

New generation of subsea BOP equipment, controls smaller, stronger, cleaner, smarter

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WITH THE HIGH price of oil, it's become more economical to go to deeper water depths and more challenging reservoirs. With those more challenging reservoirs, comes a whole new set of problems designing the next generation of drilling rigs and subsea BOP equipment. Those new challenges have inspired a new age of BOPs that have been made smaller by reducing the number of stack-mounted accumulators, stronger by increasing the available shear force, cleaner by developing a complete fluid recovery system, and smarter by improving the control system diagnostic systems.

DEPTH COMPENSATED ACCUMULATORS

Today's designed operating environment for stack-mounted accumulators is challenging. Design criteria include 12,000-ft water depths, temperatures as low as 40°F and surface temperatures of 120°F, rapid discharge (Adiabatic), as well as higher minimum system pressures.

All of these things add up to a large number of bottles on a lower BOP stack. It is not uncommon to see as many as 126 accumulator bottles on a lower BOP stack, 98 of which are dedicated to the shear system alone (Figure 1). This adds weight to the overall assembly, increases maintenance requirements and decreases stack equipment access. By using the water column pressure and mechanically boosting the hydraulic pressure, a depth compensated accumulator has reduced the total number of stack-mounted shear circuit bottles from 98 conventional 6,000-psi, 15-gallon accumulators to seven depth compensated bottles (Figure 1).

Before we can understand how this happens, it is important to understand what effect the subsea operating environment has on accumulators and gas. There are three major factors that effect gas performance subsea: temperature, discharge type and water depth.

TEMPERATURE

Colder gas equals denser gas. Take this example problem using a 15-gallon, 6,000-psi accumulator. A surface temperature of 120°F is used, assuming

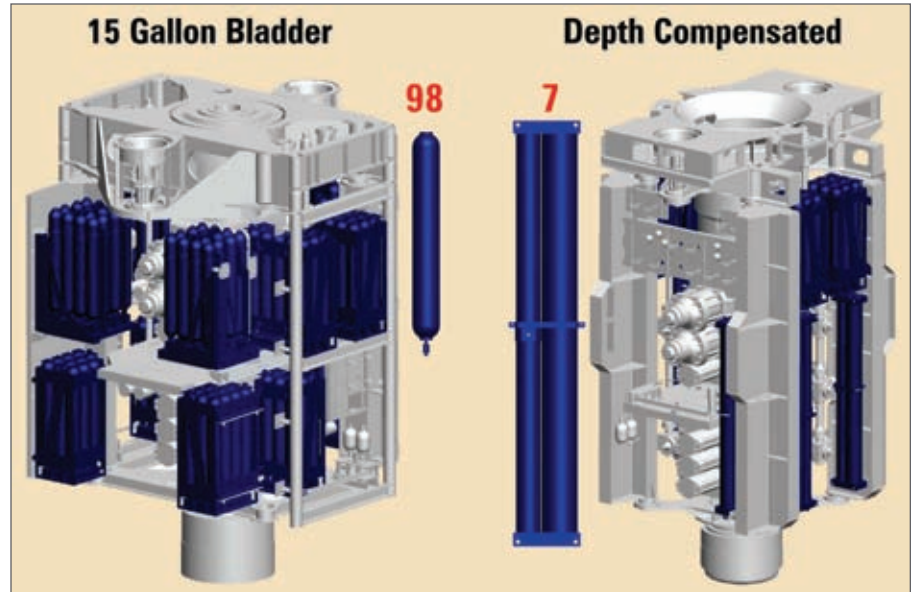


Figure 1: In this comparison of lower BOP stacks, the configuration on the left has 15-gallon, 6,000-psi N2 accumulators that can add up to more than 100, with 98 dedicated to just the shear system. At right are depth compensated accumulators that reduce overall assembly weight and maintenance needs.

the bottles are in the sun on the vessel before it is deployed and are charged to the maximum rating for those bottles of 6,000 psi. The effect on the gas from a reduction in temperature to 40°F is the gas pressure reducing to 4,785 psi. More than 1,200 psi precharge pressure is lost just from reducing the temperature.

ADIABATIC DISCHARGE

Adiabatic discharge equals rapid discharge. The definition of an "adiabatic process" is a process by which no energy is absorbed or released into the environment. When compressing a gas, that process will heat the gas. Conversely, when decompressing a gas (accumulator discharge), the gas gets colder.

Accumulators dedicated to shear are rapidly discharged, and there is no time for the outside temperature to re-heat the gas. Therefore, when the gas is discharged, it is colder in its discharged state. Remember, colder gas equals denser gas; therefore more gas is needed to compensate for this condition. About twice as much gas is required for an adiabatic discharge compared with an isothermal discharge (isothermal assumes the environment has time to re-heat the gas, and it stays at a constant temperature).

WATER DEPTH

Deeper water equals lower compression ratio. To understand how water depth effects gas performance, there is a basic measure of gas performance called "compression ratio." Compression Ratio is:

$$CR = \frac{P_{\max}}{P_{\min}}$$

Where:

- CR = compression ratio
- P_{\max} = maximum system pressure, the pressure at which the system pumps turn off.
- P_{\min} = minimum pressure required to operate a function, i.e., 3,000 psi for the shear rams.

The higher the compression ratio, the more springy the gas is, the better it performs. For example the compression ratio at surface is:

$$CR_{\text{surf}} = \frac{P_{\max}}{P_{\min}} = \frac{5000 \text{ psi}}{3000 \text{ psi}} = 1.667$$

When the bottles are placed subsea, the pressure created from the water column from depth is additive to those pressures. Therefore the compression

ratio at a 12,000-ft water depth (5,350 psi pressure from water column) becomes:

$$CR_{12000ft} = \frac{5000 + 5350}{3000 + 5350} = \frac{10350psi}{8350psi} = 1.24$$

Therefore, the gas compresses less and more volume (bottles) must be added to compensate (Figure 2).

For the following condition, one 15-gallon, 6,000-psi nitrogen accumulator yields only half a gallon of usable volume.

- Discharge type = adiabatic.
- Surface pressure = 5,000 psi to 3,000 psi.
- Surface temperature = 120°F
- Subsea temperature = 40°F
- Water depth = 12,000 ft

For those same conditions but at a water depth of zero (at surface), the usable volume is 2 ½ gallons. Imagine being able to have accumulators perform subsea like they do at surface. That is exactly what has been accomplished with the depth compensated accumulator. Figure 3 shows how it works.

The system is comprised of a double piston accumulator, with the two pistons connected by a connecting rod. This configuration creates four distinct chambers in the accumulator.

The first chamber has a vacuum or very low pressure in it; the second chamber is exposed to sea water pressure. The sea water pressure (5,350 psi at 12,000 ft) acting on the piston, with the vacuum on the opposite side, creates a large force on the piston connecting rod. The third chamber has system hydraulic fluid, and it counters the sea water pressure by holding the same pressure (5,350 psi). Now add nitrogen in the fourth chamber, and it further adds to the third chamber's hydraulic pressure (5,000 psi), boosting the hydraulic pressure to 5,000 + 5,350 = 10,350 psi. The compression ratio for the nitrogen pressure in operation at 12,000 ft water depths is the same as it is at surface.

$$CR_{surf} = \frac{4000psi}{2400psi} = 1.667$$

So how does the depth-compensated accumulator perform relative to other industry solutions? Figure 4 shows how

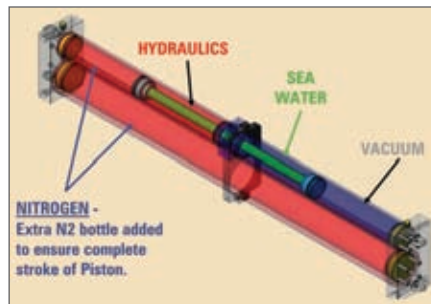
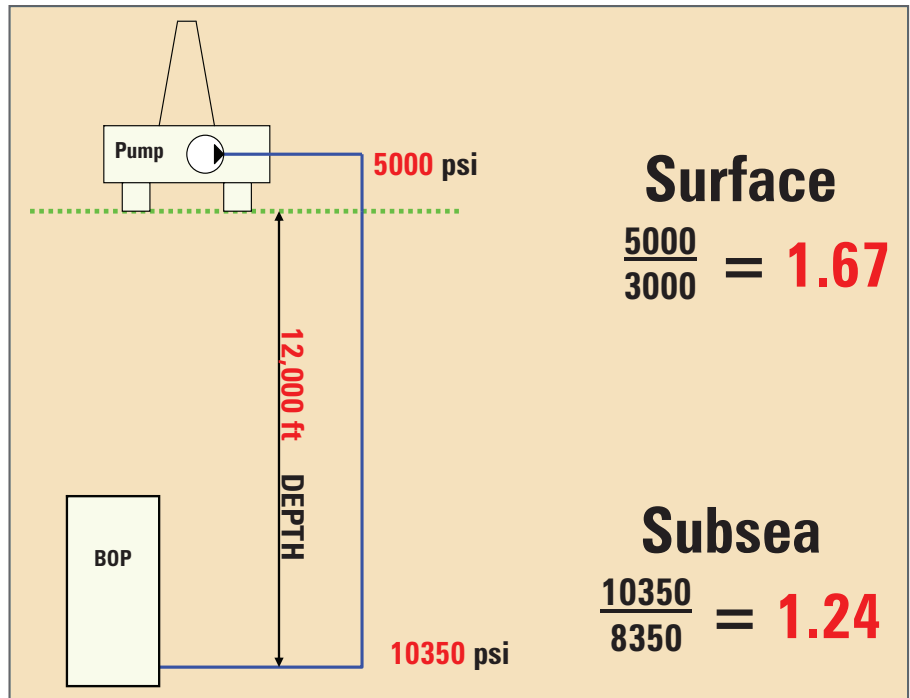
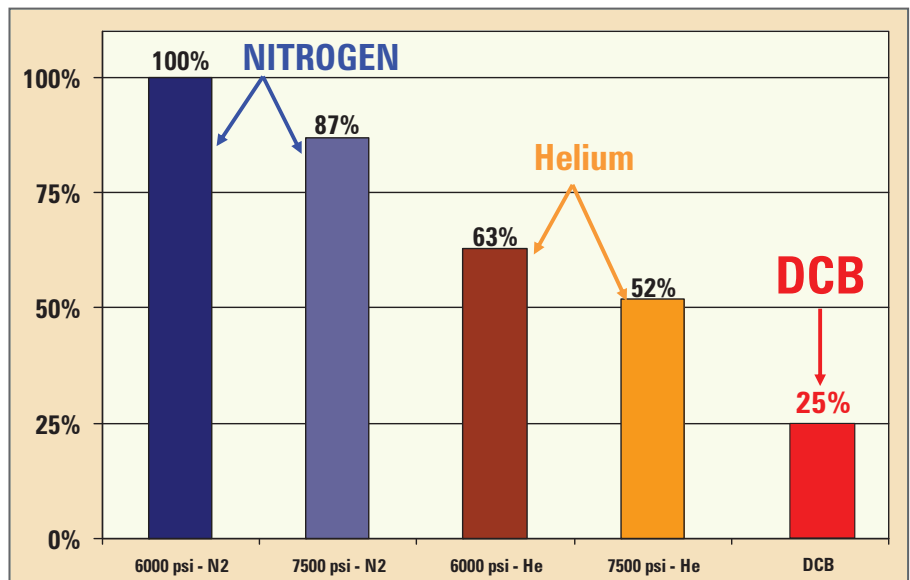


Figure 2 (above): Compression ratio measures the effect of water depth on gas performance, where deeper water equals a lower compression ratio.

Figure 3 (left) shows how a depth compensated accumulator works.

Figure 4 (below) compares the depth compensated accumulator with existing industry solutions.



nitrogen and helium perform with a 6,000-psi and 7,500-psi bladder or piston accumulator. Helium can only be used with piston accumulators, and the gas needs to be transported out to the rigs. Nitrogen is available on some rigs via a nitrogen generator and high-pressure compressors. Note the comparison is

in percentages, which shows how much gas is required for a particular function, regardless of volume of the function. As can be seen in Figure 4, the depth compensated accumulator is a major improvement over existing industry solutions.

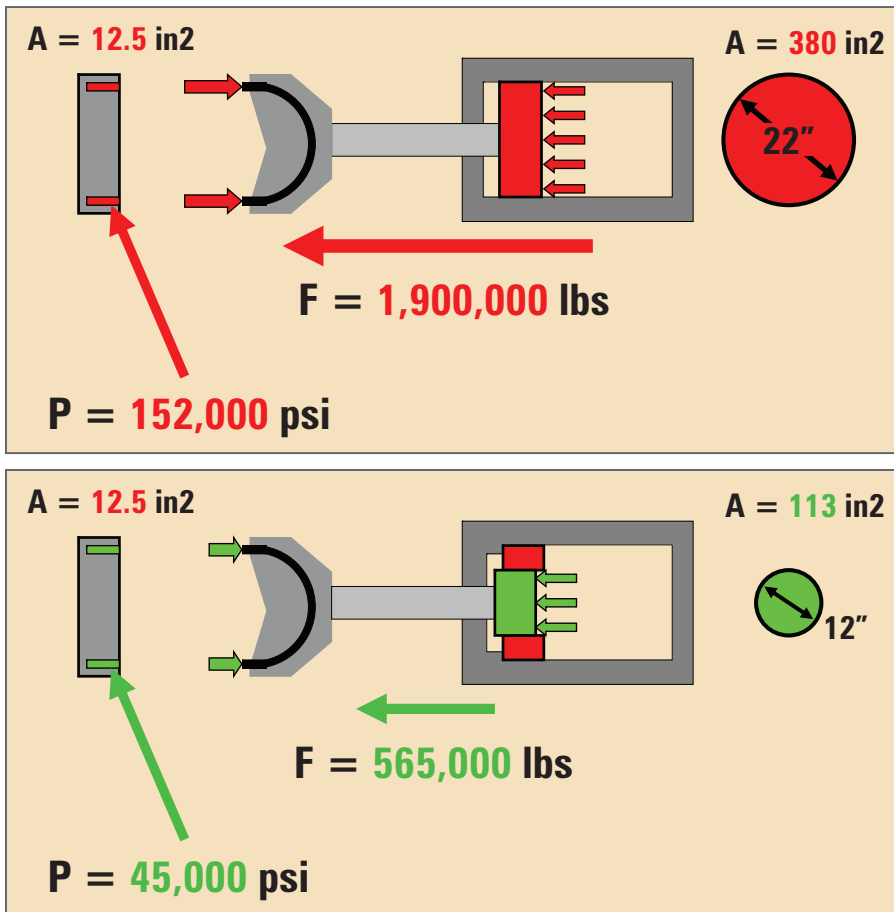


Figure 5 (top): Without the split piston, a potential rubber pressure of 152,000 psi is created. **Figure 6 (bottom):** By using an outer and inner piston, a much smaller rubber pressure of 45,000 psi is created.

22-IN. 5,000-PSI SHEAR OPERATORS

The more challenging drilling environments have required that drill pipe become stronger, tougher and heavier. Because of this, higher shear forces are required. Previous systems have been limited to 1.2 million lbs of shear force, whereas the next generation of BOP operator is capable of 1.9 million lbs. These shear rams have three basic features: high shear force, tail shaft lock and split piston.

HIGH SHEAR FORCE

Shear force is a function of cylinder size, tandem booster configurations, as well as hydraulic pressure capacity. The largest system manufactured in the past by **National Oilwell Varco** has been a 14-in. main piston with an 18-in. booster at a maximum pressure of 3,000 psi, which creates 1.2 million lbs of shear force. The next generation of BOP operator has a single piston 22 in. in diameter (approximately the same area as the 14x18 configuration, but shorter and

easier to manage) and is designed to use a maximum continuous system operating pressure of 5,000 psi, yielding a shear force of 1.9 million lbs.

TAIL SHAFT LOCK

Industry regulations require that an automatic lock be utilized that will maintain BOP integrity should there be a loss of hydraulic pressure. The 22-in. 5,000-psi shear operator has a tail shaft locking mechanism that is both simple yet robust. On the tailshaft of the operator, there is an upset (reduction in diameter) at the end of the tail shaft. When the shear operator closes nearly all the way, a series of radial locking dogs are exposed to the upset on the tail shaft. A secondary piston drives the lock dogs on to the tail shaft. Once the ram is all the way closed, the lock dogs are completely recessed on the tail shaft upset, and the secondary locking piston passes completely over the top of the lock dogs, preventing them from moving out radially again should hydraulic pressure be lost. (See Figure 5.)

SPLIT PISTON

Further to this system, there is an innovative split piston system integrated into the 22-in., 5,000-psi shear operator. In order to understand why this split piston design is required, first we must look at the force balance equation for the shear operator, as well as the shear rams with their associated seals. Once the tubular has been sheared, and the shear operators are nearly fully closed, the shear ram contacts the shear ram on the opposite side. There are rubber seals inside the shear ram blocks, which is what the rams react against. The area of rubber that makes contact is 12.5 sq in. Without the split piston, the entire force from the shear operator (1.9 million lb) is reacted on that area (Figure 5), creating a potential rubber pressure of:

$$P_{rubber} = \frac{380in^2 \times 5000psi}{12.5in^2} = \frac{1,900,000lbs}{12.5in^2} = 152,000psi$$

In order to alleviate this, there is an outer and inner piston. The outer piston has a diameter of 22 in., which is used through all of the stroke of the shear operator with the exception of the last ½ in. The inner piston has a diameter of 12 in., and it slides inside the outer piston during that last ½ in. of stroke. The force created by the inner piston is 565,000 lbs (Figure 6), which in turn creates a much smaller rubber pressure of 45,000 psi.

$$P_{rubber} = \frac{113in^2 \times 5000psi}{12.5in^2} = \frac{565,000lbs}{12.5in^2} = 45,000psi$$

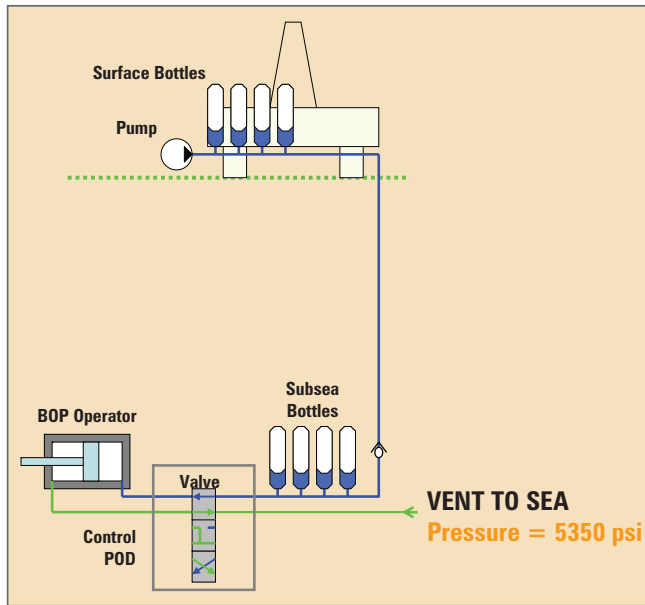
By reducing the rubber pressure, the rubber has less of a tendency to extrude which in turn increases rubber life. Lower rubber pressure also reduces the stresses on the shear ram blocks as it does not need to contain as much rubber pressure.

FLUID RECOVERY SYSTEM

Some area regulations require that the BOP control fluid be recovered for environmental reasons. Today's systems are designed such that the hydraulic fluid is water-based with additives to add some lubricity and anti-corrosion characteristics. In many areas of the world, this fluid is considered environmentally safe; therefore, when a BOP is operated, its exhaust fluid is dumped to the environment (sea). Figure 7 shows a basic layout for a conventional system.

An easy way to recover the fluid could be to run a return line to surface, wouldn't it? Unfortunately, this is not the case, as the high return flow rates create high

Figure 7 (right) shows the basic layout for a conventional fluid recovery system. Figure 8 (below, middle) shows that in a conventional system, high back pressure can cause other BOP functions to inadvertently close. Figure 9 (bottom) shows a fluid recovery system that can resolve this problem.



back pressures. The high back pressure can then cause other BOP functions to inadvertently close. This phenomena is created by the difference of area between open and close side of a BOP operator (area of close side > area of open side). The high back pressure acts on both those areas simultaneously, which then creates a net force closing the rams (Figure 8).

$$Force_{closing} = Area_{closing} \times Back.press - Area_{Opening} \times Back.press$$

This force can be as high as 60,000 lbs, plenty of force to close the BOP operator. The solution to this problem is to pump the fluids to surface with a complete fluid recovery system. The system design and its components can be seen in Figure 9.

PUMP

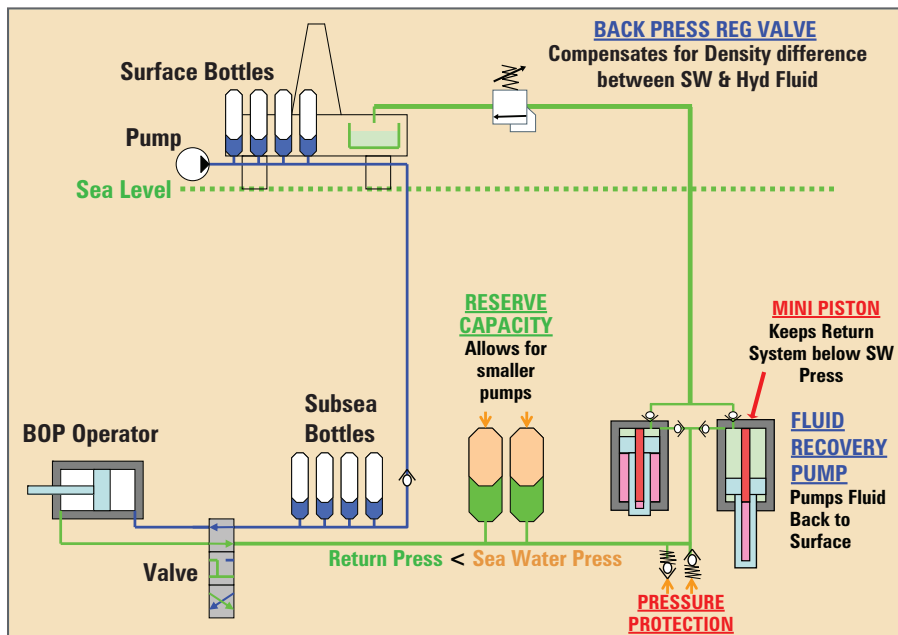
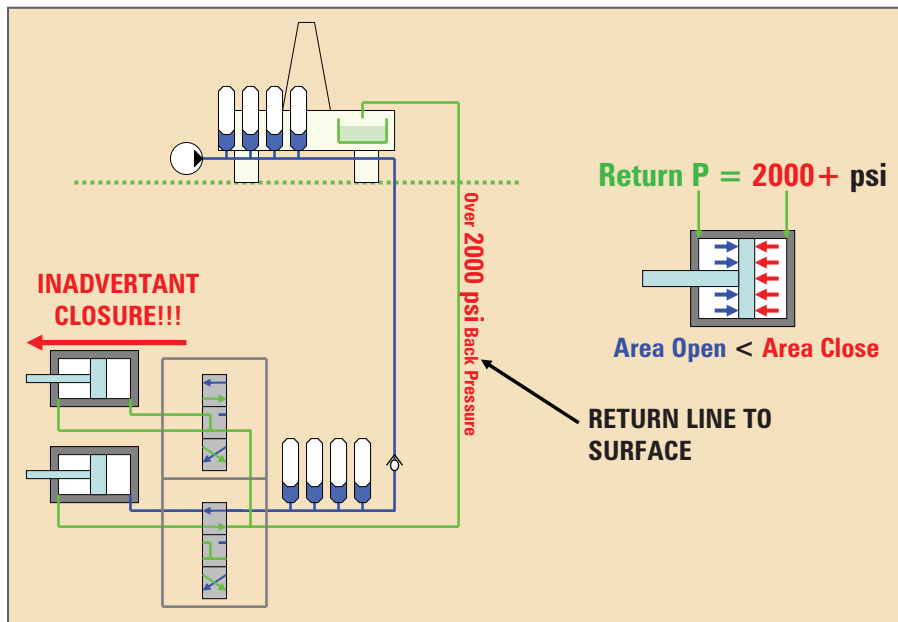
A reciprocating pump was designed to keep the system simple, easily powered by hydraulics and to use as much existing subsea technology as possible. The flow capacity and the ratio of hydraulic power section to discharge pumping section is a function of discharge pressure. Discharge pressure is a function of the length and diameter of the return tube and pump discharge flow. The piping used to pump the fluid to surface is one of the rigid conduit lines on the riser (12,000 ft and 2.32-in. inside diameter).

Some annular functions can see intermittent flows of up to 225 gallons/min, which equals a back pressure of up to 4,000 psi. A pump this size (225 gallons/min, 4,000 psi discharge pressure) would be exceedingly large and consume too much hydraulic fluid to pump it to surface. It was decided to design a more reasonable, smaller pump and add a reserve capacity. The decided ratio of the hydraulic section to the discharge section was 6:1, which yields a discharge pressure of 500 psi.

At 12,000-ft water depths, the flow capacity is approximately 60 gallons/min. Over- and underpressure protection was added to the returns line to ensure the integrity of the system when it is deployed or should the fluid recovery pump fail, the fluid is dumped to the environment and the BOP can still function in an emergency situation.

RESERVE CAPACITY

The reserve capacity serves two purposes. First, it provides a surge capacity for the high return flows from the BOPs when the return flow is greater than the



pump flow rate. Once the high return flow surge has ceased (the BOP has closed/opened), the pump can continue to pump out the reserve capacity. The second function equalizes the pressure between the environment (sea water) and hydraulic returns. By equalizing the pressure for the return fluids, the system acts the same as a system without the fluid recovery system. The reserve capacity is comprised of an 80-gallon bladder type accumulator. Hydraulic returns are fed into the steel side of the accumulator. Sea water is introduced into the bladder side of the accumulator, and the bladder is the barrier between the two.

MINI-PISTON

The challenge is to keep the hydraulic fluid evacuated from the reserve capacity bottle when the BOPs have been functioned. This is performed via an innovative mini-piston that keeps the hydraulic return side of the reserve capacity at a slightly lower pressure (up to 45 psi) than the sea water pressure. Figure 11 shows a cross section of the fluid recovery pump, where the mini piston is identified. It is simply a tube that always has system pressure on it. This tube and associated pressure forces the piston down creating a negative pressure on the return volume, as well as compensating for seal drag on the pistons of the pump.

BACK PRESSURE REGULATING VALVE

The density of sea water is heavier than that of the water-based hydraulic fluid. Although they are very close,

the difference in pressure at 12,000-ft water depths can be as high as 150 psi. Without a back pressure regulating valve, the under-pressure protection valve would open, allowing sea water to enter the return line until the pressures equalized. With the back pressure regulating valve located on the return line, this issue is resolved. The pressure setting of the back pressure regulating valve is set to the equivalent density difference between the fluids at depth.

PUMP CONTROLS

The hydraulic pump controls are simple, passive and use existing valve components. The MUX control system only needs to command when the fluid recovery system is to be turned on, the reciprocating motion of the pump is done via mechanical and pilot actuation of the valves on the pump, no discrete input/output is required for the reciprocating motion of the pumps. Once the reserve capacity is evacuated, the pump stalls and waits for another BOP function to be fired. The valves used are the same types of valves used on BOP control systems for the past 20 years.

SMART CONTROLS

Imagine a control system that knows it will fail before it fails. The more challenging reservoirs and higher burden rates require this level of diagnostics. Let's look at a basic overview of the control system to understand how this is possible (Figure 10).

On the vessel, at the surface, are redundant controllers, which communicate commands to the BOP via the MUX cable. Once the MUX cable reaches the

BOP stack, commands are received by the redundant control pods. In the pod are input / output bricks that convert those commands to signals to drive the solenoids or other field devices.

MUX CABLE MONITORING

The MUX cable is comprised of both fiber cores for communication, as well as copper cores to transmit power to the BOP. It is probably one of the most critical, complicated, robust and expensive cables on a rig today. Because of the critical nature of the cable, continuous monitoring has been implemented. The fiber signal strength can be measure by db of light signal, and the copper cores are measured by ground fault monitoring. The monitoring is then trended over time to see if there has been any degradation of any particular portion of the cable and can be rectified prior to loss of signal.

SYSTEM CHECK

Monitoring the MUX cable is only one part of the electrical controls for the BOP stack. To check the rest of the system, a complete system test is performed every 8 minutes. The system test checks the signal from the controller to the pod, through the output brick to the solenoid by sending a command for each solenoid to fire for 5 ms. This time isn't long enough to actuate the hydraulic valve, but it is long enough to confirm the integrity of all the system components. In the event that one of the redundant system components fails, an alarm is activated.

In conclusion, the next generation of BOP stacks and controls are smaller, by advent of an innovative depth compensated accumulator; stronger, by increasing the piston size and designed to continuously operate at 5,000 psi; cleaner, by way of a complete fluid recovery system; and smarter, by continuously monitoring MUX cables and doing frequent complete system checks.

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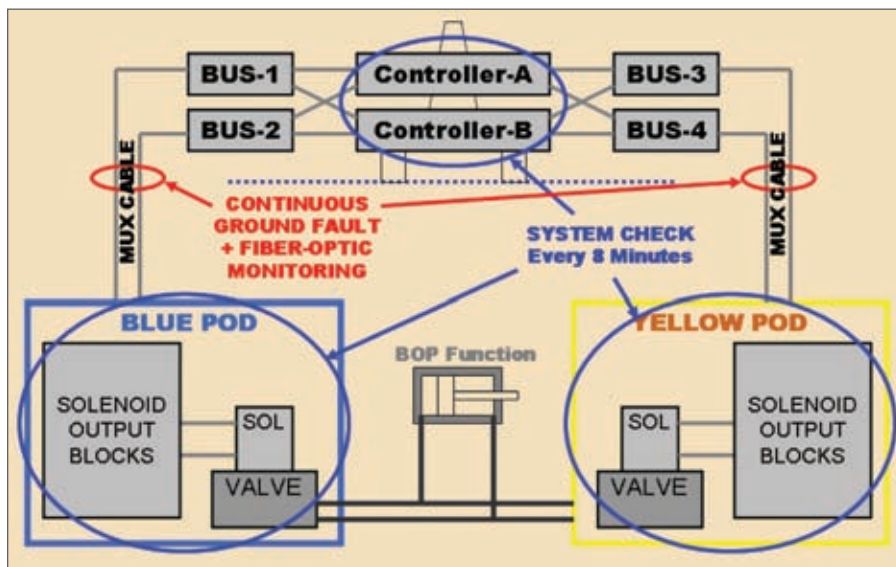


Figure 10: An overview of the subsea control system that provides high-level diagnostics.