THE PUMP-IN-PIPE
A PROGRESS REPORT

BY

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Introduction

A novel design of sea-water pump was described in the June 1976 edition of the *Journal of Naval Engineering* (Ref. 1). At that time it was still only a design, although much development work had been done and manufacture was well underway. It is now possible to update the story and report on the successes and disappointments encountered in the development to date, and to present photographs of the equipment rather than line drawings. The prototype unit (FIG. 1) has now successfully completed 5000 hours of operation in a sea-water filled test loop at the Submarine Machinery Installation Test Establishment (SMITE) at Barrow.

Pump-in-Pipe is a colloquial name for a sea-water pump for the main condenser cooling system in nuclear submarines. The significant advantages of this type of unit to the submarine designer are that:

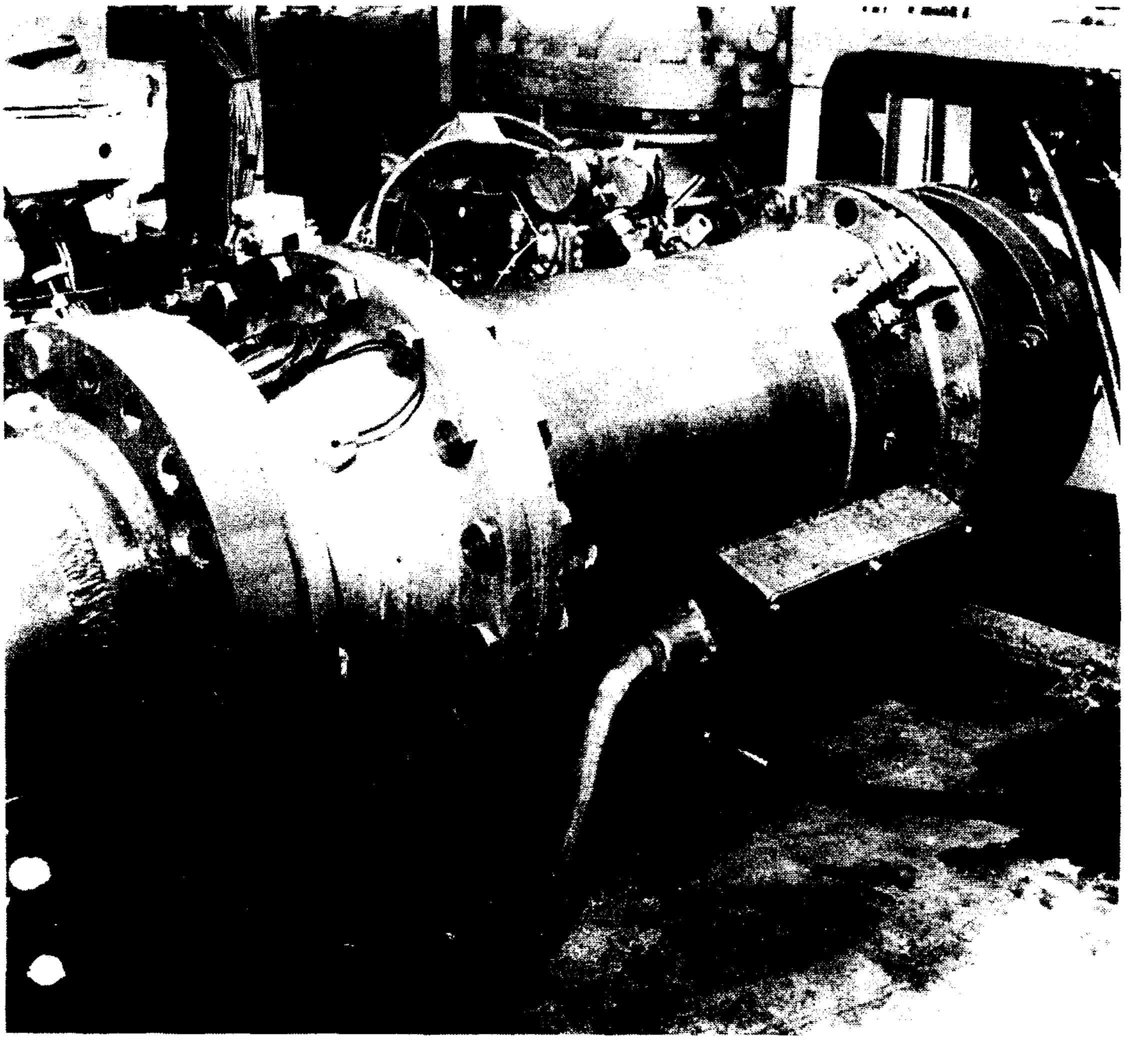

FIG. 1—THE MK I PUMP-IN-PIPE ON TRIAL AT SMITE

(*a*) it is installed in the line of the sea-water pipe and thus avoids the large moments, resulting from diving depth pressures, that occur with pumps mounted in pipe bends;
(*b*) the mechanical seal, a source of unreliability in current submarine sea-water pumps, is eliminated;
(*c*) Good inlet flow conditions lead to an efficient hydraulic design for the impeller with a good noise characteristic, this latter assuming ever greater importance in modern warship design;
(*d*) It allows novel condenser designs, such as the U-tube condenser, to be used.

During testing at SMITE, operating conditions at all depths and speeds have been simulated. The resistance of the pump to damage by particulate contaminant in the sea water has also been explored. A number of bearing materials have been examined. To date, experience gained in the design, manufacture, and testing of the prototype unit (Mk I) has allowed the design of an improved version (Mk II) to proceed. Design work on this Mk II prototype, matched to the specific needs of current submarine designs, started even before the Mk I was complete. Manufacture is now well underway and it is expected the unit will go to SMITE for testing in 1983.

Description of the Pump

A diagrammatic representation of the basic Mk I pump-in-pipe is shown in FIG. 2. The unit has a cylindrical outer casing with the pump and motor pod located inside it by support stubs and the flow guide vanes. The pumped sea water passes through the annulus between the outer casing and the motor pod. The support stubs carry electric supply cables, instrument leads, and small-bore pipes for venting and for supplying a low flow of filtered sea water to the internal circuit. These are the only external connections. No mechanical seals are needed. The rotor and stator windings are protected from the sea water within the unit by 'canning'. An auxiliary impeller circulates water through the rotor stator gap to heat-exchanger grooves

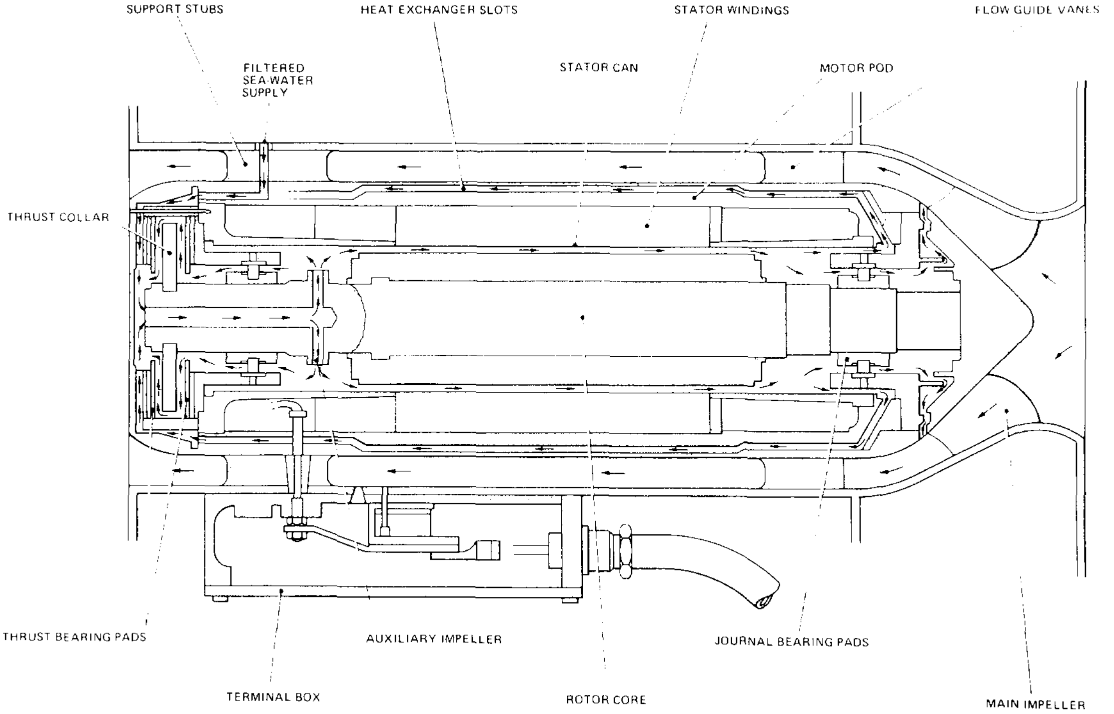

FIG. 2—DIAGRAMMATIC REPRESENTATION OF THE MK I PUMP-IN-PIPE

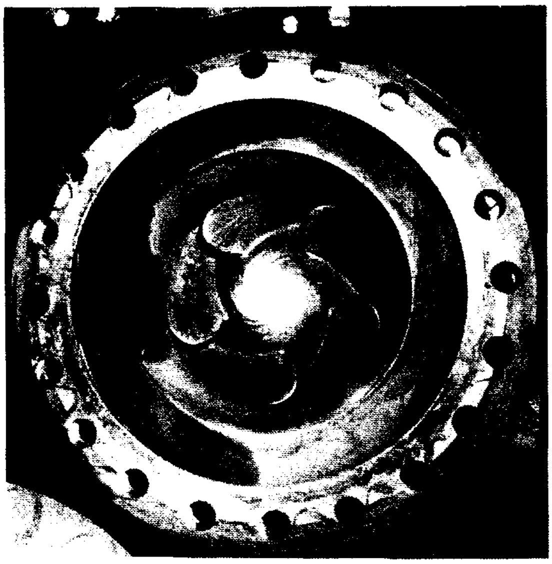

FIG. 3—VIEW OF PUMP FROM THE INLET END

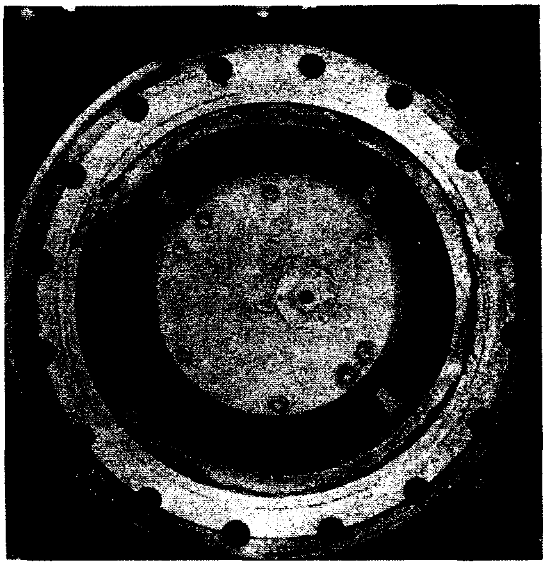

FIG. 4—VIEW OF PUMP FROM THE OUTLET END —MOTOR ROTOR INSTALLED

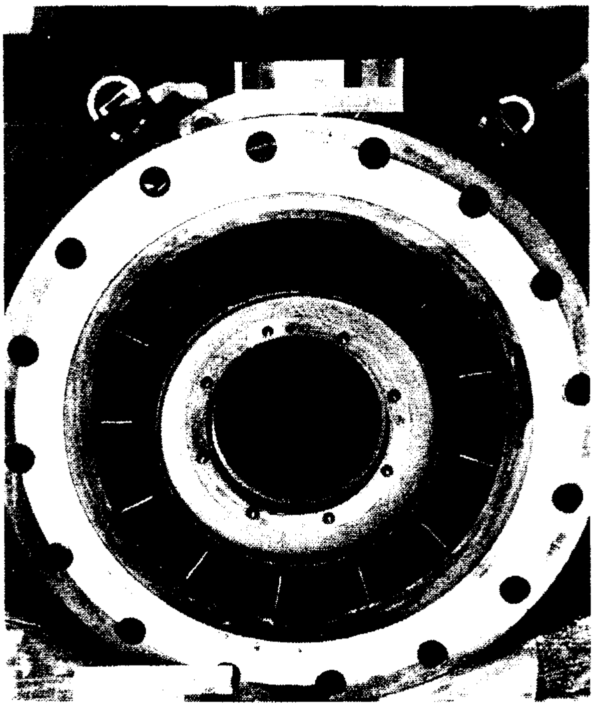

FIG. 5—VIEW OF PUMP WITH MOTOR ROTOR AND IMPELLER REMOVED. CANNING OF STATOR IS VISIBLE

adjacent to the main pump flow in order to remove the heat generated in the motor. This water also serves as the lubricant for the two hydrodynamic tilting-pad-type journal bearings and the thrust bearing. The motor is a two-speed machine of the pole amplitude modulated winding type. This permits a motor with a single-wound stator to operate at more than one speed by external switching only. FIGS. 3, 4, and 5 show internal views of the unit.

Project History

Project development started in 1973 following earlier feasibility studies. Until 1977 the project was little more than a vehicle to prove an attractive concept and the need for the programme was under constant scrutiny. In 1977, however, the ability to adopt other novel design features in the condenser and cooling-water system became entirely dependent on the availability of the pump-in-pipe. Work went ahead with a renewed impetus, but still in an atmosphere of restricted financial resources. A determined effort was made to overcome some of the technical problems encountered in the manufacture of the prototype and to break free of the stop-go environment that had characterized the development to that time. A target date for delivery of the prototype unit was set for June 1978. Relaxations in the specified performance were allowed in the interest of cost saving but without prejudice to the function of the design as a proving vehicle for the basic and novel features of the pump. Preliminary design work was also put in hand at this time for the Mk II pump which would closely match the needs of a specific submarine design. For reasons explained below, delivery of the Mk I unit did not take place until May 1979. However, by the end of that year, the concept was sufficiently proven that work on the further development and refinement of the standard submarine sea-water pump to meet the needs of future designs was discontinued.

Programme Co-ordination

As might be deduced from the authorship of the earlier article in this *Journal,* a diverse project team has been involved in this development. The work has been sponsored within the Ship Department by the Director Project Teams (Submarines) (DPT) under the auspices of the Secondary Plant Improvement Programme (SIP). Under this latter programme the management of the activities of the prime sub-contractors has been carried out by Y-ARD on behalf of the Ministry of Defence. The Ministry Project Officer has been provided by the Director Ship Design and Engineering. The prime sub-contractor with responsibility for the design and manufacture of the pump unit has been the Special Contracts Department of GEC Machines Ltd., Bradford. Inputs to the development have been made by Ministry of Defence and other Government R & D Establishments, Specialist University Industrial Support Departments, and a number of specialist high technology manufacturing and design sub-contractors to GEC.

Since there was no precedent for the design, particularly with respect to component life, reliability, and system integrity, a very detailed design and development programme was necessary. Supporting rig test work on components was undertaken with the aim of proving as many features as possible before incorporating them in the prototype. The work may be conveniently described by dividing it into four main areas broadly equating to the nature of the sciences involved but with the inevitable interfaces and interactions between each. These areas are:

- (*a*) Electrical
  - (*i*) Motor construction.
  - (*ii*) Canning.
  - (*iii*) Heat rejection.
- (*b*) Hydraulic
  - (*i*) Impeller.
  - (*ii*) Flow passages.
  - (*iii*) Hydraulic noise.
- (*c*) Mechanical
  - (*i*) Bearing design and arrangement.
  - (*ii*) Tribology.
  - (*iii*) Use of ceramics and cermets.
  - (*iv*) Plastics.
- (*d*) Materials
  - (*i*) Corrosion resistance.
  - (*ii*) Casting and forging.
  - (*iii*) Fabrication.
  - (*iv*) Welding.

Electrical

The principal features of the electrical design were described in Reference 1. This design was based on GEC's considerable experience with canned motor technology though hitherto this had not been exploited in the sea-water environment. Models and test rigs were used to establish and prove aspects of the design peculiar to the pump-in-pipe. These included a full-size slot model to examine the problems of using wire rather than strip windings in the canned motor environment. The core model was used to explore manufacturing uncertainties, in particular the 'potting' of the end windings. A model of the solid rotor bars was used to gain experience of fitting conductor bars to the solid rotor core. This proved the basic design and ensured that

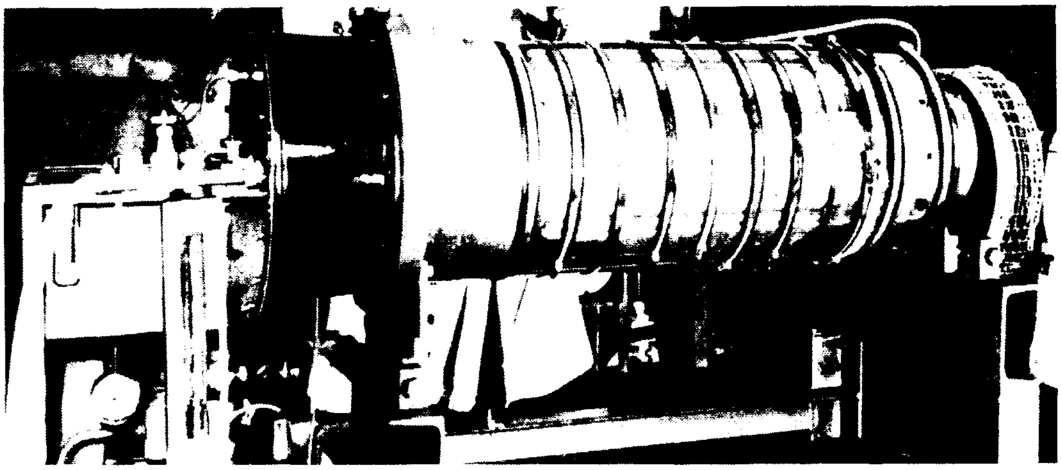

FIG. 6—MOTOR COOLING CIRCUIT TEST RIG.

machining operations produced a rotor with minimal variation of electrical and thermal properties between bars and sufficiently well balanced to meet the stringent N and V targets under all conditions.

The rotor and stator windings are 'canned' with an Inconel alloy. Thin sheet material (0·5mm) is wrapped to a cylindrical shape and welded along the longitudinal seam. The cans thus formed are fitted to the rotor and stator and sealed with circumferential welds onto suitable landings at each end. Considerable expertise is required to achieve the necessary weld quality on such thin material without either distortion or an unacceptable weld bead. A similar technique is used to make the sleeve which fits over the longitudinal channels on the stator frame adjacent to the main sea-water flow which forms the internal cooling circuit heat exchanger.

In order to prove the design of the internal flow circuits, a full-scale model with an externally-driven rotor was constructed (FIG. 6). From this model the size of the auxiliary impellers was determined and the details of the water channels refined. Information from this model and a computer thermal model formed the basis for the confirmation of the thermal performance of the motor and cooling circuit.

Normal motor tests are inadequate to check fully the design parameters of canned motors. A stator-rotor test rig was necessary to test the motor at intermediate stages of manufacture. Finally, the whole motor was tested as a unit without the pump impeller and a full temperature assessment made. During testing at SMITE, the electrical design has been well proven with only two areas causing concern. The first was associated with a known concession during manufacture and resulted in a high end-winding temperature at one end of the machine. The effect was aggravated in the test loop due to difficulties in maintaining the water in the closed loop at ambient temperature. Even after modifications had been made to the test loop, it was still not possible to keep the water at ambient temperature at the higher powers, loop temperatures rising steadily over a matter of hours. A similar situation cannot arise at sea. The second area concerned the insulation resistance of the windings. This resistance was regularly monitored and although varying above a generally satisfactory level it did on occasion fall away significantly. On one occasion, water had entered the terminal space and, after extensive pressure testing with helium, it was concluded that the water had entered the machine from the outside through an instrumentation connection peculiar to the prototype. Other variations in resistance were eventually attributed to the electrical supply cables being allowed to lie in puddles of water on the test house floor!

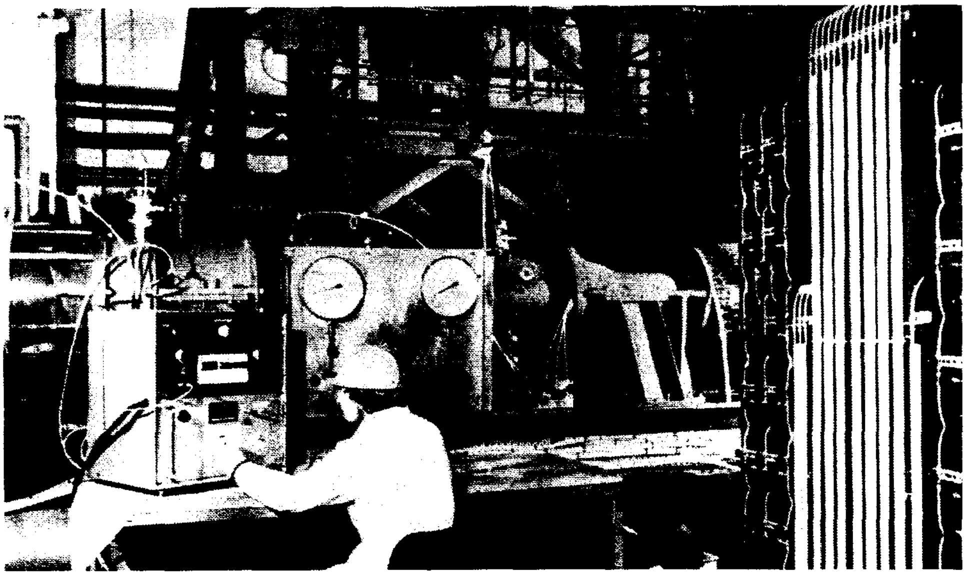

FIG. 7—MODEL TESTING OF IMPELLER

Hydraulics

The hydraulic design and development was undertaken with the aim of using a mixed flow impeller and diffuser to achieve the specified performance with minimum cavitation and to meet the stringent noise targets, both hydraulic and airborne. The design procedure adopted was very similar to that used in propeller design, that is: a paper design derived from a computer programme, translation to a model, testing of the model (full scale) in a hydraulic test loop (FIG. 7), modification of the model to optimize the noise and hydraulic performance, spacial measurement of the final model leading to production of the manufacturing drawings or direct manufacture by copy machining from the model.

The impeller hydraulic design had to be optimized to achieve the two different performance targets at the two motor operating speeds with varying scoop (the boost effect in the pump suction due to the submarine's forward motion) and inlet pressure conditions. The flow passages were designed such that the maximum allowable water speeds, to eliminate erosion, were not exceeded for the applicable materials, whilst not being so large that the machine would not pass through the hatches in the equipment removal routes.

During testing at SMITE, the hydraulic performance is assessed at frequent intervals, and during the first phase of the tests extensive noise measurement trials were conducted. The results of these tests proved the adequacy of the design. Correlation of the results from the pump with those from the model in the design phase provided a data base for the design of the impeller for the Mk II pump by similar methods. Noise is a complex subject and, in the context of submarine design, subject to a high security classification. Suffice it to say that the testing of the pump has demonstrated the capability of this type of unit to meet the stringent ship targets. The visitor to the SMITE test rig is always impressed by the absence of airborne noise, normally associated with the fans of large motor-driven pumps, and he has to study the test loop instrumentation to determine whether the pump-in-pipe is operating or not!

Some damage was caused to the pump main casing in way of the impeller during loop testing. A hard piece of plastic material with mill-scale embedded in it caught on the tip of an impeller blade and 'machined' a circumferential groove in the casing. Calculations indicated, however, that there was sufficient strength remaining to allow testing to full pressure to continue. The plastic came from a continuous coating applied to the internal surface of the steel pipes in the test loop. (Economic factors prevented the building of a complete test loop in non-ferrous materials!) A subsequent historical survey of defects in pumps with similar inlet configurations in older classes of submarines indicated that debris entering the pump had not been a problem and the failure experienced on this occasion was due to the nature of the test facility. However, it had already been decided, for reasons of manufacturing, to design the flow surface in way of the impeller in the Mk II as a replaceable insert, not as part of the pressure casing.

Mechanical

The principal feature of the mechanical design and development has been the bearing arrangement and design. Work has embraced the full spectrum of tribology including bearing geometry, the use of ceramics and cermets and, latterly, plastics. At the outset of development the objective was to achieve very long bearing lives in a lubricating medium which it was recognized could contain sand particles. High wear resistance was necessary to maintain the rotor position and to prevent the occurrence of unbalanced magnetic forces which would occur if the rotor became eccentric in relation to the stator. The most promising solution to the problem lay in having the hardness of the two bearing surfaces well in excess of that of sand. (The hard-on-hard concept.) Extensive tests eventually led to the selection of hot-pressed silicon nitride (HPSN) journal pads and tapered-land thrust discs running against tungsten-carbide coatings deposited on an Inconel alloy for journal sleeves and thrust runner. In spite of many thousands of hours of successful testing of the concept in various rigs, the performance of this material combination in the pump proved totally unsatisfactory.

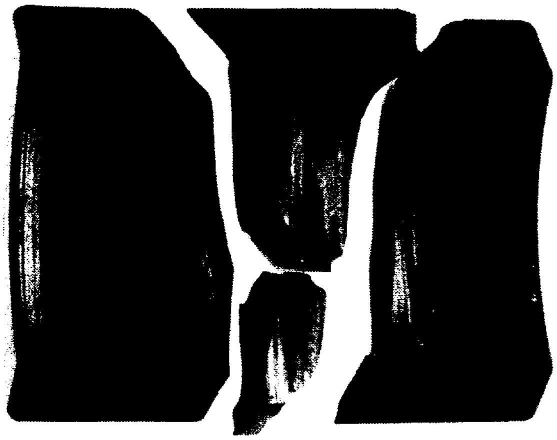

FIG. 8—HOT-PRESSED SILICON-NITRIDE TILTING PAD JOURNAL BEARING AFTER FAILURE

During motor trials in the completed pump, but without the impeller fitted, a catastrophic failure of the HPSN bearing pads occurred, suddenly and without warning (FIG. 8). Investigations demonstrated that the bearings had been starved of lubricating water due to vortex formation in the internal circuit. Although this was almost certainly the incipient cause of the failure, the precise mechanism which caused the shattering of the pads was not fully understood. Clearly such a rapid and unpredictable failure mechanism is totally unacceptable in equipment for submarines. Vortex spoilers were fitted in the internal circuit. To allow pump testing to progress in order to prove other features of the overall design, the bearings were changed to the more conventional hard on soft arrangement. The HPSN tapered-land thrust discs and the tungsten-carbide-coated journals were retained running against asbestos-filled phenolic resin facings fixed to the thrust runner and tilting pads respectively. This immediately presented a new range of design problems due to the dimensional instability of the asbestos-filled phenolic resin in sea water. Whereas gluing of the facings to the backings had proved successful in fresh water, this was not the case in sea

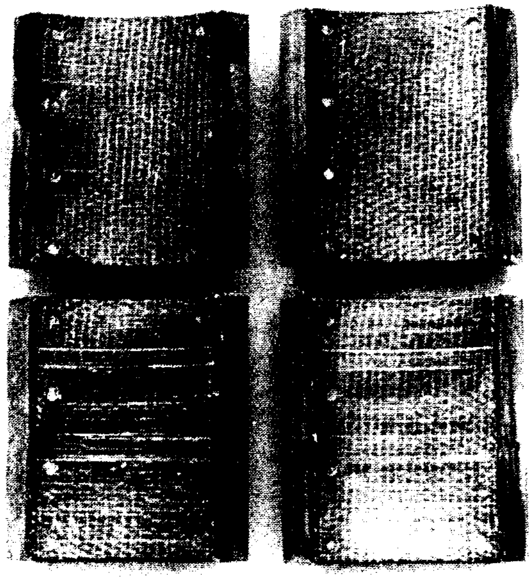

FIG. 9—ASBESTOS-FILLED PHENOLIC-RESIN -FACED JOURNAL BEARING PADS—RIVETED TYPE

water and the gluing had to be backed by riveting (FIG. 9). Initial riveting with copper rivets was soon superseded by the use of monel rivets to obviate corrosion of the rivet heads. Although riveting has been retained to date for securing the facings to the thrust runner, the facings of the journal bearing pads are now secured by spring-loaded clips to allow relative growth, circumferentially, due to water absorption.

At the time of switching to asbestos-filled resin bearing surfaces, it was recognized that the handling and machining of asbestos-containing materials was becoming more problematical due to the associated health hazards. Furthermore, current indications from pumps in service were that the material would not provide the requisite long bearing life. A better material was urgently required! Following advice from AMTE (Holton Heath) a dozen materials, some plastics and some metal, were subjected to small coupon 'rubbing pair' tests at Swansea University Tribology Centre. The best of these materials would be endurance tested as pads against tungsten-carbide-coated journals in a GEC test rig. The asbestos-filled resin was used as a datum in these trials. Although the Swansea tests indicated several materials with a superior performance, not all of them could be fabricated or engineered into the necessary configuration for full scale testing. At the end of the programme at GEC, only one alternative plastic material and one metal were found with a performance apparently superior to the asbestos-filled resin. The plastic fitted as a pad facing failed when tested in the pump at SMITE after comparatively few hours and the metal (phosphor bronze) when fitted in the pump exhibited an unacceptable corrosion characteristic on the bearing surface. Recognizing the advantage of using monolithic pads for journal bearings, rig tests are now being put in hand to evaluate the properties of Inconel alloys as bearing surfaces. Meanwhile, the pump-in-pipe continues to operate most satisfactorily on the asbestos-filled phenolic resin bearings in both clean and contaminated conditions in an operating cycle which includes a significant number of starts and stops, thus putting the bearing frequently through the arduous boundary lubrication regime. The success of the combination is probably due to the very hard journal surfaces which do not become damaged by sand particles embedded in the softer material.

Ultimately, however, it is believed that, to achieve the original objective of very long bearing lives in the contaminated environment, the hard-on-hard principle must be invoked. It is necessary, therefore, to engineer a rugged backing to the tribologically successful hard wearing surfaces. Experience in this extensive development programme for future applications indicates that there are some gains to be achieved, by exploiting the lessons learned, in pumps currently at sea in order to extend their between-overhaul lives and to improve their reliability.

Materials

Material selection has progressed concurrently with design and development. The constraint of producing the pressure containment in scantlings determined by pump flow, motor size, inlet/outlet pipe dimensions, and shipping routes has presented an interesting problem, since the selected materials must have adequate strength, e.g. proof stress, fatigue strength, erosion and corrosion resistance, and yet be suitable for fabrication by casting, forging, and welding, the latter often in mixed pairs. The material selected for the Mk I casing was a proprietary high-strength cupro-nickel. The main casing was fabricated by the welding of castings and, although success was eventually achieved, the material and procedures involved could not be handled with the confidence necessary to proceed to a full production programme, particularly if larger components were to be required. In the meantime, the Ministry of Defence had defined a nickel aluminium bronze (NAB) alloy (DGS 348) for use in pressurized castings. It was decided that design of the Mk II machine should be based on the use of this material. The highest integrity casing was to be obtained by electron-beam welding of centrifugal castings, even though these latter had to be purchased from outside the U.K. Detailing of the design was proceeding well when AMTE (Holton Heath) published the results of long-term corrosion tests of DGS 348 in sea water. The material was susceptible to crevice corrosion in the heat-affected zones of welds—not of itself a complete bar on its use but the extent of any corrosion could not be determined by currently available NDT techniques. If the pump casing was to last the life of the submarine, then this material was unacceptable unless all through welds in the pressure containment could be designed out. This was not possible and, following a re-appraisal of the design, those sections requiring fabrication by welding of NAB have been replaced by the lower strength forged 70/30 cupro-nickel. The problem might have been overcome, at great expense, by the use of titanium. However, it will probably be more cost effective to continue development and proving of high-strength cupro-nickels, which fulfil all the requirements for the production of sound castings, and with good weld and corrosion characteristics.

The Mk II Design

The development of the pump-in-pipe and the successful proving of the Mk I design has been a long and complex series of activities. The design of the Mk II unit is now essentially complete and manufacture is in progress. All the techniques used in the manufacture of this second unit are to be applicable to quantity production of the machine. The essential features that have changed as a result of the development programme and testing of the Mk I are summarized below:

(*a*) *Motor:* Revised design to recognize changes in power to meet revised pump duty.

(*b*) *Terminal box:* Improved design to overcome problems of water-tightness and arrangement accepted in Mk I design.

(*c*) *Impeller:* Design modified to match revised head and flow requirements.

(*d*) *Shaft and rotor:* Design changes to allow improved production techniques. Greater use of Iconel alloys.

(*e*) *Bearings:* Design flexible in this area so that the latest available proven bearing design and material combination can be fitted during manufacture or subsequently. Fitting of a cyclone separator in the water supply to the internal circuit to minimize contamination.

(*f*) *Casing:* Change of materials and fabrication techniques. Inner non-pressurized shaped casing in way of impeller. Central flanged joint to improve access for maintenance/inspection. Use of centrifugal castings and electron-beam welding.

Conclusion

In conclusion it can be stated with confidence that the pump-in-pipe concept has been proven. The course has been hilly and not all the specific targets quantified at the outset of the development programme have yet been achieved. However, the Mk I unit has demonstrated on trials that the pump-in-pipe has the capability of achieving improved levels of reliability over existing designs, eliminating the mechanical seal, and providing significant advantages to the submarine designer in terms of space and layout. The development work will also have some spin off to other areas. Canned motor technology in the sea-water environment may have application to pumps other than the main circulating-water pumps in future designs, and the bearing developments could find wide application in the pump field where the quest to improve reliability is ever present.

Acknowledgement

This article is based on a presentation made in the Ship Department on 13 March 1981. Views and opinions expressed are those of the author and do not necessarily represent those of the Ministry of Defence. The author gratefully acknowledges that this article has only been made possible through the contributions made to the project by a large number of people from the Ministry of Defence, Industry, Government R & D Establishments, and Universities.

Reference:

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