THE PUMP-IN-PIPE

TRANSITION TO PRODUCTION

BY

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ABSTRACT

The Pump-in-Pipe is a novel Main Circulating Water Pump (MCWP). It has undergone an extensive development programme which was successfully concluded in September 1987. This article describes the latter part of the development programme when satisfactory solutions to the outstanding technical problems were obtained and the programme met the timescale for the Production Prototype Package (PPP). Both the project management method and the principal technical issues are discussed.

Introduction

The Pump-in-Pipe (PIP) has been under development since 1969. During this period there have been two articles on it in the *Journal of Naval Engineering*, in 1976[1] and 1981[2]. As a result of an intensive development programme during the past two years and in order to meet the requirements of the Production Prototype Package (PPP) timescale at the Submarine Machinery Installation Test Establishment SMITE, the PIP has evolved to the point at which it can be put into production with confidence of achieving the specified performance. Indeed the development programme was formally terminated by The Director General Marine Engineering organization (DGME) and responsibility for procurement handed over to the Director General Submarines organization (DGSM) on 17 September 1987. For those not familiar with this equipment it is perhaps worth recapping on its *raison d'être* and the course of the project during the past 18 years.

The PIP was originally conceived as a means of avoiding pumps with mechanical seals, a regular source of unreliability and maintenance in conventional designs. Also, in submarine applications it is an efficient method of transmitting the pipe axial loads inherent in operating seawater systems at depth. The PIP considerably facilitates the use of a U-tube condenser design by avoiding the requirement for the more usual pump-in-header arrangement. This had considerable benefits in respect of the machinery space size. Over and above these advantages the PIP offered the potential benefit of improved hydraulic flow with the inherent reduction in noise that could be expected. This latter benefit was to assume increasing importance and has become a major feature of modern pump design for naval applications.

During the course of its development the PIP has seen three evolutionary stages. The Mk.1 was produced to prove the concept. This gave way to the Mk.2 which was to develop and prove the manufacturing route. Finally, the Mk.3 version is being produced for installation in the submarines. It was during the latter part of the Mk.2 production development phase, when detailed testing of the complete pump was possible, that both technical design and production problems became apparent. The associated timescale was such that problems not previously recognized, e.g. electromagnetic noise and vibration, casting technology for major components and the development of hard surface bearing materials, were in danger of being carried over into the Mk.3 production pumps. An accelerated development programme was therefore carried out during 1986 and 1987, aimed at producing proven pumps. This has been brought to a successful conclusion and the outcome is the subject of this article.

The Pump

The pump has been described in the previous *Journal* articles on this subject[1, 2]. Although it has changed in important details of its design, the basic configuration remains the same. FIG. 1 is a diagrammatic representation of the PIP. The outer casing is essentially a section of the circulating water system pipework. The pump itself is a two-speed, PAM wound, induction motor driving a mixed flow impeller. The stator of the induction motor is supported within the outer casing by four substantial spokes at the non-drive end (NDE) and by a multi-vane diffuser at the drive end. It should be noted that the NDE vanes carry most of the load and the stator is to a large extent cantilevered from the NDE vanes. The rotor is a squirrel cage construction running in water-lubricated tilting pad journal bearings and axially positioned by similarly water-lubricated taper-land thrust bearings. The bearings use particularly hard materials to withstand abrasion and wear. A clean sea water supply is provided to the bearings and is circulated internally as shown for cooling purposes. An auxiliary impeller is built into the rotor shaft to assist this circulation. Both the rotor and stator electrical components are isolated from the sea water by thin Inconel cans. Conduction of heat from the stator end windings is facilitated by a resin-based potting material. The pump construction is characterized by the use of precision engineering techniques, particularly in the design and construction of bearings and in development at the limit of current engineering capabilities in respect of electrically generated noise and vibration and manufacture of the pump outer casing.

The Development Programme

The principal development problems were associated with:

(*a*) Outer casing manufacture.
(*b*) Thrust bearing design.
(*c*) Diffuser manufacture.
(*d*) Electromagnetically induced noise and vibration.
(*e*) Corrosion.
(*f*) Design optimization between the electrical and hydraulic design features.
(*g*) Thermistor performance.
(*h*) Potting technique.

Since the production programme demanded that manufacture of the production pumps be started and pumps were required by the end of 1987 for the PPP at SMITE, there was considerable urgency that the problems be resolved and at the same time the production timescale be maintained. A co-ordinated and intensive development programme was therefore launched, combining both production and development and managed directly from DGME. This was considered necessary in order to establish the most direct lines of communication and to focus both responsibility and authority in a single, MOD Project Officer. The requirement that development and production programmes be combined was also essential since production pumps were to be used as both development and proving vehicles. Indeed, it was largely because of the changed character of the programme that the former project management arrangements whereby development was clearly separated from production were no longer suitable and a different management structure was necessary.

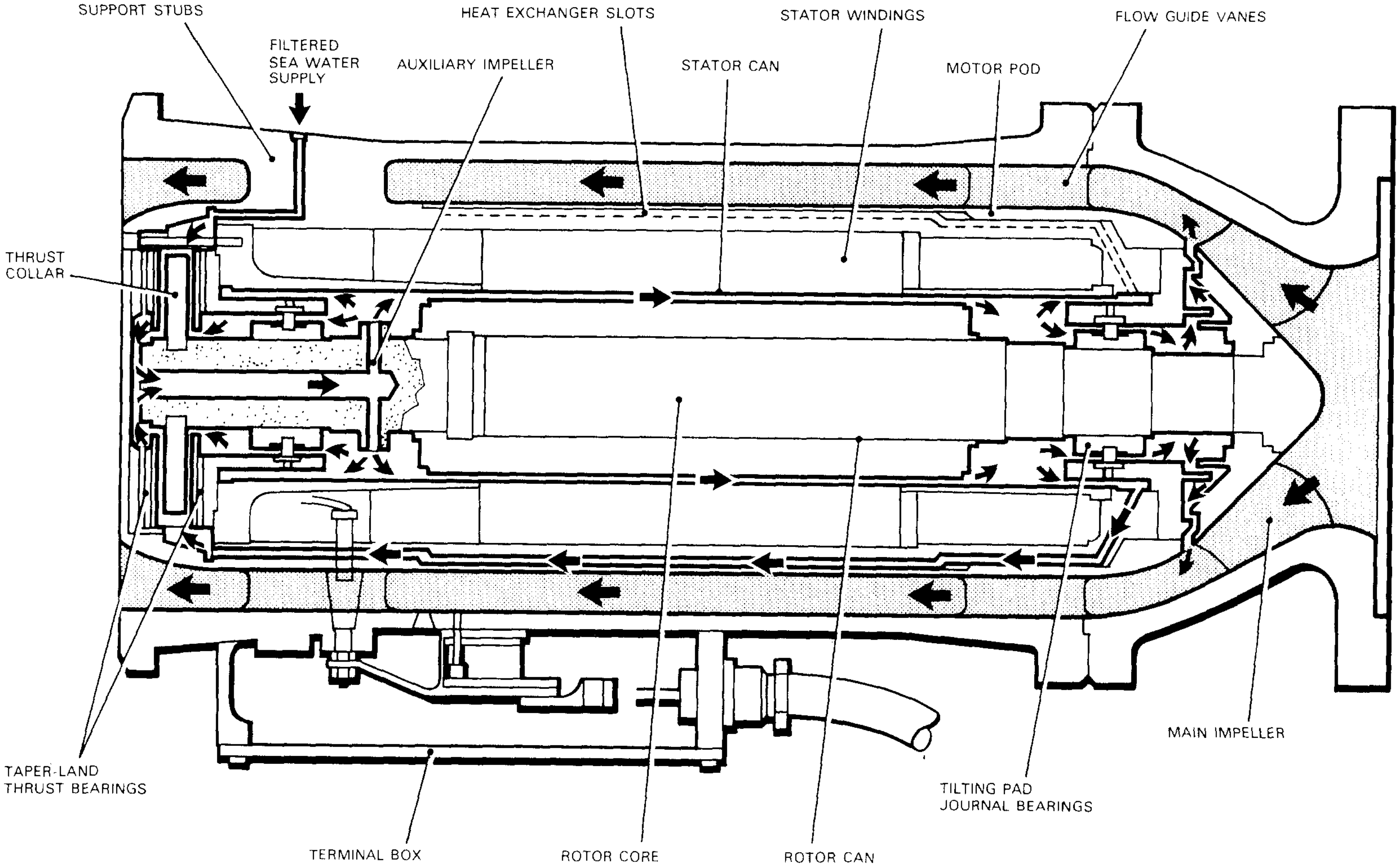

Fig. 1—Diagrammatic representation of the pump-in-pipe

Given the range of interacting development problems, the large number of specialist groups that would be involved and the relatively short timescale, good quality detailed planning and control would be vital. To this end a hierarchical, computerized PERT programme was established. This set the overall logic of the programme. From the PERT programme bar charts were produced automatically for progress monitoring and control purposes. By virtue of the computer it was possible to assess quickly the implications of inevitable changes as the project evolved and to produce new programmes to meet the changed circumstances. The planning and control system complemented the way in which project meetings were managed. To ensure that discussion and monitoring of broad project objectives were not confused with the specialist detail of individual issues project meetings were held at three levels:

(*a*) Director Level, Grade 5, (quarterly)—to appraise general progress in meeting the principal project objectives.

(*b*) Project Officer Level, Grade 7, (monthly)—to monitor, plan and control progress against the current Project Management Plan.

(*c*) Project Officer/Specialist Groups (as required)—to monitor, plan and control progress on individual specialist subjects. Detailed technical discussions most often occurred at these meetings.

The Project Management Plan was updated and formally re-issued quarterly. This project planning and control method considerably facilitated planning and managing the total project and the ability to focus upon an approach to specific issues.

Technical Issues

Outer Casing Manufacture

The outer casing dimensions placed this component at the limit of nickel aluminium bronze (NAB) casting technology in order to maintain the standards specified in NES 747. Bearing in mind that weld repair to the wetted side would not be allowed, the most appropriate casting process was considered to be ‘centrifugal casting’. In the event this was not found to be successful without further development of the casting process itself. Considerable difficulties were experienced with porosity at the internal surface of the casting. A more promising route was to be found by way of forging. This however was not without its problems. In order to meet the standards specified in DGS 1043, particular attention was necessary to both the billet composition and more importantly the post-forging heat treatment process. Although it proved possible to attain the requisite standards in respect of UTS and percentage elongation of the test specimens there were difficulties in simultaneously achieving the required impact strength i.e. Izod values. Bearing in mind the importance attached to shock resistance some significant effort was expended in tailoring the heat treatment process to achieve the required balance of material properties.

Thrust Bearing Design

The particularly long time between maintenance periods, i.e. between submarine major refits, makes conventional water-lubricated bearing materials, e.g. ferrobestos or cutless rubber, unsuitable for use in this machine. Considerable work has therefore been done in developing thrust bearing designs using hard bearing surface materials[3]. The thinking behind this unconventional approach is that the bearings will operate under normal conditions with a full hydrodynamic water film separating the surfaces. In the event of abrasive particles of sand and silt entering the bearing space the surface materials will be sufficiently hard to withstand the resulting abrasive wear. Being harder than the contaminants the bearing surfaces will, in all probability, break them up and they will be carried away in the water stream. Equally, the bearing surfaces must be able to withstand rubbing on start-up and the occasional rubbing contact at high speed under unusual operating conditions. Since the bearing would be required to operate with very small fluid film thicknesses e.g. 8–12 microns and the diameter of the thrust collar is some 26 cm the basic engineering of the assembly presented significant problems in its own right.

Early development of this bearing assembly relied upon testing in the pump itself. This proved to be expensive and time-consuming. Testing in this way provided no quantifiable information about the bearing performance and it was not possible to control the operating conditions in order to explore the full range of bearing performance characteristics. The solution was to build a test rig with comprehensive instrumentation. The first cost of such a facility appears at first sight to be high. However, in the context of the project timescales, the range of tests that are necessary and with the need for assurance that the bearings would operate effectively under the full range of pump operating conditions, the cost of the rig construction was amply justified.

Experience with tilting pad thrust bearings proved unsatisfactory in so far as the unloaded pads were unstable and rubbed their leading edges against the reverse face of the thrust runner. Whilst it may have been possible to stabilize the pads by careful hydrodynamic design or to build tilt-stops into the assembly, these were not seen as sufficiently robust solutions to the problem. A simple and robust solution was to change to a taper-land design (FIG. 2). With attention to detail in the manufacture and assembly of the components, it was possible to maintain the close tolerances that are necessary. The most difficult problem proved to be material selection and quality control during application of the hard coatings that were eventually selected.

The most satisfactory coating for thrust bearing surfaces was found to be chromium oxide applied by plasma spraying. Whilst this material gives theoretical 'Flash Temperatures' higher than would be considered desirable it has proven in practice to be sufficiently robust for the purpose. To ensure that the coating bond to the Inconel substrate is coherent, Scanning Acoustic Microscope examination techniques have been developed and are now an established feature of the bearing quality control process. Long-term investigations into the possible use of ceramics, e.g. silicon carbide, or ion deposition coatings (e.g. titanium nitride) may lead to even better solutions. The pump has been designed so that evolutionary development along these lines can be accommodated.

To ensure a viable thrust bearing for production pumps the approach taken throughout was to pursue:

(*a*) a preferred design with extensive testing,

whilst

(*b*) retaining a proven minimum fallback position,

and simultaneously

(*c*) developing a bearing using improved materials, e.g. SiC, TiN, in case the preferred bearing failed in any aspect of its evaluation programme.

Diffuser Manufacture

The diffuser is made from NAB and is a complex shape best suited to production by sand casting methods. Experience showed that this component could not be made consistently to meet the strict requirements of NES 747.

In order to find a cost-effective way forward it was appropriate to consider whether such exacting standards were justified particularly since the component's function was primarily related to the hydrodynamics of the machine rather than the structural nature of the assembly. Finite element analysis revealed that significantly larger voids could be accommodated in the body of the component than would normally be permitted, without compromising the structural integrity of the machine. This raised considerations of the inspection techniques that would be appropriate. Whilst there was no doubt that the specified standards of NES 747 could be relaxed it was necessary to ensure that the standards actually specified for the component were achieved. To this end the inspection techniques were enhanced with increased use of radiographic examination in support of the established dye penetrant and ultrasonic methods.

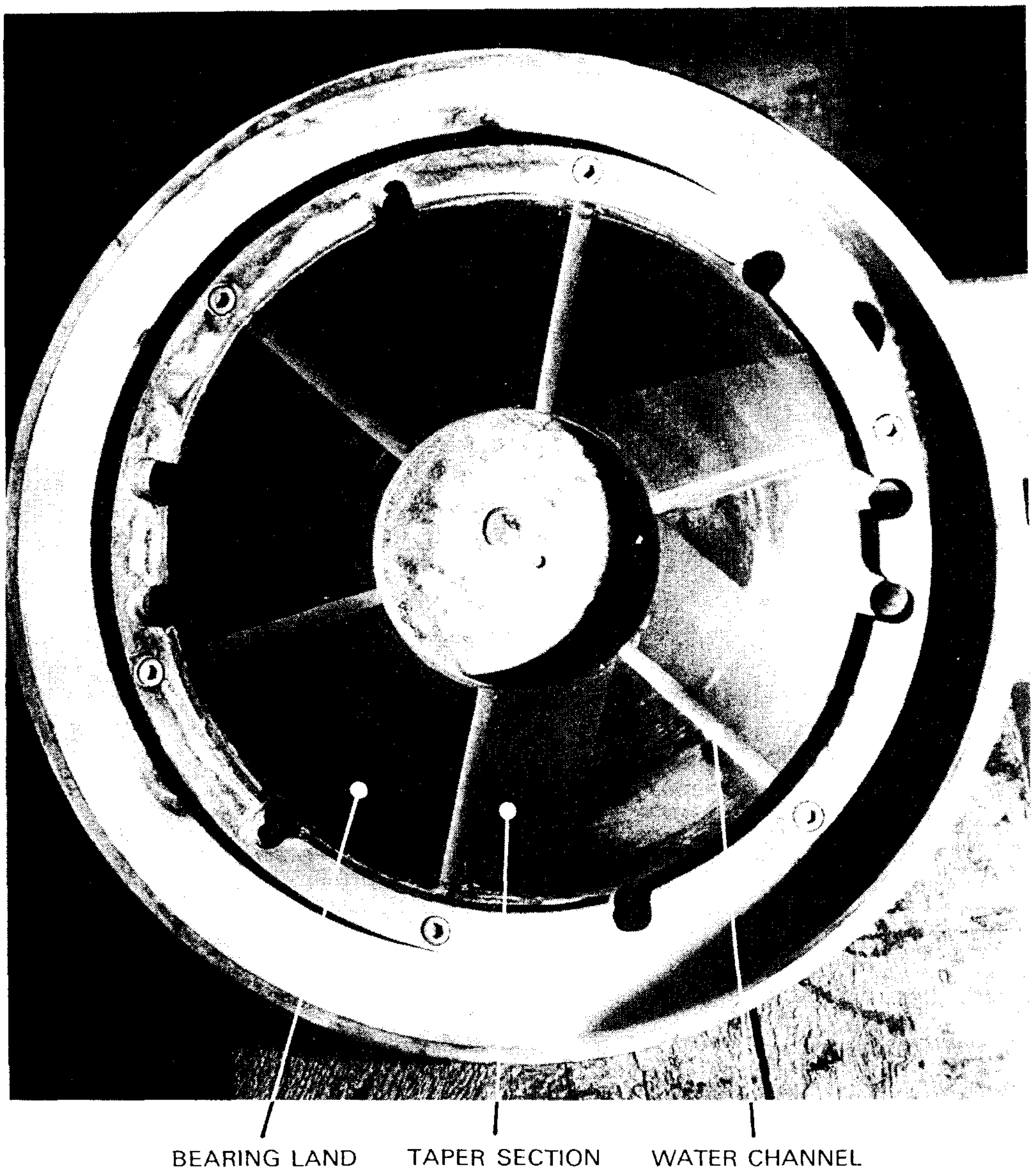

FIG. 2—A COATED TAPER-LAND THRUST DISC SECURED IN THE THRUST BEARING HOUSING

Electromagnetically Induced Noise and Vibration

It has long been recognized that the rotor and stator magnetic fields of an induction motor interact to produce distortions in the stator structure. For most normal induction motor applications this is not a significant problem. However, where the stator is immersed in the pumped fluid this distortion of the stator frame displaces the fluid and produces pressure waves. In the case of the PIP this is a potentially serious problem because there is a direct connection by way of the pumped fluid to the sea. Experimental investigations showed that this was in fact occurring with the PIP. With the intended design the problem was sufficiently serious to believe that the specified fluid-borne noise target would be exceeded by a significant margin.

This phenomenon was imperfectly understood. Theoretical models to give guidance on the most appropriate combinations of rotor bars and stator slots were not available at the time. Furthermore and adding an additional level of complexity, it was not possible to calculate with precision the effect of changes in the rotor geometry, i.e. the effects of rotor bar skew. It was necessary therefore to embark upon a programme of both experimental and theoretical work to establish the way forward.

Bearing in mind the importance attached to the noise characteristics of submarine equipments and the pressing requirement to meet the production programme, a particularly robust approach to this problem was adopted. This took the following form:

(*a*) Development of computer models to guide the design.
(*b*) Production of a range of short-life dummy rotors for test purposes.
(*c*) Parallel manufacture of production rotors such that viable alternative rotor configurations could be pursued until test results indicated a definitive solution to the problem.

This approach enabled a successful rotor design to be established and proven without any penalty to the production programme. The noise target was met for the production pumps. Indeed, theoretical studies and the accompanying tests using dummy rotors indicated the means by which, with further development, even quieter pumps could be produced.

Corrosion

Since the can material, Alloy 625, was chosen for the attractions of several of its properties, e.g. magnetic permeability, weldability, elasticity, thermal conductivity, etc., there was the risk of preferential corrosion of adjacent, less noble components. Particular care was necessary to assess the corrosion characteristics of components in close proximity to this alloy. It was found that the Kappa 3 phase of cast NAB components was particularly at risk and cast NAB could not therefore be used. Forged NAB was more resistant due to the fragmentation of the Kappa 3 phase provided that the forging was sufficiently severe to ensure that the fragmentation of the Kappa 3 phase occurred. A more attractive solution was to look towards CuNiCr alloy for a solution. As with many complex marine equipments, there were inevitably compromises to be drawn between the requirement to achieve a dominant characteristic, in this case corrosion resistance, and the many other factors bearing upon component selection, e.g. strength, manufacturing method, cost, etc.

Thermistor Performance

In accordance with NES 632 the PIP is protected against excessive stator temperatures by thermistors embedded in the stator end windings. Experience showed that the thermistor material reacted with the potting resin resulting in a rise in the temperature at which the thermistor switched. Once recognized, this problem was overcome by simply sleeving the thermistors to provide a physical barrier between the thermistor and the potting material.

Potting Material

The stator end-windings are encased in potting to assist the transfer of heat from the stator to the seawater. Early attempts used a binding resin with an inert filler. This proved to be a difficult process to implement because during the resin curing process cracks developed in the potting material. Such defects could not be accepted due to the risk of creating a hot-spot at the junction between radial and circumferential cracks. Fortunately, the cracks were predominantly radial. Despite extensive experimentation it was not possible to modify the process to eliminate these cracks. The way forward was found by reinforcing the potting with fibre-glass mesh. By careful selection of the grade of mesh, development of the technique for introducing the mesh into the end-winding space and the method of injecting the potting it proved possible to produce a coherent potting substantially free of cracks. The benefits were further enhanced by being able to apply this technique using U.K. supplied materials whereas the only alternative to achieve a relatively crack-free structure was a U.S. supplied resin having problems of both availability and a considerably higher price.

Design Optimization

To meet the general requirements for a submarine circulating water pump a compact design is necessary. This leads to a high power density which is indeed the case with the PIP. Partly as a result of the evolution of the PIP design, the PIP has a high slip factor for an induction motor. This means that the effect of any variation in motor characteristics has a large effect upon duty point speed and hence the pump flow and head. Equally, in a high power density motor there is inevitably a concern to hold the stator temperatures to limits that will not prejudice the stator insulation life. Since sufficient test data only became available part way through the development programme a careful assessment of both electrical and hydraulic performance was necessary to optimize the pump design.

As a result of tests on the first three production pumps it became apparent that the pumps were particularly sensitive to manufacturing tolerances. Particular care was therefore necessary to control the stator winding process and the assembly of the rotors. It also became apparent that production pumps were operating slightly in excess of the design speed. The resultant head and flow were broadly within the required limits, bearing in mind that the precise characteristics of the circulating water system itself were not known. Tests were carried out to assess the effects of trimming the rotor bars to reduce the pump speed. As expected it proved possible to modify the speed but there was a relatively small effect upon the head and flow and a corresponding detrimental effect upon the stator temperature. Given that there is a scatter between the performance of production pumps due to manufacturing tolerances it was concluded that the results did not justify trimming the rotor bars. The design and tuning process was further complicated by possible variations in the rotor geometry that will most probably be invoked if even quieter designs are developed.

Having established a satisfactory compromise between the electrical and mechanical features of the machine, the final assessment was to estimate the insulation life in service given the anticipated operating cycle of the equipment. This was done using an Arrhenius plot for the insulation material. Comprehensive assessment of the insulation life indicated that the pump insulation would survive considerably longer than the specified design life.

The Future

We now have a viable PIP with all the advantages that were anticipated at its inception. We also better appreciate the penalties. It is more expensive than a conventional pump and certainly more complex. The extent to which we might be dependent upon specialized sectors of the industrial base is also a valid question. Where do we go from here? The most obvious response to this question is to suggest that the current design should undergo a value-engineering exercise to see whether it can be improved upon and manufactured more cheaply. Given that we can now rely upon an established design we may be more inclined to attempt approaches which could yield benefits but which under the pressure of an intensive development programme were considered too risky at the time. Alternatively, a completely new approach to circulating water pump design might be considered attractive. During the development period of the PIP significant advances have been made in magnet drive technology which might yield benefits in both simplification and cost reduction. These are questions that will no doubt be addressed in considering the approach to be taken for SSN 20.

Acknowledgement

The author of this article was fortunate to be the MOD Project Officer during the final three years of the PIP's development programme. Throughout its development there have been many other people involved in bringing this project to a satisfactory conclusion and without whom, working together, the successful outcome would not have been possible. It is interesting to reflect upon the range of skills that have been deployed both within and without the MOD and upon the way that diverse and often dispersed resources now need to be integrated to achieve a sophisticated engineering product.

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