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Performance Patterns for Perforating Charges Optimized in Hard and Soft Materials

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Abstract

It is a well-known concept with those that design explosive shaped charges that said charges can be optimized for maximum performance in virtually any material. Charges optimized in soft materials may produce significantly less penetration in hard materials than charges initially designed in the harder materials, even though the soft material penetration is better for the “soft rock” charges.

This paper outlines tests of 3 charges optimized in soft, medium, and hard targets and compares the penetration in 7 materials. Each charge type is developed and redeveloped for each target type and the penetrations are compared to one another. Additional tests of 5 different charge designs are made in 7 target materials. These charges were designed at different times over the last 14 years and show divergent individual slopes of penetration.

Introduction

The basis of this study is to introduce the concept of “shaped charge” design for specific formation types. Shaped charges have been used since the late 1940’s for perforating oil and gas wells. In the early years, one of the ways used to test performance was to shoot the charge into a block, or blocks of mild steel. Both penetration and entry hole size were captured in the steel. Steel, which is still used today for certain applications, seems a good choice for target material, inexpensive and readily available. It does not however, allow good, workable penetration translation between itself and true formation materials.

The advent of the API RP 43[1] provided a guideline for comparison of various manufacturers’ charges. These standardized tests were divided into sections as follows: Section 1 - Concrete Test Target **(Fig. 1)**, and Section 2 - Berea Sandstone Core Target **(Fig. 2)**. Later in the RP 43, 5th Edition[2] (January 1991) Sections 3 and 4 were added. Section 3 was designed to study the effects of elevated temperature on perforating systems with the charge performance captured in steel. Section 4 is the most realistic downhole predictor since it simulates downhole conditions and allows the use of any core material. Section 4 is rarely performed due principally to its extremely high cost. Unfortunately, Section 2, which was initially meant to be used as the down hole predictor, has also fallen on hard times. The quarry, which supplied the material, closed for a period of time during which almost all section 2 testing ceased. Even after the quarry re-opened virtually no manufacturer resumed this type testing, and it was recommended to the API Subcommittee on Perforating that Section 2 be dropped[3].

What has been left to the industry is Section 1 as the sole predictor of shaped charge/system performance. While Section 1 provides a very efficient means to evaluate entry hole size[4], it is not the best predictor of downhole penetration. API RP 43 specifies the type of cement and aggregate and the ratios of these components to water to be used in the Section 1 target, however the targets are seldom if ever uniform. Additionally, two significant changes have taken place since the cessation of Section 2 testing. The first is the average compressive strength of the Section 1 concrete target has declined significantly. A large volume of API data sheets from the RP 43 4th Edition[5] (August 1985) range in the 7000-8000 psi compressive strength, with some significantly higher. Since the adoption of the 5th Edition testing procedures many, if not most, of the data sheets show compressive strengths in the 5000-6000 psi range. This is a reduction of 30%-40%. The second change is that charge penetrations in this medium have increased dramatically. Section 1 penetrations were seldom over 30” based on published RP 43, 4th Edition data. Today there are several manufacturers with published penetrations of 48”-50”, an increase of 60% or more. In addition, tests conducted for the API Subcommittee on Perforating showed that penetration variations of 10% or more can be seen due to variations in the aggregate size in the concrete matrix.[6] It should also be noted from this study that the aggregate size was the dominate factor in determining penetration. The charges tested in the targets with the finer sands shot deeper than those tested in targets with coarse sand; however, the finer sand targets yielded higher compressive strengths. It should be noted that although these tests used aggregate of disparate size, all materials fell within the sand spec. as specified by the API RP 43. This shows the tremendous amount of variation that can exist between section 1 targets. The following question needs to be answered, are we actually improving charges for downhole applications or simply designing for an improved "single, soft" medium, known as concrete?

Shaped Charge Penetration Mechanisms

There are 4 basic theories concerning transition of the shaped charge cone into a jet. These are 1) Hydrodynamic Theory Mechanism, 2) Plastic Flow Mechanism, 3) Spherical Convergence Theory, and 4) Brittle Fracture Mechanism. Of these, the simplest to understand, and the most commonly used for interpolating results for deep penetrating oil field perforators is the Hydrodynamic Theory Mechanism. This model states that the "metal of the cone is deflected by the explosive and converges at the axis of the charge where it is split, the inner surface being projected forward to form the high velocity jet and the outer surface being projected backward along the axis to produce the lower velocity slug."[7] This steady state, one-dimensional theory, is very idealistic as the penetration is directly related to the density of the jet as compared to the density of the target. Based on Bernoulli's steady state incompressible flow equation, the resulting expression for penetration (P) into the target from a jet length of (L) becomes:

$$P = L \bullet \sqrt{\frac{\rho_j}{\rho_t}}$$

Where ρ_j = jet density and
ρ_t = target density

As stated by J. A. Regulbuto, *et al.*[8], "This theory cannot explain the substantial difference in penetration that occurs between some target materials having very similar densities…" The following was also observed, " …it is observed that both Berea Sandstone and API cement (concrete) targets may have similar densities and compressive strengths, but the penetration into API cement is typically considerably deeper than the penetration of the same type charge in Berea…"

Various other factors play into the overall penetration of a jet into a target. These include target configuration[9], rock strength[10,11], rock stresses[12], and target boundaries[13]. However, no one, nor possibly all these factors combined, explains why penetrations of various charges, with similar penetrations in concrete, may produce radically different penetrations when tested in actual formation rock. The drill velocity (rate of penetration) has been shown to be significantly different between concrete and formation rocks.[14] This change in the rate of penetration also holds true when comparing one charge to another.

The Single Target Downhole Predictor

With the elimination of Section 2 to assist in the analysis and prediction of downhole performance, a method has been proposed by Ott, *et al.*, to anticipate said performance, based simply on Section 1 results.[15] Using a nomogram, translation is made from concrete penetration all the way to downhole formation penetration. Based on this proposed method the charge with the greatest penetration in concrete will almost always yield the deepest penetration in formation rock. There is some correction for compressive strength variations between charges tested in different targets, however this correction is negligible. This proposed method requires the use of formation compressive strength for translation, which of course may or may not be available. In the event compressive strength is unavailable an "approximation" can be made based on formation porosity. This poses additional problems since the authors admit that very little data is available for tests with materials below 15% porosity and only "in the range of 18% to 23% porosity, is substantial and consistent data available…" The authors also state, "Additional work should be done to improve the definition of porosity/compressive strength relationships over a broader range of porosity and over a broader range of formation rocks." This poses a great dilemma in the utilization of this system. As we drill deeper and deeper into highly consolidated formations, we are encountering formation materials far greater in compressive strength and far less porous than this method will accurately account for. Add to this the problems encountered with the Section 1 data and gross inaccuracies may result.

Most of the short comings of this simple method were addressed by E. A. Colle, *et al.*[16] These include the statistical scatter of the data used in the development of the method, and the limited number of rocks and stress conditions. The single, most important misconception of the simple method is that it "effectively assumes all charges behave the same." Charges react quite differently in the way they react to natural rock. "This leads to large errors when the nomogram is used…" The fact is penetration is a charge dependent, charge specific phenomenon. In defense of the "Simple Methods" authors they state, "We do not advocate that shaped charges be developed only in concrete." and "It would be naive to assume that the perforating industry will go down the road, focusing exclusively on Sec. 1 concrete…"[17] Unfortunately, however, this is precisely what has occurred. As noted by Behrman *etal.,* "Oil field perforators are qualified for penetration and casing hole size in surface concrete targets… As a result, over time, perforators become optimized for concrete."[18]

Charge Development and Testing Mediums

To achieve the expressed goals of this paper, 3 currently manufactured perforating charges were tested in 7 different mediums of different material strengths. The charge types selected for the study were based on generalized performance, date of original development, and history of tests in alternate materials to concrete. One of the charges selected has been in production virtually unchanged for approximately 14 years. Another selection is a much more recent design of only a few years, however it has been in a constant state of improvement. After initial control tests were conducted, each charge design was redeveloped with the intent of increasing charge performance for each of the 7 mediums. When comparing test medium extremes, major differences in penetration were seen between the baseline and redeveloped charges. Since some of the mediums are "relatively" close in material strengths, significant improvements were not realized, however differences were still observed. It must be understood that there are far too many variables effecting charge design to analyze them in a paper of this sort. There are easily 10 to 15 variables effecting the performance of a shaped charge, and it has been calculated that to test experimentally 3 values of each variable, would require more than 6 million tests.[19]

Changes made to the charges dealt principally with the liner, by changing liner thickness/mass, cone angle and taper, and liner density/material. There were many tests not reported here, made in attempt to optimize in the various mediums. After a charge was "optimized" all test mediums were shot and the data recorded.

All test mediums were potted in 7" diameter sonotube with the exception of the standard 4" dia. Q.C. concrete target and the 2" dia. steel target **(Fig. 3 and 4)**. This was an attempt to eliminate any boundary effects that could prejudice the data between target types. The targets are characterized as follows:

1. Q. C. Concrete Target - API Section 1 specification mixture with a compressive strength range of 5197 to 5755 psi.
2. Berea Sandstone Core Target - API Section 2 specification target 7X-OT10, air permeability 242 md, porosity 20.0%, compressive strength of 6387 psi.
3. Berea Sandstone Core Target - API Section 2 specification target OT3, air permeability 219 md, porosity 20.1%, compressive strength of 9338 psi.
4. Nugget Sandstone Target - Density 2.614 gm/cc, air permeability 18.06 md, porosity 11.2%, compressive strength 15,026 psi.
5. Red Granite - Density 2.621 gm/cc, compressive strength 19,960 psi.
6. Blue Top Sandstone - Density 2.581 gm/cc, compressive strength 22,347 psi
7. Steel - Mild steel ASTM A36

Charge Test Results

The tests consisted of two parts. The first part involved the optimization of 3 charges in 7 different materials. As mentioned previously, the charges chosen for optimization were based on known performance parameters and divergent design specifications. These charges are defined as follows:

Charge A) was a 2-1/8" deep penetrating exposed capsule perforator.
Charge B) was a 23 gram deep penetrating charge tested in a 3-3/8" gun configuration.
Charge C) was a 32 gram super deep penetrating charge tested in a 3-3/8" gun configuration.

A baseline for each charge was developed by shooting the "standard" perforator in each of the 7 mediums. Once the optimization process was completed for each medium the "optimized" version was retested in all mediums. Each data point recorded is the result of the average of 3 shots in each medium. This correlates to a total of 504 tests performed.

The second part involved the testing of 5 different charges of varying explosive weights and configurations. These were tested in the same mediums as in part 1, however no optimization was performed. These were as follows:

Charge D) was a 10.5 gram, 3-1/8" high shot density deep penetrating charge.
Charge E) was a 14.5 gram, 2-7/8" 6 spf deep penetrating charge.
Charge F) was a 2-1/2" deep penetrating exposed capsule perforator.
Charge G) was a 2-1/8" deep penetrating Retrievable Tubing Gun perforator.
Charge H) was a 1-11/16" deep penetrating exposed capsule perforator.

Performance values are represented on **Tables 1, 2, and 3** for the "optimized" charges, corresponding to the equivalent charge. **Table 4** is inclusive of all data for Charges D through H.

As shown in **Table 1**, the charge optimized for concrete yielded a maximum penetration of 28.83" with 5.53" in steel. When optimized for granite the penetration in concrete had dropped 4.03" to 24.80", and yet shot 7.13" in steel, an increase of 1.60". The charge optimized for steel picked up an additional .60" over the one optimized for granite, however an additional 3.37" was lost in concrete. These same type performance variations can be seen in **Tables 2 and 3**. In each case, once optimization had been performed, significant performance improvements were achieved when compared with the baseline charge. Performance variations / improvements ranged from a minimum of 7.26% to a maximum of 36.81%.

As shown by the second series of tests, represented by **Table 4**, even standard, non-optimized charges show great divergence in performance. For comparative purposes Charge H outperforms Charge D by 6.52" in a concrete medium. However, when tested in two of the harder materials, granite and blue top Charge D shows .25" greater penetration. Charge G outperforms Charge D in all of the softer mediums. When "hard" materials are encountered; specifically granite, "Blue Top" sandstone, and steel; the performance of Charges D and G invert.

Conclusions

Shaped charges have been established as the most efficient method of obtaining communication between a cased borehole and the formation of an oil or gas well. The selection of the correct perforating charge should be based on sufficient information to assure proper communication, with assurance of penetration beyond near well bore damage. Charges are individualistic in nature; each having it's own performance characteristics. Variations between perforator performance is a "charge design dependant phenomenon". When comparing the penetration of various charges, it is wrong to assume that the charge that penetrates deepest in a soft medium will maintain its superiority over another when hard formation materials are encountered.

Charge development can be accomplished in virtually any medium, including but not limited to, concrete, various formation rocks, and steel. The problems associated with designing in only one relatively soft material, specifically concrete, lead to the optimization in this single medium. This may yield a charge design that has less than optimum performance when truly hard formation rocks are encountered.

As shown by the data presented in this paper, optimization in hard materials can significantly improve performance when downhole high strength formation materials are encountered. Ideally, the charge designer would optimize in the same formation rock as found in the well. Since this is not always reasonable or possible it is recommended that the designer use a material with mechanical properties as close to the downhole formation as possible. This assures the best possible chance of communicating with the formation. In extremely hard formations where charge penetration is at it's minimum, and fluid invasion is most critical, optimization in the proper medium is not only warranted, but essential.

Nomenclature

gm = gram
cc = cubic centimeter
md = millidarcy
psi = pounds per square inch

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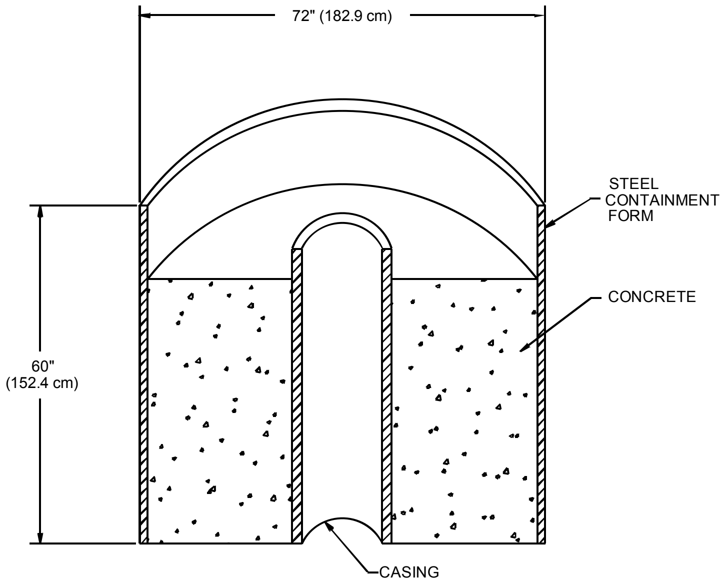
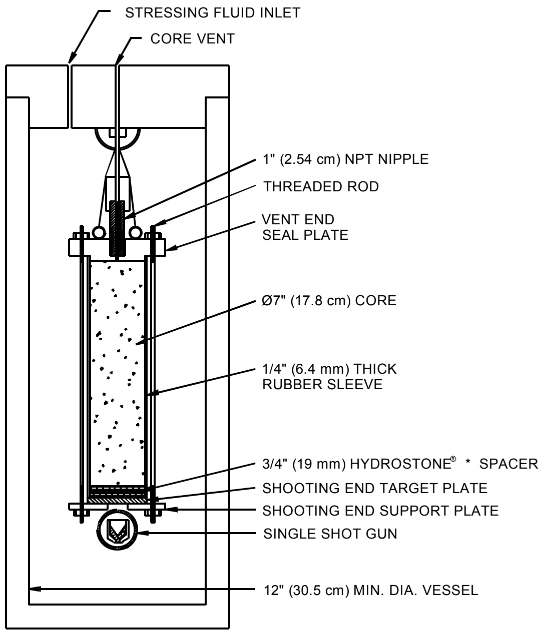


Fig. 1 - API RP-43 4th/5th Edition Section 1 (Concrete Target)



* Trade name of U.S. Gypsum Co., Chicago, IL.

Fig. 2 - API RP-43 5th Edition Section 2 (Target Configuration)

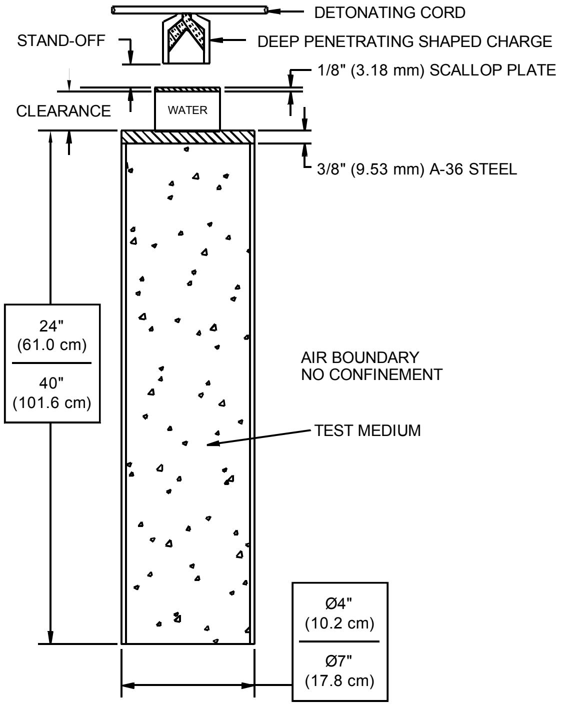


Fig. 3 - Standard QC Setup Hollow Carrier Charge

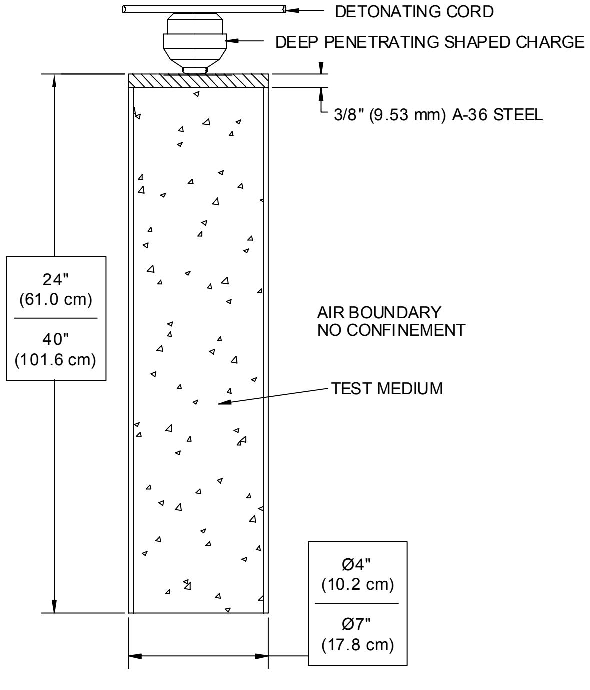


Fig. 4 - Standard QC Setup Capsule Charge

TABLE 1- CHARGE "A"

	Control	Concrete	Soft Berea	Hard Berea	Nugget	Granite	Blue Top	Steel
		A	B	C	D	E	F	G
Q.C. Concrete	24.88	**28.83**	28.13	27.00	26.50	24.80	23.63	21.43
Berea Sandstone OT-10	15.29	18.25	**18.40**	17.50	16.30	15.80	15.66	15.63
Berea Sandstone OT-3	13.50	14.15	14.50	**14.80**	14.55	14.00	14.00	13.68
Nugget Sandstone	12.11	11.80	12.20	12.70	**13.60**	13.11	13.40	12.89
Red Granite	7.50	7.01	8.01	8.24	8.50	**8.88**	8.72	8.60
Blue Top Sandstone	7.00	6.41	7.12	7.30	7.32	7.92	**8.13**	7.86
Steel	5.65	5.53	5.90	6.30	6.95	7.13	7.30	**7.73**

TABLE 2- CHARGE "B"

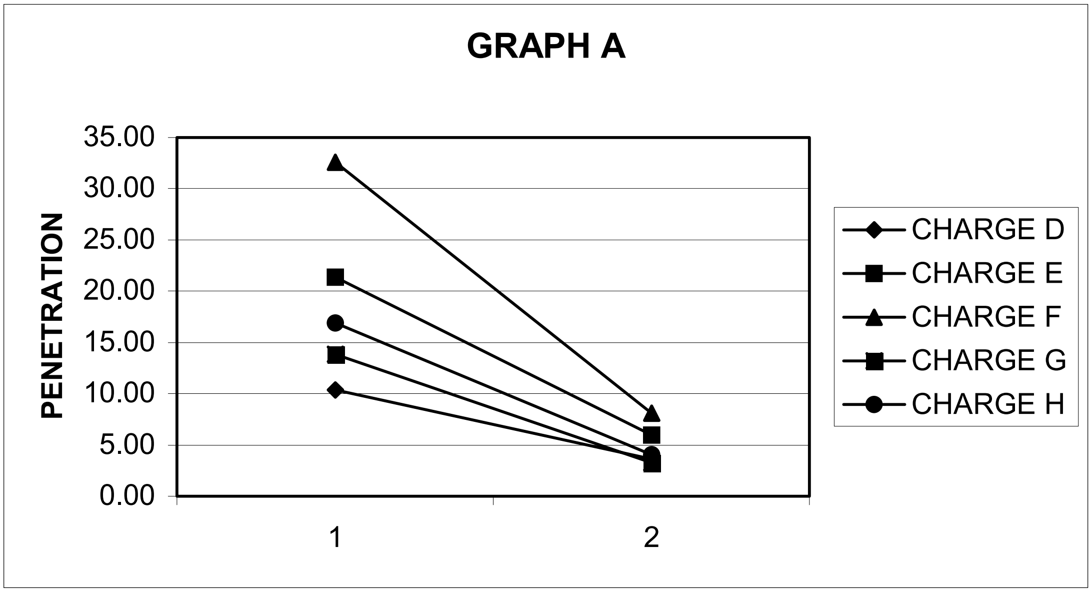
	Control	Concrete	Soft Berea	Hard Berea	Nugget	Granite	Blue Top	Steel
		A	B	C	D	E	F	G
Q.C. Concrete	20.48	**27.62**	27.62	26.76	25.25	24.33	24.12	23.91
Berea Sandstone OT-10	15.80	18.20	**18.63**	17.82	17.10	17.00	16.84	16.34
Berea Sandstone OT-3	13.30	14.40	14.63	**15.48**	14.48	14.60	14.95	14.66
Nugget Sandstone	11.10	11.63	11.81	12.22	**13.73**	12.80	12.62	11.91
Red Granite	7.60	7.40	8.26	8.50	8.80	**8.92**	**8.90**	8.60
Blue Top Sandstone	7.11	6.74	7.43	7.60	7.77	**8.13**	**8.16**	7.85
Steel	6.00	5.65	6.30	6.30	6.20	6.70	6.74	**7.26**

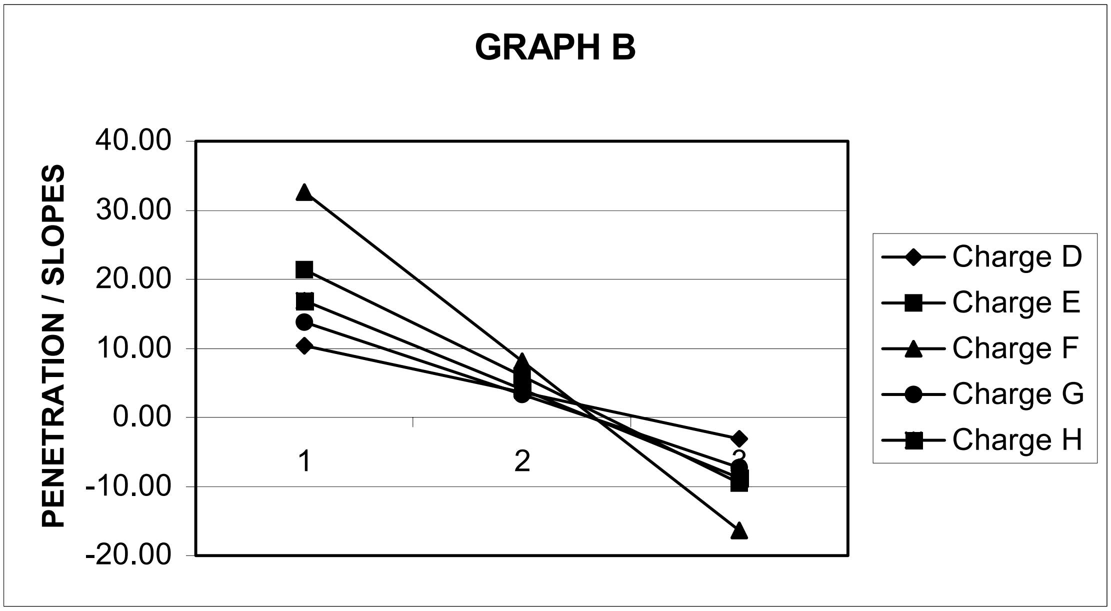
TABLE 3- CHARGE "C"

	Control	Concrete	Soft Berea	Hard Berea	Nugget	Granite	Blue Top	Steel
		A	B	C	D	E	F	G
Q.C. Concrete	33.40	**37.40**	35.32	33.60	32.15	31.76	31.36	30.10
Berea Sandstone OT-10	18.76	19.20	**20.93**	20.36	20.30	20.67	20.00	19.61
Berea Sandstone OT-3	16.80	16.87	17.90	**18.44**	18.23	17.91	17.75	17.68
Nugget Sandstone	14.32	14.20	14.45	14.80	**15.36**	15.11	15.20	14.91
Red Granite	11.13	10.61	11.10	11.69	11.86	**12.34**	**12.24**	12.10
Blue Top Sandstone	8.38	7.94	7.89	8.46	9.98	10.56	**11.20**	10.96
Steel	8.46	7.36	7.84	7.91	8.33	8.64	8.79	**9.23**

TABLE 4

	Charge "D"	Charge "E"	Charge "F"	Charge "G"	Charge "H"
Q.C. Concrete	10.36	21.36	32.60	13.82	16.88
Berea Sandstone OT-10	9.23	16.80	19.60	11.60	12.00
Berea Sandstone OT-3	8.30	14.08	17.30	10.62	10.91
Nugget Sandstone	7.45	12.76	14.60	8.30	8.63
Red Granite	5.76	7.56	10.71	5.41	5.50
Blue Top Sandstone	5.50	7.20	8.73	3.97	5.25
Steel	3.63	5.94	8.10	3.30	4.03


GRAPH A
PENETRATION
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1
2
CHARGE D
CHARGE E
CHARGE F
CHARGE G
CHARGE H


GRAPH B
PENETRATION / SLOPES
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
1
2
3
Charge D
Charge E
Charge F
Charge G
Charge H