THE VANGUARD CLASS MAIN CIRCULATING WATER PUMP

SUPPORT ARRANGEMENT

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ABSTRACT

The MK3 Main Circulating Water Pump (MCWP) is a high integrity unit installed in VANGUARD Class nuclear submarines to provide seawater for main condenser cooling. The MCWP is a novel 'pump-in-pipe' design with the fully enclosed pump and electric motor installed within the pipework.[1,2] The materials used include copper and nickel alloys selected for strength, resistance to corrosion and marine growth. In service, the pump components have suffered from corrosion, which has been greater than expected. This resulted in a need for early replacement, and presented a threat to availability due to reduced stock levels.

In 1999 the MAES Integrated Project Team took the view that a long term, strategic Partnering Arrangement should be entered into with ALSTEC.* The objective was to provide a total support package aimed at restoring stock levels and addressing design improvements to achieve an installed pump life of 11 years. The Arrangement was conceived as a SMART Procurement Initiative and has since become a model for other such partnerships.

The project is now in its fifth year and this article examines the logistic and technical developments that have contributed to the success of the Support Arrangement.

DESCRIPTION OF THE MAIN CIRCULATING WATER PUMP (MCWP)

The MCWP is critical to safe operation of the submarine. It is often described as a 'Pump-in-Pipe' since the canned electric motor is contained within the body of the pump (FIG.1). It is a First Level item subject to diving depth pressures.

Layout

VANGUARD Class Submarines have independent mirror-image port and starboard Circulating Water Systems (CWS). Each system has a MCWP to provide a flow of to the sea water condenser.

The MCWP is horizontally mounted between the inlet flexible pipe and the condenser inlet taper piece. The pump can be easily modified to allow installation in either the port or starboard CWS.

Duty

Operating the pump in three distinctive modes (Fast Speed, Slow Speed, and Trailing) controls the flow of sea water through the condensers in the boat CWS. Trailing occurs when the pump is de-energized and is caused to rotate by the flow in the system generated by the forward motion of the boat i.e. the scoop effect.

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* ALSTEC Limited was part of ALSTOM Ltd up to the management buyout in June 2000. Previous to this, it was GEC Alsthom, part of the group responsible for the original design, development and manufacture of the pumps.

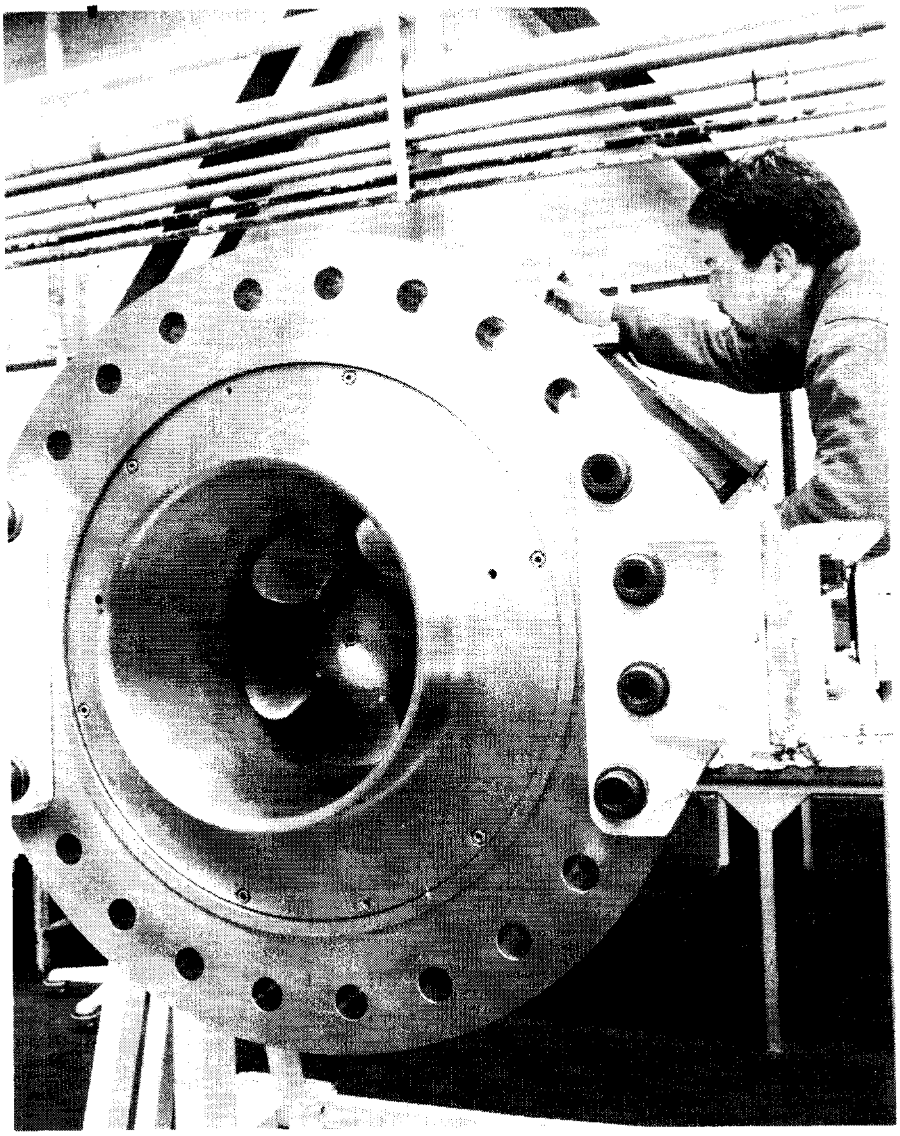

FIG.1 MCWP

Pump Design

The pump is a single stage mixed flow type with co-axial inlet and discharge. It consists of a five-bladed impeller mounted directly on the motor shaft (rotor) discharging into a thirteen-vane diffuser that supports the inlet end (Drive End, (DE)) of the motor pod. Four streamlined spokes through which the electrical and clean supplies are fed support the outlet end (Non-Drive End, (NDE)) of the motor pod. The direction of rotation is anticlockwise when viewed from the pump inlet for both pumping and trailing modes. A general arrangement is shown in (FIG 2).

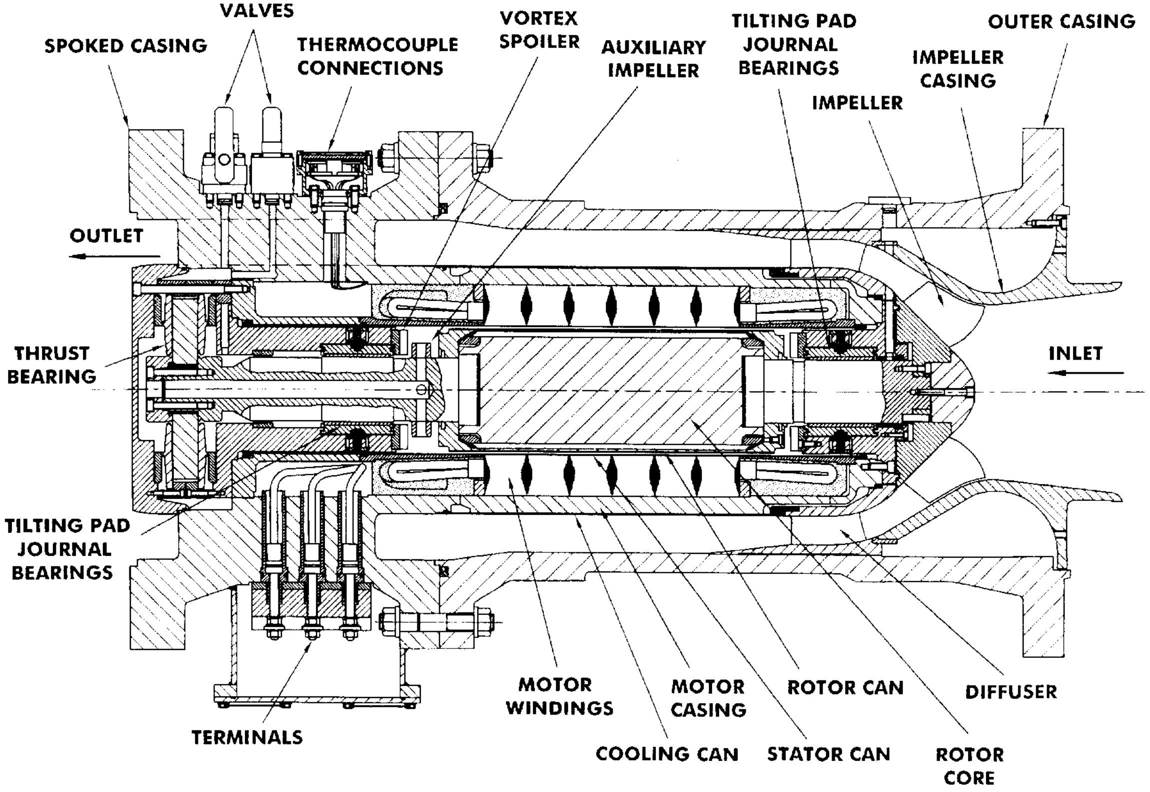

Fig.2 MCWP GENERAL ASSEMBLY

Motor

The motor is a three-phase 440Volt, 60Hz canned squirrel cage induction motor capable of operating at two speeds. To eliminate the problems associated with conventional rotating shaft seals, the pumped liquid (sea water) is allowed to enter the interior of the drive motor. The seawater is hermetically sealed off from the electromagnetic components by thin metallic cylinders known as 'cans', fitted to both the rotor and stator. The sea water acts as a coolant for the motor and a lubricant for the bearings.

The rotor has a solid core with 52 straight rectangular 'high resistance' bars (phosphor bronze) resulting in a high slip characteristic to achieve the hydraulic performance requirements.

Bearings

All bearings are seawater lubricated, hydrodynamic types with 'hard-on-hard' material combinations to minimize wear. Rotor journals and thrust bearing components are hard coated with chrome oxide and the journal pads are fitted with hard ceramic linings, manufactured from hot pressed silicon nitride.

The radial bearings consist of two identical assemblies, each comprising of four tilting pads with offset pivots. The thrust bearings consist of two similar taper-land type units, each comprising six segments to carry thrust loads in either axial direction.

Cooling

An integral auxiliary impeller on the rotor shaft generates an internal circulation of seawater coolant. The coolant transfers waste heat generated by the rotor and stator via the Cooling Can on the outside of the motor pod to the seawater flowing through the pump. This internal circuit is fed with a purge flow of filtered seawater from the Clean Seawater System to prevent ingress of particles into the internal circuit from the seawater flowing through the pump.

External facilities are provided to vent air from the internal seawater circuit to minimize the risk of loss of lubrication to the bearings.

Corrosion

The degree of in service corrosion varies in extent from pump to pump but nevertheless follows a pattern. The pumps fitted to HMS *Vanguard* suffered from severe corrosion of the Spoked Casing to such an extent that it posed a threat to the pressure boundary within the planned pump life. This was possibly due to the conditions experienced during first of class commissioning, including extended dockside times with stagnant seawater in the CWS. Improved care and maintenance procedures have since been implemented and there have been no repetitions of this problem.

Pump impellers are made from Nickel-Aluminium Bronze (NAB) and have exhibited high corrosion rates, up to approximately 300g/year (FIG.3). The resulting loss of profile adversely affects pump performance in terms of head, flow rate, motor speed, temperature and noise. The worst case resulted in an impeller running out-of-balance. Impeller corrosion is life limiting.

FIG.3 CORRODED NAB IMPELLER

Other pump components made from copper alloys suffer from corrosion, but not to the same extent as the impeller and are not life threatening. Local features deteriorate, for example in regions of low water flow between components and where there is localized erosion.

Damage due to debris

Three failures of the hard on hard ceramic coated thrust bearings have occurred due to entrainment of debris causing overload. Improved care and maintenance procedures have been implemented by fitting strainers to the CWS intakes prior to dockside working.

STRATEGIC PARTNERING ARRANGEMENT

Following the high profile in-service failures of the MCWP, ALSTEC worked closely with the MoD under a number of short term contracts to establish a repair and technical support service for the MCWP to overcome critical supply problems.

The MCWP is a high value asset with a small in-service population and the Ministry recognized the opportunity for new ways of working with ALSTEC as part of the SMART procurement initiative. A longer-term arrangement was envisaged to remove uncertainties and provide a basis of stability for both parties, with opportunities for Cost Of Ownership (COO) reductions and improvements to pump life.

In August 2000, MAES IPT entered into a 10-year arrangement with ALSTEC for MCWP support. Key features of the Arrangement are:

- A partnering approach with common goals based on availability, COO reduction and life improvements.
- Provision of a total support package for the MCWP.
- Core tasks - for management, technical support and initial production of new pumps and spares.

- Variable tasks for emergent boat visits and development investigations.
- Restoration of stock levels.
- Design improvements to reinstate a pump life of 11 years.
- Standard menu based repairs.
- ALSTEC act as the Delegated Equipment Design Authority for the pump.
- Target cost framework giving incentivisation (profit sharing) for cost reduction

Core tasks

ALSTEC set up a core team responsible for the operation of the contract and providing the main point of contact for MAES IPT. The project manager is supported by project and technical staff responsible for providing technical support to the fleet and liaison with stakeholders. The core team also manages:

- The manufacture of new build pumps.
- Spare assemblies.
- Repair and overhaul of operational pumps.
- Performance testing of new and refurbished pumps.
- The provision of development, investigation and evaluation services.

COO

A key objective of the Support Arrangement is to provide a reducing COO to the Ministry over the life of the contract.

COO is used to provide the projected whole life cycle costs incurred in the ownership of plant and equipment. It enables decisions to be made in regard to on-going maintenance and development improvements and removal of pumps from service. The output of COO analysis is in the form of simple spreadsheet based tables or graphs on a time line for various scenarios.

The assumptions made in preparing the COO model are recorded in the Master Data and Assumptions List (MDAL). The MDAL addresses factors such as:

- Purchase cost.
- Anticipated life.
- Running costs.
- Maintenance costs.
- Refurbishment costs.
- Replacement costs.
- Residual value.

It also includes Treasury Opportunity costs.

COO models are used in conjunction with Investment Appraisals to support investment decisions.

Main Cost Drivers

The Main Cost Drivers affecting the COO model have been identified as

- Frequency and cost of repairs.
- Number of spare pumps held in stores to meet availability targets.

- Project administration costs and labour rates.
- Treasury Opportunity charge (a percentage of the book value of spare pumps not installed in a boat is levied by the Treasury).

Incentivisation

The Support Arrangement operates within a Target Cost Incentive Fee (TCIF) framework to provide a financial incentive (profit/risk sharing) for ALSTEC to achieve cost reductions.

Stakeholder Involvement

A key feature of the Support Arrangement is the active involvement of all Stakeholders in the MCWP supply chain, where stakeholders have direct access to the ALSTEC core team to resolve queries. An annual stakeholder review is held to promote the exchange of information including forward plans and to review stakeholder risks associated with the MCWP.

The immediate benefits of regular stakeholder liaison are:

- Involves all parties in the supply chain.
- Good communications.
- Provision of direct technical support and liaison for routine queries and problem solving.
- Improved safety & reduced risk levels.
- Opportunities for improvements can be explored.

Technical Support

Under the Support Arrangement, ALSTEC provides a centre of expertise for all MCWP matters. Direct access to the ALSTEC core team provides an efficient support route and reduces the workload on the MAES IPT.

The scope of technical support includes:

- Condition monitoring.
- Boat and shore staff training.
- Pump knowledge database.
- Routine commissioning and in-service examinations.

Condition-Based Monitoring

Implementation of Condition-based Monitoring (CM) is a key diagnostic tool for monitoring MCWP performance and trends. The role of CM becomes increasingly important as the service life of pumps is extended beyond the current 3.5 years and minimizes the risk of unplanned failures that could adversely affect a boat mission or the cost of ownership.

Training and Education

An annual training and education programme has been established for boat and base staff. This provides the opportunity to maintain the high profile of the MCWP and to reinforce the importance of operating and upkeep procedures. The programme also provides an opportunity for updating boat staff on new developments and emerging issues.

Opportunities for naval staff to visit the ALSTEC manufacturing facilities are encouraged as a means of building good relationships and improving communications. Direct liaison with boat staff has significantly reduced the risk of accidental damage to the MCWP and has contributed to a significant increase in the interval between pump changes.

Knowledge Base

ALSTEC operates a Knowledge Management System that comprises the 20 years of historical documentation concerning the design and operation of the pumps. It is used, for example, when tracking the history of pump components when sentencing them after service and for the provision of technical support for routine queries and problems.

Commissioning and Performance Monitoring

As a risk mitigation task, ALSTEC personnel are responsible for commissioning pumps after installation and for routine follow up visits to carry out performance monitoring of in service pumps as part of condition monitoring. These checks include Remote Visual Inspection (RVI) examinations and Noise and Vibration measurements.

Risk Management

Risk management forms an integral part of the Support Arrangement and a common project risk register was established at the outset to record the key risks for both ALSTEC and other Stakeholders. An output from the management tree is shown in (FIG.4).

ALSTEC risks were mainly concerned with the difficulties in manufacture and overhaul of pumps, following a 5-year gap in production. Stakeholder risks were concerned with logistics, installation and operational issues.

The risk management strategy was to:

- Identify risks at the earliest opportunity.
- Identify risk mitigation and avoidance strategies and their cost effectiveness.
- Manage and control risk.
- Adapt mitigation and avoidance actions as new practical problems emerged.

This strategy was a significant factor in achieving deliveries on schedule and within budget.

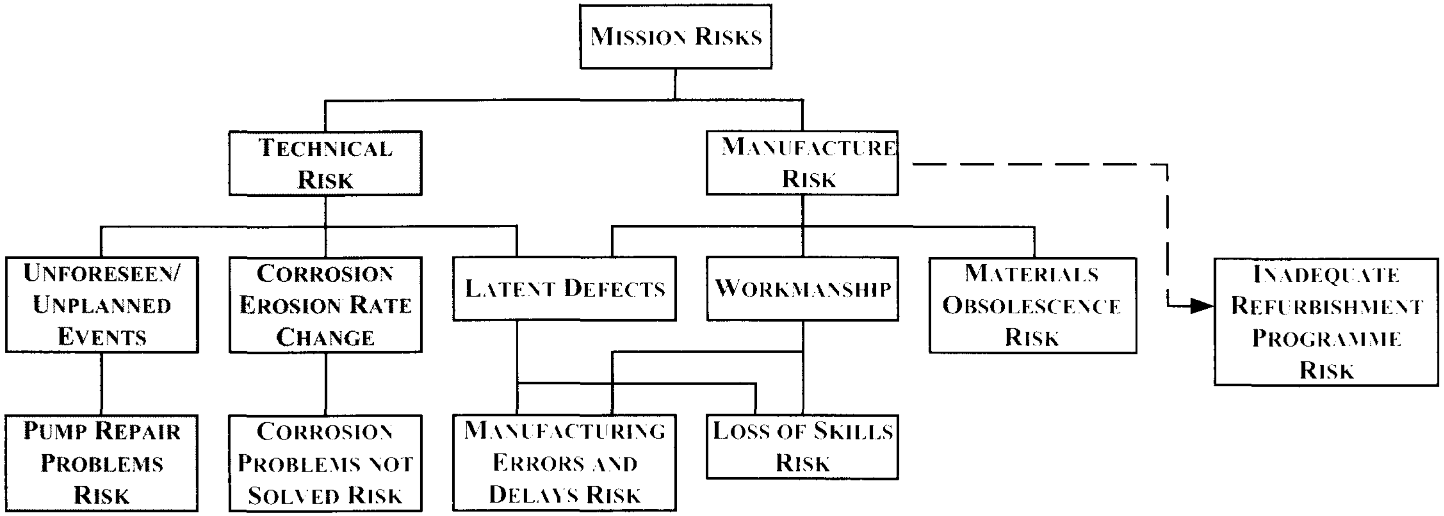

Fig 4 GENERIC RISKS

Manufacture and repair of pumps

There was a gap of some 5 years between completion of the original batch of 12 MCWPs manufactured at GEC Large Machines at Bradford and the start of this current Support Arrangement. Although drawings and background documents had been transferred to ALSTEC many skills had been lost.

Considerable engineering challenges were encountered in re-establishing capability for manufacture of seven new pumps, both within ALSTEC and in sub-contract activities.

The greatest difficulties arose with manufacture of the motor casing assembly and interpretation of the radiographic examinations.

Motor Casing Assembly

The casing assembly comprises a spoked casing, an inner casing and a drive end inner casing that are Electron Beam (EB) welded together by a specialist sub-contractor.

The three components are made from forgings of 70/30 Cu/Ni compliant to NES 780 Part 2[3] with precise male/female location features used to accurately locate the items prior to EB welding.

The material contains very low quantities of dissolved gases that are released during welding. These gases can become trapped as the weld pool solidifies and appear as porosity within the weld.

The welded assembly requires a full penetration weld of the 21mm thick casings.

EB Welding

The EB weld process is autogenous, i.e. no filler material is used.

The assembly is carefully cleaned and aligned prior to EB welding. The power, feed rate and position have to be carefully controlled during the welding process, since the EB produces a thin tapered weld approximately 0.5mm in thickness at the root (FIG.5).

Typically one circumferential weld takes approximately 130 seconds to complete. Difficulties can arise when completing the weld as the beam penetration is reduced. This has the effect of dragging inclusions contained within the terminating pool of molten material back through the weld. The root of the weld is contained within a spigot and is machined off on completion.

70/30 Cu/Ni is recognized as difficult material to weld due to the amount of dissolved gas in the alloy allowed within the limits of NES 780 part 2.[4] Extensive metallurgical investigations have concluded that the amount of dissolved gas is linked to the use of cast iron chills at the initial casting stage. Significantly this can be reduced by the use of 'white cast iron chills' with carbon in a combined form, rather than the normal 'grey cast iron chills'.

In the absence of unique international standards for EB welds, ALSTEC has generated working practices and acceptance standards based on best weld practices established by international bodies and tests.

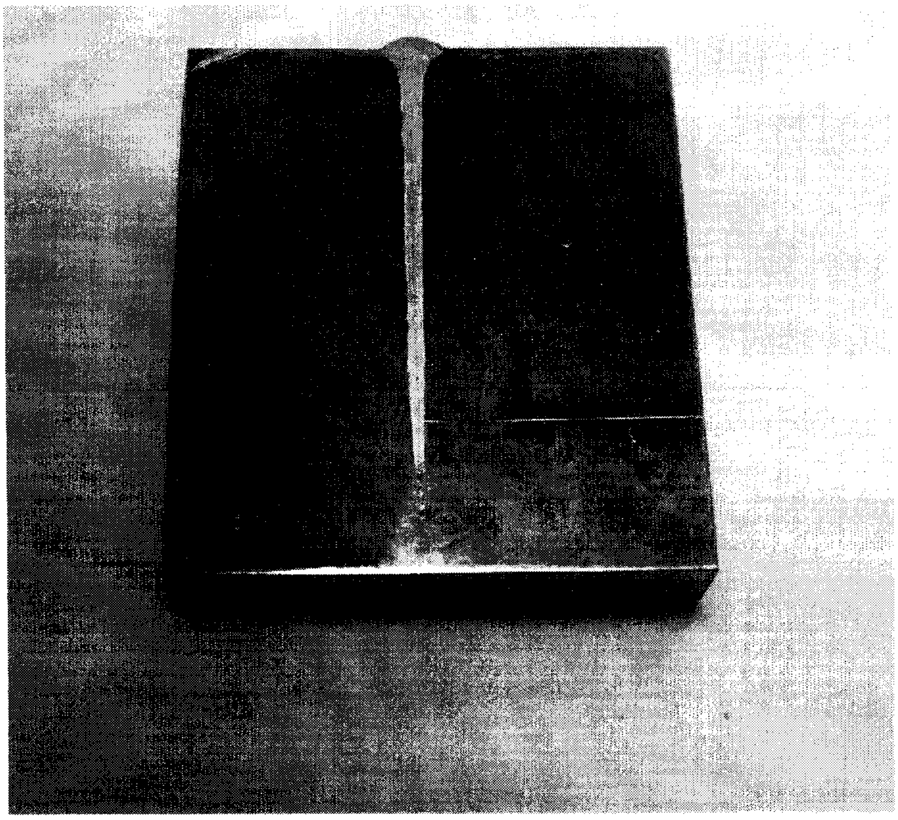

FIG.5 MACRO SECTION THROUGH A TEST EB WELD

Non Destructive Examination

After EB welding, the casing is required to be radiographed and dye penetrant examined. To improve the quality of the radiographs the casing welds are machined to remove surface blemishes prior to examination.

The acceptance standards for the weld are based on radiographic examination in accordance with NES 773,[4] which replaces the original DGS 10000. However clause 0104 specifically excludes EB welding.

Interpretation of radiographs has been difficult because the EB weld is narrow and radiography in the plane of the weld is not possible. There are particular problems in distinguishing between porosity, inclusions and missed joints.

The geometry of the welded items is not suited to normal ultra-sonic examination, and dye penetrant testing cannot be used until the weld is believed to be satisfactory because the presence of even small amounts of dye can cause problems when attempting a weld repair.

Supplementary techniques were utilized to gain as much information as possible about the nature and quality of the welds:

- 'Shift-shot' radiography (examining the weld by radiography at 30° to the plane of the weld).

- 'Time-of flight' ultrasonic testing (comparing the relative time differences of ultra-sound waves through sound and porous material).
- Pressurised helium leak testing.

Bearings

ALSTEC manufactures tilt pad bearings employing hard facings. The ceramic materials resist wear due to small hard particles in the clean sea water supply. The bearing surfaces can be ground and lapped to tight tolerances, typically 3microns roundness and cylindricity, to achieve the required reliability and noise and vibration specifications.

The original thrust bearing design employed a complex taper land disc arrangement, which was difficult to manufacture. An alternative Kemel tilting pad thrust bearing has been tested over many years in situations representative of all likely conditions that may be experienced in a boat. The results have shown that this bearing has a greater capacity to cope with adverse conditions than the current taper land bearings. A pump modified with Kemel bearings is undergoing a minor trial in HMS *Vigilant*.

MCWP DEVELOPMENT

Whilst an increase in MCWP service life has been achieved through the improvements made to date under this Arrangement, a key objective is to extend service life to match the LOP(R) interval.

A development improvement programme has been put in place, which will identify and focus on the key risks and cost drivers. The risk reduction measures envisaged will include design improvements, condition based monitoring and improvements in operating, maintenance and inspection techniques.

Since the pump forms an integral part of the CWS, it is important that any changes made to the pump do not adversely affect the rest of the system, for example by introducing other adverse galvanic corrosion mechanisms.

Corrosion Investigations

The VANGUARD class condenser is made from commercially pure titanium. Preliminary work has shown the condenser to be the dominant driver of pump corrosion, which is perhaps not surprising considering that it is electrochemically noble compared with the copper alloys used in the CWS. The headers and taper pieces connected to the condenser have suffered from corrosion, and selected items from HMS *Vanguard* and *Vigilant* have had to be replaced after failing revalidation.

Scientists from QinetiQ and independent corrosion experts from the Copper Development Association and Cerro Manganese Bronze have assisted ALSTEC in respect of corrosion examinations.

Evaluation of the components of pumps returned from service has identified those items or features most at risk for extended usage. Design changes have been made to highly vulnerable features and these have been successful in improving service life.

The highest-profile item identified for design improvement in the current review is the impeller and this is discussed in more detail below.

Corrosion Modelling

Corrosion investigations are supported by the use of computer-generated corrosion models of the pump developed under a sub-contract placed on QinetiQ.[5]

The models use boundary elements to represent the pump and sea water interface for the prediction of galvanic corrosion. Raw data[6] is in the form of polarisation characteristics for each of the wetted alloys, which describe the expected behaviour of an alloy when coupled with others in a galvanic circuit.

Typical polarisation curves are shown in (FIG.6) for materials of interest.

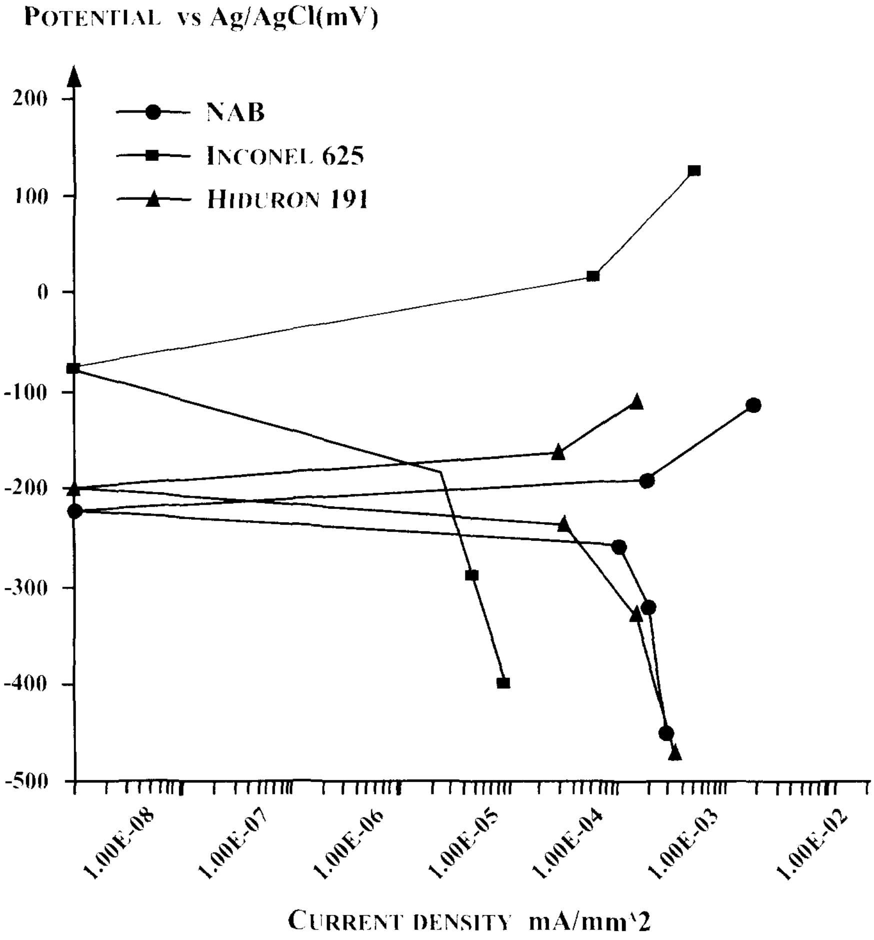

FIG.6 POLARISATION CURVES USED IN THE IMPELLER CASING MODEL

As part of the model validation process the polarisation curves for corroded samples of alloys taken from a pump returned from a boat for refurbishment have been measured and these are shown in (FIG.7) for comparison purposes.

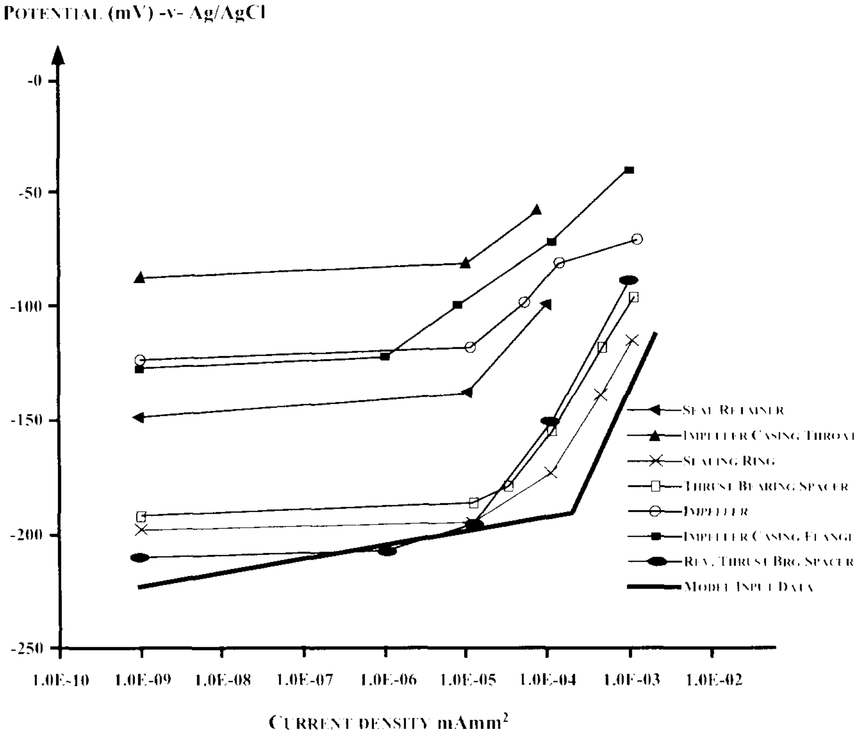

FIG.7 COMPARISON OF CORRODED AND NON-CORRODED NAB CURVES (ANODIC)

FIGS 6 and 7 show that the galvanic effect of corroded materials is less than that of fresh material samples and therefore the corrosion rate can be expected to reduce with time.

The models are used as part of the justification process in the selection of alternative materials, thus avoiding the cost and delays of extensive shore and sea-based evaluations. A wider use of the models is being considered for evaluating the corrosion resistance of the CWS.

Impeller development

The MCWP nickel-aluminium bronze impellers suffer from corrosion and erosion in service that causes degradation of pump performance.

A selection of alternative materials has been studied and the results show that Grade 23 titanium (6% aluminium, 4% vanadium in the extra-low interstitial oxygen content form) offers the optimum blend of strength, toughness and corrosion and erosion resistance in turbulent sea water.

To minimize production costs, a cast impeller has been specified (the machining times for titanium are approximately 5 times that for NAB). A full size prototype is being manufactured to prove the casting and machining techniques prior to making a pre-production impeller. Rapid prototyping is used to produce a resin model from a digital pattern, which is shell-moulded prior to casting (FIG.8). The casting is then milled in an acid bath to remove the hard oxide layer prior to machining using multi-axis CNC manufacturing techniques.

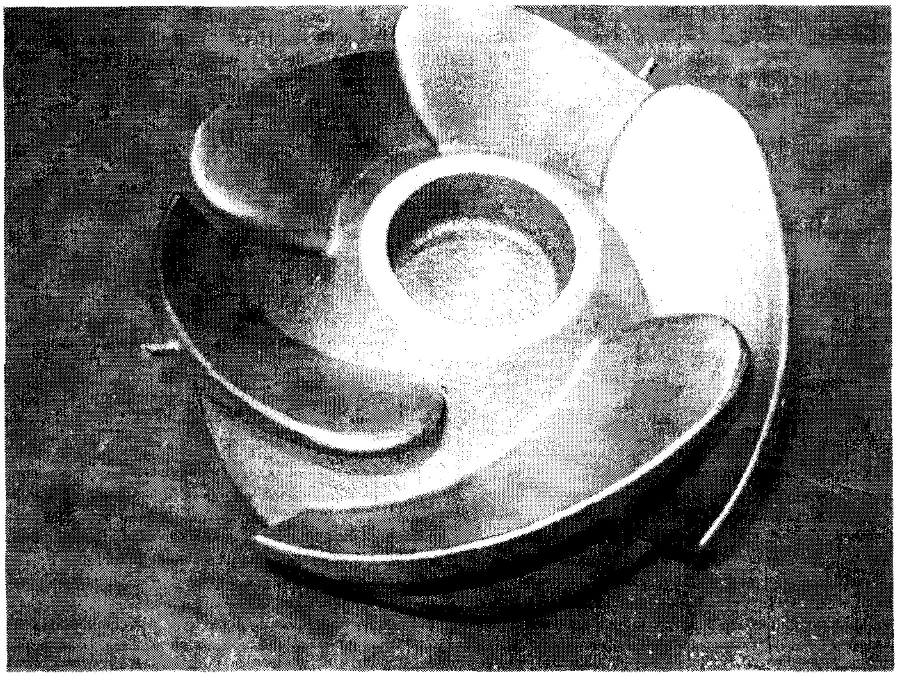

FIG.8 CAST TITANIUM IMPELLER

Condition-Based Monitoring

In conjunction with other stakeholders, ALSTEC is establishing a Condition Monitoring (CM) system which will provide operating data about the pumps, provide warning of impending failures related to hydraulic performance and noise and allow informed decisions about the risks of continued pump operation. The MoD and ALSTEC will operate the system. However, it is not possible to design an economic CM system that will be capable of giving advance warning of all failures.

For an effective system, performance parameters such as current and pump head will be collected under standard, stabilized conditions. The results will be normalized to allow for variation in the electrical supply parameters. Noise and vibration will be measured and recorded.

CONCLUDING REMARKS

The MCWP Support Arrangement was one of the first of the new style Partnering contracts awarded to industry and has proved to be a great success. The Arrangement is being used as an example for other similar MAES IPT contract initiatives.

All major objectives have been achieved including:

- The seven new build pumps and spares have been supplied on schedule and at a cost less than the target within the TCIF framework.
- Stock levels have been restored and all planned pump exchanges have been achieved.
- ALSTEC has established a total support capability for MAES IPT.

- Stakeholder involvement has improved awareness and contributed to a reduction in the failure rate through improved maintenance.
- The combined steps taken to date have increased reliability and extended the interval between routine pump changes from 3 to 4.5 years.
- A design improvement programme has been implemented to further extend the pump operational life to match the LOP(R) interval. The target is to install the first of these pumps at the *Victorious* LOP(R).

Acknowlegements

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