Abstract

This paper describes the planning, logistics, and technology used in Cascade and Chinook, the two largest deepwater high-pressure perforation jobs successfully executed to date in the Gulf of Mexico (GoM). These Lower Tertiary well completions have gross perforation intervals over 800 feet and downhole pressures higher than 19,000 psi. This paper discusses the technology used in the planning stages to predict gunshock loads on completion equipment, and the logistics and procedures used to minimize costs, rig time and risks while maintaining safe operations.

Perforating several intervals in one run was required to complement a single-trip multi-zone frac-pack system in which all downhole packers, screens and service tools are run at once, and all zones are stimulated in a single trip. Perforating all intervals with long gunstrings and then frac packing multiple zones in a single trip saves substantial rig time compared with performing conventional stacked frac packed completions requiring multiple trips per perforated zone.

Thousands of perforating jobs are conducted successfully worldwide each month. However, there are a small number of jobs, typically high-pressure deepwater wells, where gun shock is a real and significant risk. When planning perforation jobs in deepwater high-pressure wells, engineers strive to minimize the risk of equipment damage due to perforating gunshock loads, such as bent tubing and unset packers, and a potential fishing job. For Cascade and Chinook, peak gunshock loads were evaluated with software that predicts the pressure waves in the completion fluid, and the associated structural loads on all well components. Fast gauge pressure data shows that predicted wellbore pressure transients are sufficiently accurate both in magnitude and time when the input reservoir response data is close to the actual field data.

We discuss in detail the logistics and procedures used for loading and transportation of guns, building the BHA, and running the gun string in the well. The logistics for mobilizing over 700 lbs of explosives requires extensive planning to minimize time and costs. Minimizing the time needed for each gun connection is crucial to minimize rig time, and several approaches were employed.

The logistics and procedures outlined in this paper led to a rig time reduction of over 67% for the execution of the largest deepwater high-pressure perforation jobs done to date in the Gulf of Mexico.

Introduction

Petrobras’ Cascade and Chinook deepwater development projects are located in Walker Ridge Blocks 250 and 469, respectively, in more than 8,000 feet of water depth, Figure 1 (Cunha et al. 2009). Wells were designed to have a cased hole, cemented and perforated with multiple frac-pack intervals. Conventional offshore stacked frac-pack jobs take several days of rig time per interval. GoM Lower Tertiary pay-zones require 3 to 6 frac-pack intervals; therefore using a conventional stacked frac-pack approach would be very costly. For this reason a single-trip multi-zone frac-pack technique was implemented; running all downhole packers, screens and service tools at once, with all zones stimulated in a single trip. This technique has been widely applied in the past on shallower, lower pressure wells (Davis et al. 2004 and Banman et al. 2008).

We have extensive experience perforating shorter pay zones of high-pressure wells in the GoM’s Lower Tertiary formation,
however, to date the Cascade and Chinook wells are the largest single-trip multi-zone frac-pack jobs done in the GoM’s Lower Tertiary play, requiring perforation of the entire pay-zones (net over 400 ft, gross over 800 ft) in a single run.

There were many challenges in planning, mobilizing, reviewing, and executing multi-zone perforating jobs at wellbore pressures higher than 19,000 psi and in water depths over 8,000 ft. We had to minimize the operational risks inherent to perforating multiple zones in a high pressure deepwater environment by using a simple and reliable approach built on previous experience of high pressure deepwater perforation jobs. Cost reduction is the main driver because of the very high daily cost of deep water operations. With a one way trip time of 18-24 hours, eliminating just one trip in the well would save up to USD $2,000,000. Perforating three or four zones at once multiplies the savings. The perforating runs on the Cascade and Chinook wells, from picking up the first gun to laying out the last gun, averaged 85 hours each. Three zones were perforated in each well. By eliminating two perforating runs per well, the time savings in runs was 372 hours, or 15.5 days of rig time.

Planning stages

Effective planning requires dedicated personnel from the beginning, and collaboration amongst many disciplines and groups, including the Operator, Service Provider and Regulators. The planning process begins several months in advanced of the actual job date, doing job-specific simulations and arranging for materials delivery and logistics. The quantity of perforating charges needed to perform this type of job (including back-up charges on location) was enormous. The logistics plan started with the maximum quantity of explosive allowed by permit in the explosives bunker, and in areas where guns are loaded and staged for transport. There are also time limits on how long explosives can be stored at a facility or while waiting for transportation when guns are loaded. Manufacturing of the gun carriers, intermediate adapters, expendables, o-rings, back-up rings, and charges also has to be carefully planned and coordinated with the loading facility.

Logistics from the base to the rig are also complex. Domestic transport of a large quantity of explosives can require State Police and Coast Guard approval and escort. Breaking up the shipment into manageable quantities simplifies the regulatory requirements, but requires constant supervision of the loads leaving the base and arriving at the dock to be transported to the offshore rig. The vessel must be loaded in a manner that segregates the explosives and keeps the loads in a lower US Department Of Transportation (DOT) hazard classification.

Planning for these jobs began with evaluating the casing design configuration to insure that the perforating BHA could be run in and retrieved from the well with no damage, and that the casing could withstand the pressure requirements of the perforating operations. Running casing tiebacks is a common practice in deepwater operations, and careful consideration should be given to the design of the seal assembly muleshoe outside and inside diameters to allow completion equipment to be pulled out of the well without catching a square shoulder or knife edge. Tieback seal assemblies typically are spaced out in a longer PBR. This creates a “gap” between the bottom of the PBR and the bottom of the tieback seal assembly of larger ID. This gap if long enough becomes a trap for completion tools, problems have been encountered where a retrievable packer was inadvertently set while tripping through this gap. To minimize these risks, operational procedures were modified to prevent premature setting of the retrievable packer; a centralizer was manufactured to be run in the spacer pipe below the packer to keep the perforating packer centralized in the well when passing through the tieback “gap”.

The next step in planning was the design of the perforating tool and gun string to perforate several intervals in one run with minimal damage to the tubulars and perforating equipment. We scrutinized the material of the guns and centralizers, fish-
ability of the guns in the event of sanding, survivability of the perforating packer and associated well control tools run in conjunction with the guns to control fluid losses, among other factors. The connections were upgraded, to the extent possible, to provide a more robust thread form. Detailed fishing plans for the BHA and contingencies were made. Methods for releasing stuck guns were reviewed and tested. Experience garnered from other high pressure deepwater wells (>17,000 psi) was used as the basis for the preliminary design and model.

The perforating tools used in these wells utilized a proven design and were able to handle the large perforating gun string detonation without damage to the integrity or functionality of the string prior to releasing the packer to POOH. The perforating string consisted of the following main components:

- A 25K psi dual valve (DV) (Figure 3) was used to control fluid losses via low pressure annular pulse commands. This DV tool has two full-bore multi-cycle valves—a tester valve (ball valve) and a circulating valve (sleeve type). Both valves can be cycled independently or in sequence by separate command pulses. A ball valve on the ID, to isolate the formation below (bottomhole shut-in), and a circulating valve located above the ball valve, controls flow between the ID and the annulus allowing the circulation of fluids while isolated from the formation to spot loss circulation pills, reverse out hydrocarbon influx, adjust fluid weight, or condition fluid prior to POOH (Healy et al. 1991).
A pump through safety valve served as a secondary means of downhole shut-in for a well control contingency. This tool allows the well to be shut-in and killed by bull heading fluid down the drill pipe but closes when drill pipe pressure exceeds annular pressure.

A hydraulic jar was included to aid in freeing the BHA if it were to become stuck. The hydraulic jar allows for an over pull above string weight of up to 70,000 lbs to be placed on the drill pipe before a short fast upstroke to hammer or “jar” the BHA in the event formation sand sloughs in around the guns or the packer would not release.

A 3 ½-in IF cut joint was placed above the packer as a secondary release mechanism. A through tubing explosive cutter was qualified to cut this pipe after passing through the 2.25-in internal diameter of the perforating tools.

A long-stroke retrievable packer (LSRP) (Figure 4) was used to isolate the annulus from the formation and to serve as an anchor point for the gun string. As the anchor point of the perforating BHA the packer takes the brunt of the mechanical and pressure wave force generated by the detonation of the perforating guns. The long-stroke packer allows the packer to be set without pipe rotation so surface equipment can be rigged up and tested before the packer is set without the need for a swivel below the flowhead. This allows for circulation of the well fluid if surface valves are mis-aligned or leak during pressure testing and does not apply any pressure to the firing head or guns, reducing the risk of inadvertent activation of the firing head and detonation of the perforating guns. This packer also allows for easy operation in highly deviated wells as there is no chance of trapping torque in the drill pipe due to excessive rotation at surface to work the torque down to the BHA as can be required in high hole angle wells to get any rotation on the bottom of the string. Minimizing the number of times the packer was fully set helped ensure that all tool functionality was maintained until fluid loss rate was determined and manageable.

Figure 4: Long-stroke retrievable packer

3 ½-in IF centralizer was included to keep the packer centralized in the casing through the tieback “gap”, minimizing the chance to catch a shoulder on the seal assembly muleshoe.

3 ½-in IF drill pipe was used below the packer to space the packer out above the gun string and increase the distance from the packer to the perforating guns. A larger volume below the perforating packer provides more volume for the pressure wave to diminish before affecting the packer.

A 3 ½-in IF long slot debris/circulating sub (LSDS) served to fill the tubing while running in the well, and to protect the firing head from debris.

Two shock absorbers (Figure 5) were used to reduce the shock transferred to the tubing and packer. A shock absorber is rigid as it is run in hole and remains rigid until the explosive train is initiated. At the instant the guns fire, the shock absorber is transformed into an active shock absorber. A crushable element absorbs shock from above and below the shock absorber, absorbing the energy of the shock by plastically deforming the crushable element. Shock absorbers are sealed and are run within the gun string between the firing head and guns.
A 25Kpsi TCP firing head (TCFH) which is activated by low pressure command pulses down the drill pipe. The explosive initiators are immune to radio frequency; no radio silence is required during make up of the gun string, or running into the well. There are no primary high explosives used in the firing head and activation pressures are input into the firing head at surface. The arming pressure prevents the firing head from being activated prior to achieving the arming window pressure, within 25% of BHP. After reaching the arming window the firing heads will arm one hour later and a very specific command sequence must be sent to activate the firing heads. Fast gauge data is recorded by the firing head and is activated by the firing command so that the pressure seen by the firing head for the first six seconds after detonation is recorded at a frequency of 1 kHz. This data is used to validate the preliminary gun shock models and verify the reservoir response after perforation (Taylor et al. 2001).

Operational details

With the perforating string design completed the focus turned to efficiently shipping, storing, handling and running the perforating assembly into the well. Shipping the large quantity of guns was accomplished through careful timing and coordination with all parties involved: the part suppliers to have sufficient stock on hand for a timely delivery, the gun loaders to assemble and store the guns, the shop and field personnel to package and load the guns and equipment onto the trucks for transport to the dock, the trucking company to ensure trucks were standing by and available immediately for transportation to the dock, the dock to have crane operators and crew available to load the vessel, a supervisor at the dock to assist the vessel captain, the vessel to be prepared to accept and space out the load, and the rig to have the space available to place the loaded baskets of perforating guns, tools and associated equipment needed to perform the jobs.
Several meetings were held to inform all parties of their roles and responsibilities. Getting a commitment from all parties to take an active role in performing their duties was critical. The smallest details were planned out and, whenever possible, contingency plans were in place. The service engineers performing the job made sure that the equipment was packed in the proper order so that picking up the equipment from the baskets would be sequential, and not require double handling any items. Making sure the rig crew was familiar with their responsibilities through CWOP’s (Complete Well On Paper) meetings, pre-job safety meetings and rig floor JSA’s (Job Safety Analysis), was instrumental in making up the long gun strings safely and efficiently without any down times.

Two separate rigs with different crews were both able to make up the 1399-ft Cascade and 1415-ft Chinook perforating bottom hole assemblies in less than 6 hours from picking up the first gun to making up the last tool. Making the tool string up into pre-torqued assemblies saved time on the critical path at the rotary. The assemblies utilized saver subs on top and bottom to allow the rig equipment to easily handle the make up of each and minimize time for each connection. Having each assembly pre-torqued in the shop with torque-turn equipment prior to shipping to the rig, provided a computer record of every break ensured proper make-up and eliminated the possibility of over-torqued service breaks.

A fit-for-purpose set of becket and bails was built to fit the rig elevators. The becket and bails were set up to handle every lift in the perforating BHA with a single change of elevators between the guns and the 3 ½-in IF spacer tubing and the remainder of the BHA. Rigging up the becket was as simple as latching the rig elevators on the lift sub of the becket which was the same size as the workstring, eliminating the need to change the rig elevator inserts. For future operations, new lift subs will be manufactured for the 7-in perforating guns that will fit the same elevators as the spacer pipe and the tools. This will allow for one set of elevators to handle the entire BHA.

Using a pneumatic torque wrench to install and remove the safety clamps on the BHA components was another time saver. Manually it takes an average of 1.5 minutes to install and 45 seconds to remove the clamp per connection, with a pneumatic wrench that can install the clamp and remove it in 10 seconds we saved considerable time on 40-50 connections in the BHA. With 100 connections per run, at just under 2 minutes per connection leads to saving 3 hours of rig time. Saving 45 minutes in connections by building assemblies and minimizing handling equipment changes, and efficiently organizing the equipment baskets to eliminate double handling of the guns and tools contributed to significant time savings in both perforating jobs.

In summary both TCP assemblies on Cascade and Chinook were transported, deployed, fired and recovered as per plan with no HSE or operational incidents. No damage was noted to the tools that impacted downhole functionality on either run, packer seal integrity was confirmed on both runs after the guns fired and until the packers were unset. When tools were pulled to surface on Cascade#4, we did observe two packer elements were torn and some minor damage to the slips.

The Cascade#4 and Chinook#4 perforating runs averaged 85 hours each, from picking up the first gun to laying out the last gun. An analysis of rig times and the associated costs (savings) for perforating Cascade#4 and Chinook#4 is presented in the following table:

| Average rig time and cost per run (as executed) | 85 hrs | USD $3,542,000 |
| Average time and cost per run without applying execution efficiency steps | 93 hrs | USD $3,875,000 |
| Time and cost savings per well perforating all zones in one run (saving two runs/well) | 186 hrs | USD $7,750,000 |
| Total time and cost savings for perforating Cascade#4 and Chinook#4 | 372 hrs | USD $15,500,000 |

The assemblies were deployed and recovered on average 8 hours faster than planned. With an average cost of deepwater rigs in the neighborhood of USD $1,000,000 per day, saving 8 hours per run in execution efficiency steps saves USD $333,000 per well. Three zones were perforated in each well. By eliminating two perforating runs per well, the total rig time saved was 372 hours, or 15.5 days of rig time, overall this represents a rig time reduction of over 67% for the execution of the largest deepwater high-pressure perforation jobs done to date in the Gulf of Mexico.

**Prediction and verification of perforating gunshock loads**

Thousands of perforating jobs are conducted successfully worldwide each month. However, there are a small number of jobs, typically high-pressure deepwater wells, where gun shock loads constitutes a significant risk. When planning perforation jobs in deepwater high-pressure wells, engineers strive to minimize the risk of equipment damage due to perforating gunshock loads, such as bent tubing and unset packers.
For Cascade and Chinook, peak gunshock loads were modeled and evaluated with software that predicts the pressure waves in the completion fluid after the guns detonate, and the associated structural loads on all well components. Herein, we have built upon a decade of experience with modeling wellbore pressure transients in perforation jobs and two decades of perforating research; this simulation model is based on first principles, solving the governing equations for conservation of mass, momentum, and energy. All relevant aspects of the well perforating event are modeled, including gun carrier filling after firing, wellbore pressure waves and associated fluid movement, wellbore fluid re-pressurization with reservoir flow and from tubing flow/debris subs, elastic deformation of tubing and guns, plastic deformation of shock absorbers, etc. A fully coupled fluid structure interaction strategy is used for this purpose (Baumann et al. 1999). The model that computes the transient pressure field in the wellbore fluid and guns, also computes the transient gun string deformation, velocity, acceleration, and stresses everywhere in all relevant structural components (Baumann et al. 2010a-b). This software has been validated by comparing wellbore pressure predictions with fast gauge data from a large number of perforating jobs, this validation is actually a never stopping process, we continue perfecting the simulation model by using fast gauge data from new perforating jobs as they arrive on a daily basis.

In this section we present a quick overview of wellbore dynamics and gunshock predictions for the Chinook #4 well, which was perforated after the Cascade#4 well. The fast gauge data from Cascade #4 was very useful to calibrate the actual reservoir response when wellbore and reservoir fluids interact after the perforation tunnels are created.

Chinook #4 is located in Walker Ridge block 469, has a gross perforation interval 25170-26000 ft, maximum deviation of 20 degrees, a temperature of 260 deg. F, and a 14.7 lb/gal Ca/Zn/Br completion brine. An overview of perforating requirements for sand control can be found in Venkitaraman et al. (2000). The perforating gun string was composed of thirteen gun spacers, twenty-five 7.00 HP HSD, and two 7.00 HP HSD Low Perforating Shock and Debris guns (LPSD), all guns were loaded with big hole charges at 18 spf.

The two LPSD guns had not been field tested and were run for testing at the bottom of the lowest interval. In high-pressure wells, LPSD guns produce much lower gunshock loads than standard guns. Another advantage of LPSD guns is a dramatic reduction of the shaped charge’s case debris normally produced by all HSD guns; this is because the cases remain practically intact inside the gun carriers. Therefore, when using LPSD guns the effort required to clean up perforating debris prior to running completion strings is much less.

Figure 8 shows a comparison between the actual gauge pressure at the electronic firing head and the predicted wellbore pressure at the same location (depth) in the wellbore completion fluid. Fast gauge pressure data shows that the predicted wellbore pressure transients are sufficiently accurate both in magnitude and time when the input reservoir data used is close to the actual field data. Part of the difference between measured and predicted wellbore pressure is due to the location of the fast gauge within the electronic firing head.

Figure 8: Comparison between predicted and actual pressure around the firing head

Figure 9a shows the wellbore pressure vs. depth at 1.56 sec after detonation, and Figure 9b shows the transient movement of the gun string bottom nose from the instant when guns are fired up to 1.56 sec. The wellbore pressure changes very rapidly during the first 500 ms, thereafter the wellbore pressure reaches an almost constant value along the wellbore as shown in Figure 9a at 1.56 sec. The maximum amplitude of the bottom nose movements is 23 inches, a relatively low value taking into
account the large length of drill pipe between the guns and the packer, but the large mass of the gun string and the high stiffness of the 3.5-in 13.3 lb/ft drill pipe helps reduce the peak gun string movement. The low frequency of the gun string overall movement is due to the large mass of the gun string.

Figure 10a shows the wellbore pressure vs. depth at 155 ms after detonation, and Figure 10b shows the time dependent change of force on the packer up to 155 ms. The performance of the gun string as run is in red, whereas the performance of a gun string with all LPSD guns is in green. The first peak load on the packer occurs soon after the pressure wave (generated by the guns) reflects on the packer and doubles in amplitude, this is similar to a water hammer effect.

Figure 11a shows the wellbore pressure vs. depth at 1.56 sec, and Figure 11b shows the time dependent change of force on the packer up to 1.56 sec. Figure 11b shows that the peak change in packer load is approximately 750 klbf as run, and it would have been only 460 klbf with a gun string of LPSD guns (green). This represents a large reduction in the peak packer load when LPSD guns are used.
Perforating several pay zones in one run was required to complement a single-trip multi-zone frac-pack system in which all downhole packers, screens and service tools are run at once, and all zones are stimulated in a single trip. Perforating all intervals with long gunstrings and then frac packing multiple zones in a single trip saved many days of rig time compared to performing conventional stacked frac packed completions requiring multiple trips per perforated zone.

The software model used to predict gun shock loads showed good correlation with actual measurements taken by the fast gauges deployed on the Chinook perforating run, thereby validating the model predictions.

Both perforation runs on Cascade and Chinook were successful by all measures. The operations were performed with zero HSE incidents. Tools were deployed, functioned successfully and recovered in better than planned time. Planning, logistics
and procedures outlined in this paper led to a rig time reduction of over 67% for the execution of the largest deepwater high-pressure perforation jobs done to date in the Gulf of Mexico.

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Nomenclature

- BHA: Bottom hole assembly
- BHP: Bottom hole pressure
- DV: Dual valve (marketed by Schlumberger as IRIS Intelligent Remote Implementation System Dual Valve, IRIS Dual Valve or IRDV)
- GOM: Gulf of Mexico
- HP: High pressure
- HSD: High shot density
- HSE: Health Safety Environment
- ID: Internal diameter
- LSDS: Long slot debris/circulating sub
- LSRP: Long stroke retrievable packer (marketed by Schlumberger as PosiTest retrievable compression packer)
- LPSD: Low perforating shock and debris (marketed by Schlumberger as INsidr perforating shock and debris reduction technology)
- PBR: Polished bore receptacle
- POOH: Pulling out of hole
- PTSV: Pump through safety valve
- RIH: Running in hole
- SPF: Shots per foot
- TCP: Tubing conveyed perforating
- TCFH: TCP firing head (marketed by Schlumberger as eFire-TCP electronic firing head for tubing conveyed deployment)

References


