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Techno-economic analysis of well perforating in the Brazilian pre-salt utilizing different guns conveyance methods

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To a mother and a father, who
provided flawless education to a resilient son.

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"Televisão não dá camisa para ninguém.”

Rosemary Muratore

RESUMO

ZULIANI, Paulo Celso Muratore. **Análise técnico-econômica do canhoneio de poços do pré-sal brasileiro utilizando diferentes métodos de condução do canhão**. 2023. Dissertação (Mestrado em Engenharia Mineral) – Escola Politécnica, Universidade de São Paulo, Santos, 2023.

A busca por novos reservatórios ao redor do mundo levou a indústria a explorar campos de petróleo em águas ultra profundas, como os vistos no pré-sal brasileiro. O custo diário das sondas de perfuração capazes de perfurar esses poços, aumentou consideravelmente e a necessidade de reduzir o tempo operacional se tornou o principal objetivo dos projetistas. Durante anos, devido à sua capacidade de suportar esforços mecânicos muito maiores do que o cabo de perfilagem e o “coiled tubing”, a coluna de perfuração foi a primeira escolha quando projetistas consideravam canhões de maiores diâmetros ou para canhoneio de zonas produtoras com longos intervalos. Em contrapartida, o canhoneio à coluna representa uma operação com um tempo operacional elevado. Em poços “offshore”, principalmente nos campos de águas ultra profundas, esse tempo operacional chegava facilmente à 72 horas, fazendo dessa operação um dos grandes responsáveis pelos altos custos da fase de construção do poço. Pressões hidrostática e de poros extremamente elevadas, peso dos canhões e o choque, causado pela explosão das cargas dentro do poço, foram alguns dos desafios que tiveram que ser ultrapassados pelo método de canhoneio a cabo. Utilizando dados históricos e simulações de casos reais, este trabalho almeja definir um limite técnico onde os benefícios do canhoneio à coluna são superados pela eficiência operacional do canhoneio a cabo de perfilagem. Uma profunda revisão bibliográfica explica como esse objetivo foi alcançado e quais tecnologias foram utilizadas para tal realização. A eficiência operacional dos dois métodos de condução é comparada, para o caso do pré-sal brasileiro, apontando como as operadoras podem reduzir os custos operacionais, selecionando o método mais eficiente baseado no tempo operacional para o canhoneio. Ao desenvolver e utilizar novas tecnologias, como cortadores de cabo como solução para pescaria de canhões, o canhoneio a cabo conseguiu atingir marcas antes inimagináveis como canhoneios de 42 metros, com canhões de alta densidade (12 SPF) de 7 polegadas, em uma única corrida, entrando de vez na disputa para ser o método preferido de condução de canhões no poço, para intervalos extensos. Os dados mostram que, devido a aspectos de segurança e operacionais, é recomendado limitar em 5 corridas o canhoneio a cabo, o que corresponderia à uma economia de aproximadamente USD 300,000 em tempo de sonda quando comparado à operação de TCP. Também é possível concluir que podemos usar o método de canhoneio a cabo para intervalos totais a serem canhoneados de até 210 m. Acima desse comprimento total, o método a cabo não é justificado devido aos maiores riscos operacionais em relação ao método à coluna.

Palavras-chave: Canhoneio de poços. *Wireline*. TCP. Canhoneio sobrebalanceado. *Underbalance* dinâmico. Reservatórios de carbonato.

ABSTRACT

ZULIANI, Paulo Celso Muratore. **Techno-economic analysis of well perforating in the Brazilian pre-salt utilizing different guns conveyance methods**. 2023. Dissertation (Master's in Science) – Polytechnic School, University of São Paulo, Santos, 2023.

The world's pursuit of new reservoirs led the industry to explore ultra-deepwater fields like the ones found in the Brazilian pre-salt. Rigs spread rates increased significantly and the need to reduce rig time became the main goal of the project managers. For years, due to the capability of supporting larger mechanical forces than the wireline cable and the coiled tubing, the drillpipe or TCP (Tubing-Conveyed Perforation) was the first choice for large gun sizes or perforating long payzones. However, the TCP is also a time-consuming operation. Especially for wells on ultra-deepwater fields, this operational time can easily reach 72 h, making this operation one of the biggest contributors to the elevated well construction costs. Extreme hydrostatic and pore pressures, gunstrings weight, and the powerful shock loads on cable caused by the large guns were challenges that had to be overcome by the wireline conveyance. By using historical data and real case simulations, this work aims to define a technical-economic limit where the benefits of the TCP method are surpassed by the cable efficiency. An extensive literature review explains how this achievement was possible and what technologies were used to achieve these large intervals. The operational efficiency for both conveyance methods, for the Brazilian pre-salt case, is compared and addresses how the operators can reduce operational costs by choosing the right technique based on the operation time. By developing new technologies such as cable cutters for stuck-gun scenarios, the wireline has reached unbelievable milestones of 42 m perforated interval per run using a 7 in and high shot density (12 SPF) gunstring, conveyed in a single run, and entered definitively into the dispute for the preferred perforating method. Data showed that it is recommended a limit of 5 runs for the wireline perforating job considering safety and operational aspects, which would correspond to USD 300,000 of economy on rig time when compared to a TCP job. Also, it can be concluded that it is possible to use the wireline method for up to 210 m payzones. Above this, the wireline conveyance method does not justify the risks of the operation against the money savings.

Keywords: Wellbore perforation. Wireline. TCP. Overbalance perforating. Dynamic underbalance. Carbonate reservoirs.

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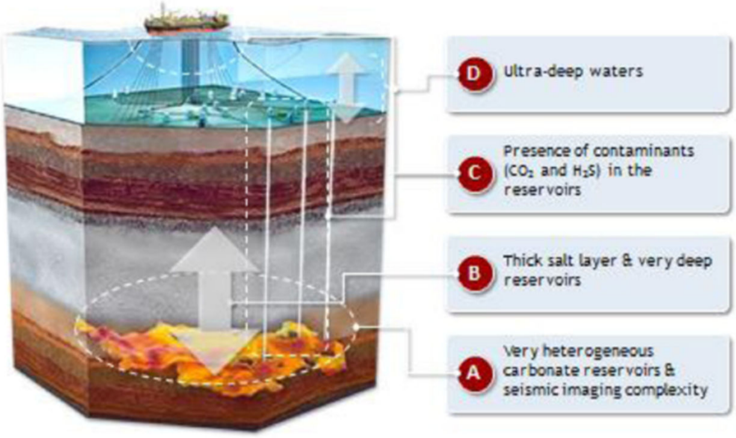
SUMMARY

1 INTRODUCTION

The discovery of the Brazilian pre-salt oil in 2006 (PINHEIRO et al., 2015) brought not only the expectation of enormous oil production but also a vast range of challenges to overcome to access these massive reservoirs. The complexity of the pre-salt basins forced the companies to invest a large sum of money and significant effort in research and development to be able to work in this demanding environment.

Located approximately 300 km from the Rio de Janeiro coast, in an ultradeepwater area, the scale of the Brazilian pre-salt region is impressive. The heterogeneous microbial carbonate reservoir is found below a salt layer that is thicker than 2,000 m in some places. To access the carbonate targets, well total depths vary from 5,000 m to 6,000 m in water depths that can reach up to 2,400 m below sea level (CAMPOS et al., 2017). The structure behind its exploration is as impressive as its costs. With drilling rig spread rates exceeding USD 1,000,000 a day (MOTTA et al., 2015), any saving on rig time is important to increase the return on investment. Figure 1, from Fraga et al. (2015), gives a visual outline of the mentioned challenges found in the development of the Brazilian pre-salt.

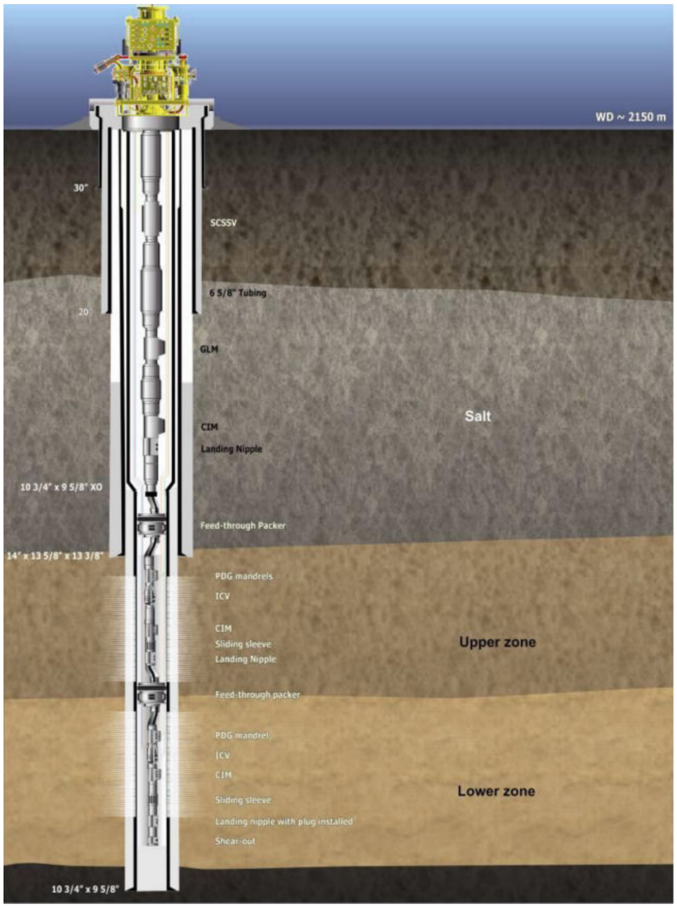
Figure 1– Visual representation of the Brazilian pre-salt challenges.



Source: FRAGA et al. (2015).

Completion lies among the several costs and time-consuming activities related to building a well and is one of the most important phases of the well life. Aiming to extract the maximum of each well and having to deal with high pressures, high productivity, and the likelihood of scaling, engineers designed the completion considering 9⅝ in and 9⅞ in production casings, as presented in Figure 2 (SCHNITZLER et al., 2015). The large casing allows the use of wider completion equipment but also requires the use of large perforating guns to maximize the penetration depth. It is well known that both penetration depth and entrance hole diameter are directly correlated with the gun positioning in reference to the target (BELLARBY, 2009; MCLEMORE, 1947). With that in mind, the service companies utilize large gun sizes to achieve the best performance when shooting. To connect the borehole to the reservoir, the engineers choose high-shot density guns with outer diameters (OD) of 7 in, loaded with 12 shots per foot (SPF). The use of these massive guns creates an operational challenge to the engineers, who must prepare the system for extremely heavy and long gunstrings and the shock that the detonation downhole causes. To perforate intervals that vary from 100 m to 500 m (SEDLACEK et al., 2020), the gunstrings can weigh close to 50 tons, considering a high-shot-density 6-m gun loaded with 12 SPF (SCHLUMBERGER, 2005).

Figure 2 – Typical well design in the Brazilian pre-salt.



Source: SCHNITZLER et al. (2015).

As stated by Hillier et al. (2019), the selection of the conveyance method for perforating guns depends on several factors, with length and weight being extremely important. Basically, there are four deployment techniques for the downhole perforating assemblies – tubing/drillpipe-conveyed perforation (TCP), wireline, coiled tubing (CT), and slickline – with each one fulfilling specific requirements, either technical or economical (BELLARBY, 2009).

As mentioned previously, the high operational costs of well construction in the Brazilian pre-salt made the engineers and designers to pursuit different ways to reduce operational time. Perforating the well can add a substantial number of hours to the completion phase and new solutions were

Until a few years ago, the TCP method was the only one suitable for heavy guns due to its mechanical tension capacity. However, technology advancements allowed the companies to challenge their limits when perforating on wireline cables. To make the two methods comparable, all the engineers needed to do was to reduce the number of wireline runs per job, which they did by increasing the capability of perforations per descent. The Brazilian challenge triggered a beneficial race among the companies for the longest 7 in gunstring in a single run. The operators have tested both TCP and wireline conveyance methods and have generated a vast database of efficiency, cost, and time metrics.

1.1 OBJECTIVES

The objective of this work is to evaluate the preferred perforating method for the Brazilian pre-salt by organizing the available operational data and then, analyzing the techno-economic aspects of each technique. The historical data will help to eliminate any doubts and confirm if the recent wireline proposal is efficient against the traditional TCP perforating.

1.1.1 Specific Objectives

Ultimately this work will set a threshold line indicating from which conditions the wireline conveyance method is an advantage over the TCP in this challenging environment.

The simulation will define the longest safe interval wireline can run utilizing the equipment present in the industry today.

This work will explain other aspects than time and costs. Very often the operators need to prioritize the decision based on operational challenges such as extreme overbalance, loss control, and simultaneous operations. Despite the discussion on these topics, the results will focus on the techno-economic analysis of both methods.

2 LITERATURE REVIEW

Perforating a well is considered a key operation in high-quality well completion. The perforating program needs to be designed aiming to the maximum well performance, considering the current well characteristics. This optimum well performance is, still today, measured by the Productivity Index (PI) of the well. The PI concept was first proposed by Moore (INAYAT-HUSSAIN; BUCKINGHAM, 1995), and is dependent on the reservoir fluids, the rock characteristics, and the system geometry (BAHRAMI et al., 2009; BELLARBY, 2009; ECONOMIDES et al., 2013; RENPU, 2011).

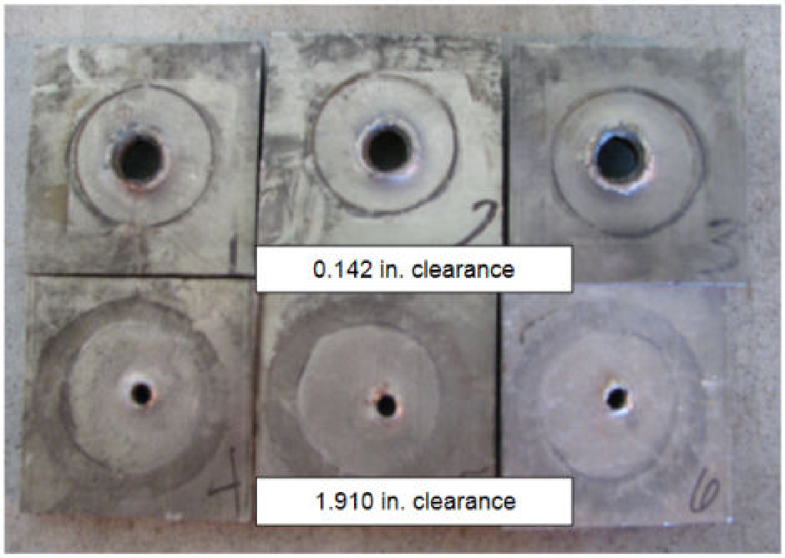
The objective of the perforation is the starting point when elaborating the strategy. The operator will determine if the well will be a producer or an injector, if the perforation is to enable fracturing hence the stimulation (FU et al., 2018; JHA et al., 2020), or if the well will flow from the channels derived from the jet perforation (SHAYKAMALOV et al., 2020). The perforating goal might just be to enable a cementing correction through a squeeze operation (COWAN, 2007; JOHANNESSEN et al., 2000) or pressure relief using shallow puncher charges (PANFEROV et al., 2016). In these last two cases, the objective is part of an intervention operation. In general, the objective of the perforation is well-known at the wellbore planning phase, when the operator decides to drill it (AWAD et al., 2018; JIN, 2019; LIU et al., 2014; LORWONGNGAM et al., 2020; WOOD et al., 2018).

After the objective is completely defined, other subjects need to be addressed to properly identify which perforating system and equipment will be used. Achieving the optimum PI during the perforation involves several variables as described by Markel et al. (2002). This information will be used to choose the conveyance method, gun size, pressure balance considerations, explosives and gun type, charge density, and perforating intervals. Apart from the guns and explosives, the characteristics of the formation, the wellbore behavior, and the completion type (RENPU, 2011) cover the rest of the data needed. Another important, but less common, factor to consider is the explosives security restriction some countries may impose (BELLARBY, 2009). Notwithstanding that explosives perforation has been used as the most efficient way to perforate, there are few places where dealing with or handling explosives is a complicated and time-consuming issue due to local regulations or security measurements. In this case, the operator can opt for a hydro jet perforating (KRITSANAPHAK et al., 2010) utilizing water or an abrasive fluid, a laser gun (BATARSEH et al., 2019), an exothermic reaction to perforate the liner (QAYYUM et al., 2009) or use the Plasma Pulse Technology to cleanup existent perforated intervals (PASHCHENKO; AGEEV, 2016). Although the last one is not a perforate technique in its essence, it was mentioned to show the path the industry is going to increase oil production by cleaning up already perforated tunnels.

2.1 THE PERFORATING SYSTEM

Pursuing the best production performance of the wells, the engineers plan the perforation system considering three basic parameters: perforation depth, shot density, and gun phasing (MARKEL et al., 2002). The first two are charges related while the last is gun carrier dependent. Both perforation depth and perforation diameter are directly correlated with the gun positioning in reference to the target (BELLARBY, 2009; MCLEMORE, 1947). As demonstrated by Quattlebaum et al. (2012), a reduction of 53% in the Casing Entrance Hole diameter is seen only by increasing the water clearance, which is the distance between the gun's outer diameter and its first target, from 0.142 in to 1.910 in. Figure 3 shows the mentioned Casing Entrance Hole diameter difference when shooting a 3⅛ in gun assembly inside a 5½ in casing.

Figure 3 – Casing Entrance Hole diameter variance for different clearances.



Source: QUATTLEBAUM et al. (2012).

Since the 1940s, it has been very well-known that the production performance of the well is strongly influenced by perforation (MUSKAT, 1943). Many authors like Allen and

Atterbury Jr. (1954), Hsia and Behrmann (1991), Grove et al. (2013), Grove et al. (2019), and Pucknell and Behrmann (1991) have presented different considerations on the mechanisms of the permeability reduction of the tunnels created by the explosives jet due to the crushed rocks. This positive or negative effect caused by the jet is known as the perforating skin factor. A considerably basic and simplistic way to demonstrate this behavior variation is using Darcy's Law to verify the permeability of the crushed zone.

API Recommended Practice 43, as a standard protocol, provides procedures to evaluate the performance of perforating equipment in the laboratory. To compare charge performances, API RP 43 is used to apply the Core Flow Efficiency (CFE), which expresses the ratio between the measured and theoretical (calculated) productivity, as shown by Equation 1. The theoretical productivity is acquired through a core rock perforation test in the laboratory. Hence, CFE is a conventional and simple way to measure perforation effectiveness. In 2001, the API RP 43 was fully replaced by the API RP 19B which has ruled the evaluation standards for well perforators since then (API, 2014; BAUMANN et al., 2014; BELLARBY, 2009; BRINSDEN, 2011).

$$\mathrm{CFE} = \frac{Q_{\mathrm{measured}}}{Q_{\mathrm{calculated}}} = \frac{k_p / k_o}{k_i / k_o} \tag{1}$$

Where:

$Q_{measured}$ = flow measured through the core after perforating;

$Q_{calculated}$ = flow through the core calculated considering an ideal perforated tunnel;

k_o = original target permeability measured before perforating;

k_p = crushed zone permeability measured after perforating;

k_i = effective permeability of the sample considering an ideal perforation of the same length of the perforated target.

The studies and modeling around the charge's performance have evolved tremendously. Different factors were piled up in the original Muskat (1943) study. For instance, the effect of the rock strength to predict the penetration is not applicable in the API RP43 Section 2 tests but is considered in Section 4 (API, 2014). However, the API procedures do consider a remarkably important factor utilized to improve the performance; the tunnel cleans up. Such fact leads to another relevant operational decision the reservoir engineers need to take when choosing the correct strategy, which is explained in the following.

2.1.1 Overbalance or underbalance perforating

Hsia and Behrmann's (1991) work has proved that the perforating skin is dependent on the underbalance pressure and rock permeability. The mentioned work shows that zero or even negative perforation damage skin can be achieved by regulating the static underbalance during the perforation. The backflow, created due to the differential pressure between the reservoir (higher pressure) and the borehole (lower pressure), pushes the crushed debris out of the perforated tunnels, cleaning it up and improving the crushed zone permeability. The considerably basic idea behind the debris cleanup is just to improve the k_p/k_o ratio on the CFE calculation (Equation 1).

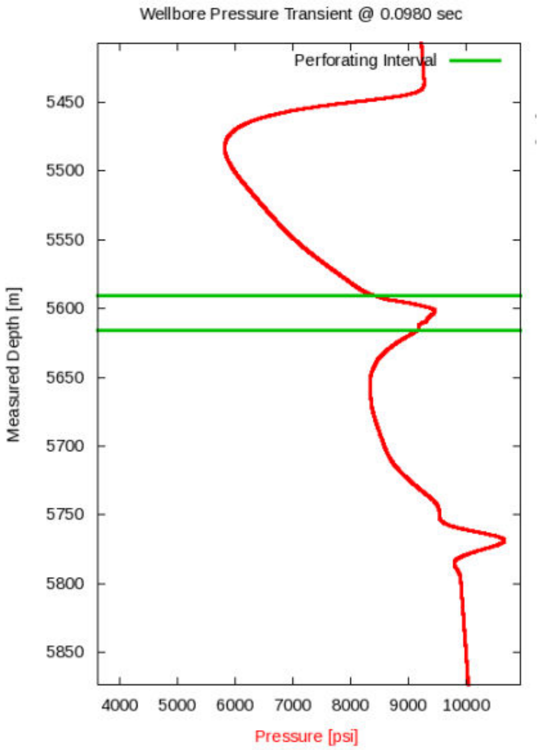
For shooting a well, choosing the best balance condition is not just a production performance decision. Commonly, engineers have technical and economic challenges that prevent the use of the best technique. For example, on recently drilled wells, an overbalance tubing-conveyed perforating (TCP) scenario is commonly chosen due to the presence of the drilling rig at the location. This condition allows the operators to maneuver the pipes using them as a conveyance for the guns. This method is utilized due to the capability of perforating long pay zones in a single run combined with a test string. This test string permits the well to flow after the tunnels are created (RENPU, 2011). In addition to the Formation Testing capability, the mechanical strength of the tubing will ensure the integrity of the system when it is submitted to the high forces of the gun blast. The shock caused by the detonation of these extensive gun strings might break a wireline cable or bend a coiled tubing if the job is not carefully planned (BAUMANN et al., 2013). In the TCP technique mentioned, the overbalance is achieved by keeping the drilling or completion fluid in the wellbore. The chosen fluid needs to have a density high enough to create sufficient hydrostatic pressure to prevent the reservoir fluid from flowing up when the guns are detonated.

On the other hand, an underbalance technique can be easily applied when a well has been already perforated and is already flowing or producing. The operator might want to re-perforate or open a new interval to increase production. In this scenario, killing the well by adding a denser fluid in the wellbore can compromise the return to production after the intervention. In such cases, the wellhead pressure is held by a pressure control equipment and gun carriers can be run in the well on wireline or coiled tubing conveyance. When the interval is shot the differential pressure, in this case, the pore pressure is greater than the hydrostatic pressure in the wellbore, induces a flow back that cleans up the created tunnels.

Also, a combination of both underbalance and overbalance perforating can be achieved and has been proven to deliver outstanding results (CHADHA et al., 2011). When perforating a well, originally overbalance or near balance, the instant wellbore pressure drops, due to the completion fluid displacement to fill the empty spaces in the gun carriers, generating an instantaneous differential pressure known as Dynamic Underbalance. This Dynamic Underbalance (DUB) can be seen in a noticeably short period – in the order of milliseconds – and produces a better cleanup, as explained and presented by Martin et al. (2005). The authors compared wells perforated on the North Sea. Their work provided clear examples of enhanced production by choosing the DUB technique. A 15% increment in production, when compared to conventional perforating, is presented during the study. The comparison was possible thanks to sophisticated simulations run in the Schlumberger Perforating Analysis (SPAN) program. Modern computer algorithms can also predict the drop in hydrostatic pressure and its transient behavior during the perforating. The operation can be designed based on the model provided by the simulation software, like the one seen in Figure 4. It considers variables like gun size, length, and shot density when predicting the DUB during the detonation.

Sensors and measurement devices are being added to the guns. By now, it is possible to have real-time information, before available only with further runs. Fast gauges combined with pressure and temperature sensors will provide the details of the perforated zone response right after the detonation (GUEDES et al., 2019). The comparison between the simulated and the actual values can be done while still pulling the gun out of the hole (BAUMANN et al. 2013).

Figure 4 – Example of simulated transient wellbore pressure on DUB perforating.



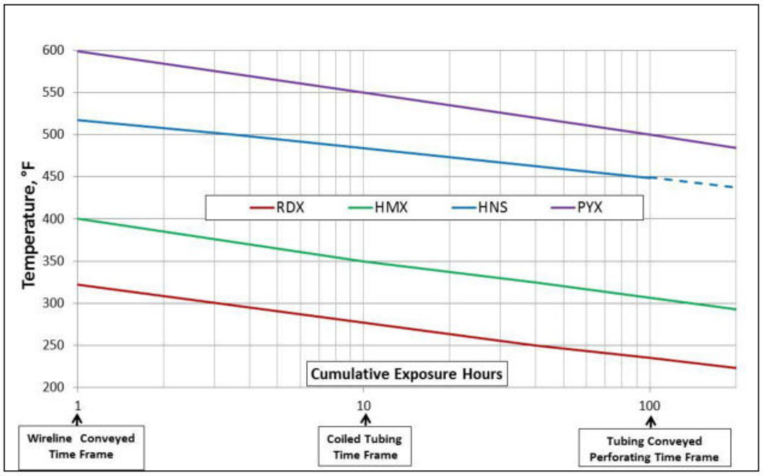
Source: ZULIANI et al. (2016).

2.1.2 Perforating and the well temperature

The wellbore temperature is a key factor that must be accounted for in the perforation design. The thermal stability and decomposition of the explosives are relevant variables in the process of choosing the charges to be employed in the guns (BELLARBY, 2009; RENPU, 2011). The thermal stability is compromised due to the polymorphism of the energetic material. Polymorphism is the ability of the same chemical substance to exist in different crystalline forms. Against external stimulation factors, such as temperature and pressure, the high-energy components of the most used explosives in the industry can change their characteristics (BERNSTEIN, 2020). Barker (2013) shows clear pictures of the different solid phases of PYX ($C_{17}H_7N_{11}O_{16}$) powder crystals. The transition between the solid-solid phases of the HMX ($C_4H_8N_8O_8$) explosives, for example, will change drastically the sensitivity to impact (AYRE; BARKER, 2017), that some armies in the world only allow the use of the explosives when in the most stable form.

Explosives are employed in the oil and gas industry to support a wide range of components. There are explosives in the charges, detonating cords, primary detonators, boosters, pipe cutters and severing tools, ignitors, powder charges, etc. Then, four types of explosives most applied are RDX (Cyclotrimethylene Trinitramine), HMX (Cyclotetramethylene Trinitramine), HNS (Hexanitrosilbene), and PYX (Bis Dinotropyridine) (BELLARBY, 2009). The details of the effect of the thermal decomposition in the above explosives and how the consequences of this stability change are linked to explosive type, among other variables (BOOCK et al.,2015). The thermal limitations are dependent on the exposure time. The chart represented in Figure 5 shows the relation between the exposure time and temperature for each of the four types of explosives mentioned.

Figure 5 – Temperature stability of perforating explosives and approximate deployment times



Source: HAGGERTY; CHRISTIE (2015)

The time-temperature relation must be analyzed carefully. If the perforating job is expected to last long hours, due to any operation challenge, the right explosive type must be chosen to avoid stability change that could lead to safety, environmental and economic risks (BOOCK et al.,2015). For instance, a TCP operation in a well with temperatures close to 300°F is within the limits of HMX charges but it is not satisfactory for RDX. According to Figure 5, the RDX explosives would keep their stability up to 5 h at 300°F, which is usually not enough for a Tubing Conveyance Perforation operation (HAGGERTY; CHRISTIE, 2015). Besides the operational efficiency of perforation and risk mitigation, the production performance may decrease due to the choice of the explosives type. Table 1 exhibits the difference in the performance of a charge from the same manufacturer and gun size but with different explosive types. The data was obtained from the Registered Data Sheet Perforating System Evaluation, API RP 19B Section 1, and it is used by the different manufacturers as a comparison of the performance of their charges. The difference in penetration performance is not only clearly seen from the API tests, but it is also evident in the production results as stated in Barker (2013), Barker and Davidson (2016), and Boock et al. (2015) works. Reductions of 20% to 34% in the well production performance were reported when selecting HNS charges to replace HMX due to increased downhole temperature exposure time.

Table 1 – API RP 19B Section 1 – Registered Data Sheet Perforating System Evaluation for Power Jet Omega 2906 charges

Explosive Type	**Gun OD (in)**	**Casing Hole Diameter (in)**	**Penetration (in)**
RDX	2.88	0.38	34.4
HMX	2.88	0.34	36.0
HNS	2.88	0.31	24.3

Source: API (2014).

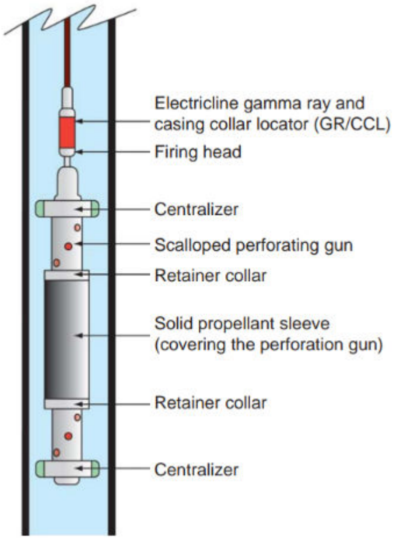
The explosive exposure time to the wellbore temperature will be determined by how efficient the service company can be to perform the operation. A normal perforating job consists in run in hole the guns, depth correlate to tie in the interval to be perforated to the open hole log and fire the charges (RENPU, 2011). Different conveyance systems will have different time frames for the above sequence to be completed. This time will be a key factor, both technically and economically, when choosing what type of gun deployment method, the operator will use.

2.2 CONVEYANCE METHODS

Nowadays, choosing the conveyance method is not as straightforward as it used to be in the past (ZAHMUWL et al., 2019). The improvement of the tension models, perforating techniques, and equipment used by the service companies are giving operators a relevant challenge to solve – which conveyance method to use? Although the conveyance methods are basically four – Tubing/Drillpipe-Conveyed Perforation, Wireline, Slickline, and Coiled Tubing – their individual capability is getting wider every day (BELLARBY, 2009).

The wireline method uses a cable to convey the guns and logging tools from surface to downhole, as presented in the Figure 6. The cable is moved by a winch connected and controlled by a logging unit at the surface. The operators drive the winch to conduct the guns to the desired depth and an electrical signal is transmitted from the surface systems to the electrical detonator installed in the guns. The triggering signal travels through the conductors in the inner part of the wireline cable.

Figure 6 – Scalloped Perforating Gun conveyed by wireline cable.

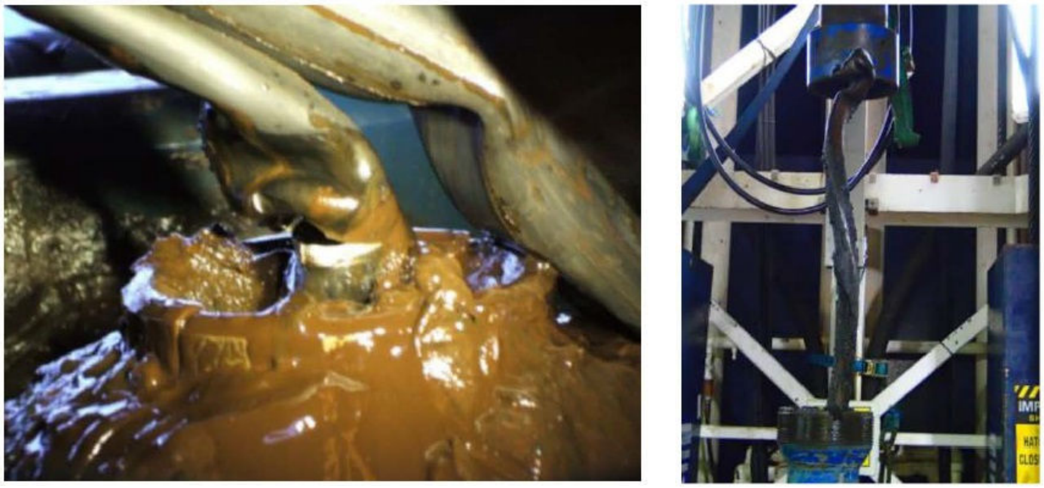


Source: BELLARBY. (2009).

The companies claim extensive perforating intervals can now be done on wireline without compromising operational efficiency (HILLIER et al., 2019). There are examples of 30 m strings of 7 in HSD (High Shot Density) guns being fired on a single descent in ultradeepwater wells in the Brazilian pre-salt (ZULIANI et al., 2016). In the past, TCP perforation would be the only option for long and heavy gun strings as above mentioned. The improvement in the ability to predict the shock downhole, combined with stronger and torque-free cables in addition to more robust weak points, allowed the change in this old concept.

The capability of predicting the downhole shock during the designing phase has also granted coiled tubing operations more confidence for long perforating intervals, and depleted, or high permeability formations. The effect on the coiled tubing can be estimated and gun lengths or perforating techniques adjusted accordingly (GILLIAT et al., 2014). A vast number of good practices can be found in the literature demonstrating what can and should be changed depending on the dynamic compression and tension forces the coiled tubing will be subjected to. The practices aim to prevent mechanical failures like the ones seen in Figure 7 (GILLIAT et al., 2017).

Figure 7 – Equipment mechanical failures during coiled tubing operation.

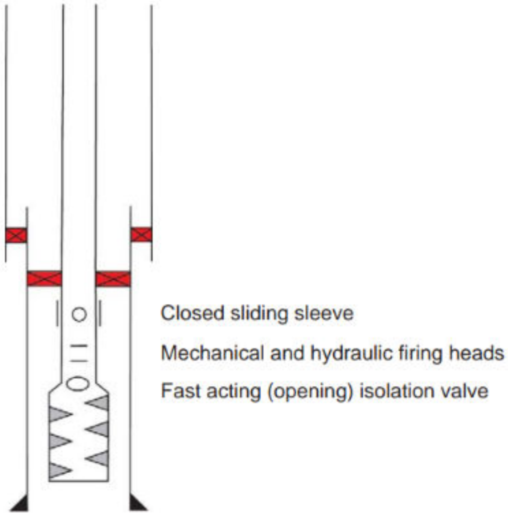


Source: GILLIAT et al. (2017).

The right conveyance choice also depends on some safety and operational factors. For instance, a well where fluid losses are likely to occur after shooting will need an option that can help to fight these losses. A TCP operation should be considered for this case since the operators will be able to pump loss control fluids through the drill pipe to avoid a significant change in the well control system. Another relevant example is the need for some acid treatment after perforating or an injectivity test. In this case, coiled tubing can be used to perform the subsequent operation straight away while the guns are still downhole (PANFEROV et al., 2016).

The TCP method is considered the most robust method due to the strong mechanical limits of the drillpipe also the most time consuming one. The method is known for conveying long perforating guns and supporting strong shocks due to the guns' detonation. The guns are connected to the drill pipe at the surface and conveyed downhole using the same technique used by the drilling rigs to move the drill bit into the borehole. Once the guns reach the planned depth, the guns can be detonated using a metallic bar, dropped from the rig floor, that travels inside the drill pipe until the firing head installed on the top of the guns. The bar triggers the detonator by mechanic shock. Another way to trigger the downhole detonator can be done by installing a pressure activated hydraulic firing head on the top of the gunstring. An increase in the pressure inside the drill pipe, provoked at the surface systems, enables the firing sequence in the hydraulic firing head and triggers the detonator. An illustration of the TCP conveyance method is presented in the Figure 8 below.

Figure 8 – Tubing-Conveyed Perforating method



Source: BELLARBY. (2009).

Recently, slickline conveyance has also received some new features. The possibility of communication with tools downhole via digital slickline systems gave it the ability to correlate in real-time and shoot the guns (JONGNARUNGSIN et al., 2017). The slickline is an important player in the well plug and abandonment projects, being able to perform downhole measurements in real-time has elevated the status of this conveyance (ARCILA; PEREZ, 2014).

Highly deviated or horizontal wells are common configurations worldwide in conditions such as thin zones, low permeability, unconsolidated, and low-pressure reservoirs (PARTIDAS, 1998). In the past, only TCP or Coiled Tubing conveyance would be feasible for this type of wells. The modern wireline tractors brought speed and reliability to the perforating scenario in non-vertical wells. Nowadays, bi-directional tractors with robust tractoring systems can reach long and deep wells. Its enhanced design allows the equipment to support higher shocks while the tractoring force can push down and pull up the heavy weight of longer gun strings (BADEGHAISH et al., 2018).

Shooting a gunstring to attend to the economic requirements on the Brazilian coast is not as simple as running in hole traditional 15 m guns and firing it. The environment is already a challenge itself. Pore pressures over 9,000 psi are not rare and require drilling fluids sometimes heavier than 12 lb/gal, to keep the well overbalanced. The heavy fluids generate high hydrostatic pressures that can be seen as a challenge-solution duality. The high pressure requires the downhole equipment to be more robust, and thus heavier, but at the same time, it brings a solution for the perforation tunnel clean-up. Dynamic Underbalance (DUB) appears as a solution since the detonation of the guns generates a downhole pressure underbalance that helps to push the debris out of the crushed zone (BAKKER et al., 2003).

To optimize the perforation performance, companies use large guns to maximize the penetration of the charges. A 7 in gun, when loaded with 12 SPF, weights in air 564 kg. A string as the one Schlumberger used for the job demonstrated by ZULIANI et al. (2016) measuring 30.80 m can weigh more than 2,800 kg, already beyond the 60% safety margin of the strongest flexible weak point available – 7,850 to 10,200 lb (3,560 to 4,626 kg) – before the development of the new technologies.

The large OD of the guns is also responsible for the expressive DUB the detonation causes. As it will be demonstrated in detail, further in this work, the DUB will present a challenge due to the gun motion downhole. The detonation of the charges generates high-speed jets with enough energy to perforate the carrier, the casing, and the formation. As explained by Baumann et al. (2012), wellbore hydrodynamics is a result of the interaction between different pressure sources downhole. The communication between the interior of the guns and the well results in the wellbore fluid being displaced into the empty carriers thus reducing the hydrostatic pressure surrounding the guns momentarily. This decompression around the guns will generate pressure waves propagating up and down and the fluid to rapidly flow from the formation to the wellbore. Both effects will apply a significant load to the wireline's weak point, which might cause its rupture.

The load is also present in the TCP system but in a much larger magnitude due to the longer gunstrings. As shown in Figure 9, the perforating gun shock can damage packers, tubing, or even the hoisting equipment and heave compensation system of the rigs (BAUMANN et al., 2019). On the other hand, the TCP system holds stronger tension and compression capacity, allowing the operators to shoot the gross pay zones in a single trip. This advantage was the main driver for the tubing conveyance option when shooting the pre-salt wells. The wireline option was significantly more risky and costly due to the rig time needed to complete the various 22 m runs. The possibility of a damaged cable or an Unintentional Pull-Off (UPO), resulting in a long fishing operation, was always considered a no-go point for cable conveyance until the new technologies were released.

To overcome the wireline limitations, the engineers worked on two different fronts: the downhole hydrodynamics models had to be improved to allow the companies to design the jobs according to their limitations, and the conveyance method needed to be more robust, to handle the heavy strings and powerful loads, preventing the mechanical fatigue of the components.

Figure 9 – Tubing damage caused by perforating gun shock.

Source: DENG et al. (2019).

2.2.1 The hydrodynamic model

Being able to predict the downhole perforating hydrodynamics was crucial to extracting the maximum of each wireline run. The new simulation application allowed the engineers to tailor the gun strings according to the forces they would generate in the wellbore. The software outputs gave confidence to push the limits. Utilizing downhole sensors, such as fast pressure gauges installed in the guns, the models were validated after the runs confirming the accuracy of the models.

The previous sections described how the interaction between the different pressures drives the wellbore hydrodynamics. The input parameters for the simulator are related not only to these pressure sources but also to the conveyance method and accessories used to lower the guns down in the hole. Table 2 lists the input parameters needed from the operators to model the perforating runs.

The above-mentioned parameters are specifically fed to the Pure Planner Simulation Software of Schlumberger. The software starts calculating the DUB and the perforation tunnel characteristics, predicting more than just the gun shock dynamic load. A wellbore pressure transient along the borehole describes the pressure wave interference as time passes, as seen in Figure 10.

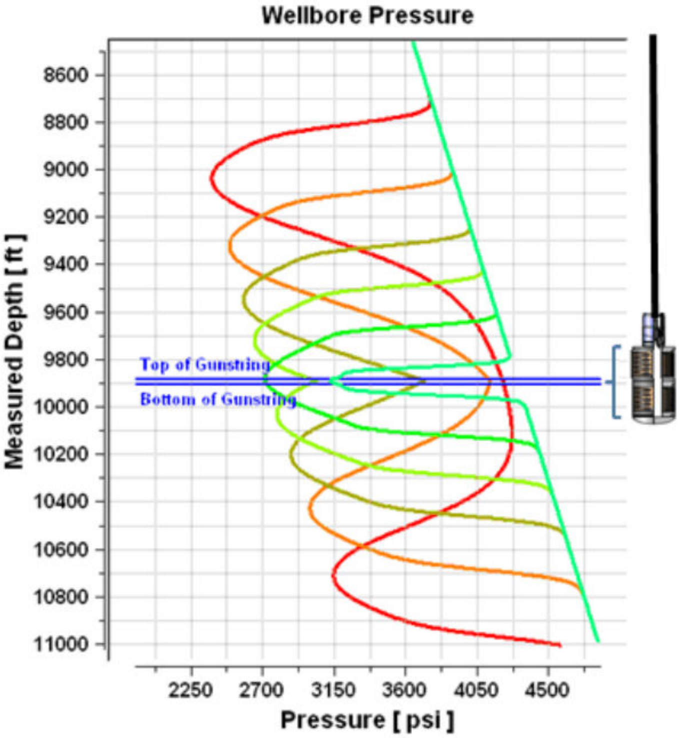
After modeling the transient pressure, the software utilizes the structural stiffness and mass of the gun string to predict the vibration that generates a low-amplitude high-frequency load on the weak point (BAUMANN et al., 2012).

Table 2 – Input parameters of the hydrodynamics software.

Parameters	Unit
Porosity	%
Permeability	mD
Temperature	ºC
Rock Strength and Overburden	psi
Pore Pressure	psi
Wellbore Fluid Weight	lb/gal
Deviation	Deg
Guns' OD	in
Interval to Perforate and Well Total Depth	m

Source: Author.

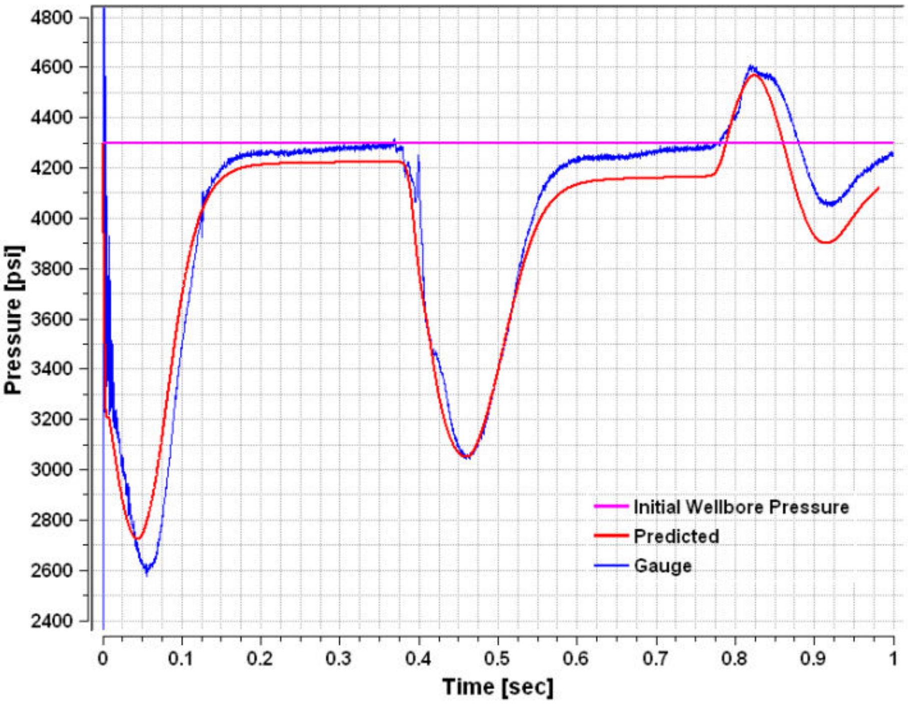
Figure 10 – Transient wellbore pressure vs. depth.



Source: BAUMANN et al. (2012).

If the load is beyond the safety margins of the weak point, shock absorbers might be considered, as well as reducing the gunstring length or the hydrostatic pressure, by reducing the fluid weight. This ability to predict the downhole forces was a game changer and encouraged one to gradually increase the length. The model proved to be reliable, and the results were checked against the data obtained from a fast-gauge pressure recorder, introduced to the string. Figure 11 compares the predicted pressure behavior and the actual measured pressure from the fast gauge.

Figure 11 – Predicted wellbore pressure vs. fast gauge extracted data.



Source: BAUMANN et al. (2012).

The three major service companies in the industry – Schlumberger, Halliburton, and Baker Hughes – provide reliable and well-proved simulation software to predict fluid pressure behavior downhole. Schlumberger Perforating Analysis (SPAN) software tool employs a numerical algorithm based on finite element analysis to predict the shock waves. It has been largely tested and validated against fast-pressure gauges for both Wireline and TCP conveyance (BAUMANN; BRINSDEN, 2014). TerraGARD from Baker Hughes applies the well-known Pulsfrac modeling software that had its algorithm and graphic interface improved to become faster, more stable, and more accurate. It has incorporated new physics and numerical algorithms and has also been proved against fast-speed gauges in a considerable amount of study cases (SATTI et al., 2018). Halliburton's SurgePro/ShockPro system is a conjunction of downhole hardware and software to manage the dynamic pressure transient (HARIVE et al., 2011). The simulation software uses a finite-difference algorithm to measure the effects of downhole dynamic pressures for both fluids and solids during the perforation event (BURMAN et al., 2011; CANAL et al., 2010).

Regardless of the software used, modeling the downhole forces and pressure dynamics is highly recommended and will help design the perforating operation properly and safely. By knowing the shock pressure transient behavior, before running in a hole, the companies can optimize the gun systems aiming for the optimum result.

2.2.2 The wireline conveyance method

Wireline conveyance utilizes a cable to deploy the perforating guns and logging tools in the hole. A hydraulic winch, controlled by the service companies, lowers the cable into the wellbore until the desired depth and brings it back when the planned operation is finished. The mechanical tension, depth, and speed of the cable are constantly monitored and are the three most basic and critical measurements during the wireline operation (BELLARBY, 2009). The tension measurement device will dictate whether the winch operator can keep pulling the cable or not. In a gun-stuck scenario, the operator will pull the cable until the measurement device shows the Maximum Safe Pull (MSP) was reached. At this point, the winch is stopped, and the engineers and the company man need to decide how to proceed.

2.2.2.1 The wireline cable

As any other working cable, the wireline cable has mechanical limitations and safety/operational risks associated with it. Normally, with very few exceptions, the safe working load (SWL) of the cable is limited to 50% of its Fixed-End Breaking Strength. The companies limit the working load to half of the mechanical tension the cable was designed to support. This high safety margin exists to prevent the cable from breaking unintentionally. It is well known the likelihood of the cable to part is higher at the surface, close to the wireline winch. The winch works as an anchor point, where no more cable elongation can exist. The mechanical tension reaches the cable end break strength very suddenly, not allowing time for the workers to stop the winch before it occurs. In the event of a cable rupture at the surface, the consequences can be catastrophic even causing fatalities to the personnel involved in the operation.

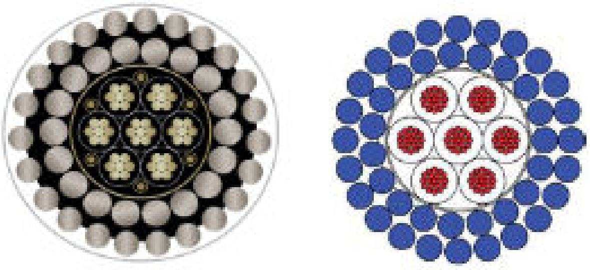
The deep wells of the Brazilian Pre-Salt already required cables with high SWL. The companies were already utilizing equipment capable of pulling 21,000 lb (9,252 kg) but these cables were not optimum to handle explosives operations. Baumann et al. (2012) present the possible damages the perforation gun shock can cause in the wireline cables such as armor breakage and "birdcage" as presented in Figure 12. When the cable is cycled by the carriers' up-down movement, due to the perforation pressure waves (similar to a jarring situation), the outer armor will open up while the inner armor will become tighter. At this point the outer armor becomes longer than the inner armor, transferring the entire load to the inner armor, usually above its safe working load (SARIAN et al., 2013).

Figure 12 – Cable birdcage.

Source: SARIAN et al., (2013).

A polymer-filled armor cable (Tuffline cable) was released and presented as a solution for the challenges of the long interval perforation. The new cable eliminates the damages caused by the gun shock during perforation, giving the companies more margin to explore wide gunstrings. By increasing the mass of the inner armor and locking the armors together to the core, using a sophisticated polymer, the researchers managed to reduce the torque of the cable, increase the mechanical limits, and eliminate the birdcage risk. This torque-free cable also presents a better dissipation of the load along its length. As presented in Figure 13, the mass of the inner armor strands is increased and the outer diameter strands are decreased, in the Tuffline cable. This modification is responsible for achieving the zero torque property, allowing the energy to be better dissipated along the cable length during the perforating shock.

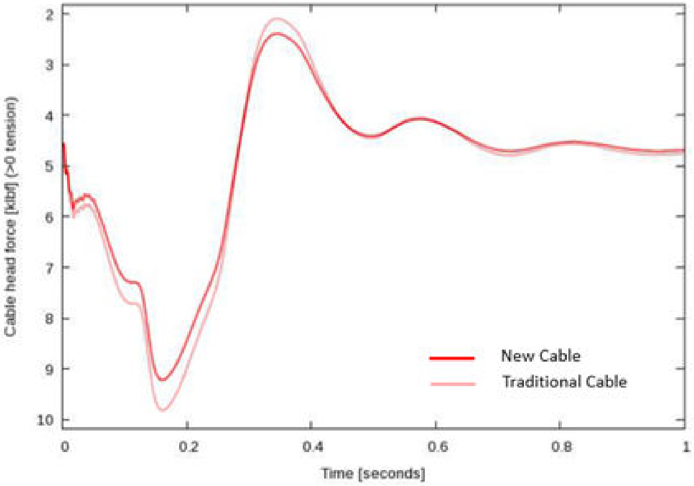
Figure 13 – Tuffline cross-section compared to a standard high-strength cable of similar specifications.



Source: SARIAN et al. (2013).

Figure 14 shows a comparison between 2 simulations for the Cable Head Force (CHF) on the weak point, for the same operational conditions, but different cables. Using the already mentioned 30.80 m gunstring example, the new torque-free cable presents a reduction of 1,150 lb (521.6 kg) on the difference between the maximum and the minimum Cable Head Force during detonation, when compared to the traditional high-tension cable. The Tuffline cable reduced the CHF peak by 700 lb (317.5 kg), increasing the safety margins or allowing the engineers to add guns to the run.

Figure 14 – New torque balanced cable comparison with traditional cable – Cable Head Force.

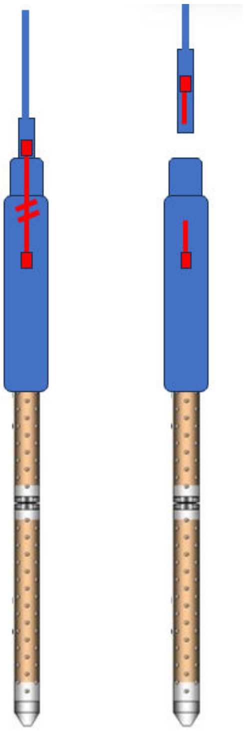


Source: Author.

2.2.2.2 The wireline weak point

When running a logging tool or a gun downhole, the companies need to be capable of releasing the cable from the downhole string in a controlled manner. If a tool string is stuck downhole, the cable needs to be released and spooled back to the surface to allow the fishing operation to happen. A wireline weak point is introduced to the system, normally at the logging or perforating head on the top of the tool string, represented in the Figure 15.

Figure 15 – Wireline weak point (in red) before and after disconnection.



Source: Author.

The weak point has a mechanical tension limit lower than the working limit of the cable, allowing the weak point to be broken before the SWL of the cable is reached. Equation 2 below is used to calculate a wireline weak point.

$$\mathrm{UWPR} < \mathrm{SWL} - \mathrm{CWM} \qquad (2)$$

Where UWPR is the Upper Weak Point Rate, i.e., the mechanical tension which the weak point will certainly break; SWL is the cable-safe working load; and CWM is the cable weight in mud.

The weak points are designed to break when a mechanical tension, within a range from the lower weak point rate (LWPR) and the upper weak point rate (UWPR), is applied to it. The calculation is done to guarantee that the UWPR will be lower than the SWL of the cable. In case of a gun stuck scenario, the right weak point selection will allow the engineer to apply enough tension on the cable to break the weak point, at the firing head, before parting the cable on an unpredictable depth. This maneuver will leave a clean fish, with known fishing necks, to be recovered with the drill pipe.

The weak point (WP) also must be strong enough to support the string weights and the loads applied to it when gun detonation occurs. Table 3 shows three of the flexible weak points available in 2013 in one of the service providers portfolio.

Table 3 – Flexible weak points mechanical limits.

Weak-Point	**Lower WP Rating kg (lb)**	**Upper WP Rating kg (lb)**
1	3,560 (7,850)	4,626 (10,200)
2	3,107 (6,850)	3,855 (8,500)
3	2,472 (5,450)	3,129 (6,900)

Source: Author

A rapid-response project was initiated to design and manufacture a weak point with a larger break tension limit. The result was a new WP designed with limits between 10,000 and 12,500 lb (4,535 kg and 5,670 kg), shown in Figure 16, and deployed to be field tested. The new limits elevated the 60% safety margin to 6,000 lb (2,721 kg) allowing a gun string to be 30 m long and weigh 2,745 kg in air, during the gun's makeup.

Figure 16 – Super flexible weak point cable: 10,000 – 12,500 lb.

Source: ZULIANI et al. (2016).

2.3 OTHER CONCERNS ABOUT PERFORATING

The previous sections gave us a general overview of how difficult it can be for the operators to choose the correct strategy to conduct a perforating operation in a wellbore. Many other variables need to be addressed before building a reasonable perforating program. For instance, a gun system should be chosen accordingly for a specific casing size. An existent nipple in the well completion might require the guns to be smaller than the ideal diameter. Even if the simulations show an optimum Productivity Index (PI), the gun system needs to be reevaluated to pass the restriction and reach the desired depth.

Different wellbore fluids can determine the gun swelling after detonation. Guns slightly smaller than a nipple's Internal Diameter (ID) will be able to pass the restriction while going down but might be stuck when pulled out of the hole due to the swelling effect caused in the carrier after the charges are detonated. Shooting in gas will have a different impact on the swelling effect than shooting in liquid (HAN et al., 2009) But not only the wellbore fluid is important when analyzing the gun post-detonation diameter. The exothermic energy, deflagrated inside the carriers, will also be a response of the shaped charges case material (HAN et al., 2010). Unless the plan is to "shoot and drop" the guns (RENPU, 2011), passing the restriction when pulling out of the hole will be a challenge.

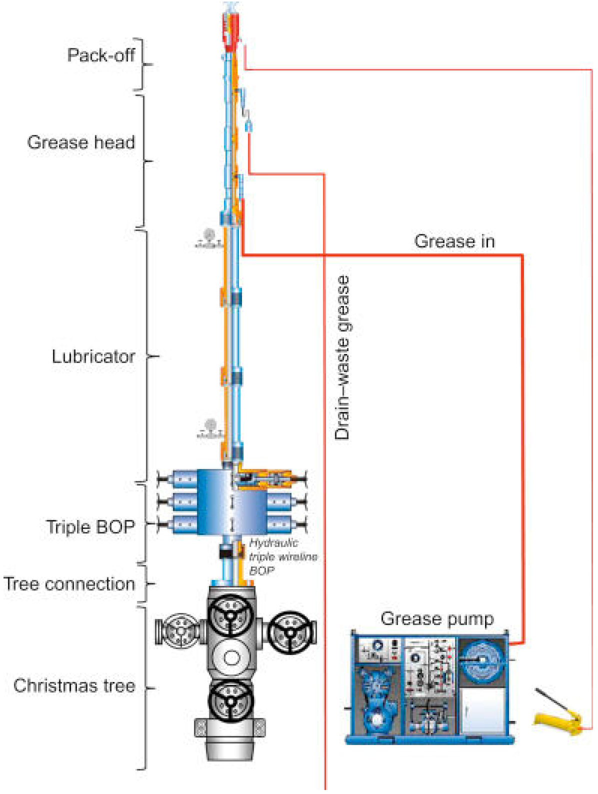
The total amount of debris generated by the shaped charges can also be a problem. The size, shape, and composition of the debris are well described in the charge's datasheet. It is also the subject of the API RP 19B Section 5, which explains in detail how the quantification is done (API, 2014). If the interval to be perforated is reasonably long, the total volume of debris downhole can be quite substantial. This can affect downhole flow control and sensors creating the need for further interventions. Low debris perforating charges are one of the goals of the charge manufacturers (ZUKLIC et al., 2016). Figure 17 shows how the debris represents an operational risk for further runs or during the completion installation. In some cases, dedicated magnet runs need to be performed to clean the wells from the debris (BANMAN et al., 2008).

Figure 17- Debris generated from perforating charges downhole.

Source: ZUKLIC et al. (2016)

The perforating program needs to consider all the aspects of the operation. If the well to be perforated is a flowing well and presents wellhead pressure, the operation cannot be conducted without a grease injection head (HGT) on the Pressure Control Equipment (PCE). Due to safety reasons, the grease injection is required to create a dynamic seal during the wireline cable movement (SARIAN et al., 2019). It is not unusual to see planned runs being split in more than one descent due to the gun's string length. If the gun string is too long it might not fit inside the lubricators, therefore more runs are needed to shoot the desired interval (BELLARBY, 2009). As shown in Figure 18, the PCE height needs to be considered during the job planning and execution.

Figure 18 – Eline pressure control equipment



Source: LYONS et al. (2016)

The gun's string needs to fit completely inside the lubricator to the wellbore pressure to be bled during rig up/down the guns. More lubricators can be added but operational and safety limits need to be taken into consideration. If the operation is being conducted rigless, the crane height needs to be good enough to accommodate the lubricators. In the event of a gun-stuck scenario, more space will be needed between the top of the lubricator and the Christmas tree for fishing the guns (BELLARBY, 2009).

The perforation for hydraulic fracturing can easily be a separate chapter or even an entire book itself. Authors like Al-Momin and Al- Saihati (2014) have presented the perforating design concerns when considering friction during hydraulic fracturing. The wrong choice on the perforation design can lead to an early screenout preventing the proppant to be correctly placed along the fracture. During the pumping phase, an increase in the fracture treating pressure can be seen due to proppant bridging (BARREE, 2022). The majority of the screenouts occur in the near-wellbore region and it is caused by the tortuosity in the perforated tunnel (AUD et al., 1994). It has been proved that consistent perforator hole size can reduce the near-wellbore tortuosity that causes early screenouts. Not only consistency but also the size and the distribution of the entrance holes have an important effect on reducing the treating pressures (QUATTLEBAUM et al., 2012). The flow distribution on a multi-cluster stage, when fracturing a well, is modeled to be equal among the clusters. Friction losses play an important role in making this even distribution hard to achieve. Completion methods such as Extreme Limited Entry (XLE) are very effective in helping improve the even distribution and can be optimized via injection rate, cluster number, and spacing, and stress difference between adjacent clusters (ZHANG et al., 2021).

Among all the mentioned aspects, the multi-disciplinary effort of developing the perforating program needs to contemplate also logistic features such as explosives transport and storage, local and international regulations, and environmental laws. People expertise is key for a successful enterprise hence the training and exposure of the involved personnel must be extensive.

Although the current perforating systems present many safety barriers, such as RF (Radio Frequency) Safe detonators, and engineered solutions to reduce human failures (GUEDES; ABOELNAGA, 2018), there is still basic and cheaper equipment that requires a lot more attention. The industry is increasingly worried about improving safety during perforating operations. The API RP 67 combines the recommended practices for oilfield explosives safety. It is a team effort to keep the API Recommended Practices 67 up to date. The document is currently in its third edition and was copiously discussed by a group of industry professionals (AYRE; BAKER, 2017). There is no margin for mistakes when handling high-energy material. Procedures in place and high-rated standards, need to be considered before planning a perforating job. Safety is a subject to be addressed carefully while following all the international regulations and practices.

2.4 CLOSING REMARKS FROM THE LITERATURE REVIEW

To summarize all factors discussed in the present work about the perforating design, Table 4 shows all works mentioned throughout the text, emphasizing the approach of each of them.

Table 4– Summary of the perforating well works by topic mentioned in the present article.

Topic	**Reference**	**Details**
Discovery of the Brazilian pre-salt and its characteristics	Pinheiro et al. (2015), Campos et al. (2017), Motta et al. (2015), Fraga et al. (2015)	Brazilian pre-salt discovery and depths, costs, and investments for exploring the fields.
Brazilian pre-salt completion design	Schnitzler et al. (2015)	Need of 9⅝ in and 9⅞ in production casings due to high pressures and high productivity.
Perforating guns used in the Brazilian pre-salt	Bellarby (2009), Mclemore (1947)	Reason for using 7" and the effect of positioning has on the entrance hole diameter.
Brazilian pre-salt perforating intervals	Sedlacek et al. (2020)	Range of payzones in the Brazilian pre-salt varying from 100 to 500m.
Mechanical information of gun carriers	Schlumberger (2005)	Gunstring weight considering 7in guns 6m long and 12SPF carriers.
Perforating and shaped charge's introduction	McLemore (1947), Forsyth (1950), Allen and Atterbury Jr. (1954)	Shaped charges history and perforating systems evolution from bullets to shaped charges.
Productivity index (PI)	Inayat-Hussain and Buckingham (1995), Bahrami et al. (2009), Bellarby (2009), Economides et al. (2013), Renpu (2011)	Productivity index concept and its utilization for well performance measurement.
Well perforation objectives and goals	Fu et al. (2018), Jha et al. (2020), Shaykamalov et al. (2020), Cowan (2007), Johannessen et al. (2000), Panferov et al. (2016), Awad et al. (2018), Jin, (2019), Liu et al. (2014), Lorwongngam et al. (2020), Wood et al. (2018)	Definition of the different perforation objectives according to the well type (producer or injector), producing strategy or the need of an intervention in the well.
Perforating technique determination and factors used to select the most appropriate one	Markel et al. (2002), Renpu (2011), Bellarby (2009), Kritsanaphak et al. (2010), Batarseh et al. (2019), Qayyum et al. (2009), Pashchenko and Ageev (2016)	Description of the variables that determine the choice of the correct perforating technique. Including mechanical gun and explosives data, formation characteristics and external factors.

Perforation parameters for optimum well performance	Markel et al. (2002)	Perforation depth, shot density and gun phasing are the three basic perforating parameters that correlate with the production performance.
Gun positioning and the relation with the perforation depth and entrance hole diameter	McLemore (1947), Quattlebaum et al. (2012)	Comparison of entrance hole diameter for different water clearances.
Skin factor	Muskat (1943), Allen and Atterbury Jr (1954), Hsia and Behrmann (1991), Grove et al. (2013), Grove et al. (2019), Pucknell and Behrmann (1991)	Mechanism of rock tunnels permeability reduction created by the explosives jet.
Core flow efficiency (CFE) definition	API (2014), Baumann et al. (2014), Bellarby (2007), Brinsden (2011), Muskat (1943)	API recommended practice for calculating the CFE through a core rock perforation test and CFE equation definition.
Overbalance and underbalance shooting	Hsia and Behrmann (1991)	Pressure underbalance influence on the tunnel cleanup during perforation and the effect on the crushed zone permeability.
Overbalance perforation	Renpu (2011), Baumann et al. (2013)	Overbalance perforation procedures and TCP and Coiled Tubing pros and cons.
Dynamic underbalance (DUB)	Chadha et al. (2011), Martin et al. (2005), Zuliani et al. (2016), Guedes et al. (2019), Baumann et al. (2013), Baumann et al. (2012)	Dynamic Underbalance concept, model comparisons and real time measurement of the perforated zone response right after the detonation.
Proprietary modelling software	Bauman and Brinsden (2014), Satti et al. (2018), Harive et al. (2018), Burman et al. (2011), Canal et al. (2010)	Proprietary modeling tools examples and characteristics of computational model based on different algorithms.
Well temperature and charges selection	Bellarby (2009), Renpu (2011)	The influence of well temperature on the explosives type decision among HMX, RDX, NHS and PYX.

Temperature effect on the explosive's characteristics	Bernstein (2020), Barker (2013), Ayre and Barker (2017), Boock et al. (2015)	Change of the phase of powder crystals due to exposition to elevated temperatures will affect the charges sensitivity to impact.
Operational factors and the explosives type influence on charges' performance	Haggerty and Christie (2015), Barker (2013), Barker and Davidson (2016), Boock et al. (2015), Renpu (2011)	Different explosives will impose distinct depths of penetration and entrance hole diameters for the same gun size and water clearance. It will also affect the time the guns can be exposed to different well temperatures limiting the use of certain conveyance methods.
Guns conveyance methods	Zahmuwl et al. (2019), Bellarby (2009), Hillier et al. (2019), Zuliani et al. (2016), Gilliat et al. (2014 and 2017)	Guns conveyance methods and current tension and shock modelling capability. The ability to produce accurate predictions for the downhole forces has changed the way the engineers design the perforating jobs.
Safety and operational factors to choose the right conveyance method	Panferov et al. (2016), Jongnarungsin et al. (2017), Arcila and Perez (2014), Partidas (1998), Badeghaish et al. (2018)	Combined operations can be done to optimize operational time when perforating. Pumping acid right after the perforation utilizing a TCP pipe or using the drill-pipe to pump loss control fluids in case of a well control risk are examples of it. For highly deviated wells the new generation wireline tractors can replace the costly and long TCP and Coiled Tubing conveyance.
DUB as a solution for tunnel clean up	Bakker et al. (2003)	The guns detonation generates a downhole pressure underbalance that helps to push the debris out of the crushed zone.
Tubing damaged caused by perforating shock	Deng et al. (2019)	Pictures of damaged tubing due to excessive perforating shock

Gun carriers swelling effects after perforating	Han et al. (2009), Han et al. (2010), Renpu (2011)	Gun carriers can present diverse levels of swelling depending on its mechanic composition and the borehole fluid where it was detonated. This is a crucial factor to consider when choosing the gun sizes.
Shaped charges post-perforation debris	API (2014), Zuklic (2016), Banman et al. (2008)	Shaped charges debris generated after detonation can be a genuine problem for long interval perforations. An additional well intervention might be needed to remove the debris from well.
Wireline conveyance	Bellarby (2009), Baumann et al. (2012), Sarian et al. (2013)	Wireline conveyance method explained with the use of torque free cable and weak point as a contingency apparatus for gun stuck case scenario.
Perforate using Pressure Control Equipment (PCE)	Sarian et al. (2019), Bellarby (2009), Lyons et al. (2016)	For flowing wells perforating utilizing Coiled Tubing, Wireline or Slickline requires the use of a PCE to prevent the well to flow while operating. The presence of the equipment creates another challenge due to space restrictions and safety concerns.
Perforating for hydraulic fracturing	Al-Momin and Al-Saihati (2014), Barree (2022), Aud et al. (1994), Quattlebaum et al. (2012), Zhang et al. (2021)	Screenout effect caused by proppant bridging due to undesired tortuosity inside the perforated tunnel.
Safety systems	Guedes and Aboelnaga (2018), Arye and Baker (2017)	Currently many safety systems exist to protect the people handling high energy material. However, there are still a large amount of basic and cheap equipment without the advance of safety barriers. For that, serious and hard procedures are in place

		to guarantee the safety of the operations.

Source: Author.

The number of variables makes the perforating operation an overly complex chapter of the life of the well. Despite its complexity, there is a solution for almost every challenge. During the literature review for this article, it was noticed that this subject is a mature theme, and a lot of time has been spent trying to improve every single aspect of it. However, the industry still has some difficulties to overcome. In deepwater scenarios, the rig time is critical, and the perforating operation can be excessively time-consuming, increasing the overall costs significantly. The charge's penetration is another obstacle to surpass in the years to come. Increasing the perforation tunnel length can change the direction the industry is going with the hydraulic fracturing segment getting stronger every day. The tunnel cleanup is also a relevant challenge with a complex solution. The static and dynamic underbalance perforation have improved the outcome but with a large room for enhancement. This subject still needs a substantial amount of research to be applied in all well zone types to provide optimized well productivity or injectivity. Explosives are widely used for perforating operations. Finding an alternative solution that replaces them, maintaining or improving the charges' performance, will be a game-changer for the industry.

The service companies and the explosives manufacturers are in a healthy race, pursuing the best equipment and techniques. The operators are designing more elaborate programs every day with the help of numerical simulations while trying different approaches to match their field's needs.

For now, the wide variety of charges offers the engineers options for sandstones, carbonate, unconsolidated formations, unconventional reservoirs, high temperature, high pressure, charges for injector wells, charges for fracturing, deep penetration, big hole, cheap charges, propellant, low-debris, zinc-case charges and so on. The options for guns are also vast. Reusable carriers, thru-tubing guns, light guns for shallow wells and low pressures, exposed, pivot guns, high shot density, dynamic underbalance chambers, escallop guns, all sorts of sizes, shot densities, and phases, among many other options.

With the amount of information available, the right thing to do is to plan properly. The service companies can help a lot with their simulation software to make the correct decision. The models are very advanced and can predict the results with a good level of precision. With all that in place, we can state with confidence that, perforating a well nowadays is not a shot in the dark anymore.

3 METHODOLOGY

The present work utilized two paths for helping the decision on which conveyance method of perforating is the most efficient one:

1. Historical data of perforating jobs executed in the Brazilian pre-salt has been thoroughly analyzed, allowing the author to base the results on real case scenarios;
2. Case studies for long perforated intervals, utilizing the formation properties and average pay zone lengths for the fields with the highest number of perforated wells.

3.1 DATA ANALYSIS

3.1.1 Defining previous limits

An extensive data gathering was done from the internal database of one service company, whose name must be suppressed in the present work. The perforated wells data were segregated according to the perforated interval, operational time, oil field, conveyance type, and date of perforating jobs. The database presents 62 wells perforated by either TCP or wireline conveyance, from the beginning of the data collection (2016) until this work was initiated (2018). Among the analyzed perforated jobs, eight pre-salt fields were identified, and the number of wells perforated in each field is presented in Table 5.

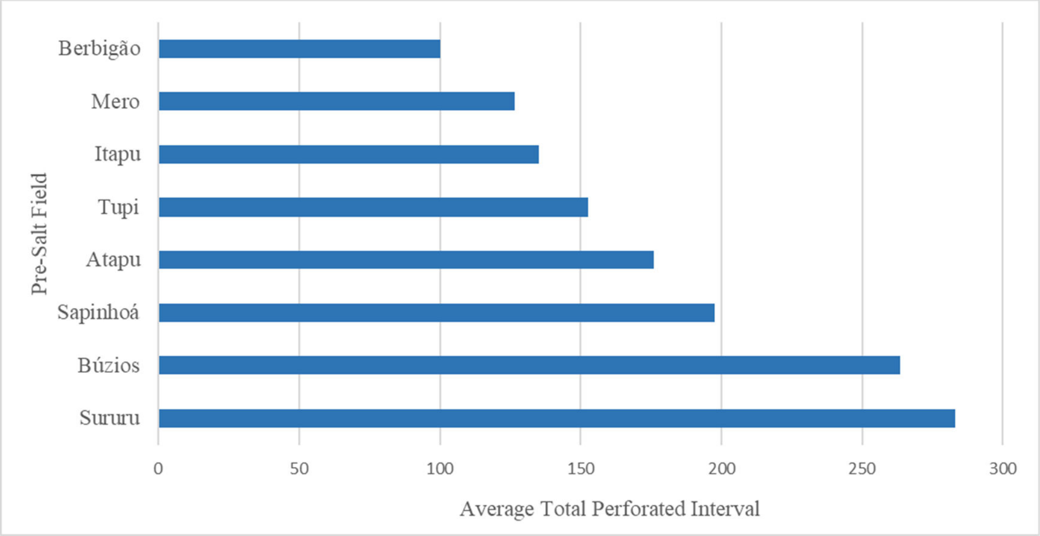
Table 5– Number of perforated wells per field in the Brazilian pre-salt from 2016 until 2018.

Field	Number of Wells
Berbigão	1
Mero	5
Itapu	1
Tupi	40
Atapu	1
Sapinhoá	2
Búzios	11
Sururú	1

Source: Author.

The fields were also separated by average perforated interval to understand, for each field, if the comparison is worthy. Figure 19 presents the segregation by perforated length. With the available data properly segregated, it was important to understand the limits of each conveyance method prior to the technology enhancement of the wireline technique.

Figure 19 – Brazilian pre-salt fields and their average perforated interval.



Source: Author.

The study had access to the declared gun footage limits for wireline runs and TCP jobs. Those limits were provided by the service companies, according to their technical capabilities. Back in 2013, the three companies providing perforating services presented their shooting limits on wireline conveyance as in Table 6.

Table 6 – Guns perforating limits per run for wireline conveyance method.

Service Company	Gun OD (in)	Shot Density (SPF)	Maximum Length per Run* (m)
a	7	12	22.5
b	7	12	15.0
c	7	12	13.0

*No presence of anchors.
Source: Author

The same data based presented the TCP perforating records until May 2013. As shown in Table 7, the maximum length of a 7 in gunstring via TCP technique was 207 m, shot in December 2012.

Table 7 – TCP perforating records with 7 in 12 SPF gunstring.

Service Company	Gun OD (in)	Loaded and/or Spacers Footage (m)	Total Length (m)
a	7	187 loaded / 20 spacers	207
b	7	153 loaded	153
c	7	-	-

*For "c" company, data were not available.
Source: Author

For both conveyance methods, the operational times were also determined and clearly stated, as shown in Table 8, giving the designers a good starting point when choosing between perforating techniques.

Table 8 – Conveyance method average operational time.

Service Type	Average Operational Time (h)
Wireline Perforating	~11 (per run)
TCP Perforating	~72

Source: Author

With the above numbers it was possible to determine the decision point at that time, based only on rig time costs. Using a simple relation among the maximum total length reported (Table 6), the number of wireline runs, and average run time, we found the total time for the different numbers of runs, as can be seen in Table 9.

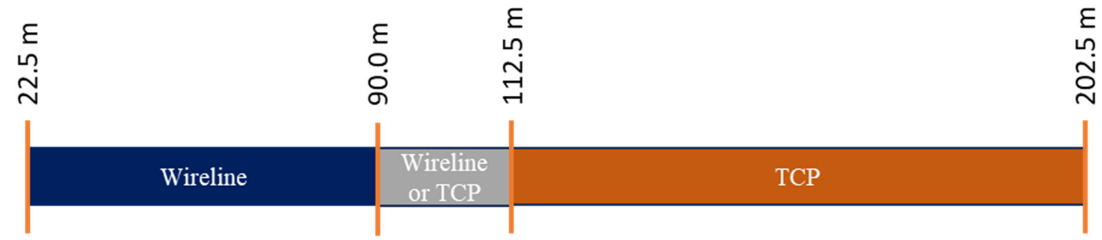
Table 9 – Length and total time for wireline runs.

Number of Runs (m)	Total Length (m)	Total Time (h)
1	22.5	11
2	45.0	22
3	67.5	33
4	90.0	44
5	112.5	55
6	135.0	66
7	157.5	77
8	180.0	88
9	202.5	99

Source: Author.

Based on Table 9 and considering only the operational time, a job with payzones longer than 112.5 m, or 5 wireline runs, would use the TCP technique due to the total operational time. It can be seen that 6 wireline runs would also have a shorter operational time than the average TCP run – 66 hours against 72 hours. However, the common understanding is that the gain in time – only 6 hours – was not enough to justify not using a safer and more versatile conveyance method as the TCP one. However, it is also an easy finding that the designers would prefer the wireline method for any job with a total interval shorter than 90 m, due to the reasonable gain in rig time. As shown in the figure 20, the limits were defined and a gray zone between 90m and 112.5m was to be considered according to the designers' understanding. Then, the present work will analyze what conveyance method will be more appropriate when the payzone length falls within this gray zone.

Figure 20 – Payzones length limits by gun conveyance method in Brazilian pre-salt.



Source: Author.

Accordingly, jobs with payzones shorter than 90 m were not included in this study. As stated above, this interval was not viable to perforate utilizing TCP conveyance due to the longer time compared to Wireline. Even before the enhanced wireline technology was available, a 90 m interval would be performed in 4 wireline runs, totalizing around 44 hours of operation, a reasonable time difference to use the TCP conveyance in relatively short intervals.

3.1.2 Data segregation for analysis

According to the procedure explained in the previous section, Table 10 was built with the wells analyzed in this study from the database. These wells were already perforated using an enhanced wireline technology and, because of this, presented improved run times which implied an improved meterage capacity per run compared to the limits presented previously. In Table 10, all selected wells (payzones ≥ 90 m) used the same gun size and a high shot density.

Table 10 – Wireline perforated wells above 90 m payzone in the Brazilian Pre-Salt.

Well	Total Interval (m)	Gun Size (m)	Gun Type	Shot Density (SPF)
A	91	7	High Shot Density	12
B	134	7	High Shot Density	12
C	95	7	High Shot Density	12
D	158	7	High Shot Density	12
E	163	7	High Shot Density	12
F	119	7	High Shot Density	12
G	114	7	High Shot Density	12
H	162	7	High Shot Density	12

Source: Author.

From Table 10, it can be seen that the service company perforated 8 wells from 2016 to 2018 with a payzone length bigger than 90 m. All wells were perforated with the wireline method, but they also met the criteria to be perforated via the TCP technique. At that time, the decision for the wireline method was made after studying the downhole forces through simulation and presented to the pre-salt operator. The operational data such as, run time, longest gunstring length and total time, gathered during the jobs were vital for the analysis and helped identify the new limits after using the released technologies on the wireline front.

Additionally, all the wells analyzed in this study were part of the microbial reservoir of the Brazilian Pre-Salt, with the relevant characteristics shown in Table 11. The petrophysics properties are found in the literature and vary depending on the well and oil fields, as stated by Johann et al. (2012).

Table 11 – Petrophysics of the Pre-Salt wells analyzed.

Reservoir Fluid	Rock Type	Porosity (%)	Temp. (°C)	Permeability (mD)	Rock Strength (psi)	Pore Pressure (psi)
Oil	Limestone	10-15	56-95	0.65-2,000	3,000-9,000	8,600-13,645

Source: Author

3.2 BRAZILIAN PRE-SALT CASE STUDIES

Besides the wells described in the previous section, the present work will analyze two real case studies that were considered important milestones in the wireline long interval perforating progress. Both cases would have been conveyed with TCP not a long time ago. The service company approached the operator project managers with the downhole shock simulations (see Section 2.2.2) for the wireline method and proved it was safe to proceed with the wireline option. None of the jobs had any additional operation planned with the drillpipe (TCP) nor circulation losses expected after perforating. These conditions made them good candidates for breaking the world record for longest gunstring per run. Both real case studies are described following.

3.2.1 – Case Study #1 – Perforating With Cable Weak Point

The first step to determine the number of wireline runs, able to cover the entire perforating interval, is to identify the longest gunstring per run that can be detonated without compromising the operation. The biggest risk for this operation is the unintentional weak point breakage of the cable due to shock waves after shooting. The gun weight in the air will dictate if it is safe to lift the gunstring, during the rig-up operation, and the downhole forces simulation will ensure the shock on the weak point is not enough to break it, dropping the gun in the hole.

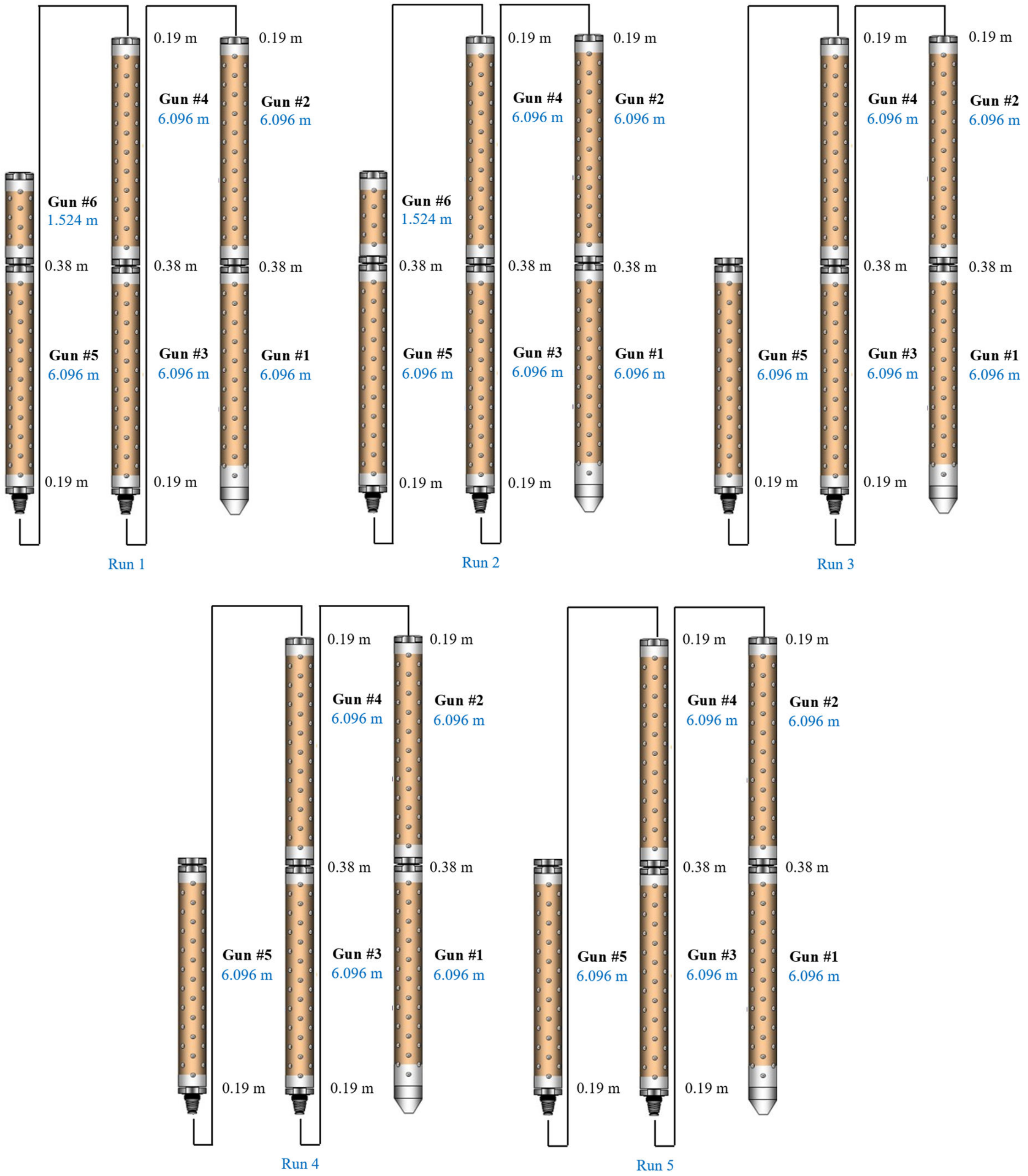
For Case Study #1, it was perforated an interval of 163 m with a gunstring of 7 in (OD) and 12 SPF. The entire interval of the operation executed was broken down and split as per Figure 21. The total interval was split into five runs, with the longest string measuring 33.92 m, from the bottom to the top shot, including the adaptors between guns. The number of runs to shoot the total payzone was within the gray zone and enough to use the rig time-saving criteria to try the wireline conveyance method. Table 12 details the configuration of runs.

Table 12 – Case Study #1: Runs configuration.

Run number	**Total length (m)**	**Weight in air (kg)**	**Number of 6 m guns**	**Number of 1.5 m guns**
1	33.90	3,008	5	1
2	33.90	3,008	5	1
3	32.00	2,854	5	-
4	32.00	2,854	5	-
5	32.00	2,854	5	-

Source: Author.

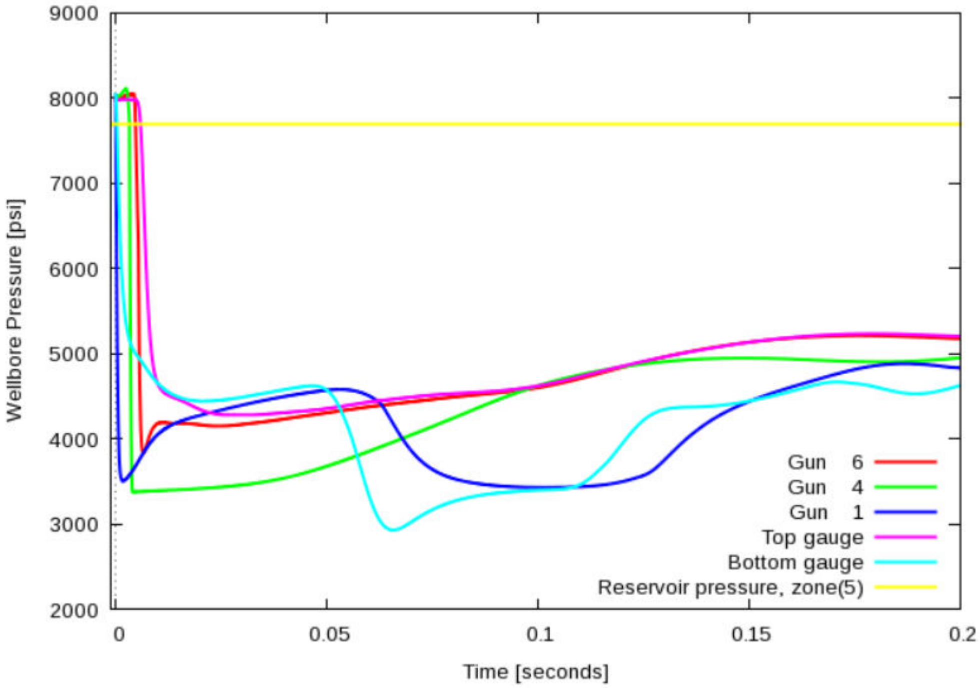
Figure 21 – Case Study #1: runs and gunstrings configurations for perforating with the cable weak point.



Source: Author.

The next step was the simulation of the hydrodynamic forces downhole, during the detonation. The software used was the Schlumberger Perforating Analysis (SPAN) Pure Planner. The input information was obtained from the operators' project engineer and inserted into the software. The parameters were explained in Section 3.2.1 of this work. Figure 22 presents the wellbore pressure transients measured at different points of the gunstring.

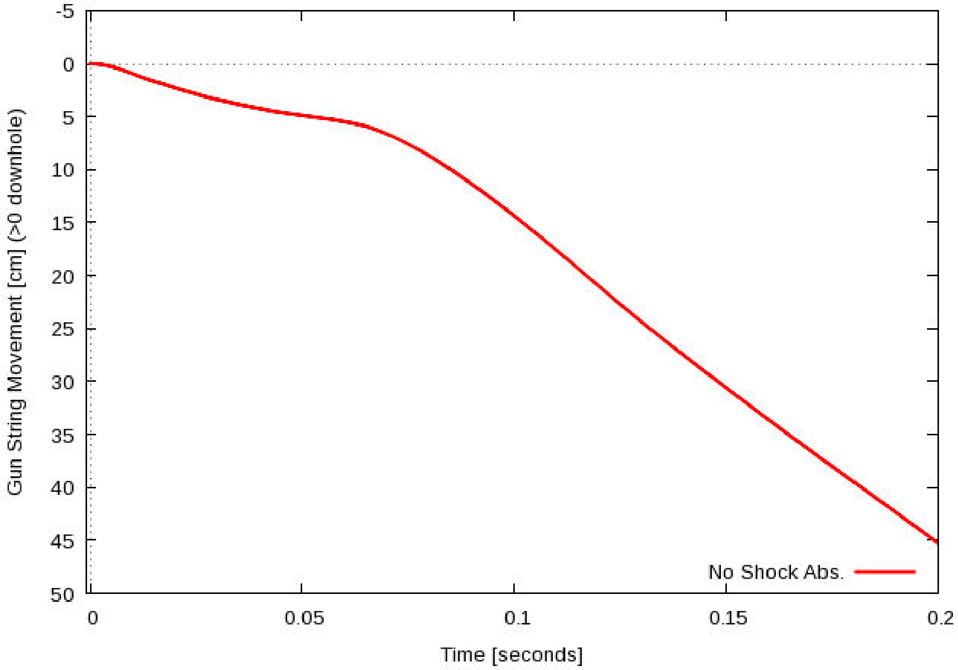
Figure 22 – Simulated Pressure transients of the 33.90 m gunstring during detonation.



Source: Author.

An instantaneous drop in the wellbore hydrostatic pressure, of around 5,000 psi, is noticed in the bottom gauge position (bottom of the gunstring). This pressure drop will drive the hydrodynamic forces imposed on the perforating head, where the weak point of the cable is located. Figure 23 shows the gunstring movement inside the wellbore during the pressure transients.

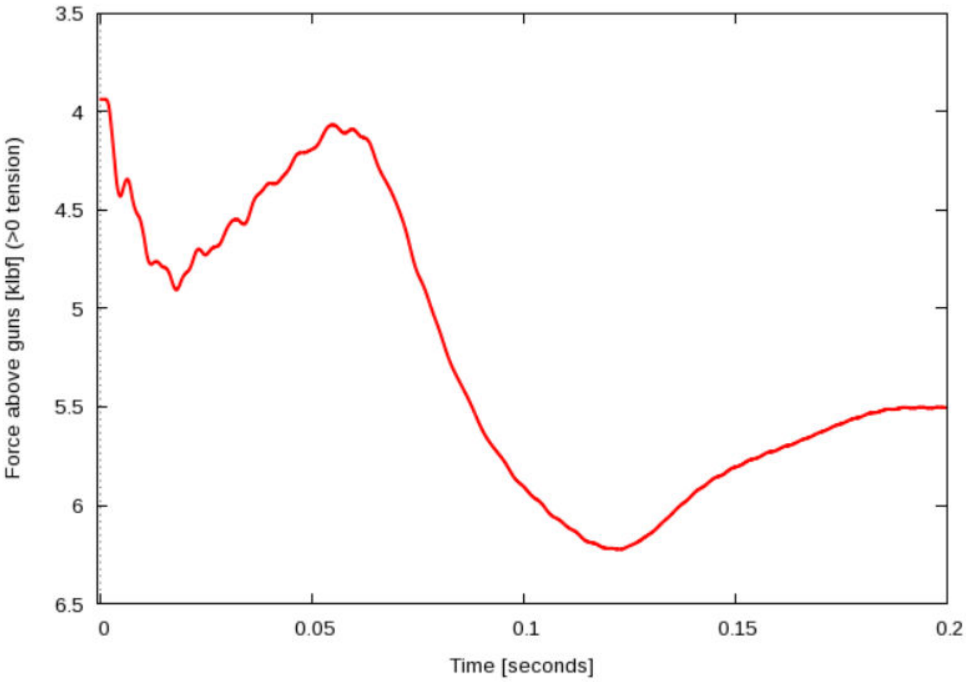
Figure 23 – 32.90 m gunstring simulated movement vs. time.



Source: Author.

The hydrodynamic forces acting on the gunstring will displace the gunstring downwards, around 45 cm. This quick displacement will change the load at the perforating head, submitting the weak point to an instantaneous increase of the forces acting on it. Before the detonation, the weak point load was the gunstring weight in the fluid. As can be seen in Figure 24, the static force above the gun was around 4,000 lbf (1,815 kgf) at the time equal to 0 (zero). Immediately after the detonation, the weak point of the cable is submitted to an increase of almost 2,500 lbf (1,130 kgf), reaching 6,500 lbf (2,950 kgf) of force acting downward on the gunstring.

Figure 24 – Case Study #1: Simulated dynamic load at the cable head.



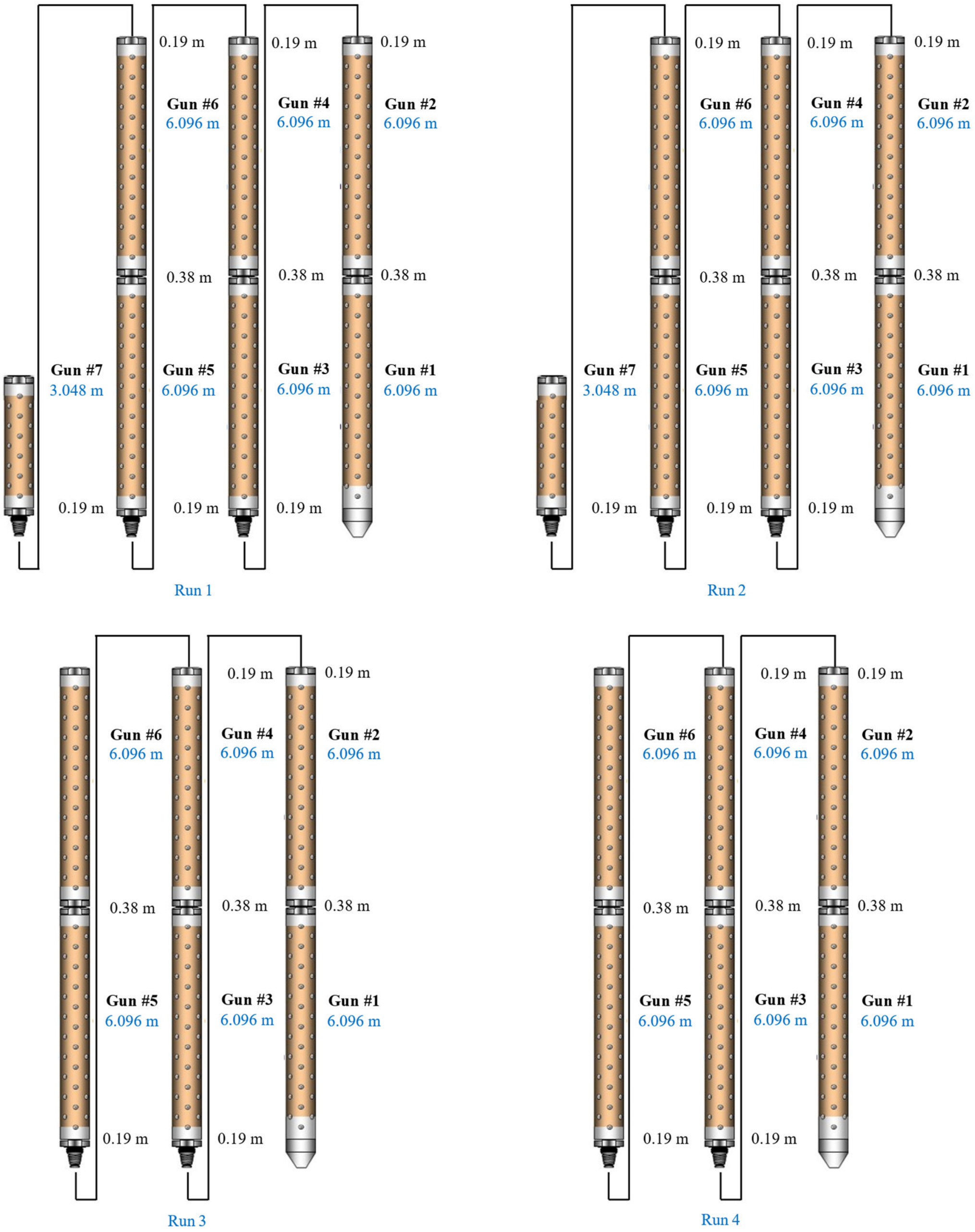
Source: Author.

3.2.2 – Case Study #2 – Perforating Without Cable Weak Point

For Case Study #2, the service company proposed a different approach for another perforating job, also with the same value of interval length (162 m) and gun parameters (7 in and 12 SPF), to test a perforating head use without a weak point in the cable. For this, it was necessary to have a contingency plan in case of a gun-stuck scenario. Then, the contingency plan was to release the cable from the gunstring for a downhole cable cutter to be dropped in the well. The cable release would allow the guns to be fished by the rig once the cable is pulled back to the surface. This solution gave the operator's engineers the confidence to experiment with this new approach proposed by the service company.

By removing the weak point from the equation, the engineers gained more margin to increase the gunstrings length. The gunstring could now be designed considering that the new limit was the cable maximum safe pull – 18,000 lbf (8,165 kgf) – and not the weak point anymore. The service company designed an adaptor to bypass the weak point, connecting the logging cable directly to the gunstring, through the perforating head. The total perforating interval – 162 m – was then split into 4 runs, as shown in Figure 25.

Figure 25 – Case Study #2: runs and gunstrings configurations for perforating without the cable weak point.



Source: Author.

The guns were distributed as per Table 13 and split into only 4 wireline runs. The engineers designed the job with an increase of 32.5% in total length for the longest gunstrings. Without the cable weak point as a limitation, rigging up the guns at the drill floor was safer, even though the gunstrings were heavier.

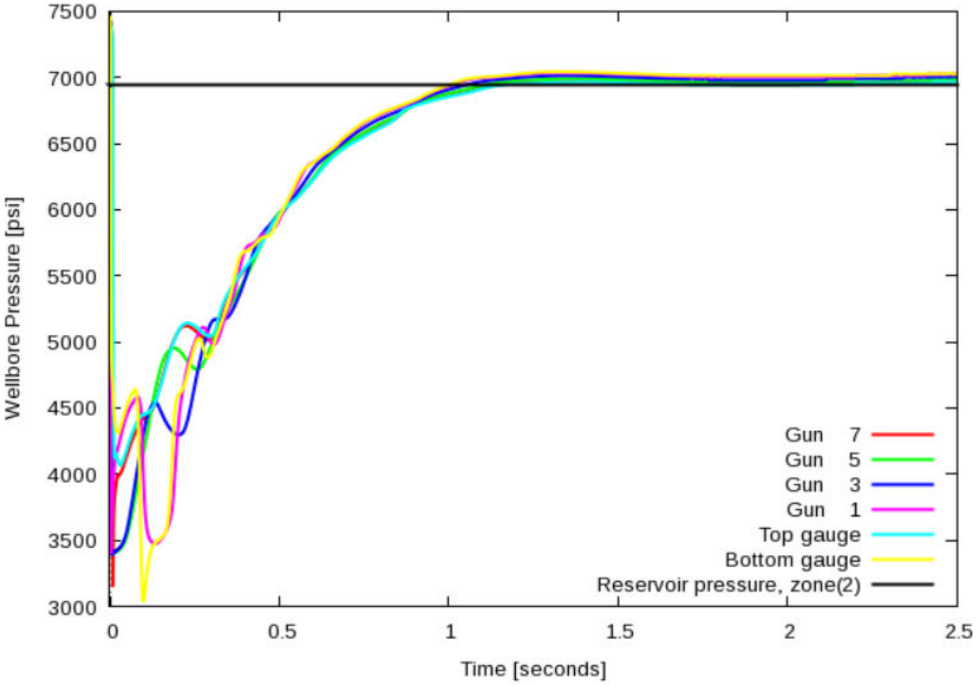
Table 13 – Case Study #2: runs configuration.

Run number	Total length (m)	Weight in air (kg)	Number of 6 m guns	Number of 3 m guns
1	41.90	3,809	6	1
2	41.90	3,809	6	1
3	38.47	3,406	6	-
4	38.47	3,406	6	-

Source: Author.

Figure 26 shows the pressure transients for the Run 1 – 41.90 m – along the gunstring. The SPAN software calculated a drop of approximately 4,500 psi on the wellbore hydrostatic pressure, seen on the bottom of the lowest gun. The hydrostatic pressure at the immediate moment before the detonation was approximately 7,500 psi.

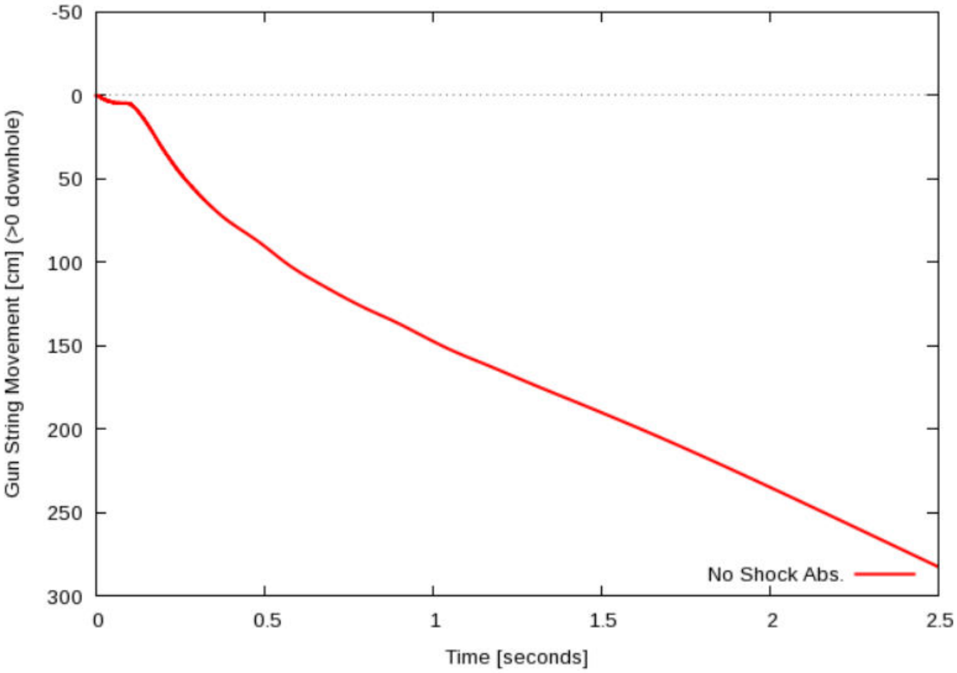
Figure 26 – Simulated Pressure transients of the 41.90 m gunstring during detonation.



Source: Author.

The hydrodynamic forces downhole would cause a gunstring displacement of approximately 2.8 m, as shown in Figure 27. Compared to the longest string displacement in Case Study #1, the guns' movement was much longer in the downward direction due to the longer length and different hydrodynamic forces downhole.

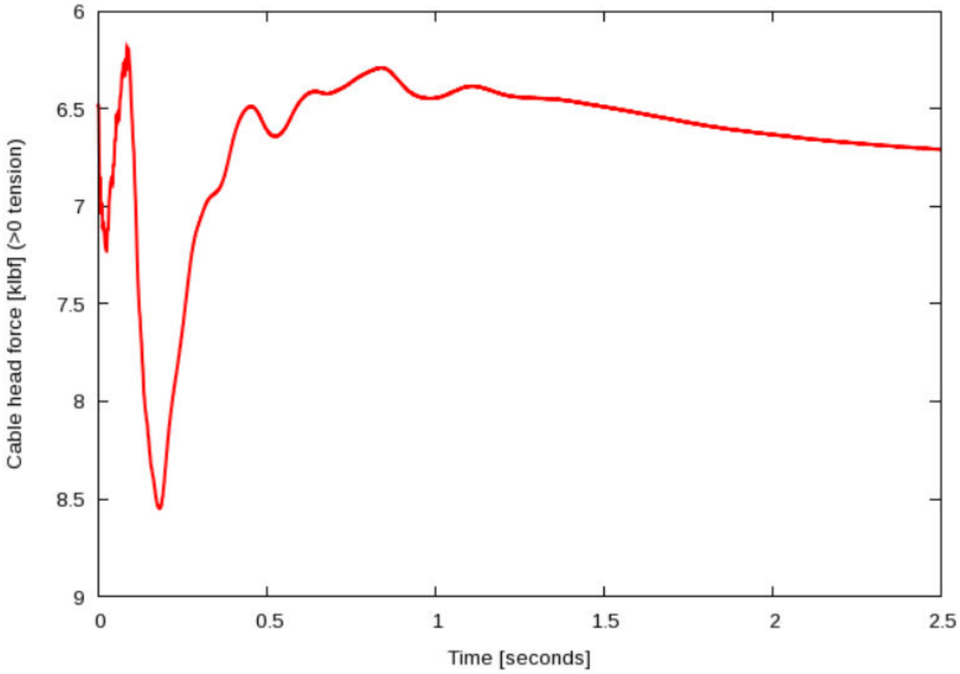
Figure 27 – 41.90 m gunstring simulated movement vs. time.



Source: Author.

The results of the simulation presented a cable head force exceeding 8,500 lbf (3,855 kgf) during the effect of the hydrodynamic forces in the wellbore. An increment of more than 2,500 lbf (1,133 kgf) from the static gunstring weigh-on fluid was observed, as shown in Figure 28.

Figure 28 – Case Study #2: Simulated dynamic load at the cable head.



Source: Author.

4 RESULTS AND DISCUSSIONS

4.1 HISTORICAL ANALYSIS OF WIRELINE AND TCP PERFORATING DATA

Until 2013, to perforate the maximum length ever perforated in the Pre-Salt basin, a service company would need at least 8 wireline runs to complete the job, according to the Tables 6 and 7. As the wireline option can use the advantage of perforating the exact interval, because of the ability of splitting the total interval, there is no need of spacers for the zones not to be perforated. The 187 m effective length would have been perforated in approximately 88 hours – considering 11 hours average per wireline run – longer than the TCP time of 72 hours, yet with fewer advantages and additional operational risks.

The analysis of the historical data, after the implementation of the discussed new wireline techniques – shown in Table 14 – proved that the enhanced wireline perforation method took an average of 8.5 ± 1.83 hours per run, showing a 22.7% improvement from the 11 hours per run reported by the service companies. Not only did the gunstring length per run become longer, but also the wireline engineers managed to improve run time. This improvement helped the wireline segment gain market share in the long-interval perforation business.

Table 14 – Wireline perforated wells above 90 m payzone in the Brazilian Pre-Salt.

Well	Total Interval (m)	Gun Size (in)	Longest Gun String (m)	Number of Runs	Operational Time (h)	Time per Run (h)
A	91	7	30.80	3	31.00	10.33
B	134	7	28.96	5	46.00	6.80
C	95	7	32.02	3	23.00	7.67
D	158	7	28.97	6	40.00	6.67
E	163	7	33.96	5	42.50	8.50
F	119	7	25.54	5	50.50	8.30
G	114	7	28.97	4	49.50	9.75
H	162	7	42.00	4	32.00	8.00

Source: Author.

The TCP team also constantly improved their efficiency to compete with the wireline method. At the time of the mentioned jobs, TCP operation was no longer taking 72 hours but 52 hours instead. Despite the maximum daily rig rate of more than 1 million dollars (MOTTA et al., 2015), the study used a more conservative daily spread rate for the drilling rigs – USD

750,000 – in the pre-salt fields. The new reference numbers for both methods are shown in Table 15 and became the guideline for perforating method selection.

Table 15 – Perforating techniques new times and lengths comparison for the Brazilian Pre-Salt.

Wireline Run Time (h)	Wireline Gun Length per Run (m)	TCP Total Time (h)	Rig Daily Spread Rate ($ USD)
8.50	42	52	750,000.00

Source: Author

The new comparison numbers proved it is now possible to execute a perforating job of 6 runs, against the 5-run previously stated, using wireline conveyance and still be faster than a TCP run if there was no other operation planned to use the drillpipe nor fluid losses were expected. The total perforating interval, on a 6-run wireline job, considering a 42 m gunstring the current maximum interval per run, is now 252 m as demonstrated in Table 16.

Table 16 – Total time and length for wireline runs – Enhanced method.

Number of Runs (m)	Total Time (h)	Total Length (m)
1	8.5	42
2	17.0	84
3	25.5	126
4	34.0	168
5	42.5	210
6	51.0	252
7	59.5	294
8	68.0	336
9	76.5	378

Source: Author.

As this study intends to analyze the technical and economic aspects of this endeavor, it will be considered only 5 wireline runs for the comparison. Even though a job with 6 wireline runs would save rig time when compared to the TCP technique, the costs saved are not enough to replace the technical benefits of the pipe conveyance technique. As explained in this work, the TCP conveyance brings the possibility of fluid loss control, or an acid treatment right after the perforation, while the wireline method increases the risks of an Unintentional Pull Off (UPO), with the weak point rupture or cable damage due to the high mechanical loads downhole. The operational time gain is not enough to trigger the use of a cable to perforate the long intervals, even saving a considerable amount of money due to the removal of blank guns from the TCP string. For the competition zone, between 90 m and 210 m, there were a total of 40 wells perforated segregated as per Table 17, from 2016 to 2019. One additional well was perforated with wireline method in 2019 being added to the data base.

Table 17 – Number of wells perforated per field with an average payzone between 90 m and 210 m.

Field	Number of Wells
Tupi	32
Mero	3
Atapu	1
Berbigão	1
Búzios	1
Itapu	1
Sapinhoá	1

Source: Author.

The chosen technique for the 40 wells is listed in Table 18. The list shows TCP as the preferred method, with 32 wells versus 8 wells perforated by wireline.

Table 18 – Number of wells perforated per field and conveyance method.

Field	Number of Wells	Conveyance Method
Tupi	6	Wireline
Mero	2	Wireline
Tupi	26	TCP
Mero	1	TCP
Itapu	1	TCP
Sapinhoá	1	TCP
Atapu	1	TCP
Berbigão	1	TCP
Búzios	1	TCP

Source: Author.

The average perforated interval for the 32 wells analyzed was 154 m. Then, for such executed TCP jobs in these 32 wells, 4 wireline runs would be enough to cover the average interval considering the new limit of 42 m per run. Taking into account only the operational time as a decision point, it is simple to calculate the amount of rig time saved if all wells were perforated using wireline conveyance. For the giving period – from 2016 to 2019 – and considering a spread rig rate of USD 750,000.00 per day, to be on the conservative side of the rig spread rate mentioned by Motta et al., (2015), a total amount of USD 18,000,000.00 would have been saved, as demonstrated in Table 19.

Table 19 – Estimated rig cost savings with wireline conveyance method for the 32 wells analyzed.

Average Run Time (h)	**Average Number of Runs**	**Average Total Time per Job (h)**	**Estimated Rig Time Saved per Job (h)**	**Number of Wells**	**Estimated Total Rig Time Saved (h)**	**Total Rig Cost Saved (USD)**
8.5	4	34	18	32	576	18,000,000.00

Source: Author.

4.2 TECHNICAL LIMIT OF WIRELINE PERFORATING

Referring to Case Study #2, where no cable weak point was used, this work simulated a fictitious situation to understand and establish what would be the technical limits utilizing the same parameters, equipment, and know-how presented in the industry today.

Considering a service request shown in Table 20, from an operator to a service company, the job was simulated to maximize the length per wireline run. It should be noted that all parameters chosen were similar to those in Case Study #2 and the total interval to be perforated was the upper limit of gray zone (210 m).

Table 20 – Theoretical service request for a perforating job.

Parameters	**Values**
Field	Theoretical
Fluid in the Reservoir	Oil
Borehole Diameter	12¼ inches
Deviation	0 degrees
Casing Size	9⅝ inches
Casing Weight	53.5 pounds per foot
Gun Size	7 inches
Gun Type	High Shot Density
Gun Density	12 shots per foot
Interval to be perforated	210 meters*
Losses expected?	No
Additional operations expected?	No

Source: Author.

The formation parameters used in the simulation, presented in Table 21, are generic petrophysics parameters found in the Brazilian pre-salt. It was previously described in the literature review section of this work.

Table 21 – Brazilian pre-salt petrophysics parameters.

Reservoir Fluid	**Rock Type**	**Porosity (%)**	**Temp. (°C)**	**Permeability (mD)**	**Rock Strength (psi)**	**Pore Pressure (psi)**
Oil	Limestone	10-15	56-95	0.65-2,000	3,000-9,000	8,600-13,645

Source: Author

For the simulation, it was also used the equipment presented in Table 22. The fictitious case adopted the same strategy used in Case Study #2, where no weak point was added to the system.

Table 22 – Wireline conveyance equipment.

Parameters	**Values**
Cable Safe Working Load	18,000 lb (8,164.6 kg)
Conveyance Method	Wireline
Weak Point	N/A
Gun Release System	Mechanical cable cutter
Shock Absorbers	No
Maximum Gun Length	6.096 meters

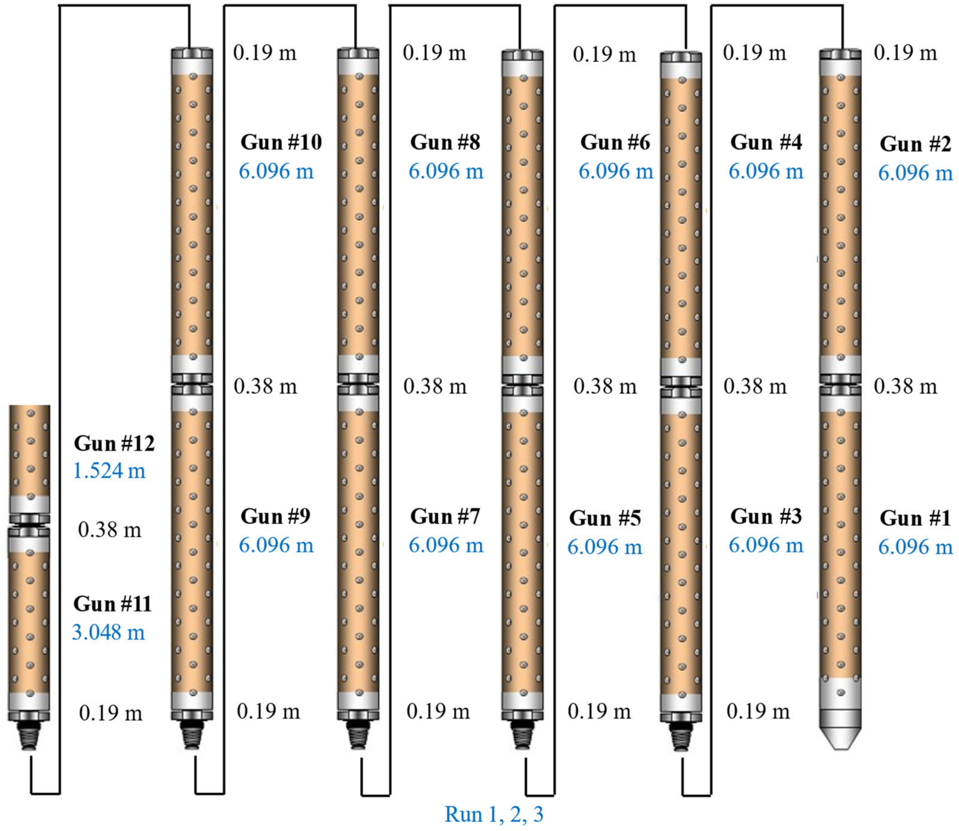
Source: Author.

When a weak point is present in the system, the service companies determine that the load limit of the cable-weak point system must be 75% of the lowest weak point rate. Then, it was adopted the same concept and margin for the wireline cable, as this is a weak point-free scenario. For this, the upper limit for the load on the cable was 13,500 lb (6,123 kg) as the used cable owned a safe working load of 18,000 lb (8,164.6 kg).

To make this scenario as close as possible to a real job design, it is necessary to evaluate the operational aspects of the job. During the gun rig-up operations, before running the gunstring in the wellbore, the guns are connected and lifted by the wireline cable. Due to safety reasons, the total weight of the gunstring should not exceed 75% of the cable working load, thus a limit of 13,500 lb (6,123 kg) for the gun's weight in the air was imposed for the simulation. According to the mechanical data sheet from one of the service companies, a gunstring with 11 guns with an outer diameter of 7 in and individual length of 6.096 m, loaded with 12 SPF, weighs 13,545 lb (6,143 kg) in air. This weight is above the 13,500 lb (6,123 kg) limit adopted for the cable-safe working load.

The total interval to be perforated was then split into 3 runs, circa 70 m each. Knowing that each gun weighs 558.456 kg, the maximum weight per run was 13,302 lb (6,033 kg), as explained in Figure 29. Table 23 presents the runs' configuration, considering the weight in air as the limit for the total length per run.

Figure 299 – Runs and guns configuration – Total length 210.54 m.



Source: Author.

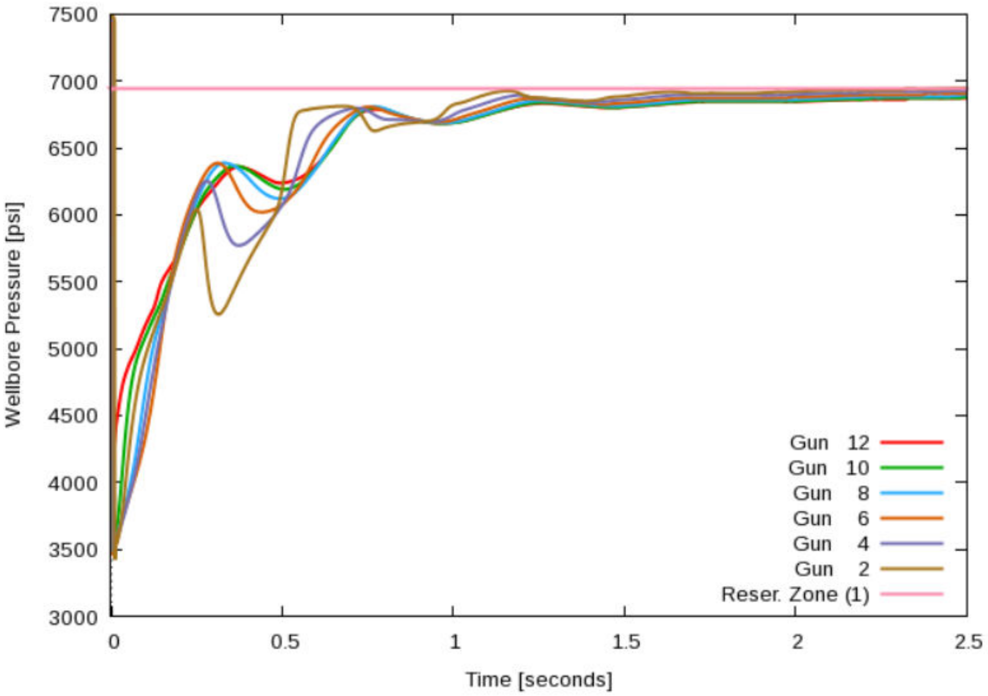
Table 23 – Runs configuration – Maximum gunstring length case.

Run number	Total length (m)	Weight in air (kg)	Number of 6 m guns	Number of 3 m guns	Number of 1.5 m guns
1	70.18	6,033	10	1	1
2	70.18	6,033	10	1	1
3	70.18	6,033	10	1	1
Total	**210.54**				

Source: Author.

Through simulation using SPAN, the proposed gunstring configuration will generate a dynamic underbalance of approximately 3,500 psi, as demonstrated in Figure 30. The wellbore pressure will be lower than 4,000 psi and is responsible for the downhole forces and gun movement.

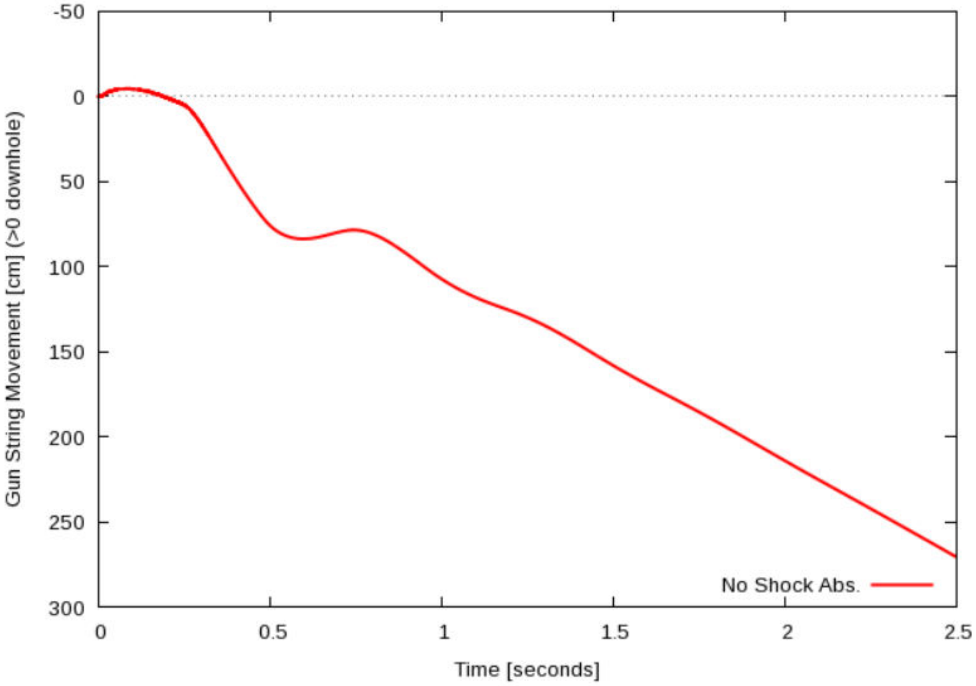
Figure 30 – Simulated pressure transients of the 70.18 m gunstring during detonation.



Source: Author.

The hydrodynamic forces caused by the dynamic underbalance will generate the gun displacement as previewed in the simulation resumed in Figure 31. As can be seen, the entire gunstring will move approximately 2.7 m in the downward direction and will cause additional stress on the cable head.

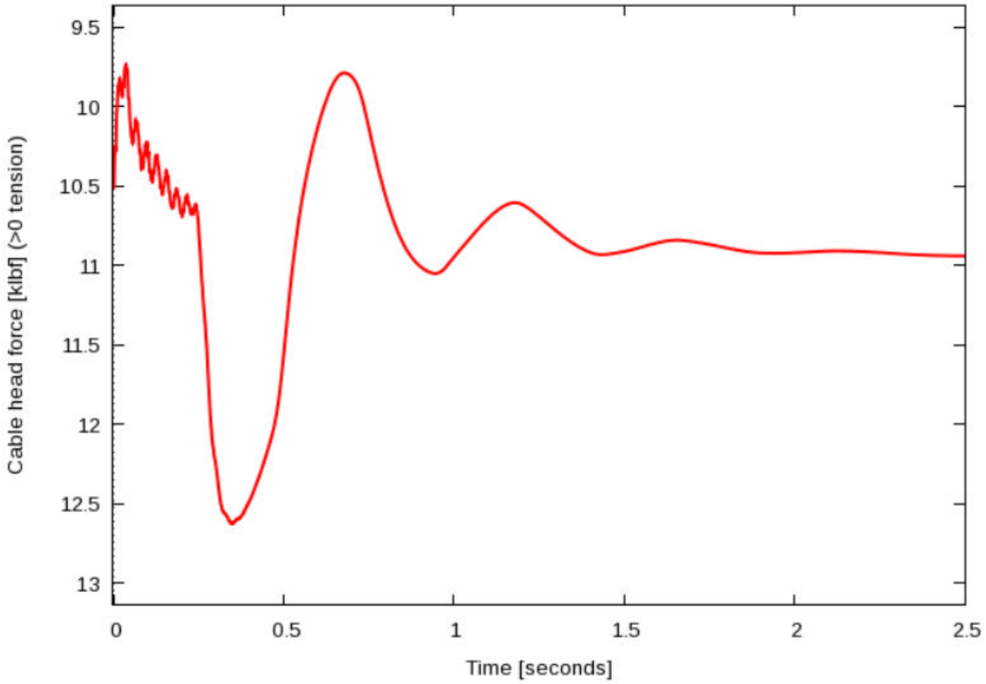
Figure 31 – Simulated gunstring movement caused by downhole hydrodynamic forces.



Source: Author.

As shown in Figure 32, before the detonation, the cable head force for the 70.18 m gunstring while immersed in the wellbore fluid was approximately 10,500 lb (4,762 kg). The shock waves will force the gunstring in a downward direction adding more than 2,000 lb (907,2 kg) to the cable head due to the charge's detonation and wellbore fluid displacement. Then, the cable head will be submitted to approximately 12,650 lb (5,738 kg) of force, still below the 13,500 lb (6,123 kg) limit imposed by the 75% safety margin.

Figure 32 – Simulated cable head force during the detonation of 70.18 m of 7 in gunstring.



Source: Author.

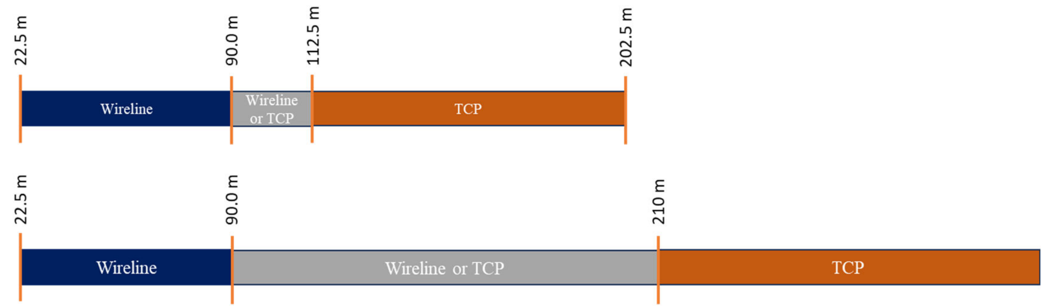
4.3 DISCUSSION

The new wireline perforation technology jobs analyzed in this study took an average of 8.5 ± 1.83 hours per run. It is a reduction of 22.7% when compared to the 11 hours considered as a reference before the enhanced wireline system was launched. This increase in operational efficiency helped by opening even more the gap between operational times. The number of hours saved was now sufficient to justify a technique with more operational risks.

As demonstrated in Case Study #2, by removing the weak point from the wireline system, the company gained a margin on the safe working load limits. The wireline cable then became the rupture limit. As the cable weak point is an important piece of the wireline conveyance method, a nonorthodox solution was proposed to overcome the risk of a stuck gunstring scenario. The company suggested a mechanical cable cutter to release the gunstring from the cable in case the guns get stuck. With this change, the engineers gained 80% on the system limits, elevating the margins from 7,500 lb (3,401 kg) – 75% of the lower weak point rate 10,000 lb – to 13,500 lb (6,123 kg) – 75% of the 18,000 lb safe working load of the cable used.

With the new tension limits, gun lengths, and operational times in place, the wireline technique extended its range of actuation to be timely competitive in perforation jobs with intervals as long as 210 m, or 5 runs of 41.90 m. Figure 33 shows the comparison between the previous and the new suggested limits per conveyance method.

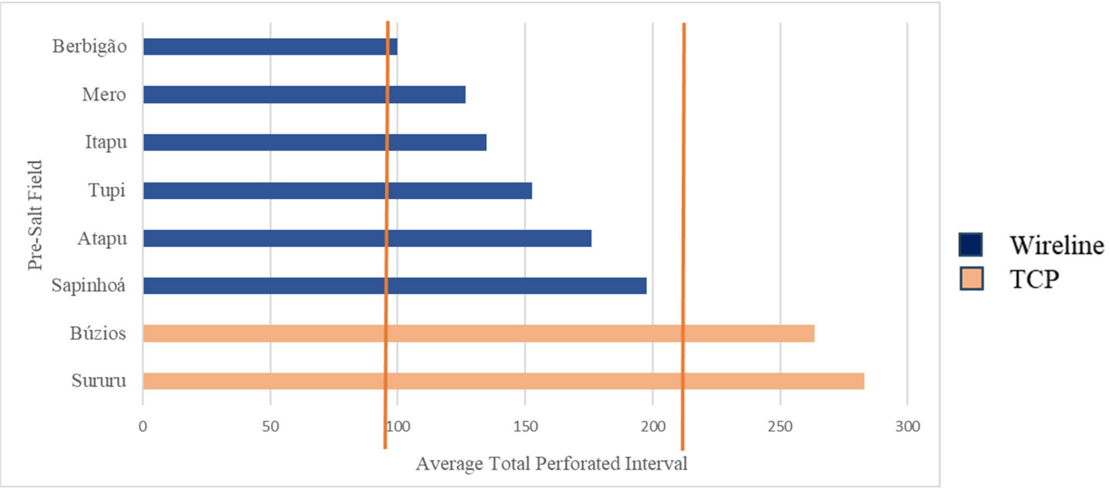
Figure 33 – Payzone lengths previous and new limits comparison per conveyance method.



Source: Author.

The historical analysis also identified the fields where the average total meterage is favorable to each technique, considering the rig time-saving aspect only. Figure 34 depicts the different meterage per field perforated between 2016 and 2019 and shows which technique would be more beneficial to each field in the Brazilian pre-salt. In 6 of the 8 fields, where the perforated wells analyzed in this study are located, the wireline method could be confidently chosen as the preferred technique considering the average perforated interval per field.

Figure 34 – Suggested conveyance method per Brazilian pre-salt field.



Source: Author.

For the economical aspect of this work, the wells analyzed comprehended those whose perforating intervals were between 90 and 210 m, as this interval was identified as the gray area where both conveyance methods can compete, taking into consideration rig time saving only. The savings on rig time per job are presented in Table 24. Data show clearly that the wireline is more advantageous for up to 6 runs when compared to the TCP conveyance method.

Table 24 – Rig cost saved per job for different numbers of wireline runs.

Wireline Run Time (h)	Number of Runs	Wireline Total Time per Job (h)	TCP Total Time per job (h)	Estimated Rig Time Saved per Job (h)	Hourly Spread Rig Rate (USD)	Total Rig Cost (USD)
8.5	2	17.0	52	35.0	31,250	1,093,375.00
8.5	3	25.5	52	26.5	31,250	828,125.00
8.5	4	34.0	52	18.0	31,250	562,500.00
8.5	5	42.5	52	9.5	31,250	296,875.00
8.5	6	51.0	52	1.0	31,250	31,250.00

As explained before, the cost reduction to run wireline guns for intervals larger than 210 m – around USD 31,000 – was not enough to justify the additional risks of the cable conveyance operation. A limit of 5 cable runs was defined for the wireline operations. For 5 runs of perforating job, the economy on rig time is approximately USD 300,000, when compared to a TCP job, and can be as large as USD 1,000,000 for 2 wireline runs, or 84 m, perforating interval.

With the ability to split runs to accommodate non-continuous payzone, wireline also presents a financial advantage over TCP. There is no need to use blank (or empty) guns as spacers to separate intervals to be perforated. This advantage minimizes the number of guns to be charged by service companies and also reduces the waste and material footprint.

The proposed simulation exercise proved it is technically possible to detonate a 70.18 m gunstring safely considering no cable weak point is used and the current equipment available in the industry. The technique proposed utilizes common industry standards for the pre-salt fields. However, every job is unique, and the simulation needs to be done considering every case. It should be noted that different parameters such as well deviation and the proximity of the guns to the bottom of the well can change the results considerably.

As the gunstring length per run increases, the operational time will also increase, as the field crew will need to connect more guns during rig up procedure. The designers will need to perform a detailed analysis to compare new and current operational times. The service companies will need to define new procedures for operators to accept longer wireline gunstrings in their wells. Longer perforating gunstrings mean more operational risks for both TCP and Wireline conveyance methods. But despite the risks associated with both techniques, the pursuit of more efficient operations in the Brazilian pre-salt fields is inevitable.

5 CONCLUSIONS

As observed throughout this present work, several variables make the perforating operation an overly complex operation in the well. However, despite its complexity, there is a solution for almost every challenge.

The present work aimed to compare the techno-economic feasibility between Wireline and TCP methods of perforating wellbores. By analyzing the data of one service company operating in the Brazilian Pre-Salt, the study was able to define the thresholds for each technique in different fields.

The new wireline perforation technology jobs analyzed in this study took an average of 8.5 ± 1.83 hours per run, which means a reduction of 22.7% when compared to the reference value of 11 hours. So, these hours saved are now sufficient to justify a technique with more operational risks as the Wireline conveyance.

As demonstrated in Case Study #2, by removing the weak point from the wireline system, making the limit be the wireline cable rupture, and using a cable cutter to the stuck gun scenario, the margin on the safe working load limits was extended to 13,500 lb, corresponding to 80% on the system limit.

For the economical aspect of this work, the wells analyzed comprehended those whose perforating intervals were between 90 and 210 m, as this interval was identified as the gray area where both conveyance methods can compete, taking into consideration rig time saving only. Then, with the new tension limits, gun lengths, and operational times in place analyzed, it was seen that the upper limit of perforated interval was pushed to 210 m.

Data showed that the wireline is more advantageous in terms of cost savings, for up to 6 runs when compared to the TCP conveyance method. However, it is recommended a limit of 5 runs for the wireline perforating job considering safety aspects, which would correspond to USD 300,000 of economy on rig time when compared to a TCP job.

It can be concluded that, below 90 meters, TCP shows no advantage due to the long run time, and above 210 meters wireline conveyance method does not justify the risks of the operation against the money savings. However, every perforating job is unique because of the complex variables involved and simulations must be carried out considering every case's particularities.

As a suggestion for future studies:

a) Open-hole completion is being largely used nowadays and perforating is not necessary for this type of well construction. A cost comparison amongst TCP conveyance, wireline, and open hole completion is indicated to evaluate the best of the 3 options.

b) Technical simulations for stronger cables. Some free torque cables with safe working loads of 26,000 lb (11,793 kg) are already available in the industry. This could improve the length per run on the wireline conveyance method.

c) Addition of other operations variables and considerations in the study to enrich the results by considering all the aspects of the operations including the necessity of additional or sequential operations such as acid treatment, and/or fluid loss prevention.

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APPENDIX A – ARTICLES FROM THE PRESENT WORK

A.1 WELL PERFORATING – MORE THAN RESERVOIR CONNECTION

The manuscript entitled “Well perforating – more than reservoir connection” was published in the Upstream Oil and Gas Technology Journal (ISSN 2666-2604), https://doi.org/10.1016/j.upstre.2023.100088. The manuscript addresses a review of perforating methods and was used as the Literature Review Chapter of the present Master’s Thesis.

A.2 TECHNO-ECONOMIC ANALYSIS OF WELL PERFORATING IN THE BRAZILIAN PRE-SALT USING TCP AND WIRELINE GUN CONVEYANCE METHODS

In compliance with the publication criteria required by the postgraduate course, the article entitled "Techno-economic analysis of well perforating in the Brazilian pre-salt using TCP and wireline gun conveyance methods" was submitted to Geoenergy Science and Engineering (the former JPSE – Journal of Petroleum Science and Engineering) and is under analysis.