Effects of Formation Damage on Productivity of Underground Gas Storage Reservoirs

Anyadiegwu C.I.C, Muonagor C.M.
drcicanyadiegwu@yahoo.com, drcicanyadiegwu@gmail.com
Department of Petroleum Engineering, Federal University of Technology, Owerri
NIGERIA

ABSTRACT

Analysis of the effects of formation damage on the productivity of gas storage reservoirs was performed with depleted oil reservoir (OB-02), located onshore, Niger Delta, Nigeria. Information on the reservoir and the fluids from OB-02 were collected and used to evaluate the deliverabilities of the gas storage reservoir over a 10-year period of operation. The results obtained were used to plot graphs of deliverability against permeability and skin respectively. The graphs revealed that as the permeability decreased, the skin increased, and hence a decrease in deliverability of gas from the reservoir during gas withdrawal. Over the ten years of operating the reservoir for gas storage, the deliverability and permeability which were initially 2.7 MMscf/d and 50 mD, with a skin of 0.2, changed to new values of 0.88 MMscf/d and 24 mD with the skin as 4.1 at the tenth year.

Key words: formation, damage, skin, deliverability, permeability, reservoir, oil, gas, storage.

I. INTRODUCTION

Formation damage is a generic terminology referring to the impairment of the permeability of petroleum bearing formations by various adverse processes. It is an alteration of producing formation near the wellbore due to the introduction of foreign fluids and the consequent interaction with the fluids and formation (McKinney and Azar, 1988). Formation damage as defined by Crowell et al., (1991) means any type of a process which results in a reduction of the flow capacity of an oil, water or gas bearing formation. It is an undesirable operational and economic problem that can occur during the various phases of oil and gas recovery from subsurface reservoirs, usually caused by physico-chemical, chemical, biological, hydrodynamic, and thermal interactions of porous formation with particles and fluids and mechanical deformation of formation under stress and fluid shear. These processes are triggered during the drilling, production, workover, and hydraulic fracturing operations. During drilling, formation damage attributes primarily from two sources: filtrate invasion from a drilling fluid and the accompanying invasion and migration of solids. The intrusion and deposition of these mobile particles lead to the blockage of pore throats, which include a reduction of permeability of the formation (Tovar et al, 1994).

The poorer the quality of a reservoir, the greater the susceptibility to formation damage, which the indicators include permeability impairment, skin damage, and decrease of well performance. The consequences of formation damage are the reduction of the oil and gas productivity of reservoirs and noneconomic operation (Harper and Buller, 1986). Therefore, it is essential to develop experimental and analytical methods for understanding and preventing and/or controlling formation damage in oil and gas bearing formations. Confidence in formation damage prediction using phenomenological models cannot be gained without field testing, hence planning and designing field test procedures for verification of the mathematical models are important. Once a model has been validated, it can be used for accurate simulation of the reservoir formation damage. Current techniques for reservoir characterization by history matching do not consider the alteration of the characteristics of reservoir formation during petroleum production. In reality, formation characteristics vary and a formation damage model can help to incorporate this variation into the history matching process for accurate characterization of reservoir systems and, hence, an accurate prediction of future performance. The research efforts in this subject area will lead to a better understanding and simulation tools that can be used for model-assisted analysis of rock, fluid, and particle interactions and the processes caused by rock deformation and scientific guidance for development of production strategies for formation damage control in petroleum reservoirs. Formation damage has long been recognized as a source of serious productivity reductions in many oil and gas reservoirs and as a cause of water injectivity problems in many waterflood projects. This paper presents the analysis of the rate at which formation damage influence the productivity of the underground gas storage developed in a depleted oil reservoir during the gas withdrawal.

Due to the mechanics of flow into horizontal wells and the fact that most horizontal wells remain as open hole completions, damage effects can be much more severe in horizontal wells than in equivalent vertical wells. Stimulation procedures required to remove formation damage in horizontal wells are costly and are often unsuccessful or marginally successful. The use of well designed laboratory programs can allow those associated with designing and conducting drilling, completion or stimulation programs to evaluate the effectiveness of specific programs, prior to their implementation in the field.

Formation damage falls into four broad categories based upon the mechanism of its origin (Bennion et al., 1994). They include: Mechanically induced formation damage (phase trapping, fines migration, solids entrainment); Chemically induced formation damage (clay swelling and deflocculating, wax deposition, solids precipitation, acid sludge, stable emulsions, chemical adsorption, wettability alteration); Biologically induced formation damage (bacterial action); Thermally induced formation damage (elevated temperatures).

The common causes of formation damage as a consequent of certain production operations are identified in Table 1below:

TABLE 1
Causes of Formation Damage

CAUSES	OPERATIONS
Cold fluid injection	-Acidizing -Fracturing job -Water flooding -Condensate treatment -Fluid dump job
Cooling by gas expansion	-High GOR wells -CO_2 floods -NGL floods
Incompatible/contaminated fluid invasion	-Hot oiling job -Acidizing job -CO_2 floods -NGL floods -Condensate job
High flow rate through formation	-Flowing well -CO_2/NGL floods -Steam floods

Source: Sutton et al., (1974).

II. MATERIALS AND METHOD

Deliverability of Storage Reservoirs

Deliverability is most often expressed as a measure of the amount of gas that can be withdrawn from a storage facility on a daily basis. It may also be referred to as the deliverability rate, withdrawal rate, or withdrawal capacity, and it is usually expressed in terms of millions of cubic feet per day, MMscf/d (American Gas Association,1997). The deliverability of a given storage facility varies, and depends on factors such as the amount of gas in the reservoir at any particular time, the pressure within the reservoir, compression capability available to the reservoir, the configuration and capabilities of surface facilities associated with the reservoir, and other factors. In general, a facility's deliverability rate varies directly with the total amount of gas in the reservoir: it is at its highest when the reservoir is most full but declines as working gas is withdrawn.

In evaluating the performance of a storage reservoir, a deliverability test (back pressure test) is carried out on the reservoir for the prediction of well flow rate against any pipeline back pressure (Anyadiegwu, 2013). He made the observation that a plot of $P_r^2 - P_{wf}^2$ (difference of the squares of reservoir pressure and well flowing pressure) versus Q_{sc}, (flow rate at standard condition) yielded a straight line on logarithm plot, which represents the reservoir performance curve. The straight line relationship for a particular well applies throughout the lifetime of the well, as long as the production remains in single phase (gas or liquid).

The back-pressure (deliverability) equation as developed by Rawlins and Schellhardt (1935) is as follows:

$$Q_{sc} = C\,[\square\, P\,]^n \qquad 2.1$$

By extending the performance curve, the absolute open flow, (AOF) was obtained. The slope of the plot of Log $(P_r^2 - P_{wf}^2)$ versus Log Q was computed and used to obtain the back-pressure exponent as:

$$n = 1 / \text{slope} \qquad 2.2$$

Then the flow capacity at standard condition was given as:

$$Q_{sc} = C\,[P_r^2 - P_{wf}^2]^{(1/SLOPE)} \qquad 2.3$$

At $P_{wf} = 0$, equation 2.3 reduces to:

$$Q_{sc} = C\,[P_r^2]^n \qquad 2.4$$

But the reservoir flow coefficient, C is expressed as:

$$C = Q / [P_r^2 - P_{wf}^2]^n \qquad 2.5$$

2.1.1 Procedure for Determining the Deliverability of a Storage Reservoir

The relationship between the permeability of the reservoir rock and the deliverability of the storage reservoir is shown in section below. The equation illustrated in section 2.1.1 for checking the effect of permeability change caused by formation damage on the storage reservoir deliverability is used to evaluate the deliverability of the reservoir at the resulted rock permeabilities over a period of 10 years.

The productivity of an oil reservoir as expressed by Tharek, (2001), is as follows:

$$q = \frac{B_o\mu\,[\ln(r_e/r_w + s)]}{0.007082Kh\,(P_e - P_{wf})} \qquad 2.6$$

Where:

K = permeability of the reservoir, mD
h = reservoir thickness, ft
P_e = reservoir pressure, psi
P_{wf} = well flowing pressure, psi
B_o = oil formation volume factor, rb/stb
μ = oil viscosity
r_e = effective drainage radius, ft
r_w = well bore radius, ft
s = skin
q = oil flow rate, stb/day

For the productivity of a gas reservoir, it is necessary to express eq 2.6, for estimating oil productivity in gas terms by replacing the oil parameters by that of gas to obtain:

$$Q = \frac{0.007082Kh\,(P_e - P_{wf})}{B_g\mu_g\,[\ln\,(r_e/r_w + s)] \bullet 5.615} \qquad 2.7$$

Where:
B_g = gas formation volume factor, rcf/scf
μ_g = gas viscosity
Q = gas flow rate, scf/day

The above equation (eq 2.7) for estimating the productivity of a gas reservoir was used in this work for evaluating the deliverability of the gas storage reservoir which is in other terms the productivity of the storage reservoir. The deliverability of the reservoir was evaluated at the initial state and after permeability reduction over a period of 10 years.

A Microsoft Visual Basic Program was written with eqn 2.7 as shown in Fig 2.1 and used to obtain the deliverability of the depleted reservoir, Q (scf/d) at different permeabilities, K (mD) and skin, s (dimensionless).

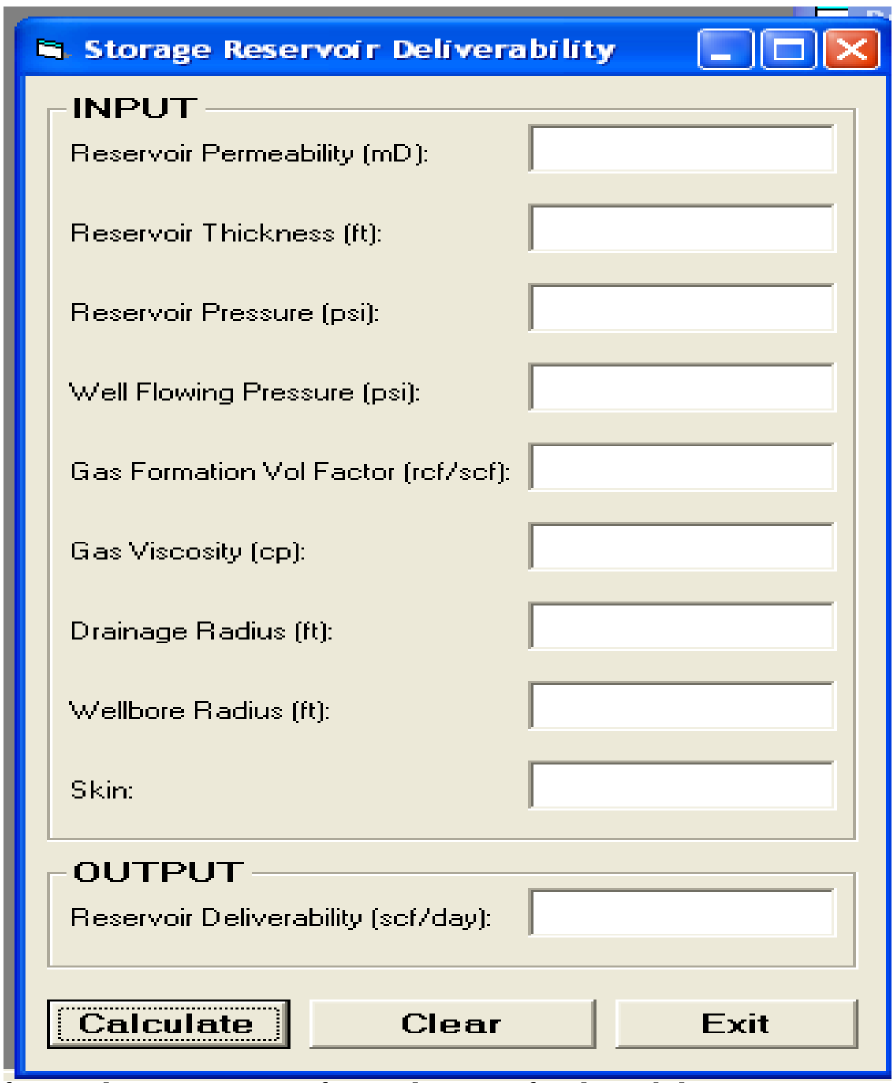

Fig 1. Microsoft Visual Basic Program for Evaluation of Deliverability at given Permeability

II. Results

Evaluation of Deliverability using the Gas Flow Rate Equation

The reservoir and fluid data for this work were obtained from a depleted oil reservoir, (OB-02) located onshore, Niger Delta, Nigeria and they are presented as shown in Table 3.1:

TABLE 2
Reservoir and Fluid Data for Reservoir, OB-02

Reservoir Pressure, psi	3426
Reservoir Temperature, ^{0}F	205
Well Flowing Pressure, psi	2800
Reservoir Permeability, Md	50
Reservoir Thickness, ft	30
Drainage Radius, ft	1000
Wellbore Radius, ft	0.3
Skin	0.2
Gas Viscosity, cp	0.4
Gas Formation Volume Factor, rcf/scf	0.004165

The data given in Table 3.1 are the reservoir and fluid data before the occurrence of formation damage. At this stage, the permeability of the reservoir is 50mD, ie the initial permeability of the reservoir rock. This period is considered the first year of the reservoir operation and it has not been affected by formation damage. The permeabilities and skin of the gas storage reservoir over a 10-year period of formation damage is given in Table 3.2.

TABLE 3
Permeabilities and Skin over the 10-year period, Reservoir OB-02

Time, yr	Permeability, mD	Skin
1	50	0.2
2	47	0.5
3	42	0.9
4	38	1.1
5	36	1.3
6	33	1.8
7	31	2.3
8	28	2.9
9	27	3.5
10	24	4.1

At this first year with the reservoir permeability as 50mD and skin, 0.2, the deliverability of the reservoir is evaluated using eq 2.7 as:

Deliverability, Q = 5.615 * 0.007082 * 50 * 30 * (3426 – 2800) / (0.004165 * 0.4 * (ln (1000/0.3) + 0.2))
Deliverability, Q = 2696528 scf/day = 2.7 MMscf/day
At the second year with the reservoir permeability as 47mD and skin, 0.5, the deliverability of the reservoir is evaluated as:
Deliverability, Q = 5.615 * 2 * 3.142 * 47 * 30 * (3426 – 2800) / (0.004165 * 0.4 * (ln (1000/0.3) + 0.4))
Deliverability, Q = 2446435 scf/day = 2.45 MMscf/day
At the third year with the reservoir permeability as 42mD and skin, 0.9, the deliverability of the reservoir is evaluated as:
Deliverability, Q = 5.615 * 2 * 3.142 * 42 * 30 * (3426 – 2800) / (0.004165 * 0.4 * (ln (1000/0.3) + 0.9))
Deliverability, Q = 2089139 scf/day = 2.09 MMscf/day
At the fourth year with the reservoir permeability as 38mD and skin, 1.1, the deliverability of the reservoir is evaluated as:
Deliverability, Q = 5.615 * 2 * 3.142 * 38 * 30 * (3426 – 2800) / (0.004165 * 0.4 * (ln (1000/0.3) + 1.1))
Deliverability, Q = 1849135 scf/day = 1.85 MMscf/day
At the fifth year with the reservoir permeability as 36mD and skin, 1.3, the deliverability of the reservoir is evaluated as:
Deliverability, Q = 5.615 * 2 * 3.142 * 36 * 30 * (3426 – 2800) / (0.004165 * 0.4 * (ln (1000/0.3) + 1.3))
Deliverability, Q = 1714586 scf/day = 1.7 MMscf/day
At the sixth year with the reservoir permeability as 33mD and skin, 1.8, the deliverability of the reservoir is evaluated as:
Deliverability, Q = 5.615 * 2 * 3.142 * 33 * 30 * (3426 – 2800) / (0.004165 * 0.4 * (ln (1000/0.3) + 1.8))
Deliverability, Q = 1492419 scf/day = 1.49 MMscf/day
At the seventh year with the reservoir permeability as 31mD and skin, 2.3, the deliverability of the reservoir is evaluated as:
Deliverability, Q = 5.615 * 2 * 3.142 * 31 * 30 * (3426 – 2800) / (0.004165 * 0.4 * (ln (1000/0.3) + 2.3))
Deliverability, Q = 1334643 scf/day = 1.33 MMscf/day
At the eighth year with the reservoir permeability as 28mD and skin, 2.9, the deliverability of the reservoir is evaluated as:
Deliverability, Q = 5.615 * 2 * 3.142 * 28 * 30 * (3426 – 2800) / (0.004165 * 0.4 * (ln (1000/0.3) + 2.9))
Deliverability, Q = 1139800 scf/day = 1.14 MMscf/day
At the ninth year with the reservoir permeability as 27mD and skin, 3.5, the deliverability of the reservoir is evaluated as:
Deliverability, Q = 5.615 * 2 * 3.142 * 27 * 30 * (3426 – 2800) / (0.004165 * 0.4 * (ln (1000/0.3) + 3.5))
Deliverability, Q = 1042301 scf/day = 1.04 MMscf/day
At the tenth year with the reservoir permeability as 24mD and skin, 4.1, the deliverability of the reservoir is evaluated as:

Deliverability, Q = 5.615 * 2 * 3.142 * 24 * 30 * (3426 – 2800) / (0.004165 * 0.4 * (ln (1000/0.3) + 4.1))
Deliverability, Q = 880968 scf/day = 0.88 MMscf/day

Evaluation of Deliverability of Reservoir OB-02 using Microsoft Visual Basic Program

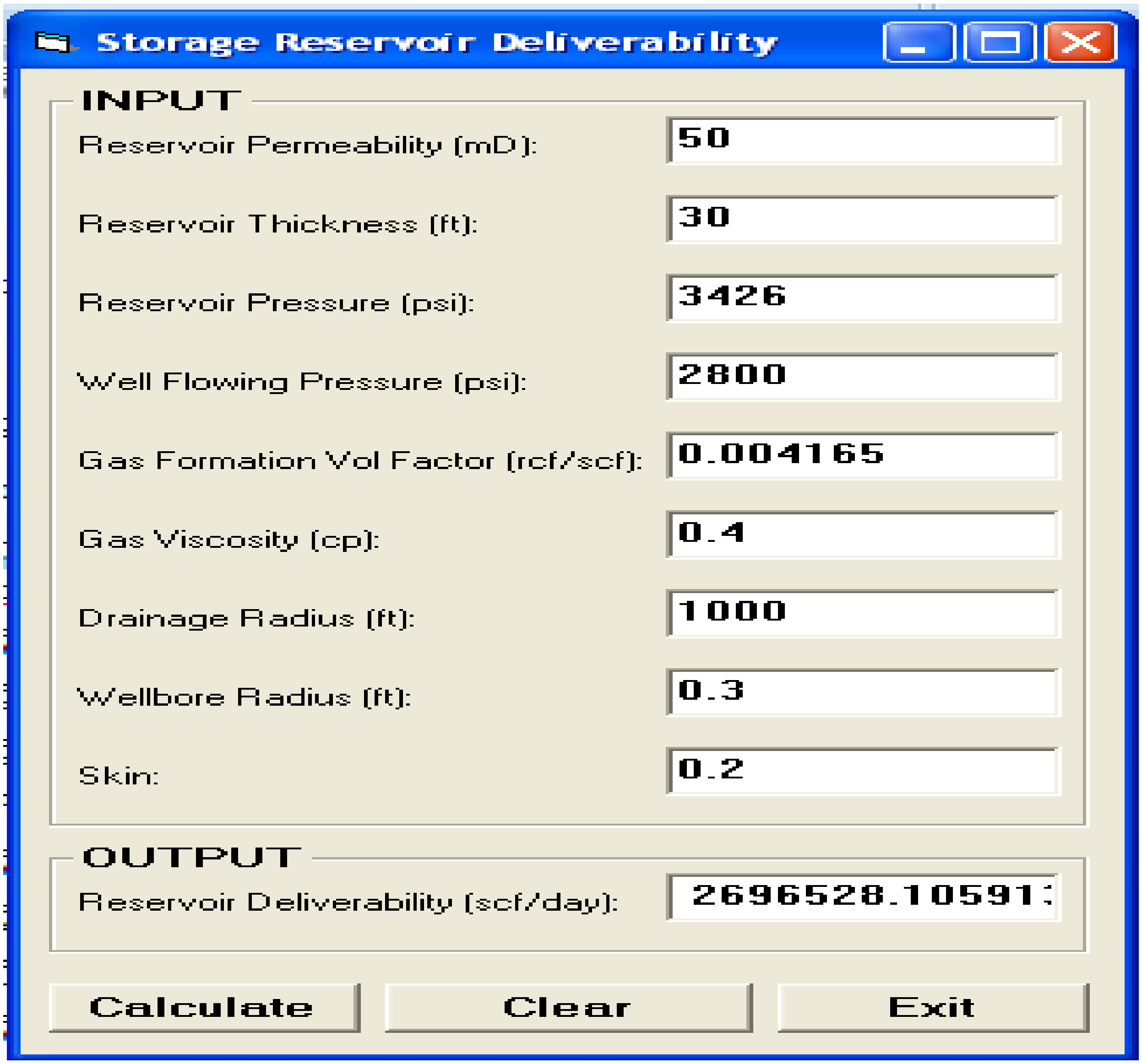

Fig 2. Deliverability of Reservoir OB-02 at Permeability, 50mD and Skin, 0.2

Deliverabilities at various permeabilities and skin of reservoir OB-02 are given in Table 3.3, as computed using Fig 2.1, and used in plotting the graphs of deliverability against permeability and deliverability against skin as shown in Figs 3.3 and 3.4.

TABLE 4
Deliverability at various Permeabilities and Skin, Reservoir OB-02

Time, yr	Permeability, mD	Skin	Deliverability, MMscf/day
1	50	0.2	2.7
2	47	0.5	2.45
3	42	0.9	2.09
4	38	1.1	1.85
5	36	1.3	1.7
6	33	1.8	1.49
7	31	2.3	1.33
8	28	2.9	1.14
9	27	3.5	1.04
10	24	4.1	0.88

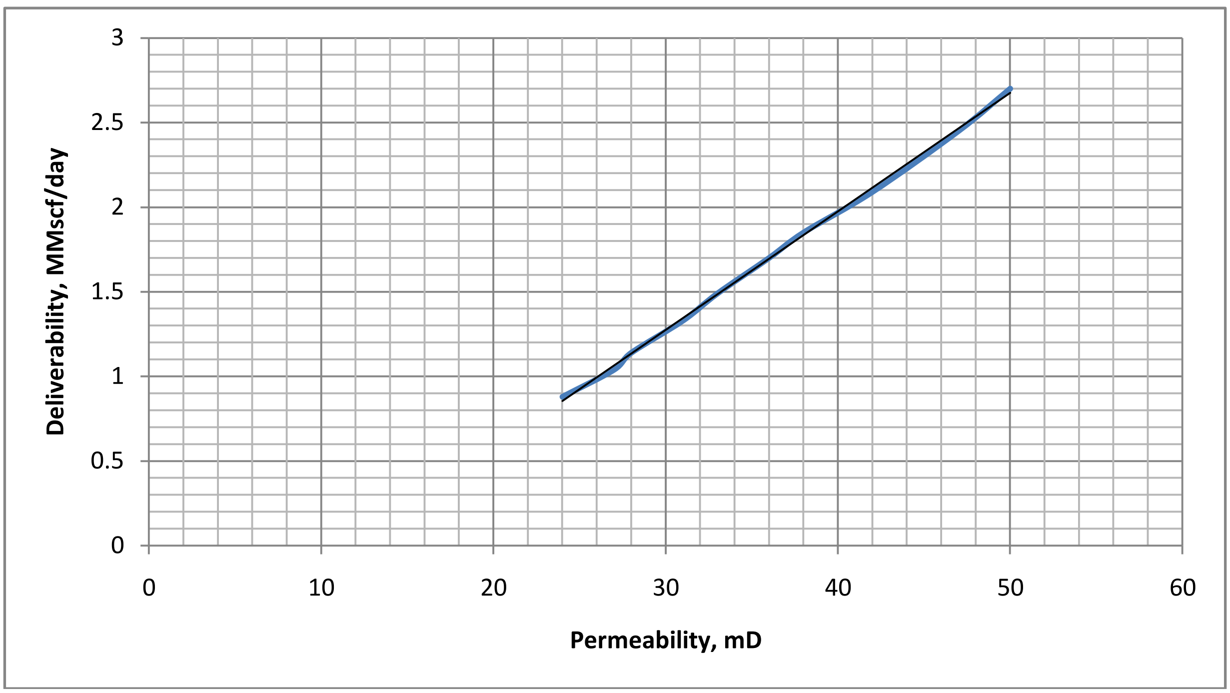

Fig 3. Plot of Deliverability against Permeability for Reservoir, OB-02

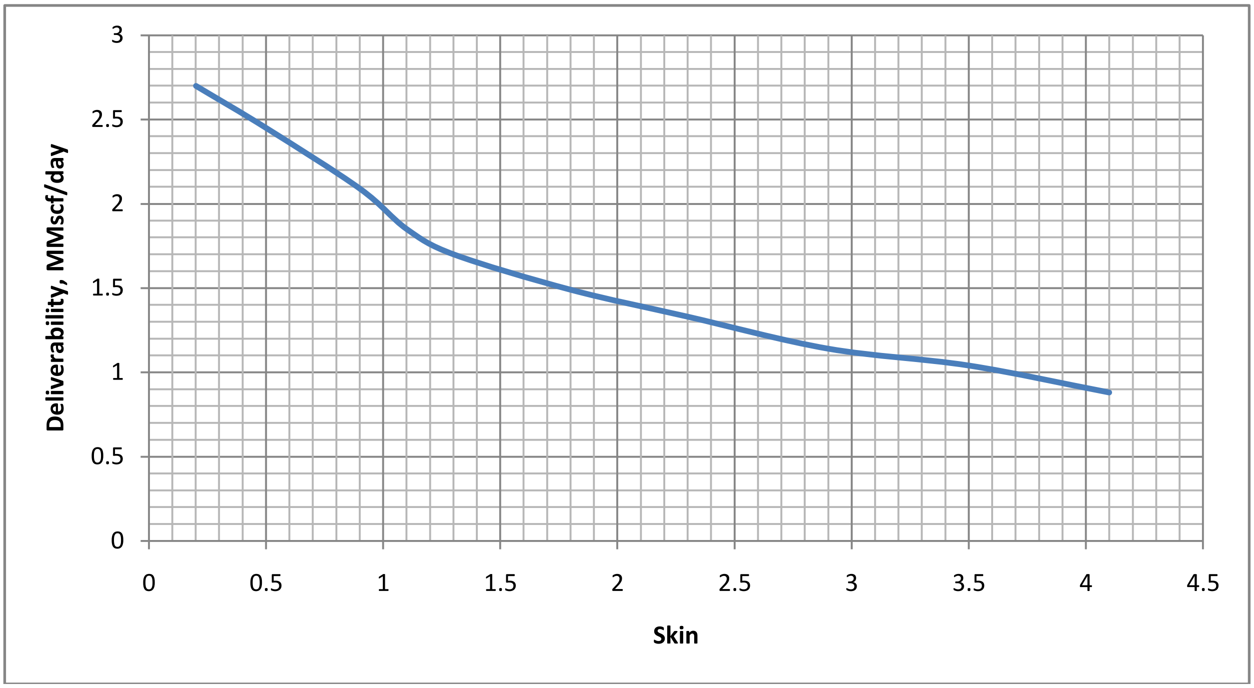

Fig 4. Plot of Deliverability against Skin for Reservoir, OB-02

III. Discussion

From the data obtained from the depleted oil reservoir, OB-02 revealed that before the formation damage occurred, the initial permeability and skin were 50 mD and 0.2 respectively. From the analyses, the deliverability of the reservoir at that first year of operating the storage reservoir was 2.7 MMscf/d as there was no blockage to achieving the expected deliverability. As formation damage occurred in the reservoir and continued over the space of the 10 years, the permeability of the reservoir decreased and its skin increased continuously although not proportionately. This continuous decrease in permeability and increase in skin affected the deliverability of the storage reservoir by reducing it to a low value of 0.88 MMscf/d when operated for 10 years.

From Fig 3, the plot of deliverability against permeability, the curve declines as the permeability decreases, this shows a decrease in the deliverability. From Fig 4, the plot of deliverability against skin, it was seen that an increase in the skin of the reservoir meant a corresponding decrease in the deliverability of the reservoir. This deliverability decrease as a result of skin increase indicates formation damage. The intensity of the formation damage resulted the reduction of the deliverability to a low value of 0.88 MMscf/d as shown in the chart.

IV. Conclusion

At the end of the analyses, observations were made, which revealed that formation damage affects the deliverability of a gas storage reservoir by causing a reduction in the reservoir permeability and an increase in its skin factor, which resist flow.

The following conclusions can be drawn based on the findings after operating the gas storage reservoir for 10 years:

1. Reservoir OB-02 is suitable for use as gas storage reservoir as its deliverability is evaluated initially to be high.
2. The permeability of the reservoir due to formation damage decreased from 50 mD to 24 mD and the skin increased from a

negligible value of 0.2 to as high as 4.1 over a ten year period of operation.

3. The deliverabilities of the reservoir before and after the effect of formation damage over 10-year period are 2.7 MMscf/d and 0.88 MMscf/d respectively.
4. Formation damage caused reduction in the reservoir permeability, increase in reservoir skin and hence decrease in gas deliverability from the reservoir during gas withdrawal.

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NOMENCLATURE

AOF = Absolute open flow
B_o = Oil formation volume factor, rb/stb
B_g = Gas formation volume factor, rcf/scf
C = Performance coefficient
h = Reservoir thickness, ft
K = Permeability of the reservoir, mD
MMscf = Million standard cubic foot
Mscf = Thousand standard cubic foot
n = Back-pressure exponent
P_r = Reservoir pressure, psi
P_{wf} = Well flowing pressure, psi
q = oil flow rate, stb/day
Q = gas flow rate, scf/day
Q = Deliverability, MMscf/day
Q_{sc} = Deliverability at standard conditions
r_e = effective drainage radius, ft
r_w = well bore radius, ft
s = skin
μ = oil viscosity, cp
μ_g = gas viscosity, cp
^0F = Degree Fahrenheit