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An economic and user-friendly EOR screening approach for a given field - A visual basic approach

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Abstract

There are three mechanisms used to recover oil from a reservoir. They are the primary, secondary and tertiary recovery mechanisms. Generally, about 50% of the oil initially in place can be recovered after primary and secondary recoveries. The remaining oil usually has low API gravity and high viscosity which makes it difficult to be recovered by the conventional primary and secondary methods. A portion of this remaining oil can be recovered by applying Enhanced Oil Recovery methods (EOR). However, the main challenge associated with EOR implementation is the selection of an appropriate EOR method to apply. Conventionally, this is time consuming going through these criteria manually to select an appropriate EOR method for a field. Available commercial software packages are relatively expensive. This work therefore uses developed a user-friendly and relatively less expensive visual basic software package to screen to select an optimal EOR method to apply for a given field. The reservoir and fluid properties for Suplacu de Barcau field were used to validate the software. The field had only 9% of its OIIP recovered after primary recovery and currently has a total recovery of 46.6% after the application of in-situ combustion. The developed software validated well. The sensitivity of each screening parameter on a particular EOR method can be analysed and used to improve the software package.

Keywords: screening, selection, enhanced oil recovery, reservoir properties, visual basic

Introduction

The methods for recovery of crude oil from reserves can be categorized under three main phases: primary, secondary, and tertiary (enhanced oil recovery) (Dankwa, 2022) [10]. While industry players continue to seek new fields rather than maximizing and increasing production for existing fields, all oil and gas operations, particularly drilling and production, generate wastes that could have a negative influence on the environment. (Dabo, 2022) [5,]. With about 80% of the world's energy coming from petroleum, there is a need to enhance recovery (Amorin *et al*., 2022a) [5, 6]. In order for the oil and gas industry to play key role in the transition face, the industry must ensure well profile optimization, improve oil recovery technics, adapt CCUS technology, and implement proper waste management. (Amorin *et al*., 2022b, Dabo *et al*., 2022) [6, 8, 9]

During the first phase of recovery which is primary recovery, the natural energy or stress already existing in the reservoir is used for pushing the reservoir fluid to surface or sometimes combined with artificial lift techniques for a better recovery of oil to the surface (Al-Ajarba and Al-Anazi, 2009). During the primary phase, just about 10% of the oil initially in place is recovered (Al-Ajarba and Al-Anazi, 2009). After the natural energy of the reservoir is exhausted, the secondary recovery methods are used. These techniques include water injection and gas injection. This is mainly done to restore or maintain pressure in the reservoir and to displace the reservoir fluids, pushing it to the surface. The secondary recovery techniques are able to recover about 20-40% of the oil initially in place (Al-Ajarba and Al-Anazi, 2009). When the general price of oil is high, producers attempt to produce a part of the substantial residual oil using Enhanced Oil Recovery (EOR) techniques.

The EOR techniques are suitable for the production of heavy oil and tar sands. Heavy oil and tar sands have high viscosity and low American Petroleum Institute degree (API°) (Huang, 2015). The major techniques of EOR have been in existence for many decades but due to economic constraints and the complex nature of the reservoir process involved in EOR, the implementation of many projects was delayed (Jelmert *et al*., 2010) [11]. Under current reservoir management practices, engineers consider EOR options much earlier in the productive life of the reservoir (Taber *et al*., 1997) [16]. The main types of EOR methods are thermal recovery methods which are subdivided into steam flooding and cyclic steam stimulation; chemical recovery methods which are subdivided into polymer flooding, surfactant flooding and caustic flooding, and; miscible gas injection methods which are subdivided into nitrogen flue gas flooding, hydrocarbon gas flooding and carbon dioxide flooding (Taber *et al*., 1997) [16]. Only one of these methods can be applied to the field at a time hence these EOR methods must be screened using various factors in order to select the best and suitable one for the field. The prediction or selection of an EOR method is complicated and complex due to the large amount of data associated with the petro-physical, geological, environmental and fluid properties that must be considered for each method (Jelmert *et al*., 2010) [11].

The present and past analysis of EOR methods provides a qualitative guidance on EOR potential. The first EOR screening criteria were published by Taber *et al* in 1976 and were later updated in 1982 after extra EOR projects commenced (Al Adasani and Bai, 2014). A lot of EOR screening approaches have been postulated ranging from applicability range, binary selection, data mining, and numerical simulation. The screening and selection of EOR projects is a data-driven process. Based on the quality and relevance of the data available, different plausible EOR alternatives can be proposed for a give field. EOR selection requires proper understanding of reservoir architecture and reservoir fluid-flow forces. Past and present EOR experiences are used during the screening process. Based on past successes and failures resulting from the applications of certain EOR methods under specific field conditions, many EOR screening criteria using reservoir and fluid properties have been developed (Aladasani, 2012) [4].

The high capital investment, high technical sensitivity and the complexity and the uncertainty associated with EOR makes the proper selection of an EOR method challenging and critical for good decision making (Kamari *et al*, 2014) [12, 13]. Manually screening EOR methods is time consuming and commercial software packages available for screening and selection for a method are expensive. This work therefore developed a relatively cost-effective and user-friendly software to screen and predict the type of EOR method to be used on a given field based on some relevant fluid and reservoir properties.

Methods

Data Acquisition

The data used in this project was acquired through literature. Various screening criteria and guidelines for EOR methods were gathered from journals, textbooks and articles. In total 16 EOR methods were screened against 9 parameters; 2 reservoir fluid properties and 7 reservoir properties. The different ranges for each screening parameter for which an EOR method is applicable were compared and a common range developed. Tables 1, 2 and and 3 show the EOR selection criteria based on reservoir fluid properties and on reservoir properties respectively.

Table 1 EOR Selection Criteria Based on Reservoir Fluid Properties

EOR Methods	Oil API Gravity (˚API)	Oil Viscosity (cp)
CO_2 flooding	22 - 45	0 -35
Water alternating gas	33 - 39	0.3 - 09
Nitrogen flooding	25 - 54	0 - 02
Hydrocarbon flooding	23 - 57	0.04 -18000
Hydrocarbon flooding	28 – 48	0.25 - 4
Nitrogen flooding	16 - 54	0 - 18000
Water alternating gas	9.3 - 41	0.17 - 16000
CO_2 flooding	11 - 35	0.6 - 592
Surfactant flooding	22 - 39	2.63 – 15.6
Polymer flooding	13– 42.5	0.4 - 4000
Alkaline polymer surfactant	20 - 35	11 - 6500
Steam flooding	8 - 33	8 - 33
Combustion	10 - 38	1.44 - 5000
Hot water	12 - 25	170 - 8000
Surface mining	7 - 11	0
Microbial recovery	12 - 33	1.7 – 8900

(Sources: Al Adasani and Bai, 2014; Al Adasani and Bai, 2011; Kamari and Mohammadi, 2014; Taber *et al.*, 1997; Oughton, 2015) [12, 13]

Table 2: EOR Selection Criteria Based on Reservoir Properties

EOR Methods	Porosity (%)	Oil Saturation (%pv)	Formation Type
CO_2 flooding	3 -37	15 - 89	SS
Water alternating gas	11 - 24	11 - 24	SS
Nitrogen flooding	7.5 - 14	0.4 – 0.8	SS/CB
Hydrocarbon flooding	4.25 - 45	30 - 98	SS/CB
Hydrocarbon flooding	5 - 22	75 - 83	SS
Nitrogen flooding	11 - 28	47 – 98.5	SS
Water alternating gas	18 – 31.9	76 - 98	SS/CB
CO_2 flooding	17 – 32	42 - 78	SS/CB
Surfactant flooding	14 – 16.8	43.5 - 53	SS
Polymer flooding	10.4 - 33	34 - 82	SS
Alkaline polymer surfactant	26 – 32	35 – 74.8	SS
Steam flooding	12 – 65	35 - 90	SS
Combustion	14 - 35	50 – 94	SS/CB
Hot water	25 - 37	15 - 85	SS
Surface mining	> 0	> 8	SS
Microbial recovery	12 - 26	55 – 65	SS

(Sources: Al Adasani and Bai, 2014; Al Adasani and Bai, 2011; Kamari and Mohammadi, 2014; Taber *et al.*, 1997; Oughton, 2015) [16, 12, 13]

NOTE: SS IS SANDSTONE AND CB IS CARBONATE

Table 3: EOR Selection Criteria Based on Reservoir Properties Cont'd

EOR Methods	Net Thickness (ft)	Depth (ft)	Temperature (F)
CO2 flooding	1 - 500000	1500 - 13365	82 - 257
Water alternating gas	> 0	3745 - 8887	194 - 253
Nitrogen flooding	1 - 250000	6000 - 18500	190 – 325
Hydrocarbon flooding	1 - 250000	4000 - 15900	85 - 329
Hydrocarbon	> 0	6000 - 7000	82 - 257
Flooding	> 0	1700 - 18500	83 – 325
Nitrogen flooding	> 0	2650 - 9199	131 - 267
Water alternating gas	> 0	1150 - 8500	82 – 198
CO2 flooding	> 0	625 - 2300	122 - 155
Surfactant flooding	> 0	700 - 9460	74 - 237.2
Polymer flooding	> 0	2723 - 9000	118 - 200

Alkaline polymer surfactant	> 20	200 - 9000	10 - 350
Steam flooding	> 10	400 - 11300	64.4 - 320
Combustion	> 0	500 - 2950	75 – 135
Hot water	> 10	> 0	> 0
Surface mining	> 0	1572 - 3464	86 – 290

(Sources: Al Adasani and Bai, 2014; Al Adasani and Bai, 2011; Kamari and Mohammadi, 2014; Taber *et al*., 1997; Oughton, 2015) [16]

Selection procedure

The selection of the appropriate EOR method is basically based on nine screening parameters. They are Oil Gravity, Oil Viscosity, Porosity, Oil Saturation, Formation Type, Permeability, Net Thickness, Depth and Temperature. The steps below show how the screening and selection process is done.

- The values for the screening parameters (reservoir and fluid properties) for a candidate field are input into the software.
- The software compares the input data to the EOR screening criteria in Tables 1 and 3.
- The software assigns a weight of 1 to an EOR method when an input data falls within the range of one particular screening parameter for which the EOR method is applicable or assigns a weight of 0 when it not. The total number of screening parameters satisfied for each EOR method is calculated and expressed as a percentage of the total number of screening parameters. The total number of screening parameters satisfied is represented in Equation 1:

$$initial\ total\ parameters\ satisfied(TP_i) = \frac{T1_i}{T2} \times 100\% \qquad (1)$$

Where

T1i = number of screening parameters satisfied for an EOR method; and

T2 = total number of screening parameters

- The mean value for each range is calculated using Equation 2

$$mean_{i,j} = \frac{a1_{i,j} + a2_{i,j}}{2} \qquad (2)$$

Where

a1 = first number in the range; and

a2 = last number in the range

- The deviation from the mean is then calculated when a range for a screening parameter is satisfied for an EOR method. They are summed up to give the total deviation. The deviation from the mean and total deviation from the mean are represented in Equations 3 and 4 respectively

$$deviation_{ij} = \frac{mean1_{i,j} + input\ value}{mean_{i,j}} \times C_{ij} \qquad (3)$$

$$total\ deviation\ for\ each\ EOR\ method(Di) = \sum\left(deviation_{i,j}\right) \qquad (4)$$

Where

I = (CO_2 Flooding, Water Alternating Gas, Nitrogen Flooding, Hydrocarbon Flooding, Hydrocarbon Flooding, Nitrogen Flooding, Water Alternating Gas, CO_2 Flooding, Surfactant flooding, Polymer Flooding, Alkaline Polymer, Surfactant flooding, Steam Flooding, Combustion, Hot Waterflooding, Surface Mining and Microbial EOR)

j = (Oil Gravity, Oil Viscosity, Porosity, Oil Saturation, Formation, Type, Permeability, Net Thickness, Depth, Temperature).

C = Conversion factor, which converts all errors to 1 (This varies for all ranges since it is dependent on the range)

- The applicability percentage of the EOR method is then calculated. This gives the appropriate EOR method to be applied on the candidate field. The applicability percentage is represented in Equation 5:

$$applicability\ \%\ of\ EOR\ method(A_i) = TP_i - D_i \qquad (5)$$

Software validation

The software was validated using fluid and reservoir properties of the Suplacu de Barcau field. The field is located in North West Romania. It is the field for the world's largest in situ combustion site. Its oil initially in place (OIIP) was estimated to be 295 million bbl. Final recovery after primary recovery was 9% (Al Manahali, 2010) [3]. In this situation, thermal recovery techniques were considered the only way to increase the oil recovery and production rate. Pilot tests were conducted on the field in order to choose the best technological method; Steam Flooding and In-Situ Combustion. The tests were conducted using different injection patterns (Costin *et al*., 2017) [7]. After the initiation of the In-Situ Combustion method on the field, the production rate reached 10 000 bbl/d of crude oil with 600 wells affected by the combustion front. In 2005, the total production was 7 900 bbl/d of crude with about 800 wells affected by the combustion front. The cumulative oil produced after 35 years was about 117 million barrels, which represents a recovery factor of 46.6%. The ultimate oil recovery was expected to be 52% of the OIIP (Al Manahali, 2010) [3]. Table 4 shows the field properties.

Table 4: Reservoir and Fluid Properties of Suplacu de Barcau Field

Reservoir and Fluid Properties	Values
Average depth (ft.)	400
Average net thickness(ft.)	33
Porosity (%)	32
Average permeability (D)	1850
Oil gravity (API)	16
Oil viscosity (cp)	2000
Formation type	Sandstone
Temperature (F)	64.4
Oil saturation (%)	85

(Sources: Al Manahali, 2010 Costin *et al*., 2017) [7, 3]

Results

A user-friendly application software for screening and selection of EOR methods has been developed. In order to show that the software works effectively, the field data from the Suplacu de Barcau was used to test the software and the results are discussed in this chapter. The results are shown in Figure 1 to 3 and Table 5. Table 5 shows the various EOR methods and their percentages for their initial total screening parameters satisfied, deviation from mean and applicability for the Suplacu de Barcau Field.

EOR methods	reservoir fluid properties		reservoir formation properties									
	Gravity	Viscoity	Porosity	Oil Saturation	Formation Type	Permeability	Net Thickness	Depth	Temperature	Total Initial screning parameters	deviation from the mean	Applicability%
CO2 (miscible)	[22 - 45] not applicable	[0 - 35] not applicable	[3 - 37] applicable	[15 - 89] applicable	[sandstone] applicable	[1.5 - 4500] applicable	[1 - 500000] applicable	[1500 - 13365] not applicable	[82 - 257] not applicable	55.556	1.776	53.779
Nitrogen (miscible)	[35 - 54] not applicable	[0 - 0.2] not applicable	[7.5 - 14] not applicable	[0.4 - 0.8] not applicable	[sandstone] applicable	[0.2 - 35] not applicable	[1 - 250] applicable	[6000 - 18500] not applicable	[190 - 325] not applicable	22.222	0.000	22.222
WAG (miscinle	[33 - 39] not applicable	[0.3 -0.9] not applicable	[11 - 24] not applicable	[33 - 55] not applicable	[sandstone] applicable	[130 - 1000] not applicable	[> 0] applicable	[7545 - 8887] not applicable	[194 - 253] not applicable	22.222	0.000	22.222
Hydrocarbon	[23 - 57] not applicable	[0.04 - 18000] applicable	[4.25 - 45] applicable	[30 - 98] applicable	[sandstone] applicable	[0.1 - 5000] applicable	[1 - 250] applicable	[4000 - 15900] not applicable	[85 - 329] not applicable	66.667	2.007	64.660
Co2 (immiscibe)	[11 - 35] applicable	[0.6 - 592] not applicable	[17 - 32] applicable	[42 - 78] not applicable	[sandstone] applicable	[30 - 1000] not applicable	[> 0] applicable	[1150 - 8500] not applicable	[82 - 198] not applicable	44.444	1.583	42.861
Nitrogen (immscible)	[16 - 54] applicable	[0 - 18000] applicable	[11 - 28] not applicable	[47 - 98.5] applicable	[sandstone] applicable	[3 - 2800] applicable	[> 0] applicable	[1700 - 18500] not applicable	[83 - 325] not applicable	66.667	2.158	64.509
WAG (immiscible)	[9.3 - 41] applicable	[0.17 - 16000] applicable	[18 - 31.9] not applicable	[76 - 98] applicable	[sandstone] applicable	[100 - 6600] applicable	[> 0] applicable	[2650 - 9199] not applicable	[131 - 267] not applicable	66.667	1.971	64.696
Hydrocarbon (immiscible)	[22 - 48] not applicable	[0.25 - 4] not applicable	[5 - 22] not applicable	[75 - 83] not applicable	[sandstone] applicable	[40 - 1000] not applicable	[> 0] applicable	[6000 - 7000] not applicable	[82 - 257] not applicable	22.222	0.000	22.222
Polymer	[13 - 42.5] applicable	[0.4 - 4000] applicable	[10 - 33] applicable	[34 - 82] not applicable	[sandstone] applicable	[1.8 - 5500] applicable	[> 0] applicable	[700 - 9460] not applicable	[74 - 237.2] not applicable	66.667	3.036	63.631
ASP	[20 - 35] not applicable	[11 - 6500] applicable	[26 - 32] applicable	[35 - 74.8] not applicable	[sandstone] applicable	[10 - 1520] not applicable	[> 0] applicable	[2723 - 9000] not applicable	[80 - 200] not applicable	44.444	1.387	43.057
surfactant	[22 - 39] not applicable	[2.63 - 15.6] not applicable	[14 - 16.8] not applicable	[43.5 - 53] not applicable	[sandstone] applicable	[50 - 60] not applicable	[> 0] applicable	[625 - 2300] not applicable	[122 - 155] not applicable	22.222	0.000	22.222
Combustion	[10 - 38] applicable	[1.44 - 5000] applicable	[14 - 35] applicable	[50 - 94] applicable	[sandstone] applicable	[10 - 15000] applicable	[> 10] applicable	[400 - 11300] applicable	[64.4 - 320] applicable	100.000	5.024	94.976
Steam	[8 - 33] applicable	[8 - 5E6] applicable	[12 - 65] applicable	[35 - 90] applicable	[sandstone] applicable	[1 - 15001] applicable	[> 10] applicable	[200 - 9000] applicable	[10 - 350] applicable	100.000	5.242	94.758
Hot water	[12 - 25] applicable	[170 - 8000] applicable	[25 - 37] applicable	[15 - 85] applicable	[sandstone] applicable	[900 - 6000] applicable	[> 0] applicable	[500 - 2950] not applicable	[75 - 135] not applicable	77.778	2.711	75.066
Surface mining	[7 - 11] not applicable	[0] not applicable	[> 0] applicable	[> 8] applicable	[sandstone] applicable	[> 0] applicable	[> 10] applicable	[> 0] applicable	[> 0] applicable	66.667	0.000	66.667
Microbial	[12 - 33] applicable	[1.7 - 8900] applicable	[12 - 26] not applicable	[55 - 65] not applicable	[sandstone] applicable	[80 - 200] not applicable	[> 0] applicable	[1572 - 3464] not applicable	[86 - 290] not applicable	44.444	1.373	43.071

API gravity 16 API
Oil viscosity 2000 cp
Porosity 32 %
Oil saturation 85 %pv
Permeability 1850 md
Net thickness 33 ft
Depth 400 ft
Temperature 64.4 F

formation type
● sandstone
○ carbonate

combustion
steam flooding

Fig 1: Display of Results by Software for the Suplacu de Barcau Field

- From the results in Figure 1, it was realised, based on the input value for:
- Gravity, 8 EOR methods could be applied to the Suplacu de Barcau field;
- Viscosity, 9 EOR methods could be applied to the Suplacu de Barcau field;
- Porosity, 8 EOR methods could be applied to the Suplacu de Barcau field;
- Oil saturation, 8 EOR methods could be applied to the Suplacu de Barcau field;
- Permeability, 9 EOR methods could be applied to the Suplacu de Barcau field;
- Net thickness, all 16 EOR methods could be applied to the Suplacu de Barcau field;
- Depth, 3 EOR methods could be applied to the Suplacu de Barcau field;
- Temperature, 3 EOR methods could be applied to the Suplacu de Barcau field; and
- Formation type, all 16 EOR methods could be applied to the Suplacu de Barcau field.

Table 5: Results on Various Initial EOR Methods Screenings for the Suplacu de Barcau Field

EOR Methods	Initial Total Screening Parameters Satisfied (%)	Deviation from the Mean	Applicability (%)
CO_2 flooding	55.556	1.776	53.779
Water alternating gas	22.222	0.000	22.222
Nitrogen flooding	22.222	0.000	22.222
Hydrocarbon flooding	66.667	2.007	64.66
Hydrocarbon flooding	22.222	0.000	22.222
Nitrogen flooding	66.667	2.156	64.509
Water alternating gas	66.667	1.971	64.696
CO_2 flooding	44.444	1.583	42.861
Surfactant flooding	22.222	0.000	22.222
Polymer flooding	66.667	3.036	63.631
Alkaline polymer surfactant	44.444	1.387	43.057
Steam flooding	100.000	5.242	94.758
Combustion	100.000	5.024	94.976
Hot water	77.778	2.711	75.066
Surface mining	66.667	0.000	66.667
Microbial recovery	44.444	1.373	43.017

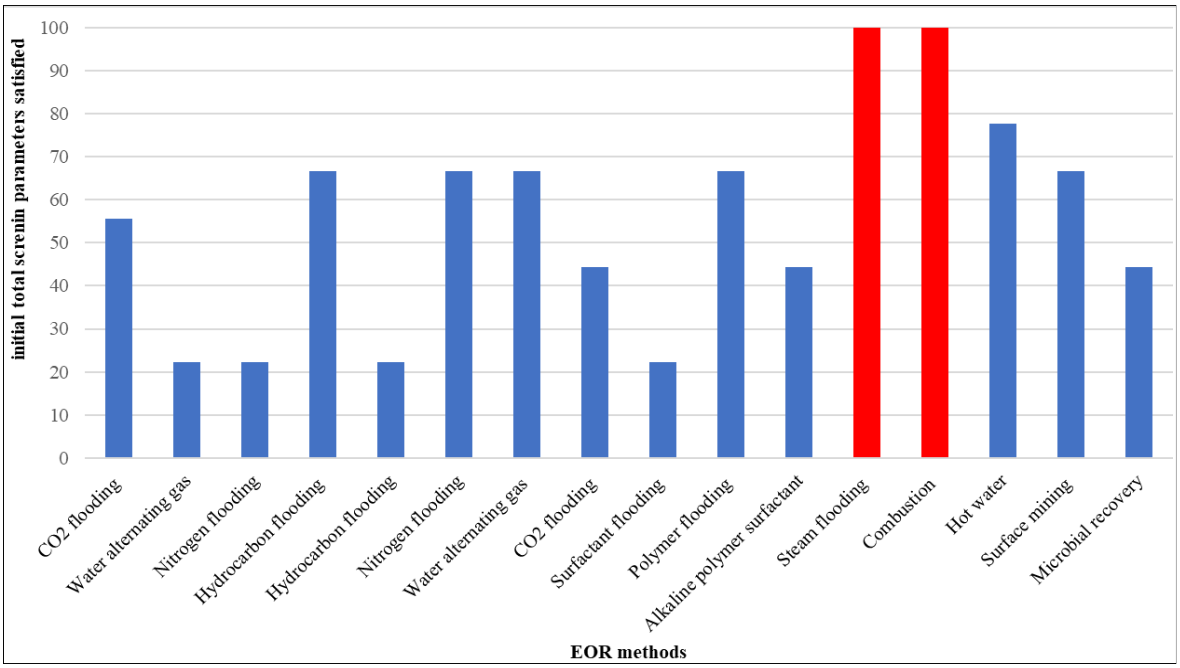


Fig 2: Initial Total Screening Parameters Satisfied by Various EOR Methods for the Suplacu de Barcau Field

From the results in Figure 2, Combustion and Steam Flooding had the highest initial total screening parameters satisfied. Both had initial total screening parameters satisfied of 100%, meaning they were able to satisfy all the nine parameters under consideration. Hot waterflooding had 77.766% which was the next best score. The ones with the least score were Water Alternating Gas, Miscible Flooding, Nitrogen Miscible Flooding, Hydrocarbon Immiscible Flooding and Surfactant Flooding; all recording a score% of 22.222. Further test was run on Combustion and Steam flooding to select the appropriate EOR method for the Suplacu de Barcau field. From the results in Figure 3, Combustion and Steam flooding had applicability percentages of 94.976% and 94.758% respectively. This was due to the total deviation in the screening process for the each EOR method. Combustion had the least total deviation amongst these two. Hot Waterflooding had an applicability percentage of 75.066% which was the third highest value. All these 3 methods are thermal EOR methods. This was due to the high oil viscosity. Based on this it was concluded that only a thermal EOR method can be applied to recover more oil and increase the production rate of the Suplacu de Barcau field. Based on the applicability percentage combustion was chosen as best EOR method for this field.

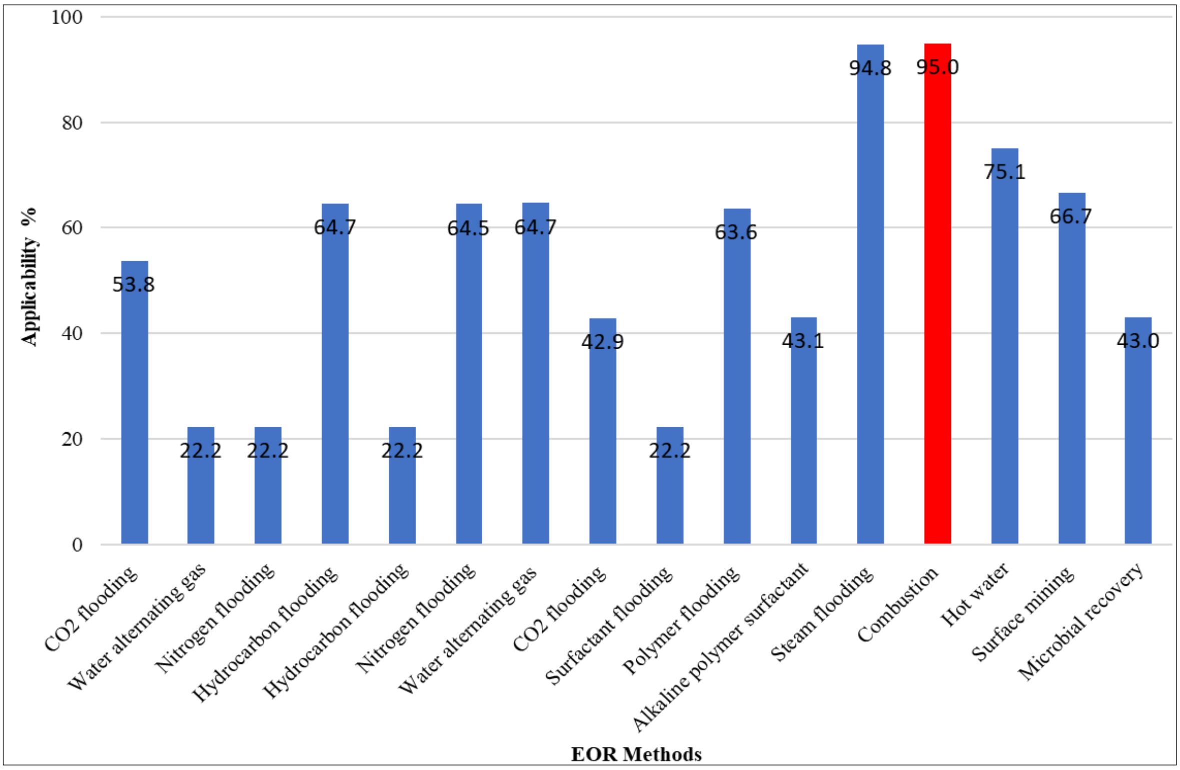
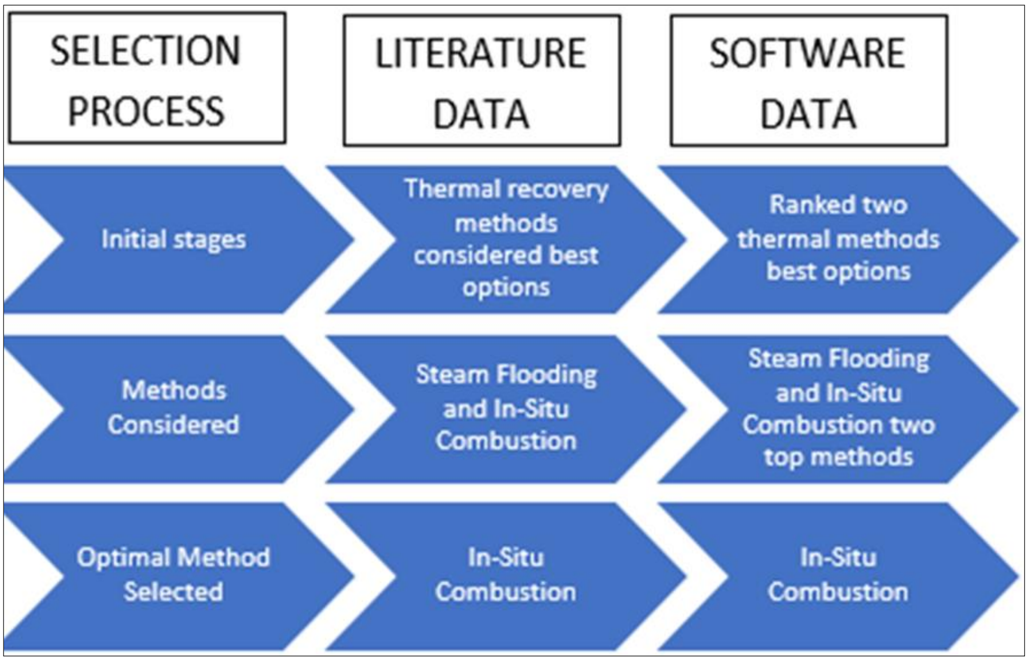


Fig 3: The Various Screened EOR Methods and their Applicability Percentage for the Suplacu de Barcau Field

Data Validation

The software was validated using fluid and reservoir properties of Suplacu de Barcau field. Thermal recovery techniques were considered the only way to increase the oil recovery and production rate with Steam Flooding and In-Situ Combustion as options. The developed screening software also initially reported Steam Flooding and In-Situ Combustion as the best options (Figure 2 and Figure 4). Tests that were conducted using different injection patterns resulted in selecting the In-Situ Combustion method for the field. Further analysis of the screened Steam Flooding and In-Situ Combustion methods by applicability percentage revealed that In-Situ Combustion is about 95.0% applicable while Steam Flooding has 94.8% applicability. The developed screening software validates well with the literature data.



SELECTION PROCESS	LITERATURE DATA	SOFTWARE DATA
Initial stages	Thermal recovery methods considered best options	Ranked two thermal methods best options
Methods Considered	Steam Flooding and In-Situ Combustion	Steam Flooding and In-Situ Combustion two top methods
Optimal Method Selected	In-Situ Combustion	In-Situ Combustion

Fig 4: Summary of Software Data Validation with Literature

Conclusions

Based on the results, it can be concluded that:

- A cost-effective user-friendly software to screen and select an appropriate EOR method for a given field has been developed using Visual Basic 6.0; and
- The application software validates well with literature.

Future Work

Future work is looking as the following:

- The sensitivity of each screening parameter on a particular EOR method;
- Other reservoir fluid properties such as salinity and oil density; and
- The reservoir productivity/performance after selecting a particular EOR method for a better analysis.

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