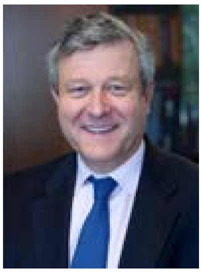
IF YOU INSTALL A PUMP SUBSEA, LEAVE NOTHING TO CHANCE

Pierre-Jean BIBET
Senior Rotating Equipment Engineer,
MPP Specialist
Total
Paris la Defense, France

Bernard QUOIX
Head of Rotating Machinery Department
Total
Pau, France

Pierre-Jean BIBET is a senior rotating equipment Engineer at Total E&P in Paris, France, working in the Rotating Machinery Department since 2003. In this position, relying on 17 years of professional experience with pumps, he is dedicated to Subsea Boosting Projects, with a special focus on multiphase pumps. He has previously worked for Sulzer Pumps France as Technical Coordinator for the multiphase pump product, this covering pump specification, testing, commissioning, technical support and troubleshooting. Mr. Bibet graduated Mechanical Engineer in 1986 from ESEM (Ecole Supérieure de l'Energie et des Matériaux), France.



Bernard QUOIX is the Head of Total E&P Rotating Machinery Department and holds this position since November 2003. He started his career in 1979 within Total Operations in the North Sea, then from 1986 to 1989 became Head of Engineering of Turbomeca Industrial Division, a small and medium size gas-turbines manufacturer, then went to Renault Car Manufacturer as Assistant Manager of the testing facilities for prototype and production engines, before joining Elf Aquitaine and eventually Total, mainly involved in all aspects of turbomachines, including conceptual studies, projects for new oil and gas field development, commissioning and start-up, and bringing his expertise to Operations of all Total Affiliated Companies worldwide.
Bernard QUOIX graduated from ENSEM (Ecole Nationale Supérieure d'Electricité et de Mécanique, 1978) and then completed his engineering education with one additional year at ENSPM (Ecole Nationale du Pétrole et des Moteurs) in Paris, specializing in Internal Combustion Engines. He has been a member of the Turbomachinery Advisory Committee since 2005. He is also President of ETN (European Turbines Network) organization based in Brussels since April 2010.

ABSTRACT

In 2011, for the first time Hybrid Multiphase Pumps have been deployed on the seafloor. This was Offshore Angola, at 800m Water Depth, to ensure the full field development of Pazflor Deep Sea Project by pumping the viscous oils of the Miocene fields. Through the example of these Pazflor subsea pumps, this paper invites the reader to discover, step by step, the thorough acceptance tests program that was put in place to mitigate as much as possible the risks before installation. This paper relates how, after 15 months of Acceptance tests, the eight Hybrid Pumps were declared *Ready for Deployment.*

INTRODUCTION

Installing a several MegaWatt rotating equipment on the sea floor, moreover in a full field development scheme, is for an Oil and Gas Operator taking a lot of risks as the economical stakes are very significant and subject to a number of critical challenges to be overcome: hostile and harsh environment, limited access, inventing new technology or using existing technology at the cutting edge of the industry state-of-the-art, no possibility of corrective maintenance, meaning that any incident, small or major, will require retrieval of the equipment.

Multiphase Pumping brings an increment of complexity due to the fact that the pumped fluid, which is a mixture of various oils, gas, water and sand, will remain unknown until the first oil. Therefore, when specifying the pumping system, one shall consider large margins and anticipate means to ensure flow assurance and preservation, knowing that these vital functions will be brought from the FPSO (Floating Production Storage and Offloading) vessel via a single umbilical cord which has its own mechanical, functional and installation constraints.

For the Rotating Equipment Engineer, the response to this technical challenge is first to permanently question the design of the pumping system and its marinisation, but indeed to rely on a strict qualification methodology and acceptance tests programme, as well as on comprehensive intervention and operation procedures. He must always keep in mind that nothing must be left to chance.

Pazflor Hybrid Pumps

In 2006, the development of the Pazflor Project with subsea gas/liquid separation and liquid pumping required a breakthrough in the Multiphase Pumping technology since no pumps were able to meet the very stringent pumping requirements. The free gas quantity (15%) was too high for a standard centrifugal pump and the required ΔP (1522 psi, 105 bar) too high for the existing MPP (Multi Phase Pump) already in operation on the sea floor, but limited to a ΔP max of 725 psi (50 bar). The solution was therefore to assemble on a same rotor gas tolerant impellers and conventional radial impellers, so to invent *the Hybrid Pump.*

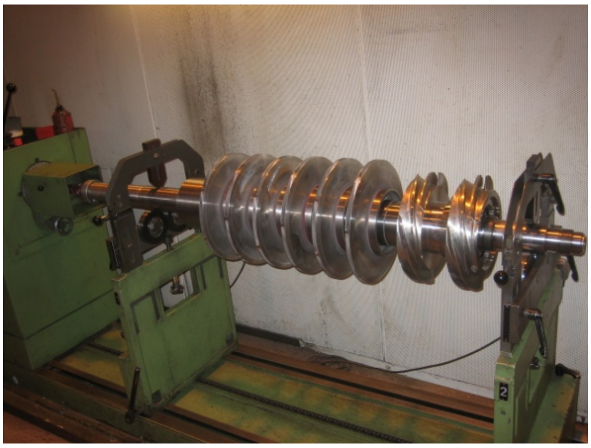


Figure 1. View of the Hybrid pump rotor (*Courtesy of Pazflor Project)*

The proof of concept of this new type of pump was described in a paper that has been presented at the 2009 Pump Users Symposium. The Pazflor Hybrid Pump supplied by Framo Engineering is a 8 stage pump where the first two stages are helicoaxial, and the 6 remaining stages centrifugal. The two helicoaxial stages generate enough pressure to reduce the GVF (Gas Volume Fraction) at the inlet of the first radial impeller to less than 10%. The pump has a rated flow of 63,600 bpd (420 m3/h), a rated ΔP of 1522 psi (105 bar), and a rated electrical motor power of 3350 hp (2.5 MW).

Electrical motor flooded with barrier oil ➔

6 radial impellers ➔

2 helicoaxial impellers ➔

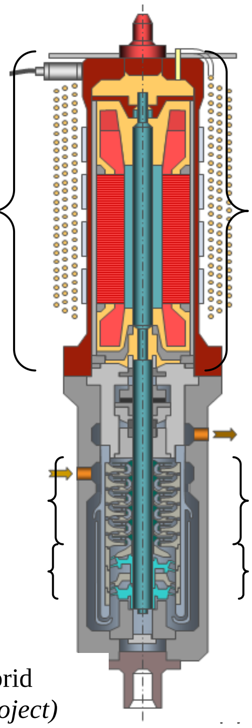


Figure 2. View of Pazflor Hybrid Pump *(Courtesy of Pazflor Project)*

You Get What You Inspect

This well known saying in our industry takes all its importance when it comes to subsea as it is crucial to closely control all the processes of fabrication, assembly and acceptance tests, this because corrective action on the installed equipment is impossible. For any anomaly, the pump will have to be retrieved, and sent back to the OEM (Original Equipment Manufacturer), and as any repaired pump, shall go through new acceptance tests requiring important means like for example a multiphase flow loop, what does not exist in host countries. In the subsea industry, each component is qualified for a MTBF (Mean Time Between Failure) of at least 5 years. Therefore, the MTBF of the whole assembled system will depend on the quality of the assembly, and on a close control of the assembly processes.

Step 1, Quality Control acceptance tests

As for any topside rotating equipment, the FAT (Factory Acceptance Test) of each subsea pumping unit commenced with the tests listed in the quality control plan, in particular the pump and motor casing hydrostatic tests, and the rotors balancing. However when it comes to a pump to be installed on the sea floor, an additional level of requirement in our quality control plan was to have the mechanical seals systematically tested to the project running conditions in terms of pressure, temperature and speed.

Step 2, Motor full load test

The objective of the motor FAT was to demonstrate the robustness of the design, and to get the overall efficiency of the motor as this will be used later to evaluate the performance of the pump.

- To validate the soundness of the design, each motor went through a full load test coupled to a water brake in order to verify the electrical, mechanical and thermal performances of the motor. Vibrations were monitored by accelerometers placed on the casing, and the transmitted torque measured with a torque meter. Each motor passed a heat run test through a 4h endurance test at full load and max continuous speed. Finally, each motor was tested in over speed, 10% above the maximum continuous speed, this to cover the VSD (Variable Speed Drive) trip speed uncertainties plus some margins.

- To determine the overall efficiency of the motor, all terms of the following equation must be known:

$$P_{SUPPLY} = P_{ELECTRICAL_{LOSSES}} + P_{FRICTION_{LOSSES}} + P_{OUTPUT}$$

P$_{OUTPUT}$ was obtained by running the motor with a water brake and a torque meter.

P$_{SUPPLY}$ was obtained from the electrical measurements.

P$_{ELECTRICAL\ LOSSES}$ are all windings and electromagnetic losses. They depend on current only and was therefore obtained from the no load test.

P$_{FRICTION\ LOSSES}$ are all the drag losses of the liquid filled motor. They depend on speed and were thus obtained from rundown tests with the motor water break decoupled.

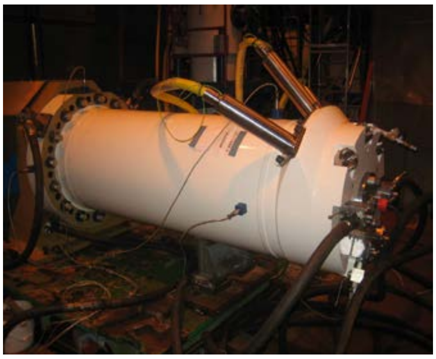


Figure 3. Pump motor during its Full Load Test *(Courtesy of Pazflor Project)*

Step 3, Pump performance test

Being fully tested, the motor could then be used as a validated driver of the pump for the pump performance test. Here again, the objective of the pump FAT was to demonstrate the soundness of the design, and to get the overall efficiency of the pump.

These tests were done using an atmospheric multiphase test loop using water and nitrogen. At this stage of the test program, the intention was only to validate the performance of the pump, meaning that only the bare pump was tested (the pump was not equipped with its cooler, ROV (Remotely Operated Vehicle) panel, subsea instruments, barrier fluid control system, etc…). This test protocol developed by the pump manufacturer brings a first key advantage to be very reactive if, for any reason, a corrective action has to be done on the pump. It brings the second key advantage to give the possibility to install on the pump additional instrumentation that cannot go subsea, such as shaft displacement probes. Therefore, this test setup allowed verifying both performance and rotodynamic behavior of the pump in a very simple manner.

Figure 4. Pump Performance Test *(Courtesy of Pazflor Project)*

The pump performance verification was conducted with three following objectives:

1) : Validation of the performances
2) : PAP (Performance Acceptance Point)
3) : 24 hours endurance test.

The first objective was to verify the pump hydraulic selection, and more generally the performance prediction tool, by comparing the measured pump curves versus the predicted ones.
A multiphase pump has hundreds of duty points depending on flow rates, suction pressure and GVF. It was therefore important to validate the performance prediction model which was based on one hand on two-phase flow efficacies measured by the OEM on similar helicoaxial impellers to predict the pump performance with gas, and on the other hand on Hydraulic Institute performance impairment correction factors to predict the performance of the pump with a viscous fluid.
This verification was done by establishing the performance curve with pure water, with water+nitrogen, with pure viscous oil, and with oil+air. Acceptance criteria, i.e. mismatch between tested curves and predicted curves, was agreed with the manufacturer before running the tests. They were all customer-based as there is no standard in the industry defining the acceptance criteria for Multiphase Pumps.

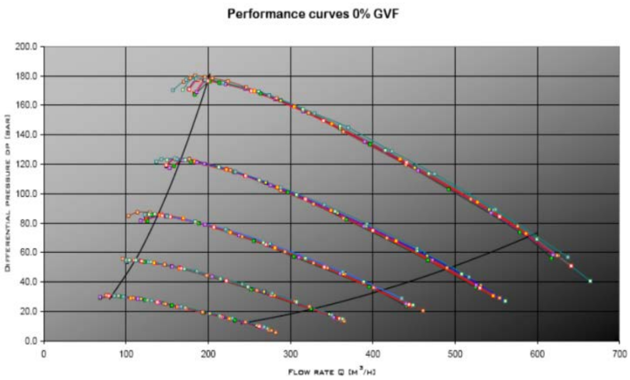


Figure 5. Performance curves for all 8 pumps, with water and 0% GVF *(Courtesy of Pazflor Project)*

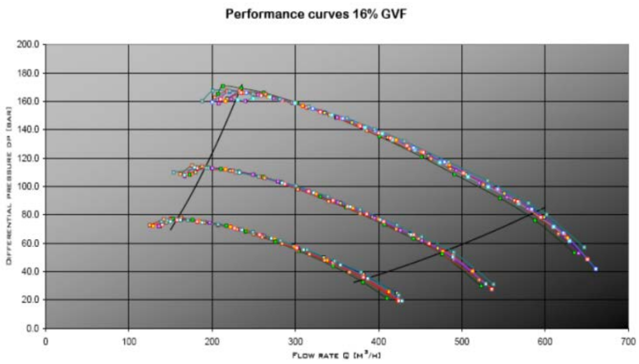


Figure 6: Performance curves for all 8 pumps, with water and 16% GVF *(Courtesy of Pazflor Project)*

The second objective was to define a contractual Performance Acceptance Point (PAP). The PAP was a test condition that reflected the pump design best operating point, and a contractual checkpoint to compare the pump against each other by verifying that they were equal in performance.
When it comes to a multiphase pump, this PAP is not easy to define as the performance of a MPP is very depending on the GVF and on the liquid-to-gas density ratio ρ_{gas}/ρ_{liquid}.

One of the difficulties to test a MPP lies in the way to reproduce the running conditions at the test bench. In water and nitrogen, the density ratio ρ_{gas}/ρ_{liquid} is less than in Oil & Gas conditions, meaning that either the suction pressure is increased to get the same density ratio ρ_{gas}/ρ_{liquid} as on field, if the test loop allows it, either the tests are performed with a different suction pressure, in which case the impellers will not work at the same relative flow, and the pump will present a lower efficiency than expected.
Testing conditions are thus very depending on the process conditions to simulate, so the exercise must be done for each project. For the Pazflor pumps, the performance tests were conducted through the following process:

1) To agree on a Field-rated duty point (Field-PAP).

2) To transform this (Field-PAP) to a (Testbed-PAP), knowing that the tests were done with a mixture of water and nitrogen, and with the same suction pressure as on field condition (333 psia, 23 bara), meaning therefore without the same density ratio ρ_{gas}/ρ_{liquid}. This was relevant here as it was verified that for this application, the most important parameter with respect to pump performance was the GVF.

3) To run the first pump in order to determine what were the speed and absorbed power required to get the (Testbed-PAP). This fixed the efficiency reference for all the pumps.

4) From this first pump test, to set the tolerance for the (Testbed-PAP). This represented the accepted deviation in performance between the individual pumps, in order to compare the pump against each other by verifying that they were equal in performance. At this stage, the acceptance criteria were simply based on the usual sensitivity of the whole data acquisition chain (Multiphase flow meter, pressure and temperature sensors, Input current and voltage, and speed measurement).

The third objective was to validate the pump final assembly by a 24 hours endurance test at full load / full speed. For this 24 hours endurance test, the pump run at maximum load (power) and speed within the defined operating range of the pump, and within the capacity of the test loop. Acceptance Criteria were thermal stabilization, low level of vibration, and mechanical seal leakage rate.

Step 4, Pump Module Integrity Test

At this level of the Acceptance Test program, the pump and the motor have demonstrated their good performance. The pump module could now be prepared into its final configuration. All temporary instrumentation such as shaft vibration probes could be removed and all auxiliaries like cooling coil, ROV panel, barrier fluid pressurizing system, electrical connectors and pumps sensors be put in place. For the first time, we were getting the complete assembled pump module.

The test objective of this step 4 was to perform the final integrity checks of the complete assembled pump module. This started with the pressure integrity of the pump module by pressure testing the whole pressure containing parts at full design pressure (barrier fluid at 5220 psi, 360 bara, for 1 hour). This continued with the pump housing electrical continuity checks to make sure that the whole module was correctly protected by the cathodic protection system. This was followed by stator winding electrical continuity and insulation checks. This ended by the verification of the good operation of the pressure and temperature probes to make sure that pressure and temperatures were healthy, as well as the verification of the hardware and communication lines.

Figure 7. Pump Module Integrity Test
(Courtesy of Pazflor Project)

From the end of this step 4, the pressure integrity of the whole pump module must be maintained, with no possibility to remove or disconnect any components, including some tubing or sensors, etc….
The pump module was fully checked and prepared for SIT (Site Integration Tests). For the first time, the pump module was ready to go under water.

Step 5, Pump Module Structure FAT

One particularity of the Pazflor subsea pumps is that the retrieved equipment is not simply the motopump, but a whole pump module holding also the minimum flow valve and the 8-shape structure where the pigtailed electrical connector is coiled up. For the final installation on this pump module on the subsea structure, the pump module is skidded by approximated 1 meter to its final position. This installation sequence had to be tested of course.

This step 5 of the FAT consisted to place the pump module on a dummy part representing the interfaces of the manifold module, then to skid it forward, backward, and to take it off. Once again, nothing was left to chance.

Figure 8. View of one Hybrid Pump module during the structure FAT *(Courtesy of Pazflor Project).*

Figure 9. View of a complete Hybrid Pump Module *(Courtesy of Pazflor Project)*

Step 6, Pump Unit Full Load String Test

Step 6 marked the beginning of the *String Tests* of the whole equipment, i.e. the system test of the two pumps mounted in the MPP station immerged in the test dock filled with water. For this test, the pumps were for the first time powered by their PCM (Power & Control Module) which included the VSD, controlled by their SCM (Subsea Control Module), cooled by their cooling coils, and protected by their Barrier Fluid system. For subsea equipment, this is almost the Commissioning of the system, and this is the reason why it is important that this phase is leaded by the Field Operation Team.

At this well advanced stage of the test program, it is no more time to check the performance of the pump, but indeed to validate/tune the whole pumping system, and above all, the protection system. And this is also time to check…the direction of rotation of the pump.

To validate/tune the whole pumping system, the pumps went through a series of tests that reproduced the normal Start and Stop Sequences, with one pump at a time, then with two pumps running in parallel. They went then through a System Load Test at full load / full speed, followed by a four hours endurance test to make sure that all temperatures were stabilized. This was important to verify as this was the first time that the pumps were cooled by their cooling coils transferring the heat by free convection in the surrounding water.

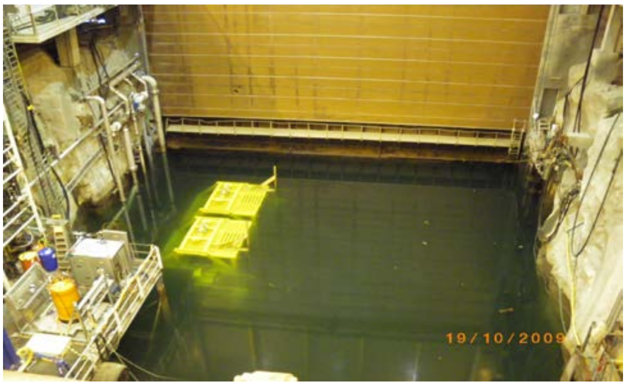


Figure 10. Pump modules during submerged tests *(Courtesy of Pazflor Project)*

Pump protection system is anything related to the minimum flow protection, and this was covered by testing the Min/Max Flow Protection, pumps running on a multiphase flow loop of course. But above all, one of the most important objectives of this test sequence was to validate the proper operation of the barrier fluid system.

Barrier fluid is the "blood" of a subsea motopump unit, and as for any human being, its pressure must ALWAYS be kept under control, meaning that its overpressure toward the process effluent must always been ensured, whatever the running or standstill conditions are. This is quite challenging since there are various reasons to change these conditions and hence the barrier fluid pressure. A pump trip suddenly cools down the barrier fluid, thus generating a sudden loss of pressure. In opposite, a pump start suddenly heats up the barrier fluid, thus generating a sudden increase of pressure. And of course, the normal mechanical seal leakage in operation permanently affects the barrier fluid pressure. All this had to be simulated, and was simulated during this step 6.

The working principle of the barrier fluid system is described in figure 11 and relies of one barrier fluid FEED solenoid valve, and one barrier fluid DUMP solenoid valve.

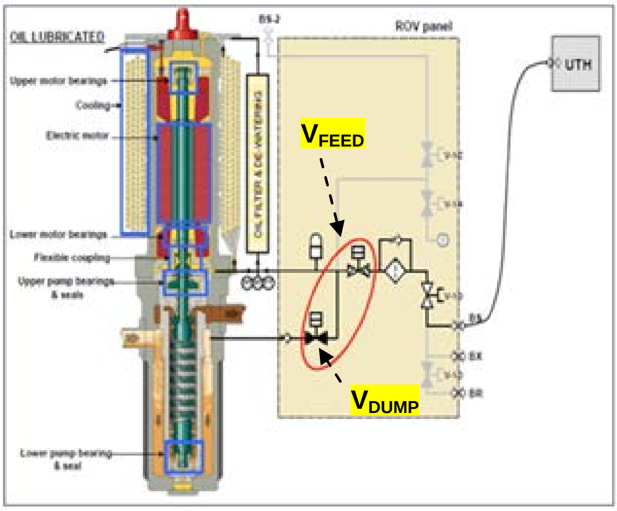


Figure 11. Subsea control of the barrier fluid *(Courtesy of Pazflor Project)*

The objective of the test was to verify the proper operation of these two subsea solenoid valves by reproducing the following operation conditions, illustrated on figure 12:

(A) Pump start up to 3600 rpm and stabilization of barrier oil pressure and temperature.
(B) Reduction of speed from 3600 to 2600 rpm.
(C) Increase of speed from 2600 rpm.
(D) Normal stop.
(E) Trip of pump from 3600 rpm.

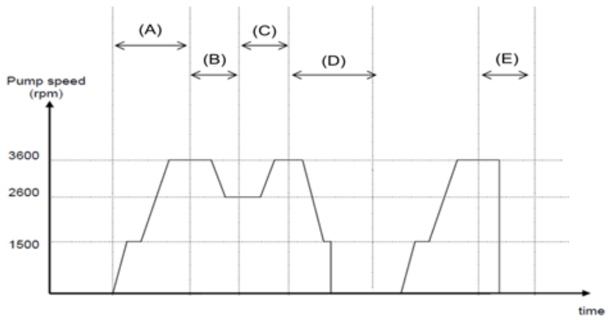


Figure 12. Operating conditions reproduced to validate the proper operation of the barrier Fluid system *(Courtesy of Pazflor Project)*

Test results showed that the mechanical seals ΔP was always kept within the expected operating range of (290 psid, 20 bar) and (940 psid, 65 bar). The good operation of the barrier fluid system was therefore confirmed.

At the end of this series of tests, the pumps were declared *Ready for Deployment*. However, they had to run an ultimate test to validate the proper operation of the whole subsea separation system. They had to go through a last SSU (Subsea Separation Unit) Functional Test….

Step 7, Subsea Separation Unit Functional Test

The objective of this ultimate test was to verify and demonstrate the capability of the systems to function and be operated as an integrated subsea station. From a rotating equipment standpoint, this last test consisted to run the 2 pumps with their separator in order to validate the whole subsea separation concept, i.e. the ability of the pumps to always control the liquid level in the separator. This Shallow Water Functional Test was done with a whole MPP package composed of one MPP station, one PCM, and the associated flying leads. This was the string test of the whole subsea separation unit.

Figure 13. SSU ready for Shallow Water Functional Test *(Courtesy of Pazflor Project)*

The pumps ran with water+air multiphase flow, and all normal and offset operating conditions were reproduced; Normal start & stop of the pumps, one pump running and then pump trip, pump trip on HH (High High) level in separator, pump trip on LL (Low Low) level in separator, loss of one pump when two pumps running in parallel, simulation of low and high slugging by varying the inflow flowrate. Each time the response of the system appeared to be very smooth.
At the end of this series of tests, the whole Subsea Separation Unit was declared ***Ready for Deployment***.

Figure 14. SSU during Shallow Water Functional Test *(Courtesy of Pazflor Project)*

CONCLUSION

May 2010, after 15 months of Acceptance tests, the eight Hybrid Pumps of Pazflor were declared Ready for Deployment.

Saturday 3th September 2011, 22h30, the first Subsea Separation unit was put into operation, and one hybrid pump started for production, very easily and very successfully. Six weeks later, all three subsea separation units were in operation and since are producing just as expected.

The lessons learnt through the completion of this World First is that a step by step methodological acceptance test program developed from a strong expertise of the pump and the subsea system Supplier, a firm commitment of the Project Management at the highest level to allow no shortcut on tests and inspections programs, and a strong in-house rotating equipment expertise to permanently question and challenge the design of the pumping system and its marinisation, is the only way to properly mitigate the risks to install a rotating equipment subsea. If you install a pump Subsea, leave nothing to chance…

ACKNOWLEDGEMENT

The authors share this paper with the whole Pazflor SSU Team. This successful step by step and thorough acceptance tests program that was conducted before the deployment on the sea floor of these subsea Hybrid pumps is a common success.

NOMENCLATURE

FAT	:	Factory Acceptance Test.
FPSO	:	Floating Production Storage&Offloading.
GVF	:	Gas Volume Fraction.
HH	:	High High.
LL	:	Low Low.
MPP	:	Multiphase Pump.
MTBF	:	Mean Time Between Failure.
OEM	:	Original Equipment Manufacturer.
PAP	:	Performance Acceptance Point.
PCM	:	Pump control Module.
ROV	:	Remotely Operated Vehicle.
SCM	:	Subsea Control Module.
SIT	:	Site Integration Test.
SSU	:	Subsea Separation Unit.
VSD	:	Variable Speed Drive.

REFERENCE

P.J. Bibet, B. Quoix, H. Grimstad, "Hybrid Pump, a new type of pump for the Pazflor Deep Sea Project", lecture at the 2009 International Pumps Users Symposium of Houston.