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GEOTHERMAL DRILLING FLUIDS

Robert Pantermuehl and Paul Scott

M-I Drilling Fluids Co., P.O. Box 721110, Houston, TX 77272

ABSTRACT

The elevated temperatures and unique geology of geothermal resources require special drilling fluid design considerations. Improperly designed drilling fluids can result in numerous drilling problems. Many products will degrade when exposed to bottom hole temperatures encountered in Geothermal drilling. This can result in increased product consumption, unstable drilling fluid properties, and wellbore instability. The thermal flocculation of solids can also lead to drilling problems. This can occur even when using thermally stable drilling fluid products. Clay flocculation increases viscosity and fluid loss. High temperature gelation and cementation can also result from poorly designed systems. The high temperature and acid gases encountered cause corrosion to occur at a greater rate. The increased rate of corrosion will reduce the drill string life and increase problems from drill string failure. Temperature stability in geothermal drilling fluids is achieved by limiting active solids, by designing the drilling fluid system using thermally stable products, and the use of high temperature stabilizing additives.

INTRODUCTION

Significant geothermal potential exists in areas where molten rock is near the earth's surface. Geothermal activity occurs within well defined "belts" associated with the margins of the earth's major crustal plates.[1,2] Geothermal potential is often located in areas of previous volcanic activity. Commercial geothermal production exists in the western United States, Japan, Philippines, Italy, New Zealand, Central America, eastern Africa, and many other areas of the world.[2] The total U.S. geothermal production currently exceeds 2500 megawatts of electricity and is equivalent to 23 million barrels of oil per year. The most prolific geothermal field is an area of Northern California known as "The Geysers." Other commercial geothermal fields in the United States are the Imperial Valley(Ca), China Lake area(Ca), Mammoth area(Ca), the Dixie Valley(Nv), Steamboat Springs area(Nv), and Roosevelt Hot Springs area(Ut). Each area will require special attention when designing a geothermal drilling fluid.[3] Consideration of the geology, temperature, and production zone is crucial to a successful drilling program.

Most geothermal activity is located in geological areas of volcanic origin. Formations in geothermal areas are mainly igneous or metamorphic. The rocks are not water sensitive, unless they have been substantially altered. Sedimentary formations in these areas are normally a result of ash falls. Formations drilled in these areas are from lava and ash flows. The following formation types are drilled in geothermal regions. Pumice is a frothy mass of glass with bubbles formed by gas escaping from the volcanic melt. These rocks are not water sensitive, but do have considerable porosity and permeability. Basalt, the most abundant of volcanic rocks, is chemically inert with little porosity. Andesite is common in geothermal areas, and is inert. Rhyolite resembles granite with individual crystals not visible to the naked eye. Tuff is solidified rock that hardens from ash falls, flows and other ejected material. Schist, slate, and gneiss are metamorphic rocks found in geothermal areas. Schist is characterized by partings along well defined planes of medium grained platy micaceous minerals. Slate has more perfect planar partings and is finer grained, so that individual minerals are not visible. Argillite is a fine grained slate found in "The Geysers" geothermal field. Argillite is not water sensitive. Problems relating to argillite are wellbore instability and sloughing. These problems occur because the formation is fractured or rubblized from tectonic activity. Gneiss is coarse grained and shows broader, less distinct foliation. Gneiss does not cleave as would a schist or slate. Serpentine is metamorphosed magnesium silicate found in "The Geysers" geothermal field that is related to fibrous asbestos. Drilling serpentine formations will increase the viscosity of a drilling fluid through the incorporation of fibrous fine solids. Although serpentine is not water sensitive, these formations frequently are unstable "in situ" or become unstable after being drilled.[4,5] Graywacke is a poorly sorted sandstone that contains feldspar and sand sized fragments of metamorphic or volcanic rocks. Drilling problems in graywacke formations rarely occur. Graywacke is the reservoir rock in "The Geysers" with production from fracture dominated formations.

The Imperial Valley geothermal field is sedimentary in origin with production from sand sections saturated with hot water. The area is a large sedimentary basin containing sandstones, siltstones, shales, and conglomerates.[4,6] Metamorphic and igneous formations are found beneath the sequence of sedimentary formations. Some fracture dominated production is from these lower sequences of the Salton Sea region.[24] Production formations in this area are not water sensitive. Production may be impaired however from particle bridging as discussed later.

Temperature gradients in geothermal areas exceed gradients found in oil and gas drilling.[7,8] Geothermal temperature gradients have been recorded as high as 12.5 deg F/100 ft. In oil and gas drilling extreme bottom hole temperatures are normally not encountered until a depth exceeding 20,000'. With current petroleum market conditions wells drilled to this depth are rare. In geothermal drilling extreme bottom hole temperatures can be encountered at depths as shallow as 2500'. Special consideration must be given to drilling fluids used in these circumstances.[4,6,9,10]

Commercially viable geothermal production has three forms. They are: 1) hot water at both bottom hole and atmospheric pressures, 2) wet steam which is hot water at bottom hole pressure and steam at atmospheric pressure, and 3) dry steam which is steam at both bottom hole and atmospheric pressure. The two basic reservoir types are fracture and matrix. Fracture reservoirs are more common and have production from high permeability large vugular fractures in host rocks of low permeability. Massive lost circulation is associated with this type of production formation. Matrix reservoirs have production from lower permeability sand, sandstone, or microfractured formations. Partial lost circulation often occurs with this type of production zone. Geothermal production zones are typically subpressured.

DISCUSSION

As stated previously, most geothermal activity is in volcanic areas. Formations drilled are usually igneous and metamorphic materials. Igneous materials such as tuff and pumice found in most geothermal areas are not water sensitive, and are sometimes water saturated. These formations can have considerable porosity and permeability. In this case the filter cake thickness must be controlled even though the actual fluid loss would not cause any problem. Problems associated with excessive filter cake thickness are differential sticking, high torque and drag, difficulty while directional drilling, and tight hole. Filter cake thickness is controlled by limiting the concentration of drill solids and reducing the fluid loss. The drill solids concentration is controlled with mechanical solids removal equipment and dilution. The fluid loss can be reduced by obtaining a wide particle size distribution and with fluid loss additives. Fractures are often drilled resulting in severe lost circulation. Efforts at plugging the fractures with various types of lost circulation material have been futile. Only two approaches to remedy this type of lost circulation have been successful. The first is to seal the fracture by spotting a cement plug at the loss zone. This may require drilling without returns to get past the loss zone. The second is to drill the interval with an aerated fluid.[4] The first method is preferred, because lost circulation should be corrected before setting casing. If lost circulation is not cured, an improperly cemented casing string will result. The thermal stresses subjected to the casing string during geothermal production requires that a continuous cement bond be achieved or the casing will fail. Igneous materials such as basalt and rhyolite are inert with little permeability and do not require special consideration.

HOLE STABILITY

Metamorphic formations in geothermal drilling are usually forms of gneiss, schist, or slate. Forms of gneiss are stable and do not require special consideration. The schists and slates do require special consideration. Schists and slates are ordinarily tectonically stressed. Schist and slates have partings along well defined planes. The combination of these partings, tectonic stresses, and erosive forces from the flow of the drilling fluid can cause these formations to slough. Various methods have been tried to stabilize sloughing formations.

One method to stabilize sloughing is to increase the density of the drilling fluid. This was done to raise the hydrostatic pressure of the drilling fluid column and balance the tectonic stresses. The increased density method is not normally effective. In addition, the cost is prohibitive and results in a reduction in the rate of penetration. It is the authors' opinion that any improvement from this technique is from the improved hole cleaning of the higher density fluid. Increasing the density is not effective in controlling sloughing formations in geothermal drilling.

A second method to stabilize sloughing is to lower the fluid loss of the drilling fluid to inhibit the sloughing formation. Usually a fluid phase viscosifier is used to lower the fluid loss. This method is effective some of the time, however, the wrong drilling fluid property is getting credit for the cure. A reduction in fluid loss does not prevent capillary wetting, and water exposure or fracture saturation would occur regardless of the fluid loss value. Metamorphic materials are rarely water sensitive. As a fluid phase viscosifier is added to lower the fluid loss, the viscosity is increased and the erosive force on the formation is decreased. It is the authors' opinion that lowering the fluid loss may help to stabilize a sloughing geothermal formation as a by-product of the increased viscosity.

The third method to stabilize sloughing is to use special asphaltic additives. These materials have an application where sloughing is caused by water wetting of highly faulted, micro-fractured, or rubblized sections. Asphaltic products work by deforming under pressure to plug and seal the wellbore. There are a variety of asphaltic products which range from the ground raw asphalt mineral to highly processed refined asphalt. For geothermal applications the softening point of the product must be considered. The application of these additives has been successful in certain areas in "The Geysers".

The fourth method to stabilize sloughing is to increase the viscosity of the drilling fluid. As discussed, this occurs with the addition of fluid loss agents. The addition of materials which are direct or primary viscosifiers is preferred. These materials are flocculants, polymer viscosifiers, and commercial clays. If filter cake quality is not a concern, flocculation of the drilling fluid with a source of calcium or carbonate is the most economical way to increase the viscosity. Flocculation will increase the yield point and gel strengths of the fluid and not the plastic viscosity. The desirable rheological properties of a flocculated drilling fluid are difficult to emulate. An alternative to flocculation is the addition of a polymer viscosifier such as hydroxyethyl cellulose (HEC) or xanthan gum (XC Polymer). With HEC the dynamic viscosity is increased but an elevated gel structure is not created. An elevated gel structure and increased dynamic viscosity can be obtained with XC Polymer. The least desirable alternative to increase the fluid viscosity is with a higher concentration of commercial clays. These commercial clays include bentonite, attapulgite, saponite, and sepiolite. The plastic viscosity will be increased at higher clay concentrations resulting in a reduced rate of penetration.[18] The use of bentonite as compared to the other commercial clays is discussed later. Elevated temperatures will cause the thermal flocculation of active clays. Higher concentrations increase the severity and reduce the temperature of thermal flocculation.[11] At temperatures over 400 deg F, commercial clays convert to various forms of the smectite.[12-15] Higher concentrations of commercial clay result in an unstable drilling fluid and possible drilling problems. The most effective method to stabilize sloughing geothermal formations is to significantly increase the viscosity of the drilling fluid.

TEMPERATURE STABILITY

Temperature stability of the drilling fluid is the next major concerned. Temperature in excess of 350 deg F are encountered as shallow as 2500'. Clay flocculation and high temperature gelation are common problems associated with extreme bottom hole temperatures. Three areas merit consideration when high temperature stability is needed. They are active solids concentration, product degradation and high temperature stabilizers. The bentonite concentration has the strongest influence on the temperature stability of a drilling fluid.[11] When the temperatures exceed 350 deg F, the methylene blue capacity of the drilling fluid must be maintained at less than 17.5 lb/bbl equivalent. This is achieved by designing the drilling fluid with minimum added clay and through proper solids control and an effective mud management system.[16] Several drilling fluid systems based on minimizing added clay have been successful in geothermal areas. To obtain increased levels of viscosity, reduced clay drilling fluids must be viscosified by other mechanisms. These systems use chemical flocculation, polymer extension, or polymer substitution to increase viscosity.

Chemical flocculation is achieved through the addition of a source of calcium or carbonate. Chemical flocculation is the most cost effective method to increase viscosity when the formation is low permeability and not water sensitive. Calcium flocculation using lime is the best method in geothermal drilling. There are three reasons why calcium flocculation with lime is usually the best method. First, in geothermal drilling the pH of the drilling fluid should be maintained above 11 for corrosion control. Lime is an excellent source of hydroxyl to maintain this level of alkalinity. Hydrogen sulfide and carbon dioxide are corrosive acid gases common to geothermal areas. Lime will precipitate the by-products from carbon dioxide and will sequester hydrogen sulfide. Second, lime flocculated systems are compatible with placing and drilling cement plugs used to seal lost circulation zones. Third, the cost of lime is low when compared to other chemicals used for flocculation. Two disadvantages of flocculation are poor filter cake and fluid loss control. If the formation is pumice or tuff with high permeability or water sensitive, then the fluid loss must be reduced and flocculation is not a cost effective option. In these cases the commercial clay content is limited with bentonite extension or substitution.

Bentonite extension is the addition of polyacrylate/polyacrylamide copolymers which flocculate clay particles to increase the viscosity. This method has been successful in geothermal areas. Bentonite substitution is the reduction of the bentonite content by using a polymer viscosifier to further increase the viscosity. Two products used for bentonite substitution are HEC and XC polymer. Although these polymers degrade at higher temperatures, they are effective in geothermal drilling. The circulating fluid temperature is much less than the formation temperature so the thermal limit of these products is rarely exceeded.[17] During trips the static fluid temperature will increase and drilling fluid products will degrade above their thermal limit. The thermal degradation of these polymers does not produce contaminating by-products. While the viscosifying contribution of the polymer is lost, thermal flocculation will increase the viscosity in a compensatory manner.[16] Therefore, the suspension and viscous properties are maintained and high temperature gelation does not occur. Product consumption is limited to the small quantity of drilling fluid exposed to the higher formation temperatures.

Geothermal drilling fluids using clays other than bentonite were developed to increase temperature stability.[10,13] Sepiolite and other clays were used to replace bentonite because they do not flocculate as severely at high temperature. These systems have two characteristics which make them inferior to bentonite drilling fluids. First, these bentonite alternative clays are poor viscosifiers. Higher concentrations must be used to produce the same viscosity as bentonite. Higher solids concentrations will reduce the drilling rate. Second, alternative clays are poor fluid loss reducers. Fluid loss additives must be used to achieve the same level of fluid loss control as a bentonite fluid.[23] Fluid loss additives are expensive and further increase the solids concentration. Since the introduction of sepiolite geothermal drilling fluids, new products have been developed which preclude the need for alternative clays.[19-22] Bentonite geothermal drilling fluids can be formulated with existing products that have stable fluid loss and rheological properties at high temperatures.[19]

Product degradation is the next concern associated with temperature stability. The rate of product degradation is a function of increased temperature and time of exposure. Product degradation of organic thinners frequently results in chemical by-products which contaminate the drilling fluid.[16] This contamination will increase product consumption to the point where continued usage is not economical. The temperature stability of organic thinners is a major design consideration for geothermal drilling fluids. These products should not be used above their thermal limit.

The following are the temperature limitations of organic thinners:

Lignosulfonate products	325-350 F
Ground lignite	400-450 F
Chrome lignite	550 F
Resin treated lignite	500 F
Modified humic acid	550 F
Synthetic polymers	550 F

Lignosulfonate products have a low temperature stability and should not be used in high temperature geothermal areas. Lignosulfonate products degrades to produce by-products which include carbonates. Chrome lignite and modified humic acid have excellent temperature stability, but environmental restrictions prohibit their use in some areas. Lignite and low molecular weight polyacrylates have high thermal stability and are widely used in geothermal drilling fluids.

The temperature stability of fluid loss additives also requires attention. Natural polymer fluid loss additives have the lowest temperature stability. Their use normally becomes uneconomical when temperatures exceed 275 deg F. Cellulose derivatives have a higher thermal stability than natural polymers. Their use is usually cost effective to temperatures of 350 deg F. Resin treated lignite is an excellent fluid loss additive with a temperature stability of 500 deg F. This product also provides high temperature rheological stabilization.[16] Synthetic polymers have the highest temperature limit. Specially formulated synthetic polymers are temperature stable to 550 deg F. These polymers also provide high temperature rheological stability. These polymers include polyacrylate/polyacrylamide, polyacrylate/amps and vinylamide/vinylsulfonate copolymers.[21,22]

The use of high temperature stabilizers will increase the temperature stability of the drilling fluid. High temperature stabilizers decrease the flocculation of clay solids and increase the stability of certain organic additives. High temperature stabilizers include low molecular weight polyacrylates, specially formulated resins, raw and modified lignite, humic acid derivatives, and sulfonated styrene/maleic acid copolymers.[16,19,20]

SPECIAL CONSIDERATIONS

A major concern with regard to formation damage is plugging of the production zone. In a sand matrix production zone solid particles can reduce the permeability of the matrix. Two major concerns are clay particle plugging and lost circulation material plugging of the production zone. Production zone damage from drilling fluids is not as much of a problem in fracture dominated formations.[24] Although large volumes of drilling fluid may invade these fractures while losing circulation, the fractures may be large enough that permanent plugging is not a problem. The conservative approach to drilling fracture dominated production is to utilize air drilling for dry steam or an aerated fluid for hydrothermal production.

Drilling fluid solids plugging has been a major concern for sand matrix production zones.[24] This type of production occurs primarily in the Imperial Valley. Cores from this region have shown significant permeability reduction resulting solely from the behavior of internal native clays.[13] Common practice has been to substitute sepiolite or attapulgite for bentonite to reduce particle plugging and increase temperature stability. The assumption was that bentonite tends to plug sand matrixes more than other clays. This assumption is valid only for low temperature reservoirs. Above 400 deg F clays are altered to very similar smectite type minerals.[12-15] After the thermal conversion to smectite the plugging tendency of all clay is essentially equal.[13] The large flat shape of a bentonite particle is preferred to other clays because it will tend to bridge and block the sand matrix from additional particulate invasion.[18] The fluid loss of bentonite drilling fluids is much lower than sepiolite or alternate clay fluids.[9,10,12-15,19,23] To prevent plugging of a matrix production zone a drilling fluid should have a wide particle size distribution and low fluid loss.

Lost circulation material(LCM) utilized to control drilling fluid losses to production zone may also cause formation plugging. To limit the severity of LCM plugging, the loss zone must be sealed quickly. A permanent plug is undesirable, as this would prevent the geothermal fluid from being produced. The lost circulation material should have the flexibility to be produced from the formation. To break the LCM it should be either water soluble or thermally degradable with time. A requirement for the proper application of a LCM is that the particles are least one-third the size of the loss zone. Particles of this size will form a bridge to prevent further formation invasion. Cottonseed hulls, sized calcium carbonate and other LCM has been successful in matrix production zones. A properly selected lost circulation material will minimize plugging of the production zone.

Corrosion is accelerated in geothermal drilling because of the high temperatures and acid gases encountered. Problems of drill string failure caused by corrosion are common in geothermal drilling. Rates of corrosion are routinely measured with drill string coupons. The most important drilling fluid property for inhibiting corrosion is the pH. The corrosion rate will be reduced with an alkaline drilling fluid. The recommended levels of alkalinity are a pH of 11 and a P_f of 1.0. If alkalinity control is not possible or if an aerated fluid is used, then a corrosion inhibitor must be used. Corrosion inhibitors include film forming amines, passivating chemicals, and scale inhibitors. The appropriate inhibitor should be selected based on an comprehensive corrosion evaluation.

CASE HISTORIES

The first case history compares a properly designed geothermal drilling fluid with a standard deflocculated system. Well number 1 was drilled with a standard deflocculated system. Well number 2 used a lime flocculated system to 6000' and a polymer extended system to 8265'. Well number 2 was a geological offset to well number 1. Well number 2 was drilled in 15% fewer days with one-third the mud cost of well number 1.(Fig. 1 & 2) Deflocculants were not used in well number 2. The use of fluid loss agents was kept at a minimum.(Fig. 3) The rheological properties were maintained in a non-dispersed state with a yield point higher than the plastic viscosity throughout the entire well. In well number 1 two-thirds of the mud costs were from deflocculants and fluid loss additives.(Fig. 4) The mud weight was increased in an unsuccessful attempt to stabilize the wellbore. The drilling fluid was not chemically flocculated and polymer viscosifiers were not used. The plastic viscosity was equal or higher than the yield point during most of this well.

The second case history is of a well where a bentonite HEC drilling fluid was used. A closed loop solids control system was also incorporated on this well. The well was drilled to a depth of 5367' in 29 days at a mud cost of $5.93 per foot.(Fig. 6 & 7) An asbestos type serpentine was drilled on this well and some fluid loss control was required. This eliminated chemical flocculation of commercial clays as a viable method to achieve the required viscosity. A bentonite HEC fluid was chosen to successfully drill this well.(Fig. 5) The yield point was maintained higher than the plastic viscosity throughout the well. The MBT (Methylene Blue Test) value was maintained at 17.5 ppb or less after the surface hole was drilled, and the total solids was maintained at a maximum of 4.5% after the surface hole. Deflocculants were added to control the gel strengths while drilling the serpentine formation. The well was successfully drilled without any lost time due to wellbore instability or mud related problems.

RECOMMENDATIONS

1. Limit MBT values to a maximum of 17.5 ppb and total solids to 5% by volume. This will reduce the effect of thermal flocculation.

2. Minimize the addition of commercial clay through chemical flocculation, bentonite extension or bentonite substitution with polymers.

3. If the formations being drilled have low permeability and are not water sensitive, chemically flocculate the fluid to increase the viscosity and reduce the clay content required.

4. If the formations being drilled are water sensitive or have high permeability, obtain the proper viscosity with polymer bentonite extenders or polymer viscosifiers.

5. An effective mud management system which includes proper solids control should be employed to maintain a temperature stable drilling fluid.

6. Sepiolite and other bentonite alternative clays should not be used because they are poor viscosifiers and fluid loss reducers.

7. Fluid loss additives and thinners should be selected that can tolerate the temperatures encountered.

8. High temperature stabilizers should be used to improve the thermal stability of the drilling fluid at extremely high temperatures.

9. Alkalinity control should be used as primary corrosion control. Corrosion should be monitored to indicate proper inhibitor application.

CONCLUSIONS

The geothermal environment requires special drilling fluid design considerations. The geology of geothermal areas requires different drilling fluid considerations than oil and gas drilling. Remedial techniques used in geothermal drilling are unique to the special problems encountered. Bentonite drilling fluids can be designed to be thermally stable and combat geothermal drilling problems. Properly designed geothermal drilling fluids have been shown to reduce the time and cost of geothermal exploration and development.

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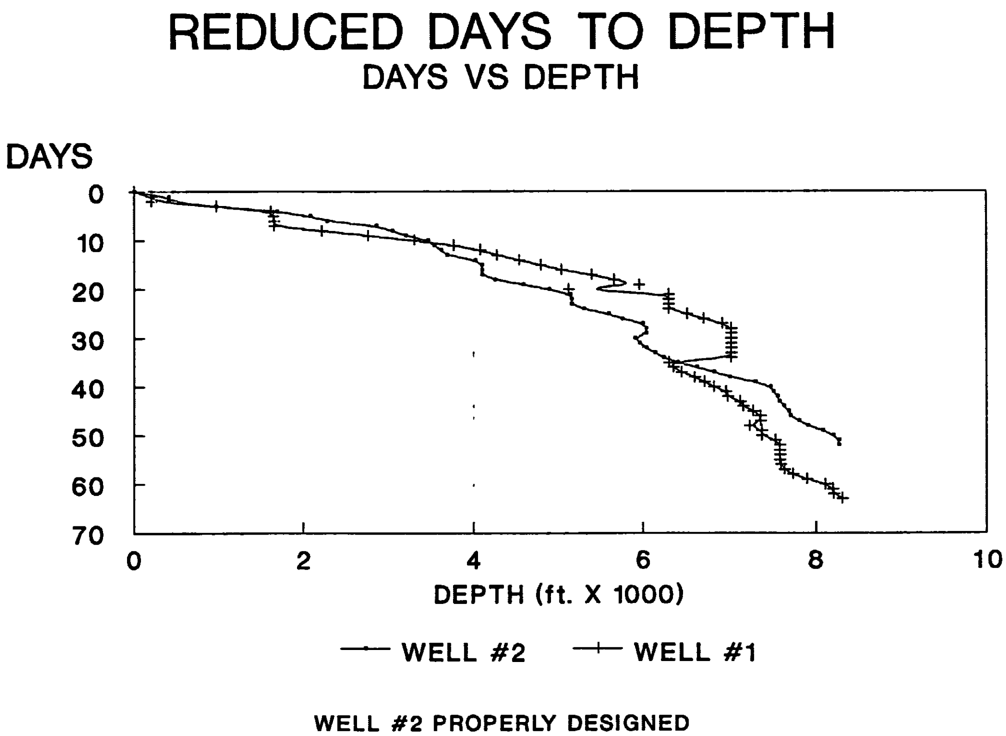


FIGURE 1. CASE HISTORY #1

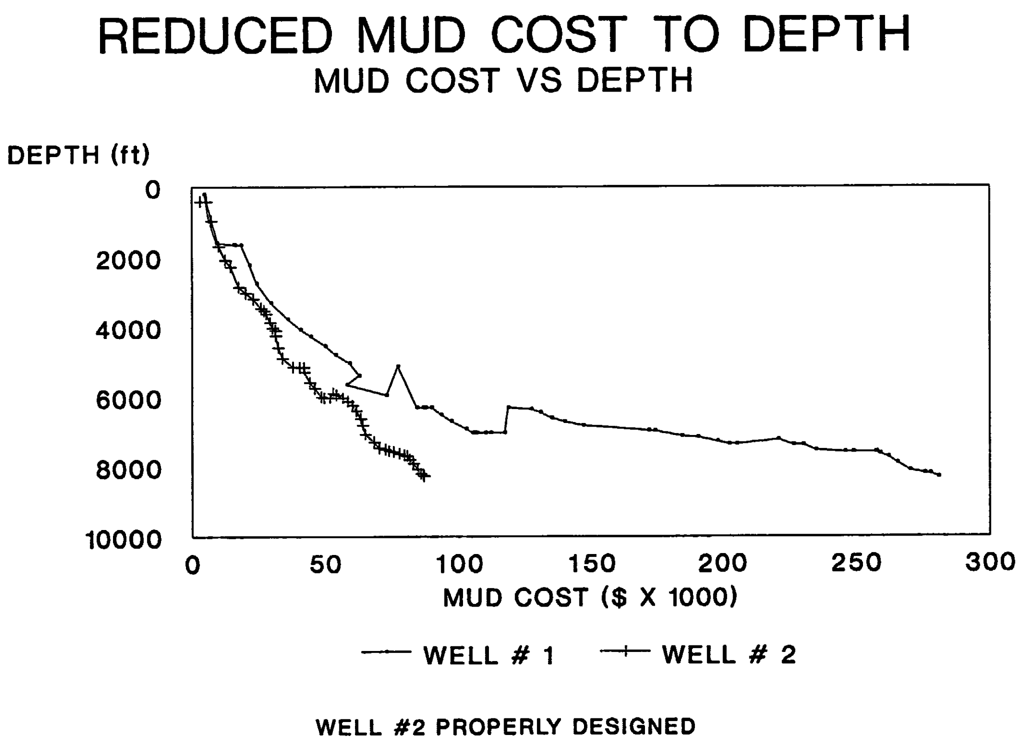
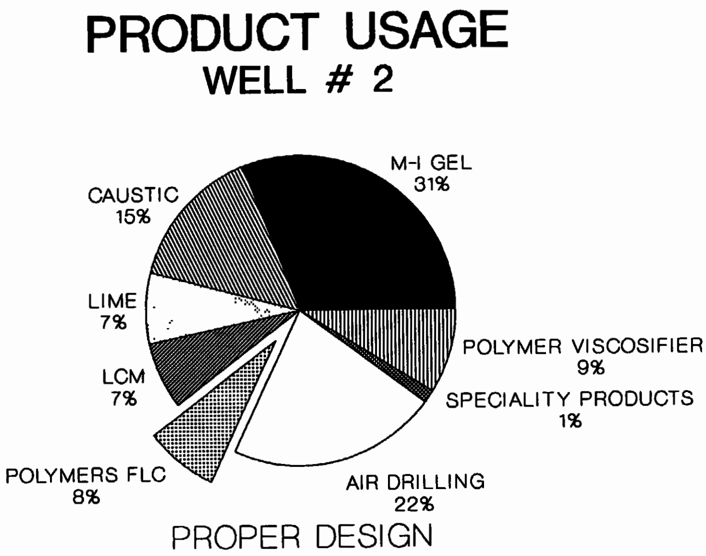


FIGURE 2. CASE HISTORY #1



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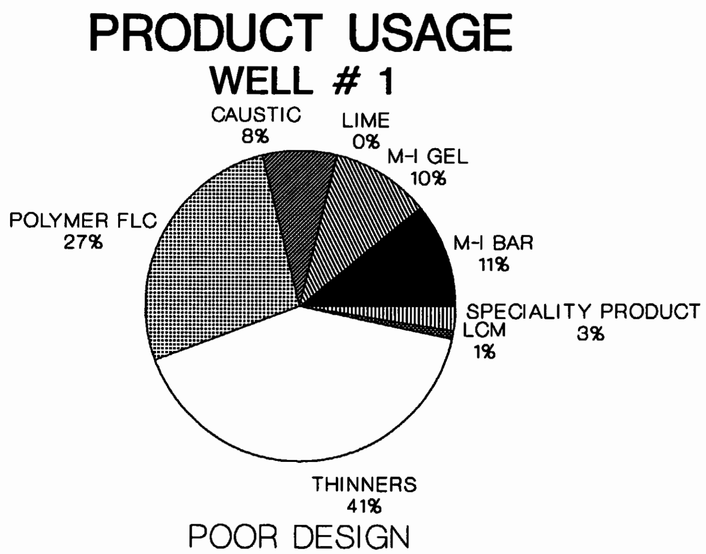

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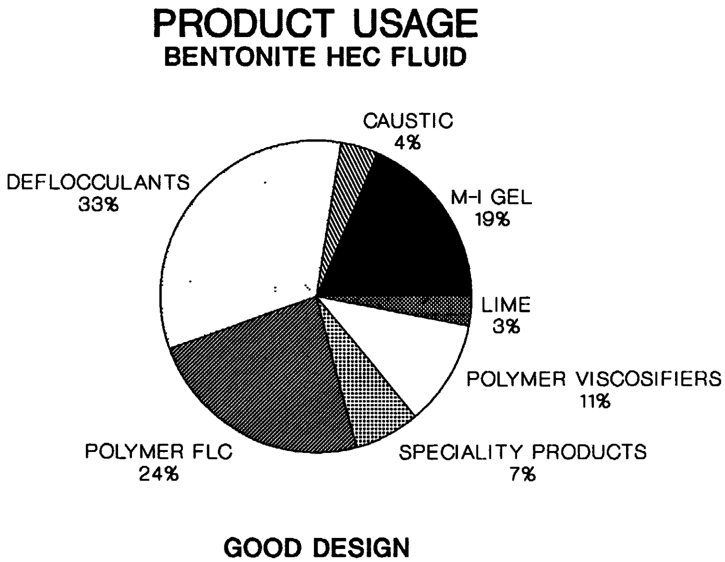
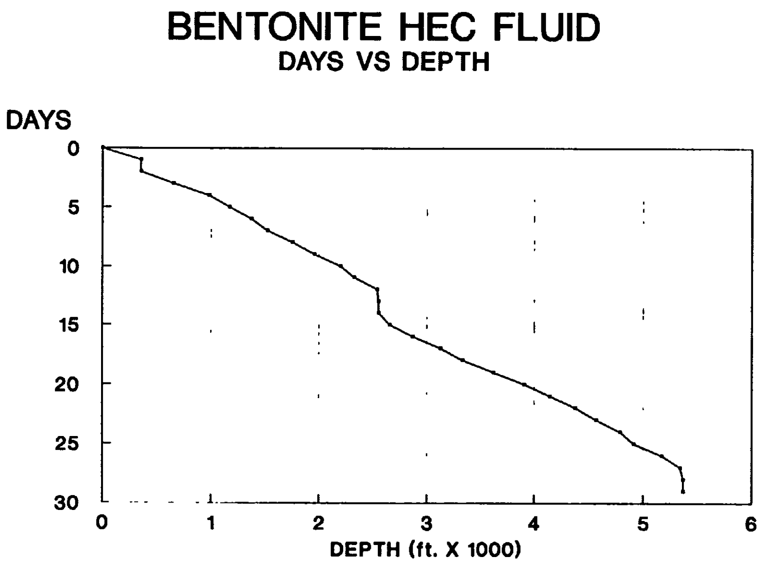


FIGURE 5. CASE HISTORY #2



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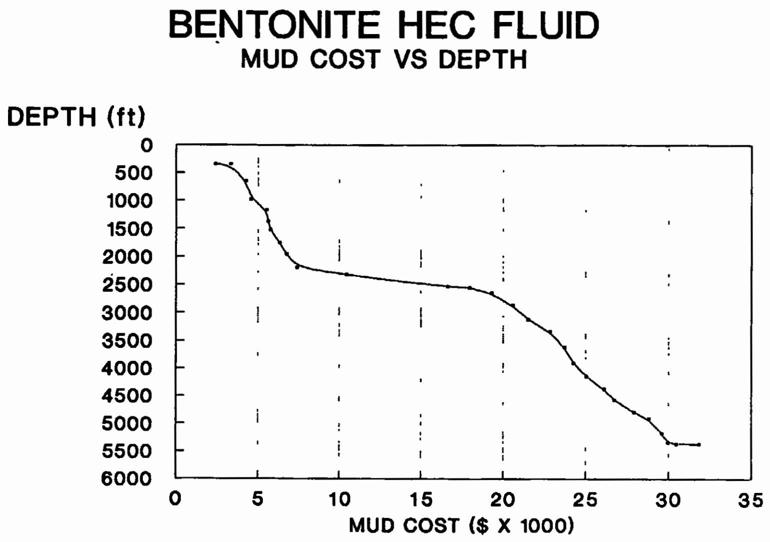

FIGURE 7. CASE HISTORY #2: GOOD DESIGN