CHEMICAL AND PHYSICAL PROPERTIES

SECTION A9
PETROPHYSICAL PROPERTIES

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CABOT

VERSION 3 – 02/14

A9.1 Introduction

Logging in formate brines has been considered a challenge to well-log interpretation because both formate-based drilling fluids and formate brine filtrates have properties that are significantly different from conventional oil- and water-based muds [1][2][3]. These include resistivity, nuclear properties, and density.

A9.2 Resistivity

A9.2.1 Introduction

Electrical resistivity (also known as specific electrical resistance) is a measure of how strongly a material opposes the flow of electric current. A low resistivity indicates a material that readily allows the movement of electrical charge. The SI unit of electrical resistivity is the ohm meter.

The electrical resistivity ρ (rho) of a material is usually defined by the following:

$$\rho = \frac{RA}{l} \quad (1)$$

Where

ρ = static resistivity (ohm m)

R = electrical resistance of the specimen (ohm)

l = length of the specimen (m)

A = cross-sectional area of the specimen (m^2)

The electrical resistivity of drilling and completion fluids is an important parameter for the loggers.

Formate brines contain high amounts of salts, and therefore have very high conductivity and low resistivity.

A9.2.2 Resistivity in single-salt formate brines

Resistivity values for sodium formate, potassium formate, and cesium formate single-salt brines as a function of salt concentration at 15.6°C / 60°F are shown in Figure 1 and Table 1. All data is based on measurements made by Westport Technology Center International, Houston and Cabot Operations and Technical Support Laboratory, Aberdeen, UK [4].

It is interesting to note how resistivity in single-salt formate brines is lowest at medium concentration. At the high end of the concentration scale (as well as the low), resistivity is significantly higher.

A9.2.3 Resistivity in blended formate brines

Blended potassium and cesium formate brines are normally composed of two saturated brines (standard blend) or a saturated cesium formate brine and a slightly diluted potassium formate brine (diluted blend, sometimes used in winter). Resistivity measurements by Westport Technology Center International, Houston and Cabot Operations and Technical Support Laboratory, Aberdeen, UK [4] have shown that resistivity is a linear function of fluid density in a mixed blend of potassium and cesium formate. The predicted resistivity at 15.6°C / 60°F for a standard blend and a diluted blend are shown in Figure 2.

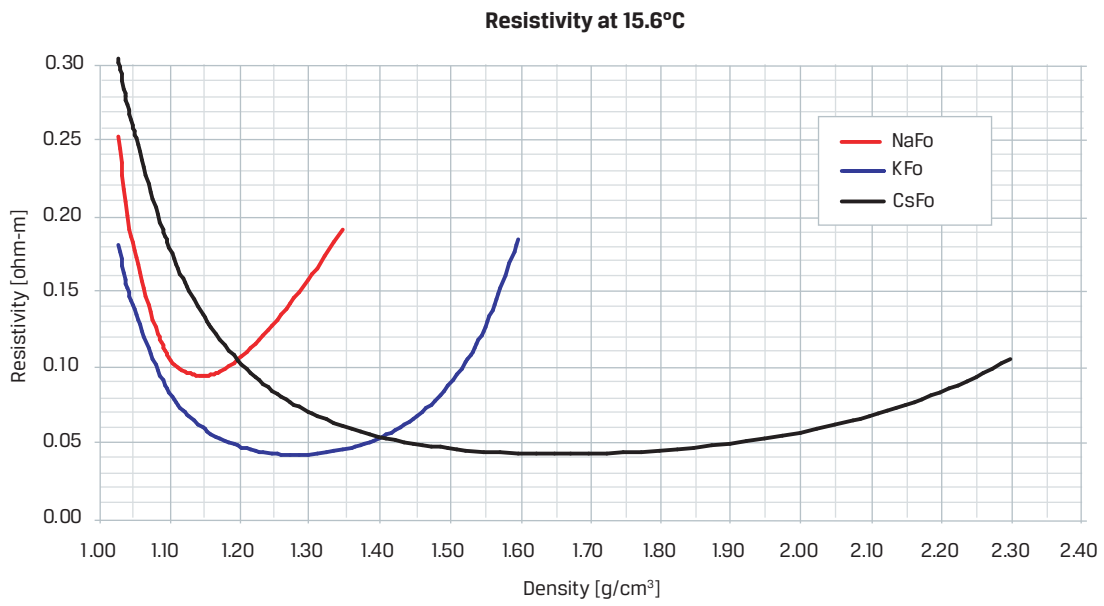
Resistivities are therefore easy to predict for blended brines by drawing a straight line between the densities of the pure brines that are blended. Similar predictions can be made for potassium / sodium formate blends and sodium / cesium formate blends.

A9.2.4 Resistivity – temperature dependence

In formate brines, as in other aqueous salt solutions, resistivity decreases with increased temperature.

The resistivity of blended potassium and cesium formate (1.92 g/cm^3 / 16.0 lb/gal standard blend) has been measured as a function of dilution and temperature. Results are plotted in Figure 3. As can be seen, temperature has a greater effect on resistivity the more diluted the fluid is. The effect of temperature on resistivity is also greater at lower, rather than higher temperatures.

METRIC



FIELD

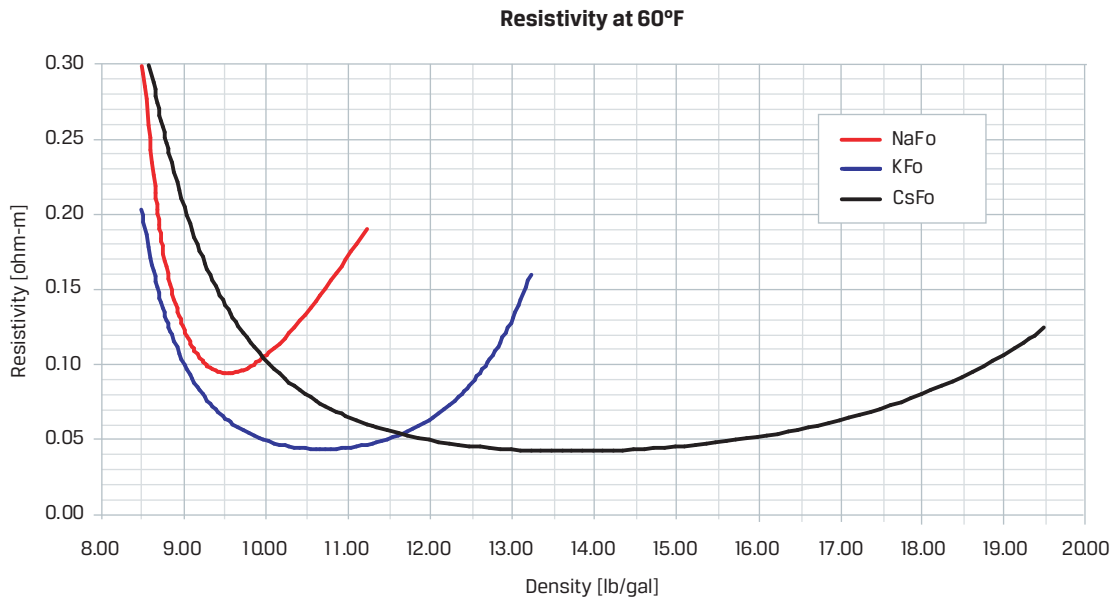


Figure 1 Resistivity of sodium, potassium, and cesium formate single-salt brines as a function of formate concentration at standard conditions (15.6°C / 60°F).

Table 1 Resistivity of sodium, potassium, and cesium formate single-salt brines at standard conditions (15.6°C / 60°F).

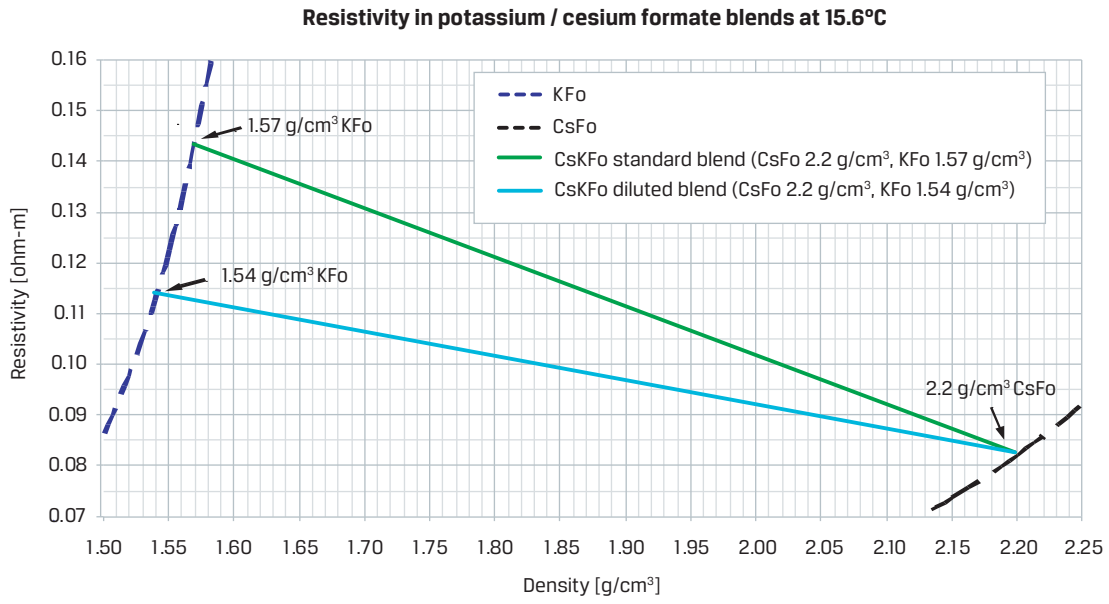
METRIC

Density [g/cm³]	Resistivity [ohm m]		
	NaFo	KFo	CsFo
1.03	0.252	0.180	0.303
1.05	0.181	0.140	0.259
1.10	0.107	0.084	0.182
1.15	0.093	0.059	0.134
1.20	0.104	0.047	0.104
1.25	0.127	0.042	0.083
1.30	0.156	0.041	0.069
1.35	0.190	0.044	0.060
1.40		0.051	0.053
1.45		0.065	0.048
1.50		0.086	0.045
1.55		0.123	0.043
1.60		0.183	0.042
1.65			0.041
1.70			0.041
1.75			0.042
1.80			0.044
1.85			0.046
1.90			0.048
1.95			0.052
2.00			0.056
2.05			0.061
2.10			0.067
2.15			0.074
2.20			0.082
2.25			0.092
2.30			0.104

FIELD

Density [lb/gal]	Resistivity [ohm m]		
	NaFo	KFo	CsFo
8.50	0.309	0.202	0.334
8.75	0.183	0.140	0.261
9.00	0.127	0.103	0.209
9.25	0.102	0.079	0.171
9.50	0.093	0.065	0.142
9.75	0.095	0.055	0.120
10.00	0.104	0.049	0.103
10.25	0.116	0.045	0.090
10.50	0.132	0.043	0.080
10.75	0.150	0.042	0.071
11.00	0.169	0.043	0.065
11.25	0.190	0.046	0.059
11.50		0.049	0.055
11.75		0.054	0.052
12.00		0.062	0.049
12.25		0.072	0.046
12.50		0.085	0.045
12.75		0.103	0.043
13.00		0.127	0.042
13.25		0.159	0.042
13.50			0.041
13.75			0.041
14.00			0.041
14.25			0.042
14.50			0.042
14.75			0.043
15.00			0.044
15.25			0.045
15.50			0.047
15.75			0.049
16.00			0.051
16.25			0.053
16.50			0.055
16.75			0.058
17.00			0.062
17.25			0.065
17.50			0.069
17.75			0.074
18.00			0.079
18.25			0.085
18.50			0.091
18.75			0.098
19.00			0.105
19.25			0.114
19.50			0.123

METRIC



FIELD

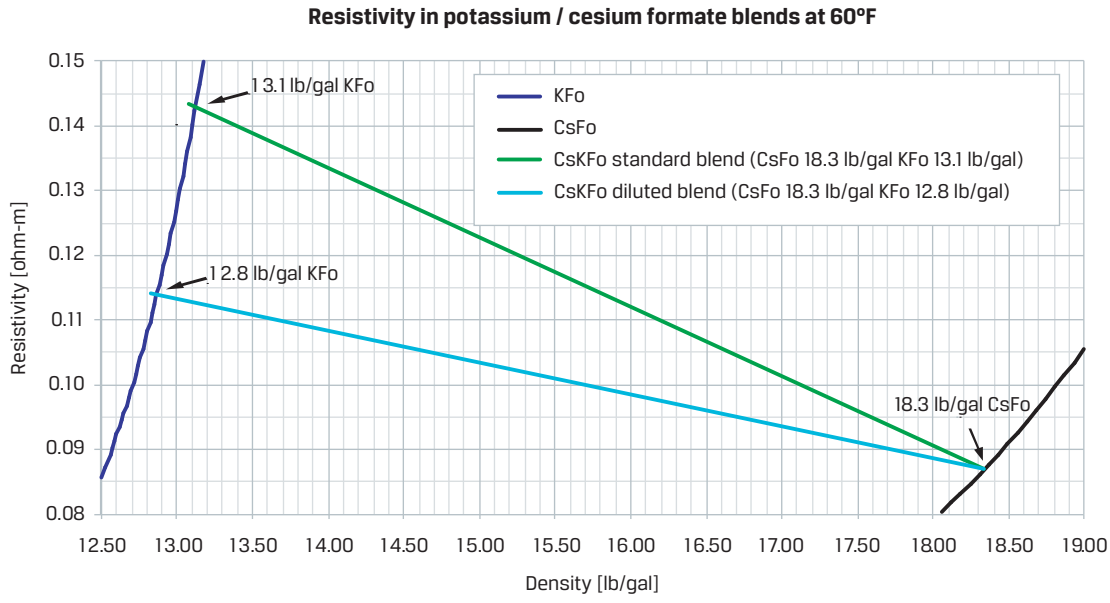


Figure 2 Resistivity as a function of brine density for two different potassium and cesium formate blends. The one blend is a standard blend based on 1.57 g/cm³ / 13.1 lb/gal potassium formate brine and 2.20 g/cm³ / 18.3 lb/gal cesium formate brine. The other blend is a diluted blend (1.54 g/cm³ / 12.8 lb/gal potassium formate and 2.20 g/cm³ / 18.3 lb/gal cesium formate) that is often used in the winter.

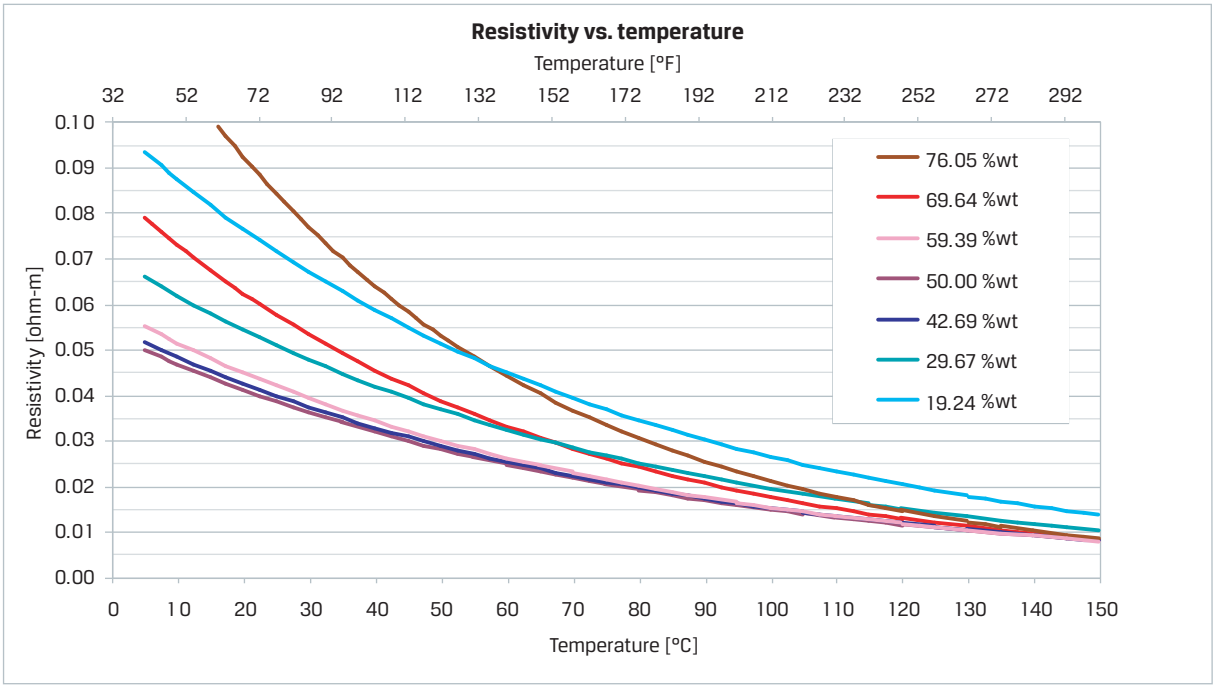


Figure 3 Resistivity as a function of temperature for various dilutions of 1.92 g/cm³ / 16.0 lb/gal potassium / cesium formate brine.

A9.3 Hydrogen Index

Hydrogen Index (HI) is an important property in the response of a neutron porosity log. The Hydrogen Index of a material is defined as the number of hydrogen atoms per unit volume divided by the number of hydrogen atoms per unit volume of pure water at 75°F.

Hydrogen Index for a brine of a given concentration (density) can be calculated when the exact composition of the brine is known. Hydrogen Index as a function of brine density for single-salt sodium, potassium, and cesium formate brines are given in Table 2 (metric) and Table 3 (field). These values are calculated from the composition data given in Section A2, Brine Density and PVT Data.

Hydrogen Index for potassium and cesium formate brine blends can be calculated easily from the Hydrogen Index of the two brines that are blended according to the following linear relationship:

$$HI_{CsKFo} = HI_{KFo}\, x \quad \frac{(HI_{CsKFo} - HI_{KFo}) \cdot (\sigma_{CsKFo} - \sigma_{KFo})}{(\sigma_{CsFo} - \sigma_{KFo})}$$

Where

HI_{CsKFo} = HI for blended brine
HI_{CsFo} = HI for stock *CsFo* brine
HI_{KFo} = HI for stock *KFo* brine
σ_{CsKFo} = Density or g/cm³ of blended brine
σ_{CsFo} = Density or g/cm³ of stock *CsFo* brine
σ_{KFo} = Density or g/cm³ of stock *KFo* brine

The equation is valid for all density units, but they need to be consistent. The Hydrogen Index for the two most commonly used cesium potassium formate brine blends are listed in Table 4 to Table 5 for metric and field units.

Table 2 Hydrogen Index for sodium, potassium, and cesium formate single-salt brines as a function of brine density.

METRIC

Sodium formate		
Density [g/cm³]	%wt NaFo	Hydrogen Index
1.00	0.0	1.000
1.01	1.8	0.995
1.02	3.3	0.990
1.03	4.9	0.986
1.04	6.5	0.981
1.05	8.1	0.977
1.06	9.6	0.972
1.07	11.1	0.967
1.08	12.7	0.961
1.09	14.2	0.956
1.10	15.7	0.950
1.11	17.2	0.945
1.12	18.6	0.939
1.13	20.1	0.933
1.14	21.5	0.927
1.15	23.0	0.921
1.16	24.4	0.915
1.17	25.8	0.908
1.18	27.2	0.902
1.19	28.6	0.895
1.20	29.9	0.888
1.21	31.3	0.882
1.22	32.6	0.875
1.23	34.0	0.868
1.24	35.3	0.860
1.25	36.6	0.853
1.26	37.9	0.846
1.27	39.2	0.839
1.28	40.4	0.831
1.29	41.7	0.823
1.30	42.9	0.816
1.31	44.2	0.808
1.32	45.4	0.800
1.33	46.6	0.793
1.34	47.8	0.785
1.35	49.0	0.777
1.36	50.1	0.769

METRIC

Potassium formate		
Density [g/cm³]	%wt KFo	Hydrogen Index
1.00	0.0	1.000
1.01	1.9	0.993
1.02	3.6	0.987
1.03	5.3	0.981
1.04	7.0	0.975
1.05	8.7	0.969
1.06	10.3	0.962
1.07	11.9	0.956
1.08	13.6	0.949
1.09	15.1	0.943
1.10	16.7	0.936
1.11	18.3	0.929
1.12	19.8	0.922
1.13	21.4	0.914
1.14	22.9	0.907
1.15	24.4	0.900
1.16	25.9	0.892
1.17	27.3	0.885
1.18	28.8	0.877
1.19	30.2	0.869
1.20	31.6	0.861
1.21	33.0	0.853
1.22	34.4	0.845
1.23	35.8	0.837
1.24	37.1	0.829
1.25	38.5	0.820
1.26	39.8	0.812
1.27	41.1	0.803
1.28	42.4	0.795
1.29	43.7	0.786
1.30	45.0	0.777
1.31	46.3	0.769
1.32	47.5	0.760
1.33	48.8	0.751
1.34	50.0	0.742
1.35	51.2	0.733
1.36	52.4	0.724
1.37	53.6	0.714
1.38	54.8	0.705
1.39	55.9	0.696
1.40	57.1	0.686
1.41	58.2	0.677
1.42	59.4	0.667
1.43	60.5	0.658
1.44	61.6	0.648
1.45	62.7	0.638
1.46	63.8	0.628
1.47	64.9	0.618
1.48	66.0	0.608
1.49	67.0	0.598
1.50	68.1	0.588
1.51	69.1	0.578
1.52	70.1	0.568
1.53	71.2	0.558
1.54	72.2	0.547
1.55	73.2	0.537
1.56	74.2	0.526
1.57	75.2	0.516
1.58	76.2	0.505
1.59	77.2	0.495
1.60	78.1	0.484

METRIC

Cesium formate		
Density [g/cm³]	%wt CsFo	Hydrogen Index
1.00	0.0	1.000
1.02	3.2	0.989
1.04	5.6	0.984
1.06	8.0	0.980
1.08	10.3	0.974
1.10	12.6	0.969
1.12	14.8	0.963
1.14	17.0	0.956
1.16	19.1	0.950
1.18	21.1	0.943
1.20	23.2	0.936
1.22	25.1	0.929
1.24	27.0	0.922
1.26	28.9	0.914
1.28	30.7	0.907
1.30	32.5	0.899
1.32	34.2	0.891
1.34	35.9	0.883
1.36	37.6	0.875
1.38	39.2	0.867
1.40	40.8	0.858
1.42	42.3	0.850
1.44	43.8	0.842
1.46	45.2	0.833
1.48	46.6	0.825
1.50	48.0	0.816
1.52	49.3	0.808
1.54	50.7	0.799
1.56	51.9	0.791
1.58	53.2	0.783
1.60	54.4	0.774
1.62	55.5	0.766
1.64	56.7	0.757
1.66	57.8	0.749
1.68	58.9	0.741
1.70	60.0	0.732
1.72	61.0	0.724
1.74	62.0	0.716
1.76	63.0	0.708
1.78	63.9	0.700
1.80	64.9	0.692
1.82	65.8	0.683
1.84	66.7	0.675
1.86	67.5	0.667
1.88	68.4	0.659
1.90	69.2	0.651
1.92	70.0	0.643
1.94	70.8	0.636
1.96	71.6	0.628
1.98	72.4	0.620
2.00	73.1	0.612
2.02	73.9	0.604
2.04	74.6	0.596
2.06	75.3	0.588
2.08	76.0	0.579
2.10	76.7	0.571
2.12	77.4	0.563
2.14	78.0	0.555
2.16	78.7	0.546
2.18	79.3	0.538
2.20	80.0	0.529
2.22	80.6	0.520
2.24	81.3	0.511
2.26	81.9	0.502
2.28	82.6	0.493
2.30	83.2	0.483
2.32	83.8	0.473
2.34	84.5	0.463
2.36	85.1	0.453
2.38	85.7	0.443
2.40	86.4	0.432

Table 3 Hydrogen Index for sodium, potassium, and cesium formate single-salt brines as a function of brine density.

FIELD

Sodium formate		
Density [lb/gal]	%wt NaFo	Hydrogen Index
8.34	0.0	1.000
8.40	1.2	0.996
8.50	3.1	0.991
8.60	5.0	0.986
8.70	6.9	0.980
8.80	8.8	0.974
8.90	10.6	0.968
9.00	12.4	0.962
9.10	14.2	0.956
9.20	16.0	0.949
9.30	17.8	0.942
9.40	19.6	0.935
9.50	21.3	0.928
9.60	23.0	0.921
9.70	24.7	0.913
9.80	26.4	0.905
9.90	28.1	0.898
10.00	29.7	0.890
10.10	31.3	0.881
10.20	32.9	0.873
10.30	34.5	0.865
10.40	36.1	0.856
10.50	37.6	0.847
10.60	39.2	0.838
10.70	40.7	0.829
10.80	42.2	0.820
10.90	43.7	0.811
11.00	45.1	0.802
11.10	46.6	0.792
11.20	48.0	0.783
11.30	49.4	0.773
11.40	50.8	0.764

FIELD

Potassium formate		
Density [lb/gal]	%wt KFo	Hydrogen Index
8.34	0.0	1.000
8.40	1.3	0.996
8.50	3.3	0.989
8.60	5.4	0.982
8.70	7.4	0.975
8.80	9.4	0.967
8.90	11.4	0.959
9.00	13.3	0.951
9.10	15.2	0.943
9.20	17.1	0.935
9.30	19.0	0.927
9.40	20.8	0.918
9.50	22.6	0.909
9.60	24.4	0.900
9.70	26.2	0.891
9.80	27.9	0.882
9.90	29.7	0.873
10.00	31.4	0.864
10.10	33.1	0.854
10.20	34.7	0.844
10.30	36.4	0.834
10.40	38.0	0.824
10.50	39.6	0.814
10.60	41.2	0.804
10.70	42.7	0.794
10.80	44.3	0.783
10.90	45.8	0.773
11.00	47.3	0.762
11.10	48.8	0.752
11.20	50.2	0.741
11.30	51.7	0.730
11.40	53.1	0.719
11.50	54.5	0.708
11.60	55.9	0.696
11.70	57.3	0.685
11.80	58.7	0.674
11.90	60.0	0.662
12.00	61.4	0.651
12.10	62.7	0.639
12.20	64.0	0.627
12.30	65.3	0.615
12.40	66.6	0.603
12.50	67.8	0.591
12.60	69.1	0.579
12.70	70.3	0.567
12.80	71.6	0.554
12.90	72.8	0.542
13.00	74.0	0.529
13.10	75.2	0.517
13.20	76.3	0.504
13.30	77.5	0.491

FIELD

Cesium formate		
Density [lb/gal]	%wt CsFo	Hydrogen Index
8.34	0.0	1.000
8.40	1.5	0.993
8.60	4.5	0.988
8.80	7.3	0.982
9.00	10.1	0.976
9.20	12.9	0.969
9.40	15.5	0.962
9.60	18.1	0.954
9.80	20.6	0.946
10.00	23.0	0.938
10.20	25.3	0.929
10.40	27.6	0.920
10.60	29.8	0.911
10.80	32.0	0.902
11.00	34.1	0.893
11.20	36.1	0.883
11.40	38.1	0.873
11.60	40.0	0.863
11.80	41.8	0.853
12.00	43.6	0.843
12.20	45.4	0.833
12.40	47.0	0.823
12.60	48.7	0.813
12.80	50.3	0.803
13.00	51.8	0.793
13.20	53.3	0.783
13.40	54.7	0.773
13.60	56.1	0.763
13.80	57.5	0.752
14.00	58.8	0.743
14.20	60.0	0.733
14.40	61.3	0.723
14.60	62.5	0.713
14.80	63.6	0.703
15.00	64.7	0.693
15.20	65.8	0.684
15.40	66.9	0.674
15.60	67.9	0.664
15.80	68.9	0.655
16.00	69.9	0.645
16.20	70.9	0.636
16.40	71.8	0.626
16.60	72.7	0.617
16.80	73.6	0.607
17.00	74.5	0.598
17.20	75.3	0.588
17.40	76.2	0.578
17.60	77.0	0.568
17.80	77.8	0.558
18.00	78.6	0.548
18.20	79.4	0.538
18.40	80.2	0.528
18.60	80.9	0.517
18.80	81.7	0.506
19.00	82.5	0.495
19.20	83.2	0.483
19.40	84.0	0.472

Table 4 Hydrogen Index for standard potassium / cesium formate blends composed of 1.57 g/cm^3 potassium formate and 2.20 g/cm^3 cesium formate.

METRIC				
Density [g/cm^3]	%wt KFo	%wt CsFo	%wt H_2O	Hydrogen Index
1.57	75.2	0.0	24.8	0.516
1.58	73.5	1.8	24.7	0.517
1.59	71.9	3.5	24.6	0.517
1.60	70.3	5.2	24.5	0.517
1.61	68.7	6.9	24.4	0.517
1.62	67.1	8.6	24.3	0.517
1.63	65.5	10.3	24.2	0.518
1.64	64.0	11.9	24.1	0.518
1.65	62.5	13.5	24.0	0.518
1.66	61.0	15.1	23.9	0.518
1.67	59.5	16.7	23.8	0.518
1.68	58.0	18.3	23.7	0.519
1.69	56.5	19.8	23.6	0.519
1.70	55.1	21.4	23.5	0.519
1.71	53.7	22.9	23.4	0.519
1.72	52.3	24.4	23.3	0.520
1.73	50.9	25.8	23.3	0.520
1.74	49.5	27.3	23.2	0.520
1.75	48.2	28.7	23.1	0.520
1.76	46.8	30.2	23.0	0.520
1.77	45.5	31.6	22.9	0.521
1.78	44.2	33.0	22.8	0.521
1.79	42.9	34.3	22.7	0.521
1.80	41.6	35.7	22.7	0.521
1.81	40.4	37.0	22.6	0.521
1.82	39.1	38.4	22.5	0.522
1.83	37.9	39.7	22.4	0.522
1.84	36.7	41.0	22.3	0.522
1.85	35.5	42.3	22.3	0.522
1.86	34.3	43.6	22.2	0.522
1.87	33.1	44.8	22.1	0.523
1.88	31.9	46.1	22.0	0.523
1.89	30.7	47.3	22.0	0.523
1.90	29.6	48.5	21.9	0.523
1.91	28.5	49.7	21.8	0.524
1.92	27.3	50.9	21.7	0.524
1.93	26.2	52.1	21.7	0.524
1.94	25.1	53.3	21.6	0.524
1.95	24.0	54.4	21.5	0.524
1.96	22.9	55.6	21.5	0.525
1.97	21.9	56.7	21.4	0.525
1.98	20.8	57.8	21.3	0.525
1.99	19.8	59.0	21.3	0.525
2.00	18.7	60.1	21.2	0.525
2.01	17.7	61.2	21.1	0.526
2.02	16.7	62.2	21.1	0.526
2.03	15.7	63.3	21.0	0.526
2.04	14.7	64.4	20.9	0.526
2.05	13.7	65.4	20.9	0.526
2.06	12.7	66.5	20.8	0.527
2.07	11.8	67.5	20.8	0.527
2.08	10.8	68.5	20.7	0.527
2.09	9.9	69.5	20.6	0.527
2.10	8.9	70.5	20.6	0.528
2.11	8.0	71.5	20.5	0.528
2.12	7.1	72.5	20.5	0.528
2.13	6.2	73.4	20.4	0.528
2.14	5.3	74.4	20.3	0.528
2.15	4.4	75.4	20.3	0.529
2.16	3.5	76.3	20.2	0.529
2.17	2.6	77.2	20.2	0.529
2.18	1.7	78.2	20.1	0.529
2.19	0.9	79.1	20.1	0.529
2.20	0.0	80.0	20.0	0.530

Table 5 Hydrogen Index for standard potassium / cesium formate blends composed of 13.10 lb/gal potassium formate and 18.36 lb/gal cesium formate.

FIELD				
Density [lb/gal]	**%wt KFo**	**%wt CsFo**	**%wt H_2O**	**Hydrogen Index**
13.10	75.2	0.0	24.8	0.517
13.20	73.2	2.1	24.7	0.517
13.30	71.2	4.2	24.6	0.517
13.40	69.3	6.3	24.5	0.517
13.50	67.4	8.3	24.3	0.518
13.60	65.5	10.3	24.2	0.518
13.70	63.7	12.2	24.1	0.518
13.80	61.9	14.2	24.0	0.518
13.90	60.1	16.1	23.9	0.519
14.00	58.3	18.0	23.7	0.519
14.10	56.6	19.8	23.6	0.519
14.20	54.8	21.6	23.5	0.519
14.30	53.1	23.4	23.4	0.520
14.40	51.5	25.2	23.3	0.520
14.50	49.8	27.0	23.2	0.520
14.60	48.2	28.7	23.1	0.520
14.70	46.6	30.4	23.0	0.521
14.80	45.0	32.1	22.9	0.521
14.90	43.5	33.7	22.8	0.521
15.00	41.9	35.4	22.7	0.521
15.10	40.4	37.0	22.6	0.522
15.20	38.9	38.6	22.5	0.522
15.30	37.4	40.2	22.4	0.522
15.40	36.0	41.7	22.3	0.522
15.50	34.5	43.2	22.2	0.523
15.60	33.1	44.8	22.1	0.523
15.70	31.7	46.2	22.0	0.523
15.80	30.3	47.7	21.9	0.523
15.90	29.0	49.2	21.9	0.524
16.00	27.6	50.6	21.8	0.524
16.10	26.3	52.0	21.7	0.524
16.20	25.0	53.4	21.6	0.524
16.30	23.7	54.8	21.5	0.525
16.40	22.4	56.2	21.4	0.525
16.50	21.1	57.5	21.4	0.525
16.60	19.8	58.9	21.3	0.525
16.70	18.6	60.2	21.2	0.526
16.80	17.4	61.5	21.1	0.526
16.90	16.2	62.8	21.0	0.526
17.00	15.0	64.1	21.0	0.526
17.10	13.8	65.3	20.9	0.527
17.20	12.6	66.6	20.8	0.527
17.30	11.5	67.8	20.7	0.527
17.40	10.3	69.0	20.7	0.527
17.50	9.2	70.2	20.6	0.527
17.60	8.1	71.4	20.5	0.528
17.70	7.0	72.6	20.4	0.528
17.80	5.9	73.7	20.4	0.528
17.90	4.8	74.9	20.3	0.528
18.00	3.7	76.0	20.2	0.529
18.10	2.7	77.1	20.2	0.529
18.20	1.6	78.3	20.1	0.529
18.30	0.6	79.3	20.0	0.529
18.36	0.0	80.0	20.0	0.530

A9.4 Sonic velocity

Sonic velocity is an important property for logging. There is very little sonic data available on formate brines in the open literature. Available sonic velocity data for some formate brines are listed in Table 6. The data is taken from various sources and might not be accurate.

Table 6 Sonic velocity for three typical formate compositions.

Brine type	Density		Temperature		Pressure		Sonic velocity		Composition
	g/cm³	lb/gal	°C	°F	Pa	[psi]	[m/s]	[ft/s]	
NaFo	1.28	10.7	20	68	–	–	1,880	6,168	–
KFo	1.53	12.8	20	68	–	–	1,960	6,430	–
KFo	1.57	13.1	20	68	689	100	1,951	6,402	76% KFo
CsKFo	1.65	13.8	23.9	75	689	100	1,895	6,218	14.36% Cs / 85.63% K, 14.366 / 85.634 ml, 30.45 / 134.44 g
CsFo	2.30	19.2	20	68	–	–	1,550	5,085	–
CsFo	2.30	19.2	20	68	689	100	1,580	5,185	83% CsFo

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