Hydraulic Fracturing Operations—Well Construction and Integrity Guidelines

API GUIDANCE DOCUMENT HF1
FIRST EDITION, OCTOBER 2009

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Upstream Segment

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Shall: As used in a publication, “shall” denotes a minimum requirement in order to conform to the publication.

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1 Scope

The purpose of this guidance document is to provide guidance and highlight industry recommended practices for well construction and integrity for wells that will be hydraulically fractured. The guidance provided here will help to ensure that shallow groundwater aquifers and the environment will be protected, while also enabling economically viable development of oil and natural gas resources. This document is intended to apply equally to wells in either vertical, directional, or horizontal configurations.

Many aspects of drilling, completing, and operating oil and natural gas wells are not addressed in this document but are the subject of other API documents and industry literature (see Bibliography). Companies should always consider these documents, as applicable, in planning their operations.

Maintaining well integrity is a key design principle and design feature of all oil and gas production wells. Maintaining well integrity is essential for the two following reasons.

1) To isolate the internal conduit of the well from the surface and subsurface environment. This is critical in protecting the environment, including the groundwater, and in enabling well drilling and production.

2) To isolate and contain the well's produced fluid to a production conduit within the well.

Although there is some variability in the details of well construction because of varying geologic, environmental, and operational settings, the basic practices in constructing a reliable well are similar. These practices are the result of operators gaining knowledge based on years of experience and technology development and improvement. These experiences and practices are communicated and shared via academic training, professional and trade associations, extensive literature and documents and, very importantly, industry standards and recommended practices.

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 (including any amendments) applies.

API Specification 5B, *Specification for Threading, Gauging, and Thread Inspection of Casing, Tubing, and Line Pipe Threads*

API Specification 5CT/ISO 11960, *Specification for Casing and Tubing*

API Specification 10A/ISO 10426-1, *Specification for Cements and Materials for Well Cementing*

API Recommended Practice 10B-2/ISO 10426-2, *Recommended Practice for Testing Well Cements*

API Recommended Practice 10D-2/ISO 10427-2, *Recommended Practice for Centralizer Placement and Stop Collar Testing*

API Technical Report 10TR1, *Cement Sheath Evaluation*

API Technical Report 10TR4, *Technical Report on Considerations Regarding Selection of Centralizers for Primary Cementing Operations*

API Recommended Practice 65-2, *Isolating Potential Flow Zones During Well Construction*

NOTE API RP 65-2 was under development at the time of publication of API HF1. However, given its subject matter, API felt is was appropriate to include as a reference. API RP 65-2 will provide guidance on well planning, drilling and cementing practices, and formation integrity pressure testing. Upon publication, API RP 65-2 will be available at www.api.org/publications, and will serve as a valuable reference for use in conjunction with API HF1.

API Recommended Practice 90, *Annular Casing Pressure Management for Offshore Wells*

3 General Principles

3.1 Protecting Groundwater and the Environment

All oil and natural gas exploration, development, and production operations are conducted to ensure that the environment, in particular underground sources of drinking water (USDWs [a], or groundwater), is protected. Statutes and regulations have been implemented in every oil and gas producing state of the United States to ensure that oil and natural gas operations are conducted in an environmentally responsible fashion. While these regulations differ from state to state in their details, their general intent and environmental objectives are consistent (IOGCC [1], 2007).

Groundwater is protected from the contents of the well during drilling, hydraulic fracturing, and production operations by a combination of steel casing and cement sheaths, and other mechanical isolation devices installed as a part of the well construction process. It is important to understand that the impermeable rock formations that lie between the hydrocarbon producing formations and the groundwater have isolated the groundwater over millions of years. The construction of the well is done to prevent communication (the migration and/or transport of fluids between these subsurface layers).

The primary method used for protecting groundwater during drilling operations consists of drilling the wellbore through the groundwater aquifers, immediately installing a steel pipe (called casing), and cementing this steel pipe into place. All state drilling regulations specifically address groundwater protection, including requirements for the surface casing to be set below the lowest groundwater aquifer, or USDW (DOE [2], 2009 and IOGCC [1], 2007). The steel casing protects the zones from material inside the wellbore during subsequent drilling operations and, in combination with other steel casing and cement sheaths that are subsequently installed, protects the groundwater with multiple layers of protection for the life of the well.

The subsurface zone or formation containing hydrocarbons produces into the well, and that production is contained within the well all the way to the surface. This containment is what is meant by the term “well integrity.” Moreover, regular monitoring takes place during drilling and production operations to ensure that these operations proceed within established parameters and in accordance with the well design, well plan, and permit requirements. Finally, the integrity of well construction is periodically tested to ensure its integrity is maintained. The monitoring activities that should be conducted prior to and during well construction and over the life of the well will be described in more detail in Section 10.

3.2 Well Design and Construction

Drilling and completing an oil and/or gas well consists of several sequential activities. A list of these activities appears below, and those that are addressed in this guidance document are shown in bold. In sequential order, these activities are as follows:

— building the location and installing fluid handling equipment,

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[a] A USDW is defined in federal statute (40 *CFR* 144.3) as any “aquifer that: (1) supplies a public water system; or (2) contains a sufficient quantity of water to supply a public water system and currently supplies drinking water for human consumption or contains fewer than 10,000 mg/L of total dissolved solids.” In addition, it cannot be an exempted aquifer. See http://www.epa.gov/region5/water/uic/glossary.htm. “Groundwater” could include other subsurface waters that do not meet these criteria.

— setting up the drilling rig and ancillary equipment and testing all equipment,

— drilling the hole,

— logging the hole (running electrical and other instruments in the well) (see note),

— running casing (steel pipe) (see note),

— cementing the casing (see note),

— logging the casing (see note),

— removing the drilling rig and ancillary equipment,

— perforating the casing (depending on completion type),

— hydraulic fracturing or stimulating the well,

— installing artificial lift equipment (if necessary),

— install surface production equipment,

— putting the well on production,

— monitoring well performance and integrity,

— reclaiming the parts of the drilling location that are no longer needed and removing equipment no longer used.

NOTE These activities may be conducted multiple times while drilling a well.

Production wells, by necessity, must penetrate the sealing formations above the target hydrocarbon reservoir. This fact alone means stringent analysis and execution of well construction and integrity is of key importance in eliminating potential leak paths. For 75 years the industry has successfully drilled and produced wells using modern drilling techniques. Continuous improvements in technology and practices have allowed these wells to maintain their integrity and provide the required isolation.

The ultimate goal of the well design is to ensure the environmentally sound, safe production of hydrocarbons by containing them inside the well, protecting groundwater resources, isolating the productive formations from other formations, and by proper execution of hydraulic fractures and other stimulation operations. The well design and construction must ensure no leaks occur through or between any casing strings. The fluids produced from the well (oil, water, and gas) must travel directly from the producing zone to the surface inside the well conduit.

The design basis for well construction emphasizes barrier performance and zonal isolation using the fundamentals of wellbore preparation, mud removal, casing running, and cement placement to provide barriers that prevent fluid migration. The selection of the materials for cementing and casing are important, but are secondary to the process of cement placement. The performance of the barrier system to protect groundwater and isolate the hydrocarbon bearing zones is of utmost importance.

All well designs and well plans include contingency planning. Although seldom needed, these contingency plans are in place to mitigate and eliminate the risk failure due to unplanned events, and most importantly, to ensure the protection of people and the environment.

3.3 The Drilling and Completion Process

Drilling a typical oil or gas well consists of several cycles of drilling, running casing (steel pipe for well construction), and cementing the casing in place to ensure isolation. In each cycle, steel casing is installed in sequentially smaller sizes inside the previous installed casing string. The last cycle of the well construction is well completion, which can include perforating and hydraulic fracturing or other stimulation techniques depending on the well type.

Drilling a well utilizes the drill string, consisting of drill bit, drill collars (heavy weight pipe to put weight on the bit), and drill pipe. The drill string is assembled and run into the hole, but suspended at the surface from the drilling derrick or mast. The drill string is then rotated by the use of a turntable (rotary table), top drive unit, or downhole motor drive.

While drilling, fluid is circulated down the drill string and up the space between the drill string and hole. This drilling fluid serves to lubricate the drilling assembly, remove the formation cuttings drilled, maintain pressure control of the well, and stabilize the hole being drilled. Drilling fluid is generally a mixture of water, clays, fluid loss control additives, density control additives, and viscosifiers. Drilling fluid is a carefully monitored and controlled mixture designed to achieve best drilling results.

Referring to Figure 1, the first hole to be drilled is for installing the conductor pipe. The conductor pipe can also be driven into place, like a structural piling, in some circumstances. This is followed by the sequentially deeper holes drilled to install the surface casing, intermediate casing (if necessary), and the production casing. Specific considerations for each of these casing strings are presented in Section 7. It is important to note that the shallow portions of the well have multiple concentric strings of steel casing installed.

In some areas, the general design shown in Figure 1 may be altered because of local environmental or geologic conditions. As such, state regulations vary to achieve the level of isolation and protection needed in different settings. For example, the number of intermediate casing strings is determined by the geologic conditions present in the well being drilled.

Horizontal wells are wells that are drilled vertically to a point and then redirected to run substantially horizontally within the targeted hydrocarbon producing formation. The vertical portion of a horizontal well is drilled the same way as vertical wells described above. However, the horizontal portion of the hole is drilled with a downhole motor in virtually all cases. While drilling the horizontal section of the well, the downhole motor, which operates using the hydraulic pressure of the drilling fluid, turns the drill bit. Downhole motors are “steerable,” meaning their direction of drilling can be controlled from the surface to stay within the target formation.

4 Casing Guidance

The design and selection of the casing is of utmost importance. The casing must be able to withstand the various compressive, tensional, and bending forces that are exerted while running in the hole, as well as the collapse and burst pressures that it might be subjected to during different phases of the well’s life. For example, during cementing operations, the casing must withstand the hydrostatic forces exerted by the cement column; after cementation, the casing must withstand the collapsing pressures of certain subsurface formations. These subsurface pressures exist regardless of the presence of hydrocarbons.

Design of the steel casing strings is a key part of the well design and a key factor in well success, including assurance of zonal isolation and wellbore integrity. It is the prime responsibility of operating companies, drilling contractors, and their drilling engineers and supervisors to design and review the design of the casing, as well as the plan to run and install the casing during well construction. Casing design and running are carefully executed technical processes.

Casing is threaded on each end, and has a coupling installed to join it to the next pipe. When several joints of casing have been screwed together they form a continuous “string” of casing that will isolate the hole. When screwing together a casing connection, applying the proper amount of torque is important. Too much torque overstresses the connection and can result in failure of the connection. Too little torque can result in a leaky connection.

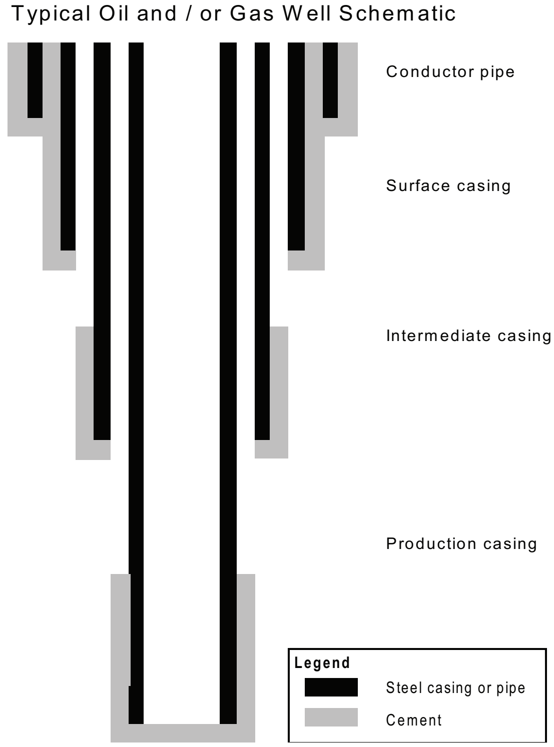

Figure 1—Typical Well Schematic

Casing used in oil and gas wells that will be hydraulically fractured should meet API standards, including API Spec 5CT. API casing specifications and recommended practices cover the design, manufacturing, testing, and transportation. Casing manufactured to API specifications must meet strict requirements for compression, tension, collapse, and burst resistance, quality, and consistency. The casing used in a well should be designed to withstand the anticipated hydraulic fracturing pressure, production pressures, corrosive conditions, and other factors. If used or reconditioned casing is installed in a well that will be hydraulically fractured, it should be tested to ensure that it meets API performance requirements for new built casing.

Casing and coupling threads should meet API standards and specifications to ensure performance, quality, and consistency, including API Spec 5B. If proprietary casing and coupling threads from a specialized supplier are used, these threads must also pass rigorous testing done by the supplier and should adhere to applicable subsets of the API qualification tests.

5 Cementing the Casing

5.1 General

After the casing has been run into the drilled hole, it must be cemented in place. This is a critical part of well construction and is a fully designed and engineered process. The purpose of cementing the casing is to provide zonal isolation between different formations, including full isolation of the groundwater and to provide structural support of the well. Cement is fundamental in maintaining integrity throughout the life of the well and part of corrosion protection for casing.

Cementing is accomplished by pumping the cement (commonly known as slurry) down the inside of the casing, and circulating it back up the outside of the casing. Top and bottom rubber wiper plugs should be used to minimize mixing of cement with drilling fluid while it is being pumped. A downhole schematic of a cement job in progress is illustrated in Figure 2.

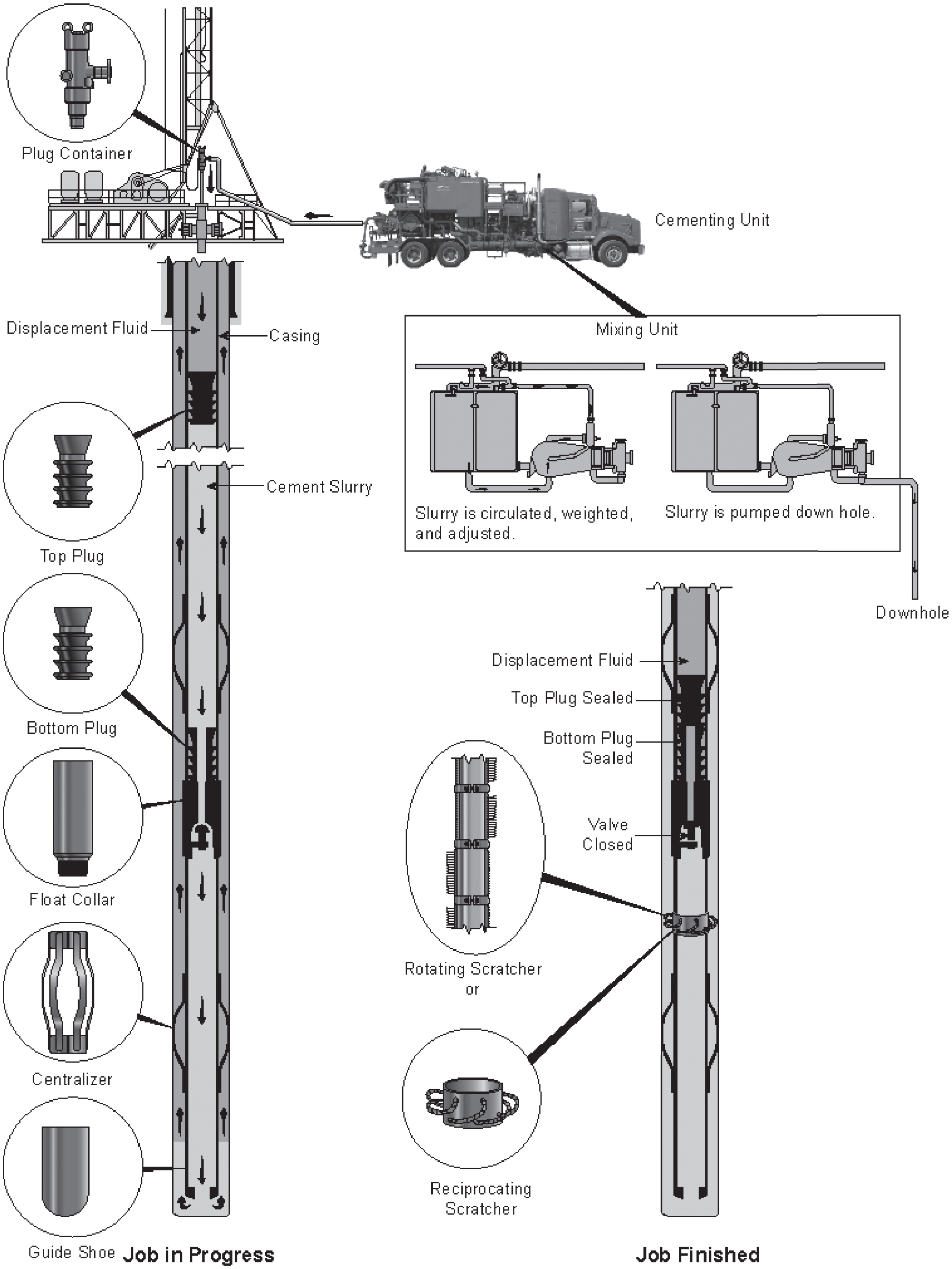

Figure 2—Cementing the Casing

5.2 Cement Selection

Oilfield cements are engineered products that are covered by API technical specifications, recommended practices, and technical reports. The cements and cement additives selected and the cementing practices utilized are an integral part of sound well design, construction, and well integrity. Various cements and cement additives are available for use. Appropriate API standards should be consulted in the selection and use of cementing products, including API Spec 10A and API RP 10B-2. Selected cements, additives, and mixing fluid should be laboratory tested in advance to ensure they meet the requirements of the well design.

Specifications and recommended practices for cementing operations, developed by API and others, are well documented and available to all companies drilling wells. These standards should be followed by operators in all wells. A general list of good cementing practices is provided in 5.4.

5.3 Zone Isolation

Placement of the cement completely around the casing and at the proper height above the bottom of the drilled hole (cement top) is one of the primary factors in achieving successful zone isolation and integrity. Good isolation requires complete annular filling and tight cement interfaces with the formation and casing. Complete displacement of drilling fluid by cement and good bonding of the cement interfaces between the drilled hole and the casing immediately above the hydrocarbon formation are key parts of well integrity and seal integrity. The absence of voids and good bonding of cement at these interfaces prevent migration paths and establish zone isolation.

5.4 Cementing Practices

The following cement practices are recommended in order to ensure that isolation is achieved.

- Prior to drilling, operators should investigate and review the history of nearby wells for cementing problems encountered, e.g. lost returns, irregular hole erosion, poor hole cleaning, poor cement displacement, etc.

- Computer simulation and other planning should be carried out in order to optimize cement placement procedures.

- Operators should use established, effective drilling practices to achieve a uniform, stable wellbore with desired hole geometry.

- Operators should ensure that the drilling fluid selection is appropriate for the designed well and the geologic conditions likely to be encountered.

- Casing hardware, including float equipment, centralizers, cement baskets, wiper plugs (top and bottom), and stage tools should be selected as necessary as part of the well design that will meet the cement design objective and challenges and ensure isolation.

- Casing centralizers should be selected to help center the casing in the hole and provide for good mud removal and cement placement, especially in critical areas, such as casing shoes, production zones, and groundwater aquifers (see 5.5).

- Appropriate cement testing procedures should be properly carried out by the service company personnel (see API RP 10B-2). Cement slurry design should include testing to measure the following parameters depending on site-specific geologic conditions.

  - Critical Parameters—Recommended for all situations:

    - slurry density;

    - > thickening time;
    - > fluid loss control;
    - > free fluid;
    - > compressive strength development;
    - > fluid compatibility (cement, mix fluid, mud, spacer).
  - — Secondary Parameters—Recommended for use as appropriate to address specific well conditions:
    - > sedimentation control;
    - > expansion or shrinkage of set cement;
    - > static gel strength development;
    - > mechanical properties (Young's Modulus, Poisson's Ratio, etc.).
- — Cement job design should include proper cement spacer design and volume. In many cases, cement placement is a two-stage process that uses a "lead" cement of lower density and a "tail" cement of higher density and compressive strength. Typically, the tail cement is used to isolate critical intervals in the well.
- — The operator should ensure proper wellbore preparation, hole cleaning, and conditioning with wiper trips prior to the cement job.
- — Rotation and reciprocation of casing should be considered where appropriate to improve mud removal and cement placement.
- — Service providers should ensure proper mixing, blending, and pumping of the cement in the field.

5.5 Casing Centralizers

Centralization of the casing is important for mud removal and cement placement that help to ensure a good cement job. The casing should be centralized in the hole in order to ensure that it will be completely surrounded or encased by cement during cementing operations and achieve the required isolation.

Casing centralizers are devices that are attached to the outside of the casing to keep the casing centered in the hole, and when the casing is cemented, this will allow the cement to completely surround the casing in a continuous sheath. There are three different kinds of centralizers: the bow-spring design, the rigid blade design, and the solid design. API RP 10D-2 and API TR 10TR4 address calculations determining the number and placement of centralizers in vertical and deviated wellbores and centralizer selection guidelines, respectively.

Casing centralizers should be used in wells. Computer programs are available that can be used to optimize the number of centralizers needed and their placement within a well.

6 Well Logging and Other Testing

6.1 General

Well logs are critical data gathering tools used in formation evaluation, well design, and construction. Also, various types of mechanical integrity and hydraulic pressure tests can be used to assess well integrity during the construction of the well. This section describes various types of well logs and other testing and the type of information that can be gathered.

6.2 Open-hole Well Logging

After drilling of the hole is completed, and before casing is installed and cementing operations begin, electrical and other instruments are often run in the drilled hole on an electric cable in an operation called well logging. When well logging is carried out prior to setting casing, it is called open-hole logging. Open-hole logging is used for many purposes, including locating and evaluating the hydrocarbon producing formations. The types of logs that are run in a well are carefully selected by geologists at the time the well is designed. Common logging tools used for evaluation include the following log types.

— Gamma Ray—A device that detects naturally occurring gamma radiation.

— Resistivity—Measures the electrical resistance between probes on the logging tool in the wellbore. Usually at least three resistivity logs are run, but up to 10 may be run; the difference being the distance between the probes. The radius of investigation is increased with the distance between probes.

— Density—A device used to measure the bulk density of, and, by inference, the porosity of the formation.

— Caliper—A physical measurement of the diameter of the wellbore. A caliper log run through a wellbore is used to calculate the hole size and volume of the wellbore, and therefore provides critical data that is used in the design of the cement job.

Logging produces valuable information on all formations logged, which is useful in optimizing the well design and drilling operation. Logging determines the actual depth and thickness of the subsurface formations in the drilled hole. This allows installation of casing strings in exactly the right place to achieve the well design objectives and to properly achieve the isolation benefits of the casing and cement.

Many other types of logging tools are available and may be run on a case specific basis.

6.3 Cement Integrity (Cased-hole) Logging

After cementing the casing, “cased-hole” logs can be run inside the casing. These logs usually include the gamma ray (described above), a collar locator (a magnetic device that detects the casing collars), and a cement bond log (CBL) that measures the presence of cement and the quality of the cement bond or seal between the casing and the formation.

The CBL is an acoustic device that can detect cemented or noncemented casing. The CBL works by transmitting a sound or vibration signal, and then recording the amplitude of the arrival signal. Casing that has no cement surrounding it (i.e. free pipe) will have large amplitude acoustic signal because the energy remains in the pipe. On the other hand, casing that has a good cement sheath that fills the annular space between the casing and the formation will have a much smaller amplitude signal since the casing is “acoustically coupled” with the cement and the formation which causes the acoustic energy to be absorbed. It is precisely this coupling which is the main feature that creates the desired isolation.

The variable density log (VDL) is a display that is commonly shown with the CBL, and is a display of the wave train of an acoustic signal.

An experienced engineer can easily identify the key features of the cement operation, such as top of cement and the location of the casing collars using data derived from the various well logs that have been run. For example, when the well is perforated, a gamma-ray detector will be run in the hole with the perforating guns, and the exact location of the perforating guns with respect to the formations is known by comparison with the gamma-ray response of the open-hole log and the CBL.

The CBL-VDL is the most common type of cement evaluation tool that is used, but other types of cement evaluation tools are available and, depending on the situation, should be considered as a part of a comprehensive cement evaluation program. Information on the various types of cement evaluation tools can be found in API TR 10TR1.

A key result of the cased-hole logging program is to know the exact location of the casing, casing collars, and quality of the cement job relative to each other and relative to the subsurface formation locations. This is important in determining that the well drilling construction is adequate and achieves the desired design objectives. It is also useful information in subsequent checks of well integrity and seals over the productive life of the well.

6.4 Other Testing and Information

It is important to remember that the quality of a cement job cannot be fully evaluated without other supporting data. All of the available well information is reviewed thoroughly when assessing the integrity of a well's cement job. Such information includes drilling reports, drilling fluid reports, cement design and related laboratory reports, open-hole log information including caliper logs, cement placement information including centralizer program, placement simulations and job logs, results of mechanical integrity tests performed on the well, and other information. The effectiveness of a cement seal should also be tested with various hydraulic pressure tests to ensure well integrity.

7 Well Construction Guidelines

7.1 General

Well design and construction are generally considered to have four main components and are focused around the various casing strings used: conductor, surface, intermediate, and production. This section discusses considerations for each casing string that should be included in well design and construction. It is important to note that because of varying geologic conditions, state regulations are developed to meet the particular need of that state and are not uniform throughout the United States. However, the general principles of groundwater protection through zone isolation are maintained.

All casing setting depths are determined in advance as part of the drilling plan. The depth of each casing string is critical in assuring isolation, meeting regulatory requirements, achieving a well system with integrity to support the rest of the drilling operation, and to contain any pressures that might occur inside the well. The actual length of the casing strings is carefully adjusted as the well is drilled based on measurements and data from the drilling process. This includes the results of logs (see Section 7), drill cuttings analysis, and analysis of pressures and drilling loads while drilling.

A frequent discussion point is whether cement is required to be placed back to surface on each casing string. This is necessary only in some cases and is fully considered in the well design and addressed by state regulations. Specific recommendations for each casing string are given below.

A general recommendation applicable to all casing strings is that after the cement is set and prior to commencing further drilling or completion operations, the cement surrounding the casing shoe should have a compressive strength of at least 500 psi and should achieve 1200 psi in 48 hours at bottomhole conditions. However, for production casing the cement should be tested to ensure that it is adequate to withstand the anticipated hydraulic fracturing pressure.

In addition, each casing string, except the conductor casing, should be pressure tested prior to "drill out." The test pressure will vary depending on the casing string, depth, and other factors.

7.2 Conductor Casing

The first casing to be installed in the well is the conductor casing. The conductor casing serves as the foundation for the well. Two purposes of the conductor casing are to hold back the unconsolidated surface sediments and isolate shallow groundwater. Below the conductor casing there is harder, more consolidated rock. Thus, the conductor pipe keeps the unconsolidated surface sediment in place as the drilling operations proceed. The conductor casing also protects the subsequent casing strings from corrosion and may be used to structurally support some of the wellhead load. Requirements for the conductor hole vary by state and area.

The conductor hole is usually drilled, with steel casing inserted into the hole and cemented in place using proper cementing practices and in accordance with the well design. There are instances where it is appropriate to “hammer” the conductor casing into place, which means it is driven directly into the ground just like a structural pile for buildings and bridges. The conductor hole should be drilled using air, freshwater, or freshwater-based drilling fluid. When determining the setting depth of the conductor casing, the depth of nearby water wells should be considered. Acceptable practice for a particular area is dictated by state regulations.

When cementing conductor casing, cement should be placed back to the surface. If cement cannot be circulated back to the surface using ordinary pumping methods, in some cases it is possible to run a small diameter pipe between the hole and the conductor casing. Cement can then be pumped around the outside of the surface pipe. This type of cement procedure is often called a “top job” or “horse collar.”

7.3 Surface Casing

After the conductor pipe is installed and cemented, the surface hole is drilled and the surface casing is run into the hole and cemented in place using proper cementing practices. One of the main purposes of the surface casing is the protection (through isolation) of groundwater aquifers. The surface casing is designed to achieve all regulatory requirements for isolating groundwater and also to contain pressures that might occur in the subsequent drilling process.

The surface hole is typically drilled to a predetermined depth based on consideration of the deepest groundwater resources and pressure control requirements of subsequent drilling. The surface hole should be drilled using air, freshwater, or freshwater-based drilling fluid. This setting depth can be from a few hundred feet up to 2000 ft deep or more. The surface casing is usually set at a depth sufficient to ensure groundwater protection. State regulations dictate the minimal setting depth of surface casing, and the vast majority of states require the casing to be set below the deepest groundwater aquifer. At a minimum, it is recommended that surface casing be set at least 100 ft below the deepest USDW encountered while drilling the well.

It is recommended that the surface casing be cemented from the bottom to the top, completely isolating groundwater aquifers. As is the case with conductor casing, a “top job” may be necessary in certain situations. In those cases where cementation from bottom to top is not required or possible, cementing across all USDWs is recommended. This will still provide the required isolation.

In some instances, unique geologic conditions that will not permit the surface casing to be run deep enough to cover the deepest groundwater aquifer or preclude the need for surface casing at all. In these cases, zone isolation should be achieved through additional strings or a combination of surface, intermediate, and/or production casing and cementing as appropriate.

After the surface casing cement has achieved the appropriate compressive strength and prior to drilling out, the surface casing should be pressure tested (commonly known as a casing pressure test). This test should be conducted at a pressure that will determine if the casing integrity is adequate to meet the well design and construction objectives.

In addition, immediately after drilling out of the surface casing plus a short interval of new formation below the surface casing shoe, a formation pressure integrity test (also known as a “shoe test” or “leak-off test”) should be performed. If the test results of the formation pressure integrity test are inadequate, remedial measures should be undertaken as appropriate.

7.4 Intermediate Casing

After the surface hole has been drilled and the surface casing has been set and properly cemented, drilling of the intermediate hole can commence. The purpose of drilling the intermediate hole and running casing is to isolate subsurface formations that may cause borehole instability and to provide protection from abnormally pressured subsurface formations.

In some cases, the well can be drilled from the surface casing to total depth. In these cases, an intermediate casing string may not be required. This is determined by the geological setting prior to drilling, and is a part of the well design or is determined by data and measurements taken during the drilling process.

In many cases, it is not necessary to cement the intermediate casing back to the surface to provide adequate isolation. This is especially true in the cases where the surface casing string and cement are fully protecting the groundwater aquifers. Also, in many cases this is not advisable, as attempts to cement intermediate casing back to the surface can result in lost circulation. If the intermediate casing is not cemented to the surface, at a minimum the cement should extend above any exposed USDW or any hydrocarbon bearing zone.

Depending on the well design, it may be appropriate to run a CBL and/or other diagnostic tool(s) to determine that the cement integrity is adequate to meet the well design and construction objectives.

After the intermediate casing cement has achieved the appropriate compressive strength and prior to drilling out, the intermediate casing should be pressure tested (commonly known as a casing pressure test). This test should be conducted at a pressure that will determine if the casing integrity is adequate to meet the well design and construction objectives.

In addition, immediately after drilling out of the intermediate casing plus a short interval of new formation below the intermediate casing shoe, a formation pressure integrity test (also known as a “shoe test” or “leak-off test”) should be performed. If the test results of the formation pressure integrity test are inadequate or indicate a failure, remedial measures should be undertaken as appropriate. In particular, in the case of a failure, remedial cementing operations should be undertaken as appropriate. This is critical to maintaining well integrity.

7.5 Production Casing

The final hole to be drilled is the hole for the production casing. After the production hole is drilled and logged, production casing is run to the total depth of the well and cemented in place using proper cementing practices. The purpose of the production casing is to provide the zonal isolation between the producing zone and all other subsurface formations, for pumping the hydraulic fracturing fluids and other stimulation techniques from the surface into the producing formation without affecting any other geologic horizon in the well. It also contains the downhole production equipment (tubing, packer, etc.). Over the life of the well, its most important function is internally containing the hydrocarbon production from the producing zone. In most cases, it serves as a secondary barrier for the production tubing and packer that are inserted into the production casing in the final completion step.

There are many options for cementation. In most cases, the production string cement does not need to be brought completely to the surface. This depends on the geologic setting, well design, and wellbore conditions. In cases where intermediate casing is not installed, cementing the production casing to the surface should be considered. At a minimum, the tail cement should be brought at least 500 ft above the highest formation where hydraulic fracturing will be performed. In all cases, the casing is cemented to achieve the required subsurface isolation between zones.

Prior to perforating and hydraulic fracturing operations, the production casing should be pressure tested (commonly known as a casing pressure test). This test should be conducted at a pressure that will determine if the casing integrity is adequate to meet the well design and construction objectives. A CBL and/or other diagnostic tool(s) should be run to determine that the cement integrity is adequate to meet the well design and construction objectives. Remedial cementing operations should be considered if there is evidence of inadequate cement integrity.

7.6 Horizontal Wells

Drilling and completing horizontal wells is an evolving technology. Horizontal wells offer benefits that improve the production performance for certain types of producing formations. Horizontal wells also allow operators to develop resources with significantly fewer wells than may be required with vertical wells. Operators can drill multiple horizontal wells from a single surface location, thereby, reducing the cumulative surface impact of the development operation. However, horizontal wells are significantly more expensive to drill and maintain. In some areas, the typical cost of a horizontal well may be two to three times the cost of a vertical well.

As discussed earlier, horizontal wells are typically drilled vertically to a "kick-off" point where the drill bit is gradually turned from vertical to horizontal. Figure 3 illustrates a vertical and horizontal well for comparison. So the considerations and recommendations for setting conductor, surface, intermediate production casing strings are the same as those for vertical wells.

In horizontal wells, an "open-hole" completion is an alternative to setting the casing through the producing formation to the total depth of the well. In this case, the bottom of the production casing is installed at the top of the productive formation or open-hole section of the well. In this alternative, the producing portion of the well is the horizontal portion of the hole and it is entirely in the producing formation. In some instances, a short section of steel casing that runs up into the production casing, but not back to the surface, may be installed. Alternatively, a slotted or preperforated steel casing may be installed in the open-hole portion. These alternatives are generally called a "production liner," and are typically not cemented into place.

In the case of an open-hole completion, tail cement should extend above the top of the confining formation (the formation that limits the vertical growth of the fracture).

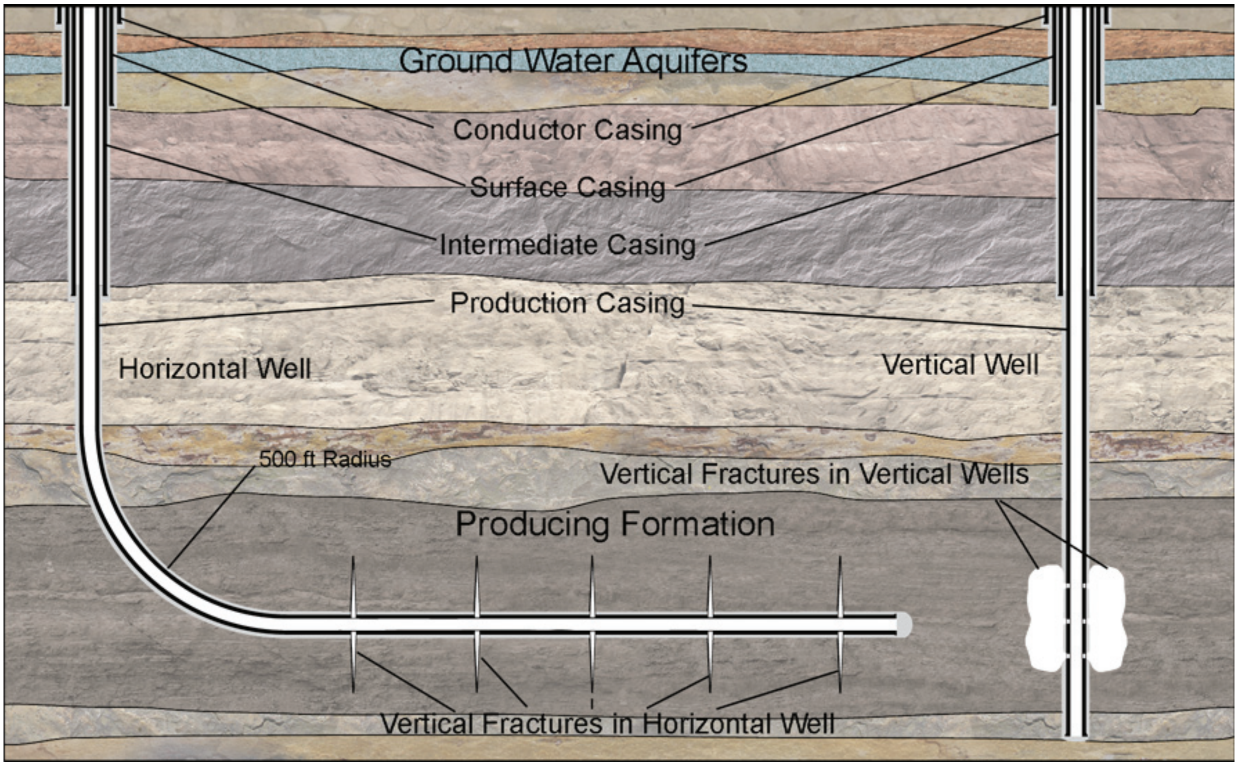

Figure 3—Example of a Horizontal and Vertical Well

8 Perforating

A perforation is the hole created between the casing or liner into the reservoir (subsurface hydrocarbon bearing formation). This hole creates communication to the inside of the production casing, and is the hole through which oil or gas is produced. By far the most common perforating method utilizes jet perforating guns that are loaded with specialized shaped explosive charges.

Figure 4 illustrates the perforation process. The shaped charge is detonated and a jet of very hot, high-pressure gas vaporizes the steel pipe, cement, and formation in its path. The result is an isolated tunnel that connects the inside of the production casing to the formation. These tunnels are isolated by the cement. Additionally, the producing zone itself is isolated outside the production casing by the cement above and below the zone.

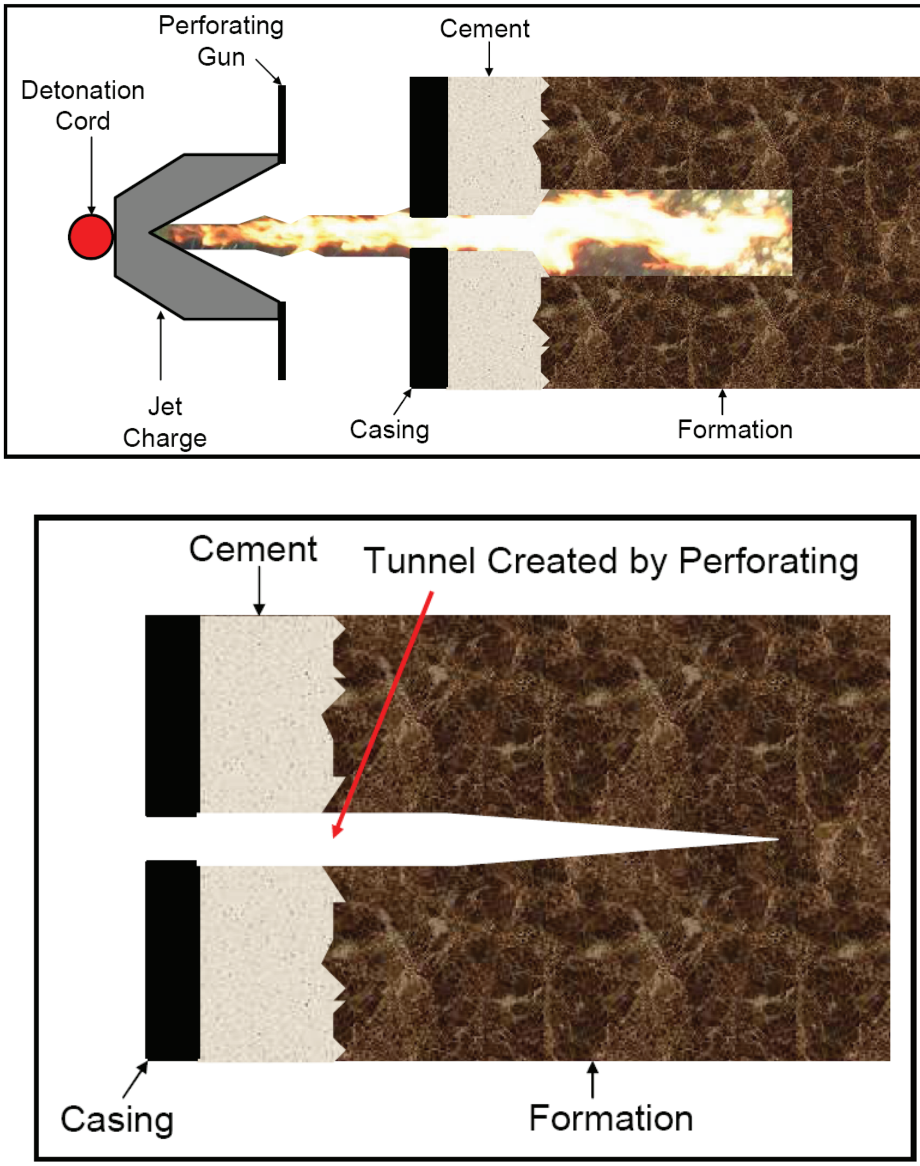

Figure 4—Perforation

9 Hydraulic Fracturing

9.1 General

Hydraulic fracturing is a well stimulation technique that has been employed in the oil and gas industry since 1947. Very low permeability formations such as fine sand and shale tend to have fine grains (limited porosity) and few interconnected pores (low permeability). Permeability represents the ability for a fluid to flow through a (somewhat) porous rock. In order for natural gas or oil to be produced from low permeability reservoirs, individual molecules of fluid must find their way through a tortuous path to the well. Without hydraulic fracturing, this process would produce too little oil and/or gas and the cost to drill and complete the well would be could not be justified by this low rate of production.

A wellbore of a “traditional” nonfractured well is schematically represented in the top part of Figure 5, where the red arrows represent the flow of fluid to the circle which represents the well. However, by creating an artificial fracture, individual molecules that are a long distance from the well can find their way to the fracture, and once there, can travel quickly through the fracture to the well. This situation is represented in the lower part of Figure 5.

The process of hydraulic fracturing increases the exposed area of the producing formation, creating a high conductivity path that extends from the wellbore through a targeted hydrocarbon bearing formation for a significant distance, so that hydrocarbons and other fluids can flow more easily from the formation rock, into the fracture, and ultimately to the wellbore. Hydraulic fracturing treatments are designed by specialists and utilize state-of-the-art software programs and are an integral part of the design and construction of the well. Pretreatment quality control and testing is carried out in order to ensure a high-quality outcome.

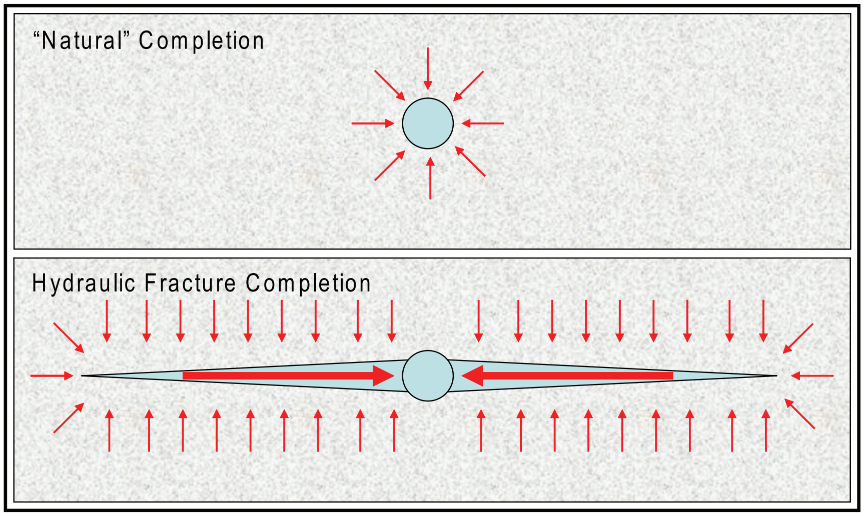

Figure 5—Illustration of a Fractured and a Nonfractured Well

During hydraulic fracturing, fluid is pumped into the production casing, through the perforations (or open hole), and into the targeted formation at pressures high enough to cause the rock within the targeted formation to fracture. In the field, this is known as “breaking down” the formation.

As high-pressure fluid injection continues, this fracture can continue to grow, or propagate. The rate at which fluid is pumped must be fast enough that the pressure necessary to propagate the fracture is maintained. This pressure is known as the propagation pressure or extension pressure. As the fracture continues to propagate, a proppant, such as sand, is added to the fluid. When pumping is stopped, and the excess pressure is removed, the fracture attempts to close. The proppant will keep the fracture open, allowing fluids to then flow more readily through this higher permeability fracture.

During the hydraulic fracturing process, some of the fracturing fluid may leave the fracture and enter the targeted formation adjacent to the created fracture (i.e. untreated formation). This phenomenon is known as fluid leak-off. The fluid flows into the micropore or pore spaces of the formation or into existing natural fractures in the formation or into small fractures opened and propagated into the formation by the pressure in the induced fracture.

As one would expect, the fracture will propagate along the path of least resistance. Certain predictable characteristics or physical properties regarding the path of least resistance have been recognized since hydraulic fracturing was first conducted in the oilfield in 1947. These properties are discussed below.

9.2 Horizontal Fractures

Hydraulic fractures are formed in the direction perpendicular to the least stress. In Figure 6, an imaginary cube of rock is shown as having confining stress exerted on it in three dimensions. Each pair of opposing stresses must be equal in order for the cube to remain stationary in space. The relative size of the arrows represents the magnitude of the confining stress. In Figure 7, the least stress is in the vertical direction. This direction is known as the direction of overburden, referring to the weight of the earth that lies above. The Earth's overburden pressure is the least principal stress only at shallow depth. Based on experience, horizontal fractures will occur at depths less than 2000 ft.

In this example, when pressure is applied to the center of this block, the formation will crack or fracture in the horizontal plane as shown, because it will be easier to part the rock in this direction than any other direction. In general, these fractures are parallel to the bedding plane of the formation.

9.3 Vertical Fractures

As depth increases, overburden stress in the vertical direction increases by approximately 1 psi/ft. As the stress in the vertical direction becomes greater with depth, the overburden stress (stress in the vertical direction) becomes the greatest stress. This situation generally occurs at depths greater than 2000 ft. This is represented in Figure 7 by the magnitude of the arrows, where the least stress is represented by the small red horizontal arrows, and the induced fracture will be perpendicular to this stress, or in the vertical orientation.

Since hydraulically induced fractures are formed in the direction perpendicular to the least stress, as depicted in Figure 7, the resulting fracture would be oriented in the vertical direction.

The extent that the created fracture will propagate in the vertical direction toward a USDW is controlled by the upper confining zone or formation. This zone will stop the vertical growth of a fracture because it either possess sufficient strength or elasticity to contain the pressure of the injected fluids.

9.4 Hydraulic Fracturing Process

In order to carry out hydraulic fracturing operations, a fluid must be pumped into the well's production casing at high pressure. It is necessary that production casing has been installed and cemented and that it is capable of withstanding the pressure that it will be subjected to during hydraulic fracture operations. In some cases, the production casing will never be exposed to high pressure except during hydraulic fracturing. In these cases, a high-pressure "frac string" may be used to pump the fluids into the well to isolate the production casing from the high treatment pressure. Once the hydraulic fracturing operations are complete, the frac string is removed.

The well operator or the operator's designated representative should be on site throughout the hydraulic fracturing process. Prior to beginning the hydraulic fracture treatment, all equipment should be tested to make sure it is in good operating condition. All high-pressure lines leading from the pump trucks to the wellhead should be pressure tested to the maximum treating pressure. Any leaks must be eliminated prior to initiation of the hydraulic fracture treatment. After this, the final safety and operational meetings should be conducted.

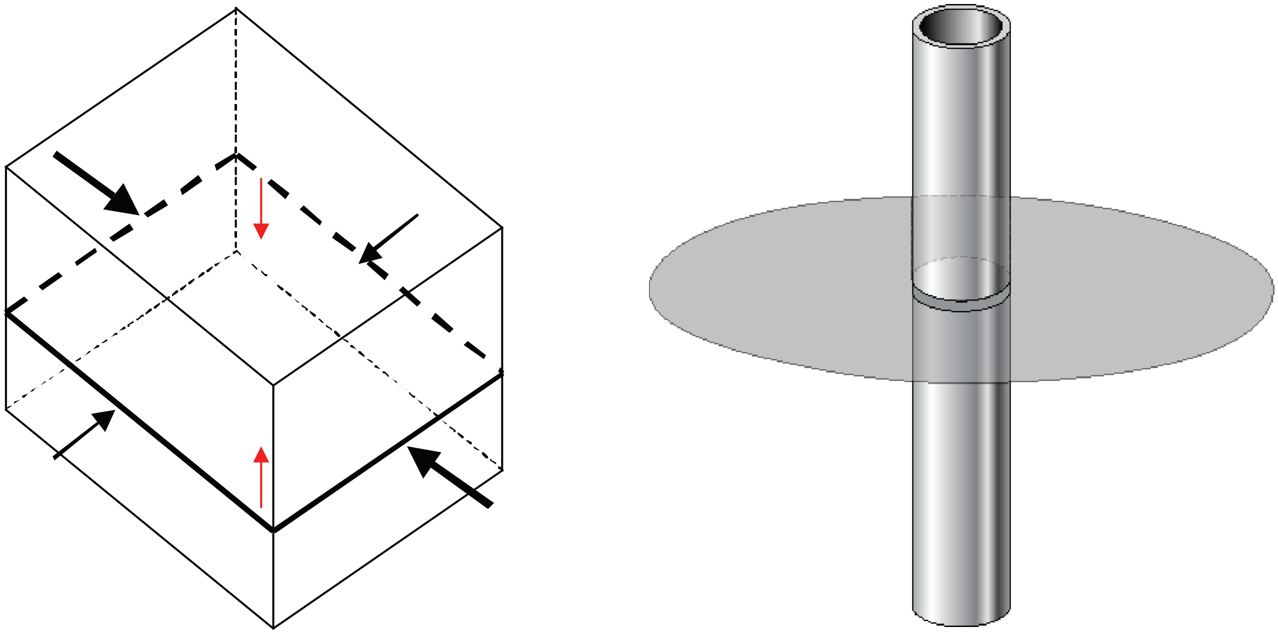

Figure 6—Least Principal Stress is in the Vertical Direction Resulting in a Horizontal Fracture

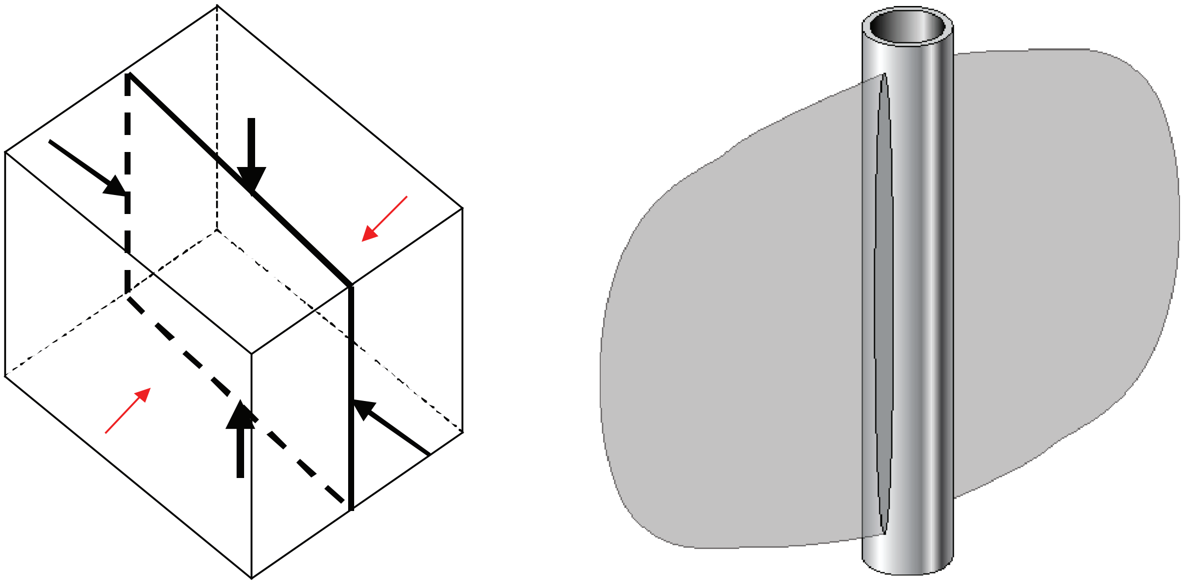

Figure 7—Least Principal Stress in the Horizontal Direction, Vertical Fracture

When these conditions are met, the well is ready for the hydraulic fracturing process. In the field, the process is called the "treatment" or the "job." The process is carried out in predetermined stages that can be altered depending on the site-specific conditions or if necessary during the treatment. In general, these stages can be described as follows.

- Pad—The pad is the first stage of the job. The fracture is initiated in the targeted formation during the initial pumping of the pad. From this point forward, the fracture is propagated into the formation. Typically, no proppant is pumped during the pad; however, in some cases, very small amounts of sand may be added in short bursts in order to abrade or fully open the perforations. Another purpose of the pad is to provide enough fluid volume within the fracture to account for fluid leak-off into the targeted formations that could occur throughout the treatment.

- Proppant Stages—After the pad is pumped, the next stages will contain varying concentrations of proppant. The most common proppant is ordinary sand that has been sieved to a particular size. Other specialized proppants include sintered bauxite, which has an extremely high crushing strength, and ceramic proppant, which is an intermediate strength proppant.

- Displacement—The purpose of the displacement is to flush the previous sand laden stage to a depth just above the perforations. This is done so that the pipe is not left full of sand, and so that most of the proppant pumped will end up in the fractures created in the targeted formation. Sometimes called the flush, the displacement stage is where the last fluid is pumped into the well. Sometimes this fluid is plain water with no additives, or it may be the same fluid that has been pumped into the well up to that point in time.

In wells with long producing intervals (e.g. horizontal wells), this process may be done in multiple stages or cycles, working from the bottom to the top of the productive interval. Staging the treatments allows for better control and monitoring of the fracture process.

9.5 Hydraulic Fracturing Equipment and Materials

The hydraulic fracturing process requires an array of specialized equipment and materials. This section will describe the materials and equipment that are necessary to carry out typical hydraulic fracture operations in vertical and horizontal wells.

The equipment required to carry out a hydraulic fracturing treatment includes fluid storage tanks, proppant transport equipment, blending equipment, pumping equipment, and all ancillary equipment such as hoses, piping, valves, and manifolds. Hydraulic fracturing service companies also provide specialized monitoring and control equipment that is necessary in order to carry out a successful treatment. Each of these components will be discussed below. Figure 8 is a diagram showing schematically how this equipment typically functions together.

During the fracture treatment, data are being collected from the various units, and sent to monitoring equipment; in some cases this is a "frac van." Data being measured include fluid rate coming from the storage tanks, slurry rate being delivered to the high-pressure pumps, wellhead treatment pressure, density of the slurry, sand concentration, chemical rate, etc.

10 Data Collection, Analysis, and Monitoring

10.1 General

The purpose of this section is to discuss what types of data collection, analysis, and monitoring activities should be carried out in order to ensure successful hydraulic fracture treatment and that groundwater aquifers are protected. Hydraulic fracturing treatments are designed using computer modeling so that the induced fractures remain below the upper confining formation. The dimensions, extent, and geometry of the induced fractures are controlled by pump rate, pressure, volume, and viscosity of the fracturing fluid. Fracture monitoring techniques provide confirmation of fracturing coverage, and allow the refinement of the computer models and enhancements to procedures for future operations.

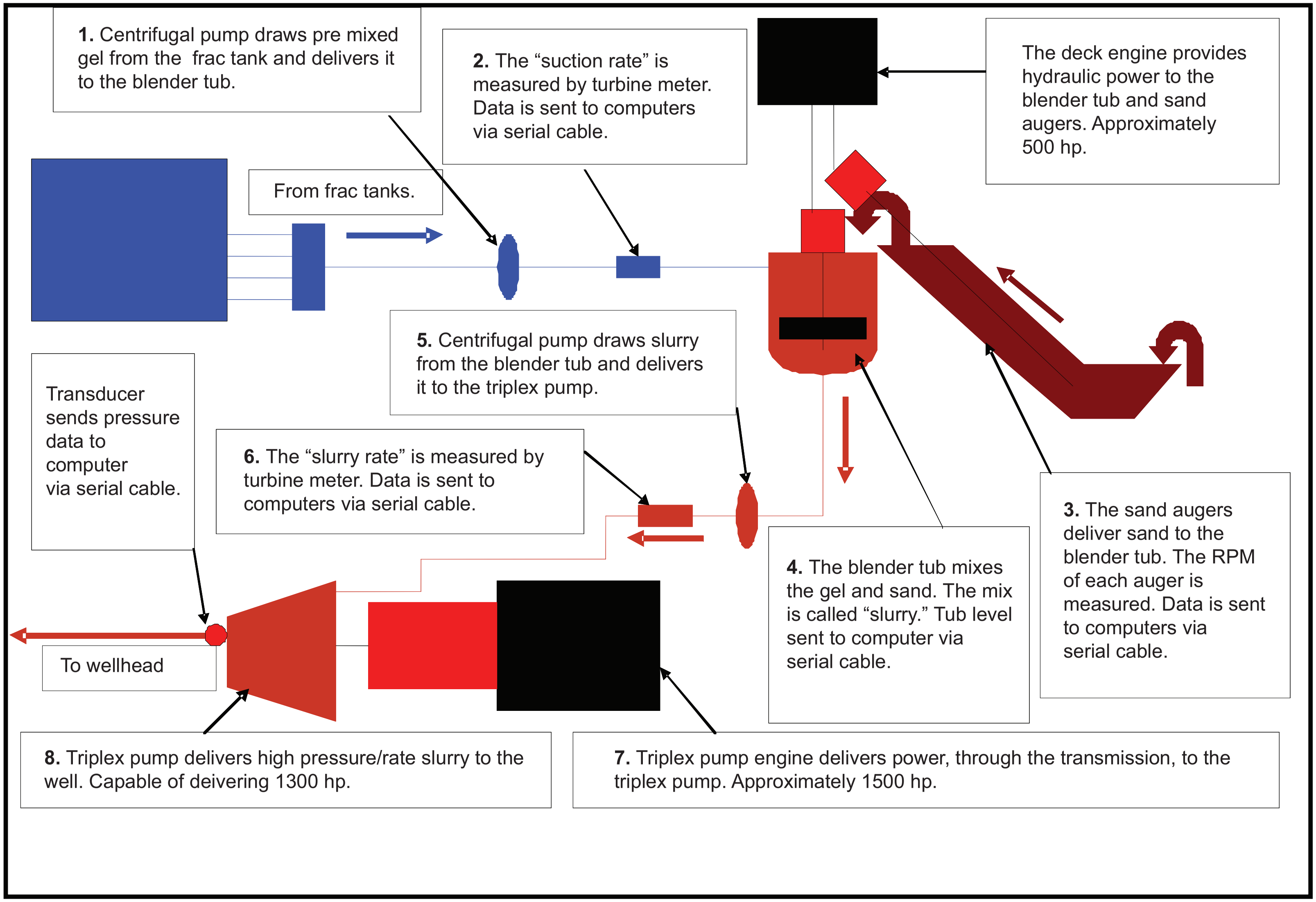

Figure 8—Schematic of Typical Fracturing Process

Data collection, analysis, and monitoring can be divided into the following activities:

- baseline assessment,
- "mini frac" treatment and analysis,
- monitoring during hydraulic fracturing operations,
- post-hydraulic fracturing monitoring techniques,
- post-completion monitoring.

10.2 Baseline Assessment

Once the location for a well has been selected and before it is drilled, water samples from any source of water located nearby should be obtained and tested in accordance with applicable regulatory requirements. This would include rivers, creeks, lakes, ponds, and water wells. If testing was not done prior to drilling, it should be done prior to hydraulically fracturing a well. The area of sampling should be based on the anticipated fracture length plus a safety factor.

This procedure will establish the baseline conditions in the surface and groundwater prior to any drilling or hydraulic fracturing operations. If subsequent testing reveals changes, this baseline data will allow the operator to determine the potential sources causing any changes. Because the constituents of the hydraulic fracturing fluid are known, a determination can be made regarding the source of the changes in the groundwater composition. However, it is important to note that changes to groundwater composition can come from other sources not related to drilling, hydraulic fracturing, or oil and natural gas development activities.

10.3 "Mini frac" Treatment and Analysis

In many cases, prior to the pad being pumped into the well to begin a fracturing job, an extended "pre-pad" stage is pumped so that certain diagnostic studies may be performed which, depending on the results, could alter how the rest of the hydraulic fracture treatment is executed. This is commonly known as a "mini frac." The data gathered during the mini frac is analyzed, any needed adjustments to the planned job are made and the results are used to refine computer models.

10.4 Monitoring During Hydraulic Fracturing Operations

10.4.1 Treatment Parameter Monitoring

Good process monitoring and quality control during the hydraulic fracture treatment is essential for carrying out a successful treatment and for protection of the groundwater. There are certain monitoring parameters that should be observed in virtually all hydraulic fracture treatments, and others that are employed from time to time based on site-specific needs. As mentioned previously, sophisticated software should be used to design hydraulic fracture treatments prior to their execution. The same software should be used during the treatment to monitor and control treatment progression and fracture geometry in real time. During the hydraulic fracture treatment, certain parameters should be continuously monitored. These would include surface injection pressure (psi), slurry rate (bpm), proppant concentration (ppa), fluid rate (bpm), and, sand or proppant rate (lb/min).

The data that is collected is used to refine computer models used to plan future hydraulic fracture treatments. In areas with significant experience in performing hydraulic fracture treatments, the data that is collected in a particular area on previous fracture treatments is a good indicator of what should happen during the treatment.

10.4.2 Pressure Monitoring

Pressure is normally measured at the pump and in the pipe that connects the pump to the wellhead. If the annulus between the production casing and the intermediate casing has not been cemented to the surface, the pressure in the annular space should be monitored and controlled. Pressure behavior throughout the hydraulic fracture treatment should be monitored so that any unexplained deviation from the pretreatment design can be immediately detected and analyzed before operations continue. Typically, variations are within normal ranges, and slight adjustments to the original design may be made as operations proceed, based on real-time data obtained from the process monitoring. Pressure exerted on equipment should not exceed the working pressure rating of the weakest component.

Unexpected or unusual pressure behavior during the hydraulic fracturing process could indicate some type of problem. Some problems such as a leak in the casing string are immediately apparent, and if this is the case, it is possible to shut down the treatment as soon as this occurs. The intermediate casing annulus should be equipped with an appropriately sized and tested relief valve. The relief valve should be set so that the pressure exerted on the casing does not exceed the working pressure rating of the casing. The flow line from the relief valve should be secured and diverted to a lined pit or tank.

10.4.3 Tiltmeter and Microseismic Monitoring

Fracture monitoring using microseismic and tiltmeter surveys is not used on every well, but is commonly used to evaluate new techniques, refine the effectiveness of fracturing techniques in new areas, and in calibrating hydraulic fracturing computer models.

A number of technologies have been developed or adapted to improve industry's ability to monitor hydraulic fracturing operations. For example, hydraulic fracture mapping utilizing tiltmeters has been employed since the 1980s. A tiltmeter is a device that measures the change in the inclination in the earth's surface. Initially, investigations centered on determining the direct propagation of a hydraulic fracture. Advances in the sensitivity of the tiltmeter instruments, capable of measuring changes of inclination as small as a nanoradian, and in computer processing power and speed, now allow tiltmeter data to be monitored in real time.

A recent technological development, known as microseismic mapping, now allows operators to monitor microseismic events associated with hydraulic fracture growth in three dimensions in real time. Microseismic mapping requires a geophone array to be placed in an observation well, and utilizes the energy of the fracturing process to make a map of the resulting microseismic events. By processing seismic events observed in a nearby observation well, the location of the microseismic events can be calculated using standard seismic technologies. Microseismic monitoring provides a way to evaluate critical hydraulic fracturing parameters such as vertical extent, lateral extent, azimuth, and fracture complexity. This represents a tool that operators can use so that the lateral and vertical extent of fracturing can be maintained within the desired reservoir unit and the results can be used to verify and fine tune computer models used to predict hydraulic fracture performance in an area.

In some cases, the integration of tiltmeter and microseismic technologies has been utilized to achieve real time mapping of a hydraulic fracture treatment in progress. Operators can utilize these technologies in real time to decide when to end one fracturing stage and proceed with the next one. For example, if the microseismic map indicates that the fracture may soon be nearing the edge of the targeted hydrocarbon formation, that stage of the fracture treatment can be terminated and the next stage of the fracture treatment can be initiated.

10.5 Post-hydraulic Fracturing Monitoring Techniques

Prior to a hydraulic fracturing treatment, the proppant, usually sand, may be "tagged" with a tracer. After the proppant has been pumped into the formation, a cased-hole log, capable of detecting the tracer, is run. The purpose of this procedure is to further confirm that the placement of the proppant was as it was intended. The radius of investigation of this type of log is relatively small, on the order of a few feet at best, but it does yield information indicating which perforations accepted proppant, and how the fracture grew immediately outside the perforations.

Another post-fracture cased-hole logging technique is a temperature log. This log can be run in conjunction with the tracer log described above. The temperature log measures the variations in temperature throughout the section of interest. The hydraulic fracturing fluid is typically at the ambient temperature of the surface, and the formation temperature at a depth of 7500 ft may be as high as 200 °F. As a result, the formation is cooled considerably during the fracture treatment. By running a temperature log, engineers can determine which perforations accepted fracturing fluid and gain some insight regarding fracture growth immediately outside the casing.

It is important to note that the use of the post-hydraulic fracturing monitoring techniques described above is declining with the advent of sophisticated computer modeling techniques.

10.6 Post-completion Monitoring

Throughout the life of a producing well, the well conditions should be monitored on an ongoing basis to ensure integrity of the well and well equipment. Mechanical integrity pressure monitoring is used to determine the mechanical integrity of tubulars and other well equipment when the well is producing and during fracturing operations.

Initially during well drilling, positive pressure tests that are part of normal well construction determine the casing and casing shoe integrity—as noted earlier in this document. During well fracturing, casing integrity is inferred by showing there is no leakage into the “A” annulus (if a frac string is used), or between the “A” annulus and “B” annulus by monitoring these pressures. After fracturing and upon final completion the tubing/packer integrity is demonstrated by showing there is no leakage of injected fluids through the tubing or packer into the “A” annulus causing pressure buildup.

It is important to monitor these annular pressures during production to determine if there are potential leaks. If an annulus is being charged with gas, an analysis of the gas content may give an indication of the source and the nature of a potential leak.

Maximum and minimum allowable annular surface pressures should be assigned to all annuli and these should consider the gradient of the fluid in each. These upper and lower limits establish the safe working range of pressures for normal operation in the well’s current service and should be considered “do not exceed” limits.

Wellhead seal tests are conducted to test the mechanical integrity of the sealing elements (including valve gates and seats) and determine if they are capable of sealing against well pressure. If non-normal pressures are noted in an annulus, a repressure test of the wellhead seal system can help determine if the source of communication is in the surface in the wellhead system.

When equipment is removed from a well or depressurized for maintenance, a breakdown or visual inspection should be conducted to document the condition of the equipment after being in service. For example, if tubing is pulled from a well, it can be inspected for corrosion/erosion damage. While the tubing is out of the well, a casing inspection log can be considered to verify the casing condition.

Regular visits by lease operators/well pumpers should identify any abnormal well conditions and should be used to monitor well pressures. This regular inspection of the casing head equipment and annulus pressures will readily indicate any leaks between any of the casing strings. In addition to wellhead pressures, gas, oil, and water production rates should be regularly monitored. This data is can be analyzed by engineers and help identify any anomalous behavior or problems.

API RP 90 covers the monitoring, diagnostic testing, and the establishment of a maximum allowable wellhead operating pressure (MAWOP) guidelines. API RP 90 is intended for use as a guide for managing annular casing pressure in offshore wells, but the dry tree recommendations are applicable for onshore wells that exhibit annular casing pressure, including thermal casing pressure, sustained casing pressure (SCP) and operator-imposed pressure.

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Sales Tax – All U.S. purchases must include applicable state and local sales tax. Customers claiming tax-exempt status must provide IHS with a copy of their exemption certificate.

Shipping (U.S. Orders) – Orders shipped within the U.S. are sent via traceable means. Most orders are shipped the same day. Subscription updates are sent by First-Class Mail. Other options, including next-day service, air service, and fax transmission are available at additional cost. Call 1-800-854-7179 for more information.

Shipping (International Orders) – Standard international shipping is by air express courier service. Subscription updates are sent by World Mail. Normal delivery is 3-4 days from shipping date.

Rush Shipping Fee – Next Day Delivery orders charge is $20 in addition to the carrier charges. Next Day Delivery orders must be placed by 2:00 p.m. MST to ensure overnight delivery.

Returns – All returns must be pre-approved by calling the IHS Customer Service Department at 1-800-624-3974 for information and assistance. There may be a 15% restocking fee. Special order items, electronic documents, and age-dated materials are non-returnable.

THERE'S MORE WHERE THIS CAME FROM.

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