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Modeling Hydraulic Fracturing of Deep Shale Gas Reservoirs at HPHT Conditions

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Abstract: *This paper is a summary for an innovative computer model which has three innovative techniques for the hydraulic fracturing operation in deep shale gas reservoirs at high pressure high temperature conditions*

Keywords—unconventional, shale gas, hydraulic frac; deep reach; high pressure high temperature, severe

1. INTRODUCTION

Hydraulic fracturing is one of the primary engineering methods for increasing well productivity. This is done by extending channels to a higher value of depth in the reservoir. Hydraulic fracture processes may be chosen for a reservoir for one of two purposes. The first purpose is to cure damage and retain the reservoir to its natural case. The second purpose is to extend deep channels inside the tight reservoir and thus increase reservoir contact and productivity. This is applicable to shale gas reservoirs to increase their permeability which is my main subject of work

The main objectives of this work are to solve the previously mentioned challenge which will achieved by the following points:

- Evaluation of geomechanical properties of shale gas reservoirs at HPHT conditions.

- Calculating shale formation properties as a function of reservoir pressure and temperature.

- Reviewing the hydraulic fracturing models for normal reservoirs and adapting the suitable model for HPHT deep reservoirs

- Calculating shale gas networks volume by calculating optimum average fractures width, length and height.

- Calculate gas production rate and predict the future stock gas production.

- Building a computer program to achieve these objectives.

2 LITERATURE REVIEW

Deep shale gas reservoirs are very popular all over the world and their estimation is very important for future development. The deep shale gas resources in USA were estimated to be 1000 TCF in 2008 and every day this number increases because of modern technology of shale gas recovery. Branette shale is the most common type of shale gas production in the USA and all over the world. This type of shale is formed mostly in the Paleozoic era and is the main source of shale gas. Other types are Woodford, Marcellus, Haynesville and Fayteville. Figure A-1 represents the shale gas plays all over the world. Deep shale gas reservoirs are estimated in 2010 to reach a depth of 13,000 ft. In 2012, studies revealed that depth can reach up to 15,000 ft. Depth is firstly introduced, because deep shale gas reservoirs require long tubing to reach over 15, 000 ft depth and a horizontal section, which reaches to 2400 ft. This long tubing faces many challenges and the main challenge is the effect on fluid properties and the resulting friction losses. Also, formation properties are affected by depth. When shale gas formation is deeper, overburden pressure and pore pressure are significantly higher, which make porosity and permeability are typically lower associating formation lower ductility.

3 METHODOLOGY

The main objective of this study is to build a model to predict fracture dimensions, describe the invasion of the slurry inside the fractures and estimate future gas production from shale gas reservoirs at deep HPHT conditions. The tubing calculations are firstly executed to calculate the final bottom hole pressure taking into account tubing pressure losses.

3.1 Tubing Pressure Losses Calculations

The target of tubing calculations is to calculate tubular pressure losses reaching deep reservoirs as they are highly considered for deep reach wells. And use the result to calculate bottom hole pressure necessary for fracturing propagation. This technique has to have innovative parts to reduce slurry pressure losses inside tubing reaching deep

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shale gas reservoirs.

3.1.1 Gel Calculations

The main equation for gel pressure losses is :

$$\frac{\Delta P}{L} = \frac{[5.7565\ Nre^{-0.5229}]\rho\ V^{\left(\frac{2}{\sqrt{n'}}\right)}}{0.0257632 d^{n'^2}} \text{)} \qquad (1)$$

Where Nre is Reynold number and n' is the power law model coefficient.

3.1.2 Slurry Pressure Losses Calculations

Tubing pressure losses value for the fracturing slurry (gel used with the proppant) is calculated from Equation (2) which accounts for a correction factor for the proppant presence in slurry.

$$\left(\frac{\Delta P}{\Delta L}\right)_{Sl} = M \left(\frac{\Delta P}{\Delta L}\right)_{Gel} \qquad (2)$$

Where :

$\left(\frac{\Delta P}{\Delta L}\right)_{sl}$ is the slurry pressure losses (psi / 1000ft)

$\left(\frac{\Delta P}{\Delta L}\right)_{gel}$ is gel pressure losses (psi / 1000ft)

M is the proppant correction factor

3.2 Fracture pressure calculations

Equation (3) will be used to calculate fracturing pressure P_{frac} responsible for fracture creation and invasion.

$$P_{frac} = BHP = P_{surface} + P_{hydrostatic} - P_{losses} \qquad (3)$$

Where

Phydrostatic (psi)= 0.052 X Slurry Density(ppg) X H (vertical height of tubing in ft)……………………………..(**4**)

L is the total length of tubing in ft

3.3 Fracture width calculations

The fracture width (ft) is calculated as as shown in Equation (5)

$$W_f = (1-\mu)\, H_f\, (P_{frac} - \sigma_{min}) / G \qquad (5)$$

Where:

σ_{min} is the minimum horizontal stress, psi

P_{frac} is the BHP, from, psi

G is the shear modulus, psi

H_f is the vertical formation height parallel to Z-Axis , ft.

μ is poison's ratio, dimensionless.

The Previous calculations give the actual width (W_f) which is not an accurate value. This value is corrected by a confidential innovative technique correlated to the experimental results to find the optimum fractures width (W_{opt}). This technique is very confidential and can not be explained here as it represents 90% of the design and the programming language.

3.3.1 Average Optimum Fracture Width Calculations

The average width (W_{avg}) (ft) for the previous optimum width (W_{opt}) is calculated using an innovative integration technique over square area of quadrant. This innovative technique is very important because it helps in understanding fractures networks complexity in shale gas targets. Figure A-2 indicates the actual quadrant plane view of fractures for each stage of fracturing increase of having 8 to 9 stages. Figure A-3 indicates the theoretical plane view of the quadrant containing fractures.

3.4 Average Optimum Fracture Height Calculations

Average fractures height is parallel to Z-Axis and calculated as follows

$$H_f = \frac{W_{avg,opt} * E}{2(1-\mu^2)} \qquad (6)$$

Where :

$W_{avg,opt}$ Average fracture width, (ft)
E Young modulus or elasticity modulus at reservoir P and T, (psi)
μ Poison's ratio at reservoir P and T, dimensionless.

3.5 Maximum Fracture Half-Length Calculation

Maximum Fracture half-length is parallel to Y-Axis and calculated as follows

$$L_f = (W_{avg,opt} * E)/(4(1-\mu^2)) \qquad (7)$$

Where :

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Wavg,opt Average fracture width, (ft)
E Young modulus or elasticity modulus at reservoir P and T, (psi)
μ Poison's ratio at reservoir P and T, dimensionless

3.6 Slurry Volume Calculations

Slurry volume is then calculated as a function of the calibrated fractures massivity measured from borehole images to the calculated ones by an innovative method.

This resulting calculated volume of slurry is 563 bbl less than Dual porosity result. My model is more accurate to fit the deep, HPHT shale gas reservoir due to making three innovative techniques to reduce pressure losses inside the tubing to minimum value, explain and calculate fractures complexity and considering HPHT effects in all calculations. My model saves cost by saving power of pumping and pumping the optimum slurry amount causing no losses to the surrounding formations. This is beneficial for the environment to prevent excessive amount of slurry from damaging fresh water sources. The calculations proceed to predict gas production rate.

4. Results and Discussion

The most effective factors on optimum fracture width involve polymer concentration, slurry density, tubing diameter and slury viscosity. Each of these factors is changed and the resulting $W_{opt,avg}$ is calculated for each value to get the final relation between the factor and $W_{avg,opt}$.

The model is used to predict the most accurate gas production rate till the end of reservoir life.

From Figure A-4, when C_p is greater than 70 Lbm/Mgal, Friction increases due to collision between heavy polymer molecules. From Figure A-5, at deep HPHT reservoirs, When ρ_{sl} is greater than 15 ppg, collisions increase and pressure losses increase. From Figure A-6, at HPHT, there is a greater area exposed to friction and this effect is indicated clearly in 3 stages. These stages indicate that when diameter increases, friction increases. From Figure A-7, curve has two stages (450 to 600 cp and 600 to 800 cp). In the first stage, as molecules have lower viscosity, the inner friction of slurry molecules "near the center of fluid trajectory" is reduced and more opportunity of friction is given to the inner tubing surface with the outer layer of slurry column.

There is a direct relationship between Pressure Losses and Q_i , Figure A-8 (A)). When injection flow rate increases, pressure losses increase as indicated by Renoyld number calculations. This increase in pressure losses leads to a decrease in BHP (Figure A-8 (B)).

4.1 Comparison With Hydrodynamic Model

The proposed model results in lower value of slurry volume pumped indicating more accuracy than hydrodynamic model because at deep reservoirs the total volume of fractures networks under deep conditions is lower. This is also cost effective and saves 262 bbls per stage of expensive slurry supported by valuable gel and proppant to work under severe conditions of deep burial. According to damaging nearby zones point, the adopted model saves 262 bbls which could damage fresh water zones because they exceed the job needs. Consequently, less slurry will be lost to surrounding information and less damage is caused to deep water sources. Although Injection flow rate in HPHT, shale gas reservoir model is higher than hydrodynamic model flow rate, average fracture width is less than hydrodynamic model value. This is because of deep burial of North Berth Basin (6500 ft). The greater the depth the higher the stresses and the lower the average fracture width. This caused a decrease in slurry volume by 262 bbls. So, the proposed model proved to be cost effective because of saving 563 bbls of expensive slurry rather than DP model and also because of saving 262 bbls rather than hydrodynamic model. This comparison made it very clear that the proposed model is optimum for modeling hydraulic fracturing process at deep, HPHT conditions of shale gas reservoirs leading to more economic and reliable results.

4.2 Effect of pressure and temperature on reservoir geomechanical properties and gas productivity

From Figure A-9, when pore pressure increases from 0 to 20,000 Psi, σ_{min} decreases from 10,000 to 3334 psi. From Figure A-10, as the pore pressure increase, fracture width increase and longitudinal variation increases. So, when pore pressure increases from 7500 to 17,500 psi, Poisson's ratio is significantly reduced from 0.5 to 0.1. From Figure A-11, it is concluded that, pore pressure is helping fracturing fluid and working against shear forces. From Figure A-12, there is a direct relation between P_p and $W_{propped}$.

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Figure A-13 represents the inverse relation between shale elasticity modulus and reservoir temperature because shale loses its elasticity at elevated temperatures. Rock elasticity is affected in a lower degree between 200 to 350 ^oF as an indication of losing shale elasticity. From Figure A-14, at elevated temperatures from 200 to 350, rock elasticity starts to be lost and this makes fracturing and longitudinal variations more difficult. This leads to increasing Poisson's ratio values from 0.07675 to 0.3786. Poisson's ratio recommended values lies between 0.05 and 0.5. From Figure

A-15, at elevated temperatures fracturing process faces the same minimum rigidity modulus between 250 °F and 350 °F which is considered as the recommended range for hydraulic fracturing. So, 250 °f is a turning point in the final propped width value as indicated in Figure A-16. This result is used to recommend making reservoir temperature less than 250 °f by controlling Proppant temperature

5. CONCLUSIONS

- The optimum average fracture width ($W_{avg,opt}$) is the key factor for model calculations and the model accuracy depends on its value..
- The optimum average fracture width is used to get the most accurate slurry volume pumped in bbls to save cost and prevent any excess amount that may damage the surrounding zones.
- The model is capable of simulating slurry invasion stages inside fracturing of deep shale gas reservoirs at HPHT conditions. Each stage has its own representative curve with a special $W_{avg,opt}$ and Q_{opt} values.
- Each stage of slurry is capable of being predicted to save cost and to prevent damage to the surrounding zones. V_{slurry} accuracy depends on $W_{avg,opt}$ and HF_{int} accurate values.
- The proposed model shows better accuracy compared to hydrodynamic model and results showed that it saves 252 bbls of expensive slurry.
- The optimum average fracture width is directly proportional to tubular diameter, gel concentration and gel density and inversely proportional to slurry viscosity.
- The model is capable of predicting shale gas production rate till the proposed end of reservoir life.

6 NOMENCLATURE

C	Concentration lbm/Mgal
DP	Dual porosity.
d	Tubular diameter, in
E	Elasticity Modulus, psi
G	Shear modulus, psi
H	Height, ft
K_f	Fractures permeability, Darcy
L	Length, ft
M	Factor for proppant correction calculations, dimensionless
Nre	Reynold number, dimensionless
n'	Power law model coefficient, dimensionless
P	Pressure, psi
Q	Flow rate, for slurry unit is bbl/min, for gas unit is SCF/day.
TOC	Total organic content
v	Velocity, ft / s
W	Width, ft
σ	Horizontal stress (Sigma), psi

Sub-scripts

avg	Average
f	Fracture
g	Gas
h	Hydrostatic
opt	Optimum
p	Polymer
prop	propped width or volume.
sl	Slurry

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8 AUTHOR BIOGRAPHIES

Mario Emad Saad Abdelmalek was born in Menia, Egypt in October 19, 1991. In secondary school, he was the first on Menia governorate with a degree equals (99.9%). in Egypt in July, 2009. He then received his Bachelor of Science Degree in Petroleum Engineering in May, 2014 with a cumulative degree of (very good with honors).

In February, 2019, Mario obtained the degree of Master of Science in Petroleum Engineering on an innovative topic specified in shale gas hydraulic fracturing then started PhD in Suez university, Egypt. While Master and Doctorate degrees, Mario worked as a well-site supervisor who is responsible for the whole drilling rig operations “Company Man” for the owner governmental company “Belayium Petroleum Company”

Mario has a strong and fluent English and German languages. He has the IELTS for the academic module.

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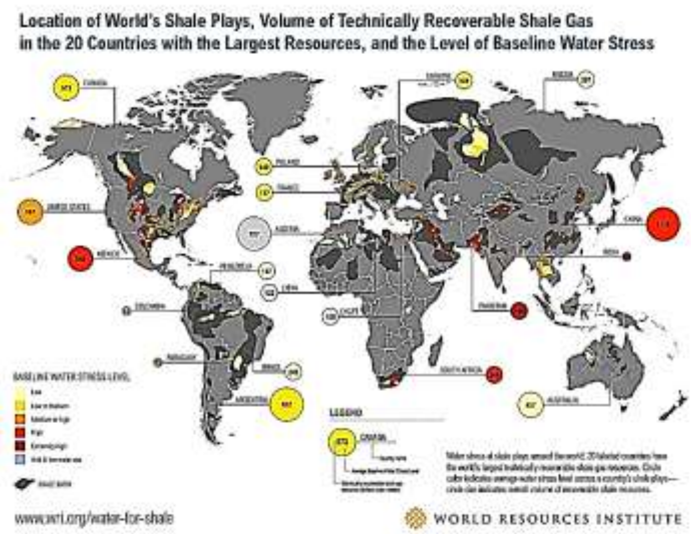
10 FIGURES



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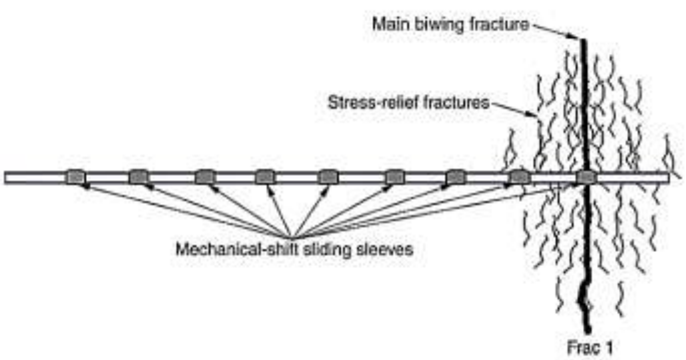

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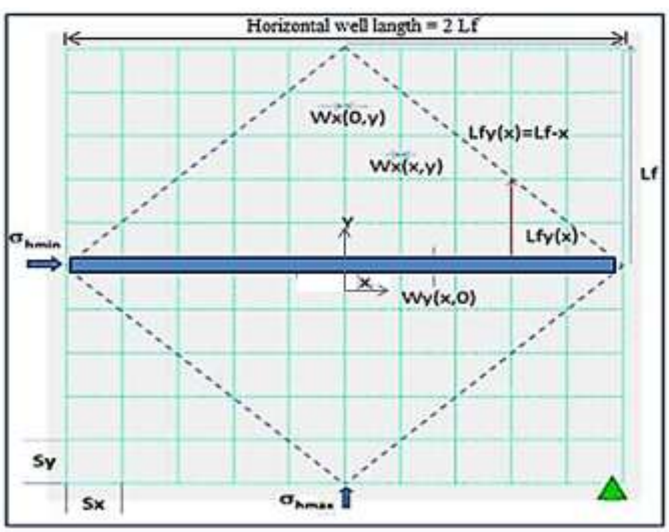

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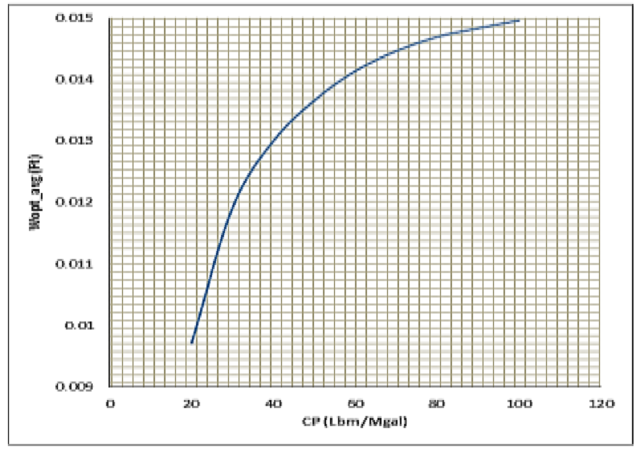

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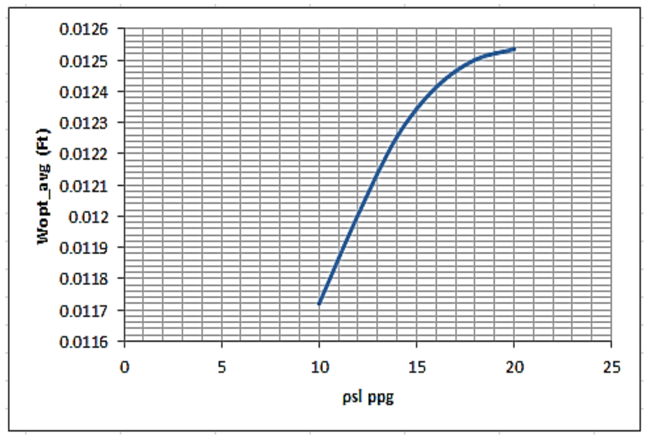

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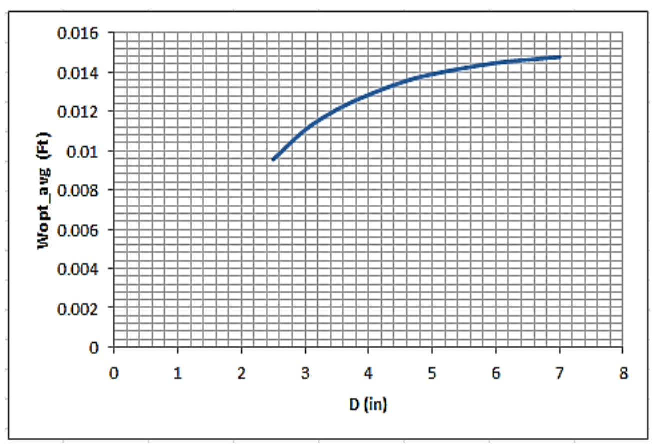

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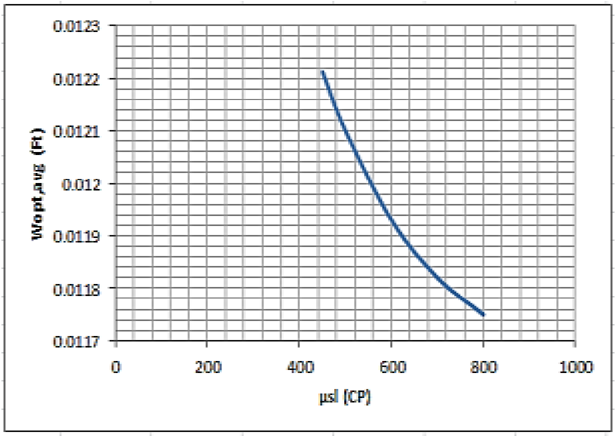

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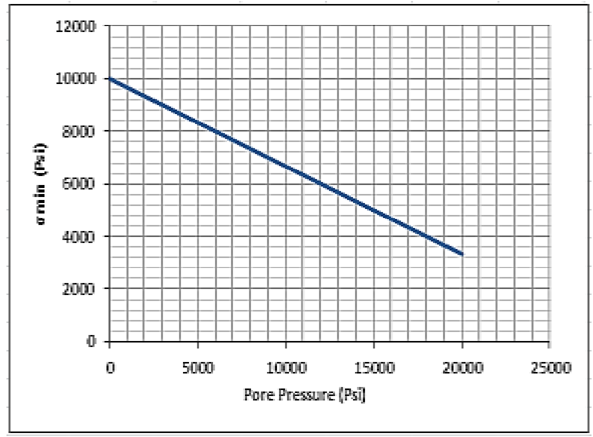

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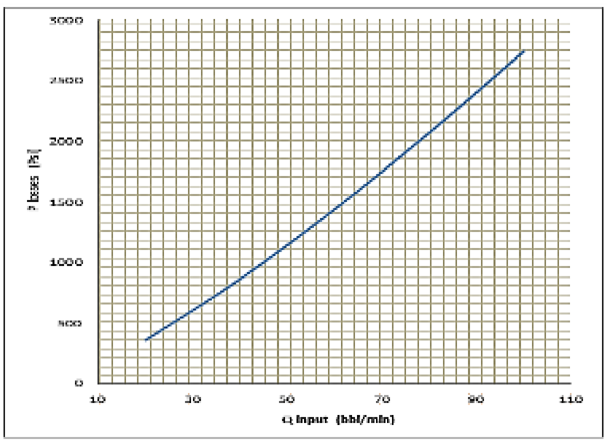

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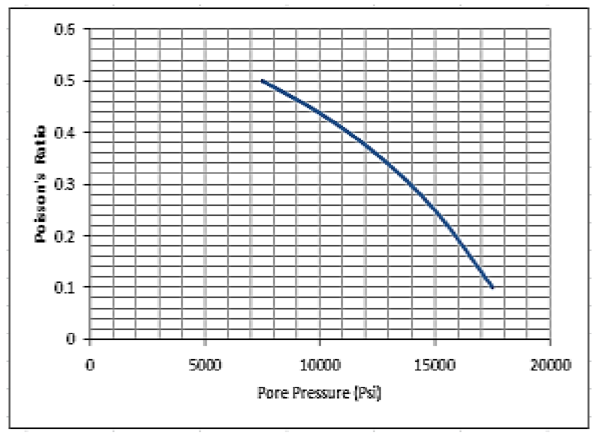

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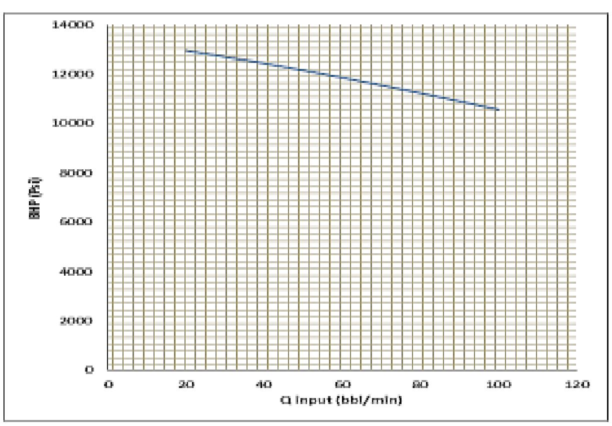

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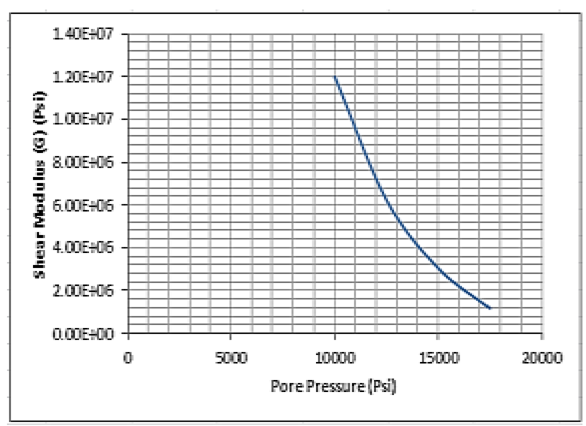

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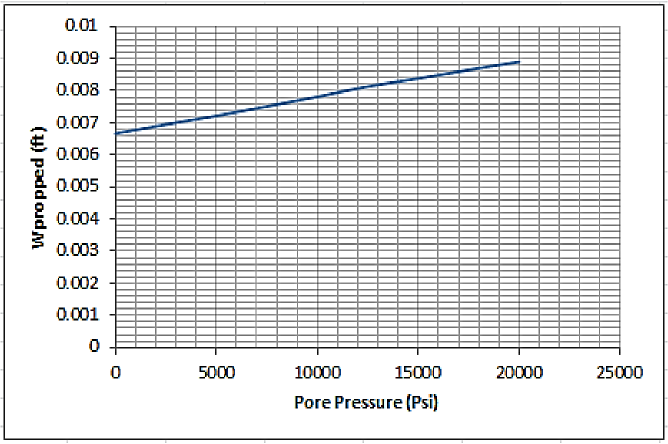

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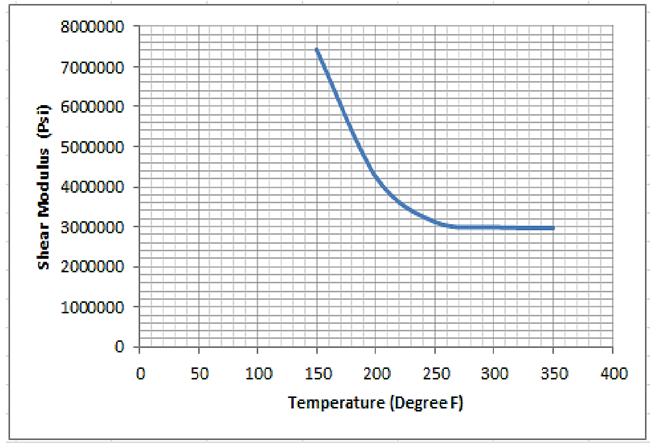

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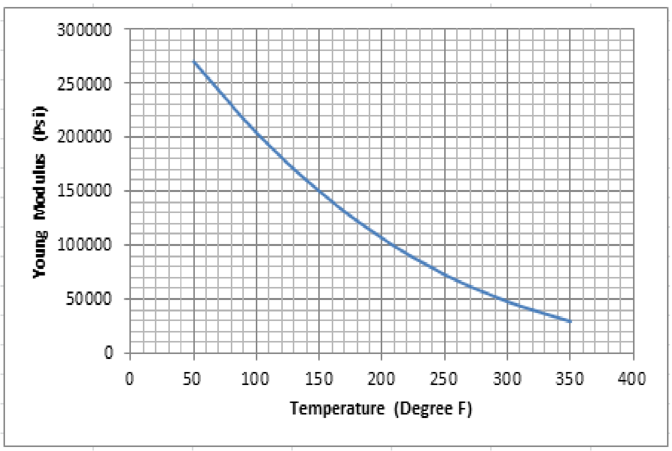

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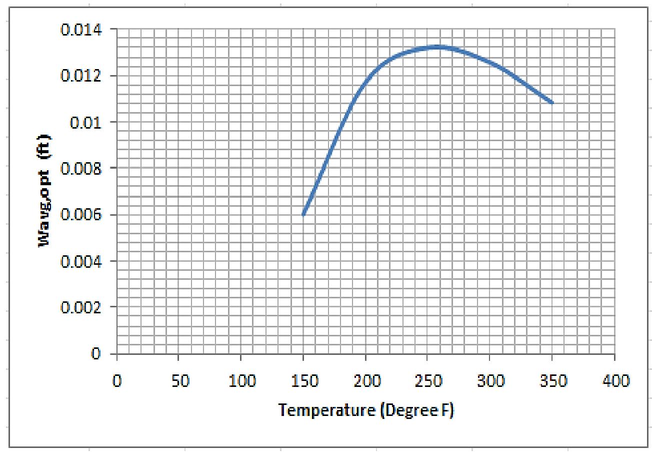

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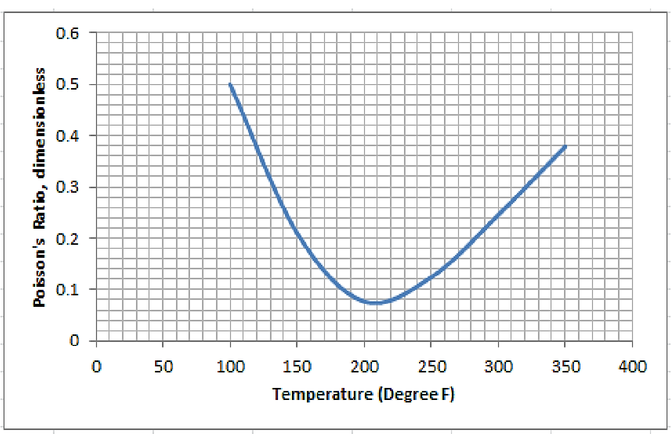

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