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IMPROVEMENT OF OIL PRODUCTION BY MATRIX ACIDIZING OF A WELL IN SANDSTONE RESERVOIR

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ABSTRACT

This paper focuses on investigating the reasons behind the low productivity of a confidentially named well, referred to as X102, in sandstone reservoirs. The objective is to enhance the well's productivity through the implementation of acidizing techniques. The paper makes a significant contribution to the existing literature in this field by expanding the knowledge base and providing an economic analysis of acidizing oil wells. The assessment of the X102 well indicates that it exhibited initial productivity from the natural energy of the oil reservoir, demonstrating an oil flow rate of 307 barrels per day with a skin value of 35. After 3 years of production, the X102 well experienced a decline in productivity due to fines migration. Excel software was employed to process well completions, reservoirs, production, well tests, and economic data. The Horner plot slope was used to calculate the damage, Pipesim software extracted the initial profile of the X102 well, and StimCADE software facilitated the acidizing design. Following the implementation of acidizing, a reduction in fines flow was observed, resulting in a decrease in skin value from 35 to 5. The acid treatment successfully dissolved the fine particles, leading to an increased oil flow rate of 1006 barrels per day. Economically, acidizing proved suitable, generating a profit of $44,062,800 and achieving a return on investment in 89 days over a 2-year production period.

Keywords: sandstone reservoir, well X102 skin value, Horner plot slope, acidizing techniques, fines migration, economical evaluation.

INTRODUCTION

Extracting hydrocarbons from the reservoir and bringing them to the surface is the fundamental process of putting a hydrocarbon deposit into production [1-3]. Improving production forecasts for an oil field constitutes one of the major concerns of reservoir engineers within oil companies [4-6]. To maximize hydrocarbon production, operators have the option of either drilling new wells or stimulating existing ones [7-9]. Early in the life of these wells, the reservoir pore throats are relatively interconnected, thus providing a clear pathway for the transportation of hydrocarbons from the reservoir to the wellbore. [10-12]. Over time, pore connectivity diminishes due to damage around the wellbore, caused by drilling, completion, production, and workover operations [13-15]. These factors include surface tension, which influences intermolecular attraction and is investigated in mineral and crude oil systems. Also, the measurements of live oil compressibility below saturation pressures revealed that the behavior of foamy oil is more influenced by viscosity rather than compressibility, emphasizing the significance of properties such as the presence or absence of asphaltenes and other polar oil components [16, 17].

Well-stimulation is a technique used to improve the flow of oil or gas from the reservoir by dissolving rocks or creating new channels around the wellbore [18-20]. Acid fracturing, hydraulic fracturing, and matrix acidizing are the types of stimulation techniques intended to remedy or improve the natural connection of the wellbore in the reservoir [21-23]. Matrix acidizing is a process that involves injecting acid at pressures lower than that of fracturing to enhance the capacity or injectivity rate of a wellbore [22].

Sandstone reservoirs generally face degradation problems depending on any factor favoring its formation [16, 17]. Thus, proposing a solution to remedy the damage problem (degradation) becomes necessary. However, treatment with matrix acidizing leads to the elimination of damage around the well and restoration of the initial permeability of the layer [1]. It would be incorrect to conclude that the injection of acid into a sedimentary formation always results in an improvement in production [18-20]. Injecting acid into a rock formation without careful study can cause much more severe damage [24]. The question that arises is: Will the development of a matrix acidizing design solve the damage problem and lead to an increase in production from the X102 well?

In the wide literature, Ji *et* al. [25] exploited aluminum chloride ($AlCl_3$) as a retarding agent in mud acid, employing solubility tests, coreflood tests, and ^{19}F nuclear magnetic resonance to assess its interactions with clay minerals. Their results revealed that $AlCl_3$ effectively slows hydrofluoric acid reactions and enhances sandstone permeability, with significant findings on reactive species and penetration depth. Also, advancements in sandstone acidizing, focusing on the efficacy of various acids like retarded mud acids and organic-HF acids in enhancing reservoir porosity and permeability was investigated by Shafiq and Mahmud [26]. They examined the challenges in high-temperature applications, outlining successful matrix stimulation techniques, and discussed future requirements for developing innovative acidizing methods and experimental approaches. Further exploration of a developed cationic gemini surfactant used as a retarding agent in sandstone acidizing with HF/HCl was carried out. Through coreflooding experiments and numerical simulations, the surfactant was shown to reduce interactions with clay and feldspar, thereby improving acid penetration and permeability, resulting in enhanced well productivity and efficient damage remediation in sandstone formations [27]. The impact of matrix acidizing design on oil recovery and economic aspects was investigated in offshore carbonate reservoirs undergoing waterflooding in Brazil [28].

This paper showcases the efficacy of matrix acidizing in enhancing the productivity and profitability of the X102 well in a sandstone reservoir. The paper aims to investigate the factors leading to the decline in production and assess the nature of the damage observed in the well. This research makes a substantial contribution to the current literature by expanding the understanding in this area and offering an economic analysis of acidizing techniques in oil wells. The other section of the paper follows the flow: Section 2 presents the data, software used, the methodology used to achieve the objectives set, and the different results. Section 3 presents the conclusion.

DATA AND RESULTS

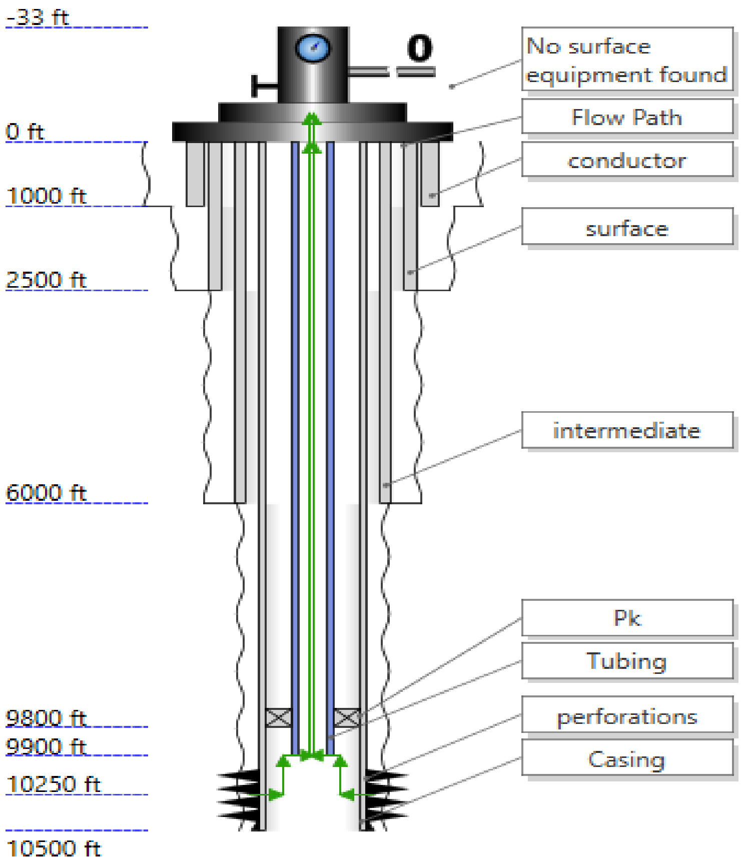
Matrix acidizing is a well stimulation technique that involves injecting an acid solution into the formation at pressures below fracture pressure. The purpose is to dissolve minerals present in the formation pores, thereby restoring permeability in the vicinity of the well. The data utilized in this study was collected by the petroleum company Perenco. Table 1 presents the data from X102 well.

Table 1. *Data from X102 well.*

Well data	
Well name	X102 (for confidential reasons)
Field	RDR
Platform	NWA
Well type	Oil Producer
Treatment Type	Matrix acidizing
Perforation interval data	
Height	10000 ft
Top	10500 ft
Total length	500 ft
Reservoir data	
Permeability k before treatment	165 md
Porosity	26.6%
BHT (Bottom Hole Temperature)	200 ºF
Skin before treatment	34
Height	37 ft
rw (Well radius)	0.5 ft
rs (Radius of the damage area)	2 ft
re (Radius of acidizing zone or drainage)	2000 ft
Bo	1.2

GOR (ratio gas/oil)	345 scf/stb
Oil viscosity	1.2 cp
Reservoir pressure	3362 psia
Production data	
Qo (Oil production rate before acidizing)	307 bpd
PI (Productivity Index)	0,95 STB/d/Psi
Economics	
CAPEX	- Equipment and chemicals used $720 000 - Taxes (10%)
OPEX	- Platform integrity, Pump Hours, Accommodation: $250 000 - Cost of producing a barrel of oil:10$ - Discount rate is 20%
Royalty	10%
Oil price	Approx $86,1 /barrel (August 2023)

This data is then processed using Pipesim, Excel, and StimCADE software. Figure 1 represents the profile and nodal analysis of X102 well before matrix acidizing.



(a)

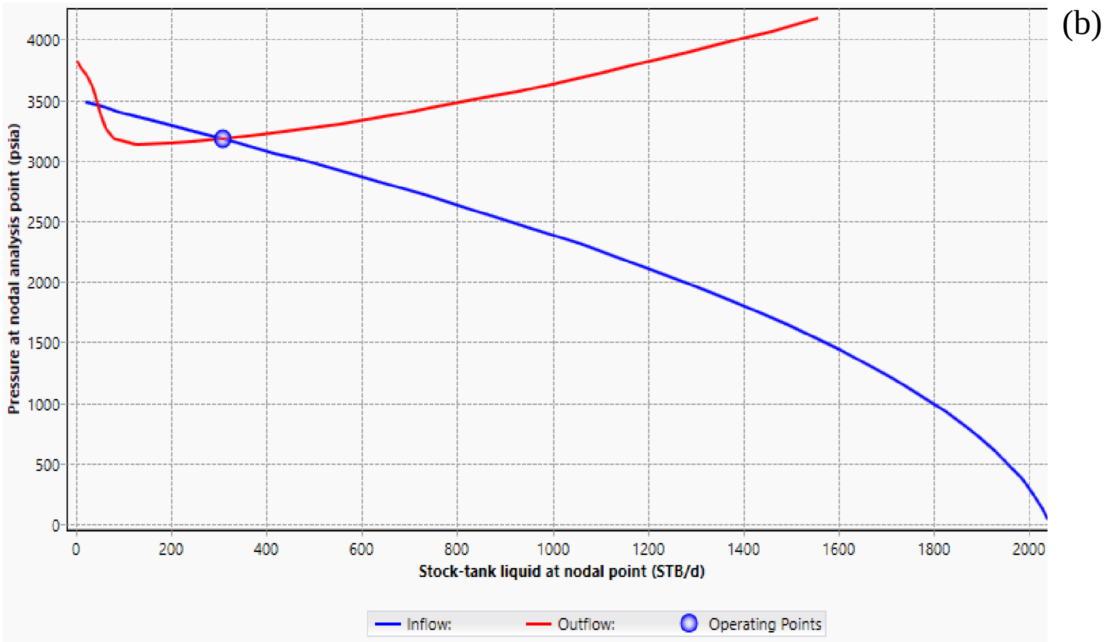
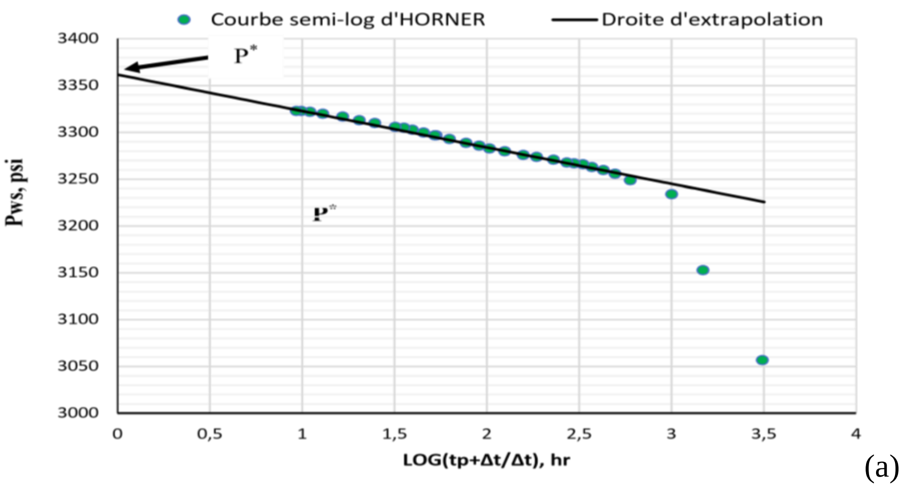
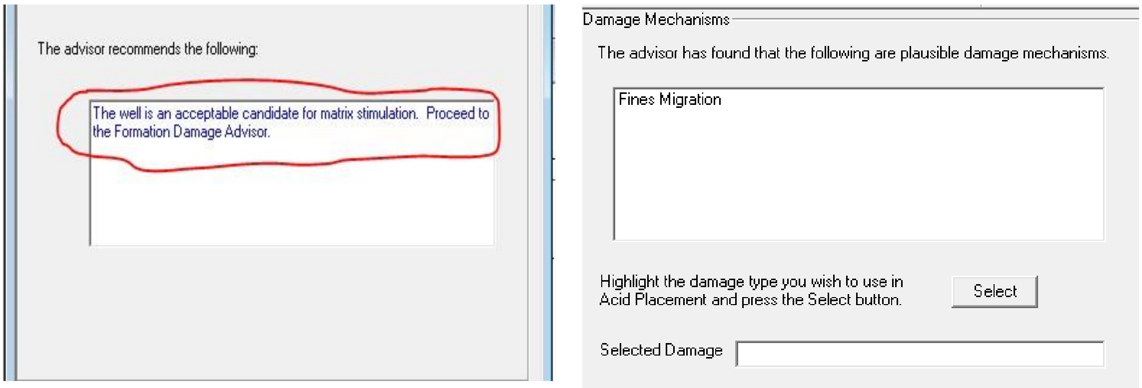


***Figure 1**. (a) Profile and (b) nodal analysis of X102 well before matrix acidizing.*

The initial profile of X102 well shown in Fig. 1 (a) is obtained from Pipesim. An oil production rate of 307 barrels per day at a pressure of 3176.7 Psia and a skin of 35 in Fig. 1(b) was obtained. The results of the build-up test are shown in Fig. 2 which represents the variation of pressure as a function of Horner time and the selection results of the X102 well. The Horner plot is a graphical technique employed in reservoir engineering to analyze pressure transient data obtained from oil or gas wells. Its purpose is to estimate key reservoir properties, such as permeability and skin factor, and forecast future well performance. By plotting logarithmic pressure changes against logarithmic time, valuable reservoir parameters can be determined from the resulting linear relationship. The Horner plot serves as a crucial tool for enhancing reservoir characterization and optimizing production strategies.





(b) (c)

Figure 2. *(a) Schematic of the Horner curve of X102 well and the selection results of X102 well, and results of: (b) selection guide and (c) damage.*

The X102 well is subjected to a matrix acidizing treatment operation as shown in Fig. 2(a). The build-up was completed in 37.54 hours. In Fig. 2 (b) circled information in red clearly mentions that: "The well is an acceptable candidate for matrix stimulation, which proceeds to the formation damage advisor''. As shown in Figure 2(c), the damage in the X102 well appears to be primarily mechanical in nature. This damage stems from the movement of fine quartz particles during production operations within the sandstone reservoir. These particles obstruct the layers, leading to a significant reduction in the rock's permeability and ultimately decreasing the well's productivity.

Results of matrix acidizing

The acidizing program runs for obtaining the distribution of the exact quantities of fluids in each zone and the total duration necessary for the injection of the fluids and to present the quantities of the fluids used. Table 2 provides information on the quantities of fluids pumped in the different zones.

Table 2. *Results of the fluid execution in the different zones*

Fluide Name	Volume (m^3)	Zone 1 (m^3/ft)	Zone 2 (m^3/ft)	Zone 3 (m^3/ft)
HCL 10 %	28.6	0.97	0.64	0.7
Mud Acid 12/3	11.4	0.41	0.24	0.27
Foamer	2.2	0.08	0.04	0.05
Regular Clay Acid	19.5	0.73	0.38	0.45
NH_4CL 5%	19.6	0.75	0.36	0.43
Total	81.3			

Key: HCL is Hydrochloric acid; NH_4CL is Ammonium chloride.

The pumped acids (acidizing of the reservoir) are injected into the formation which is subdivided into 3 zones with distinct characteristics. It appears from Table 2 that the success of this stimulation required a total volume of 81.3 m^3 of fluid, or 28.6 m^3 for the preflush, 39.1 m^3 (19.5 m^3 + 19.6 m^3) for the overflush, 11.4 m^3 for the mainflush, and

2.2 m^3 for diversion agents. Thus, the acidizing is carried out in 7 successive stages. In zone 1, the volume consumption per foot is higher than in the other zones for the simple fact that its permeability is higher than that of the other layers. At the end of the acidizing, a positive average skin of 5 is obtained. This value makes it possible to state without ambiguity that the X102 well is stimulated because the skin is stripped of a large percentage. Fluid pumping is completed in 313.4 min. Each stage has a well-defined duration as shown in Table 3.

Table 3. *Fluid pumping times and their cumulative volume.*

Time (min)	Step	Fluid Name	Liquid Rate (m^3/min)	Liquid Volume (m^3)	Cum. Liquid Volume (m^3)
35.7	PF	HCL 10 %	0.16	5.7	5.7
71.6	MF	Mud Acid 12/3	0.16	5.7	11.4
125.2	FO	Foamer	0.04	2.2	13.6
143.4	PF	HCL 10 %	0.31	5.7	19.3
158.6	MF	Mud Acid 12/3	0.38	5.7	25
212.0	OF	Regular Clay Acid	0.37	19.5	44.5
273.5	OF	NH_4CL 5%	0.32	19.6	64
313.4	DS	Nitrogen	0.43	17.3	81.3

Key: min is minutes

The preflush consisting of 2 stages is carried out in 143.4 min as shown in Table 3. The mainflush consisting of 2 stages is carried out in 158.6 min, the over flush consisting of 2 stages is carried out in 273.5 min and the diversion fluid consisting of 1 step is completed in 125.2 min. The cumulative volume of fluids increases as time progresses. Figure 3 evaluates the fall of the fines thickness in each of the 3 zones as a function of the volume and the different injected acids.

The reduction in skin value progressively decreases with the advancement of pumping stages, indicating the gradual elimination of damage around the well, as shown in Figure 3 (a). Paccaloni [30] observed that changes in skin are dependent on the pumped liquid. Zone 2 exhibits a significant drop in skin due to the mainflush (labeled as fluid 2) effectively dissolving minerals like quartz, clay, feldspar, and silicates, leading to damage elimination. The convergence of these factors contributes to the final skin value. To summarize the skin values before and after stimulation, in zone 1 the skin changes from 35 to 3, in zone 2 it changes from 34 to 7, and in zone 3 it changes from 36 to 6. Figure 3 (b) illustrates the variations in average skin depending on the injected acid across the three zones where the damaged layer was divided. This curve is influenced by the pumping of the mainflush, Mud Acid, while the pumping of other fluids has minimal impact on skin reduction, as evident from the relatively constant curve in the zone influenced by these fluids. Figure 4 presents the pressure variations, flow rates of injected acids as a function of pumping time, flow rate in each zone, and hydrostatic pressure as a function of volume.

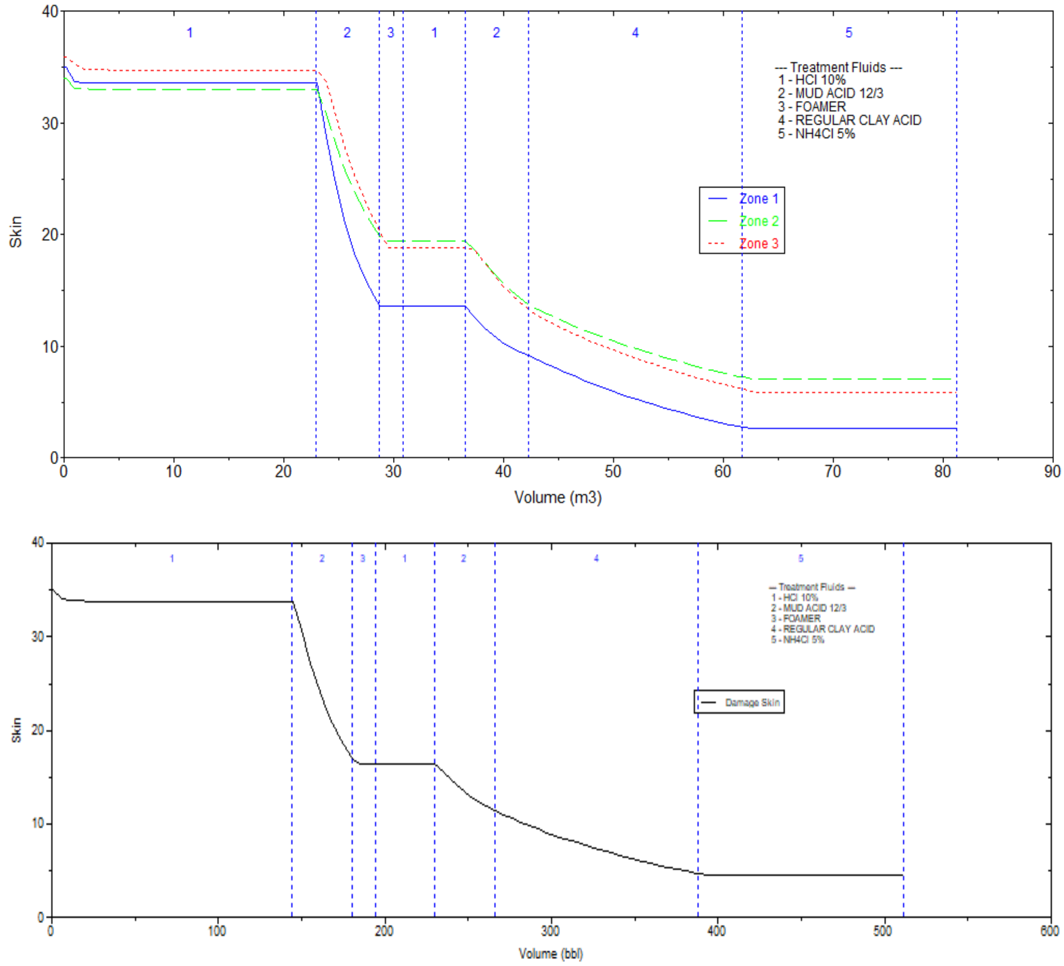


Figure 3. *Variations of the skin depending on (a) the volume per area and (b) the injected fluid.*

At the start of the injection of the acids, (see Fig. 4 (a)), the bottom pressure shown by the yellow curve reaches a maximum value of 31026 kPa. But with the evolution of time, it seeks to stabilize by converging towards a value of 24131 kPa. In essence, the reduction in bottom hole pressure induces an increase in the reaction speed of the acid in the injection reservoir. The green colored curve indicates the variation of total flow rate as we see in Fig. 4 (a). The skin value reaches its maximum when fluids 1 and 2 are pumped, and it is minimized when the diversion fluid is injected (see Fig. 4 (a)). The injection pressure curve (wellhead pressure), represented in black, exhibits variations until reaching a maximum value of 17,236 kPa. Subsequently, it decreases to a value of 689 kPa, with its evolution being closely related to the background pressure. It is controlled by the coiled tubing unit from the wellhead [29]. It is important to note that tubing serves as the pathway for acid delivery in oil wells, enabling precise placement and pressure control during acid stimulation treatments. Its durable design and corrosion resistance guarantee the safe and efficient transport of acid to the target zone, optimizing well performance.

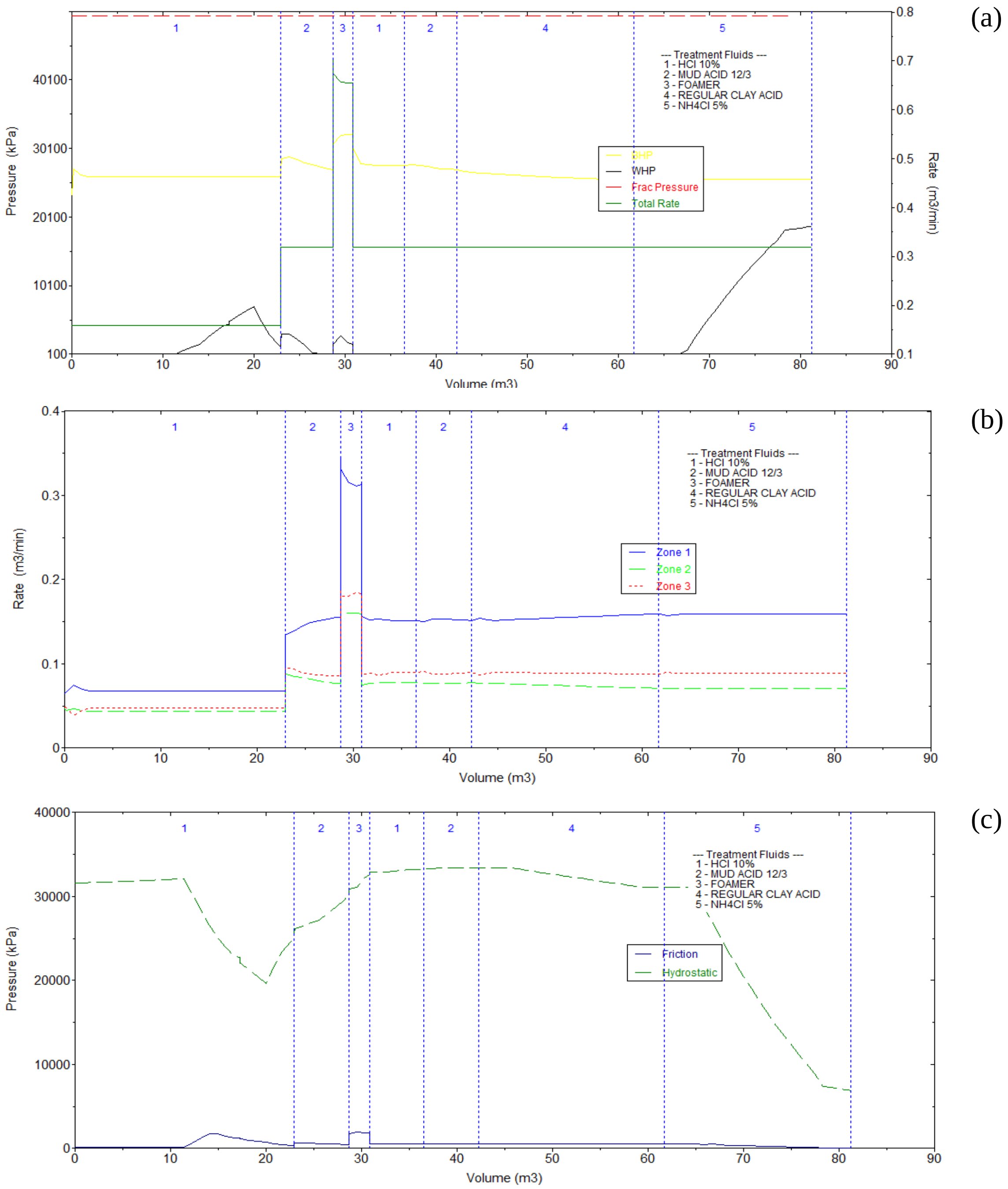


Figure 4*. (a) Variation of pressures and flow as a function of time; (b) evolution of flow rate by area, and (c) hydrostatic pressure and friction as a function of volume.*

The consistent curve depicted in light red (refer to Fig. 4 (a)) represents the fracturing pressure of the reservoir. It is crucial to avoid surpassing this pressure with other fluids to prevent rock fracturing, as it is a critical condition that must be adhered to during acid stimulation interventions. It should be noted in Fig. 4 (a) that according to pressure half of the first preflush stage is foamed. The specified fracturing pressure is 49,000 kPa. The maximum value of the injection rate is 0.32 m^3/min as shown in Fig. 4 (b). It is evident that the flow curve of zone 1 is higher compared to the other curves due to the elevated height. The green curve indicates the hydrostatic pressure which decreases sharply in stages 1 and 5 because the injection pressure increases and that at the bottom is almost constant as shown in Fig. 4 (c) (This is the case of decrease fluid density when foaming the injected fluid). The blue curve touching the abscissa axis at some of its points represents the friction load losses. The maximum value of this hydrostatic pressure is 32000 kPa and the minimum value is 6000 kPa. It plays a main role in the well because it prevents the flow of fluids (like water). And more importantly, from the two hydrostatic pressures we evaluate the fluid injection pressure. It is interesting to highlight also that nitrogen displacement is part of the diversion fluid.

Figure 5 evaluates the penetration radius of fluids into the formation. Figure 5 illustrates that the sub-rectangles contained within the horizontal rectangles represent the treatment fluids. The number of sub-rectangles corresponds to the 7 pumping stages, with respective thicknesses of 13 ft, 12 ft, and 12 ft. Zone 1 achieves a superior penetration radius in comparison to the other zones due to its higher permeability.

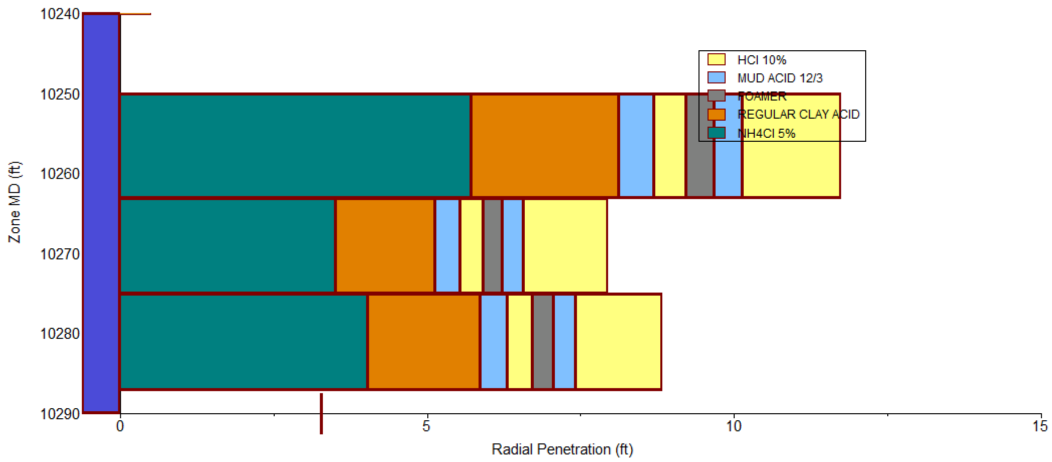


Figure 5. *Penetration radius of processing fluids.*

Figure 6 gives the different variations in permeability around the X102 well as a function of cumulative time and acid penetration radius in different zones. Careful observation of the results obtained in Fig. 6 allows us to draw the following conclusions:

- The best permeability values are obtained around the well where the deposits are concentrated and are less good as the penetration radius increases because the acid becomes exhausted with depth. We note the values 415.9, 304.6, and 377.7 which are the best permeabilities obtained respectively for zones 1, 2, and 3 for a penetration radius of 0.2 ft.
- The results are more satisfactory when the reaction time increases because certain minerals dissolve very slowly.

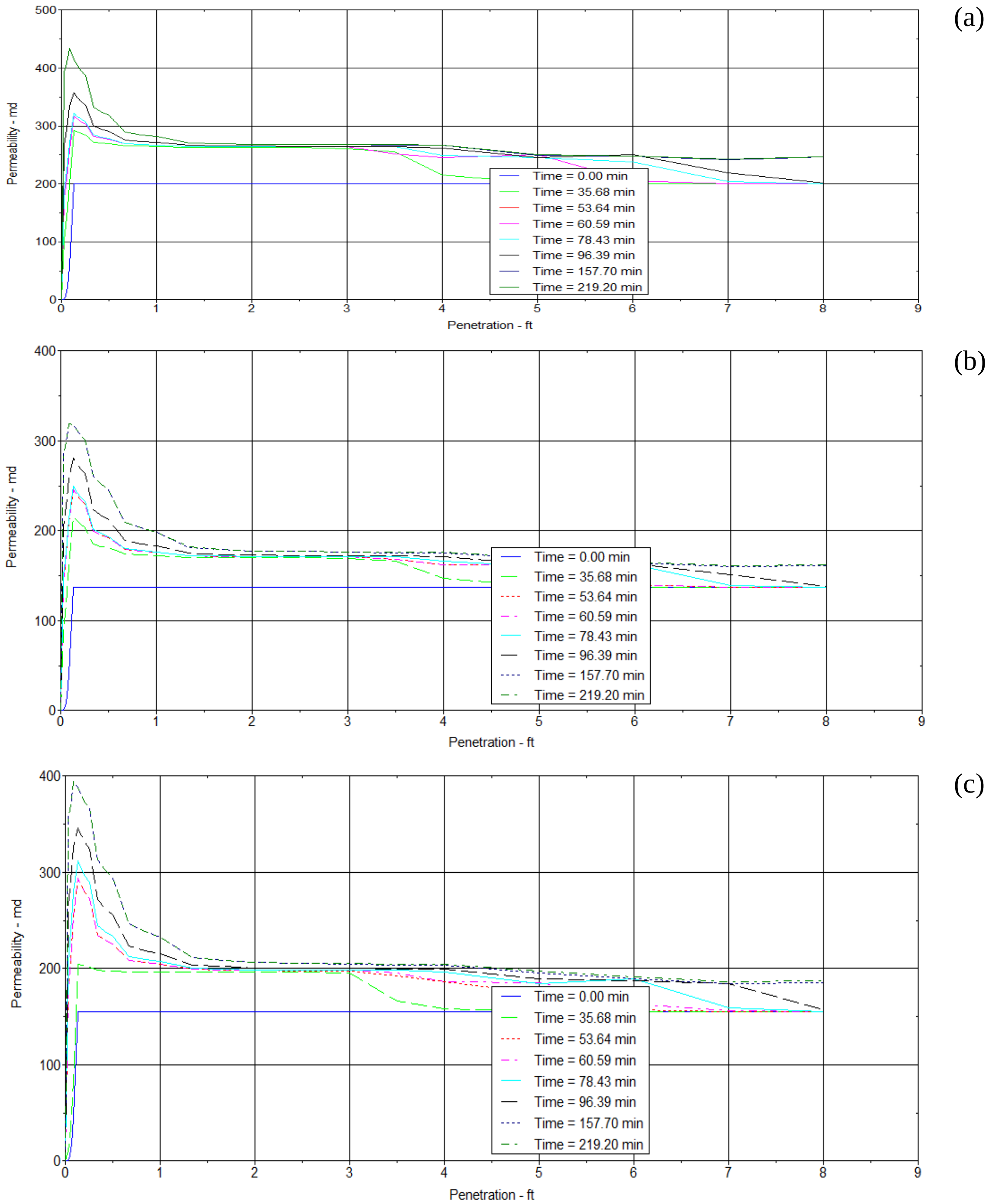


Figure 6*. Real-time permeability as a function of the penetration radius of:*
(a) zone 1, (b) zone 2, and (c) zone 3.

Figure 7 provides a real-time depiction of the porosity progression within the formation. As pumping time increases, an increase in porosity is observed. This indicates that the previously clogged layers, which hindered the interconnection of pores, have been successfully restored.

Figure 7 reveals that the values 31.1%, 38.4%, and 36.9% are the best porosities obtained respectively for zones 1, 2, and 3. Just like the permeability, the results are more satisfactory when the reaction time increases because certain minerals dissolve very slowly.

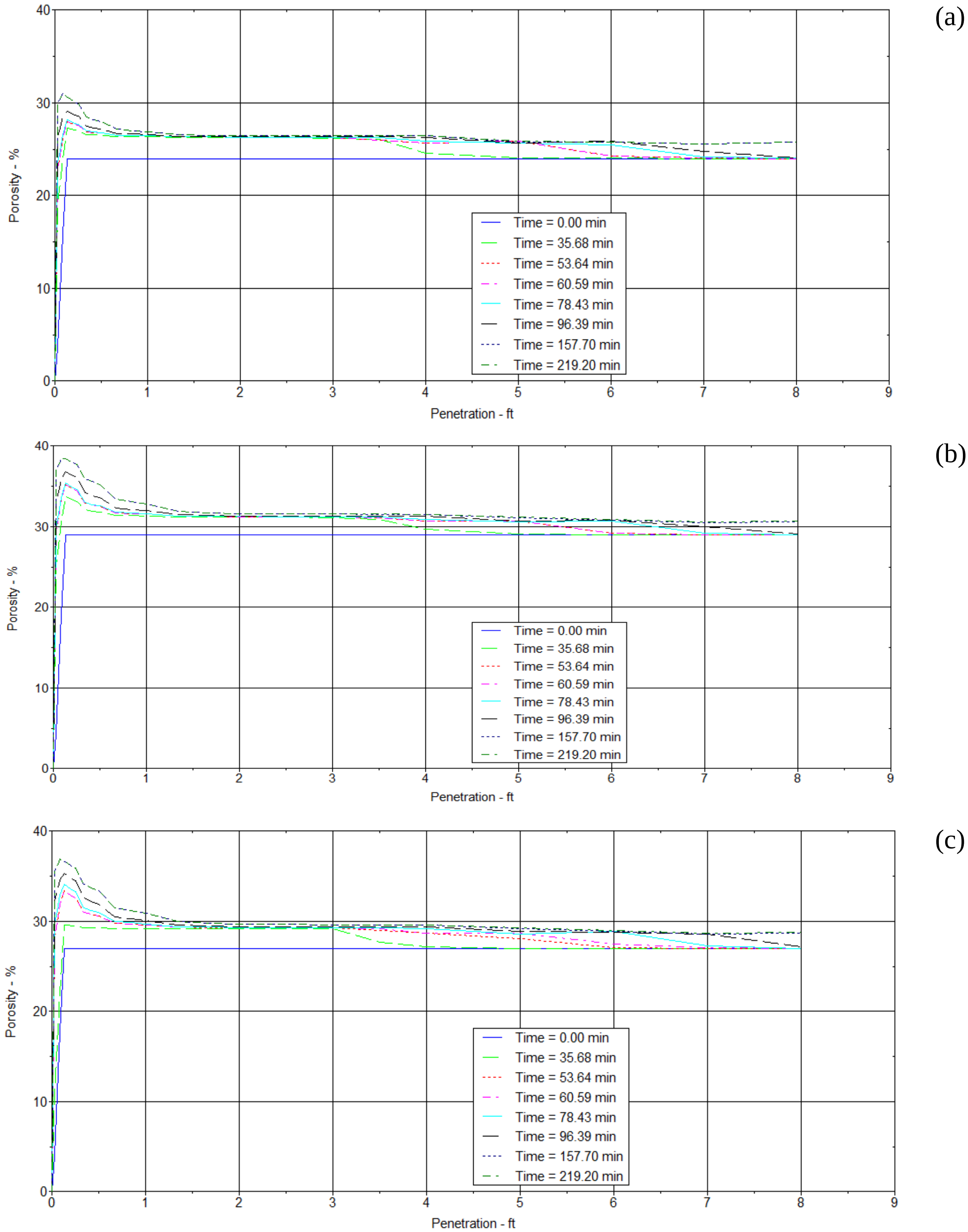


***Figure 7**. Real-time porosity as a function of the penetration radius of:*
(a) zone 1, (b) zone 2, and (c) zone 3.

Figure 8 shows the production rate and cumulative production of the non-acidized and acidized reservoirs at the X102 well. The flow rate depicted in Figure 8(a) demonstrates a substantial increase from 307 to 1068 barrels per day, representing a 71.25% growth or roughly a threefold increase compared to the flow rate of the damaged reservoir. Although a slight decline in flow rate occurs, it eventually stabilizes at a constant limit value. This suggests the development of a transient flow regime that is not influenced by the skin factor, taking into account economic and market considerations. It is important to note that despite the gradual decrease in flow rate over time, there is consistently a substantial gap between the stimulated well and the unstimulated well. The curve representing the unstimulated reservoir demonstrates the reservoir's behavior over time in the absence of intervention. In Fig. 8 (b), the cumulative production of the acidized well is represented by a linear upward trend in red, indicating a steady increase with time. Conversely, the cumulative production of the unstimulated reservoir, illustrated by the blue line, exhibits slower growth due to the presence of damage that hinders production.

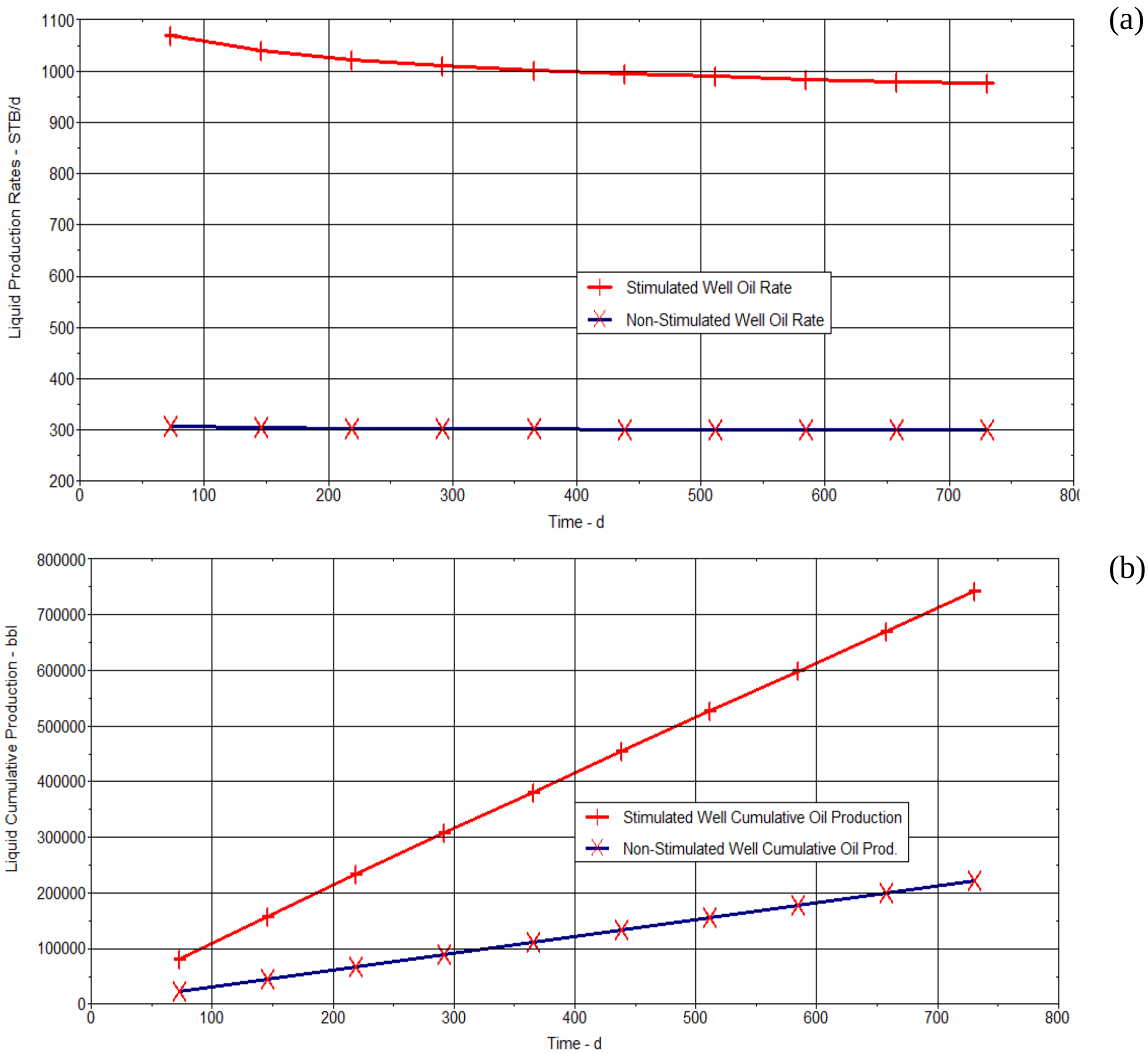


***Figure 8**. (a) Production rate and (b) cumulative non-acidized and acidized reservoir production.*

Economic evaluation results

This section holds great significance in the assessment of an acidizing project as it helps evaluate whether the undertaken work can yield a return on investment and cash benefits within the production period. Table 4 presents the economic outcomes of the X102 well following acidizing, shedding light on the financial results.

Table 4. *Economic analysis of matrix acidizing.*

Financial indicators	Results
Oil profit $ (US)	44062800
Total cost $ (US)	5376280
Net present value $ (US)	26202060
KING (%)	27.01
Payback (days)	89
Unit price in $/bbl	0.22

The outcomes presented in Table 4 are considered satisfactory, as they indicate a profit of $44,062,800. This indicates that the income generated by the project surpasses the total expenses. The positive net present value (NPV) suggests profitability, and the return on investment (ROI) value is also deemed satisfactory. Additionally, the short payback period of 89 days further highlights the project’s improved profitability.

CONCLUSIONS

The study focuses on the X102 well, which experienced a gradual decline in production due to maturity. The objective was to identify the cause of the decreasing flow and propose a solution. Well, completion, reservoir, production, well testing, and economic data were analyzed. The Horner plot was used to calculate the skin factor, indicating an initial value of 35, potentially impacting productivity. The analysis revealed the formation damage was attributed to particle accumulation and plugging caused by high drawdown. The design involved selecting appropriate acids (10% HCl, 3% HF, and 12% NH4Cl) and using nitrogen as a diversion fluid. Diverters like foamers and ball sealers were employed for proper acid placement. Simulation results showed a reduced skin value of 5, resulting in increased oil flow from 307 to 1068 barrels per day. Post-treatment evaluation confirmed the effectiveness of the design. The economic evaluation demonstrated a payback period of 89 days over a 2-year forecast and a net present value of $26,202,060.

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