SEA-WATER COOLING SYSTEMS IN H.M. SHIPS

RECENT DEVELOPMENTS IN DESIGN AND CONSTRUCTION

BY

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This Paper outlines the various troubles encountered in certain current sea-water cooling systems from the materials aspect and, in particular, the problems associated with the necessary adoption of new, higher strength and more durable materials, as well as the processes, Arising from the latter, a new philosophy in cooling water systems has been evolved. The Paper was first presented by the, Author at the Third International Corrosion Conference held in London in April 1969.

Introduction

The subject under consideration has engaged the attention of so many notable investigators and authorities, and so much has been written and published, that it is extremely difficult to make a valuable contribution. However, from special studies and developments conducted by MOD(N) on newly available materials, processes and design aspects, consequent upon various troubles and ever more stringent performance requirements, some novel and unique results have been forthcoming.

It will be relevant, therefore, to outline some of the more serious troubles and problems encountered before describing their means of resolution.

Utilization and Performance of Aluminium Bronzes

With the appearance of the aluminium bronzes, showing, initially, such great promise, a general change to this class of material for sea-water services in H.M. ships was made in the middle to late 50's. While no serious troubles occurred in the period immediately following, it is pertinent to note that the areas of application were not considered to be critical as regards safety, and, therefore, the standards of acceptance of components, particularly those in the form of castings, were most crude, to say the least.

The advent of the nuclear submarine, however, brought with it a vastly changed philosophy on the inspection of components. None were more vital than those found in the sea-water cooling systems, since, not only were they subjected to full diving pressure, but also to a stress pattern akin to high-strain, low-cycle corrosion fatigue. Hence, all forms of non-destructive test aids, such as radiography, ultrasonics and dye penetrants, were introduced, with stringent acceptance standards, in order to ensure utmost integrity. In addition, selected whole components were subjected to destruction tests.

It was at this juncture that the castability of the aluminium bronzes was found to leave much to be desired, despite their favourable solidification characteristics. Their ready oxide-forming trait demanded great care in arranging pouring, running, gating and feeding arrangements, and these were not always ideally possible in large complicated castings.

More disturbing still, however, was the absence of techniques to effect satisfactory weld repairs to these early alloys in view of metallurgical phase changes consequent upon heat and temperature differentials.

FIG. 1(*a*)—DETERIORATION OF SEA-WATER VALVE BY DE-ALUMINIFICATION

Introduction of other types of aluminium bronze, notably that of the nickel-bearing variety, has alleviated the position somewhat as regards weldability. While weldments can now be effected using filler metal of like composition to that of the parent, this was not possible until comparatively recently. Originally 'through-thickness' weld repairs had to be made, using straight 90 Cu/10-Al electrodes and the metallic-arc process up to, but not including the final layers that would be in contact with sea water. Only these, then, were laid down using the parent-composition filler. Experience proved generally that the Tungsten Inert Gas (TIG) process should be avoided where thick sections were involved, in view of high heat inputs associated with it thereby resulting in severe local Heat Affected Zone (HAZ) cracking.

While the castability characteristics of this alloy were not significantly better, nevertheless, with the fullest co-operation of the founder, designer and laboratory, much improvement in the quality of castings has been obtained. However, despite this, the Navy Department are still afflicted with unsoundness in the larger, thick-sectioned components.

In an attempt to overcome this situation, having still in mind the supreme integrity of units subjected to deep-diving pressures, weld-fabricated 'composites' of simple castings, forgings and pressings in nickel-bearing aluminium bronze were investigated but too many unknowns were presented, particularly in connection with corrosion-fatigue strength characteristics. (Subsequent work on these aspects is described later.)

Investigation of various heat treatments, with the object of eliminating residual stresses and improving properties, was also found to be of no avail, since, in general, where corrosion resistance was improved, ductility was impaired.

It should be emphasized, however, that 'composite-cast/wrought' weld-fabricated structures, *as a basic principle* are very much favoured, as will be seen later.

De-Aluminification of Specific Aluminium Bronzes

Components which found their way into service, handling flowing sea water, and manufactured from aluminium bronzes containing nil or only up to some 1 per cent nickel, and aluminium content in excess of 9·5 per cent have been found to suffer deterioration amounting to almost complete de-naturing of the material. The effects are characterized by the removal of the aluminium, leaving re-deposited copper in a rough spongy mass, and hence the term 'de-aluminification' that has been applied to the phenomenon.

The mechanism is considered to be the selective leaching-out of the aluminium via the poor corrosion-resistant continuous gamma 2 phase (formed by

FIG. 1(*b*)—DETERIORATION OF SEA-WATER VALVE BY DE-ALUMINIFICATION

differential cooling following imposition of heat in processes associated with manufacture and repairs by welding) when subjected to flowing sea-water. Where, of course, an alloy with discontinuous gamma 2 can be guaranteed, this action does not occur, but it is exceedingly difficult to ensure this wholly in practice.

The appearance is typified by the 5-inch isolating valve shown in FIGS. 1(*a*) and (*b*), the condition being attained in some ten weeks of service only.

Other forms of aluminium bronze containing some 5 per cent Ni, 5 per cent Fe and a restrictive maximum of 10 per cent aluminium (covered by DGS Specifications 8520 and 8452, for the cast and wrought forms respectively), have given better performance, provided no heat treatments have been imposed whereby some beta-phase has been retained. This latter also displays poor resistance to selective corrosion in flowing sea water. However, it is reasonably unlikely to be formed in the normal heat processes imposed.

Additionally, experience with 'straight' (non-nickel-bearing) aluminium bronze, in the form of tube plates for heat exchangers and condensers (the variety known as A.S.T.M.-B171-Alloy D) has been an unhappy one, all too frequently displaying erosion attack and de-aluminification. FIG. 2 shows a typical case. Where sizes of units were substantial, a recourse was made to cathodic protection with zinc alloy anodes and the attack generally arrested.

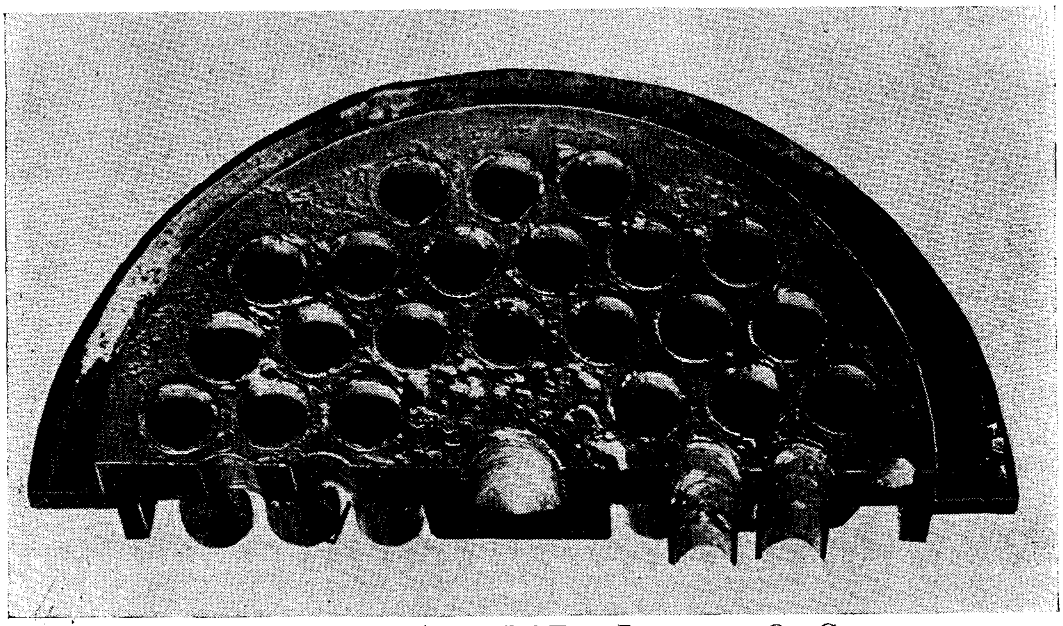

FIG. 2—EROSION OF ALLOY 'D' TUBE PLATE FROM OIL COOLER

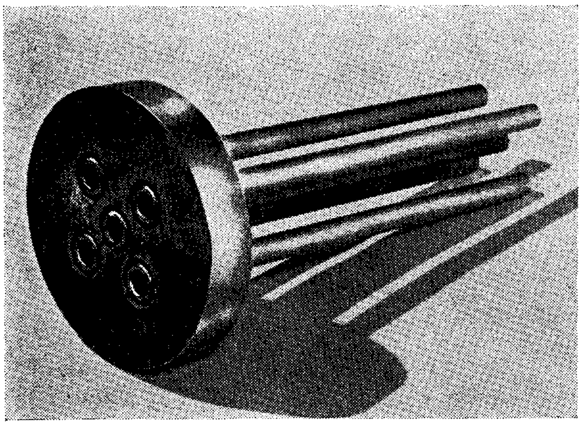

FIG. 3(*a*)—T.I.G. FUSION-WELDED 70/30 CU-NI TUBE IN 70/30 CU-NI TUBE PLATE

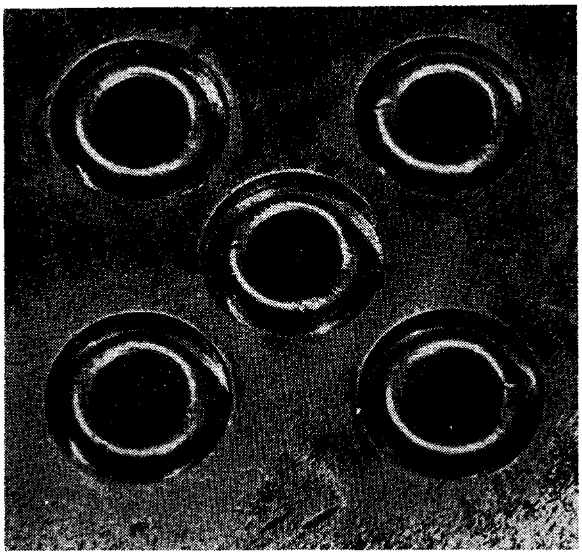

FIG. 3(*b*)—T.I.G. FUSION-WELDED 70/30 CU-NI TUBE IN 70/30 CU-NI TUBE PLATE

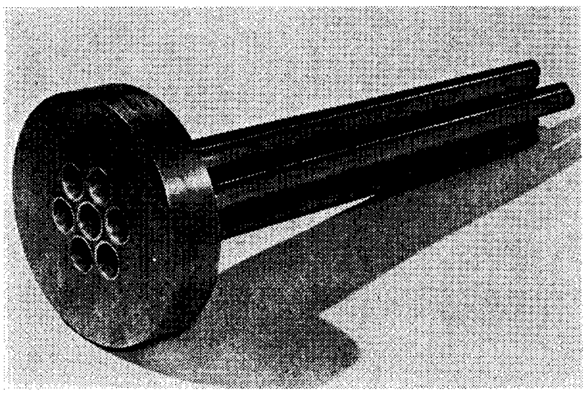

FIG. 4(*a*)—EXPLOSIVELY-WELDED 70/30 CU-NI TUBE IN 70/30 CU-NI TUBE PLATE

To adopt such a course is, however, a considerable reversion, observing the policy to abolish all steel corrosion pieces in similar positions.

The immediate action was to change, on a temporary transitory basis only, to the complex 5 per cent nickel-bearing type, and a number of tube plates, including a comparatively large one for a turbo generator, were manufactured and found their way into service. However, other evidence whereby the resistance of this material to crevice attack was suspect, caused a deep re-appraisal.

As a result, an overall policy decision was made to adopt 70/30 cupro-nickel (+ Fe), as the standard tube-plate material, where contact with sea water was involved. This is, of course, the standard tube alloy and hence, tube and tube plate will be of equi-potential. The merits and demerits of the alloy for this application are discussed in a later section, but it is convenient to mention here that extensive trials are in hand at the AML connected with another move to improve heat exchanger design and construction, namely, that of fusion welded and explosive welded tube-to-tube-plate connections. Assemblies of both types have been made (see FIGS. 3 and 4) and are even now under high-velocity flow tests, so far without sign of deterioration. It was with this ultimate end in view, that hopes were held, from an early period, to utilize the material eventually for tube plates, but, from the above considerations, the decision had to be made earlier.

In the course of initial consideration of the design of nickel-aluminium bronze headers for the main condensers of a deep-diving submarine, the basis of which had to be on 'high strain—low cycle' corrosion fatigue principles, the discovery was made that relevant data for this material was non-existent, to a world-wide extent. In consequence, an extensive crash

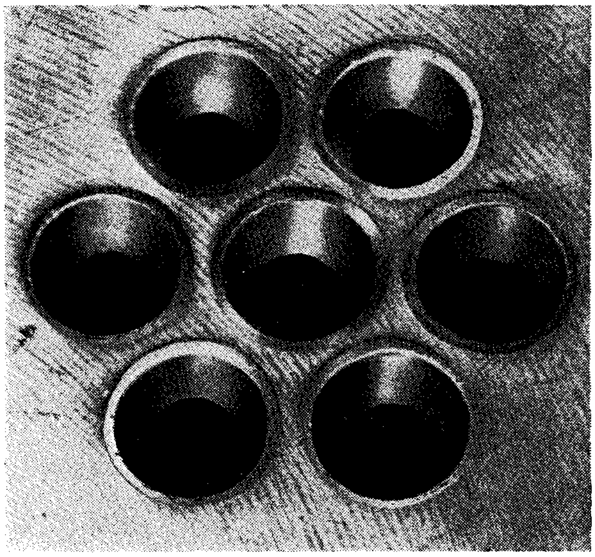

FIG. 4(*b*)—EXPLOSIVELY-WELDED 70/30 CU-NI TUBE in 70/30 CU-NI TUBE PLATE

programme was mounted at the Central Dockyard Laboratory, the British Non-Ferrous Metals Research Association, the English Electric Company, and the British Welding Institute, to obtain this information.

The tests comprised the flexing of cantilever plate-type specimens of nickel aluminium bronze through alternating cycles of prescribed strains (i.e., ranging from 0·4 to 1·0 per cent), the frequencies of which were eventually standardized at two rates, namely, one cycle per hour, and *ten* cycles per hour, and immersed, of course, in sea water. The specimens included plain, notched and welded forms. In addition, cast cylinders were pulse-pressure tested using sea water, at a rate of 600 cycles per hour to provide the multi-stress aspect. It would have been desirable, of course, to have used the same rates as in the plane-strain tests, but availability of machines and specimens precluded this, and it was hoped that a correlation test would be undertaken.

Results to date are shown in FIG. 5, where the curves are mean paths through a considerable scatter. This is thought to be related to micro-structure rather than variations in chemical composition.

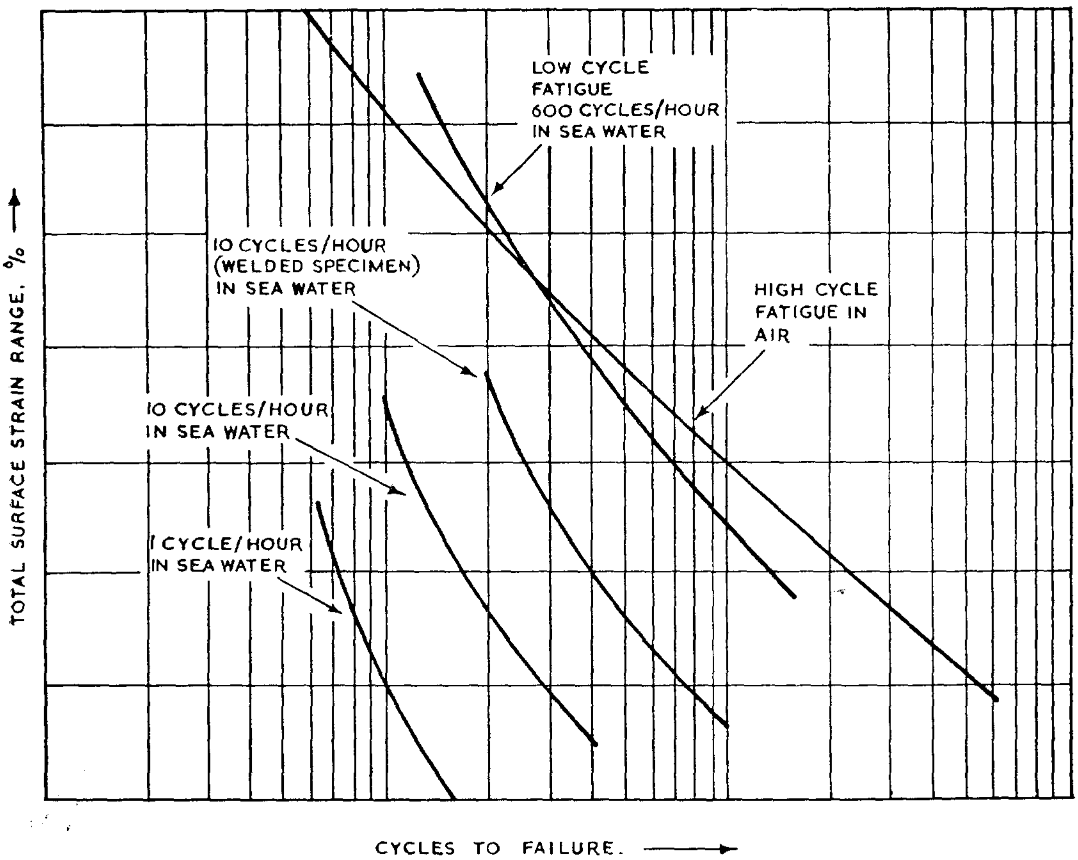

FIG. 5—RESULTS OF 'HIGH STRAIN—LOW CYCLE' CORROSION FATIGUE TESTS ON CAST NI-ALUMINIUM BRONZE

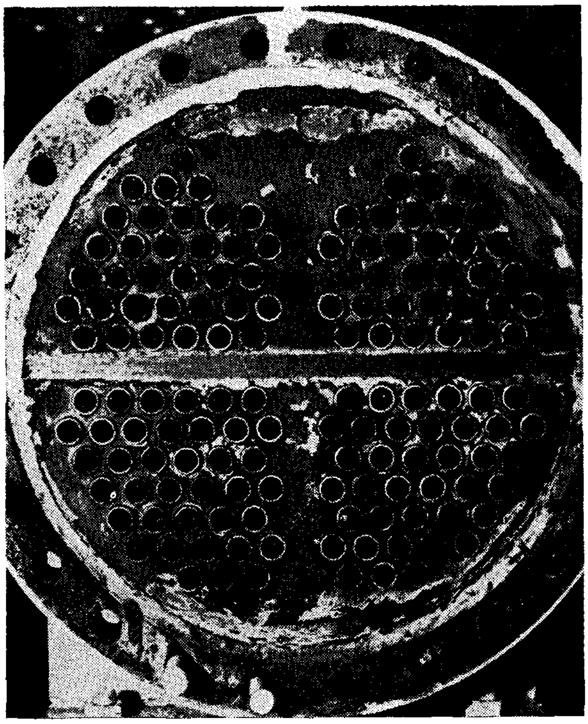

FIG. 6—EROSION OF IRON-FREE 90/10 CUPRO-NI TUBE PLATE OF AIR-CONDITIONING PLANT HEAT EXCHANGER

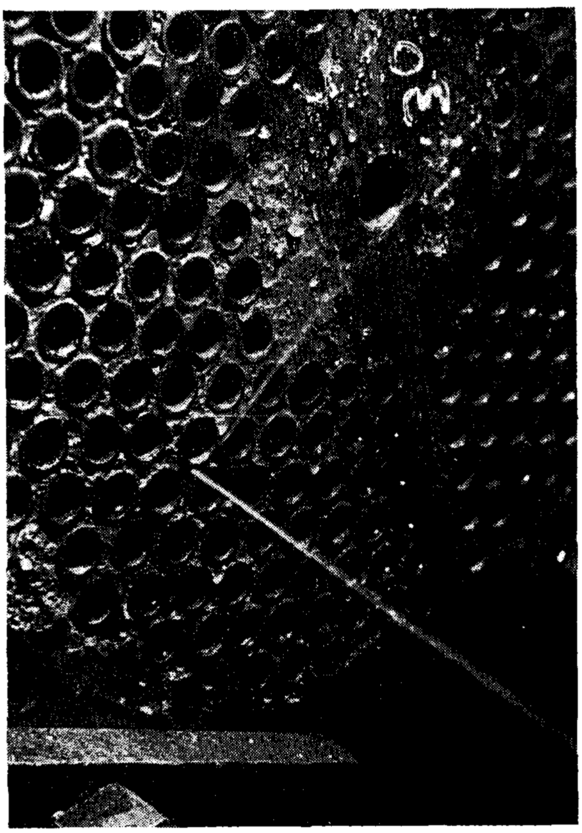

FIG. 7—EROSION OF IRON-FREE 80/20 CUPRO-NI TUBE PLATE OF OIL COOLER—WATER LEAKS DURING TEST

It will be observed that 'cycling-rate' is significant, the fatigue 'life' being lowered as the 'rate' is lowered. Of course, under such circumstances the specimen is in contact with the corrosive medium for a longer period at the lower levels, but it is nevertheless surprising that material of such high corrosion resistance as nickel-aluminium bronze should display this phenomenon.

Other interesting features are the relatively good performance of the welded specimen, and the reasonable coincidence between 600 cph low cycle 'in sea water' rate with high cycle fatigue in air.

Influence of Iron in Cupro-Nickel Alloys

A number of instances have been met in H.M. ships within the last year or so, whereby the vital part played by iron additions to cupro-nickel alloys in resisting erosion in flowing sea water, has been highlighted. In one case, due to the overriding necessity to utilize commercial air-conditioning units, tube-plates in 90/10 Cupro-Ni, *without iron* found their way into service, with the most disastrous results. The condition of the plates after only two months' service is shown in FIG. 6, from which the serious loss of metal will be readily seen. These particular units were fitted in the lower compartments of aircraft carriers and their removal presented a considerable problem, as will be appreciated.

In yet further applications of auxiliary coolers in the nuclear submarines, tube-plate material of 80/20 Cupro-Ni, *without iron*, was used, again with disastrous results, see FIG. 7. The leakage of water during test indicates the severity of the wastage. While dealing with this case, it will be of interest to report that, without authorization, the firm attempted to produce some replace tube-

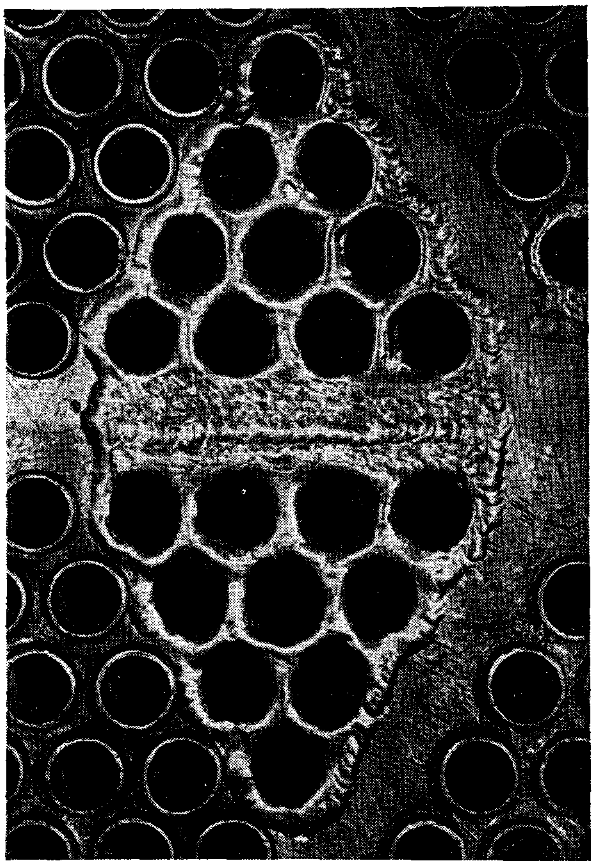

FIG. 8—WELD DEPOSITION OF 70/30 CU-NI (+FE) ON TO IRON-FREE 90/10 CUPRO-NI

plates, *with iron additions*, but in the form of castings, since no supplier of the wrought product could be found. The result was that, invariably, micro porosity caused leakage in such a high proportion of castings that it was quite uneconomical to pursue.

While demonstrating so convincingly, therefore, the vital need for a finite iron content in the cupro-nickels, an investigation was conducted to establish the desirable optimum levels in the different alloys, and it was found that the following were currently accepted:

(*a*) With 70/30 Cu Ni.......... Iron should be 0·8 per cent

(*b*) With 80/20 Cu Ni.......... Iron should be 1·2 per cent

(*c*) With 90/10 Cu Ni.......... Iron should be 1·8 per cent

(*d*) With 95/5 Cu Ni.......... Iron should be 1·2 per cent

The basis on which these figures were postulated was, 'adequate resistance to erosion and impingement in flowing sea-water, without reduction in crevice corrosion and pitting resistance, to any serious extent, which is the general trend'. This matter is discussed by Gilbert, (Ref. 1), following earlier work by Bailey.

As will be seen later, some doubts are cast on the validity of these being the upper acceptable limits, from other considerations, but where no other influences disturb achievement of the levels shown, then these should be worked to.

Although considered essential in minimal quantities, recent work has indicated that the influence of manganese in the 70/30 alloy, to resist impingement, is not of great significance.

Before concluding this section, it may be of interest to outline the method adopted to reclaim the tube plates of the large heat exchangers fitted in the carrier air-conditioning plants, since they could not be removed as whole units without considerable mutilation of ship's structure. A successful procedure was developed whereby a weld-deposit of 70/30 Cupro-Ni (+ Fe) was laid down on the iron-free 90/10 alloy actually in the ship and this has given such satisfactory service that it is now an approved process in such cases. The appearance of the coating in the course of deposition is shown in FIG. 8.

Development of 70/30 Cupro-Nickel (+ Fe) Cladding of Steel

In consequence of the overriding need to ensure the utmost integrity of submarine sea-water systems subjected to heavy cyclic strains, and the grave

FIG. 9—COPPER INFUSION DOWN GRAIN BOUNDARIES OF STEEL BASE MATERIAL WITH CUPRO-NI DEPOSITED DIRECTLY

doubts attached to the more conventional materials, as indicated above, thoughts turned to the use of fabricated steel for components such as condenser headers, piping, etc., recognizing, of course, the absolute requirement for adequate protection against the ravages of fast-flowing sea water.

For a period, the application of rubber sheeting to the wetted surfaces was pursued, on the score that the main problem would be connected with adhesion. The timely availability of details of experience and performance with a similar application in H.M.S. *Vanguard* indicated that no difficulties should arise in this respect, but that after a period of service a myriad micro-cracks could develop in the rubber. This would be signified by the appearance of rust marks from the corroding steel beneath.

Thoughts then turned to the adaptation of the new-found technology developed for nuclear applications where it was necessary to utilize metallic cladding processes on an extensive scale. Taking advantage of the existence of machines at Messrs Babcock and Wilcox Ltd. for weld-deposition of stainless steel on plates, and internally on pipes, trials were initiated using reels of 70/30 Cupro-Ni (+ Fe) filler wire instead, and suitably adjusted welding parameters, feed characteristics, etc. to achieve a satisfactory heat input. The base material was a 2 ft square, 6 in. thick rigid carbon steel plate and the filler, 1/16 in. dia. wire of nominal composition 69 per cent Cu, 30 per cent Ni, 1 per cent Fe. This was deposited *directly* on the steel using a Metal-arc Inert Gas (MIG) welding head.

Visual appearance of the product was good, and specimens cut from the plate gave highly satisfactory mechanical test results, particularly the 'top', 'bottom' and 'side' bends. However, it was not until a metallographic survey was instituted that 'copper-infusion' along the grain boundaries of the steel at the interface, as shown in FIG. 9, was detected. Obviously the process had not adversely affected the straight mechanical properties and, therefore, could well be adopted for statically-loaded structures, but, where 'fatigue'-loading was involved, as in the case of the submarine headers under consideration, the copper-incursion was ruled to be unacceptable.

Effort was therefore directed to the prevention of this occurrence, and early successes attended the deposition of a buffer layer of monel metal. However, further troubles were encountered when the layer of Cupro-Ni was laid down, in the form of fine vertical cracks along the centre line of the monel layer.

Eventually, experimentation came round to the adoption of commercially pure nickel for the intermediate layer, and this proved to be eminently satisfactory. Some minor troubles later on were quickly diagnosed to the presence of the nickel oxide, following the deposition of this layer, and, in another, to sulphur contamination from manufacturing lubricants. It is now stipulated that the nickel oxide layer is removed prior to Cu Ni deposition, and also for the filler wire to be pickled.

In the experimentation, variations of welding techniques were also adopted, and, finally the pulsed-arc process was adjudged the most suitable in view of the metal transfer being of the 'spray' type and with the minimum of heat input.

Steep angling of the wire feed, such that impingement occurred more on the last Cupro-Ni layer was found to be of considerable benefit from the point of view of minimal penetration depth.

As will have been observed, the initial work had proceeded with the deposit filler in the form of wire, and it had been quickly realized that this process was highly time-consuming. An alternative method based on wide-ribbon as developed by Babcock and Wilcox for stainless steel, was explored. This, of course, utilized the submerged-arc process, and consequently required a flux. After much investigation and trials, the most suitable were found to be of the 'fused-acid' type, predominantly SiO_2–MnO-CaF_2, and are designated E.S.A.B. OK. 4D for the nickel, and Muraflux A for the Cupro-Ni. It should be emphasized that this was not to supplant the MIG wire process entirely since the latter was essential for the internal coating of pipes, but to apply to large-size plates prior to formulation into various shapes.

The initial attempts were accompanied by various troubles including inexplicable occasional cracking of the nickel layer, which was orientated in the opposite direction to that expected, and thus could not be due to stress or contraction effects. Purely as a precaution, as in the case of the wire versions, the ribbon manufacturer was requested to ensure as complete absence of sulphur as possible, and finally, for it to be pickled. This seemingly overcame the trouble and further instances have been rare.

This, then, allowed completion of process evaluation, but, whereas most of the practical application problems had been resolved satisfactorily, another worrying situation came to the fore, namely, the amount of 'iron dilution' occurring in the processes, and thus finding its way into the Cupro-Ni layers.

As will be appreciated from earlier considerations, an iron increase to substantially more than the accepted optimum levels currently in practice, (i.e., 0·8 per cent for 70/30 Cupro-Ni) could be of serious consequence and, in actual fact, it *was* found that they tended to be so. In general, a gradation occurred from the interface to the outer surface, typical values of which are given in TABLE I.

TABLE I—*Iron Contents in Nickel–and Cupro-Ni Cladding*

	Iron Content (Percentage)	
	With Wire Filler	*With Strip Filler*
Nickel Buffer Layer	10·0/12·0	11·0/15·0
Cupro-Nickel 1st Layer	1·0/2·0	4·0/5·0
Cupro-Nickel 2nd Layer	0·8/1·1	1·25/1·5

It will be seen, therefore, that, to bring the iron content down to the present acceptable limit, requires a two-layer application of cupro-nickel, and for current components under construction this is being done. However, from consideration of cost, weight and time-consumption, it would be preferable to limit the coating to one layer, and to this end an investigation is being undertaken at CDL on the influence of much increased iron content on corrosion resistance. Already, it would appear that an order of 3 per cent displays no undue deleterious effect, and thus tests are being extended to 6 per cent and above.

Hence, with this as background, it was decided to first proceed with the design and manufacture of a facsimile condenser header, to establish formulating

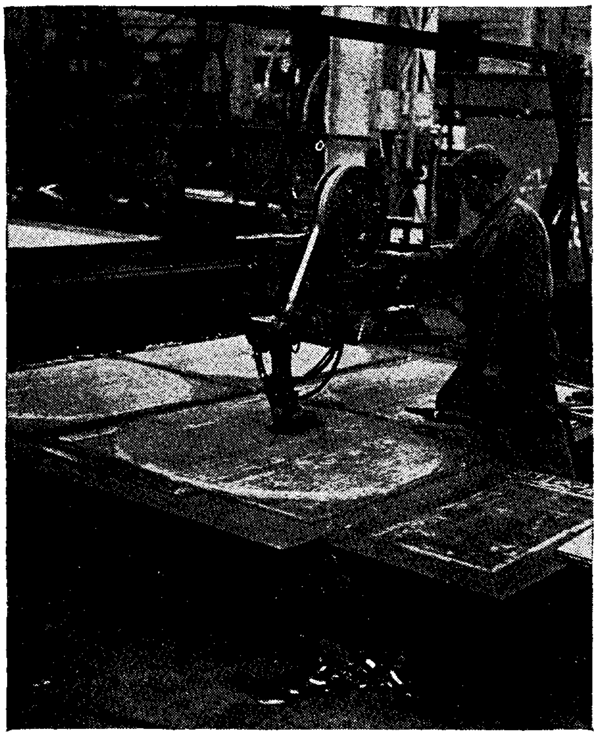

FIG. 10—FLAT STEEL PLATES BEING CLAD WITH 70/30 CUPRO-NI BY SUBMERGED-ARC 'STRIP' PROCESS

processes such as pressing, bending, etc. and eventual fabrication, prior to the construction of a full-size main ship's header. Circumstances have caused both projects to overlap, however, and both are now well advanced. It is the intention for them to be subjected to substantial 'high strain–low cycle' pulsating fatigue tests in shore rigs.

In addition, since it is necessary to have water services to such headers, it was decided to undertake the lining, with Cupro-Ni, of three steel pipes, one of 10 in. bore, 10 ft long, another 8 in. bore, 6ft long, and a third, 6 in. bore, 6 ft long, the latter with butt-welded flanges. The first was to establish feasibility of treating such a size, following which bending trials were to be undertaken. The second was to be subjected to weld-fabrication tests, and the third, for inclusion in the Bincleaves high-velocity sea-water flow rig.

Yet another component to be manufactured was a ships-side sea tube, for ducting cooling water into systems, and designed to be fitted in a vessel. (Hitherto these were made of carbon steel and had extremely short lives.)

Interesting features in the construction of these components are demonstrated in FIGS. 10, 11 and 12. The first shows flat plates being clad by the

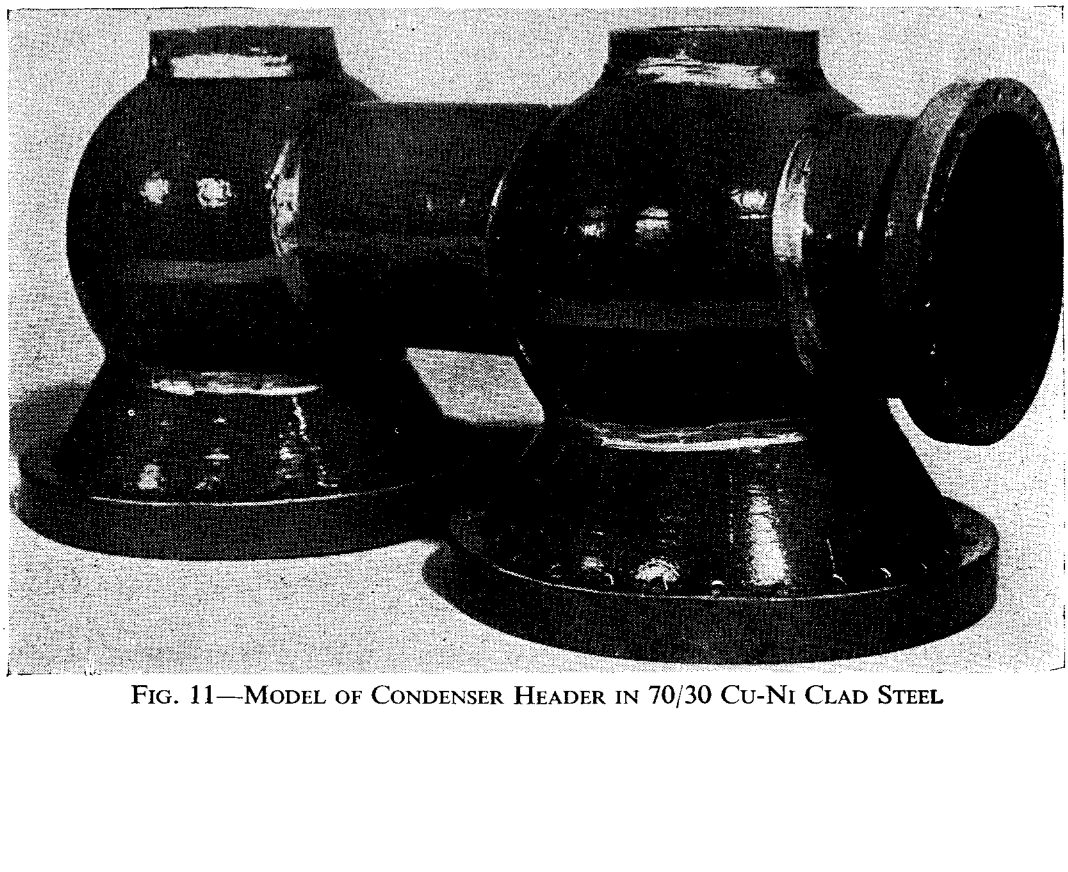

FIG. 11—MODEL OF CONDENSER HEADER IN 70/30 CU-NI CLAD STEEL

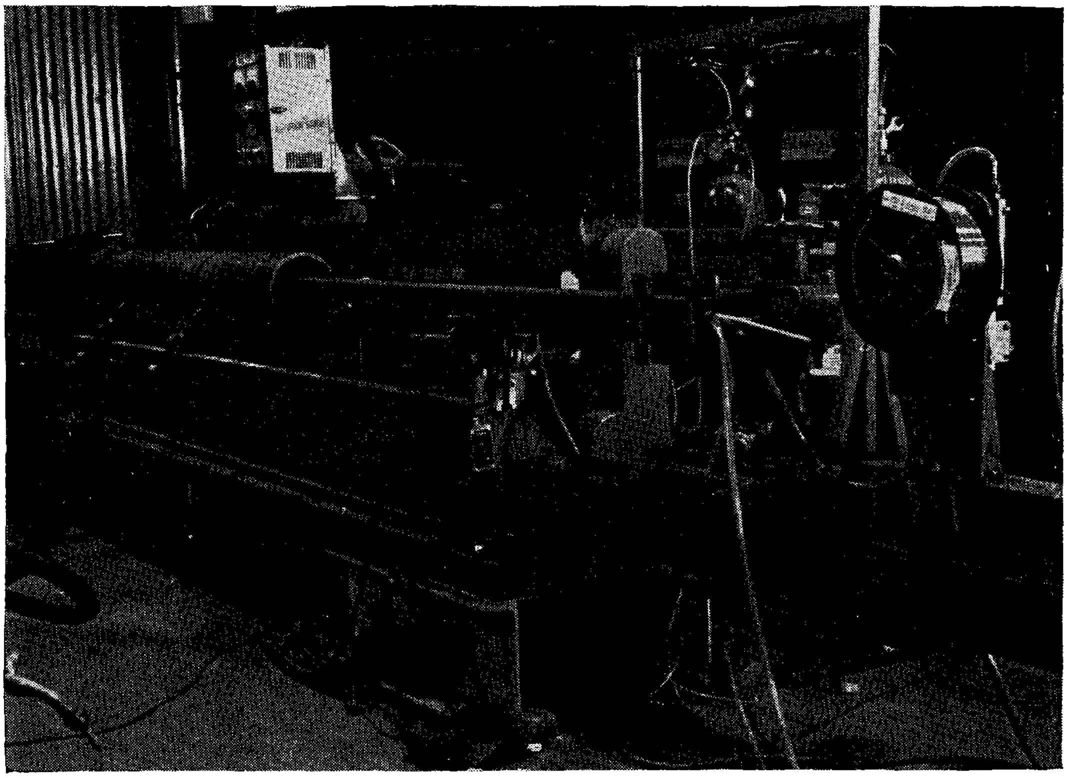

FIG. 12—SET-UP FOR CU-NI CLADDING OF PIPES INTERNALLY

strip process prior to pressing into hemispherical shapes, for fabrication into the final header, a model of which is shown in FIG. 11. In FIG. 12 can be seen the set-up for lining pipes by the wire-filler MIG method.

Since the design of the main condenser header was to be based on high-strain–low-cycle fatigue considerations, and the processes involved the deposition of a material of considerably lower tensility, and a value of one-half the modulus of elasticity of the steel base, it was deemed essential to acquire data on these characteristics. While it was accepted initially that a 'reduction' in properties was inevitable, the final outcome was nothing short of astonishing. A small number of specimens clad and unclad were prepared for a rough investigatory test. It may be a significant factor that the clad specimens had the steel base machined off until it approximately equalled that of the cladding. The all-steel specimens, of course, were of the same dimensions as those of the composites. Hence, one must take note that there was an 'over-bearing' of cladding to what would obtain in practice.

The straining applied was of a pulsating form with a frequency of 'one cycle per second', and a level from zero to maximum, repetitive. The (incredible) results obtained are shown in TABLE II.

TABLE II—*High Strain-Low Cycle Fatigue Lives of Cupro-Ni-Clad and All-Steel Specimens*

Strain Applied (per cent)		*Load (max.) (lb)*		*Fatigue Life to Fracture (cycles)*	
Unclad	*Clad*	*Unclad*	*Clad*	*Unclad*	*Clad*
39 to 35 (approx)		19,000	19,000	21	91
		18,000	18,000	239	1,946
		17,000	17,000	2,677	11,861

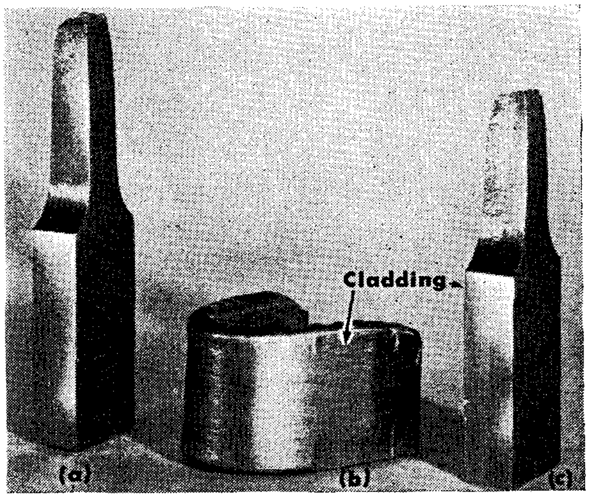

FIG. 13(*a*) AND (*c*)—'HIGH STRAIN—LOW CYCLE' FATIGUE SPECIMENS (ALL STEEL AND CUPRO-NI-CLAD STEEL)

FIG. 13(*b*)—'SIDE-BEND' TEST PIECE

As will be observed, instead of a 'reduction' in fatigue life, with cladding applied, a phenomenal increase was obtained. Also, even more surprising, the elastic modulus of the composite is equivalent to that of steel.

Typical specimens after test are shown in FIGS. 13(*a*) and (*c*). A 'side'-bend test is also shown at (*b*). A highly pleasing feature is the continued integrity of the bond following such treatments.

The fundamental reasons underlying the results are not immediately apparent, but they are considered to be of such import as to mount a deeper investigation and such a programme is now in hand. There is no doubt that a certain stiffening of the lattice of the interface material occurs without loss of ductility.

With the success achieved to date, consideration is now being given to extending the process to other applications which, so far, embrace important valves, shafts and spindles where high elastic modulus is required, and even to propellers.

In view of the fact that the steel of the components considered so far will be subjected to the physical conditions of the sea water, and particularly 'temperature' at its lowest, the type to be selected must be of suitable fracture-toughness under such conditions. In the applications to date, therefore, steel to BS1501-221 Gr. 32A LTO, has been specified. With other applications in mind, however, steels of the $2\frac{1}{4}$ per cent chromium, 1 per cent molybdenum, and, also, of HY80 types, have been utilized and successfully clad. An important attribute of the process found, has been the ability to heat treat the backing steel without affecting the cladding.

However, there is one grave characteristic which *must* be respected, namely, like all the cupro-nickels, the clad versions also display extremely poor 'hot-ductility'. No troubles are experienced at ambient or very high temperatures, but between 550 degrees and 700 degrees C, a severe trough of low ductility occurs and working between these temperatures, when *tensile* loading is applied, *should be avoided.* Formation whereby the cladding is in compression (as in the case of the half-sphere pressings) though, has been carried out quite successfully at the upper ranges of the critical temperatures.

Another important factor in hot-forming processes is the vital need to use non-sulphur-contaminated atmospheres for heating. The importance of this was made evident in the first attempt to bend the 10 in. diam. pipe, when the tendency to crack was detected early. On this matter, the trials were suspended for investigation, and are now about to be resumed.

'Hot-Spot' Corrosion of 70/30 Cupro-Ni (+ Fe) Tubes

Although the material used for tubes in minor heat exchangers had, from time immemorial been of aluminium brass, a change to 70/30 Cupro-Ni (+ Fe) was made a number of years ago consequent upon severe and widespread failures, due to pollution while vessels lay in the fitting-out basins of building

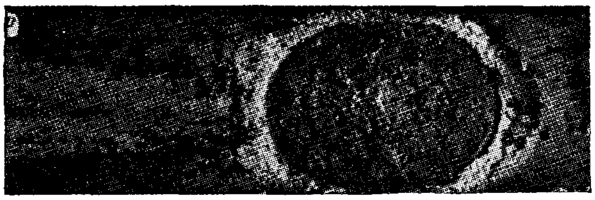

FIG. 14—'HOT SPOT' CORROSION IN 70/30 CUPRO-NI TUBE

yards. The attack was attributed to the action of sulphate-reducing bacteria, resulting in the production of sulphides, and causing an adverse change of surface protective film resistance. Failure of the film, then, would spell disaster to the underlying metal.

It was well known that 70/30 Cu-Ni was susceptible to hot-spot corrosion and that its use thus in drain coolers was therefore suspect. However a calculated risk was taken having regard to the greater evil of pollution.

In just this manner, then, 70/30 Cupro-Ni (+ Fe) found its way into the drain coolers of the County Class ships, and which very soon were found to be grossly under-designed both from the primary fluid and the sea-water sides. (At a later stage it was discovered that 'steam' was actually being condensed.)

Hence, the ingress of hot fluid on the outside of the tubes combined with excessive sea-water speeds internally, resulted in rapid and disastrous failures, to which occurrence, the term 'hot-spot corrosion' was applied. This was characterized by the highly localised removal of metal *on the sea-water side* immediately under the hot spot, as if the elevated temperature had had the effect of softening the protective film and thus allowed it to be washed away by the flowing sea water. A typical example is shown in FIG. 14. The phenomenon has been studied by Bem and Campbell of BNFMRA and Breckon and Gilbert (Yorkshire Imperial Metals)—Refs. (2) and (3).

Failures in these systems recurred with incredible regularity after some four months' service of each replacement. With the argument that the vessels were now no longer in polluted waters, it was decided to return to aluminium brass tube (the best-known material to withstand 'hot-spot' corrosion) but now, the excessive sea-water velocity caused direct tube-end impingement.

The manner in which the trouble was finally resolved is described later under the section on titanium.

Faulty Systems Design

In the course of the investigations into the 'hot-spot' failures, it became patently clear that all was not well with the design of the cooling system for auxiliary coolers in the class of ship concerned.

It was arranged in the form of a ring main supplied by any one or all of three pumps in parallel, according to the demand. More important, with such a system, it was observed that there was a complete absence of pressure and velocity sensing devices on the individual heat exchangers so served, and neither did facilities exist for temporary insertion. On contemplation, of course, such is the case, in general, with heat exchangers in H.M. ships, and never have operating conditions been accurately checked in new installations, as with other components.

In addition, a firemain connection (marked 'Emergency') was fitted to supply the drain cooler (with an orifice), and this possessed its *own* discharge overboard in parallel with the main one, through a smaller valve. Due to an unfortunate combination of several factors, ranging from the firemain being of higher pressure than normal and the special firemain discharge being undersized, thus causing action to enlarge the orifice, etc. and culminating in both 'small' and 'main' discharges being left open, it was no surprise that the conditions were excessive. Nevertheless, had adequate instrumentation been installed, these conditions would have been highlighted.

It may be stated that, arising out of these considerations, firm action has been taken for evaluation facilities to be provided in all future installations.

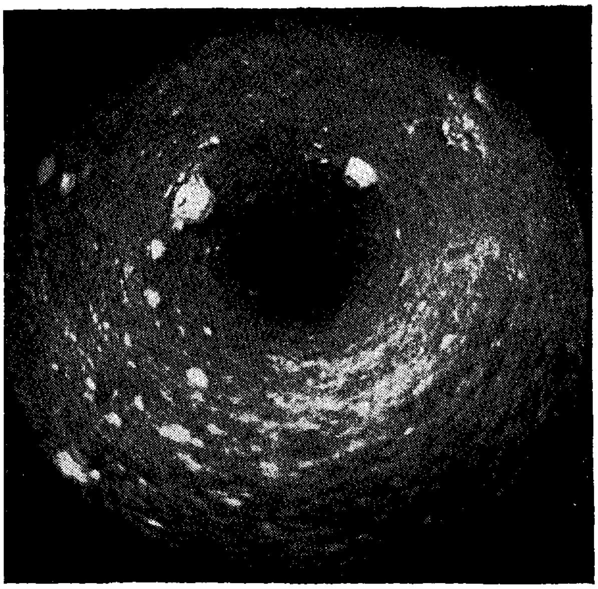

FIG. 15—PRODUCTS OF METABOLISM OF NUCLEATED BARNACLES IN A TITANIUM CONDENSER TUBE

Applications of Titanium in Sea-Water Systems

The possibility of using titanium with its known superlative qualities for resisting the erosive action of fast-flowing sea water, has been under surveillance by the British naval authorities for many years, even dating back to the time when the production of ductile metal carried many doubts. This phase, of course, has long since passed, but its continued high cost has hampered and suppressed its introduction earlier. So decisive has this influence, alone, been, that it has tended to obscure, perhaps, the most important of its failings in a sea-water environment, namely, its poor capacity inherently to resist marine fouling under stagnant, or comparatively low-velocity flow. In comparison with the copper-bearing alloys, with their copper 'poison' leach to the sea water, one can assess its capability as *nil*. Barnacles in early stage of growth following the attachment of their infant form (cyprids) in a titanium tube subjected to such conditions can be seen in FIG. 15.

There will, of course, be a 'threshold' velocity, above which such embryo marine animals cannot settle, as is, at present, postulated in the case of 70/30 Cupro-Ni tubes. This latter is currently accepted as 3 ft/sec.

Within the past few years, however, a determined attempt has been made to pursue its application in the service more positively, and to aim to design and build a vehicle suitable for practical assessment. It is also pertinent to note that, in this period, there has been a drastic reduction in price.

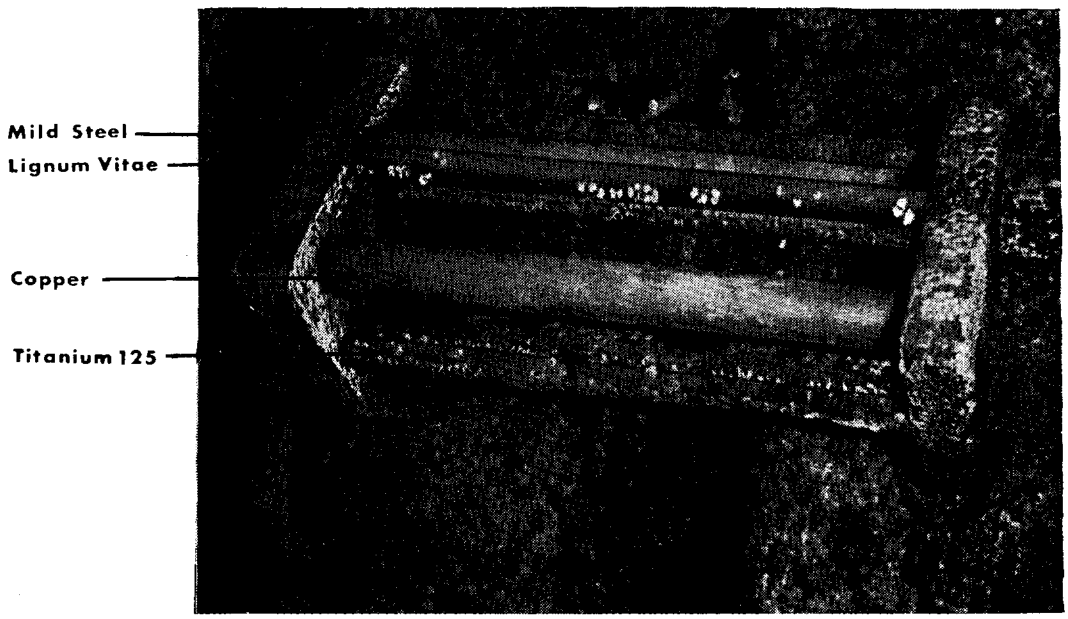

FIG. 16—TUBE ASSEMBLY OF DIFFERENT MATERIALS IMMERSED IN SEA-WATER SHOWING HEAVY FOULING OF TITANIUM TUBE. (CLEARED AREAS MAY BE DUE TO COPPER POISONS WASHED WITH TIDE)

The project that was mounted, in consequence, (the work being undertaken by the International Research and Development Co. Ltd.) commenced with a feasibility study as Phase I, when all problems and hurdles were emphasized, and, in general, these may be summarized as follows:

(*i*) It was confirmed that titanium, as a material, had no inherent resistance to marine fouling. (FIG. 16 shows a tube assembly of various materials from which this fact is admirably demonstrated.)

(*ii*) Some effective methods such as provision of chlorine dosing, artificial supply of copper poison, and maintenance of high working temperature, could be adopted to mitigate this characteristic.

(*iii*) The high nobility of titanium could cause disastrous selective attack on adjacent more conventional materials.

(*iv*) Novel methods of fabrication were necessary to be developed in view of the impossibility of obtaining castings.

(*v*) New methods of tube-to-tube-plate connections were required to be established in view of the necessity, on overall consideration, to use thinner tubes.

(*vi*) Certain types of titanium alloy were prone to stress corrosion in chloride solutions.

As a result, a Phase II programme was initiated to examine these findings further, and incorporated extensive practical investigation and trials.

A rig, consisting of a number of tubular assemblies in perspex tube plates, served with pumped sea water through the tubes at velocities varying from 0·5 to 6 ft/sec, was constructed and installed at an exposure site at Campbelltown, on the west coast of Scotland. This area was selected as being representative of the extent and form of marine fouling generally encountered. A view of the rig is shown in FIG. 17.

The pattern of testing took the form of directly comparative flow through individual test units, some with, and some without, chlorination injection. One unit also was fitted with a plain copper corrosion anode in the flow.

It may be stated categorically that the most difficult task has been the resolution of troubles with the types of chlorination units tried. For the application entailed, it is necessary for such a unit to give prolonged unattended service on all occasions when required, which would, of course, be under shut-down or low-flow conditions. The first unit investigated was a commercial type manufactured by Patterson Ltd., which comprised a bundle of platinized titanium plates, across which an electrical potential is applied. In so doing, sodium hypochlorite is released from the sea water.

When this unit was first tried in the test rig, rapid and severe build-up of magnesium hydroxide (cotton-wooling) on the plates occurred, thereby reducing and, finally, stifling the chlorinating action. The effect is illustrated in FIG. 18. During these early days, also, there was much uncertainty on the quantity of hypochlorite production required for effective protection. With further study and experience, it has now been reduced considerably, and it has now been postulated for individual units to be capable of producing 0·1 lb (50 grms) of effective chlorine per hour.

A radical change has also been made in the mechanical design of the units, the plates being replaced by rods. In the course of this development, of course, other types of equipment were investigated, including that of the 'Cumberland', but this was ruled out by the size of the re-circulation system and collection tank.

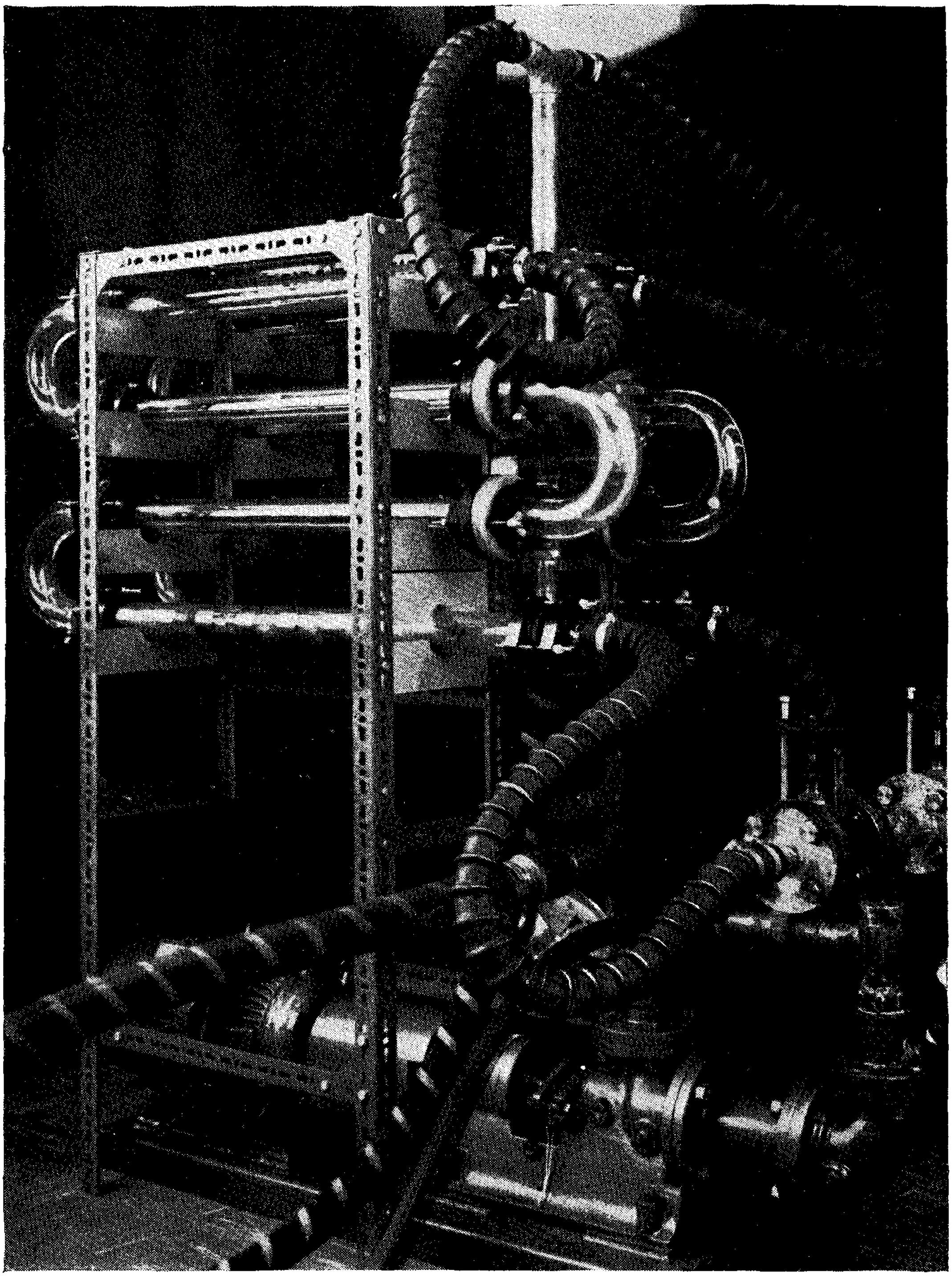

FIG 17—MARINE FOULING TEST RIG FOR TITANIUM TUBES (CAMPBELLTOWN)

On the matter of the relative nobility of titanium and the more conventional metals, extensive trials indicated that acceptable compatibility in sea water was obtained only with nickel-aluminium bronze and 70/30 Cupro-Ni.

By virtue of the intense affinity of titanium for oxygen and carbon, unless melting and pouring can be effected entirely in vacuo—only possible in the case of relatively minute components—production of castings must be ruled out. In consequence, all items of irregular shapes must be weld-fabricated from forgings, pressings, etc., and designs must be tailored to this end throughout.

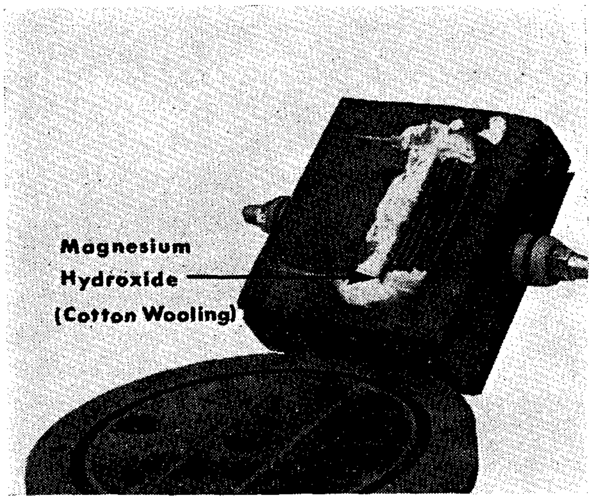

FIG. 18—PATTERSON PLATE-TYPE CHLORINATION CELL SHOWING MAGNESIUM HYDROXIDE BUILD-UP

The special investigation into tube-to-tube plate fixation was necessary in view of the need to use thinner-walled tubes, both on account of heat transfer (titanium being worse than copper alloys) and expense considerations, with the result that conventional methods of expansion would not suffice. Also, there was a need to dispense with the double tube plate form of construction, which had found favour in recent years for such heat exchangers, again, mostly on expense grounds.

As a result, it was deemed necessary to pursue a positive weldment procedure, and studies were conducted both on conventional and explosive methods. With the latter, it was thought that economy of size would be obtained due to closer pitching. A satisfactory welding method was quickly formulated using the T.I.G. fusion process on 'relieved' lips, similar to those shown in FIG. 3, but development of the explosive technique has presented many difficulties.

It must be emphasized that, with the latter, a finite molecular weldment was required to be produced across the interface of the tube and tube plate and, to achieve this, it was found that the pulse had to be introduced such that it 'ran' down-hill, as it were, thus requiring tapered holes in the tube plate. This resulted, of course, in severe deformation of the tube and tube plate material It was then apparent that no benefits accrued as regards tube pitching with the adoption of explosive welding.

Reports of certain titanium alloys being prone to stress corrosion prompted the mounting of a test programme on this aspect, the result of which established that C.P. (commercially pure), and Type 318 (6 per cent Al–4 per cent Va) titanium were not so affected. Incidentally, these were the types that had been provisionally selected for the tubes and tube plates respectively of the projected design.

Simultaneously with these studies, of course, investigations were being undertaken into the design of the heat exchanger proper, and this provided many controversial issues, particularly as to the type and form to be adopted. Extensive computer studies were conducted by I.R.D. to establish criteria and parameters in order to achieve minimum weight, space, pumping power and efficiency, observing, of course, the need *now*, for a vastly increased water velocity over conventional sets. Many ideas of multi-flow arrangements were considered, and one which held sway for a long period had the pump installed between the passes. It was thought that this would give benefits in the reduction of noise, but this was discarded due to the complication of header structure, and large suction head consequent on high water velocity.

With these intensive considerations proceeding, the main philosophy for the system, established from the outset, remained nevertheless unchanged, namely for the heat exchanger(s) (constructed wholly of titanium) to be a 'master' unit, or units, served with sea water, and cooling all the secondary cooling water used in the various other heat exchangers, which would of course be de-mineralized (as outlined by Kenworthy (Ref. 4)). Hence the materials used in these 'slave' units need only be of simple types. With this, it was hoped that a sea-water cooling system would be obtained which would be trouble-free. Obviously for such a duty, one master unit would be of large size, and further controversies involving single and double shells were resolved by the overriding demand that the system would be a 'vital' one and would have to comply with the duplication policy demanded of such in H.M. ships. However, it was agreed that the two units need be only of half ship's capacity.

By this stage, it had been decided to formulate and proceed to a Phase III, which would be the construction of a unit, or units, and subject them to searching proving tests. Finally it was agreed that all interests would best be served by building two units of a capacity that would allow one to be fitted in a surface vessel, while the other would be subjected to realistic marine fouling and pulsating pressure fatigue tests to simulate submarine conditions. In this way, practical operational experience would be obtained under fouling conditions in various parts of the world.

The most suitable application found was that of the cooling unit of the Diesel-engined *Lynx* Class, and it is for this that the ship-borne titanium cooler has been designed.

The situation to date is that both units are now under construction at the works of Messrs. Serck Ltd., and it is hoped they will be complete in the near future.

Application of Titanium in Drain Coolers

While entirely independent of the above project, the principles and lessons learned proved to be of immeasurable value in the final resolution of the hot-spot corrosion troubles encountered in the overloaded drain coolers of the County Class and described earlier.

Following the realization that all straightforward methods such as fitting of baffles, etc., could not be resorted to, consideration was given to the use of titanium tubes expanded into nickel-aluminium bronze tube plates (this being the first material adjudged compatible).

On the question of the possibility of fouling, a sufficient confidence level was built up with the substantial quantity of adjacent copper alloy components, but, nevertheless, it was decided for the first unit to have the titanium tubes fitted in the top half only. At best, then, the 'sting' of the hot incoming fluid would be reduced prior to meeting the 70/30 Cupro-Ni tubes and, at worst, if the tubes became fully blocked, one would have a titanium 'baffle', but still allowing the cooler to function partially.

This unit was fitted in H.M.S. *Fife*, and after four months' service a failure occurred in the lower Cupro-Ni tubes indicating that hot fluid had passed directly downwards, but the exciting feature was the revelation that the titanium tubes were completely free from fouling and entirely unblemished on the hot fluid side.

The lower half was then re-tubed in titanium and, to date, the cooler has functioned perfectly satisfactorily for some 10 months, with the tubes still being reported as unblemished.

Later, a second wholly-titanium-tubed stack was constructed, but this time with 70/30 Cupro-Ni (+ Fe) type tube plates and fitted into H.M.S. *Glamorgan*, and now, after eight months, trouble-free service is still being reported.

On this experience, action is now in hand to standardize on titanium for this application, particularly as an enhanced loading is envisaged in the next class of vessel.

An interesting cost comparison was obtained in this exercise. The Cupro-Ni tubes were 0·032 in. thick and they were replaced with titanium tubes 0·028 in. in thickness with a cost of 1·4 times that of the Cupro-Ni.

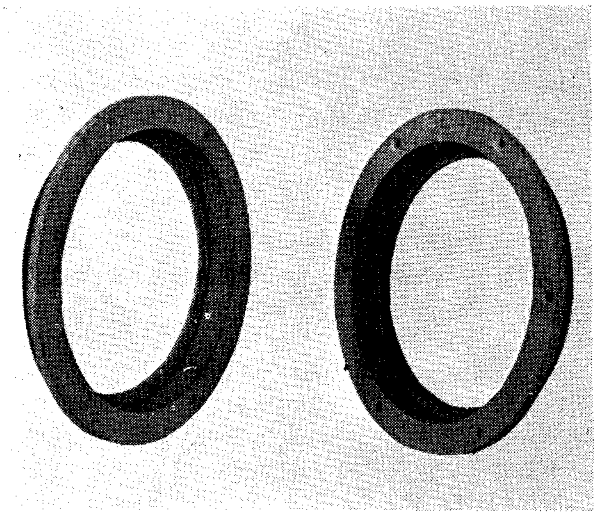

FIG. 19—PUMP SEALING RINGS IN SILICON NITRIDE

Influence of Carbon and Graphite in a Marine Environment

Although the disastrous effect of carbon and graphite in close proximity to the more conventional corrosion resistant materials, on account of their extreme nobility, has been known for many years, to find a substitute where their properties are unique, such as in radial seals, etc., has presented some difficulty. To date, therefore, carbon, in rubbing contact with stellite has been the accepted combination, and the heavy corrosion of adjacent material tolerated. The components thus affected are of vital importance too, taking the form of major and minor shaft seals, and those fitted in some designs of sea-water pumps.

In an endeavour to find a positive solution to this problem, investigations are now being directed towards the use of 'silicon nitride', a revolutionary ceramic developed by the A.M.L., as a substitute. Being entirely neutral in sea water, its potentialities are enormous and preliminary rubbing tests show promise.

A programme is therefore, being prepared to examine its characteristics in combination with itself, as well as other suitable, but non-exotic, materials.

Erosion of Pump Sealing Rings

One of the most serious instances of rapid and extensive deterioration, and which, possibly, constitutes the heaviest maintenance burden currently, has been with pump sealing rings. So long a history is attached to these components that the occurrence has almost become to be accepted as inevitable. In current designs of pumps, clearances have moved from 0·005 to 0·060 in. in two months. It has become the practice to give very fine clearances with the object of extending service life, and since this instils the possibility of a 'rub' between impeller and ring, the material of the latter has been of soft bronze.

In recent months, attention has been directed towards the adaptation of ceramics for this application, following experiences gained in the aero-space programme. Spare rings were consequently spray-coated with (*i*) alumina, (*ii*) combined 50 per cent alumina and 50 per cent zirconia and (*iii*) chrome oxide, and installed in a test pump at the AMEE, Haslar, each being given 600-hour tests. It was decided incidentally to give initial clearances of 0·015 in., to mitigate any possibility of a 'rub'.

The results of the trials, in every case, gave no perceptible wear of the working surfaces of the rings whatsoever. Some 3 to 4 thousandths wear was detected on the impeller, however, which was not unexpected. Action has now been taken to coat an impeller.

While the purely functional aspects of such coatings to meet the operational conditions are satisfactory, some concern is nevertheless felt in respect of their extreme brittleness. In the fitting of one ring the securing holes (old method) were found to be too small, and an attempt was made to drill them out. The result was, of course, cracking round the hole. This, however, did not deter the ring from giving a good performance. Obviously, therefore, other means of securing must be found.

With these considerations in mind therefore, thoughts turned to materials whereby the requisite hardness would persist through the whole section, and this resulted, once again, in the adoption of silicon nitride. Rings were successfully manufactured (FIG. 19) and on test currently, so far, have behaved most satisfactorily. It will be of interest to learn that these rings are installed with a thin rubber backing and secured in place with nylon screws. Silicon nitride is also, of course, of a brittle nature.

While these investigations have been proceeding on extreme hardness materials, some consideration has also been given to materials of directly opposite characteristics, (i.e., extreme softness), and a plastic known as Rulon has been tried. It is a P.T.F.E. loaded with hydro-carbons. In the limited time to date, when secured satisfactorily, which is difficult, some satisfactory running has been obtained.

As an extension to the work on sprayed ceramics, studies are also in hand to apply this to areas of heavy cavitation damage in pump casings. Problems are, however, encountered with access in these instances.

Other Work

There are a number of other exciting new innovations in the field of heat exchanger design under investigation, such as the use of extended surfaces and turbulence promoters, and also that of dropwise condensation, but unfortunately space does not allow an extended discussion on these aspects.

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