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OPTIMIZING TREATMENT VOLUMES FOR MATRIX ACIDIZING IN SINGLE AND MULTILAYERED RESERVOIRS

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ABSTRACT

Introduction: This paper introduces a novel approach for optimizing the treatment volume of matrix acidizing jobs. The proposed method is particularly suitable for application in multilayered reservoirs, but it can also be employed in single layer formations. **Objective**: The aim of this study is to present a generalized empirical formula that establishes a correlation between the completion factor of each layer and the volume of acid injected during the acidizing process. It should be noted that the formula requires calibration using field data, thus limiting its applicability to reservoirs that have undergone at least one previous matrix acidizing job. **Methods**: To develop and validate the proposed method, a computer program was created to simulate acid injection in a multilayered reservoir. The program utilizes the empirical formula mentioned earlier to calculate the completion factor of each layer based on the volume of acid injected. The simulation results are presented in the form of graphs, which facilitate the selection of an optimal acid volume that achieves the desired completion factor for each layer. These graphs serve as a valuable tool for engineers at the well site, enabling them to evaluate the completion factor of each layer at any given moment during the acid injection process. **Conclusion**: The presented approach offers a new method for optimizing the treatment volume of matrix acidizing jobs. By utilizing a generalized empirical formula and a computer program for simulation, engineers can effectively determine the appropriate acid volume required to achieve desired completion factors for each layer in multilayered reservoirs. The availability of these graphs aids decision-making at the well site and enhances the overall effectiveness of the acid injection process. However, it is important to note that the applicability of this method is contingent upon the availability of field data from previous matrix acidizing jobs. Future research should focus on expanding the dataset and refining the formula to accommodate a wider range of reservoir conditions.

Keywords: *Reservoir, Optimization, Multilayered reservoir, Acid, Volume, Formation, Completion, Treatment, Field Data, Matrix acidizing and Single layer.*

1. INTRODUCTION

Matrix acidizing is a widely employed stimulation technique in the oil industry to enhance productivity in formations with wellbore damage. It involves injecting acid into the reservoir below fracturing pressure, leading to chemical reactions that remove the impairment and restore or improve permeability. Planning acidizing jobs for homogeneous reservoirs with small pay is relatively straightforward, but challenges arise when dealing with multilayered reservoirs and long producing intervals due to difficulties in achieving uniform acid distribution throughout the pay zone. If any damage remains in the perforated interval, optimal well productivity cannot be achieved. Various methods are used to ensure proper fluid distribution, including straddle packers, perforation wash tools, squeeze packers with retrievable bridge plugs, ball sealers, and diverting agents. Straddle packers and perforation wash tools are considered more effective in theory as they enable selective injection, but these mechanical methods have limitations as they require a good cement bond and a working string, making them unsuitable for through tubing operations in completed wells. Ball sealers also require a good cement bond and are not recommended for long perforated pay zones with high shot density or low-rate treatments, as well as gravel packed wells. Matrix acidizing with diverting agents, such as solid particulates, acid emulsions, viscous liquids, oil soluble resins, or foams, is a preferred method for treating multilayered reservoirs or long producing intervals. However, there is currently no established methodology for tailoring and controlling these treatments. The proposed method aims to optimize acid volumes without the use of diverting agents for both single and multilayered reservoirs, providing better control over the injection process and allowing for estimation of stimulation levels in each layer during treatment.

2. MATERIELS AND MEYHDS

2.1. Injection in a homogeneous formation

One of the crucial aspects of planning a matrix acidizing job is selecting the appropriate acid type and volume. The choice of acid depends primarily on the lithological and mineralogical composition of the formation. Sandstones are typically treated with various hydrofluoric acid systems, while hydrochloric acid is commonly used in carbonate reservoirs. Several papers have been published on this subject, providing helpful guidelines for matrix acidulation, such as the work by McLeod [1]. Once the rock composition and the type of damage are known, selecting the right acid system becomes less challenging. However, determining the optimal acid volume remains a controversial topic, with recommendations ranging from 50 to 300 gallons per foot of the perforated interval, depending on the chosen approach. In our experience, both theoretical methods based on acid-rock reaction mechanisms and laboratory methods have limited utility in determining the appropriate acid volume to be pumped. The former often requires input data, such as porosity, permeability, and depth of the damaged zone around the wellbore, which are rarely available in practice. The latter faces reliability issues due to difficulties in replicating the actual amount of damage present in the wellbore using core samples. To overcome these challenges, researchers have sought an empirical correlation based on field practices that links the volume of injected acid to improved injectivity.

Through an analysis of numerous matrix acidizing treatments conducted by A gip over the past decade, performed at maximum injection rates below fracturing pressure, we have identified an empirical correlation between the completion factor (CF) and the bank radius of the injected acid (Rb). This correlation holds true for both carbonate and consolidated sandstone formations and can be expressed as: [missing equation or correlation details:

$$CF = a + m\ 1n \quad (1)$$

Where **a** and**m** are numerical coefficients to be calculated for each case. The acid bank radius is correlated to the volume of acid injected by the following equation:

$$R_b = \sqrt{\frac{5.615V}{\pi h \emptyset (1 - S_{or} - S_{wr})} + R_w^2} \quad (2)$$

Where:

Rb: Bank radius of the injected acid (ft)
Rw: Wellbore radius (ft)
V: Volume of injected acid (bbl)
H: Perforated interval (ft)
Ø: Porosity (fraction)
Sor: Residual oil saturation (fraction)
Swr: Residual water saturation (fraction)

Combine Esq. and 2, to obtain:

$$CF = a + b\ 1n\ (c\ V_s + d) \quad (3)$$

Where:

Vs: Specific volume of injected acid = V/h (bW/ft)
C: 5.615 / n 0(1-S_{or}-
d:Rw^2
b:m/2

The values of coefficients a and b in Eq.3 can be calculated using data obtained from a previous acid job on the same formation. For instance, the values of completion factor (CF) before and after treatment, as well as the specific volume of acid used, can be utilized. From a theoretical standpoint, Eq.3 is not valid for values larger than those used to derive coefficients a and b. When the specific volume (Vs) tends to 0, CF also tends to infinity. However, for practical purposes, Eq.3 can be employed to predict CF values up to 100% for sandstone and 150% for carbonates. Once the numerical coefficients are known, Eq.3 allows for the evaluation of CF variation with respect to Vs. Figure 1 depicts a typical trend of CF versus Vs. The equation was developed through an analysis of matrix acidizing treatments using the method proposed by Paccaloni (2004) [2]. This technique involves calculating instantaneous CF during acid injection based on well head injection pressures and rates, employing steady-state Darcy's law for radial injection. The validity of Eq.3, as demonstrated by Agip in numerous matrix acidizing jobs, is closely linked to the injection procedure, specifically at maximum injection rate and maximum bottom hole matrix injection pressure. This design approach aims to maintain the bottom hole matrix injection pressure at the highest possible level to maximize the likelihood of efficient damage removal throughout the completion interval. A recent paper presents this procedure and validates its effectiveness in over 500 successful acid jobs.

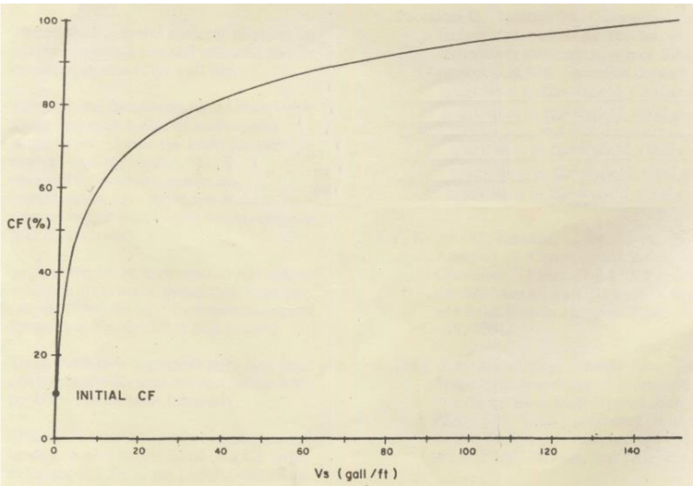


Figure1: Typical tread of completion factor (CF) versus specific volume (Vs).

To confirm the reliability of Eq.3, Table 1 presents twenty successful case histories, comparing the calculated CF during injection with CF evaluated using Paccaloni's method (2004) [2]. The agreement is satisfactory. Additionally, a notable finding is that approximately 73% of the total CF improvement occurs with around 1/3 of the total volume of acid pumped, while 2/3 of the total volume results in roughly 89% of the total improvement. It is generally preferable to achieve a higher final CF; however, the treatment volume should be minimized to reduce costs (including volumes and job duration) and facilitate faster flow-back, particularly in sandstone acidizing where prolonged presence of hydrofluoric acid may lead to precipitation and potential permeability impairment. To determine the optimum acid volume, it is necessary to establish a correlation between CF and well productivity. Based on the authors' experience, a graph of production rate versus CF, considering a range of flowing tubing head pressures (FTHP), proves valuable. This graph reveals that CF values of 90% to 100% may not always be the optimum target, as even CF values of 60% to 70% (post-acid job) can be acceptable in certain cases. This is due to the minimal difference in production rates between these two scenarios, which can be compensated by slight adjustments in FTHP (typically achieved by minor increases in surface choke diameter). By combining the CF versus acid volume and production rate versus CF graphs, it becomes possible to establish a correlation between production rate and acid volume. Example A demonstrates the preparation and utilization of these graphs. In some instances, applying 1/3 of the acid volume corresponding to CF = 100% can result in a production rate improvement equal to 95% of what is achievable with CF = 100%. These considerations highlight the importance of considering well productivity (as a function of CF) after the acid job when making the final determination of the acid volume to be used.

Table 1: Twenty success case histories.

WELL	PERFORATED INTERVAL ft/RT	FLUID	LITHOLOGY	Rw ft	Ø %	Swr %	Sor or Sgr %	CFi %	CFf %	Vs gall/ft	TYPE OF ACID	CF CALCULATED FOR 1/3 Vs REF.1	CF CALCULATED FOR 1/3 Vs PRESENT METHOD	CF CALCULATED FOR 2/3 Vs REF.1	CF CALCULATED FOR 2/3 Vs PRESENT METHOD
A - 11	10791-10827	OIL	SANDSTONE	0.35	11.1	52	20	8	85	184	MA*15-4	64	55	84	72
BA - 19	13553-14124	OIL	SANDSTONE	0.27	11.3	15.5	17.7	38	96	23	MA 12-3	82	83	88	88
F - 9	4746- 4772	GAS	SANDSTONE	0.35	13	60	10	5	98	81	MA 12-3	87	80	92	90
FI - 1	7826- 7947	GAS	SANDSTONE	0.35	8	40	20	10	100	60	MA 12-3	77	81	83	90
ON - 1	9184- 9210	OIL	SANDSTONE	0.35	12	65	31	2	57	115	MA 15-4	45	42	[illegible]	53
PW - 1	2816- 2825	WATER	SANDSTONE	0.5	26	24	0	5	95	235	MA 15-4	93	[illegible]	[illegible]	[illegible]
PW - 5	2781- 2847	WATER	SANDSTONE	0.5	20	25	0	20	92	140	HCl 15%	61	76	[illegible]	[illegible]
PW - 6	2890- 2952	WATER	SANDSTONE	0.5	23	20	0	30	75	80	MA 15-4	73	[illegible]	74	[illegible]
PW - 7	2896- 2945	WATER	SANDSTONE	0.5	24	25	0	28	80	58	HCl 15%	62	68	[illegible]	78
TT - 16	4645- 4656	OIL	SANDSTONE	0.35	23	17	24	12.5	100	192	HCl 15%	84	44	[illegible]	93
U - 3	11782-11874	OIL	SANDSTONE	0.35	16	55	25	6	123	30	CLAY AC	70	55	[illegible]	[illegible]
B - 1	8206- 8222	OIL	LIMESTONE	0.35	12	25	10	20	100	265	HCl 28%	91	88	[illegible]	95
B - 1	8360- 8440	OIL	DOLOMITE	0.35	22	23	29	17	96	64	HCl 28%	89	82	93	92
B - 2	8354- 8420	OIL	LIMESTONE	0.35	8	35	25	8	155	109	HCl 28%	62	70	112	100
B - 2	8525- 8552	OIL	DOLOMITE	0.35	28	29	43	50	124	105	HCl 28%	115	110	118	116
B - 6	8478- 8518	OIL	LIMESTONE	0.35	9	50	20	10	100	42	HCl 15%	76	62	87	84
F - 9	5346- 5412	GAS	LIMESTONE	0.35	7.5	50	25	5	100	81	HCl 28%	72	88	91	96
N - 1	5976- 5993	GAS	LIMESTONE	0.35	8.5	50	18	35	150	100	HCl 15%	120	118	142	138
T - 16	14455-14557	WATER	LIMESTONE	0.35	11	37	0	10	83	206	HCl 28%	69	69	76	76
UR - 1	9974-10030	WATER	LIMESTONE	0.35	13	20	0	11	100	99	HCl 28%	65	68	87	87
					AVERAGE VALUES			16	100	114	-	77	76	91	89

2.2. in a layered reservoir

On the subject of acid injection effect in a layered reservoir, Taha et al., (2006) deal with a numerical simulator that was developed to predict porosity and permeability changes in a layered sandstone while injecting hydrofluoric acid [7]. Their paper gives a good theoretical background; it proves that the model is a strong tool for making a sensitivity investigation on factors that play important roles for good results of matrix acidizing. However, their method has little practical application because it requires, as input data, the values of porosity, permeability and radius of the damaged zone. Unfortunately such values cannot readily be calculated, not even from production tests on single layer, as previously mentioned. For describing the effect of acid injection in multilayered reservoirs, Eq.3 correlates the instantaneous CF of each layer with the volume of acid which entered the layer itself.

To apply Eq.3, the CF of each layer before the acid job has to be known and, for layered reservoirs, such values cannot be determined by common production tests. Three methods for performing this calculation are hereby mentioned:

Numerical models, as reported in Kucuk FM, et.al[8], and Ehlig Economicdes CA and Joseph JA[9] .Estimates of the production rate of each layer by PLT measurements,

1- calculation of individual layer permeability (k) by permeability-porosity correlations (from core analyses).

2- calculation of CF by Darcy's Law.

3.Calculation of k as per 2 and estimation of CF from empirical correlations between CF and K.

Such correlation for each layer can be found if different CF - K couples are available from the analysis of selective production tests of other wells in the same formation. An example is presented in Figure 2.

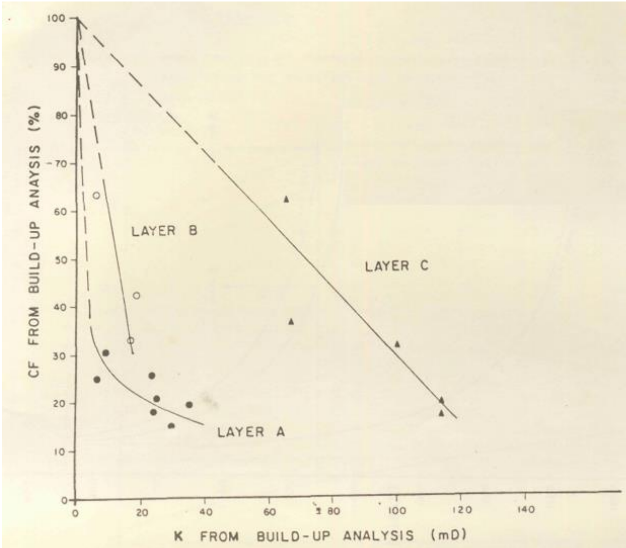


Figure 2: Selective Production Test of Wells.

The data points pertain to a real case. A smooth line, which reasonably represents the empirical correlation between CF and K, can be drawn through the data points of each layer.It is interesting to note that the lines can be extrapolated to CF = 100% for k = 0; in fact, without permeability no damage can reasonably be assumed. This extrapolation (CF = 100% for k = 0) is very useful in all cases where only a few data points are available. When initial CF and the coefficients of Eq.3 are available for each layer, it is possible to find the instantaneous acid injection rate and CF of each layer, during the treatment on all the layers. The procedure is as follows:

The injection behavior of layer ican be calculated by using Darcy's law:

$$\mathbf{Q_i}\,\frac{\mathbf{0.007082\ \Delta p\ (kh)_1}}{\mu\left[\mathbf{In}\,\frac{(\mathbf{R_b})_i}{\mathbf{R_w}}+\mathbf{S_i}\right]} \qquad (4)$$

Where:

Q_i: injection rate in layer i (BPD),
ΔP : pressure drop in the formation (psi),
$(kh)_I$: conductivity of layer i(mD-ft) ,
$(R_b)_I$:acid bank radius in layer i (ft),
μ: acid viscosity (cp),
S_i:skin effect of layer i .dimensionless.

The acid formation volume factor is not considered because this value can be approximated to 1.

Si can be correlated with CFj by Eq.5:

$$\mathbf{S_i} = \left[\frac{\mathbf{100}}{\mathbf{CF_i}} - \mathbf{1}\right]\mathbf{In}\left[\frac{\mathbf{R_e}}{\mathbf{R_w}}\right] \quad (5)$$

Inserting Eq.3 and Eq.5 in Eq.4, and rearranging, one obtains:

$$\mathbf{Q_i} = \frac{\mathbf{0.007082\ \Delta p\ (kh)_i/\mu}}{[\mathbf{In\ A + (B-1)In\ R_e/R_w}]} \quad (6)$$

Where

$$\mathbf{A} = \sqrt{\frac{\mathbf{5.615\ V_i}}{\pi\mathbf{\O_i h_i[1-(S_{or})_i-(S_{wr})_i]R_w^2}} + \mathbf{1}}$$

$$\mathbf{B} = \frac{\mathbf{100}}{\mathbf{a + b\ In}\left[\frac{\mathbf{5.615\ V_i}}{\pi\mathbf{\O_i h_i[1-(S_{or})_i-(S_{wr})_i]}} + \mathbf{R_w^2}\right]}$$

All the parameters of Eq.6, except Q_j and Vj5can be held constant since changes during injection can be neglected. AP can also be kept reasonably constant by varying Q_i during the job. Ultimately, Qj is a function of V_i only, thus:

$$Q_i = f(V_i, \text{constants}) \quad (7)$$

Q_i and V_i can also be expressed in differential form as:

$$Q_i = \frac{DV_i}{dt} \quad (8)$$

Combining Eq.7 and Eq.8 gives]

$$dt = \frac{DV_i}{Q_i} = \frac{DV_i}{f(V_{i,}\text{constant})} \quad (9)$$

By integrating between time 0 (Vi = 0) and time t (Vi = Vi), one obtains:

$$t = \int_0^{V_i} \frac{dV_i}{f(V_{i,}\text{constants})} \quad (10)$$

The above integral has no analytical solution,therefore it must be solved numerically. Many equations (such as Eq.10), corresponding to the number of layers are written and solved. Once all the Vj versus time relationships for each layer are available (after integration of Eq.10) it is possible to calculate the total volume injected, for fixed times, by Eq.11.

$$(V_{total})_{time=t} = \sum_{i=1}^{n} (V_i)_{time=t} \quad (11)$$

Where n = number of layers

To apply Eq.ll, it is necessary that, at time 0, all the layers are covered with the acid. In practice, the best method to ensure this is acid spotting using coiled tubing. The foregoing formulae have been computerized and the results are presented in graphical form. Typical graphs are depicted in Figures. 6,7,8 and 9 of the example B. Figure 6, 7 and 8 show, for each layer, the values of CF, Q, R_D and injection time versus the volume of acid that entered the layer.

With the graph in Figure 9, CF for each layer can be evaluated as a function of the total acid volume injected, and therefore can be used to estimate the optimum treatment volume, once CF (after stimulation), for each layer, has been chosen from previous calculations on well productivity.

3. RESULT AND DISCUSSION

3.1. Limitations of this new approach

When applying the present approach, it is important to consider the following factors. Firstly, the validity of the approach is limited to the specific injection procedure used, as it relies on the empirical Eq.3 derived from stimulations conducted under conditions of maximizing injection rate below fracturing pressure. Therefore, different injection procedures may yield different results. Additionally, in multilayered reservoirs, the CF values for some layers may remain below the desired target values even with high volumes of acid. In such cases, alternative stimulation techniques like the use of diverting agents or ball sealers should be considered. It is also crucial to ensure that all perforations are adequately covered with acid before starting the injection, especially in multilayered reservoirs or long intervals. Coiled tubing is recommended for this purpose due to its effectiveness in navigating the wellbore. Lastly, having knowledge of the CF values for each layer prior to matrix acidizing is essential, or at least making reasonable estimations, as this information is necessary for evaluating the effectiveness of the acid treatment and comparing it to the desired target values.

3.2. EXAMPLE A

Production Test in a well of kwale gas cycling fields shows that the formation presents severe damage (CF =11%) that causes a consistent loss of oil production rate. In order to remove such reservoir impairment and increase the well productivity, a matrix acidizing job has been planned. It is requested to define the optimum volume of acid for the treatment, assuming a homogeneous formation and that the relationship of CF versus specific volume of acid reported in Figure 1 is suitable for the present formation.

Solution

First of all a CF target after acid job has to be established. For doing this, the well performance graph must be used, see Figure 3. The graph has the bottom hole flowing pressure (BHFP) in ordinate and the oil production rate (Q_o) in abscissa, and presents the inflow performance relationship at various CF and the vertical flow performance curves for three values of FTHP. The intersection point between desired curves of CF and FTHP, values give the relevant Q_o. The data point inserted in the 'graph represents the actual situation:

CF = 11%, **FTHP** = 1840 psig, and **Qo** = 960 STB/D.

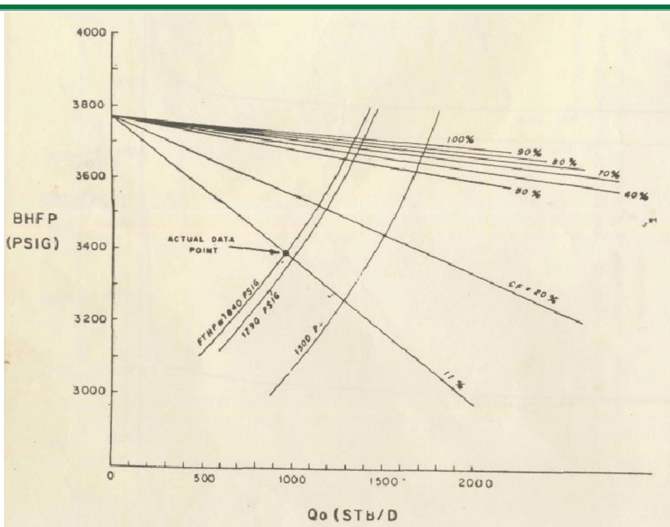


Figure 3: Well Performance Graph.

Besides, the graph shows that for the present FTHP = 1840 psig, the maximum Q_0 with complete damage removal (CF = 100%) is 1345 STB/D, with a Qo gain equal to 385 STB/D. By using such a graph, a correlation between Q_o and CF for 'different FTHP values can be drawn, this is presented in Figure 4. It shows that the mentioned maximum Q_o for FTHP = 1840 psig, is also obtainable for FTHP = 1790 psig and CF = 57%.

Therefore, in this well, it is not important to maximize the level of stimulation (max CF) because for CF higher than, say, 50%, the same Q_0 improvements are obtainable by slight changes in FTHP.
To calculate the optimum acid volume, the graph of Qo versus V_s is necessary. Such a diagram has to be built by using CF versus V_s in Figure 1, and Qo versus CF in Figure 4. The result is in Figure 5.

This graph indicates that for the range of FTHP of the well concerned (1700 to 1800 psig), the optimum volume of acid is about 10 gal/ft. Larger volumes do not seem justified because of the flattening trend of the curves.

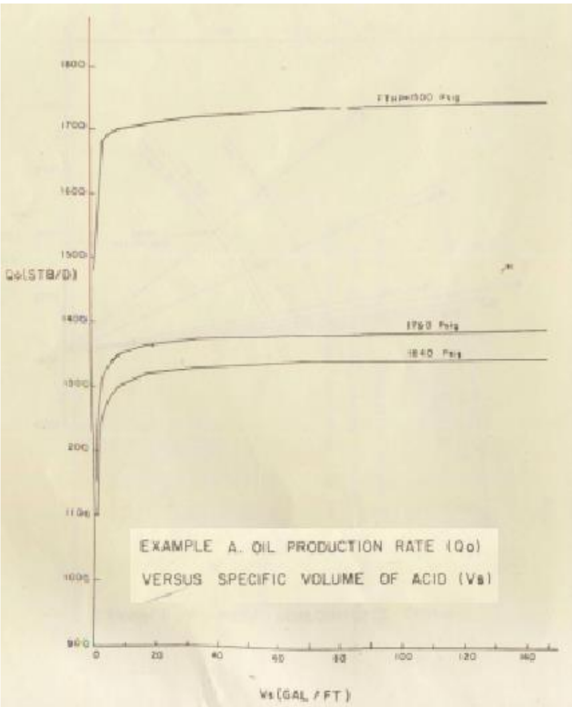


Figure 5: Graph of Oil Production rate vs Specific Volume of Acid.

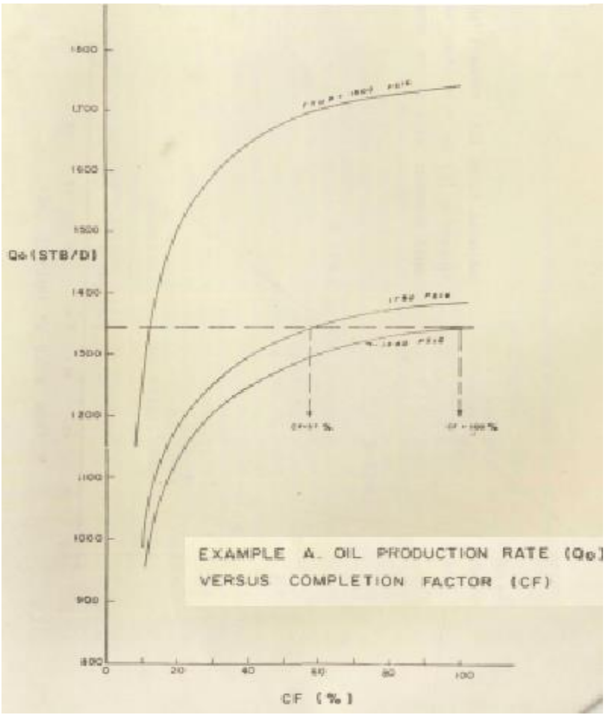


Figure 4 : Oil production Rate vs Completion Factor CF.

3.3 Example B

Find the minimum volume of acid to stimulate a multilayered sandstone reservoir whose characteristics are reported in Table 2.

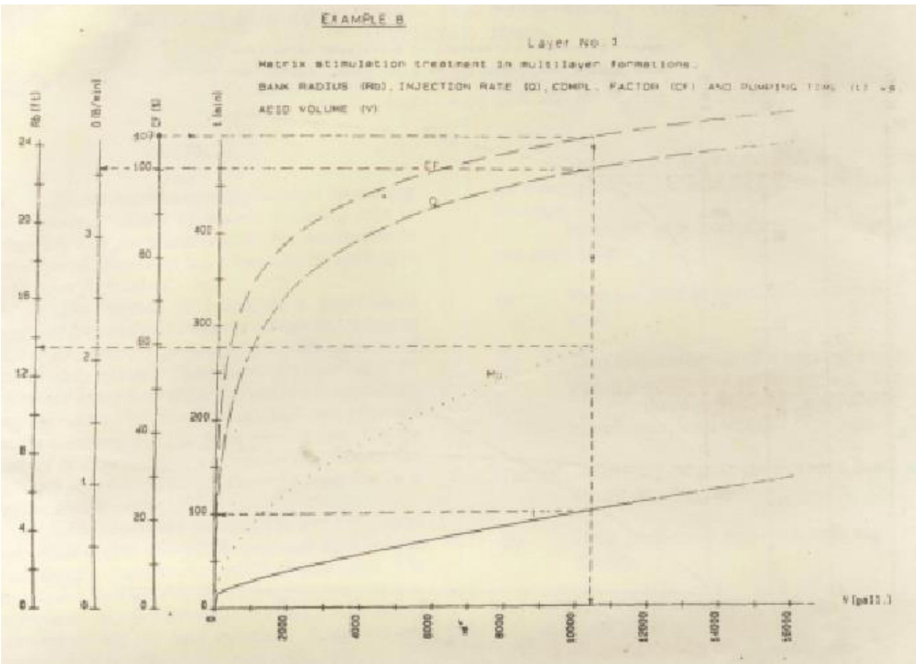
Table 2: Input Data for the Example B.

Layer n.	K mD	Ø (%)	S_{wr}(%)	S_{0r} (%)	CF (%)	h ft
1	30	18	32	22	5	30
2	12	15	34	26	15	30
3	7	10	40	30	25	45

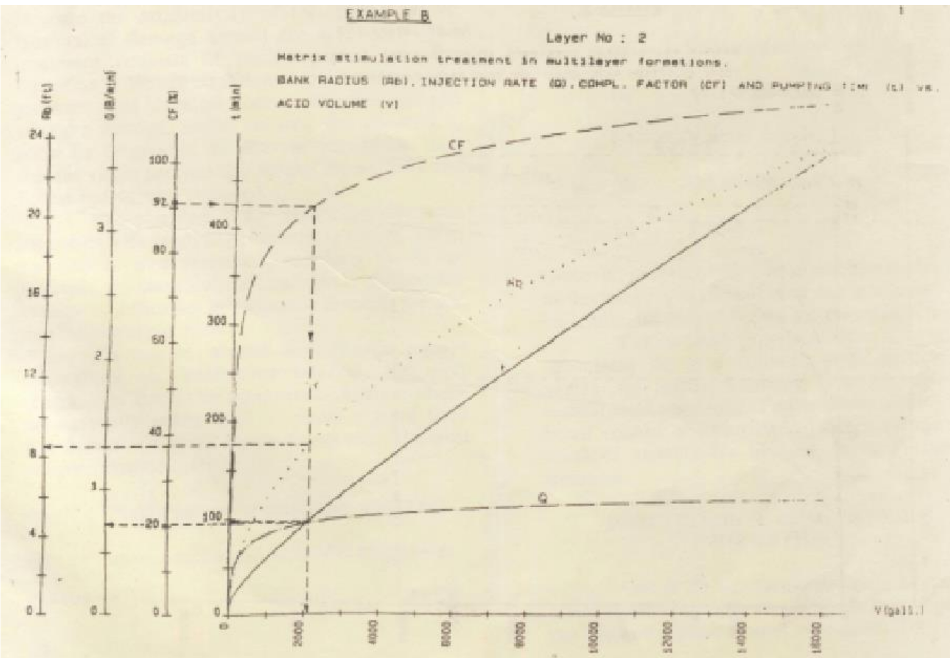
Other well data: $\mathbf{R_w}$ = 0.35 ft; $\mathbf{R_e}$= 1000 ft; **M.**=0.8 cp.

Based on previous selective stimulations in wells from the same reservoir, it has been determined that for layers 1 and 2, a volume of 100 gallons per foot of acid resulted in a CF of 90%, while for layer 3, a volume of 120 gallons per foot completely removed the damage, achieving a CF of 100%. The average acid pressure (AP) for all treatments was 2000 psi. Considering calculations on well productivity, it is required that CF after the acid job be at least 92% for all three layers.

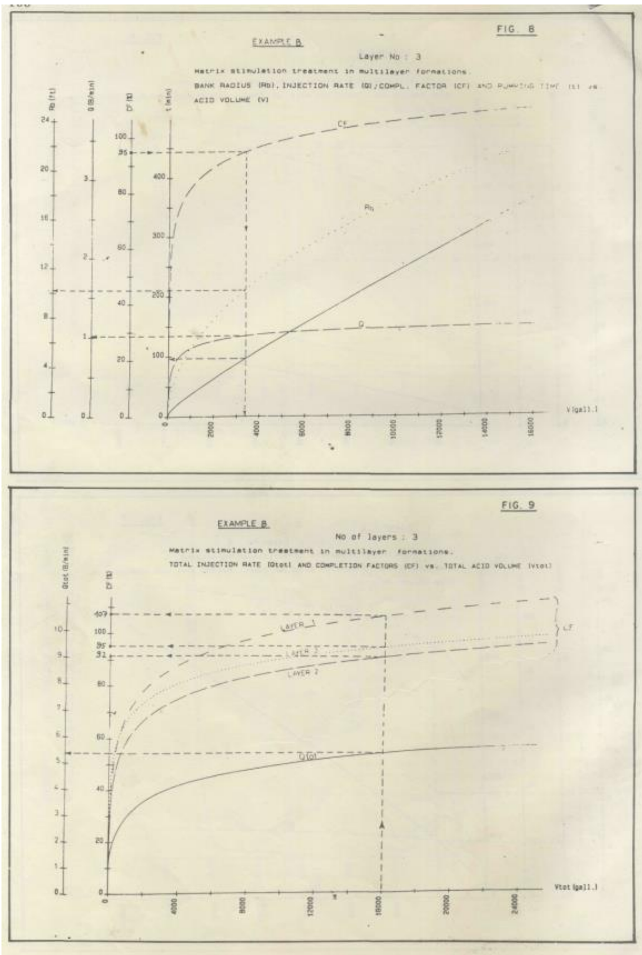
The solution involves utilizing the computer graphs presented in Figures 6, 7, 8, and 9. These graphs represent various parameters as a function of the acid volume entering the layers, including CF, Q (injection rate), Rb (bank radius), and injection time. Figure 9 displays the CF for each layer and the total injection rate (Q total) against the total acid volume. By referring to this graph, the minimum acid volume needed to reach the target CF of 92% can be estimated. For this particular case, a volume of 16,000 gallons is determined as the minimum value required to achieve the target CF. The results indicate CF values of 92%, 95%, and 107% for layers 2, 3, and 1, respectively. The relative Qtotal at the end of the job is 5.3 barrels per minute (BPM). From the graph in Figure 9, the CF of the layers can be estimated for any total volume of acid used. For example, using 5000 gallons of acid would only bring layer 1 to the desired level of stimulation (CF = 92%), while layers 3 and 2 would have CF values of 83% and 78%, respectively. By utilizing the graphs in Figures 6, 7, and 8, and starting from the CF values obtained from Figure 6, it is possible to find the volume of acid, Rb, and Q for each layer at any given time during the acid job. The values at the end of the job, when 16,000 gallons of acid were used, are presented in Table 3.



Figue 6: Graph of Formation radius vs Injection Rate.



Figue 7: Graph of Formation bank radius vs Injection Rate.



Figures 8 and 9: Values at the end of the job.

Table 3: Values of gallon of acids used.

Layer	V (gall)	Q (BPM)	Rb (ft)
1	10.500	3.55	13.6
2	2.150	0.73	8.5
3	3.350	1.02	103

The pumping time for all layers is obviously the same: it is found to be t = 100 min

4. CONCLUSIONS

A new approach has been introduced for estimating the optimal volume of acid in matrix acidizing for both single and multilayered reservoirs, applicable to both sandstone and carbonate formations. This method enables the calculation of the instantaneous completion factor (CF) for each layer based on the volume of acid injected into the well, without the use of diverting agents.

The suggested technique offers an alternative to conventional methods used for improving acid diversion across the entire perforated interval. It proves useful for planning acid jobs, including determining injection rates and volumes, as well as for operational control at the well site.

The foundation of this new approach is an empirical formula that establishes a link between the completion factor and the bank radius of acid injected into a single layer. The formula was derived from an analysis of matrix acidizing treatments conducted by Agip over the past decade, during which the acid injection rate was maximized.

The application of this technique to real matrix acidizing treatments reveals that a significant portion (approximately 75%) of the total formation damage is removed by the initial 1/3 of the acid pumped.

It is important to note that this technique can only be applied if at least one previous acid job on the same formation has been well-documented. The selection of the optimal acid treatment volume should also consider the CF target in light of the overall performance of the production system. Overall, the proposed approach provides a valuable tool for optimizing acid volumes in matrix acidizing, offering improved treatment planning and control for enhanced reservoir productivity.

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