

Evaluation of Well Perforators

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Evaluation of Well Perforators

1 Scope

This recommended practice describes standard procedures for evaluating the performance of perforating equipment so that representations of this performance may be made to the industry under a standard practice.

[Section 4](#) provides methods for evaluating perforator or system performance, or both, in four ways:

- a) performance under ambient temperature and atmospheric pressure test conditions into standard casing and concrete targets (4.1);
- b) individual shots into Berea sandstone targets at various defined stressed conditions, with wellbore and pore pressures at nominally ambient conditions (4.2);
- c) how performance can be changed after exposure to elevated temperature conditions (4.3);
- d) flow performance of a perforation under specific stressed test conditions (4.4).

[Section 4.5](#) provides a procedure to quantify the amount of debris that comes out of a perforating gun during detonation, and during conveyance out of the well. [Section 4.6](#) provides a procedure to measure the swell of a perforating gun.

The purpose of this recommended practice is to specify the materials and methods used to evaluate objectively the performance of perforating systems or perforators.

2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document applies (including any addenda/errata).

API Specification 10A, *Specification for Cements and Materials for Well Cementing*

API Standard 19C, *Measurement of and Specifications for Proppants Used in Hydraulic Fracturing and Gravel-packing Operations*

API Specification 19PT, *Downhole Perforating Tools*

ASTM A29, *Standard Specification for General Requirements for Steel Bars, Carbon and Alloy, Hot-Wrought*

ASTM C109, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)*

ASTM C150, *Standard Specification for Portland Cement*

ASTM D3740, *Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction*

ASTM D4543, *Practices for Preparing Rock Core as Cylindrical Test Specimens and Verifying Conformance to Dimensional and Shape Tolerance*

ASTM D7012-14e1, *Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures*

ASTM E389, *Standard Test Method for Particle Size or Screen Analysis at No. 4 (4.75-mm) Sieve and Coarser for Metal-Bearing Ores and Related Materials*

ASTM E1272, *Standard Specification for Laboratory Glass Graduated Cylinders*

3 Terms, Definitions, and Abbreviations

3.1 Terms and Definitions

3.1.1

capsule charge

A shaped charge with its explosives and liner exposed and sealed by itself that can be used in direct contact with a wellbore fluid.

3.1.2

cement

An ingredient of concrete.

NOTE The terms cement and concrete often are used interchangeably.

3.1.3

concrete

A mixture of aggregates and paste. The aggregates are sand and gravel or crushed stone; the paste is water and Portland cement.

NOTE The terms cement and concrete often are used interchangeably.

3.1.4

debris

Any materials or objects expelled out of a perforating gun after detonation and left in a well, which can be in solid or powder form. Explosives and powder metallic liners are not regarded as debris.

3.1.5

gun

A perforating device consisting of a carrier system, adapters or subs, and explosives.

3.1.6

hollow carrier

A steel pipe that is machined with end threads and perhaps scallops.

3.1.7

jacket

sleeve

The deformable elastomer covering used on the OD of a rock target for Section II and Section IV tests to seal out the confining fluid.

3.1.8

QC target

A target, which by design, and material are selected by the shaped charge manufacturer, to be used during the charge production process to substantiate data on the shaped charge performance.

3.2 Abbreviations

CT	computed tomography X-ray scan
DAC	data acquisition and control

HRB	Rockwell hardness measured on the B scale
HRC	Rockwell hardness measured on the C scale
ID	inner diameter
MPC	mass percentage change
OD	outer diameter
QC	quality control
UCS	uniaxial compressive strength

4 Evaluation of Perforating Systems

4.1 Evaluation of Perforating Systems under Surface Conditions, Concrete Targets (Section I Test)

4.1.1 Introduction

The purpose of this section is to describe recommended practices for evaluating perforating systems using concrete targets under multiple shot, ambient temperature, and atmospheric pressure test conditions.

The primary useful data output from these tests will be the verification of full system performance. Penetration data recorded in this section may not directly correlate to penetration downhole. [Sections 4.2](#) or [4.4](#) shall be used for this purpose.

4.1.2 Test Target

4.1.2.1 General

The tests shall be conducted in a concrete target contained within a steel form as illustrated in [Figure 1](#).

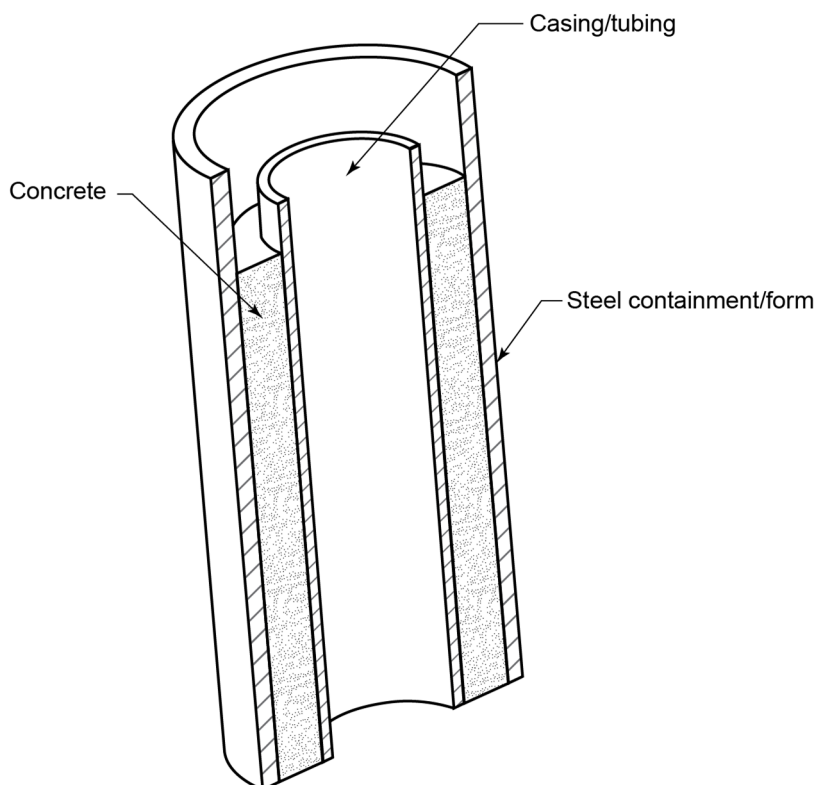


Figure 1—Example Concrete Target

4.1.2.2 Target Preparation

Concrete for the target and test briquettes shall be mixed using a cement-sand-slurry consisting of the following.

- a) One (1) part or 94 lb ± 1 % of API 10A class A or ASTM C150 Type I cement.
- b) Two (2) parts or 188 lb ± 1 % of dry sand (the sand shall meet API 19C requirements for 16 – 30 frac sand). The sand shall be stored in a dry location prior to use.
- c) 0.52 part or 49 lb ± 1 % of potable water.
- d) The ratio of sand to cement shall be between 2.02 and 1.98. The ratio of water to cement shall be between 0.5252 and 0.5148.
- e) If the amount of water is reported in gallons, use the conversion of 8.34 lb per U.S. gallon to convert to weight to determine the water to cement ratio.

4.1.2.3 Required Documentation

Each distinct quantity of concrete (truckload or similar) used in the preparation of a target shall include a written report from the concrete supplier listing the actual amounts of cement, sand, and water used. Quantities shall be reported in the units used during the measuring process, with no conversions or adjustments.

The testing company shall maintain supporting documentation that the sand complies with API 19C for 16 – 30 frac sand. At a minimum, this shall consist of sieve analysis data for all loads of frac sand received by the concrete supplier.

The testing company shall maintain a material test report that the casing used in the construction of the target meets the reported grade and weight.

4.1.2.4 Target Configuration

The shape of the outer target form shall be circular; the target size shall be determined by the shot pattern and anticipated penetrating capability of the perforating system to be tested. Positioning of the tubing or casing within the target shall be determined by the gun phasing used in the test. For zero-phased perforators, the casing or tubing shall be set in the target form such that a minimum of 3 in. (7.6 cm) of the specified concrete composition surrounds the tubing or casing in all directions.

4.1.2.5 Target Curing Conditions

4.1.2.5.1 General

The target shall be allowed to cure at a temperature within the concrete greater than 32 °F (0 °C) for a minimum of 28 days. The top surface of the concrete target shall be covered continuously during the entire curing period with a minimum of 3 in. (7.6 cm) of potable water. All strength test specimens shall be kept immersed in water at the same temperature as the concrete test target until they are used as prescribed in [4.1.2.5.6](#).

4.1.2.5.2 Target Compressive Strength Evaluation

Target compressive strength shall be evaluated using 2 in. (5 cm) cubes (briquettes) made from the same concrete as the target, prepared and tested as prescribed in [4.1.2.1](#) through [4.1.2.5](#). Prior to or within 24 hours after conducting the perforating test, the briquettes shall be tested and shall have an average compressive strength of not less than 5000 psi (34.5 Mpa).

4.1.2.5.3 Compressive Strength Evaluation Apparatus

The molds shall not have more than three cube compartments. The parts of the molds when assembled shall be positively held together. The molds shall be made of hard metal, not attacked by the cement mortar, with a Rockwell hardness number not less than 55 HRB. The sides of the mold shall be sufficiently rigid to prevent spreading or warping. The interior faces of the molds shall be plane surfaces and shall conform to the tolerances in [Table 1](#). A base plate having a minimum thickness of $\frac{1}{4}$ in. (6.35 mm) shall be used.

Table 1—Permissible Variations of Specimen Mold

Parameter	New	In Use
Planeness of side	< 0.001 in. (0.025 mm)	< 0.002 in. (0.050 mm)
Distance between opposite sides	2 in. ± 0.005 in. (50.0 mm ± 0.13 mm)	2 in. ± 0.02 in. (50.0 mm ± 0.50 mm)
Height of each compartment	2 in. $+0.01$ to -0.005 in. (50.0 mm $+0.25$ mm to -0.13 mm)	2 in. $+0.01$ to -0.015 in. (50.0 mm $+0.25$ mm to -0.38 mm)
Angle between adjacent faces ^a	$90^\circ \pm 0.5^\circ$	$90^\circ \pm 0.5^\circ$
^a Measured at points slightly removed from the intersection. Measured separately for each compartment between all the interior faces and the adjacent face and between interior faces and top and bottom planes of the mold.		

The testing machine shall conform to the requirements in ASTM C109. The molds shall be checked for tolerances and the testing machine shall be calibrated within ± 1 % of the load range to be measured at least once every two years.

4.1.2.5.4 Preparation of Molds

Apply a thin coating of release agent (aerosol lubricant for example) to the interior faces of the mold and contact surface of the base plate. Wipe the mold faces and base plate with a cloth as necessary to remove any excess release agent and to achieve a thin, even coating. Seal the surfaces where the halves of the mold join by applying a coating of light grease. The amount shall be sufficient to extrude slightly when the two halves are tightened together. Remove any excess grease with a cloth. After placing the mold on its base plate (and attaching with clamps if applicable), apply grease to the exterior contact line of the mold and base plate to achieve a watertight seal.

4.1.2.5.5 Placing Slurry in Molds

The slurry sample shall be procured midway during the target pour. For large targets requiring multiple concrete trucks, the sample shall be taken from the truck filling the middle portion of the target. Preparation of the specimens shall begin within 15 minutes of procuring the sample. Stir the slurry by hand using a non-absorbent spatula or puddling rod to minimize segregation. Place slurry in each specimen compartment in the prepared molds in a layer equal to one-half of the mold depth. The slurry shall be placed in all the specimen compartments before commencing the puddling operation. Puddle each specimen 25 times using a glass or non-corroding metal rod ~ 8 in. $\times \frac{1}{4}$ in. (20.3 cm $\times$ 0.635 cm) in diameter. After puddling the layer, the remaining slurry shall again be stirred. Fill the molds to overflowing and puddle as with the first layer. After puddling, the excess slurry shall be struck even with the top of the mold, using a straightedge. Specimens in molds which show evidence of leaking shall be discarded. For one test determination, not less than six specimens shall be prepared.

4.1.2.5.6 Curing of Specimens

As soon as possible, but no more than two hours after preparation, the molds shall be placed in the water on the top of the Section I target. The top of the Section I target shall have firmed sufficiently to support the molds. The water level in the top of the target shall be kept high enough to completely cover each mold. Within 20 hours to 23 hours after initial placement, remove the molds from the water, remove the specimens from the molds, and place the specimens in a white, plastic container, filled with potable water. Place the container in the water on top of the

Section I target, where it shall remain for the entire curing period. The container shall be at least 6 in. (15.2 cm) deep, and the specimens shall remain fully submerged in the water until immediately prior to being tested.

4.1.2.5.7 Specimen Testing

4.1.2.5.7.1 Wipe each specimen to a surface-dry condition and remove any loose material from the faces that will be in contact with the bearing blocks of the testing machine. Check these faces by applying a straightedge. If there is appreciable curvature, grind the face or faces to plane surfaces or discard the specimen.

4.1.2.5.7.2 Apply the load to specimen faces that were in contact with the plane surfaces of the mold. Center the specimen in the testing machine below the upper bearing block. Prior to the testing of each cube, it shall be ascertained that the spherically seated block is free to tilt. The load surfaces shall be clean. Use no cushioning or bedding material. Appropriate safety and handling procedures shall be employed in testing the specimen.

4.1.2.5.7.3 The rate of loading shall be 16,000 lbf $\pm$ 1600 lbf (4000 psi $\pm$ 400 psi) per minute. No adjustment shall be made to the controls of the testing machine while a specimen is yielding before failure.

4.1.2.5.7.4 The compressive strength is calculated by dividing the maximum load in pound-force (lbf) by cross-sectional area in in.² (cm²). If deviations of $\frac{1}{16}$ in. (1.6 mm) or more from the specified linear dimension of 2.00 in. (50.8 mm) are reported, use the actual area for the calculation of the compressive strength. In determining the compressive strength, do not consider specimens that are manifestly faulty. The maximum permissible range between specimens is 8.7 % of the average. If this range is exceeded, discard the result that differs the most, and check the range of the remaining specimens. Repeat until the results comply with the maximum permissible range. A minimum of three specimens is required for a valid test. The compressive strength of all acceptable test specimens shall be averaged and reported to the nearest 10 psi.

4.1.2.6 Casing or Tubing to be Used in Target

Casing or tubing sizes, weights, and grades to be used in the target are shown in [Table 2](#).

Table 2—Casing and Tubing for Use in Test Target

Pipe Size, OD in.	Pipe Nominal Weight lb/ft (kg/m)	Casing or Tubing API Grade
2 $\frac{3}{8}$	4.60 (6.85)	L-80
2 $\frac{7}{8}$	6.40 (9.52)	L-80
3 $\frac{1}{2}$	9.20 (13.69)	L-80
4 $\frac{1}{2}$	11.60 (17.38)	L-80
5	15.0 (22.69)	L-80
5 $\frac{1}{2}$	17.0 (25.72)	L-80
7	32.0 (47.92)	L-80
7 $\frac{5}{8}$	33.7 (50.15)	L-80
8 $\frac{5}{8}$	40.0 (59.53)	L-80
9 $\frac{5}{8}$	47.0 (69.94)	L-80
10 $\frac{3}{4}$	51.0 (75.90)	L-80
11 $\frac{3}{4}$	54.0 (80.36)	L-80
13 $\frac{3}{8}$	61.0 (90.78)	L-80

4.1.3 Perforating System Selection

The perforating system to be tested shall consist of standard field equipment, including a sufficient length of continuously loaded active gun, shot density, phasing, charges, explosive accessories, and other component parts representative of standard field equipment. Selection of the charges shall conform to [4.1.4](#). If a debris test is

to be conducted concurrently with the Section I test, the bottom sub/plug shall be solid or blanked off to minimize the sump affect.

4.1.4 Charge Selection and Aging

The required number of charges shall be samples taken randomly from a minimum production run of 300 charges and packaged in the manufacturing/service company's standard shipping containers. A minimum production run is a continuous run which may span multiple shifts to meet the required minimum quantities. These charges shall be stored for a minimum of four weeks (28 days) prior to testing to allow some aging to occur. Charges shall be selected from one or more unopened containers.

4.1.5 Multi-directional Firing Perforator Systems

For multi-directional firing perforator systems, a sufficient length of continuously loaded active gun shall be tested to provide a minimum of 12 shots or one foot of continuously loaded gun, whichever provides more shots. The perforating device shall be shot as it is normally positioned in the casing.

4.1.6 Uni-directional Perforator Systems

Uni-directional perforator systems, without positioning devices, shall be tested in two positions. In one position, all shots shall be fired at maximum clearance. In the other position, all shots shall be fired at minimum clearance. A minimum of eight shots shall be fired from each position. Perforator systems with positioning devices shall be fired in the position assumed in a well. A minimum of 12 shots shall be fired.

4.1.7 Test Fluid

Water shall be used as the test fluid in testing all perforating systems.

4.1.8 Test Results Validity

No test shall be considered valid if the average depth of penetration of the concrete target is within 3 in. (76.2 mm) of the terminal boundary of the target. Any shots that penetrate the terminal boundary of the concrete target or are within the top 12 in. (305 mm) or less than 6 in. from the bottom (152 mm) of the concrete target shall be noted in the reported data but shall not be counted in averaging the penetration data from the test.

4.1.9 Data Collection

4.1.9.1 General

The following measurements shall be made for each perforating system evaluated:

- a) total penetration depth;
- b) casing or tubing hole diameter;
- c) burr height;
- d) mandatory of a minimum of six QC shots.

All perforator individual or averaged penetration depths shall be reported to the nearest 0.1 in. (2.5 mm).

4.1.9.2 Total Penetration Depth

The total depth shall be reported as the distance from the original inside wall of the casing or tubing to the end of the perforation tunnel. The end of the perforation tunnel shall be established as that point where concrete material strength damage ends as qualitatively indicated by manual scraping/probing of the exposed material surface.

4.1.9.3 Casing or Tubing Hole Diameter

The casing or tubing hole diameter shall be measured along the short and long elliptical axes and reported along with the average of the two measurements. Such measurements shall be made from outside the casing or tubing (prior to cutting) with a caliper, whose arms readily pass through the perforation. The short axis shall be the smallest through-hole diameter measured. Casing or tubing hole diameter shall be reported to the nearest 0.01 in. (0.25 mm).

4.1.9.4 Burr Height

The maximum protrusion from the inside casing or tubing wall next to the perforation shall be measured and reported as the burr height. If debris from the perforator is lodged in the perforation hole in the casing or tubing and cannot be removed with finger pressure, the total height of such obstruction shall be recorded as burr height and explained. Burr height shall be reported to the nearest 0.01 in. (0.25 mm).

4.1.10 Data Recording and Reporting

4.1.10.1 General

Data shall be reported on all shots fired or attempted. Data shall be reported in the same order that it was shot ballistically, with number one being the first charge shot. It is no longer required to collect and store concrete target and casing/tubing samples after the perforating system test completion.

4.1.10.2 QC Performance Test

A minimum of six valid QC test shots shall be made. No test shot shall be considered valid if the depth of penetration of the QC target is within three inches of the bottom of the QC target or exits the side of the target. All valid shots shall be used for calculating an average QC target penetration.

4.1.11 Special API 19B Section I Tests

4.1.11.1 General

4.1.11.1.1 Well environments can require special tests to better simulate down hole conditions. Some conditions require special casing. In some cases, dual string casing is placed over a producible zone. In other situations, gas environments can require the use of special gun systems. Operators shall be able to evaluate perforating systems under these conditions with special tests.

4.1.11.1.2 This section provides a means to shoot and publish a witnessed test in a Special API 19B Section I Target, with one or more of the following exceptions:

- a) special casing may be used;
- b) multiple string casing may be used;
- c) the gun may be shot with air instead of water in the gun to casing annulus;
- d) the gun may be loaded with mixed charges (multiple different names of charges loaded into one gun).

4.1.11.1.3 All other API 19B Section I requirements shall be met. All exceptions shall be listed in the remarks section of the appropriate data sheet.

4.1.11.1.4 Casing annulus concrete slurry shall be as defined in API 19B, Section 4.1.2.2, unless otherwise specified by the customer.

4.1.11.2 Mixed Charge Perforating System Selection

The mixed charge perforating system to be tested shall consist of standard field equipment, including a sufficient length of continuously loaded active gun, shot density, phasing, charges, explosive accessories, and other components representative of standard field equipment. Selection of the charges shall conform to [4.1.4](#) for each charge name (a minimum production run of 300 charges is required for each charge name).

4.1.11.3 Multi-directional Firing Mixed Charge Perforator System

For multi-directional firing mixed perforator systems, a sufficient length of continuously loaded active gun shall be tested to provide a minimum of 12 shots or one foot of continuously loaded gun, whichever provides more shots. A minimum of six shots of each charge name shall be fired. The perforating device shall be shot as it is normally positioned in the casing.

4.1.11.4 Uni-directional Firing Mixed Charge Perforator System

Uni-directional mixed charge perforator systems, without positioning devices, shall be tested in two positions. In one position, all shots shall be fired at maximum clearance. In the other position all shots shall be fired at minimum clearance. A minimum of eight shots shall be fired from each position. A minimum of four shots of each charge name shall be fired.

Perforator systems with positioning devices shall be fired in the position assumed in a well. A minimum of 12 shots shall be fired. A minimum of six shots of each charge name shall be fired.

4.1.11.5 Test Fluid, Test Result Validity, and Data Collection

Requirements defined in [4.1.7](#), [4.1.8](#), and [4.1.9](#) shall apply.

4.1.11.6 Data Recording and Reporting

Data shall be reported on all shots fired or attempted and reported in the same order they were shot ballistically. It is no longer required to collect and store concrete target and casing/tubing samples after the perforating system test completion.

4.2 Evaluation of Perforators using Stressed Rock Targets (Section II Test)

4.2.1 Introduction

This section provides a basis for the evaluation of perforators with tests using rock cores at simplified in situ conditions. The primary useful data output from these tests is the penetration depth produced as a function of target composition and state.

The intent of this section is to provide a specification for preparing targets, conducting tests, and reporting data so that consistent and comparable results can be obtained. The data produced shall be suitable for first order estimation of downhole performance, given suitable predictive models.

The structure of this section shall be as follows:

- a) target selection—requirements, specifications, and preparation procedures;
- b) test equipment—requirements, specifications;
- c) standard qualification test—description and procedures.

The method in this section was established by a collective group, based on a large-scale round-robin test series conducted across numerous facilities. The test series aimed to identify any potential inconsistencies which might result from the specific processes, or test equipment used, at the various facilities. To ensure as much consistency

as possible across the multiple facilities, a single lot of shaped charges and single block of sandstone was used. The conclusion from the analysis of the results was that no significant variations in results were observed - within the overall data scatter - that could be attributed to the different vessels, UCS equipment, or company specific practices used.

4.2.2 Sandstone Target—Requirements and Specifications

4.2.2.1 All testing shall be conducted using natural stone targets, obtained from blocks of stone, quarried from the earth.

4.2.2.2 The standard target shall be homogeneous sandstone, such as Berea sandstone.

4.2.2.3 The porosity of the target shall be between 18.5 % and 21.5 %, which is a typical range of porosity for Berea Sandstone.

4.2.2.4 The uniaxial compressive strength (UCS) of the saturated target shall be a minimum of 5700 psi (39.3 MPa) based on plug or scratch test data, or both, as determined in 4.2.3.3.2.

4.2.2.5 The target shall be a right-circular cylinder obtained from the natural stone block. The OD of the target shall be between 4 in. to 7 in. (102 mm to 178 mm) with an allowable tolerance on the OD of ± 0.1 in. (2.5 mm) for deep penetrating charges. Big hole charges may require larger diameters. The length of the target may vary depending on the expected perforation depth. The ends of the target shall be flat and parallel to each other.

4.2.2.6 The bedding plane orientation of the target shall be parallel to the target axis. The testing company shall know the target strength in the direction of charge penetration.

NOTE Strength measurements perpendicular to bedding planes will be greater than parallel to bedding planes for most targets.

4.2.2.7 All targets shall be vacuum saturated with odorless mineral spirits (OMS) prior to testing and shall be stored in a container of this fluid, covering the target until used, in an experiment.

4.2.2.8 The rock targets should be free of any visible crack or flaws.

NOTE Cracks visible on a core after testing are common. These cracks may or may not have caused experimental error. Cracks which have visible charge debris inside them most likely were formed during the perforation event. These cracks may also propagate after removing stress from the target and may or may not contribute to experimental error.

4.2.3 Sandstone Target—Preparation and Characterization Procedures

4.2.3.1 Cutting

Diamond core barrels and saws shall be used for cutting of round targets and core plugs.

4.2.3.2 Drying

The cut and sized targets shall be oven-dried for at least 24 hours, and to a constant mass (mass percentage change of 0.01 % or less in a 24-hour period) in a ventilated oven that is maintained between 93.3 °C and 98.9 °C (200 °F and 210 °F). Once the target has been dried, it shall remain in the oven at temperature until it is ready to be evacuated. The formula for calculating the mass percentage change (MPC) is given by Equation (1).

$$MPC = \left(\frac{mass_{n-1} - mass_n}{mass_{n-1}} \right) \times 100\% \quad (1)$$

where

$mass_n$ is the most recent mass measurement, in grams (g);

$mass_{n-1}$ is the previous mass measurement, in grams (g).

4.2.3.3 Evacuation, Saturation, and Porosity Determination

4.2.3.3.1 General

4.2.3.3.1.1 Just prior to placement in the evacuation chamber, the target shall be weighed to the nearest gram on a scale, with suitable accuracy and range, to determine the dry mass of the target. The target mass shall be determined using a scale with a precision of 1 g for loads of 1000 g or greater. Scales used for this measurement shall be calibrated annually, at a minimum.

The target shall be evacuated inside of an air-tight chamber provided with a suitably sized evacuation port and vacuum pump to maintain a minimum vacuum of 29 in. of mercury for a minimum of three hours before admitting any saturating fluid.

4.2.3.3.1.2 The saturation fluid shall be odorless mineral spirits (OMS).

4.2.3.3.1.3 The target shall be saturated by slowly admitting the saturating fluid into the bottom of the chamber with the target still under full vacuum. Care shall be taken to allow the fluid to be imbibed or wicked into the target. Under no circumstances shall the liquid level be allowed to rise over the saturation line visible on the target OD. The target is completely saturated when the saturation line meets the top surface of the rock and can visually be identified as fully saturated. After full saturation, the vacuum shall be maintained for a minimum of two hours, after which the pressure shall be slowly increased to atmospheric.

4.2.3.3.1.4 After saturation is complete, the target shall be removed from the evacuation chamber, immediately wiped free of loose liquids, and weighed again, to the nearest gram, to obtain the saturated mass. The same scale and calibration requirements apply as mentioned in [4.2.3.3.1.1](#).

4.2.3.3.1.5 The pore volume V_p shall be calculated by dividing the difference in mass in the saturated and dry states by the density of the saturating fluid. The bulk volume V_b shall be calculated from the physical dimensions of each individual target. The porosity (ϕ) of the target shall then be calculated using Equation (2):

$$\phi = \left(V_p / V_b \right) \times 100\% \quad (2)$$

where

V_p is the pore volume, in cubic centimeters (cm³);

V_b is the bulk volume, in cubic centimeters (cm³).

4.2.3.3.2 Uniaxial Compressive Strength (UCS) Determination

4.2.3.3.2.1 General

All persons or organizations performing UCS testing shall meet all applicable requirements of ASTM D3740.

The UCS of each target shall be determined by a core plug test in accordance with [4.2.3.3.2.2](#) or a scratch index test in accordance with [4.2.3.3.2.3](#).

4.2.3.3.2.2 Core Plug Test

4.2.3.3.2.2.1 The first acceptable test method shall be a core plug test as described in Method C of ASTM D7012, unless specified otherwise below. Please refer to ASTM D7012, Section 1.2.3 for complete details on how to correctly perform tests that satisfy the testing criteria.

4.2.3.3.2.2.2 All core plug samples shall be prepared following the recommended and required practices listed in ASTM D4543, unless specified otherwise below.

4.2.3.3.2.2.3 Three core plugs shall be cut from each end of the target in the direction of penetration. If apparent, and possible, all three core plugs should be from the same bedding plane region.

4.2.3.3.2.2.4 The rock specimens shall be right circular cylinders of 0.95 in. (24.1 mm) minimum diameter, with a length to diameter ratio of 2.0:1, and up to a maximum of 2.5:1. Cube samples are not acceptable for this test.

4.2.3.3.2.2.5 The ends of the core plug shall be ground or machined flat and parallel to each other.

4.2.3.3.2.2.6 All core plugs and the target shall be identically prepared. Special care shall be taken to ensure core plugs or target do not dry out during UCS testing.

4.2.3.3.2.2.7 Measure the UCS of all six core plugs. A core plug measurement shall be considered valid only if the dominant failure surface observed is one of shear (e.g. diagonal to the loading direction). See [Figure 2](#) and [Figure 3](#) for examples of a shear failure.

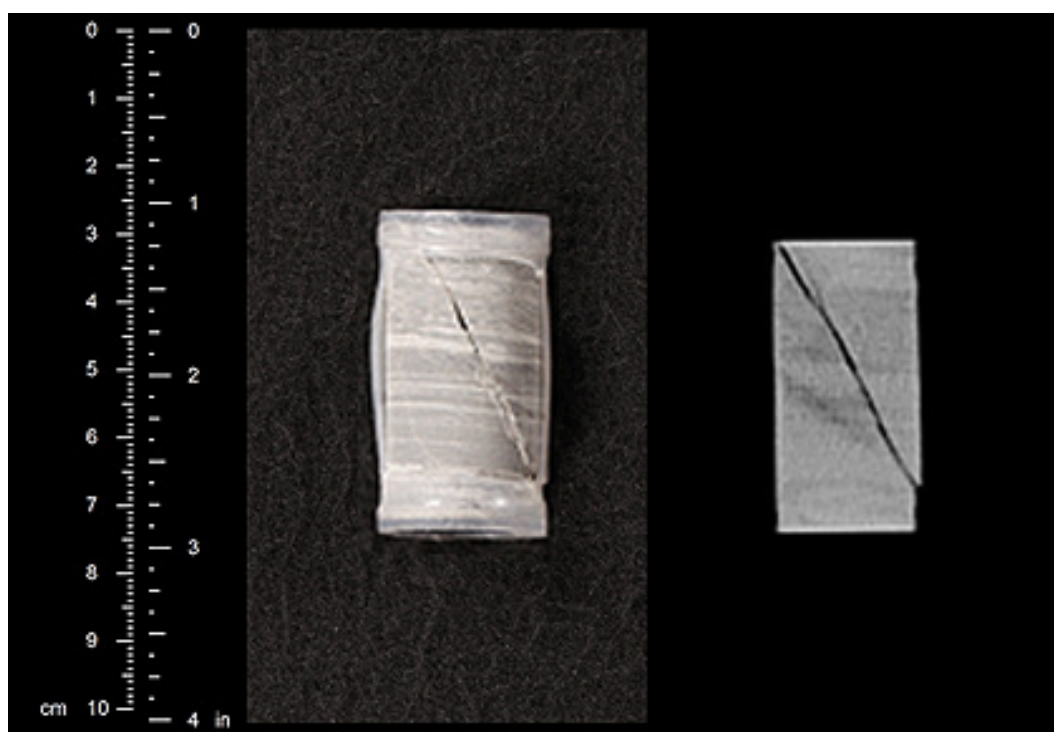


Figure 2—Diagram 1 in. × 2 in. Test Sample Post Failure; Demonstrating Shear Failure Angle Required for a Valid UCS Test

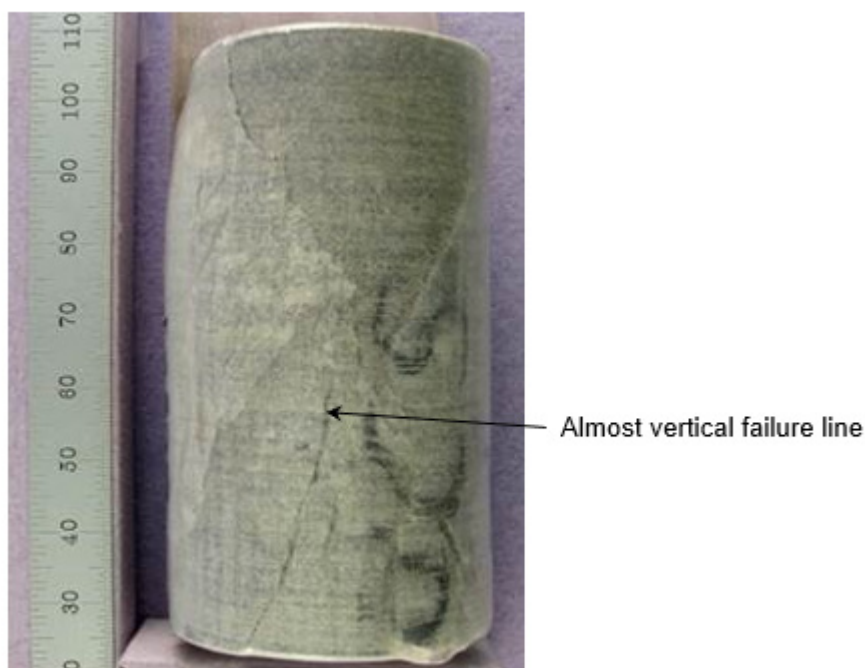


Figure 3—Diagram 1 in. × 2 in. Test Sample Post Failure; Failed to Demonstrate a Shear Failure Model for a Valid UCS Test

4.2.3.3.2.2.8 Report UCS as the average of all valid end core plug measurements. A minimum of four valid core plug measurements is required for the target to be considered for perforation testing.

4.2.3.3.2.2.9 If required by the test system design, the loaded end of the sample shall be fitted with a spherical seat or bearing surface to minimize any misalignment between the axis of the sample and the direction of the applied load.

4.2.3.3.2.2.10 The loading frame or device shall be of sufficient capacity to apply load at a rate conforming to and following the requirements of Section 10.4.1.1 in ASTM D7012-14e1.

4.2.3.3.2.2.11 Load shall be applied continuously and without shock at a stress rate between 0.20 MPa/second and 1.0 MPa/second (30 PSI/second-145 PSI/second).

NOTE This means that the loading rate in LBF/second is a direct function of the sample diameter.

4.2.3.3.2.2.12 The stress application rate shall vary by no more than 10 % during the test.

4.2.3.3.2.2.13 The stress application rate shall be chosen to produce a sample failure in compression in a test time of between 2 minutes and 15 minutes.

4.2.3.3.2.2.14 The stress rate chosen shall be adhered to for all tests for a given series of investigation.

4.2.3.3.2.2.15 Axial load shall be applied until the stress on the sample decreases, or the sample fails. The sample should fail in shear mode to be valid. Failure along a bedding plane or in a direction parallel to the bedding planes shall render a test result invalid (see [Figure 3](#)).

4.2.3.3.2.3 Scratch Index Test

4.2.3.3.2.3.1 The second acceptable method of determining the UCS shall be via a Scratch Index Test. This method uses specialized equipment available from different manufacturers and develops a strength index profile along the OD of the target, in the axial direction.

4.2.3.3.2.3.2 This test if used shall be done by trained personnel, following the procedures and specifications provided by the test system manufacturer.

4.2.3.3.2.3.3 The test machine is designed to measure a shear force and a normal force on a Polycrystalline Diamond Cutter (PDC) of known width that is cutting a constant depth at a constant speed. The equipment manufacturer's software then calculates the required compressive strength of the rock material that would be necessary to produce the measured forces.

4.2.3.3.2.3.4 For the cut to be considered valid, the ratio between the shear and normal forces being measured shall be within a specific ratio limit, as specified by each manufacturer. If the ratio is too high, the depth of cut shall be reduced, or a cutter with a narrower width shall be used, or the speed shall be reduced.

4.2.3.3.2.3.5 Two widths of cutters are available; 10 mm wide and 5 mm wide. Start with the 10 mm wide cutter in all cases, and switch to the 5 mm cutter only if you are unable to get a valid cut by reducing the depth of cut and speed of cut as noted in 4.2.3.3.2.3.4.

4.2.3.3.2.3.6 The saturated but unperforated target shall be removed from the fluid tank, placed into the scratch test machine target holder, and securely held in place, such that the target cannot be moved in any orthogonal direction.

4.2.3.3.2.3.7 Position the target in the apparatus such that the scratch will not be directly on top of a bedding plane (assuming bedding planes are visible). Scratching directly on top of the bedding plane line will produce results that may be higher or lower than the actual UCS due to the mineralogy of the bedding plane. See [Figure 4](#) for examples.

NOTE Scratching across a bedding plane can decrease the accuracy of the measurement.

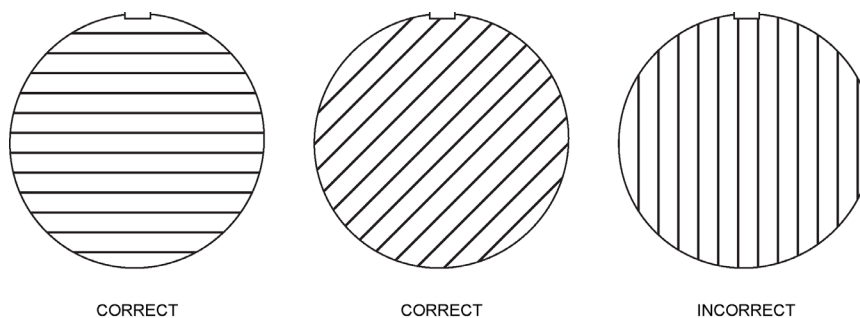


Figure 4—Suggested Position of Cutter Scratch vs. Bedding Planes

4.2.3.3.2.3.8 Preliminary clean-up cuts are performed to ensure that the cutter is making a complete cut (scratch) along the entire length of the target.

4.2.3.3.2.3.9 To ensure that clean up cuts are sufficient, the raw data shall be examined and verified that there is no drop off in the measured loads during the scratch. Typically, on smooth surface targets, about three clean up cuts are required to ensure a good scratch value is obtained.

4.2.3.3.2.3.10 Once the preliminary cuts are completed, a series of at least two individual scratches are required, following the manufacturer machine instructions, for rocks with non-visible bedding planes. For rock with visible bedding planes, a minimum of three scratches are suggested. The number of scratches above two or three is at the discretion of the testing company.

4.2.3.3.2.3.11 Reposition the target in the apparatus by rotating the target by between 90° and 120°, and then repeat the scratch process as described in 4.2.3.3.2.3.6 through 4.2.3.3.2.3.10.

4.2.3.3.2.3.12 When all scratching is completed on a target, the scratch(es) on the target OD (~3 mm deep) shall be filled with a suitable cement or epoxy-based filler, if required, and after the filler has set, the target will be returned to the fluid tank until needed for a test.

4.2.3.3.2.3.13 The scratch data shall be analyzed using the test machine's Analysis program, and then averaged and plotted, which will produce a value of the UCS Index of the target continuously along the entire length.

4.2.3.3.2.3.14 For each cut recorded, the first half inch and the last half inch of the reduced data shall be discarded. All remaining data for each cut shall be averaged and plotted as UCS Index vs. Position. Be sure to match the position data for each scratch, so that the average UCS Index obtained are comparable.

4.2.3.3.2.3.15 The average UCS Index shall be calculated for each scratch cut (discarding the first half inch and last half inch) and record this value into the results data table for that particular target.

4.2.3.3.2.3.16 The data table will then calculate an overall average UCS value for the test target. The average of both scratch UCS values (0° and $90^\circ - 120^\circ$) will be used to determine the average UCS for the target.

4.2.3.4 Storage

The target shall be stored (fully submerged) in the same type of fluid with which it was saturated; following characterization until assembly into the confinement vessel.

4.2.4 Test Setup

4.2.4.1 Target and Casing Plate Assembly

4.2.4.1.1 The target shall be provided with a faceplate on the end to be perforated that simulates the well casing and cement sheath between the casing and the borehole wall. There shall be a flexible jacket that transmits simulated overburden stress to the sample. There shall be a faceplate on the end that is not to be perforated to prevent confining pressure from entering the target.

4.2.4.1.2 The faceplate on the perforated end of the target shall consist of 0.50 in. ± 0.020 in. (12.7 mm ± 0.51 mm) thick wall simulating the well casing and shall be made of AISI 4140 steel (UNS G41400 or equivalent) as defined in and conforming to ASTM A29. The face plate material shall be in the heat treated (quenched and tempered) condition, and shall have a hardness of 18–22 Rockwell C, minimum 80 ksi yield strength. The plate shall be at least 1.5 in. (38 mm) in diameter or at least 1.5 in. (38 mm) square.

4.2.4.1.3 The cement sheath between the simulated casing and target shall be 0.75 in. ± 0.030 in. (19 mm ± 0.762 mm) thick, at least 1.5 in. (38 mm) in diameter, and shall consist of standard API class A, ASTM Type I, or ASTM Type II cement. The cement shall cure for a minimum of five days at ambient conditions.

4.2.4.1.4 The flexible jacket surrounding the target shall be of any flexible material, such as Buna-N (nitrile), urethane, or other elastomers that are compatible with both the working fluid and the saturation fluid. To ensure that the overburden stress is properly transmitted to the target, the jacket shall not be thicker than 0.75 in. (19 mm); refer to [Figure 5](#).

4.2.4.1.5 Care shall be taken to ensure that the flexible jacket is securely fastened to the faceplates; this will prevent leakage of the confining pressure into the target which will affect results. Leakage of the working fluid into the target will invalidate the test. If the working fluid is different from the target saturation fluid, the target will be deemed contaminated, and cannot be used in later official tests.

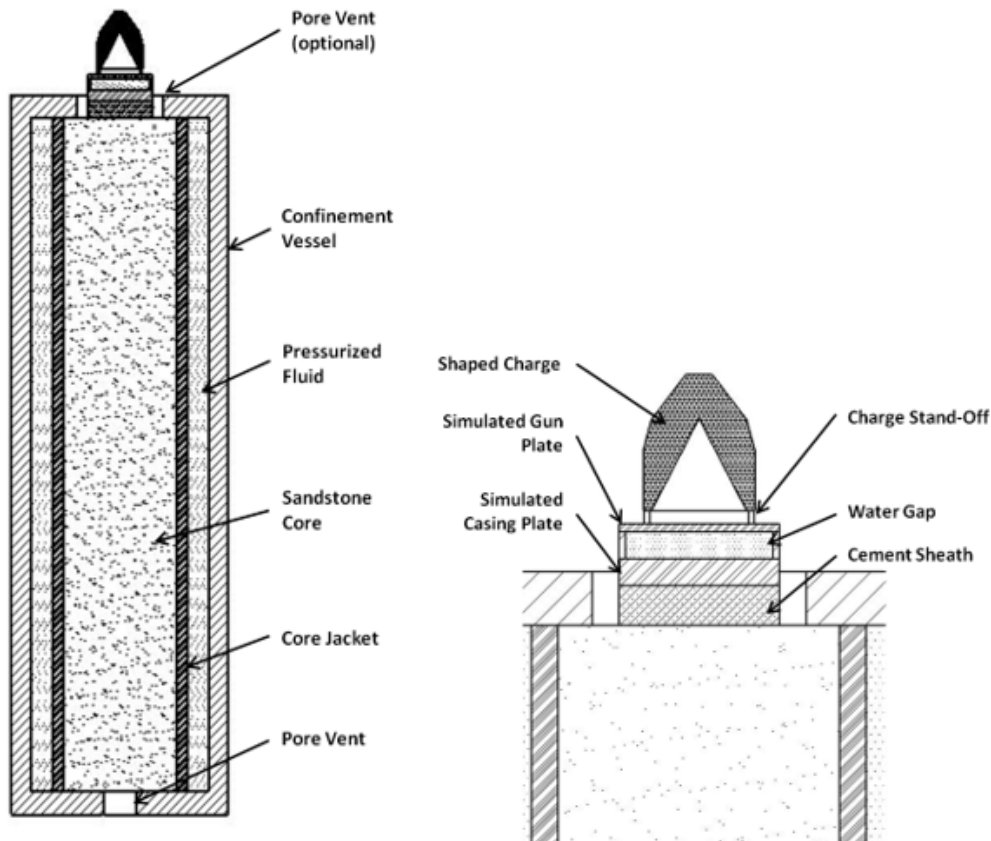


Figure 5—Test Set Up Schematic

4.2.4.2 Wellbore Fluid Clearance

A fluid clearance shall be established between the outer face of the perforated faceplate and the OD of the simulated scallop. This clearance shall be 0.75 in. (19 mm) and be filled with water or OMS. Grease or adhesive caulking may be used to prevent the liquid from leaking from the clearance gap.

4.2.4.3 Gun Body

An actual or simulated scallop or gun body shall be placed over the clearance gap. If a simulated scallop or gun body is used it shall be of the same thickness as the actual carrier that is used for the shaped charge that is being tested and may be mild steel. A stand-off ring may be used to create the internal gun configuration but shall accurately represent the actual stand-off between the face of the charge and the ID of the gun body.

4.2.4.4 Shaped Charge

The required number of charges shall be samples taken randomly from a minimum production run of 300 charges and packaged in the manufacturing/service company's standard shipping containers. These charges shall be stored for a minimum of four weeks prior to testing to allow some aging to occur. Charges shall be selected from one or more unopened containers.

4.2.4.5 Detonating Cord

The detonating cord shall be used to initiate the test charge and shall meet the same temperature rating as the charge being tested. It shall be of the same grain weight, detonation velocity type (XHV or regular), and size/configuration as will be recommended for use in the system being tested. The detonating cord shall be used

in the same orientation and manner that it would be in the actual system in which the charge being tested is employed.

4.2.5 Confinement Vessel

4.2.5.1 General Design Guidelines

The design and operation of the pressure confinement vessel shall be left to the discretion of the individual testing company. [Figure 5](#) is meant to show the concept to assist in the basic description of conducting a test. The target shall be constrained in the longitudinal direction to prevent tensile failure. However, at a minimum, the inside diameter of the pressure vessel shall be at least 1 in. (25.4 mm) larger than the outside diameter of the confinement sleeve. The test assembly shall be concentric within the test vessel, giving a minimum 0.5 in. (12.7 mm) annular fluid gap. The vessel shall also be of sufficient length to accommodate target lengths as described in [4.2.7](#).

4.2.5.2 Pressure Capability Requirements

The confinement vessel, for the purposes of this test, shall be capable of safely handling pressures up to 9500 psi (65.5 MPa), however pressure capability up to 15,000 psi (103 MPa) is recommended.

4.2.5.3 Wellbore System

A wellbore chamber is not required; however, a wellbore chamber may be used if no more than 100 psi (689 kPa) pressure exists in the chamber during the test.

4.2.5.4 Pore System Ventilation

Elevated pore pressure is not required and could have an impact on the performance of the perforator. Therefore, a suitable mechanism shall exist to bleed pore pressure which can otherwise build up during application of confining stress (Skempton effect). Pore pressure venting shall be through either a small hole through the casing plate, a hole/vent tube connected to the unperforated end of the target, or both. The minimum vent hole/port diameter shall be 0.075 in. (1.9 mm). Vent hole(s) shall be in direct contact with the target surface(s), and care shall be taken that this venting mechanism does not become obstructed with debris, sand grains, grease, etc. In conjunction with this venting mechanism, the target shall be held at elevated confining stress (prior to perforating) for a sufficient time to ensure that any induced pore pressure has fully diffused from the entire pore space. The required time is a function of the vent hole location, whether one or both ends of the target are vented, target length, and permeability. Higher permeability, shorter targets, and venting both ends all will decrease this required time.

4.2.6 Test Conditions

4.2.6.1 Pressure Conditions and Number of Shots

The pressurizing test fluid used shall be at the discretion of the individual testing company. All tests will be conducted at ambient temperature conditions. Test will be conducted at three different confinement pressure values; 1500 psi, 5500 psi, and 9500 psi (each ± 50 psi). Four valid shots are required at each pressure, and all valid shots shall be recorded.

Criteria for a shot to be considered valid are described in [4.2.7](#).

4.2.6.2 Testing Procedure

4.2.6.2.1 Upon installation of the target into the confinement vessel and proper placement of the shaped charge assembly, the confining pressure shall be increased to the desired test pressure. Pressure shall be remotely monitored using calibrated gauges; gauge accuracy shall be ± 0.5 %.

Gauges used for this measurement shall be, at a minimum, calibrated annually.