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ADDENDUM 1

Section 0.2, *replace the text as follows:*

Information on API Registration of perforator systems can be found in **Appendix A**.

Replace all of Section 4 with the following.

4 Evaluation of Perforation Flow Performance Under Simulated Downhole Condition

4.1 INTRODUCTION

The purpose of Section 4 is to provide a basis for the comparison, development, and evaluation of perforators and perforating performance in general through the use of tests looking at the flow performance of perforations shot into rock cores, shot under in situ conditions. The intent of this section shall be to ensure that all entities performing such tests do so in a way that translates improved lab performance into increased performance in the field. This section should NOT be used as a restriction on how a facility is set up and operated. This is best left to the groups performing such tests and allows for designs to be based on experience, best practices, and improvements in technology. The outline for a "standard test" that should be performed by all entities and parties that choose to perform such tests is also included.

The structure of this section shall be as follows:

a. a basic target preparation and constructions technique specification;
b. a basic equipment and technique specification highlighting common test artifacts for consideration;
c. standard qualification test description(s), including core saturation procedures; and
d. minimum requirements for comparative tests.

4.2 TARGET PREPARATION AND CONSIDERATIONS

4.2.1 Tests shall be conducted using cylindrical natural rock targets, obtained from stone quarries, field outcrops, or from well core obtained from an oil or gas well.

4.2.2 Targets may be cut either perpendicular or parallel to the natural bedding planes in the stone. The choice of bedding plane orientation has implications for test boundary conditions and for data reduction.

4.2.3 The size of the test core shall be at the discretion of the testing company. In general, for charges with 15 gm of high explosive or less, a 4 in. diameter core may be used. For charges with explosive loads greater than 15 gm, a 7 in. target should be used. This is not a strict limit. In many cases useful information can still be obtained for larger charges in smaller cores. The appropriate target size is dependent upon: the charge to be used, the rock strength, rock confinement pressure, and fluid system stiffness.

4.2.4 If necessary, a composite target may be constructed from small diameter field core and some outer shell material in order to create a larger effective diameter. The methodology for doing this shall be at the discretion of the testing company; however, in general these methods will increase experimental uncertainty and may create an indeterminate boundary condition.

4.2.5 Targets can range from 4 in. to 20 in. diameter. Current sizes in use are: 4 in., 5 in., 6 in., 7 in., 9 in. 11.5 in., and 15.5 in. In general, a lab facility can accommodate most testing requirements with three core sizes, ranging from 4 in. diameter to 9 in. diameter. Increased core diameter can reduce experimental variation.

4.2.6 Core length should be sufficient such that end effects do not influence penetration depth or flow measurements. One core diameter is the minimum required distance between the tip of the perforation and the end of the core, and more may be required. Extra core length can reduce experimental variation.

4.2.7 Target dimensions are to be ±0.1 in. for both OD and length. The ends of the core are to be flat and parallel to each other to avoid error.

4.2.8 The rock targets should be initially free of any visible crack or flaws. A crack to the OD boundary may cause experimental error. Also note that 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 core and may or may not contribute to experimental error.

4.2.9 In a given comparative study, target diameter and length should be held constant to not add additional error into the result.

4.2.10 Diamond core barrels and saws are preferred for cutting of round cores to reduce fines that may affect core permeability measurements. This effect is increased for radial flow test configurations. Loose material should be brushed off or otherwise removed.

4.2.11 The cut and sized cores shall be oven dried for at least 24 hr and to a constant weight (mass change of 1 gm or less in a 24 hr period) in a ventilated oven that is maintained at 200 °F but not higher than 210 °F.

4.3 TARGET EVACUATION AND SATURATION

4.3.1 Target saturation can be single phase (water, oil, or gas) or multi-phase (water-oil, water-gas, oil-gas, or water-oil-gas). Single-phase saturation may simplify tests and in some cases may more closely simulate the near wellbore region due to drilling and completion operations. Multi-phase saturation may more closely simulate the virgin or flowing reservoir or those situations where there are no issues from drilling and completions. Saturation state can affect the geometry of the perforation tunnel. The typical fluids used for single-phase core saturation are odorless mineral spirits (OMS), brine water (3 % KCl), or an inert gas (nitrogen). For safety reasons, one shall not use an oil that contains an aromatic fraction (live crude oil) or a combustible gas (methane or other hydrocarbon). The typical fluids used for multi-phase saturation are brine water, followed by OMS or gas.

4.3.2 Just prior to placement in the evacuation chamber, the rock core should be weighed on a scale with suitable accuracy and range to determine the dry weight of the core. The core shall be evacuated inside of an air-tight chamber provided with a suitably sized evacuation port and vacuum pump to a level of 1 mm of mercury or less for a minimum of 6 hr before admitting any saturating fluid. Lower porosity or lower permeability rocks may require additional evacuation time and/or additional procedures to ensure that the rock core will be adequately saturated.

4.3.3 The core shall be saturated by slowly admitting the saturating fluid into the bottom of the chamber with the core actively maintained at constant vacuum. Care shall be taken to allow the fluid to be imbibed or "wicked" into the core. Under no circumstances should the liquid level be allowed to rise over the saturation line visible on the core OD. After the core is completely saturated, vacuum should be maintained for a minimum of two additional hours, after which the pressure is slowly increased to atmospheric at constant rate over a period of 10 minutes.

4.3.4 After saturation is complete, the core shall be immediately wiped free of loose liquids and weighed again to obtain the saturated weight. The porosity of the core shall be calculated using the following formula:

$$\Phi = (V_p / V_b) \times 100\ \% \qquad (4\text{-}1)$$

4.3.5 The pore volume V_p shall be calculated by dividing the difference in weight 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 core. The core weights shall be determined at room temperature with a scale with a precision of 1 gm for loads of 1000 gm or greater.

4.3.6 If the core is to be saturated with a second phase, the core shall be placed under confining stress in a vessel resembling a Hassler sleeve permeameter. The confinement stress level and pore pressure should match the conditions planned for the core when tested. While under stress, a second fluid shall be flowed axially into one end of the core, displacing the first fluid. Flow at a rate that does not exceed the differential pressure level required to cause non-Darcy flow or movement of the fines or clay particles in the pore throats, and continue at this rate until the differential pressure for a given rate is constant or steady state. All cores that will be used in a common test program should be flowed at the same conditions to try and produce an irreducible saturate state to the first fluid that is constant between cores. Some consideration should be given to the gravity effects should the second fluid differ in density from the first, and it may be preferable to inject fluid from the vertical top of the core, the bottom of the core, or both.

4.3.7 After saturating, cores shall be stored in the fluid used to saturate it with, or last flowed through it, until ready for characterization.

4.3.8 After core characterization has occurred, the core shall be stored in the fluid last flowed through the core, until it is ready for use in a perforating experiment.

4.4 TARGET CHARACTERIZATION AND PERMEABILITY MEASUREMENT

4.4.1 General

Natural rock targets are at this time the best available option for this type of simulation. A significant disadvantage to these targets is the variability between sample sets, although consistency within a given sample set can be very good. Poor quality targets can be a source of considerable experimental error. Target selection and characterization therefore play a critical role in order to reduce experimental variation. Target characterization includes permeability, porosity, density, and dimensional properties, as well as mechanical properties such as compressive strength, etc. In a given sample set, it is best practice to evaluate a larger sample of targets than required and then cull targets that fall outside of the normal property range for the sample set.

4.4.2 Permeability Measurement

Sample permeability measurement requirements strongly depend on the type of final flow performance evaluation technique and may vary depending upon the rock used and the information desired from the test program. Sufficient measurements of pressure drop, flow rate, and viscosity or temperature should be collected in order to calculate the measures of flow performance as defined in Sections 4.10 or 4.11.

For test programs where the final flow performance is desired to be productivity ratio (PR), samples are recommended to be oriented with bedding planes parallel to the long axis of the core. In this case, the axial permeability shall be measured. Convergent flow measurements may also be taken in order to provide information in a strongly heterogeneous rock.

Figure 9 demonstrates a typical axial flow boundary condition setup applicable for permeability measurement. The target is configured with a constant pressure boundary condition on each end of the core and a no flow boundary condition on the core OD. This is best accomplished with a flexible jacket on the core OD and a flow distributor on each end of the core. Concentric ring distributors are recommended. Distributor design should be such that local stress and flow restriction effects are minimized. Screen may be used in conjunction with the flow distributors in order to minimize local effects of the distributors.

Convergent flow measurements are acquired in a setup similar to that shown in Figure 9, with the exception that a restriction plate is added to the outlet end of the core. The restriction plate should incorporate a sealing gasket in order to restrict the flow to a central opening. The diameter of the restriction hole should be such that the ratio of the open area to the area of the core face is approximately 1:50. For example, the appropriate diameter for a 5 inch diameter core shall be 0.75 inch, and the appropriate diameter for a 7 inch diameter core shall be 1.00 inch.

For test programs where the final flow performance is desired to be core flow efficiency (CFE), samples are recommended to have bedding planes perpendicular to the long axis of the core. In this case, both the axial permeability, and the diametral permeability in two orthogonal directions shall be measured.

Figure 10 illustrates a typical diametral permeability measurement setup. The core is configured with a constant pressure boundary condition on two opposite 90 degree arcs of length L', and a no flow boundary condition on all other surfaces of the core. The ratio of L' to the total length of the core affects the calculation of cross diameter permeability as shown in Section 4.10.1. In general the length of L' should be at least the length of the expected perforation tunnel. The annular gaps between the sample jacket and core OD shall be filled with a stress transmission media with permeability at least 100 times greater than the expected permeability of the test core. In most cases, steel rods or a high strength proppant can provide this capability. The ends of the core must be sealed to ensure that all flow passes across the diameter of the core. There are several ways to accomplish this, and it is left to the discretion of the testing company to select a method and then do the required testing to assure that there is no leakage.

These recommendations will produce conservative results, reduce experimental error, and emphasize the high permeability characteristics of the target.

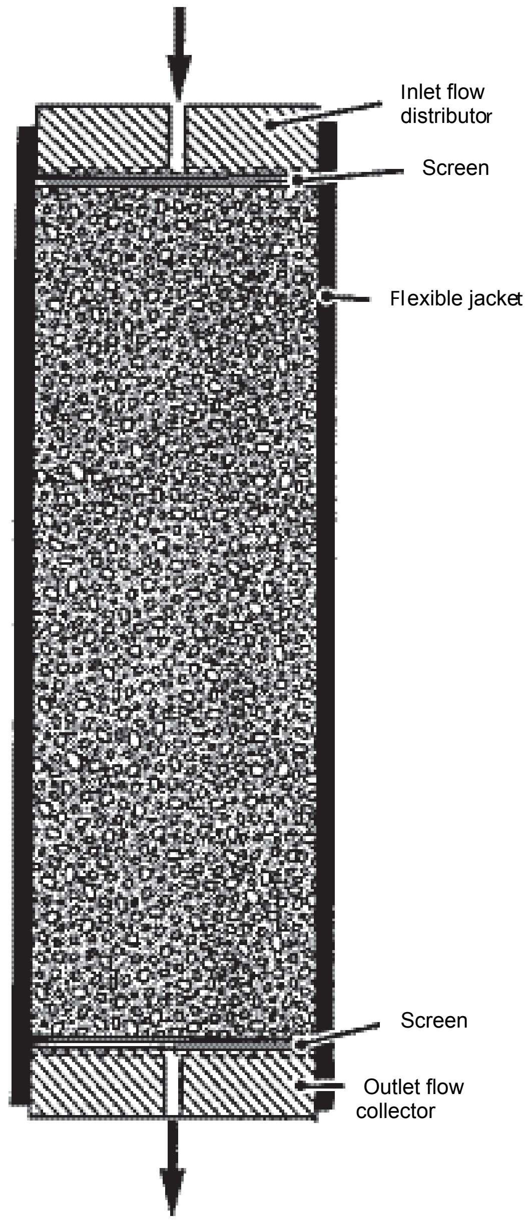
The methods for performing these measurements shall be at the discretion of the testing company except for the following.

a. The measurement should be performed under the same effective stress and pore pressure as that used to evaluate the perforated core.
b. In general, the measurement should be performed under the same effective stress as that used during the perforation test.
c. The core should be at the same fluid saturation condition as that used during the perforation test, and the same fluid and range of flow rates should be used in both tests during the flow measurements.
d. Care shall be taken to reduce sources of error as listed in 4.6.

4.4.3 Mechanical Properties

Mechanical properties may vary from core lot to core lot and sometimes target to target. Many times there are visual clues to varying mechanical properties. Permeability, porosity, and density may also provide an indication of significant difference. It is nevertheless good practice to measure various properties of each incoming lot, such as unconfined compressive strength, confined compressive strength, grain size distribution, mineralogy, and pore throat diameter. In recent years, scratch index testing has emerged as a means of quantifying unconfined compressive strength of each sample to be tested. Evaluating the mechanical properties of each core can reduce experimental variation.

Alternatively, incoming cores can be tested at standard test conditions against perforators with known performance history in order to qualify targets by batch or lot.



Not To Scale

Figure 9—Typical Axial-Flow Permeability Equipment

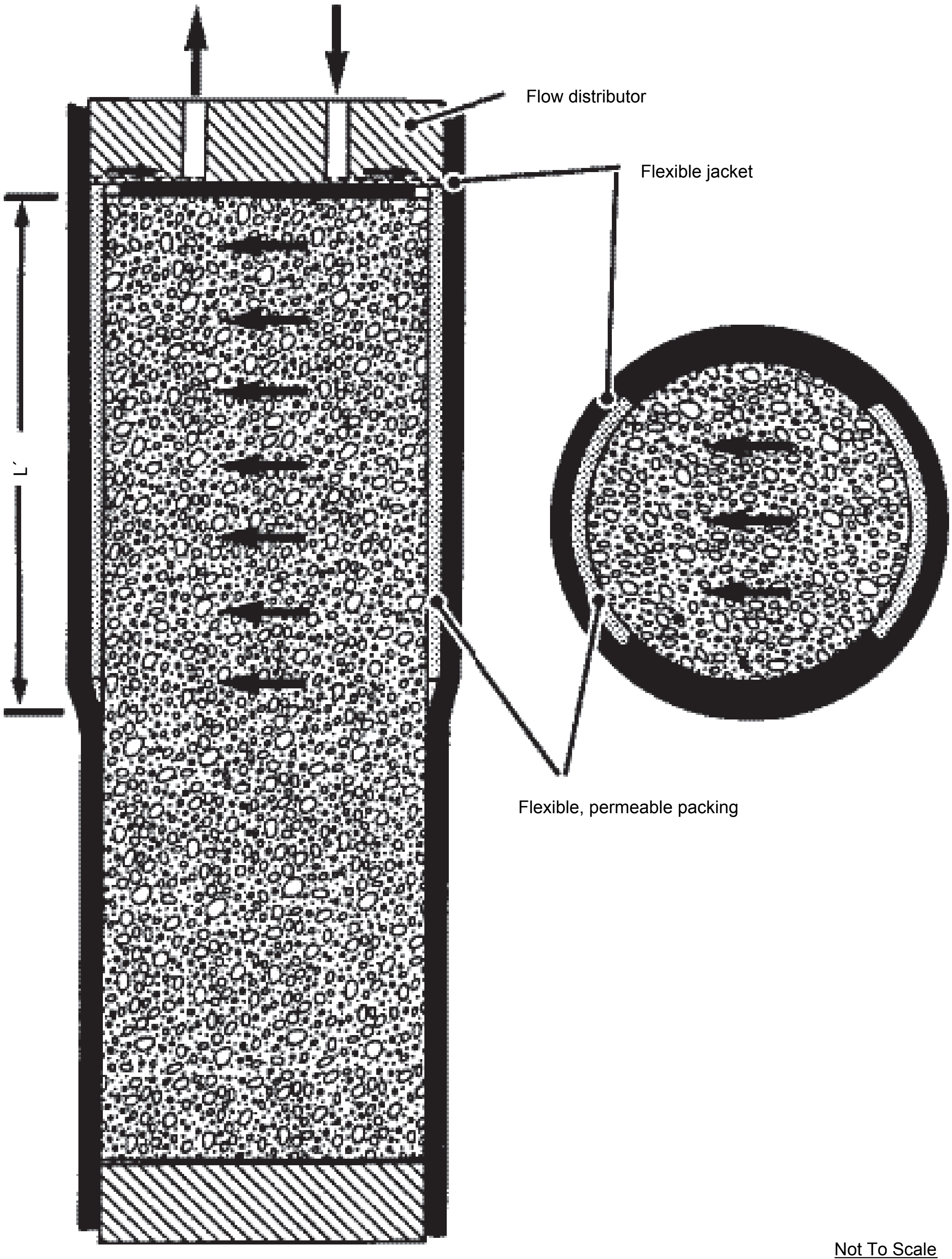


Figure 10—Typical Diametral Flow Permeability Equipment

4.5 TESTING REQUIREMENTS

4.5.1 General Requirements

Figure 11 illustrates a typical testing equipment schematic. The testing equipment required for a Section 4 experiment shall generally consist of the following:

a. target confinement system,
b. simulated wellbore system,
c. surge simulation system,
d. simulated perforating gun system,
e. pressure control and measurement system,
f. flow control and measurement system, and
g. data acquisition system.

4.5.2 Target Confinement System

The target confinement system is composed of the target assembly and a confining pressure vessel that is designed to apply uniform hydrostatic stress to the target. The inside diameter of this vessel shall be of sufficient size to not cause test artifacts. Application of load shall be controlled and be of a rate that will not cause sample problems due to loading. The composition of the jacket shall be an elastomer material, capable of adequate deformation to seal on the core and endcaps as required. Consideration should be given to the temperature and fluids that the jacket will be exposed to. System pressurization fluid is at the discretion of the testing company. Using fluids incompatible with the test process can cause target contamination and invalidate the test results.

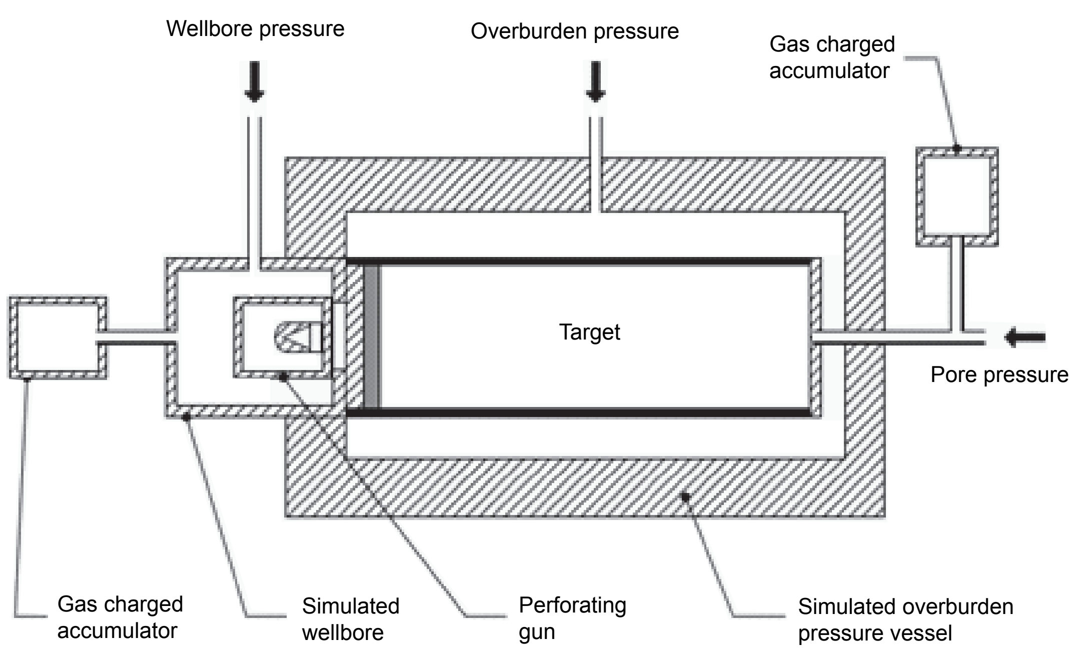


Figure 11—Schematic of Typical Testing Equipment

4.5.3 Simulated Wellbore System

The simulated wellbore system consists of the wellbore pressure vessel that when connected to the target confinement system allows for the creation of three distinct pressure regimes (confining, wellbore, and pore). The design of the vessel needs to consider the dynamic shock events that will occur inside, and appropriate factors of safety must be used to account for these conditions. The design also needs to consider the wide range of fluids that this vessel could be exposed to. Proper material selection is critical to ensure safety when designing and using a vessel that will be subject to high stress and pressure, dynamic shock, corrosives, and caustics. Improper material selection can be dangerous. The wellbore volume needs to be of sufficient volume to contain the simulated perforator gun but must be controlled as much as possible to match appropriate perforation conditions. The effect of wellbore volume and configuration is not well defined, but one should expect that changes in volume and geometry will significantly affect the response of the system to dynamic pressure events. Debris or test fixture movement during the perforation event may obstruct the perforation tunnel entrance. Depending on the parameters of the test, this may be significant or a source of experimental error. Other considerations include explosive loading procedures, proper data collection, and flow paths during and after the perforation event.

4.5.4 Surge Simulation System

The surge simulation system shall be used to supply the "surge flow" into and/or out of the test target during the perforation event. This surge flow is meant to mimic the response of reservoir and the wellbore to the creation of the perforation and casing entrance hole. This surge flow is most typically done with accumulators. In the baseline case, the goal shall be to provide a constant pressure boundary condition at the reservoir side of the target. To this end there should be minimal restriction to flow in the plumbing between the pore side accumulators and the core. Increasing the volume of accumulators on the reservoir side will also minimize the loss of reservoir pressure after perforating. The level of gas precharge on the reservoir side accumulators will affect the amount of fluid available for the surge flow and the final pressure of the pore fluid after perforating. The amount of accumulation volume and design of this system shall be left to the testing company as part of the overall design of the facility and experiment. This system can be used to tailor the amount of perforation clean up and to compensate for geometry driven dynamic system events.

4.5.5 Simulated Perforating Gun System

The simulated perforating gun system shall consist of a sealed chamber containing the charge, detonating cord (if used), and detonator. It must be designed to mimic the gun that matches the charge being used in the experiment. It must have a realistic thickness and design as a field gun in the area where the charge would penetrate the gun body, including the scallop. It must match the in-gun standoff that the charge would have in a field gun used in a relevant application. It should be positioned in the wellbore in such a way to hold and maintain the water clearance between the gun and the simulated casing endcap to match that of the field gun in the wellbore. The internal volume of the gun module is a variable that can be adjusted to affect the dynamic surges during the perforating event.

Two types of gun designs mimicking carrier guns are most common. One utilizes shooting the charge in the true geometry (out the side of the carrier). The second utilizes a design shooting the charge through a flat plate that mimics the wall thickness of the gun and scallop. Each has advantages and disadvantages. The design is left to the testing company to decide which design is possible in their particular system and which one provides the best flexibility and reliability.

Use of exploding bridge wire (EBW) detonators is recommended for safety reasons. Be sure to follow all recommendations and requirements of the EBW detonator supplier that is used, as requirements do vary from manufacturer to manufacturer.

In consideration of the charge selection for use in testing of this type:

a. every effort should be made to reduce charge performance variation in this type of testing;
b. verification of performance and repeatability is recommended prior to initiation of any test program;

c. charges to be used should be thoroughly inspected and examined prior to use to eliminate any that have deteriorated or appear to be suspect;
d. where possible, all charges for a given test program should come from the same box of charges and/or same date shift code;
e. minimum run lots are not specified for these tests as it is not useful or meaningful; and
f. origin and description of charges used should be reported.

4.5.6 Pressure Control and Measurement System

The pressure control and measurement system shall consist of the pumps, transducers, and valves used to supply, maintain, and control the high pressure confining pressure, reservoir pressure, and wellbore pressure needed for these experiments. Adequate pressure relief capacity must be supplied to protect the test vessels from over-pressure conditions due to equipment malfunction or operator error. The design and specification of this system is left up to the testing company. The expected minimum accuracies of the pressure measurement devices are discussed in 4.8. Pressure measurement and control are extremely important. Variations in pressure control or errors in the differential pressure measurement will introduce major amounts of error and variation into the test results.

4.5.7 Flow Control and Measurement System

The flow control and measurement system shall consist of the flow pumps, controllers, flow meters, and valves used to supply, maintain, and control the fluids being flowed through the test target in either the production or injection directions. Test fluids can include oil, water, or gas in single phase or in various combinations. The required accuracies for the flow measurement equipment are discussed in 4.8. The design and specification is left up to the testing company.

a. Flow measurement and rate control are extremely important. An improperly designed system will introduce major amounts of error and variation into the test results. Note that it is recommended for simplicity (but not required) to control the rate and measure the differential pressure for a liquid flow and to control the differential pressure and measure the rate for a gas flow.
b. Fluid filtration is critical. Improper or inadequate filtration will result in core plugging, which will add error to the pressure drop measurements, which will affect the final results. This should be evaluated for any system as noted in 4.8.

4.5.8 Data Acquisition System

The data acquisition system shall consist of the required equipment to accurately record all data from a Section 4 test with the accuracy required for each testing type. The equipment configuration shall be at the discretion of the testing company with the exception of the following.

a. Analog to digital conversion can be a source of significant error. The use of higher resolution A-D conversion can help to increase accuracy.
b. The system shall be capable of collecting “fast data” at the time of the perforator detonation. At a minimum these measurements should be collected from the wellbore pressure; however, gun peak pressure and pore pressure may also be useful to understand system response. In general, rates of 5000 samples per second are the minimum acceptable.
c. Care should be taken to reduce noise from detonator initiation and other electrical interference and to ensure proper placement of the transducer to avoid error due to shock reflections.

4.6 TEST TARGET SETUP

4.6.1 Perforating tests shall be performed using cylindrical cores. The core 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 unperforated end to allow for application of pore pressure to the appropriate boundaries of the sample. For axial flow only, constant pressure shall be applied to the unperforated end of the core only. For radial flow, pore pressure can be applied in two different methods. The first method shall be to apply constant pressure to the cylindrical sides of the core via a gap between the jacket ID and core OD that is filled with a permeable media AND to the unperforated end. The second method shall be to apply constant pressure to just the cylindrical sides of the sample using the same method. For most types of rock either can be used. Typical arrangements are shown in Figure 12 and Figure 13. The specific target geometry to be used shall be at the discretion of the testing company, except for the following.

a. Target diameter should generally not be less than 4 in.
b. The entrance hole shall be positioned in the center of the faceplate, and after shooting, the tip of the perforation tunnel shall not be further than one-fourth of the target diameter from the centerline axis of the target.
c. After shooting, there shall be a minimum distance equal to one target diameter between the tip of the perforation tunnel and the unperforated end of the target.
d. In general, only samples with bedding planes oriented parallel to the core axis should be used in axial-flow geometry tests. This is particularly important when K_v/K_h is low, in which case experimental variation can be significantly increased, but less important when K_v/K_h approaches 1.
e. Simulated overburden stresses shall be applied uniformly to all portions of the sample. Axial and radial stresses may be different, if desired, and if the test system allow for this.
f. The target geometry and setup used shall be tested to provide assurance that no flow is able to bypass the perforation.

4.6.2 For radial flow geometries, the target is configured with a constant pressure boundary condition on the core OD surfaces, an optional constant pressure boundary condition on unperforated end of the core, and a no flow boundary condition on the perforated end of the core. The annular gap between the sample jacket and core OD shall be filled with a stress transmission media with permeability at least 100 times greater than the expected permeability of the test core. Refer to Figure 12 for further details and descriptions. In most cases, a high strength proppant can provide this capability. This will address potential test artifacts concerning flow restrictions, media crushing, and poor stress transmission. The face of the perforated end of the core must be sealed with a gasket to ensure that all flow exiting the core comes by way of the perforation. There are several ways to accomplish this, and it is left to the discretion of the testing company to select a method and then do the required testing to assure that there is no leakage. The endcap on the unperforated end of the core should normally be configured to include a flow distributor to distribute flow across the entire face of the core and/or to direct fluid to the porous media surrounding the OD of the core.

4.6.3 For axial flow geometries, the target is configured with a constant pressure boundary condition on the unperforated end of the core and a no flow boundary condition on the core OD and perforated end of the core. This is best accomplished with a flexible jacket on the core OD, a flow distributor on the unperforated end, and a sealing gasket on the perforated end. Refer to Figure 13 for additional description and details.

4.6.4 For all testing configurations it is important to minimize all sources of bypass flow around the perforation tunnel, such as:

a. flow between the core OD and flexible jacket—use a thick deformable material for the sleeve;
b. flow between the cement in the endcap on perforated end and the core—use a gasket of some sort to stop flow path;
c. flow between the steel endcap and cement in the endcap—use a cement or grout mixture that does not shrink or that expands while curing; and
d. any bypass leaks in the flow system—ensure that all flow has to go into and through the test target and exit through the perforation tunnel.

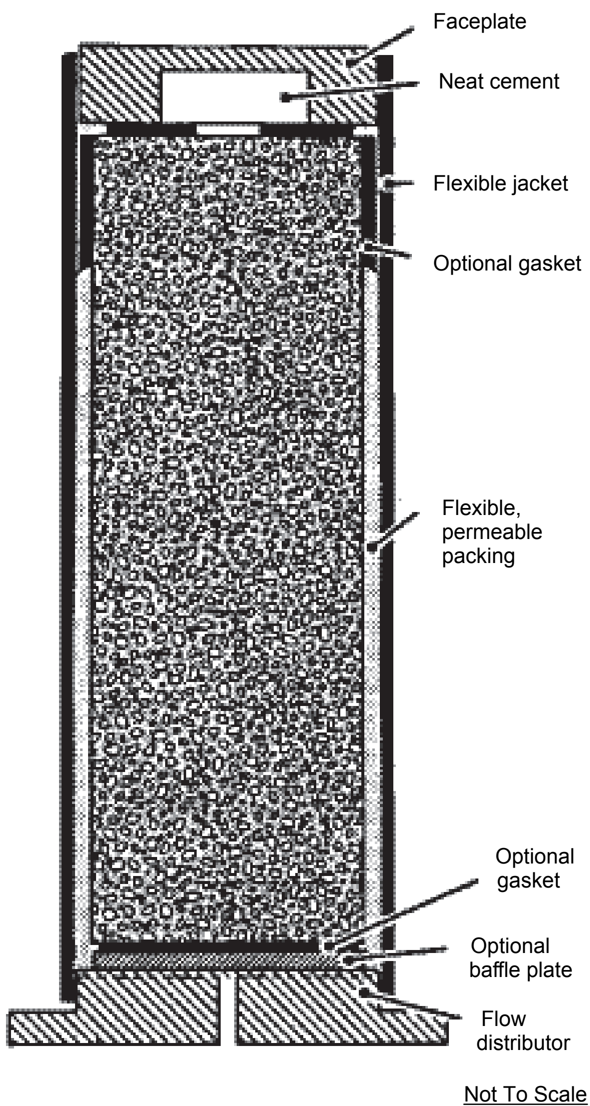


Figure 12—Typical Radial-Flow Geometry

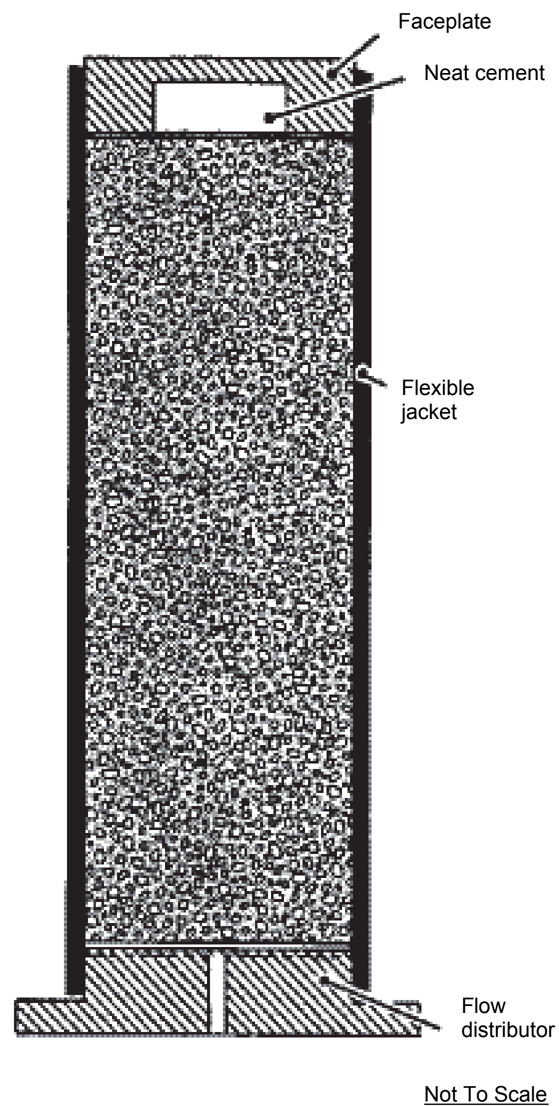


Figure 13—Typical Axial-Flow Geometry

4.6.5 The flow distributor to be used is best constructed with a series of concentric circular grooves and radial connecting grooves, such that a balance between axial stress transmission and the constant pressure boundary condition is reached.

a. Too small an area in the grooves and rings will cause excessive pressure drop.
b. Too large an area in the grooves and rings will cause an excessively high contact stress between the core and the end plate. This could cause localized failure, releasing fines and affecting the results.
c. Screens may be used between the end of the core and the flow distributor to try and better spread the fluid flow and loading out across the end of the target.
d. The screens are also needed for radial flow geometries to keep the proppant from being washed out back into the inlet flow lines.
e. Materials of construction should consider what pore fluids are envisioned for use.

4.6.6 The endcap used on the perforated end of the core should be flat and flush with both the test fixture and core. Neat oilfield cement or nonshrink grout is recommended. Avoid gaps due to shrinkage, as these will provides sources of error in the results.

4.7 GENERAL PERFORATION TESTING PROCEDURE

4.7.1 The following perforation test procedure is provided as a basic guideline for testing companies. The actual specific procedures to be followed for a perforation and flow test shall be left to the discretion of the testing company to define and follow. The testing company shall be responsible to technically justify their specific procedures.

4.7.2 Increase confining pressure to appropriate level. Avoid applying stress higher than the planned test condition to the core. Once appropriate confining pressure is reached, increase confining pressure, pore pressure, and wellbore pressure either simultaneously or sequentially until desired testing conditions are reached. A bypass line between pore pressure and wellbore pressure is useful during this operation in order to keep pressures equal until ready for final conditions. Other test conditions, such as specialized wellbore fluid, may prohibit this or require alternative configurations.

4.7.3 Allow sample to equalize. Lower permeability targets may require additional time for induced pore pressure to bleed from the target.

4.7.4 Initiate or arm trigger for high speed data collection systems if present.

4.7.5 Arm and detonate perforator.

4.7.6 Allow well pressure and pore pressure to equalize.

4.7.7 If desired, the equalized wellbore/pore pressures may be slowly reduced to a lower or ambient pressure while keeping effective stress constant. Fluctuations in effective stress or differential pressure between the pore and wellbore may invalidate the test. Backpressure can be effective in reducing test time.

4.7.8 Isolate surge system from flow lines.

4.7.9 Flow shall be initiated through the sample by applying desired draw down or flow rate. This value will depend on the flow geometry chosen and effective permeability of the perforated sample but should not exceed the clay or fines mobilization threshold rate of the target.

4.7.10 Flow should be continued at initial rate until steady state is reached, i.e. flow rate and pressure drop are constant and temperature measurements have equalized.

4.7.11 Flow at same rates or pressure draw down as when the core was characterized. These may be different depending upon the discretion of the testing company. Do not exceed the maximum flow rate of the initial characterization, or the pressure differential by twice original maximum.

4.8 SYSTEMS CALIBRATION AND TEST REQUIREMENTS

4.8.1 At a minimum, all transducers, gauges, controls, and instrumentation shall be calibrated against a suitable reference standard at intervals not exceeding one year, per ISO 9001 standards and procedures (current edition). It is best to calibrate the transducers in place, utilizing all of the cables, amplifiers and DAC in the calibration. Not doing so could introduce error and variation into the tests system and subsequent results.

4.8.2 Systems verification tests should be:

a. conducted prior to the commissioning of any new test system;
b. conducted after any major modifications to any existing system; and
c. conducted every two years, even if there are no major changes.

4.8.3 Verification tests to be conducted are to be designed by the testing company but shall include, but not be limited to, the following as a minimum.

a. *System Flow Rate*—Be able to measure liquid and/or gas flow rates with an accuracy of ±1 % of full scale. Liquid flow rates may be between 10 cc/min and 1000 cc/min for medium and low permeability targets and at rates from 1001 cc/min to 10,000 cc/min for higher permeability targets.
b. *System Pressure Drop*—For pressure drops between 1 psi and 50 psi, be able to measure within ±0.50 psi. For pressure drops between 51 psi and 250 psi, be able to measure within 1 psi. For pressure drops between 250 psi and 500 psi, be able to measure within 2 psi. For pressures greater than 501 psi, be able to measure within 0.5 % of the measured value.
c. *Viscosity/Temperature/Liquid Density*—Temperature measurements should be within ±2 °F of the measured value. Liquid density should be accurate within 1 % of the measured value. Fluid viscosity must be measured using suitable equipment and be available in tabular form.

4.8.4 Recommended system calibration tests shall be conducted by the testing company following their own procedures and shall include the following.

a. Conduct a test to determine the system pressure loss, excluding the rock core. The test should determine the pressure loss between any pressure measurement location and the rock core face (inlet or outlet end). For this test, a test fixture with infinite permeability should replace the rock core. The pressure drop measurements should be done across the entire range of flow rates that are capable for any given laboratory test system.
b. Conduct a test to verify that there is no flow bypassing the perforation tunnel in the test setup. The designs of these tests are left up to the testing company and would include verification of the following:

1. no flow leakage between the core OD and the flexible jacket in axial flow geometry tests., i.e. all flow must go through the core, not around the core;
2. no flow leakage between the core exit face and the core OD for radial flow geometry, i.e. all flow must go through the core and not around the core;
3. no flow leakage across the outlet face of the core and the perforation tunnel and hole through the endcap, i.e. all flow must exit the core through the perforation tunnel;
4. no flow leakage around the outside of the cement plug in the perforated endcap and the hole through the steel plate, i.e. all flow out of the perforation tunnel must go through the cement hole and simulated casing exit hole.

c. Conduct a test to verify that the fluid filtration system is adequate by performing a flow test through a nonperforated core and measuring the pressure drop to constant flow. Any increases in pressure differential shall indicate that pore throat plugging is occurring.

4.9 DATA RECORDING

For each sample tested, the following raw data shall be recorded as appropriate.

a. A record of the test geometry and flow boundary conditions.
b. Target properties:
   1. type;
   2. diameter, length, and orientation;
   3. preparation conditions;
   4. permeability, porosity, and density;
   5. UCS; and

6. casing and cement configuration and materials.

c. Test conditions during both flowing and shooting.

d. Perforation geometry data should be collected after all flow testing, including the following.

1. Casing entrance hole diameter, minimum through diameter, and cement exit hole diameter in two orthogonal directions.

2. Probe penetration—depth that 24 in. long $^1/_8$ in. rounded tip probe can be placed vertically into target with no external force.

3. Clear tunnel penetration—length from target face to first competent structures within the perforation. In general this can be determined by a combination of probing with moderate force, gentle washing of loose material, and visual inspection.

4. Total core penetration—length from target face to furthest evidence of penetration in the target. This can be determined visually from a split core or from CT or other noninvasive scanning methods.

5. Perforation diameter profile—the diameter of the perforation shall be recorded at 0.5 in. or 1.0 in. intervals along the length of the perforation. This may be done by recording the coordinates of the perforation walls in tabular form, by sketching the perforation on an appropriate grid, or by attaching a photograph or scan of the perforation, again with an appropriate scale grid. The average perforation diameter shall be recorded to the nearest 0.1 in.

6. Maximum tunnel geometry—the maximum potential diameter and length of the open perforation tunnel. This geometry is produced by scrubbing the perforation tunnel with a brass cylindrical wire brush to remove all weakened rock. Scrubbing shall be "calibrated" against undamaged rock so that it does not remove undamaged rock around the perforation. Diameter of resulting tunnel should be measured and recorded at 0.5 in. or 1.0 in. intervals along the length of the perforation.

e. A tabular record of all collected and calculated flow data, including flow rate, inlet pressure, outlet pressure, differential pressure, inlet and outlet temperatures, viscosity, fluid density, and permeability, or other measure of flow performance.

f. A high speed plot of the pressures during the perforation event.

4.10 LIQUID FLOW DATA REDUCTION

4.10.1 General

Flow data may be presented in either of two formats: CFE or PR. Convergent flow production ratio (CFPR) may be used as an alternative to production ratio in strongly heterogeneous targets. In general, radial flow geometry is better suited to a CFE or a modified CFPR analysis, and axial flow geometry is better suited to analysis with PR and CFPR. Neither CFE, PR, nor CFPR completely describe the flow performance of a given perforation. These calculated values should only be considered in the context of other measurements and the test program parameters. The choice of the data reduction analysis shall depend upon the goals of the testing program and shall be left to the discretion of the testing company.

Productivity index (PI) is defined as the ratio of flow rate, corrected by viscosity of the fluid, to pressure drop and is determined from the slope of a linear curve fit though a corrected flow versus pressure drop data plot, as shown below in Figure 14. PI is only valid within the context of a given set of test conditions and is dependent upon such things as boundary conditions, target properties, and fluid properties.

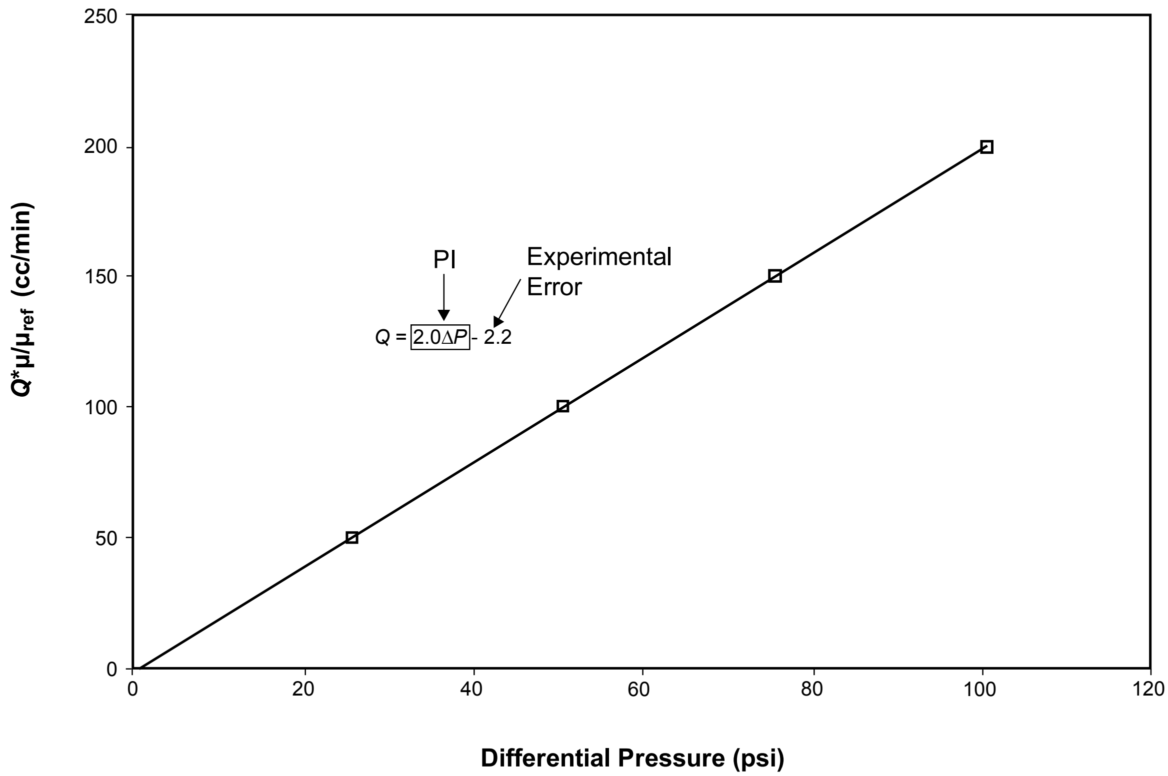


Figure 14—Productivity Index Data Reduction Graph

The corrected flow term Q^* is calculated according to Equation 4-2 and has units of cm^3/min:

$$Q^* = Q\frac{\mu}{\mu_{ref}} \tag{4-2}$$

where

Q = measured flow rate (cm^3/min;)

μ = fluid viscosity (cP);

μ_{ref} = fluid viscosity at 75 °F and 1 atm. (cP).

Alternately, PI may be calculated at a single point according to Equation 4-3:

$$\mathrm{PI} = \frac{Q^*}{\Delta P} \tag{4-3}$$

where

Q^* = corrected flow term (cm^3/min);

ΔP = differential pressure corrected for flow system pressure drop (psi.)

PI may be used to calculate perforation performance, and permeability for various boundary conditions.

Axial flow permeability, K_a, in mD, shall be calculated according to Equation 4-4:

$$K_a = 30.69\frac{PI\mu_{ref}L}{R^2} \tag{4-4}$$

where

PI = productivity index (cm^3/psi min);

μ_{ref} = fluid viscosity at 75 °F and 1 atm. (cP);

L = core length (in.);

R = core radius (in.).

Diametral flow permeability, K_d, in mD, shall be calculated according to Equation 4-5:

$$K_d = 96.43\frac{PI\mu_{ref}}{FL'} \tag{4-5}$$

where

PI = productivity index (cm^3/psi min);

μ_{ref} = fluid viscosity at 75 °F and 1 atm. (cP);

L' = length of 90° arc flow inlet and outlet area (in.);

F = cross diameter flow correction factor.

The cross diameter flow correction factor, F, corrects the apparent diametral permeability for errors due to flow beyond the test region due to axial fluid movement. This correction is especially important for targets with a high ratio of K_a to K_d but can represent a 10 % reduction in apparent permeability for even isotropic targets.

This correction is dependent upon the geometry of the cross diameter flow fixture. For 7 in. diameter by 18 in. long cores with 12 in. long 90° inlet and outlet flow distributors, *F* can be calculated according to Equation 4-6:

$$F = 1.232 - 0.2371\tanh\left[\frac{0.7162\log K_d}{K_a} + 0.612\right] \tag{4-6}$$

For other diametral flow/target configurations, similar correlations for F would need to be developed.

4.10.2 Core Flow Efficiency

CFE shall be defined as the ratio, observed perforation productivity index (PI_{perf}) to open tunnel productivity index (PI_{OT}), according to Equation 4-7:

$$CFE = \frac{PI_{perf}}{PI_{OT}} \tag{4-7}$$

CFE analysis is dependent upon the geometry used to estimate $PI_{OT,}$ as well as the cross diameter flow measurement. Both of these can be sources for experimental variability. CFE analysis is a measure of the flow performance of the entire perforation, emphasizing flow through the side walls of the perforation. In addition, since CFE is generally used in conjunction with radial flow perforation geometry, it is then a measure of the flow performance of perforations produced by radial flow testing, which generally differ from perforations produced by axial flow testing.

The CFE calculation is generally used to estimate the permeability map around the perforation tunnel, most simplistically represented as a constant thickness “damaged zone” of reduced, constant permeability surrounding the entire perforation. This estimate is an input into many perforation and well inflow models. This simplification may be significant and is an area of active investigation.

Suitable means shall be used to calculate $\mathrm{PI_{OT}}$ based on measured maximum tunnel geometry, as specified in 4.9, axial permeability, K_a, diametral permeability, K_d, and applied pressure boundary conditions. The best way to calculate $\mathrm{PI_{OT}}$ is with a numerical computational flow dynamics (CFD) model. The specific numerical means of calculating the PI open tunnel shall be at the discretion of the testing company. Alternately, for a radial flow target with bedding planes perpendicular to the long axis of the core, the following one dimensional analytical solution may be used:

$$\mathrm{PI_{OT}} = 6.516 \times 10^{-2} \frac{1}{\mu_{\mathrm{ref}}} \left[\frac{K_1 D}{\ln \frac{R}{r}} + \frac{K_2 r R}{R - r} \right] \tag{4-8}$$

where

$\mathrm{PI_{OT}}$ = productivity index of the maximum tunnel geometry (cm^3/psi min);

μ_{ref} = fluid viscosity at 75 °F and 1 atm. (cP);

D = perforation depth (in.);

R = core radius (in.);

r = maximum tunnel radius (in.);

K_1 = K_d;

K_2 = $\sqrt[3]{K_a K_d^2}$.

This analytical solution typically overestimates the PI compared to the results of CFD simulations.

4.10.3 Production Ratio

Production ratio shall be defined as the ratio of the $\mathrm{PI_{perf}}$ to the pre-shot PI of the target, calculated according to Equation 4-9:

$$\mathrm{PR} = \frac{\mathrm{PI_{perf}}}{\mathrm{PI}}$$

This analysis may be used for multiple pre-shot and post-shot geometry combinations, including axial flow and radial flow, so long as boundary conditions at the unperforated boundary are the same both before and after the perforation event.

4.10.4 Convergent Flow Production Ratio

CFPR shall be defined as the ratio of the $\mathrm{PI_{perf}}$ to the pre-shot PI of the target with restricted outlet, calculated according to Equation 4-10:

$$\mathrm{CFPR} = \frac{\mathrm{PI_{perf}}}{\mathrm{PI}} \tag{4-10}$$

This analysis may be used for multiple pre-shot and post-shot geometry combinations, including axial flow and radial flow, so long as boundary conditions at the unperforated boundary are the same both before and after the perforation event.

4.11 GAS FLOW TESTING

4.11.1 General

Gas flow testing requires additional treatment compared to liquid flow testing. In this section, basic principles, testing procedures, and treatment of data are outlined. This is not, and is not meant to be, an exhaustive compilation of all possible tests. Tests can be run with dry core/dry gas, cores at irreducible brine saturation (Swi)/humidified gas, or cores at irreducible oil saturation (Sor)/ dry gas. Data may be reduced in terms of either CFE or PR.

Gas production or injection flow, even at relatively low rates, differs significantly from liquid flow due to compressibility effects and nonlinear friction. As a result, a simple single-parameter Darcy law is not adequate to fully characterize the pressure drop. A convenient method is presented for reducing the experimental data such that the permeability and Forchheimer inertial drag coefficient (c_f) can be determined directly. The choice of the data reduction analysis will depend upon the goals of the testing program, and shall be left to the discretion of the testing company.

Nitrogen, either humidified or dry, is recommended for the gas phase. Properties such as viscosity and density may be determined from http://webbook.nist.gov for either isobaric or isothermal conditions. In many cases it is a small error to neglect the pressure drop and temperature change across the core during testing and use a constant viscosity and density for the data reduction operation.

4.11.2 Target Preparation

Targets should be prepared as recommended in 4.2 and 4.3. For targets initially brine saturated, humidified gas should be used during the Swi process and testing in order to maintain consistent saturation level. A pressure drop between 10 % and 25 % higher than desired maximum test pressure drop should be used while desaturating the target. Targets should be weighed at every opportunity to verify saturation state and stored for only short periods of time if at all prior to perforation.

Humidified gas may be produced by flowing the gas stream through a freshwater chamber located in line immediately adjacent to the target inlet. Increasing evaporation surface area may help to reduce experimental error.

4.11.3 Target Characterization

Targets should be characterized with axial flow and diametral flow in two orthogonal directions. Convergent flow testing should not be used for targets with multiple phase saturation due to potential for local changes in Swi.

The linear and quadratic coefficients, a_1 and a_2 respectively, are obtained by graphing the pressure and mass flux data as demonstrated in Figure 15 and calculating a quadratic equation curve fit in the form of $y=a_2x^2+a_1x+c$.

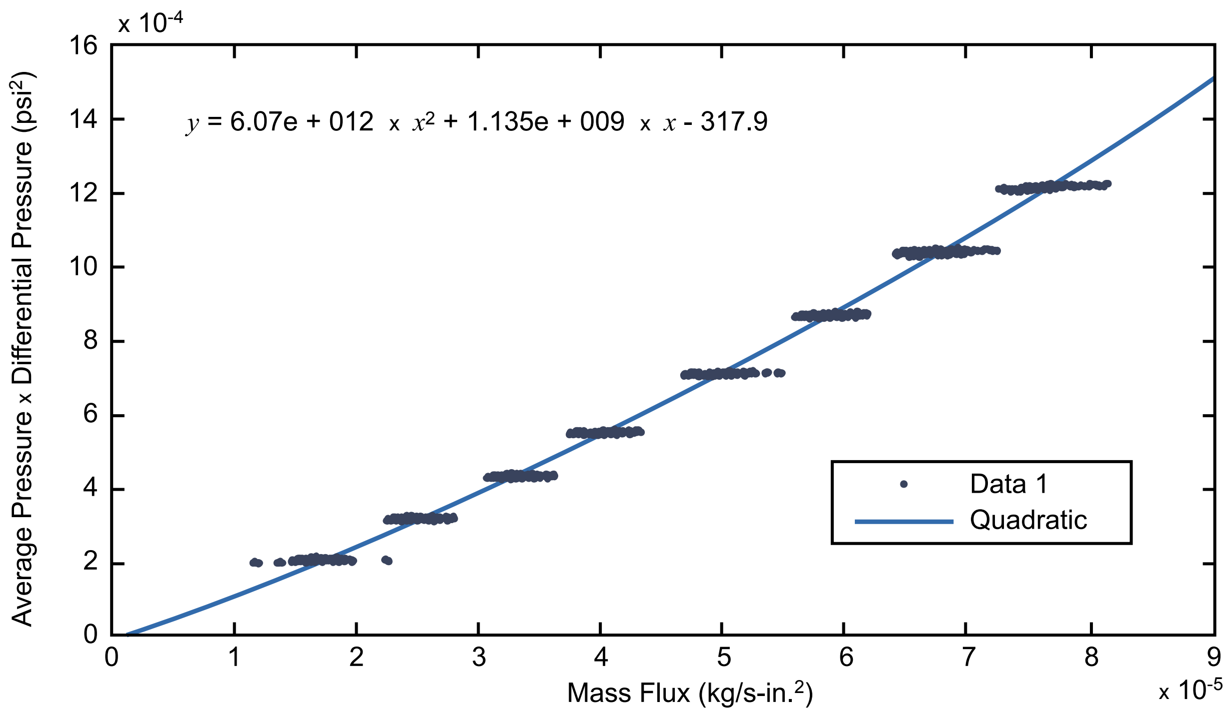


Figure 15—Example Gas Flow Curve Fit to Determine a_1 and a_2

This provides for a direct means of evaluating k and c_f for convergent flow in Equation 4-11:

$$k = 5.79x10^{6} \cdot \frac{\mu L}{a_1 \beta}$$

$$c_f = 3.55x10^{-6} \cdot \frac{a_2 \sqrt{k} \beta}{L} \tag{4-11}$$

where

k = axial permeability (mD);

c_f = Forchheimer coefficient;

μ = average fluid viscosity (cP) at $\overline{P}$;

$\overline{P}$ = average of inlet and outlet pressures (psi);

L = core length (in.);

β = ideal gas isothermal compressibility (gm/cc/psi).

The case of compressible flow in the diametral direction yields similar results to the axial flow case in Equation 4-12. The flow length is now the quadrant chord length of the core cross-sectional area. The flow area is the product of the chord length and the flowed length. Again, a_1 is the linear coefficient and a_2 is the quadratic coefficient.

$$k_{\text{h}} = 5.79x10^{6} \cdot \frac{\mu\sqrt{2}D_{core}}{2\text{a}_1\beta}$$

$$c_f = 3.55x10^{-6} \cdot \frac{2\text{a}_2\sqrt{k}\beta}{\sqrt{2}D_{core}} \qquad (4\text{-}12)$$

where

- k_{h} = diametral permeability (mD);
- μ = average fluid viscosity (cP);
- D_{core} = core diameter (in.);
- β = ideal gas isothermal compressibility (gm/cc/psi).

4.11.4 Production Ratio

Gas flow axial production ratio shall be defined as the ratio of the PI_{perf} to the pre-shot PI of the target, calculated according to Equation 4-13:

$$\text{PR} = \frac{\text{PI}_{\text{perf}}}{\text{PI}} \qquad (4\text{-}13)$$

4.11.5 Core Flow Efficiency

CFE shall be defined as the ratio, productivity index ($\text{PI}_{\text{actual}}$) to ideal productivity index (PI_{ideal}), according to Equation 4-14:

$$CFE\left(Q_m\right) = \frac{PI_{actual}}{PI_{ideal}} = 5.79x10^{6} \cdot \frac{\left(\frac{\mu}{2k_h\beta\pi\text{DoP}}\ln\left(\frac{R_{core}}{R_{tunnel}}\right) + \frac{c_f}{\sqrt{k_h}}\frac{Q_m}{\beta\left(2\pi L\right)^2 L_{eff}}\right)}{\text{a}_{1,actual} + \text{a}_{2,actual}Q_m} \qquad (4\text{-}14)$$

where

- Q_{m} = mass flow rate (kg/s);
- DoP = depth of penetration (in.);
- R_{core} = core radius (in.);
- R_{tunnel} = perforation tunnel radius (in.);
- L_{eff} = effective flow length = $\frac{R_{\text{core}}R_{\text{tunnel}}}{R_{\text{core}} - R_{\text{tunnel}}}$ (in.).

Note: Evaluation of a_1 and a_2 for radial flow requires fitting a quadratic curve to a plot of the average pressure times the pressure difference vs. the mass flow rate in kg/s, not the mass flux (kg/in.^{2}-s), as shown in Figure 16.

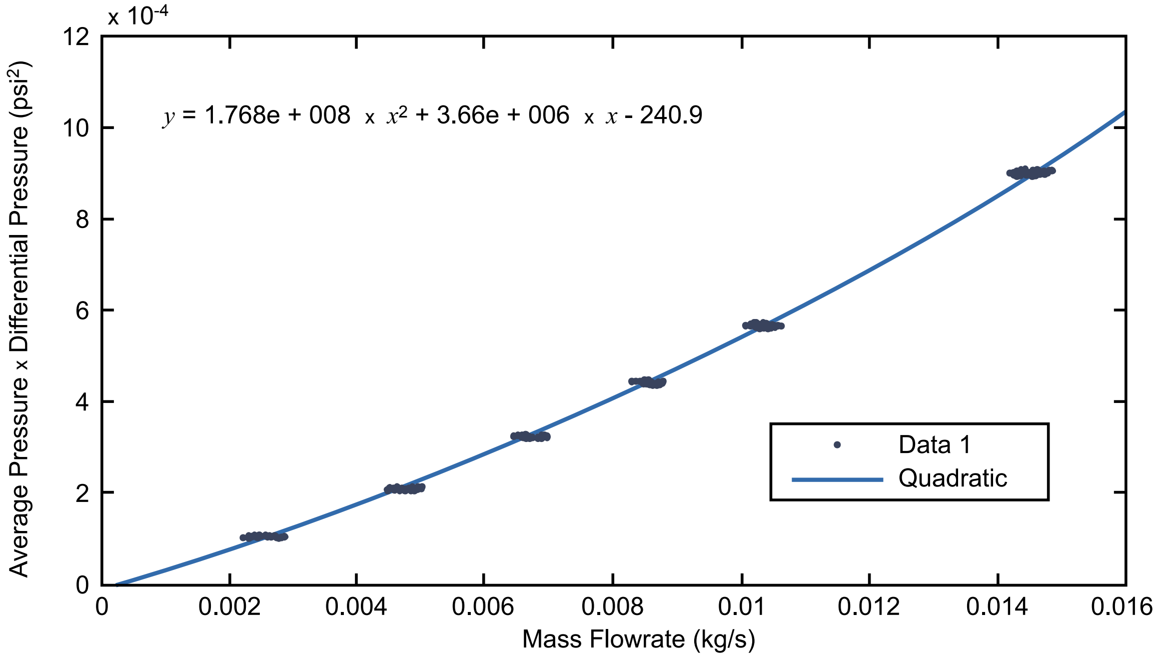


Figure 16—Post-Shot Radial Flow for a Gas Saturated Core

4.12 STANDARD TEST CONDITIONS

4.12.1 General

The following additional specifications are provided so that data can be collected and compared under common conditions. All specifications and recommendations above apply. *Data collected under these conditions do not represent, and may not be translatable to, any particular downhole conditions.* Permeability damage caused by the perforator may be different in actual reservoir rock and under actual downhole pressures. Post-shot clean up may differ from standard test results depending on actual reservoir rock properties, the underbalance used, dynamic wellbore storage effects, dynamic pressures surges introduced by the gun system, production drawdown, fluid composition and viscosity, perforating phasing and shot density, and other factors. For best site-specific results, the general test specifications above allow simulation of each of these factors.

The standard test is intended as a means of qualifying laboratory facilities as capable to produce industry consistent results. As the technology of perforation testing evolves, additional critical variables may be identified that are not accounted for in this test. This test is not meant to preclude any laboratory from performing additional measurements or a modified simulation in order to best accomplish the goals of a given internal or customer funded program. Specific recommendations for test configuration for specific programs are left to the discretion of the testing company.

In the best case, core shall be pulled from a bank of standard rock, and charges shall be supplied from a bank of standard charges. Results should be published on a standard datasheet. The compilation of results from all laboratories performing this test should be made public to the API membership.

4.12.2 Rock Samples

Test samples shall be of Berea sandstone or equivalent, meeting the specifications listed in 4.2. Ideally, a specific set of blocks will be identified. For this qualification test, targets shall be cut with bedding planes parallel to the long axis. Target diameter will be as specified by the testing company.

4.12.3 Test Charges

Ideally, two specific, commercially available lots of test charges shall be identified, nominally 15g HMX and 25g HMX. For the qualification test, the testing company may request any size charge for any size target.

4.12.4 Pore Pressure Boundaries

For the qualification test, the core shall be tested in axial flow geometry. Pore pressure shall be applied to the end of the core opposite the perforation only. All previously discussed recommendations regarding target construction shall apply.

4.12.5 Test Fluid

For the qualification test, the test fluid shall be single-phase OMS. The core shall be saturated per single-phase saturation recommendations in 4.3. The testing company shall provide a viscosity/temperature/ pressure curve which includes the range of temperatures experienced in the test for the fluid used with the test result submission.

4.12.6 Pre-Shot Target Characterization

For the qualification test, the target shall be characterized and data reported per 4.4, including and limited to measurement of axial permeability, porosity, density, dimensions, and optionally mechanical properties. Axial permeability shall be measured at flow rates of 60 cc/min, 90 cc/min, 120 cc/min, and 180 cc/min.

4.12.7 Shooting Conditions

The casing plate shall be 0.5 in. thick 4140 HT Steel, Rc 28-32. Cement shall be 0.75 in. thick neat Portland cement. A gasket as previously described shall be used between the cement and the core face.

The water clearance between the gun and casing plate (gun clearance plus scallop depth, if present) shall be 0.75 in. Internal charge standoff shall be as specified by the manufacturer of the charges used in the test. Charge manufacturer shall provide estimate of internal gun volume, but this may be adjusted at the testing company as required.

A pressure–time perforating profile for each charge size is provided. The testing company shall modify appropriate variables as required in order to best match the dynamic events of the provided profile.

Applied static pressures when the gun is fired shall be as follows:

Confining Pressure:	6500 psi
Pore Pressure:	3500 psi
Wellbore Pressure:	3000 psi

This provides an effective rock stress of 3000 psi and 500 psi underbalance.

4.12.8 Post-Shot Flow Performance Evaluation

The perforated core shall be evaluated in axial flow at, but not limited to flow rates of 60 cc/min, 90 cc/min, 120 cc/min, and 180 cc/min. Measurements shall be conducted in accordance with recommendations in 4.5, 4.6, and 4.7. Data recording shall be conducted in accordance with recommendations in 4.9. Data reduction shall be conducted in accordance with recommendations in 4.10 for axial flow and production ratio.

4.12.9 Standard Test Datasheet

A standard datasheet is provided in Figure 17 for use in reporting the results of the standard test.

SECTION 4 STANDARD TEST DATA RECORDING SHEET

Test: ______ Date: ______ Engineer: ______
ID No: Technician: ______

TARGET PROPERTIES
Rock: ______
Diameter: ______
Length: ______
Bedding: ______
Dry Wt: ______
Sat Wt: ______
Sat Fluid: ______
Porosity: ______
Density: ______
UCS: ______

SHAPED CHARGE
Charge: ______
Exp. Mass ______
DSC: ______
Gun Syst: ______
Gun Wall T: ______
In-Gun Cir: ______

CASING AND CEMENT
Size & Grade: ______
Casing Wall: ______
Cement Type: ______
Cement t: ______

CORE PREP CONDITIONS
Confining: ______
Pore: ______
Wellbore: ______
Fluid Flowed: ______
Temperature: ______

SHOOTING CONDITIONS
Flow Geometry: ______
Confining: ______
Pore: ______
Pore Fluid: ______
Effective σ: ______
Wellbore: ______
Wellbore Fluid: ______
Wellbore Temp: ______

POST-SHOT CONDITIONS
Confining: ______
Pore: ______
Pore Fluid: ______
Effective σ: ______
Wellbore: ______
Temp: ______

PRE-SHOT FLOW DATA
Pre-Shot Axial PI: ______
Pre-Shot Inj. PI: ______
Diametral 1 PI: ______
Diametral 2 PI: ______
Avg. Diametral PI: ______
Convergent Flow PI: ______

POST-SHOT FLOW DATA
Post Axial PI: ______
Post Injection PI: ______
Post Radial PI: ______

PERFORATING RESULTS
Gun Entr. Hole: ______
Casing Entr. Hole: ______
Casing Exit Hole: ______
Cement Hole: ______
Probe Depth: ______
Clear Tunnel Depth: ______
Total Pene. Depth: ______

DATA REDUCTION & ANALYSIS
Axial PR: ______
Injection PR: ______
Radial PR: ______

Convergent Flow PR: ______

Theoretical PI (CFD): ______
CFE: ______
Kc/K: ______
Single Perf. Skin: ______

Avg. As-Found Tunnel Dia: ______
Avg. Scrubbed Tunnel Dia: ______
Estimated Crushed Zone t: ______

Engineer Signature: ______
Date: ______

Witness Signature: ______
Date: ______

PERFORATION TUNNEL DIMENSIONS

DEPTH	AS-FOUND	SCRUBBED	NOTES AND COMMENTS
0"			
1"			
2"			
3"			
4"			
5"			
6"			
7"			
8"			
9"			
10"			
11"			
12"			
13"			
14"			
15"			
16"			
17"			
18"			

Figure 17—Section IV Standard Test Data Recording Sheet

Delete:

Appendix A, Appendix B, and Appendix C

Appendix A (previously **Appendix D**), *replace the text as follows:*

Applications for Perforator System Registration are available from API. To obtain an application, please access the API Certification Programs website http://www.api.org/certification-programs/witnessing-programs/perforator-witnessing-program.