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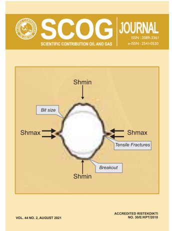

Well Integrity Study for WAG Application in Mature Field X, South Sumatra Area for the Fulfillment as CO_2 Sequestration Sink

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ABSTRACT - The most of today's global oil production comes from mature fields. Oil companies and governments are both concerned about increasing oil recovery from aging resources. To maintain oil production, the mature field must apply the Enhanced Oil Recovery method. CO_2 water-alternating-gas (WAG) injection is an enhanced oil recovery method designed to improve sweep efficiency during CO_2 injection with the injected water to control the mobility of CO_2. This study will discuss possible corrosion during CO_2 and water injection and the casing load calculation along with the production tubing during the injection phase. The following study also performed a suitable material selection for the best performance injection. This research was conducted by evaluating casing integrity for simulate CO_2 water-alternating-gas (WAG) to be applied in the X-well in the Y-field, South Sumatra, Indonesia. Corrosion prediction were performed using Electronic Corrosion Engineer (ECE®) corrosion model and for the strength of tubing which included burst, collapse, and tension of production casing was assessed using Microsoft Excel. This study concluded that for the casing load calculation results in 600 psi of burst pressure, collapse pressure of 2,555.64 psi, and tension of 190,528 lbf. All of these results are still following the K-55 production casing rating. While injecting CO_2, the maximum corrosion rate occurs. It has a maximum corrosion rate of 2.02 mm/year and a minimum corrosion rate of 0.36 mm/year. With this value, it is above NORSOK Standard M-001 which is 2 mm/year and needs to be evaluated to prevent the rate to remain stable and not decrease in the following years. To prevent the effect of maximum corrosion rate, the casing material must use a SM13CR (Martensitic Stainless Steel) which is not sour service material.

Keywords: CO_2 Water-Alternating-Gas (WAG), corrosion, casing load

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INTRODUCTION

A. Background

Most of the current world oil production comes from mature fields. Increasing oil recovery from the aging resources is a major concern for oil companies and authorities. In addition, the rate of replacement of the produced reserves by new discoveries has been declining steadily in the last decades. Therefore, the increase of the recovery factors from mature fields under primary and secondary production will be critical to meet the growing energy demand in the coming years (Alvarado & Manrique, 2010).

To maintain oil production, mature fields have to apply the Enhanced Oil Recovery (EOR) method. CO_2 water-alternating-gas (WAG) injection is an enhanced oil recovery method designed to improve sweep efficiency during CO_2 injection with the injected water to control the mobility of CO_2 (Chen & Reynolds, 2016). Injecting water and CO_2 into old wells will be difficult and will require careful consideration of a number of factors, one of which is the strength of the tubing in the old well.

This study was conducted to increase oil production by Water Alternating Gas using CO_2. This paper analyzes possible corrosion during CO_2 and water injection and the load calculation along with the production tubing during the injection phase. At the end of this study, the result will be a consideration before injection and the operation ran successfully to do CO_2 water-alternating-gas (WAG) injection.

B. Objectives

This scoping study only focused in X-Well in the Y-field, with objective:

- To evaluate casing integrity X-well in the Y-field for simulating CO_2 water-alternating-gas (WAG)
- To predict corrosion rate on production casing in Y-well for CO_2 water-alternating-gas (WAG)
- To determine suitable tubular material for CO_2 water-alternating-gas (WAG) injection well

C. Basic Theory

When performing Enhanced Oil Recovery (EOR activities, it is imperative that aside from the aspects of chemical interaction between components injected and reservoir aspects are thoroughly investigated, there is an issue of well integrity that must be rectified prior to performing the injection. As most of EOR pilot projects conducted in Indonesia are located in older fields with higher uncertainty in well integrity aspects, this publication tends to answer these questions by investigating several aspects namely tubular integrity against the aspects of burst, collapse, and tension as well as corrosion issue.

1. Water Alternating Gas

CO_2 water-alternating-gas (WAG) injection is a cyclic injection process where water and gas injections are carried out alternately for periods of time to provide better sweep efficiency and reduce gas channeling from injector to producer. This process is used mostly in CO_2 flooding to improve hydrocarbon contact time and sweep efficiency of the CO_2 (Chen & Reynolds, 2016). CO_2-WAG flooding is one of the successful enhanced oil recovery methods for a low permeability reservoir or a reservoir with fractures (Liao, *et al.*, 2013) because WAG results in better mobility control and higher microscopic miscible displacement efficiency compared to injecting water or CO_2 individually. CO_2-WAG is the preferable method due to the fact it can give higher recovery, better sweep efficiency, and cost effective than other CO_2 injection method (Karimaie, *et al.*, 2017). The WAG parameters consist of slug size, ratio, and cycle (Touray, 2013). The WAG ratio is a comparison between the amount of water injected and the number of solvents injected, both expressed in units of reservoir volume (Juanes & Blunt, 2007). The WAG ratio has a very significant influence on the design of the WAG process. Even so, basically the WAG ratio is very dependent on reservoir wettability and the availability of gas to be injected (Zahoor, *et al.*, 2011).

2. Property of Casing

a. Burst Pressure

Burst pressure is the pressure received from inside the case. Burst occurs when internal pressure is greater than external pressure (Mitchell, *et al.*, 1998). In casing planning it is considered that burst pressure is the formation pressure coming from the next casing route, when the kick casing gets the maximum pressure from the formation. An overview of the burst pressure suffered by the casing can be seen in Figure 1. If the burst pressure that occurs in the case is greater than the strength of the case to hold it, the case will tear. An overview of the bursting case can be seen in Figure 2. Based on the following equation the burst pressure can be calculated (Bourgoyne, 1991):

$$P_{br} = 0.875\,\frac{2\sigma_{yield}\,t}{d_n} \tag{1}$$

Where:

P_{br} = Burst pressure (psi)

σ_{yield} = Minimum yield pressure (psi)

d_n = Outer diameter (inch)

t = Wall thickness (inch)

b. Collapse Pressure

Collapse occurs when external pressure is greater than internal pressure (Mitchell, *et al.* 1998). In the casing design, as collapse pressure is considered the hydrostatic pressure of cement outside the casing, so the biggest collapse pressure accepted by casing at the bottom of the hole and the worst conditions occur when the casing is empty or the pressure inside the casing is zero. At zero depth or on the surface of external pressure is zero. If the collapse pressure that occurs in the case is greater than the force to hold it, then the casing will be bent in or collapse. In order to ensure casing not to collapse, the installed casing must have a collapse resistance greater than burst pressure. An overview of the collapse case can be seen in Figure 3. When the axial stress is zero, there are four kinds of range for different collapse pressure regions. They are yield strength collapse, plastic collapse, transition collapse, elastic collapse. Region of collapse pressure determined by outer diameter ratio and wall thickness. The detailed region can be seen in Table 1. The difference between the four regions is the empirical coefficients used for collapse pressure determination. The empirical coefficients for each grade can be seen in Table 2. A transition collapse region between the plastic collapse and elastic collapse regions is defined with this equation (Bourgoyne, 1991):

$$P_{cr} = \sigma_{yield}\left(\frac{F_4}{d_n/t} - F_5\right) \quad (2)$$

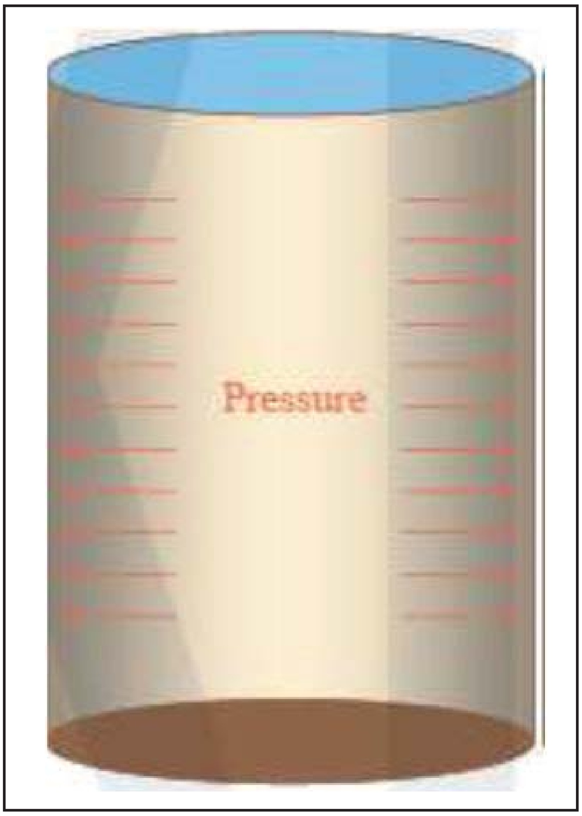

Figure 1
Illustration of burst pressure.

Figure 2
Casing when burst rating is exceeded.

Where:

P_{cr} = Collapse pressure (psi)

σ_{yield} = Minimum yield pressure (psi)

d_n = Outer diameter (inch)

t = Wall thickness (inch)

F_4 = Empirical coefficients

F_5 = Empirical coefficients

c. Tension Load

Tension is a load caused by a series of casings' (Rubiandini, 2004) tension failure will occur when the tension load is greater than the tension rating. An overview of the tension case can be seen in Figure 4. Based on the following equation the tension fore can be calculated (Bourgoyne, 1991):

$$F_{ten} = \frac{\pi}{4}\sigma_{yield}(d_n^2 - d^2) \quad (3)$$

Where:

F_{ten} = Tensional Force (lbf)

σ_{yield} = Minimum yield pressure (psi)

d_n = Outer diameter (inch)

d = Inner diameter (inch)

3. Corrosion

Corrosion is the destructive attack of a metal by chemical or electrochemical reaction with its environment (Revie, 2008). Corrosion occurs when conditions are as follows (Bellarby, 2011):

- The surface of metal that is exposed to the environment;
- Water or electrolyte;
- A corrodent (something such as oxygen, CO_2, acid, or H_2S to create the corrosion).

For normalized steels of tubing or casing the following equations are applied in the corrosion rate model (Smith & DeWaard, 2005):

$$\log(Vr) = 4.84 - \frac{1119}{t+273} + 0.58\log(f_{CO_2}) - 0.34\,(pH_{actual} - pH_{CO_2}) \quad (4) \quad (4)$$

Where:

t = Temperature (°C)

f_{CO_2} = Fugacity of CO_2 (bar)

pH_{actual} = Actual pH

Figure 3
Collapse casing.

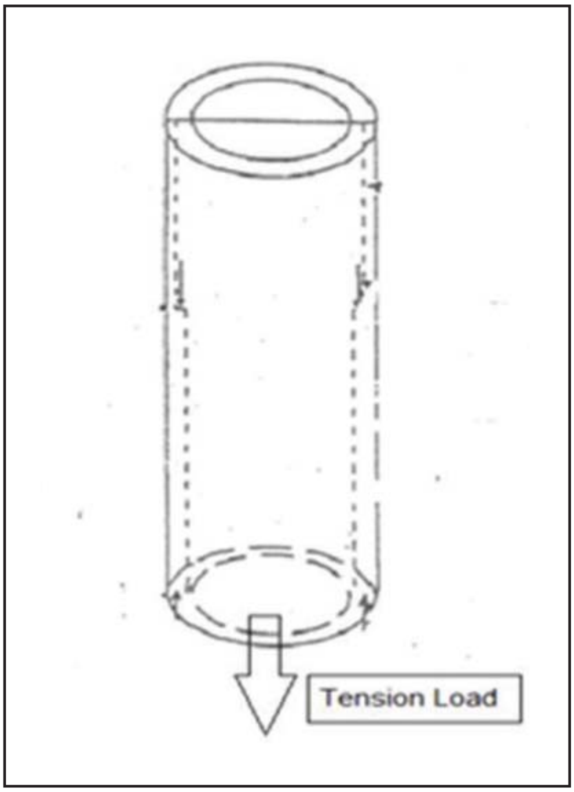

Figure 4
Tension load condition.

Table 1
Range of d_n/t for various collapse-pressure regions when axial stress is zero (reproduced from applied)

API Grade	Yield Strength Collapse	Plastic Collapse	Transition Collapse	Elastic Collapse
H-40	16.4	27.01	42.64	
J-55	14.81	25.01	37.21	
K-55	14.81	25.01	37.21	
C-75	13.6	22.91	32.05	
L-80	13.38	22.47	31.02	
N-80	13.38	21.69	31.02	
C-90	13.01	21.69	29.18	
C-95	12.85	21.33	28.36	
P-105	12.57	20.7	26.89	
P-110	12.44	20.41	26.22	

(Reproduced from Applied Drilling Engineering by Burgoyne, 1991)

pH_{CO_2} = Pure water pH saturated with CO_2 at prevailing pressure and temperature.

The CO_2 fugacity is calculated based on the following equation (Smith & DeWaard, 2005):

$$\log(f_{CO_2}) = \log(p_{CO_2}) + \left(0.0031 - \frac{1.4}{t+273}\right)P \qquad (5)$$

Where:

P_{CO_2} = Partial pressure of CO_2

DATA AND METHODS

The study was completed by following design framework, as can be see in Figure 5, by implementing the following five stages in order to optimize this study:

A. Literature Study

Review the previous research about CO_2 water-alternating-gas (WAG), Corrosion and Corrosion Rate, Standardization of Corrosion Rates, and Load on Production Casing in the several papers and books.

B. Data Preparation

In this section, well data, production casing data, and injected fluid data had been prepared for input to software.

Table 2
Empirical coefficients used for collapse-pressure determination (reproduced from Applied drilling engineering by Burgoyne, 1991)

API Grade	Empirical Coefficient				
	F1	F2	F3	F4	F5
H-40	2.95	0.047	754	2.063	0.0325
J-55	2.991	0.054	1206	1.989	0.036
K-55	2.991	0.054	1206	1.989	0.036
C-75	3.054	0.064	1806	1.99	0.0418
L-80	3.071	0.0667	1955	1.998	0.0434
N-80	3.071	0.0667	1955	1.998	0.0434
C-90	3.106	0.0728	2254	2.017	0.0466
C-95	3.124	0.0743	2404	2.029	0.0482
P-105	3.162	0.0794	2702	2.053	0.0515
P-110	3.181	0.0819	2852	2.066	0.0532

1. Corrosion Rate Prediction

Corrosion rate was calculated using the Electronic Corrosion Engineer (ECE®) corrosion model.

2. Casing Strength Evaluation

At this step, the strength of casing which included burst, collapse, and tension of production casing was assessed using Microsoft Excel.

3. Rating and Tubular Failure Analysis

Last, the output from step before this section was analysed, based on the production casing rating calculation and the result was used to give the

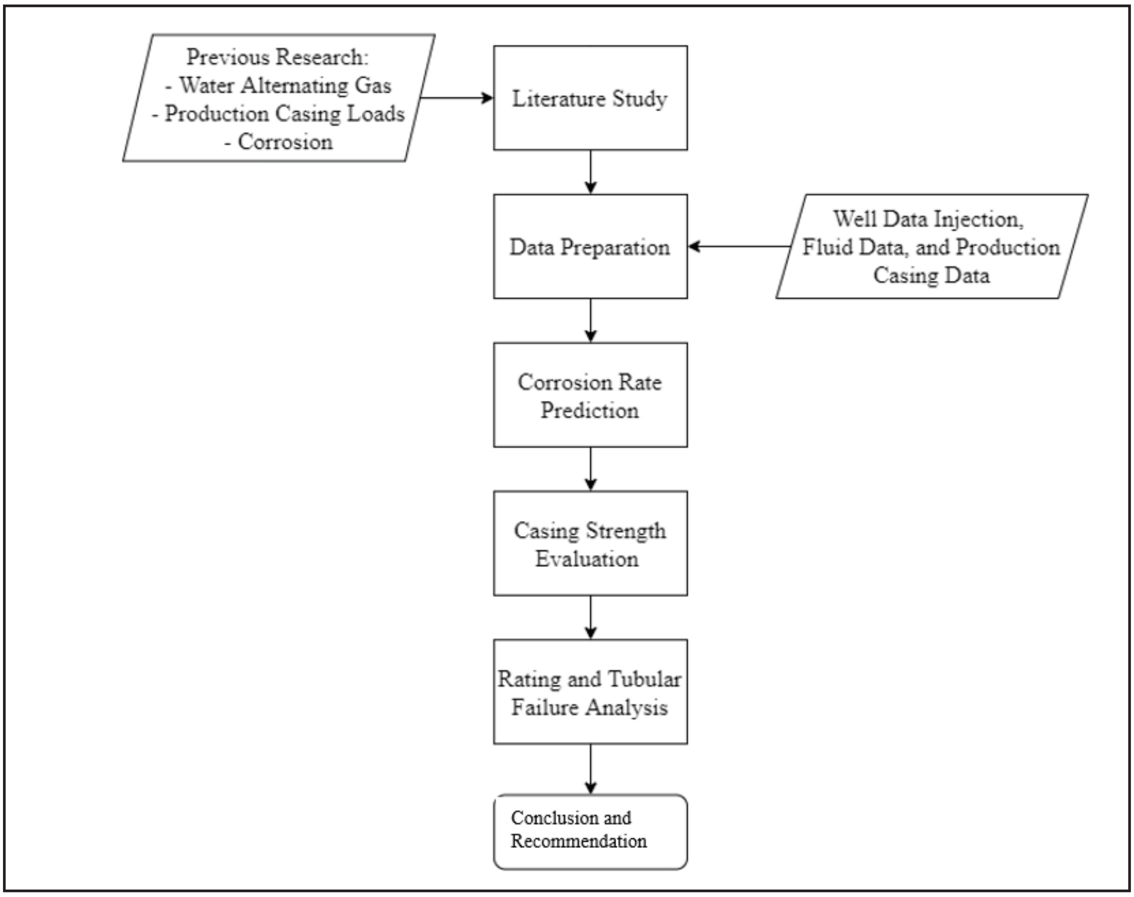

Figure 5
Methodology flowchart.

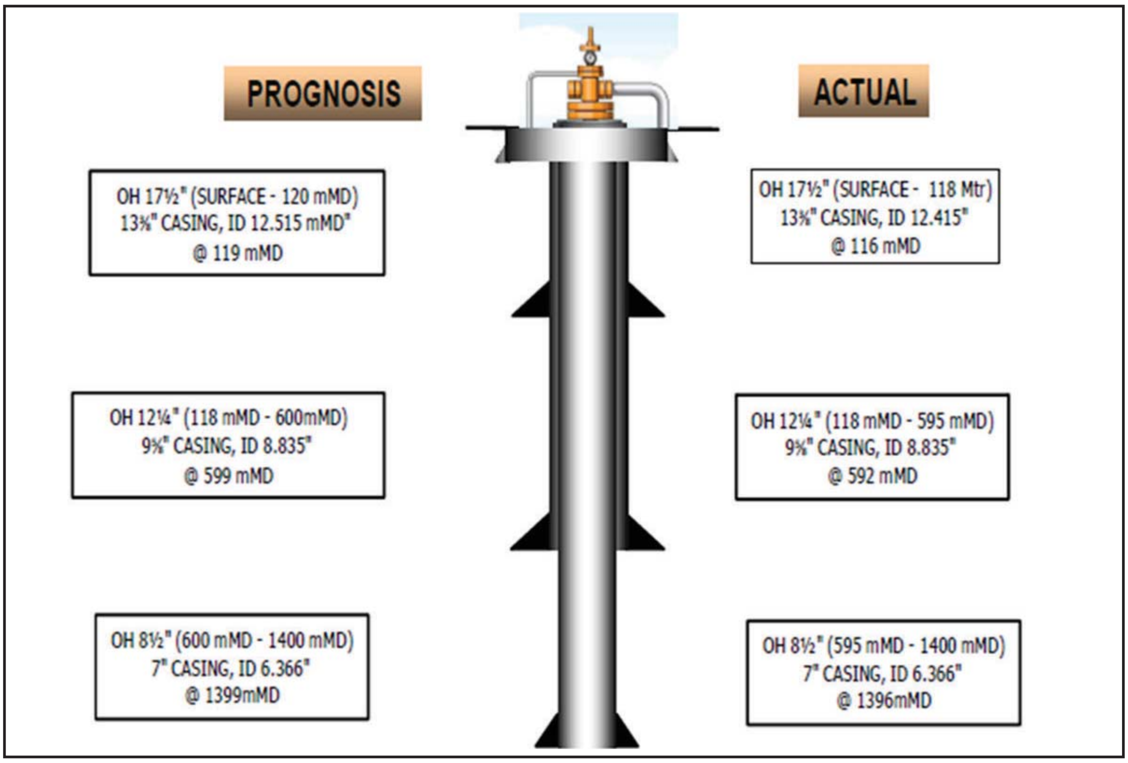

Figure 6
X-Well cross section diagram.

Table 3
Specification of casing

Data	OD (inch)	ID (inch)	Weight (lbm/f)	Wall Thickness (inch)
Surface Casing, K-55	13.375	12.675	54.5	0.38
Intermediate Casing, K-55	9.625	8.835	40	0.395
Production Casing, K-55	7	6.276	26	0.362

best recommendation for what is doing next before CO_2 water-alternating-gas (WAG) be applied.

C. Case Study

1. Well Overview

A mature oil field in Indonesia is known as Y-Field. Some development wells in this field produce oil using various recovery mechanisms. X-Well is one of the wells that has a natural decline. Figure 6 illustrates the vertical well diagram of X-Well. This well wants to use tertiary recovery to enhance oil production using the CO_2 water - alternating - gas (WAG) method in the next development.

X-Well consists of surface casing, intermediate casing, and production casing without using tubing. Table 3 lists the specifications for each casing. For inject this well using production casing. Table 12 shows the rating of each casing.

2. Production Casing Data

The production casing used in X-Well has a K-55 grade with OD size of 7" with 26 ppf for weight and for the type of connection is BTC with type of casing length range is R3, the casing was installed to a depth of 4,980 ft, additional data used in this case study shown by Table 4.

3. Injected Fluid Description

Enhanced Oil Recovery will be used on this well. CO_2 is injected, followed by an alternating brine. The CO_2 water-alternating-gas (WAG) procedure is for case 1, Injection of brine (composition is 8,600 ppm, with no bicarbonate and acetic acid containing) injection 1,500 BWPD with pump pressure is 500 psi, followed by case 2, Injection (99%; H_2S pollutant 5 ppm) as much as 7 MMSCFD with compressor pressure is 800 psi. Table 5 illustrates the detailed scenario of case 1 and Table 6 illustrates case 2.

4. Case Overview

Before doing the injection, it is necessary to evaluate the strength of the casing due to increased production and corrosion effects which will put a load on the casing. With some assumption such as the

Table 4
Detailed specification of production casing

Production Casing Data	
Production Casing Grade	K-55
Type of Connection	BTC
Weight of Production Casing, lbm/ft	26
Type of Casing Length Range	R3
Production Casing OD, inch	7
Production Casing ID, inch	6.276
Wall Thickness, inch	0.362
Minimum Yield Pressure, psi	55000

Table 5
Data input of case 1 for ECE

Case 1	
Wellhead Pressure, psia	515
Bottomhole Pressure, psia	2322
Temperature at Wellhead, F	77
Temperature at Bottomhole. F	120
CO_2 Composition, %	0
H_2S Composition, ppm	0
Water Salinity, ppm	8600
Rate Crude oil, bopd	0
Gas Rate, MMSCFD	0
Water Rate at Wellhead, bwpd	1500
Measured Depth, m	1400
OD, inch	7
Wall Thickness	0.362

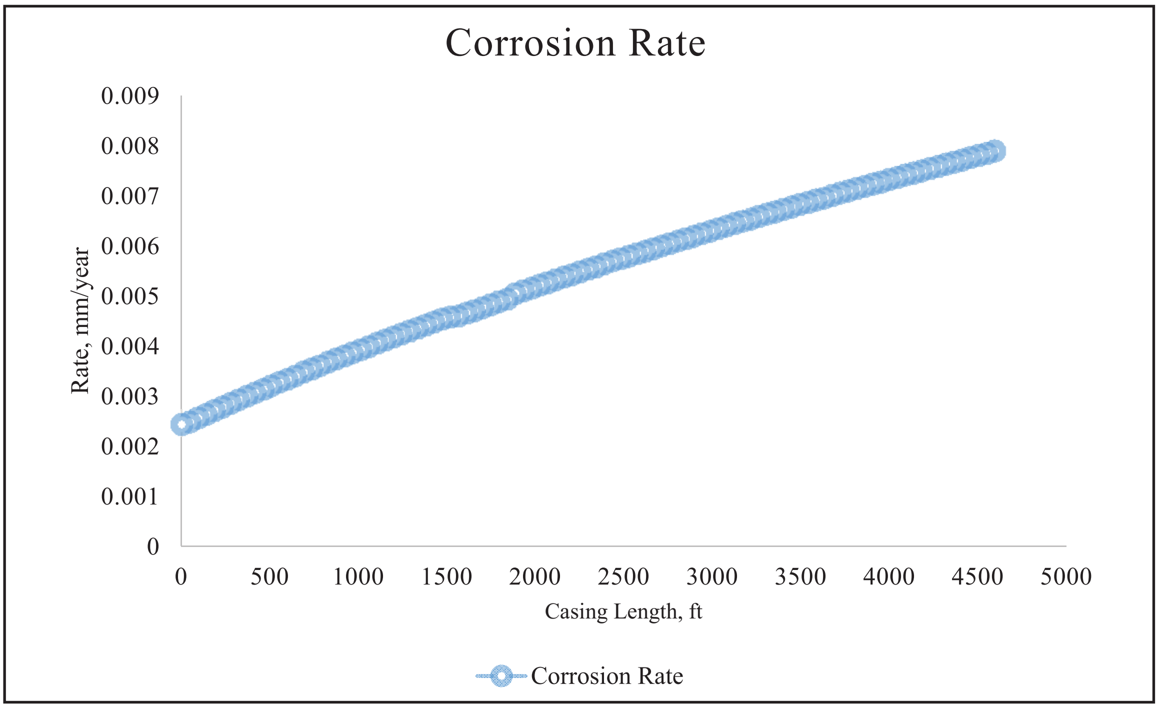

Figure 7
Case 1 corrosion rate.

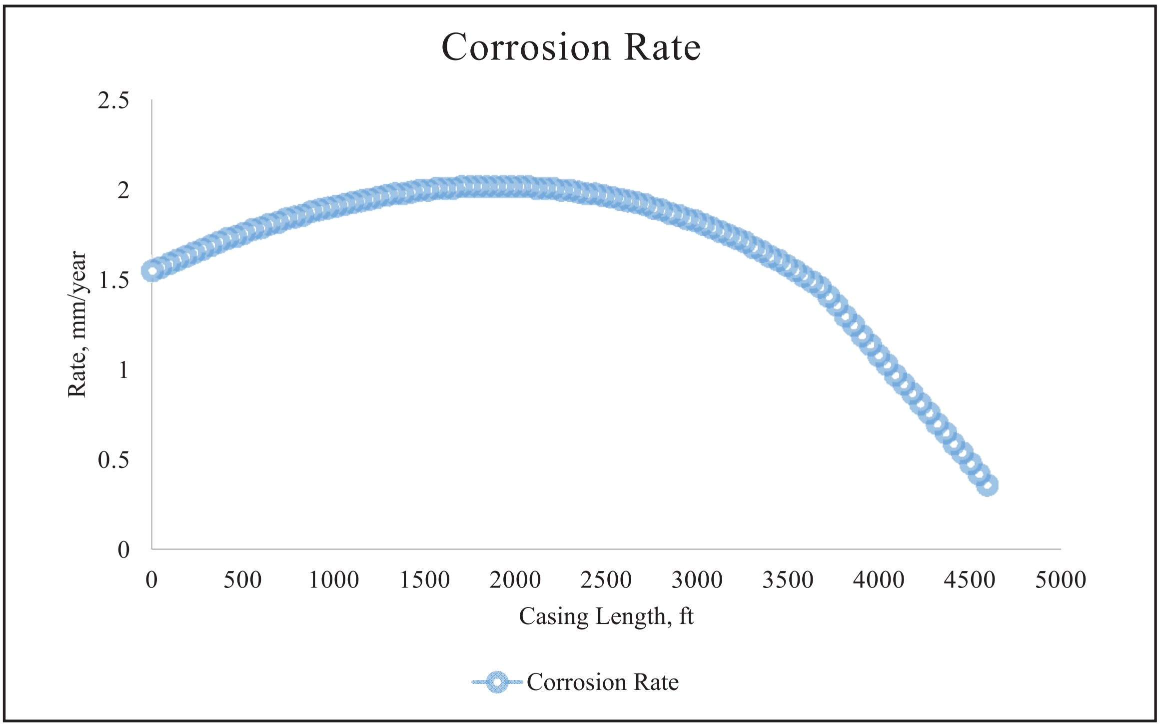

Figure 8
Case 2 corrosion rate.

well is not used production tubing and well is vertical so does not have any deviation. For the purpose of assessing tubing failure, data, and assumptions based on the injection scenario, The API 5 CT (American Petroleum Institute, 2005) rating was used.

RESULTS AND DISCUSSION

A. Corrosion

In CO_2 water-alternating-gas (WAG) injection which is injecting brine and CO_2 alternately can have an effect on the material of the case. One of the effects is corrosion. By knowing the potential corrosion that will occur, it can be avoided by selecting the appropriate casing material and able to withstand the rate of corrosion that occurs due to the injection.

The Result of the potential corrosion for two cases shown in Table 7. The corrosion rate are 0.008 mm/year maximum and 0.0025 mm/year minimum in the first case, which is brine injection with the following data is in Table 5. Figure 7 shows the corrosion rate along the production casing. Because there is no chemical lead to corrosion, the corrosion rate is low. This value, it is still within the safe limit for corrosion rate which far below NORSOK Standard M-001 of 2 mm/year.

For the second case using CO_2 injection, which the detailed data is in Table 6. The result obtained the maximum corrosion rate is 2.02 mm/year and the minimum corrosion rate is 0.36 mm/year. From the data, it can be concluded that corrosion rate for the second case can be said to fail because it is above NORSOK Standard M-001 which is 2 mm/year and needs to be evaluated to prevent the rate to remain stable and not decrease in the following years.

Tubing material selection is important to ensure well integrity in this case production casing, so it can deliver fluids safely for the entire injection life and there are no minor/major problems that can impact the injection. Based on Table 13, Table 14, and Figure 15, the casing material that will be used to inject CO_2 is SM13CR (Martensitic Stainless Steel) which is not sour service materials because there is small amount of H_2S in two different condition which is in Wellhead and Bottomhole condition.

B. Production Casing Load

With the input data shown by Table 8, it can be seen that at the Burst load, the internal pressure comes from wellhead pressure, which is assumed to be compressor pressure, and the column pressure of brine in the casing. The external pressure is generated by pore pressure, which is assumed to be 0.465 psi/ft (Bourgoyne, 1991). The burst calculation gave a pressure of 600 psi at 0-meter depth and 426.96 psi at 4,580 ft depth, the tubing's end. This value must meet the 4977.5 psi rating of K-55 production casing. Table 9 shows the details of the calculation. Figure 9 represents the graph of burst pressure. Figure 10 illustrates the burst rating.

Table 6
Data input of case 2 for ECE

Case 2	
Wellhead Pressure, psia	815
Bottomhole Pressure, psia	2322
Temperature at Wellhead, F	77
Temperature at Bottomhole. F	120
CO_2 Composition, %	99
H_2S Composition, ppm	5
Water Salinity, ppm	0
Rate Crude oil, bopd	0
Gas Rate, MMSCFD	7
Water Rate at Wellhead, bwpd	0
Measured Depth, m	1400
OD, inch	7
Wall Thickness	0.362

Table 7
Corrosion rate each case

Scenario	Corrosion Rate, mm/year	
	Minimum	Maximum
Case 1 (Brine)	0.0025	0.008
Case 2 (CO_2)	0.36	2.02

Table 8
Data input for production load calculation

Properties	Value
Depth of Production Casing, ft	4580
Injection Pressure, psi	500
Pore Pressure Gradient, psi/ft	0.465
Water Density, lb/ft^3	62.4
Water Gradient, psi/ft	0.43333333
Mud Weight, lb/gal	9.75
Weight of Production Casing, lbm/ft	26
Safety Factor Burst	1.2
Safety Factor Collapse	1.2
Safety Factor Tension	1.6

When it comes to the collapse load, this calculation must be done when the external pressure

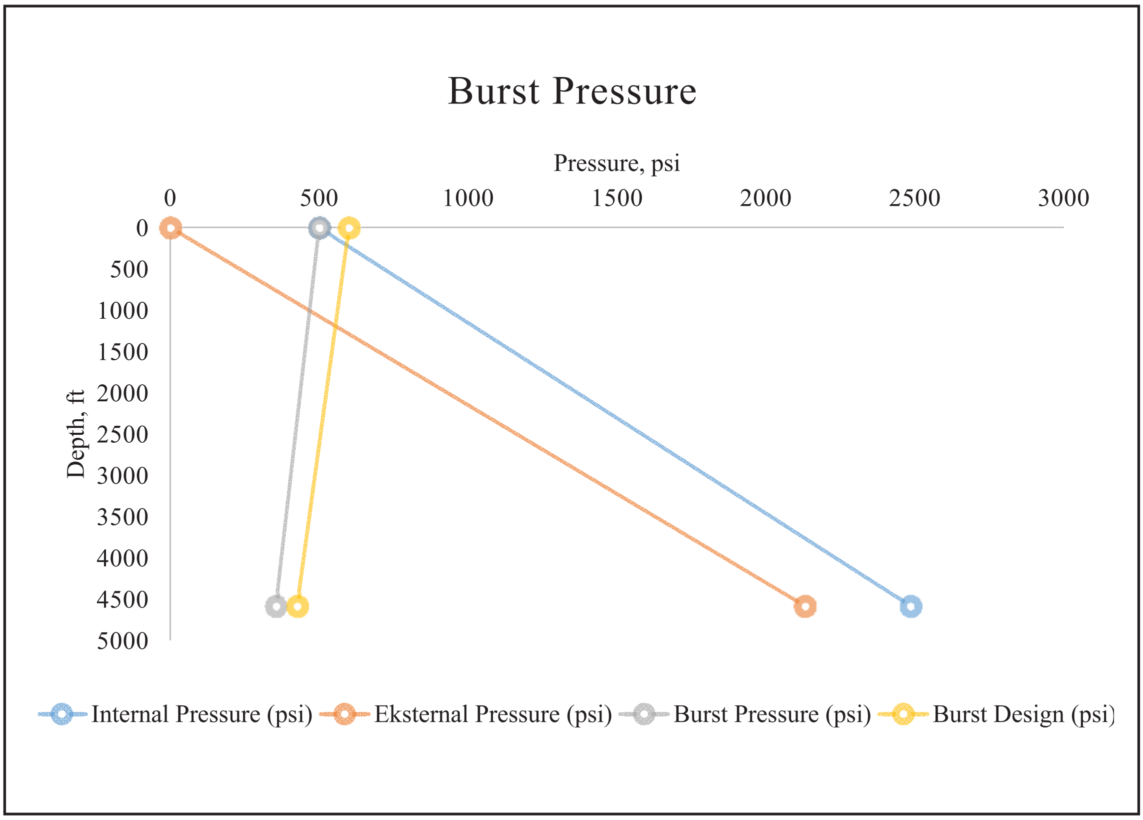

Figure 9
Burst load of production casing.

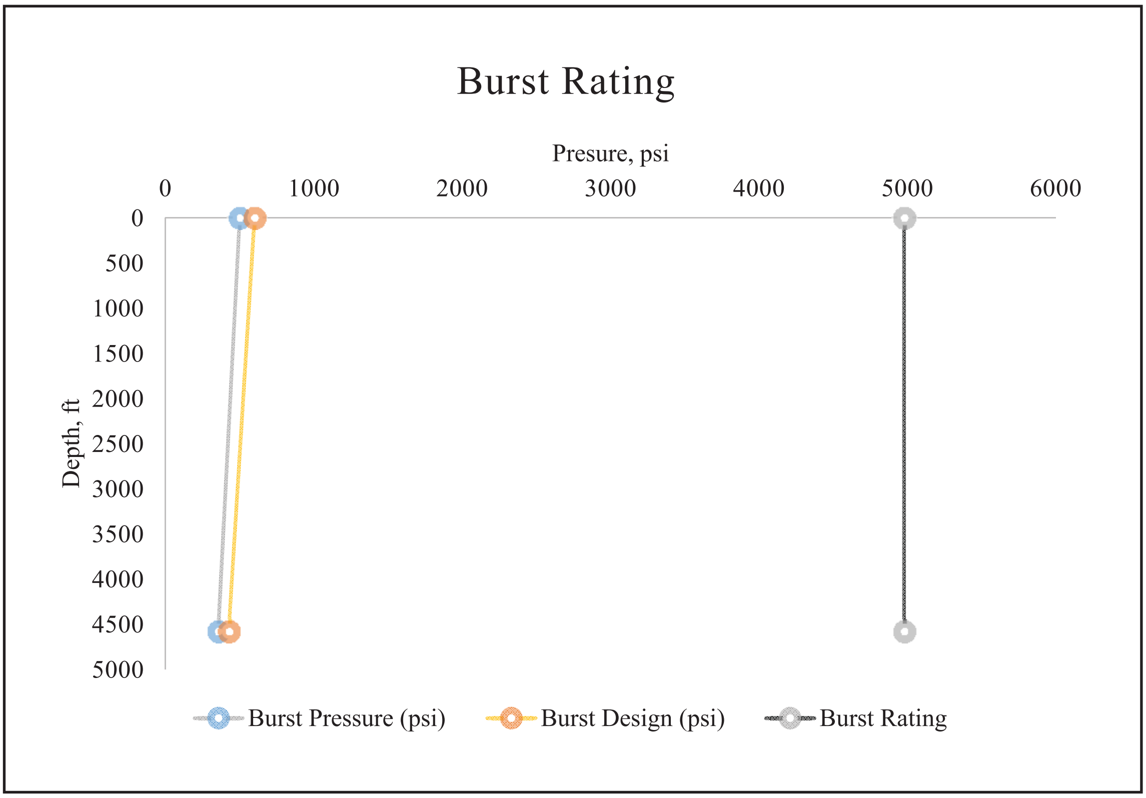

Figure 10
Burst rating of production casing.

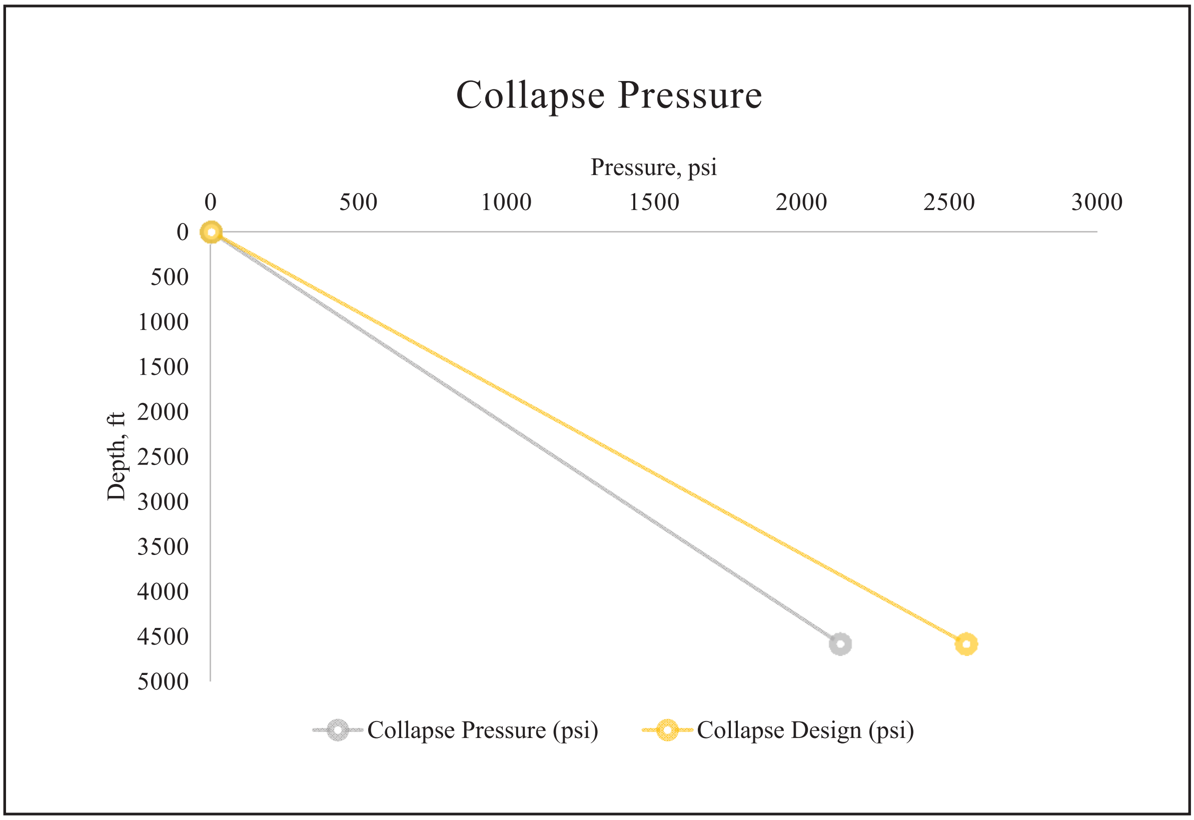

Figure 11
Collapse load of production casing.

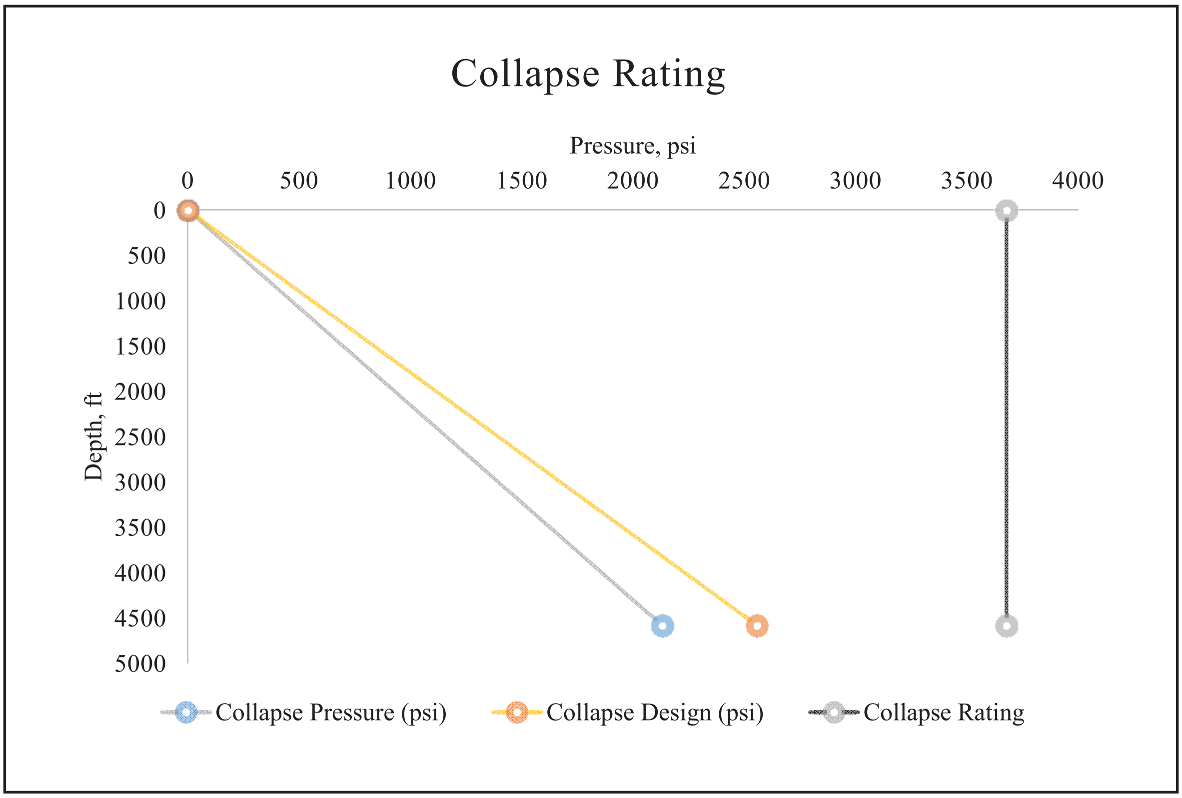

Figure 12
Collapse rating of production casing.

Table 9
Burst pressure calculation

Depth (ft)	Internal Pressure (psi)	External Pressure (psi)	Burst Pressure (psi)	Burst Design (psi)
0	500	0	500	600
4580	2484.67	2129.7	354.97	425.96

Table 10
Collapse pressure calculation

Depth (ft)	Internal Pressure (psi)	Eksternal Pressure (psi)	Collapse Pressure (psi)	Collapse Design (psi)
0	0	0	0	0
4580	0	2129.7	2129.7	2555.64

Table 11
Tension load calculation

Depth (ft)	Pounder (ppf)	Tension (lbf)	Tension Design (lbf)
0	26	119080	190528
4580	26	0	0

Table 12
Result of casing rating calculation

Casing Rating	Surface Casing K-55, 13-3/8", 54.5 ppf	Intermediate Casing K-55, 9-5/8", 40 ppf	Production Casing K-55, 7", 26 ppf
Burst Rating	4977.5	3950	2734.579439
Collapse Rating	3677.284286	2509.457143	1128.04486
Tension Rating	415200.9904	629957.6567	787695.453

is high, but the internal pressure is zero. 2,555.64 psi is the result of the collapse pressure. The collapse rating of production tubing K-55 is 3,677.28 psi, and this result meets that requirement. Table 10 shows the details of the calculation. Figure 11 captures the collapse pressure graph. The rating of collapse is presented in Figure 12.

For the tension load. This calculation calculates the weight of production tubing per feet and the tubing's true vertical depth. 190,528 lbf tension load calculation results. This value is equal to the 415,200.99 lbf rating of production tubing K-55. Table 11 shows the tension load calculation. Figure 13 illustrates the tension load graph. The rating of tension is presented in Figure 14.

All of this value when compared to its rating for burst, collapse and tension, the loads do not exceed the calculated rating limit.

Based on the calculations performed, it can be seen that the tubular configuration proposed in this publication could hold against the loads of injection as well as the corrosion effects from injecting a combination of CO_2 and brine. However, it has to be noted that further works should assume on declining tubular properties and routine monitoring is required to ensure the longevity of the operation.

CONCLUSIONS

Based on the analysis above, several conclusions can be taken to comply with this study objectives:

The production casing K-55 tubing used in X-well in the Y-field has a lower risk of failure due to CO_2 water-alternating-gas (WAG) because all of the production casing loads meets requirements with burst pressure 600 psi, collapse pressure 2,555.64, and the tension of 190,528 lbf.

In the second case, while injecting CO_2, the maximum corrosion rate occurs. It has a maximum corrosion rate of 2.02 mm/year and a minimum corrosion rate of 0.36 mm/year. With this value, it is above NORSOK Standard M-001 which is 2 mm/year and needs to be evaluated to maintain the rate to remain stable and not decrease in the following years.

Table 13
General reservoir data
for material selection in the Wellhead

Properties	Value
Reservoir Pressure, psia	815
Reservoir Temperature, F	77
CO2 Partial Pressure, psia	806.85
H2S Partial Pressure, psia	0.004

Table 14
General reservoir data
for material selection in the bottomhole

Properties	Value
Reservoir Pressure, psia	2322
Reservoir Temperature, F	120.2
CO_2 Partial Pressure, psia	2298.78
H_2S Partial Pressure, psia	0.12

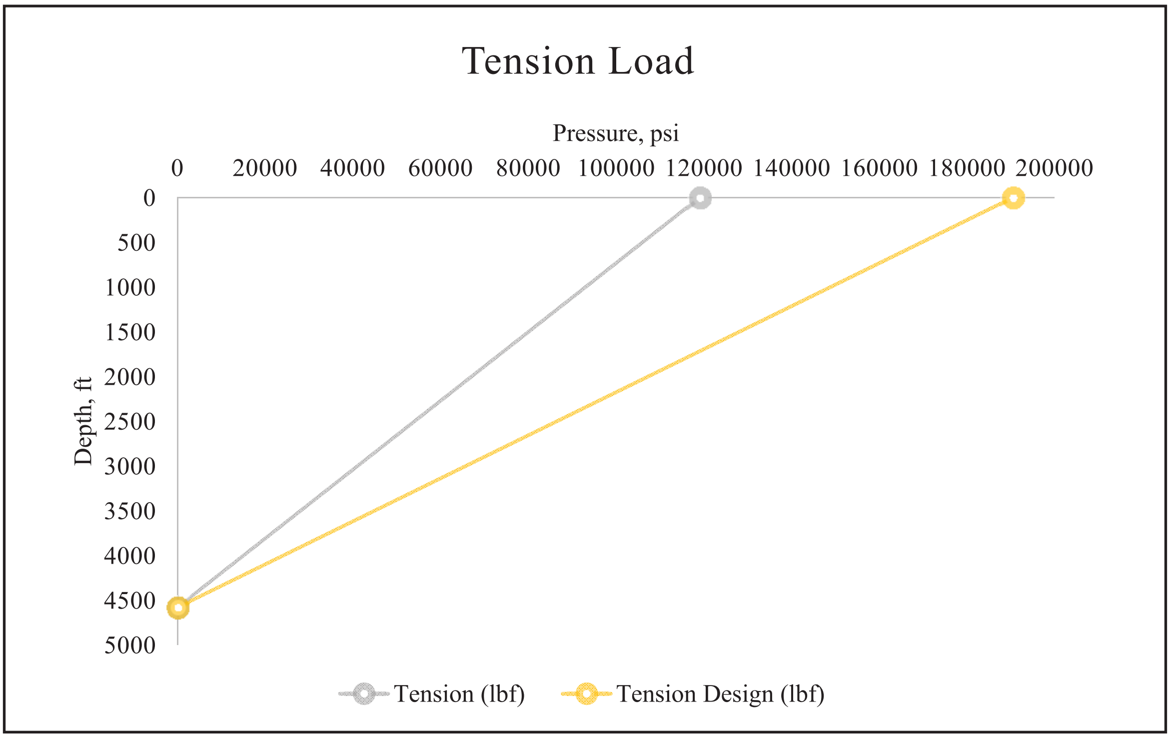

Figure 13
Tension load of production casing.

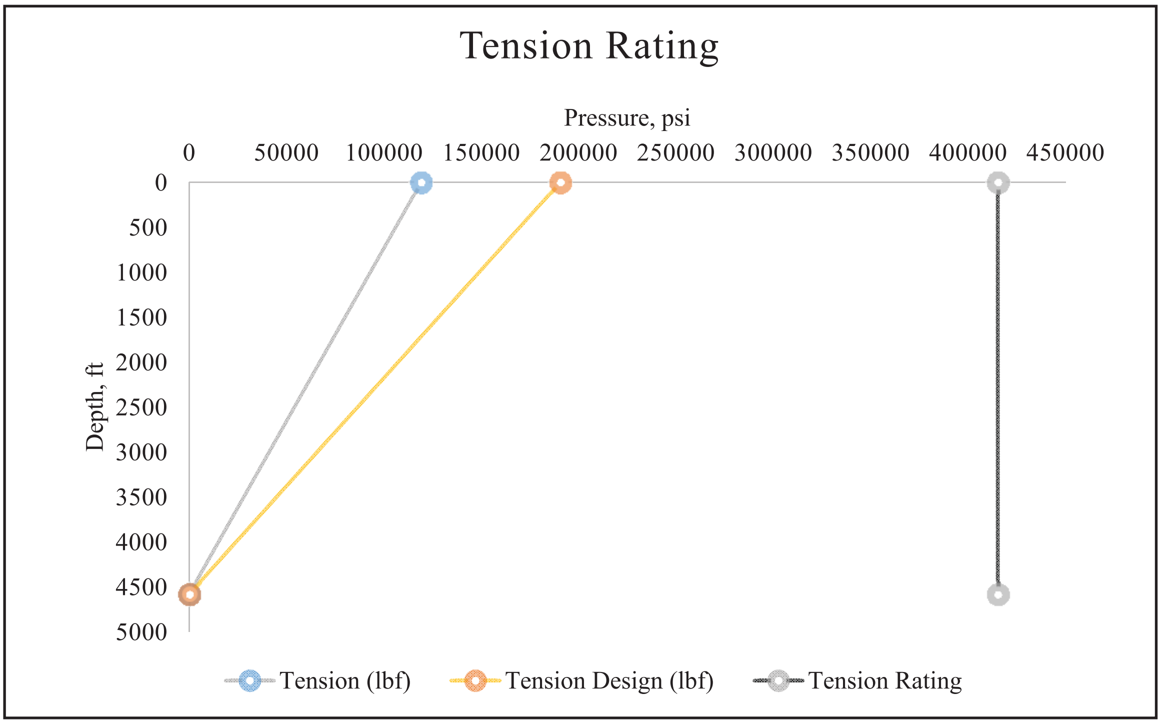

Figure 14
Tension rating of production casing.

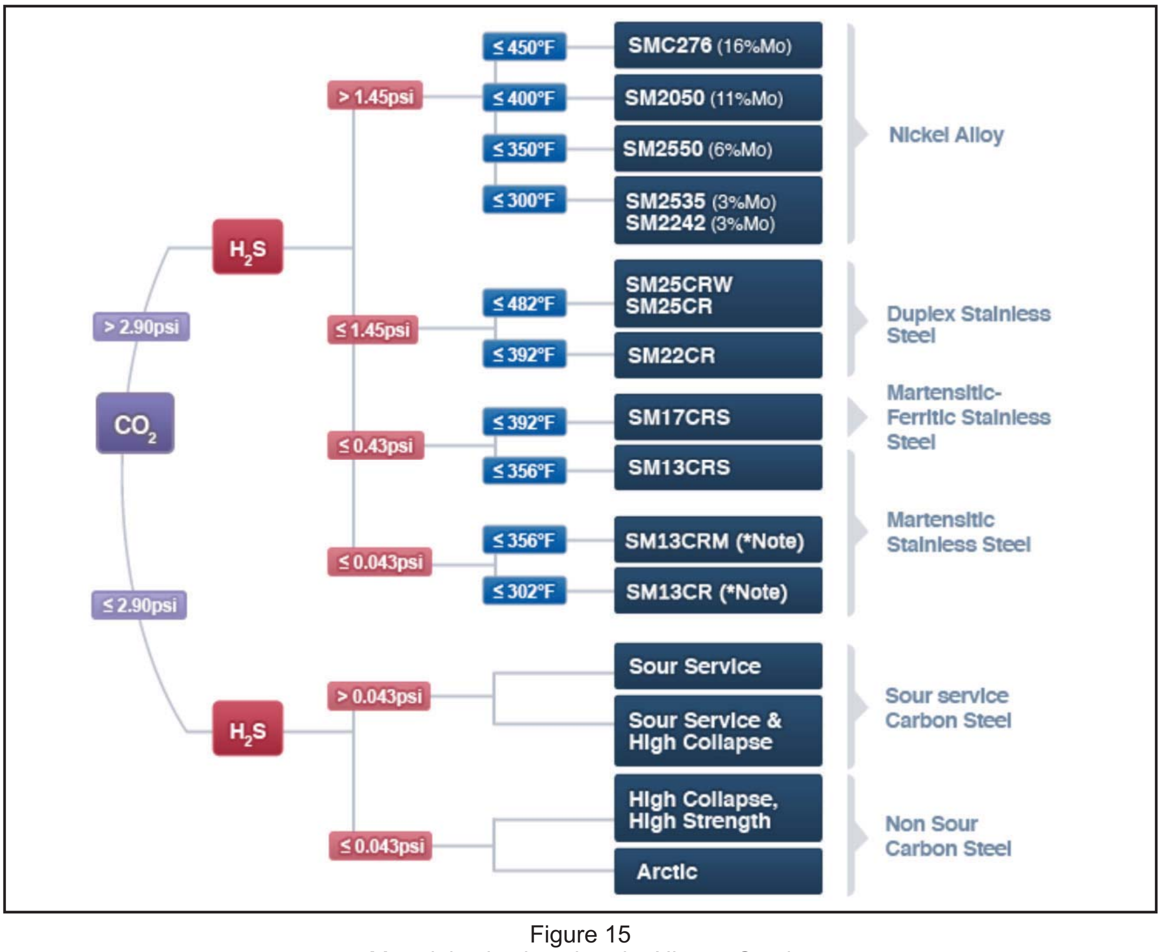

Figure 15
Material selection chart by Nippon Steel
(http://www.tubular.nipponsteel.com/productservices/octg/materials/materials/).

To prevent the effect of maximum corrosion rate, the casing material must use a SM13CR (Martensitic Stainless Steel) which is not sour service material.

Some recommendations can be applied for further development of this studies to gain more understanding and increase the implementation reliability in this field:

To reduce the impact of CO_2 injection, in addition to using the appropriate material, in this case SM13CR (Martensitic Stainless Steel) which is not sour service material can also use other alternatives for example injecting corrosion inhibitor either pre-flush or post-flush or it can also be by coating the tubing with corrosion resistance material before CO_2 injection.

GLOSSARY OF TERMS

Symbol	Definition	Unit
WAG	water-alternating-gas	
ECE	Electronic Corrosion Engineer	
P_{br}	Burst pressure	psi
d_n	outer diameter	inch
t	wall thickness	inch
σ_{yield}	Minimum yield pressure	psi
F_{ten}	Tensional Force	lbf
f_{CO2}	Fugacity of CO2	bar

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