

# A new Empirical to Predict Apparent Viscosity of Borate-Crosslinked HPG Gel in Fractures for A high-Temperature

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**Abstract** — The viscosity approximation is even more significant for borate-crosslinked hydroxypropyl guar (HPG) gel because of the gelling behavior is essential in the petroleum enhanced, depends on Temperature, a residence time in tubing- time at shear, fracture shear rate, fluid pH, and additives. These factors require that fluid characterization performed in typical field conditions. The present study describes predicting apparent viscosity developed from data gathered by Rheology Fluid Software Application and based on the procedure of versus shear rate with time. The study also extends the method to include the effect of shear on the rheology of borate-crosslinked HPG. The present study also provides main curves of the minimum acceptable apparent viscosity is 200 mPa\*s -shear rate for the borate crosslinked HPG with versus temperature. Borrowing from ideas in additives enhanced the apparent viscosity, gel stabilizer has the potential to keep the performance of the fluid and no barker during the job. From this work, we suggest critical that can be used to optimize fracture fluid additives and or manage viscosity to the best way to carry the proppant.

**Keywords—** *Rheology, Apparent Viscosity, borate-crosslinked HPG, Shear rate, Additives, Gel Stabilizer.*

## I. INTRODUCTION

Chemical stimulation is an essential method of increasing oil and gas well production which, even today, is still experiencing rapid technical growth.

The primary functions of Chemical additive to enhance the viscosity and improve the performance of Gel in fractures. HPG more stable at an elevated temperature than guar, therefore HPG is better suited for use in high-temperature wells [1]. The addition of the less-hydrophilic hydroxypropyl substituents also makes the HPG more soluble in alcohol. Guar can be derivatized with propylene oxide to produce hydroxypropyl guar (HPG). The reaction changes some of the -OH sites to -O -CH<sub>2</sub> -CHOH -CH<sub>3</sub>.

The structure of the HPG molecule is shown in Figure 1. So HPG typically contains only about 2 to 4% insoluble residue [2-3]. Hydroxypropyl guar typically is used to correlate the rheology of a polymer for high temperatures [4-5]. Also known as the time-temperature superposition [6].

The method of providing viscosity has been used earlier by other researchers to relate the viscoelastic properties of hydroxypropyl guar crosslinked with borate ions [7-8]. In the current work, the result the shear rate versus temperature is included in the method of shear rate variables with time and developed to relate the nominal shear rate with the borate-crosslinked HPG viscosity estimation at different temperatures and shear rates. The present study also provides viscosity-shear rate significant curves at different temperatures. HPG has generally been considered to be less damaging to the formation face [9].

The rheological characteristics of the fluid are often considered the most significant. However, effective hydraulic fracturing treatments require that the fluids have some other special features [10]. In further to exhibiting the proper viscosity in the fracture. Since the term of temperature and many different kinds of fluids developed to provide the characteristics of the gel in fractures [11].

Rheology treats the relationships between shear stress, shear rate, and any other variable that may influence these relationships. Thus, rheology is the science of deformation and flow of the fluids [12]. It's so important to be able to describe how the fluid will react or behave under the specific conditions of its application. The rheological characteristics of a fluid are important in evaluating the ability of a fluid to perform a specific function. Therefore, a thorough understanding of fluid rheology and the impact of shear is necessary to optimize fluid design [13]. Ideally, high viscosity is desirable only under low shear rate conditions and should decrease as the flow rate increase. Viscosity is the most significant property of any fluid resistance to flow. Therefore, the viscosity defined as the internal friction of fluid began by

molecular, which creates resist a tendency to flow [14-15].

This friction becomes apparent viscosity once a layer of the fluid is made to move in relative to another layer [16]. The higher the friction, the higher the amount of the force essential to cause this movement, which is called shear. Shearing occurs whenever the fluid is physically moved or disturbed. The viscosity of a fluid is the physical property that characterizes the flow resistance of Newtonian fluids. More viscous fluids require a higher shearing force to move than less viscous materials.[17-18].

In the oil industry, the viscosity of a fluid is usually reported either in Poise, Centipoise (cp) and or millipascal-second (mPa\*s). The fracturing fluid viscosity determines how well the proppant is suspended in the fluid and is a factor in determining the fracture's geometry. The nominal viscosity should keep pending after the fracture closes or excessive proppant settling may occur [19-20].

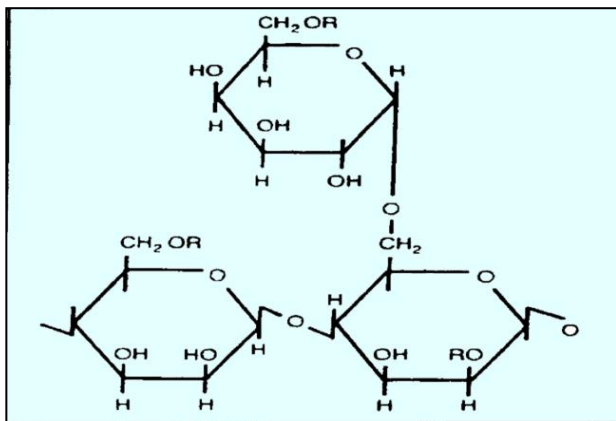


Figure 1: The structure of HPG

## II. METHODOLOGY AND PROCEDURES

The present study selected the simulation compared to the shear rate versus temperature under a specific condition, and data listed in Table 1. Additional special additives to improve the performance of gel in fractures. This simulation that can provide adequate rheological performance at a temperature up 143.3 °C by using Rheology Fluid Software Application. Following the simulation, Hydroxypropyl guar (HPG) was loaded into a high temperature to monitor apparent viscosity development at simulated gel in fracture conditions Hydroxypropyl guar is crosslinked by borax to form borate-crosslinked HPG gel. The borate ion is an active species in crosslinking that the concentrate a function of pH and temperature.

Viscosity properties of hydroxypropyl guar ( HPG ), delayed crosslinked by borate ions were used by Rheology Fluid Software Application for shear rate versus temperature with elapsed time to observe the best acceptable for apparent viscosity. Further the gel to carry and suspending the proppant if may occur.

Borate-Crosslinked HPG Gel, the following characteristics as shown in Table 2.

At primarily viscosity from 200 °F (93.3 °C) through 250 °F (121.1 °C) that it indicates the performance keep and no breaking, once the temperature arrives at the 290 °F (143.3°C), the viscosity was rapidly lower, immediately breaking and can't carry the proppant through the wellbore. So suggested adding gel stabilizer to keep the performance of the viscosity at a high-temperature during 100 minutes and capable of versus gel concentration and get a good response for the trend of the apparent viscosity and acceptable at temperature 290 °F (143.3 °C).

Table1: Treatment Parameters

Items	
<b>Treating Rate</b>	30 bpm (4.77 m <sup>3</sup> /min)
<b>Tubing Diameter (ID)</b>	2.992 Inch (7.59968 cm)
<b>Perforation Depth</b>	12350 feet (3764.28 m)
<b>Shear Rate in Tubing</b>	2000 1/sec
<b>Residence Time in Tubing (Time @ Shear)</b>	3.6 minute
<b>Anticipated Pump Time</b>	100 minutes
<b>Bottom hole Static Temperature</b>	290 °F (143.3 °C)

Table 2: Borate- Crosslinked HPG Gel

Description	Additive name	Concentration
<b>Gelling Agent Concentration</b>	Hydroxypropyl guar	6 kg/m <sup>3</sup>
<b>Gel Stabilizer Concentration</b>	A gel stabilizer for high temperature-solid	0 – 0.4794 kg/m <sup>3</sup>
<b>High pH Buffer</b>	A high pH control, is not strictly a buffer is pH control solution	2.72 L/m <sup>3</sup>
<b>Cross-linker</b>	A primary delayed crosslinker base oil solution	4.2 L/m <sup>3</sup>
<b>Cross-linker</b>	A secondary instantaneous crosslinker - high pH, water base	0.5 L/m <sup>3</sup>
<b>pH</b>	Gelling Agent	8.0 to 10.1
<b>Density</b>	Crosslinking agent additive	1277 kg/m <sup>3</sup>
<b>KCL</b>	Salt	2.0 %
<b>Lower pH Buffer</b>	A weak acid solution	0.2 L/m <sup>3</sup>

### III. RESULTS

The corresponding Power Law parameters for apparent viscosity profile with versus shear rate and temperatures with time elapsed. The results of rheology show borate-crosslinked (HPG) system is listed in Tables (3-11).

The tables show the significant results with versus shear rate and temperatures with elapsed time. Additional versus Gel-Stabilizer concentrate to improve the performance of the fluid during estimated pump time (100 minutes) and detected the breaking viscosity at the end of the job.

Table 3: Power Law Parameters for HydroxyPropyl Guar (HPG), at 200 °F (93.3 °C)

Elapsed Time (minutes) @ Test Temperature	Temperature (°F)	n'	K' value (lb*s <sup>n'</sup> /ft <sup>2</sup> )	Apparent Viscosity (mPa*s) at Shear rate		
				40 s <sup>-1</sup>	80 s <sup>-1</sup>	170 s <sup>-1</sup>
0	200	0.55	0.009100	79.2	59.65	42.82
30	200	0.26	0.498056	1550.38	932.71	534.83
60	200	0.29	0.367486	1297.9	800.10	470.92
90	200	0.37	0.188342	866.81	563.19	350.31
120	200	0.46	0.075665	482.77	337.73	225.74

$$1 \text{ (lb*s}^n\text{/ft}^2\text{)} = 47.88025898 \text{ (Pa*s}^n\text{)}$$

Table 4: Power Law Parameters for HydroxyPropyl Guar (HPG), at 250 °F (121.1 °C)

Elapsed Time (minutes) @ Test Temperature	Temperature (°F)	n'	K' value (lb*s <sup>n'</sup> /ft <sup>2</sup> )	Apparent Viscosity (mPa*s) at Shear rate		
				40 s <sup>-1</sup>	80 s <sup>-1</sup>	170 s <sup>-1</sup>
0	250	0.61	0.004608	51.97	40.40	30.36
30	250	0.32	0.305581	1185.77	743.21	445.72
60	250	0.35	0.228427	994.57	637.54	391.59
90	250	0.42	0.120329	666.66	448.77	289.98
120	250	0.5	0.050045	371.64	269.11	185.99

$$1 \text{ (lb*s}^n\text{/ft}^2\text{)} = 47.88025898 \text{ (Pa*s}^n\text{)}$$

Table 5: Power Law Parameters for HydroxyPropyl Guar (HPG), at 290 °F (143.3 °C)

Elapsed Time (minutes) @ Test Temperature	Temperature (°F)	n'	K' value (lb*s <sup>n'</sup> /ft <sup>2</sup> )	Apparent Viscosity (mPa*s) at Shear rate		
				40 s <sup>-1</sup>	80 s <sup>-1</sup>	170 s <sup>-1</sup>
0	290	0.67	0.002664	36.83	29.48	23.00
30	290	0.39	0.096818	487.89	321.08	203.12
60	290	0.42	0.073504	410.16	275.44	178.00
90	290	0.48	0.040008	276.09	193.91	131.14
120	290	0.55	0.017344	154.2	116.33	83.69

$$1 \text{ (lb*s}^n\text{/ft}^2\text{)} = 47.88025898 \text{ (Pa*s}^n\text{)}$$

Table 6: Power Law Parameters for HydroxyPropyl Guar (HPG), with 2 lb/Mgal (0.2397 kg/m<sup>3</sup>) Gel Stabilizer Concentration at 200 °F (93.3 °C)

Elapsed Time (minutes) @ Test Temperature	Temperature (°F)	n'	K' value (lb*s <sup>n'</sup> /ft <sup>2</sup> )	Apparent Viscosity (mPa*s) at Shear rate		
				40 s <sup>-1</sup>	80 s <sup>-1</sup>	170 s <sup>-1</sup>
0	200	0.55	0.009100	79.2	59.65	42.81
30	200	0.26	0.499159	1553.82	934.77	536.01
60	200	0.29	0.368299	1300.77	801.87	471.96
90	200	0.37	0.188759	868.73	564.44	351.09
120	200	0.46	0.075832	483.84	338.48	226.24

$$1 \text{ (lb*s}^n\text{/ft}^2\text{)} = 47.88025898 \text{ (Pa*s}^n\text{)}$$

$$1 \text{ (lb*s}^n\text{/ft}^2\text{)} = 47.88025898 \text{ (Pa*s}^n\text{)}$$

Table 7: Power Law Parameters for HydroxyPropyl Guar (HPG), with 2 lb/Mgal (0.2397 kg/m<sup>3</sup>) Gel Stabilizer Concentration at 250 °F (121.1 °C)

Elapsed Time (minutes) @ Test Temperature	Temperature (°F)	n'	K' value (lb*s <sup>n'</sup> /ft <sup>2</sup> )	Apparent Viscosity (mPa*s) at Shear rate		
				40 s <sup>-1</sup>	80 s <sup>-1</sup>	170 s <sup>-1</sup>
0	250	0.61	0.004608	51.97	40.40	30.36
30	250	0.32	0.317723	1232.89	772.74	463.42
60	250	0.35	0.0237503	1034.09	662.87	407.14
90	250	0.42	0.125109	693.15	466.59	301.49
120	250	0.5	0.052032	386.40	279.80	193.38

$$1 \text{ (lb*s}^n\text{/ft}^2\text{)} = 47.88025898 \text{ (Pa*s}^n\text{)}$$

Table 8: Power Law Parameters for HydroxyPropyl Guar (HPG), with 2 lb/Mgal (0.2397 kg/m<sup>3</sup>) Gel Stabilizer Concentration at 290 °F (143.3 °C)

Elapsed Time (minutes) @ Test Temperature	Temperature (°F)	n'	K' value (lb*s <sup>n'</sup> /ft <sup>2</sup> )	Apparent Viscosity (mPa*s) at Shear rate		
				40 s <sup>-1</sup>	80 s <sup>-1</sup>	170 s <sup>-1</sup>
0	290	0.67	0.004608	36.83	29.48	23.00
30	290	0.39	0.317723	589.12	387.68	245.23
60	290	0.42	0.0237503	495.25	332.57	214.90
90	290	0.48	0.125109	333.36	234.12	158.32
120	290	0.55	0.052032	186.17	140.43	101.01

$$1 \text{ (lb*s}^n\text{/ft}^2\text{)} = 47.88025898 \text{ (Pa*s}^n\text{)}$$

Table 9: Power Law Parameters for HydroxyPropyl Guar (HPG), with 4 lb/Mgal (0.4794 kg/m<sup>3</sup>) Gel Stabilizer Concentration at 200 °F (93.3 °C)

Elapsed Time (minutes) @ Test Temperature	Temperature (°F)	n'	K' value (lb*s <sup>n'</sup> /ft <sup>2</sup> )	Apparent Viscosity (mPa*s) at Shear rate		
				40 s <sup>-1</sup>	80 s <sup>-1</sup>	170 s <sup>-1</sup>
0	200	0.55	0.009100	79	59.65	42.82
30	200	0.26	0.499653	1555.35	935.70	536.55
60	200	0.29	0.368664	1302.06	802.66	472.42
90	200	0.37	0.188946	869.59	564.99	351.44
120	200	0.46	0.075907	484.31	338.81	226.46

$$1 \text{ (lb*s}^n\text{/ft}^2\text{)} = 47.88025898 \text{ (Pa*s}^n\text{)}$$

Table 10: Power Law Parameters for HydroxyPropyl Guar (HPG), with 4 lb/Mgal (0.4794 kg/m<sup>3</sup>) Gel Stabilizer Concentration at 250 °F (121.1 °C)

Elapsed Time (minutes) @ Test Temperature	Temperature (°F)	n'	K' value (lb*s <sup>n</sup> /ft <sup>2</sup> )	Apparent Viscosity (mPa*s) at Shear rate		
				40 s <sup>-1</sup>	80 s <sup>-1</sup>	170 s <sup>-1</sup>
0	250	0.61	0.004608	51.97	40.40	30.36
30	250	0.32	0.323402	1254.93	786.56	471.7
60	250	0.35	0.241747	1052.57	674.72	414.42
90	250	0.42	0.127345	705.54	474.93	306.88
120	250	0.5	0.052962	393.31	284.8	196.83

$$1 \text{ (lb*s}^n\text{/ft}^2\text{)} = 47.88025898 \text{ (Pa*s}^n\text{)}$$

Table 11: Power Law Parameters for HydroxyPropyl Guar (HPG), with 4 lb/Mgal (0.4794 kg/m<sup>3</sup>) Gel Stabilizer Concentration at 290 °F (143.3 °C)

Elapsed Time (minutes) @ Test Temperature	Temperature (°F)	n'	K' value (lb*s <sup>n</sup> /ft <sup>2</sup> )	Apparent Viscosity (mPa*s) at Shear rate		
				40 s <sup>-1</sup>	80 s <sup>-1</sup>	170 s <sup>-1</sup>
0	290	0.67	0.002664	36.83	29.48	23.00
30	290	0.39	0.127966	644.89	424.37	268.44
60	290	0.42	0.097150	542.14	364.05	235.23
90	290	0.48	0.052874	364.91	256.27	173.29
120	290	0.55	0.022917	203.77	153.71	110.56

Figures 2 through 4 show that the shape of the apparent viscosity plots is similar at all temperatures; except 290 °F (143.3 °C) although, is not included a gel stabilizer to borate crosslinked HPG system. Figures 2 through 4 also show that the shape of the curves is similar at different shear rates conditions. Therefore, the effect of shear rate includes the variables for the rheology.

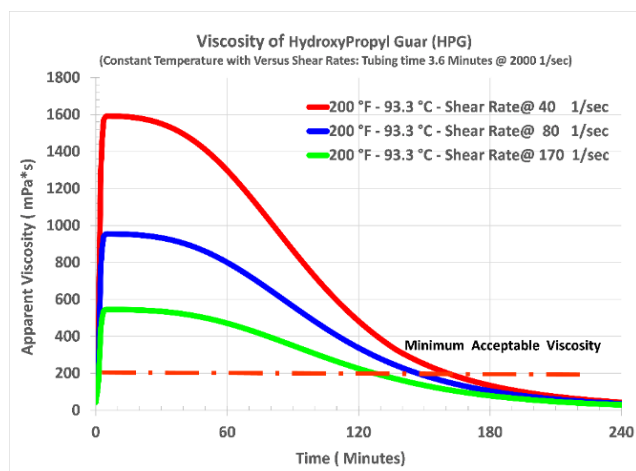


Figure 2: Comparison of Viscosity (Constant Temperature) versus Time for HPG at Shear rates, 40 1/sec, 80 1/sec, and 170 1/sec

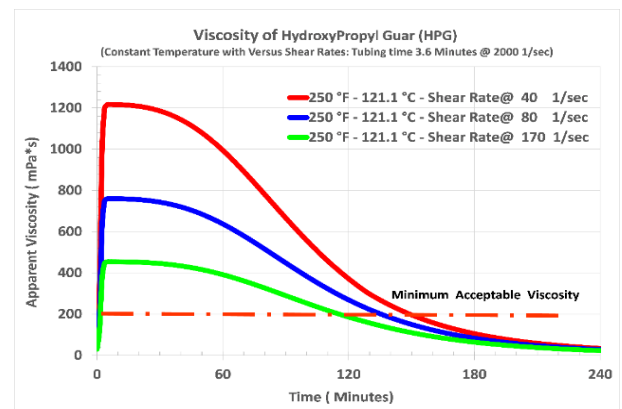


Figure 3: Comparison of Viscosity (Constant Temperature) versus Time for HPG at Shear rates, 40 1/sec, 80 1/sec, and 170 1/sec

Figures 5 through 7 show improved apparent viscosity once HPG included a gel stabilizer as a concentrate (2 lb/Mgal - 0.2397 kg/m<sup>3</sup>). This comparison in the fluid behavior shows that enhanced the viscosity for a gel in fractures at temperatures 200 °F (93.3 °C), and 250 °F (121.1 °C), not including for 290 °F (143.3 °C).



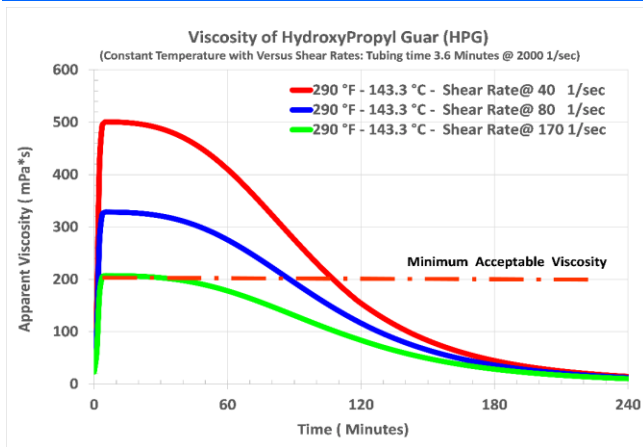


Figure 4: Comparison of Viscosity (Constant Temperature) versus Time for HPG at Shear rates, 40 1/sec, 80 1/sec, and 170 1/sec

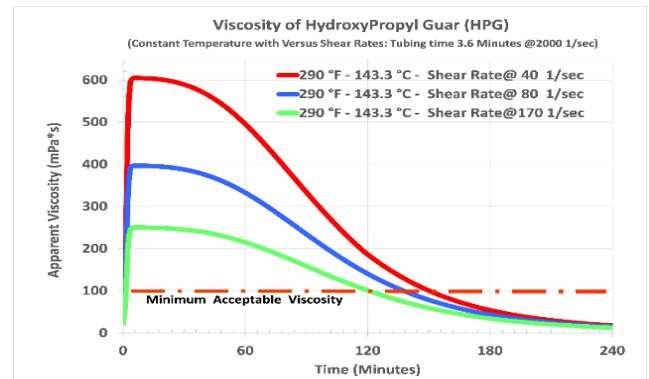


Figure 7: Comparison of Viscosity (Constant Temperature) versus Time for HPG using (0.2397 kg/m<sup>3</sup>) Proposed Gel Stabilizer Addition at Shear rates, 40 1/sec, 80 1/sec, and 170 1/sec

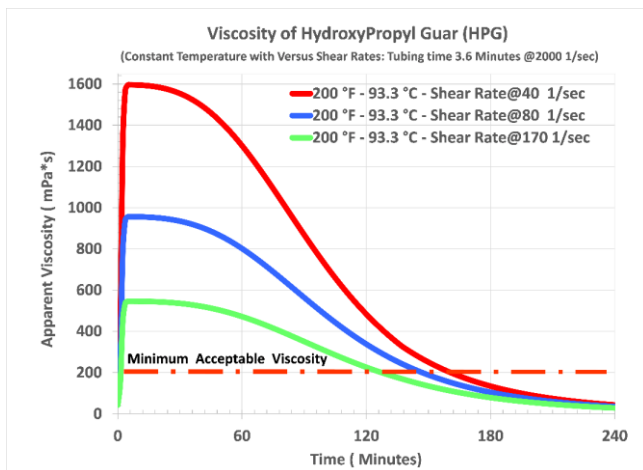


Figure 5: Comparison of Viscosity (Constant Temperature) versus Time for HPG using (0.2397 kg/m<sup>3</sup>) Proposed Gel Stabilizer Addition at Shear rates, 40 1/sec, 80 1/sec, and 170 1/sec

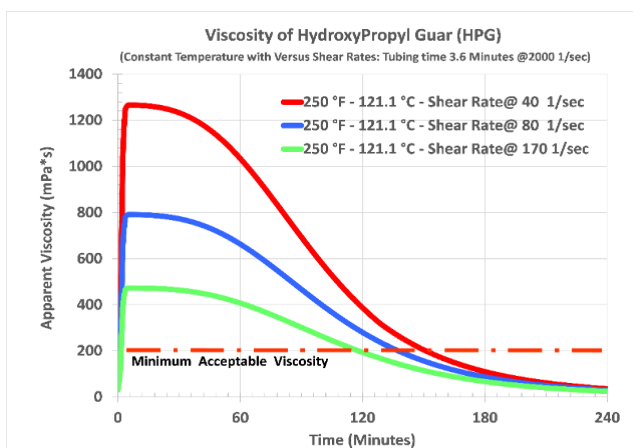


Figure 6: Comparison of Viscosity (Constant Temperature) versus Time for HPG using (0.2397 kg/m<sup>3</sup>) Proposed Gel Stabilizer Addition at Shear rates, 40 1/sec, 80 1/sec, and 170 1/sec

By comparing the results of versus shear rate and temperature with time duration are shown in Figures 8 through 10, it is the best apparent viscosity as long as improvements the fluid at the end of the job. For example, Shear Simulated at (100 minutes elapsed time), observed for that the case with the best shear rate at 80 1/sec for the viscosity. Moreover, better proppant transport to the wellbore at a temperature of 290 °F (143.3 °C).

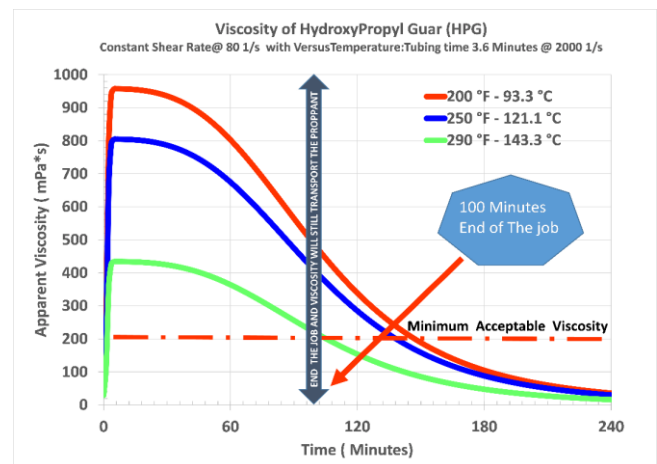


Figure 8: Viscosity Profile of revised HPG by using (0.4794 kg/m<sup>3</sup>) Proposed Gel Stabilizer after Shear Simulated

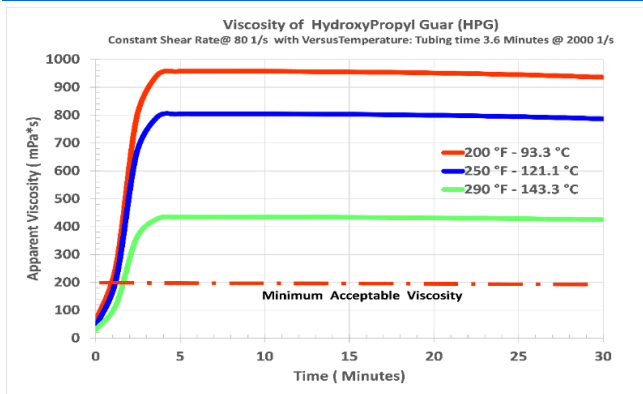


Figure 9: Viscosity Profile of revised HPG by using (0.4794 kg/m<sup>3</sup>) Proposed Gel Stabilizer after Shear Simulated (30 minutes elapsed time)

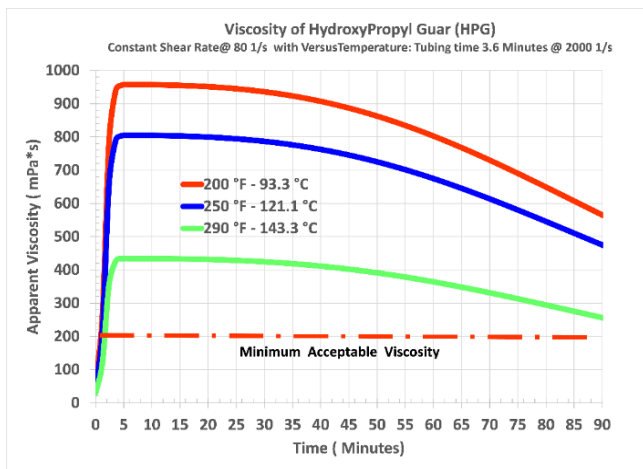


Figure 10: Viscosity Profile of revised HPG by using (0.4794 kg/m<sup>3</sup>) Proposed Gel Stabilizer after Shear Simulated (90 minutes elapsed time)

#### IV. DISCUSSION

The Rheology provides a means to calculate and display apparent viscosity,  $n'$  (flow behavior index), and  $K'$  (consistency index), versus a wide variety of input parameters. The approximate shear rate at which apparent viscosity transitions from low shear behavior to power law behavior. Consequently, describes the behavior of a real non-Newtonian fluid. For example, if  $n'$  equal less than one, the power law estimates that the effective viscosity would decrease with increasing shear rate indefinitely, requiring a fluid with infinite viscosity at the break and zero viscosity as shear rate methods infinity, but a real fluid has both minimum and a maximum effective viscosity that depends on the physical chemistry at the molecular level. For this reason, the power law is only a good description of fluid behavior across the range of shear rates to which the coefficients were fitted. There are a number of other models that better describe the entire flow behavior of shear-dependant fluids, but they do so at the expense of simplicity, so the power law is still used to describe fluid behavior, permit mathematical predictions, and correlate experimental data.

A Power-law fluid is a type of generalized Newtonian Fluid and can be subdivided into three different types of fluids based on the value of their flow behavior index, if the type fluid is  $<1$ , then the fluid is Pseudo plastic (Shear thinning), equal 1 than the fluid is Newtonian fluid, after that if the type fluid  $>1$  then the fluid is Dilatant (less common) (Shear thickening). Another benefit of use  $n'$  (flow behavior index), and  $K'$  (consistency index) to predict the friction in the tubing and indicate to see the performance of the pressures during the job.

Borate-crosslinked HPG simulation is being considered to predict apparent viscosity under well certain conditions. For these simulated gel a reliable in fracturing fluid is needed that can provide acceptable rheological performance at a temperature up to 290 °F ( 143.3 °C ) for elapsed times as long as 100 minutes. This simulated was conducted to optimize the fluid formulations available through Rheology Fluid Software Application for the performance of the gel in fractures. Borate crosslinking HPG system is conducted in a high-temperature reservoir (bottom hole temperature  $> 200$  °F - 93.3 °C), due to the improved proppant transport compared to linear polymer systems.

Rheology simulated of fracturing fluids can be used to characterize the viscosity profile of the fracturing fluid in the fracture at simulated fracturing conditions. However, earlier studies have shown that the viscosity of crosslinked fracturing fluid influenced by shear forces familiar by gel in fractures. Moreover, the best viscosity profile at a shear rate of 80 1/sec with versus temperature and better proppant transport to the wellbore.

#### V. CONCLUSION

From this study, it appeared that Based on the early prediction for apparent viscosity with varying concentrations of Gel Stabilizer addition to borate crosslinked HPG system that would provide the necessary high temperature performance and eliminate the thermal thinning at 290 °F (143.3 °C), 250 °F (121.1 °C), and 200 °F (93.3 °C).

The resulting viscosity profiles and increased the probability of varying gel stabilizer concentration to improve the viscosity and the optimum performance, was stable at a temperature approaching 290 °F (143.3 °C). The study contributes to considerate the effect of gel stabilizer concentration on the fluid and keeps the performance of the viscosity. Furthermore, suspend the proppant and interning to the wellbore.

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