Abstract

A large number of well perforation jobs are conducted successfully worldwide each year. However, gunshock related damage poses a significant risk when perforating high-pressure wells. This paper presents gunshock studies done with a simulation tool specifically developed to predict perforating gunshock loads and the associated structural loads on the equipment. This simulation effort includes results from seventeen Tubing Conveyed Perforating (TCP) jobs on high-pressure deepwater wells, with pressures ranging from 13,800 psi to the highest pressure wells ever perforated in the Gulf of Mexico at 20,700 psi. The results show very good agreement between software predictions and actual field data.

When planning perforating operations in high-pressure wells, engineers strive to minimize the risk of equipment damage from perforating gunshock loads, such as bent tubing and damage to packers. The risk of equipment damage from perforating gunshock loads increases very rapidly as the bottomhole pressure increases beyond 15,000 psi. The simulation tool used to perform gunshock studies is fast and can reliably identify perforating jobs that have a high possibility of gunshock related damage. For those cases where the chance of gunshock damage is high, design changes can be implemented to reduce or eliminate those potential risks.

In this review, computational predictions are compared with high-speed pressure gauge data, with the residual deformation of shock absorbers, and with high speed acceleration data. Fast gauge pressure data shows that predicted wellbore pressure transients are sufficiently accurate in magnitude and time. Peak pressure amplitudes measured at the gauges are, on average, within 8 percent of the predicted values. Residual deformations of shock absorbers correlate favorably with predicted peak axial loads, and available fast gauge acceleration data shows that the asymptotic gunstring acceleration is well predicted, both in amplitude and frequency. The ability to identify and reduce risks in perforating operations is important because the value of deepwater wells is very high and rig time losses are costly. With the software tool presented in this paper, engineers can optimize high-pressure well perforation designs in order to minimize the likelihood of gunshock related damage and the associated rig time losses.

Introduction

Well perforating is a critical operation in cased-hole completions where it is necessary to create an appropriate casing hole size and reservoir rock tunnels with sufficient diameter, length, and deliverability for the well objectives. Additionally, minimal crushed rock damage and tunnel debris is desired without undesirable side effects such as large amounts of wellbore debris and gunshock damage to downhole equipment.

A large number of field tests and laboratory experiments conducted by Behrmann et al. (1997), Walton et al. (2001), and Baxter et al. (2009) have been instrumental in understanding the parameters that control pressure waves in the wellbore during perforating events. It is now well understood that perforation-induced pressure waves can produce very clean perforations with low skin damage in certain types of reservoir rock. However, under certain conditions typically found in high-pressure wells, the magnitude of the pressure waves can easily damage downhole electronics/monitoring equipment, can produce permanent deformation (corkscrewing) of tubing and damage to packers. Such pressure waves can also produce other undesirable effects, such as sanding in the guns.
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. The energy released by the explosive (e.g., HMX, HNS, RDX, etc) is converted into kinetic energy of the perforating jets, elasto-plastic deformation of the perforating gun hardware, and internal energy of the detonation gas. At the instant when the charges detonate, gun pressure is spatially non-uniform, with peak values much larger than the wellbore pressure. When the perforating jets puncture the hollow carrier wall, the detonation gas inside the gun interacts with the wellbore fluid; this is the onset of wellbore dynamics effects. Wellbore hydrodynamics is driven by the interaction between three main pressure sources: detonation gas pressure inside the guns, wellbore fluid pressure around the guns, and formation pore pressure. In the context of gunshock analysis, typical wellbore completion fluids have high density and very low compressibility. Therefore the pressure difference between the guns and the wellbore produces pressure waves in the wellbore fluid propagating radially and axially up and down the wellbore at the liquid's speed of sound. These pressure waves produce forces on all surfaces exposed to the wellbore fluid. Gunshock loads are produced by transient pressure changes in the guns and around all hardware exposed to changing fluid pressure.

To predict wellbore hydrodynamics and structural loads, we developed a software model that predicts transient fluid-pressure waves and structural-stress waves in the gunstring, packers, and on all important well components. All the relevant aspects of perforating events are modeled, including the gun filling with completion fluid, pressure waves in the wellbore and the associated fluid flow along the wellbore, wellbore pressurization and/or depressurization by the reservoir pore pressure and through tubing flow/debris subs, etc. The software evaluates the associated gunshock loads and the structural dynamics response of the completion tools which includes elastic-plastic deformation of tubing and guns, plastic deformation of crushable elements in shock absorbers, etc. The software uses a coupled fluid-structure interaction model that computes the dynamic loads on all components throughout the simulated time period. Perforating gunshock can produce different types of damage. Compressive and tensile loading on the tubing can produce plastic deformation, corkscrewed tubing joints due to helical buckling with plastic deformation, damage to packer seals and slips, etc.

The software used to simulate the transient pressure field in the wellbore fluid and guns simultaneously solves for the transient gunstring deformation, velocity, acceleration, and stresses everywhere in all relevant structural components. The foundations of the simulation technique used in this software are described in Baumann (1997), and Baumann and Oden (1999a, 1999b, 2000), and Baumann et al. (1999). This simulation technique is very robust and delivers accurate solutions. Other papers describing gunshock simulation can be found in Schatz et al. (2004), Zazovsky et al. (2007), Baumann et al. (2010a, 2010b), Canal et al. (2010), Sanders et al. (2011)), and Burman et al. (2011).

**Deepwater High-Pressure tubing-Conveyed Perforating (TCP)**

![Typical gunstring diagram for TCP jobs with 7.00-in guns](image)

In the following sections we analyze deepwater high-pressure TCP jobs executed several years ago with standard 7.00-in and 6-5/8-in high-pressure high-shot-density (HP HSD) guns (a typical gun string is shown in Fig. 1). These jobs were not executed with Low Perforating Shock and Debris (LPSD) guns which were not available at the time when these jobs were executed. LPSD guns were developed in 2009 to reduce both gunshock and debris in high-pressure wells.
Fig. 1 shows the shock absorbers used with 7.00-in and 6-5/8-in guns. Shock absorbers are used to reduce the shock transferred to the tubing and packer. Shock absorbers are placed in the string between the firing head and guns; they are rigid when running in the hole (RIH) and remain rigid until the firing head starts the detonation train at the top end of the detocord. The detonation cord shatters the trigger sections and the shock absorbers become active and they are able to absorb and mitigate dynamic loads. Crushable elements inside the shock absorbers absorb energy by deforming plastically; whereas a piston helps absorb peak loads and dissipates energy.

Fig. 2 shows the programmable TCP firing head (TCFH) that is activated by low-pressure pulses. The explosive initiators are immune to radio frequency signals; therefore, no radio silence is required during make up of the gun string, or while RIH. Activation pressure values 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, in general within 25 percent of bottomhole pressure (BHP). One hour after reaching the arming window, the firing heads will arm and a very specific command pressure sequence must be sent to activate the firing heads. Fast gauge data is recorded by the firing heads when they fire. This data has been used to validate the gun shock model and evaluate reservoir responses after perforation (Baumann et al. 2010a, 2010b; Sanders et al. 2011; Taylor et al. 2001).

A long-stroke retrievable packer (LSRP) (Fig. 3) isolates the annulus from the formation and serves as anchor point for the gun string. The LSRP is set without pipe rotation; therefore, 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 misaligned or leak during pressure testing without applying pressure to the firing head or guns. LSRPs allow operations in highly deviated wells as there is no torque trapped in the drillpipe by the surface rotation needed to set the packer.

The seventeen TCP jobs included in this study have bottom hole pressures ranging from 13,800 psi to the highest pressure wells ever perforated in the Gulf of Mexico at 20,700 psi. In this paper we refer to these perforation jobs with the generic names P1 through P17. In the following sections we analyze three perforation jobs in detail: P4, P5, and P9. The main parameters of these three jobs are summarized in Table 1:

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<td>72</td>
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Table 1: Main parameters for jobs P4, P5, and P9

Job P5 was selected because a number of tubing joints were bent. Of the three perforation jobs only P5 had a very short distance to PBTD (packer plug), however this was not the reason for the bent tubing problem, as many other jobs were executed with similar short distances to PBTD without any problems. The reason for the occurrence of larger gun shock forces in P5 was guns loading.
Perforation Job P4 - TCP job with 7.00-in guns at BHP 20,350 psi

The 7.00-in HP HSD guns were loaded with steel-case charges at 18 SPF (Shots Per Foot). The net interval perforated was 28 ft, gross 32 ft, with a distance from top shot to packer of 412 ft, and from bottom-shot to PBTD 72 ft. The initial hydrostatic wellbore pressure at the firing head was 20,350 psi with 14.5 ppg CaBr/ZnBr completion fluid.

The left plot of Fig. 4 shows pressure along the wellbore at a few instants after the beginning of the detonation train. The colors used to plot pressure vs. depth go from red to light blue to indicate increasing time. The red line represents a time when the guns start to fill with wellbore fluid; therefore the wellbore pressure around the guns has started to decrease. The orange line shows lower pressure around the guns but still the pressure at plugback total depth (PBTD) is the initial undisturbed pressure, and the wellbore pressure has not changed at all 50ft above the top shot. The next green line represents the wellbore pressure when the pressure wave moving downwards has reflected partially at the sump packer. Pressure at PBTD has decreased less than 2000 psi, and the pressure wave moving uphole has propagated approximately 100ft. The following lines show the reflection of the pressure wave at PBTD. When this reflection occurs, the differential pressure of the wave (amplitude) doubles, this is a well known physical phenomenon described in most books on acoustics and propagation of waves, see Lighthill (1978). The amplitude of the pressure wave traveling uphole does so with little change in amplitude until it reaches the packer, which is shown in Fig. 5.

Fig. 4: Wellbore pressure transient, tubing axial load, and total load on the packer up to 0.075 seconds for job P4

Fig. 5: Wellbore pressure transient, tubing axial load and total load on the packer up to 0.11 seconds for job P4
The actual axial force along the tubing and gunstring depends on the applied load and the inertia of the guns. The center plot of Fig. 4 shows the axial load above the guns. The changing line color helps to correlate the time with the pressure lines on the left plot. The maximum tension force on the gunstring occurs at approx 0.065 seconds, which is after the time when the maximum applied force on the gunstring occurs because of the inertia of the guns. The right plot of Fig. 4 shows the change in packer load. All the change in packer load shown is due to a change in tubing axial load, because the annulus pressure at the packer does not changed at all until 0.075 seconds. Also the tubing load at the packer starts to change after 0.03 seconds because of the finite speed of stress propagation along the tubing, which is simulated by the structural dynamics module.

Fig. 5 shows the period when the pressure wave reaches the packer and reflects. On the left plot the red line shows the pressure distribution when the pressure wave is reaching the packer. When the pressure wave reaches the packer it reflects and doubles in amplitude; this is shown by the sequence of orange and green lines. The time of this reflection frequently coincides with the time when the peak load on the packer occurs; this is seen on the rightmost plot, where the peak differential load on the packer reaches 750 kbf for a very brief period of time at around 0.09 seconds after detonation, the changes of color along the packer load line are useful to identify the pressure vs. depth lines on the leftmost plot.

Fig. 6: Comparison of actual fast-gauge pressure data (through debris sub) and simulated pressure for job P4

Fig. 7: Wellbore pressure at 0.39 seconds, tubing axial load, and total load on the packer up to 0.39 seconds for job P4

Fig. 6 shows in blue the fast-gauge pressure recorded by the firing head and in red the simulated wellbore pressure at the same measured depth as the firing head. The pressure recorded at the firing head is in fact tubing pressure, the pressure
signal travels through the debris sub, and downwards along a tortuous path before reaching the pressure gauge. Although measured and simulated pressures correspond to different points, one inside the tubing and the other on the wellbore, the simulated pressure is very close to the actual measured pressure, this is necessary to predict gunshock reliably, because a large part of the gunshock load is generated by the pressure field around the guns.

![Fig. 8: SXVA crushable force vs. deformation, and actual crushable elements from job P4](image)

Fig. 8 shows the instant when the peak compression force on the tubing occurs. The peak compression force acting on the crushable elements is approximately 70 klbf. As we are going to see in this case, very often the peak compression force can be verified by measuring the residual deformation of the SXVA’s crushable elements, this is only possible when the peak tension load on the SXVA’s is not much larger than the peak compression load.

Fig. 8 shows force vs. deformation for a crushable element of the type used in job P4. With a peak compression load of 70 klbf, the expected residual deformation of the crushable element is 2 inches. The picture on the right shows the actual crushable elements and a new non-deformed element. This picture shows that the average deformation of the crushable elements is approximately 2 inches, which verifies the good predictive capabilities of the software.

![Fig. 9: Wellbore pressure at 1.00 second, tubing axial load and total load on the packer up to 1.00 second for job P4](image)

In Fig. 9, the left plot shows wellbore pressure vs. depth at time 1.00 second, when most of the transient pressure waves have dissipated; only a pressure wave with large period and low amplitude remains. The center plot shows the history of tubing axial load, where we observe a peak compression load of 70 klbf at 0.39 seconds, whereas the peak tension load is approximately 90 klbf, the latter value is not the peak compression value on the crushable elements due to the piston force in the shock absorber, which justifies why we are able to evaluate the peak compression load on the tubing by measuring the residual deformation of the SXVA crushable elements. The rightmost plot shows the history of total differential load on the packer, the peak downwards force of 750 klbf only lasts for a very short time, thereafter the total load decreases very rapidly,
and at 1.00 second the total differential load on the packer is mostly due to the relative decrease in wellbore pressure.

This job was executed without any problems, and the fast-gauge pressure data along with the residual deformation of the SXVA’s crushable elements were very useful to verify the gunshock software.

Perforation Job P5 - TCP job with 7.00-in guns at BHP 19,750 psi

In this job a number of tubing joints were damaged, after POOH the tubing joints were rolled and it was observed that many were bent, this is an indication of plastic deformation on the tubing’s surface due to a large compression load that produced helical buckling and plastic deformation of the steel.

Job P5 used the same 7.00-in HP HSD gun system loaded with steel-case charges at 18 SPF as was used in P4. The net interval perforated was 68 ft, gross interval 76 ft, with a distance from top shot to packer of 450 ft, and from bottom-shot to packer-plug of 9 ft. The initial hydrostatic pressure at the firing head was 19,750 psi with 15.2 ppg CaBr/ZnBr brine.

Fig. 10: Wellbore pressure transient, tubing axial load, and total load on the packer up to 0.20 seconds for job P5

The left plot of Fig. 10 shows pressure along the wellbore at a few instants after the beginning of the detonation train. The colors used to plot pressure vs. depth go from red to light blue to indicate increasing time. The red line represents a time when the guns start to fill with wellbore fluid; thereby the wellbore pressure around the guns has started to decrease. The orange line shows an even lower pressure around the guns, the pressure at the packer plug is still relatively high and the wellbore pressure has not changed much 20 ft above the top shot. The next green line represents wellbore pressure when the pressure wave moving downwards has reflected at the packer plug, and the pressure wave moving uphole has propagated approximately 200 ft. The amplitude of the pressure wave generated by gun filling travels uphole with little change in amplitude until it reaches the packer, when the pressure wave reaches the packer it reflects and doubles in amplitude; this is shown by the sequence of green lines. The time of this reflection frequently coincides with the time when the peak load on the packer occurs; this is seen on the rightmost plot, where the peak differential load on the packer reaches 700 klbf for a brief period of time around 0.12 seconds after detonation, the color changes along the total packer load line are useful to approximately place the corresponding pressure vs. depth lines on the leftmost plot. The tubing axial load depends on the applied load and the inertia of the guns. The center plot of Fig. 10 shows the axial load on the tubing above the guns. The maximum tension force on the gunstring occurs at approximately 0.09 seconds, which is after the time when the maximum force on the gunstring occurs because of the inertia of the guns.

Fig. 11 shows in blue the pressure recorded by the firing head and in red the simulated wellbore pressure at the same measured depth as the firing head. As mentioned before, the pressure recorded at the firing head is tubing pressure, the pressure signal travels through the debris sub, and downwards along a tortuous path before reaching the pressure gauge. Although measured and simulated pressures correspond to different points, one inside the tubing and the other on the wellbore, the simulated pressure is very close to the actual measured pressure, this is a necessary condition to predict gunshock reliably, because a large part of the gunshock load is generated by the pressure field around the guns.
Fig. 12 shows the instant when the peak compression force on the tubing occurs. The software predicts a peak compression force acting on the crushable elements of approximately 120 klbf. This peak compression load is well above the minimum compression load needed to produce corkscrewing of tubing joints due to helical buckling and plastic deformation of the steel. This was actually the case when job P5 was executed; after POOH several tubing joints were bent.

Fig. 11: Comparison of actual fast-gauge pressure data (through debris sub) and simulated pressure for job P5

Fig. 12: Wellbore pressure at 0.24 seconds, tubing axial load and total load on the packer up to 0.24 seconds for job P5
As in case P4, the peak compression force can be verified by measuring the residual deformation of the SXVA’s crushable elements. Fig. 13 shows force vs. deformation for the crushable elements used in job P5. With a peak compression load of 120 klbf, the expected residual deformation of the crushable elements is 3.4 inches. The picture on the right shows the actual crushable elements and a new non-deformed element. The approximate deformation of the crushable elements is between 3.2 and 3.4 inches, once again this serves to verify the good predictive capabilities of the software.

In Fig. 14, the left plot shows wellbore pressure vs. depth at 1.00 second, when most of the transient pressure waves have dissipated. The center plot shows the history of tubing axial load, the peak compression load is 120 klbf, and the peak tension load is approximately 140 klbf, the latter value is not the peak compression value on the crushable elements due to the piston force in the shock absorber. The rightmost plot shows the history of differential total load on the packer, the peak downwards force of 700 klbf only lasts for a very short time, thereafter the total load decreases very rapidly, and at 1 second the differential total load on the packer is mostly due to the relative decrease in wellbore pressure with some oscillations due to the gunstring movement, which is visible in the middle plot.

Here we analyze job P9 where 6-5/8-in HSD guns were used with steel-case charges at 18-spf. In this job an IES gauge was run inside a gauge carrier, fast-gauge pressure and acceleration data is available for comparison with predictions. The net interval perforated was 126 ft with a distance from top shot to packer of 410 ft, and from bottom-shot to PBTD 56 ft. Initial hydrostatic wellbore pressure at the firing head was 14,080 psi with a 12.5 ppg CaBr completion fluid.
The plot on the left of Fig. 15 shows in green the pressure recorded by the IES gauge and in blue the simulated wellbore pressure at the same location as the IES gauge. The simulated pressure is very close to the actual measured pressure, and as indicated before, this is a necessary condition to predict gunshock reliably, because a large part of the gunshock load is generated by the pressure field around the guns. The plot on the right of Fig. 15 shows in green the asymptotic behavior of axial acceleration recorded by the IES gauge and in blue the simulated acceleration at the same location as the IES gauge. The latter comparison shows that the asymptotic tubing acceleration is well predicted, both in amplitude and frequency.

The plot on the left of Fig. 16 shows wellbore pressure vs. depth at 1.00 second, as seen in the previous examples, most of the transient pressure waves have dissipated. The center plot shows the history of tubing axial load, with a peak compression load of 60 klbf, and a peak tension load of 85 klbf. The rightmost plot shows the history of differential total load on the packer, the peak downwards force of 380 klbf only lasts for a very short time, thereafter the total load decreases very rapidly, and at 1 second the differential total load on the packer is mostly due to the relative decrease in wellbore pressure with some oscillations due to gunstring movement, which is visible in the middle plot. This job was executed without any problems, and the fast-gauge pressure data along with the acceleration data obtained in the job were very useful to verify the gunshock software.
Summary of Results

Table 2: Peak differences between initial wellbore pressure and transient pressure at the firing head

The gunshock simulation program developed and used in this study has been fine tuned with a large database of TCP jobs, among which are the highest bottomhole pressure jobs ever done in the GoM, with BHP of 20,700 psi, and the largest high-pressure net perforation length jobs, including single-run jobs with net pays larger than 300 ft.

Table 2 lists the peak differences between the initial wellbore pressure and the transient pressure at the firing head (known as the peak Dynamic UnderBalance - DUB) for each one of the 17 perforating jobs included in this study. Blue bars are the actual measured values, and red bars are the corresponding simulated values. After adjustment of the reservoir response to match the asymptotic wellbore pressure recovery, peak DUB values predicted by the software are on average within 8 percent of the actual values measured at the gauges. Most predictions are conservative, which helps increase the safety margins. Such an agreement between predictions and actual field data indicates that the software can reliably predict the wellbore dynamics of perforating jobs.

As indicated before, peak DUB values shown in Table 2 were obtained with standard guns; they were not obtained with Low Perforating Shock and Debris (LPSD) guns. LPSD guns are available since 2009; they are used to reduce both gunshock and debris in high-pressure wells.

Conclusions

Perforating high-pressure (HP) wells requires careful planning to prevent costly time and money losses. This paper described the latest advances in simulation software to predict perforating gunshock loads reliably. With the software described here we can evaluate the dependence or sensitivity of peak loads to key gunstring design parameters, and identify design changes that may be needed to reduce potentially unsafe loading conditions; thereby, minimizing the risk of fishing operations and the associated nonproductive times.

The simulation program developed can predict simultaneously transient fluid pressure waves and structural stress waves. All the relevant aspects of well perforating events are modeled, including gun filling after firing, transient wellbore pressure waves with the associated wellbore fluid movement, flow of fluids in and out of guns, reservoir rock and tubing, and dynamic deformation of gunstring components, including velocity and acceleration at every point along the gunstring length.

The effect of all relevant perforating design elements and dimensions can be analyzed, such as:

- Size and length of conveyance
- Type and number of shock absorbers
- Types and sizes of guns and shaped charges
- Guns loading strategy
- Wellbore fluid properties
- Reservoir pressure and properties
- Length of perforated interval
- Position of packers
- Rathole length
The end goal of the simulation program described is to minimize the risk of completion tools damage due to perforating gunshock loads; thus, reducing equipment costs and time losses. Key hardware and software technologies presented in this paper enabled the successful execution of many deepwater HP perforation jobs, among which are the highest bottomhole pressure jobs executed to date in the Gulf of Mexico.

Acknowledgements

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Nomenclature

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References


