MATERIALS DEVELOPMENTS 1980

BY

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Introduction

In the 1977 reorganization, the bulk of the specialist materials engineering responsibilities of the Ship Department were combined in one Section, D123. The Section acts as a focal point for the design aspects of a wide range of problems in the field of materials and draws on and co-ordinates specialist and scientific advice from research establishments and commercial sources. As it is some years since an article on the subject of materials appeared in the *Journal*, it is timely to describe briefly a selection of current and on-going projects of general interest. Although a considerable part of the Section's effort has to be devoted to day-to-day queries as well as to the production and maintenance of materials specifications and standards, an increased proportion is to be spent on the improvement of materials and techniques. It is recognized that there is a pressing need for an improved materials information retrieval system and for the wider dissemination of design and user information. Several projects to improve the information aspect of warship materials engineering are in hand or planned.

Hull Roughness and Anti-fouling Paints

Hull Roughness

It has been estimated that during the lifetime of a frigate or destroyer about half the fuel consumed is used in overcoming the frictional drag of the water. This drag is considerably affected by the degree of roughness and fouling of the underwater surfaces. The distinction is between roughness as a feature of paint surface and the superimposed effects of the attachment of various types of marine biological fouling. An effective anti-fouling surface is recognized as essential to maintaining acceptable performance. Successful anti-fouling paints have been formulated over the years and current R.N. practice in this respect has proved

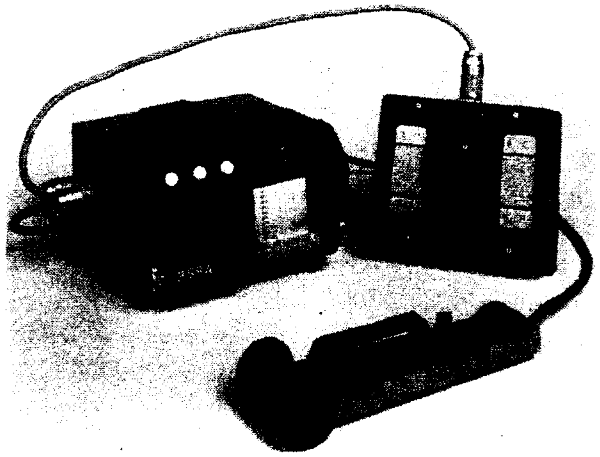

FIG. 1—BSRA HULL ROUGHNESS ANALYSER

satisfactory. R.N. anti-fouling paint (if well maintained) in combination with judicious removal of slime or weed growth by straightforward mechanical means (such as water jetting) has proved sufficient to ensure virtual freedom from significant marine fouling problems, and any that do occur are generally minimal and temporary.

The effects of paint roughness are more insidious and difficult to combat. Roughness can be introduced in many ways during building of the hull, such as defects in the steel plate, rough welds, poor surface preparation, and the quality not only of the coating but also its application. For a number of reasons, practice in these respects is achieving results in warships well below those in modern merchant ships.

In service, this roughness increases due to deterioration of the paint, mechanical damage, and corrosion, and by further coating applications. The only true remedy for such roughness is drastic re-preparation of the surface (such as grit-blasting back to bare metal) before recoating.

Surface roughness is frequently quoted in terms of mean apparent amplitude (MAA), or its equivalent, average hull roughness (AHR), a measurement obtained from a hull roughness analyser developed by BSRA. This instrument when traversed over the surface, samples test lengths of 50 mm and measures average peak-to-peak values. A large number of readings are taken and the average hull roughness figure obtained is quoted in microns AHR. A typical average reading for a new warship hull at acceptance would be of the order of 220 microns. In service the rate of increase would depend on operating conditions but a typical value should be about 50 microns per annum. There are more sophisticated ways of analysing hull roughness and much debate about the underlying correlation with frictional drag, but to date the BSRA measurement has proved a convenient method of measuring and assessing results.

For commercial vessels where operating speeds tend to be such that skin friction is more dominant than for a warship, fuel cost increases have motivated significant improvements in paints and in methods of application. Rapid application of outer-bottom coatings by airless spray is proving crucial in achieving quick and economic painting with good surface finish. A typical new merchant ship, such as a VLCC, would have a specified hull roughness of 120 microns AHR and the expected in-service increase would be about 25 microns per year—just half the typical figures for a warship. If comparable standards were achieved in a warship, it has been estimated that this would represent a saving of some 5 per cent. in overall fuel consumption (10 microns can be roughly equated to a 1 per cent. change in frictional drag.).

Current R.N. Anti-fouling Paint

The standard anti-fouling paint used on the hulls of R.N. surface ships for the past twenty years is a conventional cuprous-oxide-loaded rosin matrix type specially formulated with a high copper content to achieve effective anti-fouling for the desired minimum period of two years—the normal dry-docking interval. This paint, designated 161PE, is recognized as an outstanding example of this type of anti-fouling. Where a black anti-fouling is required for submarines or for the boot-topping of surface ships, another specially formulated paint, designated 317E, is used where the pigmentation is achieved with cuprous sulphide loading. This is a raw material that is becoming more and more difficult to import. Until recently, both these paints were made in the paint factory in Portsmouth Dockyard, but since the closure of the factory in 1978, supplies have had to be obtained from commercial sources.

As a complete paint system 161PE, whilst effective for anti-fouling, is considered to be a contributory factor to hull roughness. The specified system consists of three coats of coal-tar epoxy anticorrosive (CTE) followed by a tiecoat of aluminium bitumen (ALBIT) to give adequate adhesion, and finally four coats of 161PE. At each docking after the first application, 161PE loses its anti-fouling properties due to 'drying out' of the rosin matrix so that further coats of ALBIT and 161PE are required. A new warship receives as many as thirteen coats of paint with this system between launch and acceptance and, because application is by brush or roller with associated difficulties of controlling the standard of workmanship, the hull gets significantly rougher with each coat. The modern merchant vessel, using one of the newer type of high performance anti-foulings that do not dry out, may need only six coats of paint, each applied by airless spray. Given skilled operators, some of the reasons for the superior finish obtainable on these vessels are not difficult to deduce.

Self-polishing Anti-fouling Paint

There is understandable reluctance to change from an established and successful anti-fouling paint, such as 161PE. However, commercial developments have been so significant that a re-appraisal of R.N. policy is overdue. In particular, the new concept of a self-polishing anti-fouling paint is of particular interest, the first of these to be introduced being International Paints Self-polishing Copolymer (SPC) which appeared on the market five years ago. This is one of a number of commercial anti-foulings that represent a change from the conventional cuprous-loaded matrix type. Whereas the matrix type relies on a leaching mechanism to release the toxins and which leaves a hard skeleton of rosin behind, the newer type embodies the toxin in a polymer paint coating so formulated that the toxin molecules diffuse continuously to the surface. These are known as contact-type anti-foulings, some of which rely on organometallic compounds instead of, or in addition to, copper. SPC is such a paint with a combination of polymers containing organometallic toxins with the added feature that the copolymer is designed to be self-polishing. In effect the paint coating wears more rapidly at surface imperfections due to the associated flow disturbances and turbulence in the boundary layer. Because contact-type anti-foulings do not suffer from drying out, the need to overcoat at a docking will only arise if the paint thickness is inadequate. Furthermore, because adhesion problems should not arise, the need for a tiecoat is eliminated.

FIG. 2—PATCH OF SPC ANTIFOULING PAINT ON H.M.S. 'ARIADNE'

The first trials of SPC in the R.N. were carried out in 1976 with a number of patches on the hull of H.M.S. *Ariadne*. This experience together with the evidence

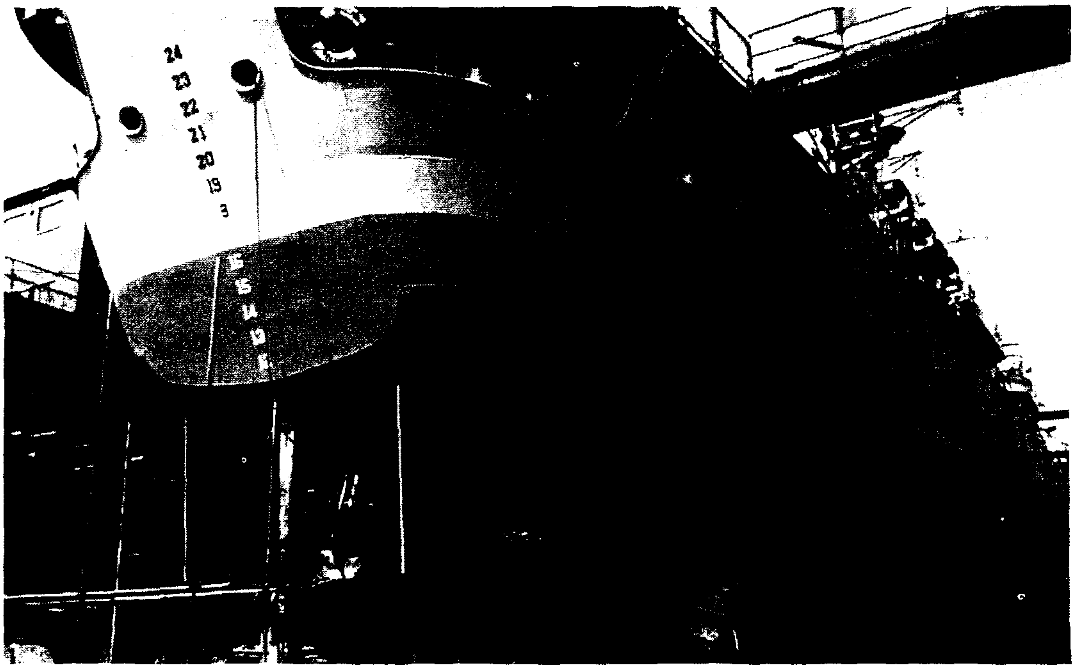

FIG. 3—APPLICATION OF SPC TO H.M.S. 'EXETER'

from a growing number of applications of SPC on commercial vessels engendered sufficient confidence to embark on a more substantial trial. Meanwhile the manufacturers had developed their paint formulation such that they were able to make more positive recommendations on the system and its application. The outcome has been a full outer-bottom coating of H.M.S. *Exeter* carried out in April 1980 at the final docking before acceptance of the ship. The existing 161PE anti-fouling and ALBIT tiecoat were removed by light grit blasting using the Hodge-Clemco water-shrouded grit process. The lightly etched coal-tar epoxy surface which resulted was overcoated with one coat of regulation CTE, one coat of vinyl-modified CTE to act as a tiecoat, and four coats of SPC, alternating green and blue and all applied by airless spray. The two-colour system will give indication in service of the polishing action of the paint. SPC is not available in black for the boot-topping area, but it was decided to apply four coats of the blue SPC to this area to avoid the possibility of a patchy appearance above the water-line. Although the ship would have preferred the standard black boot-top, this would have meant reverting to standard black anti-fouling for this area and so precluding an important part of the SPC trial.

The trials plan is to monitor hull paint condition and to measure hull roughness (including underwater inspection and measurement) over a period of at least four years. Periodically runs will be made over a measured mile or equivalent so that the shaft power speed relationship can be checked. A parallel set of measurements will be made in a sister ship, H.M.S. *Southampton*, coated with the conventional 161PE/317E system. Although these trials are considered to give the best prospect of a sound evaluation—given the ships' overriding operational requirements—ideally more hulls should be included because four years is a long time to wait before making any further commitment. It is therefore the intention to seek further opportunities for the application of SPC and, if resources are available, the evaluation of other modern anti-fouling paints that may be adjudged to promise significant advantages.

MODLAG Insulation for Machinery Systems

The lagging of machinery systems is a process the significance of which can be all too easily underrated at the design stage. It is important to recognize the need

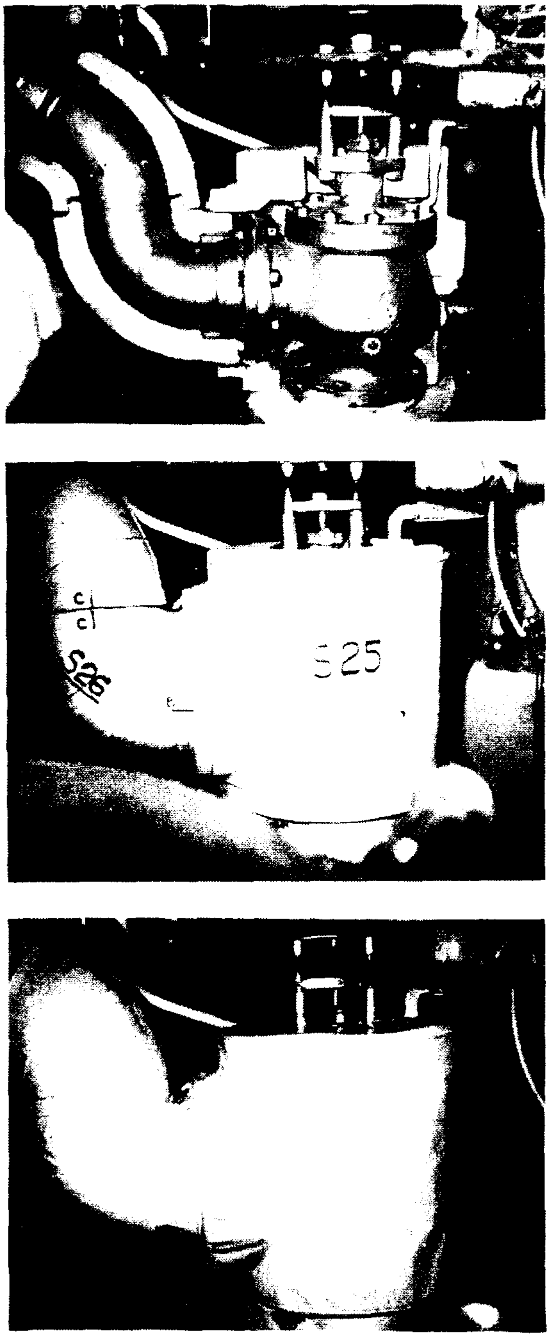

FIG. 4—TYPICAL MODLAG INSTALLATION

for care in specification and skill in application if potential production problems and consequent programme disruption during construction and subsequent difficulties of maintenance are to be avoided.

For high temperature systems, asbestos with its serious health hazard has been replaced for general insulation purposes by calcium silicate—itself a dusty material that is fragile and easily breaks up in handling and cutting, creating a problem with mess and contamination during lagging and delagging operations. There has been no reason to suspect a health hazard from calcium silicate; however, a precautionary but thorough investigation sponsored by D.G. Ships in association with the three major U.K. suppliers of the material is proceeding at the Institute of Occupational Medicine, Edinburgh.

D.G. Ships has had under development since about 1972 a modular system known as MODLAG which is designed to combat some of the problems with conventional lagging. This system is now rapidly gaining recognition and acceptance. It consists of pre-formed and carefully tailored calcium silicate sections wired to the componment or pipe and with a faced glass-cloth overall cover held in place by Velcro fasteners so that the sections can be readily dismantled, kept intact, and re-used. The system has been developed by industry under a MOD contract.

Early trials of MODLAG in H.M.S. *Galatea* indicated a need for some improvement in the materials of manufacture and these were embodied for further and successful trials in 1976 in H.M.S. *Ariadne*. A trial installation in H.M.S. *Vulcan* was also completed in 1976. A complete specification now exists for a satisfactory system of modular lagging, and experience in the manufacture of MODLAG has been accumulated at Devonport Dockyard and at Messrs. Vickers at Barrow. The first fit of a lagging kit is made either by using a section of the actual pipework or component (removed if necessary from the ship installation) or, if this is not possible, by using templates or mock-ups. Subsequent kits can be made from drawings if required. The system has been approved for the primary and for the secondary systems in nuclear submarines, and it is planned that some 37 per cent. of the systems previously insulated with conventional calcium silicate lagging will change to MODLAG. Trials at Devonport Dockyard have led to formal demonstrations in H.M.S. *Andromeda* and other vessels, and as a result MODLAG has been accepted as a satisfactory production process.

The main advantages of the system are identified as follows:

(*a*) Because dust is no longer a problem in the working space, the exclusion periods for other trades during lagging and de-lagging no longer apply.

(*b*) The finding of alternative work for the previously excluded trades is no longer required.

(*c*) The intermittent nature of insulation work is greatly improved or even eliminated, since sections can be pre-formed to fit pipework in the pipe stores while awaiting installation on board using the pipework sections themselves as templates.

(*d*) Washing down with fresh water on completion of the lagging (which encourages rust and creates a significant ship husbandry task) is no longer necessary.

(*e*) Whenever lagging sections require to be removed for defect rectification at AMPs, DEDs, and refits, dust will no longer be a problem and the sections can be re-used with considerable savings in manpower, time, and cost.

(*f*) The shorter working time in lagging near reactor plant will result in a significant reduction in radiation exposure.

Estimates of actual costs of the MODLAG system in comparison with conventional lagging demonstrate a clear life-cost advantage. For example, for one specific system in new construction, the cost of the first ship system was 92 per cent. greater with MODLAG, and follow-on (repeat) systems were 38 per cent. greater. The cost of the first ship system included design, development, drawings, and site surveys. It has been calculated that costs of this order will be more than recovered at the first AMP, DED, etc. for the reasons given in (*e*) above. MODLAG appears set to become a welcome success story.

GRP Production Methods

Production Costs and the Styrene Problem

The experience of using glass reinforced plastic (GRP) for the construction of H.M.S. *Wilton* and, subsequently, the first of the new HUNT Class, H.M.S. *Brecon*, has demonstrated the increase in cost per structural ton incurred in building such larger vessels when compared with the smaller and structurally simple boats and yachts for which this material has become commercially established. It has been estimated that a GRP hull costs at least double that of an equivalent steel hull for warships of the size of H.M.S. *Brecon*. The production of a large GRP hull structure is very much a labour intensive process, labour accounting for some three-quarters of the total cost. These costs are exacerbated by a number of problem areas:

(*a*) Maintenance of the styrene in the atmosphere at an acceptable level for personnel, i.e. a maximum concentration of 100 parts per million (the Health and Safety Executive are proposing a reduction to 50 parts per million).

(*b*) Dust, fire, and explosion hazards.

(*c*) Labour demarcation.

(*d*) Productivity.

(*e*) Quality assurance.

All GRP laminates for these vessels are virtually hand made by so-called 'bucket-and-brush' techniques. Quality control is essential, particularly in respect of 'void' content since voids are potential sources of weakness. Other

FIG. 5—RACAL HELMET IN USE

features of the laminate which are important for strength and must be closely controlled are thickness and resin-to-glass ratio. The stiffened single-skin structure of the HUNT Class involves wet laying up by a large number of men who are subjected to a styrene-laden atmosphere with a particularly high concentration during the critical working period of about half an hour when application of the resin and consolidation of the laminate is taking place. To control the styrene level inside the hull, for example, during laying up, it is necessary to install some form of ventilation. Design of a satisfactory system is difficult because styrene vapour is heavier than air and accumulates in the hull and because too high an air velocity at the surface can adversely affect the curing of the resin. Full-scale mock-up tests have been carried out at Devonport Dockyard to find a suitable system and reasonable success has been achieved; however, even the best system so far devised cannot always guarantee styrene levels that allow unrestricted working without resort to breathing protection and full monitoring of personnel. To ease these problems, a new type of fan-ventilated helmet has been successfully developed and evaluated at Devonport. This is a modification of the well-known Racal Airstream helmet, the standard dust filter bag being replaced by a charcoal cloth filter. The helmet modification was developed in collaboration with the Institute of Naval Medicine, The Chemical Defence Establishment Porton, and Racal Safety Ltd. This helmet has been found much more convenient than the customary breathing mask, and has been generally welcomed by production personnel.

GRP Consolidating Machine (MOD Design)

There is considerable incentive to develop suitable automatic processes for GRP production; the rewards are potentially very large, particularly where composite materials are increasingly replacing metals as in motor vehicles. Methods which have been tried for GRP hull production include automatic dispensers of wet resinated glass, resin spray machines, and special resin applicators. Experience with such devices on large hulls has been disappointing: dispensers are unpopular with the workforce; resin spray machines increase styrene levels, and one type tried has a potential explosion hazard; and resin applicators have not proved a worthwhile improvement on the 'bucket-and-brush' method. All such devices have, in addition, suffered cleaning problems which tend to outweigh any marginal operating advantages.

For smaller components such as dinghy hulls, pressure impregnation techniques show promise but require expensive moulds and are only viable for quantity production. Currently, for large components, attention has been focused on the automation of flat panel manufacture. Although this represents a smaller and simpler part of the production process compared with the hull skin, it provides the best chance of early success and should have the potential for

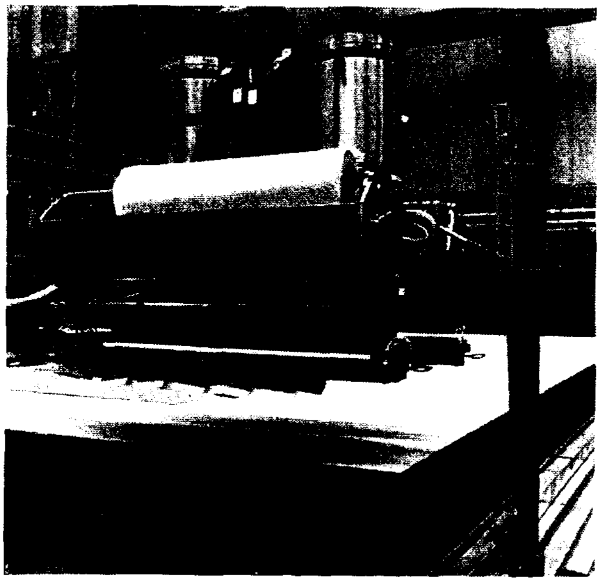

FIG. 6—PROTOTYPE GRP CONSOLIDATING MACHINE (MOD DESIGN)

further development to the more difficult shapes. Even so, it has been estimated that the automation of flat panel production for a HUNT Class MCMV could, by itself, reduce costs by about £300 000 per vessel.

The MOD machine exists in prototype form and after initial trials and demonstration at Devonport is destined for full evaluation in a shipyard production facility. The principle of the machine—which is the subject of a patent application—lies in the concept of 'minimum consolidation'. Current hand lay-up methods depend on thorough consolidation by repeated rolling to ensure full penetration of the resin and the elimination of voids. The machine aims to produce a satisfactory laminate with a single pass of a system of trailing plastic blades mounted on a travelling bridge with no manual rolling and minimum inspection. Each pass adds one layer of glass cloth to the laminate, building up the thickness by applying successive layers either in alternate directions using two sets of trailing blades or in the same direction with an idle stroke between each. The prototype has been designed for use over a lay-up table of maximum size 4·5 m by 12 m, but wider and larger laminates can be made by extending the floor-mounted track and fitting a wider beam. The lay-up surface can be flat and level, an inclined plane, or with single or double curvature not exceeding 10 cm in 9 metres.

Two main supply tanks are carried on the bridge of the machine. One tank holds resin plus catalyst and the other resin plus accelerator. These materials do not come into contact until they are dispensed on to the lay-up table. The resin is gravity fed via a simple pneumatic servo-controlled balance system that determines the resin-to-glass ratio. A typical bridge traverse speed is ten feet per minute. There are no pumps or pressure tanks and no actively mixed resin within the system. It is envisaged that the machine will require three operators and will be capable of laying up to 50 metres of glass cloth in about 30 minutes. Detailed attention has been paid to ease of cleaning and the interchange of the working components of the resin system.

Preliminary trials of the prototype have demonstrated the successful achievement of the original objectives resulting in a high-grade laminate with no rolling and no in-process inspection. In production, the machine should be capable of making considerable savings in flat panel production costs with the following unique advantages:

(*a*) Reduction in production personnel of 50 per cent.

(*b*) An increase in production rate of up to six times.

(*c*) Up to 80 per cent. reduction in quality control.

Fire Testing of Materials

When selecting materials for warships, judicious attention must be given to their fire characteristics which are assuming much greater importance with the wider introduction of plastics and composite materials. The objectives are to minimize the probability of a fire starting (ignition) and to limit the consequences of fire development. Particular care must be taken with combustible materials

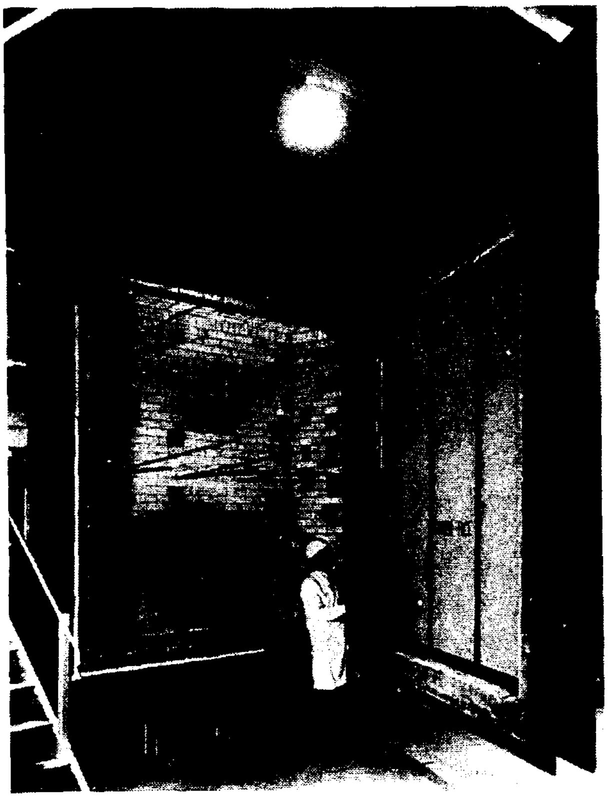

FIG. 7—FURNACE USED FOR HANGAR CURTAIN FIRE TESTS

that generate appreciable quantities of smoke and toxic fumes because these products constitute the major hazard to personnel. Unfortunately the trend with modern furnishing materials, for example, has been to worsen seriously the hazard, the most notorious example being the widespread use of polyurethane foam upholstery. Ship Department policy is to use only those materials that have been subjected to a relevant series of standard tests to which full account must be given before they are selected. The present range comprises nineteen standard tests of which only about six would be needed to evaluate a particular material. The tests cover such characteristics as ignitability, flammability, smoke production, toxicity, and surface spread of flame. A full programme which will take several years of work is in hand at AMTE establishments and commercial laboratories with priority being given to those materials judged most important in the matter of fire risk.

These tests are on small samples of material and by no means give a total assessment of the hazard in a full-size fire. Because of the complexity of the phenomenon, confidence in the ability to predict the behaviour of a material in a fire can only be achieved by full-scale testing. It is difficult to justify such tests, however, unless the risk is demonstrably high and the scenario well defined. Nevertheless, the ultimate aim for critical areas of ship design should be to demonstrate the correct selection of materials by such full-scale testing although criteria have yet to be established to justify this kind of commitment. A less costly compromise would be to carry out scale-model tests of fire situations such as the quarter scale models used for some research work in the United States of America. It is easier, however, to justify single-component testing where a direct comparison can be made between similar components made of different materials. Examples are the fire testing of hangar curtain materials to replace asbestos cloth and the improved elastomeric materials for seals on watertight doors.

There is, however, an underlying dissatisfaction with the present empirical approach to the evaluation of the fire hazards of materials. There is a growing demand, particularly in the U.S.A., for the establishment of more fundamental data on fire behaviour with the ultimate aim of being able to simulate real fire situations by computer modelling. A large long-term research programme (civilian and military) is investigating such phenomena as ignition, combustion, and complex heat transfer. Much of the impetus of this programme has its origins in the Apollo capsule tragedy in 1967. As a shorter-term objective, D.G. Ships has placed a contract with Y-ARD Ltd. to investigate the criteria for establishing basic design guidance on the application of fire test data to the selection and disposition of materials in particular compartments in a warship.

High Integrity Sea-water System Components

The established production methods for high-integrity sea-water system components include sand casting and forging as well as fabrication from steel, weld clad internally with a corrosion-resistant alloy. Improvements are being sought by the use of centrifugal casting and by more cost-effective methods of cladding. In addition, materials with better corrosion performance than those in current use are being evaluated with full attention to welding and casting.

Sand Casting

For components of many sea-water systems, the most economical production method is by casting, the preferred alloy for which is nickel aluminium bronze. A considerable programme of work has been carried out in recent years to improve the quality of these castings, and detailed guidance is now available to designers and founders in a Ship Department publication, SDP 18—*Design and Manufacture of Nickel Aluminium Bronze Castings.* The object of this guidance is to obtain sound castings which will meet the high standards required for freedom of defects under radiographic and ultrasonic inspection and with the minimum of expensive weld repair. Although considerable progress has been made, the level of weld repair still required, particularly for larger castings, is unsatisfactory and represents a major cost penalty for this production route.

Nickel aluminium bronze (NAB) is subject to selective phase corrosion in sea water and this tendency is particularly marked in the heat-affected zones adjacent to welds. In spite of efforts to improve the corrosion behaviour of NAB by tight compositional control and heat treatment (as required in D.G. Ships Specification DGS 348), the underlying problem still remains. This provides added incentive to minimize the amount of welding and weld repair necessary in components made from this alloy, which nevertheless remains one of the most useful and established alloys for these applications.

Weld Fabrication from Forgings

The use of forgings in, for example, 70/30 cupro-nickel, combined with welding if required is well capable of meeting the desired degree of integrity. Forgings are expensive however, and the welding of many of the copper alloys necessitates particularly careful operation and control so that the method can only be justified for selected critical components.

Steel Fabrication with Internal Weld Cladding

With the prevailing high standards of fabrication and inspection techniques, steel is the first choice of material for high integrity pressurized components for industrial applications. It seems logical then to adapt this technology to the sea-water environment, and adding corrosion resistance by cladding the internal surface with a suitable alloy. A number of critical system components have been manufactured by this method. A typical steel is plate to BS 1501–224 (a carbon-manganese steel grain refined with aluminium with minimum tensile strength 490 N/mm^2 and yield 290 N/mm^2). The most common cladding alloy is 70/30 cupro-nickel, but Monel and Inconel alloys have been used and in association with steel castings as well as plate fabrication.

Disappointingly, however, the economics have proved frustrating. In order to avoid degrading the corrosion resistance of the cladding alloy by 'iron dilution' (the base steel mixing at the weld interface), it has been necessary to employ two and sometimes three layers of weld deposit. To achieve the required confidence in the integrity of the cladding, each layer is subjected to non-destructive examination.

On many components, access for manual weld deposition is difficult and welding fumes create a hazard for the operator. Automatic welding devices have been developed but are usually only of limited application being unable to cope with components of different geometry. The net result has usually been highly expensive components (compared with castings) and this technology is only finding very limited use despite considerable investment in its development.

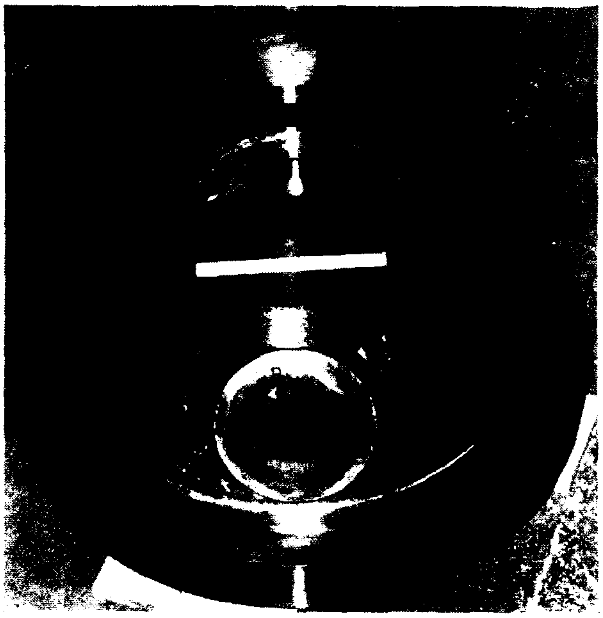

FIG. 8—CENTRIFUGALLY-CAST LARGE CONDENSER HEADER

Centrifugal Casting

The capacity of a French foundry—Les Bronzes d'Industrie near Metz—to produce large non-ferrous centrifugal castings has enabled two identical nickel-aluminium-bronze condenser headers to be made for evaluation. Each casting weighs 890 kg in the rough machined state and has a maximum flange diameter of 1120 mm and a thickness of 130 mm. Both castings have been subject to rigorous non-destructive evaluation at Portsmouth Dockyard using ultrasonic and radiographic methods without any indication of a significant defect in either. Further investigation by AMTE is concentrating on mechanical and corrosion properties and micro-structural characteristics through the thickness of the cast material. For this, one of the castings has been sectioned to provide suitable test pieces, and the second casting will be fully machined and given a prolonged pressure cycling and flow test on an existing sea-water test rig at AMTE Haslar.

The results to date are very encouraging and represent a considerable achievement compared with a conventional casting. The virtual elimination of the need for weld repair and the consequent repetition of expensive non-destructive examination indicates that such castings will not only be superior in quality to sand castings but also significantly cheaper even if the initial metal mould costs are amortized over only a small number of repeat castings.

FIG. 8 shows that the process is not confined to simple cylindrical shapes although a degree of axial symmetry is required for economical production. Costs indicate that a considerable amount of rough machining can be justified to achieve the net shape.

Another programme of work in hand is the evaluation of the casting and

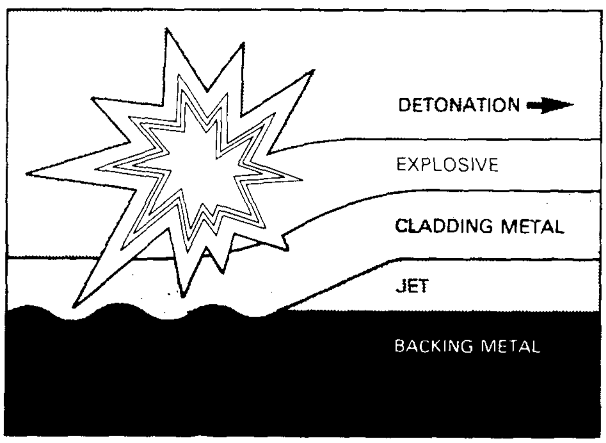

FIG. 9—EXPLOSIVE CLADDING PRINCIPLE

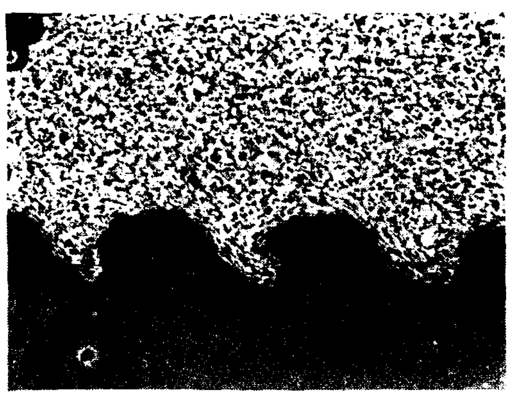

FIG. 10—INTERFACE OF STEEL EXPLOSIVELY CLAD WITH CUPRO-NICKEL (× 50)

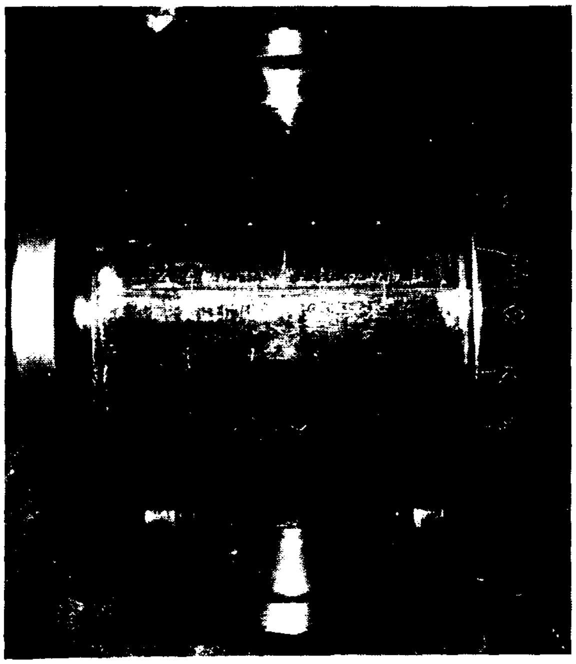

FIG. 11—HEAT EXCHANGER HEADER FABRICATED FROM STEEL COMPONENTS EXPLOSIVELY CLAD WITH CUPRO-NICKEL

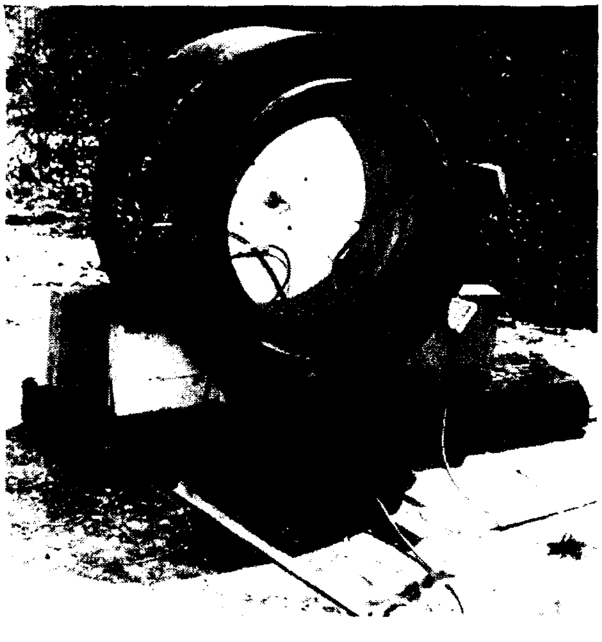

FIG. 12—EXPLOSIVE CLADDING PROCESS FOR LARGE FLANGE

welding properties of a number of high-strength cupro-nickel alloys which offer the promise of corrosion behaviour in sea water superior (and more predictable) than that of NAB. As part of this programme, two trial cylindrical centrifugal castings in different cupro-nickel alloys of particular interest have been purchased from Les Bronzes for evaluation.

Explosive Cladding

An alternative to cladding a steel component by weld overlay is to use the technique of explosive cladding. This technique was briefly described among other cladding techniques in an article in Vol. 23, No. 1 of the *J.N.E.* The principle as applied to a flat plate is illustrated in FIG. 9. The travelling wave front of the explosion disrupts the interface of the two metal surfaces causing a jet of metal which removes contamination resulting in a fully welded joint with a strong metallurgical bond enhanced by the wavy nature of the resultant interface.

An experimental heat-exchanger header has been fabricated from explosively-clad components and will undergo material and economic evaluation. One limitation of the process that has already been identified is the need for expensive and time-consuming development on each different explosively-clad component. This already indicates that the method is only likely to be viable where these initial costs can be spread over a largish number of identical items or where the item can be fabricated from explosively-clad flat plate. It was not possible in the time available for the project to develop a method of explosively cladding the branch attachments to the header, so these were weld clad by the metal inert gas (MIG) process. The header was finally assembled by electron beam welding and the end result appears technically satisfactory although the economics remain in question.

Titanium

Most of the copper alloys in sea-water systems are susceptible to some degree of corrosion, and in fact this may be regarded in many cases as desirable since the copper corrosion products can perform a valuable function in inhibiting