Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Overview of Drilling Fluids Systems and Drilling Fluids Design Principles of Geothermal Wells in Turkey

Oner Erge, Kudret Sakaoglu, Ahmet Sonmez, Gokhan Bagatir, H. Ali Dogan, Ahmet Ay, I. Hakki Gucuyener

Umit Mah. 2543. St. No:17 06810 Cankaya Ankara Turkey

oner.erge@geosdfc.com

Keywords: Turkey, geothermal, drilling, drilling fluids, high temperature

ABSTRACT

Surpassing a 1 GW installed capacity in 2017, Turkey has undeniable production and potential for geothermal energy, ranking top five worldwide. Harnessing geothermal energy has many challenges, from planning to commercial phases. This study features the challenges, experiences and latest advances in drilling fluids utilized in geothermal well construction process in Turkey; focusing to provide a comprehensive information about drilling fluids systems and their design principles in geothermal wells in Turkey.

GEOS acts as a major player in Turkish geothermal industry; providing drilling and completion fluids, solids control equipment and waste management services; having drilled more than 250 deep geothermal wells in utmost challenging downhole environments of Turkish geothermal fields with major operators.

Drilling geothermal wells came with several challenges. Most important of which may be them having high temperature, relatively high pressure, some wells happened to bear rough lithologies to drill through. Providing wellbore stability across dispersive shales or pressurized ophiolitic formation requires special attention in planning and execution phases. Another special attention has given to minimize formation damage in reservoir intervals of geothermal wells. In that manner, different options of reservoir drilling fluids are presented and discussed in detail.

Drilling fluids systems used in geothermal wells have evolved over the last decade and tailored to suit the challenges to be faced; not only in top hole and intermediate intervals, but also in reservoir intervals. The goal is to share the knowledge and experience during the learning curve over the years; extensive laboratory studies and field case studies for geothermal well drilling fluids in Turkey are reported.

1. INTRODUCTION

As of 2019, the globally installed geothermal power generation capacity isapproximately 15 GWe, with top five countries being the USA, Philippines, Indonesia, Turkey and New Zealand. Turkey has achieved substantial geothermal electricity developments in last 9 years. Installed capacity as of February 2019 increased up to 1,282.5 MWe, which was 94 MWe in 2010 (Zaim and Çavşi, 2018).

There are currently 55 operating geothermal power plants at 26 geothermal fields in Turkey (Mertoglu et al., 2019). Almost all of them are sourced by the deep geothermal wells drilled on Gediz and Büyük Menderes grabens located at the Aegean Region, Western Turkey. Generalized stratigraphy for top and intermediate sections consists of conglomerate, sandstone, mudstone, marl, limestone, claystone, shale lithologies. There are also several exploration wells in the Gediz Graben in Kütahya region, having massive serpentine lithology (ophiolitic nappes) in the intermediate sections bringing extreme wellbore stability risks. Most reservoirs of the geothermal systems in Turkey are karstic, fractured carbonated rocks and fractured metamorphic rocks belonging to the Mesozoic Menderes Massif, which is basement for Gediz and Büyük Menderes grabens.

Drilling fluids design and execution play an important role for the success of a geothermal drilling project by providing trouble-free drilling operations with minimum Non-Productive Time (NPT) and preventing formation damage to achieve maximum production/injection rates. Based on experiences with more than 250 deep geothermal wells for largest energy companies in Turkey, with varying final depths up to 4,509 m and reservoir temperature between 300 to 468 °F (149 to 242 °C), drilling fluids selection for each section is reduced to three main criteria:

- Is the formation temperature below or above 300 °F (149 °C)?
- Is wellbore stability a concern?
- Is formation damage a concern?

Regardless of the type, drilling fluids for each section is needed to be optimized for waste management, hole cleaning, Equivalent Circulating Density (ECD) management, barite sag potential, etc. However, below drilling fluid related risks are highlighted as the main ones based on experiences from geothermal wells in Turkey:

- Shallow water flow
- Tight holes due to reactive shales
- Differential sticking
- Lost circulation
- Poor cement jobs
- High torque and drag

Additionally, unit price is also a key factor when selecting the fluid type. All drilling fluid designs presented in this paper are screened after many drilling operations taking project budgets into account. There are more viable solutions available for technical aspects, however, presented fluid types are the ones optimized with regards to the balance between technical needs and unit costs. Turkish Association of Geothermal Investors (JESDER) estimates the cost of a geothermal well of up to 4,000 meters and 60 to 80 days to be between USD 3 million and USD 4 million (Richter, 2019). Total drilling fluids costs including engineering, chemicals and rental services for most of the cases contributes lower than 7% of the total well cost which is well within the globally accepted budget ranges for drilling fluids.

In this paper, readers will find drilling fluids overview based on more than 250 deep geothermal wells drilled. The discussion will take place under two parts: "A - Drilling Fluids Selection" based on the three criteria listed above and "B – Risk Mitigation Guidelines" for the six highlighted drilling fluids related risks.

2. DRILLING FLUIDS SELECTION

Six different drilling fluids type are designed specifically for the geothermal wells in Turkey and improved continuously based on ongoing experiences. Selected drilling fluids are all Water Based Mud (WBM) with all additives are in accordance with local and global regulations. Table 1 serves as a guideline for selecting these mud types for each section.

Table 1. Guideline for selecting drilling fluid types for each interval

INTERVAL	TEMPERATURE	MUD SELECTION CRITERIA	MUD TYPE
TOP HOLES			WBM TYPE-1
INTERMEDIATE SECTIONS	BHST < 300 °F (149 °C)	No wellbore stability concern	WBM TYPE-2
		Wellbore stability concern	WBM TYPE-3
RESERVOIR SECTIONS	BHST > 300 °F (149 °C)	Low level of formation damage concern	WBM TYPE-4
		High level of formation damage concern	WBM TYPE-5
		Wellbore stability concern	WBM TYPE-6

Drilling fluids selection for each section and details about fluid types are discussed in the subsequent subsections.

2.1 Top Holes (26"):

In general, conglomerate, sandstone, mudstone and marl lithologies are drilled in top holes. Most common drilling fluids related risks in this section are losses to unconsolidated formations and high gels due to Methylene Blue Test/Capacity (MBT) increase which usually occurs while drilling the reactive clays in Kolonkaya formation in Büyük Menderes Graben. Kaletepe formation in Gediz Graben is usually drilled without MBT or high gel problems. WBM TYPE-1 is the selected mud type for this section.

WBM TYPE-1 is unweighted clay-water system. This basic system consists of bentonite and water. This mud system is found effective to plaster unconsolidated formations, reduce losses or hole enlargement in top holes. Soda ash is usually required to treat make-up water before bentonite addition and caustic soda is used to adjust pH of the system to 9-10. No fluid loss control is usually required for this section and Yield Point (YP) is kept between 20-30 lb/100ft^2 by water addition or by mixing small amount of XCD polymer to ensure sufficient hole cleaning. When top hole section is relatively deep or approximately 150 m, it is important to minimize bentonite concentration in the initial formulation due to mud making nature of the formations, especially for Kolonkaya formation. Initial concentration of bentonite is reduced below 10 ppb for some cases to be able to control rheological properties. It is also recommended to have deflocculants ready at wellsite as contingency in order to lower gel strengths which is required for effective cement-mud displacement in casing cementing.

Advantages of this system are environmentally friendly formulation to protect near surface water sources and its low cost. It is important to keep WBM TYPE-1 in a good condition so that it can be transferred to the intermediate sections by mixing additional volumes and mud additives.

2.2 Intermediate Sections (17 ½" and 12 ¼")

Generalized stratigraphy for the intermediate sections has Gediz and Alaşehir formations for the wells in Gediz Graben (Alaşehir region) and Kolonkaya, Sazak and Kızılburun formations in Büyük Menderes Graben (Denizli-Aydın region). Sharp MBT and rheology increase is the most common issue faced while drilling Kolonkaya, Gediz and Kızılburun formations, therefore it is recommended to keep MBT low (<15 ppb) before hitting these formations. Another common issue to deal with while drilling intermediate sections is calcium and sulfate contamination due to gypsum and anhydrite in Sazak formation which require chemical treatment with soda ash and deflocculants. Lost circulation while drilling Sazak and İğdecik formations and differential sticking tendencies while drilling through permeable zones like the ones in Alaşehir are the risks needs to be highlighted for these sections. Mitigation guidelines for these risks are presented later in this paper.

There are two alternative mud types designed for the intermediate sections: WBM TYPE-2 is to be selected for the wells without wellbore stability issues expectation and WBM TYPE-3 is to be selected for the sections with wellbore stability problems due to existence of serpentine in the stratigraphy. Both options are compatible with each other and also with WBM-TYPE-1, therefore transferred volumes from previous section can be converted to the selected mud type with the addition of required chemicals.

WBM TYPE-2 is a conventional mud system selected for relatively easier intermediate sections with bottom hole static temperature (BHST) < 300 °F (149 °C) and no wellbore stability issues are expected. This dispersed mud system has a formulation including bentonite, deflocculants and PAC/CMC/XCD polymers. The system provided adequate rheology and fluid loss control to drill over 400 intermediate sections in more than 250 wells.

Similar to top holes, it is important to minimize bentonite concentration in the initial formulation where Kolonkaya and Kızılburun formations are to be drilled. Rheological properties of the system are adjusted by deflocculants or XCD polymer addition. Requirements for rheological properties depend on hole size, depth and drilling parameters, however as per experiences, YP of 15-20 lb/100ft^2 is found sufficient for hole cleaning in intermediate sections. Fluid loss is controlled by low viscosity PAC or CMC addition. Experiences also proved that API (American Petroleum Institute) fluid loss less than 8 ml/30 min. is optimum in terms of technical needs and cost efficiency. Chemical contaminations usually encountered while drilling Sazak formation requires treatment with soda ash together with relatively high amount of deflocculants. Gel values of the system is controlled by powder and liquid deflocculants. As one of the deflocculants used in the system requires high pH environment, caustic soda is used to adjust pH to 9.5-10.5. WBM TYPE-2 is mostly used with an un-weighted formulation unless there are shallow water flow risk or pressurized zones.

For some cases, WBM TYPE-2 is strengthened by addition of various chemicals to reduce friction and differential sticking risks especially when drilling high angle intermediate sections.

WBM TYPE-3 is selected when there are wellbore stability concerns in the subject intermediate section. As the success of WBM TYPE-2 is proven for most of the intermediate sections, WBM TYPE-3 is designed only for the intermediate sections where wellbore stability issues are expected. For example, serpentine is well-known in terms of causing wellbore stability issues. Mud formulation together with correct mud weight (MW) plan is of utmost importance to reach the section goals. Relatively high low-end-rheology is preferred to reduce near wellbore mud invasion and to ensure Wellbore Strengthening Materials (WSMs) are kept in suspension. 6 rpm dial readings are adjusted to >10 lb/100 ft^2 for this purpose. YP is adjusted to 20-30 lb/100 ft^2 to ensure good hole cleaning in case of wellbore sloughing. Gel values are kept low enough to prevent pressure fluctuations in the well due to surge and swab and while breaking circulation.

WBM TYPE-3 is a specially designed drilling fluid for drilling through ophiolitic serpentine formation. Fluid loss controlled tight as less than 5 ml/30 min., high quality mud cake, bridging capacity up to 400-800 micron fracture size and encapsulating inhibition are required to drill these sections successfully. Special polymers and WSMs are used in the mud formulation to achieve mentioned features. When designed and executed perfectly, this fluid system proved its success to drill extremely difficult formations in terms of sloughing, dispersing and pack-off potential. Liquid lubricants are also used for some cases to minimize drag when pulling string across the trouble zones.

To stabilize serpentine units, it is necessary to minimize pressure transmission between wellbore and formations. Different types of WSMs are used in the system for filling various sizes of fractures which are induced or natural. WSM-1 and WSM-2 are used to seal off micro-fractures while WSM-3 and WSM-4 are used to make sure fractures are sealed off up to 400-800 microns. Fibrous materials are also used in some cases to provide better sealing and lubricity of the filter cakes.

Extensive laboratory studies are performed while designing WBM TYPE-3. Fluids with and without particles (WSMs) are tested in the laboratory to optimize each mud parameters carefully. Synthetic polymer-1 is used together with conventional PAC polymer and bentonite in order to achieve the required API fluid loss (<5 ml/30 min.) at relatively high temperatures which can be close to 300 °F (149 °C). WSM package is designed by testing mud samples on PPA (Permeability Plugging Apparatus) with metal slotted discs having manufactured fracture sizes between 400 and 1,200 microns.

Equally important are the drilling practices to keep wellbore stable. Reducing pressure fluctuations by fixed weight on bit (WOB), rotation per minute (RPM) and flow rate parameters are recommended. Minimizing surge and swab pressures by controlled pulling and running speeds are also required. Increasing flow rate slowly when breaking circulation, i.e., after each connection, is also a recommended practice to prevent pressure shocks on the weak formation.

Carrier fluid formulation for WBM TYPE-3 and WSM package formulation are shown in Table 2 and Table 3, respectively.

Table 2. Additives in WBM TYPE-3

ADDITIVE	DESCRIPTION	FUNCTION
Non-Treated Bentonite	Non-Treated API Grade Bentonite	Viscosifier & Fluid Loss Control
PAC LV	API Grade Low Viscosity Polyanionic Cellulose	Fluid Loss Control
Synthetic Polymer-1	Synthetic Polymer with High Temperature Stability up to 400 °F (204 °C)	Rheology & Fluid Loss Control
XCD Polymer	API Grade Xanthan Gum	Viscosifier
Liquid Thinner	Copolymer Deflocculant with High Temperature Stability up to 400 °F (204 °C)	Deflocculant
Caustic Soda	Sodium Hydroxide	Alkalinity and pH Control
Soda Ash	Sodium Carbonate	Calcium Remover

Table 3. WSM Package formulation for WBM TYPE-3

ADDITIVE	FUNCTION	CONCENTRATION (ppb)
WSM-1	Seal off Micro Fractures	2-10
WSM-2	Seal off Micro Fractures	2-10
WSM-3	Seal off 400-800 Micron Fractures	2-10
WSM-4	Seal off 400-800 Micron Fractures	2-10

Based on laboratory studies, WSM package with sealing capacity of 400-800 micron fracture sizes are designed and successfully used in field applications. When designing WSM package there are several important aspects taken into account: (1) particle size distribution (PSD) and concentration of each WSM type, (2) compatibility of the particles with downhole tools (3) restrictions in terms of environmental or formation damage concerns. Once WSM package is designed, shaker configurations based on the available screen sizes and continuous treatment procedures are clarified before the section starts.

PPA test results for WBM TYPE-3 designed for a particular project are given in Figure 1. Graph shows that pressure on 400 micron slot is increased up to targeted 2,000 psi and remained there without extra pumping. This interpretation of sealing pressure versus time shows the successful sealing ability of this fluid. On the other hand, it would not be possible to reach and hold such pressure for drilling fluids without specially designed WSM package.

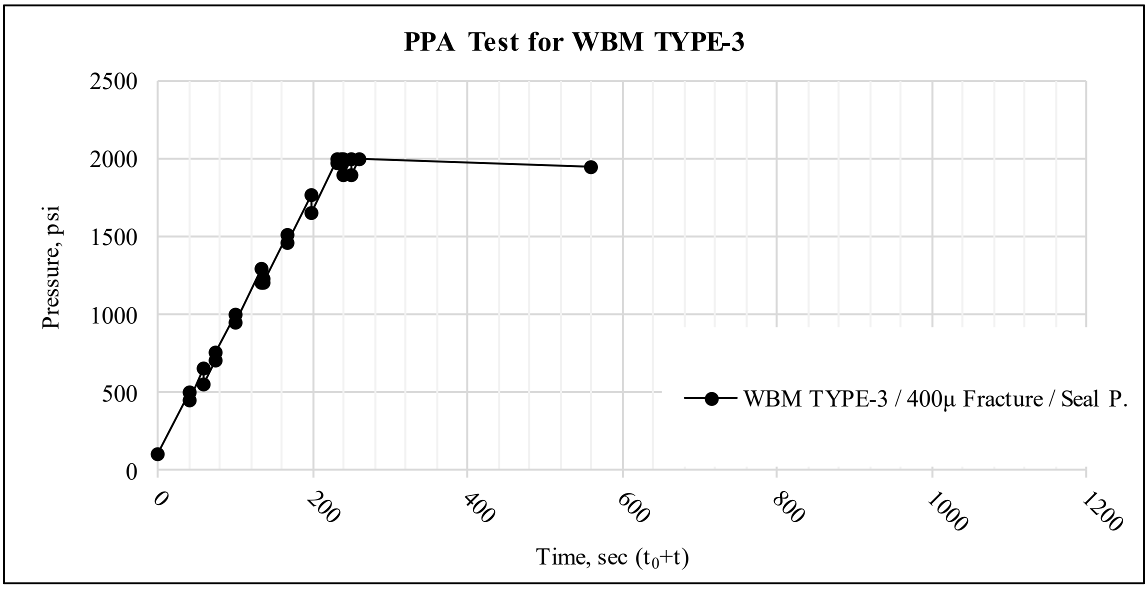

Figure 1. Permeability Plugging Apparatus (PPA) Test for WBM TYPE-3.

WBM TYPE-3 has proven its success for a well drilled in Kütahya region with 1,300 m massive serpentine block. The serpentine formation is the deepest and longest one in that area as well as in Turkey. This was the first time the reservoir below this serpentine zone was able to be reached and tested.

2.3 Reservoir Sections (8 ½”)

Paleozoic-Mesozoic Menderes Massif, which is basement for the Gediz and Büyük Menderes grabens is the reservoir for the most of the geothermal wells in Turkey. The basement consists of high to low grade metamorphics (gneiss, mica schists, phyllites, quartz schists, marbles) and granodiorite.

Main drilling fluids related concerns in reservoir sections are high temperature stability, lost circulation and formation damage. Also, some of the wells have serpentine formation in the same section together with the reservoirs. This brings a very difficult drilling situation due to having unstable/pressurized formation and lost circulation risks in the same section. For those cases, WBM TYPE-6 is designed and used successfully to reach target depth (TD) of the sections.

For reservoir drilling, there are three alternatives presented in this paper to be selected depending on the level of formation damage risks for the project and wellbore stability concerns.

WBM TYPE-4 is designed for reservoir sections for temperature higher than 300 °F (149 °C) without wellbore stability concern. After many applications, WBM TYPE-4 became well known in Turkey’s geothermal drilling industry. The success of the system is proven for many sections in terms of providing trouble-free drilling operations for more than 200 reservoir sections.

Due to the formation damage concerns, bentonite concentration is limited to 5-7 ppb in mud formulation. If possible, use of barite should be avoided for the same reason. Either Synthetic Polymer-1 (stable up to 400 °F / 204 °C) or Synthetic Polymer-2 (stable up to 475 °F / 246 °C) is used in the formulation for rheology and filtration control depending on the maximum bottom hole temperature expected. Usually PAC polymer is also used in the formulation together with temperature stability extenders in order to reduce synthetic polymer consumption and thereby reduce unit cost.

Various formulations for WBM TYPE-4 are built after extensive laboratory studies in order to prove stability of the system at various temperature conditions up to 450 °F (232 °C). Fluid formulations are fine-tuned to optimize cost/benefit for each project depending on the highest temperature expected and other technical requirements such as minimum/maximum rheology and fluid loss. Generalized fluid formulation for WBM TYPE-4 is shown in Table 4.

Table 4. Additives in WBM TYPE-4

ADDITIVE	DESCRIPTION	FUNCTION
Non-Treated Bentonite	Non-Treated API Grade Bentonite	Viscosifier & Fluid Loss Control
PAC LV	API Grade Low Viscosity Polyanionic Cellulose	Fluid Loss Control
Synthetic Polymer-1	Synthetic Polymer with High Temperature Stability up to 400 °F (204 °C)	Rheology & Fluid Loss Control
Synthetic Polymer-2	Synthetic Polymer with High Temperature Stability up to 475 °F (246 °C)	Rheology & Fluid Loss Control
XCD Polymer	API Grade Xanthan Gum	Viscosifier
Liquid Thinner	Copolymer Deflocculant with High Temperature Stability up to 400 °F (204 °C)	Deflocculant
Temperature Stabilizer -1	Powder Temperature Stabilizer	Temperature Stability Extender and pH Buffer
Temperature Stabilizer -2	Liquid Temperature Stabilizer	Temperature Stability Extender and Oxygen Removal
Caustic Soda	Sodium Hydroxide	Alkalinity and pH Control
Soda Ash	Sodium Carbonate	Calcium Remover

In order to test filtration properties of WBM TYPE-4, samples are aged at 400 °F (204 °C) in roller oven for 16 hours. High temperature high pressure (HPHT) fluid loss tests are done at 500 psi differential pressure at different temperatures. API fluid loss test is performed at 77 °F (25 °C) and at 100 psi, resulting in < 7 ml/30 min fluid loss. Figure 2 shows the HPHT fluid loss test results.

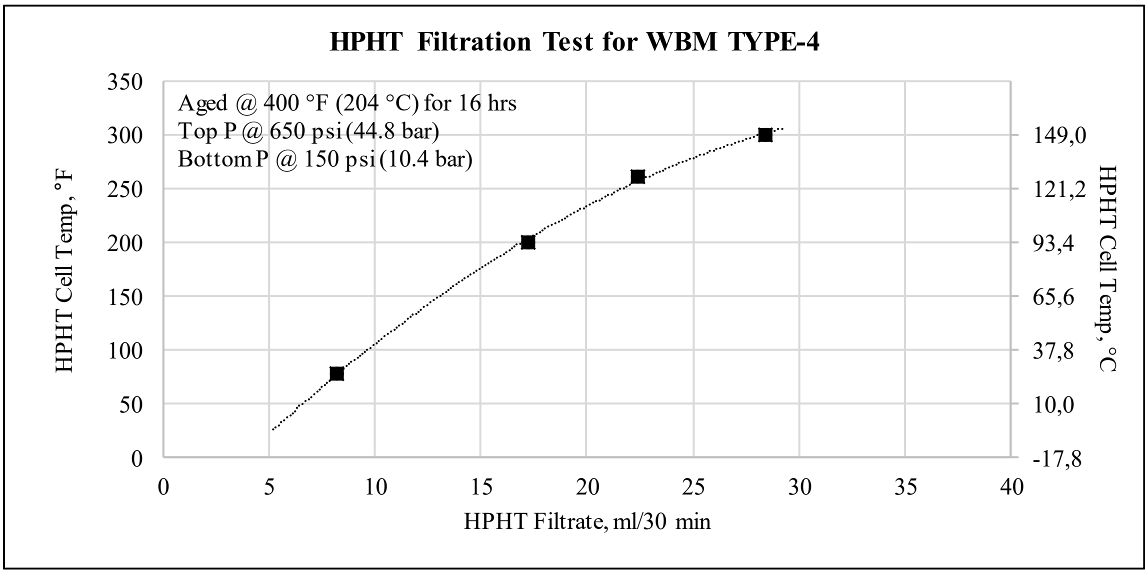

Figure 2. High Pressure High Temperature (HPHT) Filtration Test for WBM TYPE-4.

WBM TYPE-5 is to be selected when protecting the reservoir from the damage is one to the main concerns of the project. No solids are used in the formulation up to 10.0 ppg (1.20 SG) and only acid soluble weighting agent (calcium carbonate) is used up to 12.0 ppg (1.44 SG). Synthetic Polymer-2 used in the formulation is also acid soluble enhancing the success rate of the acidizing jobs after the well is completed. Table 5 lists the main additives used for WBM TYPE-5.

Table 5. Additives in WBM TYPE-5

ADDITIVE	DESCRIPTION	FUNCTION
NaCl	Sodium Chloride Salt	Weighting Agent
PAC LV	API Grade Low Viscosity Polyanionic Cellulose	Fluid Loss Control
Synthetic Polymer-2	Synthetic Polymer with High Temperature Stability up to 475 °F (246 °C)	Rheology & Fluid Loss Control
XCD Polymer	API Grade Xanthan Gum	Viscosifier
Temperature Extender-1	Powder Temperature Stabilizer	Temperature Stability Extender and pH Buffer
Temperature Extender-2	Liquid Temperature Stabilizer	Temperature Stability Extender and Oxygen Removal
Calcium Carbonate	Calcium Carbonate Fine	Weighting/Bridging Agent
Caustic Soda	Sodium Hydroxide	Alkalinity and pH control
Soda Ash	Sodium Carbonate	Calcium Remover

Drilling fluid parameters become much more stable and resistant to contaminations than a disperse WBM mainly due to the no solids formulation of WBM TYPE-5. An example field case is presented with such information: two nearby wells were drilled; Well #A was drilled with a disperse WBM in its reservoir section, and Well #B with WBM TYPE-5. Following figures illustrate the comparison of some crucial mud parameters during drilling. Figure 3 shows the comparison of some rheological parameters; i.e., YP, 3 RPM dial readings and 30 minutes gel strengths.

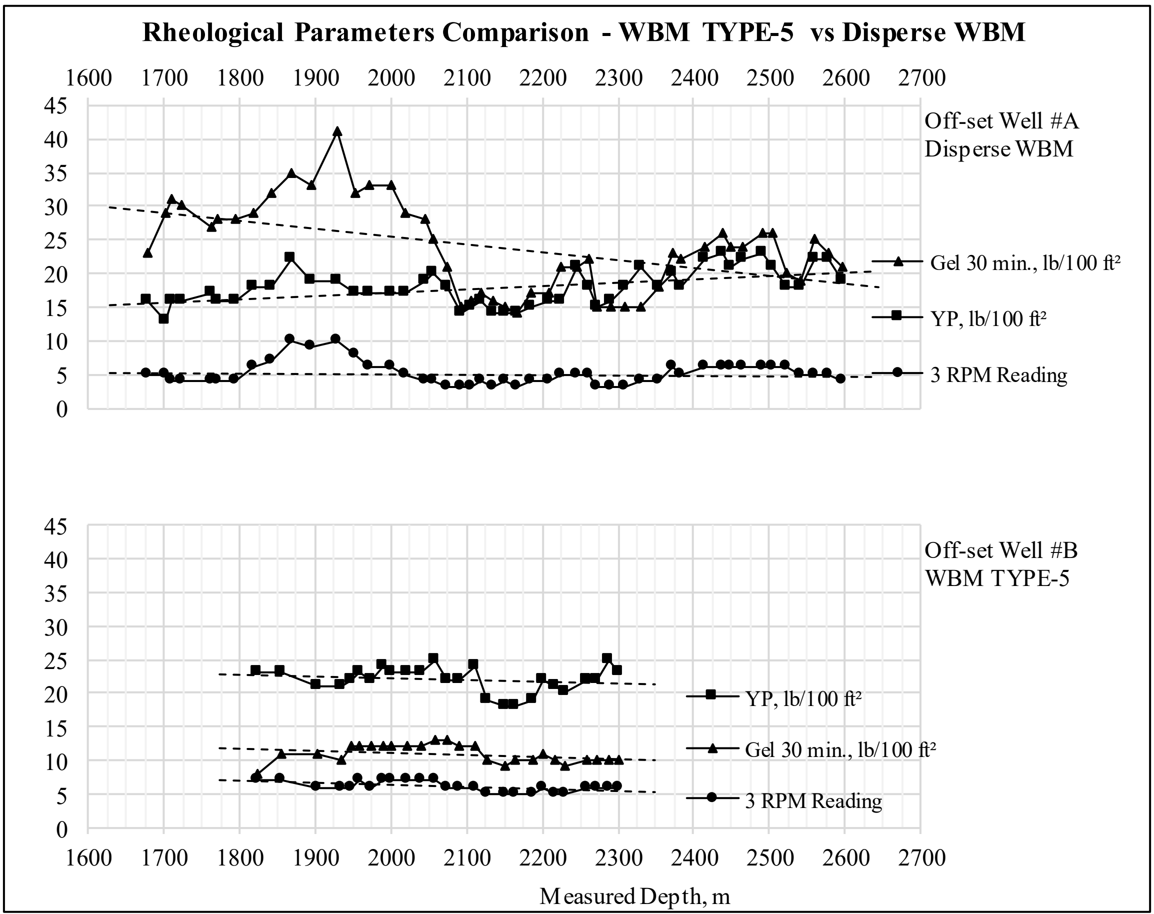

Figure 3. Comparison of rheological parameters for WBM TYPE-5 vs Disperse WBM.

Solids analysis and relevant parameters compared in Figure 4. Critical parameters such as PV, which shows the solids build-up in a system, MBT, which is the clay content of mud, and corrected solids are chosen for comparison. WBM TYPE-5 shows a consistent record with minimum solids and plastic viscosity. In addition to the minimum reservoir damage aspect, the no-solids feature of WBM TYPE-5 has many advantages; such as low parasitic pressure losses, higher rate of penetration (ROP), better solids removal efficiency, prolonged tubular life, to name a few.

WBM TYPE-5 is also noteworthy for its low fluid loss and quality filter cake characteristics. As illustrated in Figure 5, WBM TYPE-5 stands out with a much more consistent fluid loss ability than a disperse WBM.

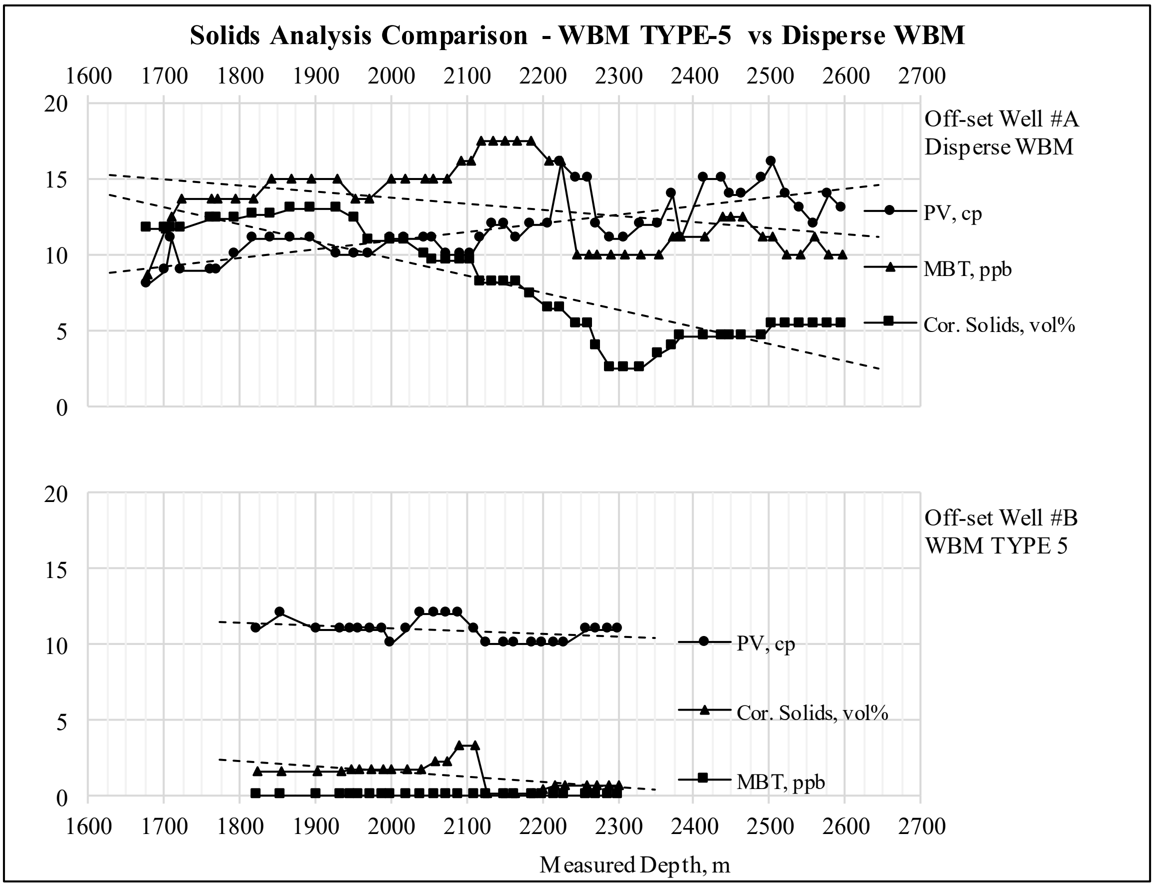

Figure 4. Comparison of solids analysis for WBM TYPE-5 vs Disperse WBM.

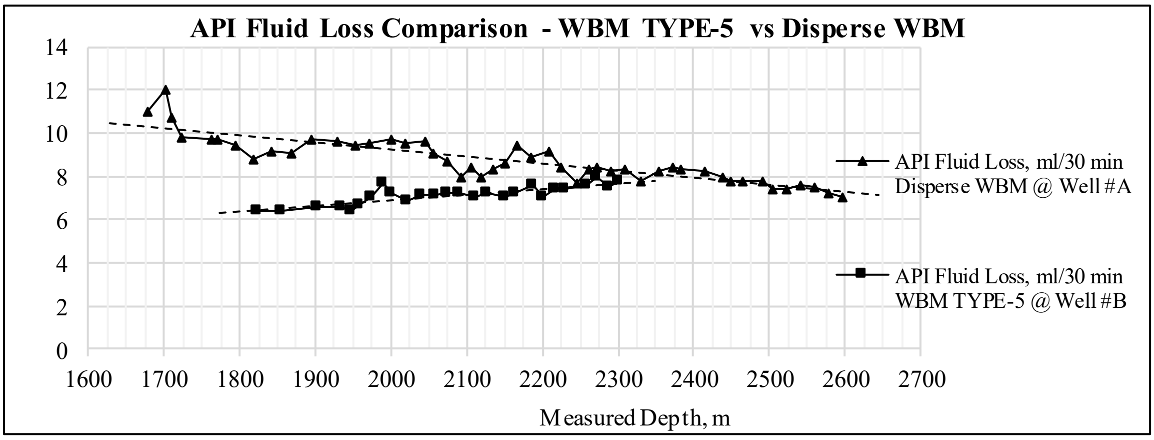

Figure 5. Comparison of API fluid loss for WBM TYPE-5 vs Disperse WBM.

WBM TYPE-5 is successfully utilized in the reservoir sections of five wells in Alaşehir region. Mud weight is achieved up to 10.3 ppg (1.24 SG) with NaCl and acid soluble Calcium Carbonate as a bridging agent. Total solids concentration is maintained below <4%. Formation damage concern is kept in a minimum level ending up with a clean and trouble-free hole.

WBM TYPE-6 is to be selected when temperature is higher than 300 °F (149 °C) and there are wellbore stability risks due to serpentine or similar formations in the same section. WBM TYPE-6 is very much similar to WBM TYPE-3, except that the conventional polymers are replaced by synthetic polymers with high temperature stability. Temperature stability extenders are used additionally to boost temperature stability of the system further. Bentonite concentration is adjusted to a minimum level of 5-7 ppb due to formation damage concerns. Moreover, only acid soluble particles are used in the WSM package for the same reason. For a more technical background, refer to WBM TYPE-3 section on page 3 and 4. Main additives and particle package formulation are shown below in Table 6 and Table 7, respectively.

Table 6. Additives in WBM TYPE-6

ADDITIVE	DESCRIPTION	FUNCTION
Non-Treated Bentonite	Non-treated API Grade Bentonite	Viscosifier & Fluid Loss Control
Synthetic Polymer-1	Synthetic Polymer with High Temperature Stability up to 400 °F (204 °C)	Rheology & Fluid Loss Control
Synthetic Polymer-2	Synthetic Polymer with High Temperature Stability up to 475 °F (246 °C)	Rheology & Fluid Loss Control
XCD Polymer	API Grade Xanthan Gum	Viscosifier
Liquid Thinner	Copolymer Deflocculant with High Temperature Stability up to 400 °F (204 °C)	Deflocculant
Temperature Extender-1	Powder Temperature Stabilizer	Temperature Stability Extender and pH Buffer
Temperature Extender-2	Liquid Temperature Stabilizer	Temperature Stability Extender and Oxygen Removal
Caustic Soda	Sodium Hydroxide	Alkalinity and pH Control
Soda Ash	Sodium Carbonate	Calcium Remover

Table 7. WSM package formulation for WBM TYPE-6

ADDITIVE	FUNCTION	CONCENTRATION (ppb)
Calcium Carbonate Fine	Seal off Micro Fractures	5-15
Limestone and Marble with Specially Designed PSD	Seal off 400-800 Micron Fractures	5-15

WBM-TYPE 6 is designed to overcome the serpentine related problems in the reservoir section of some wells in Alaşehir region. Specially designed WSM package with optimum particle size distribution is used as a wellbore strengthening additive to stabilize troublesome serpentine formation. Figure 6 shows the sealing pressure vs time graph of WBM TYPE-6 designed for a particular project. Test results show that, pressure on 400 micron slot is increased up to targeted 2,000 psi in a relatively short amount of time comparing with 800 micron slot and remained there with minimum filtration and without extra pumping. Similar to WBM TYPE-3, mentioned test results display the solid sealing capability of WBM TYPE-6.

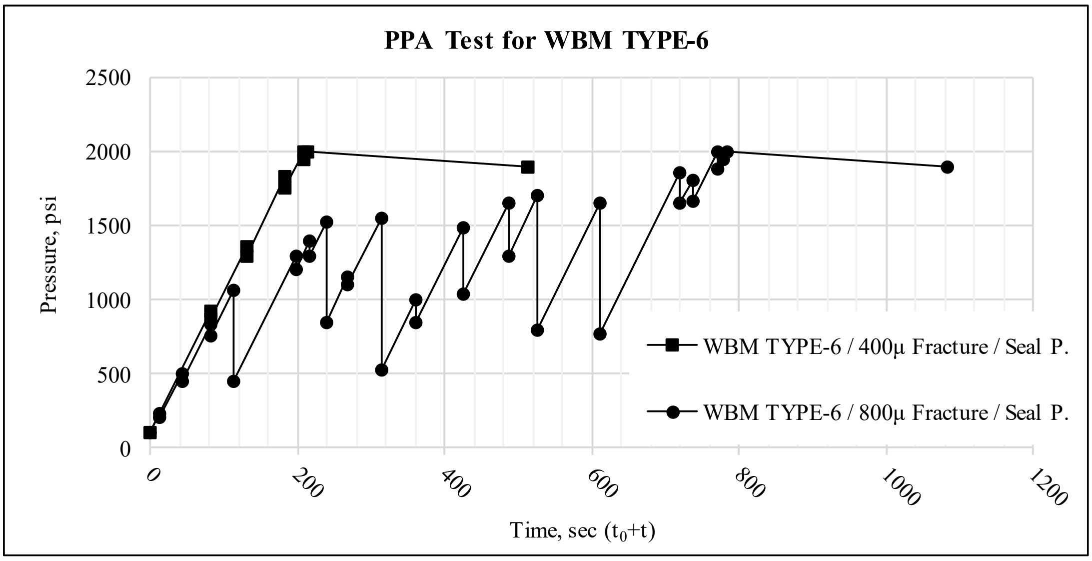

Figure 6. Permeability Plugging Apparatus (PPA) Test for WBM TYPE-6.

3. RISK MITIGATION GUIDELINES

Regardless of the drilling fluids selection, below mitigation guidelines are proven successful for the highlighted risks. In general, mud engineers and rig crew need to be briefed for the risks involved. Based on experience, two mud engineers are needed for geothermal wells in Turkey to cover the operations 24 hour a day in order to ensure that mud properties are always controlled.

3.1 Shallow Water Flow

Shallow water flow is not a very common problem for the geothermal wells in Turkey. It was experienced in 7 wells out of 267. Although it was rarely encountered, serious consequences from high chemicals costs up to loss of a well was experienced. Shallow water flows are usually from the depths of 30 to 150 m in Sazak formation, the shallow reservoir in East side of the Büyük Menderes graben. If properly planned and executed, shallow water flows in the region are controlled by increasing the hydrostatic pressure applied by the mud column. MW of 11.7 ppg (1.40 SG) were sufficient for the cases encountered. If there is a risk of high pore pressures and narrow margin between pore pressure and fracture gradient, surface casing set point and its cement integrity will be critical to control shallow water flow.

Contingency plans need to be agreed between operating and service companies, especially to agree on the roles and responsibilities of each key person and amount of barite to be kept available at location. Barite consumption went up to 275 tons for one of the wells where shallow water flow exists. Below precautions are recommended to be taken for mitigation:

- Brief warehouse personnel regarding the possible need for 7/24 logistics support. Make logistics plan involving operating company and clarify delivery time of barite upon call-out considering weekends and holidays.
- Perform kick drills and clarify duties of the key personnel.
- Optimize fluid properties considering the potential high amount of barite addition.
- Keep minimum 100 tons of barite available at location.
- Keep minimum 500 tons of barite at warehouse as contingency.

3.2 Tight Holes Due to Reactive Shales

Reactive shales are usually encountered while drilling 17 ½” and 12 ¼” intermediate sections through Kolonkaya and Kızılburun formations in Büyük Menderes Graben. Although, inhibitive, non-disperse mud types would suit better for those sections, non-inhibitive systems like WBM TYPE-2 are commonly used due to environmental concerns and based on cost/benefit evaluations. Lowering API fluid loss specs (<6 ml/30 min.) were aimed and achieved for the earlier wells in total of 267 wells. However, recent experiences showed that API fluid loss less than 8 ml/30 min. is sufficient to drill these sections. Below guidelines can be followed to reduce tight hole concerns or related risks:

- Make sure API fluid loss spec is lower than 8 ml/30 min. at all times.
- Lower gel strengths, (i.e, 10 min. gel < 20 lb/100ft^2) and MBT < 15 ppb to reduce the risk of bit and bottom hole assembly (BHA) balling.
- Make sure the procedures for abrasive pill applications are ready to mitigate bit/BHA balling.
- Make sure encapsulating polymer concentration is maintained in the mud system.

3.3 Differential Sticking

Differential sticking tendencies are usually encountered while drilling permeable Alaşehir formation. It gets more pronounced while directional drilling this formation. When fluid properties are controlled efficiently and on a 24-hour basis, risk of getting differentially stuck in geothermal wells in Turkey is very low. Below prevention measures are recommended based on experiences:

- Control MW to the lowest in the desired range and maintain there effectively by good solids control practices. Make sure decanting centrifuges are available and running continuously while drilling to maintain low gravity solids (LGS) < 6%v.
- If the risk is high based on offset wells, ensure mud cake thickness is less than 1 mm by lowering fluid loss and minimizing solids content. API fluid loss <5 ml/30 min. together with maximum 6%v LGS is found sufficient to achieve thin filter cakes.
- It is important to use materials like sized graphite and calcium carbonate to achieve desired particle size distribution to get low permeability filter cake and enhanced cake lubricity.
- Keep static drill string time to a minimum. Consider using spiral drill collars.
- If pipe is differentially stuck, immediately apply spotting fluid procedures. For the success of the spotting pill, it is required to raise the pill the same density as the drilling fluid to minimize migration of the pill. An example pipe freeing procedure would be: once the pill is placed, pipe should be worked by putting it in compression and applying torque and holding for a few minutes. Then release torque and apply tension to the string. Repeat this cycle once every five minutes and displace half barrel of excess pill remained in the string every half an hour.

3.4 Lost Circulation

Losses in top holes are usually due to unconsolidated gravels or sandstone in geothermal wells in Turkey. Based on experiences, WBM TYPE-1 with LGS/cuttings are sufficient to cure losses in top hole. Increasing rheology of mud is another course of treatment for losses in top hole. No Lost Circulation Material (LCM) pills were pumped or recommended for the top hole lost circulation events.

Losses in the intermediate sections are due to natural or induced fractures and faults or interfaces between different geological layers. These losses are more serious comparing to top hole cases resulting in high mud costs if not cured. Depending on the severity of the losses, the effectiveness of the LCM pills varies.

Losses in the reservoir sections for geothermal wells are not cured in general as the fractures causing losses are mostly the production sources as well. In case of total losses, some operators prefer to continue drilling with water + hi-vis sweeps and some other operators prefer water + continuous polymer addition to ensure continuous sweep in the wellbore.

There are two types of lost circulation classifications: (1) Dynamic losses - no loss when pumps are off. For many cases, these kinds of losses developed into major losses if not cured at first place (2) Static losses – losses with pumps off. These kinds of losses are found more difficult to cure.

After having experiences with numerous lost circulation cases, below guidelines are prepared for the losses in intermediate or reservoir sections:

For losses in intermediate sections:

- Identify risk of lost circulation per each intermediate section and facilitate lost circulation contingency plan prior to section starts. Ensure LCM products as per the contingency plan are available at rig site. Make sure LCM plan is agreed by the operating company and downhole tool providers.
- Pump LCM pill with maximum concentration at first attempt to reduce the risk of increasing losses. Pump LCM pill as soon as the losses are detected. Spending time regaining the flow rate normally will lead to increased losses and will then become more difficult to cure. Total of 100-150 ppb with 200 meters of open hole volume LCM pill is usually required to cure losses at first place depending on the severity of the case.
- Consider adding preventive LCM (Sized Graphite and/or Calcium Carbonate) 5-10 ppb each to the mud if losses are likely on the way ahead.
- Use LCM with well distributed PSD, as the fracture size is unknown. Based on laboratory fracture sealing tests at PPA, use fine, medium and coarse particles together to increase the chance of success. LCM package with D10, D50, D90 of 50, 550, 1000 microns respectively and 120 ppb total LCM concentration is found sufficient to cure losses up to 1,200 Microns. Always check with tool providers before commence pumping through the tools.

For losses in reservoir sections:

- Do not cure losses in the reservoir sections unless otherwise is requested by operating company. If losses to be cured, a mixture of Calcium Carbonate with well-adjusted particle size distribution is recommended.
- Once static loss is encountered, it is recommended to continue drilling with water and hi-vis sweeps once every 10 meters of drilling. Elevate YP of the hi-vis sweeps to more than 40 lb/100ft^2 by mixing XCD / PAC HV polymers and pump 5-10% of the well volume as a general guideline. Evaluate the drilling parameters and adjust frequency and volume of hi-vis sweeps if needed. Avoid using bentonite in the hi-vis formulations due to formation damage concerns.

3.5 Poor Cement Jobs

It is well known that casing cementing is critical for the future integrity of the geothermal wells. For cement slurry design, laboratory testing with representative samples of cement, water and additives is highly recommended. It is known that mud properties used during drilling are not always the optimum properties needed for a successful cement job. Since it is common to have high MBT and high gel values towards the end of the section, it is recommended to follow below guidelines to improve quality of the cement jobs:

- Circulate and condition mud before pulling out of hole (POOH) with drill string before running casing. Spend extra time to condition mud, if required. Use of deflocculants or dilution is recommended to achieve 30 min gel < 50 lb/100 ft^2 before POOH.
- Prior to cementing, the well is recommended to be clean. Flow rate should be increased gradually and the well needs to be circulated until mud properties in and out are equal and stabilized. If there is severe lost circulation, pump at least 1.5 times open hole volume. If possible, rotate and reciprocate the string during mud conditioning and cementing operations to break up gelled pockets of drilling fluid in order to prevent any possible viscous fingering that may jeopardize cement bond quality.
- Pump rates for the cement jobs and mud properties are critical for effective mud removal. Insufficient mud removal may result in partly cemented annulus which is difficult to repair.
- Consider pumping low-vis pill ahead of spacer in order to thin mud in the well for better mud removal.

3.6 High Torque and Drag

High torque and drag problems in Geothermal wells in Turkey are common especially for directional wells. Powder and liquid lubricants are used efficiently to reduce metal-metal and metal-formation friction factors. After greasing issues observed with various lubricants in the market, highly effective liquid lubricant was developed as a result of R&D project and used to minimize torque, drag and the potential for differential sticking by reducing coefficient of friction. No serious greasing issues were observed with newly developed lubricant. This liquid lubricant has been proven to reduce torque up to 40% have been observed. Lubricant concentration with 0.5% to 1% by volume is found optimum. This liquid lubricant is compatible with all WBM types.

Also, before trip-outs, pills with 2-5%v concentration of liquid lubricant is spotted on the bottom around 50-100 bbls covering BHA. As wells get deeper, wellbore geometry may evolve in an undesired manner; dog-legs and key-seats may be formed. BHA being stiff promotes the challenges to be faced while POOH due to wellbore geometry. Therefore, spotting a lubricant pill to bottom or near suspected intervals before POOH and/or before casing/liner RIH was observed to be vital for the sake of operations. This technique becomes most of the operators' routine application before trip-outs and at section TDs, especially at the deeper stages of the well.

4. CONCLUSION

This paper aims to provide an overview of geothermal drilling fluids systems and design principles based on numerous laboratory studies and more than 250 deep wells in Turkey. For standardization purpose:

- Drilling fluids selection has been reduced to three basic criteria and based on six mud types that were designed and successfully used .
- Six main fluids related risks were identified after examining the wells. Mitigation guidelines are prepared based on experience and implemented successfully for recent operations.

The findings in this paper can be treated as the basis of a guideline for drilling fluids utilization in geothermal wells in Turkey. These include but not limited to:

- Drilling fluids design and selection for each section is important to reach section goals with minimum NPT. Based on learnings from more than 250 deep geothermal wells, drilling fluid formulations and guidelines were continuously improved to their current versions. Although the presented versions of each fluid type in this paper are proven to be successful for the geothermal wells in Turkey, they are still open for further development and optimization.
- Drilling fluids for geothermal wells in Turkey, due to mentioned challenges in this paper, require 24-hour focus by mud engineers at well site. Additionally, a complete execution of the project requires accomplished experts on wellsite supported by office and laboratory team.
- Due to various fluids related challenges and wide variety of solutions, it is important to keep inventory of contingency materials readily available at the location or at a nearby warehouse. Fast delivery of mud materials to the rigsite is essential for the success of the applications and requires good logistical organization.
- Proper drilling fluid selection is of vital importance. Pre-spud meetings and relevant preparations should be conducted to pick the right fluid for each section. Treating each and every interval of any well with engineering viewpoint would be the right approach.
- All designs and optimizations have resulted in significant reductions in total mud costs. Standardization of mud types and formulations provided logistical advantages like transferring mud materials or fluid volumes from one rig to another. Standardization of the procedures and guidelines eliminated most of the human errors.

ACKNOWLEDGEMENT

The authors wish to express their gratitude to GEOS and all its personnel involved in geothermal projects for making this work possible. The authors are also grateful to Özgür Fırat Akel from GEOS and Erinç Tonguç from Zorlu Energy who critically read and reviewed the paper.

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