PLUGGING WELLS FOR ABANDONMENT

A STATE-OF-THE-ART STUDY AND RECOMMENDED PROCEDURES

BY

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This informal document contains information which is preliminary and may be fragmentary or of limited scope. The assumptions, views, and conclusions expressed in this document are those of the author and are not to be interpreted as those of Union Carbide Corporation, Nuclear Division, or SERDA.

PREPARED FOR UNION CARBIDE CORP.,
NUCLEAR DIV., OFFICE OF WASTE ISOLATION
OAK RIDGE, TENN.

SEPTEMBER 1976

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for

Union Carbide Corporation
Nuclear Division
Office of Waste Isolation
Oak Ridge, Tennessee

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September 1976

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PLUGGING WELLS FOR ABANDONMENT

1. INTRODUCTION

Cementing of the casing in oil wells to preclude entry of water from behind the casing was begun in a crude way about 1903¹. In 1910, Al Perkins cemented his first well for an independent operator in California, using plugs to trace the placement of the cement. In the early 1920's, the use of cementing in the California drilling boom brought about expansion into the Rocky Mountain Area. Another company was founded by Erle P. Halliburton in 1924 for cementing operations in the Mid-Continent Area. The practice of cementing the casing in the well continued to grow as its value for controlling formation fluids was proven in the flourishing petroleum industry.

Meanwhile, the holes that turned out to be dry, or the wells where oil was depleted, were abandoned without too much thought being given to plugging the hole. In many cases during the early years of oil production, wood or tree limbs were thrown or driven into the hole and considered a plug². States did not have laws requiring plugging of the wells, nor regulatory agencies who were concerned with this aspect of their natural resources. During the latter part of the 1930's, states began establishing laws and oil and gas agencies to give direction to better plugging of wells as they were abandoned.

Today, many of the problems faced by the regulatory bodies center around old holes abandoned 40 to 50 years ago. Problems with these wells have arisen in such areas as Eastern Oklahoma. When waterfloods and repressuring operations were initiated, wells outside the working area were caused to "break out" and necessitate remedial operations.

As concern grows about pollution and the protection of fresh water aquifers, more emphasis is being placed on proper plugging of wells. The magnitude of this problem can be realized when it is found that in the State of Texas, the number of wells plugged has been increasing recently at the rate of approximately 1,000 per year. In California, approximately one well is abandoned for each two new wells drilled.

Although the main thrust of this study will be concerned with plugging boreholes for abandonment, there are other reasons for placing plugs in open hole which will be discussed briefly in the state-of-the-art section.

The state-of-the-art for borehole plugging will be discussed, including tools and materials used. Procedures will be recommended for plugging boreholes in possible repository sites to obtain long life or service from the plug. Included in the procedure is a discussion of locating the wells and preparing them for plugging, as well as the materials required.

The minimum state requirements will be summarized for major oil producing states and states where radioactive waste might be stored at later dates.

¹ References will be found in the Appendix.

2. STATE-OF-THE-ART FOR BOREHOLE PLUGGING

A. Purposes for Wellbore Plugs

Cement plugs are placed in open wellbores for at least four reasons³. These are:

1. To provide a solid bottom to sidetrack the the drilled hole for bypassing unrecoverable junk or straightening a crooked hole.
2. To seal open hole below a casing seat.
3. To correct a lost circulation problem.
4. To abandon a dry hole or a depleted well.

During the drilling of a well, problems can be encountered which make it desirable to sidetrack the drilling. This can be due to loss of junk in the hole, such as tools or pipe, which cannot be recovered by fishing methods; or it can occur because of hole deviation from the required pattern. In any event, it is necessary that the plug be harder to drill than the formation in which it is set. Adequate time must be allowed for the cement plug to set and gain sufficient compressive strength before redrilling is begun. Figure 1 shows a schematic of this type of plug. Figure 2 shows a drawing of a plug set in open hole below a desired casing seat. This plug is placed in order to protect a producing formation from possible hydraulic fractures below the casing. This type plug is also used when it is desired to set casing considerably above the bottom of the hole due to water inflow or other problems encountered in the drilling operation.

Figure 1. Plug for sidetracking to drill new hole.

Figure 2. Plug to seal below casing seat.

Figure 3 shows how a cement plug is placed to be drawn into a lost circulation zone before set occurs. Each of these three types of plugs requires careful planning to select proper materials and techniques to perform the job satisfactorily. However, the type of plugging which is of primary interest in this study is the plugging of wells to be abandoned.

Figure 3. Setting plug to prevent lost circulation.

The purpose for plugging an abandoned well is two-fold. The plugs are designed to (1) prevent drainage of fresh water aquifers down the hole to lower aquifers, and (2) to prevent contamination of fresh water aquifers by brines, oil or gas from high-pressure aquifers moving upward.

B. Conditions Encountered in Plugging for Abandonment

There are a number of conditions which can be encountered when plugging a well to abandon. The well can be a dry hole or a depleted producing well, so it could have open hole or casing below the surface pipe. The various conditions which may be found are shown in the following drawings. Figure 4 shows a condition where a borehole is to be plugged and abandoned as a dry hole. The surface casing is cemented in the hole and the balance of the hole is open. Figure 5 shows a deeper dry hole where an intermediate string of pipe has been set with open hole below. The intermediate string can be partially cemented or fully cemented in the hole. The intermediate pipe is sometimes cut off and as much casing as possible is removed.

Figure 4. Dry, open hole with surface pipe cemented.

Figure 5. Dry hole with surface pipe cemented and intermediate string set.

A depleted producing well is shown in Figure 6. This shows a well where production casing has been cut off and retrieved. When the production string is fully cemented, the casing might be left intact when plugging to abandon.

Figure 7 shows schematically a deep well which has two intermediate strings and one liner. The intermediate strings could be cemented fully or could be just partially cemented. The intermediate strings could be left or removed, so there are several combinations that could be encountered, either in a dry hole or a producing well.

Figure 6. Depleted producing well with production casing cut off.

Figure 7. Deep well with two intermediate strings and liner.

The foregoing discussion applies primarily to dry holes as they are drilled, and producing wells where oil recovery has reached the point of being uneconomical. Older wells exist in many fields which were not plugged properly when abandoned. The conditions encountered in trying to properly plug these wells may vary from boreholes with no pipe, where the walls have sloughed into the hole, to partially cased holes filled with various junk.

C. Oilfield Techniques

The plugs set by oil companies in dry holes or abandoned producing wells generally tend to follow the rules and regulations of each state's oil and gas regulatory body. Some of the larger oil companies follow their own regulations, but these equal or exceed the state regulations. Typically, for a dry hole, this might include a cement plug at the bottom of the hole, extending 50 to 100 feet above a possible producing zone, a plug at the bottom of an intermediate string and the surface pipe, and a plug at ground surface.

For plugging a producing well, a cement plug is normally placed above and below each producing formation and each fresh water strata, in addition to the plugs specified above for a dry hole. These procedures will vary somewhat from one state to another.

There are three plug-back techniques which are used by service companies in plugging wells. These are:

- a. The Balance Method (and cement retainer method)
- b. The Dump Bailer Method
- c. The Two-Plug Method

With any of these methods, it is essential that the mud in the well be circulated at least once prior to placing the plug so that the hole is in excellent static condition with the mud weight equalized top to bottom. Getting a cement plug in place without contamination is the major concern in plugging.

1. The Balance Method - This technique involves running drill pipe or tubing into the casing or open hole and displacing the cement. The cement slurry is pumped down the drill pipe or tubing and back up to a calculated height which would balance the cement inside and outside the pipe. A small imbalance on the tubing side is usually practiced to reduce mud contamination. Then the pipe is pulled slowly out of the top of the cement. When the pipe is well above the top of the cement, the pipe is cleaned by reverse circulation. This technique is shown in Figure 8.

A small diameter pipe or tubing should be used in order to leave a larger annulus area for the cement. This will enable the pipe or tubing to be pulled from the well without causing an excessive drop in the cement, or a surge of the cement plug, thus decreasing the chance of mud contamination.

Figure 8. Placement of cement plug using balance method.

The balance method is simple and requires no special equipment other than a cementing service unit. However, it does require considerable skill by the service operator. When using small volumes of cement, contamination with mud is more likely than with larger volumes. When it is difficult to establish the top of a cement plug, it may be necessary to run an excess of cement. When using this method the fluid in the hole must remain static. Any fluid movement can cause a poor plug.

Moseley states⁴ that there is an alternate to this method which can be used in abandoning a cased hole. This method is the placing of cement using a retainer. The first thing to be done after the tubing is out of the hole, and the casing is fairly clear, is to make up the cement retainer on the tubing, lower it to the bottom of the well and tag bottom (Fig. 9-A). After bottom is tagged with the retainer, cement is pumped down the tubing in a calculated volume to come up to the desired level (Fig. 9-B). It must come up to a level 50 feet to 100 feet above the ultimate setting depth of the retainer. After the cement has reached a level above the retainer, the retainer can be retracted to its desired setting depth and set by manipulation of the tubing (Fig. 9-C). When the retainer is set, the tubing will be isolated from the annulus or the casing. With the retainer set, the tubing can be pressured to force some of the cement into any open perforations that might be in the

Figure 9. The use of a cement retainer plug in cased hole.

plugged interval (Fig. 9-D). A pressure of 1000 psi to 1500 psi is not uncommon in this endeavor. After some of the cement has been forced back into the formation, the tubing is picked up slightly and the valve in the retainer closed. The tubing can now be picked up out of the cement retainer, allowing any cement that might be left in the tubing to fall out (Fig. 9-E). The tubing is then picked up above the cement and reverse circulated to clean it out.

Some of the advantages of this system are: (1) The cement is positively placed below the retainer, so that when the retainer valve is closed it is an effective plug. (2) It allows the cement to be forced into the formation without subjecting the old casing to high pressures. (3) Good control of the cement is maintained. (4) Gas percolation is precluded from the formations up past the retainer, so the cement is allowed to set without any gas diffusion. (5) Immediate pressure testing can be made after the retainer is set.

The use of a cement retainer to place cement under squeeze pressure into a producing formation, either open hole or through perforations, is an excellent method. However, there are some inherent dangers in the technique described. Tagging the bottom might damage the tool and cause malfunction. Running the retainer out of the casing into the the open hole could cause problems retrieving the tool back into the casing. Placing cement above the tool before squeezing allows the cement to be at rest and possibly "set up" around the tubing.

Therefore, it would be preferable to set the packer in the casing above the production zone, perform the cement squeeze and then open the circulating valve in the retainer and let the cement equalize before proceeding to reverse excess cement out above the desired level on top of the retainer.

2. The Dump Bailer Method - This technique is usually employed at shallow depths, but by designing a retarded cement for well conditions (temperature, pressure) it has been used to depths of over 12,000 feet. A cement basket, permanent type bridge plug, or gravel pack is usually placed below the location. The dump bailer, containing a measured quantity of cement, is lowered on a wire line. The bailer dumps the cement above the plug or basket, as shown in Figure 10.

Since this type plug is run on wire line, the depth of the plug can easily be controlled. The cement quantity that can be dumped is small, however, and subsequent runs cannot be made until the slurry previously placed has taken an initial set. Because of this fact, the dump bailer method is being used primarily for plugs other than for abandonment of the well.

There is a wireline tool available which can be run through tubing to set a bridge plug below the tubing and dump cement on the bridge plug. However, this tool is normally used when it is desired to plug and abandon a lower producing zone only and not abandon the entire well.

Figure 10. Setting a plug with a dump bailer.

3. The Two-Plug Method - This method, as shown in Figure 11, involves running top and bottom cementing plugs to isolate the cement from the well and displacement fluids (similar to standard primary cementing practices).

A special tool is placed at or near the bottom of the string, then the pipe is run to the depth desired. This tool, called a plug catcher, is designed to allow the bottom cementing plug to pass through it and out of the tubing or drill pipe. Cement is then pumped out of the string at the plugging depth and fills the annulus. The top plug, following the cement, causes a sharp rise in the surface pressure to indicate its landing in the plug catcher. The latching device holds the top plug to help prevent the cement from backing up into the string, but permits reverse circulation when required. This design permits pulling the string up after cement placement to "cut off" the plug at the desired depth by reverse circulation through the plug catcher, thus allowing excess cement to be reversed up and out of the tubing. The string is then pulled, leaving a cement plug that should last indefinitely and provide good, hard support for any subsequent operation.

This method has more initial cost; however, since it minimizes the possibility of over-displacing the cement and provides a tight, hard cement structure, it often proves to cost less than other methods. It should always be considered for deep wells where the variables for calculating displacement are greater.

Figure 11. The two-plug method for setting a cement plug.

D. Tools and Materials

When placing a cement plug using the balance method or two-plug method, operators use various tools and materials in order to better insure a competent plug.

1. Tools Used in Plugging Operations - It is recommended practice to use centralizers on the lower part of the tubing to keep the string centered to minimize channeling. Rotating or reciprocating wall cleaners are also helpful in reducing channels and in cleaning filter cake off the borehole wall to help provide a better bonding surface for the cement. One oil company keeps a 100-foot section of tubing on their pipe rack with centralizers and wall cleaners attached, which is used only for plugging purposes. Rotating cleaners may also be used during the placement of the cement to keep mud or filter cake particles moving up the hole, and to result in a cement plug which should have more strength, and would not be streaked with mud.

Greenfield and Cain⁵ point out that another device which can be used to aid in proper preparation of the hole is a reamer that can be used to knock off the filter cake before the plug is set. A product now on the market is called the "precementing reamer." It is simply a Hydra-Jet tool run on the drill pipe which is used to jet the wellbore and knock off the filter cake.

However, this tool is available from service companies in certain areas only.

Cement retainers are used by some operators, and plugs are used by some to separate the mud and cement. These tools are discussed in a previous section.

Another approach available to the operator is the use of chemical washes ahead of the cement to clean the wellbore. These washes are primarily in two groups: the thinners and the acids. A very popular thinner is a mud flush that will thin the mud and remove much of the cake; another is water with a surfactant. These two are for water-base muds. Any acid wash that will shrink mud particles and disperse them is satisfactory. A surfactant with acid will also help to disperse mud filtercake, and this is a good wash material. For an oil-base mud, cleaning must be done with an oil soluble acid or diesel oil. These chemical washes are available from the service companies who perform plugging operations. A typical selection from one service company is shown in Table 1.

2. Materials Involved in Well Plugging - The two materials involved in placement of a plug in a wellbore are (a) the mud [drilling fluid] in the well and (b) the cement slurry. Each of these is extremely important in obtaining a satisfactory plug.

a. The Drilling Fluid

The drilling fluid is important both in placing the cement plug and in serving as the plugging fluid between cement plugs. The first thing to be considered in setting a plug is the condition of the well. It is extremely important that the well be perfectly static, or still, when the plug is placed. If there is any movement of the cement after it is placed, proper setting is unlikely. If gas is coming through a section and percolating up through the slurry, the cement could become inhibited and may never set up. Salt water flows will also do the same thing. A salt water flow moving the slurry may limit proper setting or may cause complete inhibition. A tipoff to this situation would be an increase or decrease in mud weight.

If wells are drilled under adverse conditions, the mud is treated with chemicals. Most of the chemicals are organic in nature, i.e., they have a carbon or are in a carbon chain, and many are adverse to cement slurries. These muds adverse to cement are primarily of two types: those that have filtration controls, and those that have thinners. Contamination of cement with these types of mud will seriously affect the compressive strength and cause nonsetting of the cement slurry if in sufficient proportion.

When an operator has to abandon a dry hole or a depleted producing well, he wants to do it as inexpensively as possible. Therefore, rather than condition the mud to the proportions of a good mixture, the operator would rather use the mud system just as it is in the well. This makes the placement of a competent plug without mud contamination very difficult.

Table 1. Mud removal solution and chemical wash selection.

<u>Chemical Wash</u>	<u>Mud Removal Solution</u>	<u>General Application</u>
Mud Cleanout Agent (MCA)	Mud Cleanout Agent (MCA)	Almost any type formation where water-base-clay mud was used and lost circulation has not been a significant problem during drilling.
Multiple Service Acid (MSA)	Multiple Service Acid (MSA)	An organic acid usually used in high temperature wells to attack filter cake without damaging the pipe or downhole casing equipment.
	Non-Emulsifying (NE Acid)	Formations with minimum of 20% acid solubility. Water-base mud system.
	HF Acid	Dirty sands. Water-base-clay mud systems. Generally used with dilute HCl or ClayFix containing TRI-S surfactant.
Mud-Flush	Mud-Flush	Non-acid treatment for almost any formation where water-base mud was used. Consider where lost circulation has occurred.
	Oilsperser	Non-acid treatment for almost any formation where hydro-carbon-base mud was used. May often be followed by Mud-Flush to preferentially water wet the casing and most formations.
Oil Soluble Acid (OSA)	Oil Soluble Acid (OSA)	Non-aqueous solution of organic acid in hydrocarbon liquids. An aid in breaking emulsions and water blocks, and dissolving calcareous material in sand formations.
	SAM-4 Spacer	An emulsion spacer fluid for all types of muds and cement slurries. May be weighted for efficient removal of drilling muds.

Likewise, the use of a mud system "as is" does not afford the best material for a plugging fluid, but this is the fluid used in many cases. The best fluid to use as a plugging fluid will be discussed in a later section.

b. The Cement Slurry

The cement slurry used for the plug is also very important. It must provide sealing to prevent movement of gas or fluids from one strata to another. It must be composed so that a long life may be expected.

The technical literature contains very little information on long-term testing of cementing materials to determine durability with time and under various temperatures. This is probably due to the relatively recent evolution of portland cements in Europe and the United States.

The first patent covering the burning of clay and limestone to produce portland cement was issued to Joseph Aspdon in 1824 in Great Britain. The first manufacture of portland cement in the United States occurred near Coplay, Pennsylvania in 1883. Cement was first used in wells in California as early as 1903 when F. F. Hill (Union Oil of California) mixed and pumped 50 sacks of portland cement to shut off bottom hole water. However, for the next 24 years, cement manufacturers in the United States manufactured only one type of portland cement, i.e., ASTM Type I, which would be the same as American Petroleum Institute (API) Class A cement today. In 1927, the first high fineness, high strength cement (ASTM Type III or today's API Class C) was made in Indiana. Oil well Type D, E, or F (retarded) cements, i.e., cements having delayed setting characteristics, were introduced in 1935, but are not available today.

The API standardization of cements, or, the development of specifications covering chemical and physical properties of oil well cement, was first published by the API as Code 32 in 1952.

In 1954, the API published a report of a comprehensive, cooperative study (from different API Standardization Committee laboratories) on the resistance of various oilfield cement slurries to sulfate environments. This report gives the result of subjective samples of different API cement types (with and without admixtures) to the influence of a curing media of 50,000 parts per million sodium sulfate. This was selected for an accelerated test to determine extent of deterioration of 1" x 1" x 12" expansion bars in that corrosive environment. While it was done under atmospheric pressure and at temperatures of 100°F, 140°F and 180°F, it does give an excellent comparison of different API classes of cement in this severe chemical environment. This work shows that the resistance to corrosive environments, such as might be encountered in disposal wells and with certain downhole formation brines, can best be achieved by using a zero tricalcium aluminate cement similar to ASTM Type 4 or 5, Maryneal Incor cement, or El Toro 35 cement, commonly used in the West Texas area of the oil industry.

In addition to the foregoing evaluation of different types of oil well cements to corrosive elements, Roman pozzolanic cements are found in Mediterranean areas of Europe in an excellent state of preservation. These construction materials, which were made from volcanic rubble ground with limestone and mixed with water, have withstood hundreds of years of sea water exposure, yet remain in a good state of preservation. The Portland Cement Association, Skokie, Illinois has continuing tests on concrete and cements used therein. Their studies have found that cements with less than 11% C₃A content have performed without concrete deterioration through 25 years of exposure to sulfate soils⁶. Although these tests are of recent origin, indications are that the life of sulfate resistant cements will be long under downhole conditions.

A successful cement plug must have a high resistance to drilling. It must have good bonding characteristics to the pipe or formation and should be capable of withstanding the weight of the drill pipe without being moved. It should have durability.

The cement used should be selected to match the formation encountered, e.g., salt saturated cement would be used for plugs set in salt formations. For special circumstances (especially for storage and disposal areas), a qualified engineer should be consulted or laboratory evaluation obtained before determining cement composition. Table 2 shows the variety of cement slurries and additives used by one service company to modify and improve the basic cement slurries for plugging different formations. Class G and H cements are generally considered to be the most acceptable for placement of plugs because this cement is expansive as it sets, and can be mixed to be very dense.

E. Problems Encountered

Plugging a well would seem to be an easy task, but plugging done correctly and efficiently requires skilled operators and cannot be done haphazardly. This is evident in wells which have been checked after plugging and found to have deficiencies. Alguire⁷ tells of 24 wells in Michigan which were redrilled after being plugged by placement of cement slurry through drill pipe. Detailed records were available on 18 of the wells and partial records on 2 others. The 49 plugs which were placed in the 20 wells were checked. Eleven of the plugs (22%) were not found, and the tools passed through the section where the plugs were supposed to be located. Six plugs were found to be soft cement containing hard streaks. In 5 of the wells (25%), the plugs were either absent or the cement was soft. In ten of the 18 wells with complete records (or 55%), the lower plug was absent or consisted of soft cement. In two of these wells, gas had migrated up the wellbore and accumulated beneath the upper plug. Two of the 20 wells also had the top plug missing, but the upper plug seemed to be the most effective in the wells tested.

There are several factors which influence the condition and effectiveness of a cement plug placed in a well. These include: (1) The condition of the mud or drilling fluid in the hole, (2) the type of cement used,

Table 2. Plug-back cementing compositions.

The additives listed below may be used with all API cements (Classes A, B, C, D, G & H) and in Pozmix Cement. Discretion must be used in the choice of cement and additives based on well conditions and the physical properties of the composition. It may be necessary to incorporate more than one additive in the design of the plug-back composition.

Application	Additive	Benefits
Reduce WOC Time (Cement Accelerators)	Calcium Chloride CFR-2 Cal-Seal	Increase early compressive strengths up to 120°F. Produces low viscosity slurry with reduced water ratio providing increased slurry density and higher strength. In cement, produces a very fast setting composition with positive expansion.
Increase Thickening Time (Cement Retarders)	HR-4 HR6-L HR-7 HR-20	Controls setting time up to BHCT's of 206°F. Liquid retarder. Primary use in bentonite cements but may be used to retard any slurry up to 206°F (BHCT). For extreme high temperatures.
Increase Slurry Density (Densifiers)	Hi-Dense No. 3 (Hemitite) Barite Sand CFR-2 CFR-1	Combats high formation pressure with slurry densities in the range of 22 to 25 lbs/gal. Slurries up to 19 lbs/gal. For slurry densities up to 18 lbs/gal Hard plugs for whipstocks. Increased slurry density as a function of decreased water ratios. Higher strengths. Same as CFR-2 for use at high temperatures

Table 2 (con't.)

Application	Additive	Benefits
Low Fluid Loss Slurries (Thickeners)	HALAD®-9	Inhibits slurry dehydration during hydration of cement - for temperatures to 206°F (BHCT).
	HALAD®-14	Same as HALAD-9; for use at BHCT's above 200°F
	Diacel LWL	Same as HALAD-9 but imparts increased thickening times to the slurry.
Special Cement Additives	Salt (Sodium Chloride)	Bonds to salt, shale and bentonite. Increases density. Accelerators at low concentrations (5-10%) - retards at high concentrations (20%-saturation).
	KCl (Potassium Chloride)	Inhibits damage to fresh water sensitive formations - improves bond - more compatible with fluid loss additives.
	Halliburton Red Plug Cement	A complete plug-back composition - good bond to shales and clays - high compressive strength - tolerates high percentage of mud contamination.
	Silica Flour (SS-1 & SS-2)	Recommended for use at temperatures above 230°F (BHST). Increases ultimate compressive strength and decreases permeability.
	Mud-Kil I & II	Not recommended for use with Class D cement. Reduces effect of mud contamination of cement slurries. Neutralizes retarding effect of tannins, starch, etc., in muds.
Lost Circulation Materials	Gilsonite	Excellent bridging properties. Reduces slurry density.
	Ground Walnut Shells	Excellent to bridge fractures and for lost returns.
	Flocele	Flake material - plating action. Minimizes lost returns
	Cal-Seal Cement	Fast setting. Will set while being pumped. Can incorporate bridging materials.

(3) the care used in placing the plug, (4) the technique used in placement, (5) the preparation technique used in the well prior to placing the plug, and (6) cross flow or fluid movement after plug was set. In actual practice, ineffective plugs are being placed due to improper planning, carelessness, cost restrictions, or unconcern in applying the above factors. Proper application of the factors will be discussed in a later section of this report.

F. Case Studies - Gas Storage Wells

One area of the oil industry where well plugging has been a very important factor is in the development of gas storage fields. About 45 to 50 years ago, the feasibility of using depleted gas fields as storage reservoirs was proven to be an acceptable solution to storing gas during summer months for use in peak demands during the cold months. During this interval, many gas companies have developed gas storage reservoirs in depleted gas fields. The techniques used in this work closely parallel the work that would be done in providing a radioactive waste repository which might be located in a similar area. Several case studies are presented to show the techniques used in finding and plugging abandoned wells existing in the gas fields.

1. Webb Storage Field, Grant County, Oklahoma - This is one of ten storage fields developed by Cities Service Gas Company in the Kansas-Oklahoma area. The ten fields include a storage for over 145 billion cubic feet of gas in about 80,000 acres. The Webb Storage Field includes 2,560 acres. Details of the field and a plat of the field are attached as Figure 12⁶.

In the development of this field, about 25 abandoned wells were found and plugged. The wells were drilled originally in the late 1920's using cable tool rigs. The wells generally followed the same pattern: (a) a 12 to 14-foot deep cellar at the surface, then about 50 feet of wooden casing 30 inches in diameter, (b) a string of 16 or 20-inch steel casing to about 250 feet, (c) 13-3/8" casing to 800-foot depth, (d) 10-3/4" casing to 1800 - 1900 feet, (e) 8-5/8" casing to 3,000 feet, then (f) 7" casing to pay zone at about 4,000 feet. None of this casing was normally cemented; however, occasionally the last string of 7-inch casing would be cemented.

Location of these wells was made primarily by search of existing records. The casing was pulled from the well when it was possible to do so. The tight fit of the successive casing joints usually prohibited removal of the casing, so windows were milled in the lower casing between pay zones. When the pipe was plugged between pay zones, the cement would be forced through the window section into the annulus area behind the casing as the plug was placed across that section. An average of five windows were milled per well.

Every permeable zone up the hole was plugged from 25 feet below the zone to 25 feet above. The cement was placed from a special cementing

WEBB STORAGE FIELD

GRANT COUNTY, OKLAHOMA

Productive History	Depleted Gas Field
Type of Reservoir	Anticline with Fault
Storage Formation	Chat of Mississippian Age
Average Producing Depth	4120.76
Date of Field Discovery	1926
Acreage Controlled	2560
Number of Storage Wells	23
Number of Observation Wells	8
Date of First Injection	April 1, 1966
Discovery Wellhead Pressure	1550 psig
Pressure Range of Working Gas	800-1550 psig
Capacity at 1550 psig.	55,600,000 Mcf
Cushion Gas Volume	30,600,000 Mcf
Working Gas Volume	25,000,000 Mcf
Estimated Peak Day Deliverability	200,000 Mcf

Figure 12. Plat and Data for Webb Storage Field

tool which jetted the cement horizontally. The tool was rotated as the cement was pumped, enabling the jetting action of the cement on the formation and the scraping action of blades extending out from the tool to aid in cleaning the wall to obtain a better cement bond.

A water wash was pumped ahead of the cement slurry for each plug. Gel flakes (mica) were used in the cement slurry for the plugs, except that Gilsonite (a solid hydrocarbon material) was used in the cement instead of gel flakes in the area containing the milled windows.

2. Lyons Gas Storage Field, Lyons, Kansas - This field, developed by Northern Natural Gas Company, contained many early wells which had been abandoned before regulations were established on plugging. Existing records were checked, but the best source of information to locate wells proved to be aerial photographs of the area obtained from the U.S. Soil Conservation files. Former well locations could be detected from the photographs, then found by using a bulldozer to unearth the cellar and the wellbore.

Since about 1945, state regulations in Kansas require the owner to leave the surface pipe in the well. Buried pipe was located in some instances using a Birdwell magnetic locator device. Most holes contained pipe cemented in the hole. Tests indicated that the cementing job was still good. Plain portland cement had been used.

A gamma-ray neutron log and a cement bond log were made in all the old wells containing pipe. If a good cement bond was not indicated, the pipe was perforated and squeezed with cement. When the pipe and cement job was not good, the pipe was removed.

After a well was found, a rotary rig was set up over the hole. A rig crew experienced in this type of remedial work was used wherever possible. Attempts were made to wash the drill pipe to the bottom of the well. Normally one or more fishing jobs were necessary to remove junk from the hole during this trip. Fishing tool specialists were used, and many items were recovered using some type of "homemade" fishing tool fabricated after making an impression on the junk in the hole. All sorts of pipe and steel tools were recovered, as well as wooden posts, tree sections, etc. The fishing operations proved to be a major part of conditioning the well so it could be properly plugged. In older wells where pipe was not cemented, the pipe was removed by washing over the pipe. The steel recovered from the holes, which had been below any source of oxygen, was in excellent condition, even from wells over 40 years old.

After the hole was reopened to its original depth, the mud in the hole was put into static condition. A retrievable type packer was then set in the zone above the pay formation. A cement slurry containing a low fluid-loss additive was then pumped under the packer, and a squeeze pressure of about 2000 psi was used with the slurry to try to permeate the formation. The plug was extended up into the pipe well above the Arbuckle sand pay formation. The packer was then unseated and removed from the well.

A cement plug was then placed from 200 feet to the surface to complete the plugging of the well. This cement was placed through open end pipe using the balance method. A total of 18 wells were plugged during the establishment of this storage field.

3. Jackson Gas Storage Field, Jackson, Mississippi - The original gas field, drilled in the 1930's, included much of the area under the City of Jackson and the adjacent areas. The gas storage field, developed by United Gas Pipeline Company, took a portion which laid under the City of Flowood, just east of Jackson, in Rankin County. When the storage area was started in 1953, the field had only a few wells still producing, and production was insignificant. There were about 80 wells to plug in the development of the storage field.

Finding all the old wells proved to be difficult. Very few records were available, and those that could be located were inaccurate. Wells were found under houses and other buildings. Many times it was necessary to uncover ten or more feet of earth to find the wells.

After finding wells, a drilling rig was set over the hole. It was necessary to tie on to the casing in the well to install blowout preventers prior to beginning operations to plug the well. Each well had to be cleaned out completely into the gas producing formation. After this, the casing in the hole was perforated above a bottom plug and tested. As long as any pressure was found, the well was "squeezed" with cement slurry. This process was continued up the hole until it was insured that the hole was completely dry and nonproducing. This same process was also followed on new wells drilled for injection or observation, since none of the old existing wells were used in the gas storage operation. Depths of the wells in this field were 2000 to 2200 feet.

The gas producing formation was a chalk-like material containing vugular spots and high permeability. This caused lost circulation problems when working on the wells. The existing wells had a gas pressure of about 960 psi, with a water drive below the gas.

Many of the old wells had crooked holes. Some holes had three or four sidetracks which also had to be plugged. Much of the casing in the wells was an odd size by current standards. Casing in some wells had been pulled by shooting off the casing.

Plugging was accomplished using portland cement. In some instances, pozzolan was added to the portland cement. Plugging was done only after the well was brought to a static condition with mud. Plugs were set to seal off the producing formations and to protect fresh water sands.

G. Summary of the State-of-the-Art

Plugging oil and gas wells in the early part of the twentieth century was a neglected phase of the oil industry; for the past 40 years, however, the importance of proper and effective plugging has been emphasized and

regulated, so that today this is a vital part of the standard practices in the production of oil or gas. Plugging is performed during drilling to sidetrack the wellbore, to seal open hole below a casing seat, or to correct lost circulation problems; but the primary emphasis of this study is the plugging to abandon a well.

Various conditions encountered in plugging for abandonment are discussed and illustrated. The three primary oilfield techniques, viz, balance method, dump bailer method and two-plug method are described, as well as the use of a cement retainer with the balance method. Placement of cement plugs by the balance method appears to be the predominate method used.

Tools and materials being used in plugging include the following: (1) mechanical devices for cleaning mud from walls of the hole and centralizing the tubing, (2) chemical washes for mud cleaning, (3) drilling mud for fluid plugs, and (4) cement compositions to form solid plugs. These have proven to be satisfactory in most instances. A few problems have arisen, apparently due primarily to carelessness and efforts to take "short cuts" because of costs or other reasons.

Case studies involving well plugging in gas storage fields have shown how careful planning and meticulous operations have been successful in widely scattered areas of the United States. These wells also provide the longest test of the cement plugging materials, but this is only about 40 to 45 years.

There was not a great amount of written material on plugging found during the study, but the literature discovered seemed to be very pertinent and informative. Much of the information in the report came from the personal experience of people who have been and are now involved in performing this kind of work.

There have been several feasibility studies made in an attempt to discover new ways to plug wells other than with cement as is currently practiced in the oil industry. One method⁹ set forth involved the possibility of forming borehole plugs by hydrothermal transport. This involves several different approaches. These are (1) hydrothermal cements, (2) hydrothermally transported quartz, or (3) calcite plugs formed as compatible plug materials in contact with a limestone or dolomite wall rock. The first two systems require high temperatures (200°C to 500°C), and the second also requires a pressure of approximately 30,000 psi. The third approach is questionable as there is a problem with percolating groundwater.

Another method¹⁰ considered is to melt in situ rock salt to form a plug. There were four approaches; downhole melting, uphole melting, chemical emplacement, and liquid spray emplacement. The first two conceptual approaches seem to be the best. The process requires extensive hardware and operation is at high temperatures. Granulated salt is introduced at the wellhead and a melter device down the well melts the salt in the downhole melter system. In the uphole melting, salt is

melted on the surface and the liquid salt is delivered to the bottom of the hole or wherever the plug is to be located.

3. RECOMMENDED PROCEDURES FOR PLUGGING WELLS IN PROPOSED RADIOACTIVE WASTE REPOSITORY AREAS

The recommendations set forth herein for materials and techniques are especially made for plugs in wells located on sites where radioactive waste may be stored in underground caverns. Some of the procedures and materials may be equally applicable to wells in other locations.

A. Location of Abandoned Wells

In many cases, a well to be plugged is a depleted producer in an established oil or gas field. At other times, it is a dry hole in an exploratory operation. But there are occasions when it is necessary to properly plug older wells which have been abandoned with little or no effort to plug the well. This could occur in a project such as a gas storage field or a repository for radioactive waste. The proper plugging of these abandoned wells is essential to the success of the planned project; however, it is possible that the passing of time has erased the location of such wells.

There are several approaches which can be used to find these hidden, abandoned wells. These include (1) search of records, (2) interviews, (3) use of aerial photographs, (4) use of magnetic type locator devices, and (5) on-site search and excavation.

1. Search of Records

This seems to be the logical starting place for finding abandoned wells, even though it may not be too successful. The records at the state (or local division) regulatory agency should disclose many of these wells. This will not locate some older wells abandoned before the agency was instituted, and these are normally the problem wells.

The records of leasing located at the county courthouse should show locations in general, and if permits were required for drilling the wells, exact locations may be specified. The county tax records would show land owners in a project area who might have made leases to oil companies for exploration.

Drilling records for oil companies known to have operated in the area should also provide information on the well locations. Service company records would be another source. The records that are available in this search should disclose up to 90% of the wells in the area.

2. Interviews

Information on old wells can often be obtained by talking with residents of the area who have lived there for many years. Land owners found in county records can be interviewed, as well as business men who have been in the area for a long time. Interviews can also be made with personnel of companies that perform services to the oil industry, such as supply houses, tool companies, well servicing companies, drilling companies, or other service companies.

3. Aerial Photographs

Use of the aerial photographs of an area is an excellent way to find old well locations. These are normally available from the United States Soil Conservation Service. Photos are remade every 5 years, so older photographs back to 1938 should be available to examine. Records may have been found which give general locations. Slush pits and cellars can be determined by the ground depressions visible in the photographs or disruptions in normal ground characteristics. If these photographs can be located, this is one of the best methods for location of old wells. Infra-red photography may be helpful, but is very expensive.

4. Magnetic Type Locators

In cases where surface casing was left in the ground, and the casing was cut off below the ground so that it cannot be seen, the well might be located by the use of a metal detector. This would require a high-powered, sophisticated type to indicate a pipe standing vertically at depths of 3 to 5 feet below the surface. Such detectors may be obtained from instrument companies (such as Birdwell) that service the oil industry.

There is a company named Holosonics in Richland, Washington that claims to have a tool which can be run into a well, and it will locate another wellbore up to about 200 feet distance.

5. On-site Search and Excavation

The final effort to locate abandoned well locations should be a thorough search of the ground in the area of a proposed project. Even when other means previously discussed are successful in locating many old well sites, the ground should be examined and excavations made at suspected well sites found from records, photographs or interviews.

The use of a bulldozer or backhoe may be necessary, since the old cellar may be under several feet of earth. Every effort should be made to search the entire area involved, so that the chance of missing a well will be greatly minimized.

B. Preparation of Wells for Plugging

After an abandoned well is located, there are several steps in preparation of the well prior to placing a plug in the well. First, the well should be cleaned out of any foreign material, then the mud system must be brought to a static condition to insure that there is not movement of water or gas through the mud, and circulated enough to insure that the mud system is uniformly weighted. Logs should be run to determine formation characteristics and wellbore shape. The pipe to be used in the section of the well being plugged should then be prepared with the desired mechanical devices attached.

1. Cleaning Out the Well

A rotary rig of sufficient size and power for the rework should be moved in and set up on the well site. A mud pit should be available beside the rig.

Pipe should be started into the hole, utilizing the mud or salt water present in the hole. As the drill bit is lowered into the hole, any area where the wall has sloughed should be drilled out. If junk is encountered, it should be recovered by a fishing operation. This may entail a long arduous procedure or be a relatively simple operation.

The cleaning out should be continued until the bottom of the hole is reached. If any portion of the hole is cased, the casing should be left in place. The salt water or mud which was left in the hole should now be replaced with a new mud system.

2. The Mud System

The mud system used should be one which will meet the needs of the hole, i.e., provide a fluid which will contain the proper additives to give a static condition without fluid loss. It should also provide a fluid which will serve adequately as a plugging fluid in the hole for an extended period of time. Using a new mud system will permit the operator to know the chemicals used in the mud, so the plugging job can be planned efficiently.

Many chemicals used in muds are organic, and as such are very detrimental to the setting ability of a cement slurry. The muds that are most adverse to cement are those that have filtration controls and those that have thinners. Unless compensation is made for these type muds, the resultant retardation of the cement could cause a faulty plug.

A common filtration control agent (fluid loss reducer) is pre-gelatinized starch, found under such trade names as IMCO® Loid, Impermex or My-Lo-Jel. Starch is not chemically stable, and it ferments with a bacterial action. It would not make a good plugging material to leave in the hole for an indefinite time¹¹. Another fluid loss reducer is sodium carboxymethyl cellulose, sold under trade names of IMCO®CMC, Cellex or Magco CMC.

In the group of thinners, which are also adverse to cement, are the lignins, tannins or quebracho. Lignins are classed as humic acids and consist of decomposed vegetable matter. They are derived primarily from coal. Lignins may appear under such trade names as IMCO® LIG, Carbonox and Tann A Thin. With caustic added to control pH, trade names are IMCO® THIN, CC-16 and Caustilig.

The quebracho, or tannin group, are acids derived from a tree of Argentina. These appear under trade names of IMCO® QBT, Tannex and M-C Quebracho, or DESCO. The thinner group also includes lignosulfanates. Calcium lignosulfanates appear as IMCO® CAL or Kembreak. The ferro-chrome

lignosulfanates are sold as IMCO® VC 10, Q-Broxin or Spersene. If these chemicals appear in any quantity in the mud system, tests should be made of the cement with mud contamination before the plug is set in the well.

The degree of contamination will depend on how the cement plug is going to be used and what the conditions are at the time the plug is placed. Table 3 shows how various degrees of contamination of the cement slurry affects the cement strength.

Table 3. Effect of mud contamination on strength of cement.

Curing time: 12 hours		
Curing temperature: 230°F (110°C)		
Slurry weight:		
Cement A: 15.6 lb/gal (1.86 kg/l)		
Cement B: 17.4 lb/gal (2.08 kg/l)		
Mud Contamination (percent)	Compressive Strength (psi)	
	Cement A*	Cement B*
0	2,910	7,010
10	2,530	5,005
30	1,400	2,910
60	340	2,315
*contains dispersant.		

In placing a mud system in a well, the requirements for mud as a plugging fluid should also be considered. The essential characteristics of a plugging material are: (1) sufficient hydrostatic head, or weight, (2) ability of the fluid to remain in place over an indefinite period of time, and (3) stability of the material for an unlimited time.¹¹

The hydrostatic head can be increased by mixing the mud with production brine, or by adding a weighting material, such as barite. The ability to remain in place is dependent upon the type and severity of lost circulation or fluid loss. Lost circulation, or the loss of fluid from the wellbore into a formation, can be controlled to some degree by the addition of lost circulation additives, such as mica flakes or ground walnut shells. The stability of a fluid depends on the materials used in the makeup of the mud. The mud has to be both physically and chemically stable, so materials should be used which are stable in nature like the basic clays.

A recommended mud for an abandoned well to be plugged would include these materials:

1. Water, fresh or brine.
2. Bentonite (IMCO® GEL, Aquagel or Magcogel).
3. Attapulgate (IMCO® BRINEGEL, Zeogel or Salt Gel).
4. Lost circulation material (if needed).

The brine (or addition of barite to fresh water mud if there are no salt formations in the well) satisfies the hydrostatic head requirement; the bentonite takes care of filtration control; and attapulgate gives the necessary thickness, viscosity or thixotropic properties. The amounts of each component would be determined by tests of the water sample, then the bentonite and attapulgate would be added in a proper ratio to obtain the desired properties in the mud. Open-hole, plug-back studies show that the preferred mud system has a Marsh funnel viscosity of 45 to 80 seconds, a plastic viscosity of 12 to 20 cp, a yield point of less than 5 lbs/100 square feet, and a water loss of less than 15cc.

It must be known if there are gas or water flows entering the well, since these will be detrimental to a cement plug set in the well. One may be aware of this condition by a change in the level of the mud pit, or by an increase in mud density caused by water entering the well. If either of these conditions exist, remedial action must be taken before a cement plug can be successfully set.

3. Logging

If casing (other than surface casing) is left in the well, a bond log should be made to see if any remedial work is necessary in the cased portion. Should such be required, normal cement squeezing operations by an oil well service company could be used.

A gamma ray-neutron log should be run for the total depth of the well, unless such record is already available for the well. Geology of the formations should be known.

A caliper log should be run after the well is in static condition. This will enable the service operator to calculate the proper amount of cement needed and help in selecting the best section of hole in which to place the cement plugs.

4. Pipe Preparation

The pipe to be used in setting the cement plug should be selected. The pipe size should be as small as practical for the hole size to minimize surge effect. For example, a 4-1/2" drill pipe in a 7-7/8" open hole would leave only a small annulus for the cement, thereby causing a long drop when pulling the drill pipe and providing more chance for mud contamination. A 3-1/2" drill pipe or a 2-1/2" tubing would be preferred. The lower joint or joints, equivalent to the length of plug to be set, should be equipped with a centralizer at each collar, and rotating type wall scratchers should be affixed to the pipe throughout that section.

C. Recommended Plugging Procedure to Abandon a Well

1. General

Wells which may require a procedure for placing a cement plug prior to abandonment may be classified under three categories:

- (1) Newly drilled wells which are unproductive, i.e., dry holes.
- (2) Old wells which have become uneconomical to produce.
- (3) Old wells which have been improperly plugged and could be a problem.

Wells in the third category will essentially have to be redrilled to total depth and may be similar to category 1 or 2.

The first part of the plugging technique is to insure that the section in which the plug is to be placed is properly prepared. For new wells (category 1), this may include a chemical wash to remove mud and disperse excess filter cake buildup from the wall of the hole. This could be water containing sand or pozzolan abrasive material to act as a scouring agent, or a chemical wash (such as listed in Table 1) compatible with the mud system could be used. Fifty barrels of wash material may be required.

For old wells (category 2), a bit gauged to the casing should be run below the depth of the desired plug. Mud, residual hydrocarbons, mineral scale, and other types of depositions may be encountered. The character of this accumulation of material will determine the type of flush to be used. It is not unusual to find unreported foreign objects in old wells (joints of tubing, packers, etc.). This could also require re-evaluation of plugging procedures.

The selection of a cement composition for a cement plug will depend on well depth, temperature and mud properties. Thickening time is suggested to be job running time plus one (1) hour at the temperature and pressure conditions for the plug depth. The cement used should also develop a high compressive strength and tolerate any mud contamination that might occur during placement.

The following precautions should be helpful in placing a successful cement plug :

1. Selecting, with the help of a caliper log, the gauge of the section of the hole to be plugged.
2. Carefully calculating cement, water, and displacement volumes. Always plan to use ample volume of cement.

3. Using a densified (low water ratio) mixture with API Class A, C, G, or H cement that will tolerate considerable mud contamination.
4. Preceding the cement with sufficient flush.
5. Rotating the tubing using tail pipe with centralizers and scratchers while placing the cement.
6. Using drill pipe wiper plugs and plug catchers.
7. Placing the plug with care and moving the pipe slowly out of the cement to minimize mud contamination.

The number and length of cement plugs will vary with the well depth, number of producing formations encountered and casing left in the hole. In general, cement plugs shall be placed opposite oil and gas showings, at the fresh-saltwater interface, atop the casing stub, at the base of the casing if the hole is open below the shoe, and at the surface. Sections of the hole between cement plugs shall be filled with mud. Minimum thickening time should be used for the cement slurry.

2. Plugging Material

It is recommended that a densified (low water ratio) cement designed for optimum strength and maximum resistance to mud contamination be used for the plugging material. Advantages of using this type slurry are:

- (1) It is less subject to mud contamination and resultant loss of strength.
- (2) It sets and gains strength more rapidly, thus reducing waiting time for the cement.
- (3) With dispersant, such slurries have water loss control and minimize dehydration of the cement slurry which could allow fluid movement in the borehole.
- (4) Can give improved bonding and minimize damage to shales or bentonite sands by addition of salt.

In most cases, an API Class G or H cement should be used as the base cement. These cements are identical except that Class H is coarser ground. Class G is used mainly on the West Coast and Northern Rocky Mountain areas, and Class H is usually predominately used along the Gulf Coast and Mid-Continent areas. Since the Class H cement is produced in larger quantity and is more widely used, data will be given on this cement as the recommended material. The Class H cement is a moderate sulfate resistant

cement manufactured for use from surface to 8,000 feet depth. The API water requirement is 0.38 (4.29 gals/sk). This would result in a slurry having a weight of 16.5 lbs/gal.

The API Class G or H cements are manufactured to a specification of 8% or less tricalcium aluminate (C_3A), which is that component in the cement which has a major influence on the cement durability in corrosive conditions that may occur downhole. However, most manufacturers of Class G and H cements use raw materials that make it possible to produce cements having 5% or less C_3A content.

The Class H cement should be densified by the addition of 1% CFR-2 dispersant. CFR-2 is a trade name for a naphthalene condensate dispersant, which is used to improve the viscous properties of cement slurries with a pronounced reduction of apparent slurry viscosity. Salt should also be added if the cement plug is to be placed in a salt formation or opposite water-sensitive shale sections. Addition of salt as indicated in Table 4 provides expansive properties to give a good, tight bond to the formation. Table 4 shows the weights of slurry that can be mixed with 1% dispersant and with either no salt or 18% salt. Table 5 shows the compressive strengths obtainable for the same Class H slurry shown in Table 4.

For plugging wells in downhole environments having high sulfate content, such as found in West Texas and New Mexico areas, special Class C(SR) cements should be considered, for they will withstand most corrosive brines found in the drilling industry. There are two unique cements manufactured in West Texas for the oil industry to API Class C specifications, but which contain no C_3A . These special Class C(SR) cements may be purchased from only two sources. These are: Lone Star Cement "Maryneal Incor," Maryneal, Texas, and Southwestern Portland Cement "El Toro 35," Odessa, Texas. These Class C high-sulfate resistant cements are normally mixed with 6 gallons of water per sack of cement, but by using a dispersant additive in the cement, they can be mixed with as little as 4-1/2 gallons of water per sack of cement.

Table 4. Mixing data for API Class H cement.

Gals/Sk	Salt Percent*	CFR-2 Percent	Slurry Weight Lbs/Gal	Slurry Volume Cu Ft/Sk	Thickening Time
					Hrs:Mins API Squeeze 8000
4.25	0	1.0	16.5	1.05	3:03
4.50	18	1.0	16.5	1.12	2:35
3.80	0	1.0	17.0	0.99	2:51
4.00	18	1.0	17.0	1.05	2:12
3.40	0	1.0	17.5	0.93	2:12
3.55	18	1.0	17.5	0.98	1:54

* Percent by weight of mixing water

Table 5. Compressive strengths for API Class H cement.

Slurry Weight Lbs/Gal	API Curing Conditions			
	110°F 1600 psi	140°F 3000 psi	170°F 3000 psi	200°F 3000 psi
- - - 12 Hours - - - 0 Percent Salt				
16.5	2075	4000	7800	9035
17.0	2850	6535	8375	10025
17.5	3975	6585	8550	10675
18 Percent Salt				
16.5	1200	3010	3885	5085
17.0	2000	3760	4735	6560
17.5	2175	4950	5810	7060
- - - 24 Hours - - - 0 Percent Salt				
16.5	5475	8985	9750	10460
17.0	6035	9060	11075	12660
17.5	7025	10125	11060	12875
18 Percent Salt				
16.5	3635	4285	5400	6585
17.0	4885	4910	5925	8335
17.5	6260	6560	6625	9825
If the well depths are shallow enough to permit the shorter thickening time, it is recommended that the slurry be mixed with the minimum water to obtain a weight of 17.5 lbs/gal.				

Another aspect of the durability versus the chemistry of set cements is that API Classes C, G, or H all have free lime liberated during the setting or hydration process with water. This is an inherent component that may be leached from the cement should fluid movement occur in the location of the plug. In setting plugs through such zones which may contain sulfate or acid waters, it is suggested that pozzolans (fly ash) be mixed with these cements to react with the free lime in the set cement. This action will render it more sound and less susceptible to the action of corrosive sulfate and acid waters. Mixture of pozzolan and cement should be in equal portions, i.e., 94 pounds of cement blended with 74 pounds of pozzolan.

In summary, the following recommendations are presented:

1. For areas not containing zones with corrosive water conditions, a moderate sulfate resistant cement (API Class G or H) would be the recommended material for the wellbore plug. This would provide a maximum strength in the plug and still afford an excellent protection and durability.
2. In areas where sulfate or acid waters are present, a special high sulfate resistant Class C cement could be used as the plug material, or 50% pozzolan could be added to the Class C or H cements to provide the higher resistance to leaching.
3. A dispersant (such as CFR-2) should be used to lower the water content requirement in order to provide better strength and durability.

3. Plugging Techniques

The lower portion of the tubing or drill pipe used to place the cement plug should be equipped with centralizers and rotating wall scratchers as shown in Figure 13. This special section of pipe should be used during placement of a plug by the balance method or two-plug method to minimize mud contamination. The rotation of the scratchers cleans the wellbore to accomplish better bonding, allows bypassed mud to mix uniformly with the cement, and tends to eliminate channels in the cement.

Figure 13. Schematic of Tailpipe with Centralizer and Scratchers

The recommended procedural steps for placing a plug are as follows:

1. Determine the number and length of plugs needed, and the locations for the plugs in the wellbore.
2. Calculate the amount of cement needed, the composition of the cement mixture for each plug, and order the cement required.
3. Determine type of plugging procedure to follow.
 - a. On an uncased hole (see Figure 14), it is recommended that the plugs be set using the two-plug method, except for the top surface plug which can be spotted in place through open tubing.

- b. For an abandoned producing well containing a cemented production string (see Figure 15), it is recommended that the plug across the perforations or open hole production zone be placed with a cement retainer tool. This would permit part of the cement to be pressured to force it into perforations or open formation. The cement on top of the retainer can be placed by tubing manipulation. If part of the casing can be removed, it is recommended that the producing zone be plugged before removing the uncemented casing.

The plug at the casing stub, and at the bottom of the surface pipe, should be placed using the two-plug method. The top surface plug could be placed through open tubing.

- c. A five to fifteen barrel spacer of salt water or SAM-4 spacer material should be used ahead of the cement in each case.
4. If necessary, circulate the mud in the hole to stabilize the mud weight.
 5. Run tubing or drill pipe in well with plug catcher and special scratcher section, then use sufficient quantity of chemical wash (or scouring type flush) compatible with the mud in the well.
 6. If a cement retainer tool is to be used, run it to required depth and set in pipe.
 7. Mix the proper amount of the cement, then place the lower cement plug at the desired location, following a procedure given in Step No. 3. Reverse any excess cement out of the tubing, after withdrawing tubing above plug top, then retrieve tubing and plug catcher.
 8. After 12 hours (or required time) waiting for cement to set, run the tubing with a bit into the well and determine if the top of the plug is at the desired location. Set the tubing weight on the plug to determine if plug has obtained satisfactory strength. If cement retainer was used, eliminate this step and proceed to Step 9.
 9. Circulate the hole to stabilize the mud. Then run the tubing, plug catcher tool, and special scratcher section; then place the next cement plug farther up the hole as in Step No. 7, leaving mud between the two cement plugs.

Figure 14: Schematic of plugs in uncased hole.

Figure 15: Schematic of plugs in hole with casing.

10. Test the plug by repeating Step No. 8.
11. Continue repeating Steps 7, 8 and 9 until all plugs have been placed in the well.

In order to further clarify the plugging technique, conditions will be assumed for an uncased hole and a well with production casing. Examples will be set forth for plugging these wells using the plugs shown in Figures 14 and 15.

EXAMPLE NO. 1 - UNCASED HOLE

Assume:

Surface Casing - 8-5/8" - 24#/ft.

Open Hole - 7-7/8"

Drill Pipe - 3-1/2" - 13.30#/ft

Cement - Class H with 1% CFR-2 dispersant

Well Depth - 3,000 feet

EXAMPLE #1 UNCASED HOLE

The steps in planning and placing the three plugs for the conditions set forth in Example 1 are as follows:

1. The quantity of cement needed for the plugs is calculated by assuming 33% extra volume above the actual theoretical annular capacity. If a caliper log is available for the well, this could be used in lieu of the above assumption.

Plug #1 (bottom) - $200' \times 0.3382 \text{ cu ft/ft} \times 1.33 =$
67.64 cu ft slurry

Plug #2 - $50' \times 0.3382 \times 1.33$ (open hole) =
16.91 cu ft slurry
 $50' \times 0.3575 \times 1.0$ (surface csg.) =
17.88 cu ft slurry

Plug #3 - $20' \times 0.3575 \times 1.0$ (top) =
7.15 cu ft slurry

Total Required 109.58 cu ft slurry

Cement needed = $109.58 / 0.99$ (cu ft slurry per sk selected cement)
= 111 sacks.

2. Place cement Plug #1 using the two-plug method.
 - a. Run 3-1/2"-13.3#/ft drill pipe into the hole to bottom. The lower 200 feet of pipe should be equipped with eight casing centralizers (1 each collar and one just above lower end) and rotating type wall scratchers. The latch-down indicating plug catcher should be placed in the drill string at the top of the lower 200-foot section.
 - b. Circulate the 9#/gal mud until all portions of the mud system have the same weight. Rotate the drill pipe to scratch the mud filter cake off the formation face.
 - c. Release the bottom cementing plug, continuing to rotate the pipe.
 - d. Pump 15 barrels of salt water (or SAM-4) as spacer.
 - e. Mix 68.3 sacks of the Class H cement with 1% CFR-2 at a weight of 17.0 lbs/gal and pump into the drill pipe behind the spacer material.
 - f. Release the top latch-down cementing plug.

- g. Behind the top cementing plug, an amount of spacer must be pumped equal in feet of length to the spacer ahead of the cement, in order to provide a hydrostatically balanced fluid system in the well at the time the cement plug is placed in the bottom of the hole. In this example (and adjusting for the 33% oversize hole), we must follow the top cementing plug with 1.73 barrels of spacer to get 233 feet of fillup required.
 - h. Finish pumping the top cementing plug to the plug catcher using drilling mud. Note the pressure buildup and subsequent drop when the top cementing plug enters the plug catcher.
 - i. If desired, pull 200 feet of drill pipe from the hole, close the drill pipe rams and reverse any excess cement out of the hole.
3. Wait 12 hours for cement to harden. Run drill bit and pipe into the hole to determine location of cement top and cement hardness.
 4. Place cement plug #2 using two-plug method.
 - a. Retrieve drill pipe from hole and remove bit. Add 100 feet of lower pipe with centralizers and scratchers. Place plug catcher above lower 100-foot section. Run pipe in hole until end of drill pipe is 50 feet below surface casing shoe.
 - b. Circulate the 9#/gal mud until all portions of the mud system have the same weight. Rotate the drill pipe to scratch the mud filter cake off the formation face.
 - c. Release the bottom cementing plug, continuing to rotate the pipe.
 - d. Pump 10 barrels of salt water (or SAM-4) as spacer.
 - e. Mix 35.1 sacks of Class H cement with 1% CFR-2 at a weight of 17.0 #/gal and pump into drill pipe behind the spacer.
 - f. Release the top latch-down cementing plug.
 - g. Pump 1.04 barrels of salt water behind the top cementing plug to balance first spacer, then finish displacing the cement with drilling mud. Note pressure buildup and subsequent drop when the top cementing plug enters the plug catcher.

- h. If desired, pull 100 feet of tubing from the hole and reverse excess cement out of the hole, then remove balance of pipe.
5. Wait 12 hours for cement to harden. Run drill bit and pipe into the hole to determine location of cement top and cement hardness. Retrieve drill pipe from hole and remove drill bit.
6. Place surface plug (#3) by running 20 feet of drill pipe into the hole. Mix 7.2 sacks of the same cement, place in wellbore and pull the drill pipe.

The steps in planning and placing the four plugs for the conditions set forth in Example 2 are as follows:

EXAMPLE No. 2 - CASED HOLE

Assume:

Surface Casing - 8-5/8" - 24#/ft.
Open Hole - 7-7/8"
Drill Pipe - 3-1/2"-13.30#/ft
Production String Casing -
5-1/2"-17#/ft
Cement - Class H with 1%
CFR-2 dispersant
Well Depth - 3,000 feet

1. In this case, four cement plugs should be used to properly plug this well: the two plugs shown in the drawing plus the plug at the base of the surface casing, as well as the 20-foot long plug just below ground level.
2. Cement volume calculations would be accomplished in the same manner as in Example 1, except that the volume required for the perforated interval would need to be obtained from well service personnel acquainted with the formation and its approximate cement requirements.
3. After gaining entry into the cutoff casing with drill pipe and drill bit, the mud should be circulated until its weight is stabilized. Pull the drill pipe and bit.
4. Run a cement retainer into the well using an electrical wireline and set the retainer approximately 30 feet above the uppermost perforation. An electrical wireline cable is much more flexible than the drill pipe, thus tending to eliminate the possibility of inadvertently damaging or prematurely setting the cement retainer before it reaches the desired setting point. In addition,

EXAMPLE #2
ABANDONED PRODUCING WELL
WITH PRODUCING CASING HAVING BEEN CUT OFF

the electrical wireline system includes a more accurate measuring system, thus providing greater assurance that the retainer is being set at the desired depth.

5. Run drill pipe equipped only with the "stinger" device which is to be inserted into the cement retainer.
6. Cement through the drill pipe (no cementing plugs required) until the predetermined quantity of cement slurry has been used, or a desired squeeze pressure has been attained.
7. Pick up the drill pipe to remove the "stinger" from the retainer and allow the excess cement slurry inside the pipe to flow up the annulus above the retainer. Pull 50 feet of drill pipe from the hole, and reverse circulate excess cement slurry out of the hole, leaving the 50 feet of slurry on top of the retainer.
8. Pull the drill pipe and remove the "stinger".
9. Add the required 100 feet of drill pipe containing centralizers and with the plug catcher device on the upper end of the section. Place bottom end of the drill pipe 50 feet down into the cut off casing. Place cement plug #2 using the procedure detailed in Example 1 for cement plug #1.
10. Test quality of cement for plug #2 as in Example 1 (Step #3).
11. Place cement plugs #3 and #4 in the same manner that plugs #2 and #3 were placed in Example 1.

4. STATE OIL AND GAS REGULATORY REQUIREMENTS

Regulations were obtained from each oil producing state pertaining to abandonment and plugging of oil, gas or water wells. In every state, the regulations specify that the body shall be notified of the intention to plug and abandon a well. Most states have forms for this purpose, detailing the information desired.

Of the thirty-four states considered, all but eight have specific requirements for the type and locations of plugs in the well. All of the eight who give general rules specify that a plan for plugging must be submitted and approved by the state geologist or a designated representative of the state body prior to plugging. All of the states also require an affidavit or notice of completion of the plugging for each well. Most of the states also have a representative present during the plugging, or in some manner inspect the plugging job. About half of the states require a permanent marker to be placed on the well giving details on well ownership and other pertinent data.

Figure 16 is a schematic of a wellbore showing typical plugs required by most oil-producing states. A listing of each state with a brief summary of requirements is also included in this section.

A. Summary of State Plugging Regulations

1. Alabama - State Oil & Gas Board, Rule B-7 thru B-14

Cement plug from bottom of hole to 50 feet above top of each producing formation. Bridge plug and 50 feet of cement above top of producing formation also acceptable. Plug (50 ft minimum) approximately 50 feet below all fresh water strata. Surface plug not to interfere with soil cultivation. Mud between cement plugs.

2. Alaska - Department of Natural Resources - Division of Oil and Gas - Regulation 25

Same plugs as above for Alabama except that surface will be marked with 4-foot high steel marker set in concrete, instead of cutting off casing below ground.

3. Arizona - Oil and Gas Conservation Commission - Rules 201-204

Cement plug from bottom of hole to not less than 50 feet above each producing formation open to wellbore. Cement plug from 50 feet above to 50 feet below each fresh water strata. Surface plug not less than 20 feet, with a steel marker to locate well. Mud between cement plugs.

Figure 16. Schematic of typical plugs required by most states.

4. Arkansas - Oil and Gas Commission - Rule B-6 thru B-11

Cement plug from bottom of hole to 30 feet above each producing stratum. Cement plug 50 feet minimum at about 50 feet below fresh water-bearing stratum when not behind surface casing. If water is behind casing, place 30-foot cement plug inside casing. Mud between cement plugs.

5. California (Onshore) - Division of Oil and Gas - Title 14 - Article 3, Rules 1723 - 1723.7

Inside casing - cement plug across producing zone and minimum of 100-foot cement plug above each zone if possible, plug above shoe or intermediate casing and from 100 feet above to 100 feet below base of fresh water strata.

5a. California (Offshore) - Title 14 - Rules 1745-1745.10

In uncased hole, cement plug shall extend from total depth (or 100 feet below producing zone) to 100 feet above zone. If open hole below casing, cement plug shall be from 100 feet above casing shoe to 100 feet below. Cement plug opposite all perforated intervals to 100 feet above. Cement plug extending 100 feet below base of fresh water (or casing stub) to 100 feet above. Surface plug of 100 feet minimum with the top 50 to 150 feet below ocean floor. Plug must be tested by 10,000 pounds weight.

6. Colorado - Department of Natural Resources - Oil and Gas Conservation Commission - Rule 327

Place plugs in such a manner that oil, gas, water or other substances are confined to their original reservoirs. Well can be marked with steel marker, or casing cut off below ground and capped.

7. Florida - Department of Natural Resources - Rules 16C - 2.07 thru 16C - 2.11

In uncased portions, plug shall extend from 100 feet below to 100 feet above producing zones. Place 100-foot cement plug opposite any formation known to produce hydrocarbons within 10 miles of well. If casing is in well, place plug 100 feet above and below casing shoe or casing stub. Cement plug opposite all perforated intervals. Surface plug of 25 feet cement on land; or 150 feet under water.

8. Georgia - Department of Natural Resources - Geologic & Water Resources Division - Rules B-7 thru B-12

Cement plug from bottom of hole to 15 feet above each producing formation. Place 50-foot cement plug at 50 feet below fresh water strata. Cement plug at surface in manner not to interfere with soil cultivation.

9. Iowa - Iowa Geological Survey - Chapter 84 - Code of Iowa

Plug well with mud, cement or plugs, singly or in combination as may be approved by State Geologist. If no log available, well to be plugged with cement from bottom to top. Cut off casing below plow depth.

10. Illinois - Department of Mines and Minerals - Division of Oil and Gas - Rule XI and XI-A

Log must be furnished or well plugged completely with cement. Otherwise, place cement plug opposite producing formation to 20 feet above. If partially cased, place cement plug from below casing seat to 20 feet above. Protect each coal seam over 30 inches thick (above 1000 feet depth) by cement plug from 100 feet above seam to 50 feet below. Cement plug from 10 feet below surface casing to 15 feet above base. Cut off surface 2 feet below ground and cap with cement.

11. Indiana - Department of Natural Resources - Division of Oil and Gas - Rule 33.

When a well is ready for plugging, a State Department field representative is called, and he tells the well owner where to place the plugs. Generally, cement plugs are placed to protect the fresh-water strata, to seal off the production zones and to plug the surface. Surface casing is cut off below plow depth. If coal seams 24 inches or thicker are present above 1200 feet depth, a cement plug is placed from 50 feet below the seam to 100 feet above.

12. Kansas - State Corporation Commission - Rule 82-2-302 to 304

Cement plug from bottom of well to top of each formation with a 25-foot minimum at top of each producing formation with heavy mud below. Place 25 foot cement plug about 25 feet below each fresh-water strata. Balance of hole filled with drilling mud not less than 36 viscosity (API Full Funnel Method). Cement plug at top of surface casing cut off to permit soil cultivation.

13. Kentucky - Department of Mines & Minerals - Division of Oil & Gas Rule 1.06 and 1.07

Cement plug from bottom of hole to 15 feet above each producing formation. Place cement plug of 15 feet immediately below each fresh-water strata. Cement plug at surface placed so as not to interfere with soil cultivation. Uncased rotary hole plugged with mud to base of surface casing, then place 15-foot cement plug. Cap casing as given above.

14. Louisiana - Department of Conservation - State Order No. 29-B
Section XIX

Plugging program shall be approved by Commissioner of Conservation prior to plugging. Cement plugs 100 feet minimum length shall be placed across perforated interval. Place 100-foot minimum cement plug from 50 feet below shoe of surface casing to 50 feet above. Cement plugs shall be from 100 feet below deepest fresh-water sand to at least 150 feet above sand base. Place 30-foot cement plug in top of surface casing. On land, cut off casing 2 feet below plow depth; on water, cut casing ten feet below mud line. Balance of well filled with mud.

15. Michigan - Department of Natural Resources - Geological Survey
Division - Circular 9, Rules 801-811

Plugging instructions will be specified by the State Supervisor of Wells. Plugging must confine oil, gas or water to the formation in which they occur. Surface pipe will be cut off below plow depth and capped.

16. Mississippi - State Oil and Gas Board - Rule 27 and 28.

Uncased holes - place cement plugs of 50-foot minimum length to protect each producing formation and at about 50 feet below all fresh-water sands. Place 50-foot cement plug at bottom of surface casing and at surface in manner not to interfere with cultivation.

17. Missouri - Department of Natural Resources - Oil and Gas Geology
Section - Rule 50 - 2.060

Well shall be plugged in a manner that will permanently confine all oil, gas and water in the separate strata originally containing them. Plugging shall be accomplished using mud, cement and plugs singly or in combination as may be approved by the State Geologist. Producing formations shall have cement plug from base of formation to 25 feet above top formation. Specific directions given if radioactive source is left in hole.

18. Montana - Oil and Gas Conservation Division - Rule 232

Plugging program must be submitted by operator and approved by the State Petroleum Engineer prior to plugging. Wells shall be marked with a permanent marker rising 4 feet above ground or cut off for cultivation if land owner desires.

19. Nebraska - Oil & Gas Conservation Commission - Rule 3(30)

Plugging program must be submitted and approved by Commission, but plugging must be done so that oil and gas or water will be confined to the reservoir in which it originally occurred. Mud, cement or a mechanical plug may be used.

20. Nevada - Oil and Gas Conservation Commission - Rules 200 thru 207

Plugs can be mud, cement and plugs, used singly or in combination, as may be approved by the Commission. Cement plugs shall be a minimum of 25 sacks of cement. A plug will be placed every 1,000 feet in uncased holes to prevent mud settlement, and at the base of any casing left in the hole. A steel well marker is placed at the surface.

21. New Mexico - Oil Conservation Commission - Section D - Rules 201-204

Well shall be plugged in a manner which will permanently confine all oil, gas and water in the separate strata originally containing them. Plugging shall be accomplished by mud, cement and plugs, singly or in combination, as approved by the Commission. Location of well shall be shown on steel marker above ground surface.

22. New York - Department of Environmental Conservation - Title 6 - Chapter 5, Part 555.

Well owner must give notice of plugging and State Department will send representative to witness plugging. Cement plug will be placed from bottom of hole to 15 feet above shallowest producing formation. A 15-foot plug will be placed at bottom of any casing left in hole and about 50 feet below deepest potable water sand. Mud to be in well between cement plugs. Cap casing so it will not interfere with cultivation.

23. North Dakota - The Industrial Commission of North Dakota - Rules 201-204

Well shall be plugged in a manner which will confine permanently all oil, gas and water in the separate strata originally containing them. This shall be done using mud, cement and plugs, singly or in combination as may be approved by the Commission. Surface casing shall be cut off below plow depth.

24. Oklahoma - The Corporation Commission - Oil & Gas Conservation Division - Rules 3-400 thru 3-408

Well will be plugged under the supervision of a representative of the Conservation Division. In uncased hole, cement plugs shall be placed from 50 feet below each productive zone to 50 feet above base, and from a point 50 feet below top of the formation to 50 feet above the top of the zone. If producing zone is cased and properly cemented, a bridge plug capped with 10 feet of cement may be set at top of formation. All fresh water strata shall be protected by a cement plug 50 feet below and 50 feet above casing shoe, or 50 feet below lowest fresh water sand to 50 feet above surface casing shoe. Any uncased hole below any casing shall be filled with cement to at least 50 feet above casing shoe. Well location and data shall be permanently marked on the surface.

25. Ohio - Department of Natural Resources - Division of Oil and Gas - Rule 1509.14 - 1509.19.

Well shall be plugged by filling hole with sediment or properly prepared clay to a point above the producing zones. One or more seasoned wood plugs (or a lead plug) shall be driven on top of sediment. Then 100 feet above the plug shall be filled with sediment or clay. After withdrawing surface casing, wooden plug or iron ball shall be placed on the casing seat and covered with 50 feet of rock sediment or prepared clay. Any fresh water strata shall be plugged in like manner. Coal seams shall be sealed in like manner from 50 feet below the seam to 20 feet above, then a wooden plug placed and the hole filled for 30 feet more. A well through a mine must leave casing from 30 feet below mine floor to 15 feet above roof, and fill with concrete from 100 feet below mine to top of casing. A wooden plug is placed at lower point and at top of casing, with another 20 feet of concrete placed on top wooden plug.

26. Pennsylvania - Department of Environmental Resources - Oil and Gas Division - Article II - Section 205-207.

For wells not underlaid by coal seam, well shall be filled with sand dumpings or mud, as Division may approve, from bottom of well to a point 20 feet above top of lowest production zone. At this point, place a plug of cement for at least 20 feet. Between this cement plug and 20 feet above highest production stratum, fill in same manner described above. Place a bridge approximately 30 feet below water casing and put 10-foot cement plug on top of bridge. Withdraw casing and then place final plug from 10 feet below surface casing to surface using mud or sand dumpings.

In a well passing through coal seams, production zones shall be plugged as described above. A plug shall be placed 10 feet below bottom of smallest coal protecting string and hole filled with 20 feet of rock or gravel. Vent pipe shall be placed on gravel to remove any free gas. Space around vent pipe shall be filled with 5 feet of sand pumpings, then with cement to 25 feet above highest workable coal seam.

27. South Dakota - Department of Natural Resource Development - Chapter 52:02:04

Wells shall be plugged by following a plugging schedule approved by the office of the State Geologist. Well shall be marked with a marker showing well information.

28. Tennessee - State Oil & Gas Board - Chapter 1040-2-9.

Wells shall be plugged with a mud fluid of sufficient weight to offset the hydrostatic pressure of any formation penetrated. Cement plugs shall be so placed to prevent the commingling of oil, gas or water from one zone to another, and to isolate potentially minable coal seams and other potentially extractable minerals. All downhole plugs must be touched to insure they have been properly placed.

29. Texas - Texas Railroad Commission 051.02.02.014 - Rule 14

All oil, gas or geothermal resource bearing formations must be protected. Place a 100 foot cement plug immediately above the uppermost perforated zone or produced horizon. If screen or perforated liners cannot be removed, place plug across zone to 100 feet above top of liner. If production casing is removed, place a cement plug from 50 feet below surface casing shoe to 50 feet above. If fresh-water horizons are exposed, place cement plug from 50 feet below base of lowest sand to 50 feet above top of sand. This plug must be checked for location by landing. Place 10-foot cement plug at surface. Use mud of 9.5 lbs/gal or better in other portions of well.

30. Utah - Department of Natural Resources - Division of Oil, Gas and Mining - Title 40-6 - Rules D-1 thru D-4

Cement plug placed from bottom of well to top of producing formation, and a cement plug of 100 feet placed immediately above each producing formation. Place cement plug from 50 feet below fresh water zone to 50 feet above zone. A 50-foot cement plug shall be placed at the base of the surface string, and a 100-foot cement plug shall be centered across any casing stub. Place 10 sacks of cement at surface of well. Fill between plugs with heavy mud-laden fluid.

31. Virginia - Department of Labor and Industry - Mining Laws - Article 4, Rules 45.1 - 128 thru 131.

Well shall be plugged in same manner as specified for Pennsylvania.

32. Washington - Department of Natural Resources - Oil & Gas Conservation Commission - Rules 23-26.

Place cement plug from bottom of cased hole to 15 feet above perforations open to producing zones. A 15-foot cement plug shall be placed at approximately 50 feet below all fresh-water strata. Place cement plug at surface so as not to interfere with cultivation. Fill between plugs with approved heavy mud. An uncased hole shall be plugged between salt and fresh water zones. Mud may be used to a surface string covering fresh water sands, but a 15-foot cement plug will be placed in lower part of surface casing. Weld steel plate to top of casing at surface.

33. West Virginia - Department of Mines - Oil and Gas Division - Chapter 22-4 - Rules 2.11 - 2.14.

Well shall be plugged in such manner as to prevent migration of oil, gas or water to any strata other than their original strata. Cement or other suitable plugs may be used. Location and length of plugs to be approved by Department.

34. Wyoming - Oil & Gas Conservation Commission - Rules 312-315

Well will be plugged in a manner sufficient to protect all fresh water bearing formations and possible or probable oil or gas bearing formations. Plugging plans must be approved by the State Oil and Gas Supervisor before plugging is done.

5. APPENDIX

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B. ACKNOWLEDGEMENTS

The authors acknowledge with gratitude the assistance given by the following people in the preparation of this report:

Mr. Tom Pugh - Assistant Division Engineer, Halliburton Services, Midland, Texas
Mr. John Bannister - Assistant Division Manager, Halliburton Services, Midland, Texas
Mr. Leon Davis - Mobil Oil Company, Midland, Texas
Mr. Joe Morris - Mobil Oil Company, Midland, Texas
Mr. John Cook - Division Manager, Halliburton Services New Orleans, Louisiana
Mr. Jim Leisk - T. W. McGuire & Associates, Shreveport, Louisiana
Mr. Bill Luck - Northern Natural Gas Co., Lyons, Kansas
Mr. Marvin Klein - Division Engineer, Halliburton Services Wichita, Kansas
Dr. Robert F. Walters - Walters Drilling Company, Wichita Kansas
Mr. Robert T. Gaut - Consulting Engineer, Oklahoma City, Oklahoma
Mr. Percy Hall - District Manager, Oklahoma Corporation Commission, Oil and Gas Division, Duncan, Oklahoma
Mr. Ben B. Bradford - Development Specialist, Cementing Services, Dowell Division of Dow Chemical, Tulsa, Oklahoma
Mr. Jerry Calvert - Engineer, Dowell Division of Dow Chemical, Tulsa, Oklahoma
Mr. Dale Hendricks - Regional Engineer, Halliburton Services, Houston, Texas
Mr. Joe D. Ramey and Mr. Dan Nutter - State of New Mexico, Oil Conservation Commission, Santa Fe, New Mexico
Mr. Phil Russell and Mr. Jim Herring - Oil and Gas Division, Texas Railroad Commission, Austin, Texas

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