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First 4.5-in Through-Tubing ESP with Downhole Wet Connect

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Abstract

Artificial Lift Company Ltd. (ALC) and ConocoPhillips Company in 2004 initiated a 5 year development program to have a fully deployed wire-line through tubing electric submersible pump (TTESP) with a down hole 3 phase electrical wet connector.

ConocoPhillips Alaska had immediate applications for this technology in its Alaska business unit, West Sak asset. The wells in this asset are multi lateral and suffer from large amounts of sand production which settles in the mother bore restricting production flow to the ESP. Historically, a Rig would be required to pull the tubing and ESP equipment to allow access for wellbore intervention. ConocoPhillips has had 10 years of experience with wireline pumps[1] which allowed pump replacement of sanded pumps but did not provide for rigless cleanout of the casing below the ESP. The ability to pull the entire ESP through 4.5” tubing providing an unobstructed tubing string for placement of lateral re-entry modules and to conduct coiled tubing cleanouts of sand in the casing was highly desireable.

This was also aligned with ALC’s objective which was to make the system compatible with the most common wellbore architecture.

System Requirements:

1. Wellbore architecture; 7 in 26 lb/ft casing and 4-1/2 in 12.6 lb/ft tubing.
2. Full bore access to the well – minimum tubing ID of 3.75 in, when the wire-line ESP components are retrieved.
3. Motor(s) to produce 300kW (400HP) from a maximum diameter of 3.80” OD
4. Down hole 3 phase wet connector rated at 5 kV and 125 A
5. Equipment string target length less that 47ft to enable live well deployment using wire-line lubricators. The string weight also had to be less than 1500 lbs. to allow the use of slick line rather than braided line.
6. Ambient operating conditions 5000psi and 150ºC (302ºF)
7. The wire-line string had to be able to deploy an industry standard ESP gauge.

Five Year, Three Phase Development Program:

Phase 1: - Key Components Evaluation

- Prove permanent magnet motor technology
- Prove electrical wet connector technology.

Phase 2: - Component & System Design and Testing

- Construction of a 300ft test well with all the necessary ancillary equipment in ALC’s Great Yarmouth (GY) facility.
- Build surface testing cells for extended testing of the motor and wet connector assembly at elevated temperatures and pressures.
- Design, manufacture and assemble a wire-line 3 phase wet connector, motor and ESP system.
- Endurance testing of Components and System in GY.

Phase 3:- Field Test Hardware

- Manufacture a field test system with a complete back up
- Perform full stack up testing in the 300ft test well
- Field test equipment in a live well (Odessa, Texas) March 2009

This paper will describe in more detail each phase of the project, a detailed description of the hardware and the potential economic/commercial value it offers to operators of ESP systems, particularly in locations where rig costs are high or rig availability is limited.

Background

ConocoPhillips had spearheaded the introduction of the technology to replace the pump section of a conventional tubing conveyed electrical submersible pump system[1] through the tubing. This demonstrated that long slim clearance components could be successfully deployed and recovered through tubing at typical ESP setting depths. However, the drawback still existed that the motor and seal sections were conveyed on the production tubing meaning that in order to access the wellbore below a rig was required to remove the completion. The impact of this was; large intervention costs; extended down time resulting in lost or deferred production as well as the loss of a rig performing other essential work over tasks.

ALC had been working on long, small diameter permanent magnet motor technology for other down hole applications, and together with its proposed side pocket electrical wet connector arrangement, addressed all the requirements for ConocoPhillips to gain full bore access to the well without employing a rig.

Phase 1:- Key Components Evaluation

Permanent Magnet Motor Technology

From specification sheets for existing “of the shelf” electrical motors the plot shown in Figure 1 was generated to provide an indication of how different motor topologies perform relative to one another. These have all been normalized for comparison purposes. The vertical axis is specific power per unit volume vs. diameter. This plot clearly demonstrates that permanent magnet based motors have power densities above every other type.

This can be explained simply as follows; a permanent magnet motor has its excitation provided by a permanent magnet rotor and all the current it its armature is torque producing. Induction machines get their excitation from the armature current directly. So for an induction motor, part of the current fed to the motor is magnetizing the circuit and not torque producing.

Furthermore, induction machines require more cooling due to the significant electrical losses in the rotor due to current circulating in the squirrel cage in the AC nature of the field in the rotor laminations. Permanent magnet motors have very small electrical losses in the rotor due to the broadly DC nature of the field in the rotor structure. Because of their efficiency, permanent magnet motors achieve much higher performance than induction motors and can have up to eight times the power output to a similar sized induction motor.

The cross plot shows different families of motor types. A progressive cavity pump is included as a comparison to show how hydraulic power compares to electrical, given the industries understanding of hydraulics.

Starting with a clean sheet, various motor configurations were modeled. The optimum design resulted in a 6 pole arrangement. A small 20 KW test motor assembly was built, and tested both in an encapsulated and non-encapsulated form. 3600 rpm synchronous speed was obtained at 240 Hz input frequency.

Thermocouples were placed inside the motor windings during motor assembly to allow monitoring of motor winding temperature, and the effect of load on this factor during testing. Extensive testing of the motor was conducted on a dynamometer test skid shown in Figure 3 (note the size difference for the 30kW induction motor and 20kW permanent magnet motor).

This testing showed that ALC designed permanent magnet motor technology could operate without sensors on standard industrial drives and was a viable option for artificial lift applications.

Electrical Wet Connector Technology

In addition to demonstrating the motor technology, a compact 125A 5KV electrical wet connector had to be packaged into the well completion so that when the ESP was deployed or retrieved from the tubing the electrical circuit could be made or broken. A fundamental consideration was that full wellbore access should be possible when the ESP was removed from the tubing. A side pocket arrangement was the eventual choice in meeting all the technical requirements. For demonstration and budgetary purposes a single pin side pocket plug arm assembly and side pocket socket was built and tested as shown in Figure 4. Figure 5a & b shows how the continuity changed over the mate and de-mate cycles during testing.

The test consisted of the following

1. lower connector and make connection
2. Apply 100 amps across connection
3. Apply impact load 5 times (to simulate jarring action to set pack off)
4. Disconnect connector
5. Mega at 5000V and measure resistance and leak off current for both completion receptacle and through tubing part of wet connector
6. Repeat a total of 25 times

Phase 1 Key Component Evaluation Conclusions

Both the motor and single pin side pocket electrical wet connector initial testing proved the feasibility of the technology. After further analysis of the oilfield application it was realized that many industry standard ESP drives are limited to 120 Hz. With this in mind and to achieve the maximum flexibility (i.e. not replace existing drives) we would revisit the motor design and make it a 4-pole machine which develops 3600 rpm synchronous speed at 120 hertz input frequency.

Phase 2:- Component & System Design and Testing

Through-Tubing ESP (TTESP) System Design

The design of the through tubing wire-line ESP system shown in Figure 6a requires the bottom hole assembly to be rig deployed on 4-1/2 in, 12.75 lb/ft tubing with a drift of 3.833 in. The bottom of this tubing string includes the no-go/re-entry guide, tail pipe, pump can (complete with side pocket wet connector), and motor shrouds. The power cable, associated cross coupling clamps, discharge pressure gauge and control line are also part of the initial rig deployment. This rig deployed bottom hole assembly remains in the ground during normal TTESP workovers.

The rig deployed bottom hole assembly was designed to allow full wellbore access with a minimum ID of 3.75 in in the no-go/re-entry guide on the bottom of the tubing string when the wire-line ESP equipment is removed.

All other equipment shown in Figure 6b, the down hole ESP sensor, plug arm assembly, sump, motors, seals, mating units, pump intake, pumps, bolt on head, hanger receptacle, stinger, check valve, tubing pack-off and tubing stop are fully deployable and retrievable with wire-line (or coiled tubing) inside the 4-1/2 in, 12.75 lb/ft tubing string.

It should be noted that the pumps and seal sections used within the design are standard ESP industry 387 and 400 series equipment with the housings turned down to 3.800 in. In some cases the head and base had to be modified to have a reduced bolt pattern.

Another important feature of this design is the ability to perform live well ESP deployment and retrieval. This is performed using wire-line lubricators attached to the top of the wellhead tree. In order to keep the lubricators to a manageable length of 70-80 feet, the maximum length of any wire-line equipment being run would need to be kept to less than 47ft.

The length of the deployed equipment in a fixed length of lubricator is also determined by the length of the running wireline tool string length. Running the heavier components may not need a long wire-line tool string to deploy the equipment to the bottom hole assembly.

The through-tubing ESP components are run in four sections, which means four wire-line runs are required to install and retrieve. If a check valve is installed, one additional run is required to equalize the tubing pressure before the pack-off can be pulled. Figure 7 shows which equipment is run on each of the four wire-line runs. It should be noted that the motors need to be short in length in order to achieve our 47ft maximum wire-line string length,

Weight is another critical factor as the components are deployed on standard slick-line units with limited slick-line safe working loads. Deployment of the pumps by ConocoPhillips in Alaska typically use 0.125 in slick-line to handle weights to 1500 lbs.

Test Well

As part of the long term capability to test the complete assembly, a 300ft test well was drilled at ALC's facility in Great Yarmouth, UK. The complete set up consisted of a 7 in 26 lb/ft cased well, cellar, wellhead, horizontal tree, flow manifold, fluid storage, heat exchanger, overhead gantry for working over the well, surface drive and well data logging systems as illustrated in Figure 8, 9 & 10.

Motor Test Bed

A self contained motor test bed for extensive motor runs under load was an essential part of the technology validation process. This consisted of a hysteresis brake water cooled load dynamometer to which we could mount the motor. In the initial test bed, the motor shared the same cooling fluid as the hysteresis brake which limited the maximum ambient temperature to 60^{o}C. The motor was tested for a total of 4200hrs, before the test bed was upgraded. This upgrade consisted of separating the two cooling systems, and increasing the number of sensors monitoring the motor. This has resulted in a test bed which can run at an ambient temperature of 180^{o}C with all sensors data being fed back to a central data acquisition and control where it is monitored, logged every second and displayed. See Figures 11a, 11b and 12.

Final Design, Manufacture & Test of a 3-Phase Wet Connector & 4-Pole Motor

Three Phase Wet Connector Development & Testing

Successful testing of the single pin wet connector moved onto the required 3-phase wet connector design, test and manufacture. The final wet connector design employed a novel internal oil cleaning and wiper system to ensure a high degree of electrical integrity in the wet mate assembly during mating and de-mating. A surface test cell was built to enable the wet connector to be tested at downhole conditions of 5,000psi and 150°C. See Figures 13 and 14. Figure 15 is an illustration of the ALC three phase low profile wet connector as deployed and mated with the bottom hole assembly. Figures 16 and 17 show the wet connector de-mated and mated in the test rig.

Additional wet connector assemblies were manufactured and incorporated into the high temperature motor test cell and the test well package where it would be tested with the entire completion at approximately 300ft. The test well string was extensively tested and refined over a six month period.

Deployment & Testing of Equipment

Once the initial design and testing of the 4-pole motors and side pocket wet connectors was completed the 4-1/2 in rig deployed bottom hole assembly components were run into the Great Yarmouth test well as previously outlined in

Figure 6a. The wire line assemblies were built up and the system run inside the 4-1/2” tubing using braided wire-line. Over the course of the following 6-months the equipment was individually tested on the previously discussed test rigs as well as in the complete assembly in the test well. The test well unit was retrieved, deployed and run many time over this period to ensure durability.

During the endurance testing of the components and the system there were many key objectives, namely:

Three Phase Wet Connector Testing:

- Mate and de-mate the connector at various pressures and temperatures while monitoring continuity.
- Mate the wet connector and pass full load current and voltage through for extended periods at varying pressure and temperature.

Several iterations of material specifications were tried and tested before ALC was able to settle on the correct design specification to meet all requirements.

4-Pole Motor Testing:

- Run motors in test rig at various loads and frequencies to map performance.
- Run motors at various loads and frequencies, with varying ambient temperatures.

Testing of the re-designed 6-pole to 4-pole motor produced the same results that had been calculated during the design process. The final motor design has the following motor performance characteristics per motor;

- Output Power 50kW (67HP)
- 340V, 105A @120Hz (3,600rpm)
- Length 3.81ft (1.16M)
- Weight 110 lbs (50kg)

Temperature rise of the motor from ambient was approximately 28°C (82°F) during full load conditions.

Motors could be tandemed together up to a maximum of six to produce the required 300kW (400HP).

System Testing in 300 ft Test Well:

- Six month function and endurance test
- Deploy, mate, and run the system at full load not less than twenty times
- De-mate the side pocket wet connector and retrieve to surface not less than twenty times.
- Introduce sand to the closed loop system and monitor the effects of wear on equipment.
- Mate the wet connector, run the system and de-mate the system several times while producing sand and assess durability.

All of the individually tested components where assembled into the complete system and installed into the 300ft test well. The system was put through extremely rigorous testing criteria to ensure that any potential problems were found and dealt with in Great Yarmouth before field trial testing actioned.

Phase 3:- System for Test Well and Field Test Hardware

Manufacture Field Test System with a Complete Back Up

Upon satisfactory completion of the 6-month function and endurance testing of the individual equipment and complete system in the Great Yarmouth two complete systems were commissioned to be manufactured for deployed in a live well. These systems were both built and put through a complete stack up test in Great Yarmouth before being deployed to the field test.

The well data for the field trial, shown in Figure 18, was analyzed and an ESP string was designed for the field application, which consisted of equipment in the rig deployed bottom hole assembly and wire-line string as outlined in Figure 19a & 19b. It should be noted that part of the requirement for the field trial was to ensure that the motors were fully loaded when running so that they were tested throughout at maximum capacity/stress. In order to achieve this, pumps were deliberately oversized to ensure maximum load was pulled from the motors.

West Texas Well Data – Figure 18	
Casing	7 in 20 lb/ft
Perforations (top)	4,618ft
Estimated Production	3,000BPD @ 120Hz (3,600rpm)
Setting Depth	4,600ft
Bottom Hole Pressure	1,800 psi
Bottom Hole Temperature	103°F
H2S	Up to 13%
Chlorides	~ 100,000 ppm
GOR	Low
Water Cut	98%

All equipment was put through a complete stack up test in the 300ft Great Yarmouth test well and run on a 4-hour soak test. On completion of this the equipment was disassembled, packaged and shipped to West Texas.

Field Trial, (Odessa Texas) March 2009.

The field trial in West Texas had specific objectives that were to be achieved. The trial was to be 90-days in duration with two complete retrievals and re-deployments of the wire-line ESP components during that period – it was agreed these retrievals and re-deployments were to be around day 30 and 60 of the 90 day run. There after the system would be left to run. The test program was designed to try and re-create an accelerated wire-line ESP run cycle, where the wire-line components would be pulled and re-run many times into and out of the permanent completion. It was also testing the durability of the permanent completion that needed to survive many wire-line work-overs.

Rig Installation:

The first installation of the through-tubing ESP system requires rig intervention so that the existing completion can be pulled and the 4-1/2 in rig deployed bottom hole assembly can be run. As this was the first installation of the TTESP, the rig first installed the bottom hole assembly (re-entry guide, pump can, motor shrouds) and ten 4-1/2" joints of tubing. The wire-line ESP equipment was then installed through the tubing via wireline. This was done to ensure the motors and wet connectors mated up correctly before running the rig deployed bottom hole assembly to bottom.

All four wire-line runs ran without any problems and the through-tubing ESP equipment was installed as designed. The rig then ran the rest of the 4-1/2 in tubing, ESP cable and control line to the bottom, before landing the hanger, installing the tree, surface manifolds and connecting up power cables etc.

The system was successfully started and ramped up to 3,270rpm (109Hz), which was motor full load current (105Amps). The system ran for 30-days without any problems. It is important to note that the unit had several shut downs and re-starts due to field production trips. Although not planned, this helped build confidence in the durability of the wet connector and motors.

Figures 20, 21, 22, 23 & 24 show the various phases of the 1st installation using the rig for the rig deployed bottom hole assembly and wire-line for the ESP equipment.

Wire-Line Retrieval and Re-Deployment(s):

On days 30 and 60 of the 90-day trial the unit was stopped and the complete through-tubing wire-line ESP assembly retrieved and re-run. On the first re-run of the unit on wire-line at setting depth some important lessons had to be learnt as to how the system behaved during the orientation and mating phase of the wet connectors. Considerations had to be made and experience gained with stretch in the wire and how this affected weight indications with reference to mechanisms functioning down hole. The lessons learned during the first retrieval and re-deployment have been incorporated into the design to improve the ease with which the system can be worked over.

One of the many advantages of the through-tubing wireline ESP is that there is no rig requirement during a work over of the ESP string. The only equipment required is as follows:

- Wire-Line truck/unit with standard equipment
- 5-1/2 in lubricator
- Crane with 100ft height capability
- Man -lift

The work-over costs, in certain parts of the world, and down time of an ESP well can be greatly reduced with this type of technology.

Figures 25, 26, & 27 illustrate the surface set up that was required to perform the work-overs. It should be noted that there is only the requirement for a crane, wire-line unit/truck with lubricating unit and a man-lift to perform the work-over. A further note is that the pull and run of the systems take approximately 36 hours to perform.

With reference to the lubricator, the length used during the West Texas work over was 75 ft, this allowed us to run a wire-line equipment string up to a maximum length of 58ft. This was required as the setting depth of the equipment in our 2nd wire-line string (pump sections) had a total length of 57.22ft.

Future Plans

Later in 2009 the tubing and bottom hole assembly will be pulled from the field test well and replaced with the an enhance bottom hole assembly. This enhanced bottom hole assembly will incorporate all of the lessons learned from the first installation and subsequent pulls/reruns of the system. This will also be the final "dress rehearsal" before deploying the TTESP for ConocoPhillips Alaska.

Application and Economics

Capacity of the TTESP (flow and horsepower) is limited due to the diameter of the tubing and the production casing.

The maximum pump capacity for a 400 series pump turned down to 3.800 in for 4-1/2 in tubing is approximately 6000 BPD. Horsepower is limited to the 0.875 in OD pump and seal shaft and with standard high strength material (718 Inconel) is approximately 400 horsepower. The ALC PM 3.800 in motor shaft capacity limitation is also in the 400 horsepower range.

One of the items that must be made robust is the cable system. Since the cable system is deployed conventionally on tubing the cable selection and performance for the application needs careful review as a failure in the cable system will requires a RIG workover. For 7 in 26 lb/ft casing and 4-1/2 in 12.75 lb/ft IBT special clearance couplings, #2 lead cable with cross coupling clamps can be installed.

The application of the TTESP will be leveraged toward environments that have high ESP pulling cost and/or low RIG availability. Initial cost of the TTESP equipment is estimated to be 1-1/2 to 2 times the cost of an equivalent conventional ESP system.

There will be a RIG requirement to pull the existing completion and install the TTESP bottom hole assembly, but after that installation pump/motor replacements can be completed with slick line and/or coiled tubing. For ConocoPhillips Alaska this was one of the biggest drivers as the rig cost keeps escalating.

An operator looking at the application of the TTESP must understand the failures causes of an ESP within their operating environment. Economics will be based upon reducing future replacement costs and minimizing the production downtime.

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- Mark Griffin, ALC
- Alan Radcliff, ALC
- Dr. Hassan Mansir, ALC
- George Ryton, ALC

References

1. Through-Tubing-Conveyed ESP Pump Replacement – Live Well Intervention: Walter Dinkin’s, Steve Telzlaff, Baker Hughes inc., John C Patterson, ConocoPhillips Company, Hai Hunt, Peter Nezaticky, James Rodgers, ConocoPhillips Alaska Inc.

Figures

Motor Figures

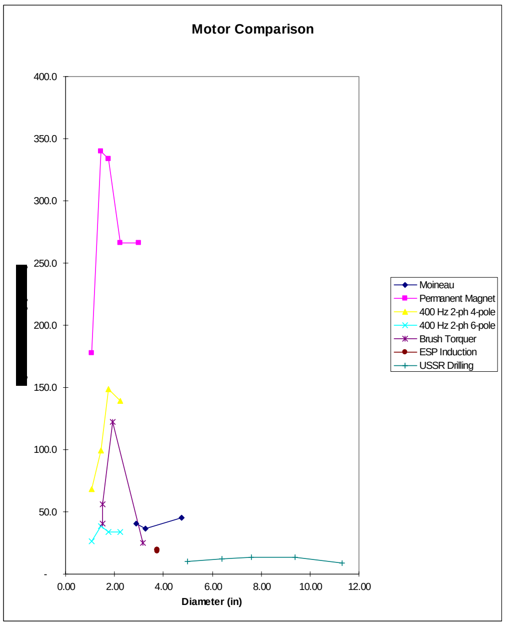


Figure 1 – Normalized motor comparison plot

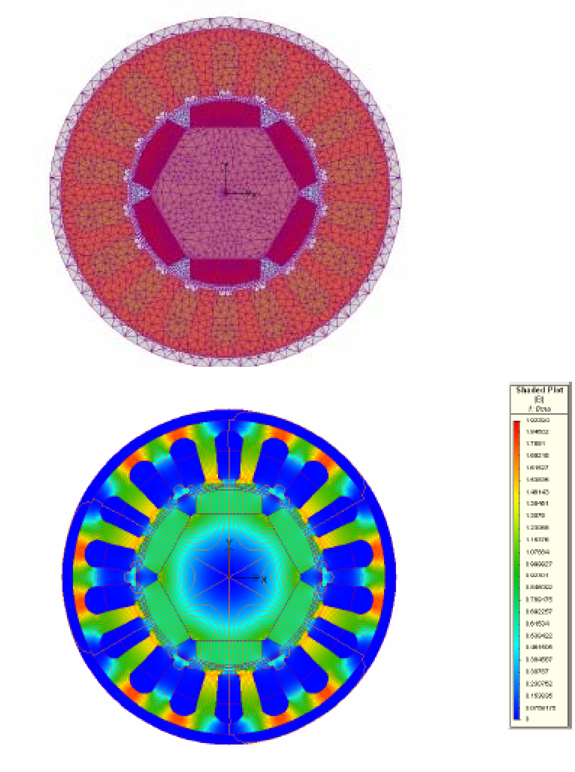


Figure 2 – Simulations of motor

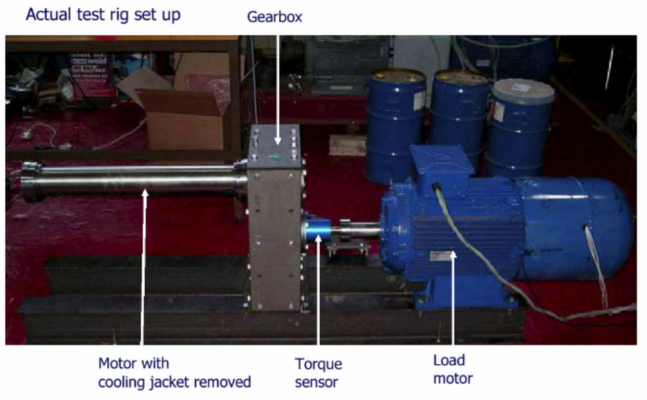


Figure 3 20kW motor testing arrangement (note size difference with 30kW induction motor)

Phase 1 Electrical Wet Connector

Figure 4 single phase test arrangment

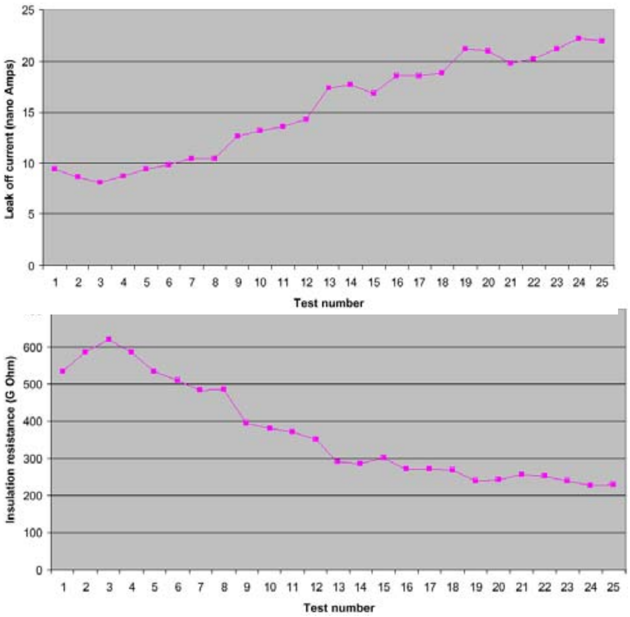


Figure 5a & b show the continuity values over the cycled mates and de-mates.

Permanent and Wireline Deployed Components

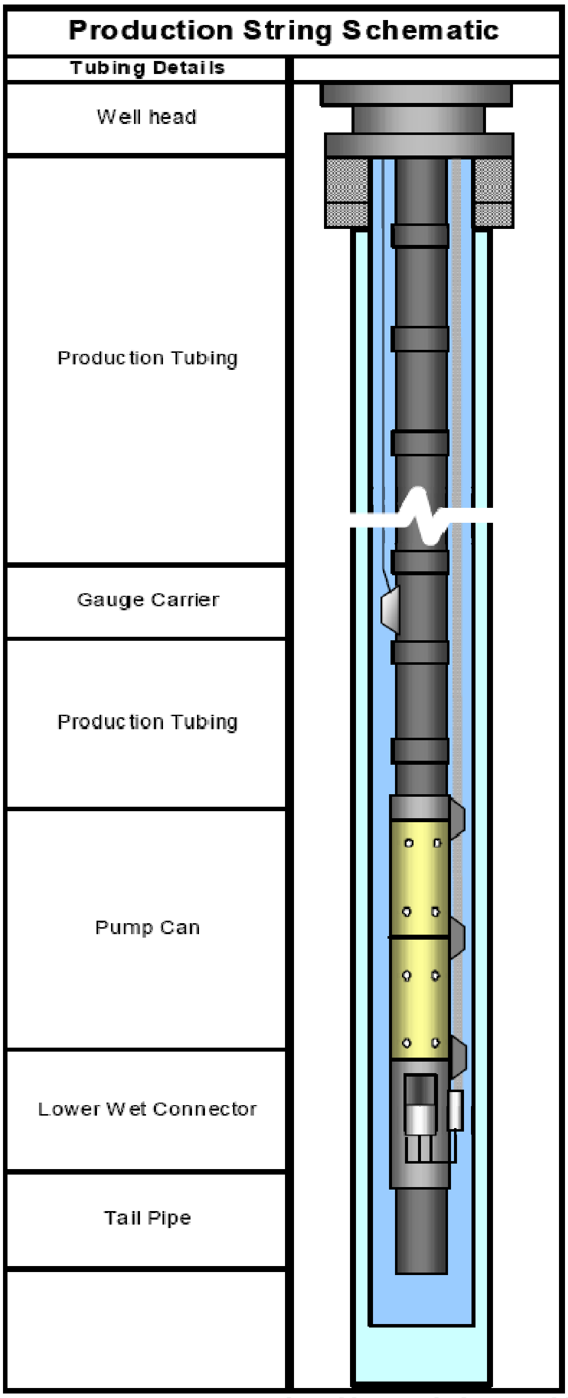


Figure 6A: 4-1/2” Rig Deployed bottom hole assembly

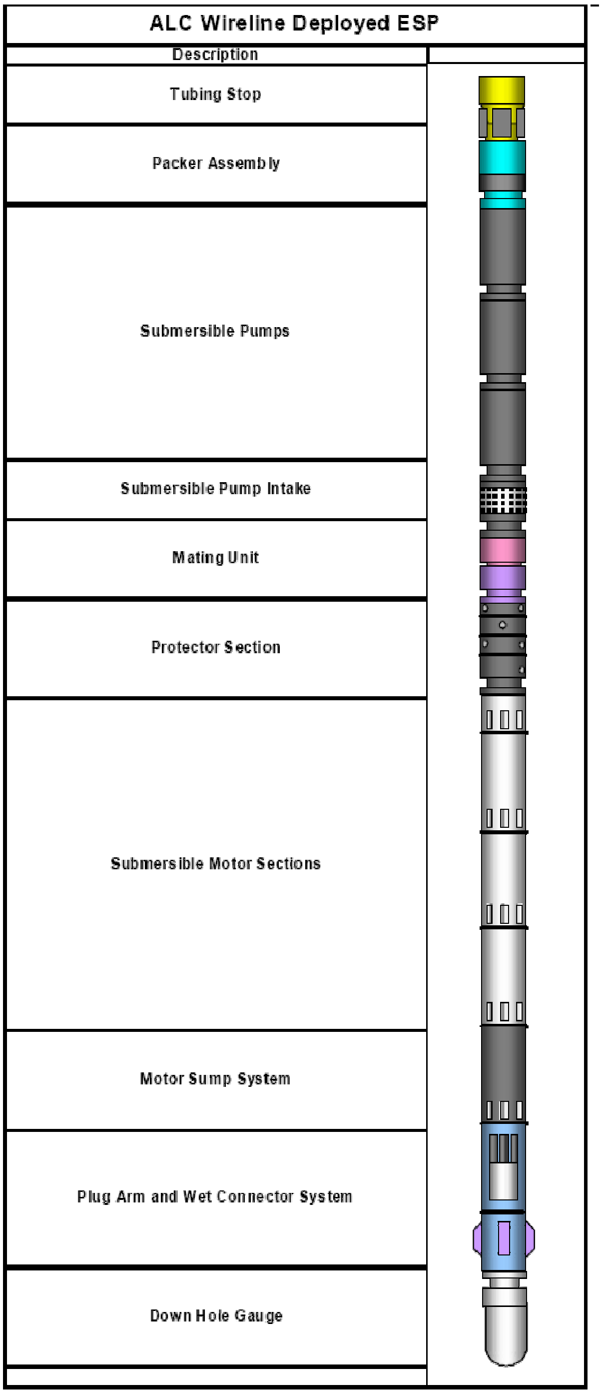


Figure 6B: Wire-Line String

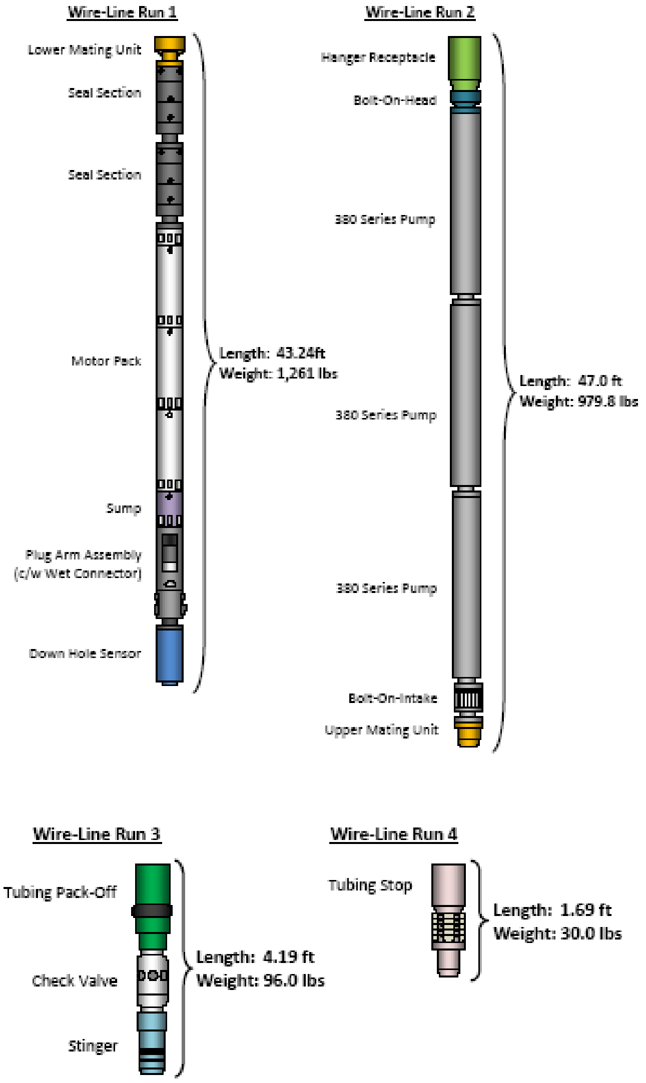


Figure 7 Typical assembly compositions for wireline runs (note, length of wire-line components can be longer depending on lubricator and wire-line tool string lengths)

Testing Facilities

Figure 8 Gantry, test well and works

Figure 9 Surface facilities

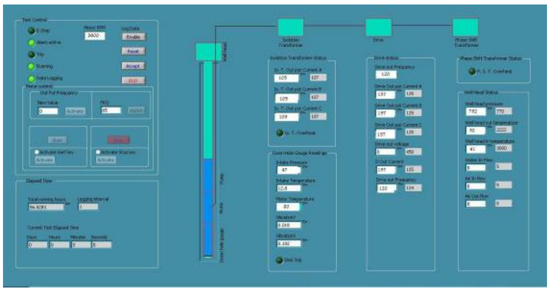


Figure 10: Program monitoring and logging all parameters of the complete system

Figure 11a – the 1st generation motor test bed (limited to 60°C water temperature)

Figure 11b – the 2nd generation motor test bed (180C testing temperature)

Figure 12: Motor testing cell (behind closed doors) with monitoring equipment

Figure 13: Wet Connector in pressure Test Vessel in Oven

Figure 14: Wet Connector Testing lab (Oven closed, control valve manifold visible on outside)

Three Phase Wet Connector

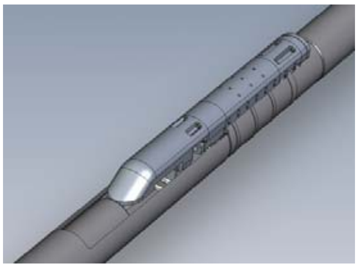


Figure 15: Illustration showing Wet Connector deployed and mated.

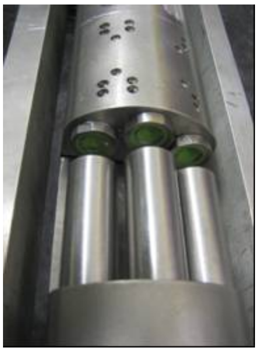
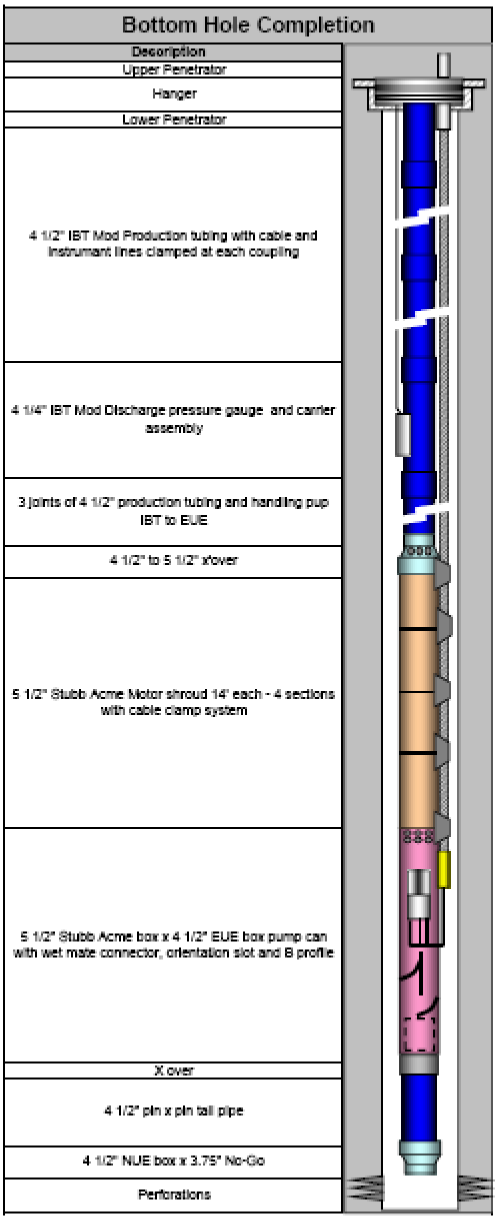


Figure 16: Wet Connector De-Mated on Test Rig

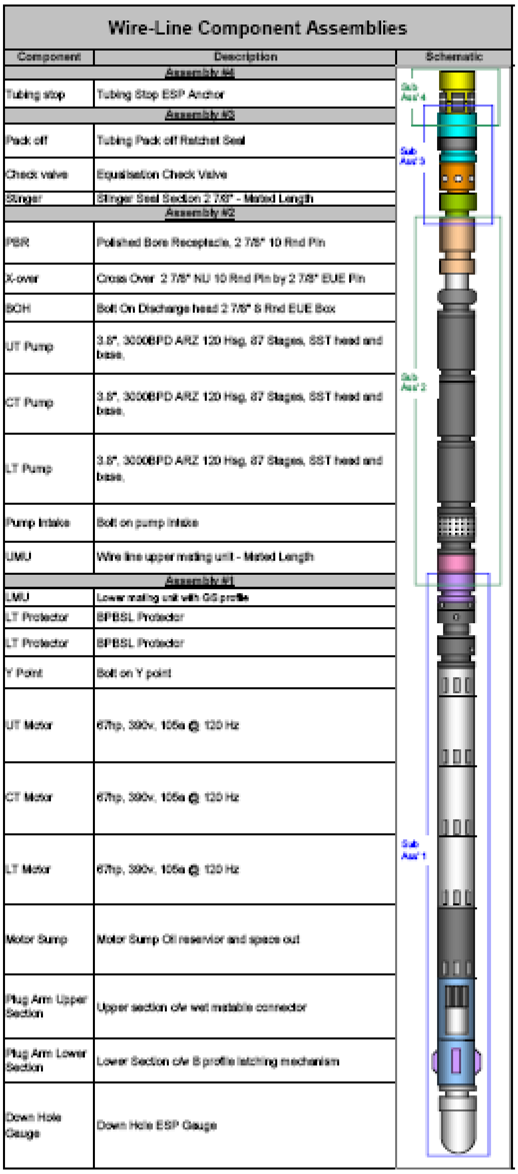
Figure 17: Wet Connector Mated on test Rig



Bottom Hole Completion

Description
Upper Penetrator
Hanger
Lower Penetrator
4 1/2" IBT Mod Production tubing with cable and instrumant lines clamped at each coupling
4 1/4" IBT Mod Discharge pressure gauge and carrier assembly
3 joints of 4 1/2" production tubing and handling pup IBT to EUE
4 1/2" to 5 1/2" x'over
5 1/2" Stubb Acme Motor shroud 14' each - 4 sections with cable clamp system
5 1/2" Stubb Acme box x 4 1/2" EUE box pump can with wet mate connector, orientation slot and B profile
X over
4 1/2" pin x pin tail pipe
4 1/2" NUE box x 3.75" No-Go
Perforations

Figure 19a: West Texas Field Trial Bottom Hole Assembly



Wire-Line Component Assemblies

Component	Description
Assembly #4	
Tubing stop	Tubing Stop ESP Anchor
Assembly #3	
Pack off	Tubing Pack off Ratchet Seal
Check valve	Equalisation Check Valve
Stinger	Stinger Seal Section 2 7/8" - Mated Length
Assembly #2	
PBR	Polished Bore Receptacle, 2 7/8" 10 Rnd Pin
X-over	Cross Over 2 7/8" NU 10 Rnd Pin by 2 7/8" EUE Pin
BOH	Bolt On Discharge head 2 7/8" 8 Rnd EUE Box
UT Pump	3.8", 3000BPD ARZ 120 Hsg, 87 Stages, SST head and base,
CT Pump	3.8", 3000BPD ARZ 120 Hsg, 87 Stages, SST head and base,
LT Pump	3.8", 3000BPD ARZ 120 Hsg, 87 Stages, SST head and base,
Pump Intake	Bolt on pump intake
UMU	Wire line upper mating unit - Mated Length
Assembly #1	
LMU	Lower mating unit with GS profile
LT Protector	BPBSL Protector
LT Protector	BPBSL Protector
Y Point	Bolt on Y point
UT Motor	67hp, 390v, 105a @ 120 Hz
CT Motor	67hp, 390v, 105a @ 120 Hz
LT Motor	67hp, 390v, 105a @ 120 Hz
Motor Sump	Motor Sump Oil reservior and space out
Plug Arm Upper Section	Upper section c/w wet matable connector
Plug Arm Lower Section	Lower Section c/w B profile latching mechanism
Down Hole Gauge	Down Hole ESP Gauge

Figure 19b: West Texas Field Trial Wire-Line String

Rig Installation of TTESP

Figure 20: BHA Being Installed

Figure 21: Wet Connector Mounted on BHA

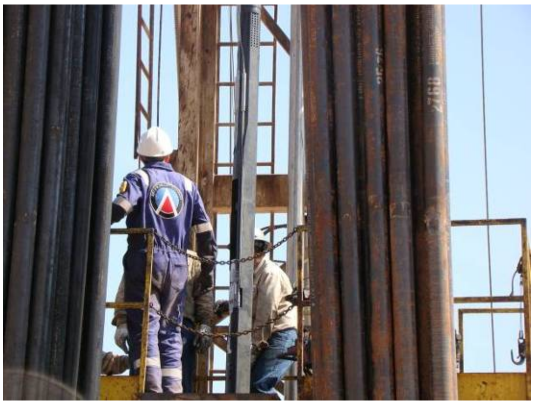


Figure 22: Wet Connector mounted on BHA

Figure 23: Install Wire-line Equipment

Figure 24: Surface Equipment

Wire-Line Pull & Run of TTESP

Figure 25: Crane Lifting Lubricator

Figure 26: Lubricator attaching to Wellhead

Figure 27: Well Site during workover