Alloys of Copper and Nickel for Splash Zone Sheathing of Marine Structures

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Ex Review Summary for Coppernickel.org

FOREWORD

Two alloys predominate as sheathing for offshore structures namely 65-35 nickel-copper (alloy 400) and 90-10 Cu-Ni. The former has been applied to the legs and risers of offshore structures for the last 50 years whereas the 90-10 Cu-Ni was first used about 20 years ago. The Cu-Ni alloy is particularly attractive for marine structure sheathing because it can provide corrosion protection and at the same time resists the build up of the thick biofouling mass that degrades the performance, structural integrity, and even the safety of the structure. In addition, Cu-Ni alloys reduce maintenance costs by minimizing the need to remove biofouling on a regular basis as well as eliminating the need for periodic reapplication of biofouling-resistant paints and coatings.

CORROSION AND PROTECTION OF STEEL STRUCTURES IN SEA WATER

The intensity of corrosion of an unprotected steel structure in seawater varies markedly with position relative to the mean high and low tide level as shown in **Figure 1**.

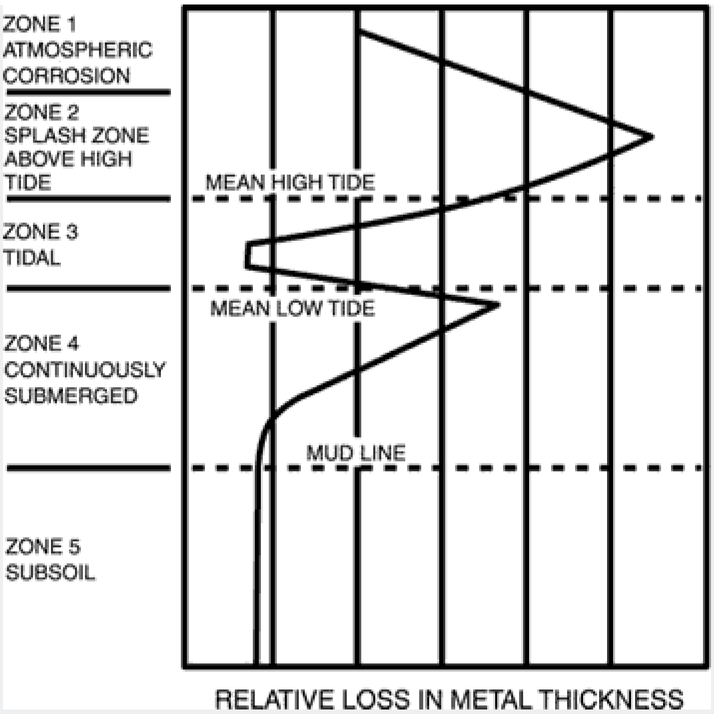

FIGURE 1. Profile of the Thickness Loss Resulting from Corrosion of an Unprotected Steel Structure in Seawater

The spray and splash zone above the mean high tide level is the most severely attacked region due to continuous contact with highly aerated sea water and the erosive effects of spray, waves and tidal actions. Corrosion rates as high as 0.9 mm/y at Cook Inlet, Alaska, and 1.4 mm/y in the Gulf of Mexico have been reported. Cathodic protection in this area is ineffective because of lack of continuous contact with the seawater, the electrolyte, and thus no current flows for much of the time. Corrosion rates of bare steel pilings are often also very high at a position just below mean low tide in a region that is very anodic relative to the tidal zone, due to powerful differential aeration cells which form in the well aerated tidal region.

Protection of a steel structure can be achieved by various means; each corrosion zone must be separately considered. Three generally accepted methods are cathodic protection, painting or coating, and sheathing. Sheathing has proved to be a very successful approach when applied in the region through the splash/spray zone to a short distance below the tidal zone. As early as 1949, 65-35 nickel-copper (Alloy 400) was utilized on an offshore platform in the Gulf of Mexico off the Louisiana coast (1,2) .

EARLY SHEATHED PILING TRIALS

The LaQue Center at Wrightsville Beach, North Carolina, USA, conducted extensive trials of sheathing using the steel piling which support the sea water corrosion test wharves at the laboratory as test specimens. Sheathing or protective materials tested included 65-35 nickel-copper (Alloy 400), 18-8 chromium-nickel AISI Type 304 stainless steel, 70-30 Cu-Ni, and both nickel (Nickel 200)-clad and 65-35 Cu-Ni (Alloy 400) clad on steel. All of these were reported to be performing very well after 39 years of exposure. (3)

A large number of proprietary coatings, including galvanizing and sprayed zinc and aluminum, were also tested; all proved to have finite effective lifetimes extending up to 13 years (4) . The 90-10 Cu-Ni alloy was not included in these early sheathing trials as it was still being developed at that time.

DIRECTLY WELDED SHEATHS-GALVANIC EFFECTS

In the early trials, the 65-35 Cu-Ni (Alloy 400) and the 70-30 Cu-Ni alloy sheaths were welded directly to the steel. It might be assumed that corrosion of the anodic steel below the tidal zone would be accelerated because it is in direct contact with the more noble sheathing alloy. A number of experiments were conducted at the LaQue Center to investigate this possibility (3) . On the contrary, steel below the tidal zone is found to be cathodic relative to the noble alloy sheathing material, since the sheathing alloy, which is 65-35 nickel-copper (Alloy 400) in this case, becomes polarized to the potential of the adjacent steel below. Hence the submerged steel below the sheathed piling corrodes at a lower rate than the submerged steel on an unsheathed bare steel piling because the resulting galvanic current between the sheathed tidal zone and the submerged steel below it is lower.

This conclusion is confirmed by the results of galvanic corrosion tests conducted to determine the effects on submerged steel coupled to other alloys in the tidal zone (4) , as shown in
Figure 2.

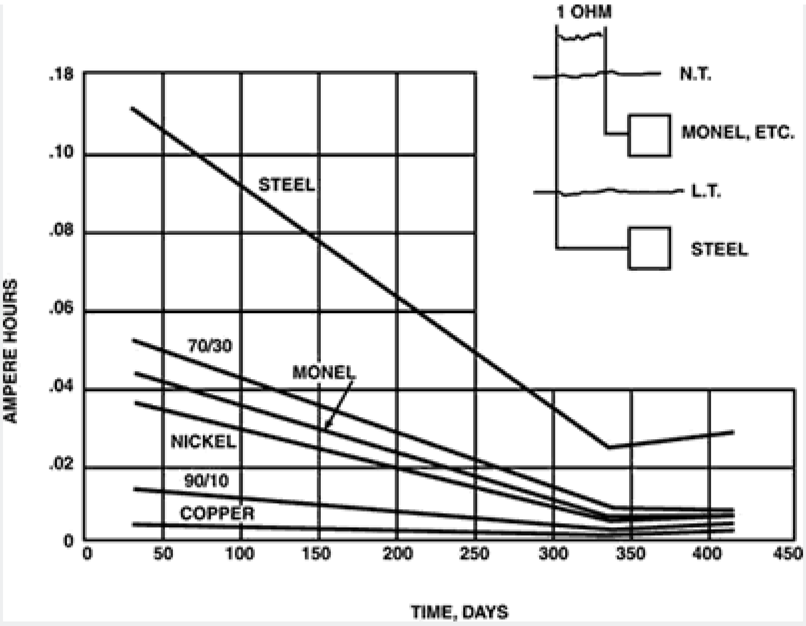

FIGURE 2. Total Current per Tide vs. Time between Plates in a Simulated Piling Test.

Plates of the alloys placed in the tidal zone are coupled to submerged steel plates, and the total current per tide was measured periodically over the 14-months of exposure. Current decreased with time, but the results demonstrated clearly that the most severe galvanic couple is steel to steel. Although the potential difference between the noble alloy-to-steel couples is significantly greater than the potential difference between two steel panels, the rapid and nearly complete polarization of the noble metal results in a lower galvanic current. More recently, the International Copper Research Association (now the International Copper Association) conducted several research programs clarifying and elaborating on these earlier findings (5,6,7) . In summary, steel under water corrodes less when in contact with noble metals in the tidal zone than when coupled to another panel of steel in the tidal zone.

The 90-10 Cu-Ni alloy provides the best combination of corrosion resistance and biofouling protection. Attachment of this sheathing material to the steel structure by welding or mechanical fasteners will result in cathodic polarization of the sheath material and somewhat of a reduction in the antifouling capability of the 90-10 Cu-Ni alloy. Therefore it is necessary to electrically insulate the sheath from the steel jacket members to gain the full advantage of the biofouling resistance properties of the alloy. Electrical insulation can be achieved by pumping cement or an epoxy into the annular space between the component and the sheath or, more simply, by use of an elastomer or rubber-base insulator. The Cu-Ni can be in the form of sheet, wire grid, particles or flame-sprayed coatings. Bonding of the steel-elastomer-Cu-Ni interfaces can be by vulcanizing, by the use of epoxy adhesives, by mechanical means or a combination of methods.

MORE RECENT SHEATHED PILING TESTS

Long term exposure of Cu-Ni sheathed steel pilings, to assess the effectiveness of corrosion and biofouling resistance as well as the cathodic protection systems in several configurations as described below was sponsored by the International Copper Association and the Copper Development Association Inc. and carried out at the LaQue Center in Wrightsville Beach, North Carolina. USA (9,10) . Over 50 ASTM Type A-36 steel pilings 17 cm in diameter were sheathed with 4.6 mm thick x 3 m long 90-10 Cu-Ni. Some Cu-Ni sheaths were directly welded to the steel, others were insulated from the steel with concrete or with 6 mm of a butyl rubber compound. Some piling were cathodically protected with Galvalum III anodes while others remained unprotected. Pilings were removed after two years, five and ten years of exposure in a natural flowing seawater channel for evaluation.

The results of biofouling accumulations on these pilings are summarized in **Table I**.

TABLE 1. BIOFOULING MASS ON 90-10 Cu-Ni SHEATHED STEEL PILINGS AFTER FIVE AND TEN YEARS

Piling	kg/m^2	Percent	Biofouling Organisms
Bare Steel*			
5 years 10 years	18.00 12.00	100.0 100.0	massive barnacles, oysters, etc.
Concrete-Insulated Cu-Ni on Steel			
5 years 10 years	0.36 0.14	1.9 1.2	only scattered barnacles
Cu-Ni Directly Welded to Steel			
5 years 10 years	7.95 4.43	44.3 36.8	moderate barnacles, oysters, etc.
Rubber-Insulated Cu-Ni on Steel			
5 years 10 years**	0.26 0.51	1.4 4.2	scattered barnacles, oysters, etc.
Rubber-Insulated Cu-Ni on Steel w/Galvanic Couple (single point contact)			
5 years 10 years***	4.59 15.39	25.5 37.0	moderate barnacles, oysters, etc.
.** unsheathed - experimental control *.** average value (3 pilings) ****.** average value (2 pilings)			

Organisms observed include barnacles, oysters, codium, tunicate, colonial tunicate, encrusting and filamentious bryozoans but not all were present on all pilings, as shown in **Table 1**. After five years the mass accumulated on the bare steel piling was more than twice as great as that which accumulated on the directly welded 90-10 Cu-Ni piling and more than 50 times higher than the average amount that attached to the concrete and rubber insulated sheathing. Only a few scattered barnacles were seen on the concrete insulated Cu-Ni sheath after five years. After ten years the unsheathed bare steel is still heavily fouled but its fouling mass is somewhat reduced. However, the fouling mass of the rubber insulated pilings shows an increase over time while the concrete insulated pilings show a decrease when the five and ten year results are compared. The variability in fouling mass over time are normal, especially when it is appreciated that this is a field test and therefore not conducted under controlled laboratory conditions. It is reasonable to assume that the two hurricanes that came ashore in the area in 1996 reduced the total accumulation of biofouling on heavily fouled pilings. All the sheathed pilings continue to resist fouling after ten years.

The galvanic anodes used on the cathodically protected piling were cleaned and weighed; mass loss and consumption rates are given in **Table 2**.

TABLE 2. GALVALUM III ANODE WEIGHT LOSS AND CONSUMPTION RATE WHEN COUPLED TO 90-10 Cu-Ni SHEATHED STEEL PILINGS

Piling Type	Weight Loss* grams	Consumption Rate kg/yr
Bare Steel**		
2 years	716.4	0.36
5 years	1880.6	0.36
10 years	2316.1	0.23
Concrete-Insulated Cu-Ni on Steel		
2 years	755.3	0.38
5 years	1256.6	0.25
10 years	181.8	0.04
Cu-Ni Directly Welded to Steel		
2 years	414.1	0.21
5 years	687.6	0.14
10 years	2050.8	0.21

***.** combined weight - two anodes per piling
****.** unsheathed - experimental control

In the two-year exposures, the directly welded piling displayed a lower anode consumption rate than the bare steel; the concrete insulated consumption rate was comparable to that of the bare steel. After five years of exposure, both the directly welded and the concrete insulated pilings displayed reduced consumption rates. After ten years of exposure, the anode consumption rate of the directly welded Cu-Ni on steel pilings returned to the rate initially observed after two years. This variability can be expected as these are field exposures and are not conducted in a laboratory under controlled conditions. The reduction in anode consumption for the directly welded piling is considered to be due to the favorable polarization behavior of the 90-10 Cu-Ni alloy. The reduced anode consumption rate for the concrete insulated piling is attributed to the high resistance path through the concrete to the underlying steel. The overall reduction in anode consumption rates for both sheathing techniques could in part be due to the reduction in current resulting from calcareous film formation on the 90-10 Cu-Ni alloy.

It was also observed that even in the case where the sheathing is directly welded to the steel and exposed without cathodic protection for five years, there was no grossly accelerated attack of the steel immediately above or below the sheath. The average corrosion rates in the steel adjacent to the sheathing below the mean low tide point did not exceed 0.25 mm/y, which is no higher than the corrosion rate of the freely corroding, unsheathed steel control pilings. Of course, exposure of any steel piling without cathodic protection is not recommended.

A second series of experiments were conducted at Kure Beach, North Carolina, USA, at an oceanfront site by the LaQue Center (11) . A total of six pilings were exposed to oceanfront wave action, three on the north side and three on the south side of a fishing pier, slightly offshore from the wave breaker line. Their biofouling mass was measured after ten years and is shown in **Table 3**.

TABLE 3. BIOFOULING MASS ON 90-10 Cu-Ni SHEATHED STEEL PILINGS AFTER TEN YEARS OF EXPOSURE ON THE OCEANFRONT AT KURE BEACH, NORTH CAROLINA, USA

Piling	kg/m^2
Bare Steel (north side)* Bare Steel (south side)*	3.61 2.92
Directly Welded on Steel (north side) Directed Welded on Steel (south side)	2.34 2.34
Concrete Insulated Steel (north side)** Concrete Insulated Steel (south side)	1.56 0.59
.** unsheathed - experimental control *.** partially shorted	

As expected, the bare steel experiment controls had the highest biofouling mass, which was 500% to 600% greater than the value obtained from one of the concrete-insulated pilings (south side). The biofouling mass on the other concrete insulated piling (north side) was two-thirds the average amount accumulated on the directly welded piling. Note that the large accumulation on the concrete insulated piling (north side) was attributed to it being partially electrically shorted and therefore is more representative of a directly welded rather than insulated sheathing. The biofouling mass of the directly welded piling was 65% to 80% of the amount which grew on the bare steel experimental control pilings. However, the fouling on the latter Cu-Ni directly welded-to-steel pilings, was poorly adherent and easily removed.

EXXON ECONOMIC ANALYSIS

The Exxon Production and Research Company carried out a generalized economic evaluation (12) for the International Copper Research Association by means of a computer aided design study of a conventional steel structure as depicted in **Figure 3**.

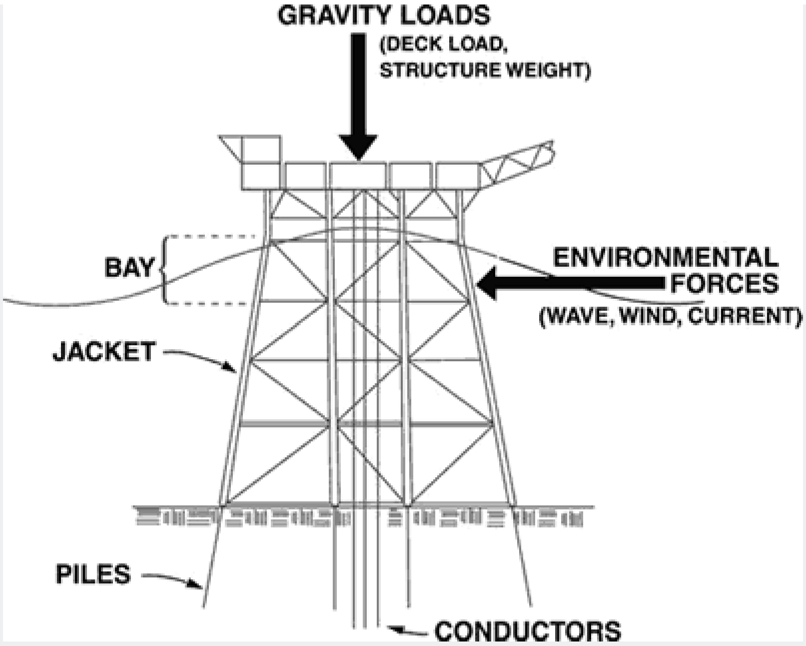

FIGURE 3. Simplified Diagram of Forces Acting on Off-shore Structures

Only insulated Cu-Ni alloy sheathing systems were considered as these gave the full economic benefits by minimizing of both marine fouling and corrosion. Design models were worked out for a range of situations, covering three different water depths, environmental conditions (wind, wave and current) ranging from mild to severe, and marine growth ranging from light to heavy. In all, 29 scenarios were considered. Potential cost savings were calculated based on the savings in weight of installed steel. The cost of the sheathing material and its installation were not included in the analysis, because of variability of the means of attachment and lack of data on these costs.

The gross savings for offshore structures per unit area of sheathing, which factors in all the total steel, fabrication and installation costs, are summarized in **Figure 4**.

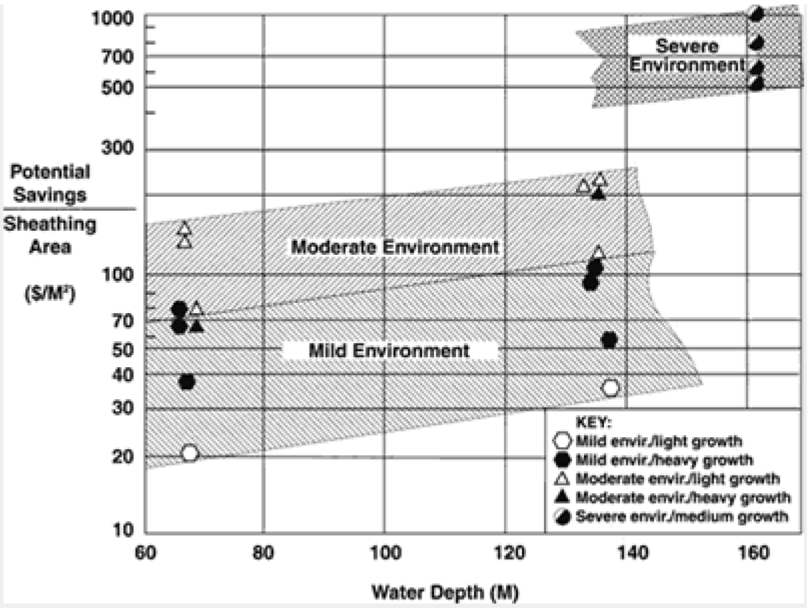

FIGURE 4. Potential Savings per Unit Area of Sheathing for Various Environments and Water Depths

In the mild environment, total weight savings, which is mostly attributable to reduction in steel, ranged from 9 tonnes up to 174 tonnes. For the various cases (depending on the depth of the water and the size and geometry of the off-shore structures), cost savings are up to a maximum of 5% of the total structure cost. In the moderate environment, weight savings ranged from 80 to 404 tons of steel and cost savings of 1.8% to 5.9% of total cost. The corresponding values for the severe environment were weight savings of 732 to 2372 tons of steel and 2.9% to 9.3% in cost savings.

Additional savings from reduced cleaning, maintenance and repair costs, again not included in the Exxon study, can be anticipated.

FIELD EXPERIENCE - CU-NI ALLOY SHEATHING SYSTEMS

British Gas -Morecambe Field, UK.

The structures deployed in Stage One of the Morecambe Field project were sheathed with 90-10 Cu-Ni alloy by welding 4mm thick plate directly to the steel legs over the tidal and splash zones from 2m below low tide level to 13m above. A production platform an accommodation platform, three drilling platforms and a flare stack have been so treated. The main purpose of the sheathing was to provide corrosion protection in the splash zone. The submerged portion of the structure was protected by zinc anodes, which were directly attached to the steel. An economic asessment (13) indicated that the 90-10 Cu-Ni sheathing was more cost effective than either the 65-35 Ni-Cu (alloy 400) or conventional systems using non-metallic coatings, which necessitate increasing the thickness of the steel because of the mandated corrosion allowance for structures.

The certifying authorities required a sacrificial steel corrosion allowance (12mm thickness) in this highly corrosive area when a paint system or neoprene wrap is specified. A sacrificial steel corrosion allowance is not required with the Cu-Ni or nickel copper metal wrap system. The economic justification was based on a platform life of 15 years. All maintenance costs were discounted to net present value at 10%. The costs at that time associated with the painted neoprene and alloy sheathing approaches to protection are summarized in **Table 4**.

TABLE 4. ANALYSIS OF SYSTEM COSTS FOR SEVERAL COATINGS OR SHEATHINGS FOR SPLASH ZONE PROTECTION - System Costs Million Pounds Sterling

	Protective Coating/Sheathing			
	Paint	**Neoprene**	**Alloy 400**	**90-10 Cu-Ni**
Initial Cost - Extra Steel	2.3	2.3	-	-
Protective Material & Labor	0.1	0.3	2.2	0.95
Maintenance	2.4(1)	Cost unknown(2)	0.15(3)	0.15(3)
Extra Weight (tonnes)	660	660	180	180
(1). Repainting 8 years after installation and every 5 years thereafter **(2).** No long-time experience; no large scale repairs assumed in less than 18 years **(3).** Minimum maintenance, confined mainly to accident repair				

and shown, on a relative cost basis, in **Figure 5**.

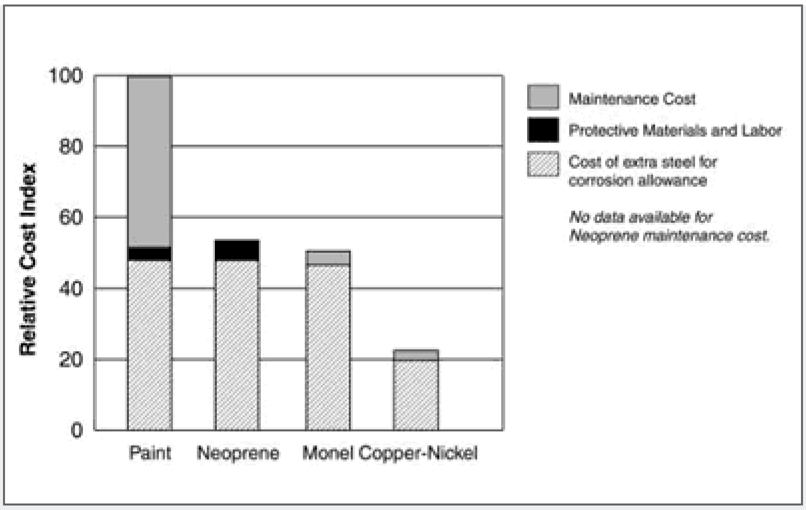

FIGURE 5. Relative System Costs for Protective Sheathing

The advantages of 65-35 nickel-copper (Alloy 400), and even to a greater extent, Cu-Ni sheathing are apparent. For life spans in excess of 15 years, the costs savings and advantages of using the metallic sheathing systems, especially the highly fouling resistant 90-10 Cu-Ni, will be even greater.

The Morecambe Field jackets have been inspected at intervals since initiation of service in 1985. Underwater video records of the condition of the steel and sheathed splash zone regions are available. These show that there is no significant corrosion of the steel or Cu-Ni sheath. As a precautionary measure, the amount of cathodic protection applied was increased significantly by applying some 500 zinc anodes. With the heavy cathodic protection, there is some marine fouling on the Cu-Ni since it is welded directly to the steel, but this fouling is very light compared to the steel below the sheath where heavy mussel fouling and soft hydroid growth ranging from 40 to 90 mm thick is seen. Divers have also commented that the fouling is more loosely attached to the Cu-Ni and easy to remove with a hand scraper.

Shell Beta Site - California.

A proprietary system called "Bio-Shield" (14) developed by the Shell Development Company, has met with considerable success on offshore installations off the coast of California. Biofouling can be quite severe along the southern California coastline with three-year marine growth exceeding 200 mm immediately above to about 12 m below mean sea level. To ensure optimum effectiveness of the Cu-Ni, an insulated system was selected. Bio-Shield consists of 1.6-mm thick 90-10 Cu-Ni sheet and a high-density 12.5 mm thick elastomer, with the trade name of Splashtron made by the Mark Tool Company of Lafayette, Louisiana. After a laboratory test program, this system was applied to the design of the 214-m water depth Eureka platform with 60 well conductors (0.6 m OD). A total of 152 tonnes of structural steel, otherwise required to handle the extra wave, tide and current loading from the marine growth, was eliminated. The platform was installed in July 1984. After several years, the Cu-Ni surface of the Bio-Shield was free of fouling while the unprotected areas were covered with an 8 to 13 cm thick layer of barnacle and mussel growth. This attests to the effectiveness of a fully electrically insulated Cu-Ni sheath. Platform response values were reduced as follows:

- wave forces -6%
- base shear -10%
- overturning moment, -10%
- deck deflection -10%
- pile load -7%

A reduction in platform response values directly translates into cost benefits. Reducing marine growth can clearly reduce platform costs. Money was saved in reduced steel for corrosion allowance and lower fatigue loads in the major platform joints (structural nodes). Estimated savings realized from installing the sheathing system on the 60 conductors from 1.5 m above mean low water line to 4.9 m below mean low tide for the 214 m structure are presented in **Table 5**.

TABLE 5. ESTIMATES OF COST SAVINGS FOR OFFSHORE INSTALLATIONS BY USING A 90-10 Cu-Ni INSULATED SHEATHING SYSTEM

Conductors - 55 tons x $1000/ton	=	$ 55,000
Paint - 10,600 ft.2 x $3/ft ^{2}	=	32,000
Anodes - $1250 each x 4	=	5,000
Structural Nodes - 114 tons x $2500/ton	=	285,000
Total	**=**	**$377,000**

Savings per cleaning were also estimated at $50,000 to $100,000. Installed costs for this system on the Eureka platform were reported to be $250,000 or about $340/m ^{2} ($31.60/ft ^{2}). Clearly, this installation of a Cu-Ni sheath system was very cost effective.

FIELD EXPERIENCE-65-35 NICKEL-COPPER (ALLOY 400)

Field experience for 65-35 nickel-copper (Alloy 400) splash zone protection of legs dates back 50 years and for 30 years for risers.

In 1949, 65-35 nickel-copper (Alloy 400) was first used in the Gulf of Mexico, three miles from the Louisiana coast. Three materials, 65-35 nickel-copper (Alloy 400),65-35 nickel-copper (Alloy 400) clad on steel and unalloyed nickel (Nickel 200) 1.5 mm welded sheathing were examined. All survived after more than five years of battering by boats. In conclusion, all were satisfactory but 65-35 nickel-copper (Alloy 400) was considered the most economic choice. The 90-10 Cu-Ni alloy had not been fully defined at the time of this work and was not included.

Aramco first used 65-35 nickel-copper (Alloy 400) in the Arabian Gulf for legs and risers in the late 1950s, as reported by Hopkins (15) .

BP experienced splash zone corrosion in 1967 in the Middle East. Prior to that, risers were coated with coal tar epoxy, then clad with concrete. A concrete coating on a riser was damaged in Umm Shaif field due to a boat collision and the coal tar peeled off under gravity. In six months the riser wall was corroded through. Oil escaped and ignited burning down the entire platform. BP then put 65-35 nickel-copper (Alloy 400) sheathing on 49 risers in the Gulf at 3 mm thickness. BP continued this practice when they began operations in the Forties Field in the North Sea in 1974. This has continued to the present day although neoprene is also now being used.

Phillips started to use 65-35 nickel-copper (Alloy 400) on risers following an explosion on 2-4 Alpha platform in Ekofisk in 1975. Again a concrete coated riser 10 in dia. was damaged but the underlying bitumen was still intact. Severe crevice corrosion occurred and corroded 7 mm of the 10 mm thick wall in two months at 90C. The riser carrying gas fractured resulting in a massive escape of oil and gas. Phillips took action to remove all the remaining risers, and sheathed them with 5 mm thick 65-35 nickel-copper (Alloy 400) over a 25-m height span.

In 1979, at salty Lake Maracaibo in Venezuela, a riser externally coated with neoprene rubber failed due to poor application and embrittlement after four years service at 100C. A spiral defect allowed the water to reach the surface, resulting in crevice corrosion and 7 mm in corrosion penetration, which subsequently led to an explosion. Again 65-35 nickel-copper (Alloy 400) was introduced for temperatures greater than 70C.

The feedback about the performance of 65-35 nickel-copper (Alloy 400) in splash zone applications over the last 50 years has been excellent. Corrosion rates are minimal, the alloy is found to withstand sizeable impacts and tearing and the initially anticipated galvanic problems have not been realized in practice.

The authors are only aware of one type of problem area occurring in the North Sea since the 1970s. From 1987 to 1990, four failures occurred in BP 20 in risers on Forties field. A cofferdam was put around the risers to facilitate removal. The divers noted a pressure release when they removed the sheathing and hydrogen gas was detected. Destructive testing failed to find any evidence of hydrogen embrittlement. Failure had occurred at the over-stressed fillet weld at the longitudinal seam due to the pressure build-up of hydrogen between the riser and the sheathing. Hydrogen had diffused through the riser causing a pressure buildup of 2000 to 3000 kilopascals (KPa) and it was at such a high level that it caused mechanical damage of the sheathing. Wave action also introduced a fatigue element. The hydrogen was produced by internal corrosion of the riser due to poor inhibition of the wet oil and was later rectified.

Several projects in S.E. Asia have selected 65-35 nickel-copper (Alloy 400) metallurgically clad pipe for hot risers; a selection are shown in **Table 6**.

TABLE 6. S.E. ASIA PROJECTS UTILIZING 65-35 Nickel-Copper (ALLOY 400) CLAD PIPE FOR HOT RISERS

Company	Project	Materials	Diameter	Thickness	Length	Tonnage
Sarawak Shell Burhad	MLNG DUA II	API X52 plus Alloy 400 cladding	998 mm	35.75 mm	70 m	60
Sarawak Shell Burhad	Bardegg	API X60 plus ASTM B127 UNS N04400	254 mm (10 in)	9.6 + 3 mm	18.3 m	11
			305 mm (12 in)	9.6 + 3 mm	18.3 m	
			470 mm (18.5 in)	9.6 + 3 mm	18.3 m	
Esso Production Malaysia Inc.	Gud and Lawit JEA07 and TAP 35 projects	API X65 plus ASTM B127 UNS N04400		9.6 + 4 mm	15.8 m	6
				12.7 + 4 mm	13.9 m	
Esso Production Malaysia Inc.	Lawit A	API X65 plus ASTM B127 UNS N04400	760 mm (30 in)	28 + 4 mm	14.3 m	9
Esso Production Malaysia Inc.	Seligi D to C	API X65 plus ASTM B127 UNS N04400	152 mm (6 in)	9.6 + 4 mm	16 m	2
Sarawak Shell Burhad	Kinabalu	API X60 plus ASTM B127 UNS N04400	203 mm (8 in)	9.5 + 2 mm	12.2 m	7
			305 mm (12 in)	9.5 + 2 mm	12.2 m	
			356 mm (14 in)	9.5 + 2 mm	12.2 m	
Esso Production Malaysia Inc.	Tapis	API X65 plus ASTM B127 UNS N04400	610 mm (24 in)	22.2 + 2.5 mm	12 m	5

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OTHER SHEATHING & COATING SYSTEMS

Thermal-Sprayed Cu-Ni

A study conducted by Perkins and Marsh (16) at Lockheed in California demonstrated that it is technically feasible to arc-spray offshore structures with either copper or 90-10 Cu-Ni. The process can be used to sheath complex shapes including nodes and welds that cannot be sheathed readily with sheet material. Free standing forms of either copper or 90-10 Cu-Ni that replicate a contoured surface can also be arc-sprayed. Both arc-sprayed copper and 90-10 Cu-Ni exhibited parabolic corrosion kinetics in seawater and both showed good resistance to biofouling during a 413-day exposure in San Diego harbor. These initial results show promise but additional experience is needed. Most importantly, the arc-sprayed coating allow non-destructive inspection of the underlying steel for fatigue cracks.

Adhesive Bonded Cu-Ni

An adhesively bonded Cu-Ni system has been used in the sheathing of pleasure boats. Wood, GRP and steel hulls have been so treated. There is no experience to date with this system on offshore structures, but it should be equally applicable there. The product consists of a 90-10 Cu-Ni (C70600) foil, 0.15 to 0.25 mm in thickness, where the thickness used depends upon on the intended application. The foil is coated on one side with a thick mastic protected with a strippable backing paper. Thicker mastic layers are used for special purposes such as applying to old and pitted steel substrate after cleaning. This mastic has high electrical resistivity and very effectively insulates the Cu-Ni from the steel ship hull or jacket member. It also allows some movement between the sheath and the steel and accommodates differences in thermal expansion characteristics. The mastic-coated foil is applied to the steel or other substrate with heat and some pressure. Two small ferries operating from Auckland harbour, New Zealand, both with GRP hulls, were sheathed in this system in 1993 and 1994 . The sheathing was evaluated during a 5 year inspection programme (17) . The results were very favourable showing the sheathing to be very durable with good corrosion resistance and reduced fouling.

Cu-Ni/Resin Composite Systems

One approach to providing biofouling resistance (18,19) uses 1 mm lengths of up to 1 mm diameter chopped Cu-Ni wire, which is embedded in neoprene. This product, has now been used for more than a decade. It consists of a mono-layer of Cu-Ni chopped wire embedded in and bonded to a 3 mm neoprene sheet. The chopped wire is uniformly distributed over the surface to give a Cu-Ni exposure area in excess of 30%. This composite can then be either hot bonded onto an elastomeric corrosion coating or cold bonded directly onto the steel piling.

Finally, a new coating system comprised of a Cu-Ni alloy applied by thermal spray to a high solid epoxy coating has been developed for antifouling application. The process, known as COPPERLOK, is applicable to fiberglass, concrete, wood and steel (20) . In the case of steel surface, the bond coat provides the necessary dielectric insulation. Good adhesion of the thermally sprayed copper is achieved by implanted hollow microspheres in the resin bond coat. These are fractured to create anchor sites for the 90-10 Cu-Ni alloy.

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