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An Innovative Drill-In Fluid System for Injector Wells to Enhance Complete Cleanup of the Filter Cake

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Abstract

As part of a comprehensive program to develop delayed filter-cake breakers, a drill-in fluid with magnesium oxide (MagOx) bridging particles and an ammonium salt based cleanup solution was developed. Thus, an ammonium-based cleanup fluid can be formulated that will dissolve the bridging particles and other drill-in fluid components without using acid-based systems. Because this technology was of specific interest for injector well applications, a laboratory study was undertaken to evaluate this novel system. This paper summarizes laboratory work performed to date and discusses possible field applications.

Introduction

A number of examples can be cited[1,2] where the performance of openhole completions has been greatly reduced as a result of damage caused by drill-in fluid filter-cake residue. Filter-cake cleanup of injection wells is especially problematic because operational constraints often preclude backflowing the well to remove the residual filter cake. In fact, even if flowback is used to lift off the filter cake, the residual filter cake may reheal if not removed from the formation face when injection has started. Consequently, fluid injection can remain impaired if the residual filter cake is not removed by other means.

The cleanup solutions for calcium carbonate-based drill-in filter cake could be acids, chelating agents, oxidizers or enzyme treatments, or a combination of these materials. A common disadvantage of these treatments is that they are highly reactive and may remove the filter cake at the point of circulation before the treatment can be placed over the openhole interval. Consequently, a need exists for cleanup solutions that have a delayed effect on filter-cake integrity, allowing the cleanup solution to be circulated across the entire interval. Ideally, the treatment's reaction with the filter cake would commence when the entire solution is in place and would continue until the filter cake is uniformly removed.

As a part of a comprehensive program to develop delayed filter-cake breakers, a drill-in fluid with MagOx bridging particles and an ammonium based cleanup solution is being developed.[3] The MagOx particles are insoluble in water and standard drill-in fluid base brine such as sodium chloride, but are readily soluble in ammonium salt solutions. Based on this possibility a laboratory study was undertaken to evaluate this MagOx system.

Previous Work

After preliminary laboratory testing of simple systems containing MagOx, an evaluation was performed on a radial flow model in the laboratory of a major operator.[4] The radial flow model is used to scale-up the volumes and to more accurately simulate the drill-in fluid placement, displacement, and cleanup in a radial flow regime. The equipment allows the use of realistic flow rates expected under field conditions.

Radial Flow Model Test. After completion of the test sequence, a 43% return permeability was measured. At the conclusion of the test, the cell was disassembled and core removed for inspection. The top half of the core was clear of filter cake, while the bottom half was layered with undissolved filter cake, most of which appeared to be the Rev Dust added to simulate drill solids. This assessment was confirmed by X-ray diffraction, which detected only ammonium chloride, quartz, halite, kaolin, and chlorite. The layering appeared to be a result of degraded filter cake sliding from the top and sides to the bottom. The following observations were made during testing:

- *A thicker filter cake and higher volume fluid loss than expected were measured.* The magnesium oxide bridging particles had a narrow particle-size distribution. However, a multi-sized MagOx blend would decrease the fluid loss, thereby laying a thinner filter cake, which would be easier to dissolve.
- *Locking the cell overnight for soaking could have negatively affected the total reaction with the mud cake. Reactive components were spent and fresh breaker was not supplied to replace them.* A longer period of soaking with the leakoff valves

opened, thereby replacing spent breaker with fresh, could improve the dissolution of the mud cake. In addition, in field applications for injectors, the initial injection water could contain breaker, removing any residual polymer and bridging material.

- *Drill solids, simulated by Rev Dust, are a major problem that prevents complete removal of a filter cake by chemical means.* Either very high dilution rates are used to minimize drill-solid content, or a new technique such as pullback under-reaming should be employed.[5] With a conventional drilling approach little can be done to mitigate the buildup of solids in the drill-in fluid other than dilution and optimized operation of the solids-control equipment. The continual flow of the drill-solids-laden fluid past the permeable, drilled borehole will continue to build solids content in the filter cake.

The proposed solution to drill solids accumulation involves using a pullback under-reamer and opening a wellbore from the bottom up. This completion technique can be applied in openhole gravel packs or horizontal wells to remove cuttings beds. It requires that the drilling/completion rig have a top drive system. When the hole is opened from the bottom up, drilled solids are circulated away from the newly opened hole. Cuttings transport is simplified because the cuttings are transported in a narrow annulus. Thus, the newly deposited filter cake only contains those agents used in preparing the drill-in fluid. Without the incorporation of drilled solids in the filter cake, the breaking of the filter cake is more likely to be successful.

To evaluate the less-than-expected break in the radial flow tester, the test conditions were replicated in the laboratory using modified dynamic filtration equipment.[6] A drill-in fluid with the same formulation as the fluid tested in the radial flow tester was run. As expected, in the case of the dynamic flow tester that deposits a uniform filter cake, the break time was relatively short. The volume of breaker fluid per unit area of filter cake in contact with the filter cake in the dynamic tester is greater than the volume per unit area in contact with the filter cake in the radial flow tester. A second test was run in the dynamic tester with concentrations of breaker reduced to simulate the lower amount of total active material available in the radial tester. Again, as expected, the break time was longer than the initial test, but not as long as in the radial tester. The increase in break time makes two points:

1. The break time can be controlled to longer times if desired.
2. The laboratory designs were more accurate for minimum break times than for the total time required.

Consequently, a test system such as the radial tester probably more accurately reflects total break times. Based on the results in the initial laboratory tests and radial flow test, additional fluid development work was performed with various particle-size distributions of MagOx and different fluid-loss polymers. The bridging combinations were tested in four brines at both low salt concentrations and near saturation. Screening tests are performed on 10-, 20-, and 35-micron filter disks. These data and further developments are presented in the following sections.

Laboratory Evaluation

Testing was conducted using various combinations of MagOx bridging material in sodium chloride (NaCl), sodium bromide (NaBr), potassium chloride (KCl), and calcium chloride ($CaCl_2$) brines. The particle-size distribution of the MagOx bridging material is shown in **Fig. 1**. It has a d50 of approximately 20 microns, but also has a bimodal distribution ranging on either side of 20 and 150 microns. The distribution range can be changed, if needed, by the grinding and classification process. These data were taken with an experimental material with size distributions that may vary somewhat from a final commercial product.

Initial testing was performed on a nominal 9.0-lb/gal sodium chloride brine, followed by evaluation of the other salt solutions normalized to this same equivalent-weight base brine. Fluid losses were determined using 10-, 20-, and 35-micron aloxite disks. The rheology and fluid-loss characteristics are shown in **Table 1**. The divalent calcium chloride fluid had the highest fluid loss, 22.4 ml total, with a corrected value of 35.8 ml, on the 35-micron disk. The corrected value is obtained by subtracting the spurt loss from the total loss, then multiplying that value by two and adding the spurt loss back. This correction is to normalize to the same filter area as used for API fluid loss paper.

Later testing was performed on fluids with respective salinities near saturation to determine possible weight ranges of fluids containing only bridging solids. These data are shown in **Tables 2** and **3**. Interestingly, the fluid loss for the calcium chloride fluid came down into the same range (11.6 mL total with a corrected value of 18.8 mL) as those for the sodium chloride and sodium bromide test samples. A second set of tests was performed on 10-micron disks with the higher-concentration brines to evaluate higher temperature applications (250°F) and to compare dynamic fluid loss (using the Fann 90) to static fluid loss. These data are shown in Table 3. Anomalous behavior was again noted for the calcium chloride fluids, where the higher temperature sample had high, but measurable rheology, along with high fluid loss, but the lower temperature sample gelled such that the rheology could not be measured. In addition, the fluid loss for the KCl went up at the higher temperature. For the other samples, the dynamic and static fluid losses were similar.

The laboratory team followed these tests by determining the maximum weights for the different fluids, adding additional MagOx (same particle-size distribution as that used for the bridging agent) as the weight material. These data are shown in **Table 4**. The weighted formulations have not yet been optimized.

When high quantities of MagOx were added to the calcium chloride brine, enough gelation occurred that this formulation was dropped from this test series. Because the data in Table 2 indicated that the MagOx could be used as a bridging agent in higher concentrations of calcium chloride, later work will determine what total weight of MagOx can be added without detrimental results. Likewise, potassium chloride was dropped from this test series because it had higher fluid-loss values than those obtained for the sodium chloride and sodium bromide. From these data, the laboratory team decided to concentrate initial efforts on sodium chloride and sodium bromide based fluids, including combinations of the two. Example data for combinations are shown in **Table 5**.

Return Permeability Testing

The test protocol used in this testing is detailed in Appendix 1. The MagOx system return permeability was adequate (65%), but not as good as what can be obtained with the current calcium carbonate system (84%) formulated with variably sized marble and modified starch materials, as shown in **Table 6**. The sodium bromide system was selected for these tests because of its somewhat better fluid-loss characteristics.

Even though initial return permeabilities are not as high as what can be obtained with our other systems, the MagOx system still has merit for injector wells and other applications where a cleanup procedure that does not employ mineral acids or other corrosive materials is required.

This merit is illustrated by a second test where an ammonium-based filter cake breaker system was applied, followed by an initial injection fluid containing an ammonium salt. The resulting return permeability after this treatment was 81%.

Discussion

Formulating a fluid that would provide the required filtration control, while also maintaining proper viscosity, was of primary concern in this project. Filtration control helps to prevent fines as well as polymeric material from entering into the pore throats of the formation, and also prevents a reduction in the permeability of the producing zone. The current materials tested appear to provide adequate filtration control.

The viscosity and filtration control of a given drill-in fluid appears to be influenced by the base brine used. The testing results indicate that lower concentrations of $CaCl_2$ brine affected the filtration control. However, control did not appear to be adversely affected in saturated $CaCl_2$ brine when 40 lb/bbl of MagOx was used as the bridging agent. Also, the filtration control appeared to be adversely affected by high KCl concentrations. These conditions may be addressed by further testing to optimize the system.

The fluids with the best filtration control, when using 370 to 390 lb/bbl of MagOx to provide the maximum density, were those built with NaBr or NaCl alone. The addition of 390 lb/bbl of MagOx to the saturated KCl fluid resulted in poor filtration control. The addition of 370 lb/bbl of MagOx to the saturated $CaCl_2$ fluid resulted in fluid gelation and high viscosities. When 390 lb/bbl of MagOx was tested in combination NaCl/NaBr fluids, the filtration loss was somewhat greater than either an all-NaBr or all-NaCl fluid would experience. The NaBr based fluid provided the most consistent viscosity and filtration control with either 40 lb/bbl or 390 lb/bbl of MagOx and so was chosen as the base fluid for return permeability testing.

A significant weight range increase can be achieved with the MagOx system over conventional calcium carbonate systems while still retaining acid solubility. The sodium bromide system was weighted to 17.7 lb/gal (Table 4).

Conclusions

Based on the preceding data, the following conclusions can be reached.

- Monovalent brine base fluids have the widest range of applications with the MagOx system.
- The filter cake from the MagOx system can be broken with ammonium salt solutions without the use of mineral acids.
- Fluid weights up to 17.7 lb/gal have been obtained that retain the ”acid solubility” of the weight material.
- Further cleanup for an injection well can be attained after breaking the filter cake by pumping ammonium salts in the initial injection water.
- Further work is required to better define weight ranges that can be attained with calcium chloride.

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Appendix 1

The automated return permeability procedure is detailed in the following section.

Automated Return Permeability Procedure. The following procedure was used with the Automated Return Permeameter (ARP) to run the production scenario return permeability tests.

1. Obtain the dry weight of a 1-in. core plug and vacuum saturate in 5-wt% NaCl as synthetic formation water.
2. Obtain the saturated weight and the length and diameter in centimeters to obtain the pore volume and porosity measurements.
3. Mount the core plug in the ARP and seal with 1,500-psi confining pressure, while raising the temperature of the core to 150ºF.
4. Begin flow of refined white oil at a constant flow rate of 3.5 mL/min in the production direction with system pressure (backpressure) of 90 psi.
5. Continue flow at a constant rate until a stable pressure drop condition across the core is reached to obtain the initial permeability.
6. Expose the test fluid to the core dynamically for two hours at 500 psid overbalance pressure in the injection direction.
7. Displace the test fluid back to refined white oil.
8. Resume production of refined white oil in the production direction with system pressure (backpressure) of 90 psi.
9. Repeat Step 6 to obtain the final permeability.
10. Percent return is calculated.

Table 1—MagOx Bridging Agent Testing in 9.0-lb/gal Brines

Fluid Materials	**NaCl**	**KCl**	**$CaCl_2$**	**NaBr**
Water, bbl	0.91	0.91	0.92	0.93
$CaCl_2$, lb	—	—	40	—
KCl, lb	—	51	—	—
NaBr, lb	—	—	—	35
NaCl, lb	46.5	—	—	—
Xanthan Polymer, lb	1.25	1.25	1.25	1.25
Starch Fluid-loss Additive, lb	7	7	7	7
MagOx, lb	40	40	40[a]	40
Hot Rolled at 150°F, hr	16	16	16	16
pH after Hot Rolling and Cooling	11	11.5	10	11.2
Mixed, min	10	10	10	10
Test Temperature, °F	120	120	120	120
Plastic Viscosity, cP	12	11	15	14
Yield Point, lb/100 ft^2	25	24	15	22
Gels, lb/100 ft^2	7/9	7/8	4/4	7/8
Fann 35A Readings				
600 rpm	49	46	45	50
300 rpm	37	35	30	36
200 rpm	31	29	24	30
100 rpm	25	22	16	23
6 rpm	9	8	3	8
3 rpm	7	6	3	6
HPHT Filtration at 150°F, 500 psid, 10-Micron Disk Size				
Spurt Loss, mL	4	4	8	4.8
Total Loss, mL	10.8	12.2	20	14
Corrected Loss, mL	17.6	20.4	32	23.2
20-Micron Disk Size				
Spurt Loss, mL	5.1	5.4	9	6
Total Loss, mL	12.6	14.4	22	15
Corrected Loss, mL	20.1	23.4	35	24
35-Micron Disk Size				
Spurt Loss, ml	6	4.8	9	6.6
Total Loss, mL	13	14	22.4	15.2
Corrected Loss, mL	20	23.2	35.8	23.8

[a] Somewhat larger particle sizes in MagOx material.

Table 2—MagOx Bridging Agent Testing in Near-Saturated Brines

Fluid Materials	NaCl	KCl	$CaCl_2$	NaBr
Fluid Weight, lb/gal	10.6	10.4	11	12.7
Water, bbl	0.84	0.84	0.87	0.8
$CaCl_2$, lb	—	—	107	—
KCl, lb	—	93	—	—
NaBr, lb	—	—	—	205
NaCl, lb	105	—	—	—
Xanthan Polymer, lb	1.25	1.25	1.25	1.25
Starch Fluid-loss Additive, lb	7	7	7	7
MagOx, lb	40	40	40	40
Hot Rolled at 150°F, hr	16	16	16	16
pH after hot rolling and cooling	10.9	11.4	9.6	10.6
Mixed, min	10	10	10	10
Test Temperature, °F	120	120	120	120
Plastic Viscosity, cP	15	14	26	20
Yield Point, lb/100 ft^2	24	24	36	25
Gels, lb/100 ft^2	6/8	8/9	3/5	6/8
Fann 35A Readings				
600 rpm	54	52	88	65
300 rpm	39	38	62	45
200 rpm	33	31	47	37
100 rpm	24	24	31	26
6 rpm	7	9	5	7
3 rpm	6	7	3	5
HPHT Filtration at 150°F, 500 psid, 10-Micron Disk Size				
Spurt Loss, mL	5	5	3.8	5.8
Total Loss, mL	11	14	10.2	10.8
Corrected Loss, mL	17	23	16.6	15.8
20-Micron Disk Size				
Spurt Loss, mL	5.8	5.8	4.8	6.8
Total Loss, mL	12	14.6	11.6	12.4
Corrected Loss, mL	18.2	23.4	18.4	18
35-Micron Disk Size				
Spurt Loss, mL	6	6.2	4.4	5.8
Total Loss, mL	12.2	16.2	11.6	11.6
Corrected Loss, mL	18.4	26.2	18.8	17.4

Table 3—MagOx Bridging Agent Testing at Higher Temperature in Near-Saturated Brines

	NaCl	**NaCl HT**	**NaBr**	**NaBr HT**	**NaCl/NaBr**	**NaCl/NaBr HT**	**CaCl2**	**CaCl2 HT**	**KCl**	**KCl HT**
10.0 lb/gal NaCl Brine, bbl	0.96	0.96	—	—	—	—	—	—	—	—
12.5 lb/gal NaBr Brine, bbl	—	—	0.96	0.96	—	—	—	—	—	—
10.6 lb/gal NaCl/NaBr Brine, bbl	—	—	—	—	0.96	0.96	—	—	—	—
11.6 lb/gal $CaCl_2$ Brine, bbl	—	—	—	—	—	—	0.96	0.96	—	—
9.7 lb/gal KCl Brine, bbl	—	—	—	—	—	—	—	—	0.96	0.96
Xanthan Polymer, lb	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
Starch Fluid-loss Additive Pulverized, lb	7	7	7	7	7	7	7	7	7	7
MagOx, lb	40	40	40	40	40	40	40	40	40	40
Hot Rolled at 250°F, hr	—	16	—	16	—	16		16		16
Hot Rolled at 150°F, hr	16	—	16	—	16	—	16		16	
Mixed, min	10	10	10	10	10	10	10	10	10	10
pH	10.4	10.1	9.8	9.5	9.7	10	[a]	6.6	11.1	10.6
Test Temperature, °F	120	120	120	120	120	120	120	120	120	120
Plastic Viscosity, cP	19	15	26	22	20	19	[a]	72	17	12
Yield Point, lb/100 ft^2	31	25	38	32	23	26	[a]	48	30	28
Gels, lb/100 ft^2	9/12	6/8	9/12	8/8	6/9	7/8	[a]	10/12	13/17	9/10
Fann 35A Readings										
600 rpm	69	55	90	76	63	64	[a]	192	60	52
300 rpm	50	40	64	54	43	45	[a]	120	47	40
200 rpm	42	33	53	45	35	38	[a]	93	41	36
100 rpm	31	25	38	32	25	28	[a]	60	33	28
6 rpm	10	7	11	8	6	8	[a]	12	14	10
3 rpm	8	5	8	6	4	6	[a]	8	11	8
Brookfield LSRV 0.0636 sec^{-1}	22,100	10,100	15,000	6,500	8,800	10,600	[a]	14,400	41,200	12,000
HPHT Filtration at 150°F, 500 psid, 10-Micron Disk Size										
Spurt Loss, mL	2	5.5	3.5	15	3	7	[a]	7	2.5	7
Total Loss, mL	6	14.5	10	35	8	19	[a]	37	9.5	22.5
Corrected Loss, mL	10	23.5	16.5	55	13	31	—	67	16.5	38
Fann 90 at 150ºF, 500 psid, 10-Micron Core Size										
Spurt Adjusted, mL	1		3.6		2.6		[a]		2.8	
15 min Adjusted, mL	4.7		8.1		7		[a]		8.7	
30 min Adjusted, mL	6		9.7		8.6		[a]		11	
45 min Adjusted, mL	7.3		11		10.1		[a]		12.9	
60 min Adjusted, mL	8.4		12.1		11.7		[a]		14.5	

[a] Sample gelled

Table 4—Maximum Weight Fluid Formulations

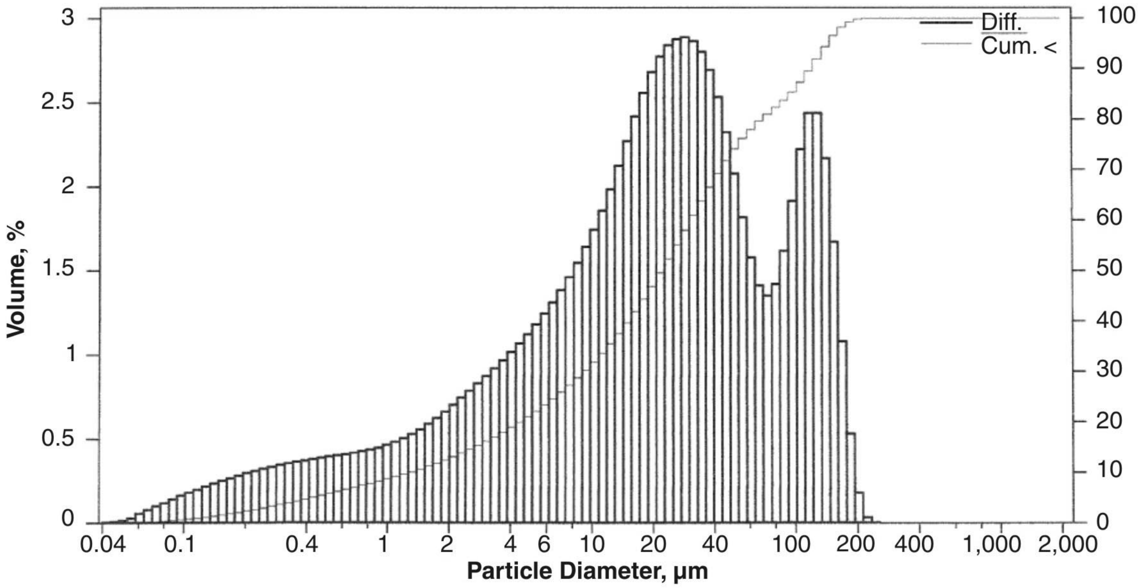
Fluid Mark	NaCl	KCl	NaBr
Fluid Weight, lb/gal	16	16	17.7
Water, bbl	0.6	0.6	0.6
NaBr, lb	—	—	154
NaCl, lb	75	—	—
KCl, lb	—	68	—
$CaCl_2$, lb	—	—	—
Xanthan Polymer, lb	0.63	0.6	0.6
Starch Fluid-loss Additive, lb	7	7	7
MagOx, lb	390	390	370
Hot Rolled at 150°F, hr	16	16	16
Mixed, min	10	10	10
pH	11.6	11.5	11.6
Test Temperature, °F	120	120	120
Plastic Viscosity, cP	46	39	56
Yield Point, lb/100 ft^2	28	28	39
10-second gel, lb/100 ft^2	3	5	4
10-minute gel, lb/100 ft^2	24	39	23
Fann 35A Readings			
600 rpm	120	106	151
300 rpm	74	67	95
200 rpm	54	51	73
100 rpm	33	33	47
6 rpm	5	6	8
3 rpm	3	4	5
HPHT Filtration at 150°F, 500 psid, 20-Micron Disk Size			
Spurt Loss, mL	2	2.2	1.8
Total Loss, mL	14	27.5	10.8
Corrected Loss, mL	26	52.8	19.8

Table 5—NaCl/NaBr Fluid Formulations

Fluid Weight, lb/gal	10.7	11.4	16.4
Water, bbl	0.77	0.72	0.6
NaBr, lb	64	162	50
NaCl, lb	67	25	52
Xanthan Polymer, lb	1.25	1.25	0.6
Starch Fluid-loss Additive, lb	7	7	7
MagOx, lb	40	40	390
Hot Rolled at 150°F, hr	16	16	16
pH after Hot Rolling and Cooling	10.7	10.6	11.6
Mixed, min	10	10	10
Test Temperature, °F	120	120	120
Plastic Viscosity, cP	19	20	57
Yield Point, lb/100 ft^2	25	30	35
Gels, lb/100 ft^2	6/8	6/9	4/17
Fann 35A Readings			
600 rpm	63	70	149
300 rpm	44	50	92
200 rpm	35	41	71
100 rpm	25	29	45
6 rpm	7	7	7
3 rpm	5	5	4
HPHT Filtration at 150°F, 500 psid, 10-Micron Disk Size			
Spurt Loss, mL	4	5	—
Total Loss, mL	9.4	10	—
Corrected Loss, mL	14.8	15	—
20-Micron Disk Size			
Spurt Loss, mL	4.5	5	2
Total Loss, mL	9.4	11	11.8
Corrected Loss, mL	14.3	17	21.6
35-Micron Disk Size			
Spurt Loss, mL	4.5	5	—
Total Loss, mL	10.2	10.2	—
Corrected Loss, mL	15.9	15.4	—

Table 6—Fluids for Return Permeability Testing

Fluid Mark	MagOx	Marble
Fluid Weight, lb/gal	12.7	12.7
Water, bbl	0.8	0.8
NaBr, lb	205	205
Xanthan Polymer, lb	1.25	—
Starch Fluid-loss Additive, lb	7	—
Premium Xanthan, lb	—	0.75
Modified Starch, lb	—	7
MagOx	40	—
Calcium Carbonate Marble, lb	—	40
Rev Dust, lb	20	20
Buffer, lb	—	1
Hot Rolled at 150°F, hr	16	16
Mixed, min	10	10
pH	10.4	8.6
Test Temperature, °F	120	120
Plastic Viscosity, cP	51	17
Yield Point, lb/100 ft^2	38	42
10-second gel, lb/100 ft^2	8	8
10-minute gel, lb/100 ft^2	10	10
Fann 35A readings		
600 rpm	80	76
300 rpm	59	59
200 rpm	48	50
100 rpm	35	39
6 rpm	9	14
3 rpm	7	11
HPHT Filtration at 150°F, 500 psid, 20-Micron Disk Size		
Spurt Loss, mL	1.5	1.5
Total Loss, mL	8	8.5
Corrected Loss, mL	14.5	15.5
Return Permeability, %	65	84



Volume Statistics (Arithmetic) max. $01

Calculations from 0.040 µm to 2000 µm

Volume	100.0%
Mean:	38.10 µm
Median:	21.07 µm
Specific Surf. Area	7689 cm^2/g

% <	10	25	50	75	90
Size µm	1.230	6.373	21.07	50.02	113.3

Fig. 1—Particle size distribution of MagOx material.