Delaware Basin Drilling and Completions

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Costs to drill and equip deep Ellenburger gas wells in the Delaware Basin have been significantly reduced in the last four years in spite of increased prices of tubular goods, labor, services and supplies. This relentless effort to further reduce costs must be continued if the future demand for natural gas is to be met. The average cost to drill and equip 28 wells in this area in 1968 at an average depth of 21,500 feet was $1,350,000 according to API statistics.[1]

Figure 1 shows the areal extent of the Delaware Basin and the location of the deep gas

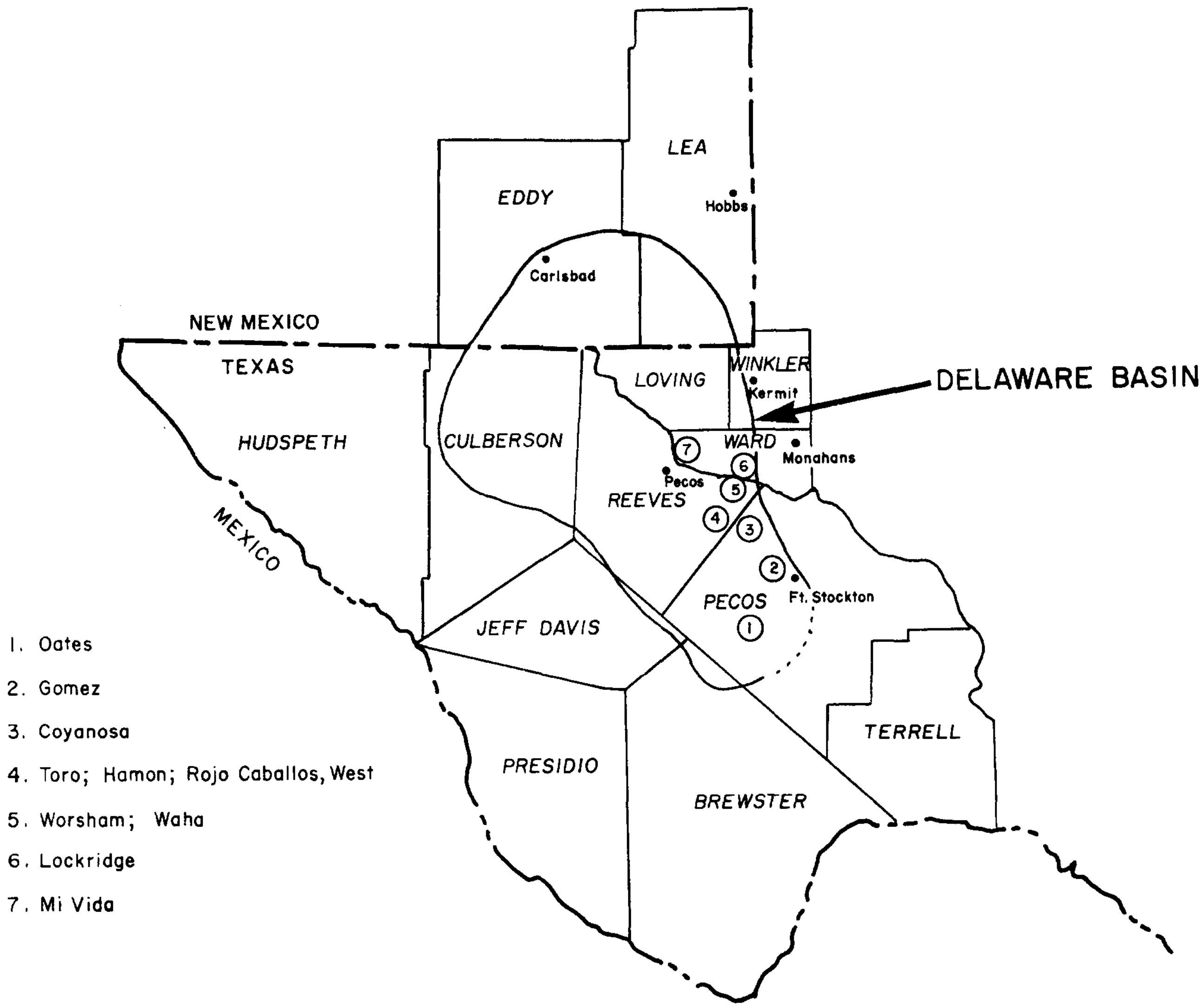


FIGURE 1

Location of Deep Producing Fields

Delaware Basin

fields. Figure 2 shows a typical geological section of the Delaware Basin. Considerable variation of this geological section is found near the flanks of the Basin. Also shown in Fig. 2 is a typical casing program for a deep gas well in the Delaware Basin.

WELL PLANNING

As each new well is planned, all available information from wells previously drilled in the field and area should be reconsidered in the light of new ideas and techniques for drilling the well with minimum cost. A carefully thought-out plan for drilling the well is essential to a safe and economical drilling effort. Well records, logs, bit records and mud records must be carefully perused. Geological information such as the position of the well on the structure or proximity to faulting may provide an indication of drilling obstacles, such as troublesome gas in the Wolfcamp or brecciated dolomite in the Ellenburger.

CASING SETTING AND DESIGN CRITERIA

The selection of optimum casing setting points usually has more to do with drilling a well safely and economically than any other one thing. Some of the factors which must be considered in selecting Delaware Basin casing setting points are:

1. to isolate and protect fresh-water-bearing strata from contamination;
2. to case-off massive evaporite sections so as to
   a. eliminate key seat problems,
   b. facilitate the use of fresh water for mitigation of loss of circulation and faster penetration rate,
3. to case-off zones with low frac gradients and/or lost circulation zones prior to drilling abnormally pressured zones;
4. to case-off abnormally pressured intervals requiring high-density drilling fluid prior to drilling normally pressured intervals with low to normal frac gradients;
5. to case-off troublesome sloughing shale intervals.

This paper presents a detailed discussion of the criteria used in selecting each of the casing setting points. Figure 2 should be useful in following this discussion.

Surface Casing Interval

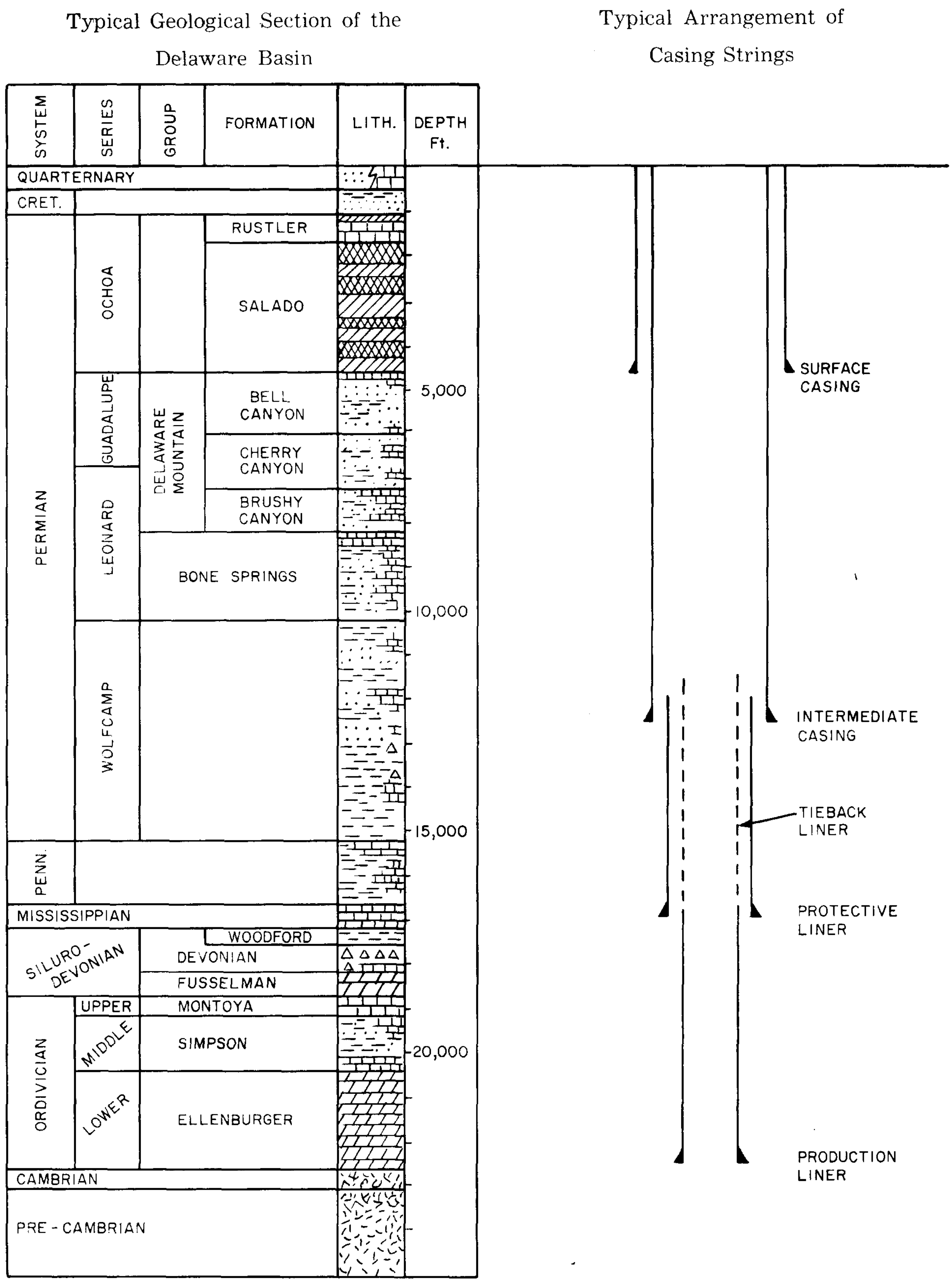
The primary purpose of surface casing is to isolate and protect fresh-water-bearing strata from saline water or hydrocarbon contamination. The Rustler is the lowermost fresh-water-bearing formation over a wide portion of the Delaware Basin. The Salado formation, an evaporite section comprised of massive alternating beds of salt and anhydrite, is found immediately below the Rustler and extends to a depth of 4000-5200 feet in a typical Basin well. There are many advantages in setting surface casing completely through the Salado and this practice is gaining increased acceptance. Casing-off the entire evaporite section allows the operator to enjoy the following benefits: (1) increased penetration rate and decreased corrosion rate by using fresh water as the drilling fluid; (2) key seat hazards are eliminated; (3) minimal hole fill after trips and less trouble in getting intermediate casing to bottom (salt is dissolved by drilling fluid and the extremely large hole makes good hole cleaning in the intermediate casing interval impossible if the salt is not cased off); and (4) lost circulation in the intermediate casing interval is usually eliminated. Surface casing is usually 13-3/8 in.

In the Gomez Field and other areas along the eastern flank of the Basin, the massive evaporite section is not present and a shorter surface casing string is used successfully. Surface casing is set in the depth range of 600-2600 feet for the purpose of protecting fresh-water-bearing strata and as a method to control gas which may be encountered at a shallow depth in the Yates formation.

Intermediate Casing Interval

Intermediate casing, usually 10-3/4 in. or 9-5/8 in., covers the Delaware Mountain Group and Bone Springs and is set several hundred feet into the Wolfcamp to a depth of 9000-13,300 feet. The purpose of the casing is to case-off the normally pressured, low frac gradient formations prior to penetration of the abnormally pressured portion of the Wolfcamp and Pennsylvanian formations. The selection of the casing seat should carefully consider anticipated pore pressures in the hole to be drilled below the intermediate casing. Mud densities as high as 16.5 ppg have been required to contain gas in the

FIGURE 2


Typical Geological Section of the Delaware Basin
Typical Arrangement of Casing Strings
SYSTEM
SERIES
GROUP
FORMATION
LITH.
DEPTH Ft.
QUARTERNARY
CRET.
PERMIAN
OCHOA
RUSTLER
SALADO
GUADALUPE
DELAWARE MOUNTAIN
BELL CANYON
CHERRY CANYON
LEONARD
BRUSHY CANYON
BONE SPRINGS
WOLFCAMP
PENN.
MISSISSIPPIAN
SILURO-DEVONIAN
WOODFORD
DEVONIAN
FUSSELMAN
ORDIVICIAN
UPPER
MONTOYA
MIDDLE
SIMPSON
LOWER
ELLENBURGER
CAMBRIAN
PRE-CAMBRIAN
5,000
10,000
15,000
20,000
SURFACE CASING
INTERMEDIATE CASING
TIEBACK LINER
PROTECTIVE LINER
PRODUCTION LINER

Wolfcamp and Pennsylvanian formations in some wells. Analysis of the pore pressure and pressure trends of nearby field wells or wells in the area will be useful in determining the need for setting casing into a pressured interval as well as selecting an approximate casing point. Pore pressure indicators in the well as it is drilled should be used to determine the exact setting point. These pressure indicators include shale volume over the shaker, drilling rate change, caliper logs and sonic log calculations.

A potential problem in attempting to drill to an interval with high pore pressure results from the unpredictable nature of the occurrence of permeability in the Wolfcamp formation. The following situation may develop: An interval may be selected as an intermediate casing seat from analysis of logs and other data from wells in the area. Drilling progresses toward this point with 9.5 to 9.8 ppg drilling fluid, the maximum density which can be supported by the Bone Springs Formation. A sand may be penetrated prior to reaching the desired casing seat with fair to good permeability. Usually, permeability of these sands is so low that no problem develops. This sand may contain gas pressure greater than the hydrostatic pressure of 9.8 ppg fluid. If this situation develops, it is necessary to place weighted mud above the gas sand but below the weak Bone Springs prior to pulling the drill string for a new bit or for running casing. Caution must be exercised both during the trip and in circulating the heavy mud from the hole after the trip.

Second Intermediate or Protective Liner Interval

A 7-5/8 in. liner is usually set through the abnormally pressured Wolfcamp and Pennsylvanian sections into the Lower Mississippian Limestone. After this liner is set and successfully cemented, the 10.5 to 16.5 ppg drilling fluid used in drilling the Wolfcamp-Pennsylvanian section is displaced with fresh to brackish water. The collapse design factor is approximately 0.8, based on the usual assumptions of known pressures or maximum mud density outside and no pressure inside the pipe. The use of this low design factor is acceptable as fluid will be maintained inside the casing as the well is drilled and a casing tie-back string will be cemented inside this protective liner prior to the completion attempt.

Production Liner Interval

In most wells in the Delaware Basin, it is possible to drill below the second intermediate liner to total depth with water as the drilling fluid; however, it is not uncommon to encounter gas in the Devonian, Fusselman, Silurian and/or Simpson formations prior to reaching the Ellenburger. If permeability encountered in any of these zones is of sufficient quality that it is not possible to trip the drill pipe with only water in the hole, slugs of weighted mud may be placed in the hole prior to tripping. This practice will allow low volume reservoirs to deplete while drilling and the hole to be drilled to the projected depth in the Ellenburger prior to setting another liner. In some wells, it will be necessary to drill a portion of the hole with weighted mud and set a liner prior to drilling the relatively low frac gradient Ellenburger. This requires drilling a small hole in the Ellenburger with slow penetration rates. The low torsional strength of drill pipe used in drilling below the 5-in. or 5-1/2 in. liner presents a twist-off problem.

Tie-Back Casing

As previously mentioned, a tie-back string should be cemented inside the protective liner through the intervals of abnormally high pore pressure prior to the completion attempt. The condition of the intermediate casing should be the determining criterion for installing a tie-back string inside intermediate casing to the surface. If sufficient remaining burst capacity to contain maximum anticipated wellhead pressure is ascertained and pressure integrity of the surface casing is established, no tie-back casing need be set inside the intermediate casing.

General Casing Design

Tubular goods account for approximately 30 per cent of the well cost. Several factors other than the usual consideration must be kept in mind in the design of casing and liners for use in these deep wells. All strings, except perhaps the surface casing, will be exposed to gas with high concentrations of hydrogen sulfide and carbon dioxide. Ideally, all tubular goods used in the well would have a hardness less than 25 on the Rockwell "C" scale (corresponding to an ultimate tensile strength of 125,000 psi) for minimal susceptibility to hydrogen sulfide cracking.

Higher strength materials are required, however, for resistance to burst and collapse. The intermediate (10-3/4 in. or 9-5/8 in.) casing may be called upon to contain wellhead pressures greater than 6000 psi if good permeability is encountered in the Wolfcamp or Pennsylvanian formations while drilling underbalanced. Measured pressures or log-calculated pore pressures from nearby wells, not anticipated mud density, are used in collapse and burst design. Care is used to assure the designer that the minimum yield of the steel is not reached. Premium couplings are used by operators for many of the casing and tubing strings. Difficulties are experienced in containing gas under high pressure with the API 8 round thread form. Also, high transverse stresses develop in the pin or box as a result of makeup torque and either internal or external pressure. Should these stresses exceed the minimum yield limit of the metal, a leak will likely develop and the susceptibility of the joint to hydrogen sulfide cracking is increased.

CEMENTING

Temperatures of 320°F or higher and long casing or liner strings with limited annular clearance between the wall of the hole and the pipe are the greatest areas of peculiarity of the deep wells.

Fluid loss additives and friction reducers are used in cementing the limited clearance annuli. Retarders to extend pumping time are used in cementing the higher temperature sections of the hole. The addition of siliceous material such as silica flour in concentrations of 30 to 40 per cent has proven to be effective in preventing not only retrogression of strength of the cement but also, of more importance, higher initial compressive strengths and no increase in permeability after exposure to high temperatures.[2] Any cement used in a well that will ultimately be exposed to temperatures above 230°F should contain siliceous material.

DRILLING FLUID SYSTEMS

The type and condition of drilling fluid utilized will greatly influence the total time and cost of the well. As a general rule, the lower the solids content of the mud system the faster the penetration rate. To meet this objective, water is used if possible in drilling all portions of the hole except the abnormally pressured sections of the Wolfcamp and Pennsylvanian formations. Saturated brine should be used in drilling the Salado formation to mitigate hole enlargement in the massive salt sections. If these salt sections are allowed to enlarge unduly, hole cleaning will be impossible, key seating may develop and cement requirements will be extremely high. Paper and/or oil may be added to the water to retard seepage or loss of circulation. A portion of the reserve pit is circulated to aid in keeping the fluid clean.

Fresh water may be used in drilling the Delaware Mountain Group of formations provided the Salado is cased off. Soon after the Wolfcamp is encountered, brine should be added to the drilling water to provide hole stability in this interval of increasing pore pressure. Usually, 9.2 to 9.6 ppg is sufficient to prevent problems with hole fill in drilling to the intermediate casing seat. Asbestos has been used effectively as an aid in hole cleaning in the water-drilled hole. The pH of the water should be maintained at 10 to 11 with lime to minimize corrosive effects. Batch treating of the drill string with filming amines and the use of internally plastic-coated drill pipe have also proven valuable in mitigating corrosion.[3]

A continuing effort to find a better drilling fluid system for drilling the abnormally pressured section of the Wolfcamp and Pennsylvanian section has been made. Ideally, the drilling fluid used in drilling this section should have the following properties and functions: allow penetration rate approaching that of water, allow gas to break out easily so that high-pressure low-volume formations can be more safely depleted, provide hole stability to reduce the likelihood of sticking the drill string and time consuming fill after trips, and the system should be relatively inexpensive. The practice of drilling underbalanced, i.e., with a hydrostatic head much less than known pore pressure, has been accepted for several years. In many wells, this practice has been thwarted by the apparent necessity to increase drilling fluid density for hole stability above that necessary for tripping the drill pipe. Many different types of drilling fluids including lignosulfonate, fresh and salt water polymers, high-density Newtonian fluids ($CaCl_2$ & $ZnCl_2$), and non-dispersed muds have been used. None of these have provided good hole stability through intervals of high pore pressure. Cautious optimism is being expressed in the use of lower density invert oil-emulsion muds with very high chloride concentrations in the discontinuous water phase for hole stability. Invert muds have been recently used over widely separated areas of the Delaware Basin and excellent hole stability achieved with significantly lower densities than was seen in offsetting wells which utilized water-base muds. For wells to be drilled in fields where it is necessary to increase drilling fluid density to allow tripping the drill pipe, the economics of utilizing this type fluid may not be favorable. With low-density invert mud, higher penetration rates in shales and slower penetration rates in limestone have been noted.

The use of fresh to brackish water instead of mud in drilling below the protective liner to total depth was a major breakthrough in reducing the time and cost to drill deep Delaware Basin gas wells. Corrosion protection should be afforded by the addition of caustic soda or lime to maintain a pH of 10 to 11. The pH of the water is lowered rapidly if significant quantities of gas are produced while drilling and batch additions of filming amines should be made to mitigate corrosive attacks on the casing and drill string. Mud costs account for five per cent of the cost of the well.

BIT SELECTION AND USAGE

Improvements in rock bits for use in Delaware Basin gas wells have been continuous and dramatic. The number of bits used has been cut by 50 per cent in a two-year period. Currently, 75 per cent of the bits used are of the carbide insert type. This type bit is available with a wide array of shapes and lengths of inserts, tooth action, sealed bearings, and in some sizes, with friction bearings.

Bit records of wells drilled in an area provide data as to how a correlative interval can be expected to drill. A careful study of these records along with other data such as mud information, well logs, etc., must be made either manually or by computer if proper bit selection is to be made. Efforts to optimize bit weight and rotary speed for lowest cost per foot drilling have been made and will continue to be made. Several problems exist in utilizing available programs for calculating optimum bit weight and speed. Bits are being improved constantly so that, many times, bits used on a well a year ago are now virtually obsolete. Programs that predict performance of a bit must consider the parameters of the bit to be used. These programs have not been able to keep up with the improved bits that are available. Unfortunately, many of the programs are not designed for use with insert-type bits. Computer programs designed for use with insert-type bits and recorded input data more precise than bit records should allow the art of bit selection and operation to become a science. Bit costs make up five per cent of the well cost.

RIG SELECTION

It is important to select a drilling rig with the capacity and features needed for drilling a particular well. It is equally important from a cost standpoint that capacity and features not needed in drilling a particular well not be specified in the bid request. Costs for a rig may be increased by as much as $200 per day by specifying more pump capacity than is actually required. An intimate knowledge of the component parts of each rig bid on a well is necessary if the rig for drilling the lowest cost well is to be selected. Rig time for drilling and completing comprises 35 per cent of the well cost.

Blow-out preventer equipment should be specified that is designed to handle well kicks that are expected with underbalanced drilling. Burst capacity of casing strings and breakdown pressures of formations below the casing to which the BOP is attached should be considered in selecting the pressure rating.

The selection of mud pump size, to be meaningful to hole cleaning capacity, must consider hole size, drilling rate, drill string geometry and the anticipated mud properties. An approach to including these items in the bid request is to specify, not pump size, but hydraulic horsepower per square in. of hole (2.5 to 4.5 $HHP/in.^2$) along with minimum annular velocities and anticipated plastic viscosities.

Calculations should be made to determine hoisting capacities required for both drill strings and casing strings. Substructure height and capacity should be considered in light of blow-out preventer stack requirements and loads to be imposed. Racking room in the derrick may become critical during casing running operations. The extra time to lay down and pick up drill string, if necessary, should be included in bid comparisons.

SUPERVISION

A large percentage of the time spent in drilling the deep gas wells of the Delaware Basin is on a day work rate; i.e., the contractor furnishes the rig, tool pushers and drilling crews at a specified cost per day. It is important for the operator to furnish on-site supervision while drilling on a day work rate and to maintain a formation correlation with other wells in the area in all parts of the hole. The operator's personnel at the rig site should not attempt to perform the functions of a tool pusher but should work with contractor personnel in planning and coordinating the operation. An aggressive approach should be made in applying good drilling techniques such as bit selection and operation, hydraulics and drilling fluid maintenance. Supervising well control operations, pipe inspection, casing and cementing operations, and the well completion make the operator's well-site representative a very important part of drilling and completing a well at minimum cost.

It is imperative that lines of communication be established and maintained between contractor personnel and operator personnel before and during the drilling operation and that a spirit of cooperation exists.[4]

WELL COMPLETION

From 600-1200 feet of Ellenburger dolomite is penetrated in the Delaware Basin wells. Casing is set through this zone and cemented. Perforations are sparingly placed within intervals of indicated porosity. Usually, 30 to 120 holes are shot with one or two holes per interval. A quasi limited-entry technique is used so that the operator may be assured that each perforated interval is broken down by the treatment. Several sources of evidence are used for determining the location of zones of porosity. These include intervals in which gas increases are seen in the drilling fluid, intervals in which increases in rate of drilling water loss is seen, drilling rate log, miscroseismogram log, gamma ray neutron, density or sonic log and resistivity logs. Production logs such as differential temperature logs are run after the well has been completed to determine which zones are actually producing gas.

Acetic acid is usually spotted over the interval to be perforated in the well. With this fluid in the hole, tubing may be run and the wellhead installed. After the well is perforated, the acetic acid is pumped into the formation, followed by treated water in the casing and tubing above. Hydrochloric acid mixed with an organic acid (formic or acetic) is used with ball sealers to open each perforation to the formation. The usual volume of this treatment is 500-1000 gal. per perforated interval. If no danger of water exists and additional treatment is deemed necessary, ball sealers may be released from the perforations and an additional treatment performed on the same horsepower setup charge. Nitrogen is usually added to all or the last part of the treatment and flushed to facilitate flow back of the load and acid water.

If a treatment larger than the "hole opening" acid treatment is deemed necessary either as a result of productivity performance poorer than anticipated or in an attempt to increase reserves connected to the wellbore, a frac-type treatment is used. The size, type and rate of the frac operation is based on the objective to be accomplished. Items to be considered in designing the job are (1) quality and quantity of indicated pay, (2) size and location of the perforations, (3) treating pressures and rate of acid injection, and (4) the size and pressure limitations of the treating string of pipe. Acid is an expensive and inefficient fracturing fluid, so water with fluid loss additives is used to initiate and extend fractures into the formation. Mixtures of hydrochloric and organic acid are used to etch the fractures and diversion from one zone to another is accomplished by the use of ball sealers and in-formation diverting material. Many of the perforations will be connected by vertical fractures and ball sealers alone can not effectively divert flow to unfractured zones. An ideal blocking material would have the following characteristics:

1. effectively bridge fractures in dolomite and withstand a differential pressure as high as 9000 psi
2. be stable at the temperature and pressure found in the fractures and in the presence of water and acid for the dura-

tion of the treatment
3. sublimate or dissolve after the treatment to allow the fracture to be open to the wellbore with a minimum of residue.

Proppants such as sand and/or glass beads are being considered for use in these deep reservoirs and will undoubtedly be tested in conjunction with fluids with high sand carrying capacity.

Many wells with high calculated absolute open flow tests have not been treated sufficiently to open all reserves to the wellbore. These wells usually experience rapid loss of pressure after being placed on production as only a thin interval is being produced. It is difficult to divert treatment and open additional zones in this type well after the most permeable zone has reached an advanced stage of depletion.

The completion expenditures account for four to ten per cent of the well cost.

OUTLOOK FOR FUTURE

Deep basins such as the Delaware Basin must be developed if the increasing demand for natural gas is to be met. The rapid improvements in drilling operations that have been seen in the Delaware Basin have been gratifying for those involved. Some of the old enemies remain to be conquered and several potential areas of improvement demand further work.

Among the problems to be solved are:

1. those associated with drilling brecciated dolomite in the Ellenburger. The drill string may become stuck or twist off as a result of these fractured, brecciated intervals. This phenomenon has been found in widespread areas and is possibly associated with faulting.
2. the expansion of drill pipe protectors after exposure to gas.
3. deviation control in certain areas, particularly the Woodford formation in the Lockridge field which defies usual techniques employed in maintaining a straight hole.
4. analytical methods for selecting intervals to be perforated.
5. techniques for connecting a greater percentage of the reserves in a proration unit to the wellbore.

Several techniques for drilling other than the conventional rock bit with rotary table rotation have been employed in the Delaware Basin. Downhole motors and diamond bits offer areas of potential improvements in drilling techniques. One can expect significant improvements in drilling methods to continue in the foreseeable future.

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