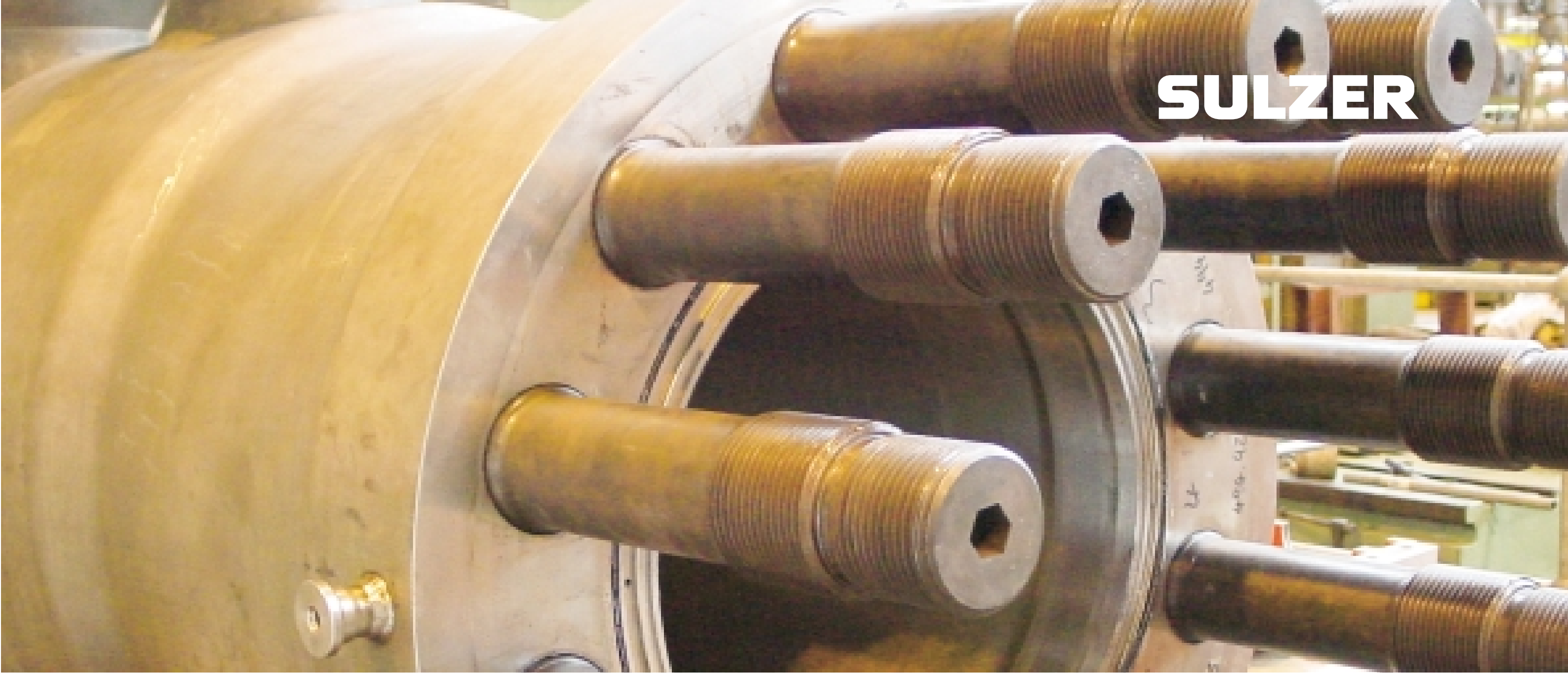
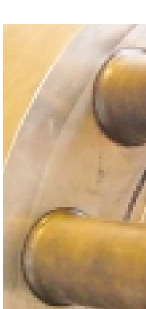


The Worlds Highest Pressure Injection Pump

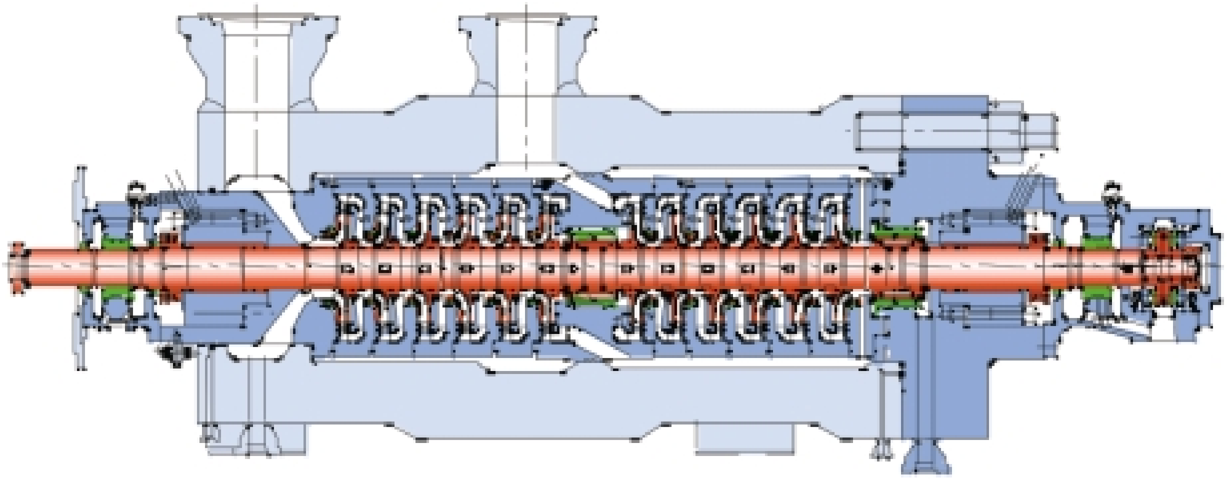
The Heart of Your Process



SULZER

The Worlds Highest Pressure Injection Pump

The following paper was written before manufacture and testing of the pump was completed. An update in the form of "Stop Press" is included at the end of the paper.



In March 2001, Sulzer Pumps was awarded the contract to build a prototype Injection pump capable of generating the highest seawater injection pressure ever achieved.

The contract was awarded by bp for the "Thunder Horse" project, which is part of the Deepwater Development programme in the Gulf of Mexico.

The pump rated duty is at a flow rate of 338 m3/hr (1458 US gpm) and a pressure of 605 bar (8575 psi). This pressure is around 50% higher than previously achieved.

Initially one prototype pump will be built which will be subjected to extensive mechanical testing at the Sulzer facility in Leeds, England. This will include testing the pump at full load, full speed and at the "end of life" condition with running clearances twice that of a new pump. On satisfactory completion of these tests, three more pump units complete with drive motors and gearboxes will be ordered and the prototype will be converted into a fully operational pump unit.

The Sulzer manufacturing facility at Leeds

Delivery of the four units is scheduled for March 2003.

The following provides some background, details of the pump design and progress to date.

Pump Development

The pump will have 12 stages arranged 6+6 in a back-to-back configuration running at 6000 rpm.

The back-to-back barrel casing design incorporating precision cast diffusers was developed by Sulzer in the late 1980's, initially to meet condensate re-injection applications demanding very high generated heads at relatively low flows and low product density where centrifugal pumps were preferred instead of reciprocating machines.

Many pumps of this design have been supplied for such applications; the pumps having up to 16 stages, arranged 8+8 in a back-to-back configuration. Generated heads up to 5840 metres (19150 feet) have been achieved (Thunder Horse generated head requirement being 5630 metres – 18480 feet).

For Water Injection applications the need to meet increasing pressures has been foreseen and can be addressed by this already existing proven pump design.
The basic difference between the condensate and water injection applications is the increased product density (1.03 for Thunder Horse) with correspondingly increased pressures and the need to transmit greater powers and torques.

Pump Design Contract

Faced with the challenge of developing the Thunder Horse field bp recognised that seawater and eventually produced water injection was not only vital to the Project success but that the required injection pressures were far beyond those previously experienced within the Oil Industry.

They decided to take the unprecedented step of funding pump companies to develop designs to meet their needs.

Sulzer Pumps acknowledge this vitally important contribution by bp that enabled much valuable analysis to be completed at the design contract stage prior to manufacture.

The design criteria established by bp were:

- "The water injection pumps are critical to the timing of the Project and the platform's overall uptime
- It is a requirement that the water injection pumps be highly reliable and safe
- Efficiency is important due to the large horsepower required, however, a small sacrifice in efficiency would be preferred over ANY sacrifice in reliability
- Therefore the pump design must consider reliability and the ability to operate the pumps safely as the two highest priorities."

Pump Design

Prior to the design contract Sulzer had identified the following key areas to be addressed: -

- Rotor Dynamics
- Static Sealing / Pressure Containment
- Abrasive Wear (due to Produced Water)

After evaluating and discounting a number of alternative pump solutions, Sulzer selected their back-to-back diffuser design as being optimum design for the service.

The back-to-back diffuser design was seen to have the following advantages: -

- Axially balanced rotor – low thrust loads.
- Pressure breakdown across throttle bushings within current experience
- Centre support bushing acts as a hydrodynamic bearing and improves rotor dynamic stability – allowing more stages to be used.
- High efficiency
- Minimum rotor excitation forces from precision cast diffusers
- Mechanical seals subject only to suction pressure
- Maximum pressure to be sealed to atmosphere in operation only 50% of discharge pressure
- Minimum casing diameter reduces cost / weight
- Full cartridge pull-out design for ease of maintenance
- Design proven in service and in field maintenance conditions.
- Natural development of Sulzer back-to-back volute designs and in-line diffuser designs

The pump model selected was:
HPcp 150-285-6s+6s / 22 @ 6000 rpm

Hydraulics

This hydraulic selection gave the following advantages: -

- Wide operating range at close to peak efficiency
- Proven hydraulics with known performance
- 12 stage solution resulting in relatively high specific speed (Ns 1100/NQ 22)
- High efficiency (78.5% at BEP)
- Tolerant to wear with relatively low efficiency degradation
- Low head per stage with resultant low internal velocities within proven experience on seawater and produced water to reduce abrasion from entrained sand.

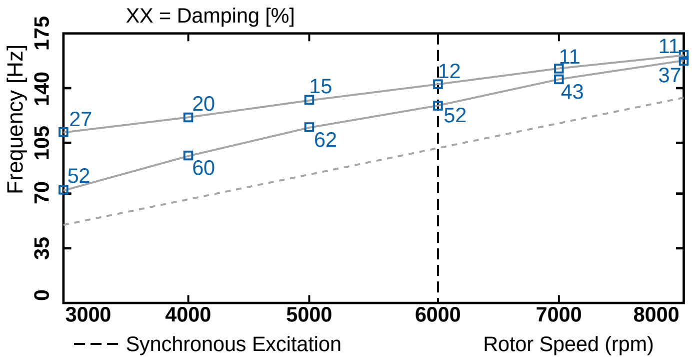
Based on this selection a detailed analysis of other key items was undertaken as briefly summarised below.

Shaft System and Rotor Dynamics

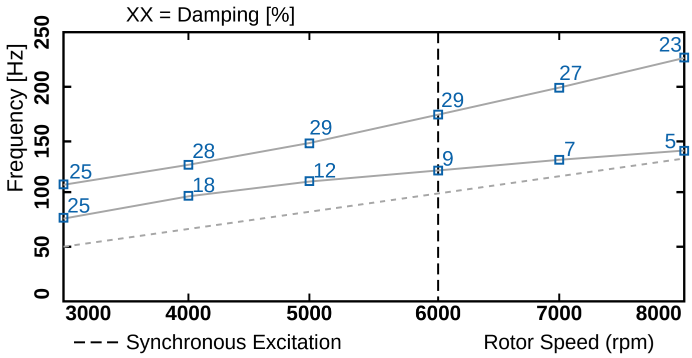
Given that the fundamental pump design was existing, well developed and proven calculation tools were used to conduct a thorough analysis of the shaft system and to establish the predicted rotor dynamic performance of the machine under all operating conditions. The following was demonstrated: -

- Shaft stress levels within proven experience
- All required safety margins on shaft stress exceeded
- Rotor dynamic analysis showed that API 610 separation margins and modal damping requirements were exceeded in the both the new and fully worn (2 x new clearance) conditions as shown on the following Campbell diagrams.

Campbell Diagrams



New Condition



Worn Condition

Mechanical Seals

An analysis of the mechanical seal requirements showed that: -

- Both mechanical seals subject only to suction pressure.
- Standard arrangement API dual seals with externally circulated barrier fluid system provided the optimum mechanical seal solution.
- Pump shaft diameter at the seal and pump speed were within mechanical seal suppliers known experience.
- “PV” (pressure / velocity) values were within mechanical seal suppliers known experience.
- Seal plate bolting was designed for full discharge pressure for “upset” conditions.

Thrust and Journal Bearings

As a result of the back-to-back design of the pump a standard sleeve radial / tilting pad thrust bearing could be used.

Sulzer standard hydraulically fitted thrust collar was used to avoid “fretting” of the collar on the shaft. A thrust bearing of only ±54 kN capacity was required.

Materials

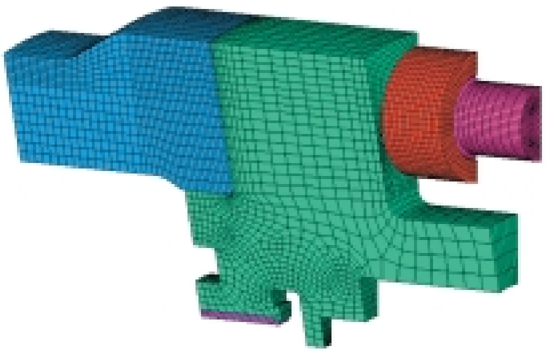
The basic pump construction utilises Super Duplex materials throughout. For seawater and produced water injection Super Duplex is now universally accepted as the standard material for pump construction.

However given the extreme pressures it was necessary to demonstrate that all materials were within current experience in terms of component design, use and most importantly manufacturing know how and capability. Through a detailed investigation with potential suppliers this was shown to be the case.

Static Pressure Seals to Atmosphere

Static sealing of the extremely high pressures inside the pump was seen as a critical concern. A full finite element analysis of the main joint areas was conducted. In particular the effects of distortion of the casing and covers under full pressure conditions were examined. The conclusions of this and the further benefits of the back-to-back design in this context are summarised below: -

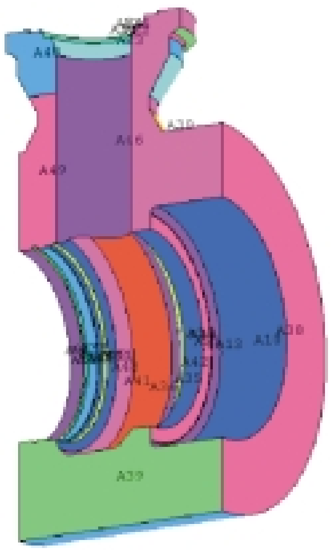
Rear Cover Joint to Atmosphere



- Forged casing and rear (NDE) cover eliminates uncertainties inherent is castings and is within proven manufacturing experience for size, weight, thickness and material.
- Most importantly, the static pressure to be sealed to atmosphere by the rear (NDE) cover with the pump in service is only 50% of the discharge pressure due to the back-to-back design.
- The resultant sealing pressure was within proven experience.

- A conventional hydraulically tightened bolted end cover design was chosen to allow the use of face ‘O’ ring seals.
- Double ‘O’ ring face seals were used for additional safety.
- Finite Element Analysis (FEA) showed that under all conditions metal to metal contact was maintained between the cover and the casing eliminating any possibility of ‘O’ ring extrusion.
- As an additional safety precaution “tell-tale” leakage detection has been included to warn against any leakage across the inner ‘O’ ring seal. This was considered particularly important for the hydro-test condition.

Suction Cover Joint to Atmosphere



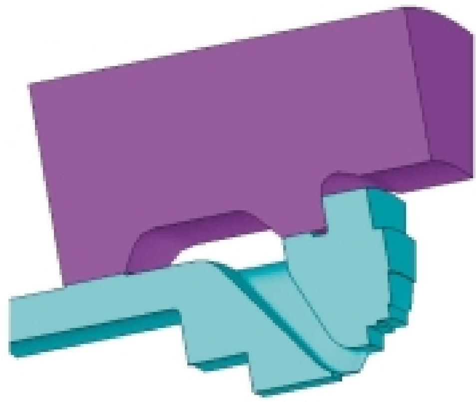
Under normal operating conditions the suction cover joint is a much more straightforward proposition since it seals only against suction pressure. However since the suction casing and chamber are designed for full discharge pressure a “tell-tale” leakage detection connection has been included – again particularly for the hydro-test condition, see below.

Internal Pressure Seals

Inside the pump are two critical seals.
Given the extremely high pressures involved these seals were required to seal against pressures beyond current experience.

1st Casing Element Seal (Cartridge to casing)

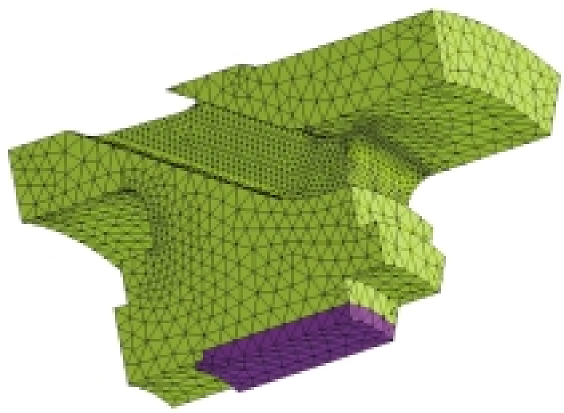
- Required to seal full discharge differential pressure
- The seal is internal with no leakage path to atmosphere
- FEA showed that under all conditions a metal to metal seal between the cartridge and the casing was maintained with a Gasket Factor (GF) >5.



- Metal to metal contact under all conditions eliminates any possibility of ‘O’ ring extrusion.
- A standard design could be employed using a face sealing ‘O’ ring

Inter-Stage Cross Over Joint

This seal, located at the cross over between 6th stage and 12th stage has to be made using peripheral ‘O’ rings. The following conclusions were drawn from the design stage investigations: -



- The seal has to be made against only 50% discharge pressure but this was still beyond current experience for the seal design.
- The seal is internal with no leakage path to atmosphere.
- FEA demonstrated that distortions due to pressures in service were within acceptable limits.
- A double seal was used.
- Prior to manufacture it was considered prudent to build a full size test rig that would simulate full pressure and full distortion to prove this critical joint.

External Nozzle Connections

The external nozzles all required connections well beyond conventional flange rating codes. Therefore all pipe connections to the pump will be made using clamp connector technology. This includes the main suction and discharge connections as well as all drains, telltale connections etc.

(Note the suction is rated for full discharge pressure)

Abrasion

Part of the specified requirements of the pump is that as the field life extends produced water will be re-injected. It is anticipated that some degree of sand will be present in the produced water. The abrasive effects of this entrained sand are to be minimised in the pump design and construction.

Influencing factors on the resistance to abrasion of such a pump can be summarised as follows: -

- Quality of the pumped liquid
- Degree of filtration
- Particulate inclusions
- Nature of particulates (e.g. quartz sand)
- Velocity of pumped liquid within the close clearance areas of the pump
- Pump selection and operation
- Operation close to BEP reduces internal velocities and thus abrasion.
- The 12 stage back-to-back design provides optimum speed
- High number of stages with relatively low head per stage and thus low internal velocities
- High specific speed with good efficiency, low internal losses and a good tolerance to reduction in efficiency due to wear.

Thus the pump design is beneficial in minimising the potential for abrasive wear.

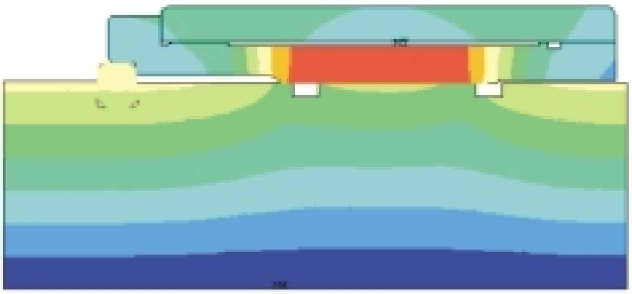
In addition the wear part materials are also critical in resisting abrasion.

Based on extensive experience with upgrading materials to resist abrasion due to quartz sand in produced water (Alaska and Norway), state of the art abrasion resistance materials were selected.

The two critical areas most susceptible to wear (centre bush/throttle sleeve) were examined in detail and the following design selected to be incorporated into the prototype machine. All are based on successful experience.

Centre Sleeve / Bush

- The differential pressure across the centre sleeve / bush assembly is only 50% of full discharge pressure due to the back-to-back design of the pump



- Pressure breakdown across the sleeve / bush assembly is within current experience.
- The sleeve assembly is made up of a solid tungsten carbide sleeve mounted on a solid molybdenum carrier.
- The bush assembly is made up of a solid tungsten carbide sleeve mounted to a Super Duplex carrier.

Impeller / Casing Wear Ring

- Head per stage is within current experience with produced water
- Velocities are therefore relatively low and within current experience
- The impeller has an “integral” wear ring protected by SUME, PUMP SA 30 HVOF overlay directly on to the Super Duplex impeller.
- The casing wear ring is replaceable and features SUME , PUMP SA30 HVOF overlay on to a Super Duplex case wear ring.

SUME , PUMP is a registered trademark of Sulzer Metco, a specialist Sulzer Group Company in Mass Transfer Technology. The material combination and deposition methods to be used on the prototype pump are all proven in service in sand laden produced water applications and are state-of-the-art.

Hydro-Test

In service the maximum static pressure to be sealed to atmosphere is 50% of the pump discharge pressure. This is inherent in the back-to-back design of the machine.
However under the hydro-test condition the complete pump is subject to the hydro-test pressure of 957 bar (13881 psi). This includes all static seals to atmosphere.

This pressure is beyond all current experience for a pump of this physical size.

Whilst it must be emphasized that this is not an operating condition the hydro-test is nonetheless a task that must be considered very seriously indeed.

The FEA included a full analysis of all critical components under this condition with the conclusion being drawn that all joints more than met the requirements under this most onerous condition. The inclusion of "tell-tale" connections on the main rear (NDE) and suction cover described above is primarily to ensure added personnel safety at these truly extreme pressures.

Performance Testing

The prototype pump will be tested in February 2002 at full speed and full load on the Sulzer test bed in Leeds, UK driven by a test bed motor and gearbox. The only new equipment required for test has been a new discharge pressure breakdown valve since the discharge pressure of the prototype pump exceeded the pressure rating of the existing equipment.

Summary of Pump Design

With any new development or extrapolation of current experience it is self-evident that as much currently proven knowledge as possible must be utilised. It is simply not wise to throw away all previous experience and to start out with a brand new, totally unproven design concept.

In responding to the challenge of designing the Worlds Highest Pressure Injection Pump, Sulzer Pumps have incorporated, wherever possible, proven design and manufacturing experience which can be summarised as follows: -

- Basic pump design
- Hydraulic fit
- Efficiency
- Shaft design / stresses
- Rotor dynamics
- Mechanical seals
- Bearings
- Materials
- Static seals to atmosphere
- Internal seals
- Nozzle connections
- Abrasion / sand handling capability
- Component manufacture
- Pump assembly / dis-assembly methods
- Hydro-test
- Performance test

Proven in service
Beyond previous experience

From the above it can be seen that this new and exciting challenge is in fact not a major departure from current experience.

It is the combination of all of the features that makes this, the Worlds Highest Pressure Injection Pump, such an interesting proposition.

This order represents a new era in the development of Water Injection pumps and opens the way for users to develop deep water and other high-pressure fields where previously this would not have been possible. Sulzer Pumps is indebted to bp for the confidence they have shown in entrusting them with this exciting and prestigious order.

Tony Waterfield,
Global Sales Manager, Oil & Gas
Sulzer Pumps Ltd.,
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Laurie Looper,
bp Thunder Horse Topsides Project Engineer.

Charles McDonald,
bp DWD Rotating Equipment Engineer.

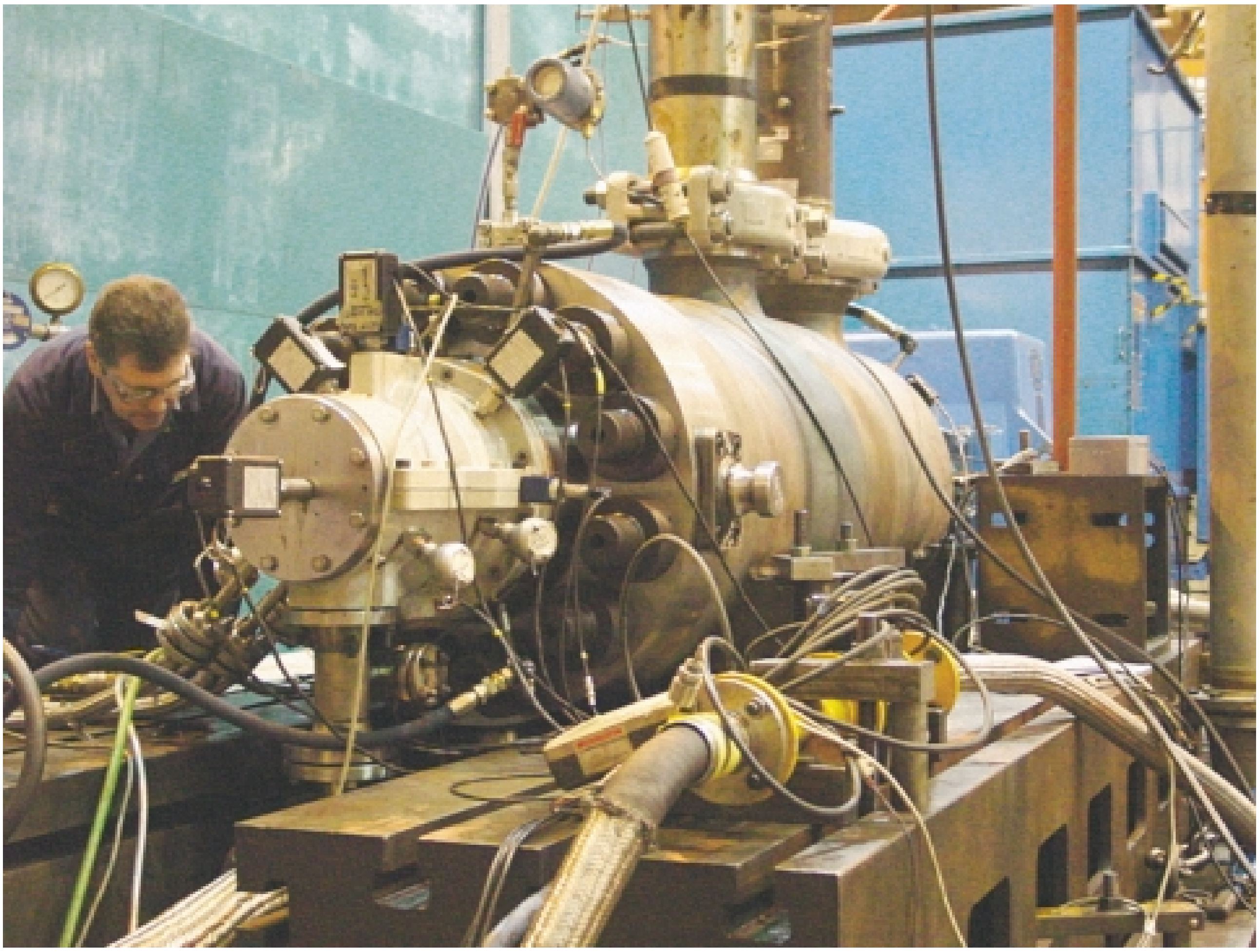
January 2002. (updated April 2002)

Stop Press as at April 2002.

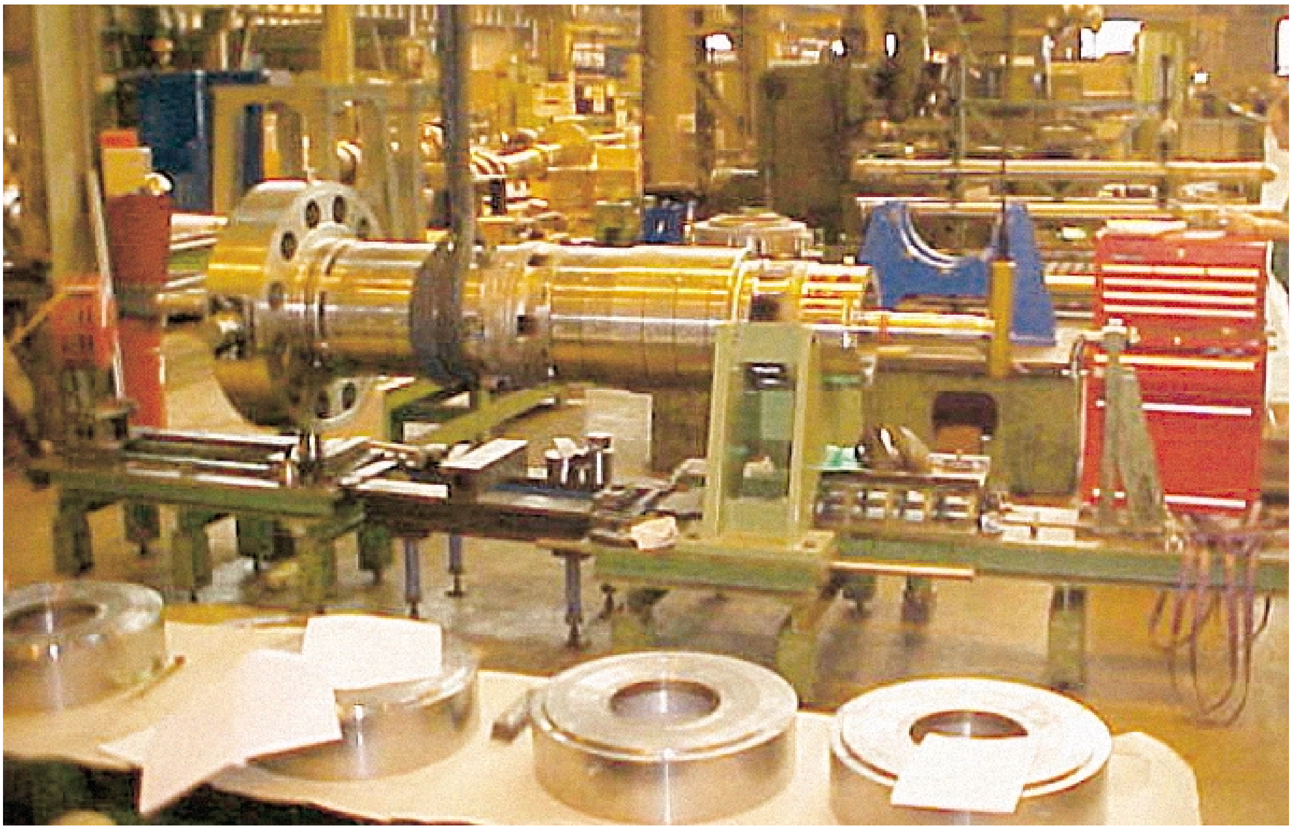
The "prototype" has now been built & tested.

This includes the following: -

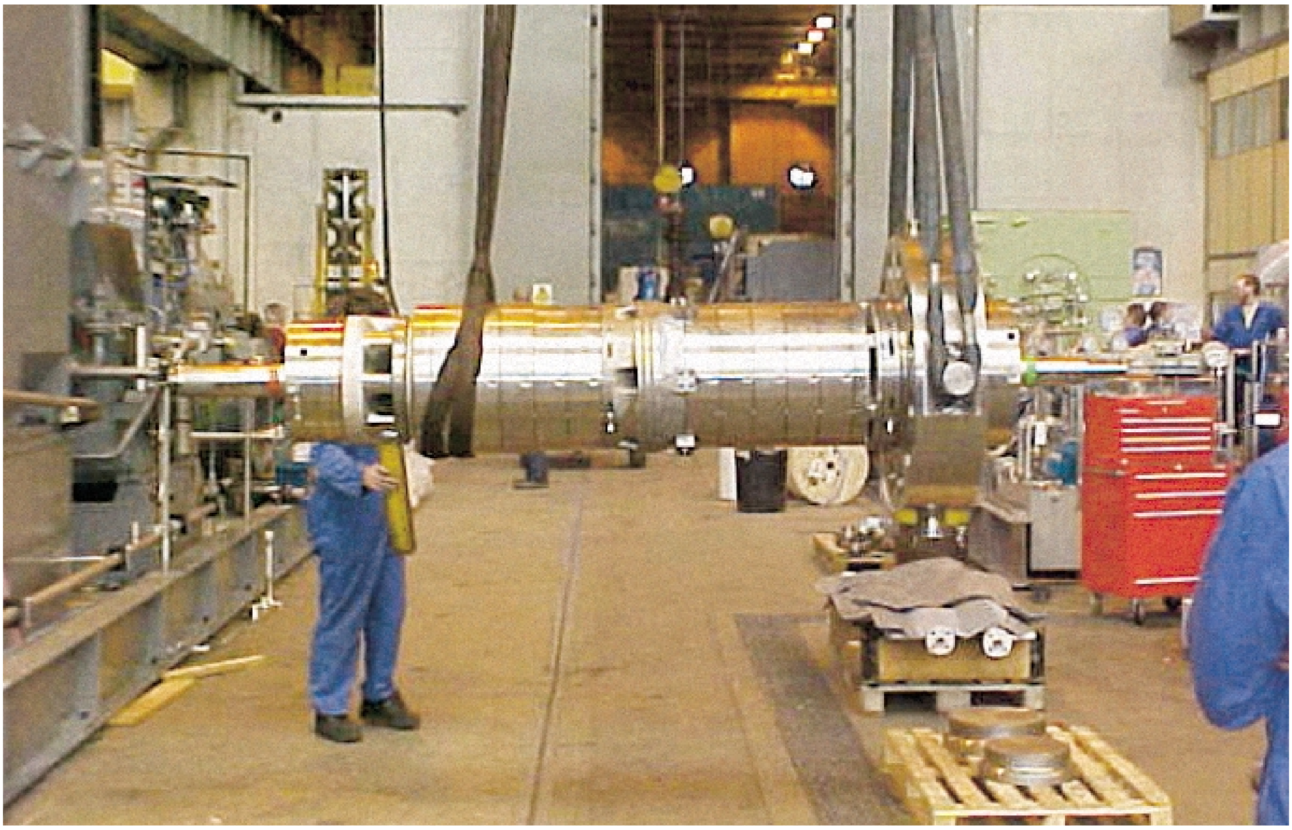
1. The casing Hydrotest at 957bar (13881 psi) has been satisfactorily completed.
2. The pump has been run at full speed, full load with internal clearances opened to 2X new condition. Vibration levels were well within the limits set out in API 610 across the full operating range.
3. An unbalanced response test has been carried out on the 2X clearance machine. This produced results entirely in accordance with predictions.
4. A full speed, full load performance test has been completed and accepted by bp. Hydraulic and mechanical performance were as predicted.
5. The order to "package" the protoype with motor, gear, etc. has been received and is being worked on. A full speed, full load string test is scheduled for September 2002.
6. An order for 3 additional complete pump units has been received and these units are now in manufacture.



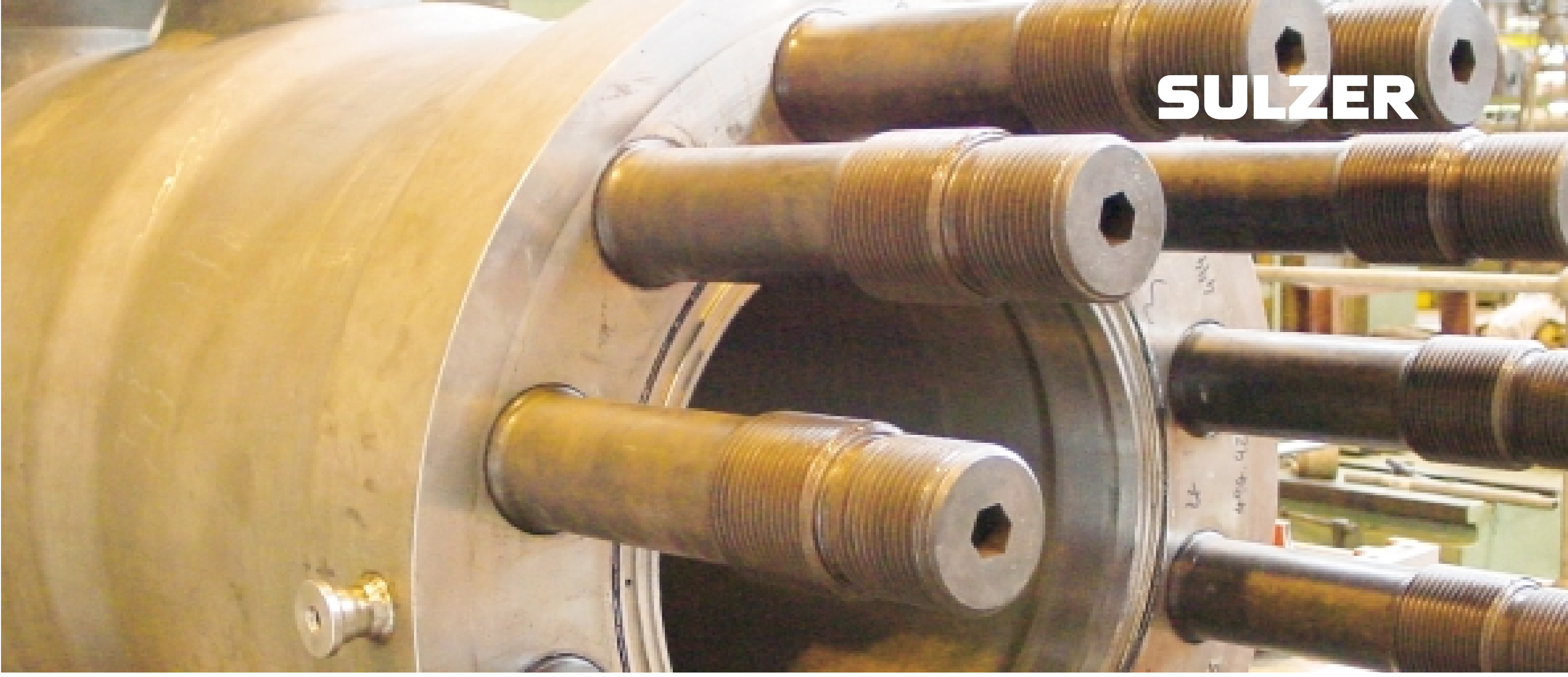
The World's Highest pressure Injection Pump on full load, full speed test at Sulzer UK



Cartridge being built



Complete cartridge



Check our worldwide offices at
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