Optimization of Esterification and Transesterification of High FFA Jatropha Curcas Oil Using Response Surface Methodology

Prerna Goyal*[1], M.P. Sharma[2], Siddharth Jain[3]

Biofuel Research Laboratory, Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand-247667, India

[1]prernagoyal282@gmail.com; [2]mpshafah@iitr.ernet.in; [3]arthjain2001@gmail.com

***Abstract*- Optimization of parameters for reduction of Free Fatty Acid content (FFA) of *Jatropha curcas* oil (JCO) and maximization of yield of *Jatropha curcas* biodiesel (JCB) (%) has gained importance for boosting the fuel industry and improving the production efficiency of biodiesel. A five-level-four-factorial Central Composite Design (CCD) using Response Surface Methodology (RSM) was employed to optimize the process variables for minimizing the FFA of JCO and maximizing the JCB (%) yield. The high FFA (14.6%) of JCO could be reduced to 0.34% by its pretreatment with methanol (6.5:1) using H_2SO_4 as catalyst (1.5% v/v) in 125 min time at 50°C temperature. A JCB yield of 98.3% was achieved with methanol/oil molar ratio (11:1) using NaOH as catalyst (1% w/w) in 110 min time at 55°C temperature. Second-order model equations were obtained to predict the FFA content and JCB yield as a function of input parameters. The models can be successfully adopted in fuel industry to reduce the FFA content of JCO and maximize the yield of methyl esters, thereby, improving the economy of the process. The prepared JCB conformed to the ASTM and IS standards specifications.**

Keywords*- *Esterification; Transesterification; Optimization; JCB Yield; FFA Content

I. INTRODUCTION

The growing environmental concerns due to increasing carbon dioxide emissions, global warming, declining petroleum reserves and rising crude oil prices have resulted in worldwide attention to biodiesel. With growing human population, more land is needed to produce food for human consumption, which poses a potential challenge to biodiesel production. *Jatropha curcas* oil (JCO) is a plant based feedstock that is unsuitable for human consumption and could be the best feedstock for biodiesel production [1]. However, the properties of these oils are not suitable to be used in engines. They have high viscosity, high flash point and low calorific value than diesel fuel, thus, making them unsuitable to be used in diesel engines. This necessitates the need to go for modification in the oils to make their properties suitable for engine use. Transesterification is the most suitable method to go for modification in oils. The type of transesterification is chosen based on the Free Fatty Acid (FFA) content of the oil. For high FFA oils, two step acid-base catalyzed transesterification process is adopted. The FFA of the oil is first reduced to less than 1% in acid catalyzed esterification process. The oil with reduced FFA is further subjected to base catalyzed transesterification process for production of biodiesel [2]. This process involves many parameters that affect the reaction and optimizing so many reaction factors require large number of experiments, which is laborious, time consuming, and economically non-viable. Response surface methodology (RSM) is a useful statistical technique for the evaluation or optimization of complex processes, as it reduces the number of experiments required to achieve ample data for a statistically pertinent result. Tiwari *et al*. [3] have optimized three reaction variables viz. catalyst concentration, reaction time and methanol quantity using five-level-three-factor Central Composite Rotatable Design (CCRD) based on RSM for the reduction of high FFA in JCO to <1% in 34 experiments. Two variables viz. methanol quantity and reaction time were optimized in 21 experiments to maximize the *Jatropha curcas* biodiesel (JCB) yield to 99%. Similarly, Boonmee *et al*. [4] have studied the effect of three process variables viz. methanol/oil molar ratio, catalyst concentration and reaction time on the methyl esters yield of JCO using a central composite design (CCD) of 20 experiments and achieved 99.87% biodiesel yield. Other groups have applied RSM to optimize process factors for biodiesel production, using rapeseed oil, soybean oil, cottonseed oil, castor oil, and lard [5, 6, 7, 8, 9 and 10].

In view of the above, it can be seen that no work is reported on the optimization of FFA content of JCO and its biodiesel yield using four process variables. The present paper, therefore, reports the results of the optimization of four process variables viz. catalyst (H_2SO_4) concentration (0-2% v/v), reaction temperature (40°-60°C), reaction time (30-180 min) and methanol/oil ratio (w/w) (3:1 – 12:1) for the esterification process of JCO containing high FFA (14.6%) and catalyst (NaOH) concentration (0-2% w/w), reaction temperature (35°-55°C), reaction time (30-180 min) and methanol/oil ratio (w/w) (6:1–12:1) for transesterification of JCO using RSM based CCD in 54 experimental runs with the help of Design Expert 8.0.6 software. A model to predict the response was formulated and validated by ANOVA. The model can be used in the industry to reduce the FFA content of JCO before carrying out its base catalyzed transesterification and improve the efficiency of biodiesel production, thereby, saving time and cost of the process in optimizing the process parameters.

II. MATERIALS AND METHODS

JCO was procured from Jatropha Vikas Sansthaan, New Delhi. All chemicals like H_2SO_4, KOH, methanol, ethanol, Na_2SO_4, NaOH were of AR grade and 99% pure.

A. Esterification of JCO Containing High FFA Content

Raw JCO was filtered to remove all insoluble impurities followed by heating at 100^{o}C for 10 min to remove all the moisture. The acid value of JCO was determined by the method used by Mahajan *et al*. [11]. The acid value was high i.e. 29.2 mg KOH g^{-1} corresponding to a FFA of 14.60%, which is far above the 1% limit for base catalyzed transesterification reaction. FFAs were, therefore, first converted to esters in a pretreatment process with methanol as solvent using conc. H_2SO_4 as acid catalyst by a process developed in the authors' laboratory for the production of JCB [12]. Hence, the high FFAs were first reduced to <1% using esterification and the resulting reaction mixture was subjected to base catalyzed transesterification process. In the present study, the esterification of JCO has been optimized using RSM for the reduction of FFAs.

B. Base Catalyzed Transesterification of JCO

Pretreated JCO (<1% FFA) was transesterified by using methanol as solvent and NaOH as base catalyst for the production of JCB [12]. The methyl ester layer was separated, washed with water, heated to remove moisture and dried over anhydrous Na_2SO_4. In the present study, the transesterification of JCO has been optimized using RSM for the production of JCB. The yield of JCB was calculated using the following equation (1):

$$\text{Yield of JCB (\%)} = \frac{\text{Total weight of methyl esters}}{\text{Total weight of oil in the sample}} * 100\% \quad (1)$$

C. Analysis of JCB

The JCB was prepared in the laboratory under the conditions optimized by RSM. The JCB was analyzed for fatty acid composition by Gas chromatograph (Model-Netal) using the process described by Jain and Sharma [12].

D. Physio-Chemical Properties of JCO and JCB

The physical and chemical properties of JCO and JCB produced under optimum conditions were determined by using standard methods [13].

E. Experimental Design

A five-level-four-factor CCD was applied for carrying out the optimization studies to reduce the FFAs of JCO in the esterification process and maximize the yield of JCB in the transesterification process respectively. A total of 54 experiments were conducted separately for getting the experimental response of FFA and JCB yield. The catalyst concentration (A) (%), reaction temperature (B) (^{o}C), reaction time (C) (min) and methanol/oil ratio (w/w) (D) were the independent variables selected for optimization. The coded and uncoded levels of the independent variables used for the esterification and transesterification of JCO are given in Table I and Table II respectively.

TABLE I
INDEPENDENT VARIABLES USED FOR CCD IN ESTERIFICATION OF JCO

Variables	Symbols	Levels				
		-1	-0.5	0	0.5	1
Catalyst (H_2SO_4) concentration (% v/v)	A	0	0.5	1.0	1.5	2.0
Temperature (^{o}C)	B	40	45	50	55	60
Time (min)	C	30	67.5	105	142.5	180
Methanol/oil ratio (w/w)	D	3	5.25	7.5	9.75	12

TABLE II
INDEPENDENT VARIABLES USED FOR CCD IN TRANSESTERIFICATION PROCESS

Variables	Symbols	Levels				
		-1	-0.5	0	0.5	1
Catalyst (NaOH) concentration (% w/w)	A	0	0.5	1.0	1.5	2.0
Temperature (^{o}C)	B	35	40	45	50	55
Time (min)	C	30	67.5	105	142.5	180
Methanol/oil ratio (w/w)	D	6	7.5	9	10.5	12

F. Statistical Analysis

The Design Expert 8.0.6 software was used for the regression and graphical analysis of the data. The minimum values of FFA were taken as the response of the design experiment for esterification process and the maximum values of JCB yield were taken as the response of the design experiment for transesterification process. The experimental data obtained by the above procedure was analyzed by the response surface regression using the following second-order polynomial equation (2):

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i>j}^{k} \sum_{j}^{k} \beta_{ij} x_i x_j \quad (2)$$

where; y is the response, i and j are the linear and quadratic coefficients respectively, x_i and x_j are the uncoded independent variables, β_o is the regression coefficient, k is the number of factors studied and optimized in the experiment. Statistical analysis of the model was carried out to evaluate the analysis of variance (ANOVA). Equation was also validated by carrying out confirmatory experiments.

III. RESULTS AND DISCUSSIONS

A. Esterification Process

The experimental and predicted values for FFA responses at the design points and all the four variables in uncoded form are given in Table I II. ANOVA results of the model showed that the associated Probability (P) value for the model was lower than 0.0001, thus, implying the significance of the model. The value of regression coefficient R^2 for the model was 0.96, indicating the good fitness of the model. The predicted R^2 was 0.92, further, proving the reliability of the model [14].

TABLE III

CCD ARRANGEMENT AND RESPONSES FOR ESTERIFICATION OF JCO

Run	A: Catalyst (H_2SO_4) concentration (%)	B: Temperature (°C)	C: Time (min)	D: Methanol/oil ratio	Free Fatty Acid (%)	
					Experimental Response	Predicted Response
1	1	50	105	12	2.22	3.03
2	1.5	45	67.5	5.25	2.82	3.35
3	1.5	45	67.5	5.25	2.96	3.35
4	1.5	45	142.5	5.25	2.48	2.80
5	0.5	55	142.5	9.75	1.11	1.11
6	1	50	105	7.5	1.02	1.08
7	0.5	45	67.5	5.25	2.73	3.54
8	1.5	55	67.5	9.75	2.94	3.18
9	1	50	105	3	1.99	0.93
10	1.5	45	142.5	5.25	2.51	2.80
11	1.5	45	142.5	9.75	2.53	2.74
12	0.5	45	67.5	9.75	7.32	7.35
13	1	50	105	7.5	0.99	1.08
14	0.5	45	142.5	9.75	3.87	3.68
15	1	50	105	12	2.26	3.03
16	1	40	105	7.5	7.64	7.13
17	0.5	55	142.5	9.75	1.09	1.11
18	0.5	55	142.5	5.25	1.87	1.95
19	1	60	105	7.5	2.98	3.12
20	1.5	45	67.5	9.75	6.17	6.28
21	1.5	55	142.5	9.75	0.65	0.06
22	1	50	105	7.5	1.06	1.08
23	1	50	30	7.5	6.84	6.18
24	1	40	105	7.5	7.56	7.13
25	0	50	105	7.5	1.57	1.52
26	0.5	55	67.5	9.75	4.49	4.36
27	1	50	30	7.5	6.78	6.18
28	1.5	45	142.5	9.75	2.55	2.74
29	2	50	105	7.5	0.51	0.28
30	0.5	45	142.5	5.25	2.61	2.87
31	1	50	105	7.5	1.01	1.08
32	0.5	55	67.5	9.75	4.52	4.36
33	0.5	45	142.5	9.75	3.81	3.68
34	0.5	55	142.5	5.25	1.85	1.95
35	2	50	105	7.5	0.53	0.28
36	1	50	180	7.5	2.04	2.39
37	1.5	55	142.5	9.75	0.67	0.06

38	0.5	45	142.5	5.25	2.65	2.87
39	1	50	105	7.5	1.05	1.08
40	1	50	105	7.5	1.04	1.08
41	0.5	55	67.5	5.25	1.91	2.19
42	1.5	55	142.5	5.25	1.33	1.78
43	1	50	105	3	2.05	0.93
44	0.5	45	67.5	9.75	7.38	7.35
45	1.5	55	67.5	9.75	3.02	3.18
46	1	60	105	7.5	2.91	3.12
47	1.5	55	142.5	5.25	1.36	1.78
48	0.5	55	67.5	5.25	1.94	2.19
49	0.5	45	67.5	5.25	2.78	3.54
50	1.5	55	67.5	5.25	1.56	1.90
51	0	50	105	7.5	1.58	1.52
52	1	50	180	7.5	2.06	2.39
53	1.5	45	67.5	9.75	6.25	6.28
54	1.5	55	67.5	5.25	1.55	1.90

The regression equation (3) for the determination of predicted values of output parameter (i.e. FFA) is given as follows:

$$FFA\ (\%) = 102.64+1.55A-4.01B-0.11C+2.54D-0.01AB+0.002AC-0.20AD+0.001BC-0.037BD-0.009CD-0.18A^2+0.04B^2+0.006C^2+0.04D^2 \quad (3)$$

The graph between the predicted and actual FFA values given in Fig. 1, shows that the predicted values are quite close to the experimental values, thus, validating the credibility of the model developed for establishing a correlation between the process variables and the FFA content.

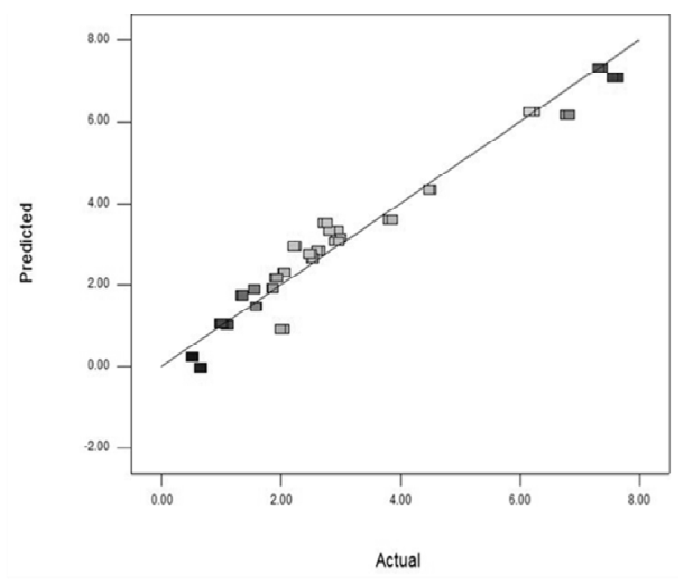

Fig. 1 Predicted Versus Actual FFA Values

1) Effect of Process Variables on FFA Content of JCO:

Fig. 2 shows the effect of catalyst (H_2SO_4) concentration, reaction temperature, time and methanol/oil ratio on FFA content. It can be seen from the figure that the FFA decreases with increase in catalyst concentration. FFA decreases with increase in temperature and time till the middle point is reached, beyond which it increases. Methanol/oil ratio is found to have very less effect on FFA content as the change in FFAs with change in the methanol/oil ratio is very small. So, very high temperature and long reaction time should be avoided as they have an inhibitive effect on the reduction of FFA content. These results were found similar to the work of Tiwari *et al*. [3].

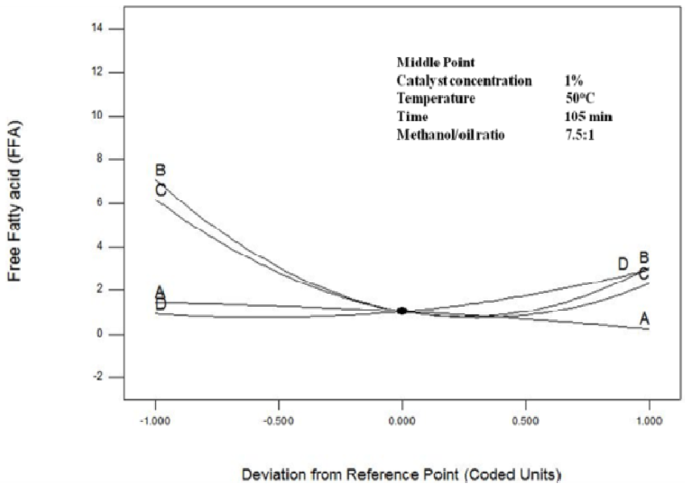

Fig. 2 Effect of Catalyst Concentration, Temperature, Time and Methanol/Oil Ratio on FFA (%) Content

B. Transesterification Process

Experimental and predicted values for JCB yield responses at the design points and all the four variables in uncoded form are given in Table IV. The associated P value for the model was lower than 0.0001, thus, implying the significance of the model. The value of regression coefficient R^2 for the model was 0.945, indicating the good fitness of the model. A high value of predicted R^2 (0.890) is an indication of precision of fitted model. The more the value of R^2 approaches unity, the better the model fits the experimental data. [14].

TABLE IV

CCD ARRANGEMENT AND RESPONSES FOR TRANSESTERIFICATION OF JCO

Run	A: Catalyst (NaOH) concentration (%)	B: Temperature (^oC)	C: Time (min)	D:Methanol/oil ratio	JCB yield (%)	
					Experimental Response	Predicted Response
1	1	45	105	9	82.6	82.84
2	0	45	105	9	89.5	89.81
3	0.5	40	67.5	10.5	78.2	80.37
4	1.5	40	142.5	10.5	88.6	87.84
5	0.5	40	67.5	10.5	77.8	80.37
6	0.5	50	67.5	7.5	87.1	86.76
7	1.5	50	67.5	10.5	73.9	76.50
8	0.5	40	142.5	7.5	91	89.83
9	1	45	105	9	82.9	82.84
10	0.5	40	67.5	7.5	86.1	87.33
11	1	45	105	9	83.1	82.84
12	1	45	105	12	85.5	84.97
13	1	45	105	9	82.1	82.84
14	1	45	180	9	93.4	92.65
15	0.5	50	142.5	10.5	97.8	99.99
16	1	45	30	9	78.2	79.56
17	1.5	50	142.5	10.5	88.3	87.10
18	0.5	50	67.5	10.5	90	87.17
19	0.5	40	142.5	10.5	91.8	91.86
20	1.5	40	67.5	7.5	85.7	84.18
21	0.5	50	142.5	7.5	90	90.98
22	1	35	105	9	92.4	91.00
23	1.5	40	142.5	7.5	81.6	84.05
24	1.5	40	142.5	10.5	83.8	87.84
25	1	45	105	12	85.9	84.97
26	0.5	50	67.5	10.5	90.4	87.17
27	1.5	40	67.5	10.5	80	78.97
28	2	45	105	9	73	73.37
29	1	55	105	9	88.2	89.69
30	1.5	50	142.5	7.5	77	75.94
31	1.5	40	67.5	7.5	85.2	84.18
32	1	45	105	9	82.4	82.84
33	1	55	105	9	87.9	89.69
34	1.5	50	67.5	10.5	74.1	76.50
35	1.5	50	67.5	7.5	74.8	74.34
36	1.5	50	142.5	7.5	77.3	75.94

37	1.5	40	67.5	10.5	80.2	78.97
38	1	45	105	9	82.8	82.84
39	0.5	50	67.5	7.5	87.5	86.76
40	2	45	105	9	73.2	73.37
41	1	45	105	6	79.5	80.76
42	1.5	50	67.5	7.5	74.5	74.34
43	0	45	105	9	89.9	89.81
44	1.5	40	142.5	7.5	81.2	84.05
45	0.5	50	142.5	7.5	90.4	90.98
46	0.5	50	142.5	10.5	98.2	99.98
47	1	35	105	9	92.1	91.00
48	1	45	105	6	79.8	80.76
49	0.5	40	67.5	7.5	86.5	87.33
50	0.5	40	142.5	10.5	92.1	91.86
51	1	45	30	9	78.5	79.56
52	0.5	40	142.5	7.5	91.4	89.83
53	1.5	50	142.5	10.5	88.7	87.10
54	1	45	180	9	93.7	92.65

The regression equation (4) for the determination of predicted values of output parameter (i.e. JCB yield) is given as follows:

$$JCB\ (\%) = 343.90+34.43A-8.34B-0.46C-15.19D-0.93AB-0.035AC+0.58AD+0.0023BC+0.25BD+0.04CD-1.25A^2+0.075B^2+0.0006C^2+0.0023D^2 \quad (4)$$

The graph between the predicted and actual JCB yield (%) given in Fig. 3 shows that the predicted values are quite close to the experimental values, thereby, validating the reliability of the model developed for establishing a correlation between the process variables and the JCB yield.

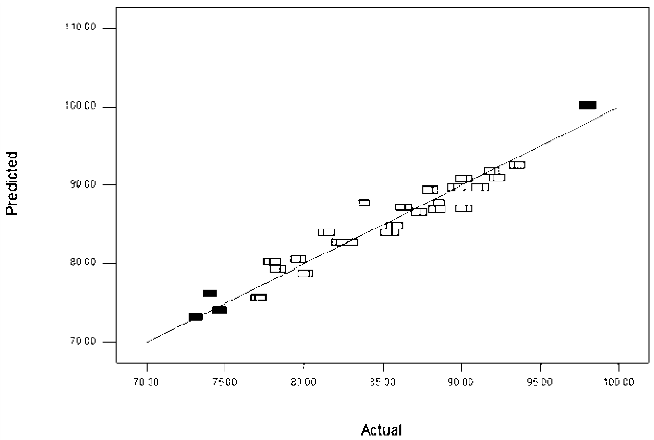

Fig. 3 Predicted Versus Actual JCB (%) Yield Values

1) Effect of Process Variables on JCB Yield:

Fig. 4 shows the effect of catalyst concentration (NaOH), reaction temperature, reaction time and methanol/oil ratio on JCB yield. It can be seen from the figure that the JCB yield decreases significantly with increase in catalyst concentration. This may be due to the fact that addition of excessive catalyst favors the saponification reaction of triglycerides to form soap which decreases the biodiesel yield [15]. JCB yield decreases with increase in temperature initially and increases at higher values of temperature. The increase in biodiesel yield at higher temperature is due to the fact that viscosity of oils decreases at high temperature which results in an increased reaction rate, thus, increasing the biodiesel yield [15]. JCB yield increases with increase in time. This can be supported by the work of Freedman *et al*. [16] who found that the conversion rate of fatty acid esters increases with reaction time. JCB yield is found to increase with the increase in methanol/oil ratio; since the transesterification reaction is reversible in nature, so excess alcohol is added to ensure the total conversion of triglycerides [15]. Thus, the yield of biodiesel increases with increase in methanol quantity.

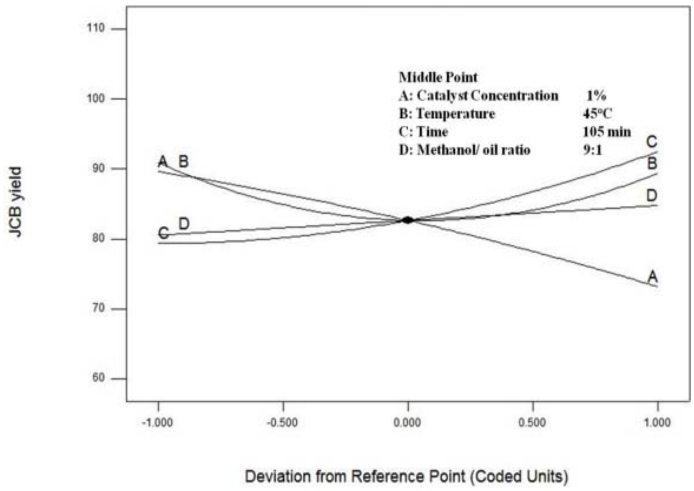

Fig. 4 Effect of Catalyst Concentration, Temperature, Time and Methanol/Oil Ratio on JCB (%) Yield

C. Optimization of Response Parameters

Optimization of individual responses was performed separately to achieve the desired reduction in FFA content and maximization of JCB yield based on the respective developed mathematical equations. The optimal value of input process parameters is given in Table V. Predicted response is found to be in good agreement with the experimental results.

TABLE V

OPTIMIZED INPUT PROCESS PARAMETERS AND OPTIMUM VALUE OF JCB YIELD

Response	Optimized value of input process parameter				Predicted value	Experimental value
	A	B	C	D		
FFA (%)	1.5	50	125	6.5	0.37	0.34
JCB yield (%)	1.0	55	110	11	98.89	98.3

D. Analysis of JCB

The Fatty acid (FA) composition of JCB prepared under the above optimum parameters and determined by Gas Chromatography (GC) is given in Table VI which shows that JCB mainly contained Oleic and Linoleic acid. The FA composition is in good agreement with the composition reported by Jain and Sharma [13]. The physio-chemical properties of JCO and JCB are reported in Table VII. The properties of JCB are in good agreement with ASTM and IS specifications.

TABLE VI

FATTY ACID COMPOSITION OF JCB

Fatty acid	Formula	% Composition
Palmitic acid	$C_{16}H_{32}O_2$ $CH_3(CH_2)_{14}COOH$	16.2
Stearic acid	$C_{18}H_{36}O_2$ $CH_3(CH_2)_{16}COOH$	8.2
Oleic acid	$C_{18}H_{34}O_2$ $CH_3(CH_2)_7$-CH=CH-$(CH_2)_7COOH$	38.4
Linoleic acid	$C_{18}H_{32}O_2$ $CH_3(CH_2)_4$CH=CH-CH_2-CH=CH-$(CH_2)_7COOH$	36.8
Linolenic acid	$C_{18}H_{30}O_2$ $CH_3(CH_2)_4$CH=CH-CH_2-CH=CH-CH_2-CH=CH-$(CH_2)_4COOH$	0.4

TABLE VII

PHYSIO-CHEMICAL PROPERTIES OF JCB

S.no	Property (unit)	ASTM D6751	IS 15607	JCO	JCB prepared under optimum parameters	JCB [9]	ASTM D6751 limits	IS 15607 limits
1	Viscosity (cSt; 40 °C)	ASTM D445	IS 1448	50	4.9	4.38	1.9-6.0	2.5-6.0
2	Density (g/c.c at 15°C)	ASTM D4052	IS 1448	0.930	0.862	-	-	0.860-0.900
3	Flash point (oC)	ASTM D93	IS 1448	241	174	172	Min. of 130	-
4	Water and Sediment (Vol%)	D2709	D2709	-	0.05	0.05	Max. of 0.05	Max. of 0.05
5	Free glycerin (% mass)	D6584	D6584	-	0.01	0.01	Max. of 0.02	D6584
6	Oxidative stability of JCB (h)	EN14112	-	-	3.3	3.27	3	-
7	Free glycerol	D6584	D6584	--	0.015	0.01	Max. of 0.02	Max. of 0.02
8	Total glycerol	D6584	D6584	-	0.14	0.12	Max. of 0.25	Max.of 0.25
9	Ester content (%)	-	EN 14103	-	98.3	98.5	-	Min. of 96.5

IV. CONCLUSIONS

Optimization studies for reduction of FFA of JCO and maximization of yield of JCB (%) were carried out. Process optimization was accomplished by five level-four-factorial CCD using RSM. The high FFA (14.6%) of JCO was reduced to 0.34% by its pretreatment with methanol (6.5:1) using H_2SO_4 as catalyst (1.5% v/v) in 125 min time at 50^oC temperature. A biodiesel yield of 98.3% was achieved with methanol/oil molar ratio (11:1) using NaOH as catalyst (1% w/w) in 110 min time at 55^oC temperature. Effects of catalyst concentration, reaction temperature, reaction time and methanol/oil ratio were studied on the esterification and transesterification processes. Second-order model equations were obtained to predict the FFA content and JCB yield as a function of input parameters. On the basis of ANOVA; the catalyst concentration, reaction time and methanol/oil molar ratio had a significant effect on JCB yield. The models can be successfully employed in the oil industry to reduce the FFA content of JCO before carrying out base catalyzed transesterification, thereby, saving time and maximize the yield of methyl esters respectively. The prepared JCB conformed to the ASTM and IS standards specifications.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support from the Ministry of Human Resource Development (MHRD), Government of India, in the form of a scholarship to carry out this work.

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A Petroleum R&D Project Portfolio Investment Selection Model with Project Interactions under Uncertainty

Danmei Zhu[1], Xingtong Wang[2]

[1] School of Science, Liaoning Shihua University, Fushun, 113001, China
[2] Fushun Research Institute of Petroleum and Petrochemicals, SINOPEC, Fushun, 113001, China
[1] zhudanmei@126.com; [2] waxito3ng@163.com

Abstract- **At present, most of petroleum R&D project portfolio researches are based on mathematical programming, decision theory and scoring method to construct R&D project portfolio multi-criteria model. These models is effective to some extent, however, it is very rare to consider the uncertainty of project and petroleum R&D project interactions in R&D portfolio selection. In this paper, firstly, fuzzy set theory and real option method have been combined in petroleum R&D project portfolio decision analysis, and we have also considered project interactions in order to seek the optimal solution. Finally, an example of petroleum R&D project portfolio carried out systematic evaluation and empirical analysis.**

Keywords- Petroleum Projects Portfolio; Fuzzy Set; Real Option; Project Interactions

I. INTRODUCTION

Nowadays, rapid technological developments, organizational changes and increased demand for efficiency in the petroleum industry have all brought risk variability to petroleum project investment. When the future outcomes of a firm's endeavors are unknown, a key strategy for dealing with such risk is betting on more than one horse. Successful research and development (R&D) policy therefore requires careful portfolio analysis to optimize the selection and the development of several concurrent alternatives. At present, the studies on R&D projects portfolio are mostly concentrated in the multi-criteria model; these models include mathematical programming models, decision theory models and scoring models [1-3]. However, there are still two problems. First, these selection models obtain optimal solutions by exact mathematical relationships between the objectives and constraints in model. But the R&D project portfolio decision deals with future events and opportunities, much of the information required making portfolio decisions is at best uncertain and at worst very unreliable. Second, the problem of project interactions has long been recognized but has received relatively little attention in the R&D project selection literatures [4-6].

Based on the above analysis, fuzzy set theory was used in this paper to deal with related uncertain information, reflecting the value coming from flexibility of project management decision-making through appending the item of real options of projects to the objective function. At the same time, the objective functions and constraints of the project interactions model will be analyzed based on the relations of benefit, technology and resource, to get the model of fuzzy 0-1 integer programming. Finally, qualitative possibility principle [7] was used to convert the model of fuzzy 0-1 integer programming model to the model of clear 0-1 integer programming, and with the software MATLAB and EXCEL to obtain the optimization solution. There are three main parts of this model: objective function construction, Constraint analysis, model solution.

II. A PETROLEUM R&D PROJECTS PORTFOLIO INVESTMENT SELECTION MODEL

The computational complexity of project portfolio selection problem is closely related to the number of initial projects. Therefore, before the decision is made, project screening is necessary. This procedure consists of two steps: firstly, project strategic consistency assessment. That is, those projects will be retained that can meet the strategic goals of the enterprise. More detailed discussion on project strategic consistency can be found in reference [8].Secondly, project portfolio constraints screening. Those projects will be eliminated from the project set if project cost, resource or other constraint is violated. After two screening process, we can get an initial project set as a preparation for further decision-making.

A. *Objective Function Construction*

1) *Petroleum R&D Project Option Character Analysis*

Assuming there are three stages in petroleum R&D project. Let $\tilde{C}_i$ $(i=1,2,3)$ be the investment cost at the beginning of the three stages, $\tilde{S}$ is the cash inflow after the market popularization, where $\tilde{C}_i$ and $\tilde{S}$ are both estimated by experts with the method of trapezoidal fuzzy numbers. After initial investment, there is a call option. The time limitation is T_1 , and the investment cost $\tilde{C}_2$ in the technology development stage is the exercise price of the first call option. If the first option can be exercised at the time T_1, investment in the stage of technology research can be started. The opportunity for market promotion will be achieved at the time T_2. So the second call option is coming into being. Its exercise price is the cost of market promotion $\tilde{C}_3$. For there are two options and the first causes the emergence of the second, and it's a compound option. Only under the condition that the value of the second option is higher than the exercise price of the first option, the compound option can be performed at the due date of the first option. The figure of stages of schematic for R&D projects is shown as follows (Fig. 1).

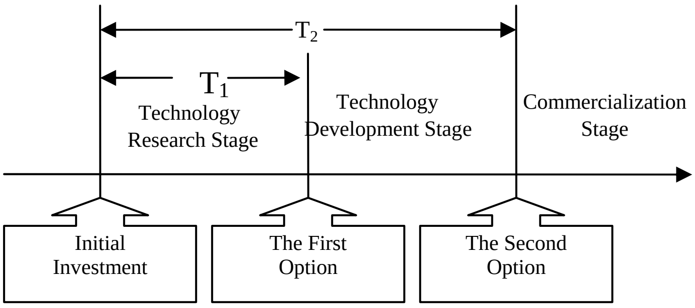

Fig. 1 Stages of schematic for R&D projects

After the above analysis, it's obvious that R&D project investment is a typical compound real option. Investment decision-making of each stage depends on the actual results of investment exercised before. The value of R&D project depends on not only the cash inflow from investment in the stage of technology development but also the value of the opportunities in the later stage of research benefit from the initial investment. If the situation is not as optimistic as expected after the initial investment of research, decision of cutting off later investment should be made immediately to avoid more losses. So by the fuzzy real option model of Carlsson and Fullér [9] and the compound option model of Geske [10], we can establish the fuzzy compound real option evaluation model of R&D project.

$$\tilde{V} = \tilde{S}e^{-\delta T_2}M(a_1,b_1;\sqrt{T_1/T_2}) - \tilde{C}_3 e^{-rT_2}M(a_2,b_2;\sqrt{T_1/T_2}) - \tilde{C}_2 e^{-rT_1}N(a_2) \quad (1)$$

Where, $$a_1 = \frac{\ln[E(\tilde{S})/S^C] + (r-\delta+\sigma^2/2)T_1}{\sigma\sqrt{T_1}}, \quad (2)$$

$$a_2 = a_1 - \sigma\sqrt{T_1}, \quad (3)$$

$$b_1 = \frac{\ln[E(\tilde{S})/E(\tilde{C}_3)] + (r-\delta+\sigma^2/2)T_2}{\sigma\sqrt{T_2}}, \quad (4)$$

$$b_2 = b_1 - \sigma\sqrt{T_2}, \quad (5)$$

and $M(a,b,\rho)$ is the bivariate cumulative standard normal distribution function, with integral upper limit a, integral lower limit b, and correlation coefficient ρ ($\rho = \sqrt{T_1/T_2}$).

$N(\cdot)$ is the single variable cumulative standard normal distribution function;

σ is the volatility of the R&D project benefit;

r is the risk-free interest rate;

S^C is the value of assets when compound option should be exercised. It can be calculated in the equation below:

$$\tilde{S}e^{-\delta(T_2-T_1)}N(c_1) - E(\tilde{C}_3)e^{-r(T_2-T_1)}N(c_2) - E(\tilde{C}_2) = 0, \quad (6)$$

Where,

$$c_1 = \frac{\ln[S^C/E(\tilde{C}_3)] + (r-\delta+\sigma^2/2)(T_2-T_1)}{\sigma\sqrt{T_2-T_1}}, \quad (7)$$

$$c_2 = c_1 - \sigma\sqrt{T_2-T_1}. \quad (8)$$

Here, the volatility and dividend of project can be calculated with $\sigma = \sqrt{Var(\tilde{S})}/E(\tilde{S})$ and $\delta = E(\tilde{C}_1)/E(\tilde{S})$ [11]. At the same time, in order to simplify the calculation, the investment cost $\tilde{C}_1$, $\tilde{C}_2$ and the project benefit $\tilde{S}$ defined in the function (2)-(8), can be substituted by their possible mean.

2) R&D Projects Interactions Analysis

The qualitative analysis of interactions of benefit, technology and resource will be performed respectively.

(a) Benefit interaction affect the overall payoff obtained from a portfolio. When benefit interactions are present, the total value of a portfolio is greater or less than the sum of the individual project values. There are two types of benefit interaction: synergism effect and substitution effect. The synergism effect is that the overall benefit of project portfolio exceeds the sum benefit of each individual project. The substitution effect is that a new product project replaces the earlier product project, e.g. the improvement or upgrading of earlier product. At this time the overall benefit of project portfolio will perhaps be inferior to the sum benefit of each individual project.

(b) Technology interactions include two cases, technology interdependence and technology exclusion. Technology interdependence refers to the technology of two projects interrelated to some degree and the implementation of one project is the prerequisite of the other. Assuming there are n projects for selecting, decision-making variables x_i $(i = 1, 2, \cdots, n)$ are defined as follows:

$$x_i = \begin{cases} 1, & \text{the i-th project is in the project portfolio;} \\ 0, & \text{other wise.} \end{cases}$$

If the implementation of project p is the prerequisite of that for project j, then constraints can be expressed as $x_p - x_j \ge 0$.

If the two projects are of the type of technology mutually exclusion, only one of them can be implemented, so the constraint is $x_q + x_h \le 1$.

(c) Resource interactions occur when the total cost of a portfolio is different from the sum of the individual costs. For example, resource interactions arise when equipment or other resources are shared among some projects so that the cost of selecting projects is less than the sum of the individual costs.

Base on the analysis above, we can construct the objective function of optimization model as the sum of real options and the net present value of R&D project portfolio, with consideration of the interactions among projects, to seek for the optimal combination through the analysis of net present value of strategic extension. So the objective function of optimization model is:

$$\max \sum_{i=1}^{n}\left(\tilde{V}_i + \tilde{N}_i\right)x_i + \sum_{j=1}^{u}\Delta\tilde{S}_j y_j - \sum_{k=1}^{v}\Delta\tilde{C}_k z_k \quad (9)$$

The first summation is the sum of real option and net present value of project portfolio; the second and third summation consider respectively the changed quantum of objective function when there exists benefit interactions or resource cost interactions among projects.

In the first part of the objective function, $\tilde{V}_i$ is the value of real option of each project, calculated according to the formula (1). While $\tilde{N}_i$ is the fuzzy set present value of each project, and it can be calculated with the formula as follows:

$$\tilde{N}_i = \frac{\tilde{S}_i}{(1+r)^{iT_2}} - \frac{\tilde{C}_{i3}}{(1+r)^{iT_2}} - \frac{\tilde{C}_{i2}}{(1+r)^{iT_1}} - \tilde{C}_{i1}, \quad i = 1, 2, \cdots, n. \quad (10)$$

The u in the second item of the objective function denotes that there are u kinds of benefit interactions in the n projects to be selected. The *j-th* interaction is composed of m_j *projects. The variable* y_j indicates whether the j-th benefit interaction occurs or not. Here

$$y_j = \prod_{r=1}^{m_j} x_{r,j}, \quad y_j \in \{0,1\} \quad (11)$$

Then y_j is the product of 0-1 variables of the m_j projects between which exists the j-th benefit interaction. It indicates that the j-th benefit interaction will occur only when the m_j projects were totally selected into the project portfolio. $\Delta\tilde{S}_j$ is the change brought by the present value of cash inflow income when the j-th benefit interaction occurs. The value can be positive or negative; and the positive value indicates synergism effect obtained from the j-th benefit interaction while negative indicates substitution effect.

Similarly, the v in the third item of the objective function denotes that there are v types of resource cost interactions in the n projects to be selected. The k-th type of interaction is composed of λ_k projects, the variable z_k shows whether the k-th resource cost interaction occurs or not. Here

$$z_k = \prod_{l=1}^{\lambda_k} x_{l,k}, \quad z_k \in \{0,1\} \quad (12)$$

Then z_k is the product of 0-1 variables of the λ_k projects among which exists the k-th resource cost interaction. It denotes that the k-th resource cost interaction will occur only when the λ_k projects is completely selected into the project portfolio. $\Delta\tilde{C}_k$ is the decrease of the cost present value of cost brought to the project portfolio when the k-th resource cost interaction occurs. Its value is positive.

B. Constraint Analysis of Optimization Model

There are various kinds of constraints of portfolio selection, such as the cost or project interactions and so on. The total funds devoted into the R&D project portfolio are limited. Due to the generally long cycle of a R&D project, corporations will alter their investment cost in the R&D project according to their own property situation and the change of competitive environment. Therefore, the total cost, denoted by trapezoidal fuzzy numbers as $\tilde{C}$, is not an accurate value. Let $\tilde{c}_i$ be the cost of i-th project, cost constraint is $\sum_{i=1}^{n} \tilde{c}_i x_i \le \tilde{C}$. Considering the interactions of resource utilization and cost among projects, therefore

$$\sum_{i=1}^{n} \tilde{c}_i x_i - \sum_{k=1}^{v} \Delta\tilde{C}_k z_k \le \tilde{C} \quad (13)$$

The technology interrelation may exist among R&D projects in the project portfolio, and the analysis is as follows. If two projects are technology interdependent, the implementation of the p-th project is the prerequisite of the implementation of the j-th project, let $P_r \subset \{1, 2, \cdots, n\}$ be the numbered set of this type of projects. So the constraint is:

$$x_p - x_j \ge 0, \quad p, j \in P_r \quad (14)$$

If two projects are technology antagonism, then only one project of the q-th and h-th can be implemented. Let $P_o \subset \{1, 2, \cdots, n\}$ be the numbered set of these projects, the constraint is:

$$x_q + x_h \le 1, \quad q, h \in P_o . \quad (15)$$

Some projects must be implemented by the corporation, and projects that are in-process can also be put in this type. Let $P_m \subset \{1, 2, \cdots, n\}$ be the numbered set of these projects, and the constraint is:

$$x_m = 1, \quad m \in P_m \quad (16)$$

To analyze formulae (9)-(16), we can obtain the fuzzy 0-1 integer programming model of R&D project portfolio selection. Among them, the formula (9) is the objective function, others are constraint functions.

III. Model Solution

For the fuzzy 0-1 integer programming model above, we can use the qualitative possibility theory to translate it into a clear 0-1 integer programming model.

With the example of formula (13), we are going to explain how to translate the fuzzy constraint function into the generally resolvable integer programming constraint function with the qualitative possibility theory. If decision-maker considers that the satisfaction degree of the constraint function (13) is higher than λ, we can get Inequality (17) as

$$C\left(\sum_{i=1}^{n} \tilde{c}_i x_i - \sum_{k=1}^{v} \Delta\tilde{C}_k z_k, \tilde{C}\right) \ge \lambda \quad (17)$$

Further,

$$\sum_{i=1}^{n} c_i^{c_r} x_i - \sum_{k=1}^{v} \Delta C_k^{c_l} z_k + \lambda\left(\sum_{i=1}^{n} x_i c_i^r + \sum_{k=1}^{v} \Delta C_k^r z_k\right) \le C^{c_r} + (1-\lambda) C^r \quad (18)$$

Where $c_i^{c_r}, \Delta C_k^{c_l}$ are respectively the right boundary value and the left boundary value of $\tilde{c}_i, \Delta\tilde{C}_k$, with the membership degree as 1. Take the trapezoidal fuzzy number $\tilde{C} = (C^l, C^{c_l}, C^{c_r}, C^r)$ as an example, a detailed explanation can seen from Figure 2.

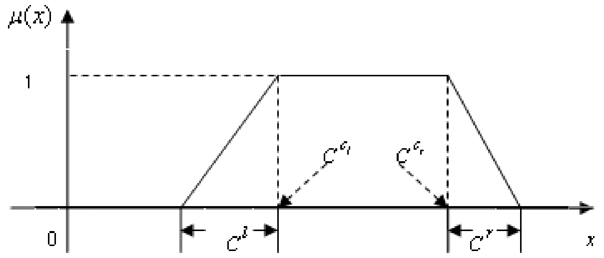

Fig. 2 Graphical interpretation of the trapezoidal fuzzy number $\tilde{C}$

Similarly, for the objective function, if the decision-maker considers that the satisfaction degree of the objective function is higher than γ , then the objective function can be transformed into

$$Max \;\; z$$
$$s.t. \quad C\left(\sum_{i=1}^{n}\left(\tilde{V}_i+\tilde{N}_i\right)x_i+\sum_{j=1}^{u}\Delta\tilde{S}_j y_j-\sum_{k=1}^{v}\Delta\tilde{C}_k z_k,\;\; z\right)\geq\gamma \tag{19}$$

Namely

$$Max \quad \sum_{i=1}^{n}\left(V_i^{c_l}+N_i^{c_l}\right)x_i+\sum_{j=1}^{u}\Delta S_j^{c_l}y_j-\sum_{k=1}^{v}\Delta C_k^{c_r}z_k -\gamma\left(\sum_{i=1}^{n}\left(V_i^{l}+N_i^{l}\right)x_i+\sum_{j=1}^{u}\Delta S_j^{l}y_j+\sum_{k=1}^{v}\Delta C_k^{l}z_k\right) \tag{20}$$

Where

$$\begin{aligned}\tilde{V}_i&=(V_i^{c_l},V_i^{c_r},V_i^{l},V_i^{r}),\\ \tilde{N}_i&=(N_i^{c_l},N_i^{c_r},N_i^{l},N_i^{r}),\\ \Delta\tilde{S}_j&=(\Delta S_i^{c_l},\Delta S_i^{c_r},\Delta S_i^{l},\Delta S_i^{r}),\\ \Delta\tilde{C}_k&=(\Delta C_i^{c_l},\Delta C_i^{c_r},\Delta C_i^{l},\Delta C_i^{r})\end{aligned} \tag{21}$$

It is clear that their definitions are similar to $\tilde{C}$.

Through the above transformation, the formulae (9) - (16) were turned into clear 0-1 integer programming problem as following:

$$Max \quad \sum_{i=1}^{n}\left(V_i^{c_l}+N_i^{c_l}\right)x_i+\sum_{j=1}^{u}\Delta S_j^{c_l}y_j-\sum_{k=1}^{v}\Delta C_k^{c_r}z_k -\gamma\left(\sum_{i=1}^{n}\left(V_i^{l}+N_i^{l}\right)x_i+\sum_{j=1}^{u}\Delta S_j^{l}y_j+\sum_{k=1}^{v}\Delta C_k^{l}z_k\right) \tag{22}$$

$$s.t. \quad \sum_{i=1}^{n}c_i^{c_r}x_i-\sum_{k=1}^{v}\Delta C_k^{c_l}z_k+\lambda\left(\sum_{i=1}^{n}x_i c_i^{r}+\sum_{k=1}^{v}\Delta C_k^{r}z_k\right) \leq C^{c_r}+(1-\lambda)C^{r} \tag{23}$$

$$x_p-x_j\geq 0,\quad p,j\in P_r \tag{24}$$

$$x_q+x_h\leq 1,\quad q,h\in P_o \tag{25}$$

$$x_m=1,\quad m\in P_m \tag{26}$$

$$y_j=\prod_{r=1}^{m_j}x_{r,j},\qquad y_j\in\{0,1\} \tag{27}$$

$$z_k=\prod_{l=1}^{\lambda_k}x_{l,k},\qquad z_k\in\{0,1\} \tag{28}$$

$$x_i,x_{r,j},x_{l,k}\in\{0,1\},P_r,P_o,P_m\subset\{1,2,\cdots,n\},0\leq m_j,\lambda_k\leq n \tag{29}$$

The above clear 0-1 integer programming model can be solved with the corresponding EXCEL Programming Solver software, thus to get the optimal solution of R&D project portfolio selection.

IV. CASE ANALYSIS AND CONCLUSIONS

In this section, we will verify the rationality of the method in this article by an example of R&D project portfolio selection in petroleum industry. There are fifty projects to be selected, according to the scores from experts; the petroleum corporation can initially screen out twenty R&D projects which are in accordance with the strategy development of the corporation. For these initially selected projects, each one is composed of three stages of production technology research, technology development testing and commercial popularization. For simplicity, we can assume all the due dates of the first and second options included in all the projects are $T_1=3$, $T_2=10$. The expected cost of the project portfolio with three stages expressed with the trapezoidal fuzzy numbers, are respectively (0, 200, 0, 20)、(0, 700, 0, 100)、(0, 1500, 0, 200), with the unit being millions of dollars; analogously, the limitation of human resources capacity of the project portfolio with three stages, are respectively (0, 374.5, 0, 50)、(0, 1964.9, 0, 250)、(0, 1319.5, 0, 160), with the unit being the number of months. Table 1 and Table 2 respectively present the stage investment cost, expected cash inflow and required human resources in each stage for the 20 projects selected initially.

In addition, these twenty projects can be divided into three types of sets, namely: the set of new production S_1, the set of derivatives of existing production S_2 (such as those re-packaged, renamed), the set of Performance improvements of existing production S_3. And the twenty projects belong to the three sets, as follows:

S_1={#13, #14, #16, #17, #18, #19, #20};
S_2={#5, #6, #8, #9, #10, #15};
S_3= {#1, #2, #3, #4, #7, #11, #12}.

At the same time, in order to achieve the strategic balance of project portfolio selection, it is required that the three types S_1, S_2, S_3 account for 40-70%, 20-40%and 10-30% in the project portfolio, respectively. Risk-free interest is 4%.

TABLE I RESOURCE DATA FOR PROJECTS

Project No.	**investment cost of stage (unit : millions of dollars)**			**Expected cash inflow $\tilde{S}$**
	$\tilde{C}_1$	$\tilde{C}_2$	$\tilde{C}_3$	
1	(2,2,0.3,0.3)	(30,30,4.5,4.5)	(30,30,4.5,4.5)	(50,50,5,5)

2	(3,3,0.45,0.45)	(50,50,7.5,7.5)	(45,45,6.75,6.75)	(100,100,10,10)
3	(10,10,1.5,1.5)	(75,75,11.25,11.25)	(100,100,15,15)	(200,200,25,25)
4	(5,5,0.75,0.75)	(65,65,9.75,9.75)	(170,170,25.5,25.5)	(200,200,10,25)
5	(20,20,3,3)	(85,85,12.75,12.75)	(200,200,30,30)	(600,600,50,50)
6	(15,15,2.25,2.25)	(40,40,6,6)	(45,45,6.75,6.75)	(100,100,5.5,5.5)
7	(7,7,1.05,1.05)	(35,35,5.25,5.25)	(30,30,4.5,4.5)	(80,80,4.5,4.5)
8	(5,5,0.75,0.75)	(55,55,8.25,8.25)	(50,50,7.5,7.5)	(100,100,4.35,5)
9	(10,10,1.5,1.5)	(75,75,11.25,11.25)	(80,80,12,12)	(180,180,20,25)
10	(18,18,2.7,2.7)	(85,85,12.75,12.75)	(120,120,18,18)	(380,380,20,25)
11	(5,5,0.75,0.75)	(35,35,5.25,5.25)	(30,30,4.5,4.5)	(80,80,7.5,10)
12	(7,7,1.05,1.05)	(40,40,6,6)	(60,60,9,9)	(100,100,10,15)
13	(15,15,2.25,2.25)	(95,95,14.25,14.25)	(180,180,27,27)	(400,400,40,45)
14	(35,35,5.25,5.25)	(120,120,18,18)	(280,280,42,42)	(700,700,50,55)
15	(25,25,3.75,3.75)	(70,70,10.5,10.5)	(100,100,15,15)	(500,500,10.5,12)
16	(15,15,2.25,2.25)	(95,95,14.25,14.25)	(150,150,22.5,22.5)	(300,300,8.5,8.5)
17	(17,17,2.55,2.55)	(80,80,12,12)	(180,180,27,27)	(350,350,20,22)
18	(20,20,3,3)	(90,90,13.5,13.5)	(220,220,33,33)	(550,550,45,50)
19	(35,35,5.25,5.25)	(120,120,18,18)	(250,250,37.5,37.5)	(800,800,50,55)
20	(50,50,7.5,7.5)	(130,130,19.5,19.5)	(350,350,52.5,52.5)	(450,450,90,85)

TABLE II REQUIRED HUMAN RESOURCES FOR PROJECTS

Project No.	Required human resources (unit: month)		
	technology research stage	**technology development testing stage**	**commercial popularization stage**
1	(2,2,0.3,0.3)	(30,30,4.5,4.5)	(30,30,4.5,4.5)
2	(3,3,0.45,0.45)	(50,50,7.5,7.5)	(45,45,6.75,6.75)
3	(10,10,1.5,1.5)	(75,75,11.25,11.25)	(100,100,15,15)
4	(5,5,0.75,0.75)	(65,65,9.75,9.75)	(170,170,25.5,25.5)
5	(20,20,3,3)	(85,85,12.75,12.75)	(200,200,30,30)
6	(15,15,2.25,2.25)	(40,40,6,6)	(45,45,6.75,6.75)
7	(7,7,1.05,1.05)	(35,35,5.25,5.25)	(30,30,4.5,4.5)
8	(5,5,0.75,0.75)	(55,55,8.25,8.25)	(50,50,7.5,7.5)
9	(10,10,1.5,1.5)	(75,75,11.25,11.25)	(80,80,12,12)
10	(18,18,2.7,2.7)	(85,85,12.75,12.75)	(120,120,18,18)
11	(5,5,0.75,0.75)	(35,35,5.25,5.25)	(30,30,4.5,4.5)
12	(7,7,1.05,1.05)	(40,40,6,6)	(60,60,9,9)
13	(15,15,2.25,2.25)	(95,95,14.25,14.25)	(180,180,27,27)
14	(35,35,5.25,5.25)	(120,120,18,18)	(280,280,42,42)
15	(25,25,3.75,3.75)	(70,70,10.5,10.5)	(100,100,15,15)
16	(15,15,2.25,2.25)	(95,95,14.25,14.25)	(150,150,22.5,22.5)
17	(17,17,2.55,2.55)	(80,80,12,12)	(180,180,27,27)
18	(20,20,3,3)	(90,90,13.5,13.5)	(220,220,33,33)
19	(35,35,5.25,5.25)	(120,120,18,18)	(250,250,37.5,37.5)
20	(50,50,7.5,7.5)	(130,130,19.5,19.5)	(350,350,52.5,52.5)

TABLE III FUZZY OPTION VALUES FOR 20 CANDIDATE PROJECTS

Project No.	Fuzzy option values	Project No.	Fuzzy option values
1	(16.35,16.35,3.65,3.65)	11	(11.32,11.32,4.50,5.30)
2	(36.89,36.89,8.59,8.59)	12	(24.60,24.60,5.45,7.28)
3	(41.85,41.85,16.07,16.07)	13	(97.83,97.83,40.67,43.45)
4	(72.71,72.71,12.65,21.49)	14	(195.18,195.18,48.70,51.22)
5	(270.34,270.34,50.24,50.24)	15	(181.94,181.94,21.96,22.82)
6	(0,0,0,0)	16	(126.59,126.59,9.06,9.06)
7	(7.55,7.55,2.36,2.36)	17	(111.02,111.02,18.94,19.92)
8	(25.42,25.42,4.22,4.49)	18	(176.98,176.98,52.40,55.50)
9	(37.03,37.03,12.48,14.40)	19	(335.18,335.18,47.91,50.80)
10	(102.10,102.10,25.25,27.89)	20	(398.15,398.15,106.74,103.56)

TABLE IV BENEFIT, TECHNOLOGY AND RESOURCE INTERACTIONS AMONG PROJECTS

Type of interactions	projects	effects of interaction
Benefit interactions	2，5	synergism effect $\Delta S1 = (50, 50, 4.5, 4.5)$
	11，17	Substitution effect $\Delta S2 = (-30, -30, 4, 4)$
Technology interactions	3，4	the implement of project 3 is the prerequisite of the implement of project 4
	16，17	Projects 16 and 17 are mutually exclusive
	6	Project 6 must be implemented
Resource interactions	2，15	Saving cost $\Delta C = (50, 50, 5.5, 5.5)$

TABLE V PROJECTS PORTFOLIO SELECTION RESULT ($\gamma = 0.95$, $\lambda_{1t} = 0.1 - 0.99$, $\lambda_{2t} = 0.9,\ t = 1, 2, 3$)

λ_{1i}	selected project			Objective value
	Strategy 1	Strategy 2	Strategy 3	
0.1	16,18,19,20	5,6,10,15	2,11	2022.91
0.2	17,18,19,20	5,6,10,15	1,2	2009.80
0.3	17,18,19,20	5,6,10,15	2	1999.75
0.4	18,19,20	5,6,10,15	1,2,7	1922.72
0.5	16,18,19,20	5,6,15	2	1908.55
0.6	16,18,19,20	5,6,15	2	1908.55
0.7	16,18,19,20	5,6,15	2,11	1714.60
0.8	16,18,19,20	5,6,15	2,11	1714.60
0.9	16,19,20	5,6,15	2,11	1714.60
0.95	16,19,20	5,6,15	1,2	1710.283
0.99	16,19,20	5,6,15	1,2	1710.283

By calculating, when $\gamma = 0.95$, $\lambda_{1t} = 0.1 - 0.99$ $(t = 1, 2, 3)$, $\lambda_{2t} = 0.9$ $(t = 1, 2, 3)$, we can get the portfolio selection result considering the interactions among projects, as in Table 5.

First of all, through the calculated results of Table 5, we can see that the project portfolio selection model has indeed considered the interactions among projects. For example, for the benefit interactions among projects, due to the synergism effect between project 2 and project 5, the emergence of both of them at the same time is able to increase the benefit of the project portfolio, which is precisely reflected in the result calculated. On the contrary, due to the substitution effect between project 11 and project 17, the emergence of them at the same time will surely decrease the benefit of the project portfolio; such relation is also precisely reflected in the result calculated. For all kinds of schemes of project selection, project 2 and project 5 will surely be at the same time, while project 11 and project 17 will surely not be at the same time. For the technology interactions among projects, as the implementation of project 3 is the prerequisite of the implementation of project 4, seeing from the calculation results, project 3 and project 4 do not emerge in all the schemes of project selection, we can conclude that this result is also in line with the assumptions of the technology interactions. For the reason that projects 16 and 17 are mutually exclusive projects, in the calculation results, in all kinds of schemes of project selection, project 16 and project 17 never emerges at the same time. The project 6 which must be implemented emerges in all the schemes. Finally, let’s look at the resource interactions between projects. Due to the resource interactions between project 2 and project 15, the emergence of both of them at the same time can save the cost of resources, and it can be seen in the calculation result that project 2 and project 15 emerge at the same time in all the schemes, which is in line with the assumptions of the resource interactions between two projects.

Secondly, by analyzing the data, we can also find when the cost constraints satisfaction degrees are different; we can get different project portfolio values (objective function value). Figure 3 shows that the project portfolio values vary with the cost constraints satisfaction degree when other conditions are the same. It can be seen when it is $\lambda_{1i} = 0.3$, 0.4, 0.6, 0.7 (i = 1, 2, 3), the portfolio value will vary rapidly, while in other parts, it is relatively smooth. Decision-makers can adjust the cost constraints according to the demonstrated results of the model. Grasping a few key points, it may lead to greater benefit for investment decision-making.

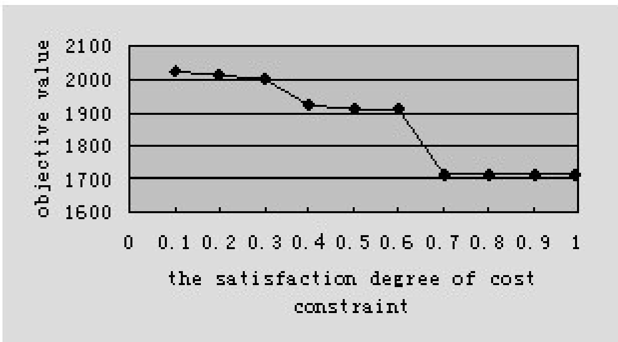

Fig. 3 Project portfolio value for different cost constraints satisfaction degree

Finally, this article is specific to different calculations of the cost constraint satisfaction. Of course, you can also use different satisfaction degree in objective function or human resources constraints. You will get a different portfolio scheme with different parameter, and we will not repeat them here.

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Construction and Consideration of America's Underground Gas Storage

Jianzhang Wu[1]
School of Petroleum Engineering, Southwest Petroleum University
Longjiang Road No.16, Chengdu City,Sichuan Province China
[1]wujianzhang@yeah.net

***Abstract*- As an important part of natural gas market, underground gas storage plays an irreplaceable role in peak shaving and guaranteeing the security of gas supply. Based on investigations and researches on the status of underground gas storage construction in the USA, information about types, numbers, reservoir site layouts, capacity and characteristics of underground gas storages managements in the USA are concluded, combined with the development of natural gas industry in China, suggestions such as optimizing construction layouts of underground gas storages, accelerating the construction pace of underground gas storages and making an early plan for natural gas strategic reserve are given[1].**

Keywords*- *Natural Gas; Underground Gas Storage; Peak Shaving; Strategic Reserve; America

I. INTRODUCTION

The underground gas storage is aiming to inject gas produced from oil field into underground where it can be conserved. It plays a non-substitutable role in peak shaving and ensuring safety of gas supply. Major countries in natural gas production and consumption regard construction of underground gas storage as a consequential partition of natural gas integration of upstream and downstream. At present, the U.S. has already achieved natural gas strategic reserve by possessing the maximum quantity and capacity of underground gas storages. Underground gas storage in China is in her inception, it would be helpful with reference of the U.S's projection and construction experience.

II. THE GAS STORAGE RESERVIOR CONSTRUCTION AND MANAGEMENT IN THE UNITED STATES

A. The Characteristics of Gas Storage Construction in the United States

The depleted oil-gas reservoir gas storages occupy the largest number of gas storages in the U.S, but the salt cavern underground gas storages develop fastest in recent years. According to the statistics from the EIA, there are 400 underground gas storages in the U.S. in 2007 and 326 of them are the depleted oil-gas reservoir gas storages, occupied 81.5% of the total number. 43 of them are the aquifer underground gas storages account for 10.8% of the total number. 31 of them are the salt deposit or salt cavern underground gas storages account for 7.7% of total number. The depleted oil-gas reservoir storages occupy the largest number of gas storages. They are short in construction cycle, low in investment and operating fees, huge in gas storage capacity and great economic profits, mainly used in seasonal peak shaving. The salt cavern underground gas storage is small in capacity, but it can meet the needs of the daily peak shaving due to its strong maneuverability, fast gas injection and high production speed as well as less cushion gas consumption so that the salt cavern underground gas storages develop fast in recent years. According to the document material[2], the U.S had expanded 47 underground gas storages including 31 salt cavern underground storages from 2004 to 2008.

The underground gas storages are mainly distributed in the central areas of gas consumption and production. In the U.S, the underground gas storages are mainly distributed in gas production areas like the northeast and south where contain the most of the consumers [3], among them about 50% of the underground gas storages are concentrated in the northeast region where the major natural gas is consumed .Underground gas storages are also distributed in the regions with adequate natural gas resources, such as Texas and Louisiana. According to the statistics from the EIA, on September, 18th, 2009, the maximum working volume of all gas storages in U.S is $998.3\times10^8 m^3$, the southern production areas and the eastern consumption areas accounting for 86.3% of the total working volume [4].

The U.S met the regular peak shaving and achieved initial strategic reserves of natural gas by increasing gas production in the peak period and increasing gas injection in the trough period. According to table 1, during the peak gas consumption in 2008 (from December to February), in order to meet the stable gas supply, the storage production gas accounts for 25.7%~32.8% of the monthly consumption gas. In addition, most of the working gas can be used as the strategic reserve because most of them are still in the gas storages and only a small proportion of gas was used. For example, in January (the maximum gas production month) of 2008, the proportion of production gas only accounted for 44% of the working gas. The maximum working gas volume of all gas storages in the U.S was $926.5\times10^8 m^3$, accounting for 14.1% of the total natural gas consumption volume ($6\ 572.4\times10^8 m^3$) and the strategic reserve days have reached 53 days.

B. The U.S Gas Storage Operating Management

1) The Operating Pattern

In the U.S, underground gas storage operators are as a member of the gas industry chains, they are independent fromthe natural gas developers and the terminal vendors. They take responsibility for gas storage and transportation.

The gas storage operators in the U.S include the interstate pipeline companies,the state pipeline companies, the city gas companies and the independent gas storage operators

The interstate pipeline company. These types of companies mainly adjust the supplement and the peak shaving during their working process by making use of their long distance pipeline. Under this circumstance, The Federal Energy Regulatory Commission developed the regulation requires the interstate pipeline companies open their rest storage capacity to the third parties. Currently, 25 natural gas pipeline companies own 172 natural gas storages, accounting for 55% of the total gas storage volume.

The state pipeline companies and city gas companies. The state pipeline companies also adjust the supplement and peak shaving by making use of their gas pipeline during the working process. The city gas companies transmit natural gas directly from the gas storages to the consumers. Such operators occupy 35% of total gas storage volume.

The independent gas storage operators. According to the law of the U.S, the gas storages can be rented to the third consumers, such as the operators and power plants. With the lifting of more restrictions, these types of operators will occupy more market share in the future. Now the gas capacity of these operators is 10% of the total storage volume.

2) Business scope

According to the gas storages investigation made by Beijing Hua You Oil Company , the business scope of gas storage in the U.S. including the seasonal peak shaving, the gas supply for the peak power stations and the emergent gas supply, "deposit and loan gas" business storage facilities of LNG, etc [5]. Due to the gas storage operators are only responsible for natural gas storage and charge for natural gas storage fees, so that operators have to ensure the safety of operating, and then maximizing the gas storage injection-production cycle times to get more profits.

The direct reasons for the rapid growth of America's underground gas storage are the lifting of the gas storage construction ban and the increase number of gas power plants , but the fundamental cause is the different gas prices in summer and winter, as well as the peak shaving gas price and peak bargaining gas, etc. The existence of different prices prompted gas distributors to store gas in the trough period and sell it in the peak period. By this operation mode, gas storage operators charge natural gas storage fees and natural gas distributors obtain profits of price difference.

III. CHINA'S GAS STORAGE CONSTRUCTION AND COUNTERMEASURES

A. General Situation of Construction

The construction of the underground gas storage in China started late in the 1970s, Daqing oilfield tried to build gas storage by making use of gas reservoir. They built Sartu No.1 underground gas storage and Lamadian gas storage [6]. Among them, Sartu No.1 underground gas storage had been dismantled but the Lamadian gas storage is still in service since it has been completed in 1975. With two expansions in recent years, the total storage capacity of Lamadian underground gas storage has reached $100\times10^4 m^3$daily, and the gas injection capacity has reached $1.5\times10^3 m^3$ annually, the total capacity reached $25.0\times10^8 m^3$.

In the 1990s, China started the comprehensive research of underground gas storage. Dagang gas field is a place nearby Tiangin city. This field used depleted condensate gas reservoirs to build Dagang gas storage system for coping with the Shanxi-Beijing natural gas pipeline and guaranteeing gas supply and peak shaving of Beijing city and Tianjin city. Now, this gas storage system has 6 gas storages. It can meet the needs of $13\times108m^3$'s seasonal peak shaving gas supply and $3400\times10^4 m^3$'s daily emergency peak shaving capacity and $1305\times10^4 m^3$'s daily gas injection capacity.

In recent years, with the increase consuming proportion of natural gas in energy consumption, CNPC (China National Petroleum Corporation) and Sinopec have strengthened their devotion in planning and constructing on underground gas storages. According to the public reports, CNPC is planning to build 10 gas storage systems with $244\times10^8 m^3$'s peak shaving capacity, those gas storage systems are located in the north, northeast and southwest China, Xinjiang province, Yangtze river delta area，etc. In the north China, CNPC and the Beijing municipal government jointly invested in a gas storage project. It has initially formed a long-term strategic planning involved 11 strategic gas storage systems. Among them, the Beijing 58 gas storage systems are predicted to have 6 $000\times10^4 m^3$/d average gas supply capacity after completion, the construction schedule has completed 76%. In the Yangtze river delta, CNPC has been building the underground salt cavern gas storage in Jintan city, Jiangsu province and in Dingyuan city, Anhui province. Among them, Jintan gas storage has basically completed at the end of August 2009. In the northeast China, CNPC plan to build Daqing oil field gas storage, Jilin oilfield gas storage, as well as Liaohe oilfield gas storage. Sinopec also started preliminary research on the construction of gas storage in Shengli oilfield, Zhongyuan oilfiled, Jianghanand oilfield and Jintan oilfield. Now, Jianghan and Jintan gas storages are continuing their preliminary works and planning to store gas around 2011. Jintan gas storage is designed to have effective gas storage for $10\times10^8 m^3$. According to the gas peak shaving and storage requirements, Sinopec plan to build it with $9.60\times10^8 m^3$'s working gas storage capacity by the end of 2020.

In addition, according to the relevant schedule, Chengdu will build its first large size underground gas storage with $2\times10^8 m^3$'s initial scale in Longquan district and Luodai district. Chongqing city also plans to build an underground gas storage with $8\times10^8 m^3$gas storage capacity in phase I and $20\times10^8 m^3$gas storage capacity after completion of phase II.

B. The Countermeasures for Acceleration of Underground Gas Storage Construction in China

In recent years, the underground gas storage construction in China has been developed rapidly, but it still in its infancy comparing with the U.S, the construction of gas storage still lags behind the rapid development of natural gas industry. With reference with American gas storage's construction and operation, China should devote great efforts to the construction of underground gas storage in following areas:

TABLE I. THE MONTHLY PROPORTION OF GAS PRODUCTION TO CONSUMPTION IN 2008

Month	1	2	3	4	5	6	7	8	9	10	11	12
Gas production/10^3m^3	252.5	183.7	99.2	29.9	15.9	22.8	25.0	25.9	27.7	25.9	71.0	174.1
consumption/10^3m^3	770.1	703.8	641.4	513.6	446.2	455.2	484.1	477.7	414.0	462.7	426.6	676.9
proportion	32.8%	26.1%	15.5%	5.8%	3.6%	5.0%	5.2%	5.4%	6.7%	5.6%	13.5%	25.7%

Data resource: EIA

Start to develop strategic reserve of natural gas as soon as possible by increasing the number of gas storages and enhancing their storage capacity as well as implementing gas storages for seasonal peak shaving. According to the forecast from State Development and Reform Commission, the demand of natural gas in energy consumption will reach 10%, the total consumption volume will reach $2000\times10^8m^3$and the import capacity will reach $800\times10^8m^3$ by the end of 2020.

Optimize the new gas storage site in those large consumption areas including Sichuan, Chongqing, the eastern China and Guangdong, etc. And increasing construction strengths of underground gas storages guarantee gas supply downstream. Over the years, the natural gas consumption data shows that Sichuan is the largest gas consumption province followed by Jiangsu and Beijing. However, the major projects and construction of underground gas storages in China are mainly concentrated around Beijing, which can only meet seasonal peak shaving of the Beijing-Tianjin region. Now, in those largest gas consumption regions like Sichuan , Chongqing and those fast gas consumption growth regions like coastal areas of China, only Jintian gas storage meets the goal of gas reserve. Other regions are still in planning phase, and are small in numbers and scales. There are plenty salt caverns in Jiangsu and Anhui province, therefore we should make full use of the terrain and find other proper formation to build adequate gas storages to ensure natural gas supply of these areas. According to the estimate from experts, strategic reserve will achieve (200~250) $\times10^8m^3$ [7] for guaranteeing the security of gas supply. With the development of economy, China's dependence on foreign natural gas will gradually improve which is a real problem encountered during the "China's 12th five-year plan". A large number of oil and gas reservoir structures in the northeast and northwest China, and there are relatively plenty of salt caverns underground gas storages in the southwest of China, thus those regions have innate advantages to build underground gas storage.

Optimize and operate depleted oil-gas reservoir resources in eastern China and start the preliminary work. With the ratio of natural gas consumption increasing in China's total energy consumption, the domestic gas price will reach the international standard so that the implementation of gas price difference is imperative. By then, with the process of construction and operation of gas storage, we can guarantee the safety of gas supply as well as getting great profit.

The eastern area of China is the core consumption market. There are many oilfields with great geographical position, such as Zhongyuan oilfield, Shengli oil-field and Jianghan oil. Depleted oil and gas reservoirs in those areas should be fully used to start the preliminary work of gas storage management.

IV. THE FUTURE DEMAND OF CHINA'S UNDERGROUND GAS STORAGE

Natural gas market demand shows rapid growth trend, so the domestic gas supply gap continued to increase. With the domestic natural gas infrastructure's ceaseless complete and the development of economy, it is expected that in 2015 the national natural gas demand will reach 2350×10^8 m^3 ,and upon the year of 2020 it will amount to 3000 ～ 3500×10^8 m^3 , in 2030 it will reach 5000×10^8 m^3.Because domestic natural gas production cannot meet consumer's demand, for the goal of protection of domestic natural gas supply, we need a large number of foreign imports of natural gas. According to the forecast, the domestic natural gas imports will increase from about 200×10^8 m^3 in 2010 to 1360×10^8 m^3 in 2020 and 2100×10^8 m^3 in 2030. The natural gas import dependency will increase year by year and the degree of dependence on foreign natural gas in 2020 will exceed 50%.

Adjustment and strategic reserve requirements determine the huge demand of natural gas storage. It is expected that by 2020 China's dependence on foreign natural gas will exceed 50%,and according to lessons from foreign countries' experience, if a country's natural gas imports occupy more than 50%, the volume of underground gas storage working gas will reach about 15% of the volume of natural gas consumption. Under this circumstance, suppose that in 2020 the domestic natural gas consumption is 3500×10^8 m^3, so the peaking capacity will reach 525×10^8 m^3 scale. And as China's natural gas external dependence degree rise ceaselessly, natural gas imports will continue to grow, disruption risk of gas supply will be bigger, therefore China should appropriately consider strategic storage requirements. Chinese imports of natural gas mainly comes from Middle Asia, Russia and shipping LNG from other countries, it should be considered near in the gas inlet channel or domestic long distance natural gas pipeline network center region to construct national strategic storage of natural gas. In 2020, according to goal of natural gas strategic reserves reached 30d's natural gas import and in 2030 natural gas strategic storage of natural gas to 60d's import target, It can be estimated in 2020 natural gas strategic storage is 110×10^8 m^3 and in 2030 the natural gas strategic reserves is 350×10^8 m^3.To sum up regulation and strategic storage requirements, in 2020 the volume of working gas of underground gas storage is $650 \times 10^8m^3$ and in 2030 working gas volume should be 1100×10^8 m^3.

Natural gas consumption structure gradually becomes diverse and the proportion of city gas peak-shaving is increasing. Before 2000, gas is the main fuel of chemical and industrial field, in 1996, this main consumption accounted for about 82% of the total gas consumption, but this demand of consumption structure on peak-shaving is not very urgent. In recent years, demand of city gas consumption and natural gas electronic power plants consumption is proportional rise, China's natural gas market gradually formed a city gas, industrial fuel, natural gas, natural gas structure which is relatively balanced, while the city gas consumption and natural gas electronic power plants on peak-shaving load demand is big, which needs to build enough load supporting implementation, especially in order to meet the demand of underground gas storage.

With the massive exploit of coal bed methane and shale gas, the construction of underground gas storage reservoir has been put forward to higher requirements. Present China are on large-scale development and utilization of unconventional natural gas, especially shale gas, coal-bed gas and tight gas, it is expected that by 2020, coal bed gas production in China will reach $500 \times 10^8 m^3$, shale gas production will reach $800 \times 10^8\ m^3$ and coal gas production will exceed $100 \times 10^8\ m^3$.Due to the unconventional natural gas's low output of a single well so its regulating function is weak, therefore it is necessary to have natural gas peak-shaving facilities for the development and utilization of these resources.

The balanced pressure and gas of long distance backbone network accelerates the growth of demand of underground gas storage peak-shaving. According to other countries experience, 5 to 10 years after accomplishment of long distance backbone network formation is the underground gas storage demand rapid growth phase, after natural gas consumption reaching to a peak point, underground gas storage demand will show a steady growth trend. At present, China's consumption of natural gas is still in the rapid growth phase and peak demand can still be adjusted through the new pipeline which does not reach full load running point. The demand for underground gas storage is more urgent when China's long distance pipeline is completed and the basic operation is at full load by 2020.

To sum up, as a result of natural gas consumption structure has been changed, peak-shaving and natural gas strategic storage requirements' development, unconventional natural gas utilization and many other factors, China's underground gas storage grow rapidly, which is expected until 2020 the work of underground gas storage gas demand will reach $650 \times 10^8\ m^3$ and in 2030 it will reach $1100 \times 10^8\ m^3$.

V. CHINA GAS STORAGE FIELD BOTTLENECK PROBLEM

Underground gas storage construction lags than natural gas pipeline construction. Since twenty-first Century, China's rate of long distance natural gas pipeline construction is unprecedented and growth rate of gas supply is very fast, but the construction of underground gas storage is often after the completion of natural gas pipeline construction, and the construction cycle needs 5～8a's time, leading that the construction of underground gas storage speed cannot follow the speed of natural gas pipeline construction which cannot meet the growth needs, peak-shaving demands.

The methods of natural gas pipeline manipulation and gas peak-shaving control is weak and it simply cannot satisfy the needs of gas in downstream market. Due to the vast territory of China, natural gas resource distributes widely and natural gas resources are mainly concentrated in the western region of China. But the gas consumption market is mainly concentrated in the eastern and southern regions, also all long distance natural gas pipeline exceeds 1 000km, moreover long distance natural gas pipeline called "West second-line" is over 3 000km. So making use of the upstream gas field and natural gas pipeline to satisfy the downstream market of natural gas peak-shaving is not possible, meanwhile the operation is difficult with poor economic benefit.

The design of underground gas storage is inadaptable with construction technology and complex reservoir geological condition in China. As to the gas reservoir which has been incorporated into the building target, it is buried deeply and has low permeability also seriously watered out. All of these problems are waiting for a solution. Eastern and southern region of China is characteristic of layered distribution of salt, interlayer, small thickness, difficulty of cavity making. And these problems are also faced in the international construction of salt cavern gas storage. While there is no precedent experience for aquifer and oil-reservoir construction in China, this kind of geological selection standard of underground gas storage are still groping.

VI. CHINESE DEVELOPMENT FACES THE CHALLENGE OF UNDERGROUND GAS STORAGE

A. Resource Challenge

East China oil and gas reservoir has been basically brought into underground gas storage future constructing place. Due to complicated geological conditions in eastern region, finding the right place to build underground gas storage requires a lot of work. The oil and gas exploration in southern region did not make any break through, which cannot be used as oil gas reservoir and the water reservoir exploration task is very hard. The single average underground working gas storage volume around the world is 5 × 108 m3. According to the average level of the world, if we need a new 500 × 108 m3 volume of working gas then we need to build 100 new underground gas storage and need to find, search, evaluation about 300 traps.

B. Technical Challenges

Other countries like America, Russia have formed a set of mature underground gas storage system and process of evaluation, selection, construction and management technology, yet in these areas China has just started so the technical system is not mature.

Compared to foreign underground gas storage construction, in China, the construction object is rather complicated, for instance, it is a considerable challenge how to build underground gas storage in low permeability, ultra deep, complex geological conditions of oil gas water system. From the current construction target, the depth of underground oil storage reservoir is generally deep, almost more than 2 000m, the deepest reaches 5 000m. The reservoir physical property is poor, the permeability of partially area is only a few millidarcy and some targets have been flooded, so the expansion of capacity is very difficult. In addition most of these reservoirs are development well from 1960s to 1970s, so the well condition is complex and the effort of processing or repair is difficult. At the same time, many gas reservoir depletion rates is high, pressure coefficient is low, drilling, completion, cementing is difficult.

VII. THE FUTURE DEMAND AND THE MAIN DRIVER OF GROWTH AROUND THE WORLD

With the growth of natural gas consumption demand, the demand of underground gas storage will grow too. According to the IGU predictiction, until 2020 the global demand for natural gas will from 3×10^{12} m^3 in 2005 to 3.7×10^{12} m^3, and in 2030 it will increase to 4.5×10^{12} m^3.At the same time, it is expected working gas volume underground gas storage will be from 2005 of 3300×10^8 m^3 grow to 5430×10^8 m^3 in 2030 on the globe scale.

The main growth areas of underground gas storage are still Europe, North America and the CIS countries. According to the forecast, the working gas of underground gas storage volume is from 790×10^8 m^3 in 2005 to 1350×10^8 m^3 in 2030. North America's working gas of underground gas storage volume is from 1160×10^8 m^3 in 2005 to 1870×10^8 m^3 in 2030 and CIS countries are from 1360×10^8 m^3 in 2005 increases to 1770×10^8 m^3 in 2030. Three traditional underground gas storage areas will remain the key point of growth of underground gas storages for the future demand. Due to the constraints of natural gas pipeline network system and underground geological conditions of gas storage construction in Asia Pacific area, and Japan, South Korea and other traditional natural gas market are dominated by LNG, so the underground gas storage growth rate in this area will not increase a lot, and proportion of these areas will account still less than 1% than overall global underground gas storage working gas volume.

According to the IGU analysis of underground gas storage, the future demand driving growth force mainly comes from the following aspects:

1) Lots of countries start to pay attention to natural gas strategic reserve. Russia, as the representative of these countries, already has begun to increase natural gas strategic reserve.

2) The change of natural gas supply mode. LNG trading has big impact on traditional pipeline natural gas market, which will stimulate the demand for underground gas storage.

3) The short term natural gas trade needs. Short term trading requires underground gas storage as an effective turnover.

4) Network system needs further balance, including the balance of the conveying capacity and pressure balance.

5) Oil development leads to a large number of associated gas emissions which will cause atmospheric pollution, so construction of underground gas storage will also need to meet the needs of associated gas storages.

Specific to different areas, the main driving forces of underground gas storage are also different. The demand growth of underground gas storage in Western Europe countries comes mainly from the increase of dependence on natural gas import countries. Counties which have high natural gas dependence on foreign countries must build underground gas storage system to meet the need of natural gas reserves. In Europe case, according to the IGU experience, once the natural gas external dependence has achieved more than 30%, and then the working gas of underground gas storage volume would need to exceed more than 12% of natural gas consumption volume. If the gas dependence on foreign countries is more than 50% then most of the working gas of underground gas storage volume will exceed 20% of natural gas consumption. For instance, France, Austria and so on reached about 30%. With the decline of local natural gas production and growth of dependence on import natural gas in Western European countries, the demand of the gas underground storage will be increasingly urgent in the future.

Underground gas storage demand growth patterns in North American area rely mainly on unconventional natural gas development. Especially in the United States, because of the new large-scale unconventional natural gas development, it not only changed the regional natural gas supply and demand balance, but also changed the local supply direction of natural gas flow. The new underground gas storage construction needs mainly meet the unconventional natural gas development and utilization as well as adaptation and assure the unconventional natural gas supply, peak-shaving.

CIS countries, due to influence of geopolitics and national economic development, start to add efforts in protection of local gas supply also increase their underground gas storage construction efforts and inputs.

VIII. CONCLUSION

China's construction of underground gas storage is in the early stages of development, although its underground gas storage construction is faced with many challenges, but once pay enough attention to the important and indispensable position of underground gas storage in the natural gas industry, meanwhile pay attention to digest and absorb foreign advanced experience and technology, through technical innovation and management creation, and constantly increase construction strength. Then underground gas storage in China will boom along with the rapid development of natural gas business which plays an irreplaceable important role in stabilization and secure gas supply.

ACKNOWLEDGMENT

World natural gas Summit the most important event of International Gas Union (IGU), which is held every 3 years at the country of chairman of the IGU, and it is the world's highest level event of natural gas industry.

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Jianzhang Wu, Bachelor' degree in Petroleum Engineering will be issued in 2013 by School of Petroleum Engineering, Southwest Petroleum University ,Chengdu City, Sichuan Province ,China.

He is still studying Petroleum Engineering in Southwest Petroleum University.

Comparative Study of Sand Control Methods in Niger Delta

Abubakar Mohammed[1, 2*], Ikeh Lesor[1, 3], Sunday Aribo[1, 4], Marcus B. Umeleuma[3]

[1]School of Mechanical Engineering, University of Leeds, Leeds, United Kingdom

[2]Department of Mechanical Engineering, Federal University of Technology, Minna, Nigeria

[3]Department of Petroleum & Gas Engineering, University of Port Harcourt, Port Harcourt, Nigeria

[4]Department of Metallurgical & Materials Engineering, Federal University of Technology, Akure, Nigeria

***Abstract*- Sand production like water and gas production is one of the perennial problems plaguing the oil industry because of its safety, economics or environmental impact on production. In order to properly optimise production and monitor sand controlled well, it is imperative to evaluate the well performance, sand control effectiveness and durability of the treatment type installed in order to achieve the main aim of hydrocarbon production. The principal methods of sand control that are available to oil industry in Nigeria are internal gravel pack (IGP) and sand control using chemicals (SCON). This paper compares the principal methods of sand control measures installed in terms of their effect on performance, durability and sand control effectiveness in Niger Delta. Production and well data from 10 different wells were gotten for their flow rate, sand production and water production. Actual and ideal productivity index are calculated. Well inflow quality indicator (WIQI) was used as a criteria to determine the performance of the well for their treatment types. A graph of the production data was plotted against time (years). A bar chart of the treatment type before installation is plotted against time (years) and also a bar chart of sand produced after the treatment type installed was made to determine the durability and sand production effectiveness of the treatment types installed. The result show that SCON wells have better performance than IGP wells with WIQI values ranges from 0.6 – 1 to that of 0.2 – 0.6 for IGP wells. SCON wells recorded 2-4 years to that of 6 – 12 years of IGP wells for durability. SCON wells recorded sand production of about 55Ib/1000bbl, to that of 34Ib/1000bbl, for IGP wells after their installations. Based on these findings IGP wells are recommended for Niger Delta formation.**

Keywords- Reservoir; Sand Control; IGP; SCON; Niger Delta; WIQI

I. INTRODUCTION

Sand production (or sanding) is the production of the formation sand alongside with the formation fluids (gas, oil and water) due to the unconsolidated nature of the formation. Produced sand has essentially no economic value. On the contrary, formation sand do not only plug wells to reduce recovery rates, it also erode equipment and settle in surface vessels. Controlling formation sand is costly and usually involves either slowing the production rate or using gravel packing or sand-consolidation techniques. As a result of this, sand production is a major issue during oil and gas production from unconsolidated reservoirs. Its effect is a peculiar problem of the Niger Delta oil province which describes the Niger Delta as complex and its geology. The production of sand is a worldwide problem. Areas of major problems include the U.S Gulf Coast, California, Canada, China, Venezuela, Trinidad, Western Africa, and Indonesia. At least some problems are reported in all areas of the world where oil and gas are produced. Sand production is initiated when the formation stress exceed the strength of the formation [1, 2]. The formation strength is derived mainly from the natural material that cements the sand grains, but the sand grains are also held together by cohesive forces resulting from immovable formation water (residual water). The stress on the formation sand grains is caused by many factors notably; tectonic actions, overburden pressures, pore-pressures, stress changes from drilling, and drag forces on producing fluids. In some cases, the onset of sand production occurs late in the life of a field when pressure have declined to the extent that the overburden is being supported mainly by the vertical component of inter grain stress rather than by the pore pressure [3]. This may cause shearing of the cementing material allowing the sand grains to move and hence be produced into the wellbore or, below a certain pore pressure, the point stress between the sand grains exceeds their fracture strength and the grains collapses causing instability and onset of sand production.

Sand production is one of the oldest problems of oil field. It is usually associated with shallow formations as compaction tends to increase with depth. But in some areas, sand production may be encountered to a depth of 12,000ft or more. Sand production higher than 0.1% (volumetric) can usually be considered as excessive, but depending on the circumstances, the practical limit could be much lower or higher.

Several factors are responsible for the production of sand oil and Gas wells in Niger Delta area of Nigeria. Firstly, by virtue of the considerable porosity of the Niger Delta, reservoir sands tend to be weakly consolidated or totally unconsolidated and are thus produced when the well flows. The unconsolidated sands are loose and are susceptible to being produced into the wellbore and to the surface unlike the consolidated (compacted) sands that are carried by fluid drag force. Secondly, the rate at which the formation is produced can lead to sand production in a well. Every reservoir has a threshold pressure, which is the pressure at which a well will produce sand free. But this threshold pressure is below economic producing rate; therefore, the engineer tends to ignore the threshold pressure so as to produce at a maximum rate from a sand stone reservoir, sand will be produced. Thirdly, when the wellbore pressure is small compared to the reservoir pressure, this will lead to high rate of fluid flow from the reservoir into the wellbore. The high viscosity fluid that flows with high velocity from the reservoir into the wellbore may be produced with the reservoir sand. Fourthly, in Nigeria, hydrocarbon bearing reservoirs are characterized by relatively thin sand with broken shale that breaks and are mostly unconsolidated often due to high permeability and porosity. By virtue of the unconsolidation of the sands, they are produced into the well when the well flows if not properly controlled. And finally, a reservoir that might have been certified sand free may begin to produce sand after a long time because a lot of factors changes with time. Some of these changes could be reservoir depletion, water production and increased overburden stress.

The general sand production can be classified into three categories: transient, continuous and catastrophic. The transient sand production is commonly encountered during clean-up after perforation or acidizing. At this stage, sand production will decline with time. The continuous sand production occurs during production from unconsolidated sandstone reservoir that has no sand control equipment. For this case, sand production is observed throughout the life of the well. The catastrophic sand production refers to events where a high rate of sand influx causes the well to die and/or choke. This occurs when the reservoir fluids are excessively produced and this is the worst case of sand production.

The production of formation sand with the oil and gas from the sand prone formation creates a number of potentially dangerous and costly problems. These effects are summarised in Table 1 below.

TABLE I EFFECTS OF SAND PRODUCTION

Area	Problem	Effect
Reservoir	Wellbore fill	• Restricted access to production interval • Loss of productivity • Loss of reserve
Subsurface Equipment	Sand fouling	• SSSV not operating • Difficult wire line operation
	Erosion	• Equipment replacement • Equipment failure.
Surface installation	Sand accumulation	• Malfunctioning of control equipment • Unscheduled shut down
	Erosion	• Deferred production • Sand separation and disposal

Whatever sand exclusion method that is adapted, it cannot be guaranteed that they will work indefinitely. Consequently, it is essential that the sand content of the produced fluids be monitored so that if a well starts producing sand it can be shut-in before subsurface or surface equipment becomes blocked or damaged. The methods of monitoring sand production can be batch, probe or downhole sand detection. The batch monitoring system is the cheapest method of sand monitoring. It involves periodically taking a sample of produced fluid from the well head, filtering out and washing the sand, drying it and weighing it [4, 5]. Unfortunately, this method can be inaccurate because of the random nature of sand production, particularly if the well is slugging or on intermitted pump. However, if a greater weight of sand is collected over a longer sampling period after passing a known quantity of produced fluid through a filter, better accuracy may be obtained. The probe monitoring involves a continual monitoring and leads to a greater accuracy than periodic observation. Sand probes may be used to shut in a well or to monitor and record the quantity of sand produced [5]. These probes can be mechanical probe, sonic probe or piezo-electric probe. The downhole sand detection uses a system known as SANFLOG, which operates on the same principle as the SAFLO detector [5] to detect sand influx in a dry or wet gas wells or single liquid phase wells. The system can also be used as a listening device operating on audio signals between 0.3 and 10 KHz [6]. This dual capability allows the operator to use the tool to listen for flow from producing interval while simultaneously recording sand impacts. If only part of the producing formation is contributing to sand production, the operator may elect to selectively treating the specific zone.

The methods/techniques that is being used to control sand in formations producing sand can be grouped as mechanical, chemical or combination methods. The mechanical exclusion of sand is effected by setting up a physical barrier to the sand movement, which still allows for the passage of reservoir fluids. The barrier takes the form of a screen surrounded by fine gravel, which is sized so that the formation sand cannot pass through the pore throats of the gravel. As such, the mechanical exclusion of sand is based upon the relationship between the size of the formation sand, the gravel, and the screen slot widths. This is achieved through Gravel packing (open hole and cased Hole), Frac Packs, Stand-alone screen, Wire wrapped screen, and Expandable sand screen method. The chemical control method involves the injection of chemicals usually resin into the formation through perforations to cement the sand grains. The most commercially available systems employ resins are phenolic, furan and epoxy resins [3,7]. These chemicals bind the rock particles together creating a stable matrix of permeable, consolidated grains around the casing. Clay concentration can hinder the effectiveness of the consolidation process, so a clay stabilizer is often used as a pre-flush. The sand consolidation process relies on a process comprising of four distinct stages: Placement of resin in the formation using a carrier fluid; Separation of the resin from the carrier fluid; accumulation of the resin around the grain contact points; Curing of the resin. In addition to the mechanical and chemical sand control methods, several combinations of sand-control techniques that use both gravel and plastic have been employed. The aim is to consolidate the gravel pack after it is placed but without the use of a screen or slotted liner. The *epoxy* and *furan* techniques involve resin-coated gravel mixed at the surface and pumped into the well. The gravel plastic slurry is then allowed to settle and cure. After curing, the residue is drilled out of the well before it is placed on production. The phenolic resin-coated gravel processes involve phenolic-coated gravel that is partially polymerized. Upon being subjected to temperatures higher than 57°C, the resin cure is completed so that the gravel is consolidated. Unlike the *epoxy* and *furan* processes, the phenolic resin-coated gravel is dry and can be handled much like ordinary gravel.

This paper evaluates the performance of two chemical sand control methods; sand consolidation (SCON) and internal gravel packing (IGP). The durability and effectiveness of the sand control methods are also compared.

II. METHODOLOGY

The comparative study of the sand control methods is based on the performance, durability and sand control effectiveness of the treatment type used in a well. The treatment type that is been evaluated in this paper is sand control using chemical (SCON) and internal gravel packing (IGP). The comparative study of this treatment type is carried out on Niger Delta wells. Production data for oil production (b/d), sand production (Ib/1000bbl) and water production (%) of different wells that sand control job has been carried out are listed.

A. Performance of the Sand Control Methods

Well inflow quality indicator (WIQI) is the criteria used to determine the performance of the treatment types. It is the ratio of the actual productivity index (PI_{actual}) to the ideal productivity index (PI_{ideal}) assuming no impairment or formation damage for a given draw down.

$$WIQI = \frac{PI_{actual}}{PI_{ideal}} \quad (1)$$

Skin was not included in this WIQI correlation due to time constrain and lack of data.

Thus, WIQI ≤ 1; this indicates that when the WIQI is closer or equal to 1, the better the performance of the well. However,

$$PI_{actual} = \frac{q}{\Delta P} \quad (2)$$

$$PI_{actual} = \frac{q}{Pr - Pwf} \quad (3)$$

This q is the average flow rate after the sand control job has been carried out.

PI_{ideal} is calculated using this equation:

$$PI_{ideal} = \frac{7.08E{-}3 \times ko \times h}{\mu o \times Bo \times In(\frac{re}{rw})} \quad (4)$$

B. Durability of the Sand Control Methods

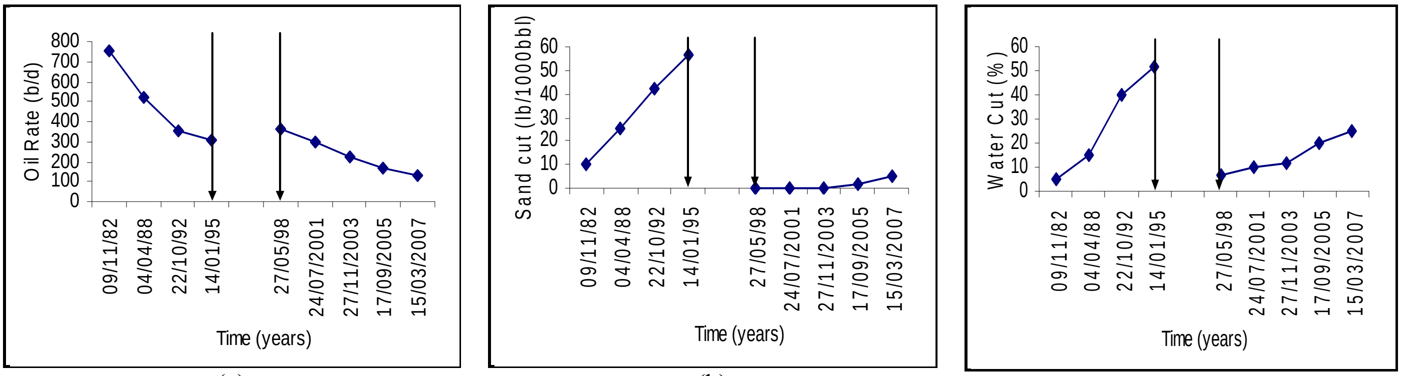
A graph of sand production (Ib/1000bbl) is plotted against time (in years). From this graph, a bar chart is made for time versus treatment type after the job to know which of the treatment type is more durable.

C. Effectiveness of the Sand Control Methods

A bar chart of sand produced (Ib/1000bbl) after instalment of treatment type versus time is made to know the effectiveness of the treatment types.

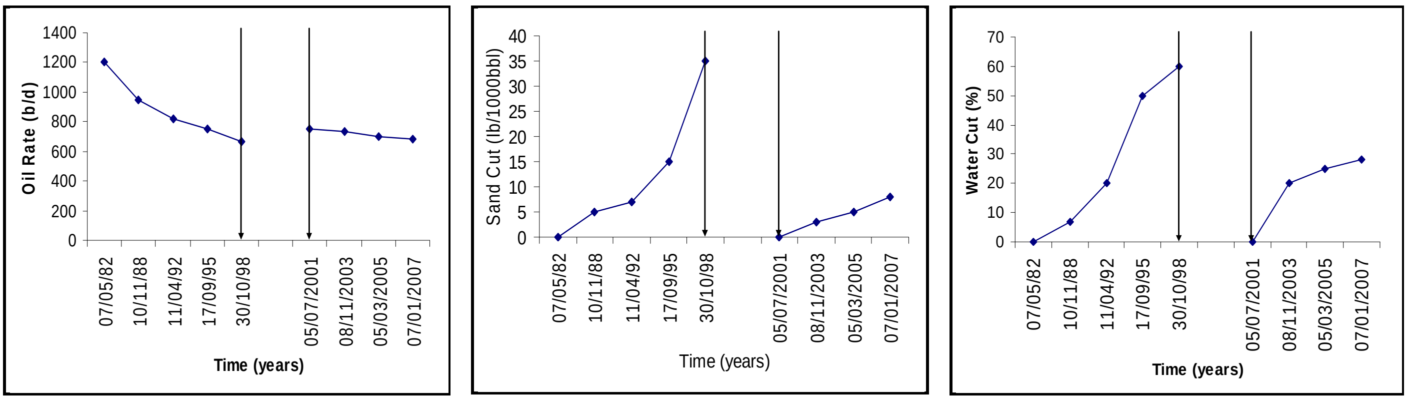
III. RESULTS

The production data of all the 10 wells for oil, sand and water production are shown in figure 1 to 10 below.



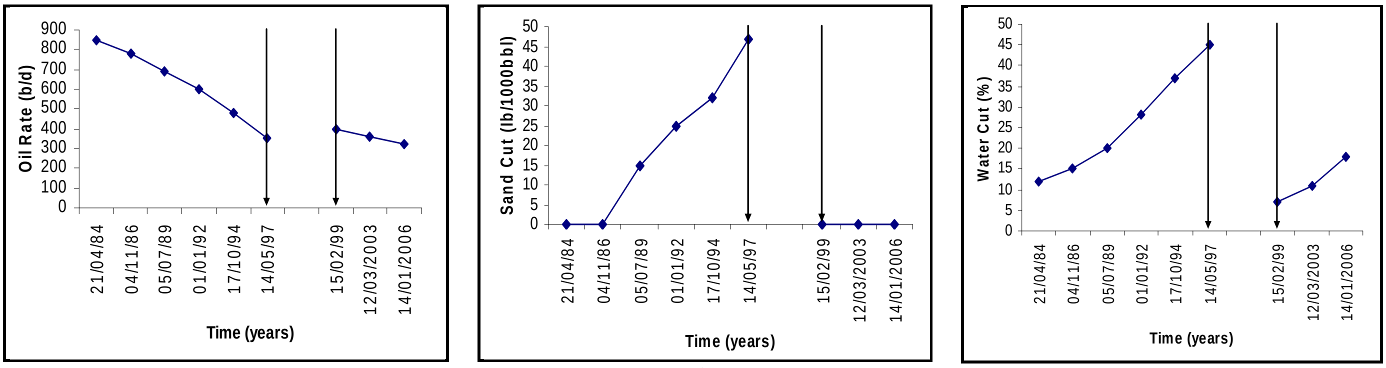
(a) (b) (c)

Fig. 1. Well 1 (a) Oil production rates, (b) Sand cut Production and (c) Water cut Production in years



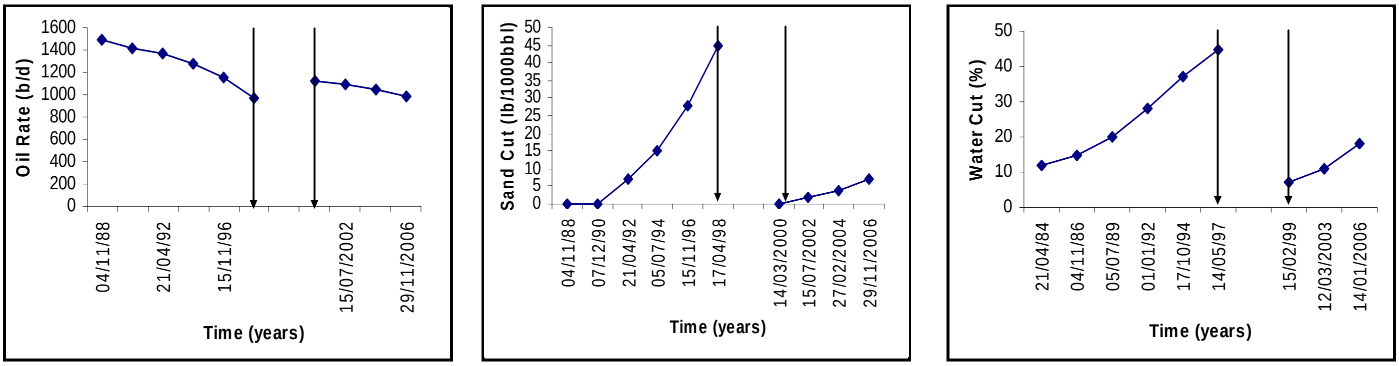
(a) (b) (c)

Fig. 2. Well 2 (a) Oil production rates, (b) Sand cut Production and (c) Water cut Production in years



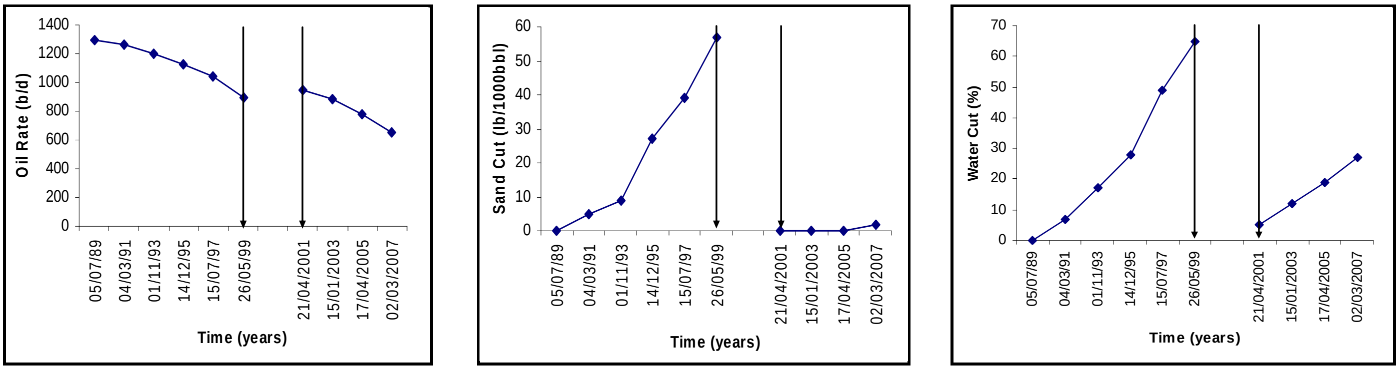
(a) (b) (c)

Fig. 3 Well 3 (a) Oil production rates, (b) Sand cut Production and (c) Water cut Production in years



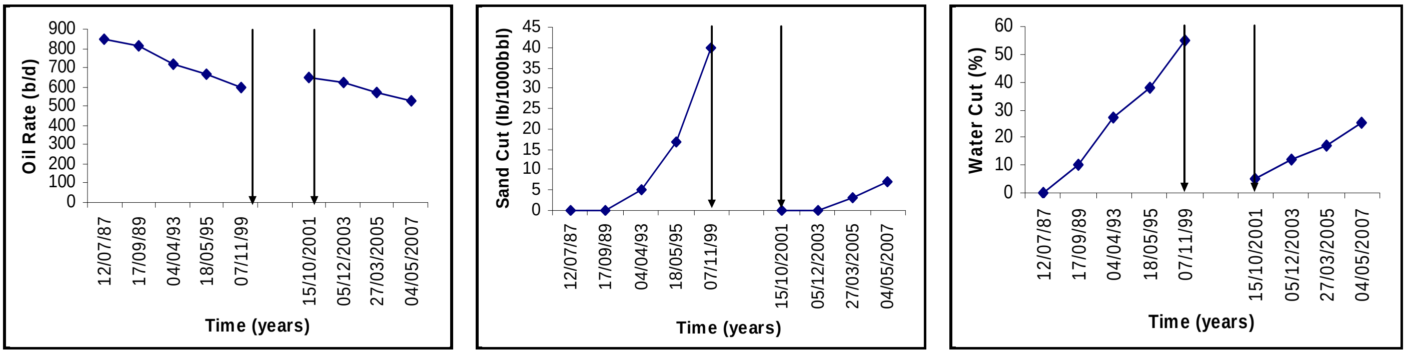
(a) (b) (c)

Fig. 4 Well 4 (a) Oil production rates, (b) Sand cut Production and (c) Water cut Production in years



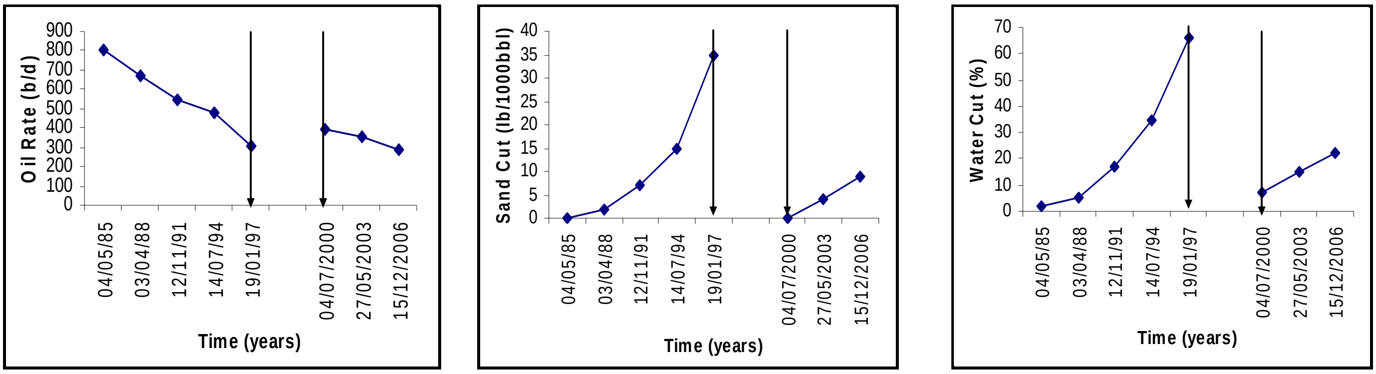
(a) (b) (c)

Fig. 5 Well 5 (a) Oil production rates, (b) Sand cut Production and (c) Water cut Production in years



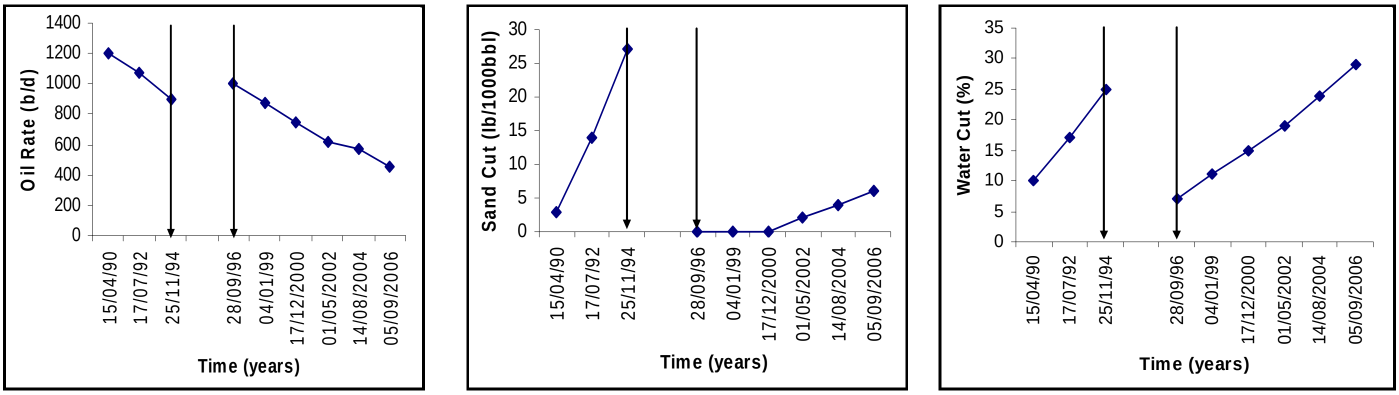
(a) (b) (c)

Fig. 6 Well 6 (a) Oil production rates, (b) Sand cut Production and (c) Water cut Production in years



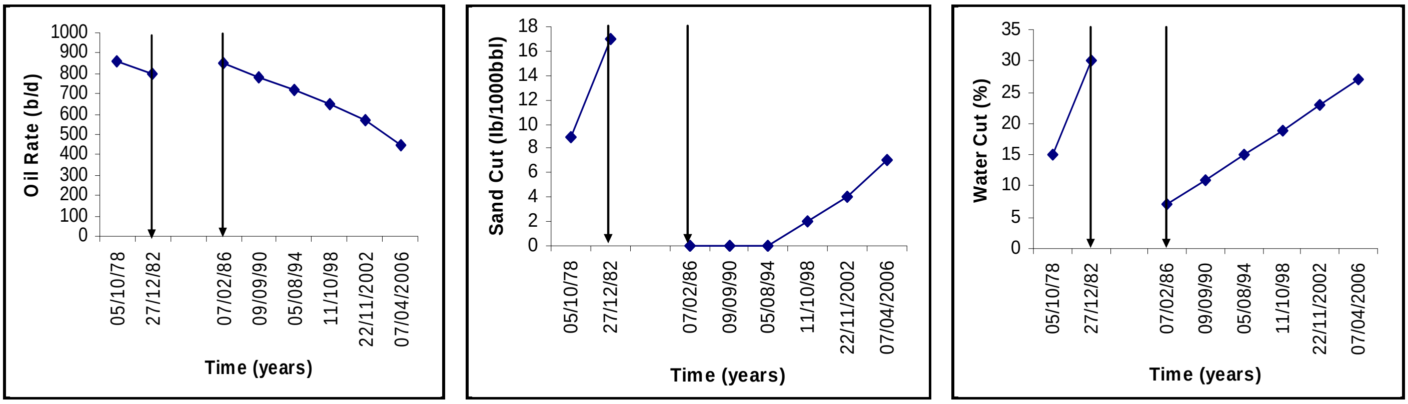
(a) (b) (c)

Fig. 7 Well 7 (a) Oil production rates, (b) Sand cut Production and (c) Water cut Production in years



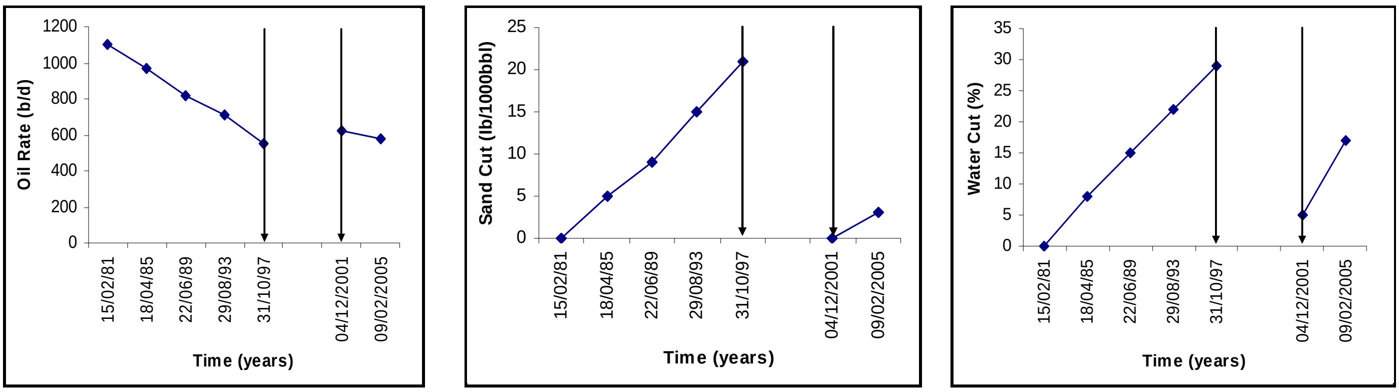
(a) (b) (c)

Fig. 8 Well 8 (a) Oil production rates, (b) Sand cut Production and (c) Water cut Production in years



(a) (b) (c)

Fig. 9 Well 9 (a) Oil production rates, (b) Sand cut Production and (c) Water cut Production in years



(a) (b) (c)

Fig. 10 Well 10 (a) Oil production rates, (b) Sand cut Production and (c) Water cut Production in years

IV. RESULTS ANALYSIS

From Figure 1 to Figure 10 and Equation 1 to Equation 4 above, the value of WIQI was calculated to determine the performance of the control methods used. Further analyses are carried out to determine the effective and durability of the sand control method used.

A. Performance of the Sand Control Methods

Individual sand controlled well data are collected to enable the PI_{ideal} and PI_{actual} to be calculated. PI_{actual} data source is from BHP survey which is the reservoir pressure (P_r), flowing well pressure (P_{wf}) and oil production rate (q), which is the average oil production after the sand controlled mechanism has been installed. The data used for each well are shown below. The well inflow quality indicator (WIQI) which is the parameter used to determine the performance of the treatment types for each well are calculated using the data below and the values tabulated in Table 2. Figure 11 shows the pie chart for the percentage WIQI for each treatment methods from all the wells.

Well 1: r_e = 1500ft, r_w = 0.4ft, K_o = 1000md, H = 10ft, μ_o = 2.5cp, B_o = 1.5rb/stb, P_r = 3000psi, and P_{wf} = 2803psi.

Well 2: r_e = 1500ft, r_w = 0.4ft, K_o = 1000md, h = 15ft, μ_o = 2cp, B_o = 1.5rb/stb, P_r = 3000psi, and P_{wf} = 2810psi.

Well 3: r_e = 1500ft, r_w = 0.7ft, k_o = 900md, h = 14ft, μ_o = 1.5ft, B_o = 1.3rb/stb, P_r = 3200pis, and P_{wf} = 3100psi.

Well 4: r_e = 1500ft, r_w = 0.5ft, K_o = 1100md, h = 12ft, μ_o = 3.5cp, B_o = 1.7rb/stb, P_r = 2800pis, and P_{wf} = 2212psi.

Well 5: r_e = 1500ft, r_w = 0.45ft, K_o = 1200md, h = 11ft, μ_o = 2.7cp, B_o = 1.6rb/stb, P_r = 2900psi, and P_{wf} = 2330psi.

Well 6: r_e = 1500ft, r_w = 0.3ft, K_o = 900md, h = 8ft, μ_o = 1.5cp, B_o = 1.5rb/stb, P_r = 2850psi, and P_{wf} = 2537psi.

Well 7: r_e = 1500ftg, r_w = 0.4ft, K_o = 1300md, h = 9ft, μ_o = 1.5cp, B_o = 1.8rb/stb, P_r = 2800psi, and P_{wf} = 2646psi.

Well 8: r_e = 1500ft, r_w = 0.5ft, K_o = 1300md, h = 22ft, μ_o = 1.5cp, B_o = 1.1rb/stb, P_r = 3500psi, and P_{wf} = 3299psi.

Well 9: r_e = 1500ft, rw = 0.5ft, K_o = 1200md, h = 20ft, μo = 1.7cp, Bo = 1.2rb/stb, Pr = 3300psi and P_{wf} = 3085psi.

Well 10: r_e = 1500ft, r_w = 0.4ft, K_o = 1350md, h = 7ft, μ_o = 1.7cp, B_o = 1.5rb/stb, P_r = 3000psi and P_{wf} = 2806psi.

TABLE II TREATMENT TYPE AND THEIR WIQI

Well No.	Treatment Type	PI_{actual} (bbl/d/psi)	PI_{ideal} (bbl/d/psi)	WIQI
1	IGP	1.20	2.30	0.52
2	SCON	3.76	4.30	0.87
3	IGP	3.60	6.00	0.60
4	SCON	1.80	2.00	0.90
5	IGP	1.43	2.70	0.53
6	SCON	1.89	2.70	0.70
7	SCON	2.23	3.73	0.60
8	IGP	3.53	15.33	0.23
9	IGP	3.12	10.40	0.30
10	SCON	3.09	3.19	0.97

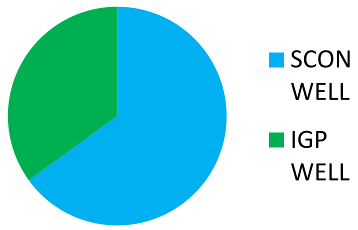


Fig. 11 A Pie Chart of WIQI for treatment types

B. Effectiveness of the Sand Control Method

A bar chart for sand production against the treatment type is made from Table 3 to know the effectiveness of the treatment types. Figure 12 shows the bar chart of sand produced after the installation of the treatment type.

TABLE III SAND PRODUCED AFTER APPLICATION OF IGP OR SCON

Well No	Treatment Type	Sand Produced (Ib/1000bbl)
1	IGP	7
2	SCON	16
3	IGP	0
4	SCON	13
5	IGP	2
6	SCON	10
7	SCON	13
8	IGP	12
9	IGP	13
10	SCON	3

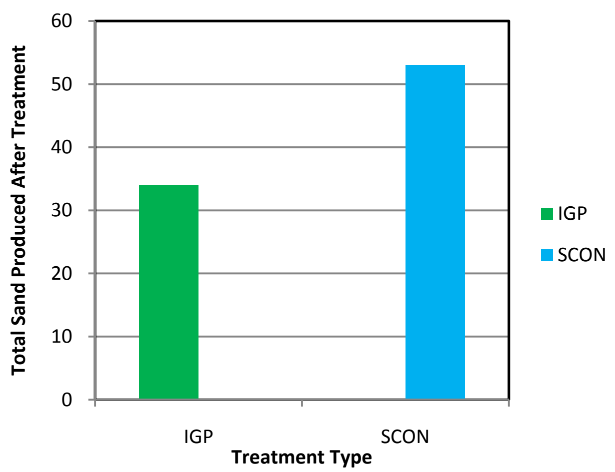


Fig. 12 Bar Chart of Sand Produced after the Job

C. Durability of the Sand Control Methods

The durability of the sand control method is based on the duration in years before the well start producing sand.

TABLE IV DURATION BEFORE THE WELL STARTS PRODUCING SAND AFTER THE SAND CONTROL JOB

WELL NO	Treatment Type	Before Sand Was Produced	Sand Production Begins	Duration (Yrs)
1	IGP	1998	2005	7
2	SCON	2001	2003	2
3	IGP	1999	2006	7
4	SCON	2000	2002	2
5	IGP	2001	2005	6
6	SCON	2001	2005	4
7	SCON	2000	2003	3
8	IGP	1996	2002	6
9	IGP	1986	1998	12
10	SCON	2001	2005	4

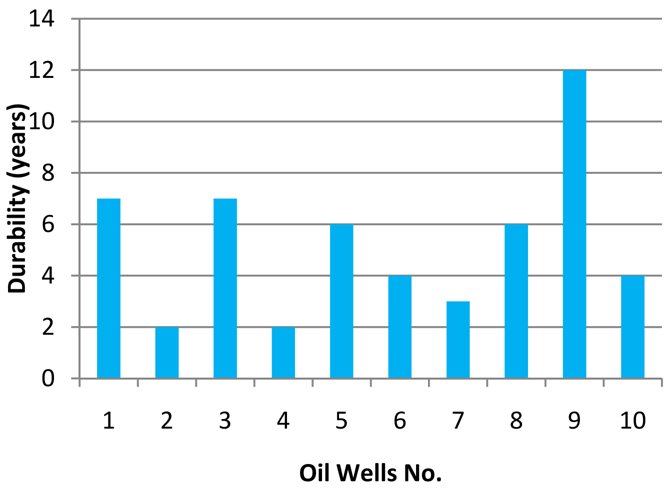


Fig. 13 Bar Chart of treatment type vs. Duration in years

V. DISCUSSION

From table 2; IGP wells have ranges of WIQI from 0.2-0.6 and SCON have ranges of 0.6-1.0. From fig 11, wells that are treated with SCON recorded a WIQI success of 65% and those treated with IGP recorded 35% success. The decrease in IGP well performance may be due to debris and loose sand from the formation during production which plugs the pore spaces in the gravel pack. It can also be caused by unclean completion fluid which causes contamination, wrong gravel size selection, wrong selection of screen slot to retain the gravel and ineffective placement technique. From fig. 12; after the sand control job have been done, wells that are sand controlled using SCON technique tend to produce more sand when the mechanism starts to be weak compared to wells that are installed with IGP. Thus, SCON recorded 55Ib/1000bbl to IGP which is 43Ib/1000bbl. This might be caused by the weakness of the chemical used for the job because during production, the producing fluid tends to wash away the chemical used which will reduce the effectiveness of the SCON well. From fig 4.3; wells that are installed with IGP last longer than wells that are installed with SCON. IGP last about 6-12 years after the mechanism have been installed to that installed with SCON which is about 2-4 years. This might be due to high temperature in the subsurface which reduces the consolidation of the sand as time goes on which thus reduces the durability of the SCON installed well.

VI. CONCLUSION

Based on the findings of this comparative study of sand control using SCON and IGP, their performance, durability and sand control effectiveness, the following conclusions were made:

- Wells that are sand controlled using SCON have high WIQI values than that of IGP.
- The values of WIQI for SCON and IGP controlled wells have WIQI values ranging from 0.6 -1.0 and 0.2- 0.6.respectively.
- Wells installed with IGP are more durable than that of SCON wells.
- It took IGP wells a period of 6 - 12 years and SCON wells a period of 2 - 4 years before sand is being produced from the wells.
- Wells that are sand consolidated (SCON) produces more sand when the mechanism gets weak than wells that are gravel packed (IGP).
- SCON wells produces 55Ib/1000bbl of sand when the mechanism becomes weak to that of IGP wells which is 43Ib/1000bbl.
- Consequently, SCON should be installed when the interval is less than or equal to 10ft and IGP should be installed when the interval is greater than or equal 10ft. Thus, this paper also recommend that IGP wells are more durable and effective than SCON wells while SCON wells have better performance than that of IGP wells. Hence, IGP is recommended for Niger Delta formation.

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