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Building and Testing a Battery-Operated Subsea Shut-Off System

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Abstract

A deepwater exploration drilling system has been designed (Leach and Bamford 2005) to deploy a slim, one trip riser from a mono-hull vessel using jetted-in conductor. To deploy the subsea shut-off system from a lightweight monohull vessel it must weigh less than 30 t.

Accumulators become inefficient with increasing water depth as their size and weight needed to store a given quantity of energy increases.

The need for a rapid and reliable method of disconnecting the riser lead to the development and testing of a battery powered shear ram system. Batteries also power the alternative annular cutting tool pipe severance method. This provides an even radial cut for full bore re-entry compared with the belled over profile of sheared pipe.

A prototype subsea pod was built consisting of military specification batteries connected to an electric motor and variable displacement hydraulic pump. By the direct supply of hydraulic fluid to and from the shear rams, high pressure Stack Plate Mounted (SPM) valves are removed from the control system. The resulting high power to weight ratio enabled the pod weight to be kept around 500 kg.

Successful and repeated shear tests were conducted on concentric 194 mm (7-5/8 in) and 140 mm (5-1/2 in) casings with a small battery set without recharge. The results are presented here.

The four pod subsea control system was developed with Triple Modular Redundancy (TMR) architecture. This provides a high degree of reliability and ensures that spurious signals to disconnect are ignored.

It was concluded that a reliable, battery powered subsea pod can operate over the design life of a 100 days well and be charged in-situ using a Remotely Operated Vehicle (ROV).

Introduction

A typical subsea control system used in safety critical "Class 1" applications consists mainly of an accumulator bank for hydraulic fluid storage; two replaceable pods (duty and standby) containing electronics and pilot valves for each controlled hydraulic function; pressure reducing valves to control initial overpressure from the accumulators; pilot operated valves installed permanently on the structure for supplying fluid to each function; and a shuttle valve to direct flow from the commanded valve to each function.

Notably, accumulators are accepted to be an increasingly inefficient means of energy storage as the depth of operation increases and control valves are known to be a common cause of control system failure. Additionally, in the event of a pod failure, and even though function is maintained, operations are stopped until the faulty pod can be replaced and full redundancy is restored.

The points in the system that are susceptible to single point or common mode failures are the accumulator bank and pressure reducing valve(s); the single hydraulic high pressure hydraulic header; the shuttle valves; and the piping to each function.

For deployment to depths of 3000 m (9,843 ft), an accumulator system becomes so large and heavy that it impacts significantly on the overall proposed Geoprobe Shut-Off System (Geo-SOS) architecture. Furthermore, as safety critical Class 1 functions must be available independently of any surface hydraulic supply or the ROV system, energy must be stored at the Geo-SOS to provide shearing and sealing capabilities when required.

Several less conventional systems for provision of stored energy that could provide significant advantages regarding size, weight, reliability and availability were identified and taken into consideration.

The preferred architecture recommended for the Geo-SOS includes the use of Direct Current (DC) electric motors close-coupled to variable displacement hydraulic pumps for each actuator, with energy being stored in a local rechargeable battery system. The key advantages are:

- No electrically operated valves in the system (valve-free system);
- The ability to store significantly greater energy than much larger accumulator systems;
- By recycling the hydraulic fluid, to provide much greater volumes and higher pressures than accumulator based systems;
- Significantly reduced system weight, impacting on equipment handling systems and vessel equipment;
- Significantly reduced system complexity.

The Problem

Hydraulic accumulators are a well known technology commonly used for the provision of stored energy for subsea systems. The major drawback with accumulators is that they lose efficiency as energy storage devices as ambient pressure increases.

Assuming that rams with the following dimensions will be used:

Piston Diameter = 362 mm
Rod Diameter = 112 mm
Stroke = 225 mm

The hydraulic swept volume to close is 23.3 L.

Assuming that ram boosters with the following dimensions will be used:

Piston Diameter = 362 mm
Rod Diameter = 112 mm
Stroke = 50 mm

The hydraulic swept volume to close is 4.65 L.

Each function (i.e., blind and shear) has two pairs of rams. Additionally, the shear rams also have one pair of boosters. The regulatory requirement API *Spec 16D* requires that the hydraulic control system for a subsea Blowout Preventer (BOP) stack shall have a minimum total stored hydraulic fluid volume, with the pumps inoperative, to satisfy several operating conditions. In order to satisfy the requirements the total hydraulic volume needed is 251 L or 5 bottles (55 L).

Assuming that the rams will require a force to shear equivalent to that generated by a pair of standard 375 mm (14-3/4 in) actuators fitted with equal area tandem booster cylinders, operated at 207 Bars (3,000 psi). At full system depth of 3000 m, the total gas volume required is 1982 L or 36 bottles (55 L).

Therefore, the system requires a total number of 41 bottles with a total weight of 10.5 t.

Please notice that gas volumes are based upon using Helium as the fill gas. It should also be noted that gas back up bottles are based upon the standard 55 L size.

Weights are based upon accumulator cylinders with a working pressure of 690 bar (255 kg for a 55 L bottle). Although the maximum working pressure (gauge) of the accumulators will only

be 350 bar on the seabed, this will enable full gas pre-charge to be applied at the surface. If lower working pressure bottles are used they will have to be topped up with high pressure gas on the seabed.

Savings in accumulator size and weight could be gained by relaxing the assumptions for required storage volume and/or load pressure characteristics.

Different types of accumulator arrangement may be implemented. Assuming the use of a single bank of accumulators connected into the system supply header, see for instance Figure 1, the system pressure starts at some value greater than the design pressure and is arranged to finish at the design pressure, and thereby retain the mechanical performance of the actuator throughout its range. In this case additional pressure regulation at the accumulator output is needed to avoid overstressing the actuator.

Figure 2 shows the correlation between stroke variation and discharge characteristic of the accumulator pressure, and the actuator load pressure characteristics.

It is clear that for the assumptions made for the load characteristics, the load and supply are poorly matched where the area between the two represents energy that is wasted during delivery.

Efficiency of this type of arrangement can be improved by splitting the accumulator bank into one or more sections where each section is allowed to depressurise to a point that is more appropriate to the load characteristic.

It should be noted that splitting the accumulator bank introduces an additional level of complexity in the form of an extra control valve for each bank of accumulators, so that the correct pressure can be manifolded into the high pressure header at the right stage of the actuation process. These extra valves have to be operated by the control system in the correct order and in response to measurement of flow, actuator position or system pressure, in order to ensure that sufficient fluid is available.

Solution

Battery systems have a long record of subsea use in oceanographic and submersible

applications down to full ocean depth, so their use in an application such as this would not involve any technical innovations.

Considering the single bank of accumulators discussed in the previous section, the total energy used to compress back up gas on the surface is 1080 MJ; the total energy available in the fluid on the surface is 14.1 MJ; the energy available in the fluid at 3000 m is 6.6 MJ; and the energy required for the assumed ram operations with 50% spare capacity is 3.7 MJ.

It can be clearly seen that the energy efficiency of this method is approximately one third of one percent!

Storing electrical energy in batteries overcomes many of the inefficiencies associated with accumulators, not least of which are independence of ambient pressure and much better load matching capability. A single 12V, 162 kC (45 A-hr) rated battery, as used in a "reasonably priced car" contains 1.9MJ of electrical energy.

For the present application, a DC motor running at a nominal voltage of 72 V with an average shaft output over the actuator closing cycles of 23 kW has been considered. To achieve the required voltage, six standard 12 V batteries would be connected in series, and the average running current would be approximately 375 A.

Considering the energy required it would appear that batteries with capacity of only 54 kC (15 A-hr) would be sufficient. There are, however, a number of factors that act to decrease available capacity and suitability such as:

- Low temperatures reduce the amount of energy that can be drawn from the battery. At 0° C the available capacity can be expected to be reduced by 20%;
- High current rates reduce the amount of energy that can be drawn from the battery. At the current rates specified and for the type of battery considered available capacity can be expected to be reduced by 80%;
- Small batteries cannot supply high current without damage to the internals. To cope with starting current for this motor current capacity in excess of 1000A will be required.

Taking the combination above, the required battery capacity will have to be greater than 338 kC (94 A-hr). The specification for a typical 360 kC (100 A-hr) battery capable of providing “cold cranking current” over 1000 A is commercially readily available.

Each of these batteries weigh 34 kg, and therefore, a bank of six would weigh 204kg. Adding in estimated weights for the pump and motor and an oil filled box to hold them all, the total estimated weight for the energy storage system is approximately 500 kg, which is less than the weight of two high pressure accumulators.

Figure 3 gives an idea of how great the difference in size and weight is between an accumulator and a battery system for the proposed application.

Subsea Control Module (SCM)

After careful analysis of the cost and performance criteria of potential configurations, the use of a Triple Modular Redundancy (TMR) SCM system was recommended for the Geo-SOS. This is achievable due to the reduced number of functions required to be operated by the emergency release system, and will offer significant improvement in reliability and availability when compared to conventional dual SCM architectures.

The use of three SCM allows a number of configurations to be implemented that offer increased operability and reliability when compared to dual and single SCM systems. The most effective of these architectures is known as TMR, and is where all three SCM process the same input data and generate the same outputs, but are connected together in such a way as to provide hardware voting logic on their output signals. This voting logic ensures that at least two SCMs must agree in their output state for that output to be energized. Figure 4 illustrates the control logic behind the TMR concept.

Use of this architecture ensures that state contention is avoided, and provides increased system availability and integrity. For these reasons, TMR architectures are widely used in industries and technologies where ultimate

system reliability and availability is needed (e.g. Fly-by-Wire aircraft, gas turbine systems and weapons systems).

In the event of a failure of one SCM, the system automatically reconfigures itself to a duty/standby dual architecture. A further SCM failure would still allow operation of the system with a single control module.

The three emergency release SCM that are required to provide the TMR functionality are all identical. They are identified as POD A, B and C. Each SCM comprises an oil-filled pressure compensated painted steel enclosure, inside which there is a pressure compensated lead-acid gel type battery system, two electrically driven hydraulic pumps (one for each BOP ram pair), two high-power oil-filled contactors (one for each HPU) and a single one atmosphere subsea electronics module. On the top of the SCM housing there is a running-tool mandrel to allow the SCM to be retrieved using a crane whip-line with assistance from the ROV. An integral compensation oil bladder provides equalisation of the compensation oil pressure inside the SCM housing. Figure 5 show a diagram of the emergency release SCM.

Acoustic telemetry is provided by an integral acoustic modem system whose transducer is mounted on the top of the SCM. Outtrigger arms may be deployed, depending on the water depth to provide a clearer acoustic “view” upwards to the host vessel.

On the underside of the base of the SCM there is an array of hydraulic and electrical couplers. These provide connections between the Geo-SOS hydraulic systems and the SCM, and allow the interconnection of signals between the three SCM, the support ROV and the non-critical “Class 2” utility SCM.

In addition to the three TMR configured emergency release SCM, there is a fourth “simplex” SCM – the utility SCM. This fourth SCM is permanently installed on the Geo-SOS and is local to the ROV landing stage. It performs three main functions: 1) Operation of certain hydraulic functions on the Geo-SOS when the ROV is not docked on but is in the vicinity of the Geo-SOS; 2) Provide instrumentation feedback from all Geo-SOS instruments and sensors, either with the ROV docked on to the system or with the ROV local to the Geo-SOS; 3) Provide a telemetry and power conduit for communication with all the

emergency release SCM to allow status monitoring, system testing and battery recharge.

A detailed fluid system analysis for the Geo-SOS concluded that the hydraulic system should be closed-loop, using a conventional mineral hydraulic fluid system (e.g. Nuto, Tellus, Hyspin, etc.). This will allow the use of "standard" hydraulic components with well-documented reliability data and performance criteria.

Prototype

The prototype used a hired Scan Tech 800T Hydraulic Shear cutter to simulate the cutting demands of a BOP shear rams. Batteries were used to store the required energy. When energised, contactors connected the battery terminals to a DC motor which was used to drive a hydraulic pump. The output from the pump was directly connected to the 800T cutter actuator which closed as fluid was delivered and cut a pipe sample held within the jaws of the cutter. Figure 6 shows a photograph of the test layout used as prototype. Figure 7 shows the DC motor, pump sets inside the prototype SCM pod.

Energy for the cutting process was provided by three separate banks of military specification batteries, each providing the motive power for one motor-pump set. Each battery bank had a capacity of 346 kC (96 A-hr) and operated at a nominal 72 V, with a maximum cold cranking capacity of more than 2000 A.

Each battery bank was isolated from its motor-pump set by means of high current contactors, whose coil side was energised from a separate low voltage (24 V) supply. The contactors were energised by means of relays and switches sited in the operator's control box.

The control box enabled the operator to select which of the motors were to be used during a specific test and had a single switch to run or stop whichever of the motors were selected.

The three pumps were constant horsepower controlled, with a maximum set pressure of 200 bar. They outputted into a common header via a non return valve on each pump outlet. The common header contained a system relief valve and high pressure filter.

Quick connect hoses attached the circuit to the cutter for pressure supply and return to the tank. The return side of the circuit contained a low pressure filter for pump protection.

The motor-pump equipment was positioned in a safe location directly behind the cutter. Output from pressure and other sensors were fed to a data logger and computer located in a safe location.

Results

Several tests were carried out and some representative results are presented here.

Shear Test 1 consisted of the attempt to shear 194 mm (7-5/8 in) 44.2 kg/m (29.7 lbf/ft) L80 casing only, without liner pipe present. Figure 8 shows the Shear Test 1 data results.

At 0 seconds the motor was turned on and the pump delivered a pressure of 40 bar to close the cutting jaws. The jaws were not yet in contact with the pipe.

At 22 seconds the cutting jaws contacted the pipe and the current drawn from the batteries increased to supply a higher pressure which overcome the resistance and deformed the pipe. The slower rate of extension of the driving cylinder corresponded to the deformation of the pipe.

At 62 seconds the jaws have completely crushed the pipe. The first pressure spike seen in Fig. 8 corresponds to the drop in resistance felt by the cutting jaws as the top half of the pipe is sheared. The pressure built again until the cutting jaws sheared the bottom half of the pipe. Thereafter, the pressure dropped since there was no resistance being felt.

The total time to complete test was 62 seconds, the total time needed to shear the pipe after contact was made was 40 seconds and the pressure required to shear the pipe was 143 bar (2,074 psi).

Shear Test 4 consisted of the attempt to shear 194 mm (7-5/8 in) 44.2 kg/m (29.7 lbf/ft) L80 casing with 76 mm (3 in) liner pipe inside to represent coiled tubing. Figure 9 shows the Shear Test 4 data results.

At 0 seconds the motor was turned on and the pump delivered a pressure of 40 bar to close

the cutting jaws. The jaws were not yet in contact with the pipe.

At 28 seconds the cutting jaws contacted the pipe and the current drawn from the batteries increased to supply a higher pressure which overcome the resistance and deformed the pipe. The slower rate of extension of the driving cylinder corresponded to the deformation of the pipe.

At 68 seconds the jaws have completely crushed the pipe. The first large drop in pressure corresponds to the drop in resistance felt by the jaws as the top half of the pipe is sheared. The second large drop in pressure corresponds to the coil tubing being sheared. The pressure builds again until the jaws shear the bottom half of the pipe, which corresponds to the third large drop in pressure.

The total time to complete test was 68 seconds, the total time needed to shear the pipe after contact was made was 40 seconds and the pressure required to shear the pipe was 140 bar (2,030 psi).

Figure 10 shows a photograph of the sheared 194 mm (7-5/8 in) casing with 76 mm (3 in) liner pipe removed from the test piece.

It should also be noted that one battery set successfully completed six shearing tests without recharging. Three tests with casing pipe only and three tests with casing pipe and liner pipe inside.

Conclusions

It is well known that hydraulic accumulators lose efficiency as water depth increases and for the proposed application at depth of 3000 m such a system would require 41 bottles with a total weight of 10.5 t.

The new proposed system consists of three ROV replaceable control pods, organised as TMR SCM, containing control electronics, batteries for energy storage, communications and power links, and a motor/pump unit for supplying hydraulic fluid to each function. The total weight for the new system is approximately 500 kg.

Additionally, the energy storage is much increased; the system preserves operability with one pod down; there are no hydraulic

control valves in the system; and there are far fewer points in the system that are susceptible to single point or common mode failures.

All the tests carried out with the prototype clearly demonstrate the capability of the Electro-Hydraulic system to shear 194 mm (7-5/8 in) casing with 76 mm (3 in) liner pipe. Further work is in progress to optimise the system to do this inside within the regulatory requirement of 45 s.

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We especially thank David Dowell of Chevron and Alastair Buchanan of Statoil for their participation in the testing programme.

We also acknowledge the assistance of Hugh Williams and Gareth Kerr of Fathom Systems on the development of the subsea control system.

References

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Spec 16D, Specification for Control Systems for Drilling Well Control Equipment, second edition. 2004. Washington, DC: API.

Figures

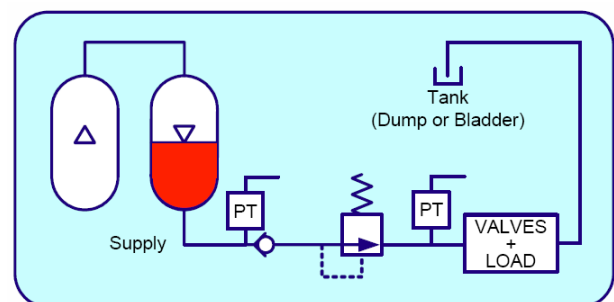


Fig. 1 – Single bank of accumulators diagram.

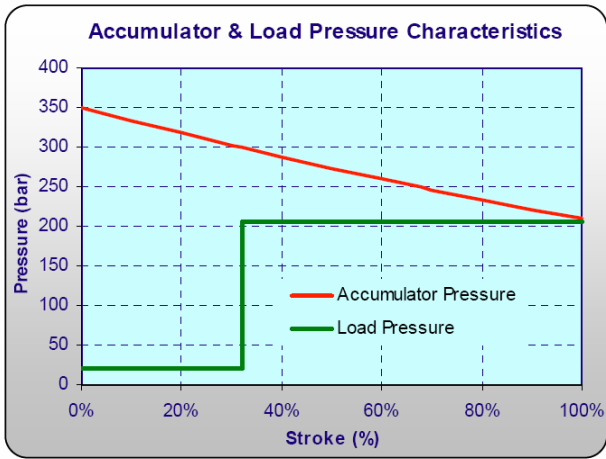


Fig. 2 – Single bank of accumulators pressure characteristics.

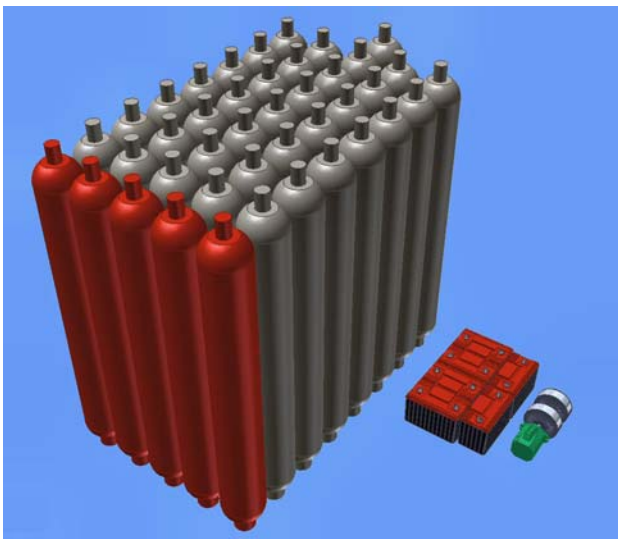


Fig. 3 – Comparison between accumulator and battery systems.

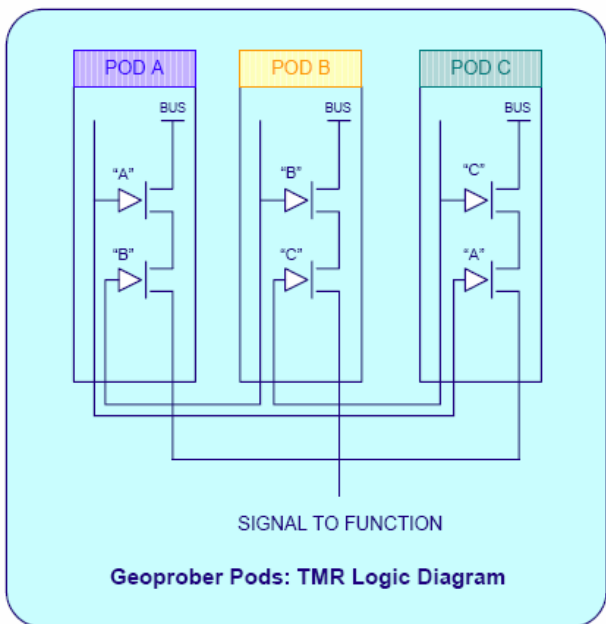


Fig. 4 – TMR logic diagram.

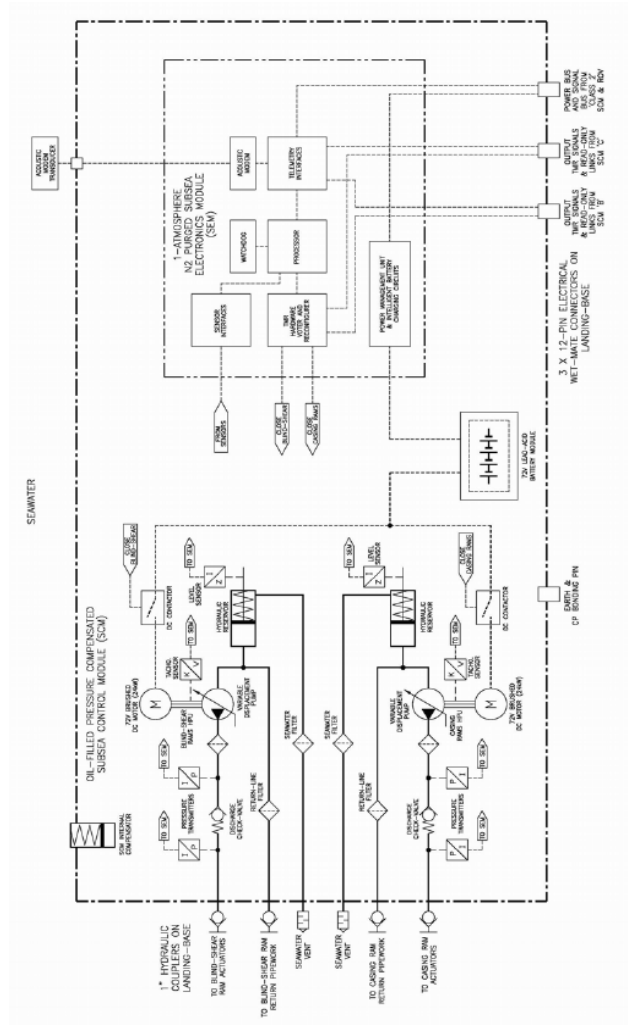


Fig. 5 – Emergency release SCM diagram.



Fig. 6 – Emergency release SCM prototype.



Figure 7 – DC Motor Pumps in SCM Pod



Fig.10 – Sheared 194 mm (7-5/8 in) casing with 76 mm (3 in) liner pipe removed from the test piece.

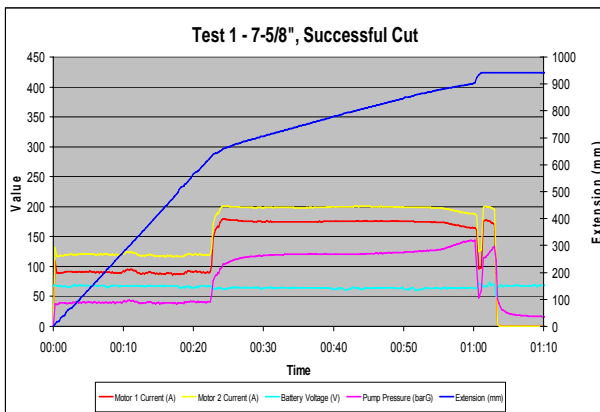


Fig. 8 – Shear Test 1 data results.

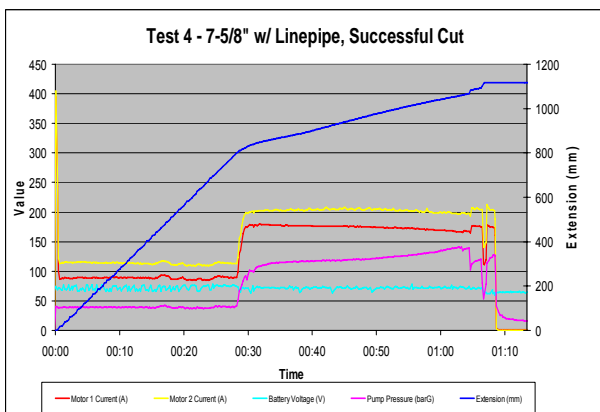


Fig. 9 – Shear Test 4 data results.