Proceedings of the Institution of Mechanical Engineers

I MECH E

Fluid Machinery for the Oil, Petrochemical and Related Industries

Fifth European Congress

Sponsored by the Fluid Machinery Committee
of the Power Industries Division of the
Institution of Mechanical Engineers

IMechE 1993–3

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Development of main oil line and seawater injection pumps for oil industry application

P A SMITH
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SYNOPSIS

Offshore production continues to provide a significant portion of total oil production, and the ongoing development of offshore technology is certain to facilitate further exploration for both land and sub-sea reserves.

This market is providing an interesting challenge to pump manufacturers, reliability and economy being of paramount importance. This paper reviews recent developments in centrifugal pump design including vertical multistage arrangements, high-speed geared configurations and application of advanced materials for oil transfer and water injection duties. The range of applicability of these new developments and established concepts are put into context.

INTRODUCTION

The offshore market is providing a challenge to the pump manufacturer in the areas of oil transfer and water injection. Installation constraints and customer preference in the selection of driver, maximum speeds and form of construction, leads to a diverse selection of machines to meet similar applications.

This variation in user requirement implies that a pump manufacturer servicing this market must not be restricted to a single pump type. The size of the machinery involved and the variation in duties to be accommodated result in the use of Engineered Products, i.e. pumps specifically designed to meet the requirements of an individual contract, rather than the application of a standard range.

Difficulty in access to the unit modules for major maintenance work, a shortage of space for the installation of standby equipment and the high cost of a loss in production, place great emphasis on reliability. This emphasis is reflected in the purchaser's specification, which generally includes stringent inspection requirements at all stages of manufacture and testing.

Comprehensive testing is of paramount importance. The manufacturer must have facilities to run machinery at full speed and load, both to demonstrate the hydraulic performance and to prove the mechanical integrity.

If maintenance work is required then the operation must be simple with a minimum of disruption.

PUMP DUTIES

The development of an oilfield takes several years, with production rising sharply to a peak, after which continued exploitation leads to a gradual decline in output, until the field becomes uneconomic. Initial production is often achieved by utilising the natural water or gas pressure within the oil field. As oil extraction continues the well pressure decays. If the oil recovery rate is to be maintained or increased then the reservoir pressure must be artificially elevated by the injection of water or gas. The injection rate and pressure are functions of the geological conditions of the individual well being exploited and the productivity required. The duty of the injection pump is consequently only established through operational experience and can alter substantially with oil extraction. This results in the use of series and parallel pumping systems and necessitates a wide operational range from the injection pump.

Flexibility of operational range is achieved by careful hydraulic and mechanical design. The ability to adapt further is often necessary and can be achieved by destaging or using different hydraulic bundles or cartridges, one for the initial injection duties and a second when the field has been fully developed. Speed control is one means of accommodating the changing field characteristics, and horizontal machines of higher power rating are likely to have this facility by virtue of being driven by a gas turbine.

Typical pressures range from 100 bar in the Gulf of Mexico to 350 bar in the Ekofisk field of the North Sea.

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To match oil transfer rates with achieved production levels, Main-Oil-Line pumps are often driven through combined speed increasing gearboxes and Turbo couplings.

SELECTION CRITERIA

Operators and Consulting Engineers demand that M.O.L and injection pumps must satisfy the following requirements:

(1) Proven Reliability - Designs to be of proven pedigree.

Parentage of mechanical and hydraulic designs to be traceable in similar operating conditions.

Material selection to be demonstrated as suitable for the site fluid and operational conditions. On injection applications this translates to being capable of withstanding cavitation, corrosion, high velocity erosion and perhaps also abrasive wear.

Rotor dynamics to be insensitive to pump internal wear and drive train dynamics.

(2) Economy

High efficiency over operating range.

Compact design, low weight and small deck area requirement. The current cost of deck area is £234 thousand/m^2, with every tonne of equipment carried "deckside" requiring approximately 1.4 tonne to support it.

Ease of maintenance with minimal loss of production.

Competitive initial cost.

Long life due to a simple design.

(3) Adaptability

Wide operational range coupled with ease of modification to accommodate inevitable changes in well characteristics.

As stated in the Introduction, installation constraints and customer preference has led to a diverse selection of machine constructions to meet similar applications. The fact that they exist along side each other, without one being dominant, is testimony that each type has real or perceived advantages for certain applications and hydraulic duties, whilst having short-comings in others. The following review of pump constructions, currently available commercially, attempts to define their range of applicability and hence put the new developments and established concepts into context.

PUMP TYPES

Horizontal Axial Split Casing Multi Stage Volute Pumps (Fig 1)

High heads may be developed in relatively low speed pumps by the use of multi-stage axial split casing designs. A natural progression from the single-stage pump is the use of multi-stages arranged in opposition. Such an arrangement has the advantage of allowing the designer to offset the axial thrust generated in each impeller without having to resort to the use of elaborate thrust compensation devices.

Volutes are usually employed for axial split casing pumps in preference to diffusers as they reduce the complexity of the machine.

This type of machine, mounted horizontally, became universally used during the development of both oil transfer and water injection techniques. First designed in the USA and under American influence applied as first line M.O.L and injection pumps throughout the world, at a time when operating pressures were relatively modest.

Axial split casing pumps may be designed to withstand the high test pressures, necessitated by high discharge pressure, although the barrel casing pump, with circumferential joints, is arguably better suited. However, by use of Finite Element Analysis coupled with higher strength steel alloys and improvements in foundry methods, axial split casings can now operate successfully at working pressures up to 330 Barg. This implies test pressures up to 495 Barg.

The ability to inspect the rotating element whilst still within the bottom half casing, aligned and coupled to the driver is a major advantage of this construction. However, top half removal is time consuming if mechanised stud tensioning is not employed.

Barrel Casing Pumps (Figs 2 & 3)

Traditionally the barrel case pump was considered more difficult to maintain with significant work being required to dismantle or rebuild a pump on site. Manufacturers have developed their latest range of barrel casing pumps to resolve this traditional difficulty. The introduction of the total withdrawal cartridge and the shear ring design has now made the maintenance of such machines simple in the field and enables the more complex work to be carried out in a workshop, where good maintenance facilities are available.

This type of pump utilises a replaceable cartridge construction with access for cartridge withdrawal from the non-drive end on horizontal units, and from the drive end on vertical units. This mode of construction employs radial diffusers in preference to a volute arrangement, although volute designs may be used for the double entry first stages.

Later developments in water injection applications have seen the emergence of this type of unit to meet the need for higher pressures and flows, and also for use in M.O.L applications where space limitations have necessitated vertical configurations. Its pedigree can be traced to the Power Generation Industry and in

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particular to Boiler Feed Pumping. Unlike the modern Horizontal Axial Split Pump which was an oil industry related unit applied to water duties, occasionally as standard design, but normally with significant modification, (split casing in a Barrel), the Diffuser Barrel was a purpose designed water pump.

Developments in Boiler Feed duties had already included investigation into impeller life, hydraulic effects at part capacities, shaft stiffness, etc. It is not surprising therefore that this type of unit was initially easier to apply to the harsh Water Injection duties.

Horizontal versus Vertical Construction (Fig 4)

In certain applications by adoption of vertical barrel casings, it has been possible to eliminate the need for a booster pump. This is due to the possibility of mounting the unit at a lower level, because of its reduced deck area requirement, (only circa 24% of a equivalent horizontal set), coupled with the inherent advantage that by virtue of the units construction, the suction impeller has a higher N.P.S.H available relative to the units suction branch elevation.

A weight advantage is also achieved as vertical sets are approximately 6 to 8% lighter than the comparable horizontal set. Its construction and maintenance are simplified as no lube oil system and only one mechanical seal is required. This allows further simplication by minimising the need for instrumentation. Motor to pump alignment is also unaffected by pipework forces or deck movement (1) however these advantages have to be considered against the following limitations :-

1) Pump Running Speed dictated by drive motor slip speed, as insertion of a gearbox, whilst not impossible, is not currently practical because of the units power and ease of maintenance requirements. It would also increase the units height significantly.

2) Size of pumpsets limited by present 2-pole induction motor technology. Maximum power currently available 7 MW at 3600 R.P.M.

3) To maintain the pump cartridge, the drive motor has to be disconnected from its power supply, mechanically removed from the set and safely stored on the site or platform until the pump is fully re-assembled.

4) Maintenance lift heights increased.

5) Increased complexity in the Analysis of Set Structural movement due to "mast" type construction, necessitating interactive design process between Motor, Pump and Foundation Designer. (Fig 5).

The choice between vertical or horizontal construction is therefore not simple. The reduced weight, and apparent simplicity plus a smaller foundation area of the vertical set has to be offset against increased overhaul difficulty and lay-down space requirements. The potential conflict is between third-party purchasers favouring reduced initial purchase costs whilst plant operators favour ease of overhaul.

High Speed Geared Configuration (Fig 6 & 7)

These units, with absorbed powers in excess of 1 MW, were first introduced in 1987, and consisted of two single stage, double volute pumps, direct mounted on the output shafts of a speed increasing gearbox, with a separately driven booster stage. They have now been refined to incorporate a booster stage driven by step down gears in the same gearbox.

In comparison to conventional horizontal multi-stage pumpsets they offer a reduced footprint with virtually nil maintenance or laydown area required for the pump related components. Maintenance weights for pump casings are only circa 250 kg in comparison to 2 to 3000 kg for a total withdrawal cartridge.

Maintenance times are short, with one impeller and its respective mechanical seal being able to be removed and replaced in 2 hrs. The high pressure casings are interchangeable but impellers are not due to differing effective rotational directions.

Reduced mechanical complexity is claimed, however this depends upon the specific application. The number of components within the pumping element is reduced and the high-speed drive coupling is eliminated when compared to a conventional long coupled gear driven unit. However, for many applications a direct drive motor can be employed, without the need for the complication of a gearbox and extra coupling. In comparison to a vertical unit, the need for a lube oil system and multiple mechanical seals also negates this claim.

One cause of concern has been possible oil contamination in the event of a catastrophic mechanical seal failure, leading to internal damage of the gearbox. Due to the application of very conservative PV values, (circa 30% of the recommended maximum), by use of pressure breakdown bushes and regulated seal chamber pressure, the risk of seal failure is minimised. Should it occur, double carbon labyrinths with atmospheric drains upstream and downstream of the first element, prevent ingress of water into the gearbox. In comparison to conventional units the proximity of the mechanical seal to the bearing housing seal is similar. However the bearing seal system is superior to many conventional units currently operating in the field.

If one compares a High Speed Geared Configuration with a vertical unit for the following water injection duty:-

Nett Generated Head 1760 m
Rated Flow 228 m^3/h
N.P.S.H.A (Deck Level) 10 m

then the High Speed Geared Configuration has a deck footprint of 4.6 x 2.1 m and an operational weight of 18 000 kg, whilst the vertical unit is 1.78 m (over motor terminal box) x 1.2 m and 20 310 kg respectively, i.e. 4.5 times the deck area but only 89% the weight of the vertical unit.

Of greater significance is the difference in power consumption between the conventional and the High Speed Geared units. The conventional unit would have a rated efficiency of 72% with a peak efficiency of 74%. The High Speed Pump would have efficiencies of 62.5% and 65.8% respectively. Due to additional gear losses within the High Speed Geared Configuration this unit would consume almost 21% additional power and also require a 1.9 MW rated motor in comparison to 1.69 MW rating for the conventional units. As the absorbed power increases the difference in efficiency reduces and the additional power consumed by the High Speed Geared Unit becomes approximately 5% at 4.3 MW absorbed power.

PRODUCED WATER APPLICATIONS (Fig 8 & 9)

On water injection applications where groundwater or produced water is reinjected into the formation rock, it is often physically or environmentally difficult to remove the suspended solids from the injection fluid. This necessitates the injection pump handling a very abrasive and corrosive fluid, that may become more abrasive and corrosive as the field is further worked.

The original technology supplied for such services in the early to mid 1980's was Duplex Stainless Steel Impellers and Diffusers with hard faced wear surfaces, in cobalt based alloys, on wear rings and balance drums .

In certain applications, in Alaska, the quality of the injection fluid deteriorated and the typical operating time between major overhauls reduced to between 6 and 8 months. The units suffered from severe erosion, tripping out on high vibration levels due to excessive wear ring and balance drum clearances. The rear shrouds on all impellers, with the exception of the delivery stage, were found to be very heavily eroded at the hub/shroud intercept, with perforations into the impeller's flow passage in several places (Fig 8). The impeller vanes at inlet also showed signs of erosion at the hub. Impeller wear rings were loose due to erosion of the securing pins, with the hub ring clearance at 9 times the Maximum Design Clearance and the balance drum clearance at 3 times the Maximum Design Clearance.

In late 1989, Weir Material Ltd's Super Duplex Stainless Steel "Zeron 100" and Boarts Hot Isostatic Pressed Sintered Tungsten Carbides "S6" and "S10" were brought together to solve the erosion, corrosion and wear problems associated with pumping produced water containing large quantities of formation and or "frac" sand.

Using installation techniques pioneered for the retention of Silicon Carbide sleeves in product lubricated bearings, coupled with Finite Element Analysis of assembly, transportation, and operational stress levels in both carbide and metallic carriers, stationary and rotating wear surfaces have been fitted with solid carbide components. The advantage of this being the available depth of wear surface. Carbide coatings have a more limited life due to their radial thickness being only circa 0.8mm after finish machining. With solid carbide however the minimim radial wear depth available is 3mm.

After 24 months operational experience on site, it is projected that by utilising this new development, service life between overhauls should be circa 4 years, i.e. 35 000 hours. This represents an increase in average operational life of 600%.

MATERIAL SELECTION

As wells become older and more marginal fields are exploited, M-O-L and water injection equipment have to resist more erosive and corrosive pumped fluids. M-O-L applications are often not the gentle service that they were, with produced or injection water carryover and silicates now within many hydrocarbons. Because of this and higher fluid temperatures, many M-O-L pumps supplied in the early 1990's have had identical materials of construction to that of water injection pumps, i.e. full Duplex or Super Duplex Stainless Steel construction for all metallic components in contact with the pumped fluid.

To guarantee the corrosion performance of stainless steels and hence that of the pumpset, the steels used must be of known Pitting Resistance Equivalent (PRE_N) value, as this parameter is used to control those elements which determine the corrosion resistance of the material. Currently, few suppliers control the minimum PRE_N value of their alloys. Many quote typical values which can be significantly higher than the minimum values which can occur in materials as supplied. Thus equipment can be purchased which has inferior corrosion, erosion performance and cavitation resistance. Control of the ferrite/austenite phase balance in Duplex materials is also necessary to ensure that their low temperature impact toughness is maximised.

NOISE CONTROL

The close proximity of the living quarters of rig personnel to high powered equipment poses a noise control problem.

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Pumps, gearboxes and drivers generate high sound levels and in the case of pumps the pipework helps to transmit noise to locations in the rig far removed from the equipment module. It is possible however, to meet the set parameters. Two courses of action may be taken. The individual item of equipment may be supplied with acoustic enclosures, or the rig module can be acoustically treated. The latter approach is now often preferred by the operators as it simplifies maintenance. None of the pump constructions considered here are simpler or easier to attenuate than any other. Double case pumps should offer lower emissions, but in practice this does not appear to be the case, consequently there is no advantage in selecting one particular configuration in preference to another.

CONDITION MONITORING

One of the major developments in offshore technology has been in condition monitoring. In the 1970's bearing, pump casing, motor winding and lubricating oil temperatures were monitored along with shaft vibration level, lubricating oil and suction and discharge pressures. Alarm and trip functions were active on most of these parameters, thereby protecting plant from catastrophic failure in the event of a malfunction. It was in fact, a damage limitation system for "after the event".

With advances in electronics and the continual striving by operators to achieve the unmanned rig the Main-Oil-Line and Seawater Injection package in the latter half of the 1980's and early 90's is now computer monitored and controlled. In addition to the functions of the 1970's the computer systems are capable of continually updating history files so trends can be identified and possible malfunctions detected before the event. This enables preventive maintenance to be instigated and minimises costs associated with unscheduled loss of production. It also means that simplification and reduction in instrumentation levels on pumpsets is not as advantageous as perhaps it may have been prior to computerised monitoring.

DISCUSSION AND CONCLUSION

The possibilities open to the designer to meet a given duty are considerable and as such, the role of the Pump Applications Engineer at the tender stage of a project is important. The user may specify his preferred pump type but specifications are often open to modification if an improved system can be offered. This may result in more than one proposal from each manufacturer tendering, thus leading to a highly competitive market situation. Offshore applications place great emphasis on reliability, with efficiency, weight and space considerations being also of paramount importance. With the emphasis on reliability, considerable credence is placed by the user on application lists citing similar designs in service. If an innovative solution is necessitated, then previous experience cannot be used to validate designs. In this situation more extensive analysis is required, coupled with a more stringent test programme.

The configurations reviewed here all offer viable solutions to water injection and oil transfer pumping applications. Each has advantages, disadvantages and constraints which need to be evaluated on an application specific basis.

The relative cost of each configuration is however difficult to assess. The conventional horizontal units should be more expensive to purchase than both the High-Speed Geared and Vertical pumpsets, due to its higher weight and traditional design. The inclusion of a gearbox in the high-speed unit should give the vertical pumpset the lowest initial purchase price. Marketing strategies and fluctuations in exchange rates however, will in all probability, continue to alter their respective purchase prices and make such simple comparisons very difficult.

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(1) HOFMANN, H.; A vertical heavy-duty pump concept opens up new platform dimensions in offshore technology - topside cost savings. I.Mech.E 1990 C403/024.

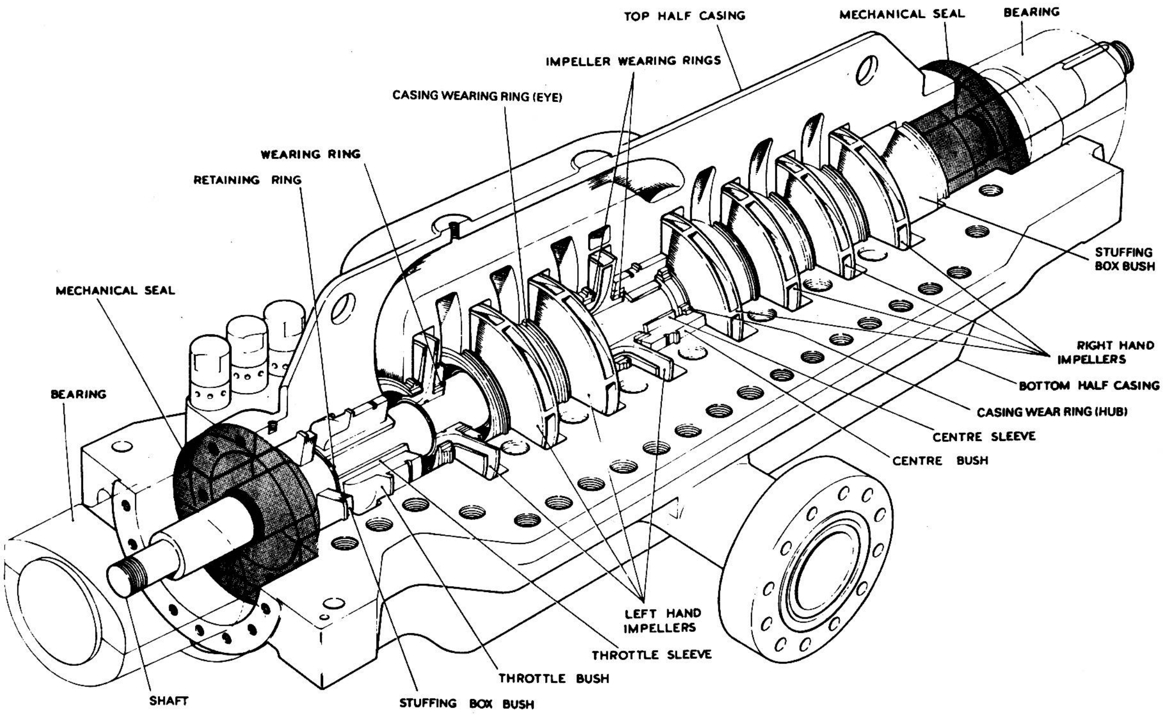

Fig 1 Cut-away of 8 stage axial split (horizontal) casing pump

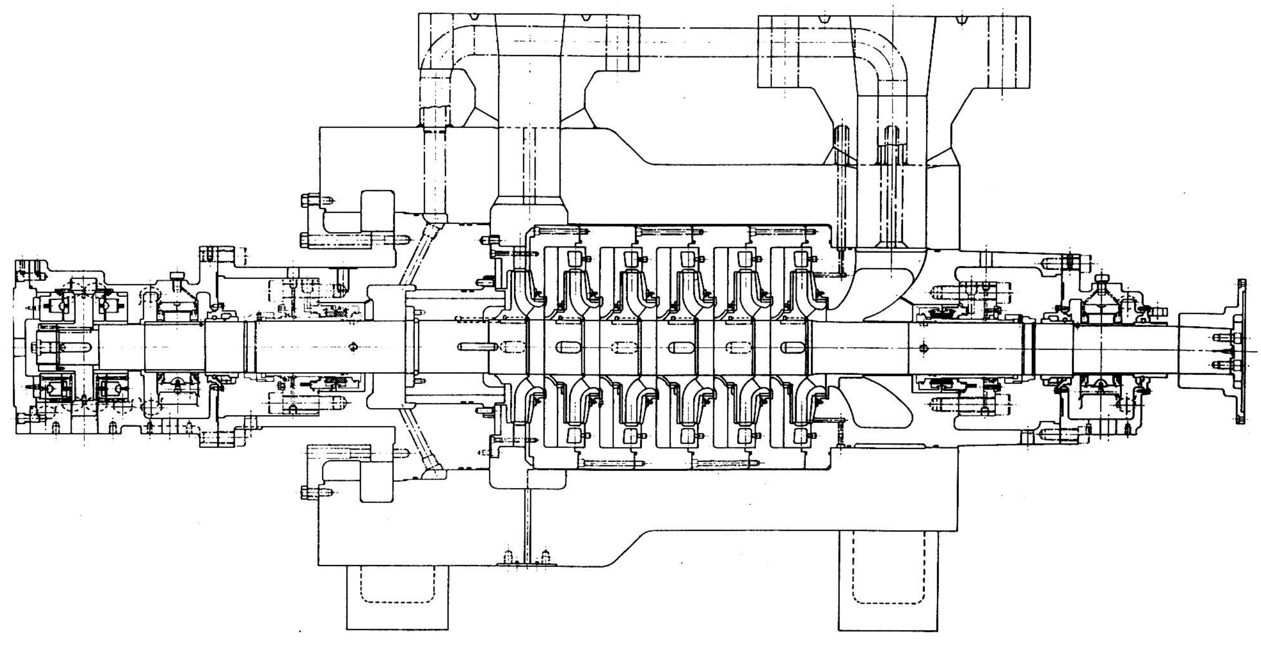

Fig 2 Sectional arrangement of 8"/10" 6 stage barrel casing pump constructed in duplex stainless steel (Ekofisk Field)

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Fig 3 8"/10" Vertical oil export pumps 3.6MW at 3600 rpm

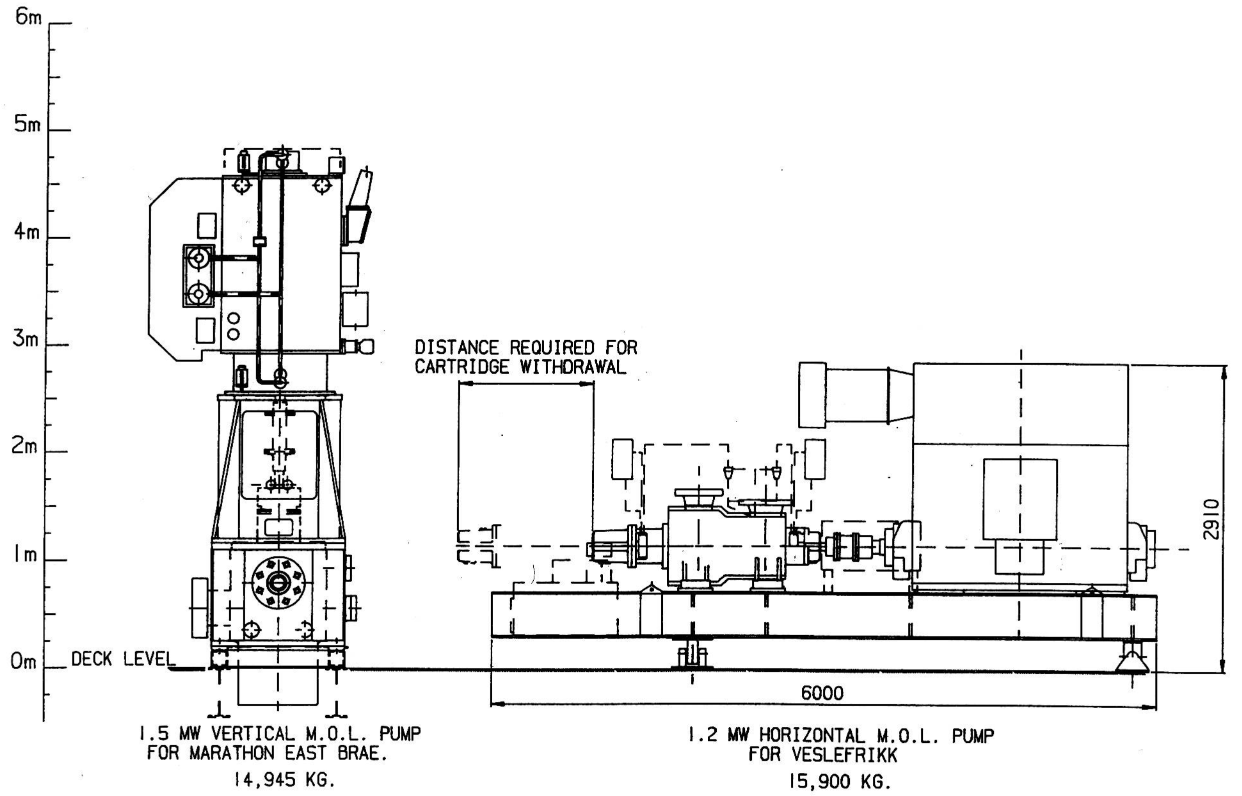

Fig 4 Comparison of horizontal and vertical pumpsets

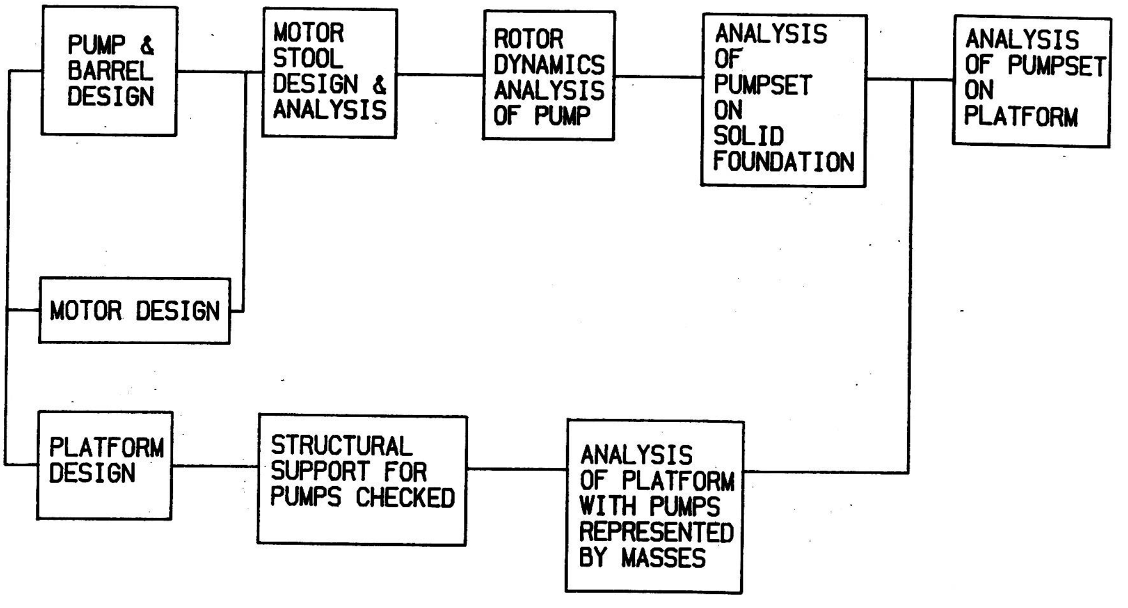

Fig 5 Plan of design/analysis for vertical pumpset

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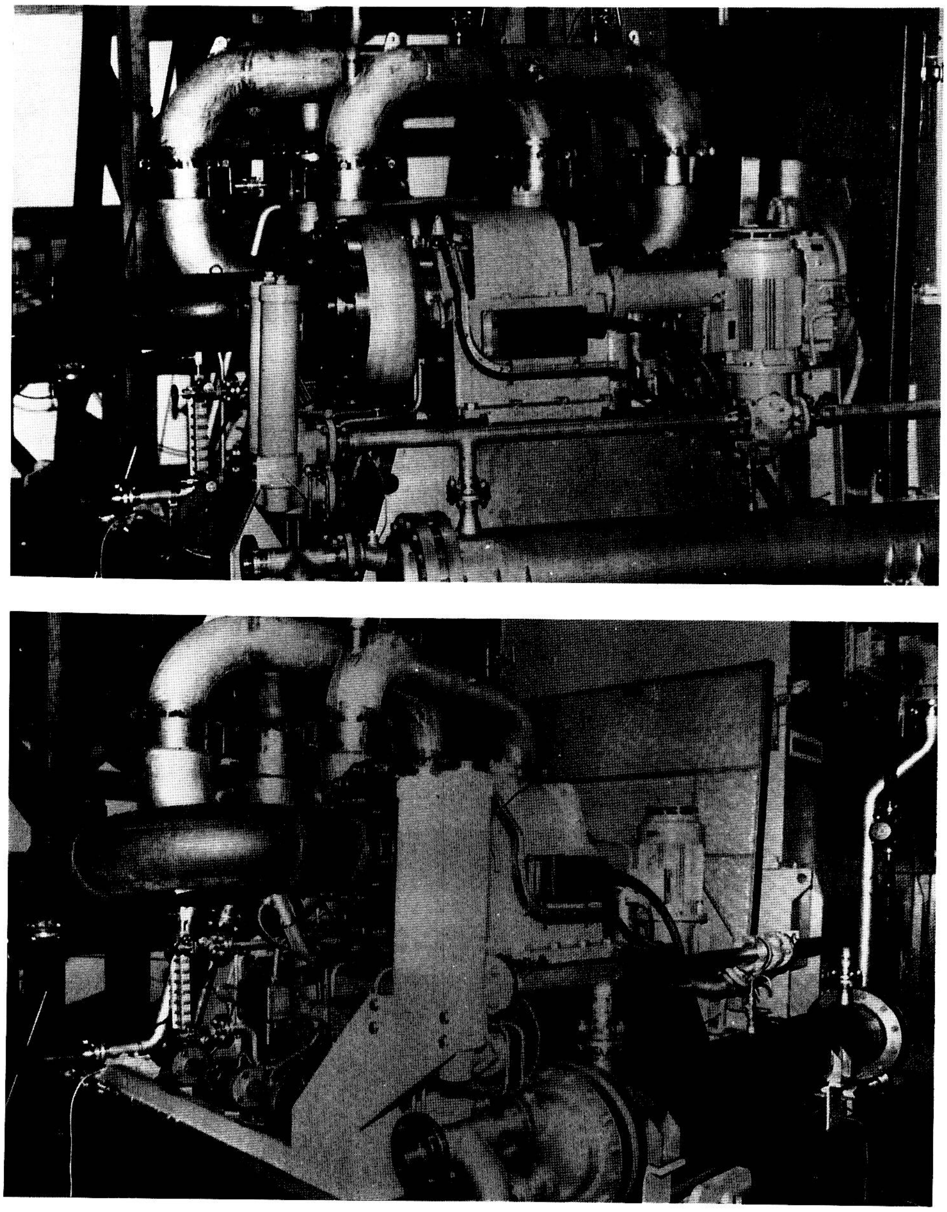

Fig 6 12 200 rpm high speed geared configuration

Capacity 748m^3/hr., Suction pressure 0.37 bar g., Discharge pressure 235 bar g., Motor rating 6600 kW.

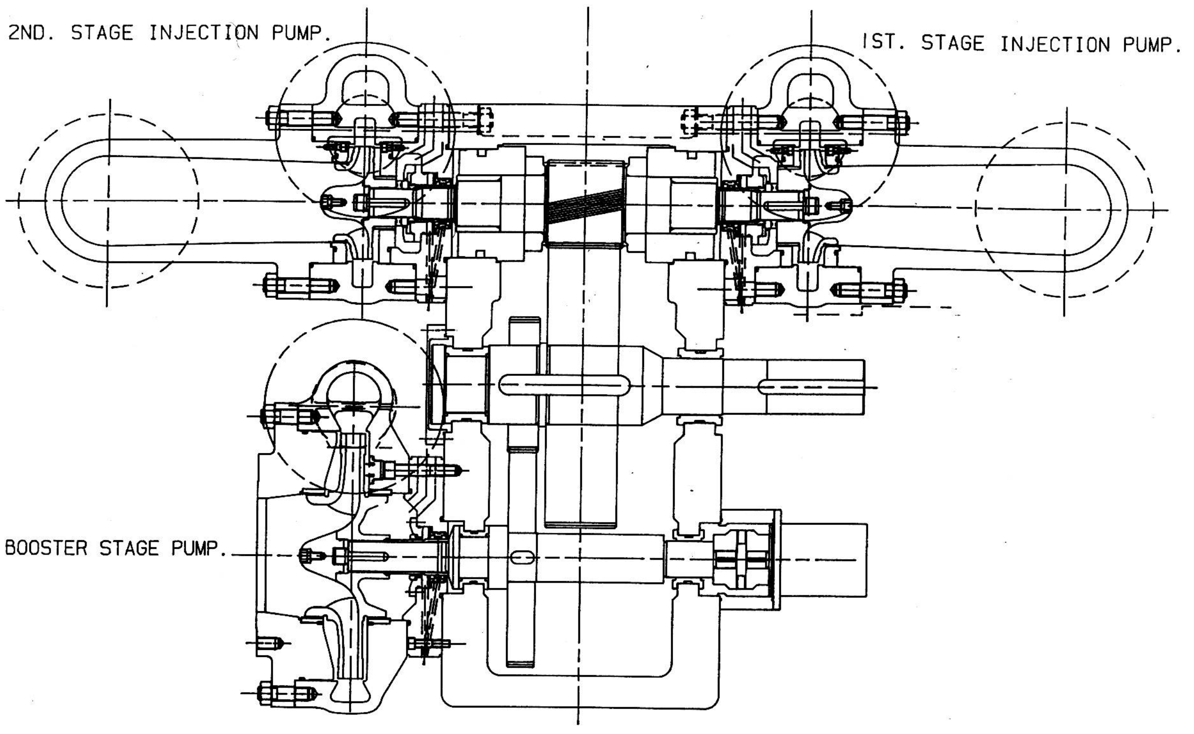

Fig 7 Sectional arrangement of 12 200 rpm high speed geared configuration with integral booster stage

Fig 8 Duplex stainless steel impeller after 6 months in produced water service

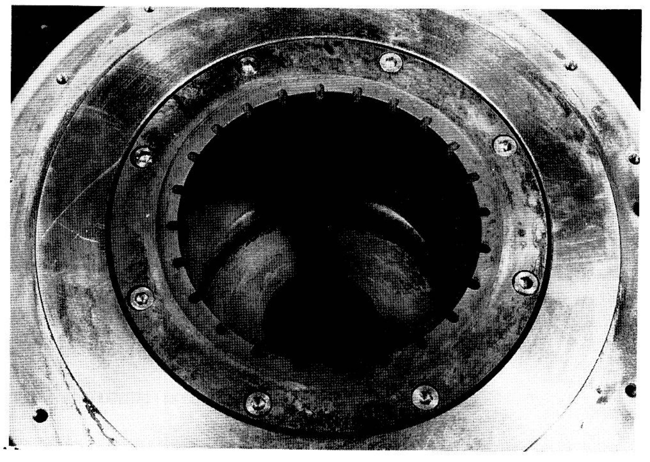

Fig 9 Balance drum bush in Sintered Tungsten Carbide after 6935 hours in produced water service

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