Abstract

In this paper we describe the challenges and the techniques used to deliver zero perforation skin wells in the Blacktip gas field offshore Australia. We describe the software models used to evaluate both the well perforation design and the operational risks, and the approach used to reduce rig time. Software modelling based on historical experimental data and newly developed rock perforating models, showed that cleanup with dynamic underbalance would deliver the highest well productivity. Minimum rig time utilization was achieved with wireline conveyed guns. Two methods of deployment were used. To perforate long intervals quickly and safely guns were conveyed on wireline and anchored in the casing with a system that automatically dropped the entire string into the sump after firing. This technique requires less rig time, but it is only applicable to wells with a total gunstring weight lower than the wireline safe working load. The second technique for multiple spaced out payzones used conventional, multiple wireline trips.

All relevant aspects of the perforating jobs, including gun carrier filling after firing, wellbore pressure waves, reservoir flow, and perforation tunnel cleanup were predicted. For each job, guns were custom loaded so as to produce enough dynamic underbalance (DUB) to remove the low permeability crushed rock zone around perforations, thus minimizing perforation skin and maximizing well productivity.

The Blacktip wells were safely perforated for Eni Australia. In addition, we achieved the objective of zero perforation skin and saved more than one day of rig time. The technologies described in this paper can be applied worldwide, saving significant amounts of money and delivering highly productive wells.

Introduction

The Blacktip field is located in the Timor Sea, Australia, approximately 110 km offshore in the Bonaparte Basin, at a water depth of 50 meters.
Figure 1 illustrates the initial Blacktip project milestones: drilling of two development wells, installation of a wellhead platform (WHP), laying 108 km of offshore pipeline, and construction of an onshore gas plant. Production from the Blacktip field started in 2009. Gas is sent from the WHP to the onshore gas plant through 108 km of offshore pipeline. The gas is treated at the onshore gas plant and sent to Darwin via a pipeline operated by a third party.

Well perforating is a critical operation to any cased-hole completion. The objective is to create many holes or tunnels connecting the virgin reservoir rock to the wellbore that are clean with sufficient diameter and length for oil and or gas to flow unimpeded into the well. To achieve this, a good understanding of the perforation process is required. Well perforating with hollow-carrier guns begins with the detonation of shaped charges contained inside thick-walled tubes called gun carriers. The shaped charges detonate, perforate the casing, and create tunnels in the reservoir rock in less than 1/10 of a millisecond. In particular, within a few tens of a microsecond the shaped charges detonate and fluidized particles form a high-velocity jet that travels at speeds reaching 25,000 ft/s, creating a pressure wave that exerts in excess of 6 million psi on the casing and formation rock, and produces the perforation tunnel in the reservoir rock. However, the very completion of this event presents us with two main issues. Firstly, not only does this process produce a perforation tunnel, which is the very aim, but it also creates a layer of damaged reservoir rock surrounding the tunnel (crushed rock grains with low permeability; this is described below and shown in Figure 3). Secondly, the tunnel itself is usually filled with debris (pulverized rock and charge remnants) that can impair flow along the tunnel and block pore throats if completion fluids are injected into the reservoir.

Until a few years ago the preferred approach to clean up perforation tunnels was the use of static underbalance. However, this approach is impractical with wireline conveyed guns due to the risk of guns being blown-up uphole, and it may also be inadequate due to the limit on the amount of static underbalance available to cleanup perforations, see Bakker et al. (2003).

A large number of field tests and laboratory experiments reported by Behrmann et al. (1997), Walton et al. (2001), Behrmann et al. (2002), Bakker et al. (2003), Stutz and Bhermann (2004), Martin et al. (2005), Minto et al. (2005), Baxter et al. (2007), Baxter et al. (2009), Heiland et al. (2009), Filho et al. (2010), Busaidy et al. (2011), and Grove et al. (2011a,b) have been instrumental in understanding the parameters that control pressure waves in the wellbore during perforating events and their role in perforation damage removal. Thanks to the work done over the last decade it is now well known that perforation-induced pressure waves can produce very clean perforations with low skin damage in many types of reservoir rock.

A new perforation cleanup method named Dynamic Underbalance (DUB) was developed in the last decade. Bakker et al. (2003) and Baxter et al. (2009) illustrate the benefits of DUB with rock core samples as illustrated in Figure 2, wherein the DUB method removes most of the crushed (or damaged) rock around the tunnels walls and debris from inside the tunnels, and can be used with all gun conveyance types, including wireline conveyance. The DUB technique can be applied at an initial wellbore pressure (BHP) that can be underbalanced, balanced, or even overbalanced with respect to the undisturbed reservoir pressure. The amount of DUB (the underbalanced transient pressure that acts on the perforation tunnel) is optimized by designing perforating systems that take into account the properties of the reservoir, wellbore, gun size and perforating charges. The DUB technique produces maximum effective transient underbalance on the sand face to eliminate or minimize perforation damage. This novel technique has been successfully applied in oil and gas reservoirs, in hard- and soft-rock formations.

Figure 2: Perforation damage removal with DUB (top), underbalance (middle), and overbalance perforating (bottom)
Typical deep-penetrating charges produce perforations that extend beyond the drilling-induced formation damage. Figure 3 shows three distinct rock zones that exist after charge detonation: a perforation tunnel with loose rock and debris (top inset photograph), a damaged reservoir rock zone (highlighted in red) consisting of shattered matrix grains (bottom right inset photograph), and the rest being the virgin reservoir rock (top right inset photograph). Rock properties along a radial direction normal to the perforation tunnel axis are shown on the plot (bottom left), where rock strength (pink line), porosity (green line), and permeability (blue line), are all affected by the perforating jet’s interaction with the virgin rock. It is observed that permeability of the crushed rock immediately next to the tunnel wall is very low, and increases to the undamaged rock permeability value with increasing radial distance. Similarly, rock strength is lowest near the perforation surface and also increases to the virgin rock strength value with radial distance; whereas porosity is not significantly affected by the perforation damage, see Heiland et al. (2009).

The lefthand side of Figure 4 shows the difference in wellbore pressure vs. time between the initial static underbalance (orange) and the DUB approach (blue). In the latter approach the initial wellbore pressure is balanced with the formation pore pressure, and drops rapidly to a minimum wellbore pressure, creating a maximum DUB. With initial static
underbalance (orange) the pressure is initially well below the formation pore pressure, but rises rapidly due to the release of
gun detonation pressure, and then drops slowly creating an underbalance condition that in general is much smaller than the
minimum pressure attained with the DUB approach. The righthand side of Figure 4 illustrates the damaged rock removal
mechanism. The tensile stress wave produced by the DUB approach (blue) generates a much larger stress gradient in the
damaged reservoir rock zone which causes its breakup from the undamaged rock and subsequent removal from the tunnel due
to fluid suction. Consequently the tunnel size increases and the rock surrounding the perforation tunnel is not as damaged, or
not damaged at all. In the case of initial static underbalance (orange), the pressure wave produces a much smaller stress
gradient in the damaged reservoir rock zone, the force the amount of damaged rock removed from around the perforation
tunnel is much less, leaving a larger zone of damaged rock having lower ratio of crushed-zone permeability to formation permeability ($K_c/K$) still in place. A great amount of experimental data has confirmed that the DUB approach improves the ratio of crushed-zone permeability to formation permeability ($K_c/K$).

![Figure 4: Effect of lower perforation skin on a gas well production rate](image)

Figure 5: Effect of lower perforation skin on a gas well production rate

Figure 5 from Bakker et al. (2003) shows the effect of increasing the value of $K_c/K$ on the gas production rate of
wells in the Brady gas field of Wyoming. This plot shows the performance of wells that historically had perforation skin in
excess of +20, whereas similar wells perforated with the DUB approach yielded perforation skins less than -1 (stimulated),
which led to wells with much higher production rates under similar BHFP. See Stutz and Bhermann (2004).

**Prediction of Dynamic Underbalance and Perforation Damage Removal**

In the previous section we have described the well known benefits of DUB perforating, namely the dynamically
produced (post gun detonation) dynamic underbalance or wellbore pressure reduction and its role in rock perforation damage
removal. DUB is generated with guns specially designed for this purpose, namely, guns have special types of charges in
addition to the ones responsible for reservoir rock tunnel creation. These charges are called DUB charges and are used to
trigger ultra fast gun filling with wellbore fluid, thereby generating the large amplitude DUB environment that removes the
perforation rock damage. The DUB gun\(^1\) loading design is done with software tools that predict the magnitude and duration
of DUB or pressure reduction, and the perforation performance in terms of skin after damage removal and the well
productivity.

DUB is the result of the interaction between three main pressure sources: detonation gas pressure inside the guns,
wellbore fluid pressure around the guns, and formation pore pressure. To predict DUB we used a software tool herein
referred to as DUB Planner (DUBP); Baumann and Willimans (2009). This software tool predicts transient fluid-pressure
waves in the wellbores, guns, and reservoir. All the relevant aspects of perforating events are modeled, including gun filling
with wellbore fluid, pressure waves in the wellbores and the associated fluid flow along the wellbores, wellbore pressurization
and/or depressurization by the reservoir pore pressure and through tubing flow/debris subs, etc. Comparisons between fast-
gauge pressure data and DUBP predictions have shown that this software delivers accurate predictions. Usage of the DUBP
is described in Baumann and Williams (2009), and details on applications can be found in Baumann et al. (2010, 2011), Filho
et al. (2010), Busaidy et al. (2011).

To predict perforating performance we used a software tool herein referred to as Perforating Analysis Software
(PANS). Using PANS we optimized the well completion efficiency by comparing a variety of gun/charge configurations
under different reservoir conditions. PANS guided us thorough a logical path to the best perforation design. Casing, cement,
and formation information was combined with wellbore geometry and completion fluid characteristics. This information was matched with the gun system’s performance characteristics and positioning data to predict perforating performance under the specified conditions. Also using PANS users can match well parameters with available perforating gun systems to create a customized well development plan. PANS generates Penetration and Productivity Analysis reports for up to six perforating systems in a format that is easy to read and use. In calculating productivity, perforation skin is derived from state-of-the-art correlations. Sensitivity and Underbalance plots show the effect of productivity and charge performance as a function of one or more parameters. As part of the decision process, the system was used to model different combinations of formation, well, and perforating guns.

**Perforation of Development Wells**

In this section we discuss two strategies used to minimize rig time depending on the pay zones to be completed. The first approach uses guns supported by an automatic Monobore Anchor Release System (MARS) which is run in hole and set on wireline, whereas the second approach uses multiple wireline runs. Figure 6 (left) illustrates a single run with MARS: (1) Wireline RIH with MARS and Guns, (2) Guns are anchored and then wireline is POOH, (3) Well is completed and then perforated, (4) MARS with detonated guns automatically fall in rathole after firing. Figure 6 (right) illustrates multiple wireline runs (through completion) for non-contiguous reservoir zones (right): (1) Wireline RIH to perforate top zone, (2) Perforation on wireline and POOH, (3) Wireline RIH to perforate a lower zone, (4) Perforation on wireline and POOH. Subsequent runs were made until all pay zones were perforated. The use of wireline to convey the MARS and gunstring takes less rig time when compared with TCP jobs, but it is only applicable to wells with a total gunstring weight lower than the wireline safe working load. For multiple spaced out payzones, where a single gunstring would be too heavy for wireline conveyance, multiple wireline trips were used. These multiple wireline runs were made from top to bottom, to ensure that the liquid level was above subsequent deeper gun runs. The well was surged only after all 7 wireline runs were completed.

In both wells we used the perforating DUB technology described in the previous section to remove the crushed rock from around perforation tunnels, thus minimizing perforation skin and maximizing well productivity. However, due to the difference in gun conveyance method, fast-gauge data to verify the DUB being predicted was only available in the second well where multiple wireline gun runs were made. In the first well, where MARS was used to drop the gun assembly immediately after perforation, no such data was available. In both cases, we used 4-1/2” DUB guns loaded with deep-penetrating HMX charges. As described previously these guns are loaded with two types of charges; one for tunnel creation and the other for adequate DUB generation. These DUB charges trigger ultra fast gun filling, thereby generating the large amplitude DUB environment that removes perforation rock damage. Figure 7 and Figure 8 show the reservoir zone logs for the zones that were perforated with the first four wireline runs.
Figure 7: Wireline runs 1 and 2 – Reservoir zones – Logs

Figure 8: Wireline runs 3 and 4 – Reservoir zones - Logs

Figure 9: Wireline Run 2, fast-gauge pressure measurement vs. predicted DUB

Figure 10: Wireline Run 3, fast-gauge pressure measurement vs. predicted DUB
The DUB guns used were designed with software that predicts the magnitude and duration of DUB or pressure reduction, using job definition data, including completion fluid properties, wellbore and estimated reservoir pressure, gun type and loading, etc. With the job data defined we ran the simulation to predict the DUB magnitude and duration. Each one of the wireline runs had a fast-gauge recorder attached to the bottom of the gunstring. The fast-gauge recorders allowed us to verify the DUB magnitude and duration. Figure 9 and Figure 10 show comparisons of actual transient wellbore pressure (fast-gauge) with the DUBP software predictions. These comparisons serve as a verification of the software capabilities when the input data defined is sufficiently close to the actual field values.

Good predictions of DUB are needed in the design stages to determine if the DUB generated by the guns will be enough to remove the rock perforation damage. Both Figure 9 and Figure 10 show an ultra fast pressure decrease immediately after gun detonation because of the instantaneous opening of gun carrier surface to the surrounding higher pressure completion fluid. This produces a very fast pressure decrease right in front of the perforations, precisely where it is needed to produce good cleanup, this is a characteristic of the DUB technology. Other approaches to reduce wellbore pressure use surge chambers with valves which are not located right in front of the perforations and do not have sufficient cross sectional areas for adequate DUB creation right at the sand face. Technologies based on surge chambers with valves may be able to produce a good decrease of pressure on a nearby placed gauge, however because specially designed guns are not used, this pressure signal is not fully transmitted to the perforation tunnels. This is because standard guns allow the release of detonation gas from the gun carrier into the wellbore resulting in the prevalence of a compressible gas-liquid mixture in the wellbore which attenuates the DUB before it can reach the perforation tunnels to remove the damaged rock. Only DUB guns are capable of generating a very large DUB at the sand face right in front of the perforations, because not only are such guns designed to keep detonation gas from escaping into the wellbore, but also because DUB charges are placed all along DUB guns to allow the incompressible wellbore liquid to rapidly fill the gun carrier causing a dramatic drop in wellbore pressure.

Figure 11 shows a plot of perforation Darcy skin vs. shot density for the DUB gun system used for all runs. This plot was generated with PANS and shows that perforation skin decreases when the shot density increases. This is a well known fact but is presented to make a comparison with other gun systems that may have higher effective shot density (SPF), but that produce much larger perforation skins. This is illustrated in Figure 12 which shows a plot of perforation Darcy skin vs. Kc/K, also generated with PANS. The plot shows the perforating performance of two guns systems and the open-hole performance as reference. We see that even though the 4-1/2” HSD guns have a higher SPF, the perforating Darcy skin is close to +1.5, whereas the perforating Darcy skin of the 4-1/2” DUB gun is -0.6 due to the lower value of Kc/K.

![Figure 11: Perforation Darcy skin vs. Shot Density with DUB guns](image-url)
Figure 12: Perforation Darcy skin vs. Kc/K – Comparison between standard and DUB guns

Figure 13: Very low total and perforation skin values for the development wells perforated with DUB guns

Well tests performed after the perforation jobs indicated that the total skin for both wells was approximately 1.6. Figure 13 shows the total skin of the first exploration well which was perforated with standard guns, producing a total skin of value 5.0, and the total and perforation skins for the two development wells which were perforated with DUB guns, delivering wells with a total skin of value 1.6, confirming the prediction of perforating skins of value -0.6 or lower.

Conclusions

The Blacktip wells were safely perforated using DUB guns which are capable of generating a very large DUB at the sand face, right in front of the perforations were DUB is needed to remove most of the crushed reservoir rock and debris from inside the perforation tunnels. Not only did we achieve the objective of at most zero perforation skin, in fact estimates from well test indicate that the perforation skin value in each well was approximately -0.6 (negative), but we also saved more than one day of rig time. Planning of the perforation jobs included software modeling of perforating performance, DUB and cleanup, as these tasks are essential to guide the perforation design process in the selection of the best possible perforating solution for any given well. The DUB perforating technology used to perforate the Blacktip wells can be applied to a wide range of wells under different conditions, saving significant amounts of money and delivering highly productive wells.
Acknowledgements

The authors would like to thank Eni Australia and Schlumberger for allowing the publication of this paper and for setting high-technical standards for our work. In particular, we would like to thank Eni Australia for publishing field data information, Andy Martin and Larry Behrmann (Schlumberger) for reviewing this work, and Alex Moody-Stuart and Ram Shenoy (Schlumberger) for their support of perforating research activities.

Nomenclature

BHFP Bottom hole flowing pressure
BHP Bottom-hole pressure
DUB Dynamic Underbalance (marketed by Schlumberger under the name PURE)
DUBP Dynamic Underbalance Planner software (marketed by Schlumberger under the name PURE Planner)
HSD High shot density (also a mark of Schlumberger)
HMX High temperature explosive
Kc/K Crushed-zone permeability / formation permeability
MARS Monobore Anchor Release System (marketed by Schlumberger under the name MAXR)
PANS Perforating analysis software (marketed by Schlumberger under the name SPAN)
POOH Pulling out of hole
PURE Schlumberger PURE perforating for clean perforations
RIH Running in hole
SPF Shots per foot
TCP Tubing conveyed perforating
WHP Wellhead platform
WL Wireline

1 Marketed under the name PURE gun
2 Deep-penetrator marketed under the name PowerJet 4505
3 Marketed under the name PURE puncher

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