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An In-Depth Analysis of Mixed Metal Oxide Fluids and Their Suitability for Lost Circulation

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Abstract

Drilling budgets always fluctuate widely between various probabilities like P10 and P90 where a well plan may show best-in-class drilling taking 30 days or, worst-case scenario, being 60 days as an example. This leads to complications in planning and budgeting for well AFE's, especially in the current economic environment. A key reason for this variability in cost is unscheduled events with the major NPT contributors being lost circulation, stuck pipe, and wellbore instability.

Most of the time, operators and service companies aim at solving lost circulation by adding lost circulation materials to the drilling fluid before evaluating the suitability of the fluid itself to address losses without the aid of lost circulation materials. This practice adds more complexity to the operation due to logistics, cost, and deployment limitations depending on particle size.

One fluid that is under-estimated in its inherent ability to combat losses is the mixed-metal-oxide-based slurries. The simplicity of the fluid, combined with its unique thixotropic profile, allows it to significantly improve well drilling economics due to the noteworthy reduction in total volume lost and reduction in days combating losses on most wells where it has been used.

The authors believe that the fluid's under-utilization stems from lack of sufficient technical and laboratory-based studies to show how to control the properties of the fluid and establish the limits to its application. Consequently, it has become obvious that there were some inherent misconceptions around the variability of test results and the suitability of current laboratory testing equipment leading to misinterpretation of the thixotropic profile.

Introduction

Drilling fluids based on mixed metal oxides (MMO) have been around for decades. Throughout that time, MMO fluids have gone through various generations to make it more consistent and robust for field applications while also making it more economical to use. Much of the history behind the fluid has been covered in prior publications, especially the 2018 review article by Richard and Enriquez. The evolution of MMO technology is summarized in Figure 1. This progression includes the current ongoing R&D efforts to create the next-generation, robust MMO fluid for deeper drilling applications while addressing many of the short-comings of prior generations.

The first generation, mixed metal hydroxides (MMH) were the most sensitive of the MMO systems – prone to contamination and field challenges coupled with cost. The MMH system led the way to the later generations of MMO fluids, including those used nowadays which are more stable systems with much less challenges in the field and higher chances of success.

Success in the case of MMO fluids is typically measured primarily as a function of reduction of volume lost compared to offset wells like that shown in Figure 2 which highlights a well that used MMO fluid in green compared to offset wells using a generic water-based spud drilling fluid in blue. In this case, the interval was a shallow fractured carbonate formation where the operator utilized the MMO fluid for this section, but not for deeper fractured carbonate sections due to concerns about fluids ability to be weighted up and withstand higher temperature. Achieving stability with higher temperature and contaminants are drivers behind the MMO work presented herein.

Figure 1: Evolution of Mixed Metal technology.

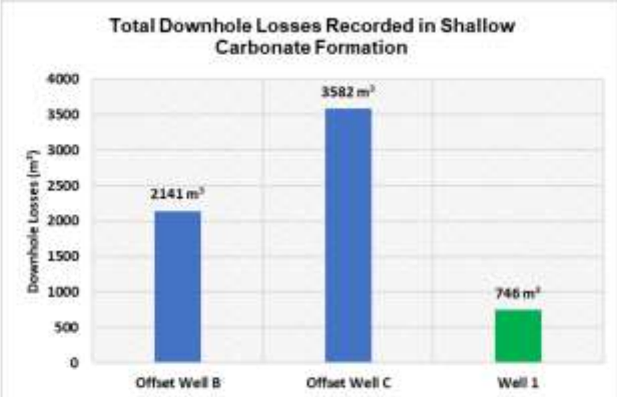

Figure 2: Comparison of well using MMO fluid (green) to two offset wells using generic water-based spud muds (blue).

The susceptibility of MMO fluids to certain compounds, that compromise the thixotropic properties extends to influencing the selection of lost circulation materials (LCM). Selection of LCM material has become based on issues such as materials that do not carry organic residues, rather than selection decided by which LCM is most effective in sealing the loss zone. Table 1 shows the results of a study done to pre-select which LCM is compatible with the MMO system. However, it is important to remember that avoiding and treating lost circulation was the primary and original reason for using MMO fluids.

One way of addressing the side effects of using material that has an anionic nature, which is probably the most incompatible of all additives to MMO, is the use of anionic suppressants. That said, anionic suppressant usage is an art in itself, focused around concentration and timing. Unlike most water-based fluids, one can't simply pre-treat the system as these anionic suppressants thin the fluid if there is no contaminant in the system to consume the anionic suppressant. Table 2 shows how typical contamination vs. treatment method being post- or pre-treatment works for an anionic suppressant.

Consideration of these points leads the authors to believe that if the newer generation of MMO can address these shortcomings, MMO systems would be applicable to various downhole intervals and loss scenarios rather than being limited to just use for surface holes. This paper will also explain the common pitfalls around laboratory evaluation of the MMO fluid and other suggested test methods to validate it as well as establishing some key operational limits and parameters.

Table 1: Pre-Selected LCM for Use in MMO Systems

Selected LCM	Description
Type A	Extrusion-spun mineral fiber (fine grade)
Type B	Blend of inorganic sealants and bridging agents (fine grade)
Type C	Blend of inorganic sealants and bridging agents (medium grade)
Type D	Elastomeric sealant
Type E	High solids/high fluid loss squeeze product
Type F	Specially treated synthetic fiber
Type G	Swellable copolymer
Type H	Calcium carbonate (medium grade)
Type I	Calcium carbonate (coarse grade)
Type L	Graphite based product
Type M	Extrusion-spun mineral fiber (coarse grade)

Table 2: Example of Contamination vs. Treatment for Pre- and Post-Treatment Methods

Product	Base	Base + Lignite	Base + Lignite, treated with AS	Base pretreated with AS	Base Pretreated with AS + Lignite
Water, bbl	0.667	0.667	0.667	0.667	0.667
30-lb/bbl bentonite gel slurry, bbl	0.333	0.333	0.333	0.333	0.333
Soda Ash, lb/bbl	0.25	0.25	0.25	0.25	0.25
MMO, lb/bbl	1	1	1	1	1
Caustic, ppb	0.5	0.5	0.5	0.5	0.5
Lignite, ppb	-	0.25	0.25	-	0.25
Anionic Suppresant, ppb	-	-	1.5	1.5	1.5
Rheology Temp (°F)	120	120	120	120	120
600-rpm Dial Reading	143	10	26	90	45
300-rpm Dial Reading	128	7	24	86	36
200-rpm Dial Reading	119	5	23	85	33
100-rpm Dial Reading	104	4	22	81	30
6-rpm Dial Reading	58	2	19	37	16
3-rpm Dial Reading	50	1	15	33	13
LSYP, lbf/100 ft^2	42	0	11	29	10
PV, cP	15	3	2	4	9
YP, lbf/100 ft^2	113	4	22	82	27
10-sec Gel, lbf/100 ft^2	61	2	11	21	8
10-min Gel, lbf/100 ft^2	72	4	10	20	8
pH	12.01	12.06	11.80	11.98	11.81

MMO Fluid Formulations and Properties

Salinity Tolerance

Unlike legacy MMH/MMO fluids, the current MMO technology has been improved which allows the material to be compatible with salt solutions. This later MMO fluid works in seawater and calcium chloride brine, as well as in freshwater. The formulation shown in Table 3 uses a mixed metal oxide compound blend that is tolerant to divalent cations to at least 10,000 ppm of Ca^{2+} or Mg^{2+}. This allows the product to be used in the divalent brines environment, expanding the usability of the MMO fluid system. The typical ratio of bentonite clay to MMO compound is 10:1, like the previous MMH/MMO systems. The mix is straightforward: pre-hydration of bentonite clay, addition of mixed metal oxide compound blend, followed by pH adjustment to 10–11.

Table 3: MMO Fluid Formulation in Seawater with 10,000 ppm Calcium

Formulation	#1
30-lb/bbl bentonite gel slurry, bbl	0.400
Freshwater, bbl	0.447
Sea salt, lb/bbl	14.68
Calcium chloride powder, lb/bbl	11.16
MMO (New generation), lb/bbl	1.2
API Evaluation base clay, lb/bbl	35
Barite, lb/bbl	169.29
Lime, lb/bbl	1.8

Typical, stable MMO fluid properties can be reflected in its high low-end rheology, high YP to PV ratio, and flat gel structure. The high YP to PV ratio results from remarkably low PV and high YP values which enhances the thixotropic, shear thinning properties of the MMO fluid system. Compared to initial fluid properties, after hot rolling at 300°F, the fluid rheological properties remain the same or show a slight decrease, as shown in Table 4. High YP to PV ratio along with flat 10-sec/10-min gels demonstrate that the MMO fluid in Formulation 1 (Table 4) is stable to at least 350°F.

Table 4: Formulation #1 Fluid Properties Before and After Hot Rolling at 300°F and 350°F Rheology Tested @ 120°F

Formulation #1	BHR	AHR @ 300°F	AHR @ 350°F
Lime to adjust pH, lb/bbl	-	0.3	0.3
pH	10.44	11.47	11.34
600-rpm Dial Reading	153	157	134
300-rpm Dial Reading	148	140	126
200-rpm Dial Reading	146	138	122
100-rpm Dial Reading	142	129	113
6-rpm Dial Reading	72	63	59
3-rpm Dial Reading	41	40	43
LSYP, $lb_f/100\ ft^2$	10	17	27
PV, cP	5	17	8
YP, $lb_f/100\ ft^2$	143	123	118
10-sec Gel, $lb_f/100\ ft^2$	44	45	41
10-min Gel, $lb_f/100\ ft^2$	46	55	48

Density Improvements

Higher density MMO fluids can also be achieved. Table 5 shows MMO fluid formulations ranging from 12 to 16 lb/gal. The MMO fluids were stable after hot rolling at 300°F, demonstrating high YP/PV ratio, flat gels, and high low-end rheology (Table 6).

Table 5: MMO Fluids Formulated for Different Densities

Formulation	#2	#3	#4
Mud Weight, lb/gal	**12**	**14**	**16**
30- lb/bbl bentonite gel slurry, bbl	0.414	0.379	0.344
Freshwater, bbl	0.463	0.424	0.384
Sea salt, lb/bbl	15.20	13.92	12.61
Calcium chloride powder, lb/bbl	11.56	10.58	9.59
MMO (new generation), lb/bbl	1.25	1.14	1.03
API Evaluation base clay, lb/bbl	36.27	33.19	30.07
Barite, lb/bbl	132.97	236.55	351.07
Lime, lb/bbl	1.86	1.71	1.55

Table 6: MMO Fluid Properties after Hot Rolling at 300°F Rheology Tested at 120°F

Formulation	#2	#3	#4
Lime to adjust pH, lb/bbl	1	1	1
Mud Weight, lb/gal	12	14	16
600-rpm Dial Reading	162	173	226
300-rpm Dial Reading	148	165	216
200-rpm Dial Reading	139	163	211
100-rpm Dial Reading	130	161	201
6-rpm Dial Reading	53	75	81
3-rpm Dial Reading	47	49	51
LSYP, $lb_f/100\ ft^2$	41	23	21
PV, cP	14	8	10
YP, $lb_f/100\ ft^2$	134	157	206
10-sec Gel, $lb_f/100\ ft^2$	37	26	44
10-min Gel, $lb_f/100\ ft^2$	37	26	44

Building MMO Fluid

Once losses occur while drilling, the ability to build volume of loss circulation material quickly is a crucial step in mitigating losses with the least NPT. Legacy MMH/MMO fluid used to require extra time for the pre-hydration of bentonite gel to build MMO fluid. Current technology of MMO, on the other hands, requires no preparation of the bentonite slurry before mixing in with MMO to achieve the desired viscosity in freshwater system. Table 7 shows the formulation using dry bentonite clay mixed with MMO at 10:1 ratio. By adjusting pH to its optimal range with caustic soda, the anticipated rheological properties can be reached immediately after mixing and the newly mixed MMO fluid is comparable to fluid after it's been allowed to fully yield overnight, as shown in Table 8.

Table 7: MMO Formulation in Freshwater

Formulation	#5
Freshwater, bbl	0.978
Untreated bentonite, lb/bbl	15.0
MMO, lb/bbl	1.5
Caustic soda, lb/bbl	1.0

Table 8: MMO Fluid Properties After Mixing (Initial) and After Aging at Ambient Temperature Overnight Rheology Tested @ 120°F

Formulation #5	Initial	ASA Ambient
pH	12.34	12.42
600-rpm Dial Reading	247	228
300-rpm Dial Reading	224	204
200-rpm Dial Reading	217	193
100-rpm Dial Reading	190	177
6-rpm Dial Reading	84	80
3-rpm Dial Reading	67	75
LSYP, $lb_f/100\ ft^2$	50	70
PV, cP	23	24
YP, $lb_f/100\ ft^2$	200	180
10-sec Gel, $lb_f/100\ ft^2$	75	71
10-min Gel, $lb_f/100\ ft^2$	72	71

Effect of pH

Alkalinity is a crucial property for MMO fluid to effectively yield and reach its optimal viscosity. Figure 3 shows the YP of multiple MMO fluid formulations with different concentrations of MMO and bentonite gel. After dynamic aging, the pH usually stays in a neutral range closer to pH ~7 with lower YP than expected. Once the pH has been adjusted, in these specific examples with lime to pH ~11, fluid viscosity rebounds as shown with a higher YP in Figure 3.

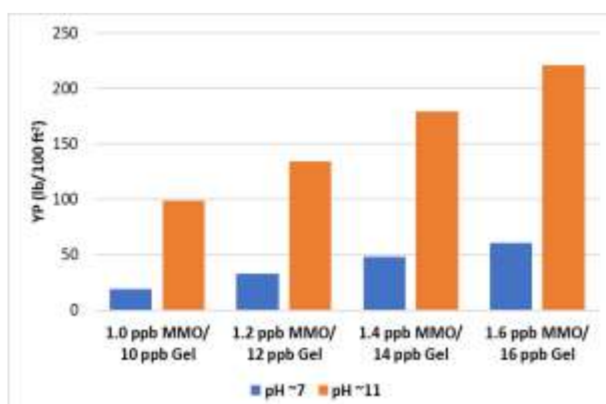

Figure 3: Yield point (YP) of fluids with various concentrations of MMO and bentonite before and after pH adjustment.

One may anticipate that the reason contributing to this phenomenon of viscosity rebound is possibly the improvement in the distribution of the cations such that better clay-to-clay contact occurs resulting in greater electrostatic interaction, thus improving the apparent hydration and resulting viscosity.

Test Equipment Shortcoming

Rheology measurement of any MMO fluid is tricky. Unlike other drilling fluids, six-speed viscometer readings are not typically reproducible for MMO muds. The same MMO fluid could be measured multiple times with vast differences in dial readings. Table 9 shows two significantly different rheology profiles for the same fluid. Repeatability in viscosity measurement can sometime hinder the practical evaluation of the system. The unique thixotropic nature of the MMO fluid introduces a fluid trap between the bob and the sleeve of the viscometer as seen in Figure 4. The volume of this trapped fluid may possibly contribute to the variations in viscometer readings from one measurement to another. Thus, the authors suggest that viscosity readings for MMO fluids should not to be taken as absolute values, but rather as a tool to provide the trend of fluid properties to evaluate the stability of the MMO systems.

Table 9: Variation in Rheology Measurements of a Single MMO Fluid, Rheology Tested at 120°F

Formulation #6	Measurement #1	Measurement #2
600-rpm Dial Reading	300	151
300-rpm Dial Reading	267	148
200-rpm Dial Reading	232	141
100-rpm Dial Reading	200	139
6-rpm Dial Reading	119	83
3-rpm Dial Reading	106	74
Calculated Rheologies from the above Readings		
LSYP, $lb_f/100\ ft^2$	93	65
PV, cP	33	3
YP, $lb_f/100\ ft^2$	234	145
10-sec Gel, $lb_f/100\ ft^2$	163	65
10-min Gel, $lb_f/100\ ft^2$	142	69

Figure 4: MMO fluid residue on bob and sleeve of viscometer affecting the rheology measurement.

Conclusions

The results indicate a greater engineering and operational flexibility can be achieved with newer MMO fluids than what may have been either accomplished or perceived with earlier generations of MMO fluids. With proper engineering, the newer MMO formulations achieve stability under the following conditions:

- 16-lb/gal density (and possibly higher)
- 350°F (and possibly higher)
- 10,000 ppm calcium or magnesium contamination (shown repeatedly under a wide range of testing)
- Ability to add dry gel to the fluid and achieve immediate viscosity by controlling the alkalinity.

Viscometer readings continue to be a source of inconsistent values and should be used for trend work only. This is most likely due to a "fluid trap" between the bob and sleeve created by the thixotropic nature of the MMO fluid.

Nomenclature

AFE = *Authorization for expenditure*
AHR = *After hot rolling*
ASA = *After static aging*
BHR = *Before hot rolling*
LCM = *Lost circulation material*
LSYP = *Low-shear yield point*
MMH = *Mixed metal hydroxides*
MMO = *Mixed metal oxides*
NPT = *Non-productive time*
P10 = *10% chance of success*
P90 = *90% chance of success*
PV = *Plastic viscosity*
YP = *Yield point*

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