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The Use of Mixed Metal Oxide Drilling Fluid Systems for Geothermal Drilling

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Keywords
Loss circulation, drilling fluids, mixed metal oxides, geothermal, drilling, MMO

ABSTRACT

Geothermal drilling places great stress on the design of drilling fluids to meet the combined challenges of minimising drilling fluid losses in surface zones; drilling fluid losses in steam producing fractures; hole cleaning and cuttings suspension; wellbore enlargement in poorly consolidated zones; and thermal stability. The choices of drilling fluid for geothermal drilling are many, but recent developments in the technology of Mixed Metal Oxide products has resulted in a system especially suited to geothermal drilling as illustrated in the three case histories presented.

Introduction

Steep temperature gradients are one of the extreme drilling conditions required for geothermal drilling. Other drilling challenges include minimising fluid losses, hole cleaning, and thermal stability. This paper presents a drilling fluid that has been used successfully in these extreme environments and overcoming many of the drilling hazards found in geothermal wells. Case histories from the Far East are presented in which the performance of the fluid is exemplified.

Hazards Associated with Geothermal Drilling

Some of the main issues associated with drilling geothermal wells are briefly discussed below.

High Static and Circulating Temperatures

The drilling fluid may experience bottomhole temperatures as high as 400°C. This places severe constraints on the type of drilling fluid product selection. “Drill and burn” is the current philosophy in which low-cost drilling fluid products thermally degrade over a period of time, and are replaced with new products.

Lost Circulation

The nature of geothermal reservoirs is that they are fractured and there is communication between the producer and injector wells. This presents a major hazard in that total lost circulation in all hole sections is frequent. Standard lost circulation material is usually ineffective because of the fracture width. Hydrostatic pressure is difficult to maintain and subsequent wellbore instability problems result.

Formation Damage

Formation damage may occur as large volumes of fluid and lost circulation material invade the producing fractures, indeed, communication may occur between the producing and injector wells leading to loss of steam production in adjacent producing wells directly affecting the power plant production.

Wellbore Stability

The upper sections of geothermal wells are usually composed of loose, poorly consolidated sediments and are susceptible to mechanical erosion. Large volumes of eroded sediments often result in hole cleaning problems. Whole fluid losses into the formation are frequent and adequately cleaning the hole and maintaining hole stability are critical issues. Lack of attendance to this may result in poor cement jobs, especially in the surface and intermediate strings which are usually the most critical for well control and good cement shoes. Surface formations are usually poorly consolidated and hydrothermal clays associated with volcanic activity (usually associated with geothermal wells) may be rich in smectite. Upon contact with water, these highly water sensitive clay minerals swell and could potentially result in stuck pipe, bit bailing and ‘gumbo’ problems.

Cementation

It has been mentioned that a stable in gauge hole results in better executed cement jobs, especially when the well is producing
steam. Poor cement jobs, combined with the thermal expansion of casing and cement has been known to cause the casing to collapse of ejected from the well. Cement plugs are frequently used to plug and control losses into fractures, but because of the nature of the losses, the success rate is poor.

**Environmental**

Geothermal reservoirs are frequently found in mountainous regions, often with volcanic activity, and in areas of outstanding natural beauty. Loss or breach of fluid to ground water and surface water courses through surface rubble zones can be environmentally disastrous.

Many of these issues are interrelated to the extent that one problem very often leads to another with costs escalating. Cost associated with rig time and lost drilling time increase.

**Geothermal Drilling Fluid Requirements**

The following key drilling fluid requirements are regarded as being essential for geothermal drilling fluids:

- Potential use of one fluid for all hole sections for ease of logistics especially in remote locations.
- Good hole cleaning in all sections, especially in surface sections and maintenance of a stable wellbore.
- Minimising whole fluid losses with savings in fluid costs and lost rig time.
- Reduced communication with water injection wells and producing wells. No loss of steam production.
- Reduced well costs through savings in rig time, increased penetration rates, reduced cementation costs, lower mud volumes.
- Decreased formation damage and improved steam production with increased well life.

**Geothermal Drilling Fluid Options**

*Clear water drilling:* This fluid is normally used with high viscosity sweeps and air assistance. The fluid is normally high pH using lime and some potassium hydroxide for stabilizing reactive claystones. Losses are not addressed. Corrosion control is increased under alkaline conditions and aminated corrosion inhibitors are added. Disposal of alkaline fluids may present HSE issues.

*Extended Bentonite:* This is polymer-treated bentonite used mostly in top hole drilling for hole cleaning and some formation stability. As the well gets deeper and hotter, this fluid has to be watered back, and is not recommended for reservoir rock. It normally has a high content of insoluble solids and cannot be remediated once it has been dehydrated in the well. Losses are addressed with a blend of course and medium sized material that is selected for operating temperatures, and with air assist. Corrosion controlled with pH, nitrites and amines. During air drilling, with little or no returns, amines are batched down the drill pipe and annulus, and scale inhibitors injected with the air assist equipment.

**Cationic Inhibition:** Inhibitive fluids are programmed where there are sequences of reactive claystones. Losses are addressed with blended LCM and air assistance. This type of fluid is recommended for drilling the hydrothermal clays and paleosoils when encountered in long sections.

**Dispersed Systems:** If surface volume is not restricted and there are no environmental constraints on water discoloration, some hydrothermal clays and paleosoils may be dispersed into the active system using lignite and chrome-free lignosulfonate. The density will be controlled by dilution. Excess volume may present HSE issues in disposal. If the cap rock of the reservoir is hot, the fluid will experience gelation and will require a good supply of fresh water to control viscosity. High quality solids-control and solids-handling equipment is essential. Corrosion is addressed with nitrite additions, batch treatment on connections and down the annulus when air assisted.

**Mixed Metal Oxide Systems:** The most versatile system is an environmentally benign, temperature stable fluid that contains no polymers and is low in solids. The Mixed Metal Oxide system is a unique, high performance drilling fluid developed for drilling high angle or horizontal wells, for reservoir drilling, for stabilising mechanically weak or poorly consolidated formations, and for curing losses in both seepage and highly fractured zones.

**The Mixed Metal Oxide System**

Mixed Metal Oxide (MMO) systems are based on a complexed group of metal oxides that reacts with bentonite to form a new compound (Figure 1). The new compound modifies the rheology of existing bentonite systems to provide a highly shear thinning fluid with high yield point, low plastic viscosity and high, flat gel strengths (Figure 2). The system is capable of remarkable solids suspension, yet it screens easily and gives low circulating pressures and high rates of penetration. The fluid behaves like an elastic solid when at rest or conditions of minimal mechanical displacement. This pseudo-solid is extremely shear thinning in nature, the high flat gels being overcome with minimal resistance, and can be transformed into an extremely low-viscosity fluid under conditions of high shear. It is this unusual rheology of Mixed Metal Oxide Fluid systems that provides superior hole cleaning, cuttings suspension, leak-off control into fractures, as well as the ability to stabilize unconsolidated formations with no...
interruptions in the drilling process that makes these fluid systems suitable for geothermal drilling.

A typical Mixed Metal Oxide fluid formulation and properties are shown in Table 1.

Although the MMO system is bentonite based, it has an established cleanup procedure for eliminating the viscosity prior cementing or for reservoir clean up. Mixed Metal Oxide Systems are easily aerated and does not require degassing for reuse. The MMO system mitigates whole mud losses with its unique rheological profile. The pH profile of the fluid reduces oxygen corrosion when air drilling and it is not affected by 12+ pH. The major benefits with the MMO system are:

- Reduced number of products required in the system.
- Less reliance on standard LCM plugging materials and reduced rig time dealing with whole fluid losses.
- Better wellbore stability
- Reduced communication with water injection wells and producing wells. No loss of steam production.
- Better bit hydraulics
- Higher solids removal efficiencies
- Easy de-aeration.

**The Rheology of Mixed Metal Oxide Systems.**

Figure 2 illustrates the shear thinning behavior of MMO systems. In high shear regimes at the bit, around heavy weight drillpipe and inside the drillpipe, the effective viscosity of all the fluids are very similar and very low. Circulating pressures and pressure losses are minimized and bit horse power is maximized for maximum rates of penetration. Conversely, in the low-shear-rate regime, such as in the annulus, Mixed Metal Oxide, more than other water-based drilling fluid systems, has a higher effective viscosity, that leads to more effective cuttings carrying capacity and hole cleaning efficiency.

Most drilling fluids demonstrate a consistent trend of decreasing viscosity with increasing temperature. Uniquely, the viscosity of MMO systems does exactly the opposite. The Fann 70 rheogram in Figure 3 is an unweighted Mixed Metal Oxide system. In this example the pressure was maintained at 4,000 psi in all the tests. The Plastic Viscosity and Yield Point at 40°F was recorded at 35 cP and 40 lbs/100ft² respectively, but changed to 6 cP and 103 lbs/100ft² respectively at 180°F.

| Bentonite | 11.0 lb/bbl | (31.4 kg/m³) |
| Freshwater | 1.0 lb/bbl | (1 m³) |
| Mixed Metal Oxide | 1.1 lb/bbl | (3.14 kg/m³) |
| Caustic Soda | 0.5 lb/bbl | (1.43 kg/m³) |
| Soda Ash | 0.3 lb/bbl | (0.86 kg/m³) |
| Plastic Viscosity | 8 cP |
| Yield Point | 60 lb/100 ft² |
| Gels | 35/40 lb/100 ft² |
| 6 rpm | 35 |
| 3 rpm | 34 |
| pH | 10.5 - 11.0 |

Figure 3. Temperature dependence on the MMO Rheogram.

- Reduced well costs through savings in rig time, cementation costs, and lower mud volumes.
- Decreased formation damage and improved steam production with increased well life.

![Figure 2](image1.png)  
Figure 2. Shear-thinning properties of Mixed Metal Oxide Fluids Systems.

![Figure 3](image2.png)  
Figure 3. Temperature dependence on the MMO Rheogram.

![Figure 4](image3.png)  
Figure 4. Simulated downhole rheology of Mixed Metal Oxide Systems.
The Fann 70 rheogram in Figure 4 is of a 9.2-lb/gal Mixed Metal Oxide system tested under simulated downhole pressure and temperature conditions. The characteristic rheology of MMO systems are maintained with high low-shear-rate rheology, high yield points and low plastic viscosity, all of which ensures optimum hydraulics and hole cleaning performance.

**Hole Cleaning and Stabilizing Poorly Consolidated Formations**

The consequence of shear thinning fluids of low plastic viscosity and high yield point is that the velocity profile is ‘plug’ flow. Normal fluids exhibit a parabolic velocity profile. It means that in areas of low shear, the annular velocity is low, and conversely, in regions of high shear, the annular velocity is high. When drilling fragile, poorly consolidated formations, the wall shear stress is near zero and hole erosion is significantly reduced. Furthermore, we believe that a thin and near stationary fluid forms adjacent to the wellbore and we term this the 'hydraulic wellbore' (Figure 5).

Another feature of MMO systems is the gel strength development of the system. When static, the MMO/Bentonite complex provides a fluid with viscoelastic properties that is reversible with the onset of an applied shear stress. Under static conditions therefore, this behaviour provides additional support, not only to stabilising fragile wellbore formations, but also suspended solids and cuttings. The gelling behaviour of MMO fluids is instantaneous, but non-progressive, meaning that as the gelling properties do not continually increase with time, but reach a maximum after 10 seconds and remain constant thereafter. Uniquely, it requires only very low shear stresses applied to static MMO system to break the gel strengths resulting in low swab and surge pressures. The hole cleaning capabilities of MMO system are therefore exceptional and ideally suited to geothermal.

**Lost Circulation Control with MMO systems**

The unique rheology of MMO systems also provide for improved lost circulation control. High effective viscosities at low shear rates (Figure 6) mean that whole fluid lost into a fracture will invade less with MMO systems than with other fluid systems.

![Figure 5. Schematic Diagram illustrating the annular velocity profile of MMO systems and the 'Hydraulic Wellbore'.](image)

![Figure 6. Schematic diagram illustrating the lost-circulation-control mechanism of MMO systems.](image)

Whole fluid will flow into this existing open fracture if the hydrostatic pressure exceeds the formation pressure. Because of the shear thinning nature of MMO systems, the greater the volume of fluid that flows into fracture, the greater the pressure required to maintain that flow rate into the fracture. Since the hydrostatic pressure is constant, the flow rate into the fracture will decline. As the flow rate (shear rate) declines, the effective viscosity increases and as the effective viscosity increases, the loss rate declines further, until there comes a point when the loss rate falls to zero and losses to the fracture cease. This mechanism applies to all drilling fluids, but because of the highly shear thinning nature of MMO systems, losses into fractured formations will be significantly less than conventional fluids.

**Prejob Planning**

The drilling fluid system plays an important role in the successful completion of geothermal wells and strict attention to detail at the planning stage is required. Offset well data, logistics and solids control are always important. Centrifuges set up for barite recovery are normally used and the surface system must include a good degasser. Accurate pore pressure and formation strength prediction are also needed and advanced kick detection systems, which give continuous density readings should be used. In addition physical modeling and laboratory testing of fluids is an essential part of the prejob planning.

Accurate and detailed physical modeling, including a thorough hydraulics analysis and temperature prediction, is important in well planning and can be a valuable on-site tool to aid in pressure control, especially when combined with real-time annular pressure-while-drilling measurements. Engineering software enables changes to rheological properties that occur due to temperature and pressure to be predicted as well as the compressibility and expansivity of the fluid under different pressure and temperature conditions. Mud weight changes and flow produced from the annulus during trips can then be predicted. An integral part of the software is a temperature module that accurately predicts temperatures in and around the wellbore under dynamic and static conditions. This is critical not just for lost circulation prediction but also the prediction of ECD and downhole pressure losses that...
can translate into financial savings for the operator with improved performance and safety.

Most geothermal wells require extensive laboratory testing to optimize fluid design. The testing is often complicated by poor reproducibility and skilled interpretation of results is required. Critical factors include:

- Equipment calibration (including oven temperatures)
- Test methodology needs to be precise and repeatable. This includes mixing, shearing, pressurizing and cooling of aging cells, pH adjustment etc.
- Material selection - results are very sensitive to the quality of barite and bentonite.
- Equipment design - the standard HTHP fluid loss cells are not designed for operation above 350°F and reproducibility at this temperature is poor.
- High temperature and high pressure viscometers assists in the design of geothermal fluids and permit the measurement of fluid viscosity up to 480°F (250°C) and 20,000 psi and also allow measurement of long-term gel strength under HTHP conditions.

Illustrative Case Histories

Case History 1: Japan

One of the first geothermal wells in Japan drilled with an MMO system was used to cure losses in fractures in steam-producing zones. Previous wells had experienced massive total losses into the fractures, resulting in lost rig time, high drilling fluid costs and communication with water injection wells, causing reduced power output from the power station. A MMO system was used to drill the 8½-in. section from 2,139 to 3,936 ft (652 to 1,200 m) with BHST’s ranging from 176 to 302°F (80 to 150°C). The MMO system used Bentonite (10 lb/bbl); MMO (1 lb/bbl) and Caustic Soda (0.5 lb/bbl). As almost immediate losses were expected, the MMO system was run with elevated rheologies. The Yield Point varied between 50 and 60 lb/100 ft² and the Plastic Viscosity was between 10 and 26 cP. Drilling rates were controlled and losses were taken while drilling. Pills of high viscosity MMO were pumped in instances of severe losses and circulation on each occasion was regained. The section was successfully drilled and cemented.

Case History 2: Japan

To drill a 17½-in. top hole section through a loss zone for a geothermal well. The MMO system formulation was similar to the formulation above and the resulting Yield Point and Plastic Viscosity was 10 cP and 60 lb/100 ft² respectively. A gel-bentonite fluid was used to drill a 17½-in. pilot hole to 300 m, however, partial losses occurred at 220 m and a cement plug was spotted to cure. TD was reached at 300 m and while running 18½-in. casing, total losses occurred prior to cementing. The fluid level was 40 m in the hole and the bottomhole temperature was 100°C. Ordinarily, the casing would have been pulled and attempts made to cure the losses, however, a 10-m³ MMO pill was spotted and circulation obtained. A further 5 m³ was spotted 1 hour later. Full returns were established and the 18½-in. casing cemented with a 1.60-sg lead and 1.85-sg tail slurry without incident. Several other MMO systems were subsequently used in the region, both as a lost circulation cure and as a drilling fluid.

Case History 3: Philippines

The MMO system was used to drill the 22-in. section from surface to 505 m of a geothermal well. The formations were weak, highly unstable unconsolidated formations containing hydrothermal clays containing 60 - 70% smectite from 305 m. An offset well had taken 11 days to drill using a Bentonite mud and required 6 cement plugs to cure lost circulation. An MMO system was programmed to drill and control losses between 72 m and 130 m. Total lost circulation occurred at 74 m and 115 bbl of mud were lost and then full circulation regained, but lost again at 130 m. On this occasion, 40 bbl of mud were lost and then full circulation regained. The well was drilled in 9 days and all downhole losses were successfully cured using MMO. The average ROP was 5.2 m/hr compared to 3.1 m/hr on the previous well representing a 67% improvement, and a potential saving of 2.5 days rig time. The actual ROP was much higher, up to 9 m/hr as there were several operational problems relating to poor cementing around the cellars due to the water flow (14 hours) and a twist off due to stripped thread on a cross-over sub (11.75 hours fishing and tripping plus associated fluid costs). Hole problems experienced on the offset well such as poor wellbore stability and fill on connections were not experienced. Although cement plugs were required on 2 occasions to control a water flow, total well savings of $11,728 were realised on this section alone.

Conclusions

Geothermal drilling places great stress on the design of drilling fluids to meet the combined challenges of minimising drilling fluid losses in surface zones; drilling fluid losses in steam producing fractures; hole cleaning and cuttings suspension; wellbore enlargement in poorly consolidated zones; and thermal stability. The choice of drilling fluid for geothermal drilling are many, but recent developments in the technology of Mixed Metal Oxide products has resulted in a system suited to geothermal drilling.

1. The number of products needed to build a MMO system are few for ease of engineering in remote locations.
2. All products required for the MMO system pass the strictest environmental regulations and are environmentally benign. In addition, the MMO system is thermally stable to temperatures in excess of 250 °C - suitable for most geothermal applications.
3. The interaction between MMO and Bentonite provides a unique rheological profile that is highly shear thinning. This is highly desirable for:
   - Higher fluid velocities in the annulus for improved hole cleaning ability.
   - Cuttings cleaning and suspension in horizontal and highly deviated wellbore sections.
   - Reducing whole fluid losses into fractures and a porous matrix.
- Lower frictional pressures and pump pressures for a given flow (pump) rate.
- Lower ECD's minimising the risk of formation breakdown
- Improved bit hydraulics in hard rock formations
- Low fluid velocities at the wellbore, minimizing erosion of mechanically weak formations.
- Thin rheologies at low temperature mud line and flow lines
- Optimum hole cleaning capability under downhole conditions

The MMO has a successful track record of success in geothermal drilling, mostly confined to the Far East at present. However, the MMO system is widely used in South America as a conventional drilling fluid in areas of low geothermal gradients.

Acknowledgments

The authors wish to thank the management of PEMEX and M-I for permission to present this paper and all the individuals who assisted in its preparation.

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