FINAL

TECHANICAL MANUAL
INJECTION WELL ABANDONMENT

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1. INTRODUCTION

Provisions have been included in the Underground Injection Control (UIC) regulations (40 CFR Section 122.42(f) and Section 146.10) to ensure that abandoned injection wells do not endanger underground sources of drinking water. The regulations specify that the well be plugged "with cement in a manner which will not allow the movement of fluids either into or between underground sources of drinking water." The regulations also contain specific criteria regarding techniques available for setting a cement plug(s) and the need for establishing static equilibrium in the well prior to setting the plug(s).

The purpose of this document is to provide technical guidance to assist the regulator in reviewing proposed well-abandonment plans. Emphasizing that proper abandonment consists of more than cement plug placement, the document discusses all aspects of well abandonment.

Many procedures and materials are available for well abandonment; their selection is influenced by a number of factors and depends on the specifics of the situation. Frequently, there is no one best method. The approach taken in this document is to identify and to discuss the considerations needed to plug and to abandon wells of Classes I, II, or III. This approach will enable the regulator to make decisions regarding a specific abandonment plan. The general sequence of events to be followed when abandoning a well is illustrated in Table 1.

The information contained herein was developed from numerous sources. A literature search was conducted which yielded a number of pertinent articles and reports; however, it was found that while there is considerable documentation of well abandonment in the oil and gas industry, virtually no written material exists which specifically addresses problems associated with Class I and Class III injection-well abandonment. Consequently, much of the material contained in this document was developed through discussions of abandonment problems with experienced service company representatives.

In this document four major chapters follow. Chapter 2 considers injection-well construction, general considerations important to abandonment, and special Class III abandonment considerations. Chapter 3 discusses the preparation of the well prior to plugging. Procedures for plugging are covered in Chapter 4; Chapter 5 concludes the report with an analysis of abandonment costs.

TABLE 1
SEQUENCE OF EVENTS FOR ABANDONMENT OF INJECTION WELLS

Event	Activity
1	Review drilling records and well-construction records
2	Review operations records
3	Review regional hydrogeologic data
4	Determine plugging intervals
5	Develop preliminary plugging and abandonment plan
6	Remove tubing, packers, and salvagable casing, as applicable
7	Inspect well casings and primary cement for corrosion breaks and voids
8	Implement all necessary well repairs and clean out procedures
9	Finalize abandonment plan, i.e., make any necessary modifications based on results of Events 7 and 8
10	Establish static equilibrium of plugging fluid, if necessary
11	Install bottom plug
12	Allow cement adequate time to set, if necessary
13	Pressure test plug for basic integrity
14	Install intermediate plugs, if necessary
15	Repeat Events 12 and 13 for each intermediate plug
16	Install top plug

2. WELL ABANDONMENT: BASIC PROCEDURES AND CONSIDERATIONS

The proper abandonment of injection wells must provide long-term protection against the migration of displaced formation fluids or injected fluids into underground sources of drinking water. To accomplish this objective, the abandonment process uses procedures designed to ensure the well's basic mechanical integrity and to emplace one or more effective cement plugs at selected depths. The abandonment process can be categorized as two phases: (1) well preparation and (2) well plugging.

Well preparation involves all activities necessary to ready the well for plug setting and final abandonment. The location of aquifers requiring protection and the means of isolating these aquifers need to be determined. In many cases, the well can be entered and inspected to ascertain its condition. Tubing, packer, salvageable casing, and other materials can be removed. Remedial activities such as well cleanout, fishing, milling, or squeeze cementing may be necessary to ensure well integrity and the effective placement of the cement plug(s).

Plugging involves placing cement in a well either over its entire depth or at a series of discrete locations. If a series of plugs is set, a plugging fluid (generally drilling fluid) is left in the well between the plugs. In addition to cement plugs, mechanical plugs can also be used. A variety of techniques which generally involve pumping the cement through the drill pipe or tubing are available for placing the cement in a well.

The procedures used for proper abandonment of an injection well are dependent on the construction characteristics of the well, particularly the casing and cementing program and completion method used; however, certain design characteristics can be altered in final preparation for abandonment. In many cases well preparation involves the removal of tubing and packer, if present, damaged or salvageable casing, and/or screens or liners; consequently, the regulator may be reviewing a plugging plan for a well configuration substantially different than that shown in the well design documents. The most common well configurations after well preparation (i.e., tubing, packer and casing removal) are illustrated in Figure 1.

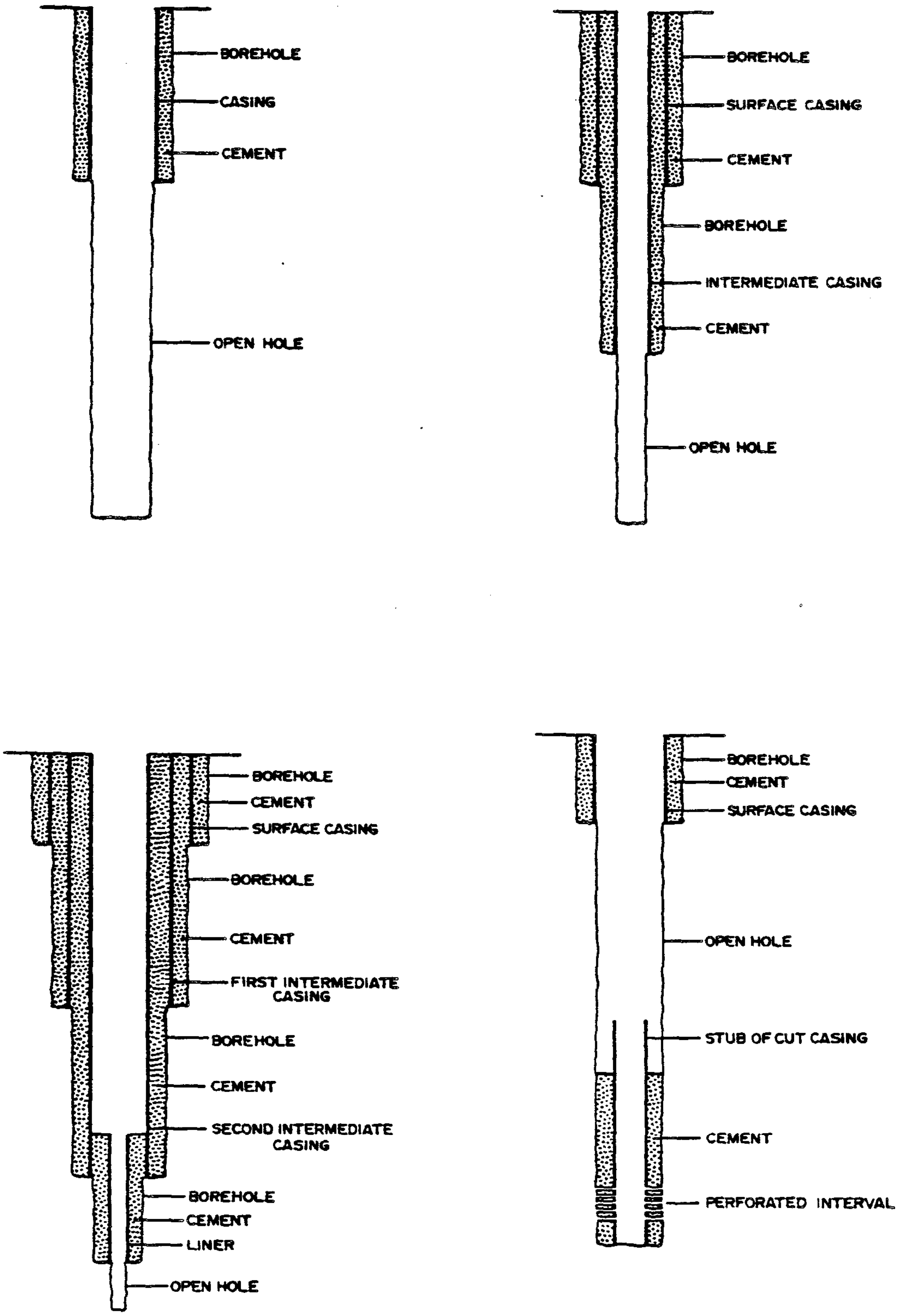


Figure 1. Common well configuration after well preparation

2.1 GENERAL CONSIDERATIONS DURING INJECTION-WELL ABANDONMENT

An effective well-abandonment plan must address all aspects of the abandonment process and be formulated with regard to a number of varied considerations. These considerations can be roughly categorized as follows:

- Plug location
- Control of injection-zone pressure
- Conditions of the well
- Removal of well materials
- Positioning and solidification of the plug
- Establishing static well conditions
- Equipment availability and expense

These considerations impact a number of aspects of an abandonment plan and accordingly should be taken into account when formulating the specifics of both the preparatory and plug setting phases of injection-well abandonment. Frequently, the issues are interrelated, and decisions regarding one issue affect decisions regarding other issues. The solutions to these problems are site specific, requiring flexibility when adapting well-abandonment procedures to each injection well.

2.1.1 Plug Location

A variety of approaches are used to determine plug location (Herndon and Smith, 1976; and Walker and Cox, 1976). It is generally agreed that placement of a continuous plug of cement from the top to the bottom of the well is not necessary. The added placement of cement provides few additional benefits and the cost is prohibitive. A series of plugs separated by plugging fluid is often sufficient.

Plugging plans may specify placing a plug(s) to isolate the injection zone. Many states require this plug be set over the entire depth of the injection zone and extend 50 to 100 ft (15 to 30 m) into overlying confining beds. While the need to isolate the injection zone from overlying formations is obvious, the practice of setting a plug over the entire length of the injection zone should be examined carefully for any specific abandonment plan. In some instances, injection can occur over hundreds to a thousand feet of formation. The benefits of placing cement over the entire zone needs to be examined relative to expense, noting that service companies recommend that no more than 500 ft (152 m) of plug be placed at any one time. In some instances it may be appropriate to place a plug only at the top of the injection zone and extend it into the overlying confining bed(s), leaving a plugging fluid in the bottom of the hole.

In wells in which some portion of the intermediate or injection casing has been removed, consideration may be given to placing a plug on top of the casing stub left in the hole. Such a plug will prevent migration of fluids in the annular space as well as between cased and uncased portions of the well.

After the extent of the bottom plug and the location of any intermediate plugs are surmised, the location of plugs which will isolate underground sources of drinking water should be determined. Many states require the placement of cement at the base of the previously installed surface casing to protect fresh water. The option exists for setting one plug over the entire depth of the well in which water containing 10,000 ppm TDS is found; however, as with the bottom plug such an approach may be excessively expensive with little added benefits. More commonly, cement plugs are placed above and below each aquifer with a plugging fluid left between. Alternately a series of plugs are set across the aquifer, extending 20 to 50 ft (6 to 15 m) above and below it. A plug of at least 20 to 30 ft (6 to 9) is almost always set at land surface. When evaluating the various plug-location options, the relative cost of each should be considered and the protection provided each aquifer should be examined, paying particular attention to the potential for the long-term development of leakage through the casing into and out of the borehole.

2.1.2 Injection-Zone Pressure

Control of injection-zone pressure can be an important consideration during abandonment. Many injection fluids contain corrosive and otherwise hazardous materials that should not circulate back up into the well prior to plugging. Consequently, flow from the injection zone should be suppressed prior to undertaking any downhole activities.

Eventually the operator will be required to establish static conditions within the well; implicit is control of flow from the injection zone (see Section 2.1.6 on static well conditions). However, static conditions in the well are not required until immediately prior to setting the plug(s). A number of preparatory activities including removal of tubing, fishing operations, well logging, casing removal, and remedial activities, will necessarily precede plugging operations, and injection-zone pressure should be controlled during all these activities. A number of techniques are available for pressure control. Probably the most applicable is the use of weighted drilling fluids or workover fluids which allow easy access into the well.

2.1.3 Well Condition

The condition of the injection well immediately prior to abandonment is an important factor in determining which procedures are necessary to ensure adequate and safe abandonment. Careful examination of well conditions prior to formulation of an abandonment plan may identify the necessity for remedial actions or the alteration of otherwise normal abandonment procedures.

Injection-well casing and cements are subject to corrosion and degradation by injection fluids and formation fluids. Corrosion of the well casing or degradation of primary cement can significantly impair any attempt to prevent leakage up the borehole. The placement of plugs to prevent migration of fluids inside the well casing will serve little purpose if injection fluids or formation fluids are able to migrate through a poorly cemented annular space between the casing and the formation.

Injection wells are also subject to mechanical stresses during installation and operation that may result in casing damage and leakage. The deformation of casing may also result, weakening the casing, or making the entry and normal functioning of tools necessary to plugging operations difficult. In addition, the well may contain debris that may significantly compromise the effectiveness of the abandonment program.

2.1.4 Removal of Well Materials

Frequently there are compelling reasons to remove equipment from the well during abandonment. However, before removing any well equipment it is important to ascertain the impact of such action on the effectiveness of well-abandonment procedures.

The injection tubing is commonly removed since tubing left in the hole serves no practical purpose after abandonment and can greatly inhibit downhole activities such as fishing or milling, as well as procedures used to place cement slurry in the hole. There is almost always a strong economic incentive associated with salvaging the injection tubing.

Associated with the decision to remove the injection tubing is the decision concerning the removal of the packer into which the tubing may be inserted. Many packers are designed to be retrievable, whereas others are not and their recovery can require considerable expense and effort. If the packer used in the well contains a valve which closes upon removal of the tubing, the packer must be removed to permit the placement of cement into the well below it. This removal may be unnecessary if the plug was placed through the injection tubing before it was removed from the packer. If the packer has an open center or valve which permits fluid flow down and through it, the necessity of removing the packer is generally dependent on the method used to place the cement slurry for the bottom-most plug.

In addition to the removal of tubing and packer, the operator and regulator may also be faced with decisions relating to the removal of casing from the well. In some instances, intermediate casing may not be cemented in place. It may be possible to cut and salvage the uncemented portion of casing. The impact of this practice on well abandonment is varied and should be evaluated with regard to the specifics of the particular abandonment program.

Casing left in the hole helps to contain any plugging fluids left in the well between the plugs. However, if the annulus around this casing is uncemented, no barrier exists to prevent migration of fluids which might escape through any plug or primary cement. It may be necessary to squeeze cement this annular space to provide exact protection.

By removing well casing, lost circulation of fluid into the exposed formations may make establishing static conditions in the well prior to setting the plugs difficult. In addition, difficulty may arise in running the plug setting tools into an open hole and then back into a casing string left in a lower portion of the well.

Removal of screens or liners placed in the bottom of the hole across the injection zone may also be required. While these materials generally have little economic value, their removal may be preferred to allow better placement of the plug across the injection zone.

2.1.5 Proper Positioning and Solidification of Cement Plugs

Design and placement of cement slurries to achieve a solidified and properly positioned plug, is one of the major concerns of any well-abandonment plan. The installation of effective plugs is surrounded by a number of potential problems and requires careful planning and considerable operator skill. The difficulty associated with obtaining effective plugs has been illustrated in a survey of abandoned wells performed in Michigan (Alquire, 1973). Twenty abandoned wells reported to contain a total of 49 plugs were redrilled to verify the position and condition of cement plugs placed during previous well abandonment activities. Eleven of the plugs were never found, and six plugs were found to consist of soft cement, containing only a few limited streaks of hard cement. In five of the wells examined, either the plugs placed in the well could not be located or they consisted of soft cement; in ten of the wells the lower plug was either missing or consisted of soft cement.

A number of factors influence the installation of effective plugs. One of the first considerations is the design of the cement slurry. Since the hydration and setting of cements can be significantly affected by borehole conditions such as temperature and pressure, cement slurries are designed with attention to these factors. Other cement-slurry design considerations include compensating for fluid losses from filtration and ensuring proper viscosity. In many instances in which the plug is set in an open hole, it may be necessary to adjust the chemical composition of the slurry to prevent any adverse influence on the competence of the formation.

The second major consideration for installation of effective plugs is the placement of the slurry without contamination of the cement. Drilling fluids and their additives, natural brines, other formation fluids, and injection fluids can act to inhibit or prevent hydration of the cement slurry.

The potential for contamination of the cement slurry is minimized by establishing and maintaining static conditions in the well prior to and during the plug setting. Spacer fluids can be used to separate the cement slurry and fluid in the hole during placement. The surface of the casing or borehole wall should be cleaned to prevent cement contamination and to ensure the proper bonding between cement and casing or formation.

2.1.6 Establishing Static Well Conditions

Establishing static conditions in the well prior to placement of the cement slurry is essential. Any motion of fluids in the well during and immediately after placement of the cement slurry can result in contamination and/or migration of the cement slurry.

Static conditions are established in the well by controlling all flow of fluids into or out of the well. When the well is completely cased, this generally involves control of pressures in the injection zone. However, if a portion of the casing has been removed, the fluid flow from and/or into the exposed formations also has to be controlled. This is generally accomplished by using a drilling fluid specially weighted to overcome formation pressures or to prevent lost circulation.

In addition to suppressing flow into and out of the well, the weight of the plugging fluid throughout the well should be equalized so that pressure gradients do not exist within the column of fluid itself. Equalizing the weight of fluid within the well facilitates placement and setting of the cement slurry. Because density differences between the plugging fluid and the cement slurry can upset the hydrostatic balance established in the well, the cement slurry is designed to minimize density differentials between the slurry and well fluids.

2.1.7 Long-Term Integrity

The design of a cement plug needs to provide for the long-term resistance to degradation and to downhole temperature and pressure. Similarly, plugging fluids left between plugs should be chemically and physically stable and be capable of staying in place indefinitely. Finally, the potential for corrosion of casing left in place should be minimized. Plugging fluids need to be noncorrosive and frequently require treatment with biocides and corrosion inhibitors.

2.1.8 Equipment Availability and Expense

All decisions made during development of an abandonment plan should be made with regard to expense and to availability of equipment. In many instances, decisions concerning a particular aspect of abandonment involve a choice between materials or techniques which offer only marginal improvements in integrity. Frequently, compromises inherent in one decision can be easily offset by more rigid specifications for another facet of the abandonment procedure.

Regional availability of equipment such as workover rigs should be factored into abandonment decisions. In some instances, equipment may not be available to complete the job as specified due to the peculiarities of well design.

One notable example is the large diameter municipal injection wells for which it can be impossible to find properly sized cement baskets, bridge plugs, or cement retainers. Plugging procedures for such wells may have to be modified, or special equipment may need to be fabricated.

2.2 SPECIAL CONSIDERATIONS FOR ABANDONMENT OF CLASS III WELLS

There are special considerations which influence the procedures and resources required to abandon Class III injection wells. These special considerations result from the differences in design, construction, and environment in which these wells are placed. In some cases, Class III wells require less sophisticated and inexpensive procedures for abandonment. Many wells with reduced depths and small diameters are easily and inexpensively abandoned by cementing from bottom to top using no bridge plug or only an inexpensive rubber plug. In other wells, unique environments or special designs require more sophisticated procedures to compensate for the special problems associated with their abandonment.

Some of the highly specialized problems encountered during abandonment of Class III wells are illustrated by the special consideration associated with the abandonment of geothermal wells. Geothermal wells are completed in highly corrosive environments with temperatures in excess of 500°F (260°C) and require special consideration to the long-term integrity of the well. Cement plugs placed using conventional cement mixtures may initially exhibit satisfactory compressive strength; however, with continued exposure to high temperature, the compressive strength of the cement degenerates, resulting in increased cement permeability. The high temperature encountered in these wells may cause the premature setting of the cement slurry during placement. Drilling-fluid displacement can also be a problem during placement of the cement slurry. High temperatures tend to thicken the drilling fluid, resulting in the contamination of the cement slurry and the reduced removal of drilling fluid from the casing or borehole wall.

Other problems encountered during abandonment of Class III wells are illustrated by the special considerations associated with the abandonment of injection wells used for solution mining. During the operation of these wells, highly corrosive solutions are frequently injected. These solutions can damage casing and cement in the borehole. Areas in which solution mining has been extensively practiced are frequently associated with subsidence. Subsidence can present particularly difficult problems for obtaining a secure abandonment. Movement of formations during subsidence can fracture and increase the permeability of cement plugs left in abandoned wells. Consequently, the use of plugging fluids instead of solidified cement is frequently preferred during well abandonment. Cementing wells used for solution mining of salt can present an additional problem; if the cement comes in contact with the salt formation, it can dissolve the formation and therefore, require special salt saturated cements.

It is beyond the scope of this report to document all the special problems associated with the numerous Class III wells in operation today. Specification of an adequate abandonment plan for these wells require a detailed knowledge of the specifics of each well. The details of each case must be evaluated to ascertain their impact on the various aspects of abandonment, and the abandonment plan developed accordingly. For further information regarding the design and construction characteristics of Class III wells, see the manual on Injection Well Construction Practices and Technology prepared for the UIC program (Geraghty & Miller, 1982).

3. WELL PREPARATION

A variety of preparation activities are necessary to ready the well for plugging and abandonment. Well preparation involves activities necessary to ensure not only a proper environment for setting the plug but also the general integrity of the well prior to plugging. As such, these activities are critical to achieving an abandonment that will ensure the long-term protection of underground sources of drinking water. These activities include:

- Collection of available data
- Removal of tubing and packer
- Well inspection
- Well cleanout
- Selection of plugging fluid
- Establishment of mud system
- Formulation of cement-slurry composition

3.1 COLLECTION OF AVAILABLE DATA

The first step in the abandonment process is to investigate available records to determine the construction details of the well and to characterize the local geology. An adequate knowledge of well construction and local geology is essential for designing an abandonment plan which is suitable for the individual well. This information influences decisions made during every aspect of abandonment. Most of the needed information should be available from permit applications, well completion reports, and operation records.

Sufficient information concerning local geology must be obtained to determine the location and characteristics of underground sources of drinking water and the formations separating them. Location and characteristics of the injection zone and confining bed(s) are equally important. Characteristics of intervening geologic formations including permeability, structural competence, and water quality are also required. Such geologic information provides much of the basis for determining plug location, cement-slurry and plugging-fluid system design, and casing removal programs. Much of the required information should be available from geologic and geophysical logs made during well construction.

Necessary construction details include the design of all casings with a complete description of the cementing programs used to install all casings. Particular attention should be given to factors which might influence the long-term integrity of the well such as corrosion resistance of cement and casing materials used during construction. The exact configuration of the bottom-hole completion must be clearly identified, as well as any tubing and packer equipment used in the well.

Finally, the characteristics of the injection fluid and conditions in the injection zone must be fully documented. Injection fluid characteristics are essential to the design of a properly setting cement slurry as well as to the design of the mud system used in the well during abandonment. Knowledge of injection-zone pressure is necessary to ensure it is properly controlled during well preparation and plug setting.

3.2 TUBING AND PACKER REMOVAL

The first step in the actual preparation of the well is removal of the injection tubing, if present. The packer can also be removed at this time. Tubing and packer removal involves several activities including set up of a workover rig over the well, establishment of a workover-fluid system in the well, fluid circulation for well cleanout, and equipment removal.

Selection of the workover rig is dictated by lifting requirements; deeper wells generally demand larger rigs. Rigs are equipped to pull the pipe string, to turn the pipe while in the hole, to stand pipe in a derrick, and to circulate the workover fluid in the well or control pressure with high-pressure pumping equipment (Petroleum Extension Service, 1971 a, b).

An appropriate workover fluid consisting of brines or specially prepared muds is placed in the tubing/casing annulus and circulated to remove debris such as congealed drilling fluid or sand particles which can collect in the annulus above the packer and lead to sticking pipe. In addition, the workover fluid can provide formation pressure control and wall support when the open hole is encountered.

After circulating of the workover fluid, the tubing is unseated from the packer and removed. If residual particles remain packed in the well or if the release mechanism of the packer is frozen, the tubing can be cut off above the packer and removed. The workover fluid can be circulated again directly above the packer. Packer removal can then be accomplished. If efforts to this point are unsuccessful, the packer can be ground with a carbide-tipped mill. If a permanent or drillable packer is used, the tubing is pulled and the packer is drilled or milled up and the debris is circulated out of the hole.

3.3 WELL INSPECTION

After the workover-fluid system has been established, and the tubing (and packer if required) has been removed, the actual condition of the well should be determined. The primary objective of the well inspection is to examine the mechanical integrity of the well. The condition of casing regarding the presence of, or potential for leakage should be determined; this includes examining the casing for corrosion and any structural deformation. Structural deformations can be important in determining the potential for leakage and also the ability to lower plug-setting tools into the well. In addition, the integrity of casing cements should be verified. Deteriorating or improperly placed cements can result in annular migration of fluids which can significantly compromise the efficacy of an abandonment program.

A variety of techniques are available for determining the mechanical integrity of a well. Pressure tests can be used to verify the overall integrity of the well. The condition of the cement and the annular migration of fluids can be examined by using tracer tests as well as other geophysical logging techniques such as noise and cement-bond logs. Casing condition and leaks can be investigated using temperature surveys, electromagnetic casing inspection logs, and caliper logs. Weight loss specimens or other corrosiveness testing techniques may have been used during well operation, and examinations of these test records can help identify any corrosion which might have occurred during well operation.

The choice of specific investigation techniques depends on the expected condition of the well and should be made accordingly. For more detailed discussions concerning these techniques, see the guidance document on Mechanical Integrity Testing of Injection Wells prepared for the UIC program (Geraghty & Miller, Inc., 1982).

3.4 WELL CLEANOUT, SALVAGE, AND REPAIR

Prior to plugging, various cleanout, salvage, and repair techniques may be required to gain adequate access to the hole to prevent fluid migration and to remove salavageable material. The presence of formation material, surface debris, buckled or leaking casing, or downhole equipment can prohibit access to the plugging zones or limit the effectiveness of plugging.

3.4.1 Casing Removal/Cutting

Parts or all of casing strings can be removed before plugs are set, depending on the type of injection well and the primary or secondary cementing programs used in construction. For example, casings cemented only at the shoe allow the casing to be cut off at that point, pulled, and salvaged. The decision to remove or salvage casing is part of the overall abandonment strategy and should be compatible with formation conditions.

Specialized tools are used in casing cutting operations and are selected for specific applications. Casing characteristics, condition, and internal/external accessibility will influence tool selection. Jet, chemical, mechanical, and explosive cutters are available for different applications applied both inside and outside the casing.

3.4.2 General Cleanout and Fishing

During well abandonment, materials ranging from small particles to large objects may have to be removed from the well. (Fish and junk are the general terms applied to anything left or dropped in the hole.) Generally, sand, formation materials, cuttings, and other small particles can be removed by circulating a workover fluid. Any debris in the hole such as cutter parts, parts of well equipment that have been left in the hole, metal pins, and metallic cuttings that cannot be removed by circulation is generally removed by using specialized junk retrievers.

Several types of junk baskets are used. The simplest is the finger-type basket which is a cylindrical device with protruding flexible fingers. The basket is lowered over the junk and when weight is applied to the tool the junk is trapped inside. This type is best suited for removing small solid pieces lying on the bottom of the hole. When junk is imbedded in the formation a core-type basket can be used, which has the capability of cutting away protruding edges of the material. Reverse circulation junk retrievers use hydraulic pressure to stir-up the junk from the bottom and lift it into the tool. Fingers at the bottom of the tool prevent the debris from falling. Hydrostatic junk retrievers also use fluid pressure to enhance movement of junk into the tool. Magnetic fishing tools are used to remove metallic junk. A jet bottom-hole cutter can be employed when junk is oddly shaped or too large to fit into regular baskets. Shaped charges may be used to break the junk into small pieces for removal by conventional junk baskets.

In many cases, large pieces such as drillpipe may be lost or stuck in a hole. Various methods of retrieval are used depending upon the condition and position of the material in the well. If the top of the pipe is free and is burred or split, a milling device can be used to dress the top of the pipe. Once the top of the pipe is smoothed, an overshot tool can be lowered over the pipe and then rotated to cause the tapered inside of the tool to engage the pipe.

Recovery of pipe can also be accomplished by using a spear, a tapered tool, which fits inside the pipe if accessible. Once the spear is positioned, it is released or expanded to engage the pipe for removal. Taps and die collars can be used to thread the pipe for reattachment to a drill string.

Fishing techniques are often successful in removing downhole material. In this case, the material can be milled or drilled out depending on its hardness.

3.4.3 Casing Repair and Remedial Cementing

Casing repair may be required to provide access to the zone to be plugged. When buckled or collapsed casing impedes access, a casing roller or swagging tool can be used. If the casing has been cut off, the edges of the casing stub are ground or beveled to avoid premature setting of, or damage to cementing tools. The most common remedial measure is squeeze cementing. In this process a cement slurry is placed in the well near the failure and forced under hydraulic pressure into the formation. If the casing is intact but the primary cement is inadequate, perforation of the casing may be required.

3.5 SELECTING A PLUGGING FLUID

Once well cleanout, inspection, and repair activities are completed, the well is ready for plugging. Of primary importance is selecting and establishing a fluid system in the well that will provide an environment suitable for the proper placement and setting of cement plugs, and serve as an adequate plugging material between the cement plugs. It is important to realize that fluids used during drilling or well cleanout activities are not necessarily designed with these objectives in mind. Consequently, these fluids may not have the proper characteristics and a more suitable fluid should be implaced prior to plug setting.

To meet the basic objectives of providing a static environment for plug setting and a suitable plugging fluid between plugs, Gillespie, et al, (1973) have recommended that the fluid have the following essential properties: (1) ability to provide sufficient hydrostatic head or weight; (2) ability to remain in place over an indefinite period of time; and (3) physical and chemical stability for an indefinite period of time. Sufficient hydrostatic head is required to maintain pressure control and suppress fluid motion in the well during setting of the cement plugs. The ability to remain in place is necessary both during plug setting to maintain static conditions and after plug setting to permit the fluid to stay in place indefinitely.

A mud-laden drilling fluid is frequently considered the best plugging fluid. Drilling fluids can be formulated with sufficient variability to meet most circumstances encountered. Their density can be adjusted easily to meet requirements for control of pressure. Lost circulation additives can be used to prevent filtration of the plugging fluid out of the hole. Clay and other natural earth materials used in drilling fluids are resistant to chemical deteriorations and once they are placed in a stable environment and the clay particles hydrate, very little settling and stratification occurs.

In fully cased wells where pressure control is not a problem, the properties of specially formulated plugging fluids may not be considered important and sufficient hydrostatic head to control pressure in the injection zone can be provided by water or brine solutions. In other circumstances in which the well is fully cased but injection-zone pressure is a problem, pressure can be controlled during setting the bottom plug using blowout preventers or retainers. After the bottom plug sets, bottom-hole pressures are controlled and as a result, low density fluids are sufficient to maintain static equilibrium in the well. In other situations, a fully weighted plugging fluid can be used to set the bottom plug; after the plug sets, it can be removed for use elsewhere and a cheaper material can be substituted. In some cases it may be desirable to leave a dense fluid in the well to develop sufficient hydrostatic pressure at the bottom plug to reverse or eliminate any hydraulic gradient across the plug, and thereby reduce the potential of fluid migration through the plug into the well.

3.6 ESTABLISHING THE PLUGGING-FLUID SYSTEM

Establishing an effective plugging fluid requires the placement of a carefully formulated fluid which meets the needs of the specific situation. This requires that any workover, cleanout, or other fluid in the well be replaced with the new plugging fluid. The plugging fluid is formulated and circulated into the well using a drill pipe or other tubing. This process will necessarily involve some dilution of the plugging fluid with the original fluid and requires several complete circulations to ensure proper conditions.

It is difficult to adequately compensate for all well conditions when originially formulating the plugging fluid, and it is frequently necessary to add materials as the plugging fluid circulates to adjust its properties to precisely meet well conditions. Once the plugging fluid has been adjusted, it should be circulated several times to ensure uniform properties throughout. Continual monitoring of fluid weight and viscosity will verify the uniformity of plugging fluid throughout the well. Once the fluid column has been established, the pump should be stopped and the fluid allowed to come to a static condition. If pressure, fluid loss, and lost circulation have been adequately controlled, the level of plugging fluid in the well should remain constant. If this does not occur, the plugging fluid should be recirculated and appropriate materials added. When a static condition is achieved, the well is ready for setting the plugs.

3.7 SELECTING AN APPROPRIATE CEMENT SLURRY

The selection of an appropriate cement slurry is essential to setting a safe and effective abandonment plug. The slurry should be designed to provide a durable, impermeable barrier to the flow of fluid in the borehole. The slurry should provide an adequate bond with the casing or formation and be formulated to ensure proper placement in the well including adequate displacement of any fluids in the borehole. The effects of cement slurry contamination should be minimized. Any special conditions in the well such as high temperature and pressure, high filtration potential, or cement/formation compatability problems should be taken into account.

These conditions can generally be met using a densified cement such as API classes A, G, and H, with a dispersant added (Petroleum Extension Service, 1977; Herndon and Smith, 1976). This general cement design sets and gains strength rapidly, thereby reducing time spent waiting for the plug to harden. It provides a cement less subject to contamination and results in a strong, relatively impermeable plug. The dispersant provides increased control of filtration and/or fluid loss, reducing the potential for dehydration which might result in premature setting of the cement or unwanted motion of the slurry in the well during and after placement.

If cement degradation is expected to be a problem, a densified, resistant cement should be utilized. Class H cements offer moderate resistance to sulfate attack. However, if highly active environments are expected, a specially formulated cement with low tricalcium aluminate content (Class CGR cements) should be considered.

Special care should be taken to ensure that chemical additives, many of which are organic, in the plugging fluid will neither retard nor inhibit the setting of the cement. If additives are present in the plugging fluid which severely affect the setting of the cement, it may be necessary to add accelerating agents. If severe problems are expected, it may be appropriate to test samples of the cement slurry contaminated with different amounts of plugging fluid to gauge its effect on the cement.

The physical properties of the cement slurry can also be adjusted to minimize the potential for contamination by improving the displacement of the plugging fluid during the placement of the cement slurry in the borehole. Displacement will be more effective if the cement slurry has a higher yield strength and plastic viscosity than the plugging fluid. Density adjustments in the cement slurry will also help to minimize contamination during placement, but the difference between density of the cement slurry and the plugging fluid should be minimized to help in maintaining hydrostatic control of pressure in the well after placement of the slurry.

Special cement additives may be required to compensate for special conditions in the well. Both high temperature and pressure act to accelerate the setting of cement. If these conditions exist in the well, retarding agents should be added to the slurry to prevent flash setting. In some cases, fluid loss or lost circulation can be a problem. Filtration and lost-circulation control agents are available for addition to cement slurries in these situations.

4. INSTALLATION OF PLUGS

Once well preparation activities are complete and static equilibrium has been established the well is ready for the final stage of abandonment, the installation of cement plugs. Proper placement of cement plugs requires the selection and proper execution of an appropriate technique. The plugging techniques available for injection-well abandonment and the other special techniques and equipment commonly used during plugging are discussed in this chapter.

4.1 SELECTION OF PLUGGING METHOD

A variety of methods are available for the installation of plugs during injection-well abandonment. These methods include the balance, cement retainer, dump bailer, and two-plug method. Each of these methods has advantages as well as limitations. The selection of a method for setting each plug is influenced by a number of factors, including the position of the plug and the well condition and configuration. Each method is discussed individually below. Table 2 is included to provide a summary of potential application of each method.

4.1.1 The Balance Method

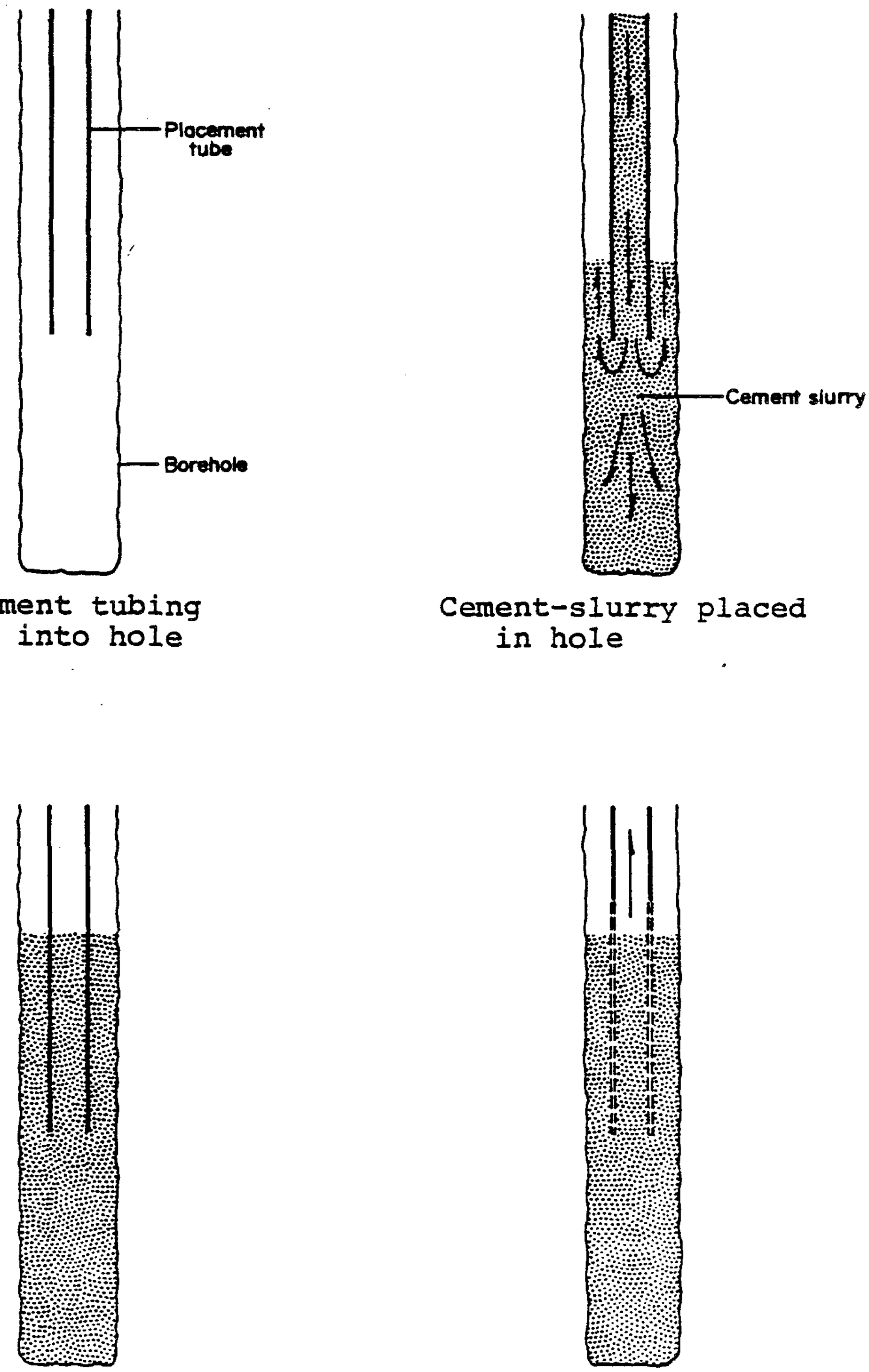
The balance method has been one of the most commonly used methods for setting plugs in oil and gas wells. It is frequently used because the only special equipment need is a cementing service unit. However, the technique is not necessarily simple in its implementation and requires considerable operator skill to ensure the placement of a safe and effective plug.

The balance method involves displacing the plugging fluid with a cement slurry that is placed through drillpipe or tubing into the borehole. The cement volume is carefully calculated so that the amount of cement placed matches the level of cement in the drillpipe or tubing to the level of cement required in the borehole. The tubing is then slowly pulled back out of the top of the cement, leaving behind a solid plug of cement with minimal contamination by the plugging fluid (Figure 2). After the tubing has been pulled back above the top of the cement, it is cleaned by reverse circulation.

TABLE 2
POTENTIAL APPLICATIONS OF PLUGGING METHODS

Application or Use	Balance Method	Retainer Method	Two-Plug Method	Dump-Bailer Method
Cased wells	3	3	3	3
Uncased wells	3	1	3	3
Large diameter wells	3	3	3	1
Small diameter wells	3	3	3	3
Deep wells	2	3	3	1
Shallow wells	3	2	2	3
Reduced need of establishing static equilibrium	1	2	1	1
Reduced need of thorough well cleaning	1	2	1	1
Reduced need of thorough well inspection	1	2	1	1
Placement of bottom-hole plugs	3	1	3	3
Placement of intermediate depth plugs	2	3	2	1
Ability to squeeze cement slurry	1	3	1	1
Potential for adequate cement bonding to formation and casing	2	3	2	2
Prevention of cement slurry contamination	2	2	3	1
Prevention of cement movement of migration	2	3	2	2
Accuracy of depth of placement of cement	2	2	2	3
Ease of calculating adequate cement volume	2	3	3	2
Ease of installing adequate cement volume	3	3	3	1
Effectiveness in minimizing time and expense of plug testing	1	3	1	1

Note: 3 - good
2 - fair
1 - poor



Placement tubing run into hole

Cement-slurry placed in hole

Level of cement-slurry balanced

Placement tubing removed

Figure 2. Principles of the Balance Method

The balance method may be used in both cased and uncased holes to place plugs either at the bottom or at an intermediate depth in the well. When plugs are placed at intermediate depths, a bridge plug is commonly set in the well prior to placing the cement slurry. Although not strictly necessary, bridge plugs help to position the cement plug and prevent it from migrating before setting. In some instances, a sand pack can be placed in the bottom of the hole or on top of the bridge plug before placing the cement slurry. The sand pack helps strengthen the cement as it sets and allows filtrate to leave the plug as it sets, forming filter cake at the bottom of the plug. When the plug is set off-bottom, this filter cake can serve as an impermeable barrier to the flow of gas or liquid up through the plug.

The success of the balance method depends partly on the ability of the operator to remove the tubing without causing significant contamination of the cement slurry. To minimize the possibility of disturbing the slurry while removing the placement tube, a small diameter tubing is required. The small diameter tubing increases the size of the annulus between the placement tubing and casing or borehole wall which allows the withdrawal of the tubing without causing an excessive drop in the cement or a surge of the cement plug.

Balancing cement levels requires careful planning. Volume calculations take into account not only cement volumes but also any prewashes and spacing fluids used during cement placement. In uncased holes, careful measurements of borehole diameter using caliper logs ofter becomes critical in making the necessary volume calculations. A slight overbalance of cement in the tubing is commonly practiced to compensate for the difficulties involved in precisely matching cement levels prior to withdrawal of the placement tubing and in minimizing contamination of the cement during tubing withdrawal.

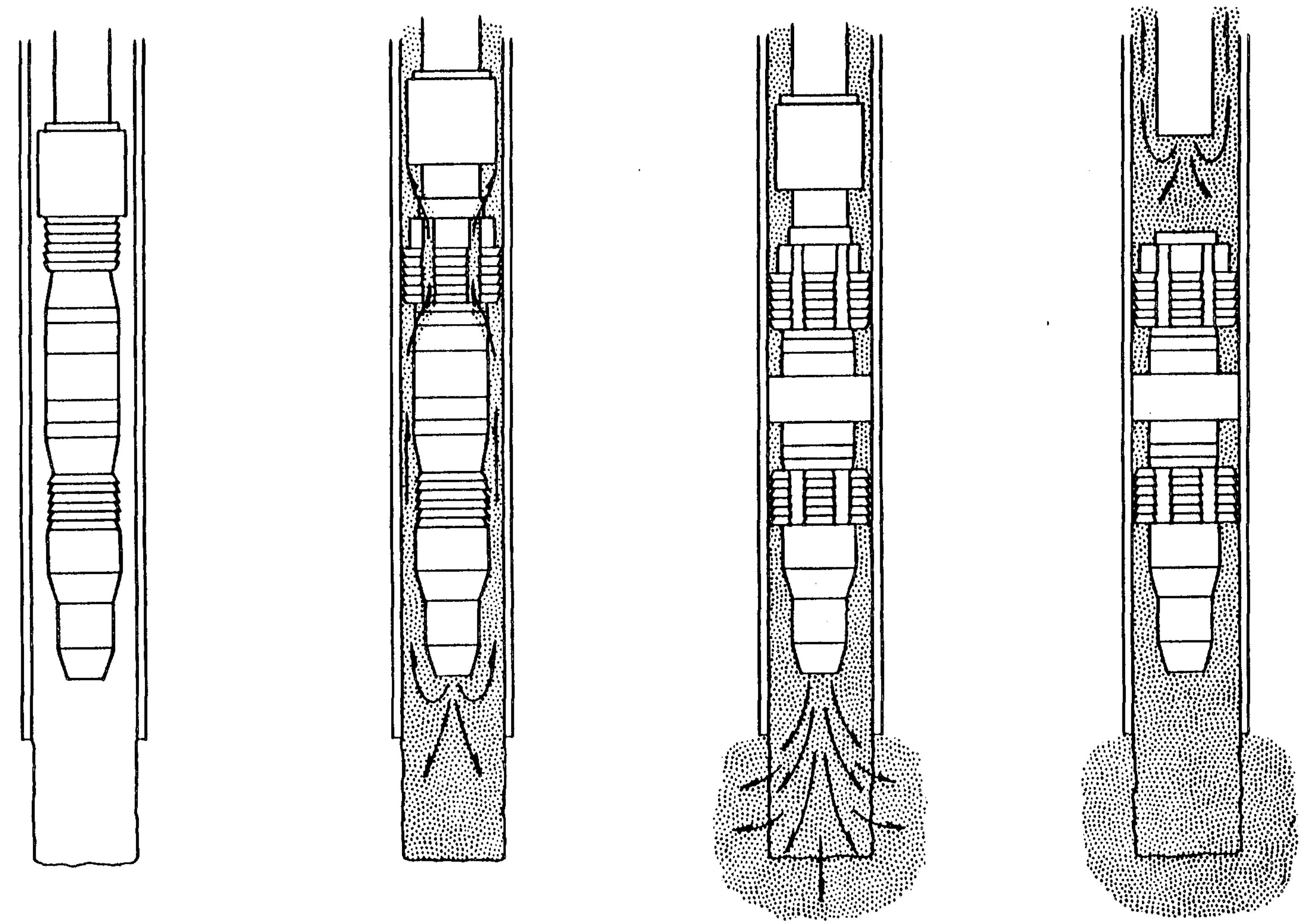
4.1.2 The Cement Retainer Method

The cement retainer method is generally classified as a specialized application of the balance method that utilizes a retainer allowing cement slurry pressurization. The retainer is attached to the bottom of the placement tubing and can be expanded to seal the annular space between the placement tubing and casing. Cement is pumped through a valve in the retainer and the valve is closed. The placement tube is disengaged from the retainer which is left in the hole. The technique is used to set plugs across uncased portions of the borehole or across perforated casing. The ability to pressurize the cement increases the penetration of cement into the annular space between the casing and formation as well as into the formation itself. Although more expensive than the conventional balance thecnique, the cement retainer method offers a number of advantages which make its application to setting the bottom plug in injection wells frequently preferred.

The procedure begins by attaching the retainer to the placement tubing and lowering it to the bottom of the well (Figure 2). The cement slurry is then pumped through the retainer and back up into the hole until the cement level rises 50 to 100 ft (15 to 30 m) above the ultimate setting depth of the retainer. The retainer is then retracted to its desired depth and set. After the retainer is properly set, the tubing is pressurized and cement is forced out into the surrounding formation(s). Pressures of between 1,000 psi and 1,500 psi (6.9×10^6 to 1.0×10^7 N/M^2) are commonly used. After the desired amount of cement has been forced out into the formation, the retainer valve is closed. The emplacement tubing is disengaged from the retainer and slowly raised out of the cement, allowing cement in the pipe to fall out. Thus, a plug is left behind consisting of cement "squeezed" into the formation and held in place by a retainer which in turn is overlain by another layer of cement. Once the pipe has been raised sufficiently above the cement, it is cleaned by reverse circulation.

Since the success of the retainer method depends on the ability to set the retainer properly and isolate the hole below it, it is seldom possible to set the retainer in an uncased portion of the well. The retainer has only a limited ability to expand and to engage the walls of the borehole. Some service companies offer inflatable packers which are capable of greater expansion; however, plugs set using this equipment are not generally considered as reliable as those set with a retainer plub. Thus, if the retainer is first lowered into the uncased portion of the hole, it must be pulled back into a cased portion of the hole and set. This can be a problem since the tool might not easily reenter the casing.

Some service company representatives recommend that the retainer never be lowered beneath the casing into the open hole. Instead, the retainer should be set in the lower portion of the cased holw and the desired amount of cement pumped into the well beneath the retainer forcing all fluids in the hole out into the formation in front of the cement slurry. Similarly, in wells in which an intermediate portion of the casing has been previously salvaged or



Retainer run into hole

Cement-slurry placed

Packer set and cement squeezed into formation

Placement tubing removed

Figure 3. Principles of Retainer Method

is otherwise absent, problems can arise when the retainer is forced back into a casing after running down through the uncased portion of the hole. In these cases, it may be better not to salvage the intermediate casing until after the retainer plug is set.

The cement retainer method offers a number of potential advantages. By forcing cement out under pressure into the surrounding formation, this technique ensures the adequate bonding between the plug and the formation. When the plug is to be placed at the bottom of the casing, the cement retainer method creates more reliable barrier not only to flow inside the casing but also to flow in the annulur space between the casing and formation. In some cases, it may offer an effective alternative to squeeze cementing the lower portion of a casing when the reliability of a primary cement job is in doubt.

Once the valve is closed, the cement retainer serves as a barrier to flow past the plug and thereby increases the reliability of the plug. In addition, immediately after the plug is set, it can be pressure tested. The reliability of the plug thus proved, the need to reenter the hole after the plug sets for testing is eliminated. The method provides excellent control of the cement slurry, and by providing a barrier to gas percolating up through the well, the retainer helps to prevent any potential contamination of the cement while it is setting.

The use of the irretrievable retainer and the additional time necessary to set the plug, may initially cause the cement retainer method to appear expensive compared to some of the other techniques (see Chapter 5). However, the extra expense will be offset if an initial attempt to set a plug using another technique fails and the plug must be reset. In addition, a plug set using the retainer method does not require testing after the cement sets and the operator can move immediately up the hole and set a second plug, thereby saving the expense of additional rig and equipment time while waiting for the first plug to harden.

4.1.3 The Two Plug Method

A variety of methods utilizing cementing plugs are available for setting abandonment plugs. Cementing plugs are typically placed inside the placement tubing either before or after the cement slurry and help to separate the cement slurry from other fluid in the tube, reducing the possibility of cement contamination. The most commonly cited method for setting cement plugs is the two plug method.

This method not only helps prevent contamination of the cement as it is pumped but also eliminates the possibility of over or under displacement of cement. The method can be used in both cased and uncased wells.

The two plug method involves a top plug, bottom plug, and a latch-down type plug catcher. The procedure begins by running the placement tubing with the attached plug catcher into the hole to the depth desired for the bottom of the cement plug (Figure 4). The bottom plug, followed by the desired volume of cement slurry, is pumped into the pipe. The top plug is placed on top of the cement slurry and followed by a plugging fluid. When the bottom plug reaches the catcher, it passes through and out into the well. The cement slurry is then displaced into the well; when the top plug reaches the plug catcher, it is unable to pass through preventing any further displacement of fluid. The placement tubing can then be slowly raised out of the cement leaving a solid plug behind. The plug catcher is designed so the pressure can be reversed to allow fluid to flow back into the placement tubing; therefore, the pipe can be raised in the hole and reverse circulated to establish the top of the cement plug, if needed.

This technique offers several advantages over the balance method, although it does involve additional expense with the added equipment involved. The plugs act to separate the plugging fluid and cement slurry, reducing the potential for cement contamination. In addition, the bottom plug helps wipe plugging fluid from the inner walls of the placement tubing as it is pushed down into the well in front of the cement slurry, further reducing cement-slurry contamination. Most importantly, the two plug method offers excellent control of the cement and eliminates over displacement of cement into the well. This is particularly important in deeper wells in which volume measurements and control of cement displacement is generally difficult.

It is also possible to vary the two plug method by using different combinations of cementing plugs or additional equipment. It is possible to use a single plug run in behind the cement slurry. This method offers the same control on over displacement but not the added protection from contamination by plugging fluid run in front of the cement. Additional plugs can be added in front of the cement slurry to segregate any preflushes or spacer fluids placed in the well before the cement slurry. These plugs are designed to pass through the plug catcher in a manner similar to the plug immediately below the cement slurry.

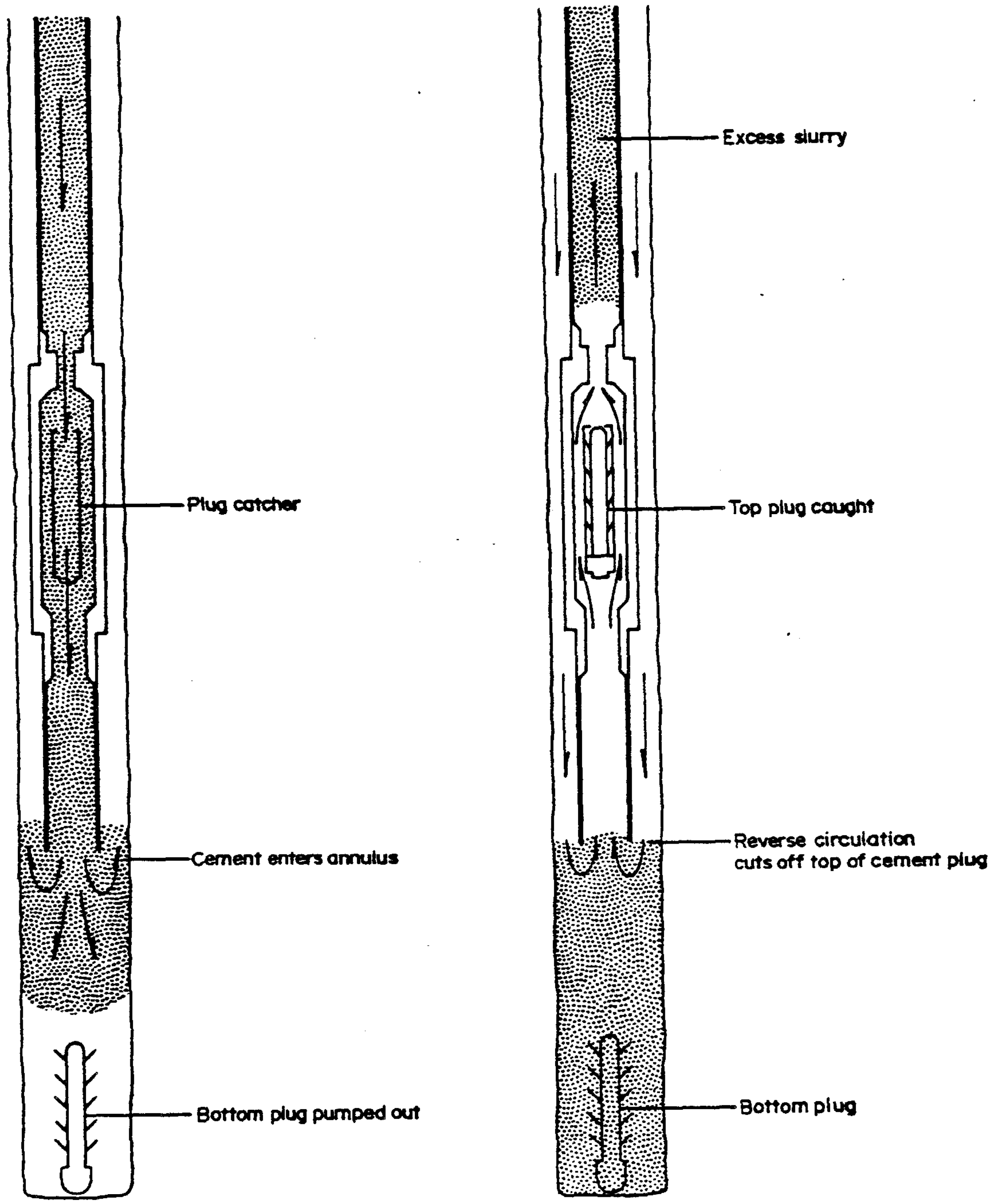


Figure 4. Principles of Two-Plug Method

4.1.4 The Dump Bailer Method

The dump bailer method is available for setting plugs; however, the method is seldom used for plugging for abandonment because of a number of limitations. This method utilizes a bailer lowered into the well on a wireline. A measured amount of cement is then released at a desired depth. Generally, a bridge plug or cement basket is previously placed in the hole at the specified depth (Figure 5). Since this is a wireline method, it requires very little special equipment. Wireline techniques offer excellent depth control, frequently important in setting abandonment plugs; however, the technique is severely limited by the amount of cement that can be placed on a single trip into the hole. The limited capacity of dump bailer is further aggravated by the inability to place additional loads of cement before the previously placed cement slurry sets. Thus, the large plugs associated with injection-well abandonment can require numerous trips into the hole with long waiting times between trips. Deeper wells may require the use of severely retarded cement to prevent setting before placement.

4.1.5 Existing Casing Plugging Method

Several additional methods are available for setting plugs in injection wells. The method of greatest potential application is for setting the bottom plug. The basic approach is to place the cement slurry in the well using the injection casing rather than a placement tubing. A measured amount of cement can be pumped in the top of the well followed by another fluid. The plug of cement is pumped down the well to the bottom. Any fluid in the well in front of the cement is consequently forced out into the injection zone. Once the plug has fully displaced all well fluids beneath it, and is located at the bottom of the well, the plug is in place and pumping can stop. Alternatively, pumping can continue and force a portion of the cement out into the formation and provide a squeezing action similar to that available from the retainer method. Cementing plugs as well as spacer fluids can be placed in front and behind the cement slurry to reduce the potential for contamination with well fluids. Once the cement is in place, it is possible to control any pressure at the bottom of the well by shutting in the well.

This is an effective method for setting a squeezed bottom plug. By reducing the need for extra equipment, the expense should compare favorably with other methods. Pressure control in the well is relatively easy and the need for

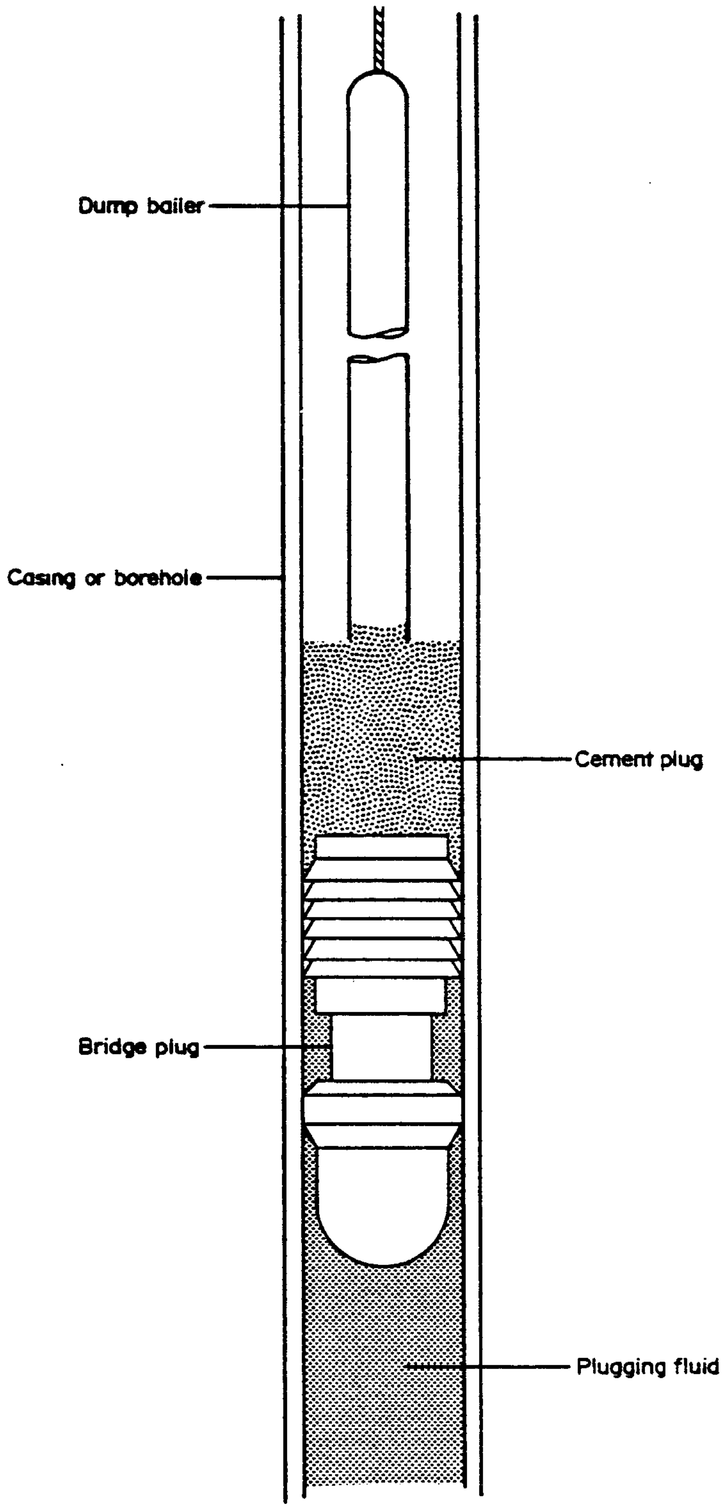


Figure 5. Principles of the Dump-Bailer Method

establishing static equilibrium is eliminated prior to setting the bottom plug.

To be effective the injection zone must be capable of accepting any fluids in the well prior to cement slurry placement. The well must be in good condition and capable of withstanding the pressures involved. Any deformation of the tubing may prevent the passage of cementing plugs used to separate the cement slurry from well fluids.

A slight variation of this method would be placement of the bottom plug through the injection tubing and packer. While offering many of the same advantages as the basic approach, this technique is associated with a number of additional problems. The injection tubing must be able to withstand the pressures involved since the technique might damage the tubing and reduce its salvage value. Since the tubing must remain in place until after the cement sets, removal of the tubing from the well may be complicated. In addition, failure to remove the tubing before setting the bottom plug may make difficult or impossible particular techniques used to examine the well condition. Finally, the original position of the packer may not allow for setting the plug over a sufficient amount of the confining bed. This can require resetting the packer or placing additional cement on top of the packer after removal of the tubing.

4.2 SPECIAL PROCEDURES FOR PREVENTION OF CEMENT CONTAMINATION

A number of special procedures and types of equipment may be used to help minimize contamination of the cement. Use of these special procedures and equipment is intended primarily to remove wall cake from the pipe or face of the formation and to maintain adequate separation of plugging fluid and cement slurry. Removal of wall cake is essential for adequate bonding of cement to the pipe or formation to occur and to prevent mud streaking in cement slurry.

4.2.1 Scratchers and Centralizers

Special scratching devices are utilized to remove wall cake. These devices are attached to the lower end of the pipe used to place the cement slurry and are of two basic designs. One type removes wall cake with a rotating motion of the pipe while the other utilizes a reciprocating motion. These devices are lowered into the well when the pipe is lowered to place the cement slurry. When they are opposite the zones in which the plug is to be set, the pipe is rotated or reciprocated to remove wall cake. The cement slurry is placed in the well as soon as sufficient time has elapsed for proper removal of the wall cake.

Centralizers may be attached to the bottom of the placement tubing to position it in the center of the hole. This helps avoid channelling cement to one side of the annulus to permit displacement of the plugging fluid.

4.2.2 Prewashes

In addition to wall scratchers, chemical washes may be injected before the cement slurry to aid in borehole preparation. These washes are effective for removal of wall cake and for cleaning mineral and other deposits which might affect cement bonding. Chemical washers are of two general types: thinners and acids. Thinners are most effective in water-based plugging fluids and act to disperse any flocculated clay particles. Acid washes act to shrink mud particles and thereby disperse wall cake. Prewashes must be used with care as they contain chemicals which can retard or inhibit the setting of the cement.

4.2.3 Spacer Fluids

Spacer fluids are used to prevent contamination of the cement slurry. These fluids can be placed in front of and/or behind the cement slurry as it is placed in the placement tubing. They act to physically separate the plugging fluid and cement slurry and are frequently used with cementing plugs. Fluids similar to the chemical washes discussed above, or specially designed fluids provided by service companies, can be used for this purpose.

In addition to prewashes or spacer fluids, small amounts of non-chemically treated drilling muds may also be placed before the cement slurry. These muds are used to prevent any adverse reactions which might occur in the plugging-fluid system below the plugging location when it comes in contact with chemical washes or cement slurry itself. These muds generally consist only of bentonite, water, and a weighting material, if needed.

4.3 PROCEDURAL STEPS FOR SETTING MULTIPLE PLUGS

Most abandonment programs will require the placement of multiple plugs in a well. Certain procedural steps need to be followed during the setting of each plug. In most cases, each plug should set before placing the next plug in the well. This is necessary primarily to allow the cement slurry to solidify in a static environment to prevent contamination; displacement of cement slurry into the well for setting a second plug will likely disturb the fluid below. In addition, it is necessary to locate the position of the plug with pipe (called tagging) after solidification to verify its position and solidification. This requires a waiting time of from 8 to 12 hours. After tagging the plug, it may be necessary to recirculate the plugging fluid to ensure fluid weight equalization throughout the unplugged portion of the well. The plugging fluid then is brought back to a completely static state before setting the next plug.

Setting multiple plugs requires the repetition of a basic sequence of steps for each plug. The one exception is setting the bottom plug. If the retainer method is used to set this plug, the operator can raise the placement tubing to set the next plug immediately after setting the bottom plug. This is possible because the retainer assures the position of the plug and isolates the cement below it from influences in the borehole above the plug.

5. UNIT COSTS OF WELL ABANDONMENT

The cost for abandoning an injection well depends largely on the depth and diameter of the well, the condition of the casing and other materials in the well, and on any procedures that have to be taken to clean out the well or otherwise prepare it for plugging. The unit costs presented herein are for basic procedures and illustrate the relative importance of the various components of abandonment. Not included are costs for additional rig time for fishing and remedial squeeze cementing which can be substantial in many instances and cannot always be anticipated before the well records and the borehole are examined. Also, additional costs related to site location and extreme borehole temperatures and pressures can be significant, but are considered on a case by case basis.

Unit costs are developed for plugging fluid preparation, cementing, and general rig cost. General cost discussions are developed for logging, fishing, and well cleanout techniques. No attempt is made in this report to determine average costs for complete abandonments of "typical" wells. These costs represent estimates for specific operations based on cost data from a limited number of companies, and may not represent regional differences.

5.1 PLUGGING-FLUID PREPARATION

Development of a plugging-fluid system is usually required in preparation for plugging, and is charged by the barrel. The cost for water-based plugging fluid ranges from $15 per barrel for 10 lb/gal plugging fluid to $65 per barrel for the 20 lb/gal plugging fluids. Engineering costs to design the plugging fluid are included, but these costs do not include delivery which could be $60/hr for a truck and operator. In cases where an oil-based plugging fluid is required, cost may range up to $85 per barrel for a 20 lb/gal fluid. These prices represent custom engineered plugging fluid; if used or junk fluids are available locally (e.g., from a drilling or workover operation) prices may be substantially less.

5.2 CEMENTING

The cost of cementing includes the cement and related materials, mechanical aids, cement placement, material and equipment transportation to the job site, and related engineering costs. Only unit costs are presented in this section; the actual costs of cementing depends on well depth, diameter, and condition, and the number of plugs to be set.

Location of the well site is critical in estimating the cost of cementing because th cost of cementing materials is sensitive to hauling requirements. In fact, in operations distant from "cement supply camps" the transport cost can exceed the cost of the material. Also, requirements for additional supplies can be expensive since suppliers have minimum delivery charges. Rig time and pumping unit costs are also sensitive to location. Plugging operations can involve substantial down time for crews; if the crew cannot be released, due to impractical traveling time, the time on site and costs can increase substantially.

Type 2 or Class H cement, without loss-of-circulation material, is normally used in well abandonment. The costs of this type of cement ranges from $5.20 to $7.80 per sack. In addition to the basic cost of the material, a haulage cost of approximately $0.70 per ton-mile is charged. This cost can be significant as mentioned, particularly when the well site is located hundreds of miles from the nearest supplier. A handling charge of about $1.00 per sack may also be added to this cost. Other types of cements and additives can be more expensive and are often required when cementing in lost circulation zones, salt sections, and abnormally high temperature areas.

Cement placement cost depends largely on the depth that the plugs must be set. Table 3 presents the cost of the cement pumping unit for 8 hours of operation. These costs are based on the lowest depth of cement circulation and assume setting through placement tubing using the balance placement method. The large variation in cost is primarily a function of equipment sizing as larger, more expensive pumping units are required. The same pumping units can be used for squeeze cementing at the same hourly cost.

Transportation of mobile equipment incorporates a mileage charge or hourly rate for each piece of equipment sent to the job. Normally, a cement mixing/pumping unit and a pick-up truck will be sent for a cementing job. The mileage charge to and from the job is $2.10/mile for the pumping unit and $0.72/mile for the pick-up truck.

A variety of mechanical devices are used in plugging operations. The bottom hole plug is often set by use of a cement retainer which is permanently set in the hole. Costs for the retainers range from $1,200 to $3,100 depending on well diameters (Table 4). This includes the cost of basic service involved when other cementing equipment is used. Where the two-plug method is used, permanently installed rubber plugs are required. These range in cost from $24 for

TABLE 3
COST OF CEMENT PUMP PER 8 HOUR SHIFT
(Halliburton, 1981)

Depth (ft)	Cost ($)
0 to 300	375.00
300 to 1,500	375.00
Plus per foot below 300	0.42
1,500 to 3,000	879.00
3,000 to 5,000	879.00
Plus per 100 or fraction below 3,000	10.80
5,000 to 7,000	1,095.00
Plus per 100 or fraction below 5,000	14.50
7,000 to 9,000	1,385.00
Plus per 100 or fraction below 7,000	23.50
9,000 to 11,000	1,855.00
Plus per 100 or fraction below 9,000	46.50
11,000 to 13,000	2,785.00
Plus per 100 or fraction below 11,000	82.50
13,000 to 18,000	4,435.00
Plus per 100 or fraction below 13,000	91.00
18,000 to 25,000 and below	8,985.00
Plus per 100 or fraction below 18,000	93.00
Each additional 8 hours or fraction on location, per unit	800.00

TABLE 4
COST OF PERMANENTLY SET CEMENT RETAINERS
(Halliburton, 1981)

Casing Diameter (inches)	Cost ($)
4-1/2	1,300
5	1,200
5-1/2	1,100
6-5/8	1,400
7	1,400
7-5/8	1,500
8-5/8	2,000
9-5/8	2,100
10-3/4	2,600
11-3/4	3,100
13-3/8	3,100

a 4-1/2 inch plug to $165 for a 13-1/8 inch plug. A plug catcher is also required with this method, however, it is retrievable and can be rented out for about $200.

There are significant cost trade-offs between methods to be used in a variety of applications. For example, the use of a retainer allows immediate testing of the plug and would be less likely to migrate in the hole. Individual plugs set by other methods are usually tagged by running the placement tubing into the well verifying its location. This requires an 8 to 10 hour waiting period and could be costly if the crew could not be released. Placement of large plugs can lead to higher material costs; this will be a function of the local geology and well condition. Experience of the service company or operator generally determines the selection of specific plugging methods. Local experience in plugging similar holes may also influence selection of a technique. In remote areas or in critically placed wells, the costs of reentry to replace a defective plug can be more expensive than the initial abandonment.

5.3 GENERAL RIG COSTS

A workover rig is required for most abandonment operations. In some cases where a wireline truck can handle all well cleanout and cementing support, the workover rig will not be necessary. This could result in significant cost savings since a wireline truck is less costly.

Rig costs include all costs associated with the workover rig and crew. This is usually charged on an hourly basis. Hourly rig costs are presented in Table 5. The range in cost for each depth represents variations in charges among companies and variations in regional demand. The upper range represents rig costs in Eastern California whereas the lower end of the range was obtained from mid-continent sources.

The hourly requirements of the rig for abandonment will vary with well cleanout and logging requirements and the depth of the hole. The following estimates of rig time are for well preparation (pulling tubing) and cementing support only and do not include time in transport.

Depth (ft)	Hours
1000 - 2000	30
3000 - 5000	40
5000 - 9000	60
9000 - 15000	70

TABLE 5
WORKOVER RIG RENTAL CHARGES*

Depth of Operation (ft)	Hourly Cost ($)
0 - 7,500	115 - 170
7,500 - 10,000	117 - 170
10,000 - 12,500	120 - 170
12,500 - 15,000	125 - 170
15,000	130

*Transport Costs vary from the hourly rate of the operating rig to a reduced rate of about $70/hour. Additional charges for equipment such as power tongs can be significant, e.g., $200/day.

5.4 FISHING AND WELL CLEANOUT

Fishing and well cleanout costs are well specific and can be a substantial portion of abandonment costs. These costs can be reflected in additional rig time, specialized personnel, and rental of specialized equipment, such as fishing and milling tools. Cost of tool rentals depends on the well diameter, success of the operation, and standby time. Table 6 illustrates the range in rental costs for commonly used fishing tools. The magnitude of the cost range reflects mainly the diameter of the hole as this determines the size of the tool. Regional differences are not considered and costs for specific locations could vary. As with rig time, the use of fishing tools in remote locations can rapidly increase abandonment costs.

5.5 GEOPHYSICAL LOGGING

The cost of geophysical logging techniques that are sometimes used in abandonment procedures are outlined in Table 7. Some techniques are more costly than others; however, the principal determinant of cost tends to be the depth of the well, or more specifically the total footage of the well surveyed. Selection of a specific technique depends on the type of well, well condition/age, existing data on the well, location and local experience.

TABLE 6
COST OF FISHING TOOL RENTAL*

Tool	Cost ($)
Cutters (internal)	600 - 800 per cut
Cutters (multistring)	1,025 - 2,300 per cut
Cutters (external)	900 - 1,230 per cut
Mills	150-650 per job
Overshots	250 - 1,300 First day 100 - 500 Additional day
Casing & Tubing Rollers	660 - 950 per run 330 - 475 per Additional run

*Additional fees are charged depending on wear or damage to the tool. This is particularly important when using tools that wear rapidly, e.g., mills.

TABLE 7
COST OF GEOPHYSICAL LOGGING
(Schlumberger, 1978)

Depths (feet)	Geophysical Log Cost ($)				
	Caliper	Flow Meter*	Gamma-Neutron	Cement Bond	Pipe Analysis*
1,000	1,925	1,550	1,475	1,220	1,125
2,000	1,925	1,550	1,475	1,220	1,125
3,000	2,250	1,862	1,775	1,500	1,437
4,000	2,575	2,175	2,150	1,800	1,750
5,000	2,900	2,487	2,525	2,100	2,062
10,000	4,525	4,050	4,400	3,600	3,625
15,000	6,950	8,300	7,175	5,900	5,950

*For some locations an additional cost of $2,000.00/log charged for flying in the Flow Meter and Pipe Analysis Tools.

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