THE INSTITUTE OF MARINE ENGINEERS
76 Mark Lane, London EC3R 7JN Telephone: 01-481 8493 Telex: 886841

TRANSACTIONS(TM)

THE INTRODUCTION OF MAGNET DRIVE PUMPS INTO NAVAL SERVICE

P. J. Lidgitt and J. W. Veness

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The Introduction of Magnet Drive Pumps into Naval Service

P. J. Lidgitt,* BSc, MSc, PhD, CEng, MIMechE and J. W. Veness†
*Ministry of Defence and †H. M. D. Seal/Less Pumps Ltd

SYNOPSIS

If a review of naval equipment problems was carried out the highest proportion giving cause for concern would be pumps. In analysing pump problems the predominant reason for machinery stoppage is premature failure of dynamic seals or excessive leakage from them. In certain applications, for example seawater heavily laden with silt and debris, seal lives are totally unacceptable within the timescale of normal service routines. For this reason the Royal Navy instigated a programme to evaluate improvements in mechanical seal design and the alternatives to these, such as seal-less magnetic drive and canned motor designs. Reviewing similar experiences in the chemical industry in pumping hazardous and corrosive/abrasive liquids, the magnetically driven seal-less pump was selected as being most suitable for the arduous conditions experienced during ship-board duties. This paper outlines the principle features of the seal-less magnetic drive pump and indicates the advantages and limitations of this type of unit. Applications in naval (both military and merchant marine and civil) installations will be discussed and experience in RN use will be presented with a review of development work carried out to adapt this type of machine to the peculiar problems of the marine environment.

INTRODUCTION

Trends in marine technology, both naval and commercial, require equipment that has high reliability, low maintenance, durability and low first cost. In addition, naval machinery must be silent and shock resistant. Early in 1983 MoD embarked upon a programme with the limited objective of improving the durability and maintainability of heat-exchanger pumps. The initial objectives were:

1. To reduce maintenance problems associated with mechanical wear.
2. To improve the life of the equipment by reducing bearing wear.

Development work had already been carried out to improve seal design and 'canned' motor type units had been evaluated to remove the seal problem. These units, however, incorporated by necessity motor cooling circuits with fine clearances and sand and silt were found to build up easily in these circuits. Furthermore, the 'can' which separates the seawater from the motor electrical windings must be thin to allow cooling and reduce losses and may be breached easily.

As a result of the early stages in this exercise it became apparent that magnet drive technology had reached a point where it was particularly appropriate to meet certain RN requirements. With the additional objective that any new equipment should replace existing pumps on a one for one basis (for reasons of backfitting), a development/evaluation programme for magnet drive pumps was undertaken. Such equipment would possess no mechanical seals and was itended to use hard-on-hard water lubricated journal and thrust bearings. As the work progressed it became apparent that such an approach could in due course be applicable to a wider range of marine equipment, eg boiler feed and condenser extraction pumps.

For many years magnetically driven seal-less pumps have been in use in the chemical, nuclear and refinery industries. Introduced in the early 1950s, they provide a means of transferring torque magnetically into an hermetically sealed pump housing without the need for mechanical seals. Figure 1 shows the primary differences between a conventional mechanically sealed pump and a magnetically driven machine.

Peter Lidgitt is a member of the Royal Corps of Naval Constructors and leads the Pump Section of the Directorate General Marine Equipment within MoD(PE). A graduate in Mechanical Engineering, he specialised in the field of tribology before joining the Ministry of Defence. He has since held various posts within the Ministry, including appointments to the Royal Dockyards, Whitehall and on secondment to University College London.

John Veness has been involved in the design and application of magnetically driven pumps for nearly 20 years. He is the Senior Technical Manager at HMD Seal/Less Pumps Ltd, with responsibility for product development. Educated at Brighton Polytechnic, he has written papers for the Institute of Mechanical Engineers and technical journals and is a member of the British Pump Manufacturers Technical Committee.

An extensive testing programme both ashore and at sea was undertaken and included pressure cycling, endurance testing, noise and vibration evaluation and abuse tests, ie shock, temperature excursions, air entrainment and trash ingestion.

This paper outlines the principle features of the seal-less magnetic drive pump and indicates the advantages and limitations of this type of unit (see Table I). Applications in naval installations, both military and merchant marine and civil, will be discussed and experience in RN use will be presented with a review of development work carried out to adapt this type of machine to the peculiar problems of the marine environment.

DESIGN CONCEPT

The magnetically driven seal-less pump in simple concept is a conventional centrifugal pump with rotating seals replaced by a static shroud to form a closed system. Prime mover energy is transmitted to the hermetically sealed liquid

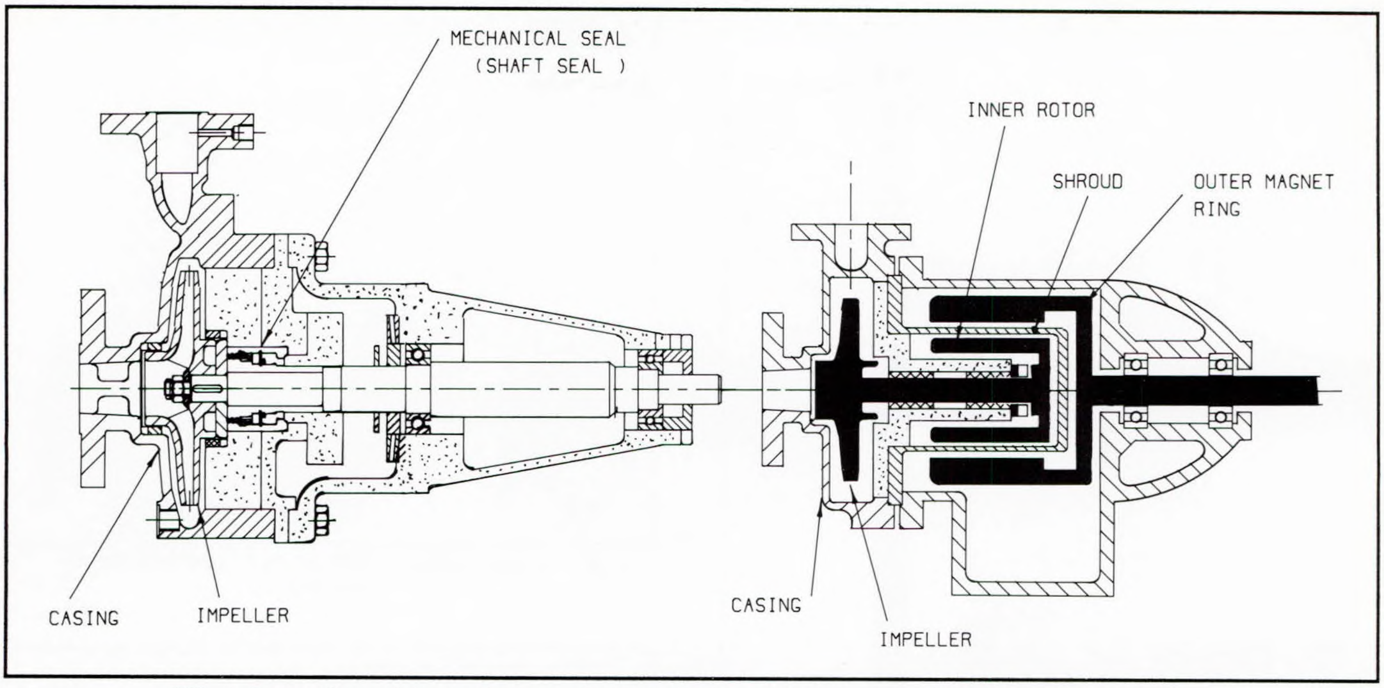

FIG. 1: Comparison of design features of mechanically sealed and magnetically driven seal-less pump

Table I: Advantages and disadvantages of magnet drive seal-less pumps

	Mechanically sealed pump	*Canned motor pump*	*Magnetically driven seal-less pump*
First cost	Pump cost low but mechanical seal and support systems can be expensive	Increased cost dependant on materials of construction	Increased cost dependent on materials of construction
Power absorbed	Apparent power consumed low, but cost of services supplied should be considered in total energy analysis	10% to 20% more than 'apparent' mechanical seal pump	10% to 20% more than 'apparent' mechanical seal pump
Auxilary services	Clean flush required for solids or hot applications	Clean flush required for solids or hot applications	No auxillary services required for solids to 450 °C
Prime mover	Standard electric motor	Special electric motor integral with design. Factory repair required	Standard electric motor
Mechanical design	Mechanical seal fragility is limiting factor	'Can' must be thin to allow cooling and reduce losses - typically 0.8 mm maximum	Can be designed to ASM VIII. 'Can' can be up to 8 mm thick. Designs up to 450 bar possible
Effect of suction pressure	Increase in suction pressure results in increased axial loads	Negligible unless auxiliary feed is fitted	Negligible
Space envelope	Reasonable space envelope if close coupled design	Generally shorter than mechnical seal pump/ motor combination compact	Equal length to mechnical seal pump/motor combination
Solids tolerance	Pump limited only by materials of construction - mechanical seal poor	Poor - small clearances	Excellent - large clearances
Reliability and Maintainability	Typical mechanical seal life 3 to 9 months	Must be maintained/ serviced at factory	7 years or more bearing design life. On site maintainence/ repair

end by a bank of external magnets passing motive force through the sealing shroud to the impeller shaft. Magnetic power is received internally by an internal flux receiving rotor.

The drives employ high-strength permanent magnets, magnetised and stabilised before use. There is no magnetism ageing and under correct operation the couplings never lose power. Indeed, the only possible cause of degradation is extreme temperature.

As there are electrical losses in the magnetic drive, a small tapping is taken off the discharge side of the pump and introduced to the coupling to remove the heat that is generated. This feed system is also used to provide liquid to the sleeve bearings, which are lubricated by the pumped liquid.

Until some ten years ago, magnetically driven seal-less pumps were characterised as being relatively large and inefficient. They also had poor ability to handle other than clean liquids.

However, their reliability was well proven and service lives of many years were being experienced on clean liquids, where power and installed space was not at a premium. At that time pumps to 55 kW were installed as a matter of routine and special pumps were produced up to 100 kW. Many thousands of seal-less pumps are found in chemical plants and nuclear installations.

Rare earth metal high-energy magnets subsequently became available in the quest for miniaturisation in the consumer market. Applied to magnetically driven pumps these magnets were capable of producing four times the transmitted torque, allowing the sizes of magnet drives available to be expanded (Fig. 2) and for a given power transfer the size of drive to be reduced. As magnetic losses increase by approximately the third power of the diameter, this reduction resulted in a significant increase in magnet drive overall efficiency (Fig. 3).

These magnets also displayed another characteristic – extreme resistance to demagnetisation. The Alcomax magnets previously used could be demagnetised by slipping the outer magnet ring excessively against the inner. In contrast, rare earth metal magnets are resistant to this condition. Resistance to demagnetisation in a magnet is measured by its coercivity (*H*). The comparison betwen Alcomax and rare earth metals can be seen in Fig. 4.

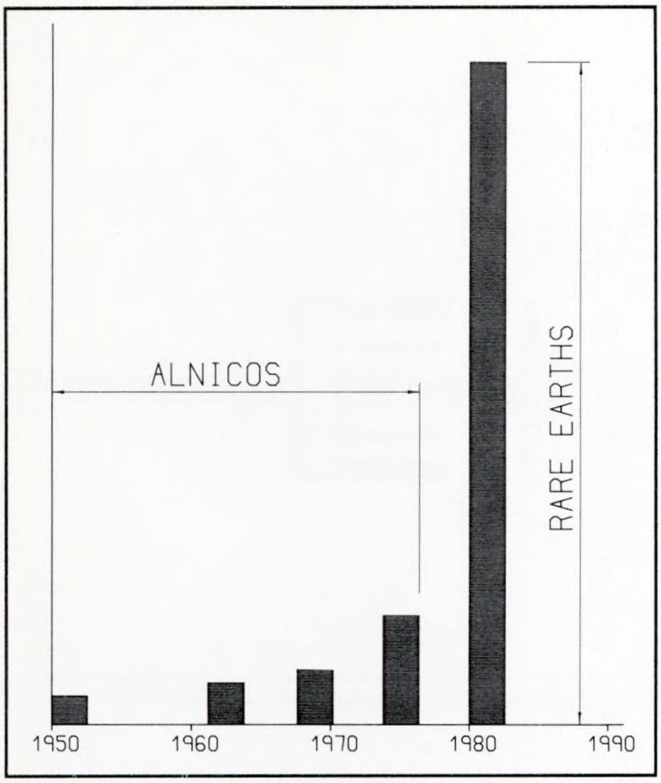

FIG. 2: Improvement in magnetic output

APPLICATION FOR DEVELOPMENT

A particular application in naval service was the pumping of raw unfiltered seawater in submarine cooling systems. This application was selected in 1983 for the development of a seal-less magnet drive pump for marine service.

Design criteria

The pump had to be dimensionally interchangeable with the existing mechanical seal design. The liquid to be pumped was raw seawater with unspecified particulate levels. Reasonably high system pressures are associated with submarine service and the pump had to withstand the fatigue conditions. Also required were low noise and vibration characteristics, extreme shock resistance and ease of maintenance.

Dimensional interchangeability

The requirement to meet the design envelope for existing mechanically sealed units dictated the use of high-energy magnets. The magnetic drive was designed with a decoupling torque in excess of the motor pull-out torque to ensure that if the magnetic coupling seized the motor would be tripped on overload.

The existing liquid end was retained having been found to exhibit satisfactory noise, vibration and hydraulic characteristics.

Materials

The construction materials selected were nickel aluminium bronze with critical items manufactured from Inconel (pump shaft, inner magnet ring cladding and shroud). Initially, asbestos filled phenolic resin was used for journal sleeve and thrust bearings running against a tungsten carbide coated shaft. Work on 'hard-on-hard' bearings had been started some time before with a view to increasing the solids tolerance of seal-less pumps but it was decided in the early stages of the programme to provide a design where these could be retrofitted as it was the seal-less concept that required proving in naval service. It was thought that blockage of feed holes with sand/silt would be more limiting on pump performance than bearing wear.

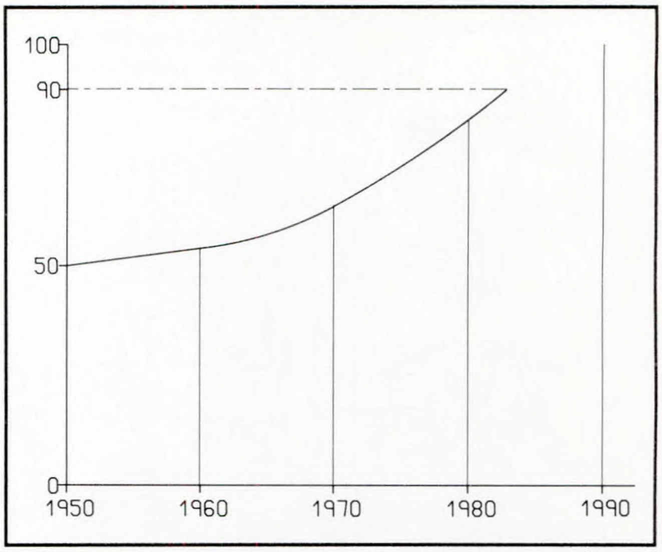

FIG. 3: Improvement in efficiency of seal-less magnet couplings

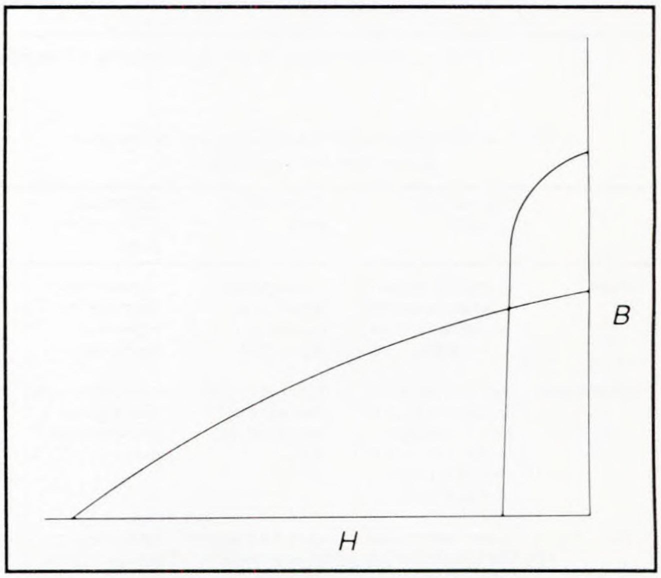

FIG. 4: Comparison of magnet *B* against *H* curves

System pressure

Owing to repeated pressure cycling, fatigue strength rather than material yield strength was the design limitation. All pressure boundary components were designed to already established safe fatigue strength limits.

A design feature of seal-less pumps is the absence of unbalanced axial force arising from the cross-section area of the pump shaft projected through the mechanical seal to the atmosphere. Excessive bearing loads at high suction pressures do not therefore need to be accommodated.

Noise and vibration

No quantitive noise and vibration data were available for seal-less pumps as their inherent low-noise characteristic (damped because of fluid/mass and absence of seals) had not previously required detailed studies. Low residual out-of-balance levels were set for design/manufacture and spigot fits for rotating parts were specified to the minimum practical limits.

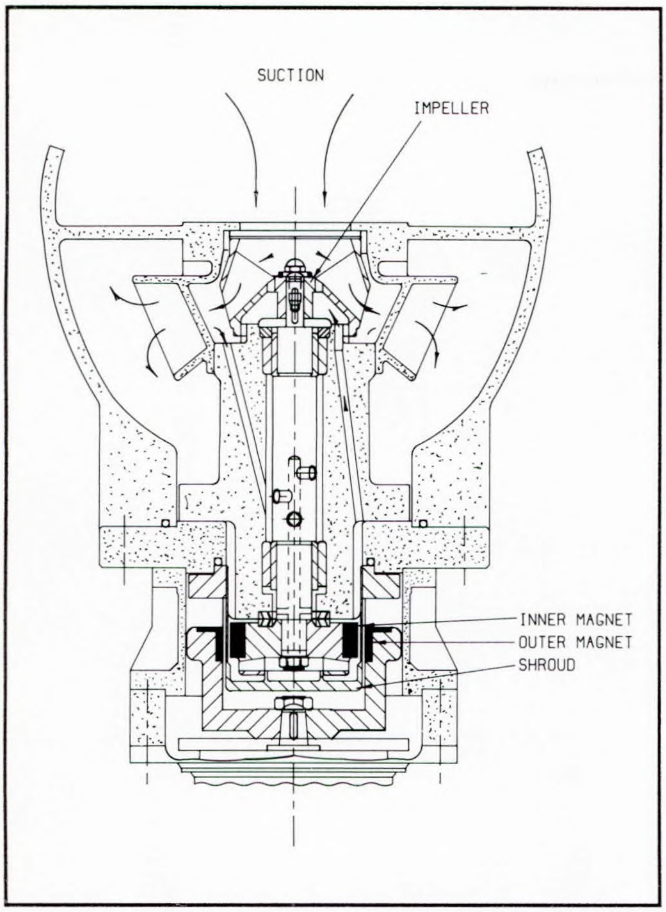

FIG. 5: Seawater pump design

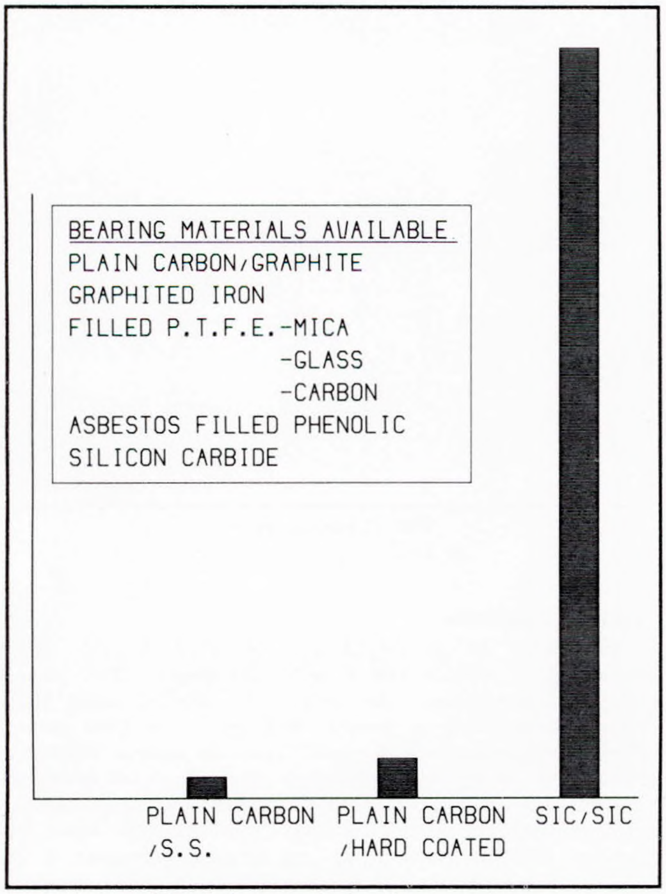

FIG. 6: Increase in bearing capacity

Shock

The design shock levels were significantly in excess of normal naval ruggedness requirements. All components were designed to the maximum stress levels specified in the Naval Shock Manual. The overhung outer magnet assembly was identified as a possible risk area that could lead to overstressing of the motor shaft extension. A close running clearance was introduced between this and its housing to prevent deflection from overstressing the shaft. This clearance is smaller than that between the outer magnet ring and the shroud (can) and therefore the shroud will not suffer contact damage in the event of shock loading.

Ease of maintenance

The reason for investigating the seal-less concept was its promised service life resulting in zero maintenance. The magnetic seal-less design is inherently simple and comprises a small number of rugged parts accurately located/assembled with the minimum of fixings. Recognising the severe space limitations, the pump was designed to allow disassembly in situ within the smallest axial withdrawal length possible.

The design produced (Fig. 5) is essentially similar to that used in the chemical industry. Major differences included expanded flow holes in the internal feed system and an auxiliary impeller at the rear of the inner magnet ring to boost the flow through the magnet coupling to avoid the build up of sediment.

Testing

The pump was tested initially for hydraulic performance and power absorption in a test loop pumping clean water. The power absorbed was within the capacity of the electric motor fitted to the original mechanical seal pump. A feature of the test rig was the ability to read directly the axial thrust and to adjust this with balance holes in the impeller rear balance chamber to ensure that this was a minimum over its operating range.

The pump was then installed in a test loop with the facility to pressurise to submarine diving depths and with seawater having a controlled chemistry/solids content. During nine months operation the pump was subjected to pressure cycles equivalent to 30 years service. The noise and vibration signature of the pump was compared with that of mechanically sealed pumps previously installed and found to be satisfactory. Electromagnetic compatibility tests established that no strong magnetic fields were present that could interfere with local electrical/electronic instrumentation or controls.

After nine months in service, inspection showed no measurable bearing wear, erosion or solids accumulation. Indeed, for economic reasons, the test-rig pipework had been manufactured from carbon steel and large quantities of pipescale were removed from the rig on shut-down. The presence of this did not leave any fouling in the pump internal flow passages.

There followed a series of tests to establish the effect of outer magnet ring misalignment and differing magnet pole phasing on the pump noise and vibration signature. These tests showed good repeatability.

Having proved the magnet drive concept, it was decided to modify the pump to hard-on-hard bearings to realise a pump life limited only by the erosion/corrosion rate of the pump construction materials.

Hard-on-hard bearings

HMD had for some time been investigating and supplying in small numbers bearing assemblies based on the hard-on-hard concept. These were used in the chemical industry mainly for pumping acids where traditional carbon had insufficient corrosion resistance and the 'soft' alternative, filled PTFE, would not give satisfactory service life.

Silicon carbide running against silicon carbide has been used because of its excellent bearing characteristics. Being extremely hard, this material has the ability to grind solids passing through the bearing into fine particulate which can pass harmlessly through the remainder of the pump. Despite its hardness, there is some evidence to indicate that it has an ability to 'run in', and unlike many ceramics it has a high coefficient of thermal conductivity. This makes it well suited for use as a bearing with low-viscosity fluids (Fig. 6).

Like all ceramics, however, it is brittle and has a low coefficient of thermal expansion. This necessitates particular care in design when used with metallic counterparts to ensure that any stresses in the material are transmitted without damage to the more compliant support parts.

A set of bearings was installed in the prototype pump and after three months running with no measurable wear it was subjected to shock testing.

Shock testing

The pump was installed in a small test loop sufficient to circulate continuously without overheating. The complete loop was firmly fixed to the bed of a 2 tonne shock test machine and subjected to shock on three axes. The shock loading was applied by pneumatic 'canon' to the support baseplate (Fig. 7).

After shock test the pump continued to operate satisfactorily. On stripdown all silicon carbide components were dye penetrant crack detected with no indication of fracture. The pump was returned to its seawater test loop where it continued to run in order to establish the long-term corrosion characteristic of its component parts.

Sea trials

At an early stage of the prototype tests there was sufficient confidence to order two production units for ship trials. These were manufactured and installed with the intention of removing for inspection after several months in service. During its first inspection, one of the units showed two areas for concern :

1. A support ring for one of the ceramic parts had been fixed with less noble metal screws, the heads of which had been corroded away after only a short while. The failure of these did not result in any damage and they were replaced for future units with non-metallic screws.
2. One of the ceramic sleeves on the shaft had fractured along its length and a section had disintegrated and become detached from the shaft. The missing material, although not insignificant, had not resulted in failure of the unit, which was running satisfactorily at the time of removal.

Failure mode analysis of this component showed that this fracture was most likely to have occurred as a result of the bearing overheating. This would result in the shaft expanding and overstressing the sleeve. A series of tests on the prototype unit showed that sufficient heat could not be generated under realistic operating conditions to produce this effect. However, specific tests whereby the sleeve/shaft assembly was heated to well above normal operating conditions did reproduce the sleeve failure.

Non-destructive testing of ceramics is extremely difficult to carry out. Ultrasonic or X-ray techniques will indicate large defects, but failures in ceramics may be propagated from defects of only a few micrometres. A series of destructive (bursting) tests was carried out on the shaft sleeves and it was found that a significant number failed at relatively low stress levels. For subsequent units all sleeves were subjected to a proof stress test before use, to ensure safe operation when built into the pump. Work still continues on non-destructive techniques to detect defects in components of irregular section, which are not as easily proof tested as a plain sleeve.

As a result of the successful completion of these tests, units to the original design are being installed over the next 12 to 18 months as pumps with mechanical seals are removed from service.

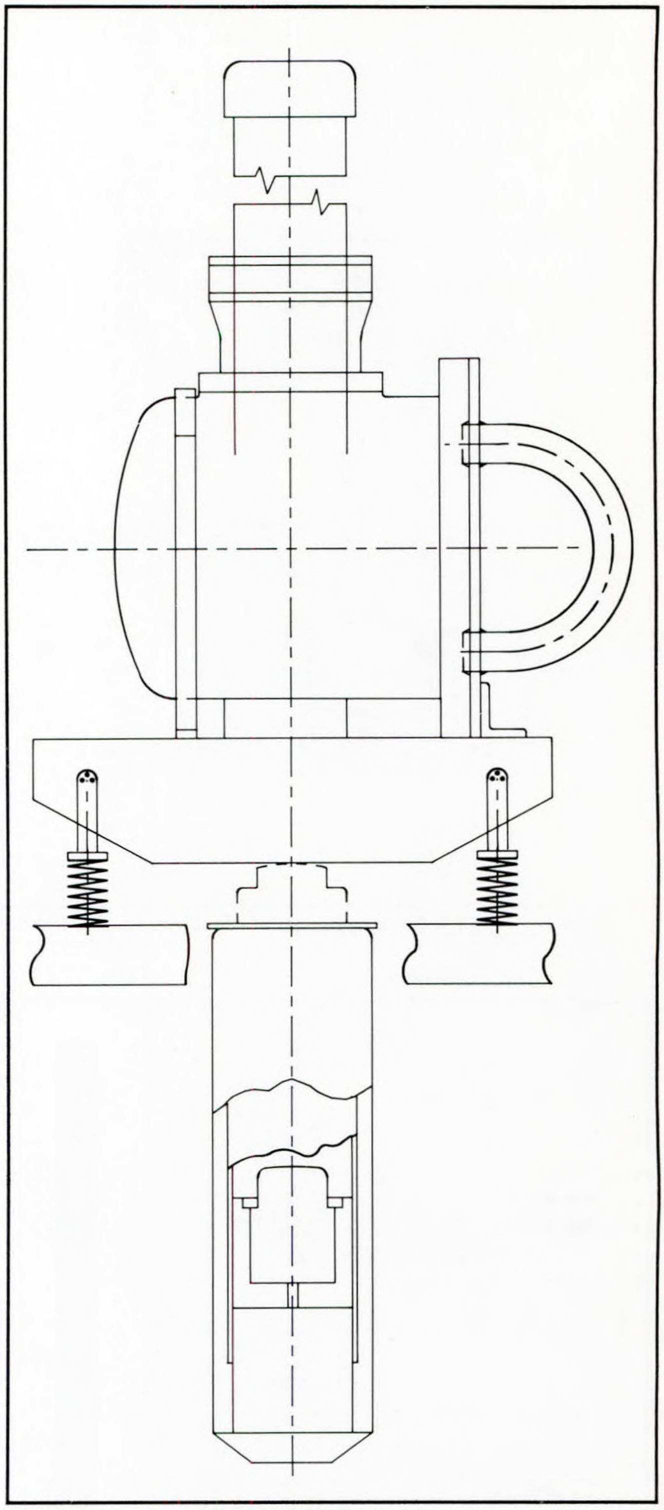

FIG. 7: Shock test rig

Vertical operation

Following the successful use of units in this initial application, it was decided to apply the magnet drive concept to other installations. The first units supplied were either horizontal machines or vertical with the motor (and shroud) pointing downwards. It is more usual in marine and naval service for pumps to be installed vertically with the motor upwards to provide a more compact and space-efficient configuration. For a seal-less unit with magnetic drive this presents problems because air can become entrapped in the shroud. Some of the first seal-less pumps supplied by HMD for the Pluto and Dido reactors at Harwell over 25 years ago

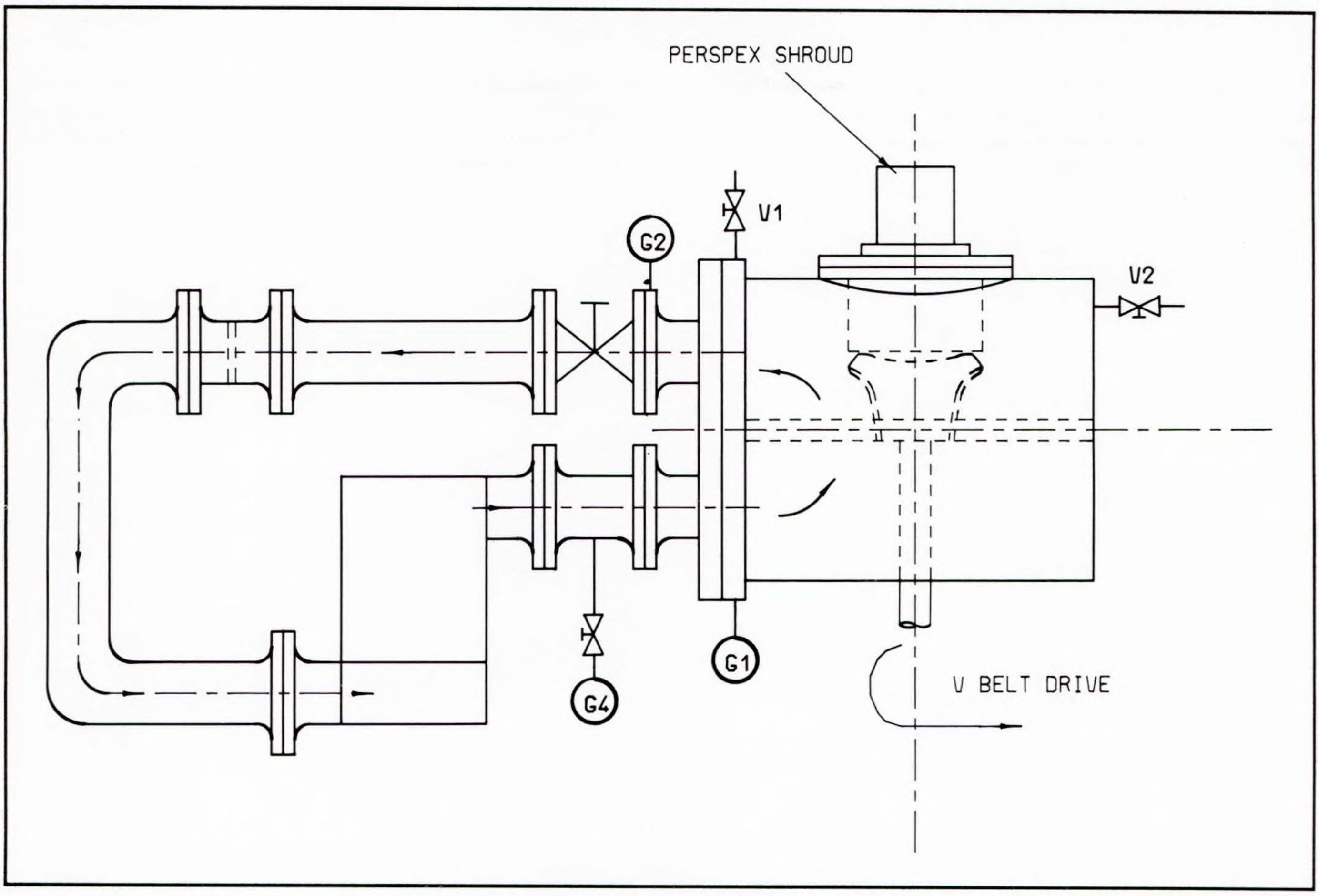

FIG. 8: Air elimination test rig

were indeed vertical machines, but it was necessary to draw a vacuum on the system to ensure that the shroud in these cases was filled completely.

It was thought that a suitable feed system could be developed to use the differential pressure generated by the impeller to purge the upturned shroud of air on start-up and ensure that any air entrained in the liquid be carried through the magnetic coupling without forming a vapour pocket at its core, so preventing damage to the hard-on-hard bearings.

As only a small amount of liquid is required to cool the magnetic coupling and lubricate the bearings, inference of successful operation by runs of extended duration or by strategically placed temperature sensors was thought to be unsatisfactory and too indecisive. It was decided therefore to build a test rig to allow visual observation of liquid flow and air removal during various operating conditions. The rig (Fig. 8) was arranged with the pump driven from the impeller end and the outer magnet ring and driver removed, the metallic shroud being replaced with a clear perspex component. This allowed viewing of the liquid level in the magnetic coupling prior to start-up, measurement of the time to achieve full prime and assessment of the transport properties of the feed system.

It was important to design a vent arrangement for the pump which would flood the journal and thrust bearings before start-up to ensure that these did not run in completely dry condition. This left the majority of the magnetic coupling itself in an air pocket before starting. The feed system purged this air pocket in a few seconds. When shut down the shroud remained full of liquid. Special venting was therefore necessary only on initial installation.

The rig allowed air to be injected into the main pump circulation loop and from this into the magnetic coupling via its feed system. Direct injection into the shroud was possible and both air and dye were used to assess fluid transport characteristics and the velocity/flowrate distribution.

A seal-less pump with the modified feed system has been operating in service satisfactorily for two years. On removal after twelve months for inspection, this pump showed no sign of wear, erosion, corrosion or blockage by sand/silt.

THE FUTURE

Magnetically coupled seal-less pumps will find increasing use in naval and general marine applications. It has been established that this pump type can be adapted to the arduous conditions found in seawater applications. The first unit supplied was found on inspection to contain, in addition to sand and silt, fishing line, adhesive tape, elastic bands and miscellaneous organic matter normally found in the world's shipping lanes.

In excess of forty units from 5 to 15 kW are currently in production for horizontal and vertical installations, and a vertical 100 kW axial flow machine is currently undergoing trials for a similar seawater service. A smaller unit has been manufactured for evaluation of its performance pumping saturated brine in the production of onboard fresh water.

Ideally suited for high-security areas, this type of pump is also applicable for less arduous duties, with its higher first cost being recovered through savings in maintenance. The seal-less pump may also be used for environmental considerations when pumping fuel oils and similar hydrocarbons. It is established on merchant vessels for waste heat boiler (200 °C) water circulation and may also be used for refrigeration and general chemical service.

Magnetic couplings may also be used for hermetic power transfer on machines other than pumps. Helium blowers, hydrogen compressors and various fans and mixers have all been driven by magnetically coupled seal-less drives.

ACKNOWLEDGEMENTS

The authors thank the Ministry of Defence and HMD Seal/Less Pumps Ltd for permission to publish this paper. Tests on pumps developed for naval service were carried out at HMD and AMTE-HASLAR.

Acknowledgement is made to YARD and Vickers Shipbuilding and Engineering Ltd, who provided project and engineering support in the development of the units now operating satisfactorily at sea.

Discussion

Captain R. F. JAMES (Ministry of Defence): Mr Veness in his presentation noted that there are two methods of achieving magnet drives, the synchronous drive and the induction drive. In the particular applications being described the synchronous drive appears to have been used. Would the authors please elaborate on the reasons for this choice.

In addition I would like to reinforce Dr Lidgett's plea for any information or comments leading to a better understanding of how to verify, through NDE or similar techniques, the fitness for purpose of ceramic components.

Commander R. N. LANGMAN (Admiralty Research Establishment): I would first like to congratulate the authors on an excellent presentation of a most interesting paper, and to thank them for their acknowledgement of Haslar's work on the testing of these pumps. I should however point out that we are now the Naval Auxiliary Machinery Division of the Admiralty Research Establishment, ie ARE Haslar not AMTE.

The shore trials outlined in this paper were completed before I personally joined the Establishment some 11 months ago, but after interrogating the Project Officers concerned I understand that they failed to achieve their objective — they could not break it!

One area of particular concern was whether water-borne debris could lodge in and block the cooling water passages and clearances within the shroud. However, although we fed the pump with a varied and rather nasty diet of sand, scale and assorted litter, the system proved to be remarkably self-cleaning and no problems were encountered, apart from a tendency for the larger items such as fishing-line etc. to form a 'birds nest' inside the impeller, with no adverse effect apart from a reduction in flow.

The paper mentions that debris was found when the pumps were examined during sea trials, and it would be interesting to know if it was found in a similar formation.

The same tale was related on the ceramic bearings which also came out smiling after some arduous endurance, shock and vibration trials.

In all, the pump appears to be fulfilling its promise of rugged simplicity and we look forward to shore testing its big brother in due course.

P. M. LOW (Shell International Marine Ltd): My company's experience of magnetic drive goes back to the late 1960s when they were used on waste heat boiler forced circulation pumps. This is a very arduous service but it proved to be very succesful.

The principal problem experienced was on starting up after a prolonged idle period, for example refit. The accumulated debris in the boiler system could cause damage and the fact that some of the debris could be magnetic compounded the problem. However, these problems were overcome and several units are still in service. Is this particular application still seen as attractive and, if so, could the authors say what special features would now be incorporated?

The authors suggest that application on pumps handling fuels could be envisaged. Bearing in mind the need to retain very fine clearances in the magnetic couplings, would the authors comment on the limiting viscosity of fluids which they anticipate the magnetic drive could be designed for.

The advanced technology of the rare earth metal magnets has made possible dramatic improvements in the drive efficiency to 85-90%. However, if they were to be widely applied in shipboard drives, such losses could still be significant in the total electrical loading. Would the authors comment on the prospects for further improvements in efficiency in the future.

Finally, I should like to add the comment that, in the merchant marine in particular, the reduction of engineering staff onboard will require all equipment to be very reliable, needing minimum of maintenance. With that in mind, there must be many potential applications for magnetic, seal-less drives.

Authors' reply

In reply to Captain James, although both types of drive have equal efficiency and would be similar dimensionally, the synchronous drive was selected for several reasons.

The first pump fitted utilised an existing liquid end, which had been poven in service. It was important to maintain the output from this. The induction drive has a small slip between the outer and inner rotor (5%). This would have resulted in a drop in performance from the pump requiring a larger impeller to compensate. The synchronous drive does not exhibit this slippage.

Furthermore, there had been no work carried out previously on the water-borne noise characteristics of seal-less magnet drive pumps and it was feared that the induction drive might emit a recognisable 'rod to pole' passing frequency.

To answer Commander Langman, experience during sea trials showed that the ability of the pump to handle water-borne debris was extremely good. There was no evidence of a 'bird's nest' inside the impeller. A small quantity of fibrous material was found between the shaft bushes but this did not impair the effective performance of the pump. Otherwise there was no significant accumulation of sand and silt in the pump. This indicates that flushing of the internal passages and the shroud is effective and there is no tendency to blocking during extended service.

As regards the silicon carbide journal bearing bushes, evidence to date indicates that the improved quality control procedures adopted and the lower viscosity adhesive have resolved the cracking problem. However, it is possible that in the longer term bearing materials that are less brittle and perhaps cheaper will become available and will be suitable for this application.

The pump is indeed fulfilling its promise of rugged simplicity with a very low maintenance demand. Magnet drive technology will undoubtedly see increased application in naval service.

In reply to Mr Low, waste heat boiler circulation is still a major market for magnet drive seal-less pumps where mechanical seals have proved unreliable. The problem of accumulated debris in the pump generally occurs on shutdown or with the standby pump. A catch pot in the suction of the pump which can be occaisionally blown down has been found to be effective in reducing the problem.

Silicon carbide would appear to be an ideal bearing material for this particular application where particulate is present. However, it is necessary to accommodate boiling throughout the pump under certain conditions such as soot blowing. Silicon carbide has been found to be unsatisfactory when running dry. Substantially improved soft bearing combinations have been developed to accommodate these conditions.

Regarding viscous handling, the magnet drive seal-less pump has relatively large running clearances (1 mm) compared with a canned motor pump for example (0.3 mm). Therefore viscous liquids up to 200 cP may be handled routinely and with special design to 500 cP. However, as the pump is centrifugal it is governed by the limitations placed on this type of machine.

In time, seal-less magnet drive positive displacement pumps will be developed to handle extremely viscous liquids.

With respect to efficiency, improvements in magnetic output continue to push efficiencies higher, but there is a practical limit of 90-95% because of the metallic shroud used as the rear pressure boundary for high-temperature/high-pressure applications (eddy currents are induced by the rotating magnetic field).

Small pumps are already available with non-metallic shrouds (reinforced plastic). However, the limitations on these make them advantageous over mechanical seals only in aggressive low-temperature/low-pressure applications. Improvements in polymers and the quality of ceramics will result in drives of 98-99% efficiency in the foreseeable future.