Paper #2-25

PLUGGING AND ABANDONMENT OF OIL AND GAS WELLS

Prepared by the Technology Subgroup
of the
Operations & Environment Task Group

On September 15, 2011, The National Petroleum Council (NPC) in approving its report, *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic and White Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic and White Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 57 such working documents used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix C of the final NPC report provides a complete list of the 57 Topic and White Papers and an abstract for each. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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* Individual has since retired but was employed by the specified company while participating in the study.

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EXECUTIVE SUMMARY

Modern regulatory standards in all US jurisdictions require specific provisions for plugging and documenting oil and natural gas wells before they are abandoned. Plugging and abandonment (P&A) regulations vary to some degree among states but all state regulations prescribe the depth intervals which must be cemented as well as the materials that are allowable in plugging practices

The basic technologies associated with the plugging and abandoning of wells has not changed significantly since the 1970s. Water-based slurries of cement and drilling mud are still the basic materials used to plug most wells although progress has been made in use of additives to customize the cements and muds for specific types of wells.

Recent shale-gas developments have rediscovered some P&A issues in the forms of older oil or gas wells which never were adequately plugged but which now pose possible cross-contamination or leakage risks. Furthermore, eventual retirement of uneconomical shale-gas wells must address P&A practices that are specific to issues affecting gas wells and especially horizontal gas wells.

The lack of progress in P&A practices is attributable to absence of a long-term vision, and inattention to corresponding research, that recognizes the benefits of P&A to oil and gas development projects. Specific findings are that:

- Benefits from reduced operational costs and/or increased production, especially in redeveloped, older fields, generally has been underappreciated.
- By plugging wells correctly, future environmental issues, related to fluid or gas leakage, can be avoided and thereby preserve savings otherwise eroded by remediation or litigation costs.
- Research has lagged on materials and methods for plugging wells although advances in technologies for drilling and completion should be applicable to practices in plugging and abandonment.

INTRODUCTION

The plugging and abandoning (P&A) of oil and gas wells that are no longer economically viable for production, or which have wellbore issues that require closure, has historically been conducted as an afterthought in the oil and gas production business. Production wells that can no longer be used must be plugged to prevent the oil and gas reservoir fluids from migrating uphole over time and possibly contaminating other formations and or fresh water aquifers. A well is plugged by setting mechanical or cement plugs in the wellbore at specific intervals to prevent fluid flow. The plugging process usually requires a workover rig and cement pumped into the wellbore. The plugging process can take two days to a week, depending on the number of plugs to be set in the well. The P&A work takes capital to complete and provides no return on the investment for the oil companies. Most wells are plugged at the lowest cost possible following the minimum requirements set forth by the oil and gas regulating agencies.

As older oil and gas fields are re-entered to exploit bypassed reserves or to develop reserves deemed uneconomical in the past, the plugged and abandoned wells within the fields become a potential problem as new technologies are applied to old fields. In many of the older fields previously abandoned, many of the wells were potentially left unplugged and their locations not properly documented (Pennsylvania DEP, 2000). As these old fields are reentered to apply newer technologies such as solvent or CO_2 flooding, the reservoir pressure is increased due to the injection of fluids for oil recovery. When this higher pressure is applied to unplugged or poorly plugged wells, there is a chance that the formation fluids will bypass the plugging materials and migrate uphole. This can cause problems with the fresh water aquifers in the area by allowing gas, oil or salt water to contaminate the fresh water.

This paper presents an overview of the methods and materials used to plug and abandon wells along with a discussion on the environmental and economic benefits of proper well plugging. The discussion includes a synopsis of P&A research and the issues that impede the progress of the research.

HISTORY OF WELL-PLUGGING PRACTICES AND REGULATIONS

When oil and gas drilling began in Pennsylvania in 1859, there was no regulation regarding the treatment of a well at the end of its useful life (Pennsylvania DEP, 2000). Those early wells could simply be abandoned as gaping holes in the ground. In the 1890s, when Pennsylvania started regulating that wells should be plugged, the requirements were designed to protect the production zones from flooding by fresh water (Pennsylvania DEP, 2000). Much of the regulation of the oil and gas industry in the early days was driven by the need to protect the oil and gas resources and not the environment. The promulgation of plugging and abandonment regulations trailed behind advancements in drilling and production practices because the adverse environmental and safety implications of improperly abandoned wells had not yet been revealed. As more and more dry holes were abandoned, other states began recognizing the need to institute a set of standards associated with plugging oil and gas wells.

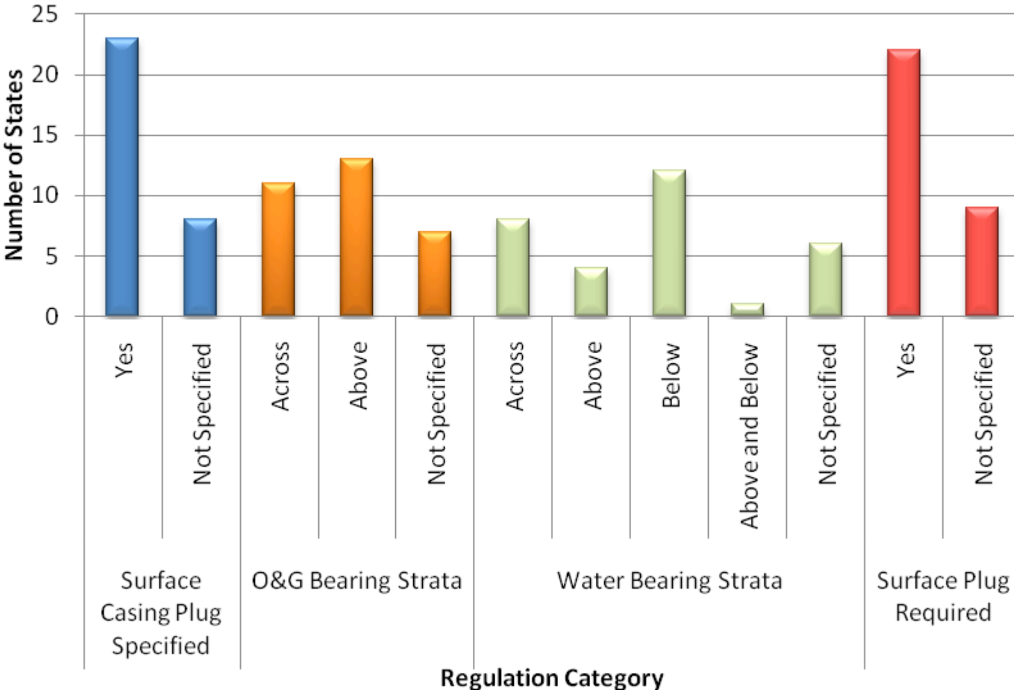
For instance, in Texas, the first well was drilled in 1893 although it was not until 1919 that the Texas Railroad Commission (RRC) gained authority to regulate well plugging (Texas RRC, 2000). By that time, thousands of wells had been drilled with little to no information recorded on the location or construction of the wells. In 1919, Article 3 of the RRC regulations laid out general requirements by stating that "dry or abandoned wells be plugged in such a way as to confine oil, gas, and water in the strata in which they are found and prevent them from escaping into other strata" (Texas RRC, 2000). Like most regulations at the time, the rules were designed to protect the loss of oil and gas to other strata, not to protect the environment. As the oil and gas industry progressed, the RRC continued to update their plugging regulations by issuing specific cementing instructions in 1934 and then requiring the plugging of fresh water strata in 1957 (Texas RRC, 2000).

Plugging regulations in many other states progressed similarly, and as a consequence, thousands of wells prior to the 1950s either were not plugged at all or plugged with very little cement in them. Additionally, when cement was required, the regulations was so vague that wells were plugged with brush, wood, rocks, paper and linen sacks, or a variety of other handy items that would serve to hold a sack of cement (Ide et al., 2006). As states began to regulate the oil and gas wells more closely starting in the 1950s, cement became a required material for sealing the producing intervals and the top of the wellbore. Over time, plugging regulations have progressed to describe the specific intervals at which cement should be placed and the types of materials allowed between the cement plugs (Texas RRC, 2000; Ide et al., 2006).

The regulations for the oil industry started changing significantly in the 1970s when environmental protection became a bigger driver in the regulation of the oil and gas industry. Congress passed the Safe Drinking Water Act (SDWA) in 1974 which increased the requirements for fresh water protection. As a result, many state regulations were updated to include stricter requirements for protection of the fresh water zones and for minimizing the flow of fluids between formations (GWPC, 2009). Currently, state regulations specify the intervals to be cemented, such as above or through producing and water-bearing zones, inside and outside of casing below fresh water aquifers, and at specified distances from the surface. Figure 1 provides a comparison of the plugging requirements in different states with focus on key elements of plugging the oil and gas strata, plugging the fresh water zone, and surface casing plugging.

As an example of how individual state regulations have evolved into specific details, California's plugging regulations require cement plugs to be placed at the following locations: a 200-foot plug straddling the surface casing shoe, a plug across oil and gas bearing strata that extends 100 feet above the strata, a plug extending from 50 feet below to 50 feet above the base of water-bearing strata, and a 50-foot plug at the surface of the wellbore (State of California, 2007).

Figure 1. Elements of State Well-Plugging Regulations



Source: Ground Water Protection Council

Additionally, most State regulations typically permit the placement of the following materials within the wellbore: cement, drilling mud, gels, mechanical plugs, and other non-porous materials such as clays. In recognition of its strength and low permeability, cement typically is used to create a seal between formations or to seal off the surface of the wellbore. Other materials which do not offer the same strength or durability as cement, including drilling mud, gel, and clay, are used to fill in the spaces between cement plugs. Additionally, many states allow the use of mechanical bridge plugs in lieu of a large cement plug since the bridge plug is extremely strong and nearly completely impermeable. However, mechanical plugs are susceptible to corrosion, and therefore the regulations typically require the bridge plugs to be capped by a specified amount of cement.

WELL-PLUGGING METHODS AND MATERIALS

A. General Methods

Figure 2. Typical Bulk Cement Truck

Source: Photo courtesy of Halliburton.

The plugging methods employed on oil and gas wells have improved over time as regulators required better well plugging plans and as operators began to see the benefits of sealing the abandoned wells more securely. When cement was first being used to plug wells, the cement tended to not set up correctly and was often contaminated by the drilling mud and wellbore fluids. Through the implementation of cementing standards by the American Petroleum Institute (API) and more standardized plugging programs, the cement plugs became more uniform (Ide et al., 2006).

When wells were plugged in the late 1800s and early 1900s, cement was often emplaced in the well by pouring the cement from the surface. The wells were shallow and this method was somewhat effective. As the wells became deeper, cement was pumped down tubing to place the cement at the desired depth. To be able to pump cement down hole, oilfield cement companies developed specialized equipment that could transport the dry cement to a well site and then blend the cement mix while pumping it down the hole. Figure 2 shows a bulk cement truck that brings the dry cement blend to a well site for pumping. The dry cement is pumped into a cement pumping truck which adds the water at the desired blending rate and then pumps the liquid cement down the well.

As operators started pumping cement downhole for cementing operations, they initially did not understand the need for hole cleaning prior to cementing. Therefore, many of the early plugs did not harden as desired. After the passage of the SDWA a new technique for placing cement in the well was researched and improved, now being known as the displacement method or the balance plug method (Ide et al., 2006). The displacement method minimizes the contamination of the cement by use of a cement that has good hole-cleaning characteristics and can displace leftover drilling mud. First, tubing is run into the well to the depth desired for the bottom of the cement plug where the cement is then placed into the well by pumping down the tubing. The cement goes out the bottom of the tubing and then flows back up the outside of the tubing. Second, after the desired amount of cement is pumped, water is pumped behind the cement to displace the cement in the tubing to a predetermined depth. At that point the tubing is pulled out of the well and when done correctly, the cement in the tubing fills the space the tubing occupied in the well which leaves a good solid section of clean cement. When using the displacement method, operators can fairly accurately place the cement in the well at the desired depth and thereby prevent flow in the wellbore from the targeted depth intervals.

The types of materials used for plugging abandoned wells have not changed significantly over the last 100 years. While cement is the most common plugging material used to seal the abandoned wells, drilling mud, bentonite and mechanical plugs also are used frequently in conjunction with cement. In wells plugged prior to the more modern regulations and standards set in the 1950s and onward, many wells were abandoned with plugs consisting of brush, wood, paper sacks, linen or any other material that could be pushed into a well to form a basis for the dumping of one or two sacks of cement to "plug" the well (Ide et al., 2006). While that use of sundry materials was fairly common in the early days of the oil field, current procedures are significantly more disciplined and have higher success ratios of providing seals adequate to prevent future contamination issues.

B. Cement

A basic and widely used plugging material is formulated as a slurry of water and Portland cement that is compositionally managed in terms of gallons (gal) of water or pounds (lb) of additives per 94-lb sack (sk) of cement. Cement used in plugging of oil and gas wells has improved significantly over the past few decades. The cement composition in the early days of the oil industry is similar to what is used today, but today's cement uses a number of additives that enhance the sealing of the cement in the wellbore (Ide et al., 2006). With the advances in well drilling technology and the types of wells being drilled and completed, the cementing technology has improved to allow for cementing of horizontal wells, high-pressure wells, high-temperature wells, low-temperature wells, CO_2 wells, and other specialty applications. Those same cement technologies can be used in the plugging of abandoned wells.

The American Petroleum Institute (API) first developed a classification system for oilfield cements in 1952. The API cements are all Portland cement-based with similar ingredients but are mixed in different proportions. The different classifications are ground to a different fineness and have different water requirements for mixing (Petrochem, 2002). Table 1 summarizes the different API classifications of cement.

When using the API cement for cementing a well or for plugging, various additives are blended into the cement for specific purposes. Each cementing company uses additives and blends cement based on the customer's specific cementing plan. Most companies have proprietary additives for specific applications along with the standard additives such as barite and bentonite. Some of the additives commonly used are:

- Retarder. A retarder is added to slow down the setting time to allow for longer pump times and/or the removal of the tubing used to place the cement.
- Accelerator. Accelerators are used to shorten the setting time. These are used in wells to allow the cement to set up faster to prevent gas or fluid channeling, to prevent backflow in the tubing and when plugging the additive can shorten the wait time between plugs.
- Pozmix. Pozmix™ (a Halliburton Co. product), which includes pozzaline (a mixture of lime and volcanic ash), is added to Portland cement to achieve a more durable calcium

silicate cement mixture. The use of pozzaline also reduces the amount of Portland cement in the mixture which reduces the overall cost of the cement.

- Lost Circulation Material. Selected materials are added to cement to reduce the loss of cement to the formation prior to hardening. Materials such as walnut shells, cottonseed hulls, fibers, flaked cellophane (including Flocele™, a Halliburton Co. product), diesel oil, and other proprietary mixtures are used to reduce the loss of circulation.
- Density-Increasing or Weighting Additives. Materials are added to the cement to increase its weight to combat higher formation pressures. Materials such as barite, sand, and other proprietary mixtures are used as weighting materials.
- Light-Weight Additives. These materials are added to cement to reduce the cement density and thereby lessen the chances of losing cement to high-permeability or low-fracture-gradient formations. Materials such as Pozmix™, gel, foam, and other proprietary mixtures are used to "lighten" cement mixtures.
- Water-Loss Additives. Water-loss additives are combined with the cement mixture to reduce the rate of water loss from the cement mixture. By reducing water loss prior to setting, the cement can harden properly and avoid premature drying which can reduce the strength of the cement (Halliburton, 1981).

Table 1. API Cement Classifications

API Classification	Depths (Ft)	Water Requirement (gal / sk)	Slurry Density (lb / gal)	Description
Class A	0 to 6,000	5.2	15.6	Common or regular cement
Class B	0 to 6,000	5.2	15.6	Moderate to high sulfate resistance.
Class C	0 to 6,000	6.3	14.8	High-Early Cement. Fine grind, good availability
Class D	6,000 to 10,000	4.3	Varies	For Moderate Temperature and Pressure. Coarse grind plus retarder
Class E	10,000 to 14,000	4.3	Varies	High pressure, high temperature. All depths with retarders
Class F	10,000 to 16,000	4.3	Varies	Use for extremely high temperature and pressure
Class G & H	0 to 8,000	G -5.0 H – 4.3	G - 15.8 H – 16.4	Basic cement. Used at all depths with retarders.

Source: Halliburton Company, *Halliburton Cementing Tables, Technical Data Oil Well Cements and Cement Additives* (Duncan, OK: Halliburton, 1981).

Specialty Cements. While most wells can be cemented with standard cements, there are situations that can require a special cement blend to create the best seal in the well. Some of the well types that require a specialized blend of cement include moderate to high-pressure gas wells, horizontal wells, wells completed through salt zones, high temperature wells, and wells that are very deep (below 15,000 ft.) (Salehi and Paiaman, 2009). Plugging such wells with conventional systems can be done in many instances but there is a risk of channeling or mud contamination from gas or fluids that can create a pathway for fluids to migrate out of the zones being plugged. The following paragraphs discuss the types of wells and situations that require specially cement blends.

- Moderate to high pressure gas wells. Cementing of natural gas wells to prevent the flow of gas outside the casing has plagued the oil and gas industry for years. As the demand for gas increases, this issue becomes larger as more wells are drilled and the gas migration causes casing pressure problems and gas leaking into other formations and the fresh water. The cements used for these wells require that the cement be designed to reduce the gas migration while the cement is curing. Many cementing companies have developed additives that can reduce the gas cutting through the cement.
- Horizontal wells. The horizontal orientations introduce different gravitational effects compared with vertical wells. In a typical vertical well, where there is a large column of cement, some migration of the solids downward or the water upward does not cause a significant change in the cement properties. In a horizontal well, the solids migrating to the bottom of the section and the water migrating to the top can provide areas of the well that do not have a complete seal. If the water in the cement separates from the mixture before the cement is set, it can migrate to the top of the wellbore and form a channel along the top of the wellbore which can allow migration of formation fluids. If the solids in the cement mixture settle to the bottom of the cement before the cement can harden, the solids can cause the cement to not set up correctly and the weakened area along the bottom of the wellbore can fail under pressure during stimulation activities (Salehi and Paiaman, 2009).
- Salt zones. Salt mixed into cement functions as an accelerator of solidification. If a well is drilled through a natural salt zone and the cement mixture is not adjusted for the salt, the cement can set up prematurely. When cementing wells that have been drilled through a salt layer, special precautions must be taken to prevent contamination of the cement by the salt. Special additives must be used to prevent the premature setting of the cement caused by salt entering the cement mixture as the mixture it is pumped past the natural salt layer.
- Deep wells. Cementing of deep wells requires long pump times to get cement pumped to the bottom of the well and displaced upward. With long pump times there is a chance that the cement could harden prematurely and cause pumping problems. Special cement retarders are used to allow for adequate pumping time to place the cement where desired. In addition, with the long stands of pipe to pump through, friction becomes an issue and friction reducers may be required to make pumping the cement easier.

C. Bentonite and Drilling Mud

In many of the wells currently being plugged, drilling mud and bentonite are still being used to fill those portions of the well that are not cemented. Bentonite, which is a natural material rich in swelling clays, is used commonly to form the base of most drilling muds. Bentonite powder is mixed with water to form a fluid that has the ability to lift cuttings from a well and suspend them at times when the mud pumps are shut down. Drilling mud has historically been used to plug most wells in the United States. A review of historical well records will show that most wells were filled with heavy mud, or drilling mud at the time of plugging. In California, records from wells in Los Angeles County that were drilled and plugged in the 1930s through the 1950s in many cases had a small cement plug at the top of the production zone and then were filled with mud that ranged from 9.1 pounds per gallon (ppg) to over 12 ppg depending on the depth (State of California, 2004).

The use of drilling mud for well plugging relies on the characteristics of mud weight and gel strength to prevent upward flow of reservoir fluids. For upward flow of fluids to occur, the formation fluids must overcome the downward pressure exerted by the weight and gel strength of the mud column in the wellbore. The gel strength of mud is the resistance to shear that develops when the mud is not moving. When mud is being pumped (moving) it has gel strength of less than one pound per one-hundred square feet (1 lb/100 sq. ft) but once the mud stops moving the gel strength increases by up to 100%. A study of the pressure effects of the static mud column in abandoned wells, found that over time the gel effect is reduced slightly due to the mud drying out, but that the gel strength should still be calculated at around 25 lb/100 sq. ft (Johnston and Knape, 1986). Gel strength increases the pressure required to start fluid moving uphole in a mud-filled well.

Bentonite plugging of wells is still used in some areas. In the Bakersfield and Coalinga Districts of California bentonite is approved as an alternative to cement to plug wells. The bentonite must be in a compressed form and can only be used in wells that are larger in diameter than 2-7/8 inches. The bentonite must be hydrated for 24 hours and, if the plug is to go across the fresh water zone, the surface casing must be cemented through the fresh water interval. The rules state that bentonite may not be used when there is a 500 pounds per square inch (psi) pressure differential between zones of a wellbore (State of California, 2004).

Bentonite, when placed as a compressed solid and then hydrated, will form a dense and low-permeability solid mass in the wellbore based on its character as a clay material that swells when water is added. Bentonite clay is often used in surface applications where low-permeability clay is needed to prevent migration of liquids such as the liner for a landfill or pond.

D. Mechanical Plugs

Mechanical plugs are used in some wells to reduce the amount of cement required to plug a well or to provide additional protection from formation pressure in the well. Two types of mechanical plugs utilized to plug and abandon wells are a bridge plug or a cement retainer. The choice of which plug type to use is based on whether cement needs to be pumped below the plug to seal the perforations (squeeze cementing). If cementing below the plug is not required, or if a balanced cement plug was installed below the mechanical plug setting depth, a bridge plug can be used. Mechanical plugs can be set in the well using workstring tubing, coiled tubing, or with a wireline. When working in wells with pressure, the use of tubing and or coiled tubing is typically required.

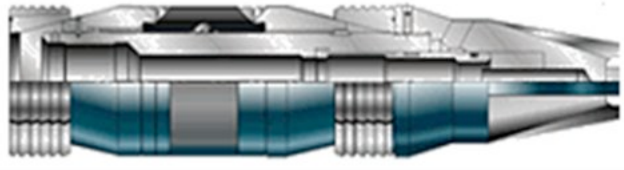
The mechanical plugs consist of four major parts: 1) the body of the plug which can be made of steel, cast iron and composite material; 2) the slips which are metal parts that grab the casing to hold the plug in place; 3) the packing material which is a rubber or nylon ring that is squeezed outward when the plug is set in the well; and 4) the on/off tool that allows the plug to be set and then released to pull the tubing or wireline out of the well after setting (Baker Hughes, 2011). Setting the tool downhole is accomplished in a number of ways depending on the specific manufacturer's design. Typically the tool is lowered to the desired location and then rotated to release the slips that will grab the casing to hold the plug. Then the plug is raised or lowered (depending on the specific application) to expand the sealing element against the casing. Once the desired tension on the tool is applied, either the tool is set and can be released, or, if required, it is rotated to release a secondary set of slips that will keep the tool expanded and set prior to release. In the case of a wireline set tool, some versions use explosives or hydraulic systems to set the slips and packing element prior to release.

Figure 3. Cast Iron Bridge Plug

Source: Photo Courtesy of Baker Hughes.

- <u>Bridge Plugs</u>. Bridge plugs are a mechanical plug that is used to provide a solid seal within a wellbore for plugging. Some bridge plugs are designed to be easily drillable in case the well is desired to be reentered at a later date. Bridge plugs are typically made of cast iron with duel slips with a sealing element between the slips. The plug is designed to be set in a wellbore and then have cement set on top to provide a complete seal of the reservoir below. In cases where there is a potential for moderate or high pressure gas to be flowing from the area below the setting depth, a bridge plug can be set to seal the wellbore prior to cementing to reduce the chances of the pressurized water or gas to contaminate the cement. Figure 3 shows a typical cast iron bridge plug used to plug and abandon wells.
- <u>Cement Retainer</u>. A cement retainer is a mechanical plug that can be set above a zone to be cemented. This type of plug is especially useful when plugging higher pressured zones that need to be squeeze-cemented prior to plugging. Cement retainers are usually built from drillable material so will yield to later re-entry of the reservoir as needed. The cement retainer is set in the well in a method similar to that used for a bridge plug. Once the tool is set in the well, cement can be pumped through the plug to squeeze cement through the perforations or open-hole area below the retainer. Pressure can be applied to

Figure 4. Cement Retainer



Source: Diagram Courtesy of International Completion Solutions, LLC.

the area below the retainer without a concern for cement traveling uphole past the cement retainer. The application of pressure to squeeze the cement through the perforations provides a good method of sealing the well at plugging. Once the desired amount of cement is squeezed below the retainer, the tubing is pulled upward out of the retainer and a mechanical flap closes the hole to effectively seal the cement below the cement retainer. Cement is then typically placed on top of the cement retainer to provide a more complete seal of the reservoir. Figure 4 shows a typical cement retainer.

RESEARCH ON ALTERNATIVE METHODS AND MATERIALS

The technology associated with the P&A of wells has not changed significantly for more than 100 years. Cement and drilling mud is still the basic material used to plug many of the wells plugged by operators. While the plugging of wells has become more reliable over time due to advances in cementing materials and volumes placed in a well, the overall methods for plugging remain similar as to what was used during the early oilfield days.

The use of cement as a plugging material was the first major change in the plugging of wells, followed by the requirement to place cement below and across the fresh water zones (Pennsylvania DEP, 2000; Texas RRC, 2000). As regulations became more stringent, operators were required to place cement plugs above the productive zones and below the fresh water zones. Some areas began to allow the use of mechanical plugs to seal of portions of wells, but in most cases cement was required to be placed on top of the mechanical plug if it was for permanent abandonment (GWPC, 2009).

Most research into cements and tools for use in oil and gas wells historically has been associated with the completion of the wells and not the plugging of the wells (Bruffatto et al., 2003). As such, little actual research has been done on the materials and procedures for plugging oil and gas wells.

A research project conducted in 2000-2001 looked into the use of fly ash as a cementing material to plug wells in Oklahoma. The two-phase project gathered fly ash samples from five coal-fired power plants in Oklahoma and tested each of them to determine if they could be used as a plugging material for shallow wells (Shah and Sublette, 2004). First, each sample was tested in a laboratory to determine the optimum grout formulation for plugging wells. Pumpability tests were also conducted to verify that the grout formulations could be pumped through coiled tubing and straight pipe. The results for Phase 1 showed that an optimum fly ash grout formulation could be found and that it had a compressive strength of over 500 psi which meets the minimum strength criteria for P&A. The pumpability test showed that the cement / fly-ash grout can be pumped through coiled tubing which allows wells to be plugged without a conventional rig on the site (Shah and Sublette, 2004).

Phase 2 of the study involved testing the fly ash grout in a test well situation to determine the bond strength and gas permeability. This testing showed that the fly ash grout had low permeability and adhesion properties and that the grout provided a good seal to the casing , meaning that the fly-ash grout should be effective in preventing fluids or gas from migrating upward. Ultimately, the testing showed that the fly ash grout performed similarly to Class H cement and could be used to plug wells at depths up to 6,000 feet (Shah and Sublette, 2004).

ENVIRONMENTAL BENEFITS OF WELL PLUGGING

Unplugged or poorly plugged wells are an environmental hazard as they provide potential conduits for fluids to migrate between formations and potentially into the fresh water zones. Poorly plugged wells also might provide pathways for natural gas to seep to the surface and potentially cause fire or be a health hazards. An abandoned well's potential for causing a potential hazard is largely dependent on the original use of the well. Oil wells that have been pumped for years will typically be very low pressure and the risk of contamination is low while a gas well that is flowing at a rate that is non-economical can still posses enough pressure to be a risk to the environment.

As oil prices rise to high levels, many abandoned oil fields are re-entered with new technologies meant to produce oil that was not economical to produce in years past. With the new activity in the oilfield, any idle or unplugged wells not targeted for re-development must be plugged to prevent the escape of gas and oil from the reservoir. In areas where CO_2 is being injected as a tertiary recovery project, well plugging becomes an issue due to the high pressure of the CO_2 flood in the reservoir. Old wells that are not being used to inject or produce the oil must be plugged in a manner that also protects the fresh water from the high formation pressures. The ability of these plugs to seal the well from the migration of CO_2 gas will protect the fresh water sources from potentially becoming contaminated with CO_2 or the produced fluids (Ide et al., 2006). As old fields are revitalized, failure of older plugging jobs will be an issue due to the increased pressure created during re-development of the reservoir (Ide, Friedmann, and Herzog, 2006). The risks presented by older P&A wells must be quantified by operators and the wells properly monitored to reduce any impacts to the environment.

In areas where shale-gas reservoirs are being newly developed, plugging of older wells has become an issue due to the potential for stray gas to migrate from the shale formation to other formations that are open to the old wells in the area. The old wells can transmit gas from the formation to the fresh water or even the surface, thereby posing an environmental risk to the local area. Older wells are a risk if they are poorly plugged or not plugged across the shale production zone. Even if the older well has casing, the casing might not be adequately cemented across the shale production zones.

Even the newly developed shale-gas wells eventually will become uneconomical and must be plugged. The P&A of those wells must be designed to minimize the future risk of gas migration that might pose environmental hazards.

The proper plugging of wells provides a great environmental benefit by protecting the environment from potential contamination from oil and gas. Properly plugged wells prevent the movement of fluids between formations which reduces the chance of oil or gas getting into a formation that may be connected through an old, unplugged well nearby. Properly plugged wells also prevent contamination of the drinking water aquifers. In areas where groundwater use is important, protecting those water sources from oil and gas wells must include well-planned and implemented P&A programs for oil and gas wells.

ECONOMIC BENEFITS OF ADVANCES IN WELL-PLUGGING TECHNOLOGY

Well plugging is often seen by some operators as a cost that provides little benefit to the company bottom line. While in some instances that may be true, properly plugged wells can save the operators substantially through avoidance of lost production from fields that are candidates for high-technology recovery projects (NETL, 2010). Properly plugged wells can prevent cross-contamination from other zones in a production field. Proper well plugs can also prevent the loss of pressure in pressure maintenance water floods and CO_2 floods. Both of those merits can result in higher oil and or gas production from the targeted reservoir.

Technological changes have been made in the areas of cementing and downhole equipment for oil and gas well construction and production operations and at least some of those advancements should be beneficial to P&A practices. With the development of deep high-pressure gas projects and shale gas projects, the advances in well cementing technology, along with new mechanical systems, can potentially be applied to plugging of gas wells. By advancing the technology of plugging wells, the overall cost of plugging can decrease. In addition, the newer plugging materials and methods can reduce the plugging failures along with the problems associated with leaking well plugs.

For CO_2 flood projects, the application of cement that can prevent the loss of CO_2 and gas pressure could potentially increase the ultimate recovery of oil while reducing the overall cost of the CO_2 project (NETL, 2010). Operators would spend less over the life of the project in CO_2 purchases as well as less spent on remedial projects dealing with leaking wells.

With the current development of numerous shale-gas basins in the US, the eventual plugging of all of those new gas wells is a concern. Most of those shale-gas wells are horizontal completions, which can pose an issue for plugging operations due to gas channeling and solids settling. If those wells are not plugged correctly, gas channeling can occur and the well could become a potential liability from gas leaking into the upper fresh water zones. Improved P&A practices in the shale-gas basin developments should allow more economical and sustainable development of US gas production. It can also increase the density of the development as wells can be installed closer together if the abandoned wells are properly plugged to withstand the potential impact of fracturing treatments nearby.

BARRIERS TO PROGRESS

Some of the barriers to advancing the science of plugging and abandoning wells can be attributed to the lack of research and the lack of a clear vision of the role that plugging and abandonment can play in the production cycle of the oil field.

- Lack of Research. The science of well P&A has not been the focus of research in the oilfield. Most relevant research is focused toward maximizing the production of oil and gas or reducing the cost of finding and producing the oil and gas. P&A has typically been seen as a waste of capital dollars and has only been done when required; then, the work is done as cheaply as possible. Most operators have historically not see the benefit of properly closing wells. As a result, there are many wells in the oil field that are poorly plugged or have been left in an unplugged status for years. As operators have been reentering old oil fields to apply new production technologies, these poorly abandoned wells have become a liability. To continue the application of the newer production technologies in the fields, these old wells are being reentered and replugged. As these wells are being plugged, the newer, higher-tech plugging processes are not being used; instead, the wells are being plugged using traditional methods. If operators had newer methods and materials that would make the plugs stronger, less prone to contamination, and less expensive to install, the new production technologies would be more cost-effective and would reduce potential environmental issues.
- Lack of Long-term Vision. The long-term vision of P&A's importance to the oil production program is not readily seen in the oil and gas production arena. The traditional view of P&A is that it is a necessary evil and should be done as cheaply as possible. As a result, many wells are poorly plugged and over time these poor plugging jobs may result in significant environmental problems. This is especially true in the gas well area. Cementing of gas wells is a constant issue due to gas channeling. If operators plan poorly for the cementing of a gas well and try to cut costs by using cheaper materials and methods, those gas wells could potentially become a hazard due to gas leaking through the plugs. Implementation of new regulations, training, or an industry outreach program to bring the issue to the forefront could reduce the potential problems in the future.

FINDINGS

The plugging and abandonment of oil and gas wells has not changed significantly over the past 100 years. There has been improvement in the quality of the materials and changes to the methods used to plug wells, but there has not been a specific change that has elevated the technology of plugging wells.

Most wells are still plugged with cement using methods and materials developed in the 1970s. Cement additives have improved, but gas channeling and contaminated cement jobs are still operational issues.

Plugging wells is still regarded by some operators as a requirement with little or no corresponding benefit. Benefits from reduced operational costs and/or increased production, especially in redeveloped, older fields, generally has been underappreciated. Accordingly, the true benefits of quality plugging jobs has not been realized in most areas.

By plugging wells correctly, future environmental issues, related to fluid or gas leakage, can be avoided and thereby preserve savings otherwise eroded by remediation or litigation costs.

Research has lagged on materials and methods for plugging wells although advances in technologies for drilling and completion, taken in proper context, should be applicable to practices in plugging and abandonment.

By doing research and educating operators to the benefits of proper well plugging, the science of well plugging will be advanced and the environment will benefit from better protection.

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