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Perforating System Selection for Optimum Well Inflow Performance

KENT FOLSE, MELISSA ALLIN, Halliburton Energy Services, Inc., CHRIS CHOW, ProDuce Consulting,
and JOHN HARDESTY, Jet Research Center

Abstract

Oilfield operators and service companies continually are faced with challenges to provide completions that not only produce at optimum levels but also accelerate return on investment (ROI). The operational demands faced today are further complicated by a rapid expansion of the range of reservoir scenarios. When attempting to find methods to accomplish the above goals, the industry often overlooks one very important component of the completion process—perforation.

In the energy industry, many companies base selection of shaped-charge perforators solely on API Section I criteria such as depth of penetration or casing-exit hole size. This paper is proposing that other factors, such as the actual performance of given shaped charges at in situ conditions, also should be evaluated when making perforating decisions for the completion process. Focusing perforator system performance on reservoir productivity rather than on the shaped-charge performance optimized for concrete testing (which is the case with API Section I) can ultimately lead to significant improvement in well-inflow performance.

Although API RP43 Section IV perforating procedures (to evaluate well perforators under in-situ conditions) have existed since 1985, field validation of experimental results and model predictions based on these procedures has been limited. This paper will discuss insights gained from a series of Section IV tests conducted with Berea and Castlegate sandstone cores under varying in-situ conditions. The Section IV lab experiments represent physical models of the near-wellbore region during perforation and completion processes under in-situ stress. The results of these experiments indicate that understanding the inherent system inadequacies and experimental conditions is critical to proper integration of the results with theoretical models and field data.

Introduction

Jet perforating has been used since the late 1940's, and although the hardware and systems could be considered a mature technology, analysis tools for designing and optimizing perforated completions are fairly rudimentary and often based on "rules of thumb." Furthermore, the range of application for the multitude of perforating options (e.g., charge type and size, shot phasing and density, tubing versus wireline conveyed, under- versus over- or extreme-balance pressure differential) lacks definition.

Accurate quantitative tools and processes are critical to accurate analysis of real time data and are critical to the delivery of value-added real-time solutions. Several different technical tools and methods have capability to predict inflow performance. However, their range of accuracy and range of applicability generally have had minimal validation, in part due to reservoir characterization issues. Furthermore, theoretical equations for "skin" (i.e.; the parameters used to quantify the difference between theoretical predictions and actual results) have limited applicability in predicting performance to assess design options. Consequently, optimization has traditionally focused on costs, often resulting in sub-optimal system performance and tremendous loss in value. The industry now recognizes the need for a validated, quantitative method to predict inflow performance and its associated range of accuracy.

Although perforating is the primary (and sometimes sole) means for establishing connectivity with the reservoir in all cased completions, it is often taken for granted in the completion design process. The selection of shaped charge perforators is based solely on API Section I (concrete targets shot under surface conditions). Data such as penetration and inflow performance of given shaped charges under in-situ conditions are often not considered. Rarely is there sufficient field data to validate the impact of charge performance on well productivity. Consequently, the natural conclusion is to assume that the largest penetration and/or exit hole size delivers the best productivity. A change in focus towards reservoir productivity and well inflow performance (i.e., not just shaped charge performance in Section I) will ultimately improve selection of perforator system design and implementation, as well as performance.

Perforation: Penetration vs Performance?

Most would agree that understanding and predicting perforation inflow performance is critical for predicting well inflow performance in natural (cased and perforated) completions. The same is true to a lesser degree in fractured or sand control completions where additional operations are conducted to enhance or assure a reliable connection to the reservoir.

The first requirement for predicting perforation inflow performance is an accurate description of the perforation geometry. *API Section I* tests are designed to provide a simple means to assess charge penetration performance using standard field guns. The multiple-shot tests are conducted in concrete, and measured penetration depths are recorded. Concerns have been raised that charges can be designed to optimize performance in any material, and hence, comparison in concrete targets may be misleading for selecting charges for rocks with different properties. .

Section IV Tests: Art or Science?

The Section IV test arises from a set of recommended API procedures designed to assess performance of perforating gun systems. The purpose of the Section IV test is to assess perforation inflow performance for a single shaped charge explosive under simulated in-situ stress and perforating conditions.

Numerous papers have been written on pioneering work and results using Section IV tests; in particular, inflow damage created during the perforating operation and optimal perforating conditions to remove the damage have been documented. However, literature has limited documentation on the standardization or repeatability in conducting these tests, in part, because of test complexity, and perhaps, because there are limited test facilities with which to compare results. Furthermore, a large percentage of the published results are based on small charges (3.2 and 6.5 gm weight explosives) not typically used in well completions. Depending on whether inflow performance is unique to each charge, some questions remain regarding the universality of the results and how to implement these results to design and optimize perforating gun systems for field application.

Perforating Hardware Solutions

There are a multitude of perforating options varying in charge type, gun size, shot density, phasing, conveyance method (tubing vs wireline), wellbore fluids, and perforating shot conditions (under/over/extreme over balance). While many combinations of these options have been applied in field perforating systems, debate still exists over their relative benefits (e.g., shooting under- versus overbalance, tubing conveyed versus wireline, and charge selection). In addition, technical analyses have been developed to quantitatively address components of an optimized perforating system (e.g., optimum underbalance or charge performance), but rarely, the entire system itself. This is in large part due to the magnitude of parameters and the difficulty in validating the quantitative impact in the field. Many questions still exist concerning the entire range of perforating systems and their application:

1. How to predict their impact on inflow
2. When should a given perforating system be applied
3. Can different parts be interchanged (e.g., does each charge have the same optimum underbalance based on permeability)
4. What are the risk factors to achieve predicted performance?

The Engineered Completion: Is It Possible?

This presentation will discuss insights gained from a series of more than 70 Section IV laboratory tests conducted with Berea and Castlegate sandstone cores with shaped charges ranging from 14.7 to 39 gm weight explosive under different in-situ conditions. The laboratory setup is designed to achieve results that are representative for scale up to actual field conditions. The principle parameters that can be modeled in the laboratory are the overburden stress and the initial wellbore and pore pressures. In addition, other parameters can be evaluated in the perforation flow laboratory to assess the affects on well productivity, such as:

- Gun Design – charge type, phasing, shot density, gun types and sizes
- Charge Performance – penetration, hole size, tunnel geometry, gun standoff, eccentricity
- Conveyance Method – tubing conveyed perforating, wireline, extreme overbalance, oriented guns
- Reservoir Characteristics – permeability, porosity, grain size, compressive strength, unconfined compressive strength (UCS), formation fluid type, completion fluid type

The laboratory tests represent one component of a multi-pronged approach to engineer completions based on a whole-life, whole-value philosophy.

Perforation Flow Laboratory Setup

The fundamental configuration of the Jet Research Center's Perforation Flow Laboratory is based on the *API Recommended Practice 19B Section IV Specification* (see **Fig. 1**). In this system, a sample target can be perforated with a single shaped-charge explosive under in-situ stress and pore pressure conditions, and then, flowed to simulate well inflow performance or injectivity for various completion and production operations.

The system consists of a pressure chamber to apply in-situ stress to a reservoir or outcrop cylindrical core sample, a wellbore section mounted against one face of the sample, and a flow loop to apply pore and wellbore pressure to appropriate sample boundaries. The test methods will be discussed in the conference presentation.

The Test Results

The first test series was performed with Berea sandstone outcrop rock using a 14.7 gm deep penetrating shaped charge. Berea sandstone is a consolidated formation with permeability ranging from 150 to 300 md and an average porosity of 20%. The results presented for one of the eight cores was performed at the same effective stress condition. Other factors such as underbalance condition (balanced\over\under) and dynamic surge chamber volume were also varied to evaluate their impact on productivity (see **Table 1**).

Perforation geometry is classically described as an open cylindrical tunnel where the diameter is independent of the length. The perforation geometry is cylindrical for much of the tunnel, except near the tip where it is more conical. In some cases, the tunnel is filled with crushed target material and residual liner debris, forming a "plug tip." While perforating debris has been reported before, it is traditionally reported as loose debris in an open tunnel. Loose debris is also observed in some tests; however, in Fig. 1, the tunnel is clearly not completely open. The total penetration into the core is designated as total penetration length (L_P), whereas the total penetration length minus the plugged tip length is referred to as the productive tunnel length (L_{PT}).

The second series of tests was performed with Castlegate sandstone outcrop rock using a 14.7 gm deep penetrating shaped charge. The test conditions for the four cores under study are presented in **Table 2**. The Castlegate sandstone is a weakly consolidated formation with permeability ranging from 750 to 1,050 md and an average porosity of 25%. For the Castlegate series of tests, the dynamic surge chamber volume is held constant, and the initial static differential pressure is varied to study effects on productivity. The core that was shot with an overbalance of 3,500 psi exhibits the greatest degree of perforation plugging (lowest L_{PT}) and a correspondingly low PI ratio. The core that was shot with maximum underbalance of 3,500 psi revealed an L_P equal to L_{PT} resulting in the highest PI ratio. For the Castlegate series, the data show that L_P is primarily a function of the type of charge and the effective stress applied to the core; however, the L_{PT} is primarily a function of the static differential pressure.

Discussion

The plug at the end of the open perforation tunnel was observed in different tests and is related to shot conditions where a larger under-balance pressure differential results in a greater L_{PT}. For a given shaped charge, there is an optimum shot condition to achieve a productive tunnel length equal to the total penetration. The magnitude of L_{PT} is also related to flow

Table 1—Test Data Berea Samples

Test	**Perm**	**Under / Overbalance**	**Dynamic Surge Chamber Vol**	**Overburden**	**Pore Pressure**	**Productivity Ratio**
No.	(md)	(psi)	(cc)	(psi)	(psi)	
1	289	0	308	4500	1500	0.8296
2	234	-500	562	5000	2000	1.1439
3	207	-500	562	5000	2000	0.9521
4	180	0	562	4500	1500	1.0518
5	218	0	1430	4500	1500	1.0727
6	152	2000	2860	4000	1000	1.0518
7	215	0	2860	4500	1500	1.2168
8	263	-500	0	5000	2000	1.0454

Table 2— Test Data – Castlegate Series

Test	Perm	Under / Overbalance	Dynamic Surge Chamber Vol	Overburden	Pore Pressure	Productivity Ratio
No.	(md)	(psi)	(cc)	(psi)	(psi)	
1	1044	0	335	9000	5000	1.082
2	751	-3500	335	9000	5000	1.4275
3	1068	3500	335	5500	1500	0.9921
4	761	-3500	335	5500	5000	1.847

geometry (i.e., axial versus radial). While the API recommended practices allow radial or axial-flow geometry, and methods are given to analyze flow data for either geometry, flow test results under the same shot conditions can be very different. The actual flow geometry downhole is different from both axial and radial lab flows and depends on perforation spacing (i.e., shot phasing and density) and reservoir parameters such as permeability stratification. The task of scaling lab results to downhole conditions is not trivial.

Damage from the perforating event has been classically described via a "crushed zone." In this model, the shock waves generated by the explosive impact of the perforating jet lower the matrix rock's permeability in a radial zone surrounding the perforating tunnel. Lab measurements on cores perforated with a single shot indicate that the permeability of the rock immediately adjacent to the tunnel in some cases may actually be higher than the virgin rock. This phenomenon has resulted in the theory that the initial boundary of the damaged zone is located in the rock matrix, extending 0.4 inches or more beyond the perforating tunnel. The results from this work suggest an alternative (or possibly complementary) theory. Further studies are required to understand how these parameters vary with static and dynamic underbalance, and if cores with a plugged tip have additional damage.

The industry has generally recognized that static underbalance pressure differential is the primary means to optimize perforation damage cleanup. Through proper design, a dynamic surge can be achieved to give LPT equal to LP. While this has been demonstrated in the laboratory, further tests are required to calibrate for field utilization. The dynamic surge is a complicated event with many variables that are difficult to quantify with a high degree of accuracy. Field data from high-speed recorders (micro-to milli-seconds) can be used to quantify these parameters and to understand other physical phenomena during live field perforating operations under downhole wellbore configurations. It has been suggested that the understanding of the dynamic event (explosive and surge) is possible with numerical simulation models in combination with the use of high-speed recorder data. An example of the dynamic surge event from an actual field run with a high-speed pressure recorder on a TCP job is shown in Fig. 2.

Conclusions

- The test results confirm some long-held beliefs in the industry and also shed some new insights into the perforation process
- The common belief that higher underbalance is required to achieve more productive perforations is apparent in the test results for most cases
- The results also show that balanced and overbalanced shot conditions can also result in similar productivities when properly designed
- Field validation and further optimization can be achieved with additional high-speed data
- Lack of industry standards for API Section IV testing makes it difficult to make comparisons with other results published in literature because of the differences in test setups and test methodology.

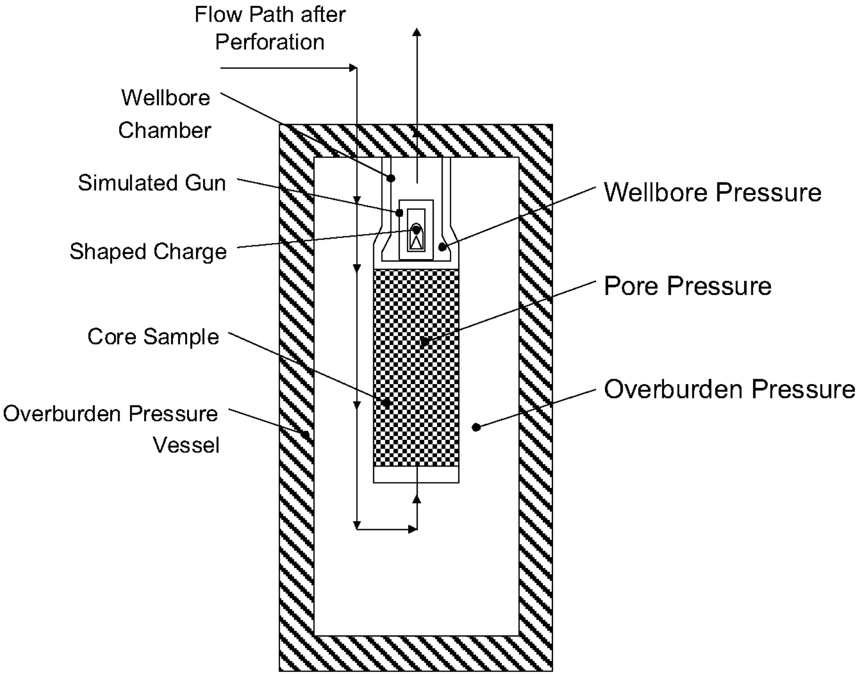

Fig. 1 — Perforation Flow Laboratory

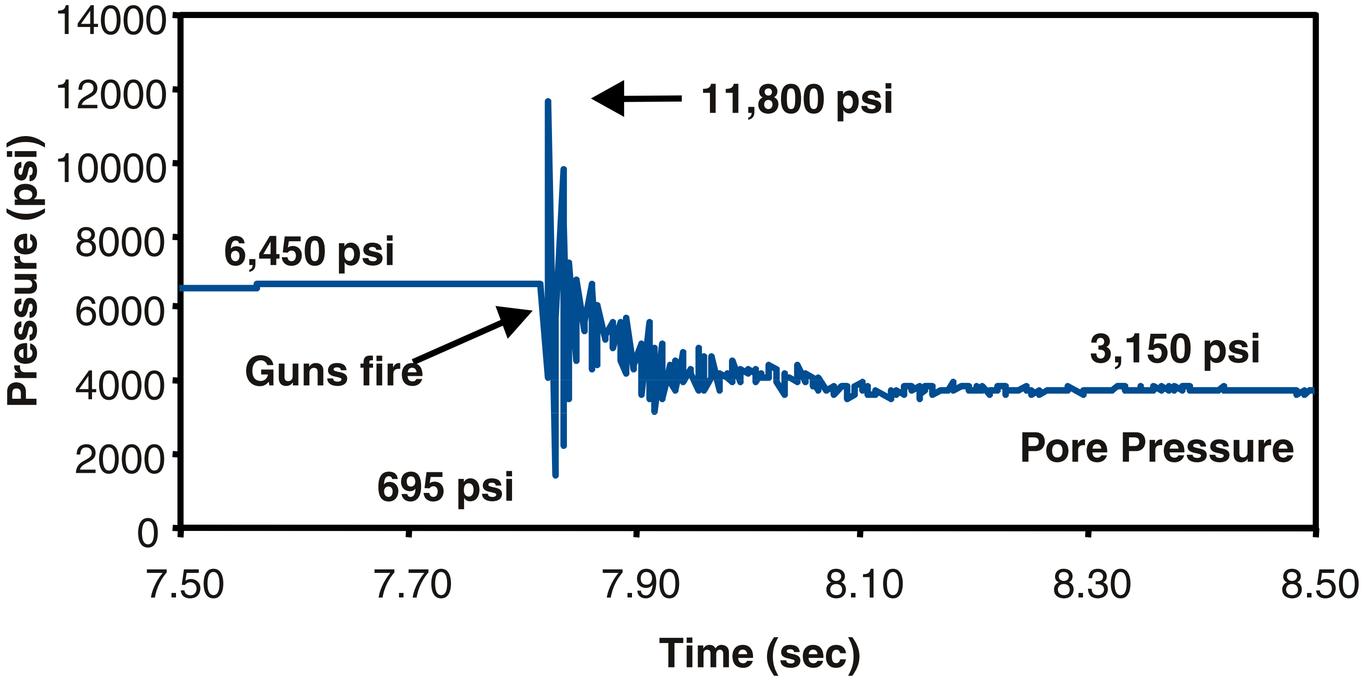

Fig. 2 — High-Speed Pressure Data TCP Job