GLANDLESS PUMPS WITH MAGNETIC COUPLING DRIVE

BY

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Introduction

The field of application of centrifugal pumps throughout the world is so wide and diverse, in terms of fluids handled, flow rate, and pressures at inlet and outlet, that there are many hundreds of individual designs. The vast majority are driven by external prime movers and have one shaft penetration requiring a seal (or two shaft penetrations in some cases). For many years, compressible gland packings performed the sealing function, adequately enough where the pressure at the shaft penetration was low and aqueous liquids were being pumped. To obtain reasonably long packing life at anything other than very slow speeds, a small amount of leakage is necessary for lubrication and cooling. Obviously, this type of gland was soon found to be inadequate for inflammable, toxic or high-value liquids, so the development of either mechanical seals or glandless pumps became essential.

Many different makes and designs of mechanical seal are now available; continuous development of face materials and manufacturing processes has pushed the frontiers of pressure and velocity of seals based upon the self-adjusting rubbing-face principle into areas previously thought to be impossible. Furthermore, cheap, mass-produced mechanical seals are now available for the highly-competitive markets for small pumps, such as washing machines and automobile cooling systems.

However, the bewildering choice of production seals available and the claims made in advertising campaigns have sometimes led equipment manufacturers to select seals that are not suitable for the particular application. This is probably the main reason why the MTBF of mechanical seals varies widely between different applications of the same seal, and why mechanical seals have a mixed reputation among pump users. Main and auxiliary sea water circulation pumps operating at depth pressure are a typical case; the seal designs used until recently were prone to 'hang-up', that is, the faces not maintaining contact under all conditions due to various causes[1]. Replacement of mechanical seals is often expensive, on account of the high quality and materials of the seals themselves and the amount of dismantling necessary to expose the shaft end. Moreover, breaking and re-assembly of shaft couplings introduces possibilities of misalignment and noise. Sprays of sea water at high pressure can cause degradation of motors or other equipment. Glandless pumps clearly have potential advantages in these applications.

There are two main types of glandless pump drive: the submerged motor, and the magnetic coupling. Both types are well established in the process plant field, but not for sea water, where there is not much demand (because suction-side pressures are usually low and leakage is a nuisance rather than dangerous). The Royal Navy has a number of submarine sea water pumps of each type either in service or undergoing shore testing. Each type has its advantages, depending upon the circumstances; for example canned motors tend to be more compact, but more expensive for backfit applications, where the ability of the magnetic coupling to use existing motors may make it less costly.

Submerged motors are of three types, in increasing order of robustness and cost: wet-winding, canned stator with exposed rotor, and fully canned. The first makes use of special watertight insulation sheathing and is widely used for non-aggressive environments and cost-constrained applications, e.g. well pumps and central heating circulators. The second is used for hydrocarbons and mildly corrosive fluids, and the third for ultra-high integrity (e.g. primary water circulation) or aggressive fluids such as acids and sea water. A large mixed-flow circulating water pump (known as the pump-in-pipe) has been under development for some years[2,3] and the Mk. 3 version has been chosen for the Trident submarines. At the other end of the flow range, small units made by APV-Osborne Craig are currently used as lye pumps in the CJB Mk. V electrolyser and as replacement shaft seal pumps in some of the SWIFTSURE Class.

Development of the Magnetic Coupling

The fact that one magnet will drag another with a non-magnetic membrane interposed is so well-known that the principle of a magnetic coupling is as old as permanent magnets themselves. The device in FIG. 1 is little more than a toy; a more practical form of coupling with a 'top-hat' shaped fluid barrier is shown in FIG. 2.

Early magnetic couplings tended to use electromagnets, as the size and weight of the permanent magnets available before the second world war was a severe disadvantage for the configuration of FIG. 2; large overhanging masses encourage bearing and vibration problems, and high moment of inertia on the motor shaft is not good for line starting. However, electromagnets require d.c. supplies through slip rings, with all the attendant disadvantages, so it is no surprise that there was no market for drives of this type.

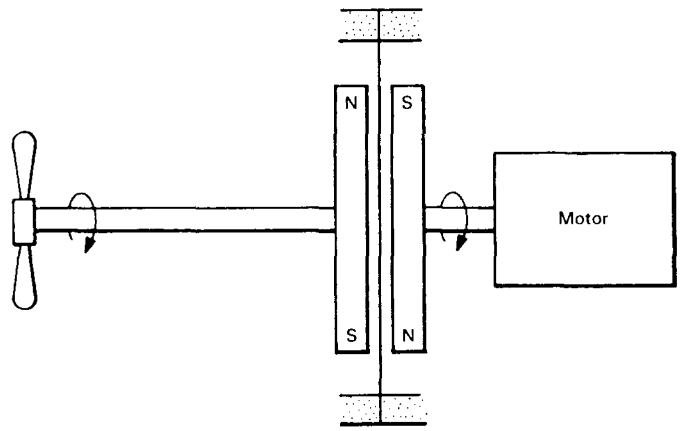

FIG. 1—SIMPLE MAGNETIC COUPLING

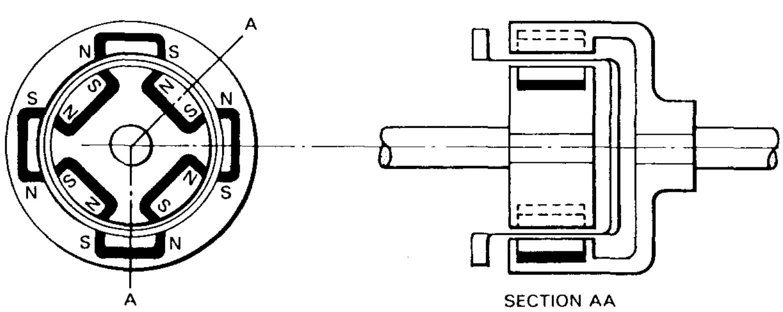

FIG. 2—MAGNETIC COUPLING WITH FOUR POLE PAIRS

In the late 1940s, the development of cobalt-based anisotropic alloy permanent magnets such as Alnico, and later Alcomax, began to make permanent magnet drives attractive.

A coupling having magnets on both driving and driven rotors must, by the nature of things, run synchronously—if the driven rotor drops behind, due to overload, it experiences alternate forward and backward torque pulses and cannot transmit any torque. Moreover, Alcomax magnets de-magnetize if the coupling slips; this is a serious snag, and it is essential to over-size the coupling so that it cannot reach its 'pull-out' torque. It is obvious that rotodynamic pumps are better suited to synchronous magnetic drive than positive displacement pumps, because the former are limited in the torque that the impeller can absorb. However, the possibility of excess torque due to rubs or foreign bodies is still a hazard.

There is a way round this serious snag, however—the asynchronous coupling, which has proved commercially viable. This coupling does not have magnets on the inner (driven) rotor but uses squirrel-cage copper conductors in a slotted iron ring like an ordinary induction motor. The principle is obvious, since the rotating array of permanent magnets produces a rotating flux field the same as a stationary polyphase a.c. winding. Because increased slip produces torque (up to a peak value) the induction-type magnetic drive can be rated higher for a given volume of Alcomax material than a synchronous coupling, with no fear of demagnetization. There is a small penalty in efficiency, because the slip-induced currents in the copper and iron of the driven rotor result in resistance and hysteresis losses as in an induction motor.

During the sixties, new magnetic super-alloys were developed, using the 'rare-earth' metals cerium or samarium alloyed with cobalt. These were prohibitively expensive at first, but since 1980 the price has come down dramatically, and so has the size of couplings (Fig. 3). For a given size, a samarium magnet coupling will transmit almost four times the torque of Alcomax. Moreover, it does not demagnetize on desynchronization, so that pull-out margins can be reduced. An occasional pull-out due to solids ingestion in a pump is tolerable, whereas demagnetization is not. Rare-earth magnets also do not lose strength as a result of shock, as does Alcomax.

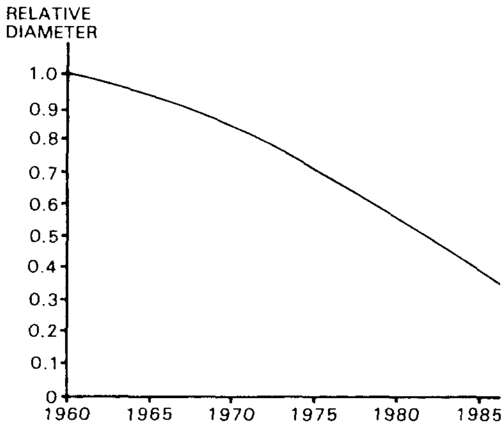

Fig. 3—Relative sizes of couplings since 1960

A strange feature of these new magnetic alloys is that the repulsive force of like poles is two or three times greater than the attractive force of unlike poles.

The efficiency of a synchronous coupling will vary between about 82% and 88%, losses being due to:

(*a*) Eddy currents in the stationary pressure barrier interposed in the 'air gap'.

(*b*) Drag or fluid in the narrow space between the pressure barrier and the inner rotor.

(*c*) Pumping losses due to circulation of pumped fluid to remove heat generated by eddy currents. (If the circulation is taken from the discharge of the impeller and returned to suction, the effect will be a small loss of output, but if flow is boosted by an auxiliary impeller it will be a parasitic power loss).

One of the attributes of the magnetic coupling driven pump, of special interest in the process industry, is its ability to withstand high temperatures—up to 450°C in the case of Alcomax magnets, which retain their strength at higher temperatures than rare-earth magnets. At such temperatures, a canned-motor pump requires special insulation, a cooler in the internal flow circuit and a thermal barrier between the pump casing and the motor casing. In addition to the pumping of heated process liquids, hot oil is used as a heat transfer medium; glandless pumps eliminate the fire hazard associated with shaft seals and hot oil, so the market has welcomed the magnetic coupling development.

Mechanical Design and Reliability

Besides the magnetic rotors and conventional pump parts, the components of a magnetic coupling driven pump which hold the key to reliability are the thin pressure membrane, and the journal and thrust bearings which are lubricated by the pumped liquid.

For all applications involving significant pressures, the pressure barrier is in the form of a top hat—sometimes known for brevity as a shroud—with a substantial flange and a crown which may be dished for strength and lightness. The cylindrical portion in the 'air gap' must be as thin as possible (the thicker the material, the greater the eddy-current loss and the larger the magnet volume required to produce the required flux density). The properties required of the material are, therefore:

(*a*) High yield and/or fatigue strength.

(*b*) High magnetic permeability (the flux must pass through it).

(*c*) High resistivity (to reduce eddy current).

Fortunately a number of materials combine these properties with good resistance to corrosion and erosion—e.g. austenitic stainless steels and nickel-base alloys such as the proprietary Nimonics, Incalloy and Inconel. Such materials are also used—for the same reasons—for the cans which cover the windings of canned motors. Both shrouds and stator cans have pressure inside the cylinder; the essential difference is that the 'can' of a submerged motor is supported by the stator core and is not subject to primary membrane stress, only to bending where it bridges the narrow slots.

The safety of the pressure shroud is sometimes called into question, from the point of view of fatigue, particularly with corrosive fluids. In fact, the combination of good design and material selection with inspection procedures as used in canned motors provides the necessary assurance. The stress pattern is simple, with the thin section in pure tension and no stress-raising geometry except for possible weld defects in fabricated components, or machining marks in forged sections. The HMD units currently type-approved for back-fitting to SWIFTSURE Class have shrouds of Inconel 718 machined from solid forgings which are subject to ultrasonic and dye-penetrant inspection at several stages. Inconel 718 is a nickel-base alloy with corrosion resistance in sea water approaching that of the outstanding 625 alloy, but with higher yield strength which enables it to withstand over-pressure excursion to hull-collapse depth without yielding. The prototype was subjected to 20 000 cycles to deep diving depth pressure (DDP) and 100 cycles to depth dependent systems test pressure (DDSTP) in sea water and to two years immersion with no sign of corrosion or fatigue cracks. Finally, in terms of submarine safety, it should be pointed out that the connection of the thin pressure vessel to the sea water system is through passages of small area relative to 'critical' size, so that extreme safety measures do not have to be taken.

A common feature of all glandless pumps is the incorporation of at least two journal bearings and a thrust bearing, all lubricated by the pumped liquid. Water-lubricated bearings are prone to significant wear, because they operate with hydrodynamic film thicknesses of the same order as the roughness of the sliding surfaces, and sea water often carries suspended sand and silt which increases the wear still further.

Throughout most of the several decades of growth of the commercial glandless pump industry, carbon has been the most frequently used material of bearing bushes, against journals hard-chrome plated or sleeved with stainless steel. Hard chrome plating is not suitable for sea water: it is not impervious, and the galvanic potential between carbon and the journal substrate in sea water severely corrodes the latter. Asbestos-reinforced phenolic resins such as Railko and Ferobestos have good wear resistance, but tend to wear soft shaft materials. Very hard shaft surfaces resistant to sea water corrosion can be produced as coatings (tungsten carbide, aluminium oxide or chrome oxide) on nickel alloy 625 shafts or sleeves. These do not wear in sandy sea water, but the phenolic resin bearing then wears, albeit fairly slowly. Since warships may have to run auxiliary sea water pumps for long periods in shallow waters, and since the R.N. is looking for overhaul intervals of up to ten years, 'hard-on-soft' material combinations are unlikely to meet this target.

In the last 15 years, MOD has sponsored long-term testing of hard-on-hard water-lubricated bearings, particularly in connection with the pump-in-pipe (canned motor) project, and several commercial firms have also tested numerous material combinations[4,5]. One of the most effective is silicon carbide as a 'like-on-like' pair. Silicon carbide (SiC) is one of the hardest synthetic materials, and it has the great advantage over other ceramics of much higher thermal conductivity. Thus, it is less likely to fail in thermal shock due to local loading and heat generation resulting from imperfect alignment or from the lack of hydrodynamic damping to which water-lubricated journal bearings are sometimes prone. The cost of reaction-bonded silicon carbide has come down steadily owing to increasing use for mechanical seal faces, as well as numerous applications of its superior thermal-shock resistance.

Although silicon carbide in some forms has one of the highest tensile strengths among ceramic materials, it is brittle like all such materials, and care must be taken in the design of composite metal-ceramic assemblies to ensure that it is not subject to tensile or bending stress: for example, sleeves cannot be an interference fit on shafts. Various designs which overcome this have been developed, and some have been shock tested. Also, techniques are being developed for ultrasonic detection of small sub-surface defects in sintered components or lack of bond of hard coatings.

Sea water circulating pumps, having duties of high flow and low head, are often of mixed-flow or axial-flow design, and these develop large hydraulic thrust which must be carried by water-lubricated thrust bearings in glandless pumps—much higher than typical journal load. The high load-carrying capacity of the SiC v. SiC combination can be used to good effect here. Tilting-pad thrust bearings of this material can be run water-lubricated at specific loads of well over 100 bar (1500 p.s.i.) and even simple flat-faced rings, with radial grooves and generous water flow, can carry remarkably high bearing pressure if made self-aligning.

Magnetic Coupling Pumps for Current Nuclear Submarines

There is no well-defined limit to the torque capability of the rare-earth magnet synchronous coupling; although the size of magnets that can be made at present (by powder-compaction and sintering technique) is only a few cubic centimetres, magnets can be stacked along the length of a rotor and the number of poles can be increased in proportion to the diameter. However, there are practical limitations on diameter, especially for pressure applications, as the thickness of the pressure barrier must increase with diameter. Thus, there is no possibility of foreseeing a main shaft glandless drive transmitting several megawatts at low speed. FIG. 4 shows approximately the present limits of torque and of power at 3500 r.p.m.

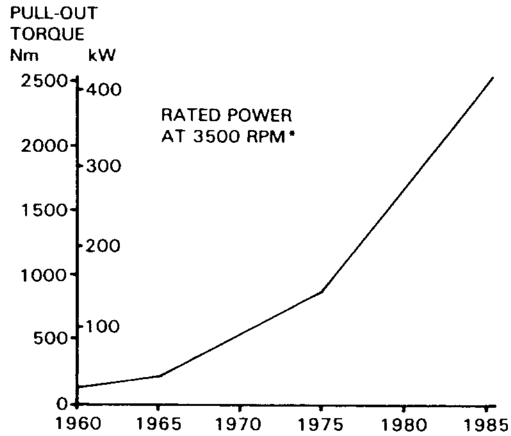

FIG. 4—GROWTH OF CAPABILITY OF SYNCHRONOUS COUPLINGS
*RATED POWER BASED ON TYPICAL INDUCTION MOTOR DRIVE:

$$\text{RATED TORQUE} = \frac{\text{PULL-OUT TORQUE}}{2.25}$$

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The only supplier to the MOD at present is HMD Seal/less Pumps Ltd., who were world pioneers of permanent magnet coupling technology, and developed the induction coupling when the synchronous type was baulked by the pull-out problem described above. HMD export worldwide, but competition is increasing: the German firm of Klein, Schanzlin and Becker (KSB) also have a share of the world market, and other firms—including one traditional manufacturer of marine pumps—are developing their own versions of coupling, using samarium magnets from a continental source which probably supplies all the coupling manufacturers at present.

Two examples of couplings designed for current nuclear submarines are shown in sectional arrangements, FIGS. 5 and 6. The larger unit, FIG. 5, is a conversion of the TRAFALGAR Class combined ship/reactor heat exchanger sea water service pump, with a two-speed motor rated at 18.5 and 6.0 kW (at 1750 and 1170 r.p.m. respectively). These and the smaller SWIFTSURE Class pumps have impellers located half-way across the heat exchanger return header and thus have relatively long pump shafts with the impeller and inner magnet ring (IMR) overhung, and the silicon carbide bearings in a common bush holder (which ensures good alignment). A special feature of this unit is that it is designed for installation with the shaft nearly vertical, which means that the top-hat shroud cannot be statically vented. The circulation of water for cooling the shroud returns through the hollow shaft, and tests with a perspex model showed that the shroud is self-venting when the pump is started at either fast or slow speed. Dismantling of the unit is easy, but it is necessary to withdraw the motor axially by the height of the shroud member, which requires more installation and removal distance than does the present pump with its flange coupling. Contrary to what might be expected, the outer magnet ring (OMR) does not clamp itself to the shroud in an effort to cling to the IMR during the assembly: the net radial force is much less than the potential driving force. The coupling is designed to take the high shock levels: hence the rubbing band on the OMR, which restricts the bending of the motor shaft due to the overhung mass.

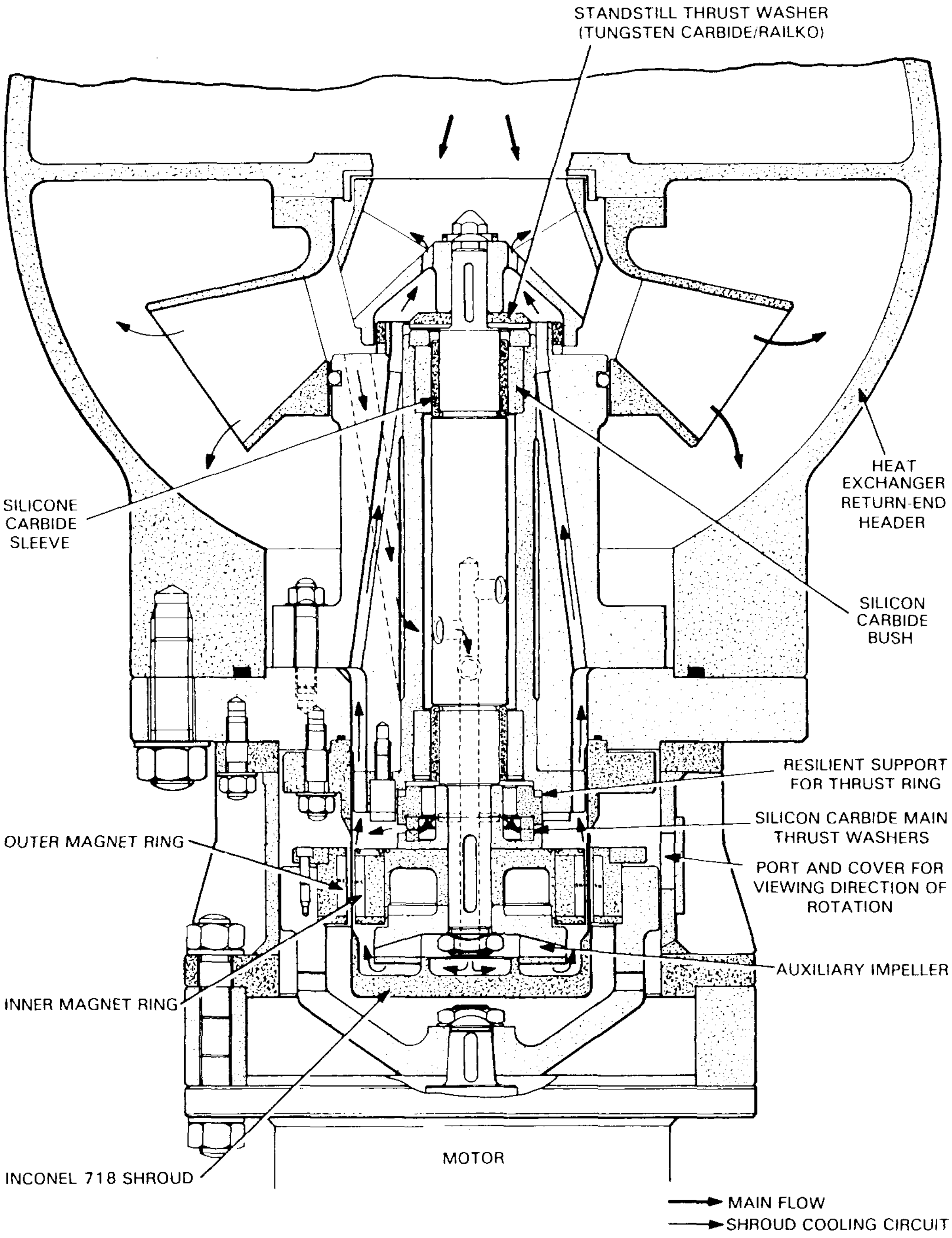

FIG. 5—SHIP AND REACTOR COOLING SYSTEM SEA WATER PUMP WITH MAGNETIC COUPLING DRIVE

The smallest unit, FIG. 6, is an evaporator brine pump which can be back-fitted in place of the present close-coupled pump which has frequent seal failures, largely due to salt crystallisation. The design is particularly compact, as the coupling end journal and reverse thrust bearings are tucked inside the IMR, with the other journal and thrust bearing mounted on the front of the impeller. Corrugated Inconel 'tolerance rings' are used to secure the bearing components, taking up differential expansion between silicon carbide and metal, because the unit might sometimes operate at 80° to 90°C. (The sea water service pump in FIG. 5 experiences a much smaller temperature range, so the shaft sleeves there are secured with Loctite 601). The brine pump does not have much pressure difference across the shroud, which is fabricated with a wrapped sheet cylindrical portion.

The largest unit (not illustrated) is a prototype conversion of a SWIFTSURE Class cooling water pump, with a motor rated at 100 kW at fast speed. This pump has a silicon carbide thrust bearing designed to take the peak (shut valve) thrust of over 20 kN.

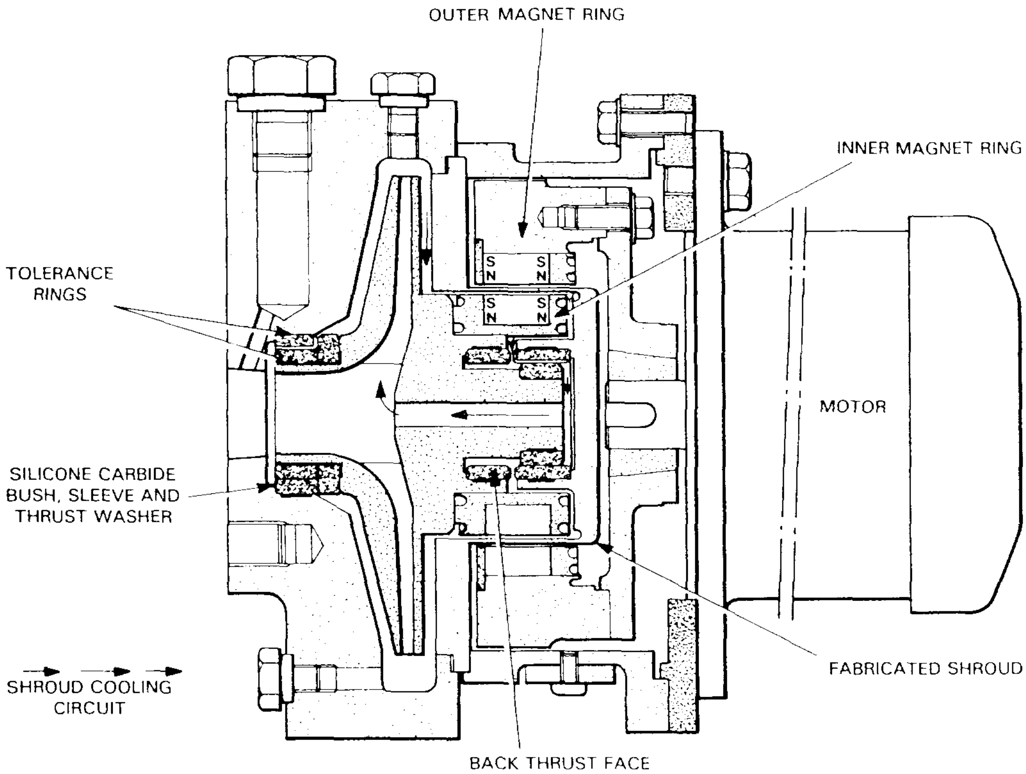

FIG. 6—BRINE EXTRACTION PUMP WITH MAGNETIC DRIVE

Comparison of Canned Motor and Magnetic Coupling

It is possible that, in future classes of submarines (and for some applications in surface ships) both types of glandless pump will be used. In new construction, the advantage of the magnetic coupling in being able to use existing motors will not apply, and the two principles will be competing on criteria of cost, space, weight, and more stringent noise and vibration targets. Present indications are that the reliabilities and maintenance burdens will not be widely different. Canned motors of pump-in-pipe form are economical of space but are very expensive, with both inner and outer casings of corrosion-resistant alloys. On the other hand, centrifugal pumps based upon commercial process-type canned units would have mild steel motor casings and are comparatively cheap. More work remains to be done to reduce the electromagnetically generated noise of canned motors and the residual unbalance vibration of the two-shaft magnetic coupling arrangement.

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