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Predicting Downhole Shaped Charge Gun Performance – Viability of Method

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Abstract

The viability of predicting shaped charge gun penetration in the reservoir—from API published performance data in concrete—is examined in the light of significant new data.

Examined are the influence of the major factors affecting the method, namely, accuracy of the API RP 43 published data utilized in the prediction, suitability of the projection curves (Thompson/Weeks) being used, data quality/statistics, aspects of charge optimization and effect of prediction error on computed well productivity.

This review confirms that the method is reasonably accurate and that the current API SC 19 (RP 43) Committee program to improve accuracy and credibility of data will enhance its utility.

Introduction

A simple method for predicting downhole Shaped Charge gun performance from API RP 43 data was published in 1994.[1] Questions have since persisted as to the accuracy of the method, with particular focus on whether the Thompson/Weeks relationships[1,2,3] are valid with today's shaped charges.

Suitability of the published API data[4] utilized in the prediction has been under question.[5] Effects of target sand grain size are shown to produce "significant" variations in the data (10% or more).[6,7] That the API data published by the manufacturers indeed represents performance of the field charges persists as well.

The observation that charges can be optimized for a particular formation has further fueled concerns about accuracy of the method when utilizing base data in the API Section I concrete target.

This paper reviews the basis of concern for accuracy, utilizing data from a recent SPE paper[5] and data developed by the API Subcommittee on Perforating.[6] Discussed are the viability of the predictive method in light of the new data, the significance of optimization of charge performance in specific formations, accuracy aspects of the shaped charge and current API actions to improve data accuracy and credibility.

Suitability of the Predictive Method in Light of Recent Data

The method[1] utilizes API RP 43 data, fitted to the Thompson/Weeks curves to project to downhole shaped charge penetration. The manner of fit was based on an extensive data base of Section I concrete vs Berea sandstone penetration from years of API testing. In other words, concrete penetration was related to Berea which was in turn applied to the Thompson/Weeks curves for projecting downhole. In the process, other corrections were made to compensate for Section I target properties and to introduce the influence of effective stress.

Introduced in 1994, the method has been extensively used in Nodal analysis programs. But no further effort to investigate its validity has been performed, until now.

A recently published series of tests (SPE 52203)[5] represents perhaps the most comprehensive set of test data developed in many years. The test series comprises some 504 test shots, into 7 different target media, using several different charges. A unique approach was followed to optimize each charge in each of the media, then test firing in all others.

While intended primarily to illustrate the principle that a shaped charge can be optimized in any particular target media — an objective previously established in the literature[8] — the data serves also to check the viability of the predictive method.[1]

Concurrence of data with the predictive method is first examined by applying the test results of the author's principal data on Optimized Charges A, B and C to the model, shown in Figs. 1, 2 and 3 respectively. Here a general trend to fit the model is suggested, along with possible problems due to data scatter (addressed later). And Nugget is an unexplained anomaly evident across the entire test series.

Examination of the Unoptimized data of Charges D, E, F, G and H shows similar conformance to the prediction.

However, since the predictive model utilizes only API Section I concrete data to estimate downhole penetration, conformance to the model is examined henceforth using only concrete data as reference performance. Fig. 4 shows the normalized data of Charges A, B, C, D, E, F, G, H and Control charges in the various targets. (Normalization is done by determining "best fit" to the Thompson/Weeks curve for each charge, locating the Y axis penetration intercept, then dividing each target data point by the intercept value). From the plot, it is apparent that the bulk of the data points fall within an approximate ± 10% envelope along the Thompson/Weeks curve.

Now, an average of the normalized data is plotted in Fig. 5, where the composite result is seen to conform much closer to the model, at about 5%. This figure is well within the previously published accuracy of approximately ± 10%.[9]

The raw data of all the figures reflects, however, that individual data points can vary widely from the predictive curve by roughly ± 15 to 18%. This range can stem from statistical problems in data development and handling, including:

- The three test shot series, employed in developing data for SPE 52203, presents large potential errors, as will be demonstrated later.
- Questionable handling of compressive strength measurements can result in errors as high as 47%.[10] For example, an error in the Nugget value of 3,500 psi or 23%, would shift the data to precisely fit the predictive curve. Likewise, an error of 10% with the soft Berea brings that data into conformance.
- Higher than usual standard deviation of the charges used in the test, not defined in SPE 52203, can give rise to errors in excess of the typical standard deviation of 5-10% (Detailed below).

To address the evident problem of data scatter and test uncertainties, the authors elected to normalize the data for a collection of charges onto a common predictive curve. Once the data were synthesized in this manner, the data could be averaged in order to mitigate variations in the test parameters. In other words, permit random errors and uncertainties to cancel out in an effectively larger database. So, while test results for an individual charge with it's unique data and corresponding random errors may not appear to conform to the predictive curve, charges in general appear to follow a common algorithm in predicting downhole penetration.

Perspective on Optimization of Shaped Charge Penetration in Hard Rocks

Clearly, optimization in hard rocks can result in penetration gains that would evidently not have been realized from optimization in the API concrete target.[5,8] Fig. 6 shows penetration gains of Optimized Charges A, B, and C. Comparing charges optimized in the typical granite with charges optimized in cement and shot in granite, gains of 16 to 27 % were realized. This is based on penetration increases from 7.01" to 8.88" (+1.87") with charge A; 7.40" to 8.92" (+1.52") with charge B and 10.61" to 12.34" (+1.73") with charge C. Note the insignificant gains in soft Berea in two of the three charges tested.

These small gains in downhole penetration appear insignificant in terms of materially affecting well completion performance, prompting the question, "Is optimization in hard targets truly achieving significant well performance enhancement?"

Interestingly, an inquiry among completion specialists and their geologic colleagues indicate that when reservoir rocks have low porosity and high compressive strength, such as:

- For carbonate formations in the 6-10% porosity range (approximate compressive strength of 9.2 to 13.4 ksi), and
- For hard sandstones in the 12-15% porosity range (approximate compressive strength of 11.9 to 15.5 ksi),

--they would not normally be completed naturally. Rather, these hard, tight rock reservoir systems would be stimulated and therefore emphasis on penetration depth would not be a priority.[11] Shot density, phasing and hole size will likely be more important completion design considerations.

A plot of normalized penetration vs compressive strength is presented in Fig. 7. Natural completions are typically appropriate when compressive strengths are below and/or within the transition zone. Stimulation is indicated in the hard, tight reservoirs shown. Of course, there are exceptions to any such generalization.[8]

Another contention is that optimizing charges in hard rock reservoirs that are naturally fractured is justified on the basis that deeper penetrating charges will intersect more natural fractures and thus increase productivity. Referring to the penetration data above, the question is raised, how much is to be gained by only a 1.5” increase in penetration (over 7.0”) in the two-thirds of the charges tested and/or from 8.0” to 11.5” in the single best case?

If optimization in hard rock is desired, the use of steel as a target would appear to be a far more practical alternative, avoiding high target costs and problems associated with proper compressive strength measurements. Fig. 8 illustrates the surprisingly close agreement in penetration values of charges A, B and C (SPE 52203) optimized in steel and in the respective hard targets. The same data is shown normalized in Fig. 9, where a relatively close fit to the Thompson/Weeks curves is evident. It must be observed, however, that a previous study does not show such close conformance.[8]

It can be concluded from Fig. 8 that optimizing in hard materials for charges to be used in natural completions is ill-advised. For penetration losses are mounting in the lower strength materials where penetration depth is important to natural completion effectiveness. On the other hand, it appears that optimizing shaped charges in API concrete (or other soft material) will insure the desired highest penetration needed for the natural completion.

Optimization of shaped charge penetration in hard formations remains a specialized procedure available for use in specific instances where it might, on occasion, be warranted.

Lack of Performance Consistency of Typical Shaped Charges

Today’s shaped charge performance data is tenuous to use in a study of the type under review because of inconsistency or statistically marginal data. Indeed such variations in data are often greater than expected changes from the parameters being investigated; parameters such as target properties, effects of gun clearance, etc.

Because of this inherent characteristic, studies must be carefully crafted and controlled. Statistical aspects must be heavily emphasized. It must be constantly borne in mind that the results of a study cannot be more accurate than the measuring devices (consistency of the charge and target) being employed. Interpretations and conclusions must therefore be tempered accordingly.

Ordinarily, published API RP 43 data would be used to illustrate typical charge performance variations. Such is discouraged, however, because of widespread concern over the credibility of today’s published data due to questions of quality control, target accuracy, etc. However, a recent test program conducted by the API Subcommittee on Perforating,[6] aimed at refining Section I procedures and targetry, provides opportunity to illustrate the point. That study specified that four charges be selected providing a wide range of penetration, from about 16” to 35”, be very consistent in penetration level (low standard deviation) to minimize errors in evaluating the effects of sand grain size in the concrete target. Target preparation and testing were witnessed by API Sub committee designees. The data, therefore, are considered to be credible.

Results of these tests are shown in Table 1. Detailed results on C33M sand, which is the closest to the existing API specification, are summarized in Fig. 10. Note that Standard Deviation percent (or Coefficient of Variation) ranges from 4.7% to 24.5%. Corresponding dispersion in data ranged from 16.7% to 98.9%. Charges II and III are considered more typical since they performed like their published API RP 43 data—showing Std Dev. % of 4.7% to 10.3%, with dispersion of 16.7% to 37.7%. This latter data are what one would expect to be typical.

Now, the statistical problem of conducting tests using only three (or too few shots) can be readily seen. Observe the spread of data points for charges I and III in Fig. 11. Consider the question, “what three data points will be obtained on a specific three shot test”? The error could be as high as 83% on charge I and 15% on charge III.

Other general observations on the controlled and witnessed API data can be drawn as follows:

a) The test objective of having a wide penetration range of about 16” to 35” was compromised by lack of consistency in performance of charge I; and by the fact that charge IV penetrated 9” or 26% lower than expected. Thus the evaluation of target properties vs. penetration depth across the desired range of penetration was not achieved.

b) 50% of the charges tested (I and IV) did not reproduce their published API RP 43 test data. They dropped respectively from 14% to 26% lower than published values.
c) Performance of charges II and III show that performance consistency can be maintained to a typical level of Std Dev. % of 4.7% to 10.3% with corresponding data dispersions of 16.7% to 37.7%.
d) On a controlled test of this type, given the requirement to provide consistent performing charges, what can one expect of existing published data when 50% of the charges tested fall short of expectation? No wonder the problem of data credibility prevails today. Such is more disturbing, considering that the manufacturers of all the charges are ISO certified.

The API RP 43 Subcommittee on Perforating — Current Program

Foregoing comments on data credibility are not directed to existing procedures per se, rather to the aspect of maintaining proper control of charge performance quality. While one can argue that the API has not provided an adequately "accurate" target because of the issue of sand grain size, it must be remembered that the maximum error anticipated would be somewhat greater than 10%. And in actual application, that value would typically be less due to the randomness of sand grain size naturally occurring in target construction.

Resolution of the above problems in API data quality and credibility is currently being addressed by the Subcommittee:

1) The Section I target is being retained as the primary target for reporting shaped charge performance. In light of the above interpretations, this is entirely appropriate in terms of reasonable accuracy and utility in the determination of downhole penetration (for Nodal Analysis application).
2) Accuracy of the Section I target is being improved from the current 10% or more to a somewhat lower figure.
3) Standardized and improved quality control targetry and procedures are being incorporated.
4) The revised procedure under development will emulate the API Monogram program, which will include auditing and/or witnessing, thus finally addressing the issue of data credibility.

Effect of Shaped Charge Penetration Accuracy to Predicting Well Productivity

When field charges penetrate less than published API data, well productivity will typically be reduced in the natural completion as compared to prediction.

Data from Fig. 10 and Table 1 are used to illustrate the effect, using Charges I and IV which penetrated 13.9% and 26.3% less than published API values.

A simplified presentation of a nodal analysis computation[12] of the effect in both cases is shown in Fig. 12, using a typical sandstone model of mid range compressive strength of 8,000 psi, a permeability of 50 md and an interval of 20'. Other parameters assumed are—Permeability Reduction Factor (PRF), 0.3; 6 SPF; phasing 0 degrees; E.H. as published, 35 gravity oil; 8,000'well depth; 2 7/8" diameter 7,800' long production tubing; reservoir pressure of 3,850 psi; 150 psi well head tubing flowing pressure; well bore damage of 8.0" with Kd/Ko of 0.4.

Pertinent data is outlined as follows:

- Charge I – loss in well productivity, 185 BOPD, or 23%.
- Charge IV – loss in well productivity, 110 BOPD, or 10%.

Of course, the above estimates would change depending on the values assigned to the various parameters in the sensitivity analysis. For example, should no well bore damage be assumed, the above losses would be reduced to 40 BOPD (4.6%) and 80 BOPD (7.2%) for charges I and IV respectively. Also, the interpretation neglects the 5-10% reduction in penetration (under published API data) from one production lot to another as permitted by the respective manufacturing specification.

The above emphasizes that significant losses in well productivity can occur as a result of substandard performance (poor quality control) which is clearly demonstrated to be a potential problem when optimum well flow is being sought.

Conclusions

1) Recent data supports the viability of the predictive method[1] for determining downhole penetration using API RP 43 Section I concrete data.
2) API RP 43 Subcommittee directions to refine the Section I concrete target and improve field quality of the shaped charge support the existing methodology for determining downhole

penetration. These objectives, when finally realized, will enhance accuracy of the determination.

3) While optimization of shaped charge penetration in various rocks is demonstrated as a viable technique, the practice applied to improving penetration in hard rocks is questionable in terms of realistic gains in well performance. On the other hand, optimization in soft rocks is supported as improving well performance in the natural completion — where increased penetration enhances well productivity.
4) Typical "accuracy" of published API RP 43 penetration values range from 5-10% standard deviation. These values typically translate to lesser errors in well flow of about 1-2% respectively, depending on well parameters.[9] This suggests that current levels of performance consistency are practical for field use.
5) Neglecting the basic statistical problems associated with shaped charge performance in industry tests is to be discouraged as it results in misconceptions and confusion. For example, prevailing concern over the viability of predictive methodology for downhole penetration appears to be misplaced. In reality, the main problem lies in improper test design, inadequate attention to statistics, lack of control of quality and consistency of the test charges and other test parameters.

Acknowledgements

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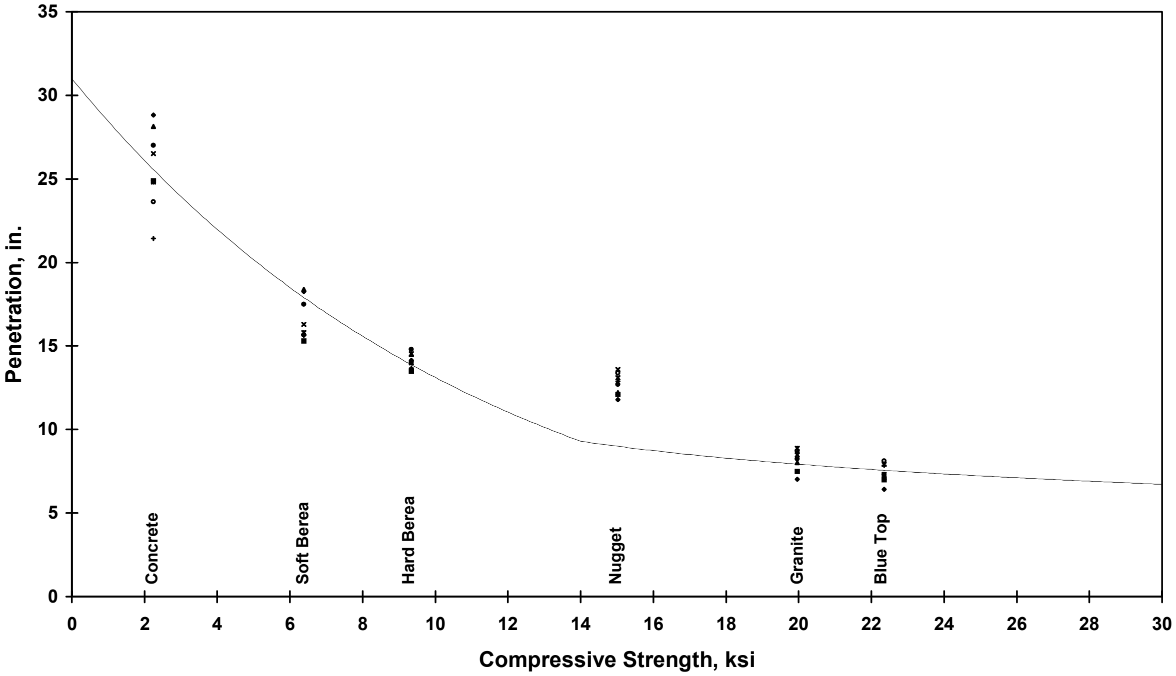

Fig. 1 – Optimized Charge A plotted over Thompson/Weeks curve.
Concrete compressive strength plotted by method of SPE 27424.

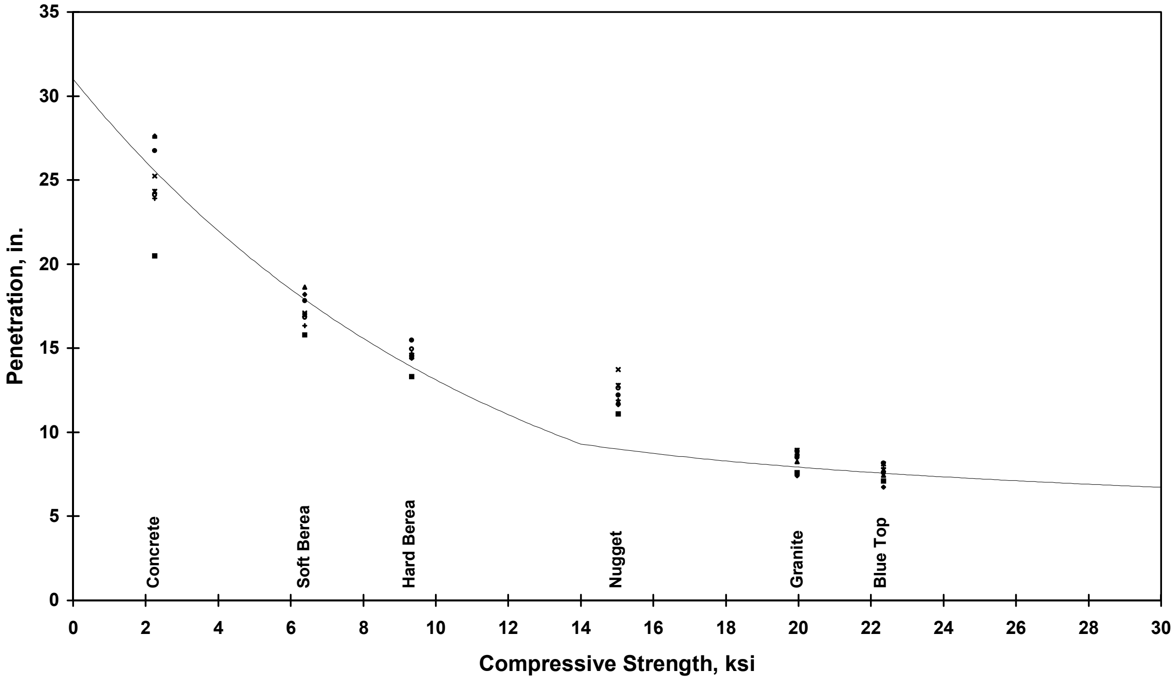

Fig. 2 – Optimized Charge B plotted over Thompson/Weeks curve.
Concrete compressive strength plotted by method of SPE 27424.

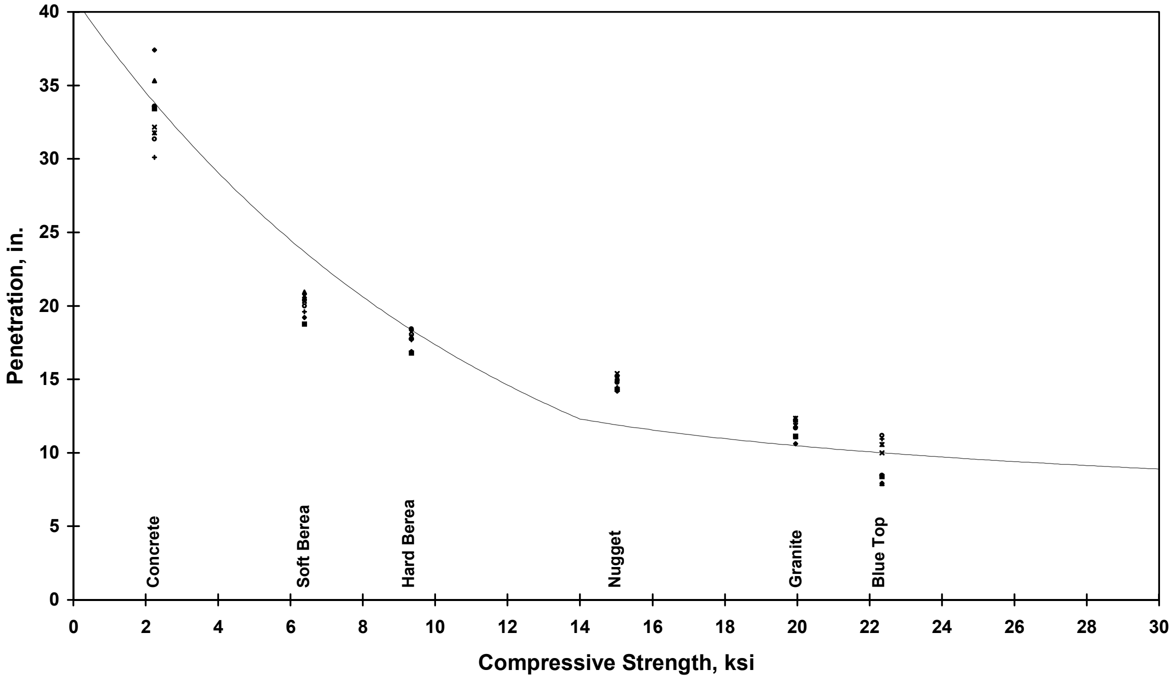

Fig. 3 – Optimized Charge C plotted over Thompson/Weeks curve.
Concrete compressive strength plotted by method of SPE 27424.

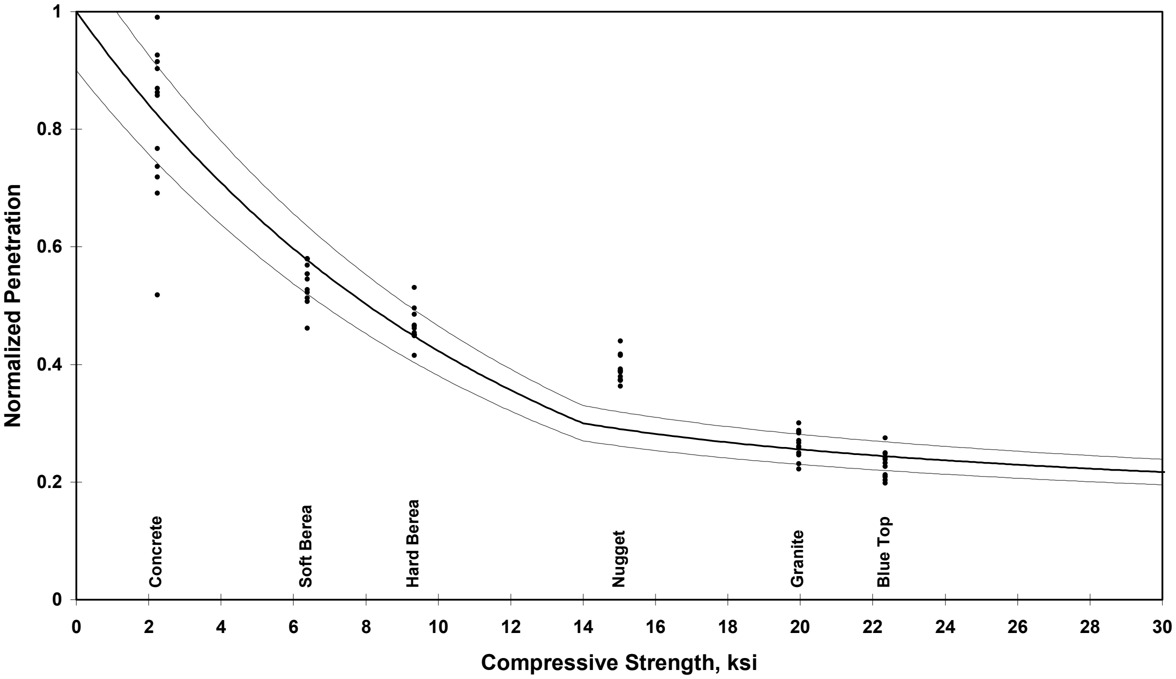

Fig. 4 – Normalized Charges A thru H and Control Charges A, B & C plotted Over Thompson/Weeks curve (light curves +/- 10%).
Includes all unoptimized charges and all charges optimized in concrete.
Concrete compressive strength plotted by method of SPE 27424.

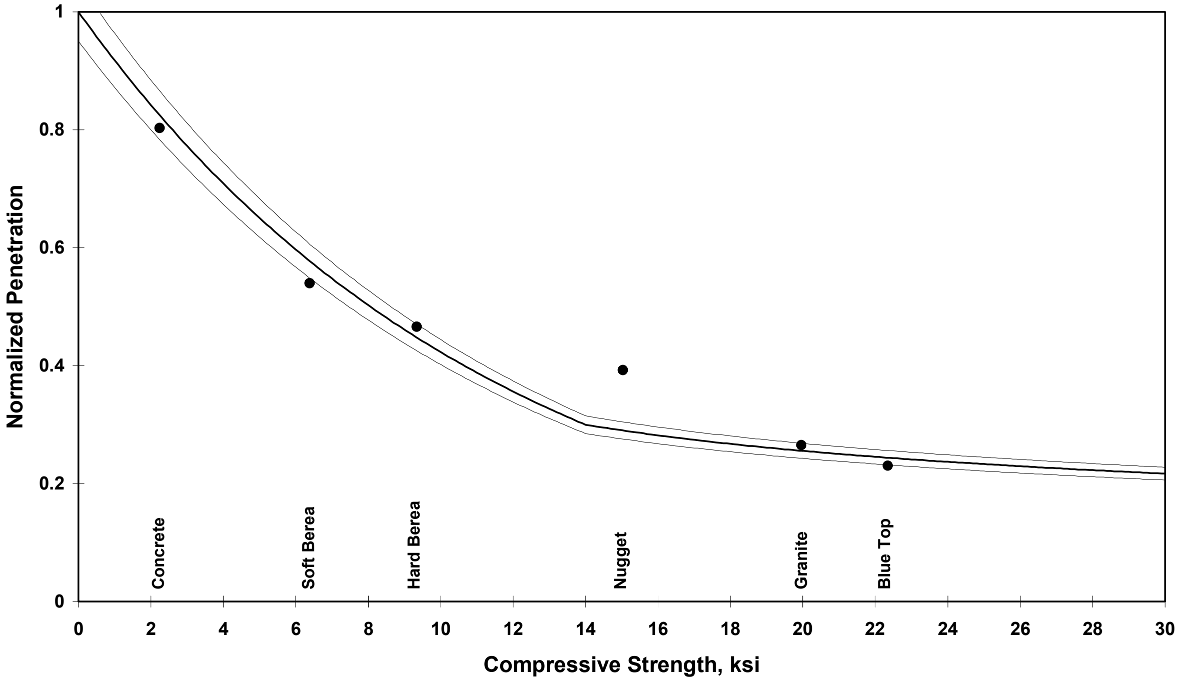

Fig. 5 – Target medium averages of normalized Charges A thru H and Control Charges A, B & C plotted over Thompson/Weeks curve (light curves +/- 5%).
Includes all unoptimized charges and all charges optimized in concrete.
Concrete compressive strength plotted by method of SPE 27424.

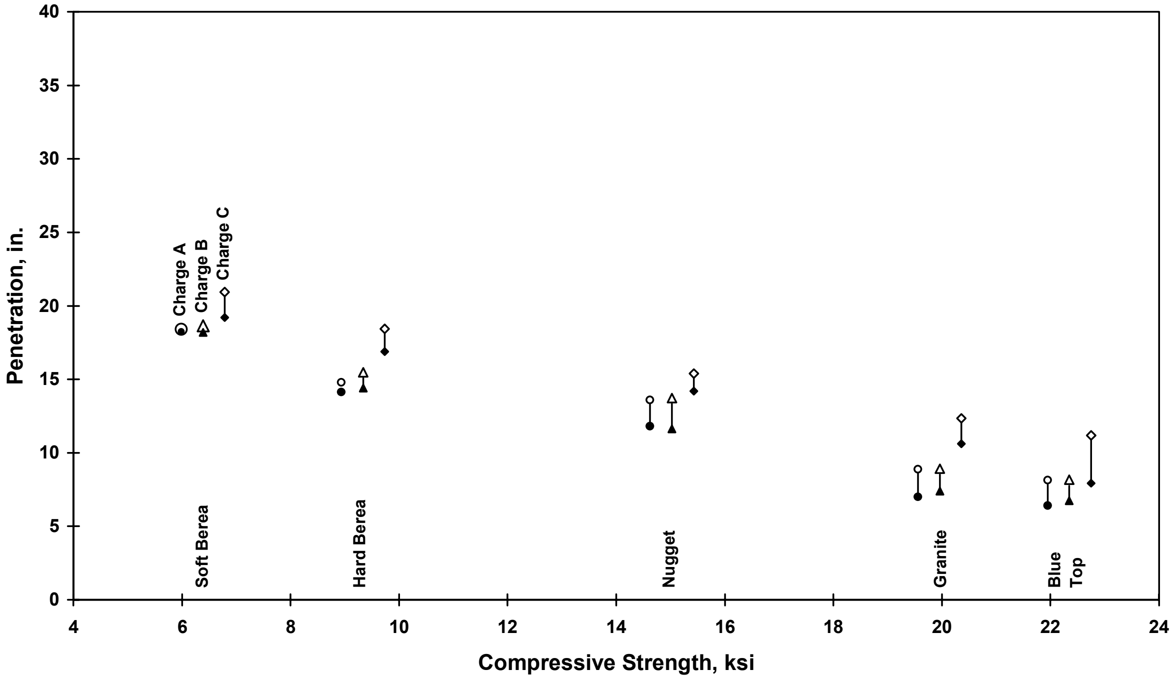

Fig. 6 – Improvement by optimizing in corresponding rock target.
Open data points represent data optimized in corresponding rock target.
Closed data points represent data optimized in concrete.

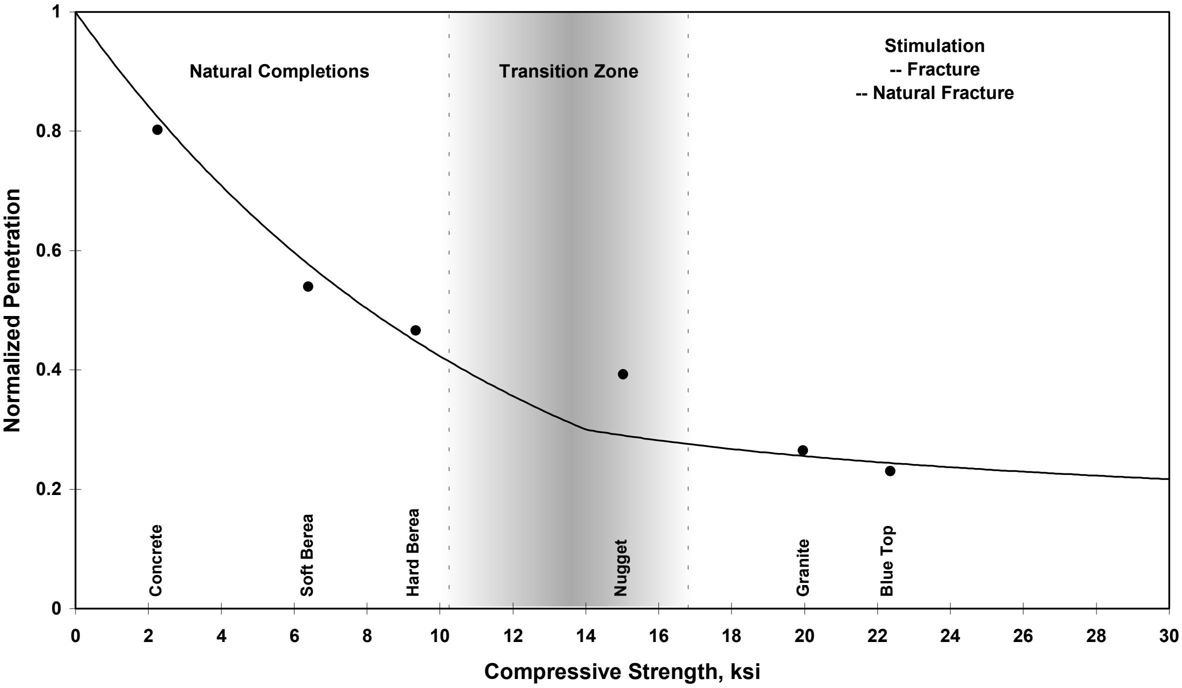

Fig. 7 – Target medium averages of normalized Charges A thru H and Control Charges A, B & C plotted over Thompson/Weeks curve.
Includes all unoptimized charges and all charges optimized in concrete.
Concrete compressive strength plotted by method of SPE 27424.

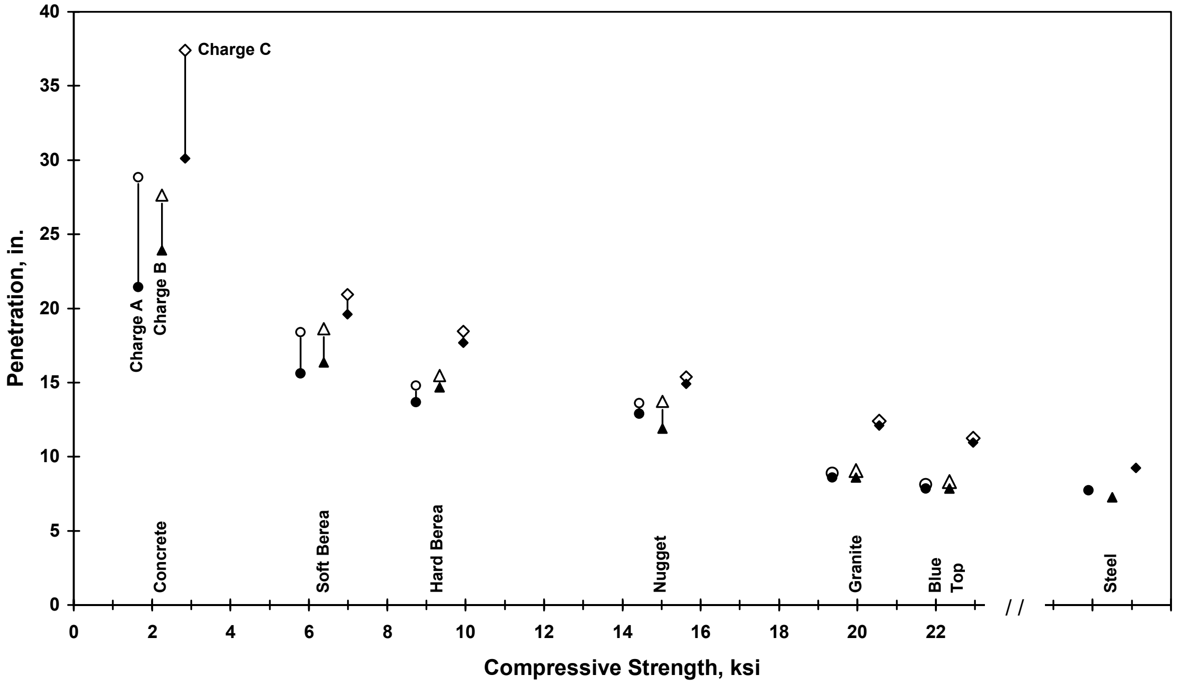

Fig. 8 – Improvement over steel optimization by optimizing in corresponding target medium.
Open data points represent data optimized in corresponding target medium.
Closed data points represent data optimized in steel.
Data for Charges B & C separated slightly for clarity in both granite and blue top.

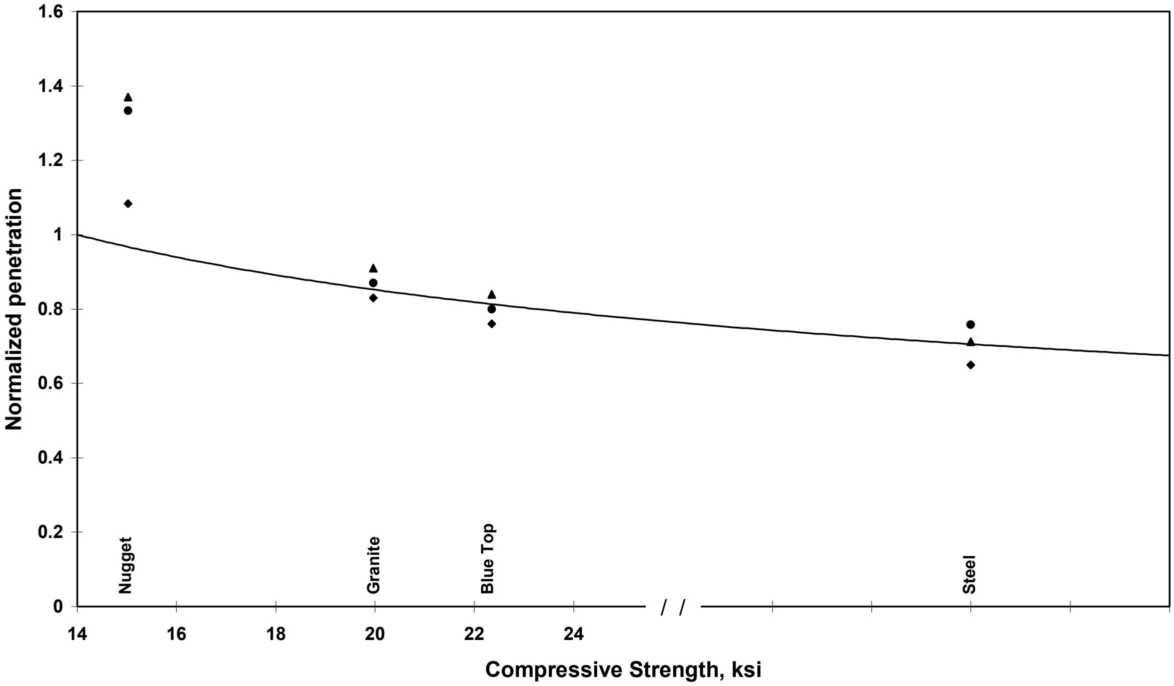

Fig. 9 – Normalized steel data plotted over "hard rock" region of Thompson/ Weeks curve with optimized Charges A, B & C.
Data for charges A, B & C separated slightly for clarity in both granite and blue top.
Data for charges A & B separated slightly for clarity in nugget.

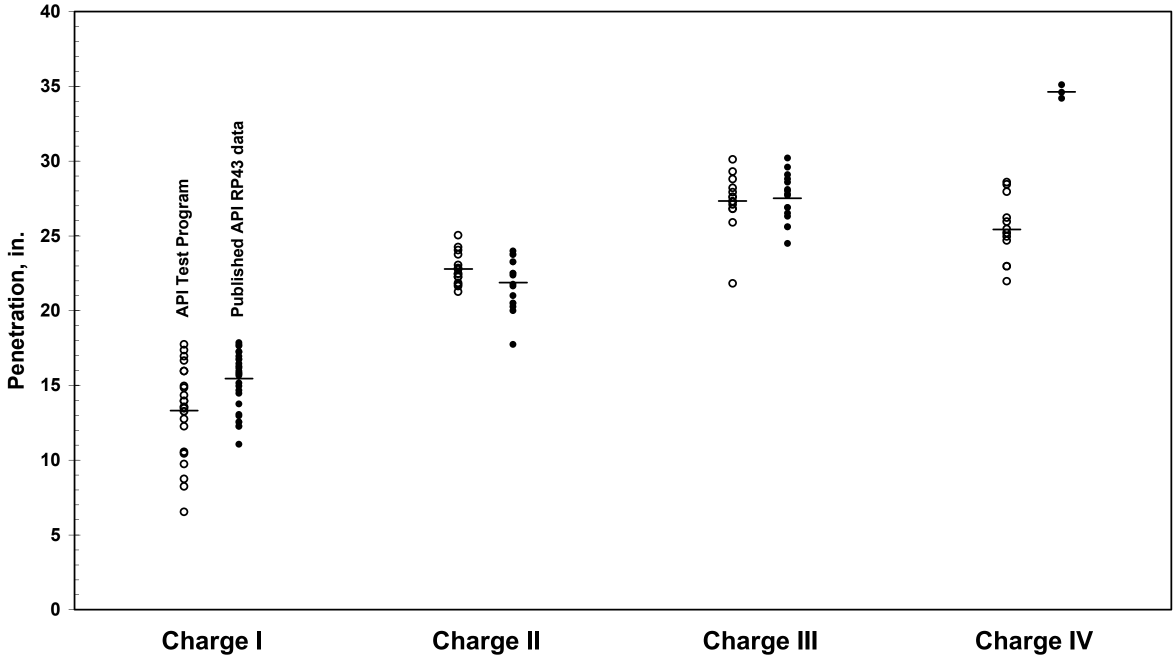

Fig. 10 – Shot data, API Test Program and corresponding published API data.
Open data points represent data from API test program.
Closed data points represent published API RP-43 data at same clearances.
Horizontal bars represent averages of all data points in that set.

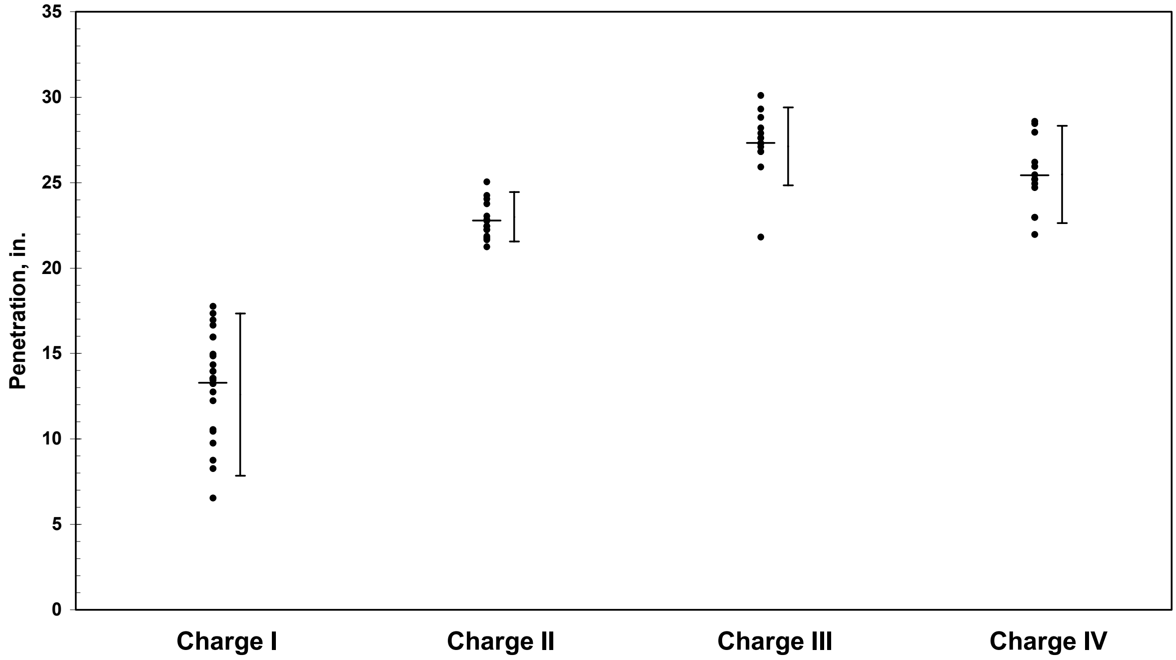

Fig. 11 – Range of possible 3-shot averages for data of API test program.
Vertical bars represent range of possible 3-shot averages.
Horizontal bars represent average of all data points.
Data based on results in C33M sand targets.

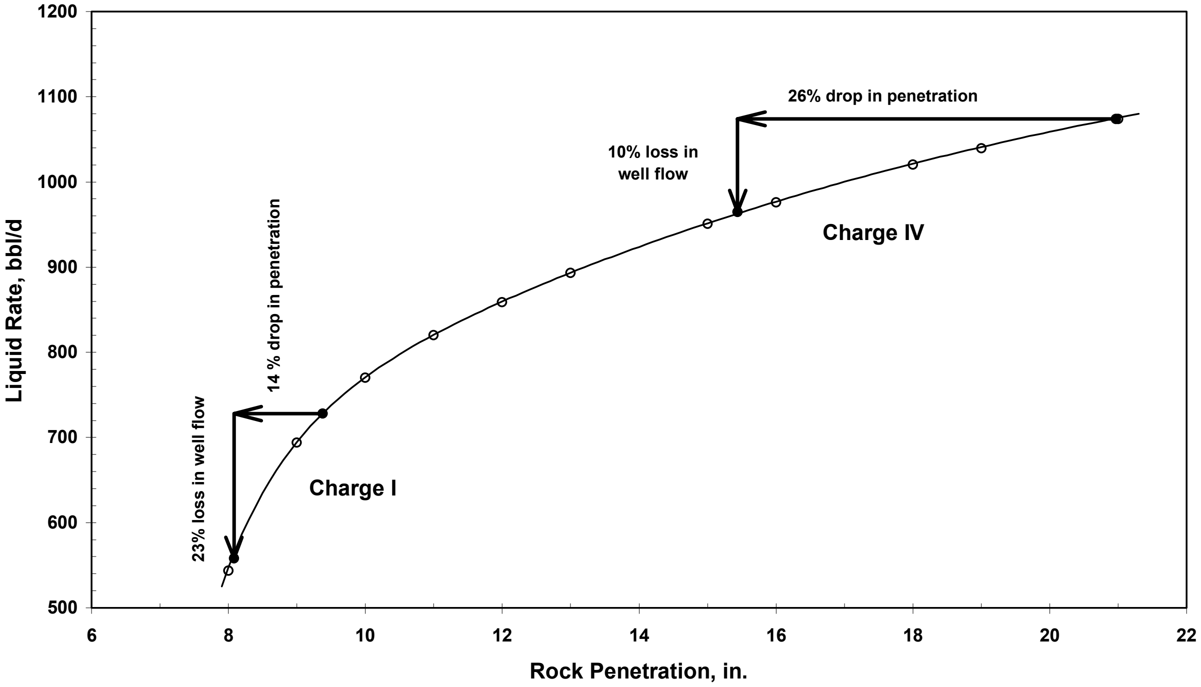

Fig. 12 – Nodal analysis well flow computation, Charge I & charge IV.

TABLE 1 - TEST RESULTS FROM API STUDY

		API Published	Test Results (Sand Type Listed)				
			C33M	12/20	16/30	20/40	30/70
CHARGE I	Average Penetration	15.45	13.30	12.38	11.83	15.61	15.17
	Standard Deviation	1.91	2.91	1.35	2.9	2.62	3.32
	Coeff. Of Var. (% Std. Dev.)	12.3%	21.9%	10.9%	24.5%	16.8%	21.9%
	% Dispersion (low to high)	44.0%	84.2%	45.2%	98.9%	70.5%	97.6%
CHARGE II	Average Penetration	21.88	22.78	19.34	21.53	22.07	24.48
	Standard Deviation	1.63	1.08	1.99	1.17	1.15	1.71
	Coeff. Of Var. (% Std. Dev.)	7.4%	4.7%	10.3%	5.4%	5.2%	7.0%
	% Dispersion (low to high)	28.6%	16.7%	37.7%	15.8%	14.5%	25.7%
CHARGE III	Average Penetration	27.51	27.32	25.76	26.08	27.97	30.58
	Standard Deviation	1.58	1.86	1.65	1.62	1.42	1.58
	Coeff. Of Var. (% Std. Dev.)	5.7%	6.8%	6.4%	6.2%	5.1%	5.2%
	% Dispersion (low to high)	20.7%	30.4%	26.0%	23.8%	20.4%	16.4%
CHARGE IV	Average Penetration	34.50	25.42	25.86	27.18	27.78	28.17
	Standard Deviation	0.53	2.07	1.82	2.28	1.92	2.29
	Coeff. Of Var. (% Std. Dev.)	1.5%	8.1%	7.0%	8.4%	6.9%	8.1%
	% Dispersion (low to high)	2.9%	26.1%	27.1%	27.6%	23.4%	32.4%