi (3.3×10^8 N/sq m) to 62,000 psi (4.3×10^8 N/sq m)

Table 1.2 PROTOTYPE CAGE ACCOMPLISHMENTS

1) Proved marine biofouling resistance of 90-10 Cu-Ni mesh and compatibility with fish culturing.

2) In spite of the light weight, showed great structural strength, withstanding the worst winter storms in 100 years (Feb. 1978) with no damage to cage and repairable damage to float hinge joints.(The rest of the farm being destroyed around it.) This survival amidst destruction has been repeated at least three more times over seven years and in two countries.

3) Demonstrated simple practical system for lifting cage completely clear of the water for inspection or maintenance.

4) Proved efficiency of basic modular design approach using 90-10 Cu-Ni expanded metal, pultruded fiberglass sections and electrically isolated galvanized steel-hard points.

5) Proved merit of novel elastic suspension system connected to cage bottom corners and to centers of bouyancy of corner floats of articulated float collar.

6) Demonstrated a simple and practical method for crowding fish in a rigid cage for grading or harvesting.

7) Twice demonstrated ability to be readily dissassembled, transported and reassembled.

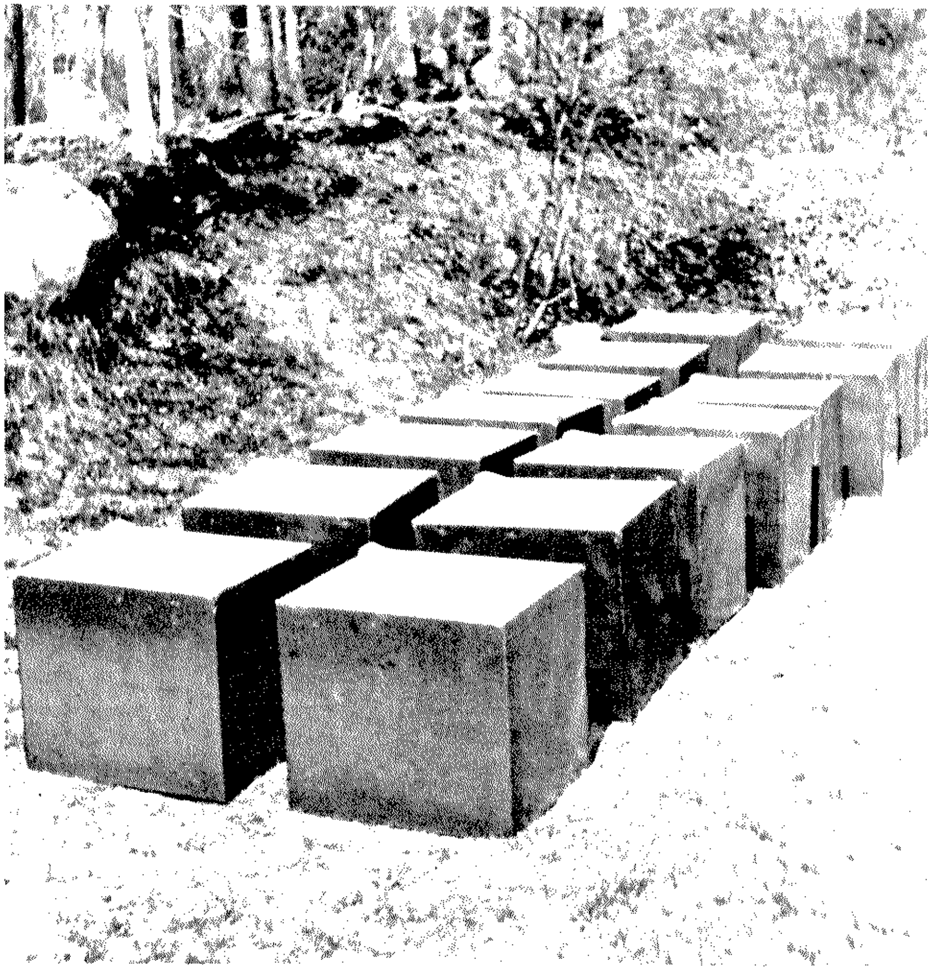


Figure 1.1 Fourteen 90-10 Cu-Ni wrapped polystyrene floats used with INCRA Cage Prototype. Each with volume of 8.2 ft^3 and bouyancy of about 490 lbF.

Figure 1.2 PROTOTYPE OF FAMILY OF SMALL INTAKE SCREENS. This example intended to mate to base but can be modified to mate to standard pipe flange. 2'dia.x2½'ht. with 8.6 ft^2 of open area thru mesh.

Simultaneously with the design and development of the prototype fish cage, tests of various types of shellfish trays utilizing the same mesh were initiated. These tests were also successful, proving the viability of using biofouling resistant Cu-Ni mesh in close proximity to delicate shellfish (Huguenin & Huguenin, 1982, see Section 4).

While copper alloys have long been used in marine applications, their use in aquaculture is new. In addition, the combination of Cu-Ni with fiberglass and plastics for complete structures has lead to new design and manufacturing techniques. The same techniques and methods have proven to be applicable to the design of seawater intake screens both large and small (Ansuini, Huguenin & Money, 1978; Huguenin & Huguenin, in press). Such intakes can be used for hatcheries, aquariums and a variety of shore based aquaculture facilities as well as nonaquacultural industrial and utility uses (see Figure 1.2). Considerable background research has been necessary to develop and document this new technology. Some of this research has been in areas such as: the long-term effects of seawater on pultruded fiberglass, documentation of biofouling resistance of mesh, fastener design and selection, loads/deflections and hydrodynamic drag on expanded-metal mesh, and manufacturing/bonding techniques. Much of this was documented in a "Seawater Screening Design Guide"(Gularte & Huguenin, 1980). The primary purpose of the present guide is to simplify, update with new data, and direct this accumulated technology specifically towards aquaculture applications.

2.0 MATERIALS SELECTION

There are a number of alloys that are both good marine materials and possess significant resistance to marine biofouling (Tuthill and Schillmoller, 1965). These materials include 90-10 Cu-Ni, 70-30 Cu-Ni, and to a lesser degree, a number of brasses and bronzes. Generally an alloy needs 70% or more copper to have really meaningful biofouling resistance. Among the possibilities, 90-10 Cu-Ni is rated among the highest in fouling resistance (Hunt and Bellware) and is the material with which we are most familiar. Most of the data and experience contained in this publication were acquired with 90-10 Cu-Ni alloy. The fouling resistance of 90-10 copper-nickel in seawater is well documented (Efird, 1975) and, while it is considerable, it is not absolute. Under conditions of low-flow velocity or stagnation, the alloy may require occasional brushing with a stiff brush to maintain completely clean surfaces. Long-term corrosion test data (Efird et al., 1975) shows that the stabilized corrosion rate of 90-10 copper-nickel is in the order of 0.1 mils per year or less, and this corrosion tends to be uniform. The alloy is in many other ways a superb engineering material for marine applications (Hunt and Bellware, 1967).

While most of the interest to date has been in applications involving modest velocities (under 10 fps), there are data on the effects of much higher water velocities (Efird, 1977). Because of its combination of properties, it is possible to design and build very long-life structures even with relatively thin gauge materials. Under many circumstances, copper-nickel alloys can be used in areas with even relatively low water flow velocity without detrimental effects on marine organisms (Huguenin and Ansuini, 1975). This lack of any biological problems under normal operating conditions has been confirmed by experience (Huguenin, Hammar and Tucker, 1975; Huguenin et al., 1979; Huguenin and Ansuini, 1980; Huguenin and Huguenin, 1982); therefore, structures made from this alloy are likely to be environmentally acceptable.

When designing equipment primarily for fouling resistance, extra care should be taken to avoid setting up galvanic cells, which can reduce or even nullify the corrosion rate and hence the fouling resistance of copper alloys. Copper alloys tend to be cathodic to other structural metals such as steel or aluminum. Therefore, the use of these metals in electrical contact with copper alloys should be avoided if the structure is to maintain its fouling resistance. In particular, care has to be taken, in the absence of copper-nickel fasteners which may be hard to find, to ensure that the fasteners are either non-metallic (none of suitable strength and price have yet been found) or that the fastener materials are cathodic to the 90-10 Cu-Ni. If the fasteners were to be anodic, the unfavorable area ratios would quickly result in the destruction of the fastener as well as the loss of fouling resistance on the mesh. Considerable care must be exercised in the selection of fasteners (see Section 5). The alternative of electrically isolating the fasteners can be made to work but does involve some risk. In fact, after assembly each fastener has to be electrically isolated and should be checked with a meter. During field assembly isolation bushings can be crushed due to slight hole misalignments or their coatings punctured. Proper quality control checks are also often difficult due to accessibility and environmental conditions. In addition, there is always the possibility of breakdown of the electrical isolation with time due to fretting, materials deterioration or dynamic effects. This approach can be made to work effectively but requires some care. By following the simple guideline of ensuring that the copper alloy is in a freely corroding state, fouling resistant structures can and have been constructed.

Various metallic mesh constructions can be produced from copper-nickel. However, expanded-metal mesh offers greater design flexibility, because it can be produced in a large variety of mesh sizes, open areas and strand gauges, coupled with the extra advantage that the nodes are fixed, thus providing freedom from both fretting and crevice corrosion. Expanded metal for screens can be made, at a minimum, with holes of 1/8 to 2 inches and in materials thickness of .005 to .150 inches. The few previous cases where copper-nickel expanded metal has been used in seawater applications have generally involved considerable over-design with resultant high materials cost. This has been partly due to the fact that no technique for predicting deflections and stresses on thin gauge expanded metal panels subject to uniform loading has previously existed (see Section 9).

In order to avoid problems with galvanic corrosion, the selection of materials for structural elements was limited to either similar alloys as the mesh or a non-metallic. Pultruded fiberglass structurals were selected (Extren Series 500 Improved Structural Shapes, Morrison Molded Fiberglass Co.) for example on the basis of ready availability in a variety of section sizes as well as for their high strength and low weight. Similar structural shapes are also made by Westinghouse Electric Corporation and others. Panel frames are built with 2 x 9/16 in. x 1/8 in. C channel; space frame structurals are a variety of shapes chosen for each application (see Section 10). In this way a variety of structural shapes and sizes can be developed from common components (see Figure 2.1), and easily assembled and disassembled due to their modularity.

In 1977, when pultruded fiberglass sections were first chosen as the structural material to be used with 90-10 Cu-Ni expanded metal mesh, there was no available recorded information on its prior use in seawater. There were concerns that moisture uptake combined with freeze-thaw cycles on exposed portions might produce destructive delaminations and changes in material properties from prolonged exposure in seawater. As a consequence, in order to validate the screening concept, it has been necessary to also monitor the material properties of the fiberglass pultrusions (see Section 6). These data, all from only one batch from a single manufacturer, showing four years of

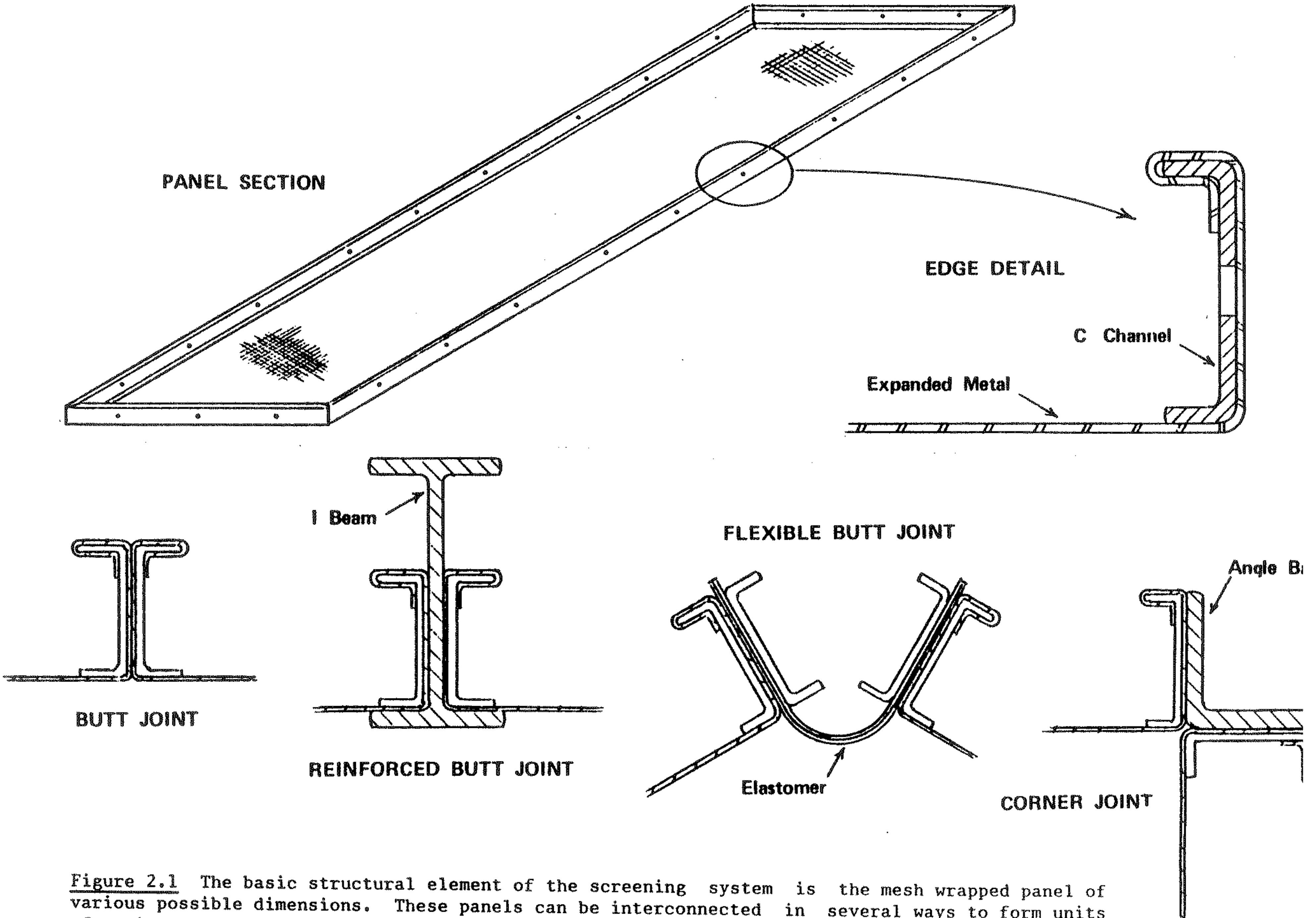


Figure 2.1 The basic structural element of the screening system is the mesh wrapped panel of various possible dimensions. These panels can be interconnected in several ways to form units of various shapes and sizes.

exposure, indicate that water uptake by the fiberglass does reduce its strength but that much of it can be regained on drying. It is postulated that there probably isn't any time related degradation in material properties per se, although the reduced performance of the structurals due to moisture uptake must be considered during design.

Structural reinforcements may be needed at corners, joints and at points where loads become concentrated. Strong points are needed to transfer loads, and sometimes moments, from the fiberglass space frame to the surrounding support structure or foundations. Hot dipped galvanized steel weldments have been used at these points for periods of time up to seven years with success (Ansuini and Huguenin, 1978; Huguenin et al., 1979). However, considerable care is needed to assure electrical isolation of the steel from the copper alloy mesh. Even if installed properly, there is always a small risk of later electrical contact from material changes or dynamic factors. For long-term use the galvanized steel reinforcements also require sacrificial anodes at each piece to protect the steel from marine corrosion. If properly maintained, these reinforcements should be good indefinitely.

Because of potential, but not necessarily real, problems with the use of galvanized steel reinforcements, there has been considerable thought and effort applied to finding more practical alternatives. A fiberglass reinforced corner intended to hold an 8,000 lb (3,600 Kg) concentrated load has been designed and built from fiberglass sheets and structural shapes. It still required some metallic fasteners and cost at least ten times that of an equivalent galvanized steel unit. The cost was due to very high labor content and more expensive materials. In short, while technically feasible, it had little advantage and very high cost, i.e. impractical.

More promising for use in high stress areas, is the use of copper alloys compatible with 90-10 Cu-Ni in terms of electropotentials (see Figure 2.2). The best would be 90-10 Cu-Ni structurals. These are available and can be welded into desired form but may be rather expensive. From a cost/benefits standpoint the most attractive material appears to be silicon-aluminum bronze. Corner brackets of this material are being built and deployed, and if designed and built to withstand service loads should work nicely.

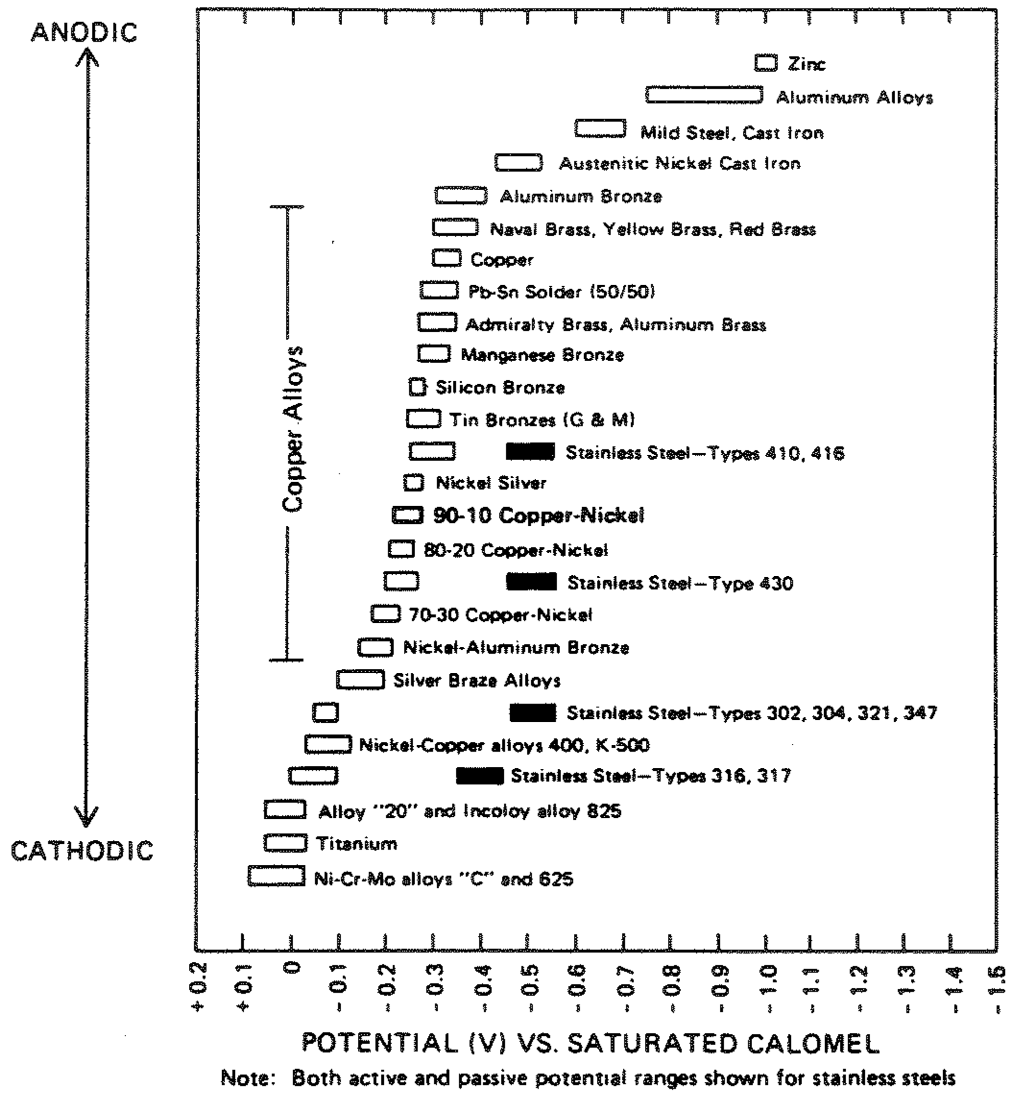


Figure 2.2 Galvanic relationships in flowing seawater (8 to 13 ft/sec, 50° to 80° F.) Seawater conditions involving different velocities or temperatures may result in potentials outside the indicated ranges, but as a general rule, will not alter the relative galvanic positioning of the different materials (Tuthill & Schillmoller, 1965).

The INCRA cage prototype was deployed for in-service testing at an operating marine salmon farm at Wiscasset, Maine in July 1977. The design of this unit with its many innovative design features has previously been described (Ansuini and Huguenin, 1979) and is shown on Figure 3.1. The prototype experienced a very unusually severe first winter with six major storms, including the 100 year storm, (Feb. 1978), solid ice and a Richter 4 earthquake. There were also severe storms in subsequent winters. During this time the farm was essentially destroyed three times and had major damage on additional occasions. After each storm new mooring lines would be emplaced and some of the conventional cages would be salvaged, and severely damaged cages scrapped. During all this the INCRA cage survived with only minor damage and the structural integrity of the whole complex became keyed to the INCRA cage. These experiences, as well as operational data, are documented in Huguenin et al., 1979. The accomplishments of the prototype and the advantages of the INCRA design concept are listed on Table 3.1

In constructing the 10 x 20 x 10 ft. unit, twenty-four panels were interconnected to each other and to heavier gauge fiberglass structurals, which comprise a space frame (see Figure 3.2). This type of modular construction is easy to assemble in the field with unskilled help and simple hand tools. A modular design was selected on the basis that mass production of a few discrete components would lower their unit cost. Yet, these same components can be assembled in a variety of configurations to meet the needs of individual installations. Modularity also implies that with a little care during design, it may be relatively easy to remove and replace individual screen panels. To construct units of other sizes or configurations only the space frame design need be changed.

While the panels can individually take very high loadings, they must be well supported in a space frame of sufficient load bearing capacity to take the combined loads of a number of panels. Obviously, the space frame must be specially designed for each installation and its form will be dependent upon both the configuration and performance requirements of the total system. The individual unsupported panels are quite flexible but when assembled with a suitable space frame, the resultant structure is very strong and rigid (see Figure 3.3).

The INCRA prototype was inspected and serviced approximately on a yearly basis. The cage unit was found to be in good shape and detail reports of these inspections were made. Yearly servicing of the cage is estimated to take less than two man-days, although inspection, sampling and mobilization/demobilization activities for a remotely located single unit required more time. These cages can be easily lifted clear of the water for inspection and maintenance (see Figure 3.3). The prototype

FIGURE 3.1

MARINE FISH CAGE

PROTOTYPE

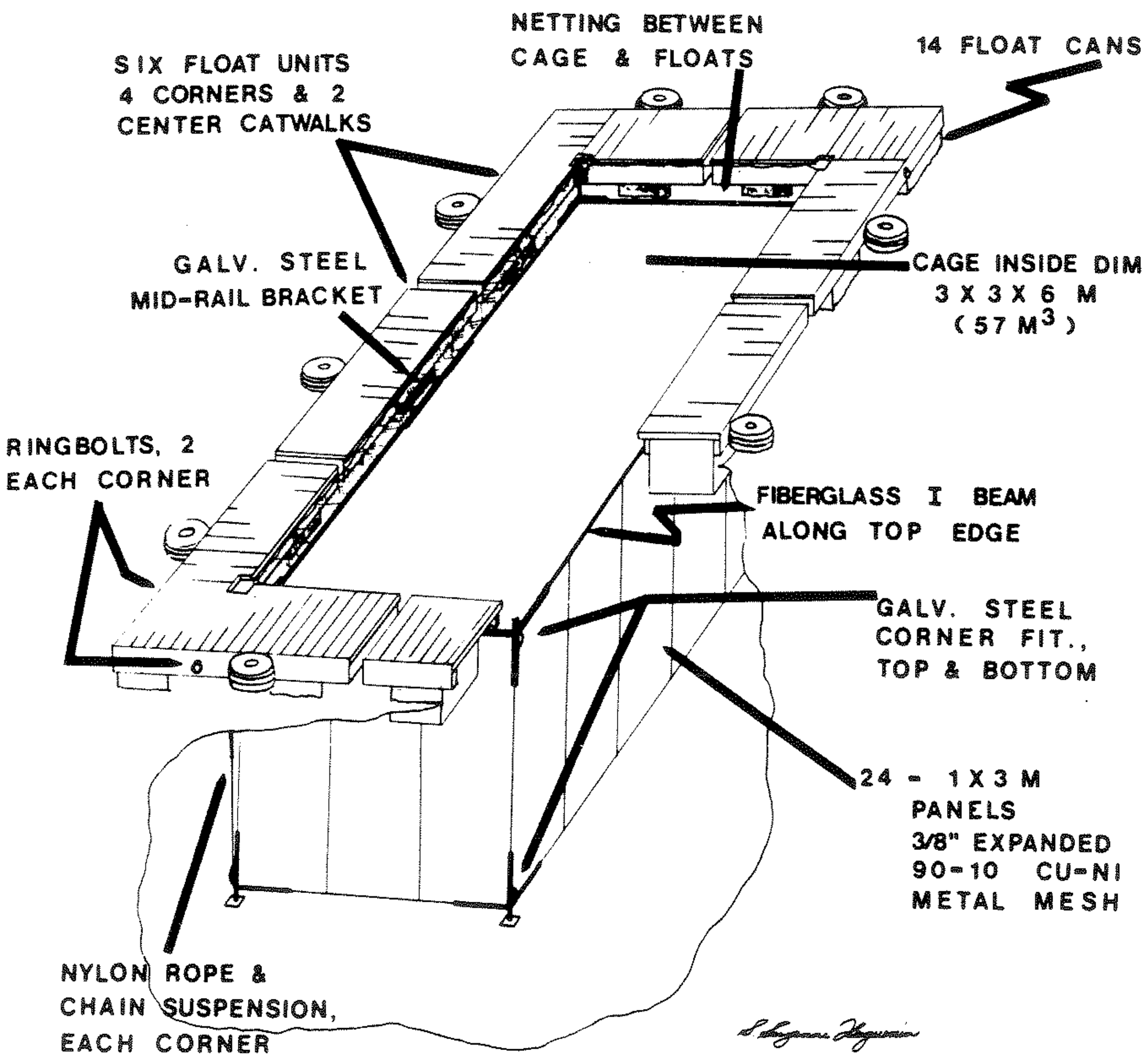


Table 3.1 ADVANTAGES OF INCRA TYPE CAGES OVER CONVENTIONAL UNITS

- Longer service life.
- Reduced maintenance (possibly, substantially less).
- Reduced biofouling means more water flow, this translates into higher stocking densities and faster growth.
- Greater strength (can be used in rougher environment).
- Greater crop security (low probability of losses) and reduced insurance premiums.
- Reduced predation (possibly, substantially less).
- Modular construction of cage and float components.
- Rigid shape (doesn't collapse like netting in a current to crowd fish).
- Can be disassembled, transported and reassembled.

Table 3.3 C-21 FISH CAGE DOCUMENTS

- Cage Construction Drawings INCRA Type C-21 Cage. July 1980, revised September 1982. (18 pages)
- Assembly Instructions INCRA Model C-21 Float Collar. (31 pages)
- Assembly Instructions INCRA Type C-21 Fish Cage. (15 pages)
- Instructions for Use of Lifting Frames, INCRA Type C-21 Fish Cage. (7 pages)

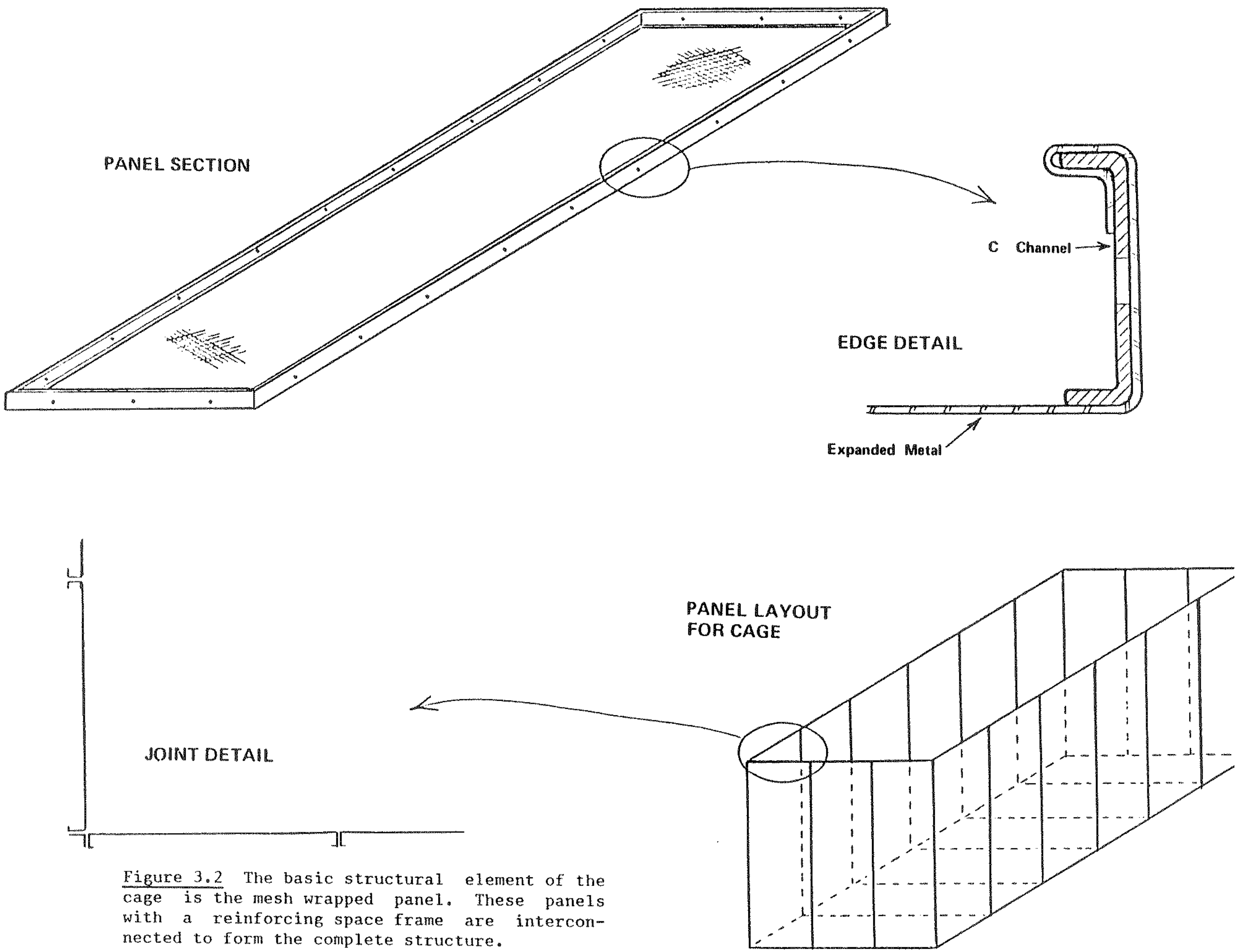


Figure 3.2 The basic structural element of the cage is the mesh wrapped panel. These panels with a reinforcing space frame are interconnected to form the complete structure.

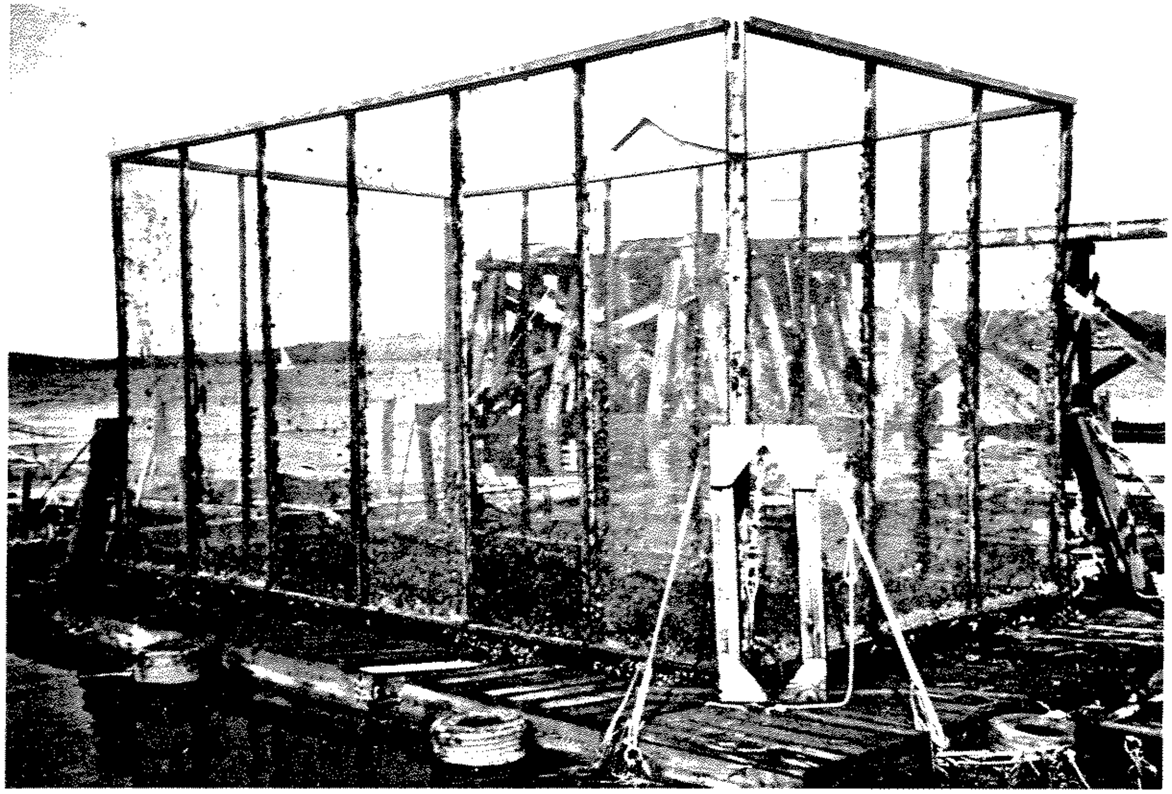


Figure 3.3 Prototype cage inspection after four years of tough operational use.

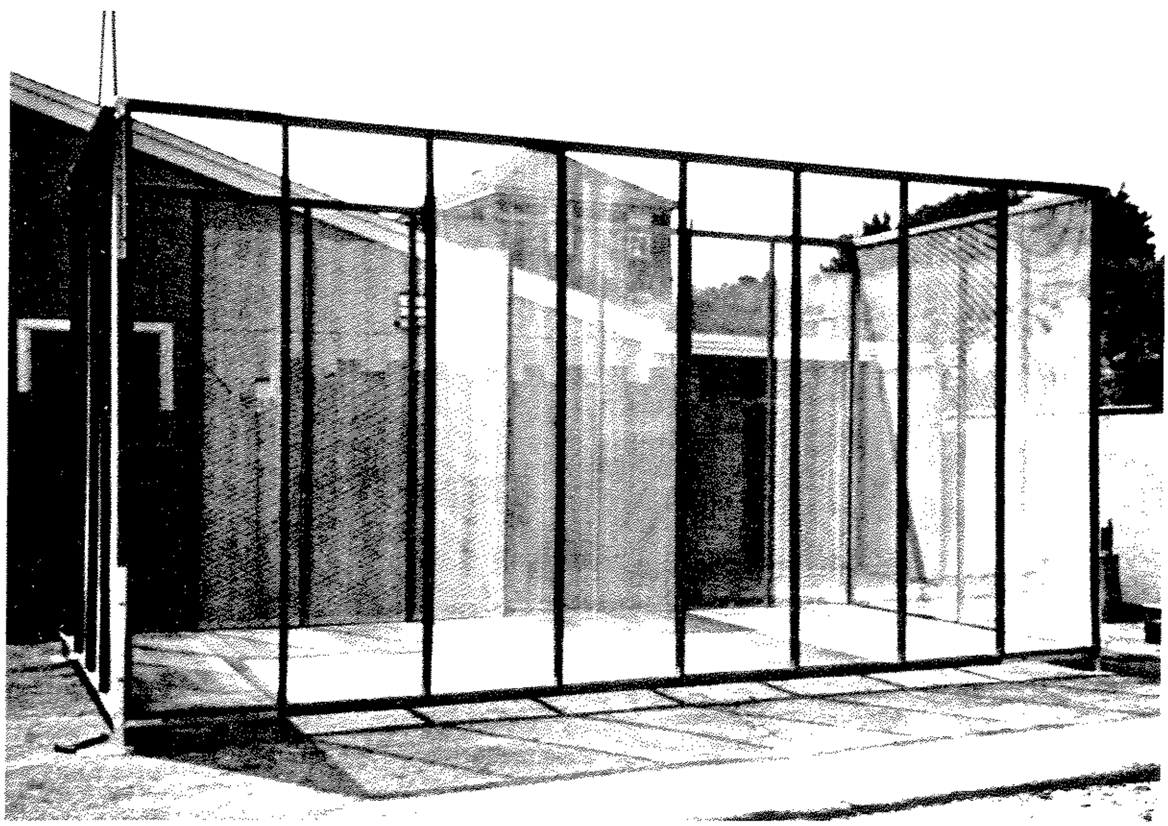


Figure 3.5 First C-21 cage during trial assembly, note different number of panels for same overall dimensions compared to prototype.

cage after more than four years in the water, was disassembled in late 1981 and shipped by INCRA to an operating marine fish farm in Canada. The prototype cage was reassembled and deployed in Dark Harbor, Grand Manan Island, New Brunswick, Canada during May 1982. The cage was found to be in excellent condition, even after years of deployment in a tough environment, although some of the floats were damaged during shipment. All indications are that the design will easily survive its design goal of 10 years of service. It was subsequently moved again to another farm in New Brunswick, Canada in 1983 without any problems and again survived several punishing storms in December 1983.

The economics of the INCRA cage concept have been described elsewhere (Huguenin et al., 1979). These economic analyses were based on comparisons of relative materials cost only, between the INCRA concept and more conventional fish cages. These analyses, with adjustments for passage of time and recognition of the inherent assumptions, are believed to still be valid. While materials were more expensive than those of conventional units, the conclusions were that longer service lives, reduced maintenance, greater security of stocks, reduced insurance costs, and increased water flow through the mesh more than compensated for the increased materials cost. The considerable world-wide interest in INCRA type cages is indicative of the validity of the concept.

In early June 1980, INCRA ordered from Woods Hole Engineering Associates, Inc. (WHEA) two modified cages with the same overall dimensions as the prototype. While conceptually the same, and having the same features, this required a completely new detail design effort to incorporate technical and economic changes resulting from experience with the prototype unit. These are summarized on Table 3.2. This redesigned cage has been designated the C-21 cage (see Figure 3.4). In addition, specifications had to be clear and detailed enough to enable cage component construction by WHEA's subcontractors, float construction by recipients, assembly by inexperienced personnel and servicing without direct WHEA support. The INCRA prototype had been designed, built, assembled and serviced all by the same people, requiring a minimum of documentation. The C-21 design effort included the production of a substantial number of documents and they are listed on Table 3.3. Copies can be acquired through INCRA. This design effort and the manufacture of two cages along with the trial assembly of one unit, took less than two months from "go" to the total order being packaged and ready for shipment (see Figure 3.5). The C-21 has also been manufactured in Scotland; it is also deployed in Northern Ireland, and one is going into Spain. The C-21 design is particularly noteworthy because it earned WHEA, Inc. a Merit Award from the magazine Materials Engineering for the creative and competent use of materials (see Materials Engineering, Oct. 1981).

The C-21 unit is ideally sized for research and commercial trials but is somewhat small for optimum commercial production (Huguenin and Ansuini, 1978). As a consequence WHEA has carried out a preliminary

TABLE 3.2

DESIGN DIFFERENCES BETWEEN INCRA PROTOTYPE CAGE AND C-21 CAGE

- Major redesign to produce same overall cage side with 30"-wide panels rather than 40"- as shown on prototype. This was due to availability of 36"-wide sheet in the U.S. and unavailability and/or high cost of 48"-wide material.
- Switching fasteners to 6mm 90-10 Cu-Ni fasteners. This meant smaller hole diameter than on prototype.
- Redesigned the spacing of fastener holes to somewhat reduce number of fasteners required relative to prototype.
- Redesigned and simplified float units, including use of commercially available float cans and redesign of articulated joints.
- Reduced gauge of corner unit angles.
- Used coped joints at corners of mesh panel frames rather than mitered joints.

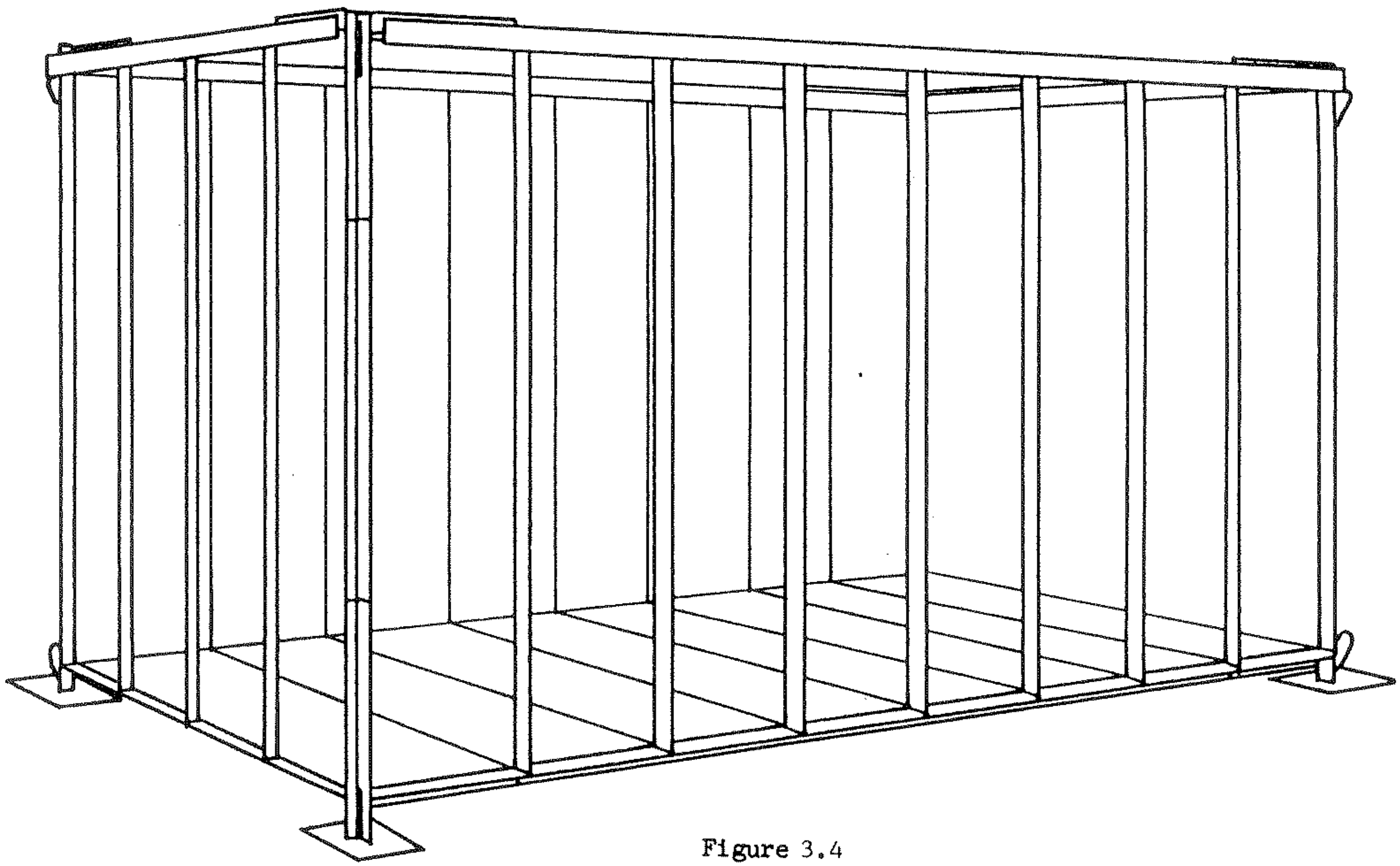


Figure 3.4

Inside Dimensions: 20 ft. long
10 ft. wide
10 ft. deep
Internal Volume: 2000 cu. ft.

Woods Hole Engineering Associates, Inc. P.O. Box 133, Woods Hole, Massachusetts, 02543, USA		
SCALE: None DATE: 7/19/80	APPROVED BY:	DRAWN BY F J A REVISED
Fish Cage Assembly		DRAWING NUMBER C 21 - 100

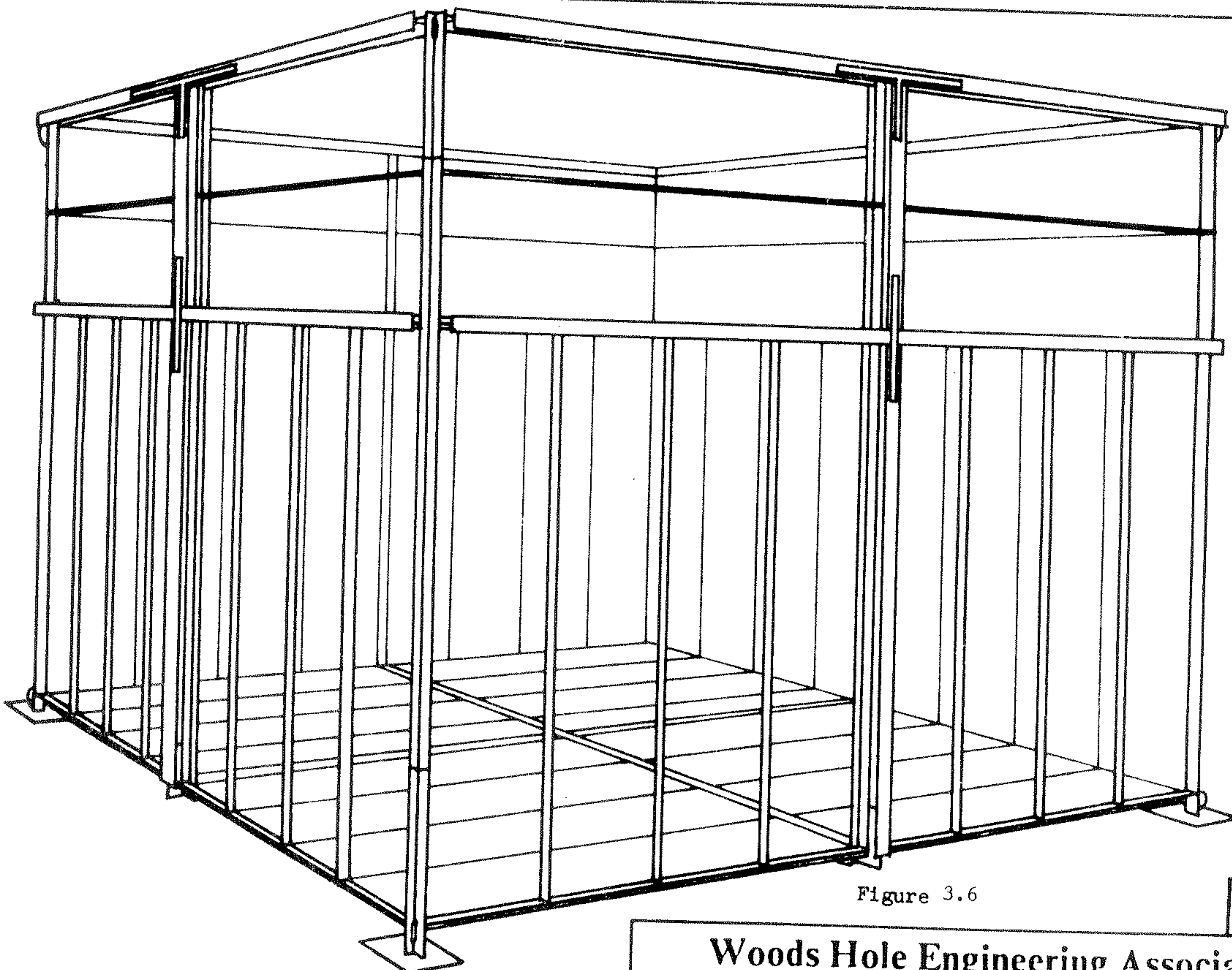


Figure 3.6

Inside Dimensions: 20 ft. long
20 ft. wide
15 ft. deep

Internal Volume: 6000 cu. ft.

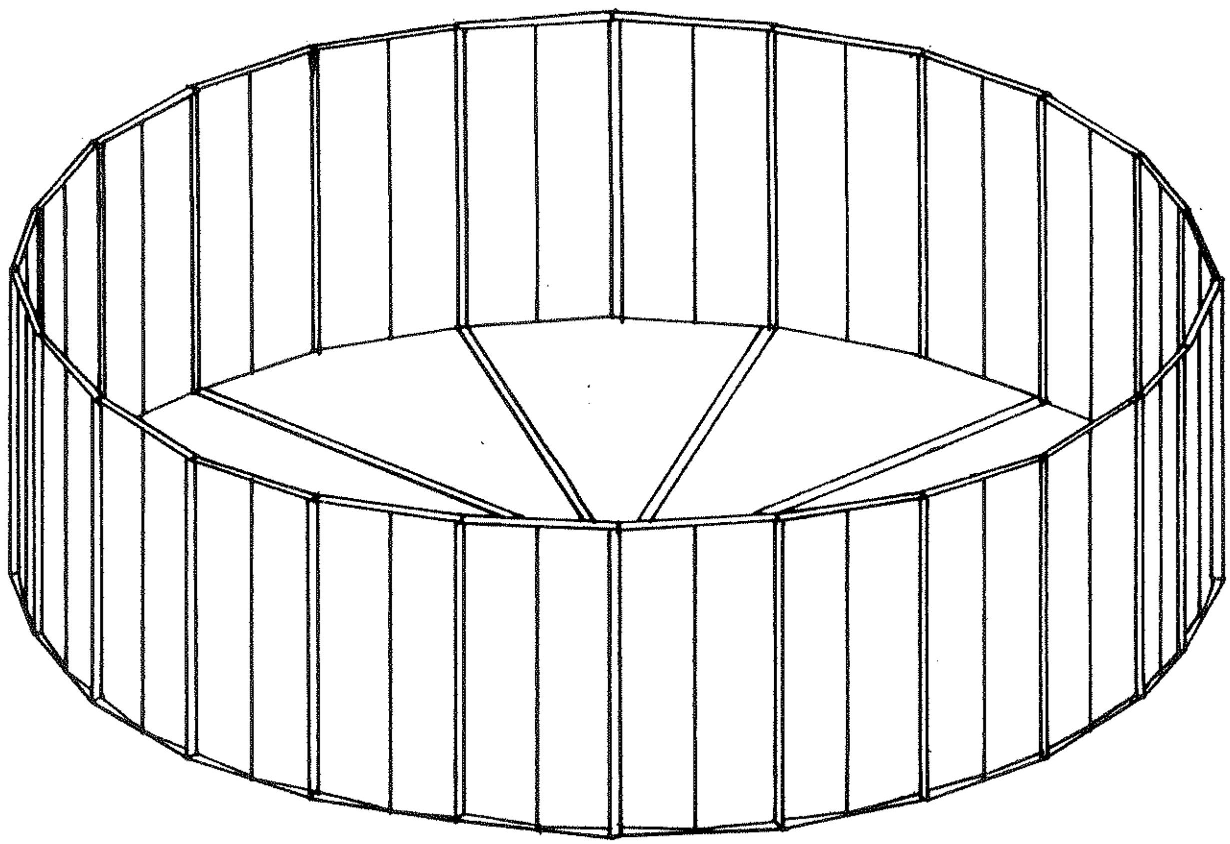
DRAWING NUMBER C22-100		
Woods Hole Engineering Associates, Inc. P.O. Box 133, Woods Hole, Massachusetts, 02543, USA		
SCALE: None	APPROVED BY:	DRAWN BY FJA
DATE: 2/25/81		REVISED
FISH CAGE ASSEMBLY		

design, dimensioning and costing exercise of a larger cage called the C-22 (see Figure 3.6). This cage uses the same mesh panels and types of fiberglass structurals as the C-21 and retains all the advantages of its predecessors. Since manufacturing costs are related to surface area, this cage costs about twice as much as a C-21 but fish production is volume related and it has three times the internal volume. While all the design decisions on the C-22 have been made, the detail construction drawings and supportive documents have not yet been produced, similarly with an even larger C-23 cage (Figure 3.7). The C-23 promises to have a volumetric cost ($/unit volume) less than 1/3 that of the C-21.

Since the design and deployment of the INCRA prototype fish cage, there has been considerable worldwide interest in the concept of using biofouling resistant meshes in fish culturing. These are summarized here (see Table 3.4) even though WHEA, Inc.'s participation in some of these projects has been indirect. INCRA has participated in all these efforts to varying degrees. These projects are listed in rough chronological order and some of the data is estimated. All of these projects are based on the use of 90-10 Cu-Ni mesh. Except for two which used woven wire mesh, all the others use 90-10 in expanded-metal form with a nominal mesh of about 3/8 in. Several of these projects are commercial tests of prototypes, with good possibilities of large-scale use if successful.

Submersible cages may be especially attractive. Biofouling-resistant meshes are particularly advantageous for submersible cages because of the long deloyment periods and difficulty of access for maintenance or cleaning. Submersible cages promise to circumvent many of the constraints inherent in floating cages, but may have a whole new set of problems. In particular, some marine fish need periodic access to the surface and may not be suitable for submersible-cage culturing. With the possible exception of use in Japan, they have not yet been proven practical in commercial operations. However, if successful, the potential is immense, since many sites otherwise not suitable may be farmed with this approach. In addition, the concept has considerable potential for tropical applications due to phenomenal biofouling conditions which can occur.

There is another set of serious projects, which involves the Japanese, who are clearly pioneers in the whole field of commercial marine farming. The first participants were Kiyomine Metal Industry Co. of Tokyo, Japan and the Kagoshima Prefectural Fisheries Experiment Station. They used 90-10 Cu-Ni alloy in chain-link form and experimented for a number of years with 22 x 22 x 19 ft. deep floating cages for culturing yellow tail (Seriola quinqueradiata) ("Development of Kiyomine Cupro Nickel Cage for Fish Farming," Kiyomine Metal Industry, 1980). It should be noted that this cage is approximately the same dimensions as the Norwegian cage and is of commercial size. More recent information indicate even larger square cages of 10 M per side have also been built and tested. More recently a newer entrant, Mitsui Metal Industry, Co., has designed, built, and tested a similar hexagonal



Inside Dimensions: 38 feet dia.
10 feet deep

Internal Volume: 11,500 cu. ft.

Figure 3.7

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Woods Hole Engineering Associates, Inc. P.O. Box 133, Woods Hole, Massachusetts, 02543, USA		
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FISH CAGE ASSEMBLY		

TABLE 3.4 COPPER ALLOY FISH CAGES

Cage	Manufacturer	Size	First Deployment	# Built To Date	Comments
INCRA Prototype	Groton Associates, Inc. (WHEA, Inc.) USA	10'x20'x10' (2,000 ft^3)	July 1977 in Maine, USA	1	• Proved validity of design concepts and engineeering designs. • After 5 years of use in Maine now in N.B., Canada.
Turbot Test	Whitefish Authority Scotland	6'x6'x4' (137 ft^3)	Mid-1979, Ardtoe, Scotland	1	• 90-10 Cu-Ni wire mesh rather than expanded-metal mesh. • Used for biological tests.
Rotating Cage (SMBA)	William Rutherford and Sons, Perth Scotland	6'x6'x13' (847 ft^3)	Feb. 1980 Dunstaffnage, Scotland	1	• 90-10 Wire mesh rather than expanded-metal mesh. • Used for bioassay of trout and tested against control unit. • Removed after completion of trials (1982).
C-21	WHEA, Inc., Woods Hole, MA, USA	10'x20'x10' (2,000 ft^3)	Two units sent to New Brunswick, Canada, Aug.1980, deployed Spring 1982	2	• Similar in concept and overall dimensions to INCRA prototype but but quite different in detail design.
Scottish Cage	William Rutherford and Sons, Perth, Scotland	10'x20'x10' (2,000 ft^3)	Loch Carron, Scotland Fall 1980	(1, & 1 more in process for Spain)	• Basically the same as the C-21. • Reports of serious interest for purchase of a number of such cages for commercial use in Scotland. • Assistance is being provided for construction of such a cage for testing in Spain (1984). • Two Ireland, one more for Spain.
Whitefish Authority Turbot Cage	William Rutherford and Sons, Perth, Scotland	15'x15'x2½' (2,000 ft^3)	Spring 1981, Scotland	At least 1	• Conceptually the same as C-21. • Commercial prototype.
Norwegian Cage	A/S MOWI	19.7'x19.7'x 19.7' (7,600 ft^3)	Bergen, Norway Sept. 1981	1	• Conceptually similar to INCRA cages but very different in detail. Submersible cage. • Possible commercial prototype.
Marseille Cage	R. Lavaux	Unknown, but 1700 ft^3	Nov.1981,Marseille France	3	• Expanded-metal mesh but a number of design differences from C-21 type cages. • Submersible cage. • Used PVC angle for framework. • Deployed in Matseille, Toulon, and Corsica. • Fxperienced sabotage from local fishermen.
French Guiana	?	small($\sim 8m^3$)?	Late 1984?	6	
Japanese	Kiyomine Metal Industry Company	10 x10 x10 M	1980?	?	• At least three different designs, all large.
	Mitsui Mining & Smelting Company	hexagonal $\sim$1000 M^3	1982-'83?	?	• The first two designs use Cu-Ni chain link and Cu-Ni pipe for structure, and have been extensively tested.
	Suitomo Metal Mining & Brass Sales Company	in planning			

unit. The Japanese claim, as we do, that increased lifetime and reduced maintenance more than compensate for the increased initial cost of copper-nickel materials. These cages are already in commercial use in at least two farms for the raising of yellowtail and sea bream (*Sparus major*). There are also some indications that a submersible cage variation has been built and tested. Considering the size and economic importance of marine fish farming in Japan, this is very significant.

4.0 SHELLFISH TRAYS

The use of 90-10 Cu-Ni expanded-metal mesh in the construction of shellfish trays to solve serious biofouling problems is another area going back to the start of Project 268 (1975). The background information and data on earlier field tests are included in earlier Project 268 reports (1980, 1983) and have been summarized and evaluated in a scientific paper (Huguenin & Huguenin, 1982).

Biofouling of shellfish trays, while highly dependent on site and season, has in many situations either completely prohibited the use of trays or required considerable labor for tray cleaning. The use of 90-10 Cu-Ni alloy expanded-metal mesh on the critical screening parts of trays has been shown, under normal operating conditions, to be effective in preventing biofouling of the mesh. Furthermore, it has been demonstrated to be harmless to the shellfish, practical in operations, and acceptable to culturists. Since 1977 over 1000 trays, of at least 11 different designs, using 90-10 Cu-Ni expanded-metal mesh, have been employed by more than 25 commercial, hatchery and research bivalve culturists in seven countries (see Table 4.1). Field experiences to date indicate that the use of 90-10 Cu-Ni mesh in shellfish trays improves shellfish growth through better water circulation and substantially reduces labor requirements.

More than forty commercially available polypropylene shellfish trays were modified over a period of several years using 3/8 inch nominal 90-10 Cu-Ni expanded-metal mesh on the side panels. Sharp reductions in shellfish growth due to biofouling have been documented with unmodified trays of this type (Michael & Chew, 1976). The 90-10 Cu-Ni mesh used in this modification, as well as in all other trays described, has a gauge of 0.9 mm (0.035 in.), strand width of 1.3 mm (0.050 in.), 76% open area 20 degrees to vertical and holes of about 0.9 x 1.5 cm (0.35 x 0.6 in.). The mesh in the modified trays was secured with 90-10 Cu-Ni wire and the edges melted into the polypropylene with a heat gun. These trays were distributed, starting in August 1977, to a number of users, representing a considerable range of operating environments and culture species for comparative evaluation against unmodified trays (Table 4.1). In all cases similar control trays with conventional mesh were either available or were supplied (see Figure 4.1). Field-test conditions covered the range from hatchery, nursery, and grow-out operations to the maintenance of brood stocks and a wide variety of shellfish species. The tests were designed to determine productivity increases resulting from better water circulation, practicality, maintenance, possible design improvements and possible problem areas. A number of organizations have also been supplied with 90-10 Cu-Ni expanded-metal mesh and other Cu-Ni materials to enable them to modify some of their own shellfish trays, some of unique design. These are also included in Table 4.1. As a consequence, some commercially available circular polystyrene shellfish trays, about 46 cm (18 in.) in

Table 4.1 HISTORY OF SHELLFISH TRAY DESIGNS USING 90-10 Cu-Ni EXPANDED-METAL MESH

Tray Name	Basic Materials	Approx. # Made	Date First Deployed	# of Sites or Operations	Locations
Modified Nestier	Mesh/Plastic	46	Jan. 1978	13+	Worldwide (8+ countries) 2,500 in process for Baja, Mexico
Modified McNichols	Mesh/Plastic	9	Fall 1978	2	Canada
Mod. Tayside Engr. LTD.	Mesh/Wood	20	Late 1980?	2	U.K.
Mod. Darling Center	Mesh/Wood	2	July 1979	1	U.S.
Dart Oyster Fisheries	Mesh/Wood	3	May 1981	1	U.K.
Devon Oysters LTD.	Mesh Tray	4	March 1981	1	U.K.
	Mesh Bag	1	March 1981	1	U.K.
Trefimetaux	Mesh/Cu-Ni Strips	2?	Mid 1981?	2	France
Aqui. del Atlantico	Mesh/Fiberglass Framework	1 module (20 trays)	Late 1980?	1	Spain
Innovative Aquaculture	Mesh/Plastic	a few (?)	Late 1981	1	Canada
Finisterre Mar	Mesh/Cu-Ni Framework	1 module (10 trays) others in process	Late 1982	1	Spain
Torquay Oyster Co.	Mesh	3	Late 1982	1	U.K.
Blue Point Oyster Co.	Mesh/Plastic	200+	June 1982	1	U.S.

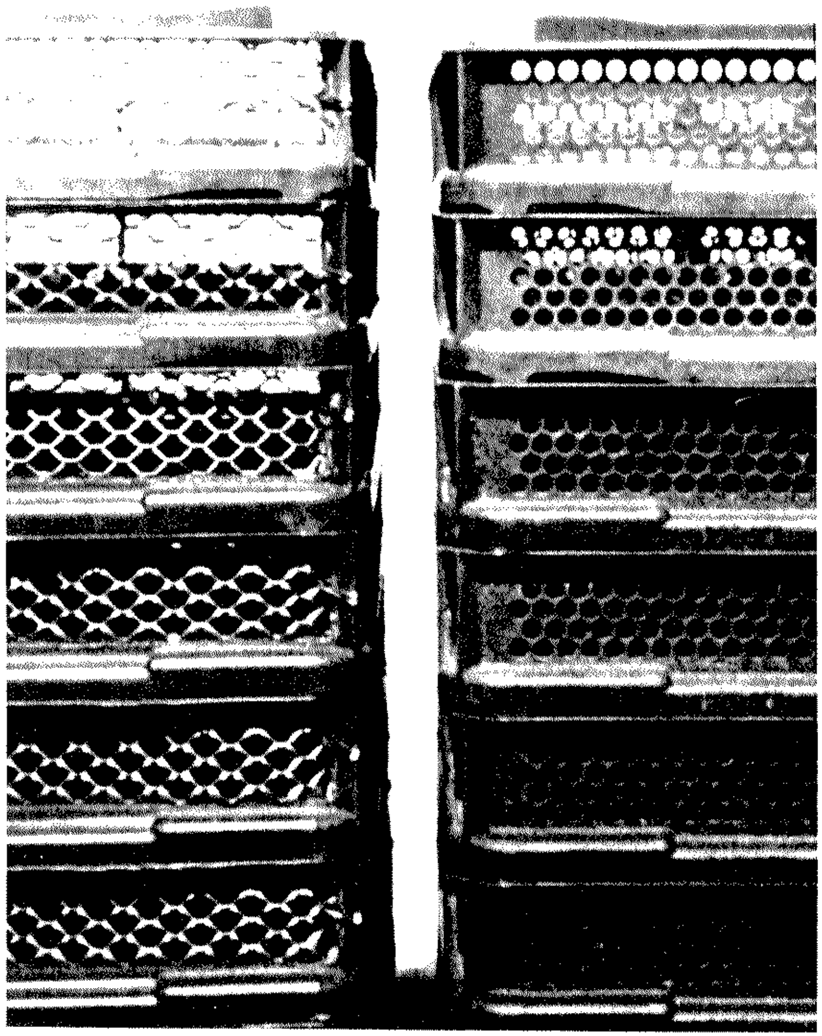


Figure 4.1
Modified and unmodified Nestier trays. In addition to biofouling resistance, Cu-Ni expanded metal offers increased flow area.

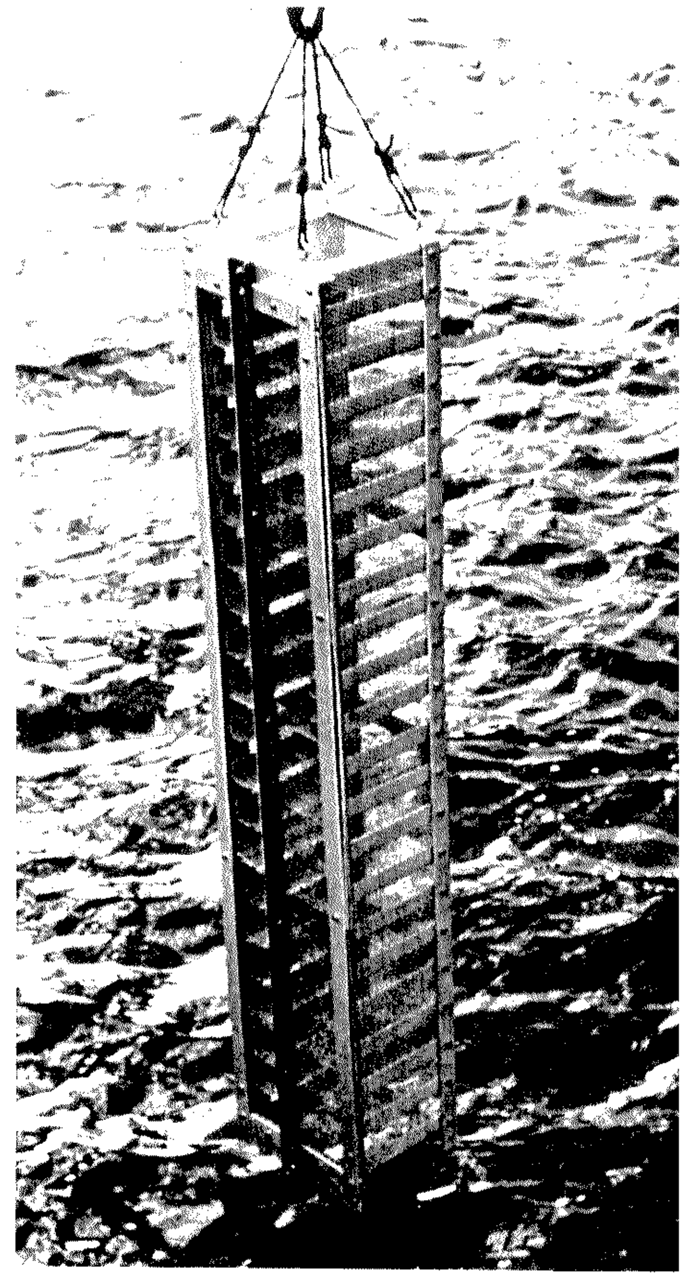


Figure 4.4
Aquicultura del Atlantico, Spain, showing module of twenty 35 x 35 x 25 cm 90-10 Cu-Ni expanded-metal trays in fiberglass frame.

diameter, and 5 cm (2 in.) deep, have also been modified and tested. To date, shellfish trays of at least eleven different designs have been built or modified using Cu-Ni mesh. All of the organizations are either involved with shellfish culture, shellfish research and development or are commercial shellfish culturists.

Feedback on field experiences with several types of modified trays has been received from most organizations that acquired such trays or modified their own. This feedback has ranged from high quality scientific data and qualitative judgments to "no results, equipment lost at sea." The most important results to date have been the universal acceptance by the participants of Cu-Ni materials as compatible with shellfish culture and their recognition of the fouling resistance of these materials. In addition, no detrimental effects on any of the bivalves, due to the use of copper alloys, have been observed. Shellfish growth and survival in the modified trays have been in all cases equal to or better than that in the control trays. In some cases growth and survival were based on subjective judgments of culturists or on only a few rudimentary measurements; in other cases careful experimental design and measurements were carried out. In one series of comparative tests with oysters in Canada, not only was the growth in the modified 90-10 Cu-Ni trays about 40% better than that in controls but the standard deviations in size were about 30% less than that in the controls. The implications from this and other tests are that improved water circulation not only improved growth but produced more uniformly sized animals. Most of the concerns and doubts of the participants involved the future costs of such trays and the merits of tray culture, per se, in comparison to other shellfish culture methods.

Tray culture involves a relatively high initial expenditure for shellfish trays and constant attention is generally required, as exemplified by the frequent cleaning practices of some culturists. To date many culturists have handled the modified trays as they would any other trays, placing them in with other trays and using the same cleaning schedules. Therefore, these culturists did not receive all of the benefits inherent in the new materials. Quantitative data on the degree of reduced maintenance produced by the fouling resistance of Cu-Ni meshes have been acquired in only a few cases. However, all feedback to date clearly indicates the existance of substantially reduced biofouling in actual culture operations. The few quantitative values received from culturists who altered their cleaning schedules because of the Cu-Ni mesh trays indicated savings of 60-100% of the labor previously used to maintain the trays.

Field modification of commercially available trays to insert a 90-10 Cu-Ni mesh is a laborious process and can be justified only in the context of a research operation or to verify design concepts. Two such plastic tray designs were modified and tested. However, preliminary calculations and discussions indicate that a factory produced tray of improved design and compound construction (90-10 Cu-Ni expanded-metal mesh for water circulation, plastic for structure) would cost 10-30%

more than the same tray with plastic mesh. In this case the loads on the mesh are minimal and the primary requirement for selection of a mesh thickness is to assure a long useful service life. Therefore, the relatively expensive Cu-Ni is used only where it is needed most for fouling control and in gauges appropriate for the intended service life.

A 1981 survey of six commercially available and utilized shellfish trays in the U.S. indicated that purchase price vary from $15.60-$29.05 per square meter ($1.45-$2.70 sq. ft.) of tray-bottom area depending on tray type, materials, and purchase quantity. Copper-nickel trays would be on the high side of this range but this does not take into consideration their substantial scrap-metal value not inherent in other materials.

Some existing tray designs lend themselves to a substitution of materials. Tayside Engineering of Scotland, has designed, tested, and now commercially offers a 90-10 Cu-Ni expanded-metal mesh version of their standard wooden tray system(see Figure 4.2). This tray is about 75 x 75 x 6.5 cm (30 x 30 x 3 in.) and a small number are being used in Scotland and a few in Northern Ireland. Additional modifications of standard wooden trays with 90-10 Cu-Ni mesh have been carried out by the University of Maine, Darling Center, with their 61 x 61 x 15 cm (24 x 24 x 6 in.) trays and by Dart Oyster Fisheries Ltd., of the U.K., with their 183 x 81 x 8 cm (72 x 32 x 3 in.) trays. Any tray constructed of an electrically non-conductive, structural material, such as wood or plastic, including home built trays (Richmond, 1974), can usually be readily modified to accept a 90-10 Cu-Ni mesh. If wire or staples are used to secure the mesh, they must be made of the same material or one cathodic or at least neutral to 90-10 Cu-Ni, such as Monel. Many common materials, such as steel, are unsuitable. In addition, there is some interest is using a single, removable, wrap-around sheet of Cu-Ni mesh with a large cylindrical ten shelved plastic tray system. The danger with this approach, is in assuring that the various materials used, especially any fasteners or staples, are galvanically compatible with the 90-10 Cu-Ni alloy.

Another approach is to make a tray constructed entirely of Cu-Ni mesh. Mariculture Ltd., in England, made a small number of 64 x 58 x 8 cm (25 x 23 x 3 in.) oyster trays by folding up the mesh and securing the corners. These trays have been in service without any problems since March 1980. Devon Oysters Ltd., in England, also followed this approach with two different designs (see Figure 4.3) currently under test. The limitations of this approach involve problems of nesting multiple trays, possible structural problems if thin gauges are used, joining of materials especially in corners, and the possibly unnecessary and excessive use of a relatively expensive mesh material. A variation on this approach is the 28 cm (11 in.) diameter by 8.5 cm(3.3 in.) deep cylindrical trays made by Trefimetaux of France. These trays nest readily, are reinforced with solid strips of 90-10 Cu-Ni material, and are similar in design to an available Spanish plastic tray. Trefimetaux's trays have been sent to several French shellfish

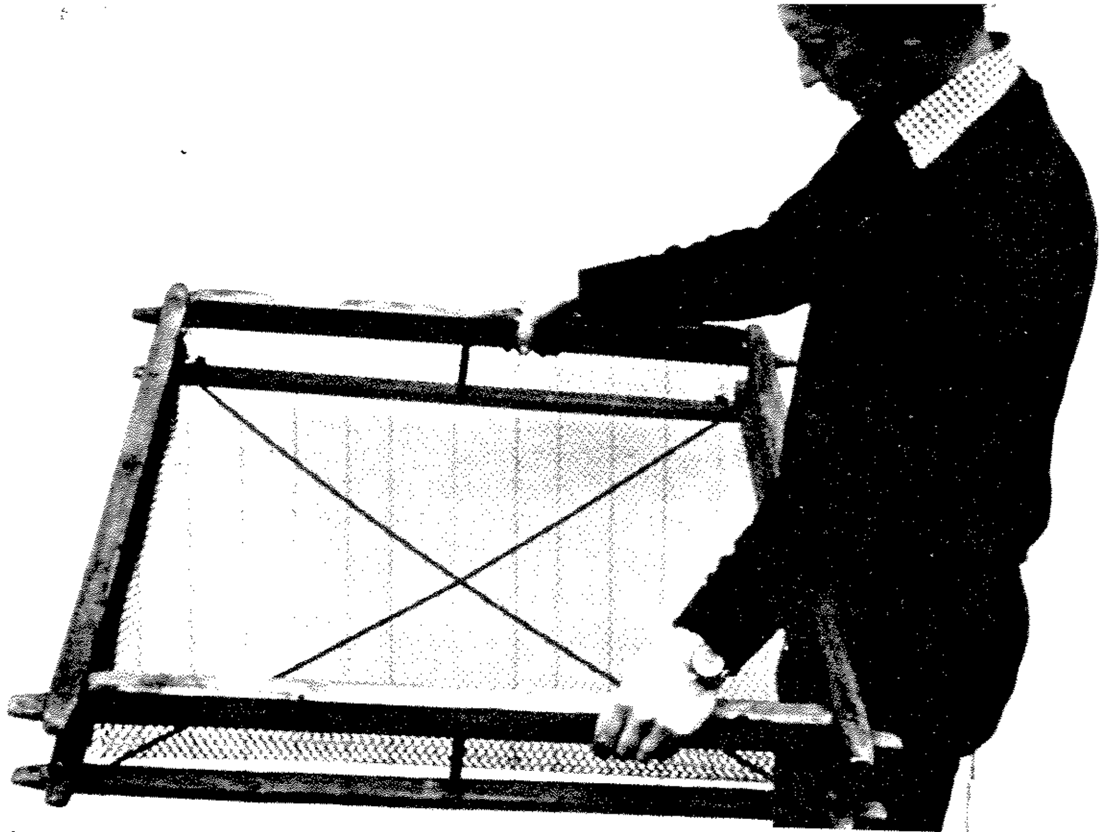


Figure 4.2 Tayside Engineering LTD, England, showing wooden frame and 90-10 expanded-metal mesh tray.

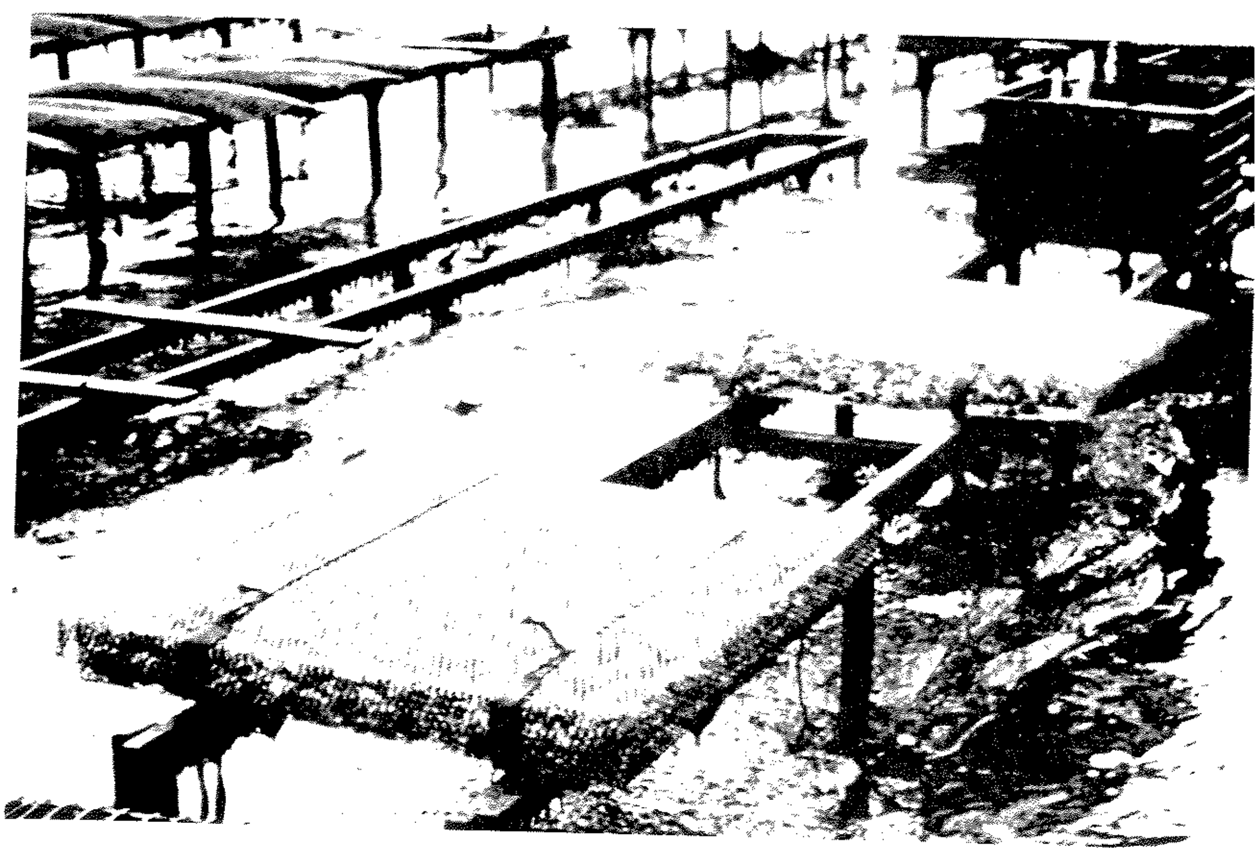


Figure 4.3 Devon Oysters LTD, showing two different designs of all 90-10 Cu-Ni expanded-metal trays.

culturists for testing and evaluation.

Another approach is being tested by Aquicultura del Atlantico SA of Spain. They built frames constructed of commercially available fiberglass shapes to form shelves which hold twenty 35 x 35 x 7.5 cm (14 x 14 x 3 in.) trays made of 90-10 Cu-Ni expanded-metal mesh (see Figure 4.4). Once advantage of this approach is that the individual trays do not need much strength and can be made of thin-gauge materials because structural support is provided by the frame. Some frames made of 90-10 Cu-Ni have also been built and deployed resulting in all Cu-Ni systems.

Estimating the world market for shellfish trays is very difficult at best. While pearl culturing in Japan alone uses about 100,000 trays (Mizumoto, 1976), the numbers of trays used in other activities and regions are much more modest. A marketing survey on shellfish tray-user requirements was conducted by the authors in 1978, and resulted in approximately 50 replies from culturists in North America and Europe. In response to a question on the importance of developing a tray with biofouling-resistant meshes, 52% responded "extremely valuable," 33% "important" and only 15% of "minor value." This survey also indicated that the demand for trays capable of holding a substrate for clam culture was about one-half of that for more conventional trays and that the average commercial sale would probably not exceed 1,000-2,000 trays. However, individual operations exist with substantially larger needs. Large volume tray-users tend to make their own trays. In addition, because of individual user preferences and requirements, no single tray design is likely to cover the total market, although a design-family of related trays might come close.

There are a number of possible approaches and variations in design for use of 90-10 Cu-Ni mesh in shellfish trays. It is clear that such mesh has considerable biofouling resistance and can substantially reduce labor requirements while increasing growth through improved water circulation. It is also clear that Cu-Ni mesh trays are acceptable and promising for a wide variety of field conditions and culture species. With careful design, such trays should be only slightly more expensive than similar trays of more conventional mesh material. They should also provide considerable improvements in performance over conventional systems.

5.0 COMPATIBILITY OF FASTENERS FOR USE WITH 90-10 Cu-Ni EXPANDED-METAL MESH IN SEAWATER APPLICATIONS

John E. Huguenin & Frank J. Ansuini

The research and development effort to exploit the biofouling resistance of 90-10 Cu-Ni expanded-metal mesh in marine screening applications has been characterized by a continuing effort to find compatible and economic fasteners. The viability of the Cu-Ni mesh/fiberglass system has been at least partially limited by uncertainties about the fasteners. Ideally the fasteners should be non-conductive but none with suitable strength or price have yet been found.

The initial fasteners on the prototype fish cage as deployed in July 1977 were made of 304 stainless steel electrically isolated form the mesh with nylon bushings. While this approach does work if electrical contact is in fact avoided, it involves risk of inadvertent electrical contact. Such contact in the prototype unit has resulted not only in rapid corrosion of some fasteners but also has at least partially nullified the biofouling resistance of the mesh. This type of stainless steel is particularly prone to crevice corrosion under washer, nuts and bolts, where it cannot be seen from the outside, making it twice as risky. As a consequence of rapid corrosion of some 304 fasteners, aided by a very unfavorable area ratio with the 90-10 Cu-Ni mesh, these fasteners on the prototype fish cage in Maine were switched to Monel fasteners after one year's service. Monel is much more noble than 90-10 Cu-Ni but is unfortunately expensive.

A surprising observation on some Monel fasteners removed for inspection, after 2 years in seawater, was the presence of a copper blush in the creviced area. This was noted under the bolt head where it bears against the nylon bushing. In one excellent example, the blush was noted along the shank and threaded area in way of the bushing and nuts. Cementation of copper from seawater would not normally be expected on Monel, because it is more noble than copper. However, the increased concentration of copper in the crevice could have altered the environment to one in which cementation or deposition of copper could occur. In a sense, this could represent a case of denickelification following one of the proposed dealloying mechanisms: total dissolution followed by selective redeposition. Alternatively, it could be the result of dealloying by selective leaching. To the best of our knowledge, denickelification of Monel is an extremely rare occurance, although there are reports of its occuring in 70-30 Cu-Ni in warm stagnant seawater. In addition, a few Monel bolts after three years in seawater have shown broad pitting in the threaded area adjacent to the nut. Removal of these bolts showed the threaded area within the nuts to be in good condition. This form of crevice corrosion, in which the attack occurs outside the crevice, is peculiar to Monel and some copper alloys. Fortunately, corrosion at this location will not affect the strength or function of the fastener. However, inspection during reassembly in May 1982 of the Prototype after more than four years in seawater showed severe wastage on a small percentage of the fasteners, some of it surprisingly and clearly in crevice on bolt shanks. These few fasteners may have inadvertently had 304 SS washers instead of Monel. Monel fasteners worked well, but, as said before, are expensive.

Due to the expense associated with Monel, less expensive 90-10 Cu-Ni fasteners were procured from Europe in 1980. These fasteners having been made of the same material as the mesh, were assumed to be compatible. However, there are a number of other considerations, such as the complex shapes of the fasteners, possibilities of oxygen concentration cells due to water circulation, biofouling of the fiberglass, and possibly other factors. As a consequence a number of mesh/fastener tests were initiated to test not only 90-10 Cu-Ni fasteners but other, possibly more available and/or less expensive fastener materials. The following data is condensed and revised from a much more detailed prior report (WHEA, 1983).

Table 5.1 shows the range of corrosion potential for all the fastener materials discussed in this report in increasing order of reactivity. These values were derived from the two references cited and related to a silver/silver cloride reference cell, as used in our field work. It should be noted, these two references did not always agree on the ranges of values. Based only on corrosion potentials, any fastener material with an electropotential above 90-10 Cu-Ni on this list should be suitable (excluding stainless steel due to its active mode) and those below unsuitable. Due to variations in values and other factors this is not necessarily always true.

In 1979, after problems with the stainless steel fasteners and the expense of the Monel, silicon-bronze fasteners were suggested due to their availability and economy. The overlap and closeness of silicon bronze's electro-potential range with that of 90-10 Cu-Ni and the possibility of other complications, suggested caution. Two 2 1/2 sq.ft. pieces of 3/8 in. expanded-metal mesh were cut to be electrically connected to a single silcon-bronze fastener set. This mesh to fastener area ratio was the same as on the prototype cage and likely to be typical of any similar marine screening applications. The mesh was rolled into cylinders and kept from opening by the silcon-bronze fasteners bolted with the mesh between two small fiberglass 2" x 3 3/4" x 1/8" plates at about 1/2 the length of the cylinder. To assure good electrical contact between the fastener and the mesh a small piece of looped 90-10 Cu-Ni wire was also placed between the fiberglass plates. All components were carefully weighed before and after deployment and electrical continuity between the fastener and mesh was checked. The cylinders were deployed about three feet below the water surface under a dock in Great Harbor, Woods Hole, Massachusetts, on April 12, 1979. Both cylinders were recovered 30 months later. The units were periodically checked during this time and the mesh stayed free of biofouling, while the small fiberglass plates were heavily fouled. For

Table 5.1

Expected Ranges of Electro-Potentials for Isolated Materials in Seawater Relative to Ag/AgCl Reference Electrode

Monel 400	-.06 to -.16 V
304 Stainless Steel	-.08 to -.14 V passive
	-.50 to -.58 V active
Nickel Aluminum Bronze	-.16 to -.22 V
90-10 Cu-Ni (CA-706)	-.15 to -.30 V
Silicon Bronze (CA-655)	-.28 to -.32 V
Narcoloy (1)	-.33 to -.44 V

(1) Estimate based on compositional similarity to Aluminum Bronze, Narcoloy (92% Cu, 7% Al, 0.75% cobalt, 0.25% tin) from N.C. Ashton.

References

Dexter, S.C., 1979. Handbook of Oceanographic Engineering Materials, John Wiley & Sons, N.Y., 314 pp.

Tuthill, A.H. & C.M. Schill Moller, 1971. Guidelines for Selelction of Marine Materials, Interational Nickel Company, N.Y., 38 pp.

these two tests the fastener was clearly the cathode and the fasteners were acceptable.

In an effort to carry out a more comprehensive fastener test, two identical units each with three different types of fasteners attached to 3/8" Cu-Ni expanded-metal mesh were designed and fabricated. Each fastener type had two samples, each attached to 2.5 sq.ft. of 90-10 Cu-Ni mesh. One fastener was electrically connected by a waterproof wire to a remote above-surface terminal for corrosion potential determination and the other unconnected, to test for possible effects of the connection itself. In addition, two samples of each fastener set were bolted to the fiberglass frame, without mesh, to determine free standing characteristics; one of these was wired for corrosion potential measurements. All fastener components were carefully weighed before deployment and electrical continuity checked. One unit was deployed a few feet below the surface in Great Harbor, Woods, Hole, Massachusetts, on September 25, 1980 and the other similarly at the southern exit of Cape Cod Canal on October 28, 1980. These units were identical and in similar environments. They were monitored monthly; the first recovered after 18 months; the second after 30 months. Mesh and fastener components were carefully weighed before and after deployment. On recovery, all fasteners were in good serviceable condition and all mesh samples relatively free of biofouling.

Analysis of the considerable data from the two fastener test units produced some interesting results. The 90-10 Cu-Ni fasteners proved to be excellent and the preferred choice. Unfortunately, due to present lack of volume demand, they are a custom item and not readily available. The Narcoloy (Aluminum bronze) with Ni-Al bronze nuts also was acceptable. While the tests with the two cylinders of silicon-bronze previously described, indicated acceptability of the fasteners. The fastener test unit data was not as clear cut. Of the four silicon-bronze fasteners tested with mesh in two locations, two indicated neutral and acceptable and two (the longer-term deployment) indicated the fasteners were the anode and not acceptable. It should be noted that the silicon-bronze fasteners on the cylinder were from a different source than those on the fastener test units. This points out one of the potential problems of choosing a fastener, even when the materials are thought to be the same.

In summary, the 90-10 Cu-Ni fasteners are excellent and very compatible with 90-10 Cu-Ni mesh. There are no problems with producing 90-10 Cu-Ni fasteners; there merely has not been any demand to date to stimulate production. Monel and Narcoloy bolts with nickel-aluminum-bronze nuts are also suitable. Silicon-bronze fasteners under some conditions may also be adequate but their use might introduce a risk factor and they should, if possible, be avoided.

6.0 STRUCTURAL PROPERTIES OF FIBERGLASS PULTRUSIONS AFTER TWO AND FOUR YEARS OF SEAWATER EXPOSURE

John E. Huguenin

Pultruded fiberglass shapes appear to be an attractive material for framing and structure in marine applications, particularly where an electrically non-conductive material is desirable. This is in spite of the fact that data on the long-term effects of seawater on fiberglass laminates are somewhat limited (Mandell & McGarry, 1976). Pultruded sections are a relatively new product and are promising materials for structural applications (Tickle, 1977; Bailey & McNish, 1980), with many attractive engineering properties (Werner, 1979). The chosen pultrusions (Exten Series 500 improved glass reinforced structural shapes, Morrison Molded Fiberglass Company) are made from fiberglass and an isophthalic polyester resin and are available in a number of common structural shapes. These sections have been used to design a number of marine screening products in combination with 90-10 Cu-Ni expanded metal in both the USA and in Europe. However, no data on their prior use in submerged marine applications are available. For these reasons, it became clear early in the development program for these products that monitoring the long-term performance of the fiberglass in seawater was also necessary to validate the basic design approach.

One characteristic of prolonged exposure of pultruded polyester and glass composites is the weathering of the above water parts. This weathering is a type of stress fatigue due to cyclic variations of humidity and temperature in conjunction with solar radiation and the action of water and oxygen (Werner, 1980). The degree of weathering is highly dependent on the types of resin (Whitehoust & Wildman, 1964) and on the presence or absence of ultraviolet inhibiters in the composites. Fortunately, weathering can only provide a small reduction in ultimate strength even after many years of exposure (Werner, 1980). It appears to be primarily a surface phenomenon with the most noticeable effects being the popping or blooming of the glass fibers, once sufficient resin has been degraded and eroded to expose the fibers. This can cause skin irritations on handling of the equipment and can be aesthetically displeasing but fortunately does not appear to be a structural problem.

After two years exposure (1977-1979) of a prototype unit in Maine some very minor "blooming" of the fiberglass in the above water fiberglass was noticed due to sun and weathering. Rather than take a chance of further degradation with the expensive prototype, the above surface fiberglass systems were painted, thereby eliminating this potential problem. However, since it was necessary to learn if this was in fact a serious problem, two weathering test units were quickly installed on the floats just above the waterline, one on the south side and one on the north, during the fall of 1979. These units were one foot long and made of 2" x 2" x 1/4" pultruded fiberglass angle. With the angle tilted so as to catch the most sunlight, and water. Holes were provided to enable the water to drain out. They thus would get the maximum sun, wave action, spray, debris, ice and freeze/thaw exposure. Both of these units were recovered from the prototype in May 1982, after about 1 1/2 years of rugged exposure. The cumulative weathering effects, although noticeable, were negligible even for the south-facing unit. These units have been redeployed facing north and south to a roof top in Massachusetts for longer-term exposure, with no change after two more years. In short, this appears to be a non-problem for these fiberglass pultrusions and painting of above surface sections is probably unnecessary except for aesthetic reasons or as a hedge against very prolonged exposure.

It was decided that tensile testing and three point bending tests would most easily characterize the structurally important parameters of the material and show any material deterioration due to submerged seawater exposure. All test samples are from the same lot of materials; three treatments were tested in December 1979 and two additional treatment were tested in December 1981 (see Table 6.1) The first test series involved virgin material and materials exposed in seawater for two years. The second series involved materials exposed for four years. Unfortunately only half of the four year materials were recovered, the rest being lost at sea.

Since only one brand of fiberglass pultrusions from a single shape and lot were tested, there may be risks in extrapolating these results to other product forms or manufacturers. Differences in size, type and orientation of reinforcements, resin, or manufacturing processes may significantly alter the conclusions. It is recommended that potential users inquire about long-term seawater-performance parameters of specific materials directly from manufacturers.

6.1 TENSILE TESTS

The tensile tests to find the failure stress and the modulus of elasticity were done in general accordance with ASTM Designation D638-68 (Standard Methods of Test for Tensile Properties of Plastics). The equipment used was a Super L Universal Testing Machine, an S-400-2A Extensometer and a Model 51 Recorder, all from Tinius Olsen Testing Machine, Co.

Five samples for each treatment were prepared and measured in accordance with the ASTM specification. Each sample was 6½ inches long

Table 6.1

FIBERGLASS TEST SAMPLES

General

- all test samples taken from web of 2 x 9/16 x 1/8 in. C-channel.
- all channels from same batch.
- all samples tested lengthwise.

Treatment #1 (Samples 1.1-1.5)

- virgin material, never utilized or exposed to elements.

Treatment #2 (Samples 2.1-2.5)

- July 22, 1977 to May 23, 1979 (22 months) exposed in seawater at Wiscasset, Maine.
- placed 3 to 7 feet below water level.
- all holes and cuts made during construction were sealed with epoxy resin.
- materials kept damp after recovery and after test samples were cut in mid-November 1979.

Treatment #3 (Samples 3.1-3.5)

- same as Treatament #2, except materials allowed to dry between recovery and testing ($\sim$6 months).

Treatment #4 (Samples 4.1-4.5)

- materials transported damp from Maine after recovery on May 23, 1979, reployed for further long-term seawater exposure in Woods Hole, Massachusetts (very similar environment, including depth and seasonal temperature profile) on June 1, 1979.
- recovered on Oct. 9, 1981, 50+ months exposed in seawater and kept damp until tested in Dec. 1981.

Treatment #5 (Samples 5.1-5.6)

- same as 4, except materials allowed to dry between recovery and testing ($\sim$2 months).
- sample for treatment 4 and 5 divided evenly from available materials to avoid any biases.

overall and 1/2 inch wide at the test section. Each sample was tested, with the extensometer attached, to a load of 400-600 lbs, which is a fraction of the breaking load. However, the rate of travel of the platen, due to need for manual control, was around a constant 0.01-.05 inch per minute rather than the 0.1 inch per minute suggested by the specification. The slope of the load-deflection curve was very linear for all samples in treatments 1 to 3 and somewhat less so for treatments 4 and 5. The material appears to maintain this linear behavior even to high loads. Perfectly elastic behavior all the way to failure is apparently characteristic of these types of materials (Bailey & McNish, 1980). The extensometer was then removed; the sample and the load increased until failure. The loading rate for treatments 1 to 3 was approaching the suggested 0.1 inch per minute rate but was slower for treatments 4 and 5 (approx. .01 in./min.). Failure generally occured quickly with considerable cracking noises. The samples from each of the three treatments in 1977 and the two treatments in 1981 were tested in alternative order to average out any procedural or learning biases. This sequence and the resulting tests' data are presented on Table 6.2.

From an examination of Table 6.2 it is clear that the material's tensile strength and modulus do not deteriorate even after more than four years in seawater (treatment 1, 3, and 5). However, it is also clear that in the wet condition there are some significant differences. There is a 17% decrease in tensile strength and a 7% decrease in modulus at two years of exposure. The four year samples show corresponding decreases of 10% and 7%. This indicates that these losses do not get worse with time and are probably due to the "wet" condition. In addition, the samples kept in the wet condition have a noticeably different sound when tapped (more of a "thunk" or dead sound) than dry samples. After recovery and during fabrication of the test samples, the "wet" samples were kept in damp paper but not immersed in any liquid. It should also be pointed out that most results were below the manufacturer's specifications for this material (see Table 2) as was the virgin material. This might be attributable to the slower loading rates used relative to those normally used for these tests.

In summary, it is clear that seawater exposure does not by itself permanently degrade the properties of fiberglass pultrusions. However, the pultruded materials in the "wet" conditions do not have the tensile properties of the same materials in the dry condition. This must be considered during the design process even before applying factors of safety. For framed connections and conditions of load reversal, the manufacturer recommends a factor of safety of four based on ultimate strength (Extren Tech. Bull. MMFG 1000). A conservative ultimate strength of 20,000 psi should continue to be used as a maximum value in design for uses involving immersion in seawater.

TABLE 6.2 PULTRUDED FIBERGLASS TENSILE TESTS

Sample Number	Test Sequence	Failure Load (lbs)	Failure *1 Stress (PSI)	Modulus *2 of Elasticity (PSI)
1.1	1	1590	24,693	2.1925×10^6
1.2	4	1410	21,976	2.5209×10^6
1.3	7	1620	25,249	2.0374×10^6
1.4	10	1400	21,780	2.0961×10^6
1.5	13	1530	23,806	2.1394×10^6
mean		1510	23,501	2.1973×10^6
sample standard deviation		101	1,570	$.1897 \times 10^6$
2.1	2	980	15,399	1.9339×10^6
2.2	5	1090	17,206	2.1047×10^6
2.3	8	1520	24,009	2.0929×10^6
2.4	11	1290	20,344	2.0459×10^6
2.5	14	1340	21,003	2.0899×10^6
mean		1244	19,592	2.0535×10^6
sample standard deviation		213	3,367	$.0704 \times 10^6$
3.1	3	1450	23,016	2.5505×10^6
3.2	6	1690	26,299	2.3343×10^6
3.3	9	1375	21,558	2.4277×10^6
3.4	12	1450	22,766	2.3761×10^6
3.5	15	1570	24,474	2.3094×10^6
mean		1509	23,623	2.3996×10^6
sample standard deviation		123	1,820	$.0955 \times 10^6$
4.1	1	1420	22,187	2.3256×10^6
4.2	3	1420	22,187	2.4306×10^6
4.3	5	1720	26,875	2.6786×10^6
4.4	7	1410	22,031	2.5144×10^6
4.5	9	1480	23,125	2.5735×10^6
mean			23,281	2.5045×10^6
sample standard deviation			2,055	$.1348 \times 10^6$
5.1	2	1700	26,563	3.1250×10^6
5.2	4	1670	26,563	2.6515×10^6
5.3	6	1910	29,844	2.5000×10^6
5.4	8	1360	21,250	2.6042×10^6
5.5	10	1610	25,156	2.8017×10^6
5.6	11	1710	26,719	2.4038×10^6
mean			25,938	2.681×10^6
sample standard deviation			2,788	$.2562 \times 10^6$

*1 Specification value = 30,000 PSI
*2 Specification value = 2.5×10^6 PSI
Reference: "Extren Glass Reinfoced Structurals - Engineering Manual", Technical Bulletin MMFG 1000, 1978.

6.2 THREE POINT BENDING TESTS

The three point bending tests to find the maximum stress at failure and the flexural modulus were done in general accordance with ASTM designation D790-70 (Standard Methods of Test for Flexural Properties of Plastics) using Method #1. The equipment used was a Super L Universal Testing Machine, 3/8" diameter loading nose and supports as per ASTM specification and a Baush & Lomb Metallurgical Microscope graded in 1/10 mm (Cat. No. 31-36-02) distributed by Tinius Olsen Testing Machine Company.

Five samples for each treatment were prepared and measured in accordance with the ASTM specification for treatments 1 through 3. Treatments 4 and 5 were somewhat limited by lack of enough material. Samples were normally 3 inches long by 1 inch wide. Through an error some of the treatments' 5 samples were only 0.82 inches wide. Each sample was loaded in steps to a load of 100 lbs or less and deflections measured with the metallurgical microscope. The average rate of motion during this process being about one-third of the suggested 0.0533 in./min. rate. No less than 8 load-deflection measurements were taken for each sample. These data were converted to the proper units and fitted to a least-squares linear regression. The extreme linear behavior of the material is confirmed by the fact that the correlation coefficients for all samples, in treatments 1 through 3, except one, were 0.999+ and the low one was 0.998. The correlation coefficient for treatments 4 and 5 were somewhat less with the lowest being 0.992. This linear behavior extended right to start of failure, usually noted by a sharp cracking sound. If start of failure occured before reaching 100 lbs load, subsequent data were not used in the calculation of the flexural modulus. The rates of motion to complete failure were around or somewhat above the recommended value of 0.0533 in./min. rate (highest .18 in./min.). As in the tensile tests, samples were tested alternatively to remove procedural and learning biases. The testing sequence and all test results are presented in Table 6.3. The results from samples 5.3 to 5.6, were not very different from that of samples 5.1 and 5.2 after compensating for their somewhat smaller widths, are included in the averages.

As in the tensile test, from Table 6.3 it can be seen that the material certainly does not deteriorate with seawater exposure (Treatment 1, 3, & 5). However, its performance is definitely less in the "wet" conditions (Treatment 2 & 4) with the maximum fiber stress at failure reduced by about 20% and the flexural modulus by about 11% from the dry conditions for the two year data. The corresponding reductions for the four year data are 32% and 21%. The increasing differences may indicate even more degradation with additional time. It should be noted that in the dry condition (Treatment 1, 3, & 5) the maximum fiber stress is slightly above the manufacturers book value. In the "wet" condition, the maximum stress at failure is about 17% below book value at 2 years and 24% below at four years. In addition, the start of

TABLE 6.3 PULTRUDED FIBERGLASS FLEXURAL TESTS

Sample Number	Test Sequence	Flexural*1 Modulus (PSI)	Load at Start of Failure (PSI)	Failure Loads (lbs)	Maximum *2 Fiber Stress at Failure (PSI)
1.1	1	1.457×10^6	108	150	28,800
1.2	4	1.538×10^6	---	180	34,560
1.3	7	1.533×10^6	130	165	31,680
1.4	10	1.438×10^6	115	165	31,680
1.5	13	1.441×10^6	112	148	28,416
mean		1.481×10^6	116	162	31,027
sample standard deviation		$.0499 \times 10^6$	10	13	2,506
2.1	2	1.305×10^6	95	116	22.272
2.2	5	1.305×10^6	90	119	22.848
2.3	8	1.336×10^6	88	113	21.696
2.4	11	1.357×10^6	97	136	26.112
2.5	14	1.323×10^6	104	161	30.912
mean		1.326×10^6	95	129	24,768
sample standard deviation		$.0214 \times 10^6$	6	20	3,838
3.1	3	1.574×10^6	---	169	32,448
3.2	6	1.693×10^6	140	180	34,560
3.3	9	1.747×10^6	125	156	29,952
3.4	12	1.536×10^6	122	172	33,024
3.5	15	1.705×10^6	137	174	33,408
mean		1.651×10^6	131	170	32,678
sample standard deviation		$.0909 \times 10^6$	9	9	1,709
4.1	2	1.059×10^6	115	125	24,000
4.2	4	1.1328×10^6	90	117	22,464
4.3	6	1.927×10^6	105	112	21,504
4.4	7	1.156×10^6	95	120	23,040
mean		1.1075×10^6	101	119	22,752
sample standard deviation		$.0394 \times 10^6$	11	5	1,046
5.1	3	1.4157×10^6	100	179	34,368
5.2	5	1.3051×10^6	115	148	28,032
5.3	1	1.6798×10^6	130	168	38,816
5.4 3*	8	1.3072×10^6	103	151	35,356
5.5	9	1.5379×10^6	123	162	38,258
5.6	10	1.1248×10^6	111	116	27,095
mean		1.3951×10^6	—	—	33,654
sample standard deviation		$.1953 \times 10^6$	—	—	5,618

1* Specification Value = 1.6×10^6 PSI
2* Specification Value = 30,000 PSI
Reference: "Extren Glass Reinforced Structurals- Engineering Manual", Technical bulletin MMFG 1000, 1978.
3* Less Than 1" width, (.82in.)

failure, when obvious permanent damage occurs, takes place at about 60% of the book value stress in the "wet" condition and at about 75% for the virgin material.

6.3 MOISTURE UPTAKE

Since the properties of the pultruded fiberglass appear related to its being "wet" it is important to investigate moisture uptake over long periods of time in seawater. The three pieces of 2" x 9/16" x 1/8" C channel which were used for treatment #5 (see Table 6.1), after cleaning of all fouling, were kept in seawater wetted newspaper until weighed in the wet condition. They were then allowed to dry and their weights taken at intervals to monitor the drying process. These weights are given on Table 6.4. Graphing of these values indicates that additional drying time would not have resulted in much more weight loss as the curves had flattened out. The average moisture content of the three pieces, based on the last drying weight, is 1.4%. This should also be valid for the material used for the "wet" test (Treatment #4), because the material for the two treatments was evenly split after recovering and cleaning, following a 4 1/2 years in seawater. These values can be compared to the specified maximum 24 hour moisture uptake 0.6% (Morrison Molded Fiber Glass, 1978).

While not from the same materials as those tested, there are other available long-term data on moisture uptake (Table 6.5). This is the same type of material from the same manufacturer but not the same form, being from 1/8 sheet, and also was not purchased at the same time. However, here there exists very precise weight data before immersion in seawater (2 1/2 years) in the same environment as that for the samples used in the previously described tests. These small fiberglass plates were used for other tests and the edge cuts were not sealed. After 2 1/2 years, these pieces show a moisture uptake of 0.3%, which corresponds well with the maximum 24 hours 0.6% specified value.

The relatively higher moisture content of the C channels compared to the 1/8" plate might be explained by the longer immersion period (2 1/2 vs. 4 1/4 years). However, the difference may also be related to the form of the products or to their specifics of construction: undirectional fibers in the channel verses bi-directional fibers in the plate (?). In contrast, the small 1/8" plates had cut edges all around where water could very easily enter, while the C channels had very little in the way of cut and exposed surfaces.

Table 6.4 DRYING OF PULTRUDED FIBERGLASS 2" x 9/16" x 1/8" C-CHANNEL DEPLOYED IN SEAWATER JULY 23, 1977 TO OCTOBER 9, 1981 (4 1/4 years). All WEIGHTS IN GRAM USING HARVARD BEAM BALANCE

	Initial (wet) Wt. Oct. 14, 1981	Oct. 28	Nov. 12	Nov. 18	Moisture % Based on Nov. 18 Wt.
Piece #1	185.92	184.25	183.70	183.60	1.3%

	Initial (wet) Wt. Oct. 14, 1981	Oct. 28	Nov. 12	Nov. 18	Moisture % Based on Nov. 18 Wt.
Piece #3	187.00	184.55	184.05	184.00	1.3%

	Initial (wet) Wt. Oct. 14, 1981	Oct. 28	Nov. 12	Nov. 18	Moisture % Based on Nov. 18 Wt.
Piece #4	185.27	183.25	182.73	182.70	1.4%

Table 6.5 WATER UPTAKE AND SUBSEQUENT DRYING OF SMALL PULTRUDED FIBERGLASS PLATES (2" x 3 3/4" x 1/8")

USED ON SILICON BRONZE/MESH CYLINDER TESTS, DEPLOYED WOODS HOLE HARBOR

APRIL 12, 1979, RECOVERED OCTOBER 9, 1981 (2 1/2 Yrs.)

	Initial Wt. Before Deployment	Wet Wt. After Recovery Oct. 14, 1982	Water Up Take %	Wt. Oct. 28	Wt. Nov. 12	Wt. Nov. 18	Wt. Feb. 10, 1982
Unit #1 (2 plates)	50.794	50.935	0.28%	50.865	50.820	50.821	50.777

	Initial Wt. Mar. 1979	Wet. Wt. After Recovery Oct. 14, 1982	Water Up Take %	Wt. Oct. 28	Wt. Nov. 12	Wt. Nov. 18	Wt. Feb. 10, 1982
Unit #1 (2 PLATES)	50.545	50.717	0.34%	50.656	50.619	50.620	50.575

All weights in grams and taken with same Mettler P-162 balance.

6.4 CONCLUSIONS

In summary, for both tensile and flexural properties, there is no evidence of any time-dependent seawater exposure materials' deterioration in the dry condition. In fact, strength and modulus may even go up slightly. However, there does appear to be some significant degradation in performance due to being in the "wet" condition. Some of these may be time dependent. If adequately compensated for during design, there is no reason this material should not live up to its promise of being a superb structural material for seawater applications.

7.0 MARINE BIOFOULING OF SYNTHETIC AND METALLIC SCREENS

J.E. Huguenin & F.J. Ansuini

Biofouling of meshes can create serious problems in seawater intake or discharge systems, and in aquacultural applications, by reducing water flow and increasing drag forces and pressure drops. Due to a lack of quantitative data needed for design purposes, biofouling tests on a number of different meshes in the size range of ¼ to ½ in. (0.5 to 4 cm), including both synthetic and metallic meshes, were carried out at two sites in New England. Some of the samples tested, especially the 90-10 Cu-Ni expanded-metal mesh, showed considerable biofouling resistance compared to other mesh types. Under many conditions, a 10% biofouling allowance for Cu-Ni mesh is more than adequate for design calculations. These data for a four year period were reported in Huguenin and Ansuini (1981) and an additional year of data in WHEA 1983. Much of what follows is condensed from these two references.

In spite of the economic and operational importance of biofouling, there are very little quantitative data on biofouling rates for various kinds of meshes. This is in part due to the considerable variations in biofouling as a function of specific site, season, mesh material, mesh parameters, geographic area as well as a number of other factors. As an example, there can be major differences in biofouling at two different sites only a few miles apart. However, comparative mesh tests at a given site should be indicative of the relative performance of meshes at other sites or conditions. Some work has been done at three sites in Hawaii with nine types of mesh, including knotted nylon, two galvanized chainlinks, one PVC coated chainlink, two galvanized hardware cloths and three high density polyethylene meshes. The results ranged from extremely high fouling at one site (100% blockage in two months) to relatively low fouling at another (Rothwell and Nash, 1977). Another set of experiments were conducted with 10 meshes at four sites in Scotland. The meshes included five types of synthetic netting, three types of rigid polymeric mesh, galvanized chainlink and galvanized weldmesh. These tests showed moderate to heavy fouling (Milne, 1975). Similar tests are in process in Hong Kong (Greene & Morton, 1980), Malaysia (Cheah & Chua, MS.), and by the Nova Scotia Department of Fisheries. In addition, at least three other sets of related tests by industrial groups are known to have taken place, but unfortunately these data are proprietary.

The work leading to this paper was prompted by the lack of data concerning fouling rates of copper alloy screens compared to more conventional mesh materials. The fouling resistance of some of the copper alloys, particularly 90-10 Cu-Ni and 70-30 Cu-Ni and their advantages for marine applications were well known (Hunt & Bellware, 1967) but not specifically in mesh form. As the long-term corrosion rates of those alloys are very small, under many circumstances they are biologically acceptable even in culturing applications (Huguenin & Ansuini, 1975) and have considerable potential in a variety of other marine screening applications (Ansuini & Huguenin, 1978). In addition, there were no quantitative data available on the effectiveness of various antifouling treatments when used on knotless nylon mesh.

7.1 QUANTIFICATION OF MESH BIOFOULING

The quantification of mesh biofouling is difficult at best. This is due to the difficulty of choosing appropriate parameters as well as problems of acquiring accurate measurements. From an engineering standpoint it is not the wet weight, dry weight or species composition of the fouling communities that is of direct interest but rather the amount of blockage or occlusion of the mesh and its hydrodynamic properties. Data and measurement techniques from work on biofouling of flat plates are not particularly applicable to meshes, due to difficulties in computing mesh blockage, which will change with time, and the fact that flow though the mesh may alter the composition of the biofouling communities. In addition, scraping the organisms off of the meshes for dry weight determinations is much more difficult than for flat plates.

In the past, mesh biofouling has been quantified by removing fouling panels from water and weighing them after intial draining (Milne, 1975; Rothwell & Nash, 1977) and by also taking their weight in water (Rothwell & Nash, 1977). The in situ weight determination would compensate for the very large differences in the capability of various fouling organisms to trap water. Since fouling organisms can vary considerably in surface area to weight measurements, weights by themselves are of questionable value without knowing the composition and abundance of the fouling organisms. Subjective estimates of the critical mesh blockage or occultation have also been done (Rothwell & Nash, 1977). In addition, photographs and characterization of the dominant fouling organisms are usually carried out.

Unfortunately, there is no satisfactory way to measure the important hydrodynamic properties of biofouled meshes in situ. While recognizing the limitation of subjective judgment, mesh blockage is one of the most critical factors, as it limits essential flow through the mesh and can lead to vastly increased loads on structures. Another critical factor is the drag coefficient for various meshes both clean and fouled. There is relatively limited data on mesh drag coefficients, even for clean meshes, and such data for some of the meshes included in this paper are available along with a summary of the literature (Gularte & Huguenin, 1980). There are some indications that, not only may the blockage area increase due to biofouling, but that the numerical value of the drag coefficient may also increase substantially.

7.2 EQUIPMENT AND PROCEDURES

Biofouling tests on various mesh materials were conducted at a Wiscasset, Maine test site from July 23, 1977 until recovery of the test unit on May 23, 1979. This is a brackish water site, varying around 22 0/00, and situated in the discharge area of the Mason Power Station and is considered to be a relatively high fouling area. The test unit was composed of five 18 inch wide by 40 inch long mesh samples placed on a 40 x 120 inch fiberglass C-channel panel frame. It was deployed horizontally from the outboard edge of a float with the samples being three to seven feet below the surface. The mesh samples included a 3/8 inch nominal 90-10 Cu-Ni expanded-metal mesh (gauge of .035 inch, strand width .050 inch, 76% open area), an expanded-metal aluminum-bronze mesh (1 1/2 x 1 inch diamond, gauge of .065 inch, 60% open area) a galvanized hardware cloth (5/16 inch-square mesh, 80% open area), regular knotless nylon netting (7/8 inch stretch mesh, about 60% open area) and the same nylon netting dipped in a copper based anti-fouling paint (EPA No. 2693, 21.3% cuprous oxide, 18.8% elemental metal). While the intent was to compare relative biofouling of various mesh materials at the Wiscasset site, the test was not completely fair due to the differences in mesh size. The aluminum-bronze mesh in particular had an advantage, since mesh size is known to be an important factor in mesh biofouling.

In an effort to continue biofouling tests with a better testing situation and more accessibility for monitoring, it was decided to deploy test panels in Woods Hole, Massachusetts. Two test units were deployed from a dock in Woods Hole's Great Harbor on April 12, 1979 and were removed August 6, 1982. This is also a relatively high fouling marine site (approx. 32 0/00) and the test samples were three to six feet below water level at low tide. Each test unit was a 3 x 5 foot frame made from 2 inch PVC pipe. Each frame was made to hold three 1 1/3 x 3 foot mesh samples. One frame was to test the three competitive types of rigid meshes. The samples were 3/8 inch expanded-metal 90-10 Cu-Ni (0.035 in gauge, .050 inch strand width, 76% open area), 5/16 inch galvanized hardware cloth (.035 inch diameter strands, 82% open area) and approximately 1/2 inch square Dupont high density polyethylene mesh (100 CDS 29, 66% open area). The samples were as close in mesh size as it was possible to find. The other frame was outfitted with three pieces of 1 inch stretch knotless nylon netting made of No. 222 twine (68% open area, untreated). One piece was treated with an International Paint Company, Inc. marine antifouling paint using cuprous oxide in a vinyl matrix (U.S. Reference No. 5475). Another with a Flexabar Corp. developed antifouling paint (Formulation B-1) specifically developed for use on synthetic meshes in fish culture. This antifoulant uses Tributyltin oxide (TBTO), also in a vinyl matrix. The third sample was untreated and used as a control.

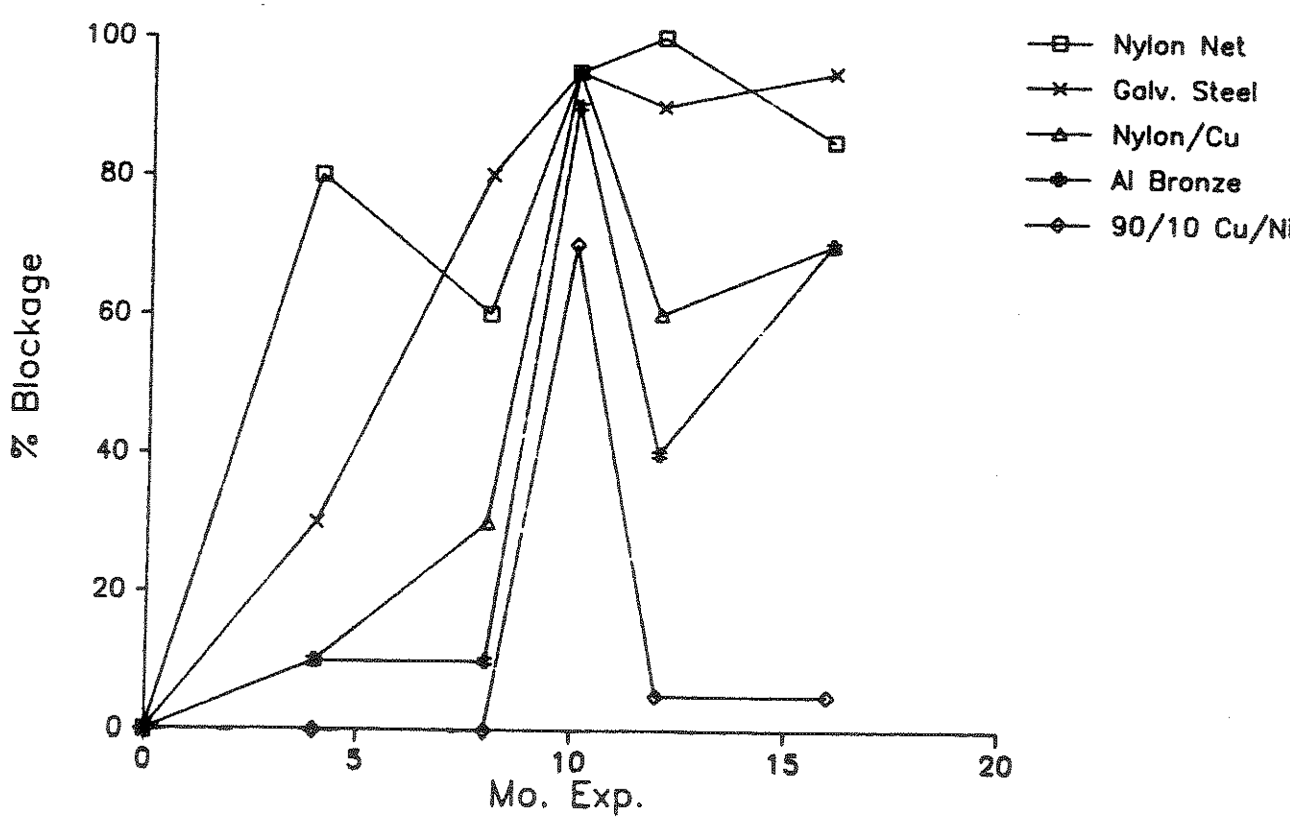
The test procedure at each sampling, in both Wiscasset and Woods Hole, has been to briefly remove each unit from the water for visual inspection and photography. The Wiscasset panel was monitored irregularly on visits to Maine, while the Woods Hole panels were inspected at approximately one month intervals. The panels were shaken in the water to remove trapped sediment and loose debris and are exposed briefly in air during inspection. At no times have any test panels been cleaned. The estimates of mesh blockage are subjective judgments usually arrived at by discussion between two or more persons present. Fortunately it is easy to determine relative degrees of fouling because the differences between mesh samples were usually very substantial. The percentage estimates are for blockage of the original open area of each mesh. Since the percent of original open areas of the various meshes did not vary greatly, this procedure was judged unlikely to result in large errors.

7.3 RESULTS AND DISCUSSION

The subjective estimates of mesh blockage and observations on dominant fouling organisms with the Wiscasset panel are given on Figure 7.1. The algal bloom from April to July 1978, which affected even the 90-10 Cu-Ni, was apparently a most unusual event. It did not reoccur in 1979 and according to local observers had not previously occured, at least not to this degree. Interesting, all the materials containing copper recovered to varying degrees without any outside help. Not sur-

Figure 7.1 Wiscasset Test Panel

Test began 6/77



prisingly, meshes with copper not only had less total fouling but also fewer types of organisms contributing to the fouling than other materials. In particular, the fiberglass frame, over time, accumulated a thick and very diverse fouling community, including large kelp fronds. The last measurements were on December 19, 1979. Sometime between December and May 1980 the frame dropped off the float and was later recovered from the bottom. The galvanized weld mesh, which was already showing signs of advanced corrosion, had come off the frame and was not recovered.

The Woods Hole biofouling data is given on Figures 7.2 and 7.3. Additional information and details are in Huguenin & Ansuini (1981) and WHEA 1983. As in Wiscasset, the galvanized hardware cloth gave some biofouling protection relative to other meshes but disintegrated in about 20 months. This is not surprising considering the high corrision rate of zinc in seawater. The spectacular, but not surprising, performance of the 90-10 Cu-Ni mesh in both Wiscasset and Woods Hole, is impressive. However, care was taken to assure no electrical contact of the 90-10 Cu-Ni mesh with other metals and to avoid any part of the mesh being buried in bottom sediments. Both of these circumstances can at least partially nullify the biofouling resistance of 90-10 Cu-Ni. This biofouling resistance is, however, not absolute, as the mesh often had a light slim coating and an occassional hardy organism, such as a single large barnacle, can sometimes remain attached. In particular, the data shows, that for temperate sites allowing about 10% mesh blockage for this material should be more than adequate under most circumstances. However, this should be tempered by the short-term intense diatom bloom experienced once at Wiscasset, although the mesh cleaned itself shortly thereafter without any assistance. In addition, a co-located fish cage in Wiscasset made of the same 90-10 Cu-Ni mesh has at times had higher blockage rates than the test panel under identical conditions. The removal of the trapped sediment during the sampling process may explain the differences, because the cage at times has accumulated impressive amounts of sediments. Therefore, applications where periodic removal of sediment through water motion or brushing is not possible may wish to use more conservative blockage allowances. However, both test sites are moderate to heavy fouling areas and test samples of the same mesh material have been distributed to a number of marine sites around the world with consistant reports of negligible fouling, even after prolonged exposures.

It is clear from both the Wiscasset and Woods Hole data that treating nylon netting can substantially reduce biofouling but that this protection is limited to the service life of the treatment, usually less than two years. The copper-based paint used in Wiscasset is an average priced paint and was effective for a little over a year. The copper-based paint used in Woods Hole is a very expensive paint with a high loading. Eventhough it might not be surprising that it did well, its performance is nevertheless impressive. In contrast, the TBTO paint, especially formulated for this type of application, did not do well, and this panel was actually more fouled than the untreated control after 18 months exposure.

Figure 7.2 Rigid Mesh Test Panel, Woods Hole

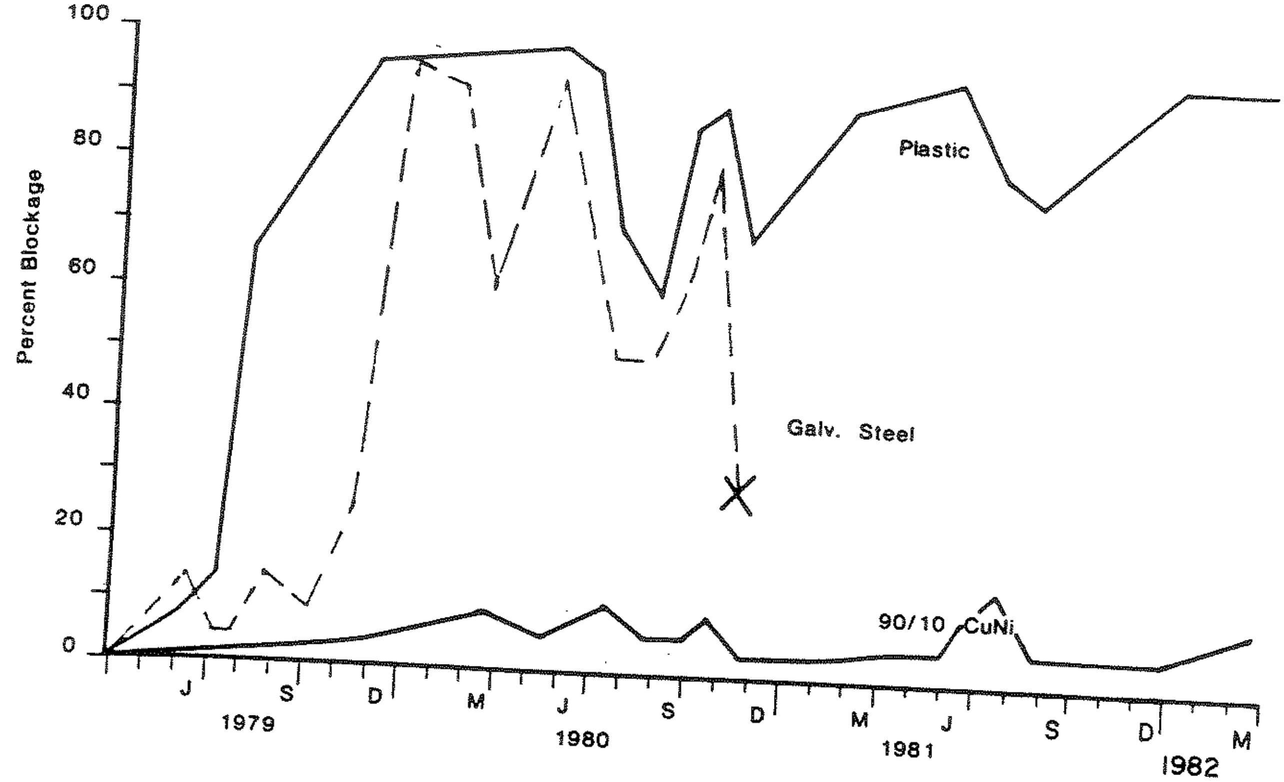
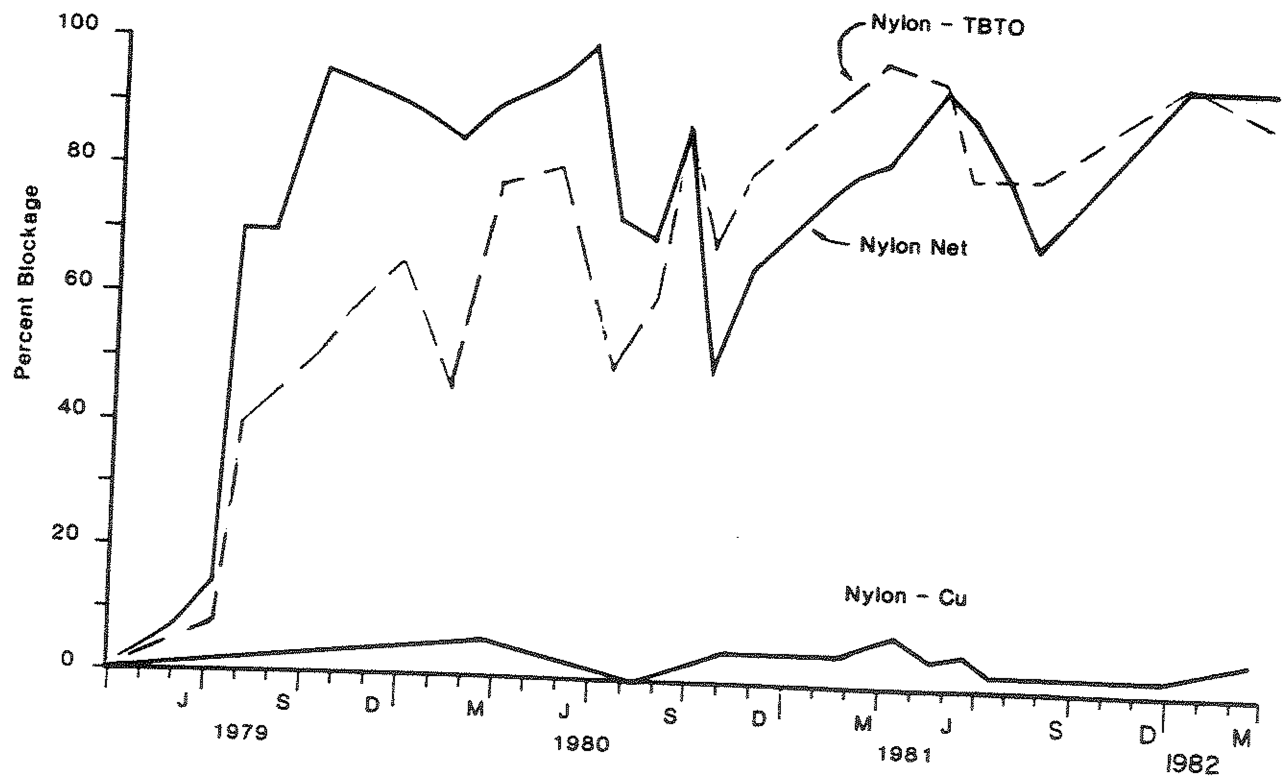


Figure 7.3 Nylon Mesh Test Panel, Woods Hole



8.0 MESH HYDRODYNAMIC DATA

Ronald C. Gularte & John E. Huguenin

Past design calculations of water current and wave forces on expanded metal have been based on limited prior data. This has included data on drag on fish netting (Kawakami, 1964; Baranov, 1969; Friedman, 1969; Milne, 1970; Kawalski & Giannotti, 1974) and some theoretical and test data on screens (Hoerner, 1965). However, the screen data were not for expanded-metal screens, contained certain assumptions and are stated to be valid in the range of Reynold's numbers from 10^4 to 10^6; furthermore, the Reynold's numbers for the expanded-metal panels, based on mesh gauge, can go down to values of approximately 3×10^2.

Several factors have combined to make the accurate determination of the drag coefficients on expanded-metal meshes very important. Calculated loadings on mesh panels are directly proportional to the assumed drag coefficients and these values can vary considerably, such as a factor of about two. In addition, these coefficients, for at least some shapes, can be dependent on velocity as expressed through the Reynold's number. This is further compounded by the questionable applicability of data on flexible fish netting and on screens with mesh shapes and orientation considerably different from the unsymmetrical nature of expanded metal.

An approximately 100 ft-long x 10 ft-wide by 4 ft-deep tow tank has been used to test 1 square-foot samples of selected meshes. This tow tank has a controllable moving carriage, which can be moved at velocities up to 6 ft./sec. and is highly instrumented. An adjustable test frame, to hold one square foot pieces of mesh for test, has been built. It can be adjusted as to the angle of the mesh test panel to the water velocity.

Since no previous data exists specifically on the drag properties of expanded metals, the initial test program has been devised to test whether various parameters are in fact important. Five meshes, of which four are expanded metals, and four velocities have been chosen. This is to determine if the drag coefficients are in fact velocity dependent. In addition, the frame, without the meshes attached, has been tested at each speed to enable the subtraction of the drag due to the frame from the test data. An additional series of tests with a single mesh and a single velocity, but with ten different angles have been carried out. This is to determine the importance of aspect angle on the drag properties of the expanded-metal meshes. These tests are summarized on Table 8.1: A, B, C.

Before discussing test results, it is necessary to have an understanding of drag coefficients. The force acting on the mesh due to

Table 8.1

DEFINITION OF MESH HYDRODYNAMIC TESTS

Table 8.1 A

MESHES TO BE TESTED AT VARIOUS SPEEDS WITH MESH SAMPLES ORIENTED PERPENDICULAR TO THE WATER VELOCITY

Mesh	% of Area Obstructed by Mesh When Seen from Perpendicular to the Mesh Samples
3/8" 90-10 Cu-Ni Exp. Metal	27%
1/2" Al-Bronze Exp. Metal	38%
3/16" 36Fe50 Steel Exp. Metal	47%
3/4" 60Fe101 Steel Exp. Metal	22%
3/4" Polyethylene	34%

Table 8.1 B

VELOCITIES FOR PERPENDICULAR TESTS

ft./sec.	Knots	m/sec.
0.427	0.253	0.133
0.853	0.505	0.267
2.99	1.77	0.934
5.97	3.53	1.87

Table 8.1 C

ASPECTS ANGLE TESTS OF 3/8" 90-10 Cu-Ni EXPANDED METAL SAMPLE AT A FIXED FORWARD VELOCITY OF 1 ft./sec. (ANGLES FROM PERPENDICULAR, 10 SETTINGS IN ADDITION TO 0 degrees)

± 10 degrees

± 20 degrees

± 30 degrees

± 40 degrees

± 50 degrees

the free stream approach velocity (V) of a fluid should be a function of the percentage of the mesh area which is blocked (δ) and the shape of the elements making up the mesh. The mesh drag coefficient (C_{dm}) is a function of the actual free-flow drag coefficient of the individual mesh members (C_d).

$$F_d = \frac{C_{dm} \delta A \rho V}{2} \qquad (8.1)$$

C_{dm} = mesh drag coefficient

F_d = drag force of fluid on mesh

A = overall mesh area perpendicular to the velocity

ρ = density of fluid

δ = percent mesh blockage

A similar expression for the drag on meshes can be written in terms of the drag coefficient of the individual mesh members (Eqn 8.2). It assumes that there are no hydrodynamic interactions between mesh members and implies that the approach velocity of the fluid is essentially perpendicular to the mesh. Test data given in Hoerner (1965) substantiates that this theoretical expression is valid for percent blockages of mesh from 0 to 40%.

$$F_d = \frac{C_d \delta A \rho V_x^2}{2} \qquad (8.2)$$

In the above expression C_d is the drag coefficient of the individual mesh members and V_x is the increased fluid velocity past the mesh members as a consequence of the presence of the mesh in the flow. From continuity it can be shown that:

$$Q = A V = V_x (1 - \delta) A$$

$$V_x = \frac{V}{1 - \delta} \qquad (8.3)$$

Equating expression (8.1) and (8.2) and substituting into (8.3):

$$C_{dm} = C_d \frac{\delta}{(1-\delta)^2} \qquad (8.4)$$

Valid for $0 < \delta < 0.4$

The test results on the five meshes are given on Table 8.2. These drag coefficients were plotted as a function of Reynold's number, which varied for these tests from 3.8×10^4 to 5.3×10^5. It is clear that for the conditions and meshes tested that the drag coefficients are essentially independent of Reynold's number and velocity. As a result, an average mesh drag coefficient (C_{dm}) has been calculated and is shown on Table 8.2. In addition, using the drag coefficient of the individual mesh member (C_d) of 1.55 from Table 10.1 results in a predicted mesh drag coefficient (C_{dm}*) also shown on Table 8.2. These predicted values are seen to be conservative in all cases for a clean mesh.

The angle of attack test data for a single mesh are given on Table 8.3. It can be seen that while the minimum projected area occurs at -20^o, this point does not exactly coincide with the point of minimum drag coefficient. Neither did the maximum drag coefficient coincide with the maximum projected area, which occurs at about -70^o and is outside of the range tested. However, it is clear that there are aspect angle differences with a difference of 217% from the low to the high values and a difference of 55% for the 0^o value to the maximum drag coefficient. This could translate into a factor of two difference in loads in the flow direction depending on conditions. In addition, side loads were measured during these tests and self-excited oscillations occurred under some conditions, due to Strouhal shedding from the frame.

The three dimensional and unsymmetrical nature of expanded metal undoubtedly results in complex hydraulic flow around the mesh elements. It further suggests the conservative choice of drag coefficients for use in design calculations when the future service conditions at all times may not be known. These tests also suggest that the drag coefficients of individual mesh elements presented on Table 10.1 are conservative for clean meshes. However, some allowance for fouling must be made (see Section 7), even for 90-10 Cu-Ni alloy, and an adjusted blockage factor (δ) used to calculate a design mesh drag coefficient (C_{dm}).

Table 8.2 PERPENDICULAR VELOCITIY DRAG COEFFICIENTS

MESH	0.427 ft/sec	0.85 ft/sec	2.99 ft/sec	5.97 ft/sec	Average	
	C_{dm}	C_{dm}	C_{dm}	C_{dm}	C_{dm} (1)	C_{dm} (2)
3/8" Cu-Ni	0.52	0.39	0.41	0.44	0.41	0.79
1/2" Al-Bronze	1.25	0.89	0.74	0.89	0.84	1.53
3/16" Steel	0.93	0.68	0.74	0.84	0.75	2.59 (3)
3/4" Steel	----	0.22	0.16	0.24	0.21	0.56
3/4" Plastic	----	0.53	0.52	0.55	0.54	1.21

(1) C_{dm} apparently not a function of Reynolds number or velocity over range tested.

(2) Predicted value based on using value of C_d = 1.55 from Table 10.1.

(3) δ = .47, which is outside of Hoerner's range of applicability.

Table 8.3 ASPECT ANGLE TESTS ON 3/8" Cu-Ni MESH AT SPEED OF 0.853 ft/sec

Angle(1) # of Degrees:	-50	-40	-30	-20	-10	0	+10	+20	+30	+40	+50
C_{dm}	0.23	0.41	0.29	0.48	0.51	0.47	0.73	0.62	0.63	0.58	0.59

(1) Expanded metal strands are set at an angle when viewed perpendicularly, this sample is set at -20 degrees, for which its blockage is at a minimum (24%).

9.0 MESH ANALYTIC MODELS & LOADS DATA

Ronald C. Gularte & John E. Huguenin

Rectangular expanded-metal panels have anisotropic structural properties. In other words, their physical properties are a function of direction. In addition, for thin gauge materials, the maximum deflections at the centers of the panels even within the elastic range can be appreciable, making techniques based on small deflection assumptions, if not unusable, at least very questionable. This is further compounded by the unavailability of any data on uniform loading of expanded-metal panels. Past uses of expanded metal have usually involved point loadings of thick meshes with negligible deflections and designers extrapolating from empirical data and adding large factors of safety. These precedents have been of little use for seawater screening applications.

It was necessary early in the development program to develop a simple mathematical model of the mesh for the purposes of predicting stresses and deflections and comparing these predictions to an experimentally loaded panel. An analytic prediction method based on modeling each element of the mesh as two very small crossed beams was developed and compared to test data on a single mesh type and panel size (Gularte & Huguenin, 1977). In this single case, the predictions and measured values compared very well. Both the mathematical model and the test equipment were acknowledged to have possible deficiencies, which in turn raised several questions. Was the agreement between the 1977 test data and the crossed-beams model luck or did it truly verify the analytic technique? Would the predictions be good for other mesh sizes, panel sizes and mesh orientations? Would a more comprehensive and elaborate model accomodating other factors be even more predictive? These questions are obviously of critical importance in design calculations for seawater screening systems utilizing expanded-metal mesh.

In addition to the simple crossed-beam model, a more rigorous analytic method for large deflections of an anisotropic membrane was developed. The mathematics of both the cross-beam and membrane models have been presented elsewhere (Gularte & Huguenin, 1980) and will not be presented here. These models predict both deflections and stresses.

In order to refine design techniques a steel test fixture was designed and built to test load, with small sand bags, 30 in. (76 cm) wide expanded-metal panels of either 60 in. (1.52 m) or 120 in. (3.1 m) length. A number of expanded-metal meshes and expanded-metal panels were load tested for comparison of predicted and actual maximum deflections. The characteristics of only the copper-alloy meshes tested are given in Tables 9.1 and 9.2. This includes the 3/8" nominal 90-10 Cu-Ni expanded-metal mesh in three different panel sizes. The empirical

Table 9.1 EXPERIMENTAL LOADING OF EXPANDED PANELS (30" x 60" & 30" x 120")

Material	Mesh Designation	Mesh Size	Mesh Orientation	Panel Size	Max. Loading	Exhibit "Yielding"
90-10 Cu-Ni	3/8" hex mesh	3/8"	Mesh long axis in panel width direction	30"x 60"	39 lb/sq.ft	Yes
Al-bronze		1/2"	same as above	30"x 60"	43 lb/sq.ft	No
90-10 Cu-Ni	3/8" hex mesh	3/8"	Mesh long axis in panel width direction	30"x 120"	21 lb/sq.ft	Yes
90-10 Cu-Ni (1977 data)	3/8" hex mesh	3/8"	same as above	40"x 120"	12 lb/sq.ft	No?

Table 9.2 MESH PARAMETERS

Mesh	Thickness OT (in.)	Band Width SW (in.)	0 (^{o})	SWM (in.)	LWM (in.)	% Open Area	lb/sq.ft
3/8" 90-10 Cu-Ni	.035	.050	29.54	0.425	0.750	73	.38
1/2" Al-Bronze	.085	.108	22.83	0.500	1.188	62	1.61

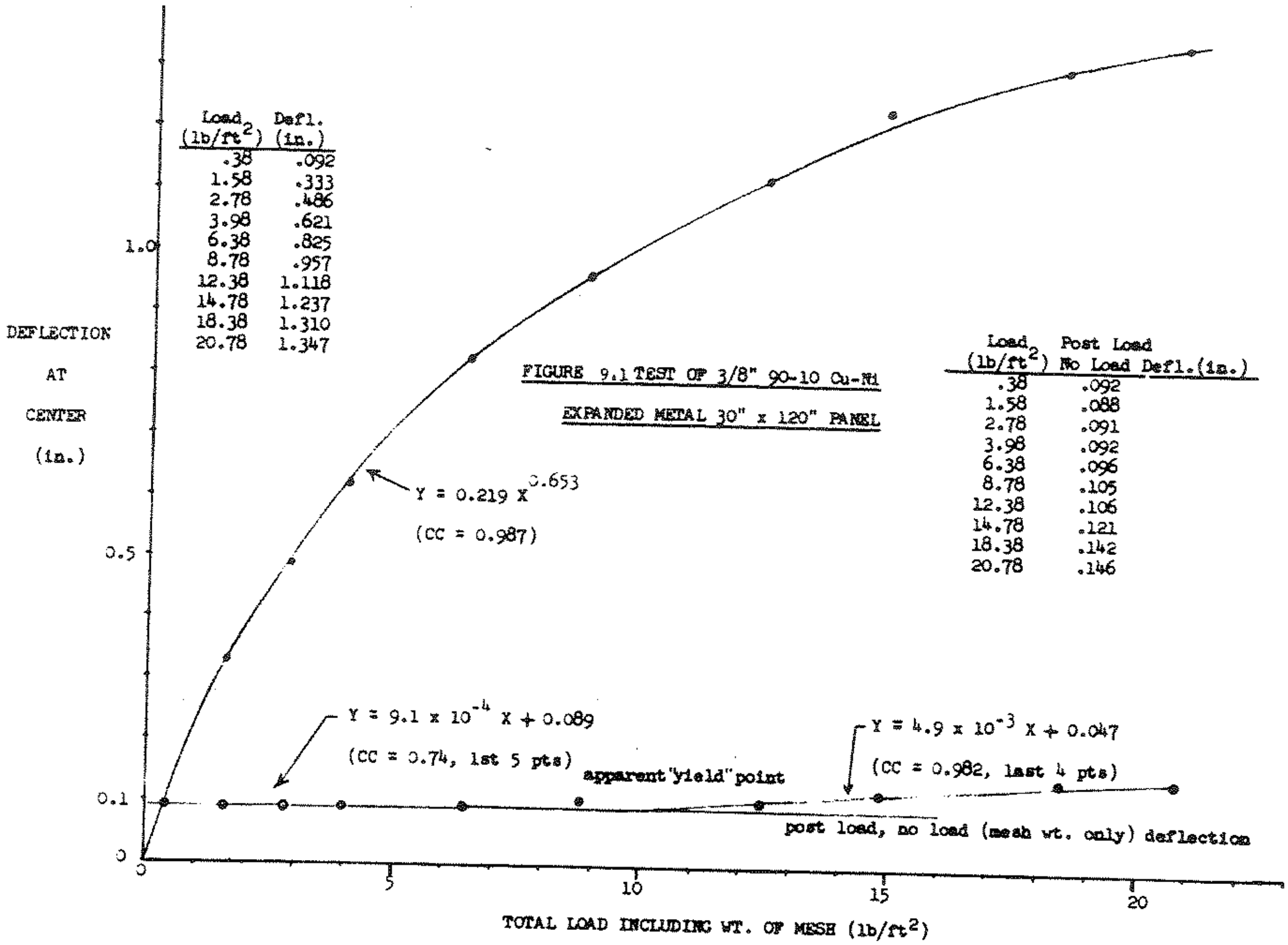


FIGURE 9.1 TEST OF 3/8" 90-10 Cu-Ni EXPANDED METAL 30" x 120" PANEL

Load (lb/ft^2)	Defl. (in.)
.38	.092
1.58	.333
2.78	.486
3.98	.621
6.38	.825
8.78	.957
12.38	1.118
14.78	1.237
18.38	1.310
20.78	1.347

Load (lb/ft^2)	Post Load No Load Defl. (in.)
.38	.092
1.58	.088
2.78	.091
3.98	.092
6.38	.096
8.78	.105
12.38	.106
14.78	.121
18.38	.142
20.78	.146

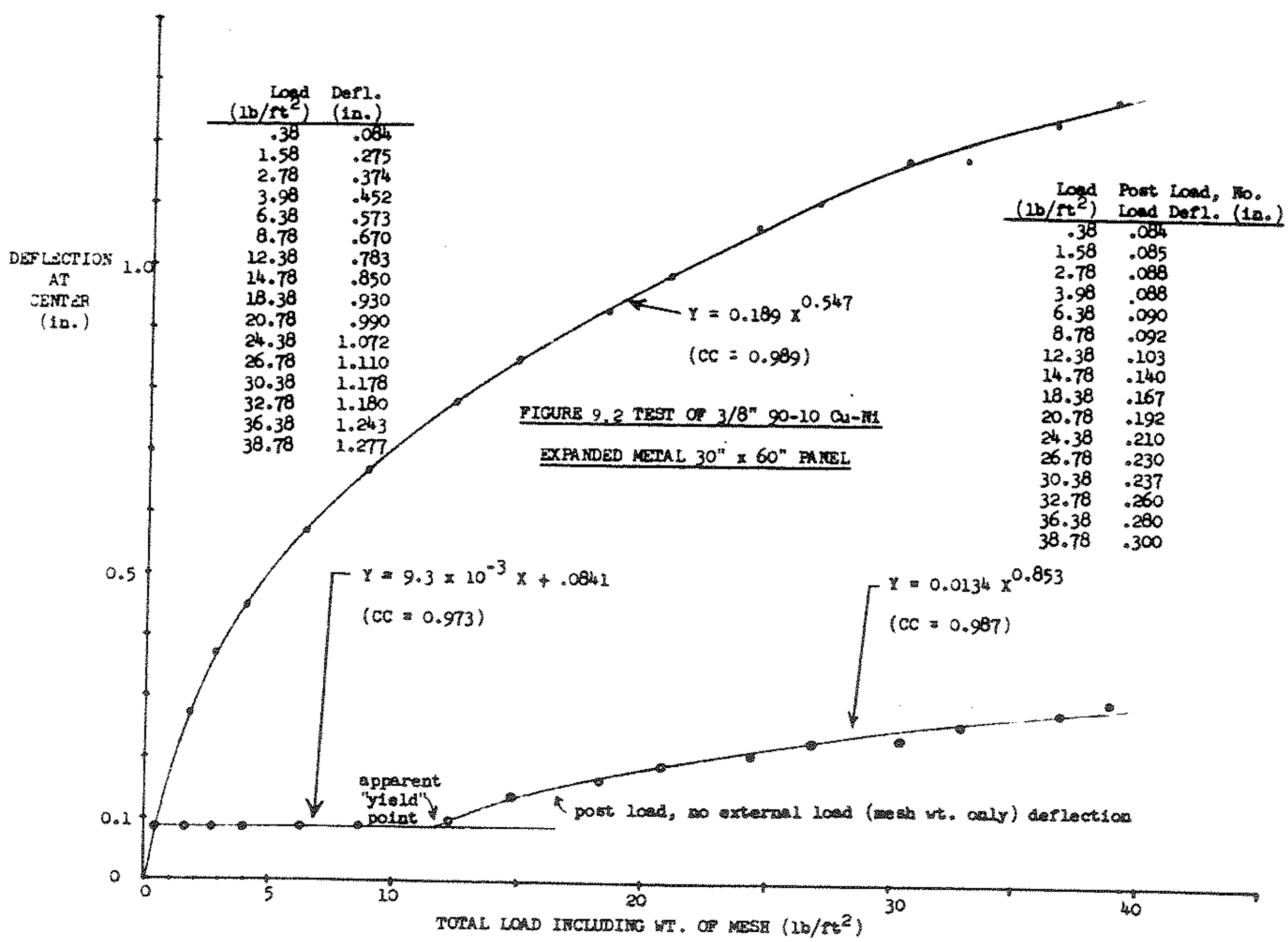
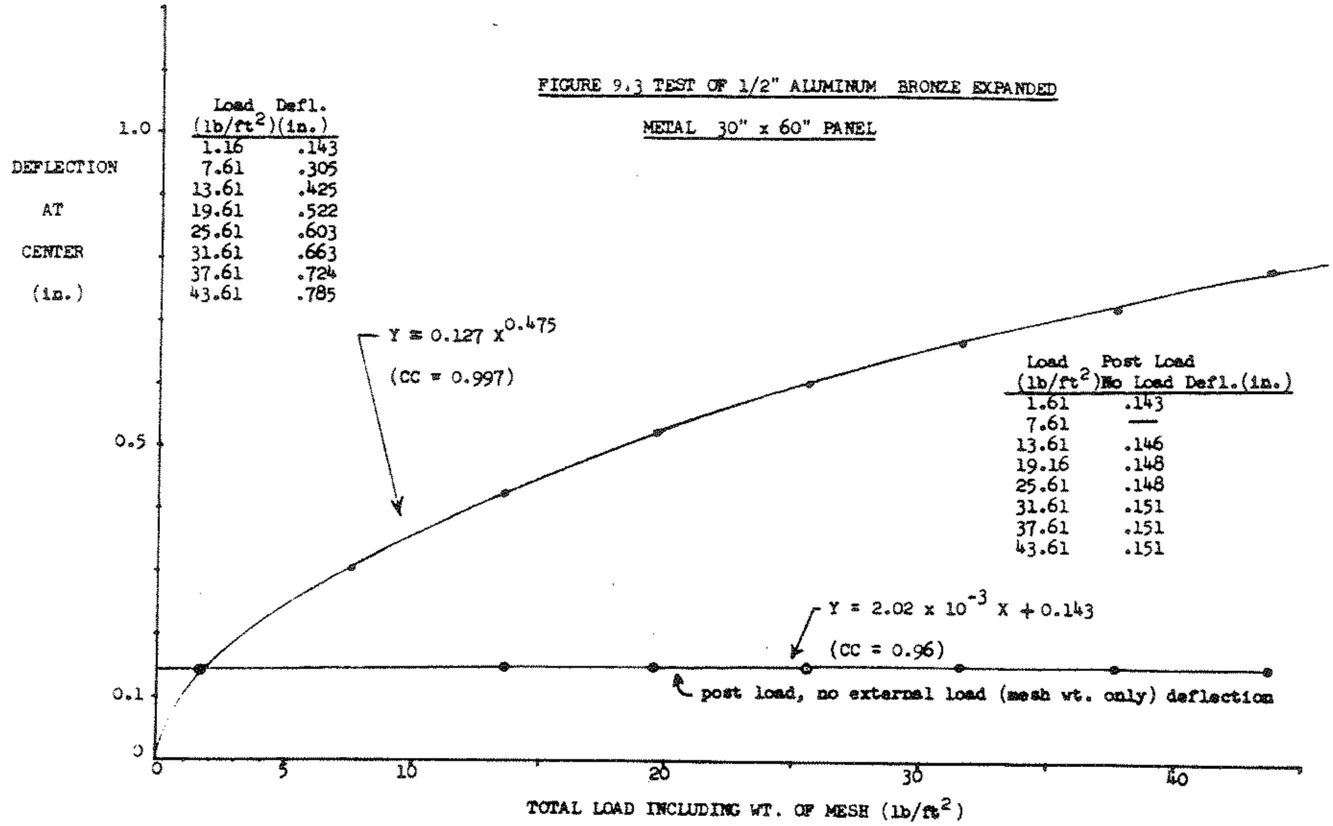


FIGURE 9.2 TEST OF 3/8" 90-10 Cu-Ni EXPANDED METAL 30" x 60" PANEL

Load (lb/ft^2)	Defl. (in.)
.38	.084
1.58	.275
2.78	.374
3.98	.452
6.38	.573
8.78	.670
12.38	.783
14.78	.850
18.38	.930
20.78	.990
24.38	1.072
26.78	1.110
30.38	1.178
32.78	1.180
36.38	1.243
38.78	1.277

Load (lb/ft^2)	Post Load, No Load Defl. (in.)
.38	.084
1.58	.085
2.78	.088
3.98	.088
6.38	.090
8.78	.092
12.38	.103
14.78	.140
18.38	.167
20.78	.192
24.38	.210
26.78	.230
30.38	.237
32.78	.260
36.38	.280
38.78	.300

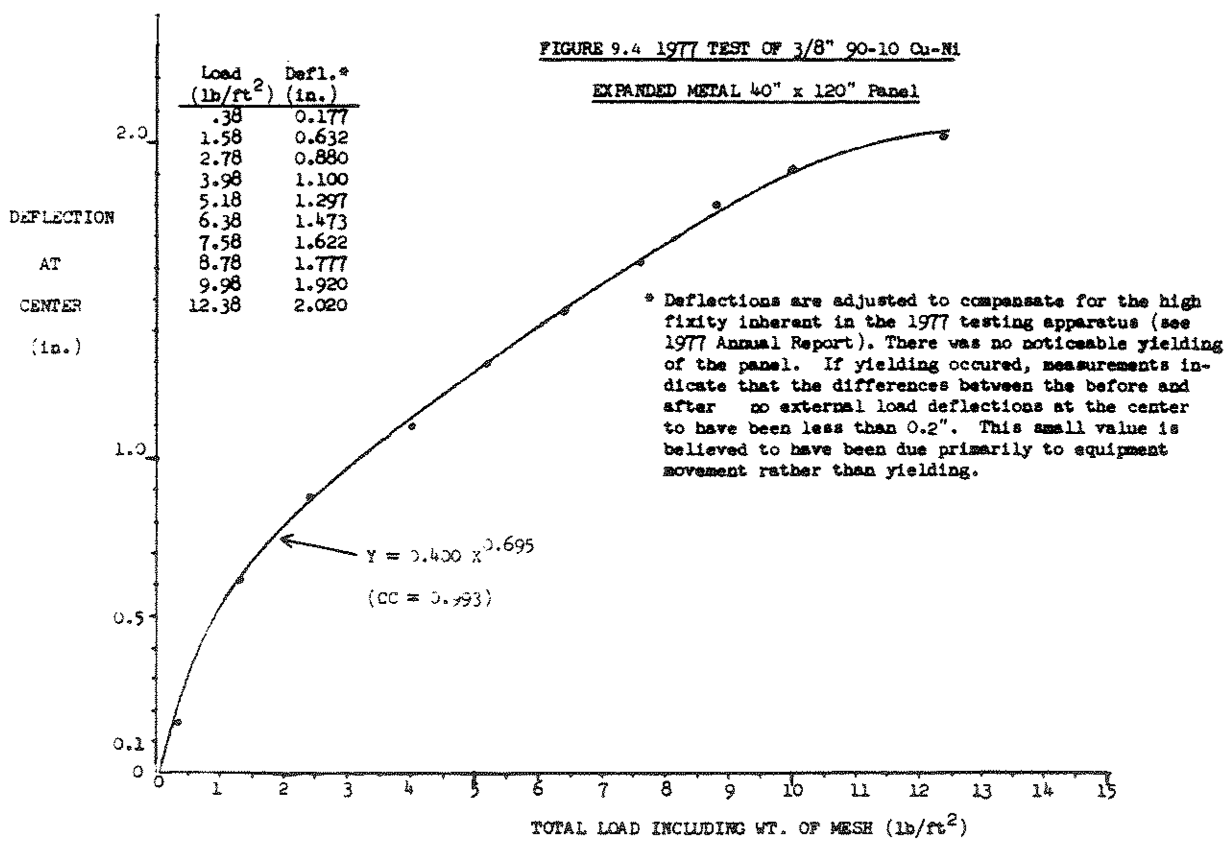
FIGURE 9.3 TEST OF 1/2" ALUMINUM BRONZE EXPANDED METAL 30" x 60" PANEL



Load (lb/ft^2)	Defl. (in.)
1.16	.143
7.61	.305
13.61	.425
19.61	.522
25.61	.603
31.61	.663
37.61	.724
43.61	.785

Load (lb/ft^2)	Post Load No Load Defl.(in.)
1.61	.143
7.61	—
13.61	.146
19.16	.148
25.61	.148
31.61	.151
37.61	.151
43.61	.151

FIGURE 9.4 1977 TEST OF 3/8" 90-10 Cu-Ni EXPANDED METAL 40" x 120" Panel



Load (lb/ft^2)	Defl.* (in.)
.38	0.177
1.58	0.632
2.78	0.880
3.98	1.100
5.18	1.297
6.38	1.473
7.58	1.622
8.78	1.777
9.98	1.920
12.38	2.020

* Deflections are adjusted to compensate for the high fixity inherent in the 1977 testing apparatus (see 1977 Annual Report). There was no noticeable yielding of the panel. If yielding occured, measurements indicate that the differences between the before and after no external load deflections at the center to have been less than 0.2". This small value is believed to have been due primarily to equipment movement rather than yielding.

test results are given on Figures 9.1, 9.2, 9.3, and 9.4. A test comparision of measured versus predicted values for maximum deflections are given on Tables 9.3 and 9.4. More complete details are in Gularte & Huguenin, 1980.

The anisotropic membrane model deflection predictions are contained on Table 9.4 for comparison to the crossed-beams model and the actual measured values. It can be seen that the membrane model gives either more accurate or more conservative predictions than the crossed-beams model. This includes better values for all three 90-10 Cu-Ni meshes tested. The reasons for a few of the large errors which exist for the membrane model are not known, although the consistency of the errors suggest the possibility of simple causes. The membrane approach is felt to be sound. In general, there doesn't appear to be any clear-cut superiority of one method over another for predicting deflections.

The model stress predictions are given in Tables 9.5, 9.6, 9.7, and 9.8 for each panel as a function of load. Some of the values are believable and some are at least questionable. The two models tend to give quite different values, with the crossed-beams model generally appearing more credible. It should be noted that predictions for panels under small deflection conditions have been known to become erratic and inconsistent with panel length to width ratios greater than two (Koltunov, 1952).

Three test panels indicated some type of permanent deformation to have occured under test. It should be noted that the actual yield stresses of these materials are not precisely known. The 90-10 Cu-Ni was supposed to be quarter-hard in its original sheet form with a yielding stress of about 48,000-49,000 psi. However, microhardness tests using a Knoop Indentor and a 200 g load indicate a Rockwell hardness of B-73 (4 readings) at the nodes and B-78 (5 readings) on the strands. Since a Rockwell hardness of B-75 corresponds to a half-hard condition, the material is essentially half-hard with a yield stress of 62,000-63,000 psi depending on yielding criteria. The difference may be due to the cold working that occured on making the expanded-metal mesh. It is clear that none of the predicted stresses at the points of initial deformation are close to the expected yield stresses. It is possible that the permanent deformation noted in these cases was not yielding in the classical sense of an area reduction. It might have been due to rotation and/or bending at the nodes or even possibly some edge effects which could have occured at stresses well below the yield stress. It is quite possible that the 1977 test, with the 40 x 120 in. panel, did have some similar permanent deformation, although it was undetected at that time. It should be pointed out that these permanent deflections at the panel centers were quite small and were beyond the precision of the 1977 test equipment.

Table 9.3

EXPERIMENTAL DEFLECTION EQUATIONS AT CENTER OF PANELS COMPARED TO MODEL EQUATIONS
(Q = PANEL LOADINGS IN lb/sq.ft, Y = MAX. DEFLECTION AT CENTER OF PANELS IN INCHES)

Mesh	Experimental (Actual) Deflection Equation	Crossed-Beams Deflection Equation	Anisotropic Membrane Deflection Equation
3/8" Cu-Ni 30" x 60"	$Y = 0.189\ Q^{0.547}$	$Y = .417\ Q^{0.333}$	$566Y^3 + 59Y = 23.4\ Q$
3/8" Cu-Ni 30" x 120"	$Y = 0.219\ Q^{0.653}$	$Y = .422\ Q^{0.333}$	$328Y^3 + 188Y = 93.6Q$
3/8" Cu-Ni 40" x 120"	$Y = 0.400\ Q^{0.695}$	$Y = .619\ Q^{0.333}$	$442Y^3 + 113Y = 166.4\ Q$
1/2" Al-Bronze 30" x 60"	$Y = 0.127\ Q^{0.475}$	$Y = .215\ Q^{0.333}$	$6974Y^3 + 1158Y + 23.4\ Q$

Table 9.4

COMPARISONS OF MODEL MAXIMUM DEFLECTIONS (AT CENTER OF PANEL) AND MEASURED VALUES

		Crossed-Beamed Model			Anisotropic Membrane Model		
Mesh Material	Size	Model Deflections Predictions	Average Error	Trends of Prediction To Actual	Model Deflections Predictions	Average Error	Trends of Prediction To Actual
Cu-Ni	3/8"-30"x60"	over predicts	+ 22%	over to under	under predicts	- 5%	over to under
Cu-Ni	3/8"-30"x120"	under predicts	- 10%	over to under	over predicts	+ 27%	over to less over
Cu-Ni	3/8"-40"x120"	under predicts	- 24%	over to under	under predicts	- 16%	over to under
Al-Bronze	1/2"-30"x60"	over predicts	+ 3%	over to under	under predicts	- 47%	under to less under

Table 9.5 3/8" COPPER-NICKEL MESH, 30" x 120" PANEL

		CROSSED-BEAMS MODEL			ANISOTROPIC-MEMBRANE MODEL		
LOAD (lbF/ft^2)	ACTUAL DEFLECTIONS Y_A (in.)	PREDICTED DEFLECTIONS Y_m (in.)	DEFLECTION ① DIFFERENCES WITH ACTUAL (%)	STRESS PREDICTIONS σ_c (psi)	PREDICTED DEFLECTIONS Y (in.)	DEFLECTION ① DIFFERENCES WITH ACTUAL (%)	STRESS PREDICTIONS (psi)
0.38	0.092	0.306	233	2,208	.18	+96	124
3.98	0.621	0.669	+8	10,561	.86	+38	2,825
8.78	0.957	0.871	-9	17,901	1.23	+29	5,779
12.38	1.118	0.977	-13	22,513	1.40	+25	7,487
14.78	1.237	1.036	-16	25,327	1.50	+21	8,595
18.38	1.310	1.114	-15	29,296	1.63	+24	10,149
20.78	1.347	1.161	-14	31,783	1.70	+26	11.040
			-10 ②			+27 ②	

① % = $\frac{\text{PREDICTED-ACTUAL}}{\text{ACTUAL}}$

$E = 16 \times 10^6$ psi

② **Average** of errors below indicated line

Table 9.6 3/8" COPPER-NICKEL MESH, 30" x 60" PANEL

		CROSSED-BEAMS MODEL			ANISOTROPIC-MEMBRANE MODEL		
LOAD (lbF/ft^2)	ACTUAL DEFLECTIONS Y_A (in.)	PREDICTED DEFLECTIONS Y_m (in.)	DEFLECTION ① DIFFERENCES WITH ACTUAL (%)	STRESS PREDICTIONS σ_c (psi)	PREDICTED DEFLECTIONS Y (in.)	DEFLECTION ① DIFFERENCES WITH ACTUAL (%)	STRESS PREDICTIONS (psi)
0.38	0.084	0.306	+264	2,093	0.13	+55	21
3.98	0.452	0.660	+46	10,007	0.48	+6	283
8.78	0.670	0.866	+29	17,216	0.66	-1	535
14.78	0.850	1.022	+20	24,022	0.81	-5	806
20.78	0.990	1.145	+16	30,159	0.92	-7	1,039
30.38	1.178	1.300	+10	38,819	1.05	-11	1,354
38.78	1.277	1.410	+10	45,700	1.14	-11	1,596
			+22 ②			-5 ②	

① % = $\frac{\text{PREDICTED-ACTUAL}}{\text{ACTUAL}}$

$E = 16 \times 10^6$ psi

② **Average** of errors below indicated line

Table 9.7 1/2" ALUMINUM-BRONZE MESH, 30" x 60" PANEL

		CROSSED-BEAMS MODEL			ANISOTROPIC-MEMBRANE MODEL		
LOAD (lbF/ft²)	ACTUAL DEFLECTIONS Y_A (in.)	PREDICTED DEFLECTIONS Y_m (in.)	DEFLECTION DIFFERENCES WITH ACTUAL ① (%)	STRESS PREDICTIONS σ_c (psi)	PREDICTED DEFLECTIONS Y (in.)	DEFLECTION DIFFERENCES WITH ACTUAL ① (%)	STRESS PREDICTIONS (psi)
1.16	.143	.226	+58	5,590	0.02	-86	1
7.61	.305	.422	+38	19,583	0.14	-54	54
19.61	.522	.579	+11	36,806	0.27	-48	199
25.61	.603	.632	+5	43,976	0.32	-47	280
31.61	.663	.678	+2	50,598	0.36	-46	354
37.61	.724	.719	-1	56,815	0.39	-46	416
43.61	.785	.755	-4	62,702	0.42	-46	482
			+3 ②			-47 ②	

① % = $\frac{\text{PREDICTED-ACTUAL}}{\text{ACTUAL}}$

$E = 16 \times 10^6$ psi

② **Average** of errors below indicated line

Table 9.8 3/8" COPPER-NICKEL MESH, 40" x 120" PANEL

		CROSSED-BEAMS MODEL			ANISOTROPIC-MEMBRANE MODEL		
LOAD (lbF/ft²)	ACTUAL DEFLECTIONS Y_A (in.)	PREDICTED DEFLECTIONS Y_m (in.)	DEFLECTION DIFFERENCES WITH ACTUAL ① (%)	STRESS PREDICTIONS σ_c (psi)	PREDICTED DEFLECTIONS Y (in.)	DEFLECTION DIFFERENCES WITH ACTUAL ① (%)	STRESS PREDICTIONS (psi)
0.38	0.177	0.449	+154	2,631	0.36	+103	230
3.98	1.100	0.981	-11	12,597	1.07	-3	2,030
6.38	1.473	1.149	-22	17,254	1.28	-13	2,905
7.58	1.622	1.217	-25	19,355	1.36	-16	3,279
8.78	1.777	1.278	-28	21,347	1.44	-19	3,676
9.98	1.920	1.333	-31	23,250	1.50	-22	3,989
12.38	2.020	1.433	-29	26,842	1.62	-20	4,653
			-24 ②			-16 ②	

① % = $\frac{\text{PREDICTED-ACTUAL}}{\text{ACTUAL}}$

$E = 16 \times 10^6$ psi

② **Average** of errors below indicated line

10.0 STRUCTURAL ANALYSIS

Ronald C. Gularte & John E. Huguenin

In the general case we are dealing with a structure of arbitrary shape. It might be a rectangular square box or even a polygon with many sides and approximating a cylinder. Its purpose might be as a fish cage or an intake screen and intended for either floating or submerged use. It is assumed that it is made up of a number of standard (30" x 120") panels along with a pultruded fiberglass structural space frame, whose sizing of component parts remains to be determined. Even with a given size and shape it is quite possible to have differences in the space frame to compensate for varing severity of use.

10.1 SOURCES OF LOADS

The major sources of loads on such a structure are due to water currents, waves and winds. Water currents are usually assumed to be uniform in magnitude, depth, horizontal distance and direction. This may not always be true in estuaries and sheltered areas due to nearby objects, structures or bottom topography. It is important to know both: the normal water currents, usually predominantly due to tides; and those due to extreme high and low tides associated with major storms. The maximum tidal velocities need to be known for design calculations. The setting of design currents is dependent not only on a large number of specific site and service conditions but also on the desired probability (risk) of actually encountering the design values (i.e. whether to design for 25, 50, or 100 year maximum conditions?). In sheltered areas tide induced water currents are usually the most severe load input.

In exposed areas or if storms hit from an open side, waves can provide significant loads. If the open distance is known (called fetch), the maximum wind velocity and the period of time the wind blows in this direction the wave heights can be predicted (U.S. Army, 1975), assuming a water depth of at least ½ of a wave length. This "deep water" wave assumption is not always accurate in shallow areas but is conservative, since it will predict a larger wave than will actually be seen. Waves hitting structures produce not only drag forces but also inertia forces, they decay hyperbolically with depth and are very dependent on wave parameters, in short a complex subject. A critical aspect of waves is to assure the avoidance of breaking waves, whose forces can be a hundred fold that of non-breaking waves. Since the maximum design wave is likely to concide with a major storm, the timing may occur with an unusually low tide. A very low tide along with a large wave will produce breaking waves where they are not otherwise expected. It is important to pick a site where this doesn't happen and there are several wave breaking criteria available. One is called

Monk's criteria and is given below, where to avoid breaking waves the water depth must be greater than d_b.

$$d_b = 1.28 H_b$$

d_b = breaking depth

H_b = wave height of incoming wave

Wind loading is unlikely to be important for our types of applications except under unusual circumstances. These might include appreciable parts of the structure being above water level during a hurricane. Wind forces are calculated just like water current forces with appropriate adjustment for fluid density, velocity and possible Reynolds' number differences. Other sources of loads which have to be addressed on an individual basis are ice loads, which can be very high, impact loads from moving objects, mooring loads possibly transmitted from other units and total mesh blockage due to drifting debris, such as plastic or cloth sheet. In any given situation, there might be specific circumstances which might dramatically alter the conclusion of a simplified methodology and some care should be exercised, with particular attention to assumptions and limitations.

10.2 SIMPLIFIED SPACE-FRAME ANALYSIS

A simplified but complete space-frame analysis was presented in Gularte and Huguenin, 1980. This analysis assumed water current loading was dominant and the other sources insignificant, a reasonable assumption under many conditions, and a rectangular box shaped unit. The rest of this section presents a qualitative review of this methodology, the main equations and the needed structual input parameters.

The forces on the possibly unequal sides and the subsequent sizing of structural members has to be done independently for each side. Even if the walls were equal in size, separate calculations might have to be done, if the service conditions indicated that much higher water velocities, with resulting higher forces, could be expected on some sides and not others. Expected placement and orientation with respect to nearby walls, piers or shoreline could create this situation. The placement, orientation and service conditions on the unit, the maximum design water velocity for each side and the overall shape and dimensions of the unit have to be determined before the sizing of individual structural members can proceed. It should be remembered that the structural members between any two panels automatically includes the two 2" x 9/16" x 1/8" C-channel component parts of the panels and the exercise is to determine, in addition to horizontal members, what additional structural reinforcement, if any, is required at each seam.

We will assume for calculation purposes an imaginary horizontal cut on the side at mid-depth and consider the top and bottom halves separately. We will assume that the mesh transfers loads to the structure but does not itself carry loads or stiffen the unit. This is a conservative assumption. It is necessary to consider three sources of loads. One is the drag force on the mesh, another is the drag force on the horizontal structural member and the last is the drag force on the vertical members. These are calculated separately and added to find a distributed load on the top and horizontal members per unit length of wall.

The drag forces on the mesh are determined by the equation below:

$$F_m = \tfrac{1}{2} C_d A \rho V_H^2$$

F_m = drag force in lb.

C_d = drag coefficient, see section 8 and Table 10.1

A = total perpendicular area of mesh, for 1/2 of the side,

$$A \approx \frac{\text{length x depth}}{2} \qquad (ft^2)$$

ρ = density of seawater $\simeq$ 2 slugs/ft^3

V_H = an adjusted velocity (see Hoerner, 1965) = $V_o\left(\frac{1}{1-\gamma}\right)$

V_o = free stream velocity (ft/sec), a maximum value for design purposes

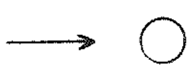
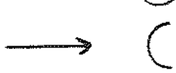
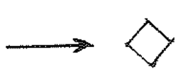
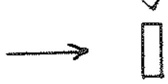
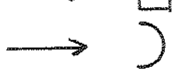
γ = fractional mesh blockage factor (method stated to be good for $0 < \gamma < 0.4$, Hoerner, 1965)

The fractional mesh blockage factor for the expanded-metal mesh used to date is $\gamma = 0.27$. However, even 90-10 Cu-Ni mesh is not completely biofouling free and additional fouling debris factor of 0.1

is adequate for most circumstances (Huguenin and Ansuini 1981) for a value of $\gamma \approx 0.37$.

Now it is necessary to consider the drag forces on the structurals, starting with the top horizontal. A version of the equation used for the forces on the mesh is used but the terms and values are somewhat different (see below). In particular, the area A_s is the actual projected area of the structural member perpendicular to the current. Since the structural member has not yet been sized, it is an indeterminant problem. In addition these structurals, can, over time, become highly fouled with the total projected area A being considerably greater than the physical dimension A_s. The differences in the physical projected areas of the various structural shapes available, in a high fouling environment, may be small compared to the increased area generated by fouling. Based on experience to date this increased area, or fouling factor (α), for fiberglass structurals can, in high fouling conditions, easily reach values of $1.5 < \alpha < 2$. Without periodic removal and in the presence of certain fouling organisms, such as mussels, this factor may even be higher. Factors as high as 3 have been seen. It is recommended that one guess at the sizing of the structurals and the fouling factor and re-examine adequacy of guesses after completing the calculations and reiterating if necessary. C_{ds} is the drag coefficient for the structural shapes (see Table 10.1).

Table 10.1 ESTIMATED DRAG COEFFICIENTS FOR TWO DIMENSIONAL SHAPES AND REYNOLDS NUMBERS IN THE RANGE OF 10^4 to 10^6. (DERIVED FROM HOERNER, 1965). FLOW DIRECTION IS FROM LEFT. SHORTENED FROM TABLE IN GULARTE AND HUGUENIN, 1980.

Section Shape	Drag Coefficient "C_d"(Dimensionless)
	1.16
	1.20
	1.55
	1.98
	2.05
	2.30

Under fouled conditions these coefficients will probably change, but there is no better data available. It should also be noted that the velocity in the equation below is the free stream velocity V_o.

$$F_{TH} = \frac{1}{2} C_{ds} \rho V_o^2 A$$

Now it is necessary to consider the forces placed on the top horizontal structural by a number of vertical members. Taking a length of D/2 (the half-side depth dimension) of any one of the vertical structurals, assuming a size with associated C_{ds} and A, we have the equation below:

$$F_{VL} = \frac{1}{2} \rho C_{ds} V^2 A$$

$$A = S_W D/2$$

S_W = actual width of structural perpendicular to normal incident current

Now we must add the forces on the side and find the distributed load. The forces due to the verticals are distributed at regular intervals and to simplify calculations will be assumed to have a uniform distribution. We also assume that this top horizontal structural is a simply supported beam. This is a more conservative assumption than fixed ends because the maximum mid-span moment used to size the structural will be higher.

$$W_D = \frac{F_M + F_{TH} + N F_{VL}}{L} \quad \text{lb/in.}$$

N = number of identical verticals per side

L = horizontal length of wall

W_D = distributed uniform load on horizontal

We can now determine the maximum moment on the top horizontal structural as given by the equation below. It is time to consider the allowable stress in the pultruded structurals being used. The manufacturer recommends a factor of safety of four for conditions of dynamic or cyclic loading (Morrison, 1978). This is conservative for our case, especially if wave forces are insignificant. This gives an allowance stress of 5,000 psi. This stress can be related to the maximum moment by use of the equation below.

$$M_{TH} = \frac{W_D L^2}{8}$$

σ all = allowable stress in fiberglass

T = tensile strength of material = 20,000 psi

$$\sigma \text{ all} = \frac{T}{4} = \frac{20,000}{4} = 5,000 \text{ psi}$$

$$\sigma \text{ all} = \frac{M_{TH}\ C}{I} = \frac{M_{TH}}{Z_{reg}} = 5,000 \text{ psi}$$

I = moment of inertia (in.^{4}), see Table 10.2

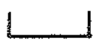
C = distance from centroid of section to extremity (in.)

Z_{req} = required section modulus

$$Z_{req} = \frac{M_{TH}}{5,000} \quad (\text{in.}^3)$$

Table 10.2 gives a selected listing of section moduli for various pultruded structural shapes and combinations of shapes. It assumes no shear transfer between shapes in a composite structural, which is a very conservative assumption. The table is assembled assuming the vertical axis goes through the centroid of all the shapes in a composite. Since this is the worst case, displacing any shape horizontally relative to the others will improve both the section modulus and the moment of inertia. More precise evaluation of improvements in section modulus or moments of inertia can be calculated using the parallel axis transfer theorem. Therefore, the values in the table are also conservative in this regard. Additional combinations can be developed from the table by adding the Z's and I's of the component parts. The structural member can be sized by selecting a combination of shapes such that the Z selected $\geq Z_{req}$, remembering that there is essentially at least one 2" x 9/16" x1/8" C-channel due to the panels attached to the top horizontal member. If the top member of the unit is stiffened in any way, such as being secured to a foundation, or if the top member and parts of the mesh are out of water, the results will be more conservative. The bottom horizontal structural member can be sized

Table 10.2 SECTION MODULI AND MOMENTS OF INERTIA FOR COMPOSITE FIBERGLASS SECTIONS WITH BENDING ABOUT VERTICAL AXIS THROUGH CENTROIDS AND ASSUMING NO SHEAR TRANSFER. (DERIVED FROM MORRISON MOLDED FIBERGLASS, 1978) SHORTENED FROM TABLE IN GULARTE AND HUGUENIN, 1980.

Sections (Load Directions) ⟶ ⟵	Dimensions (in.)	Actual Z ($in.^3$)	Actual I ($in.^4$)
	2 x 9/16 x 1/8	0.18	0.18
	2 x 2 x 1/4	0.24	0.34
"	3 x 3 x 1/4	0.54	1.18
	3 x 1½ x 1/4	1.17	1.75
"	4 x 2 x 1/4	2.20	4.40
"	6 x 3 x 1/4	5.32	15.92
	two 2 x 9/16 x 1/8	0.36	0.36
	2 x 2 x 1/4∠; 2 x 9/16 x 1/8	0.42	0.52
"	3 x 3 x 1/4∠; 2 x 9/16 x 1/8	0.72	1.36
	3 x 1½ x 1/4; 2 x 9/16 x1/8	1.35	1.93
"	4 x 2 x 1/4; 2 x 9/16 x 1/8	2.38	4.58
"	6 x 3 x 1/4; 2 x 9/16 x 1/8	5.50	16.10
	3 x 1½ x 1/4; two 2 x 9/16 x 1/8	1.53	2.11
"	4 x 2 x 1/4; two 2 x 9/16 x 1/8	2.56	4.76

in the same way as the top member. However, the results will be even more conservative, due to the stiffening provided by the bottom cross members.

Now we will address the sizing of vertical members. Here again there are several load components to consider. One is the load on the mesh and the other is the load directly on the vertical structural. In calculating the mesh loads on the vertical structurals, imaginary lines are drawn down the middle of each adjacent 30" x 120" panel. The same equations as before for mesh drag force and loads on structural shapes are again valid. The maximum moment at mid-span is calculated with a moment equation of the same form as used for the horizontal members. The structural member, similar to before, can be sized. However, it should be remembered that there are automatically two 2" x 9/16" x1/8" C-channels between two panels. Each vertical member is sized until all members on a side have been selected. Each side is in turn analyzed. This now leaves only the bottom side (or top) to be sized.

The bottom of the unit is somewhat different from the sides. The maximum water currents through the bottom can be expected to be minimal. Therefore forces from perpendicular currents can be neglected. However, the bottom must support its own weight and the in-water weight of fouling on the structurals, in a high fouling environment, has been estimated to have an in-water weight of as much as 0.3 lb/in. This can be considered as a uniformed distribution load (W_F). The other part of vertical loading is the dead weight of the mesh, structurals, and any accumulated debris (W_{DW}). This includes a 30" x W (width of mesh assigned to each structural) in bottom area of mesh times its weight per unit area divided by W, to give a distributed load, added to the in-water weight per inch of the assumed structural shape. The section can now be tentatively selected.

M_B = maximum bending moment on bottom at mid-span

$$M_B = \frac{(W_F + W_{DW})\, W^2}{L} \quad \text{(in.-lb)}$$

$$Z_{req-1} = \frac{M_B}{\text{all}} = \frac{M_B}{5{,}000} \quad (\text{in.}^3)$$

$$Z \text{ first approximation} \geq Z_{req-1}$$

(including two 2" x 9/16" x 1/8" C's)

However, this treatment does not account for the important horizontal forces from the adjacent sides pushing on the ends of the structural beam and tending to buckle it. The end force P can be acquired from the combined distributed loading on the horizontal member previously calculated. Considering the beam with end loads, a new maximum mid-span moment (M_{BP}) can be calculated with the equation below. If the last equation concerning Z value requirements does not hold, choose new bottom structural section and iterate.

$$M_{BP} = \frac{(W_F + W_{DW})\ E\ I}{P} \left(\text{Sec} \frac{90W}{\pi} \sqrt{\frac{P}{E\ I}} - 1\right)$$

E = modulus of elasticity of structurals $\simeq 2.3 \times 10^6$ psi

I = moment of inertia of selected section,
see Table 10.2 (in.^{4})

$P = 30'' \ W_D$(lb)

$$Z_{req-2} = \frac{M_{BP}}{\sigma_{all}} = \frac{M_{BP}}{5{,}000} \quad (\text{in.}^3)$$

$$Z \text{ selected} \geq Z_{req-2} \geq Z \text{ first approx.} \geq Z_{req-1}$$

This section has attempted to provide a general guide and methodology for sizing structural members in a three dimensional unit. It has, by necessity, been a simplified presentation and has ignored many considerations, which often can be of minor importance. In any given situation, there may be specific circumstances which might dramatically alter the conclusions drawn from this simplified methodology and it should therefore be used with caution, with particular attention to its assumptions and limitations.

11.0 MANUFACTURING METHODS AND OPERATIONAL EXPERIENCE

John E. Huguenin & Frank J. Ansuini

The data base upon which this publication is based includes the fabrication of the INCRA Cage Prototype, its deployment and servicing over more than five years, the manufacturing of several C-21 cages, a variety of test units and design studies, intakes screens, and feedback information on U.S. and foreign design and construction of related hardware. In all of these efforts, a number of design and construction methods were tried and INCRA Project 268 has always contained an element of manufacturing engineering, whose intention has been to reduce construction costs. In addition, the project had to develop practical methods for servicing the cages and for handling and harvesting the marine animals.

11.1 MANUFACTURING AND TOOLING

The original INCRA cage deployed in 1977 was constructed primarily by project personnel using home-made tooling and conservative manufacturing techniques. Tooling included panel frame corner fixtures (see Figure 11.1), drilling and cutting jigs to eliminate repetitive measurments on fiberglass pultruded sections and a double acting brake forming machine on all four sides (see Figure 11.2). The brake forming machine was used to wrap the expanded-metal mesh around the perfabricated fiberglass frame to form large fiberglass/mesh panels. The final clamping of the mesh about the outside flange of the C-channel was done by hand with sheet-metal pliers to get a firm hold. Although made of wood and piano hinges, it worked well for the limited production undertaken with it. A steel unit would have been more rigid and longer lived.

In 1980, two additional cages were built for deployment in New Brunswick, Canada. These cages not only served to give the concept wider exposure, but also to test new manufacturing techniques in an effort to reduce the cost of the cage. In particular, this included considerable documentation and preparation of drawings, which now belong to INCRA. Among the innovations were:

A) Reduction in panel width to 30" to allow the use of narrower mesh, which has a significantly lower unit cost.

B) Use of 90-10 Cu-Ni fasteners, which are less expensive than the Monel fasteners used on the prototype.

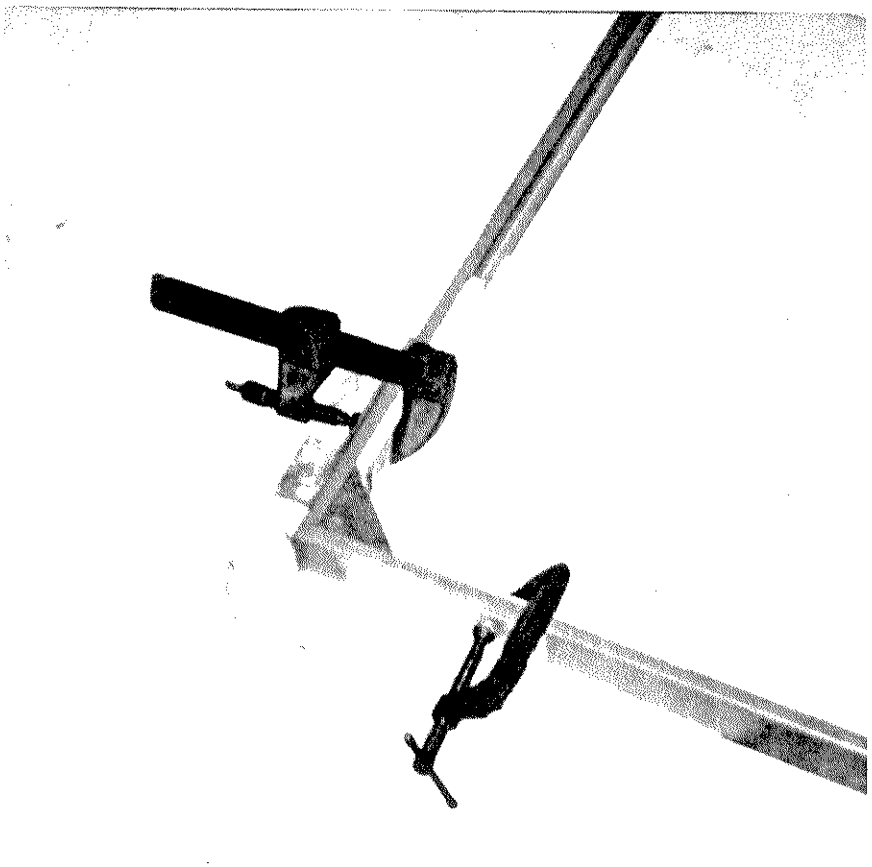


Figure 11.1 One of four jigs used for assembly of panel-frame corners.

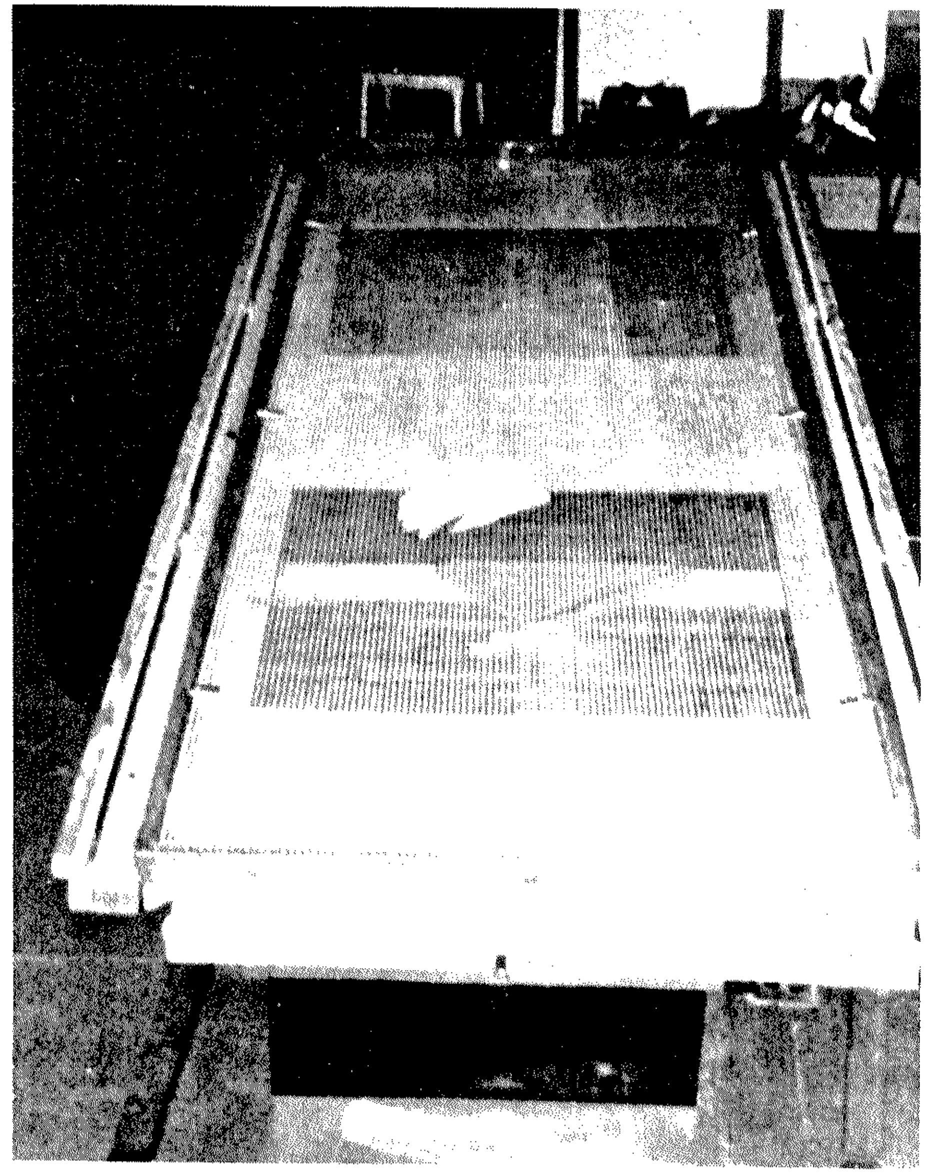


Figure 11.2 Double acting four-sided mesh panel wrapping tooling, showing finished mesh panel in place. While it worked fine for the prototype, a steel unit would be preferred for series production.

C) Punching rather than drilling holes on the 1/8" thick fiberglass structurals.

D) Use of a coped rather than a mitered corner on the panel frames (see WHEA Drawing C-21-111).

E) Sub-contracting all construction operations to a sheet metal shop to gain access to more efficient cutting and forming equipment.

The subcontractor used a few of the prototype jigs but not the double acting brake, rather using a conventional bender for each of the four sides. While all these modifications did serve to reduce the cost of the modified cages from that which would have been incurred if an exact copy of the prototype were built, there was still room for further improvement. One particularly troublesome area was the large amount of labor used for assembly of the panel frames. These rectangular frames are made from four pieces of fiberglass channel joined by means of a brace cut from a length of fiberglass angle (see Figure 2.1). The brace is epoxy cemented to the inside of the channel after the mating surfaces have been sanded to remove the glaze. This joint is then reinforced by securing a sheet-metal screw through the parts. WHEA drawing C-21-111, shows this assembly in detail.

The primary function of the brace is to keep the panel frame together until it has been wrapped with mesh. After the wrapping, the frame is held in place by the mesh, although the brace still serves to keep the frame in one piece. Once the cage has been assembled, the panels are held rigidly by the space frame so the function of the brace is relatively unimportant.

Personal observation and discussions with the foreman at the fabricators, indicated that much of the time in assembling the panel frame was spent in sanding the mating surfaces prior to cementing in the brace. While the prototype frames had been successfully assembled without sanding and in the absence of hard data, as a conservative measure, sanding or grinding of the mating surfaces was specified for production C-21 cages. In addition, similar panels were being constructed in Great Britain at a lower labor cost. These U.K. panels were assembled using a different adhesive and mating surfaces were not being sanded. Thus, it was felt that a brief program to evaluate adhesives and surface preparation techniques would be in order.

Fiberglass pultrusions are extremely anisotropic in their mechanical properties. The fiber reinforcements run more or less parallel to the long axis of the structural, making them able to withstand loading in that direction. Their transverse strength is very low, essentially that of the polyester resin, because the only transverse reinforcement consists of a thin surface veil of glass mat. The panel frame is subject to two types of loading during the course of handling. When the frame is placed in shear, the load on the cement joint is one of tearing. Once the frame is wrapped with mesh, this type of loading becomes insignificant. The other type of loading, which can occur until the panel is incorporated into the cage, is twisting. This applies a torque loading to the cement joint. The load on the brace itself in both these cases is in the transverse direction where the material has the least strength.

A test program involving two types of loading, three different adhesives, three types of surface preparation (sanding, solvent wipe, and none) was carried out. These tests are reported fully in WHEA, 1983 (P-106-115). The results of these tests indicated for this specific type of application, that the joint doesn't fail along the joining boundaries. Therefore, any of the epoxys tested were acceptable and a solvent wipe was sufficient surface preparation. The labor intensive sanding for this specific application is therefore unnecessary. These results for INCRA-type panel frames should not be generalized to other situations.

The fabrication of the cage results in four types of components which can be shipped to the deployment site. This includes the fabricated mesh panels, which must be packaged carefully, since they are somewhat fragile and can be easily twisted or punctured during shipment. The other parts are the space frame, comprising measured, cut and drilled fiberglass sections, the metallic corner brackets and the fastener sets. The general fabrication sequence is given on Table 11.1. The complete specifications and manufacturing instructions for all the parts are included in Cage Construction Drawings INCRA-type C-21 Fish Cage, July 1980,(revised Sept. 1982), 17 pages. The float collar has six parts and is manufactured and assembled separately (see Assembly Instruction C-21 Float Collar, July 1980, 28 pages). These drawings belong to INCRA. The C-22 and C-23 fish cages are generally similar.

11.2 CAGE ASSEMBLY

The assembly of an INCRA cage is rather straightforward. Five subassemblies of mesh panels and space-frame components are assembled. These include the bottom, and parts of each of the four sides. The two corner panels are carefully placed at each corner (see Figure 11.3) on the bottom pan. At this stage the panels lack rigidity and they must be supported. The short-wall subassemblies are then installed followed by the long wall subassemblies. Once assembled the cage is extremely rigid and strong but the components need careful handling and temporary strong backs during assembly. Once assembled it is vital that all the fasteners on the metallic corner brackets be checked to assure that there is no inadvertent electrical contact between the corner brackets and the mesh. Under good conditions, a C-21 cage can be fully assembled by three men in about four hours (see Figure 3.5). These assembly instruction are more fully documented in Type C-21 Fish Cage Assembly Instruction, July 1980, 12 pages.

Table 11.1 FABRICATION SEQUENCE FOR INCRA PROTOTYPE OR C-21 FISH CAGES

1) Cut and drill fiberglass frame parts from C-channel, two sizes.

2) Cut small piece of fiberglass angle for panel corner reinforcement.

3) Using jig assemble and fix fiberglass frame at four corners with screws and epoxy.

4) Trim expanded metal mesh sheets to size.

5) Wrap fiberglass frame with expanded metal mesh sheet.

6) Cut and drill space-frame structurals.

7) Manufacture corner brackets and reinforcements, suspension system components and floats.

8) Package mesh panels carefully, packaging of other components is not critical. Total shipping weight is about 1,150 pounds, not including float collar.

Table 11.2 CAGE SERVICING TASKS

1) Remove fish and any floating debris from cage.

2) Install lifting frames and winches.

3) Lift cage uniformly, using water jet removing fouling and debris from structurals as it rises.

4) Lift cage until bottom is just below waterline. With high pressure water jet flush silt and debris from cage bottom.

5) Lift cage clear of water. Place short wooden beams across corners for safety.

6) Inspect cages for any holes and/or corrosion. Make any repairs that might be necessary.

7) Inspect sacrificial anodes on galvanized fittings, replace if necessary.

8) The cage is now ready to be relowered or towed to new site.

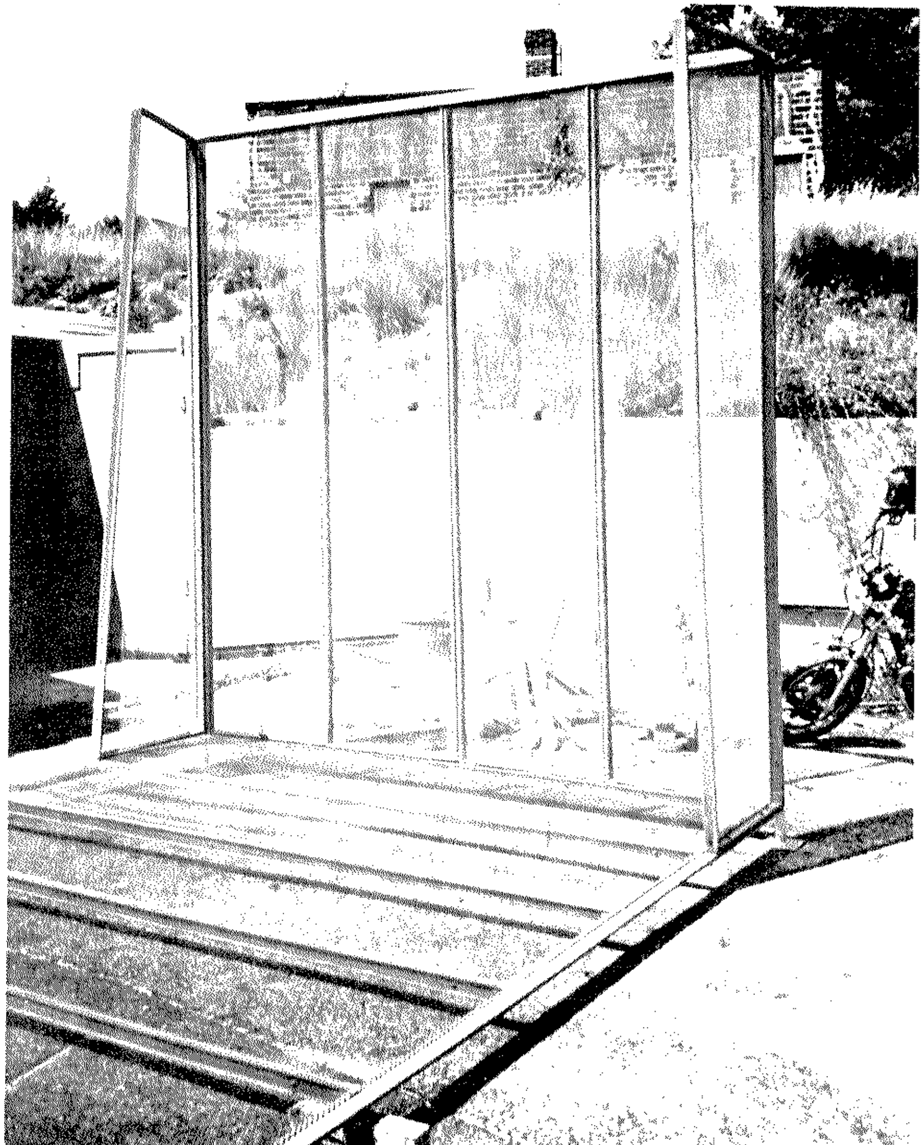


Figure 11.3 Trial assembly of first C-21. Short-side subassembly has been installed between corner panels. Note supporting blocks under bottom pan.

Figure 11.4 An important servicing function is to remove accumulated debris from bottom of cage before lifting the cage clear of the water. Very impressive weights in debris may be involved, and if not periodically removed

11.3 CAGE OPERATIONS AND SERVICING

INCRA cages are rigid cages. While rigid cages are used commercially in Japan and elsewhere, little was known about how to operate and service such cages. As a consequence, the INCRA project had to solve many of the practical questions involved with using these cages. A net cage is harvested by collapsing the bag and concentrating the fish. For the INCRA type cages a crowding device had to be successfully developed, built and tested (see Huguenin and Ansuini, 1980). Likewise a practical means of inspection, repair and servicing had to be developed. This involved the use of lifting frames and winches in each of four corners. In spite of the size and weight of INCRA cages, this lifting system is simple and practical (see Figure 3.3 and Figure 11.4). This method with small changes is expected to work equally well with the larger C-22 and C-23 cages. Additional data on hardware and technique are in Model C-21 Fish Cage Instructions for Use of Lifting Frames, July 1980, 6 pages. A number of servicing functions using lifting frames are listed on Table 11.2. The quickest and most effective cleaning techniques tested is shown on Figure 11.4. It is important to remember that while the mesh has considerable biofouling resistance the fiberglass frame does not, and the mesh has no immunity to drifting debris. In addition, the bottom can under some conditions accumulate very high loads of silt and organic debris which must be periodically removed.

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