EXPERIMENTAL ANALYSIS OF WATER BASED DRILLING FLUID AGING PROCESSES AT HIGH TEMPERATURE AND HIGH PRESSURE CONDITIONS

A Thesis

by

BRANDON SCOTT ZIGMOND

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2012

Major Subject: Petroleum Engineering

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Approved by:

Co-Chairs of Committee, Gene Beck
Jerome Schubert
Committee Member, Terry Kohutek
Head of Department, A. Daniel Hill

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ABSTRACT

Experimental Analysis of Water Based Drilling Fluid Aging Processes at High
Temperature and High Pressure Conditions. (August 2012)
Brandon Scott Zigmond, B.S., Texas A&M University
Co-Chairs of Advisory Committee: Dr. Gene Beck
Dr. Jerome Schubert

In efforts to render the safest, fastest, and most cost efficient drilling program for a high temperature and high pressure (HT/HP) well the maximization of drilling operational efficiencies is key. Designing an adequate, HT/HP well specific, drilling fluid is of most importance and a technological challenge that can greatly affect the outcome of the overall operational efficiency. It is necessary to have a sound fundamental understanding of the behavior that water-based muds (WBM) exhibit when exposed to HT/HP conditions. Therefore, in order to adequately design and treat a WBM for a HT/HP well specific drilling program, it is essential that the mud be evaluated at HT/HP conditions.

Currently, industry standard techniques used to evaluate WBM characteristics involve aging the fluid sample to a predetermined temperature, based on the anticipated bottom hole temperature (BHT), either statically or dynamically, for a predetermined length, then cooling and mixing the fluid and measuring its rheological properties at a significantly lower temperature. This, along with the fact that the fluid is not subjected to the anticipated bottom hole pressure (BHP) during or after the aging process, brings to question if the properties recorded are those that are truly experienced down-hole. Furthermore, these testing methods do not allow the user to effectively monitor the changes during the aging process.

The research in this thesis is focused on evaluating a high performance WBM and the current test procedures used to evaluate their validity. Experimental static and dynamic aging tests were developed for comparative analysis as well to offer a more accurate and precise method to evaluate the effects experienced by WBM when subjected to HT/HP conditions. The experimental tests developed enable the user to monitor and evaluate, in real-time, the rheological changes that occur during the aging of a WBM while being subjected to true BHT and BHP.

Detailed standard and experimental aging tests were conducted and suggest that the standard industry tests offer false rheological results with respect to true BHT and BHP. Furthermore, the experimental aging tests show that high pressure has a significant effect on the rheological properties of the WBM at elevated temperatures.

DEDICATION

This thesis is dedicated to my loving mother and father. Every great achievement accomplished throughout my life is a direct result of their love, support, and counsel.

ACKNOWLEDGEMENTS

The research for this thesis would not have been possible without the support of many people. I would like to express my gratitude to my committee chair, Dr. Gene Beck, who was abundantly helpful and offered invaluable assistance, support and guidance. Gratitude is also due to the other members of the committee, Dr. Jerome Schubert and Dr. Terry Kohutek for their knowledge and assistance during this research.

I would also like to thank John Lee and MI-Swaco for the donation of a high performance water-based mud formulation. The experimental research conducted in this thesis would not have been possible without the donation of this drilling fluid.

Special thanks also to all of my fellow colleagues for support during this research, especially Arash Shadravan for his assistance in training, trouble shooting, and development of experimental test schedules with regards to the Chandler 7600 Viscometer.

Lastly, I would like to express my gratitude to my mother, father, brother, and all my friends who supported me throughout the completion of this thesis.

NOMENCLATURE

API	American Petroleum Institute
BHP	Bottom Hole Pressure
BHT	Bottom Hole Temperature
ECD	Equivalent Circulating Density
ESD	Equivalent Static Density
HT/HP	High Temperature and High Pressure
ISO	International Standards Organization
LWD	Logging While Drilling
MWD	Measuring While Drilling
OBM	Oil-Based Mud
PV	Plastic viscosity
RPM	Rotations Per Minute
SBM	Synthetic-Based Mud
UHT/HP	Ultra High Temperature and High Pressure
UKCS	United Kingdom Continental Shelf
WBM	Water-Based Mud
XHT/HP	Extreme High Temperature and High Pressure
YP	Yield Point

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CHAPTER I

INTRODUCTION: ESSENTIALS OF HT/HP DRILLING

Characteristics of HT/HP Wells

Currently there are a variety of definitions that exist for a high temperature and high pressure (HT/HP) well. Originally industry leaders followed the definition that was introduced by the Department of Trade Industry for the United Kingdom Continental Shelf (UKCS). The UKCS defines a HT/HP well as one “Where the undisturbed bottom hole temperature (BHT) at prospective reservoir depth is greater than 300˚F and the maximum anticipated pore pressure of any porous formation to be drilled through exceeds a pressure of 10,000 psi.” Due to the continuous search for petroleum progresses wells are being drilled at more extreme depths. As the depth of the well increases so does the temperature, pressure, and challenges faced. Maldonado et al. (2006) have come up with a classification in an effort to better identify HT/HP operating environments, safe operating envelopes, and technology gaps. The classification developed divides operating windows into three tiers. **Fig. 1.1** shows a summary of the three HT/HP operational categories. According to this classification Tier I wells are characterized by wells with reservoir pressures up to 15,000 psi and temperatures up to 350 ˚F. Tier II wells are what is referred to as “extreme” HT/HP (XHT/HP) wells and are characterized by reservoir pressures up to 20,000 psi and temperatures up to 400 ˚F. Tier III wells are referred to “ultra” HT/HP (UHT/HP) wells and are characterized by reservoir pressures up to 30,000 psi and temperatures up 500 ˚F. Tier III wells present the most challenging issues and technological gaps.

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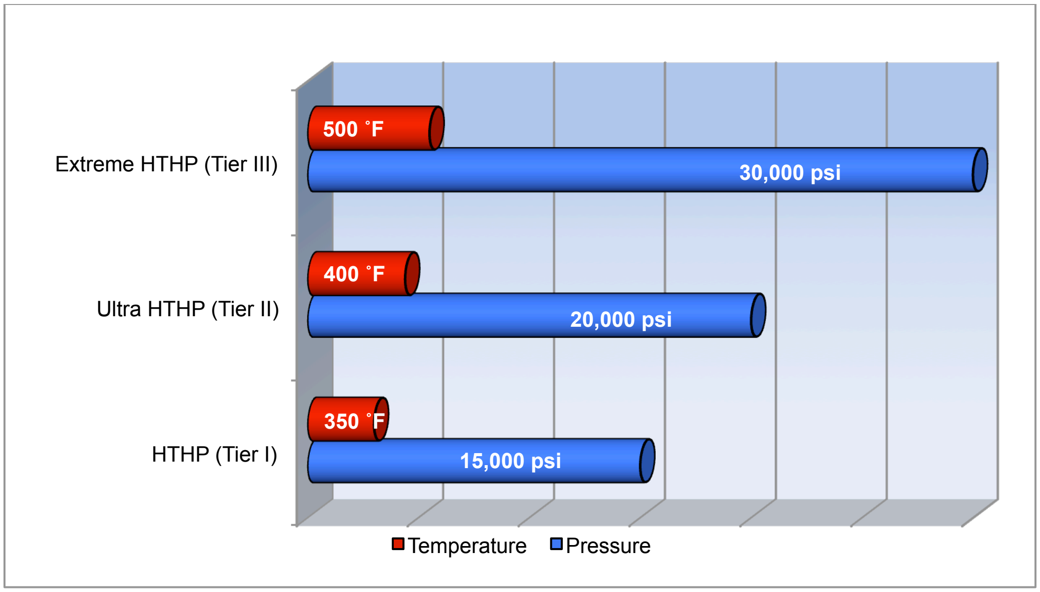


Fig. 1.1 - Graphical representation of HT/HP operating windows

The experiments of this thesis will explore the effects of all three classifications in order to progress towards a standardized test procedure to analyze the effects of HT/HP on the rheological properties of drilling fluids.

Challenges Faced Drilling HT/HP Wells

As the industry pushes deeper into the earth's crust and ultimately into HT/HP environments many challenges arise that need careful consideration during the planning and drilling of a well. According to Payne et al. (2007), less than 1% of all wells drilled in the US have penetrated below 15,000 ft. and ultimately into HT/HP environments. Even though these wells are relatively lacking they account for 7% of domestic production. These numbers show how high reserves and production rates are in HT/HP wells and how big of an impact they will have on future exploration and production. Although this thesis will emphasize the challenges faced in the development and

Table 1.1 - Issues faced when drilling HT/HP wells

Limited Evaluation Capabilities	• Most tools work to 425˚F on wire line with very limited tool availability from 425˚F to 600˚F
	• Current battery technology works to about 400˚F for MWD applications
	• Sensor accuracy decrease with increasing temperature
	• LWD/MWD tools are reliable to 275˚F with an exponential decrease in dependability to 350˚F
	• Tools risk of failure increases with increased exposure to HT/HP impacting attempts to drill for long periods of time without breaks.
Slow Rate of Penetration in Producing Zones	• In deep wells there is a slow rate of penetration due to highly competent rocks or poor drilling fluid selection/optimization
	• Crystalline structure breaks down in polycrystalline diamond compact bits in deep well environments
	• Roller cone bits are unsuitable for HT/HP environments
	• Impregnated cutter drilling is often slow in deep wells
Well Control	• Pore pressure is near fracture gradient at greater depths allowing for only a small range of mud weights that can be used to drill hole sections.
	• Mud loss is an issue causing lost circulation at greater depths due to lithology and geopressure
	• Hole ballooning causes mud storage problems. Ballooning occurs when the walls of the well expand outward due to the increased pressure during pumping. When pumping stops, the walls contract and return to their previous size causing excess mud to forced out of the well.
	• Methane (CH_4) and hydrogen sulfide (H_2S) are soluble in OBMs and are released from the solution as pressure decreases. As the gas approaches the surface it expands and the fluid column is thereby lightened.
	• Wellhead design above 25,000 psig and 450˚F is ; Current rating is at 15,000 psig and 350˚F.
Non-Productive Time	• Stuck pipe and twisting off due to differential sticking caused by excessive overbalance.
	• Trip time increases drastically with depth and caused by problems such as tool failure and bit trips.
	• Suboptimal decision making due to the lack of HT/HP drilling experience.
	• Safety issues associated with handling hot drilling fluids and hot drill strings

design of WBMs under high temperatures and pressures a brief overview of the challenges faced in planning and drilling a HT/HP well will be discussed. A variety of significant challenges are currently faced during the planning and drilling of a well. During these phases the goal of kick prevention, kick detection, and well control are of the upmost importance. As drilling depths increase so do the bottom hole pressures (BHP). In order overcome the high pressures one must design an adequate drilling fluid. At these same depths the down hole tools that measure such parameters as pore pressure are limited in their abilities. Well control is of upmost importance and at these pressures and temperatures rig equipment is pushed all the way to their design loads. For example, when drilling HT/HP wells gas kick detection becomes more difficult due to the increase in hydrocarbon gas solubility in a non-aqueous drilling fluid. Extra safety must also be taken into consideration on site due to the handling of hot drilling fluids and drill strings on site during the drilling of a well. Ibeh (2007) discusses some of the major issues involved in drilling HT/HP wells on the basis of limited evaluation capabilities, slow rates of penetration in producing zone, well control, and non-productive time. **Table 1.1** summarizes these concerns.

This chapter was intended to give an overview of what defines a HT/HP well, including classifications, as well as the challenges that are faced, for every element of a drilling system, during the planning and drilling of a well. The next chapter will express the importance of drilling fluids in drilling systems and investigate their occurrence in HT/HP environments. Emphasis will be placed on challenges, applicability, and developments. The following chapter will ultimately aim to justify the use of WBMs in HT/HP wells and discuss its advantages when compared to oil-based muds (OBM) and synthetic-based muds (SBM).

CHAPTER II

DRILLING FLUIDS: FUNCTIONALITY AND HT/HP CONCERNS

Drilling Fluid Precedence

As shown in the previous section, there are a multitude of challenges faced when drilling in HT/HP environments. The three main elements affected on a drilling rig under these conditions are the rotary system, hoisting system, and mud circulation system. Of the three the latter is the most crucial element especially when entering HT/HP environments. The major component necessary for the mud circulation system to perform properly is the drilling fluid and for the system to perform properly it is imperative that the drilling fluid is designed and able to with stand these HT/HP conditions. A chosen drilling fluid must offer a host of functionalities, which include:

1. Ability to maintain the integrity of weak rocks
2. Ability to minimize fluid loss into permeable rocks
3. Ability to provide stable well control
4. Ability to move cuttings to the surface
5. Ability to efficiently transfer hydraulic power
6. Provide steel/steel and steel/rock lubricity
7. Provide protection against all forms of corrosion
8. Allow formation evaluation
9. Pose little or no hazard to rig personnel
10. Have little or no effect on the environment
11. Cause minimal damage to the native permeability of the reservoir rock

The drilling fluid concerns stated above are magnified as drilling operations penetrate into the environments of deep HT/HP wells. Failure to adequately address mud related concerns could lead to excessive well costs, unscheduled trouble time, unnecessary high-risk activities, and poor performance. Because of these issues repeated fluid testing and treatment must be carried out during the planning and drilling of a well. There are many tests used to define drilling fluid properties and depending on well type, drilling environment, and drilling progression one or more these tests will be of primary concern. **Table 2.1** shows the different properties that are used for analysis and testing of a drilling fluid.

Table 2.1 - Drilling fluid properties

Drilling Fluid Properties			
Weight	**Viscosity**	**Fluid Loss**	**Reactivity**
Specific weight	Funnel viscosity	API Filtrate	Chemical Content
Density	Plastic viscosity	Leak off	Solids content
Specific gravity	Yield point	HT/HP filtrate	Lubricity
	Gel strengths	Dynamic Filtrate	pH
	n & K		

These properties are affected by factors including temperature, pressure, composition, and the shear history. During the planning and drilling of conventional wells these properties are tested and determined by various standard methods accepted in industry today and pose little problems. They are fairly adequate until operations approach HT/HP environments presenting a number of challenges in the design and testing of a particular drilling fluid.

The rheological characteristics, specifically density and viscosity, of a drilling fluid have one of the biggest effects on drilling operations. These properties have a major impact on the hydraulics system's objectives of maintaining acceptable pressure controls and cleaning the cuttings from the wellbore. Major emphasis must be placed on sufficiently explaining the variations in fluid properties that occur due to frequency and location the fluid is occurring in the system. As a fluid is circulated throughout the hydraulic system it experiences cyclical changes in temperature and pressure. These changes can have a significant impact on the fluid and cause variations in its rheological properties. Due to the nature of deep HT/HP drilling operations fluctuations in temperature and pressure can be very significant and pose a challenge in designing a drilling fluid that has relatively consistent rheological properties when it is subjected to a continuous cyclical change in temperature and pressure. For instance, the rheological properties greatly affect the degree of frictional pressure drop occurring during circulation. In turn the frictional pressure drop affects the change in the effective density exerted by the circulating fluid at the bottom of the wellbore, known as the equivalent circulating density (ECD).

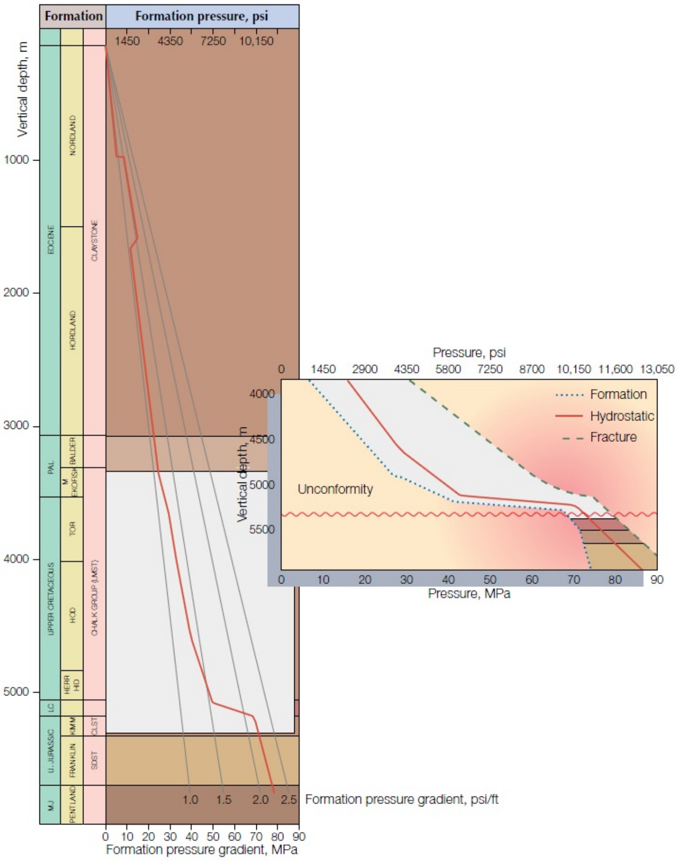


Fig 2.1 - Elgin field pressure gradient profile (Adamson et al. 1998)

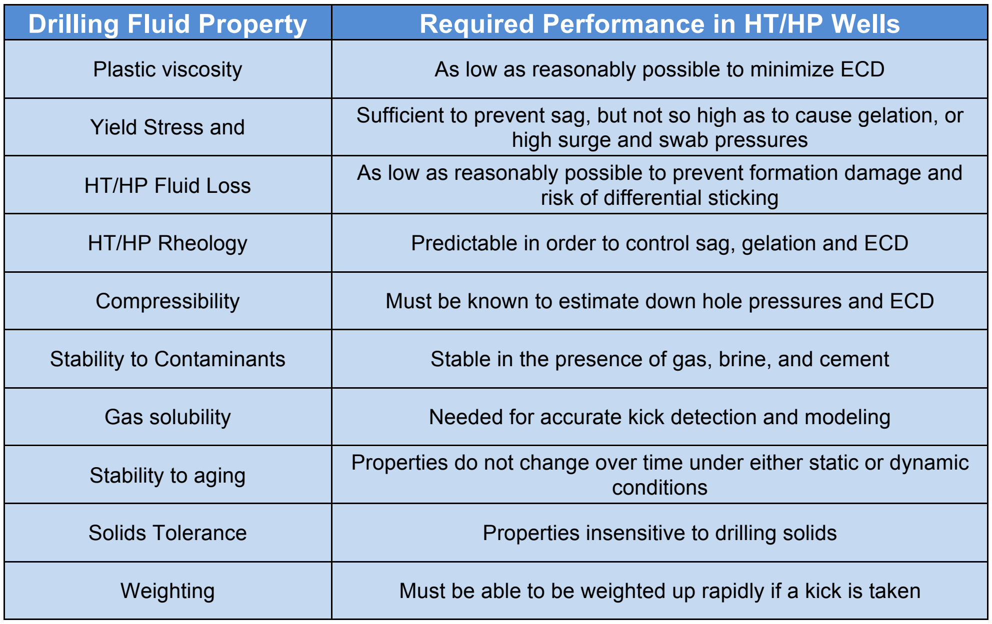
As drilling depth increases the hydrostatic overbalance decreases (caused by the close margin between the pore pressure and fracture pressure) calling for special attention to the fluids viscosity and ECD, which can be greatly affected by the cyclical changes in temperature and pressure. **Fig. 2.1** depicts the pressure gradient profile of a well in the Elgin field in the North Sea and illustrates the small margin between fracture pressure and pore pressure typical of a HT/HP (Adamson et al. 1998). At 15,000 ft. (4750 m) a 1400-psi hydrostatic pressure window exists which leaves only a small allowable change in mud weight, about 1.8 ppg. These small allowances call for special attention when choosing what drilling fluid is to be used in a HT/HP drilling system.

HT/HP Hydraulics & Drilling Fluid Concerns

Drilling fluids are subjected to the two main counteracting forces, pressure and temperature, down hole. As the depth, pressure, and temperature increase so does the need for an adequately designed HT/HP drilling fluid. Pressure and temperature greatly impact a drilling fluids behavior down hole. Traditional drilling fluids tend to have limits when entering HT/HP drilling environments. Godwin et al. (2011) specifies that the high loading of barite in conventional muds create high frictional pressure losses during circulation in long sections, leading to unacceptably high ECDs. HT/HP drilling almost always requires a high density fluid to offset the pressures experienced down hole. Most often, the increase in density is accomplished by adding a dispersed weight material such as barite. The addition of the dispersed weight material increases the dispersed solids concentration, increases drilling fluid viscosity, limits available hydraulic horsepower at the bit, and reduces cutting efficiency (Bland et al. 2002). At the same time HT/HP wells can degrade the solids-carrying capacity of traditional muds, causing both dynamic and static barite sag. Barite sagging is a direct result of inadequate drilling fluid rheological properties that are needed to keep barite particles suspended. Proposed solutions to minimize sag include increasing low shear rate viscosity and improving suspension properties. Careful engineering and monitoring is needed in the design and performance of drilling fluids. **Table 2.2** illustrates a table developed by Adamson et al. (1998) of various requirements in HT/HP wells and the corresponding drilling fluid property to achieve adequate results.

Fig. 2.2 (Zamora and Roy 2000) illustrates the simulated temperature variation of the plastic viscosity (PV) and yield point (YP) of a WBM and SBM in a contrasting HT/HP well and an 8,000 ft. well assuming equal surface density and temperature. There is a clear distinction,

Table 2.2 - Required performance and corresponding fluid properties



Drilling Fluid Property	Required Performance in HT/HP Wells
Plastic viscosity	As low as reasonably possible to minimize ECD
Yield Stress and	Sufficient to prevent sag, but not so high as to cause gelation, or high surge and swab pressures
HT/HP Fluid Loss	As low as reasonably possible to prevent formation damage and risk of differential sticking
HT/HP Rheology	Predictable in order to control sag, gelation and ECD
Compressibility	Must be known to estimate down hole pressures and ECD
Stability to Contaminants	Stable in the presence of gas, brine, and cement
Gas solubility	Needed for accurate kick detection and modeling
Stability to aging	Properties do not change over time under either static or dynamic conditions
Solids Tolerance	Properties insensitive to drilling solids
Weighting	Must be able to be weighted up rapidly if a kick is taken

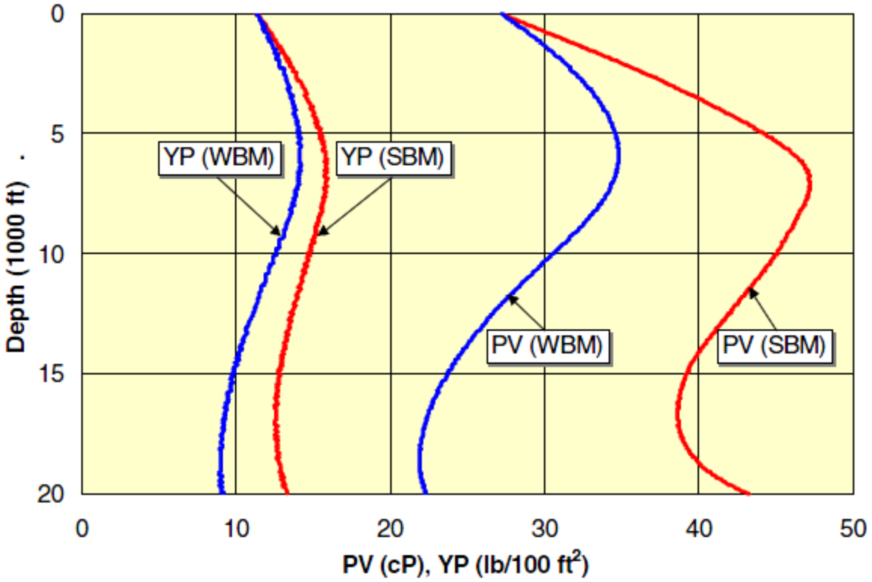


Fig. 2.2: Temperature variations effect on YP and PV (Zamora and Roy, 2000)

especially in the case of the WBM, that the YP and PV at bottom hole conditions do not show any resemblance to that of the surface conditions. Rheological property variations can have a detrimental impact on such things as ECD. The ECD is a key parameter in the hydraulics system and in order to predict particular attention is needed in the determination of rheological properties. Without actively and accurately managing these parameters using hydraulics software can result in major issues such as stuck pipe, lost circulation, or an influx of formation fluids into the wellbore. Equivalent static density (ESD) and standpipe pressure (SPP) predictions are also important and are affected by the rheological properties of a drilling fluid. The HT/HP environment has a significant effect on the ESD and needs to be clearly understood to differentiate from the density of the surface mud in order to accurately determine the true down hole hydrostatic pressure. **Fig. 2.3** shows the variation of ESD for a SBM and a WBM from a contrasting HT/HP well and an 8000 ft. well assuming equal surface density and temperature. This illustrates a distinct difference in ESD from the impact of temperature variations.

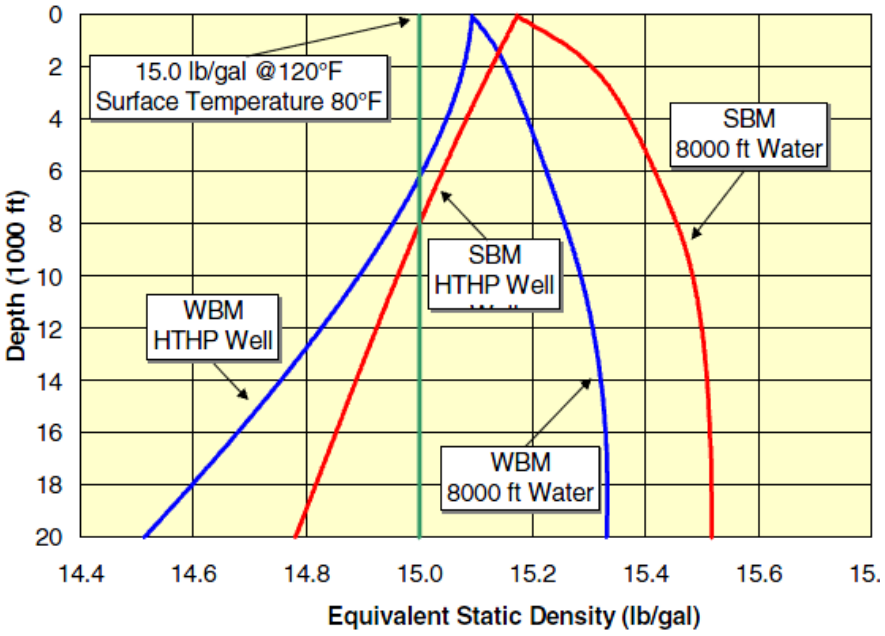


Fig. 2.3 - Temperature variations effect on ESD (Zamora and Roy, 2000)

Ibeh (2007) states that despite considerable experimental studies over the years there is still not a relatively systematic understanding of a drilling fluids flow behavior changes with down hole conditions. It is generally acceptable that the measurement of a fluid's flow characteristics at ambient surface conditions be extrapolated by some method to that of the anticipated down hole conditions. These methods must be adequate enough to model the rheological changes while taking into account the cyclical variations in temperature, pressure, and shear history during circulations through the wellbore. These concerns become increasingly important as operations approach greater depths and ultimately HT/HP environments. Bland et al. (2006) shows that the accuracy of any hydraulics model is dependent on the accuracy of the input variables and that an effective model should utilize rheological properties measured from a HT/HP viscometer operating at down-hole pressures and temperatures as well as a drilling fluid model reflective of the actual mud used.

Fig. 2.4 and **Fig. 2.5** present a sensitivity analysis of down hole pressures on the rheology of an invert emulsion fluid. The lines that are labeled as “Good Fit” are modeled from viscometer measurements at actual down hole conditions the well experiences.

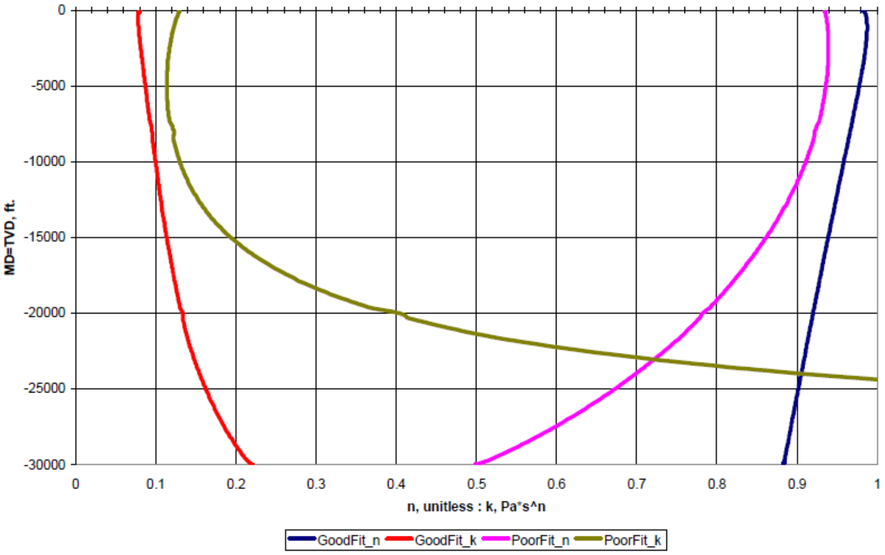


Fig. 2.4 - Calculated rheological coefficients fit from HT/HP data (Bland et al. 2006)

Whereas, the lines labeled “Poor Fit” are modeled from viscometer measurements that do not mirror the actual conditions down hole. In order to correct for this the model has to extrapolate rheological coefficients from data that was insufficient. The study shows that extrapolation of fluid behavior from data obtained at lower pressures and temperatures induces significant errors and that there is the need for accurate rheological parameters measured from a HT/HP viscometer to accurately predict drilling fluid behavior at down hole conditions.

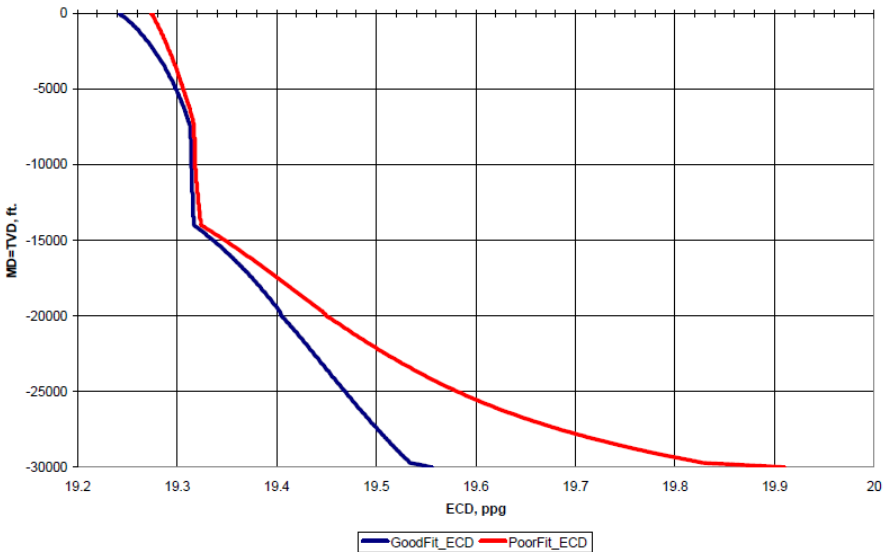


Fig. 2.5 - ECD results with calculated coefficients (Bland et al. 2006)

Water Based Mud Alternative in HT/HP Wells

There are three basic classifications of drilling fluids widely used in industry today based on what their base fluid consist of. These fluids are defined by their “base” fluid and include:

1. **Oil Based Muds** (OBM): Mud where the base fluid is a petroleum product such as diesel fuel.

2. **Synthetic Based Muds** (SBM): Mud where the base fluid is a synthetic oil

3. **Water Based Muds** (WBM): Mud consisting of water and other additives to provide specific fluid properties.

Each drilling fluid has advantages/disadvantages and are chosen based on their applicability to effectively assist in drilling a specific well. Early drilling projects in the United States and other countries where completed with OBMs. The early uses for OBMs were well completions but broadened with time to include coring, stuck pipe release/prevention, annulus packs, wellbore stabilization, HT/HP applications, corrosive environments, and directional drilling (Bland et.al, 2002).

Bland et al. (2002) states that *"the undesirable characteristics of WBMs include the ability to impede hydrocarbon flow through porous rocks, hydration/plasticization and/or disintegration of cuttings, loss of wellbore support through pore pressure elevation, and the ability to dissolve salt and corrode metals. Alternatively the desirable characteristics of oil/synthetic fluids include better lubrication, higher boiling points, and lower freezing points."* Although OBM's desirable characteristics have distinct advantages when drilling into HT/HP environments their cause for concern with respect to environmental awareness, economic considerations, and well control issues have led to an increase use of WBMs. Due to the environmentally unfriendly nature of OBMs there has been an increase in regulations around the world that explicitly prohibit the drilling and discharging of OBM and SBM byproducts. Most environmental concern is directed to the contamination of the ecological systems near offshore drilling platforms than that of onshore drilling operations. Although onshore drilling operations have less of a contamination issue, OBMs and SBMs can often contaminate the ground in and around an onshore drilling operation. The resulting contamination, although often minimal, can have a negative impact on the environment and if not dealt with properly lead to a negative connotation with onshore drilling operations in the US. Of more concern, is the contamination imparted in the sea from offshore drilling operations. The most often used technique of disposal, cleaning and dumping, involves the cuttings to be cleaned in a separator, upon removal from the drilling fluid and then discharged overboard. The amount of contamination left on the cuttings during cleaning and after disposal is much higher when drilling with OBMs and SBMs. The discharging of OBM/SBM drill cuttings, settling in and around the near vicinity of an offshore rig, can adversely affect the ecological environment as well as the biological community. As with any drilling operation minimizing cost is essential and these costs are increased with the use of OBM and SBM. SBM are significantly more expansive than OBM and in turn OBM are more expensive than WBM. Along with the raw materials cost, there is the added cost of hauling and disposing of these wastes onshore during any offshore operation. Along with the economic and environmental issues, OBM/SBM have inherent well control challenges. OBM/SBM are typically more prone to lost circulation issues during deep-water operations. Zamora et al. (2000) states that lost circulation while running casing in high-unit-cost SBMs and OBMs is arguably the most challenging mud-related problem in deep-water drilling by noting that SBM and OBM are very sensitive to cold temperatures and resulting increases in density and rheological properties further intensify surge pressures and promote lost circulation. Along With the narrow margin between fracture pressure and pore pressure lost circulation issues become a major issue while drilling with OBM/SBM. Additionally, OBM/SBM high solubility of gas into the

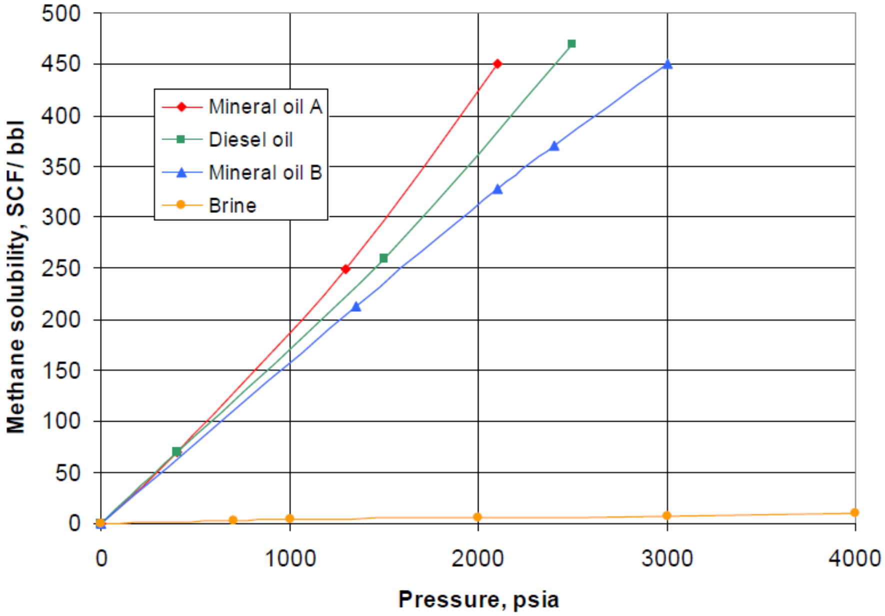


Fig. 2.6 - Methane solubility in various fluids (Bland et al. 2006)

base fluid makes it more difficult to detect gas kicks. Gas entering into solution in an OBM creates less of an observable pit gain and may take longer to manifest than an equal influx in a WBM. **Fig. 2.6** shows contrasting methane solubility in three different base oils and in brine at 100 ˚F against increasing pressure. Clearly, there is a greater degree of methane solubility in OBM compared to WBM. Due to the high solubility, a gas influx while drilling with OBM will go into solution with the base fluid and remain there without causing any significant observable pit gain until it is near the surface. The gas rapidly increases in volume, requiring careful monitoring and quick reactions to well control issues, upon closer migration to the surface and eventually emerging out of the base fluid as it falls below the bubble point pressure. However, the low solubility of WBM, results in the gas being encased in discrete bubbles and migration to the surface without the sudden influx in volume as there is with OBM. Furthermore, barite stripping caused by gas diffusion in OBM further complicate well control issues.

Scope of Continuing Research & Testing

As shown in the previous chapter, drilling fluids play a pivotal role in a drilling system and even so more as drilling depth increases and ultimately enters HT/HP environments. Chapter I and II in this thesis, as of now, have examined the importance and concerns of drilling fluids, including occurrences in HT/HP environments, and demonstrated why WBMs are justifiable alternative to OBMs. Therefore, the majority of the continuing research will discuss the development of WBMs and assess the current testing methods used in industry to evaluate their performance for use in HT/HP wells. Currently there are only a small handful of standardized test procedures used in industry with a variety of projected downfalls. The aim of the continuing research will be to evaluate the current standardized testing procedures alongside developed experimental test procedures to justify and evaluate the validity of their results. Chapter III will discuss the design/formulation of WBMs, their exposure to HT/HP environments, current testing methods used to evaluate their performance, and the proposed experimental test alternatives. Chapter IV will begin with a synopsis and review the proposed standardized and experimental testing methods that will be ran. Upon review, each method will be ran, discussed, and compared for validation. This chapter will seek to clarify if current industry test methods are sufficient and/or if the proposed experimental test schedules show a more acceptable series of results. Chapter V will end this thesis with a conclusion and further recommendation based on the obtained results.

CHAPTER III

WATER-BASED MUD: OPTIMIZING HT/HP DESIGN & TESTING

Design and Formulation

HT/HP drilling environments expose drilling fluids to extreme conditions usually at deeper sections of the well during circulation through the hydraulic system. Historically, invert emulsion fluids have been the fluid of choice and utilized to combat with these extreme conditions, but environmental and economic concerns have led to the need for WBMs. Given the functional advantages mentioned in the previous chapter, WBMs still require a high degree of concern and evaluation during the design and formulation. Headly et. al (1995) states, “Any water-based replacement fluid must possess those characteristics that make the oil-based fluid a good choice for the given application. OBMs can provide superb borehole stability, are highly resistant to contamination, and are stable under high temperature conditions”. In order to produce an adequate HT/HP WBM that replicates that of an OBM, additives are needed to maintain rheological, fluid loss, and electrochemical properties.

According to Fernandez and Young (2010), dispersed WBMs are among the most popular drilling fluids and can be designed and engineered to be suitable for HT/HP environments. Typical WBMs contain water, clay, and a variety of additional components to control fluid loss and rheological stability. Almost all formulated WBMs consist of weighting materials, viscosifiers, thinners, dispersants, and other well specific additives. Van Dyke (2000) divides drilling muds into three phases which consist of the following: continuous, non-reactive, and reactive. The continuous phase consists of the base fluid and constitutes for the majority of the drilling fluid volume. Chemically inert solids compose make up the non-reactive phase and consist of such solids as cuttings and weighting/lost circulation materials. The reactive phase is compromised by additives that can chemically react with the base fluid or each other such as clays and deflocculants. The National Research Council (1983) divides WBM into 18 different distinct elemental ingredients. **Table 3.1** summarizes each of these elements.

Table 3.1 - WBM ingredient functional categories (NRC 1983)

Functional Categories		
Weighting materials	Viscosifiers	Thinners, dispersants
Alkalinity, pH control additives	Batercides	Calcium reducers
Corrosion inhibitors	Defoamers	Emulsifiers
Filtrate reducers	Flocculants	Foaming agents
Lost circulation materials	Pipe-freeing agents	Shale control inhibitors
Surface-active agents	Temperature stability agents	Lubricants

According to Neff (2005), most WBM formulations contain no more than about 20 additives and most exist in relatively small amounts in order to change mud properties in order to tackle specific down hole problems with the most abundant ingredients consisting of barite weighting material, salts, and bentonite viscosifiers. **Fig. 3.1** illustrates the composition of a typical WBM and its respective additives. Each of these

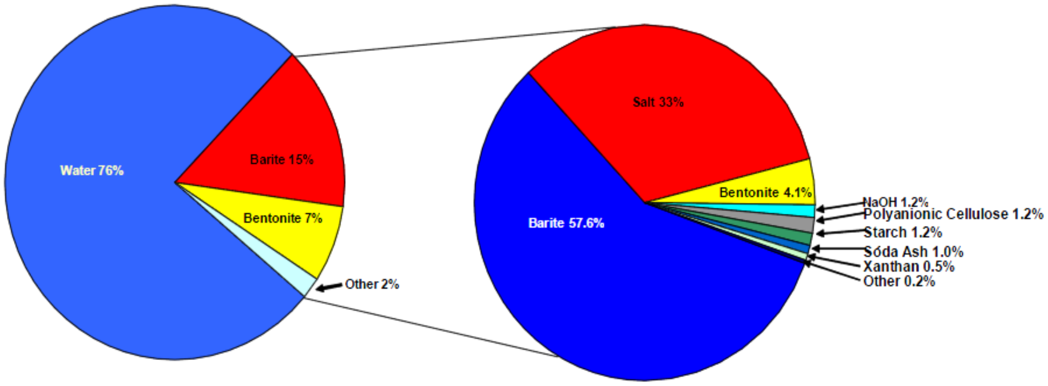


Fig. 3.1 - Typical WBM and its additives (Neff 2005)

components has a specific function and can achieve the desired mud characteristics needed to drill a well by the inclusion of a variety of strategically added chemicals and minerals. Each chemical additive serves a purpose and sometimes can be used for more than one function. **Table 3.2** presents a summarization, developed by Neff (2005) from the detailed descriptions by Boehm et al. (2001), of typical WBM materials based on

Table 3.2 - WBM functional categories (Neff 2005 & Boehm et al. 2001)

Functional Category	Desired function	Typical Chemicals
Weighting Materials	Increase density (weight) of mud, balancing formation pressure, preventing a blowout	Barite, Hematite, Calcite, Ilmenite
Viscosifiers	Increase viscosity of mud to suspend cuttings and weighting agent in mud	Bentonite or Attapulgite Clay, Carboxymethyl Cellulose, and other polymers
Thinners, Dispersants, and Temperature Stability Agents	Deflocculate clays to optimize viscosity and gel strength of mud	Tannins, Polyphosphates, Lignite, Ligrosulfonates
Flocculants	Increase viscosity and gel strength of clays. Clarify or dewater low-solids muds	Inorganic Salts, Hydrated Lime, Gypsum, sodium Carbonate and Bicarbonate, Sodium Tetraphosphate, Acrylamide-based Polymers
Filtrate Reducers	Decrease fluid loss to the formation through the filter cake on the wellbore wall	Bentonite Clay, Lignite, Na-Carboxymethyl Cellulose, Polyacrylate, Pregelatinized Starch
Alkalinity, pH Control Additives	Optimize pH and alkalinity of mud and controlling mud properties	Lime, Caustic Soda, Soda Ash, Sodium Bicarbonate, and other acids and bases
Lost Circulation Materials	Plug leaks in the wellbore wall, preventing loss of whole drilling mud to the formation.	Nut Shells, Natural fibrous materials, Inorganic solids, and other inert insoluble solids
Lubricants	Reduce torque and drag on the drill string	Oils, Synthetic Liquids, Graphite, Surfactants, Glycols, Glycerin
Shale Control Materials	Control Hydration of shales that causes swelling and dispersion of shale, collapsing the wellbore wall	Soluble Calcium, and Potassium salts, other inorganic salts, and organics such as Glycols
Emulsifiers and Surfactants	Facilitate formation of stable dispersion of insoluble liquids in water phase of mud	Anionic, Cationic, or Nonionic Detergents, Soaps, Organic Acids, and Water-based Detergents
Batercides	Prevent biodegradation of organic additives	Glutaraldehyde and other Aldehydes
Defoamers	Reduce mud foaming	Alcohols, Silicones, Aluminum Stearate, Alkyl Phosphates
Pipe-freeing Agents	Prevent pipe from sticking to wellbore wall or assist in freeing stuck pipe	Detergents, Soaps, Oils, Surfactants
Calcium Reducers	Counteract effects of calcium from seawater, cement, formation anhydrites, and gypsum on mud properties	Sodium Carbonate and Bicarbonate, sodium Hydroxide, Polyphosphates
Corrosion Inhibitors	Prevent corrosion of drill string by formation acids and acid gases	Amines, Phosphates, Specialty mixtures
Temperature Stability Agents	Increase stability of mud dispersions, emulsions and rheological properties at high temperatures	Acrylic or Sulfonated Polymers, Lignite, Lignosulfonate, Tannis

their functional category with their respective functions in WBM formulations and the typical chemical additive used to achieve the desired effects. Table 3.2 undoubtedly shows the abundant types of chemicals that can be added to a WBM. Most of these additives exist in relatively small portions in a WBM with the exception of the base fluid (water), weighting materials, and viscosifiers, thinners, and dispersants.

Water itself is not sufficient enough to provide the required viscosity in order to provide adequate hole cleaning and lift cuttings to the surface. The use of viscosifiers, typically the second most abundant additive to the base fluid, is introduced to WBM fluid formulations in order to overcome the lack of viscosity. Bentonite or attapulgite clays are typically chosen to increase viscosity and maintain the desired gel strength properties. These clays provide the necessary thixotropic characteristics required to suspend cuttings in the wellbore and progress up to the surface. Clay hydration gives the clay the ability to perform the necessary properties. When the clays come in contact with water they begin to swell. **Fig. 3.2** depicts the process of bentonite clay due

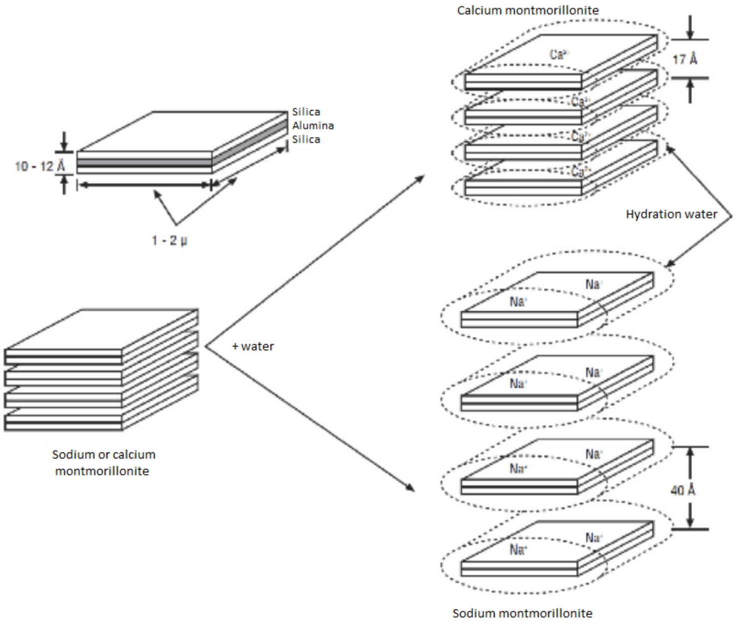


Fig. 3.2 - Bentonite hydration (Neff 2005)

to the increase in space between the particles as water absorption begins. This figure also shows that the degree of spacing, hydration, and ultimately the resulting increase in viscosity of the fluid, is dependent on whether the cations attached to the outer unit layers are sodium or calcium. Alternate polymers can also be used in place of bentonite to enhance WBMs rheological properties. Additives such as carboxymethyl cellulose and xanthan gum are typically used to increase viscosity and solids carting capacity with negligible change in the solids content of the fluid.

In order to overcome the rising down hole pressures experienced as drilling depths increase fluid formulations require a subsequent increase in density. WBM density is increased by the introduction of weighting materials, most commonly barite. Barite, as well as most other weighting agents, is insoluble and non-reactive resulting in a poor distribution of material to control the bulk density of the fluid. This phenomenon typically referred to as barite sag and in order to effectively distribute a uniform density the addition of viscosifiers such as bentonite must be present. Bern et al. (1998) defines barite sag as the undesirable fluctuations in mud weight that occur due to down hole settling of the weighting agent. Barite sag is caused both statically and dynamically and tends to increase in deviated wells. **Fig. 3.3** illustrates four different possible variations of barite sag depending on the deviation of the well and the strength of the bed.

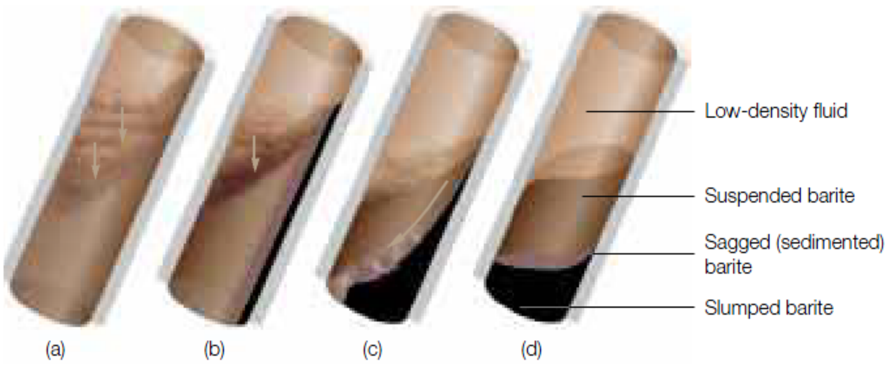


Fig. 3.3 - Barite sag (Adamson et al. 1998)

Barite sag can lead to problems such as mud weight variations, mud losses, unforeseen well control issues, and induced wellbore instability.

Exposure to HT/HP Environments

Most of the common additives previously mentioned and summarized in Table 3.2 can easily be formulated to cope with the typical conditions presented in average depth wells. As BHTs exceed 350˚F the formulations and design of drilling fluids become increasingly difficult with a variety of different problems. Oakley et al. (2000) outlines the critical issues faced with WBM and their respective causes and concerns that arise when entering HT/HP environments as the following:

1.) High-Temperature Gelation: As a WBM is at static conditions for a prolonged amount of time under high temperatures gelation occurs due to clay (bentonite) flocculation and is compounded by the thermal degradation of chemical thinners, a drop in pH and an increase in the filtrate loss.

2.) High-Temperature Fluid Loss: Static and dynamic fluid loss increases with the temperature and are affected by the gelation and degradation of synthetic polymers.

3.) Rheological Property Control: In order to maintain the hydrostatic pressure and well control high-density drilling fluids must be formulated correctly. Efficient solids-control equipment and high performance additives are needed in order to control the rheological properties. A small increase in colloidal-sized drilled solids can increase the fluids rheological properties and possibly lead to unacceptable pressure losses, drilling fluid gelation, and excessive surge and swab pressures.

4.) Product Degradation: Most drilling fluid enhancement products are susceptible to thermal degradation at elevated temperatures. Upon break down of these products other fluid properties tend to be negatively affected.

It is observed that most WBM formulation issues at HT/HP arise due to the gelation and degradation of additives. Fluid loss (i.e filtrate loss) occurs when the liquid phase of the mud is being lost into a permeable formation due to the resulting pressure differential. Fluid loss is offset by the addition of an adequate filter cake. Filter cakes impede fluid flow by blocking pore spaces in the borehole walls with lager size particles in the drilling fluid. **Fig. 3.4** illustrates the typical accumulation of filter cake on the wellbore formation.

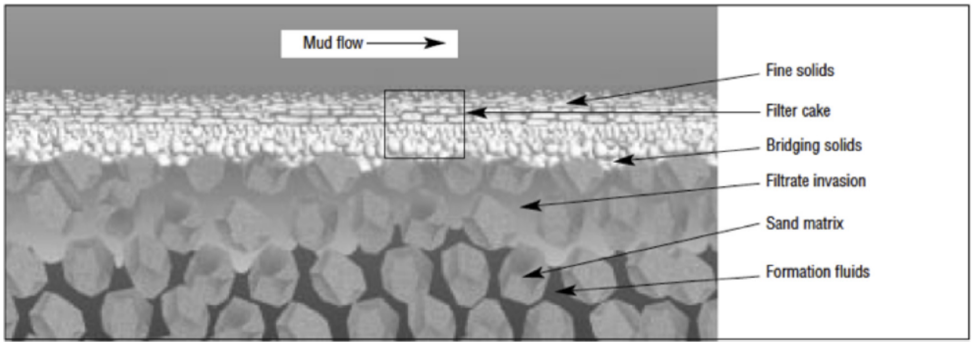


Fig. 3.4 - Filter cake accumulation (MI Swaco 2002)

Bentonite is the most commonly used additive for the formation of filter cakes due to its relatively large surface are giving it the potential to form low permeability filter cakes. When entering HT/HP environments bentonite particles in suspension flocculate and resulting in gelation and increased filter cake permeability. In order to control HT/HP gelation, filtrate loss, and adequate rheological properties deflocculants (i.e. Thinners and dispersants) are added to fluid formulations. These two additives help prevent gelation by maintaining the effects of flocculation experienced from the increases in temperature. Ibeh (2007) explains that the balance between the inter-particle attractive and repulsive forces, affecting the degree of dispersion and flocculation, are due to electrochemical activity. As the temperature increases it causes and increases the ionic activity of any electrolyte and the solubility of any partially soluble salt that may be present in the fluid and in turn directly affecting the degree of dispersion and flocculation. Additives such as lignosulfonates and lignites are used to prevent clay platelets from bonding together by satisfying the clay plate edge charges and eliminating the electrochemical attractive forces between the clay particles (Fernandez and Young, 2010). **Fig. 3.5** illustrates two WBM, one without dispersant and the other with an efficient dispersant, aged 450˚F for 16 hours.

Fig. 3.5 - WBM without dispersant (left) and with dispersant (right) (Tehrani et al. 2009)

This figure clearly demonstrates extreme differences and the importance of having thinners and dispersant in fluid formulations to combat with gelation at high temperatures. **Table 3.3** summarizes the four states of clay particle association as defined by MI-Swaco (2002) and their respective influence on the viscosity of a fluid and **Fig. 3.6** illustrates their orientation with respect to one another.

Table 3.3 - Clay particle association (MI Swaco, 2002)

Aggregation	Is referred to as face-to-face linking of clay particles. This orientation results in the formation of packets of clay and therefore reduces the net number of particles in suspension thereby reducing the viscosity of the fluid.
Dispersion	Occurs when the clay particles are separated completely from one another. This leads to an increase in the total number of particles in suspension and thereby increases viscosity of the fluid.
Flocculation	Is described as an edge-to-edge or edge to face orientation of clay particles. This orientation also increases the viscosity of the fluid.
Deflocculation	Is the opposite of flocculation and leads to a reduction in viscosity.

Fluid viscosity increases due to the increasing temperature of the bentonite particles causing transition from the dispersed state to the flocculated state. These issues require that fluids be subjected to extensive and adequate testing to perform the desired characteristics.

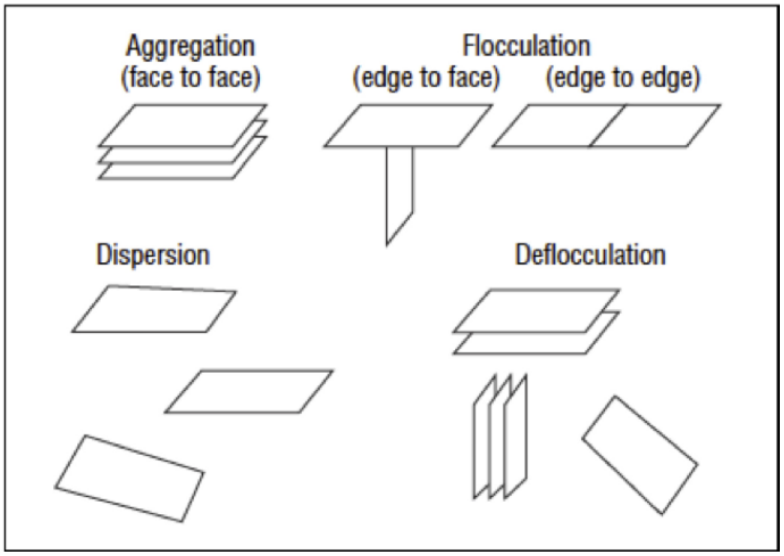


Fig. 3.6 - Clay particle orientations (MI Swaco 2002)

Fig. 3.7 shows the typical progression of gelation on three different WBMs. Fluid A is a combination of 20 ppg of both Wyoming and Southern bentonite. Fluids B and C have the same basic formulation with treatment additives to reduce viscosity and ultimately high temperature gelation. This figure shows that there is a drastic viscosity increase when the temperature reaches 350˚F. At this point the fluids become operable showing that there is a significant operating threshold. It is clear that higher temperatures can cause various issues in WBMs and is accepted that in most cases these higher temperatures will have the greatest effect on rheological property control. That being said one should never overlook the effects of other contributing factors influencing the rheology of WBMs in HT/HP environments. As temperature and pressure increase, the rheological properties of WBMs are more susceptible to the effects of pressure. Briscoe et al. (1994) conducted experiments on the rheological properties of WBMs at HT/HP showing that at high temperatures there is a considerable effect on the rheological properties with increasing pressures showing that the sensitivity of the pressure effect on rheological properties is temperature dependent.

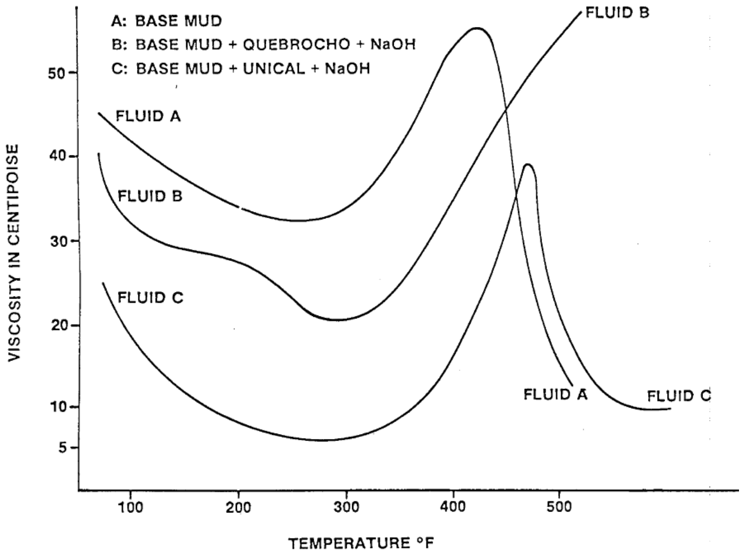


Fig. 3.7 - Progression of bentonite gelation (Carney et al. 1982)

Briscoe et al. (1994) show the effect of increasing pressure and temperature of a WBMs normalized 10-minute gel strength, plastic viscosity, and yield stress respectively. **Fig. 3.8** shows the resulting 10-minute gel strength with respect to pressure of an 8% clay at 27 ˚ C (81˚F), 65 ˚C (149 ˚F), and 80 ˚ C (176 ˚F). It is clear that the effects of pressure on the normalized 10-minute gel strength are negligible until the sample reaches relatively high pressures showing that the mud tends to thicken more rapidly at higher pressures. **Fig. 3.9** and **Fig. 3.10** show the resulting plastic viscosity and yield stress, respectively, with respect to pressure of an 6% Clay and 60% barite content at 27 ˚ C (81˚F), 65 ˚C (149 ˚F), and 85 ˚ C (185 ˚F).

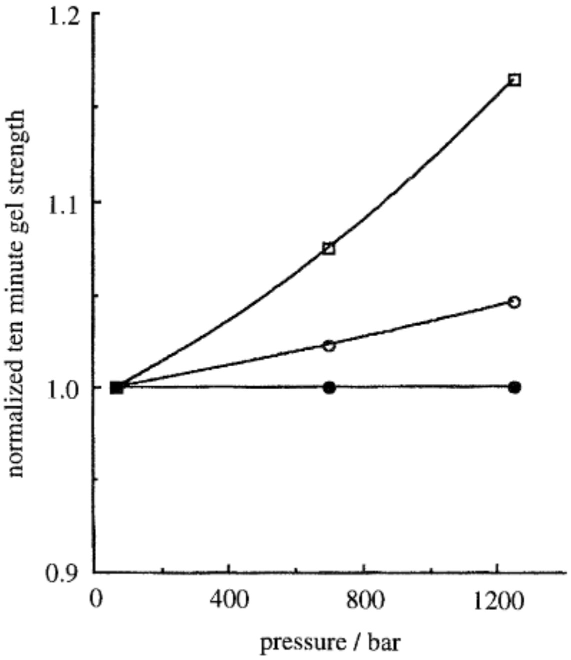


Fig. 3.8 - 10-minute gel strength of 8% clay WBM (Briscoe et al. 1994)

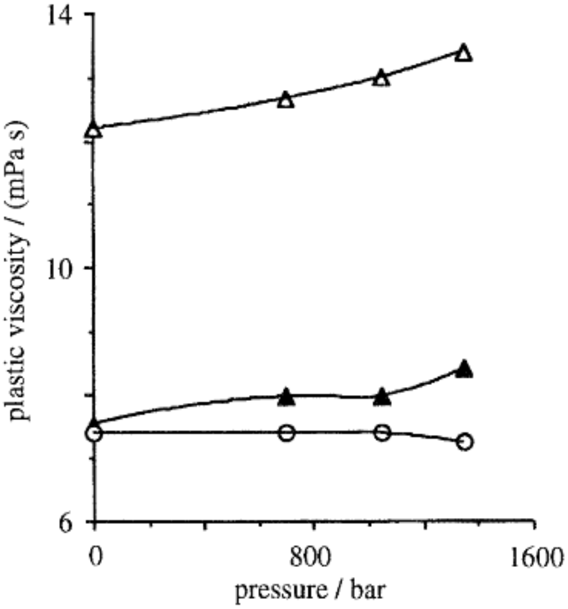


Fig. 3.9 - Plastic viscosity of (6% clay, 60% barite) WBM (Briscoe et al. 1994)

It is apparent that WBMs rheological properties are highly temperature sensitive, as shown with a noticeable increase in rheological properties with increasing temperature. It is also shown that at higher temperatures the effects of pressure on the rheological properties of WBMs can be significant. Furthermore, Briscoe et al. (1994) only tested temperatures in the range of 80˚F-180˚F, only half of the classification of HT/HP (Tier 1, 350˚F). It can be expected that when these muds enter HT/HP, UHT/HP, XHT/HP the rheological properties effected even more. Careful consideration and selective additives are thus needed to combat with the additional effects of pressures on WBMs when entering HT/HP environments. Furthermore, it has been shown that the rheological properties of WBMs are also time- dependent.

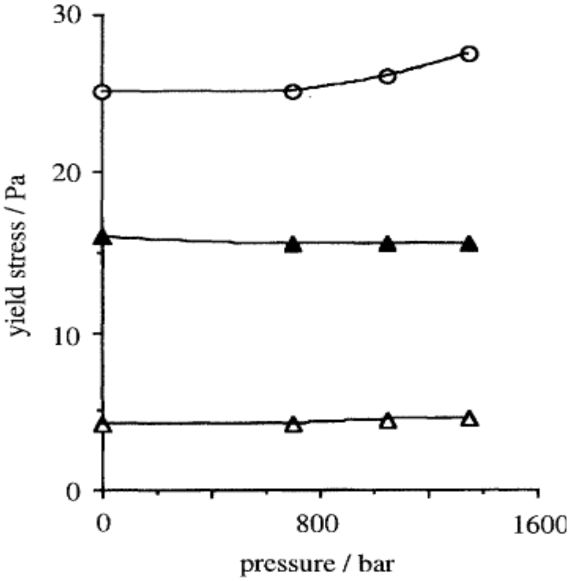


Fig. 3.10 - Yield stress of (6% clay, 60% barite) WBM (Briscoe et al. 1994)

The rheological properties of WBMs muds can be affected due to past shear history as well as cyclic loads of temperature and pressure.

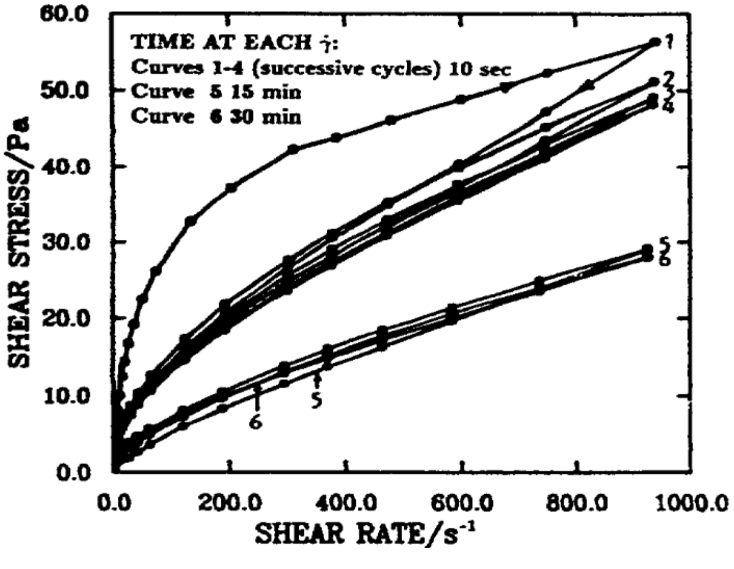


Fig. 3.11 – Shear rate vs. shear stress WBM sample (Alderman et al. 1988)

As a WBM is circulated through the hydraulic system it is subjected to various amounts of shear at a variety of different time intervals depending on the task being performed. Alderman et al. (1988) suggests that the rheology of WBMs is influenced by the shear history of the fluid alongside pressure, temperature, composition, and electrochemical character of the components and of the continuous phase. The various clay structures formed in a WBM result in its respective rheological properties, this structure can consequently break down due to an increase in shear rate resulting in a shear thinning effect. **Fig. 3.11** shows the effect of shear rate on the shear stress of an unweighted bentonite WBM Sample. It can be seen that as the time increases the shear stress begins to decrease (i.e. shear thinning). Alderman et al. (1988) states, “The dynamic nature of this structure and its sensitivity to applied stress means that the resulting bulk rheological properties are extremely time and shear-history dependent”. Additionally, WBMs are subjected to ever-changing temperatures and pressures as they are circulated through the hydraulic system during drilling operations. Piber et al. (2006) conducted a test on a bentonite suspended WBM to quantitatively evaluate its time-dependent rheological behavior under cyclic temperature and pressure loads.

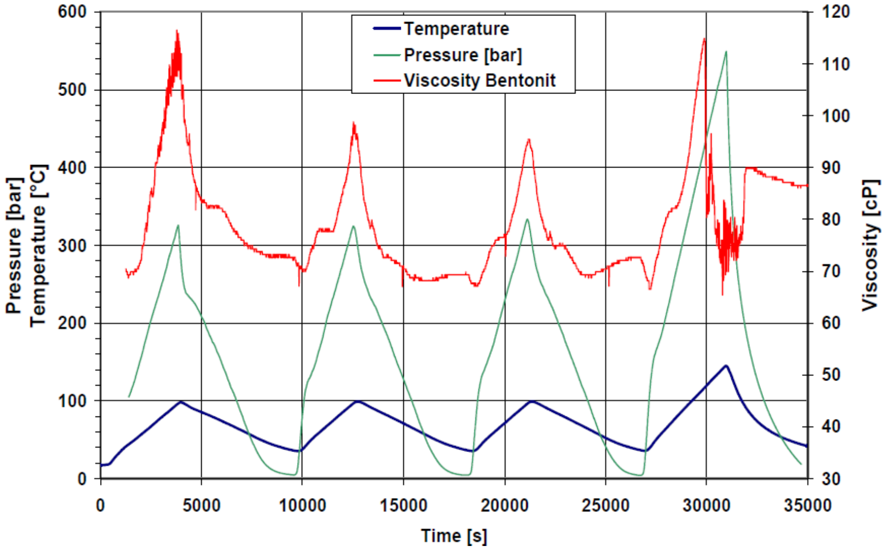


Fig. 3.12 - Effect of shear history on WBM sample (Piber et al. 2006)

The test, seen in **Fig. 3.12**, is conducted with constant shear rate of 300 rpm during the entire test with relatively small intervals for recording shear stresses at 600 rpm. The test schedule consists of a temperature increase to 100˚C (212˚C) for a duration of 60 minutes and then cooling period to 35˚C (95˚C) for a duration of 90 minutes. Three cycles of this schedule are conducted along with a fourth cycle where the temperature is raised to 150˚C (302˚F) to identify a point at which the fluid begins to show a "break down" point. Likewise, the pressure, for the first three cycles is, raised to 330 bars (4786 psi) with the fourth cycle being raised to 550 bars (7977 psi). By comparing the peak viscosities for the high temperatures during cycle 1 and 2 a viscosity reduction of 10% is recognizable. The fourth cycle shows a drastic reduction in viscosity as the temperature begins to exceed 110˚C (230˚F). The fluid viscosity begins to increase, a reverse trend when compared the previous three cycles, is seen as the fluid is cooled during the fourth cycle indicating a "breakdown" of the fluid.

This section was intended to give an overview of common WBM formulations and their design considerations when extended into HT/HP environments. It is evident that careful concern and consideration needs to be taken into the design and testing of HT/HP WBMs to effectively combat with extreme effects on the rheological properties at these conditions. The next section will begin to discuss HT/HP testing alternatives of WBMs, the central theme of this thesis, to determine when the fluids rheological properties begin to change and consequently begin to exhibit unfavorable rheological characteristics.

Standard Static/Dynamic Aging vs. HT/HP Viscometer

In order to be confident that a formulated WBM designed for a particular HT/HP drilling program will perform adequately without complications or failure the mud must be analyzed for any potential breakdown in rheological properties. When an operator needs to determine if a certain formulated mud will perform adequately without "failing" and becoming inoperable they will send it to a respected oil and gas service company for a complete analysis of the rheological properties under HT/HP conditions. It is beneficial for the drilling engineers to know the temperature and length of time a WBM will continue to exhibit operationally acceptable properties. Failure is often seen as a relative term, depending on what one defines a significant change in rheology that can be tolerated in a drilling system. In the context of this theis "failure" will refer to the period of time, with no definitive length, at which a drilling fluid exhibits considerably unfavorable rheological changes at elevated temperatures and pressures (caused by phenomena such as flocculation, gelation, shear thinning, etc.), rendering it virtually unusable during critical drilling operations. Drilling engineers are especially interested in finding how the mud will perform during certain operational drilling procedures where the mud will be subjected to relatively long exposure to HT/HP down hole conditions such as bit trips and well logs. The most typical analysis technique used by service companies to determine the point at which a fluid becomes inoperable or exhibits a drastic change in rheological properties under HT/HP conditions is by either static or dynamic aging tests at extremely elevated temperatures. Although this is commonly the industry accepted procedure there could be underlying operational differences when compared to a HT/HP viscometer that can possibly lead to faulty analytical results. This issue governs the core reasoning for this thesis as it aims to evaluate the validity of using static/dynamic aging cells in efforts to determine the period of time at which a WBM "fails", showing significant changes in rheological properties, by comparison with a HT/HP viscometer.

The aging of muds is often completed under static or dynamic conditions from ambient to elevated temperatures. For the purpose of this thesis only aging techniques for WBMs at elevated temperatures will be discussed and evaluated. API RP 13I (2008) defines drilling fluid aging as, "the process of allowing a drilling fluid sample that contains all the required ingredients and that has been subjected to a period of shear to more fully develop its rheological and filtration properties through additional time for the hydration, etc. of its components." Discussions and evaluations in this thesis will only reference aging occurring at extreme elevated temperatures, in order to evaluate the moment at which a WBM virtually “fails”. Static aging is the testing technique where a non-agitated mud sample is aged in a cell at a predetermined elevated temperature and time. Rheological testing of post static aged WBMs, with stirring, is used to simulate the effect of elevated temperature on a mud that is stationary in a well during operations such as bit trips or logging. Rheological testing of post static aged WBMs, after being stirred and sheared for a predetermined time, is used to simulate a mud that has been agitated during circulation to the surface. Furthermore, dynamic aging is the testing technique where the mud is mildly agitated by rolling in a specially designed oven for the entire duration of the test. The rolling and agitation of mud is considered to simulate the effect of circulation down hole via pumping. API RP13I (2008) lists basic procedural recommendations for aging WBMs at elevated temperatures (<150˚F) as the following:

1.) Oven apparatuses must be able to maintain a temperature of 350˚F or greater and aging cells should be constructed from metals that are that can withstand exposure of drilling fluids at elevated temperatures. Aging cells should be selected in such a way to meet or exceed the temperatures and pressures, selected from anticipated maximum bottom hole conditions, that they will be subjected to during testing. During the use of metal aging cells at elevated temperatures care should be taken to ensure the cells are not overfilled. Liquids enclosed will expand as the temperature increases, and an inadequate air gap can lead to a piston effect. During operations ranging from 150˚F to 400˚F it is recommended to not fill the cell more than 85% to 90% of its volume, or leaving gaps around 1-9/16 in to 1-15/16 in between the top of the liquid and the cell cap.

2.) Before fluids are static or dynamically aged they are often mixed and sheared for a sufficient amount of time to ensure a homogeneous mixture. Drilling fluid formulations are commonly mixed with shearing devices at fixed or variable speeds. Some of the common mixers include the Hamilton beach

936, Dispersorator, and the Multimixer Model 9B. The shearing imparted by each mixer can vary widely, so it is recommended that one shearing device be used during testing in order to maintain consistent results.

3.) Often during elevated temperature, fluid alkalinity can be rapidly lowered and in turn decrease the optimal functions of certain drilling fluid additives. Therefore it is sometimes necessary to raise pH levels after either aging technique in order for these additives to perform at their desired levels.

4.) Once the correct selection of metal aging cell and drilling fluid is established in regards to the temperature it will be subjected to, the samples can be statically or dynamically aged in a suitable oven. Dynamic aging should be conducted in rolling or rotating ovens that are able to safely maintain temperatures of 350˚F or greater at a suggested minimum aging time of 16 hours for such tests. Static aging can be conducted in any qualified oven or rolling oven with the rollers switched off at a suggested minimum aging time of 16 hours. For high-temperature wells, the usual 16 hr aging interval is a reasonable simulation of the time a drilling fluid is left down hole during a bit trip. For longer operations, such as extended well-logging runs, a 48-72 hr aging period is more appropriate.

Readings are often taken before and after the selected aging process to evaluate the changes in rheological properties of the WBM. In the oil and gas industry it is typical for readings to be taken by a traditional “cup and bob” rotating viscometers. The Fann 35 and other “cup and bob” rotational viscometers are based on the assumption that the required torque to turn an object in a fluid is a direct function of the fluids viscosity. Rotational viscometers have two geometries that are used to determine the viscosity of a fluid known as “Couette” or “Searle” systems. The Couette system is distinguished by the cup remaining stationary as the bob rotates, while the Searle system is distinguished by the cup rotating as the bob remains stationary. The Searle system sometimes preferred because it reduces the onset of Taylor vortices, but is often more difficult to measure accurately. Therefore, for the purpose of this thesis, and most of the industry, the Couette system is preferred. Couette flow refers to the laminar flow of a viscous fluid in the space between two surfaces, one of which is moving relative to the other. The moving surface imparts friction and thereby shears the entire fluid present between the two surfaces. The sheared fluid then exerts a force on the stationary surface that can be used to give a measurement of the fluids viscosity as a function of the shear stress. **Fig. 3.13** shows a schematic of the processes occurring in Couette flow geometry.

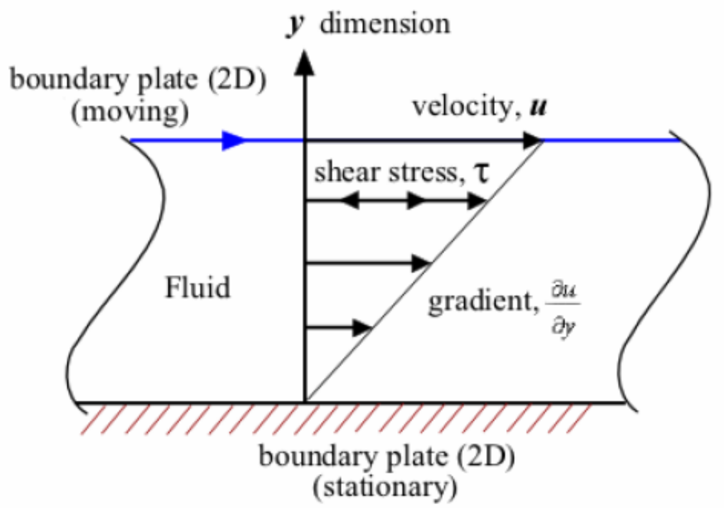


Fig. 3.13 - Couette flow (Ibeh 2007)

The parallel plate theory used for Couette flow is approximated in rotational viscometers by the surfaces of a cylindrical and concentric "cup and bob". The cup is held stationary while the bob rotates enabling the fluid between the two surfaces to be sheared. **Fig. 3.14** shows an illustration of a traditional Couette rotational viscometer system. Simple rotational viscometers such as the Fann 35 viscometer, give the resulting shear stress in terms of the torsional force exerted on the bob during predetermined angular velocities where the shear stress is recorded as a value deemed the "dial reading". The dial reading is determined from a calibrated dial that is attached to a torsional spring that is directly connected to the rotating bob.

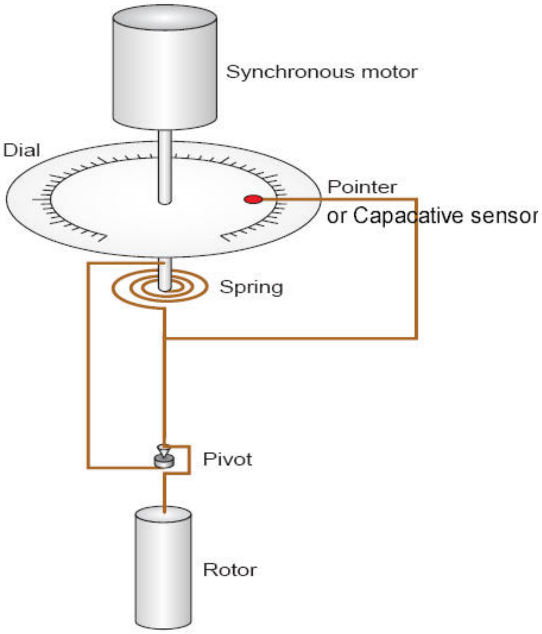


Fig. 3.14 - Couette rotational viscometer

The term "dial reading" is the true centipoise viscosity fluid and most oil field viscometers come available with a preset of 6-speeds. The 6-speeds are used to simulate the resulting shear rate the fluid experiences in a drilling operations hydraulic flow loop. **Table 3.4** shows the predetermined speeds respective to the experienced low, medium, and high shear rates and how they relate to the location the fluid is in the circulating system.

Table 3.4 - Dial reading vs. shear rate

Couette Viscometer		Circulating System	
RPM	Equivalent Shear Rate (sec^{-1})	Location	Shear Rate Range (sec^{-1})
3	5.11	Tanks	1-5
6	10.22	Annulus	10-500
100	170	Pipe	100-700
200	341	Collar	700-3,000
300	511	Nozzles	10,000-100,000
600	1022		

Traditional Couette viscometers are often used in the oil industry to evaluate the rheological properties of drilling fluids, fracturing fluids, and cements. The American Petroleum Institute (API) and the International Standards Organization (ISO) have developed and defined certain criteria based on testing procedures, testing conditions, equipment geometries, and shear rates used for determining fluid characteristics. These along with other conventional viscometers become insufficient when trying to determine the rheological properties of drilling fluids that begin to enter HT/HP conditions. The use of static and dynamic aging is used to try and overcome these issues by enabling readings to be taken by traditional rotational viscometers after returning to some predetermined minimal temperature and pressures. The methods used for static and dynamic aging lead to question whether or not the readings recorded are representative of the actual rheological changes during exposure to extreme elevated temperatures and pressures. Furthermore, these methods should be evaluated to see if pressure has any significant during the effect during the aging process while at the same time identifying the period of time when fluids rheological characteristics begin to significantly change.

Most if not all of the current industry leaders in drilling fluid technology and testing follow these general recommendations, with variations in procedures within each company, when they statically/dynamically age WBMs. The procedural test and use of static aging vs. dynamic aging is subjective between companies without any standardized procedures available for aging drilling fluids. This can lead to a variety of different results and conclusions, with the final recommendations on the fluids ability to adequately perform down hole relying on the experience and expertise of the company performing the tests. Typically, Readings are conducted with a traditional rotational viscometer, such as a Fann 35 viscometer, before and after aging with the time and temperature at which readings are taken varying greatly. There is currently not a standard time and temperature at which the fluid’s rheological properties are recorded after the aging period. **Table 3.5** shows typical static aging results for 6 different fluids aged for 16 hours at 450˚F.

Table 3.5 - Rheology of static aged WBMs at 120˚F (Tehrani et al. 2009)

Fann Readings	Units	#1	#2	#3	#4	#5	#6
600 rpm	lb/100	155	225	150	181	171	177
300 rpm	lb/100	91	130	84	100	101	99
200 rpm	lb/100	67	97	60	72	77	70
100 rpm	lb/100	39	56	36	41	47	39
6 rpm	lb/100	5	6	6	6	11	5
3 rpm	lb/100	3	4	4	3	9	3
PV	cP	64	95	66	81	70	78
YP	lb/100	27	35	18	19	31	21
10-sec Gel	lb/100	3	4	6	3	9	4
10-min Gel	lb/100	21	8	22	29	64	14

The readings for this procedure were taken at 120˚C, showing time for significant cooling after the aging process. Alternatively **Table 3.6** shows readings that are taken after aging for series of predetermined times at 450˚F when the fluid has cooled to 25˚C (77˚F). The lack of standardization as to what temperature dial readings should be taken after aging leads to question if there is some error induced in the resulting rheological properties due to the variation of evaluation temperature. Rheological properties of an aged mud at the current anticipated BHT and BHP after aging will vary from those that are taken after the mud has cooled to ambient temperatures and pressures after aging. Therefore, a test using a HT/HP viscometer, discussed later in the thesis, would be useful to analyze the change in rheology that occurs as the WBM approaches ambient temperatures and pressures. Furthermore, Standard aging tests are commonly performed, at the minimum 16 hr length, only at the expected anticipated maximum BHT and BHP. This type of procedure only justifies that a mud will definitely fail at the maximum temperature after the 16hr aging time it is subjected to. These types of procedures do not define at what point in time during the aging period the WBM begins to exhibit rheological properties that are unsatisfactory for down hole operations. Dormán (2010) attempts to overcome this issue by conducting a series of multiple static aging tests designed to find the moment at which the subjected WBM sample began to exhibit undesirable fluid properties. The test, seen in Table 3.6, subjects a WBM to a max temperature of 195˚ C for a series of predetermined time intervals at which a complete rheology analysis is conducted.

Table 3.6: Static aging rheology with increasing time intervals (Dormán 2010)

Fann Readings (25˚C)	Units	14 hrs	40 hrs	65 hrs	85 hrs
600 rpm	lb/100 ft^2	64	75	76	148
300 rpm	lb/100 ft^2	33	40	46	138
200 rpm	lb/100 ft^2	22	28	35	131
100 rpm	lb/100 ft^2	12	16	23	120
6 rpm	lb/100 ft^2	1	2	8	104
3 rpm	lb/100 ft^2	0.5	1	7	98
PV	cP	31	35	30	10
YP	lb/100 ft^2	2	5	16	128
10-sec Gel	lb/100 ft^2	1	2	5	74
10-min Gel	lb/100 ft^2	3	16	28	105

It is clear that during the aging process the fluid exhibits excellent rheological properties until it reaches a static aging length of 85 hours, where it then displays an erratic change in rheological properties, likely due to flocculation and gelation. However, this still brings to question if the results are skewed due to the fact the readings are taken after the mud has considerably cooled to 25˚C (77˚F). Furthermore, there is still a 20 hr window, between the 65-85 hr period, that the mud was not tested, leading to question if the mud could have starting showing undesirable rheological properties well before the 85 hr period. This thesis will go one step further and use a HT/HP viscometer procedure, discussed later in this thesis, enabling the user to see a definitive time at which failure begins to occur at the selected max temperature without the cooling effect. Table 3.6 also shows the need for longer aging times, other than the standard minimum 16 hr, to obtain a change in rheological properties. It is also widely accepted that pressure has minimal effects during HT/HP aging, and thus almost all aging tests are ran without the added effects of pressure. As discussed in the previous section the effects of pressure on the rheological properties of WBMs tend are temperature dependent, with pressure affecting the rheological properties greater with the increase in temperature. These results were done on non-aged muds, leading to question what the effects of pressure are at elevated temperatures during a much longer period of time. Therefore, the effects of pressure will be evaluated later in the thesis alongside experimental tests ran on the HT/HP viscometer to evaluate the effects on rheological properties during aging process of WBM at elevated temperatures. The use of a HT/HP viscometer will help to evaluate all of the concerns discussed as well as help to identify any issues that may have been overlooked

In order to get accurate and detailed evaluations of the changes that occur under extreme temperatures and pressures the implementation of a HT/HP viscometer is needed. There are currently a variety of HT/HP viscometers on the market today with various pressure and temperature limits. For the purpose of this thesis and consistency of experimental results being performed the Chandler 7600 model HT/HP viscometer developed by Chandler Engineering will be used. **Fig. 3.15** shows an image of the 7600 viscometer with the exposed test cell. The Chandler 7600 is the same as traditional rotational viscometers in the sense that it is a concentric cylinder Couette viscometer that uses rotor and bob geometries.

Fig. 3.15 - Chandler 7600 viscometer

Furthermore, it is the highest pressure rated viscometer available on the market and its design meets the requirements implemented by ISO and API standards for the use of measuring rheological characteristics of drilling fluids at HT/HP conditions to a maximum temperature and pressure or 600˚F and 40,000 psig, respectively. **Table 3.7** shows a complete list of specifications for the Chandler 7600 viscometer. One of its major features, unlike that of traditional viscometers, is that there is no mechanical linkage between the servo motor, being purely magnetic, allowing for fluids to be subjected to extreme pressures without the risk of leakage. Additionally, the dial reading system is purely magnetic, not like that of a spring system, where values are recorded electronically by a magnetic encoder that transmits data in real time. The Chandler 7600 model is a fully automated viscometer and is coupled with a powerful data acquisition software program that can be run on almost on computer system that aids in nearly any test cycle being programmed and analyzed allowing for control over shear rate schedules, data collection, rheological model fits, display, calibration.

Table 3.7 - Chandler 7600 viscometer specifications

Sample Conditions	
Maximum Pressure	40,000 psig
Maximum Temperature	600˚F
Maximum Sample Heat-up Rate	3˚F/min
Rheology	
Shear Stress Range	5.1 – 1533 dyne/cm^2
Viscosity Range	5 cP @ 600 rpm – 300 cP @ 300 rpm
Shear Stress Resolution	0.1 degree, 5.1 dyne/cm^2, 1 cP @ 300 rpm
Shear Stress Accuracy	± 0.50% of F.S. from 51.1-1533 dyne/cm^2
Shear Rate Range	1.7 – 1533 sec^{-1} corresponding to 1 – 900 rpm
Sample Gel Strength	Peak values at 3 rpm
Couette Geometry	
Bob Radius	1.7245 cm
Rotor Radius	1.8415 cm
Bob Length	3.805 cm

This enables the user to control the rates and variations of the motor speed, temperature, and pressure at any time in the test schedule. Furthermore, the software provides a real-time digital display of the changes in dial readings, temperature, and pressure of the occurring in the fluid sample with a minimum display rate of one data point every two seconds. Along with the standard dial readings the viscometer is able to capture peak gel strength values. All data collected is exported in CSV format and easily transferable to programs such as Excel. The pressure in the test cell is maintained using an air over water system with the use of mineral oil as the hydraulic fluid. The temperature is maintained through a heater coil assembled around a thermal well allowing the test cell to easily be removed. **Fig. 3.16** shows a cross section, developed by Ibeh (2007), of the test cell that is used in the Chandler 7600. The test sample vessel assembly depicted in the figure below can be completely removed to be clean and serviced. In summary, the extensive enhancements found within the Chandler 7600 model, when compared to traditional rotational viscometers, enables the user to accurately monitor the rheological changes that occur in real-time.

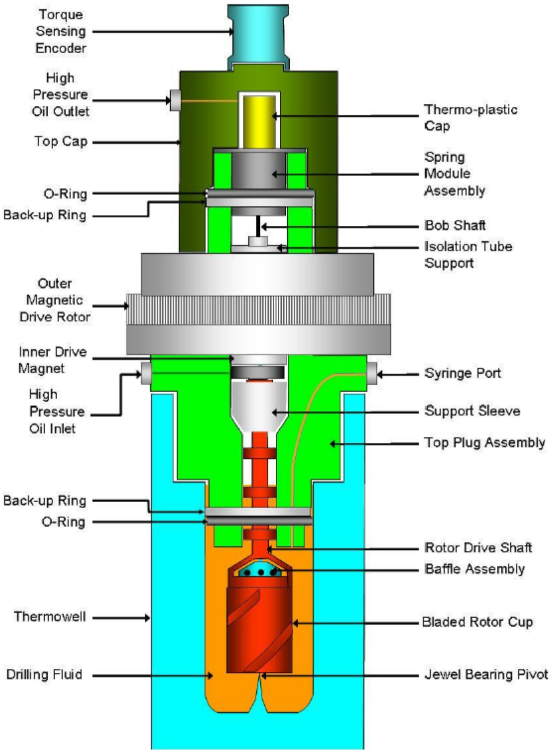


Fig. 3.16 - Test cell schematic (Ibeh 2007)

Furthermore, unlike that of traditional viscometers the 7600 model is able to produce almost any variety of operational test schedules, including controls over temperature, pressure, and rotary speed, while giving full programmable freedom to the user. Finally, the 7600 model is able to test muds at extreme conditions, including pressures, without worrying about flaws in the accuracy of data collection.

CHAPTER IV

EXPERIMENTAL PROCEDURES: SYNOPSIS & RESULTS

Testing Synopsis

To successfully asses the real time changes and absolute rheological effects that occur during and after static/dynamic aging a series of standard and experimental test procedures have been evaluated. All tests have been conducted with the same unchanged WBM formulation sample for consistency and allowing for the best-case scenario for comparing and analyzing alternate testing methods. It is generally accepted that statically aging muds is often more harsh on a mud sample relative to dynamic aging. Muds previously exposed to elevated temperatures, pressures, and shear rates tend to show better post performance than a fresh non-exposed formulated mud. Therefore static aging tests are often used to evaluate muds that have been previously used and circulated through a well. Alternatively, dynamic aging is often preferred to test the properties of a pre-exposed fresh mud. The dynamic state of the mud sample helps to prevent gelation, barite sag, and ultimately ensure that the additives of the mud are sufficiently mixed throughout the aging process so that they perform to their desired results. Therefore dynamic aging is often used to test pre- and post- exposed muds and/or to simulate aging during circulation in the hydraulic system, while static aging is often only sufficient to test post-exposed muds that are then static in the wellbore during certain drilling operations. For the purpose of this thesis dynamic aging has been conducted on pre-exposed muds while static aging will be ran on post-exposed muds. As mentioned in the previous text, muds are often dynamically aged to simulate circulation through a HT/HP well and therefore when running a static aging test, on the same mud formulation, a previously dynamic aged sample will be required to replicate a post-exposed field mud. The mud chosen, detailed in the following section, has had very few tests ran to determine when its rheological properties become unfavorable at certain conditions.

Therefore, before beginning the experimental assessment testing using the Chandler 7600 HT/HP viscometer it was necessary to determine the point at which the mud begins to exhibit unfavorable rheological characteristics after running the standardized, and industry accepted, static and dynamic aging processes. Accordingly, a series of the two standard industry aging tests, static and dynamic, have been conducted at various temperatures on a chosen WBM sample with rheological properties being taken before and after the aging process to show any possible changes of rheology due to the aging process. These tests were used for evaluation and comparison of standard static/dynamic aging and the tests following. Further details of procedures and concerns regarding the standard aging tests will be discussed in the upcoming section.

The other remaining tests were run via the Chandler 7600 HT/HP viscometer. Three tests were ran, typical of that used in industry, to evaluate the rheological properties and

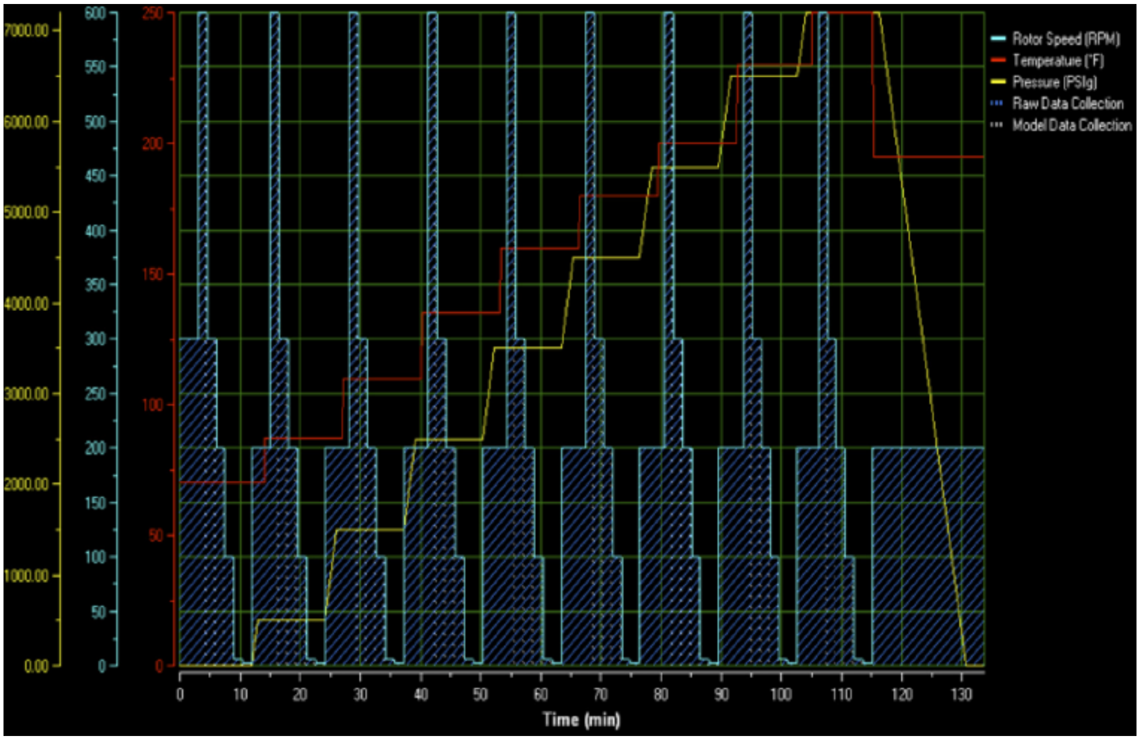


Fig. 4.1 - Typical profile of stepped test schedule

performance of the base mud, static aged mud, and dynamically aged mud at elevated temperatures and pressures. Before conducting the performance tests on the static and dynamic aged sample a baseline test was conducted using a non-aged sample of the chosen mud so that there will be a reference point to identify any differences or similarities in rheological characteristics of the WBM when running the aged experimental test schedules. The baseline test, non-aged fresh mud, follwed that of a typical stepped increase test schedule that is often used in industry to evaluate the rheological performance of drilling fluids at elevated temperatures and pressures. This type of test schedule, graphically depicted in **Fig. 4.1**, consists of an individual increase of temperature and pressure, with complete rheology sweeps, at chosen time intervals until the anticipated predetermined max temperature and pressure is reached. The temperature/pressure ramp rate and frequency of rheology sweeps is fully programmable and is at the discretion of the user. The baseline test schedule will be discussed in more detail in the upcoming section. Upon completion of the baseline HT/HP viscometer test, a performance test was run on a static and dynamic aged sample selected based on specific aging temperature. In effort to identify the performance of a post static/dynamic aged mud the same stepped test schedule was ran using the HT/HP viscometer. Two tests were conducted, using a static and dynamic aged mud that followed the standard baseline test schedule and then compared for differences. The series of standardized static and dynamic aging tests ran initially were used to determine the aging temperature, right before unfavorable rheological properties are seen, at which the performance evaluating tests will be conducted. These two tests assisted in identifying the future potential performance of an aged mud and the change in rheology that occurs after aging.

Additionally, there was a series of experimental tests run using the HT/HP viscometer that replicated the static and dynamic aging process and evaluate, in real-time, the changes in rheology during both of these standard aging tests. These tests were executed, with the inclusion of pressure, in order to replicate each aging process in effort to identify the differences in the observed rheological performance. Each test will be discussed and outlined in detail along with results and discussions in the following section.

Mud Design

The primary mud sample selected is a freshly formulated and mixed 18 ppg HT/HP mud that is commonly used in industry. A 2-gallon batch of this mud formulation was provided from a highly respected service company known throughout the world. In order to preserve their status and reputation, the quantity of each component in the formulation will be omitted. However the components that makes up the mud sample will be mentioned. This mud consists of 8 components that serve various functions for optimum performance. The WBM includes your basic drill water, caustic soda, CALOSPERSE®, CALOVIS FL®, RESINEX®, ASPHASOL SUPREME®, SAFE-CARB 20®, and EMI-1012 UF®. The drill water compromises most of the formulation and is used as the base of the WBM. Caustic soda makes up a relatively small portion of the formulation and is used to increase the pH of WBM and also helps to dissolve acidic additive compounds that are difficult to dissolve in low or neutral pH conditions. CALOSPERSE® is a thinner, consisting of a blend of polymeric and organic thinners, that is used as a deflocculant and fluid-loss additive. CALOSPERSE® improves temperature stability by reducing flocculation and gelation, is temperature stable up to 400˚F, easily soluble and disperses in all types of water, assists in reducing fluid loss, effective across a broad pH range, inhibits bentonite and/or shale hydration, and is not subject to bacterial degradation. CALOVIS FL® is a synthetic polymer additive used for fluid-loss reduction and rheological stabilizing agent and is most noticeable when exposed to higher temperatures. CALOVIS FL® is able to improve thermal stability of the entire mud system, maintain the integrity of the cuttings, helps reduce differential sticking, and stable to 400˚F. RESINEX® is a resin and lignite complex that is used as a filtration-control additive at high temperatures. RESINEX® has minimal effects on the viscosity of the mud system, resistant to contamination, improves filter cake, reduces the potential for wall-sticking, increases the efficiency of drilling in-gauge holes, and helps stabilize rheological properties. ASPHASOL SUPREME® is a shale inhibitor partially water-soluble sulfonated asphalt that helps stabilize shale sections, control solids dispersion, and improve wall-cake properties. ASPHASOL SUPREME® assists in reducing HT/HP fluid loss, swelling of shales, torque and drag, while improving filter cake quality and increasing the fluid lubricity. SAFE-CARB 20® is a acid soluble calcium carbonate that is used as a bridging and weighting agent in drilling fluids. SAFE CARB 20® minimizes formation damage, has minimal effect on fluid properties, and has high hardness ground marble that is resistant to particle-size degradation. Finally, EMI-1012 UF®, is a barite blend that is used for density adjustments. All of the quantities of the components used in this sample were strategically quantified to make up a high performance HT/HP WBM. The only rheological testing on this sample prior to running the experiments discussed in this thesis consisted of a rheology sweep at ambient temperature and pressure along with 120˚F and ambient pressure. It is commonly practiced in industry to test the rheological properties of WBMs at 120˚F and at ambient pressure. This is due to the fact that when the mud exits the whole and circulates in the pits it rarely reaches ambient temperatures and therefore the rheology at temperatures greater than 100˚F are of concern.

Table 4.1 - Base fluid rheological properties at ambient pressures

Fann Readings	Units	T_{AMB}	120 ˚F
600 rpm	lb/100 ft^2	130	74
300 rpm	lb/100 ft^2	68	38
200 rpm	lb/100 ft^2	47	27
100 rpm	lb/100 ft^2	25	16
6 rpm	lb/100 ft^2	4	4
3 rpm	lb/100 ft^2	3	3
PV	cP	62	35
YP	lb/100 ft^2	6	3
10-sec Gel	lb/100 ft^2	5	7
10-min Gel	lb/100 ft^2	27	28

All of these rheology sweeps, and the ones to be followed in this thesis, were performed with a standard Fann 35 Viscometer with an attached thermo cup to reach 120˚F. **Table 4.1** details the fluid properties at ambient temperature and 120˚F of the 18 ppg HT/HP WBM formulation to be used. Due to increase of temperature, rheological thinning occurs and it can be seen that as the temperature increases to 120˚F the fluid shows acceptable rheology. These readings were used to compare with the upcoming standardized and experimental tests.

Procedural Outlines

The following sub sections will be used to clarify the procedures that will be conducted for this thesis and justify the reasoning behind their technical construction. Three basic tests were ran that include: standard industry static and dynamic aging methods, industry accepted performance tests using a HT/HP viscometer, and experimental static and dynamic aging tests using a HT/HP viscometer.

Standard Static and Dynamic Aging

In order to fully evaluate the rheological characteristics during the aging process of the 18 ppg WBM a series of industry standard static and dynamic aging tests were ran at various increasing temperatures. The static and dynamic testing procedures that follow were conducted as close as possible to the static and dynamic test procedures that are currently conducted in industry. For the sake of simplification, testing frequency, and consistent analysis all aging tests were run for the minimum recommended time given by API 13I of 16 hours long. Although 16 hours is the minimum, longer times are often analyzed in industry and should be considered for future testing and evaluation. Current industry aging test consist of aging a fluid, statically or dynamically, at predetermined increments of temperature until the fluid exhibits unacceptable rheological properties. For the purpose of this thesis the testing procedure will consist of a series of aging tests that are spaced 50˚F in an ascending format. As discussed previously, the rheological properties of WBMs are almost always conducted at or near 120˚F and ambient pressures. Therefore, before and after every aging test the rheological properties of the fluid were evaluated at 120˚F and ambient pressure. All the testing of fluids was conducted using a Fann 35 viscometer with an attached thermo cup to reach the desired 120˚F temperature. After the aging process has been completed it is conventional to mix the fluid sample for a constant and consistent predetermined time. Mixing after dynamic aging is used to replicate the shears experienced during circulation in the hydraulic system and to breakdown any thermal degradation that might have occurred to the fluid additives. In the case of static aging, mixing is used only to breakdown any thermal degradation that occurs. This brings to question if mixing the fluid after static aging enhances the fluids rheological properties when compared to a sample that has not been mixed. Furthermore, when a fluid is down hole and static for an extended period of time the amount of shear experienced is minimal relatively to a circulating fluid. Therefore, the rheological changes that are recorded after static aging has been completed consists of the results after mixing. **Table 4.2** details the testing outline that will be used during static and dynamic aging analysis and evaluation of the 18 ppg WBM.

Table 4.2 - Standard aging schedule

Test	16 hr Aging Temperture			
Static Aging	300 ˚F	350 ˚F	400 ˚F	450 ˚F
Dynamic Aging				

As mentioned at the beginning of this chapter, muds that are statically aged are usually pre-exposed to circulation through the hydraulic system of a well. In order to have consistent and precise comparable results, every static aging test was run on a 300 ˚F post-dynamically aged 18 ppg sample.

Before starting either aging method the sample was mixed at a high and constant shear rate and then rheological properties were recorded at 120 ˚F and ambient pressure. The mixer used to conduct all of the experiments was consistently set at 8,000 rpms during the mixing before or after all aging tests. Before either aging process, dynamic or static, the sample was mixed for 10 minutes before being pressurized in a cell. Therefore, Dynamic tests consisted of mixing the fresh non-aged mud whereas the static tests consisted of mixing a 300˚ F Dynamically aged sample. After sufficient mixing was achieved the sample was placed in a thermo cup, heated to 120 ˚F, and the rheological properties were recorded. Upon completion of mixing and recording their respective rheological properties at 120 ˚F each sample was placed in a test cell and pressurized. Each aging test was conducted using a 300 ml fluid sample and all tests were conducted using a 500 ml type 316 stainless steel test cell rated to 450 ˚F. All tests conducted at 300˚F and below were pressurized to 100 psi via a compressed nitrogen tank. Alternatively, all tests conducted above 300 ˚F were pressurized to 300 psi via a compressed nitrogen tank. The pressurization process relative to the aging temperature is justified based on information collected from the processes used in industry. The samples were then placed into a standard aging oven following the pressurization of the test cell. The oven used was able to achieve and hold temperatures up to 500˚F and is also equipped with rollers to dynamically age fluids. The oven was turned on and set to the desired temperature an hour before preparation of the samples and test cells to provide adequate time to reach and stabilize at the desired temperature.

Table 4.3 - Standard aging procedure summary

Static Aging	Dynamic Aging
• Turn on oven and set aging temperature (1 hour before preparation of sample and test cell)	• Turn on oven and set aging temperature (1 hour before preparation of sample and test cell)
• Acquire a 300 ml, 16 hr (300 ˚F) dynamic aged, sample	• Acquire a 300 ml sample of fresh non-aged mud
• Mix sample at 8,000 rpms for 10 minutes	• Mix sample at 8,000 rpms for 10 minutes
• Heat sample in thermo cup and stir until temperature reaches 120˚ F	• Heat sample in thermo cup and stir until temperature reaches 120˚ F
• Record rheological properties of sample using the Fann 35 Viscometer	• Record rheological properties of sample using the Fann 35 Viscometer
• Pour fluid into 500 ml test cell (type 316 Stainless Steel)	• Pour fluid into 500 ml test cell (type 316 Stainless Steel)
• Pressurize cell with nitrogen (@100 psi for < 300 ˚F; @300 psi for > 300 ˚F)	• Pressurize cell with nitrogen (@100 psi for < 300 ˚F; @300 psi for > 300 ˚F)
• Place cell static in an upright position in the oven	• Lay cell on top of rollers in the oven
• Allow test cell with sample to Age for 16 hr	• Allow test cell with sample to Age for 16 hr
• Take cell out of oven and cool in water for 10 minutes	• Take cell out of oven and cool in water for 10 minutes
• Depressurize cell	• Depressurize cell
• Mix sample at 8,000 rpms for 10 minutes	• Mix sample at 8,000 rpms for 1 0 minutes
• Heat sample in thermo cup and stir until temperature reaches 120˚ F	• Heat sample in thermo cup and stir until temperature reaches 120˚ F
• Record rheological properties of sample using the Fann 35 Viscometer	• Record rheological properties of sample using the Fann 35 Viscometer

When dynamically aging samples, the test cells where placed on their sides on top of rollers that allow the fluid to mix during the entire testing process whereas during static aging the test cells were simply placed up right and allowed to sit for the entire test. Upon completion of each aging test the cells were removed and placed in tub of water for 10 minutes in order to cool down for safe handling when they were then depressurized. After each cell was depressurized the fluid sample was mixed using the same mixer set at 8,000 rpms. All static and dynamically aged samples were mixed for 10 minutes after the aging process was complete. After sufficient mixing was achieved the samples were placed in the thermo cup, heated to 120 ˚F, and the rheological properties were recorded. **Table 4.3** summarizes the procedures for both the static and dynamic aging tests that were conducted for this thesis.

HT/HP Viscometer Performance Testing

Following the completion of the standard aging test a sample for each test, dynamic and static, a sample was chosen at a certain temperature and subjected to a performance test using the HT/HP viscometer. The temperature was chosen after identifying the point at which the fluid sample begins to exhibit unfavorable rheological characteristics upon completion of the chosen aging method. Thus, the temperature was chosen as the one before the temperature at which the fluid is deemed unfavorable based on the rheological properties recorded. The performance test was used to show how the fluid will perform for future use in the hydraulic system after a certain aging length and temperature. Therefore, a performance test was ran on a static and dynamic sample to assess their performance after aging for 16 hr. The performance test resembles tests ran in industry using HT/HP viscometers to asses a fluids characteristics for analysis and use in hydraulic simulation programs. In order to ensure accurate analysis and comparison of the performance results, a baseline performance test was conducted. The baseline test was performed on a fresh sample of the 18 ppg WBM. The baseline performance test, static aging performance test and the dynamic aging performance test follow the same test schedule in order to have accurate and consistent results. **Table 4.4** and **Fig. 4.2** outline the technical aspects of

Table 4.4 - Performance test schedule

Performance Test Schedule													
Stage at Which Rheological Properties Are Recorded													
Temperature (˚F)	75	120	150	150	250	250	350	350	450	450	500	500	550
Pressure (ksi)	0.015	0.015	0.015	10	10	15	15	20	20	30	30	35	35
Performance Timeline →													

the performance test schedule. Before each test was conducted, the mud sample follows the same procedure as that of the standard aging tests and is mixed, 10 minutes for static and 10 minutes for dynamic, then heated to 120 ˚F with a thermo cup and its rheological were recorded for comparison to validate the readings being taken during the HT/HP viscometer performance test.

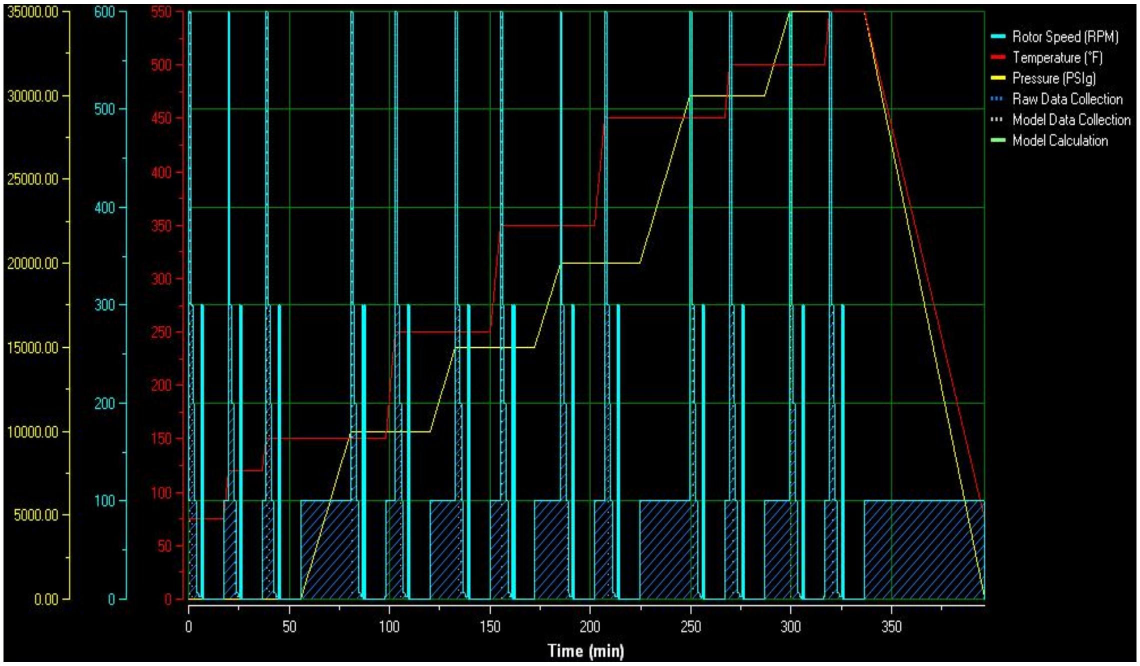


Fig. 4.2 - Performance test schedule profile

The test schedule was created to rapidly record the rheological properties at various temperature and pressure conditions. Due to the fact that every well has different temperature and pressure gradients it is nearly impossible to replicate all possible conditions with one schedule. The conditions for this test schedule were chosen to match temperature and pressures in order to represent most accurate conditions in an artificial well bore. For future testing, if a wells temperature and pressure gradient are known the test schedule can easily be revised and corrected for accurate matching. The first portion of this test does not include the artificial well conditions, but is used as a tool for verifying the accuracy of the readings being taken by the HT/HP viscometer. Subsequently, at each temperature and pressure match point a complete rheology sweep is taken that includes dial readings, plastic viscosity, yield point, 10-second gel strength, and 10-minute gel strengths.

Experimental Static and Dynamic Aging

Upon completion of conducting the industry standard aging tests and their respective HT/HP viscometer performance tests a set of experimental static and dynamic aging tests were performed using the HT/HP viscometer. These tests attempt to simulate, as closely as possible, the processes that occur during the industry static and dynamic aging tests. Additionally, the tests included the effects of pressure to replicate actual down hole conditions. The test also allows the user to evaluate the rheological property changes in real time during a particular aging process.

In the case of the static aging process, the experimental test were run on a 300 ˚F, 16hr long, dynamically aged fresh mud in order to keep consistency with the standard industry static aging tests performed initially. The test were also conducted for the predetermined minimum aging length of 16 hours as preformed on the standard aging test. **Table 4.5** and **Fig. 4.3** outline the technical aspects of the HT/HP viscometer static

Table 4.5 – Experimental static aging schedule

HT/HP Viscometer Static Aging

Points at which rheological properties are recorded

Time, (hr)	…	2	…	4	…	6	…	8	…	10	…	12	…	14	…	16
Rotor speed, (rpm)	0	RS	0	RS	0	RS	0	RS	0	RS	0	RS	0	RS	0	RS
Temperature (˚F)	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c
Pressure (psi)	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c

Static Aging Timeline →

aging test schedule. As this is supposed replicate as closely as possible to a standard static aging test the mud should experience minimal amount of shear during the aging process. In order to minimize the amount of shear experienced there will only be eight points at which the rheological properties will be recorded. Furthermore, each rheological sweep (RS) only imparted shear on the fluid for approximately 4 minutes. During the entire 16 hour aging period the fluid only experienced shear for a total of 32 minutes, approximately 3.3 % of the aging process. These shears were justified by the fact that after the standard industry aging test the fluid is subjected to very high shears, sometimes exceeding 10,000 rpms, for a period of ten or more minutes in order to break down thermal degradation to enhance and improve the fluids rheological properties. For the purpose of this

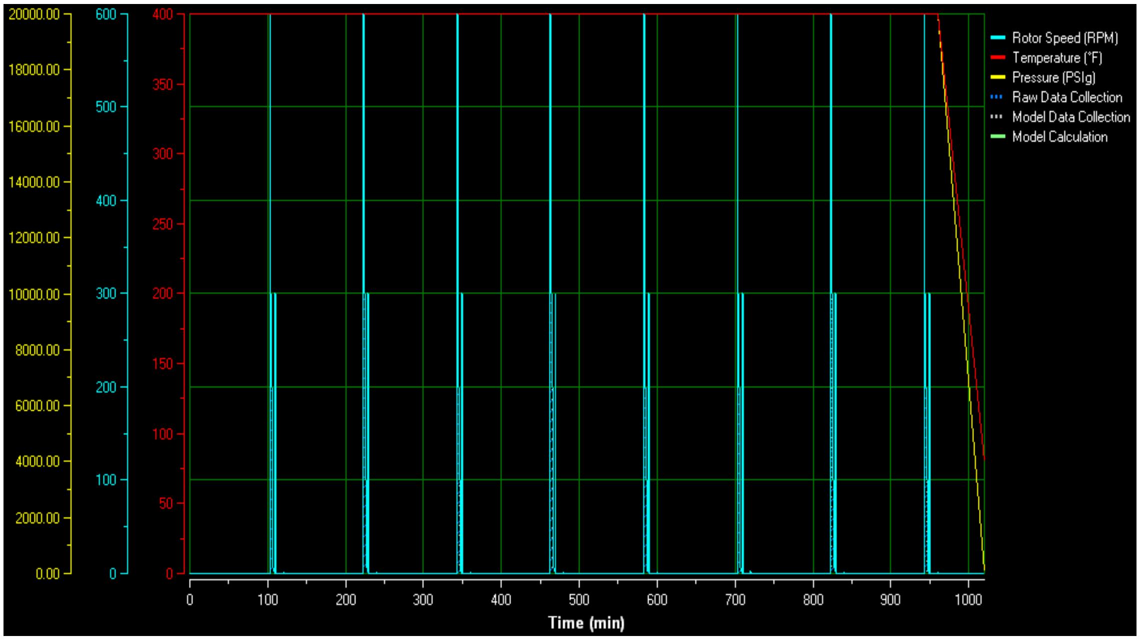


Fig. 4.3 - Experimental static aging profile

thesis, and based on average times used in industry, the mixing was only performed for 10 minutes but at relatively high shears, 8,000 rpms. During the experimental test the shears experienced never exceed 600 rpms at a maximum time of 30 seconds, with very low shears, all the other times during rheology recording, relative to those used to mix the fluid sample after standard aging processes. Furthermore, when a mud is assumed static in the wellbore during bit trips and other drilling operations it is still subjected to small shears due to small fluctuations of fluid movement. The rest of the experimental static aging test, 97.6 % of the aging process, the rotor speed was set to zero rpms and the fluid is truly static. During each rheology sweep (RS) the dial readings, plastic viscosity, yield point, 10-second gel strength, and 10-minute gel strength were recorded. Additionally, the temperature and pressure remained constant during the entire static aging test. The constant temperature (T_c) was chosen based on the industry standard static aging tests conducted. For comparison and analyses, the temperature chosen was the same as that of the static aging test that begin to show unfavorable rheological properties. Alternatively, the constant pressure (P_c) was chosen with respect to the temperature pressure matching used in the HT/HP viscometer performance test.

Subsequently, the experimental dynamic aging test was conducted on a fresh non-aged sample of the 18 ppg WBM in effort to stay consistent with the industry standard dynamic aging test conducted and enhance analysis of the rheological changes on the

Table 4.6 - Experimental dynamic aging schedule

HT/HP Viscometer Dynamic Aging

Points at which rheological properties are recorded

Time, (hr)	…	2	…	4	…	6	…	8	…	10	…	12	…	14	…	16
Rotor speed, (rpm)	50	RS	50	RS	50	RS	50	RS	50	RS	50	RS	50	RS	50	RS
Temperature (˚F)	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c	T_c
Pressure (psi)	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c	P_c

Dynamic Aging Timeline →

fluid. The experimental dynamic aging test was also be conducted for the minimum aging length of 16 hours as preformed on the standard dynamic aging test. **Table 4.6** and **Fig. 4.4** outline the technical aspects of the HT/HP viscometer dynamic aging test schedule. As this is supposed replicate as closely as possible to a standard dynamic aging test the mud should experience a constant low shear during the aging process. The rollers on the oven used during the standard dynamic aging tests rotated at a constant 50 rpms. Therefore, whenever rheological sweeps are not occurring the mud was subjected to a constant shear of 50 rpms via the HT/HP viscometer.

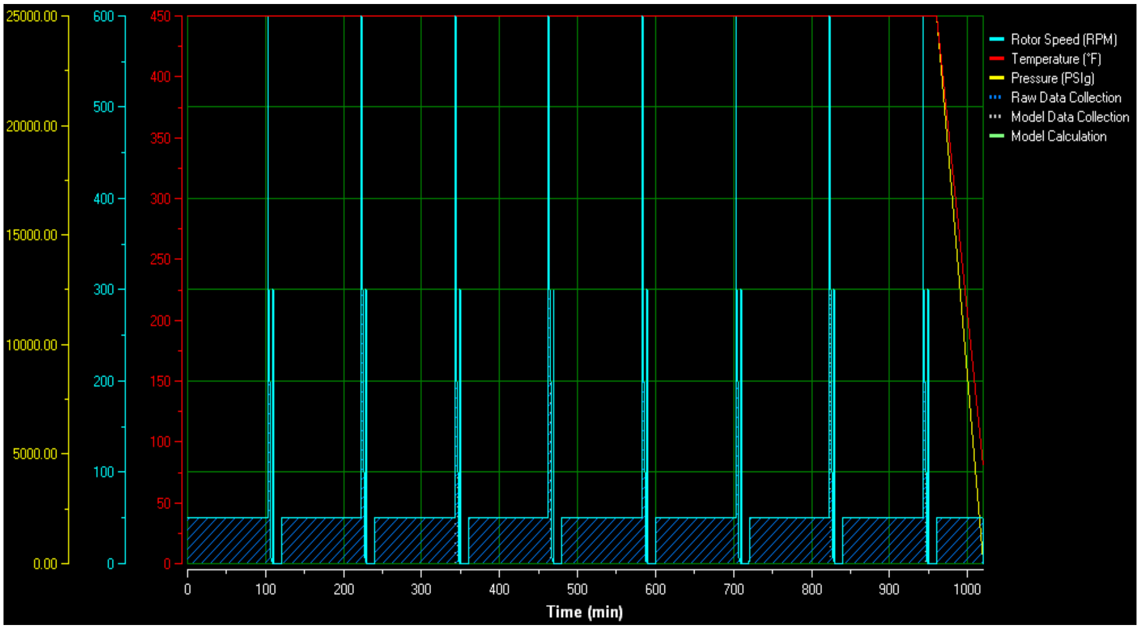


Fig. 4.4 - Experimental dynamic aging profile

The test schedule will be similar to that of the experimental static aging test in that there will only be eight points at which the rheological properties will be recorded. During each rheology sweep (RS) the dial readings, plastic viscosity, yield point, 10 second gel strength, and 10 minute gel strength were recorded. Additionally, the temperature and pressure remained constant during the entire dynamic aging test. The constant temperature (T_c) was chosen based on the industry standard dynamic aging tests conducted. For comparison and analyses, the temperature chosen was the same as that of the dynamic aging test that begin to show unfavorable rheological properties. Alternatively, the constant pressure (P_c) was chosen with respect to the temperature pressure matching used in the HT/HP viscometer performance test. Due to the fact that dynamic aging test are supposed to simulate circulation through the well, a more accurate dynamic aging test would simulate the cyclical changes of temperature and pressure based on a particular temperature and pressure gradient of the well. This type of test was unable to be performed due to the lack of a cooling jacket that attaches to the HT/HP viscometer and allows for rapid cooling of the fluid. These types of tests, along with a test schedule, will be discussed in the recommendations section of this thesis for future testing and research. As of now, the experimental dynamic aging test aim to serve as an alternative method for dynamic aging by enabling real time data collection while allowing for the inclusion of pressure.

For both the experimental static and experimental dynamic aging tests the fluid samples were prepared in the same fashion as the standard aging tests. Therefore, before conducting the experimental static aging test a 300˚F (16 hr) dynamically aged sample was mixed for 10 minutes and then its rheological properties will be recorded at 120 ˚F via a thermo cup and the Fann 35 viscometer. Alternatively, before conducting the experimental dynamic aging test a fresh non-aged sample mud was mixed for 10 minutes and then its rheological properties will be recorded at 120 ˚F via a thermo cup and the Fann 35 viscometer.

Testing Results

The following sub sections will detail the results collected during testing along with analytical interpretations used to accurately discuss the correct meaning of the data. In to evaluate and determine if a fluid is exhibiting unfavorable rheological characteristics a “failure” needs to be defined. After researching industry evaluation techniques it was concluded that a fluid begins to exhibit unfavorable rheological characteristics when it begins to exhibit a relatively erratic or extreme noticeable change in rheological properties with respect to its initial properties. Three test results being discussed include: standard industry static and dynamic aging methods, industry accepted performance tests using a HT/HP viscometer, and experimental static and dynamic aging tests using a HT/HP viscometer. All tests point to an exceptionally high performance limit of the HT/HP WBM formulation being tested.

Standard Aging Results

Standard dynamic and static aging was conducted on the 18 ppg WBM formulation reviewed previously before running experimental procedures with the HT/HP viscometer and to assess the rheological characteristics as currently done in industry based on standards set by the API recommended practices for laboratory testing of drilling fluids. Four 16 hour dynamic aging tests were conducted in the procedural manner as detailed in Table 4.3 at 300 ˚F, 350 ˚F, 400 ˚F, and 450 ˚F. All samples were evaluated with the Fann 35 viscometer at 120 ˚F and ambient temperature. The standard dynamic aging tests had a temperature limit of 450 ˚F as a result of the aging cells being rated and reliable only up to 450 ˚F. Additionally, a rheological analysis was conducted on the fresh non-aged sample at 120 ˚F and ambient pressure for comparison against the results achieved during the dynamic aging tests. **Table B-1**, available in appendix B, details the raw data obtained during the standard dynamic aging tests and **Fig. 4.5** illustrates a graphical representation of the dynamic aging data. Fig. 4.5 displays a plot of dial reading vs. temperature for the standard rotor speeds and aids in showing the progression of rheological properties as the aging temperature increases. The results obtained substantiate the design of the 18 ppg WBM formulated to have high performance and the ability to perform well under ultra to extreme high temperature conditions.

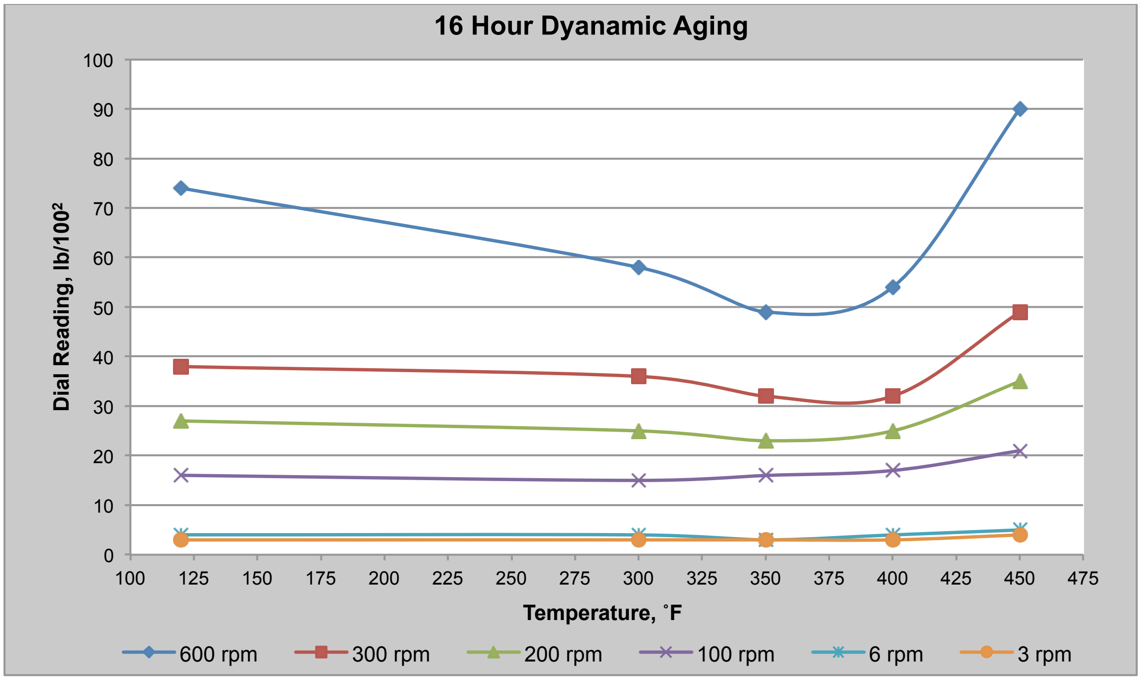


Fig. 4.5 - Dynamic aging (dial reading vs. temperature)

As the aging temperature increases form 300 ˚F to 400 ˚F the mud exhibits temperature thinning. The thinning most likely arises due to deflocculation and/or aggregation of the particles in the mud as well as a result of the specific additives in the 18 ppg mud that promote thinning at higher temperatures. The mud begins to exhibit thickening, known as thermal gelation, after temperatures exceed 400 ˚F with a substantial increase in rheological properties at 450˚ F.

This trend reversal is a result of thermal degradation of organic additives used in the mud and in turn flocculation and dispersion of the mud particles. It is theorized that the mud will continue to exhibit increased rheological properties at higher aging temperatures. This mud is therefore, based on standard dynamic aging tests, determined to be adequate for circulation in a hydraulic program for 16 hours at aging temperatures up to 400 ˚F and possibly 450˚ F depending on the well and drilling program requirements with the possibility for more circulation time if the mud can be treated to re-establish its original rheological characteristics.

In addition to the dynamic aging tests, a series of standard static aging tests were conducted in the same procedural manner as that of the dynamic aging tests. Alternatively, the static aging tests were conducted on a fresh 18 ppg mud sample that has been dynamically aged at 300 ˚F for 16 hours, as discussed previously, to replicate the conditions experienced of a mud that has been previously subjected to circulations in the hydraulic system. As with the dynamic aging tests, Four 16 hour dynamic aging tests were conducted in the procedural manner as detailed in table 4.3 at 300 ˚F, 350 ˚F, 400 ˚F, and 450 ˚F. All samples were evaluated with the Fann 35 viscometer at 120 ˚F and ambient temperature Furthermore, the standard static aging tests also had a temperature limit, as that of the dynamic aging tests, of 450 ˚F as a result of the aging cells being rated and reliable only up to 450 ˚F.

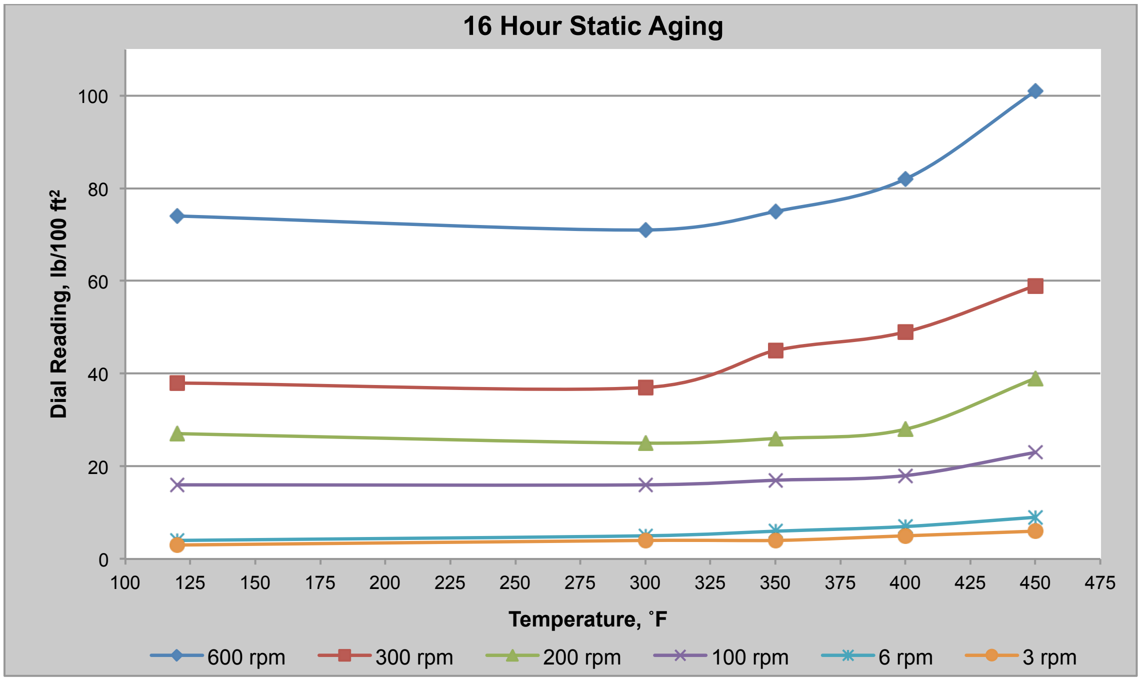


Fig. 4.6 - Static aging (dial reading vs. temperature)

Table B-2, available in appendix B, details the raw data obtained during the standard dynamic aging tests and **Fig. 4.6** illustrates a graphical representation of the static aging data. Like that of the dynamic aging plot, this figure displays a plot of dial reading vs. temperature for the standard rotor speeds. In comparison to the dynamic aging tests, the static aging results also show that the mud exhibits favorable rheological characteristics from 300 ˚F to 400 ˚F. Alternatively, as the mud is subjected to increasing aging temperatures it does not exhibit the temperature thinning experienced in the dynamic aging tests. The lack of thinning is indicative of fluid degradation experienced during dynamic aging, without post treatments, prior to the static aging to replicate a mud that has been previously circulated. Despite the progression of degradation the fluid experienced, it was able to show acceptable performance until aging temperatures reached 450 ˚F where it then begin to display unfavorable changes in rheological characteristics due to further fluid degradation and thermal gelation most likely due to flocculation and dispersion. Likewise, This mud is therefore, based on standard dynamic aging tests, without treatments, determined to be adequate in a well statically for 16 hours at aging temperatures up to 400 ˚F and possibly 450˚ F depending on the well and drilling program requirements. Even though this mud was determined, based on industry used aging techniques, it is possible that the mud began to show unfavorable characteristics at lower aging temperatures. The industry standard of mixing the mud for a predetermined time after the static aging process most likely enhances the fluids rheology by breaking down thermal gelation experienced during the aging process. These issues will be addressed in the following experiments to evaluate the effects of mixing as well as the addition of high pressures.

HT/HP Viscometer Performance Results

Up to now the 18 ppg WBM has been evaluated based on standard industry aging techniques. Before conducting experimental aging procedures with HT/HP viscometer a set of tests were run on post-aged muds. These tests were run to evaluate the post aged rheological performance of the 18 ppg mud sample and all the tests conducted followed the same test schedule outlined in table 4.4. Likewise, before each test was conducted the mud samples rheological properties were evaluated at 120 °F and ambient pressures in order to validate the readings taken by the chandler 7600 HT/HP viscometer during the performance tests. The physics of heat distribution from the heater and the mud sample on the 7600 viscometer make it nearly impossible to predict the mud will truly achieve the set temperature. Therefore, the readings taken by the 7600 viscometer that were closest to 120 °F where then compared to those taken by the Fann 35 viscometer.

Firstly, In efforts to have a base rheological comparison, for the post performance of a static and dynamic aged mud, a pre performance test was ran on a fresh non-aged 18 ppg WBM sample. **Table 4.7** details the rheological comparison of the two instruments. The 7600 viscometer reading was taken at 135 °F and show a slight decrease in the dial readings when compared to that of the Fann 35 viscometer. These decreased readings are due to the small increase in temperature and the subsequent result of temperature thinning experienced by the fluid sample. Thus, the dial readings taken by the 7600 viscometer would converge to the readings taken by the Fann 35 as the temperature decreased and are therefore deemed accurate and valid. **Fig. 4.7** illustrates the rheological changes that occurred during the baseline performance test

Table 4.7 - Non-aged rheology comparison

Rotor Speed, rpm	Fann 35 (120 °F)	Chandler 7600 (135 °F)
600	74	68
300	38	35
200	27	24
100	16	13
6	4	2
3	3	1

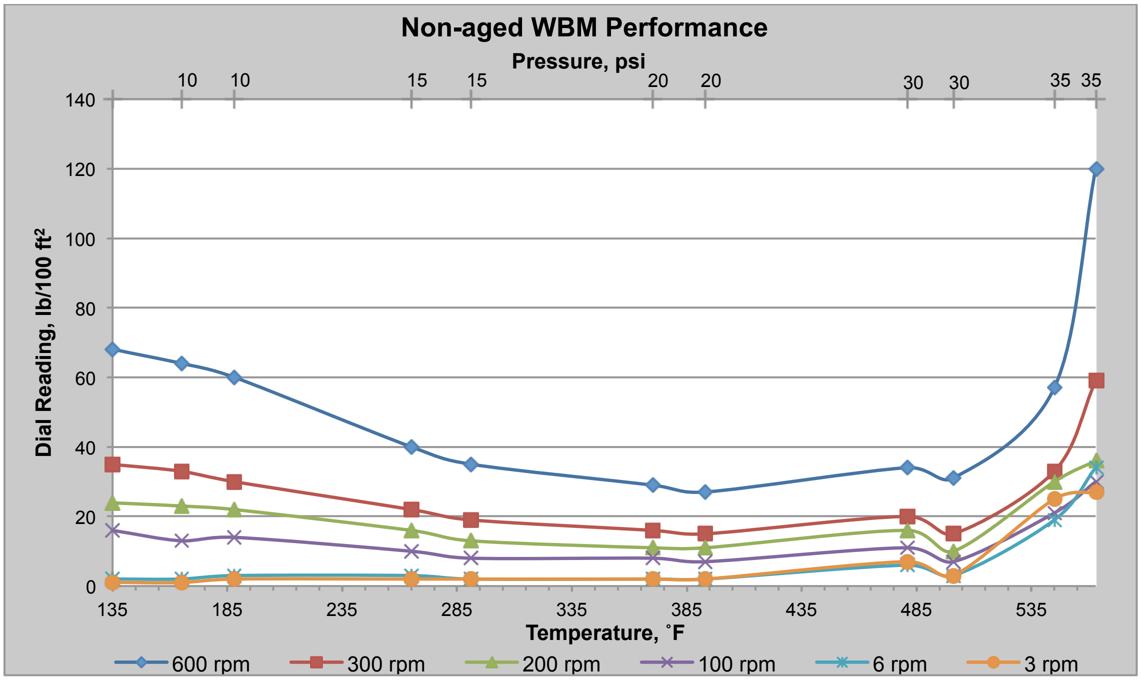


Fig. 4.7 - Non-aged performance (dial reading vs. temperature/pressure)

schedule conducted on the fresh non-aged 18 ppg WBM sample. **Fig. A-1** and **Table B-3** illustrates and details the real-time data obtained during the test. It can be seen that as the temperature and pressure increases the fluids rheological properties begin show a decreasing trend until it reaches temperatures greater than 500 °F. The decrease in dial readings are indicative of temperature thinning and are affected little by the increase in pressure. Furthermore, certain fluid additives designed to thin the fluid as temperatures increase achieve thinning. Once the temperature begins to exceed 500 °F the data shows a trend reversal and the fluids rheological properties are increased until complete failure occurs. This is indicative of thermal gelation as well as flocculation and dispersion of the fluids particles until the fluid fails completely due to thermal degradation of the fluids additives. **Fig. 4.8** shows the resulting failed fluid sample after the test schedule was complete. The results obtained are indicative of a strong performing HT/HP WBM mud formulation.

Fig. 4.8 - Failed fluid sample

Following the baseline test performed on the non-aged fluid sample, two tests were conducted on post-aged fluid samples. A performance test was conducted on both a 16-hour dynamic and 16-hour static aged fluid sample. The samples were chosen based on the standard aging results obtained and selected at the temperature before the fluids begin to show trend reversal in rheological characteristics. For the dynamic aged performance test, a 400 °F post dynamic aged fresh 18 ppg WBM sample was chosen based on the results and conclusions obtained previously from the standard dynamic aging tests. **Table 4.8** details the comparison of dial readings

Table 4.8 - 400 °F dynamic aged rheology comparison

Rotor Speed, rpm	Fann 35 (120 °F)	Chandler 7600 (135 °F)
600	55	57
300	33	37
200	25	26
100	14	17
6	3	4
3	2	3

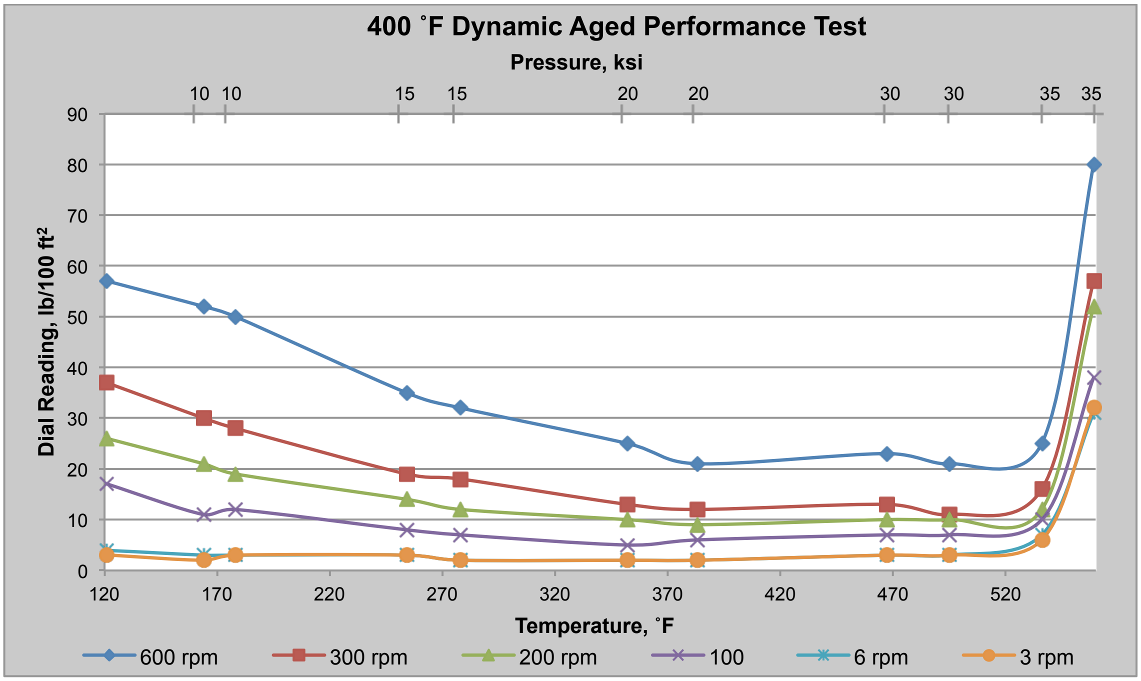


Fig. 4.9 - 400 ˚F dynamic aged performance (dial reading vs. temperature/pressure)

recorded by the Fann 35 viscometer and the 7600 viscometer. For this test, the 7600 dial readings were recorded at 121 °F and show a very close agreement with those taken by the Fann 35. This confirms the validation of this test and furthermore that of the baseline test schedule when the dial readings were taken at 135 °F. **Fig. 4.9** illustrates the rheological changes that occurred during the performance test schedule when conducted on the 400 °F post dynamic aged fresh 18 ppg WBM sample. **Fig. A-2** and **Table B-4** illustrate and detail the real-time data obtained during the dynamic performance test. The results show the same rheological characteristics that were seen with the base line schedule in which the fluid thins and dial readings decrease as the temperature increases. Alternatively, the fluid displays thinning only up to 450 °F when the fluids rheological characteristics show a trend reversal and begin to increase as temperatures exceed 450 °F. These results suggest that when a fluid experiences time to age dynamically its rheological performance is thereby significantly reduced. This is likely due to thermal degradation experienced during the dynamic aging process. In the case of static aged performance test, a 350 °F post static aged sample was chosen based on the results and conclusions obtained previously from the standard static aging tests. As mentioned previously, the static aging was conducted on a WBM sample that was previously dynamic aged for 16 hours at 300 °F in order to replicate a mud that was previously subjected to circulations. **Table 4.9** details the comparison of dial readings recorded by the Fann 35 viscometer and the 7600 viscometer. For this test, the 7600 dial readings were taken at 125 °F and show a close comparison with those taken by the Fann 35. As discussed earlier, with a reduction in temperature the readings taken by the 7600 viscometer will converge to those taken

Table 4.9 - 350 °F static aged rheology comparison

Rotor Speed, rpm	Fann 35 (120 °F)	Chandler 7600 (125 °F)
600	73	70
300	39	34
200	27	24
100	17	18
6	5	4
3	4	3

by the Fann 35. Therefore, these readings are deemed accurate and valid for analysis. **Fig. 4.10** illustrates the rheological changes that occurred during the performance test schedule when conducted on the 350 °F post static aged sample. **Fig. A-3** and **Table B-5** illustrate and detail the real-time data obtained during the static performance test. The results obtained show the same rheological characteristics that were seen with the previous two performance tests in which the fluid thins and dial readings decrease as the temperature increases. As with the dynamic performance test, the fluid displays thinning only up to 450 °F when the fluids rheological characteristics show a trend reversal and begin to increase as temperatures exceed 450 °F.

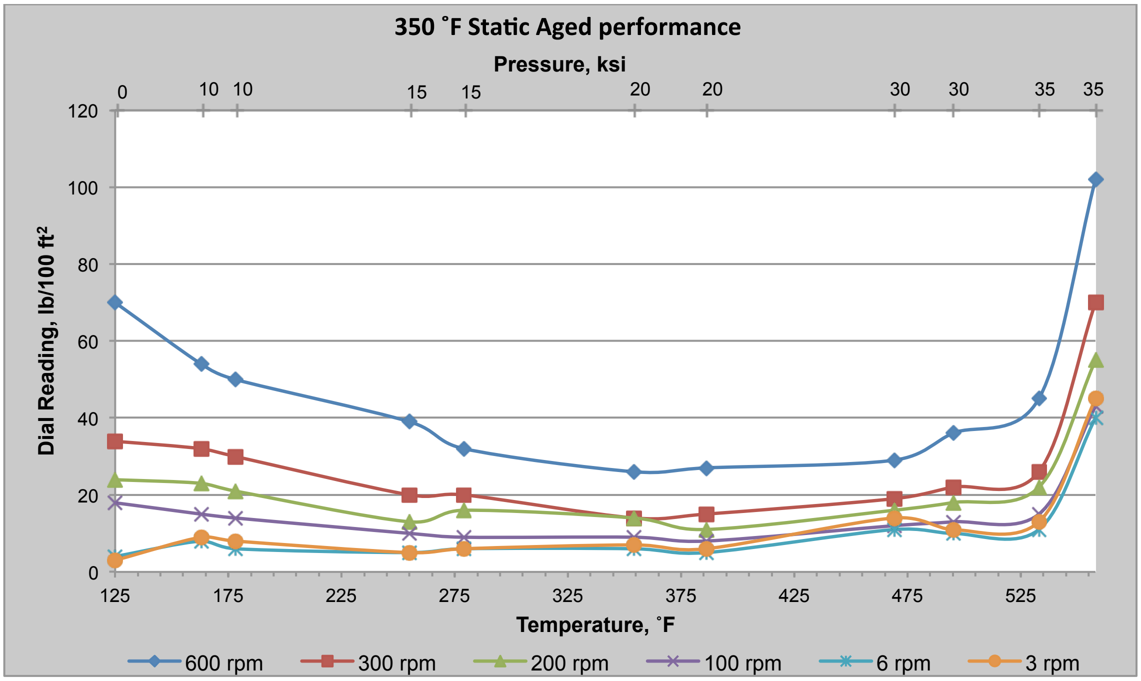


Fig. 4.10 - 350 ˚F static aged performance (dial reading vs. temperature/pressure)

The results achieved during the standard static aging tests suggest that the mud is adequate up to 400 °F. Due to limits on mud availability a test was only able to be conducted on a 350 °F static aged sample. Nevertheless, the performance test conducted on a 350 °F static aged sample showed a decrease in rheological performance comparable to that of a 400 °F dynamically aged sample. Understanding, based on conventional wisdom, that static aging is harsher on a fluid samples the results indicate that if a performance test were conducted on a 400 °F static aged sample that the reduction in rheological performance would be greater than that of a 350 °F static aged sample. Therefore these results suggest that when a fluid experiences time to age statically its rheological performance is thereby significantly reduced when compared to a dynamically aged sample at the same conditions and even more when compared to a non-aged sample of the same mud formulation.

Experimental Aging Results

Up until now, thorough testing was conducted on the 18 ppg WBM formulation using standard industry techniques to evaluate the rheological characteristics after static and dynamic aging including HT/HP performance evaluations. The following experimental tests were run with the 7600 viscometer in order to offer an alternative test method for aging that gives the user the ability to view real-time rheological changes. Furthermore, these tests methods are able to include the effects of increasing pressures. Experimental static and dynamic aging were conducted based on the procedures outlined in Table 4.5 and Table 4.6.

Static and dynamic aging tests were conducted at the minimum standard length of 16 hours. The temperature at which they were tested was chosen based on the conclusions made from the standard static and dynamic tests. Furthermore, the results obtained by the 7600 viscometer were validated at ambient temperature and pressure before each test using the Fann 35 and then comparing the results to those obtained manually by the 7600 viscometer before the test was started. The rheology had to be taken at ambient temperature and pressure due to the fact that the test schedules did not operate any where near 120 °F and ambient pressure. All results obtained before each test by the Fann 35 had a strong agreement with those taken by the 7600 viscometer with a variance of ± 2 %, and thus ensuring validity of the experimental results.

All static aging was conducted on a post 16 hour dynamic aged sample of the 18 ppg WBM. The standard static aging results concluded that the fluid was adequate after static aging at 400 °F and possibly 450 °F. Therefore, the first experimental static aging test was conducted at a constant temperature of 400 °F. Additionally, the fluid was subjected at a constant pressure of 20 ksi. **Fig. 4.11** illustrates the results obtained for the experimental static aging test conducted for 16 hours at 400 °F and 20 ksi. The real time data is available in **Fig. A-4** and **Table B-6**. The data obtained clearly show that the fluid is able to retain its rheological properties during the entire static aging test and therefore confirm that he fluid is stable after static aging occurs at 400 °F and 20 ksi. It should be noted that the test shows a significant drop in rheology when compared to the rheology taken at 120 °F only as a resultant of the thinning that occurs at high temperatures.

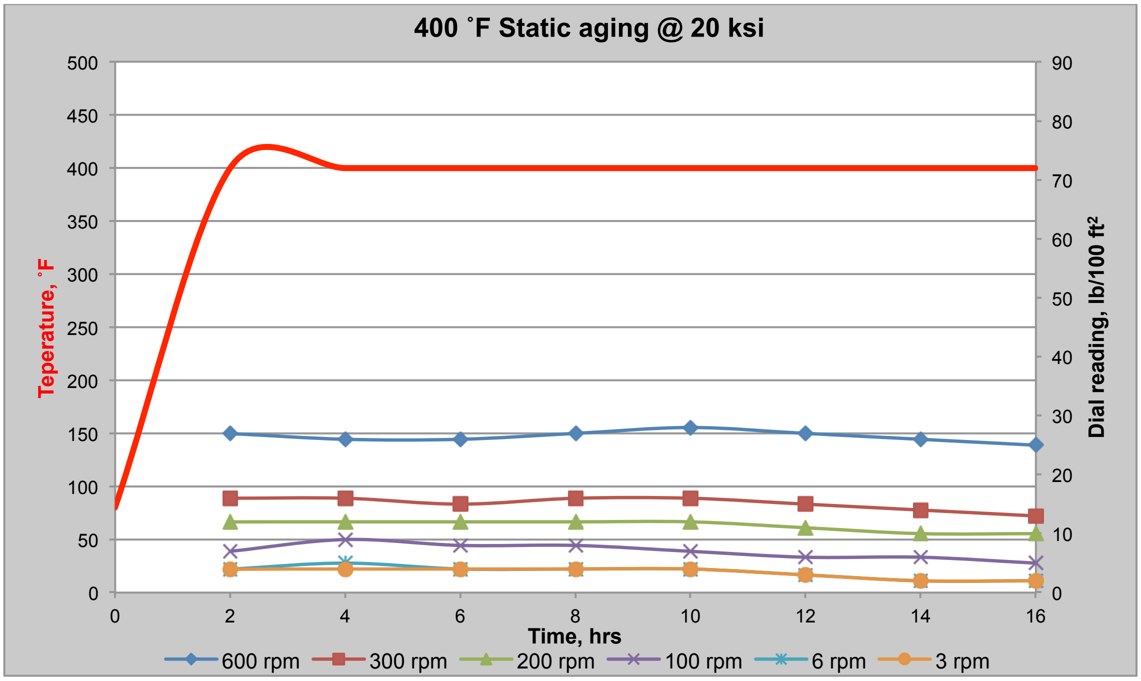


Fig. 4.11 - 400 ˚F static aging at 20 ksi (dial reading/temperature vs. time)

The drop in rheology should not be mistaken as an erratic change or failure of the fluid. Furthermore, unlike the results obtained during the standard static aging results, the experimental static aging readings give a true picture of what you can expect the fluids rheology to be down hole at 400 °F and 20 ksi. This gives a more accurate determination of how the fluid can be used during drilling operations. As mentioned previously, the fluid was subjected to a variation of shear during rheological sweeps for 3.3% of the time during the entire aging test. In order to confirm the assumption that the mixing occurring during the rheology sweep does not affect the true static aging process an additional test was run at the same conditions. This test however only took one rheology sweep that occurred after the entire 16-hour duration of static aging. **Table 4.10** details the dial reading results obtained after the true static aging test was conducted.

Table 4.10 - Dial readings at the end of experimental static aging test

Rotor Speed, rpm	Static aging with 3.3% of mixing	True static aging
600	74	68
300	38	35
200	27	24
100	16	13
6	4	2
3	3	1

These results show that the mixing that occurs during the experimental test have very little effect on the true rheology during the static aging process and conclude that this test scheduled is an adequate alternative to that of the standard static aging tests. In an effort to analyze the effects of high pressures at high temperature conditions the previous test was coupled with a separate test that was run at 400 °F and 300 psi. It should be noted that even the test schedule was set to 300 psi the pressure increased during the test. The increase of pressure was the direct result of the increase of temperature and eventually stabilized at 2000 psi when the temperature stabilized at 400 °F. Additionally, the same increase in pressure can be expected during the standard static aging processes.

Fig. 4.12 illustrate the results obtained for the experimental static aging test conducted for 16 hours at 400 °F and 300 psi. The real time data is available in **Fig. A-5** and **Table B-7**. The results show that the fluid is still able to retain its rheological properties during the entire experimental static aging test. However, the significant decrease in pressure results in the fluids rheological properties dropping by almost 18%. This shows that with a significant increase in pressure during aging processes the rheological properties of a WBM will tend to slightly increase. An additional experimental static aging test was conducted at 450 °F and 25 ksi upon concluding that the WBM mud was adequate after 16 hours of static aging at 400 °F and 20 ksi.

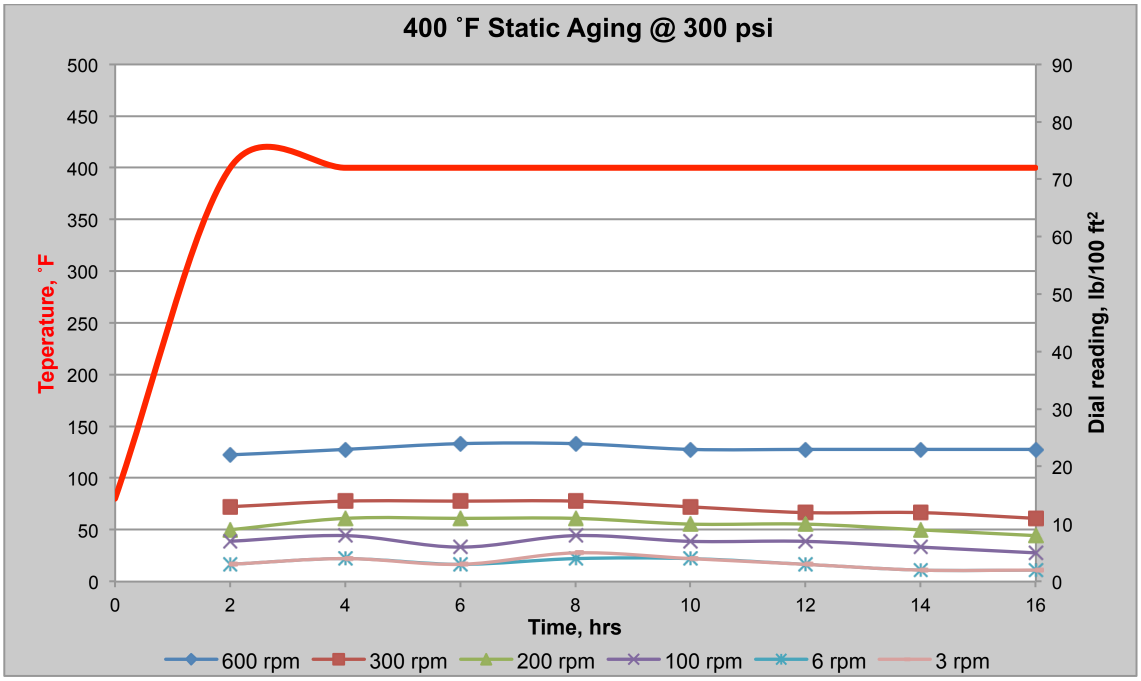


Fig. 4.12 - 400 ˚F static aging at 300 psi (dial reading/temperature vs. time)

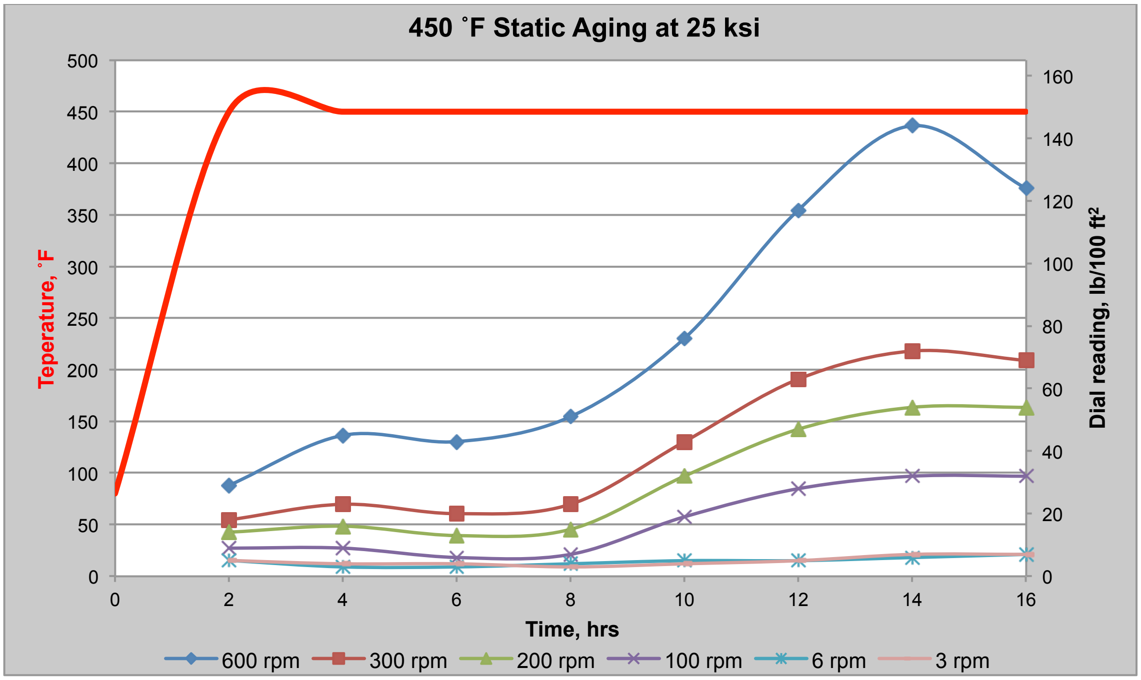


Fig. 4.13 - 450 °F static aging at 25 ksi (dial reading/temperature vs. time)

Fig. 4.13 illustrates the results obtained for the experimental static aging test conducted for 16 hours at 450 °F and 25 ksi. The real time data is available in **Fig. A-6** and **Table B-8**. It can be seen that at the 2 hour mark period the fluid retains nearly the same rheological characteristics seen during the experimental static aging test conducted at 400 °F and 20 psi. After 2 hours of static aging the fluid begins to exhibit an increase in rheological properties in result of the rapid static gelation the fluid experiences. The increase in rheology continues for a period of 12 hours. After being subjected to 14 hours of static aging at 450 °F and 25 ksi the fluid begins to exhibit erratic changes in fluid properties and is considered to have failed. The fluid displays acceptable rheological characteristics although the dial readings increase during the aging process. Based on the data obtained during the experimental static aging test it is concluded that the fluid is adequate for a static aging period of 10 hours at 450 °F and 25 ksi. Furthermore, this shows that by using the experimental static aging test the user can get a more accurate detail of the fluids performance when compared to the standard static aging tests.

Likewise, an experimental dynamic aging test was conducted at 450 °F and 25 ksi. Experimental

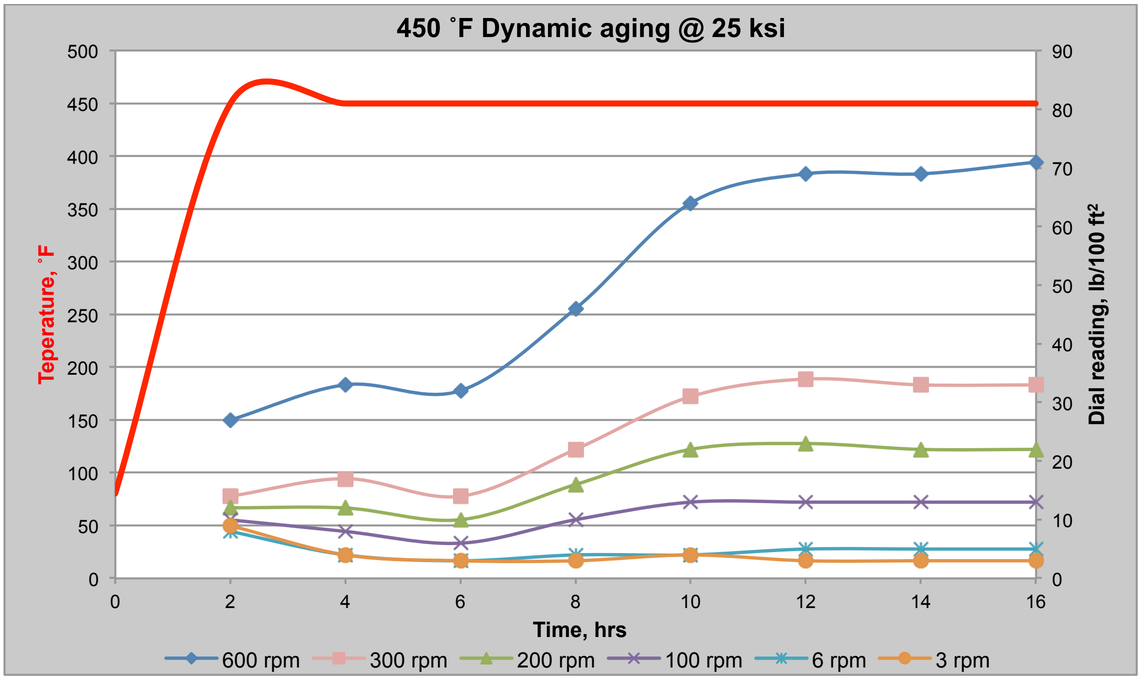


Fig. 4.14 - 450 ˚F dynamic aging at 25 ksi (dial reading/temperature vs. time)

dynamic aging was not conducted at any lower temperatures or pressures because of a limit on mud availability. Nevertheless, the fluid is assured to retain its performance at 400 °F and 20 ksi based on the results seen from the experimental static aging test. This notion is based on the conventional wisdom that dynamically aged fluids will exhibit better rheological performance than that of a static aged mud at the same conditions. **Fig. 4.14** illustrates the results obtained from the experimental dynamic aging test conducted for 16 hours at 450 °F and 25 ksi. The real time data is available in **Fig. A-7** and **Table**

B-9. These results confirm the presumption that during dynamic aging process a fluid will display better rheological characteristics than that of a static aging at identical conditions. The dynamic aging process shows that the fluid is able to retain its properties longer than the experimental static test as well as have lower overall rheological properties. Therefore, the experimental dynamic aging test at 450 °F and 25 ksi is sufficient for comparative analysis. It can be seen that the fluid retains its rheological properties 6 hours into the aging process where it then begins to show signs of rapid static gelation up to the 16-hour period. It is theorized that the fluid will continue to gel, like that during an experimental static aging test, as the aging length passes the 16-hour period. Further, testing and research will need to be conducted to evaluate and confirm these assumptions. Furthermore, at the 16 hour mark the fluid rheological properties show rheology that is comparative to that experienced by a fresh mud sample at 120 °F and ambient pressure. It should be noted, for the purpose of correct analysis, that when the mud begins to cool it will experience a dramatic increase in rheology when the readings are taken at 120 °F and ambient pressure rendering completely different analytical result than that seen from these results. Therefore this mud is determined to be adequate, based on standard dynamic tests for 6 hours of dynamic aging at 450 °F and 25 ksi. After 6 hours the mud is technically still considered adequate, but because of the cooling that would be experienced during circulation the mud will exhibit a substantial amount of thickening as the aging length increases. Nevertheless, It can be concluded that as the mud exceeds 6 hours of aging at 450 °F and 25 ksi it is unable to retain its rheological characteristics. In conclusion, unlike the experimental standard static aging tests, this test is not able to simulate the true conditions that are experienced in the well. Mainly, the mud during dynamic aging is circulated and experiences a cyclical variation of temperature, pressure, and shear rate. This was unable to be achieved due to the absence of the cooling jacket that attaches to the 7600 viscometer, allowing for rapid cooling of the fluid sample. This test is only to be used as an alternative to that of the standard dynamic aging test by allowing the user to see the real time effects that temperature and pressure have on the mud during the standard dynamic aging test. An alternative dynamic aging test schedule will be outlined in the recommendation section for future testing with a HT/HP viscometer that is equipped with a cooling jacket. This test will enable the user to evaluate the effects of circulation in the well and mainly the cyclical variations of temperature, pressure, and shear rate experienced.

CHAPTER V

CONCLUSION AND RECOMMENDATIONS

Conclusion

The research presented in this thesis establishes the importance and necessary care that is required when designing, monitoring, and drilling with WBMs at high temperatures and pressures. Furthermore, the use of WBMs muds in HT/HP environments will continue to grow as environmental regulations increase. Therefore, research and testing is needed to evaluate the effects that HT/HP conditions have on WBMs during drilling operations. This thesis and future research is conducted to aid in the advancement of cheaper, safer, and faster drilled HT/HP wells when using WBMs. The testing in this thesis was conducted to analyze the methods of aging WBMs at HT/HP along with its effects on the fluids rheology. Based on the test results presented in this thesis the following conclusions are drawn upon:

- A High performance 18 ppg WBM formulation was tested that was able to retain excellent rheological properties at aging temperatures and pressures exceeding 400 °F and 20 ksi, respectively.

- The Chandler 7600 viscometer is an acceptable alternative viscometer that can operate at extreme temperatures and pressures, while being able to record reliable rheological properties, based on result oriented validation with the industry standard Fann 35 viscometer.

- Using the performance test schedule, it was evident that, at the same aging length, untreated post dynamically aged muds show a better rheological performance than that of an untreated post statically aged mud.

- Standard static and dynamic aging methods only allow the user to evaluate the fluids at the end of a predetermined aging length and at temperatures (120 °F) much lower than that experienced in the well. Furthermore, the standard aging tests are unable to subject the fluid to the true pressures experienced down hole.

- Consequently, an alternative static experimental test procedure was developed that gives the user the ability to subject the fluid to true down hole conditions while being able to monitor the rheological changes in real-time. This test proves to be a more detailed and improved aging technique when compared to the standard static aging method.

- Likewise, an alternative experimental dynamic aging test was developed that enables the user to monitor the rheological changes in real time during a standard dynamic aging test. This test also allows the user to subject the fluid to elevated temperatures during the aging process.

- Unlike the experimental static aging test, the experimental dynamic aging test does not allow the fluid to be subjected to the true conditions experienced during circulations and therefore should only be used as a tool to monitor the changes during the standard dynamic aging test.

- Therefore, An alternative experimental dynamic aging method is outlined in the recommendations section that, when used with a HT/HP viscometer with an attached cooling jacket, allow the user to subject the fluid to the true conditions experienced during circulation.

- Based on standard static and dynamic aging methods the fluid was determined to retain its rheological properties up to 400 °F and possibly 450 °F. Experimental aging tests were able to aid in confirming and finding an exact time at which the fluids rheological properties begin to change at 450 °F and 25 ksi, proving it to be a more detailed alternative approach for aging WBMs.

- At 450 °F and 25 ksi the experimental static aging test was able to show the fluid retaining rheology for 2 hours until rapid thickening occurred. Alternatively at 450 °F and 25 ksi the experimental dynamic aging test was able to show the fluid retaining its rheological characteristics for 6 hours until rapid thickening occurred. Furthermore, the dynamic aging process showed a lower overall rheology change when compared to the static aging process, concluding that the static aging is much harsher on a fluids rheology than dynamic aging.

- The experimental test schedules show that when subjected to high pressures, at elevated temperatures, the fluid shows an increase in rheological properties greater than 15% than that of the same fluid formulation, at the same temperature conditions, but substantially lower pressures. Proving that although temperature affects a WBMs rheology the most, at higher temperatures the pressure also has a slightly significant effect on the fluids rheology.

Recommendations for Advancement

Although the research and testing conducted for this thesis supplied sound analytical conclusions, it has only scratched the surface in terms of testing the aging effects of extreme temperature and pressure conditions on WBMs and furthermore, OBMs. Based on the research and testing conducted in this thesis the following outlines the recommendations for future testing:

- Similar testing procedure should be run on different mud types, such as OBMs and SBMs, in an effort to quantify their rheological characteristics during HT/HP aging.

- Testing on other WBM formulations, without such high performance characteristics, should be tested in the same manner carried out in this thesis in an effort to identify the possibility of contrasting rheological changes that can occur due common WBM formulations.

- Further experimental static and dynamic aging testing should be conducted at greater aging lengths to identify the rheological changes that occur after the minimum 16-hour aging length.

- Testing with the attachment of the cooling jacket should be conducted, enabling the user to identify the rheological effects of rapid cooling.

- Most importantly, via the attachment of a cooling jacket, an alternative dynamic test schedule should be designed to replicate the conditions experienced during circulation through the well for a predetermined aging time, and not just the rheological changes experienced during standard dynamic aging tests. In an effort to promote future dynamic aging research a sample test schedule is suggested below:

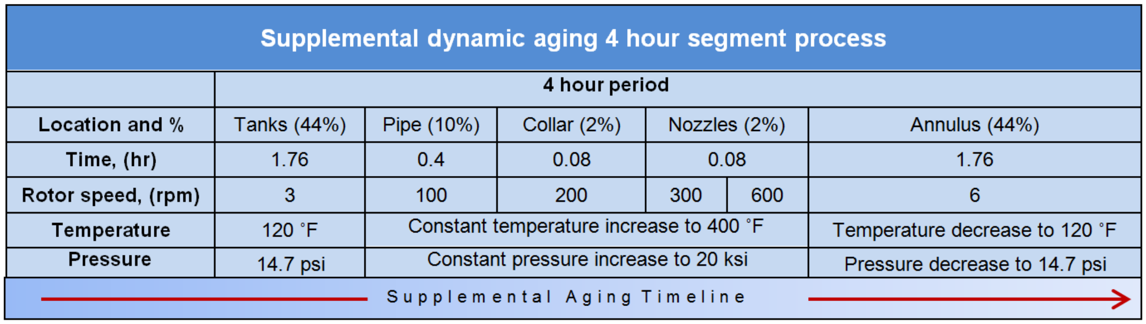
The following test schedule is based on an artificial and relative deep well. It is assumed based on a constant pump rate that it takes approximately 4 hours for 1 ft^3 of fluid to circulate completely through the drilling system. Furthermore, the pressure and temperature gradients are assumed to be constant and result in a HT/HP deep well with a BHT and BHP of 400 °F and 20 ksi, respectively. All conditions can easily be changed based on well characteristics. The experimental schedule is based on the average amount of time spent in each drilling system component during the 4-hour circulation period and, consequently subjects the fluid to the various shears experienced during a complete circulation in the drilling system. The shears subjected are based on the natural course the fluid takes through the drilling system and rotor

Table 5.1 - Drilling system components

Location	Time spent in component, %	Shear Rate Range, sec^{-1}	RPM
Tanks	44	1-5	3
Annulus	44	10-500	6
Pipe	10	100-700	100
Collar	2	700-3,000	200
Nozzles	2	10,000-100,000	300 & 600

speeds are chosen to represent the shears experienced in each component of the drilling system. **Table 5.1** details each drilling component, the shear rates they experience and the corresponding rotor speeds as well as the average time the fluid spends in each component. **Table 5.2** outlines the experimental test schedule in further detail for each 4-hour period. Furthermore, **Figure A-8** details the supplemental experimental dynamic aging profile. In summary, detailed monitoring and concern must be conducted during the design, testing, and optimization when using WBMs in HT/HP drilling operations. As drilling equipment is consistently developed and produced to withstand greater temperatures and pressures, it puts greater emphasis and concern on the drilling fluid formulations used. Furthermore, as environmental regulations are tightening the advocation of WBMs will continue to increase. Therefore, in order to provide cheaper, safer, and faster drilling programs further research on WBM formulations at HT/HP conditions are recommended.

Table 5.2 - Supplemental 16 hour dynamic aging process



Supplemental dynamic aging 4 hour segment process

	4 hour period					
Location and %	Tanks (44%)	Pipe (10%)	Collar (2%)	Nozzles (2%)		Annulus (44%)
Time, (hr)	1.76	0.4	0.08	0.08		1.76
Rotor speed, (rpm)	3	100	200	300	600	6
Temperature	120 ˚F	Constant temperature increase to 400 ˚F				Temperature decrease to 120 ˚F
Pressure	14.7 psi	Constant pressure increase to 20 ksi				Pressure decrease to 14.7 psi

Supplemental Aging Timeline →

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APPENDIX A

REAL-TIME RHEOLOGY PLOTS

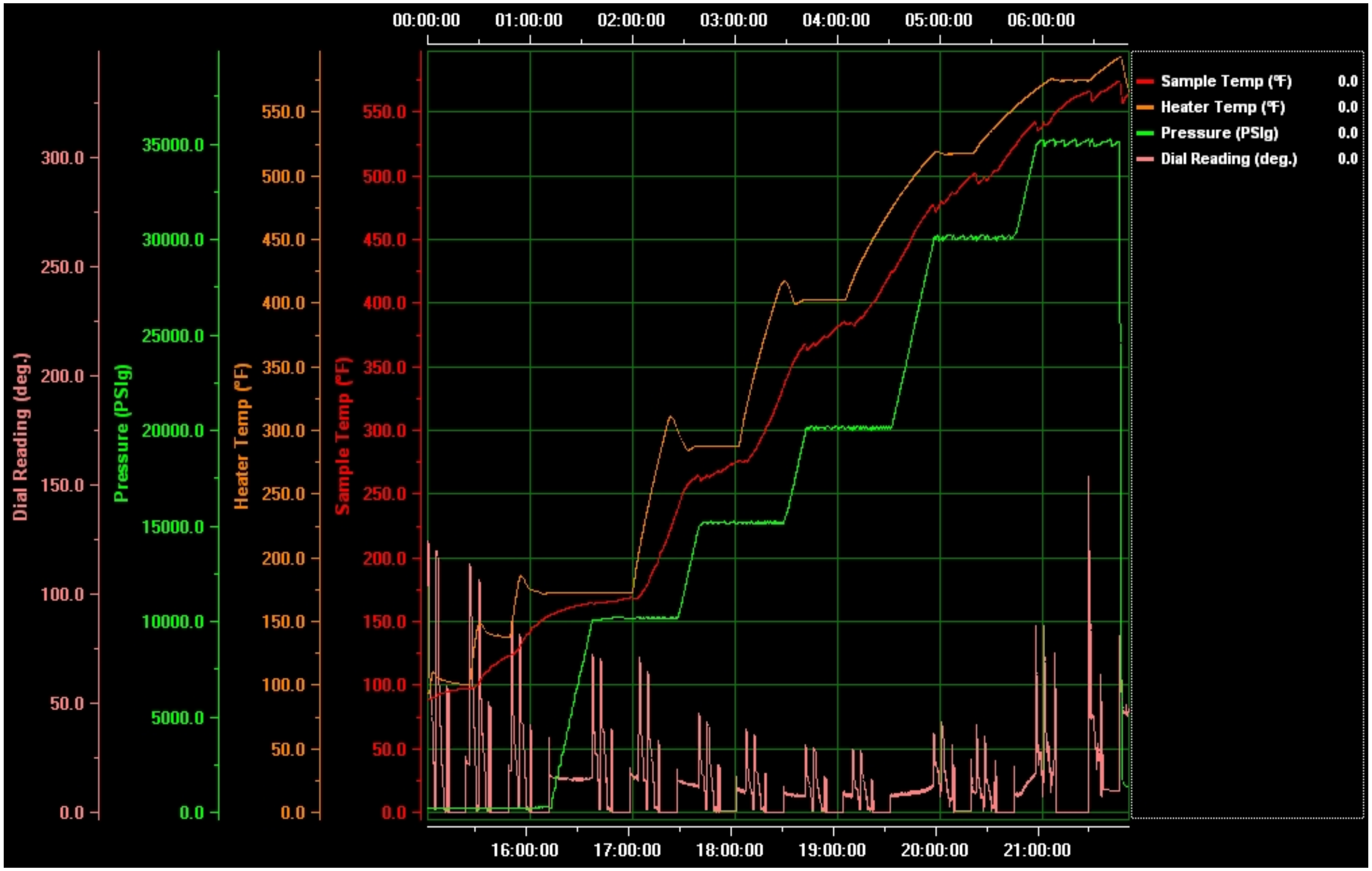

Fig. A-1 - Non-aged performance test

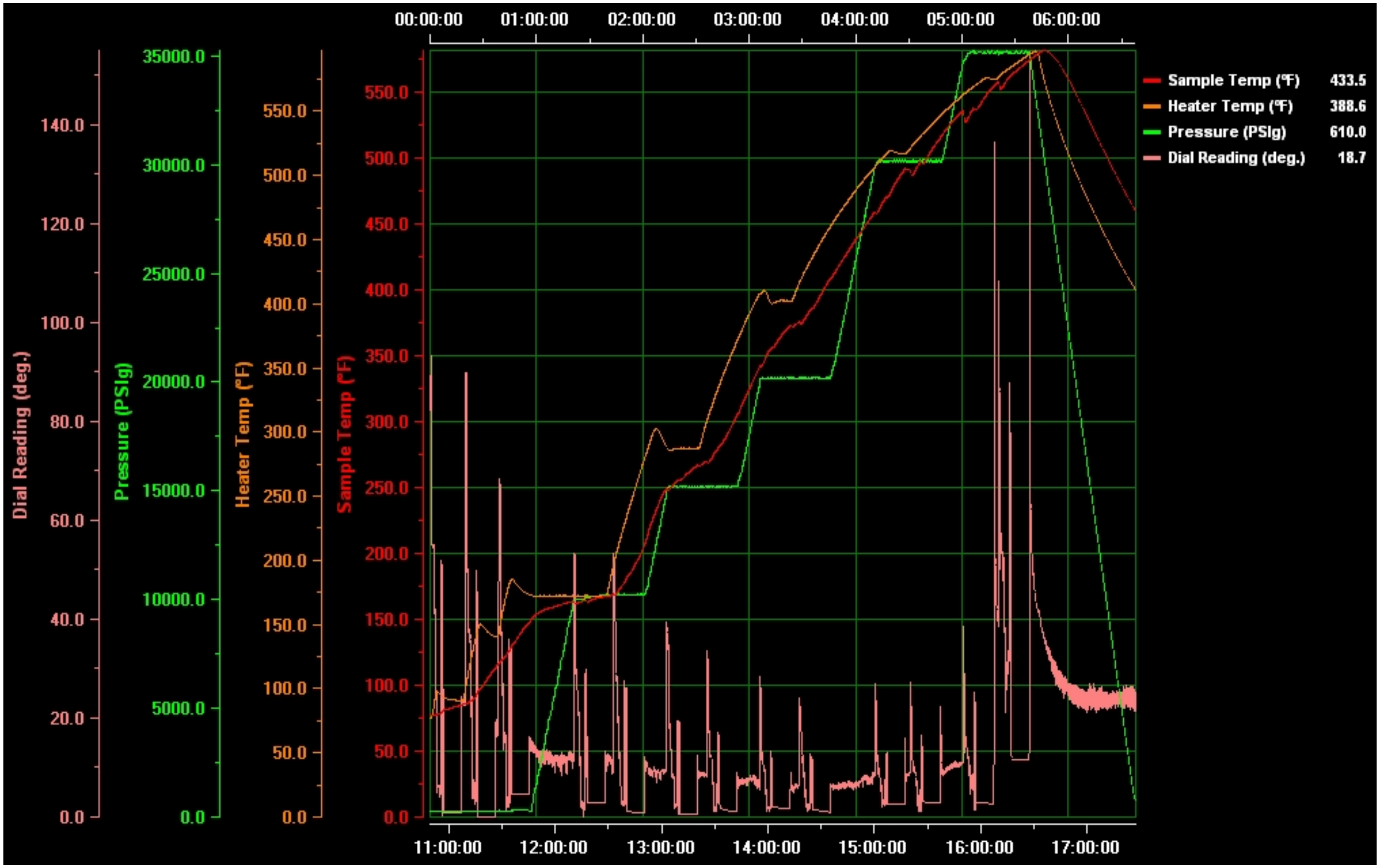

Fig. A-2 - 400 ˚F dynamic aging performance test

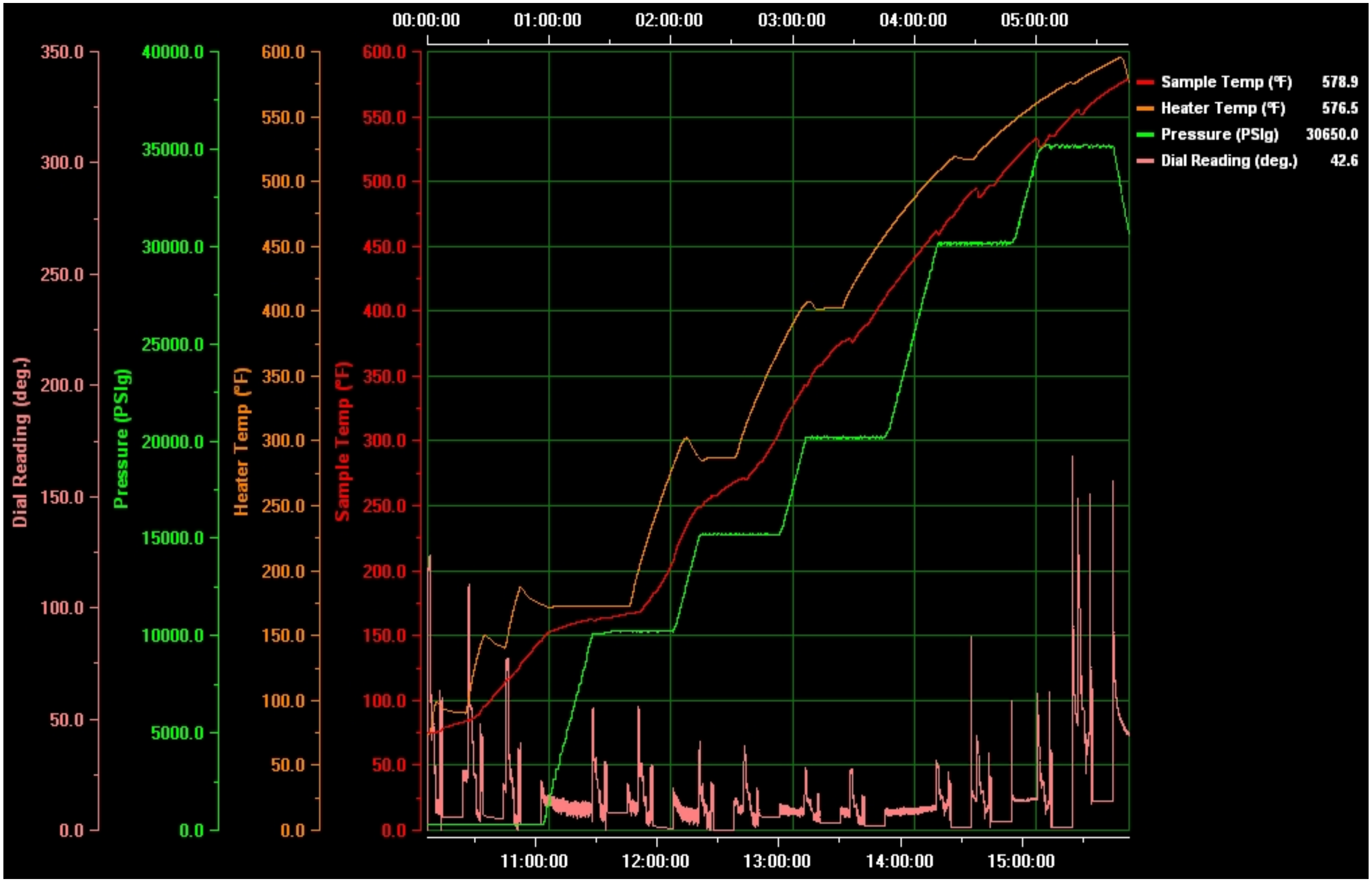

Fig. A-3 - 350 ˚F static aged performance test

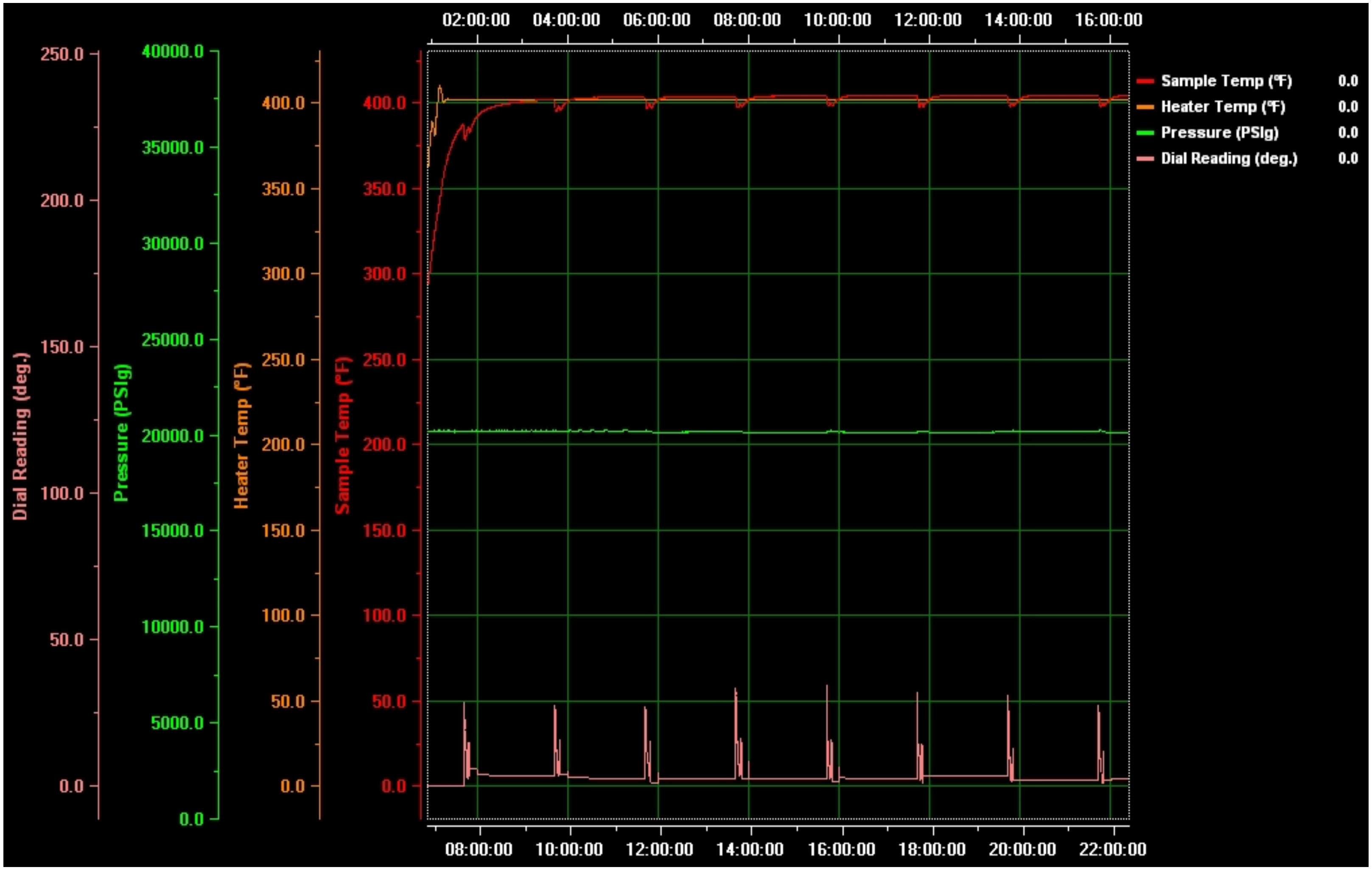

Fig. A-4 - Static aging @ 400 °F and 20 ksi

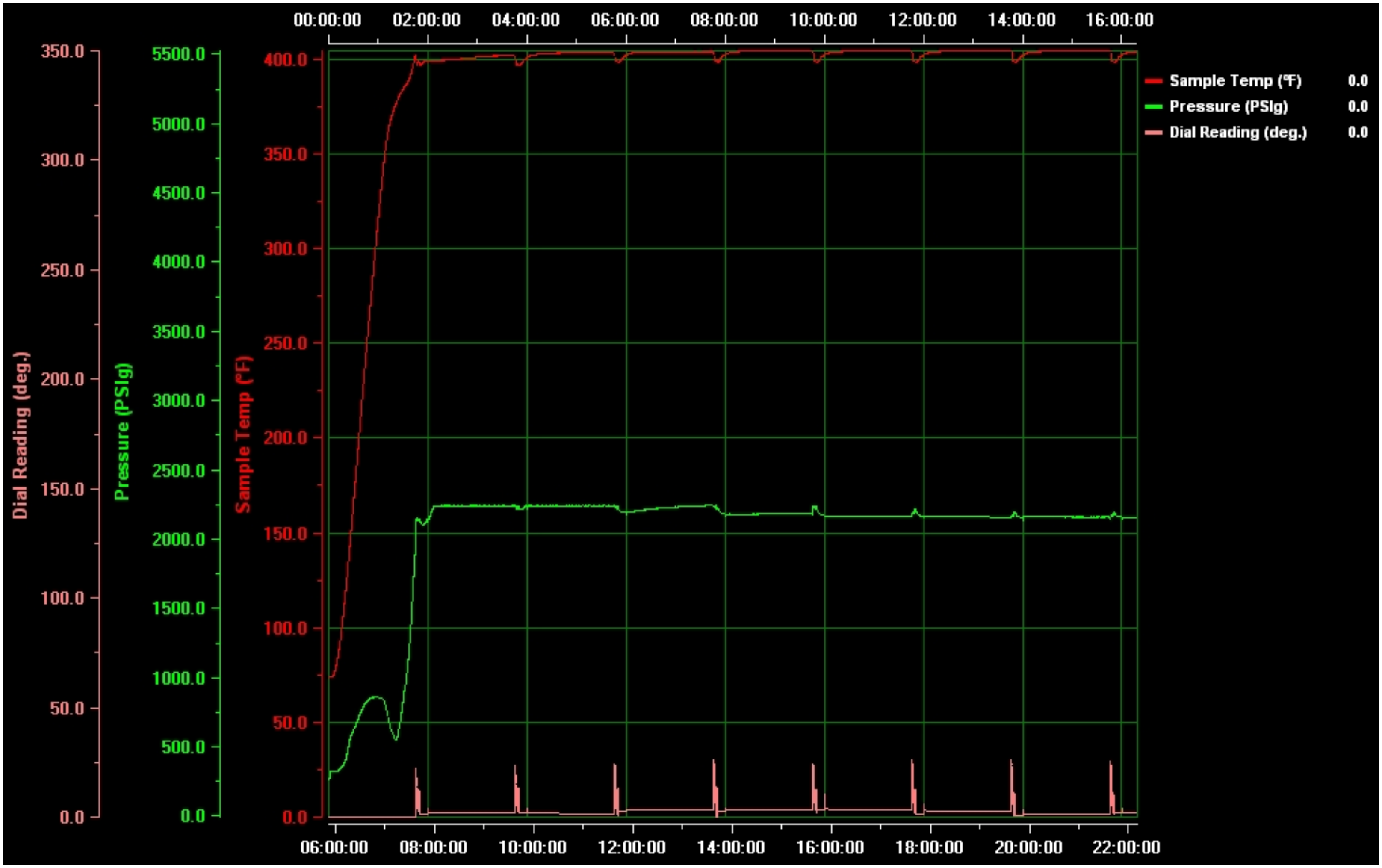

Fig. A-5 - Static aging @ 400 °F and 300 psi

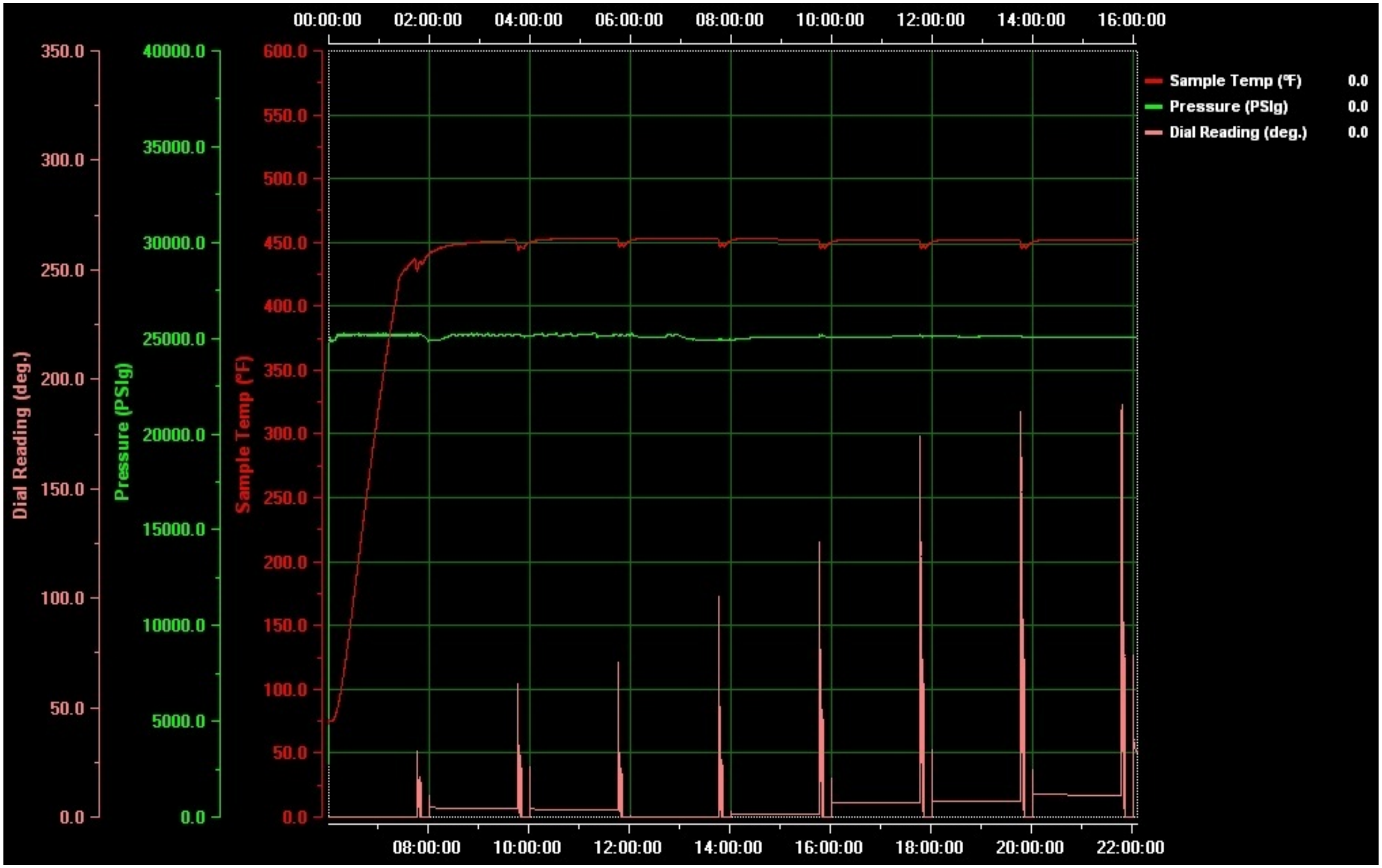

Fig. A-6 - Static aging @ 450 °F and 25 ksi

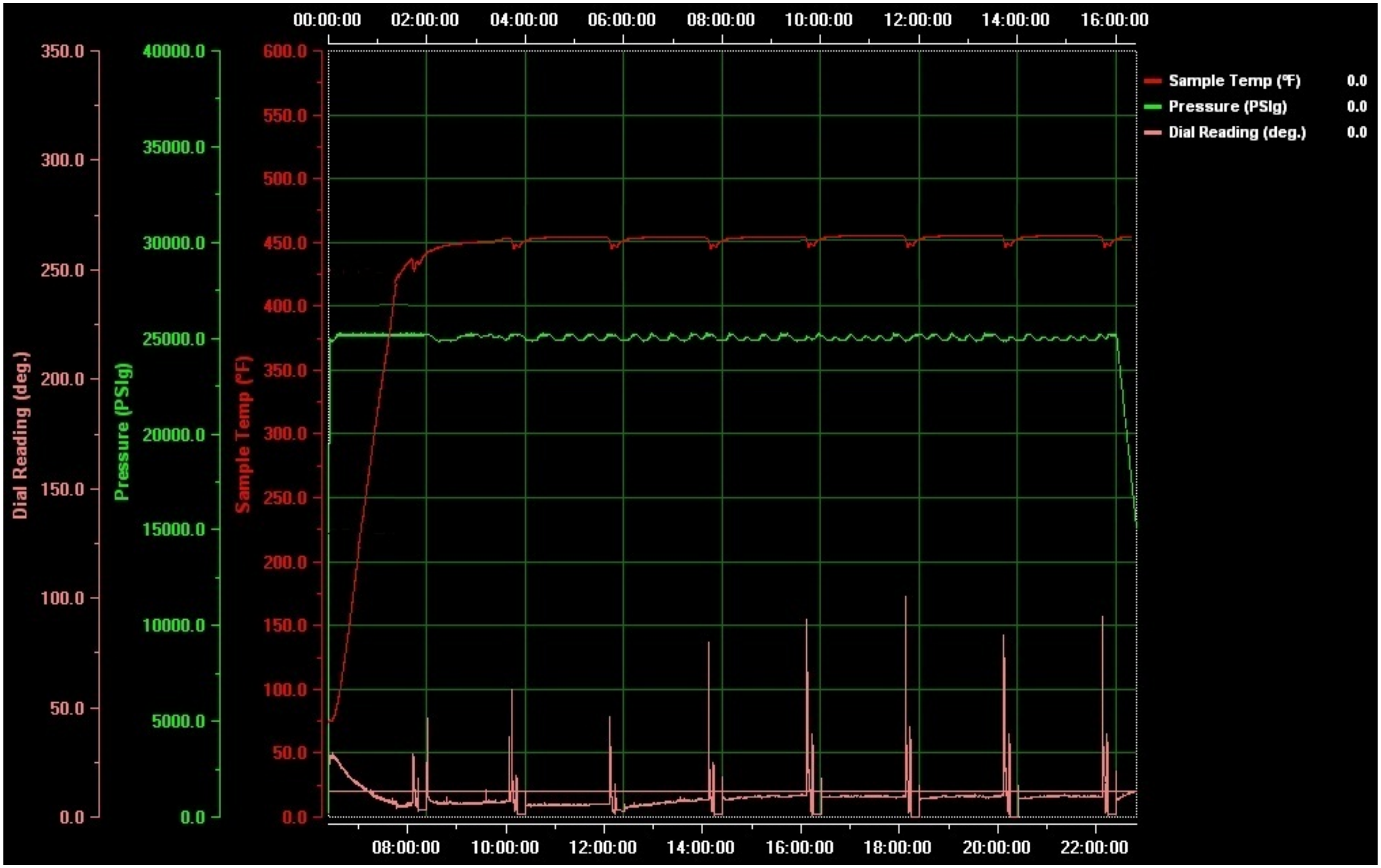

Fig. A-7 - 450 °F dynamic aging @ 25 ksi

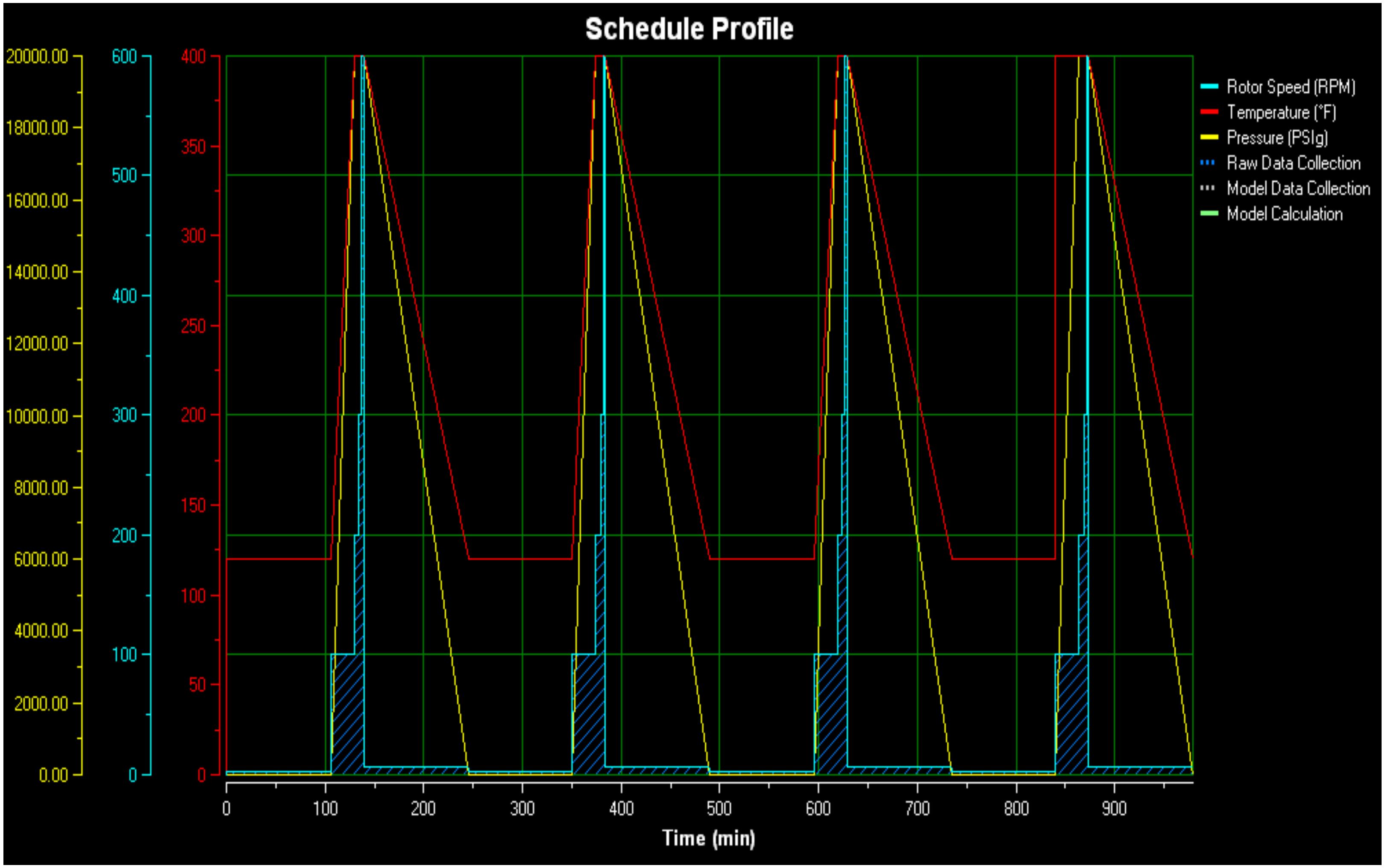

Fig. A-8 - Supplemental dynamic aging profile

APPENDIX B

RAW DATA

Table B-1 - Standard dynamic aging

		Fresh Mud @ 120 ˚F	Standard 16 hour Dynamic Aging Results @ 120 ˚F			
rpm	units	Non aged	300 ˚F Aging	350 ˚F Aging	400 ˚F Aging	450 ˚F Aging
600	lb/100ft2	74	58	49	54	90
300	lb/100ft2	38	36	32	32	49
200	lb/100ft2	27	25	23	25	35
100	lb/100ft2	16	15	16	17	21
6	lb/100ft2	4	4	3	4	5
3	lb/100ft2	3	3	3	3	4
PV	cP	35	22	17	22	41
YP	lb/100ft2	3	14	15	10	8
10sec	lb/100ft2	7	7	6	6	2
10min	lb/100ft2	28	17	15	15	9

Table B-2 - Standard Static aging

		Fresh Mud @ 120 ˚F	Standard 16 hour Static Aging results @ 120 ˚F			
rpm	units	Non aged	300 ˚F Aging	350 ˚F Aging	400 ˚F Aging	450 ˚F Aging
600	lb/100ft2	74	71	75	83	93
300	lb/100ft2	38	37	42	49	55
200	lb/100ft2	27	25	29	33	35
100	lb/100ft2	16	16	17	18	21
6	lb/100ft2	4	6	5	7	9
3	lb/100ft2	3	4	4	5	6
PV	cP	35	34	33	34	38
YP	lb/100ft2	3	3	15	15	17
10sec	lb/100ft2	7	7	8	4	9
10min	lb/100ft2	28	15	25	15	30

Table B-3 - Non aged WBM performance

Time	Temp	Pressure	600	300	200	100	6	3	10-sec gel	10-min gel	YP	PV
h:mm:ss	˚F	psi	lb/100 ft^2									cP
0:17:20	93	14.7	117	58	40	22	2	1	3	13	-1	59
0:37:05	106	14.7	104	53	36	20	2	1	1	18	2	51
0:56:00	135	14.7	70	41	29	16	2	1	0	15	12	29
1:38:26	165	10115	69	38	27	16	2	1	3	24	7	31
2:00:56	188	10204	62	33	24	14	3	2	4	18	4	29
2:30:51	265	15156	40	22	16	10	3	2	0	13	4	18
2:53:21	291	15157	35	19	13	8	2	2	2	11	3	16
3:23:16	370	20163	29	16	11	8	2	2	1	10	3	13
3:45:41	393	20145	27	15	11	7	2	2	0	9	3	12
4:28:11	481	30134	34	20	16	11	6	7	2	27	6	14
4:48:06	501	30111	31	15	10	7	3	3	0	22	-1	16
5:18:07	545	35140	57	33	30	21	19	25	11	26	9	24
5:43:34	563	35147	120	59	36	30	34	27	--	--	-2	61

Table B-4 - 400 °F dynamic aged WBM performance

Time	Temp	Pressure	600	300	200	100	6	3	10-sec gel	10-min gel	YP	PV
h:mm:ss	˚F	psi	lb/100 ft^2									cP
0:17:20	79	14.7	93	55	42	25	7	6	2	11	17	38
0:37:05	92	14.7	90	50	37	24	7	6	4	10	10	40
0:56:00	121	14.7	57	37	26	17	4	3	3	12	17	20
1:38:26	164	10049	52	30	21	11	3	2	9	8	8	22
2:00:56	178	10222	50	28	19	12	3	3	3	11	6	22
2:30:51	254	15206	35	19	14	8	3	3	1	11	3	16
2:53:21	278	15221	32	18	12	7	2	2	3	10	4	14
3:23:16	352	20195	25	13	10	5	2	2	4	7	1	12
3:45:41	383	20209	21	12	9	6	2	2	3	5	3	9
4:28:11	467	30167	23	13	10	7	3	3	3	17	3	10
4:48:06	495	30175	21	11	10	7	3	3	1	17	1	10
5:18:07	536	35106	25	16	12	10	7	6	6	28	7	9
5:43:34	559	35184	80	57	52	38	31	32	33	36	34	23

Table B-5 - 350 °F static aged WBM performance

Time	Temp	Pressure	600	300	200	100	6	3	10-sec gel	10-min gel	YP	PV
h:mm:ss	˚F	psi	lb/100 ft^2									**cP**
0:17:22	77	14.7	121	60	47	26	12	12	1	10	-1	61
0:37:08	91	14.7	107	55	35	25	7	6	19	6	3	52
0:56:03	125	14.7	70	34	24	18	4	3	11	5	-2	36
1:38:28	163	10125	54	32	23	15	8	9	1	11	10	22
2:00:54	178	10220	50	30	21	14	6	8	5	5	10	20
2:30:54	255	15206	39	20	13	10	5	5	10	3	1	19
2:53:19	279	15209	32	20	16	9	6	6	2	10	8	12
3:23:20	354	20194	26	14	14	9	6	7	5	7	2	12
3:45:45	386	20199	27	15	11	8	5	6	4	7	3	12
4:28:10	469	30138	29	19	16	12	11	14	8	30	9	10
4:48:10	495	30169	36	22	18	13	10	11	3	28	8	14
5:18:05	533	35123	45	26	22	15	11	13	8	20	7	19
5:43:34	558	35167	102	70	55	43	40	45	28	33	38	32

Table B-6 - 400 °F static aging @ 20 ksi

Time	Temp	Pressure	600	300	200	100	6	3	10-sec gel	10-min gel	YP	PV
hr	˚F	psi	lb/100 ft^2									cP
2	400	20000	27	16	12	7	4	4	4	7	5	11
4	400	20000	26	16	12	9	5	4	5	6	6	10
6	400	20000	26	15	12	8	4	4	4	6	4	11
8	400	20000	27	16	12	8	4	4	5	12	5	11
10	400	20000	28	16	12	7	4	4	3	10	4	12
12	400	20000	27	15	11	6	3	3	1	6	3	12
14	400	20000	26	14	10	6	2	2	5	2	2	12
16	400	20000	25	13	10	5	2	2	3	3	1	12

Table B-7 - 400 °F static aging @ 300 psi

Time	Temp	Pressure	600	300	200	100	6	3	10-sec gel	10-min gel	YP	PV
hr	˚F	psi	lb/100 ft^2									cP
2	400	2000	22	13	9	7	3	3	4	6	4	9
4	400	2000	23	14	11	8	4	4	4	6	5	9
6	400	2000	24	14	11	6	3	3	2	9	4	10
8	400	2000	24	14	11	8	4	5	2	12	4	10
10	400	2000	23	13	10	7	4	4	3	12	3	10
12	400	2000	23	12	10	7	3	3	2	8	1	11
14	400	2000	23	12	9	6	2	2	3	5	1	11
16	400	2000	23	11	8	5	2	2	1	5	1	12

Table B-8 - 450 °F static aging @ 25 ksi

Time	Temp	Pressure	600	300	200	100	6	3	10-sec gel	10-min gel	YP	PV
hr	˚F	psi	lb/100 ft^2									cP
2	450	25000	29	18	14	9	5	5	3	19	7	11
4	450	25000	45	23	16	9	3	4	1	2	1	22
6	450	25000	43	20	13	6	3	4	3	11	-3	23
8	450	25000	51	23	15	7	4	3	3	5	-5	28
10	450	25000	76	43	32	19	5	4	4	4	10	33
12	450	25000	117	63	47	28	5	5	4	20	9	54
14	450	25000	144	72	54	32	6	7	4	24	2	72
16	450	25000	124	69	54	32	7	7	5	4	14	55

Table B-9 - 450 °F dynamic aging @ 25 ksi

Time	Temp	Pressure	600	300	200	100	6	3	10-sec gel	10-min gel	YP	PV
hr	˚F	psi	lb/100 ft^2									cP
2	450	25000	27	14	12	10	8	9	8	26	1	13
4	450	25000	33	17	12	8	4	4	4	7	1	16
6	450	25000	32	14	10	6	3	3	2	6	-4	18
8	450	25000	46	22	16	10	4	3	1	12	-2	24
10	450	25000	64	31	22	13	4	4	1	12	-2	33
12	450	25000	69	34	23	13	5	3	4	8	-1	35
14	450	25000	69	33	22	13	5	3	2	16	-3	36
16	450	25000	71	33	22	13	5	3	2	16	-5	38

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