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Tubing Strength Analysis and Failure Assessment of Electrical Submersible Pump (ESP) Well: A Case Study on Production Well "X"

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ABSTRAK

Studi ini akan membahas evaluasi kekuatan tubing pada sumur X yang menggunakan *Electrical Submersible Pump* sebagai metode pengangkatan buatan. Evaluasi akan dilakukan untuk mengetahui resiko kegagalan pada tubing produksi akibat kerusakan erosi serta kegagalan akibat beban pada tubing selama operasi produksi menggunakan *Electrical Submersible Pump*. Beban *burst*, *collapse*, dan *tension* akan menjadi fokus utama dalam evaluasi beban pada tubing dengan mempertimbangkan kondisi terburuk yang mungkin dialami selama operasi produksi. Perhitungan beban pada tubing ini dilakukan menggunakan Microsoft Excel. Hasil perhitungan beban pada tubing akan dibandingkan dengan kapasitas beban maksimum yang dapat dialami tubing berdasarkan kelas tubing. Prediksi kerusakan erosional dilakukan dengan menggunakan perangkat lunak untuk mengetahui nilai kecepatan erosional pada tubing produksi.

Studi ini akan mengevaluasi tubing produksi yang digunakan pada sumur X dengan diameter luar 3.5 inch dan kelas tubing L-80. Tubing L-80 ini memiliki kapasitas beban burst sebesar 7240 psi, kapasitas beban collapse 10533.92 psi, dan kapasitas beban tension 107581.11 lbf. Kapasitas beban tubing akan menjadi batasan yang menentukan integritas sumur selama masa produksi. Berdasarkan hasil evaluasi, tubing produksi L-80 dengan penggunaan *Electrical Submersible Pump* sebagai metode pengangkatan buatan mampu menahan beban dari *burst*, *collapse*, *tension*, dan efek erosional dari fluida terproduksi. Oleh karena itu, penggunaan *Electrical Submersible Pump* pada sumur X sebagai sistem pengangkatan buatan dapat dijalankan tanpa mengganti kelas dari tubing produksi yang sudah ada.

Keywords: Tubing; Burst; Collapse; Tension; Kapasitas Beban; Electrical Submersible Pump; Kecepatan Erosi.

ABSTRACT

This study will discuss the evaluation of tubing strength in Well X that using Electrical Submersible Pump as an artificial lifting method. The evaluation will be carried out to determine the risk of failure of production tubing due to erosional damage and the failure due to loads on tubing during production operation using Electrical Submersible Pump. Burst, collapse, and tension loads will be the main focus in evaluating the tubing load by considering the worst conditions that may be experienced during production operation. The calculation of the tubing load is done using Microsoft Excel. The result of tubing load calculation will be compared with the tubing rating based on tubing grade. Erosional damage prediction is carried out using software to determine the erosional velocity on the production tubing.

This study will evaluate the production tubing used in Well X with an outer diameter of 3.5 inch and L-80 tubing grade. Tubing L-80 has a burst rating of 7240 psi, a collapse rating of 10533.92 psi, and a tension rating of 107581.11 lbf. Tubing is rating will be the limit that determines the integrity of the well during the production period. Based on the evaluation result, L-80 production tubing that using Electrical Submersible Pump as an artificial lifting method is able to withstand the burst load, collapse load, tension load, and the erosional effect of the produced fluid. Therefore, the Electrical Submersible Pump in Well X as an artificial lift system can be carried out without changing the grade of the existing tubing production.

Keywords: Environment; Geology; Geophysics; Mining; Petroleum (alphabetically arranged and lowercase) Tubing; Burst; Collapse; Tension; Load Rating; Electrical Submersible Pump; Erosional Velocity.

I. INTRODUCTION

Artificial lift is the method of adding energy to the flow stream within the completion to increase the flow rate (Bellarby, 2009). Approximately 50% of wells worldwide need artificial lift systems and the commonly used artificial lift methods is Electrical Submersible Pump (ESP) which is highly effective to increase oil production in both onshore and offshore oil fields (Guo, Lyons, & Ghalambor, 2007). In case of using ESP as an artificial lift method to increase production flow rate from a particular well, there are several cases of production tubing load due to ESP operation need to be consider. High pressure could be generated during ESP operation, especially from ESP discharge pressure that might be the highest-pressure scenario from internal tubing load.

This study was conducted to evaluate the production tubing integrity of Well X which using ESP as an artificial lift production system. The tubing strength evaluation considers burst, collapse, and tension load during production period and the erosional damage will be evaluated due to production using ESP artificial lift method. At the end of this study, the best recommendation for production tubing's grade will be consider whether the tubing's grade must be upgraded or not based on the load evaluation. The objective of this study is to evaluate the tubing integrity of Well X that used Electrical Submersible Pump (ESP) for its production. The evaluation including:

1. Erosional damage prediction and compare the result with available standard allowance.
2. Production tubing evaluation including burst, collapse, and tension load.

This study has several assumptions:

1. The internal pressure in burst load calculation was using discharge pressure from the ESP operation that acquired from bottomhole pressure gauge. Packers completely seal the space between tubing and casing, therefore the fluid that fills the annulus between tubing and casing is neglected.
2. The collapse load calculation was using the worst condition scenario with high external pressure and the internal pressure is zero.
3. The buoyancy effect in tension load calculation is neglected because is not significant enough to affect the calculation.

The limitations for this study are following:

1. This study only focused in tubing strength analysis from production well X which using ESP.
2. The Electrical Submersible Pump (ESP) design and calculation is not included in this study.
3. The thermal effect from ESP operation is neglected because the temperature changes is not significant.
4. The corrosion rate prediction was not carried out in this study due to lack of data.

II. METHODS

2.1. Electrical Submersible Pump

Electrical Submersible Pump (ESP) is one of the artificial lift systems that used to increase well production flow rate. ESPs are pumps made of dynamic pump stages or centrifugal pump stages (Guo, Lyons, & Ghalambor, 2007). The illustration of conventional ESP installation can be seen in **Figure 1**. In ESP operations, electric energy is transported to the down-hole electric motor. These electric motor drives the pump and the pump imparts energy to the fluid in the form of hydraulic power which lifts the fluid to the surface.The seal system separates the well fluids from the electric motor lubrication fluids and the electrical wiring (Takacs, 2018). Centrifugal pumps that used in the ESP system create a relatively constant amount of pressure increase to the flow system. The output flow rate depends on backpressure. The pressure increase is usually expressed as pumping head.

In case of load calculation during the ESP operation, the fluid discharged by ESP to enters the tubing string, the discharge pressure of the pump should overcome the sum of pressure losses along the flow path of produced fluid. This means, the discharge pressure will be the highest pressure generated by ESP operation. The pressure profile during ESP operation can be seen in **Figure 2**.

2.2. Tubular Load Design

2.2.1 Burst Pressure

Burst pressure is the pressure is the pressure received from inside the casing. Burst occurs when internal pressure is greater than external pressure (Miska, 2011). The illustration of burst load on casing or tubing can be seen in **Figure 3.** The burst rating of the casing is the amount of internal pressure that the pipe can withstand prior to failure (Adams, 1985). The API burst rating is based on Barlow's formula for thin-walled pipe (Bellarby, 2009):

$$pbr=0.875\ 2\ Yp\ tdnp_{br} = 0.875\ \frac{2\ Y_p\ t}{d_n} \qquad (1)$$

where:

p_{br} = Burst pressure (psi)

Y_p = Minimum yield pressure (psi)

d_n = Outer diameter (inch)

t = Wall thickness (inch)

2.2.2 Collapse Pressure

Collapse pressure rating is the minimum external pressure that will cause the casing walls to collapse in the absence of internal pressure and axial loading (Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986). The illustration of collapse failure on casing or tubing can be seen in **Figure 4**. Collapse resistance equations vary as a function of d_n/t ratio (Adams, 1985). Therefore, the calculation of collapse resistance must consider d_n/t ratio in selecting the proper equation. There are four formulas might be used in collapse strength calculation based on d_n/t ratio. The yield strength collapse pressure (p_{yp}), when then stress on the inner wall of the casing reaches the minimum yield strength under external collapse pressure can be expressed as:

$$p_{yp} = 2\ Y_p \left[\frac{(d_n\ /\ t) - 1}{(d_n\ /\ t)^2}\right] \qquad (2)$$

The applicable d_n/t ratio for yield strength collapse are shown in **Table 1**.

The minimum collapse pressure for the plastic range (p_p) of collapse can be expressed as:

$$p_p = Y_p \left[\frac{F_1}{d_n\ /\ t} - F_2\right] - F_3 \qquad (3)$$

The factors and applicable d_n/t range for the plastic collapse formula are shown in **Table 2** and the empirical coefficients for each grade can be seen in **Table 5**.

The minimum collapse pressure for the plastic to elastic transition zone (p_t) can be expressed as:

$$p_t = Y_p \left[\frac{F_4}{d_n\ /\ t} - F_5\right] \qquad (4)$$

The factors and applicable d_n/t range for transition collapse pressure formula are shown in Error! Reference source not found.. The empirical coefficients for each grade can be seen in **Error! Reference source not found.**.

The minimum collapse pressure for the elastic range (p_e) of collapse can be expressed as:

$$p_e = \frac{46.95 \times 10^6}{(d_n\ /\ t)\ [(d_n\ /\ t) - 1]^2} \qquad (5)$$

The applicable d_n/t range for elastic collapse is shown in **Table 4**.

2.2.3 Tension Load

Axial tension loading results primarily from the weight of the casing string suspended below the joint of interest (Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986). Body yield strength is the tensional force required to cause the pipe body to exceed its elastic limit. Joint strength is the minimum tensional force required to cause joint failure. The illustration of the tension failure in pipe body and joint can be seen in **Figure 5**. The pipe body strength can be expressed as:

$$F_{ten} = \frac{\pi}{4}\ Y_p\ (d_n^2 - d^2) \qquad (6)$$

2.3. Erosional Velocity

Experience has shown that loss of wall thickness occurs by a process of erosion/corrosion. (American Petroleum Institute, 1991) This process is accelerated by high fluid velocities, presence of sand, corrosive contaminants such as CO_2 and H_2S. API RP (Recommended Practice) 14E introduces the erosional velocity equation as an empirical equation that can be expressed as:

$$V_e = \frac{c}{\sqrt{\rho_m}} \qquad (7)$$

Where V_e is fluid erosional velocity in ft/s, c is empirical constant in $\sqrt{\frac{lb}{ft\,s^2}}$, and ρ_m is gas/liquid mixture density at flowing pressure and temperature in lb/ft^3. The selection of c (constant) is based on **Table 6**.

2.4. Methodology

This study was completed by performing several steps that illustrated in **Figure 6**. The following step explains the methodology of this study:

1. Literature Study
   Literature study was done by reviewing books and papers to gain theories about Electrical Submersible Pump, erosional velocity prediction, burst, collapse, and tension load. In this step, several assumption and limitation were used to complete this study.
2. Data Preparation
   In this section, several data were collected to complete this study including well and Electrical Submersible Pump (ESP)'s configuration data, fluid production data, and reservoir properties.
3. Erosional Velocity Prediction
   Erosional velocity was calculated using software in this section. The input parameters for erosional velocity prediction consist of wellhead and bottomhole condition, gas composition, water chemistry, flowrate, and wellbore angles.
4. Production Tubing Load Evaluation
   In this step, the strength of Well X production tubing was evaluated including burst, collapse, and tension load. These loads were calculated using Microsoft Excel.
5. Rating and Tubular Failure Analysis
   For the last step, the output from steps before were analyzed based on the production tubing evaluation and compared by production tubing rating including burst rating, collapse rating, and tension load rating.

2.5. Case Study

Well X is one of many productions well that already has natural decline in a mature field in Indonesia. In order to increase production flow rate from Well X, an ESP artificial lift system is installed on Well X. Well X configuration consists of surface casing, production liner, and production tubing. The illustration of Well X configuration can be seen in **Figure 7**. The detailed specification of casing and tubing is shown on **Table 7**.

The production tubing used in Well X has a L-80 grade with OD size of 3½", 9.3 ppf of tubing weight, and the type of connection is external-upset-end (EUE) connection. The production tubing and ESP was installed to a depth of 4,658 ft, and the tubing depth is assumed to be equal to the depth of the gas separator as a fluid intake at depth of 4,603 ft. The additional data used in this case study shown by **Table 8** and **Table 9** showed the chemical composition of L-80 tubing grade. During ESP operation, Well X is expected to produce up to 1,000 BFPD. The downhole gauge has recorded the discharge pressure from ESP is 2,500 psi. Tubing evaluation will be performed to see feasibility of the tubing during production. The tubing evaluation consists of:

1. Erosional velocity calculation.
2. Burst, collapse, and tension load calculation during production using ESP.
3. Evaluate the result of burst, collapse, tension, and erosional velocity that have been calculated by comparing with tubing's rating.

III. RESULTS AND DISCUSSION

3.1. Erosional Damage

Erosional damage rate is predicted using software with calculation input data shown on **Table 10**. Using erosional velocity empirical equation from API RP (Recommended Practice) 14E, the value of c is chosen to be 150 since the fluid is solids-free and corrosion is not anticipated. Erosional damage rate graph in **Figure 8**, shows that the erosional damage rate is very small. Therefore, the risk of failure due to erosional damage is low. **Figure 9** illustrate that the tubing production is safe for more than 10 years production operation using ESP.

3.2. Production Tubing Load Evaluation

Using the input data shown by **Table 11**, burst calculation is done by using safety factor 1.2. The internal pressure comes from wellhead pressure and discharge pressure from ESP operation, which is 2,500 psi. Since the packers completely seal the space between tubing and casing and the annulus fluid is neglected, the external pressure is generated by pore pressure that assumed to be 0.465 psi/ft (Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986). The burst calculation gave a pressure of 160 psi at 0 ft depth and 359.60 psi at 4,602 ft depth, the tubing's end. This value must meet the 7,240 psi rating of L-80 production tubing. The detailed result of burst calculation is shown in **Table 12** and represented in **Figure 10**. Burst rating graph can be seen in **Figure 11**. Safety factor of 1.2 is used in collapse pressure calculation (Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986). Calculation of collapse pressure is done by using the worst-case scenario when the external pressure is high and the internal pressure is zero. External pressure is generated by pore pressure. The calculation using the equation for the plastic range of collapse since d_n / t ratio is 13.78. The result of collapse calculation gave 2,140.39 psi, this collapse pressure does not exceed the collapse rating for production tubing L-80 which is 10,533.92 psi. **Table 13** shows the detail of the calculation. **Figure 12** illustrates the collapse pressure calculation. **Figure 13** shows the collapse rating requirement.

Tension load calculation using safety factor of 1.6 (Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986). Since the buoyancy effect is neglected, the calculation considers tubing hanging condition using 9.3 ppf as the weight of tubing per feet. The result gave 42,809.9 lbf of tension load for tubing hanging condition. This value does not exceed tension rating of 207,063.03 lbf for L-80 tubing grade. **Table 14** shows the details of the tension load calculation. **Figure 14** illustrates the tension load graph. **Figure 15** shows the tension rating requirement.

The calculation of burst, collapse, and tension load were compared to its rating for L-80 tubing grade and the loads do not exceed the calculated rating limit. During ESP operation, there are several cases that may occur such as deadhead of the pump and the pressure this could generate or even a dead pump due to electrical issue and causing the tubing to empty. Since the L-80 tubing grade has high enough minimum yield pressure (80,000 psi), so that it can withstand the burst pressure load due to deadhead of the pump up to 7,240 psi. For the case of empty tubing, the collapse pressure calculation has been carried out with the worst condition when the internal pressure is zero. This condition has represented empty tubing condition and the L-80 tubing grade is able to withstand on this collapse pressure condition, therefore the L-80 tubing can withstand in empty tubing conditions.

IV. CONCLUSION

Based on the result and discussion above, several conclusions are shown below:

1. The production tubing that used in X-well using ESP artificial lift system has a low risk of failure due to erosional damage.
2. The production tubing L-80 that used in X-well has a low risk of failure due to production using ESP because all of the production tubing loads meet the requirements for L-80 tubing's grade rating pressure with burst pressure of 359.60 psi, collapse pressure of 2,140.39 psi, and tension load of 42,809.9 lbf.

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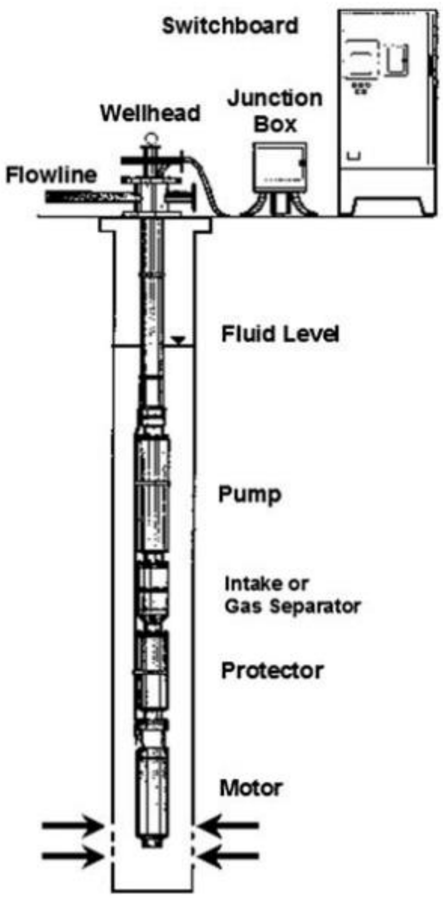

Figure 1. Conventional ESP Installation
Source: ESP Manual by Takacs, 2018

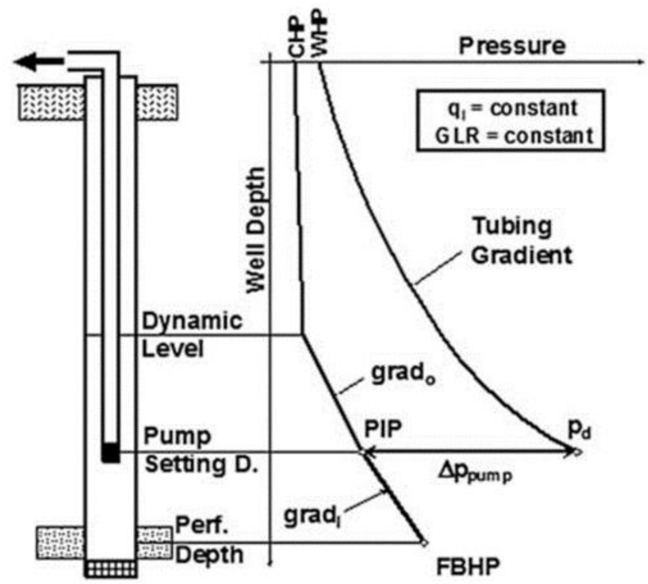

Figure 2. Pressure Profile on Typical ESP Operations
Source: ESP Manual by Takacs, 2018

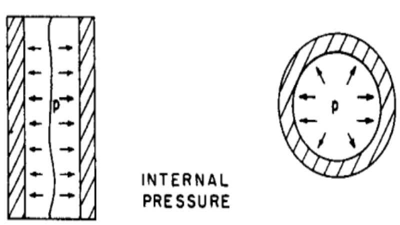

Figure 3.
Burst Load from Internal Pressure

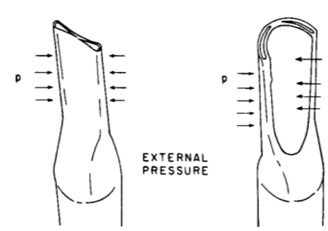

Figure 4.
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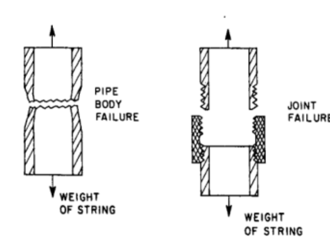


Figure 5.
Pipe Body and Joint Failure due to Axial Loads

Source: Applied Drilling Engineering by Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986

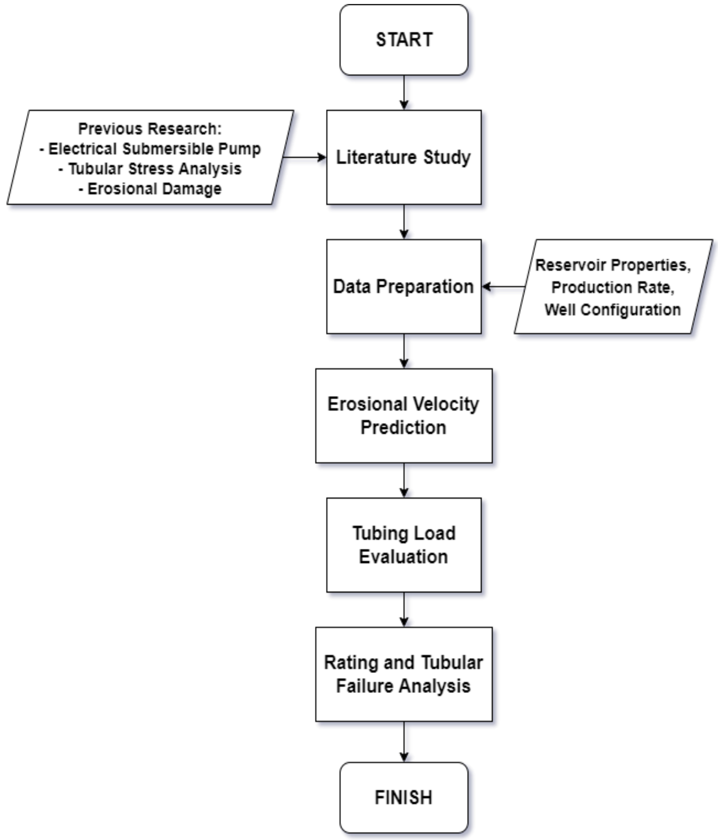
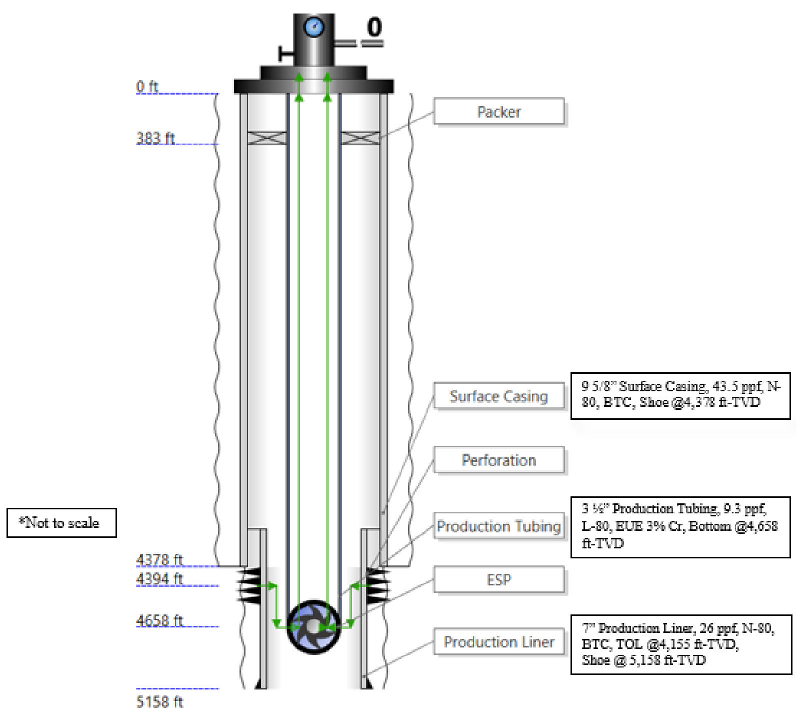


Figure 6. Flowchart of Methodology



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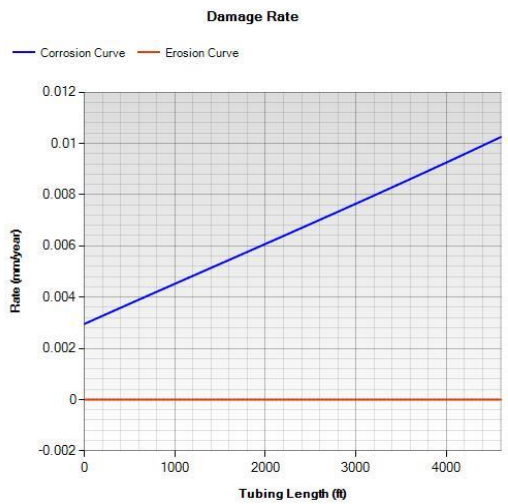

Figure 8. Modeling Results on Damage Rate due to Erosional Velocity

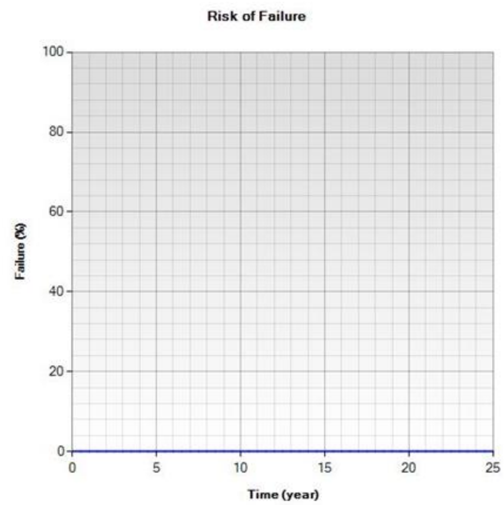

Figure 9. Risk of Failure on Production Tubing due to Erosional Damage

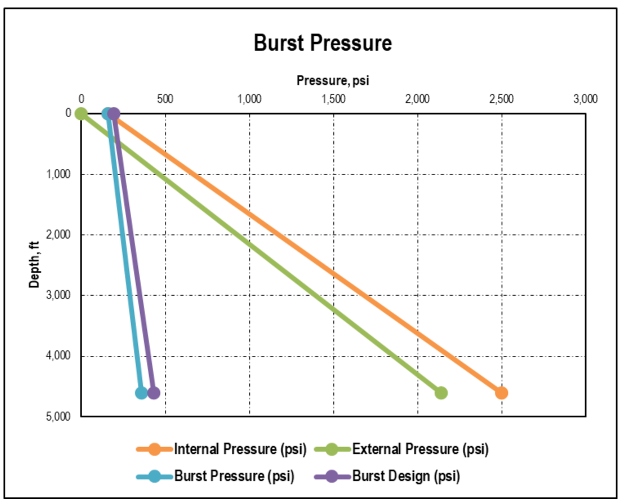

Figure 10. Burst Load of Production Tubing

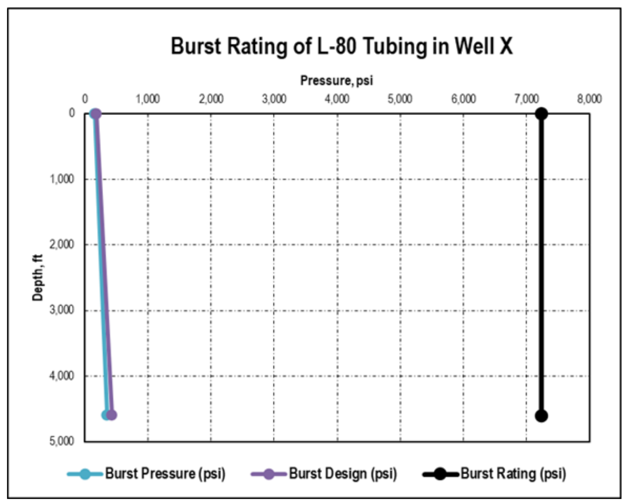

Figure 11. Burst Rating of L-80 Production Tubing in Well X

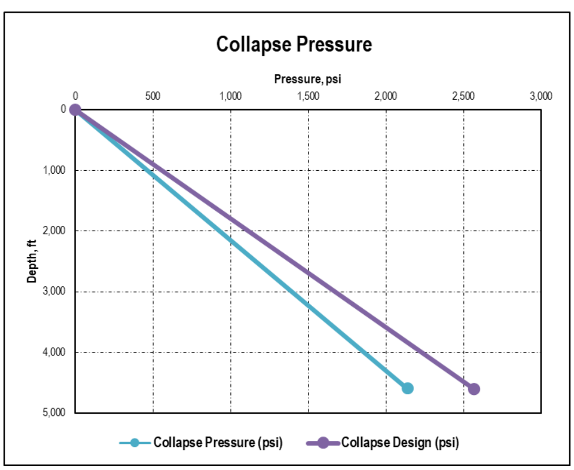

Figure 12. Collapse Load of Production Tubing

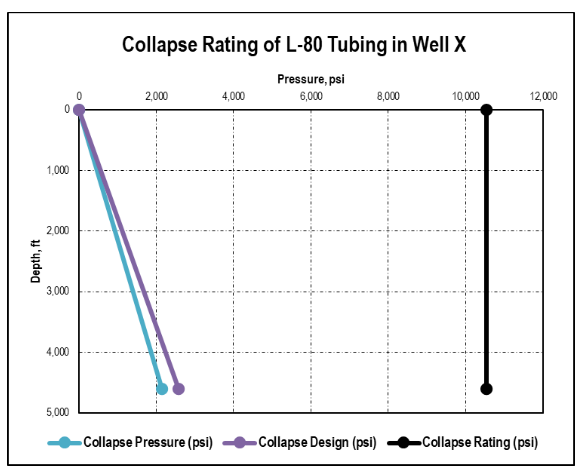

Figure 13. Collapse Rating of L-80 Production Tubing in Well X

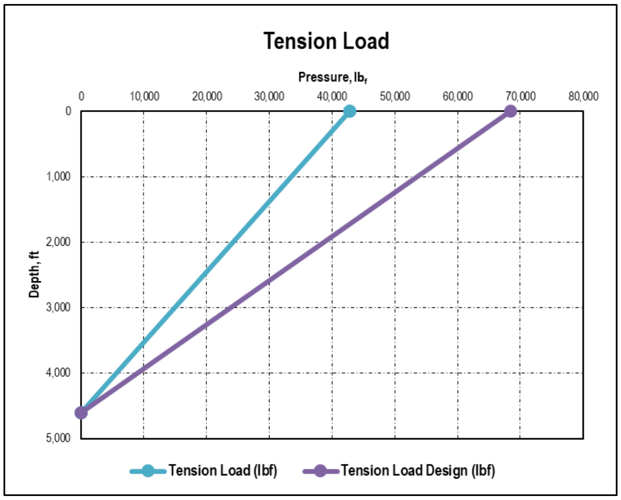

Figure 14. Tension Load of Production Tubing

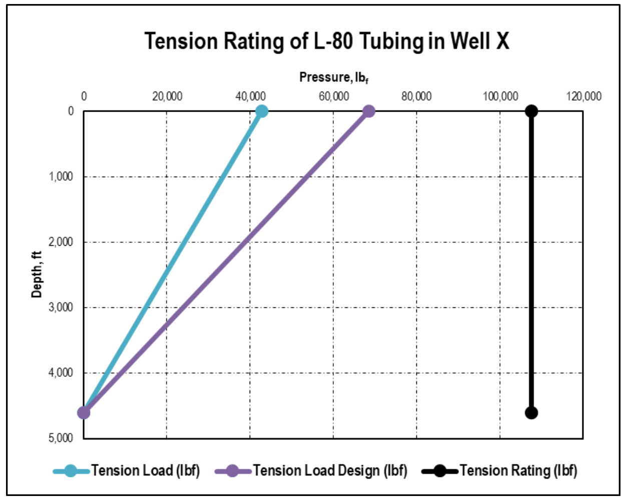

Figure 15. Tension Rating of L-80 Production Tubing in Well X

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Table 1. Applicable d_n/t Range for Yield Strength Collapse Bourgoyne Jr., Millheim, Chenevert, & Young Jr. 1986

Grade*	d_n/t Range
H-40	16.44 and less
H-55	15.24 and less
J-K-55 & D	14.81 and less
-60	14.44 and less
-70	13.85 and less
C-75 & E	13.60 and less
L-80 & N-80	13.38 and less
C-90	13.01 and less
C-95	12.85 and less
-100	12.70 and less
P-105	12.57 and less
P-110	12.44 and less
-120	12.21 and less
-125	12.11 and less
-130	12.02 and less
-135	11.92 and less
-140	11.84 and less
-150	11.67 and less
-155	11.59 and less
-160	11.52 and less
-170	11.37 and less
-180	11.23 and less

Source: Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986

Table 2. Applicable d_n/t Range for Plastic Collapse Bourgoyne Jr., Millheim, Chenevert, & Young Jr. 1986

Grade*	d_n/t Range
H-40	16.44 to 27.01
H-55	15.24 to 25.63
J-K-55 & D	14.81 to 25.01
-60	14.44 to 24.42
-70	13.85 to 23.38
C-75 & E	13.60 to 22.91
L-80 & N-80	13.38 to 22.47
C-90	13.01 to 21.69
C-95	12.85 to 21.33
-100	12.70 to 21.00
P-105	12.57 to 20.70
P-110	12.44 to 20.41
-120	12.21 to 19.88
-125	12.11 to 19.63
-130	12.02 to 19.40
-135	11.92 to 19.18
-140	11.84 to 18.97
-150	11.67 to 18.57
-155	11.59 to 18.37
-160	11.52 to 18.19
-170	11.37 to 17.82
-180	11.23 to 17.47

Source: Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986

Table 3. Applicable d_n/t Range for Transition Collapse Bourgoyne Jr., Millheim, Chenevert, & Young Jr. 1986

Grade*	d_n/t Range
H-40	27.01 to 42.64
H-55	25.63 to 38.83
J-K-55 & D	25.01 to 37.21
-60	24.42 to 35.73
-70	23.38 to 33.17
C-75 & E	22.91 to 32.05
L-80 & N-80	22.47 to 31.02
C-90	21.69 to 29.18
C-95	21.33 to 28.36
-100	21.00 to 27.60
P-105	20.70 to 26.89
P-110	20.41 to 26.22
-120	19.88 to 25.01
-125	19.63 to 24.46
-130	19.40 to 23.94
-135	19.18 to 23.44
-140	18.97 to 22.98
-150	18.57 to 22.11
-155	18.37 to 21.70
-160	18.19 to 21.32
-170	17.82 to 20.60
-180	17.47 to 19.93

Source: Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986

Table 4. Applicable d_n/t Range for Elastic Collapse Bourgoyne Jr., Millheim, Chenevert, & Young Jr. 1986

Grade*	d_n/t Range
H-40	42.64 and greater
H-55	38.83 and greater
J-K-55 & D	37.21 and greater
-60	35.73 and greater
-70	33.17 and greater
C-75 & E	32.05 and greater
L-80 & N-80	31.02 and greater
C-90	29.18 and greater
C-95	28.36 and greater
-100	27.60 and greater
P-105	26.89 and greater
P-110	26.22 and greater
-120	25.01 and greater
-125	24.46 and greater
-130	23.94 and greater
-135	23.44 and greater
-140	22.98 and greater
-150	22.11 and greater
-155	21.70 and greater
-160	21.32 and greater
-170	20.60 and greater
-180	19.93 and greater

Source: Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986

Table 5. Empirical Coefficients Used for Collapse Pressure Determination Bourgoyne Jr., Millheim, Chenevert, & Young Jr. 1986

Grade*	Empirical Coefficients				
	F_1	***F_2***	***F_3***	***F_4***	***F_5***
H-40	2.950	0.0465	754	2.063	0.0325
H-55	2.976	0.0515	1,056	2.003	0.0347
J-K-55 & D	2.991	0.0541	1,206	1.989	0.0360
-60	3.005	0.0566	1,356	1.983	0.0373
-70	3.037	0.0617	1,656	1.984	0.0403
C-75 & E	3.054	0.0642	1,806	1.990	0.0418
L-80 & N-80	3.071	0.0667	1,955	1.998	0.0434
C-90	3.106	0.0718	2,254	2.017	0.0466
C-95	3.124	0.0743	2,404	2.029	0.0482
-100	3.143	0.0768	2,553	2.040	0.0499
P-105	3.162	0.0794	2,702	2.053	0.0515
P-110	3.181	0.0819	2,852	2.066	0.0532
-120	3.219	0.0870	3,151	2.092	0.0565
-125	3.239	0.0895	3,301	2.106	0.0582
-130	3.258	0.0920	3,451	2.119	0.0599
-135	3.278	0.0946	3,601	2.133	0.0615
-140	3.297	0.0971	3,751	2.146	0.0632
-150	3.336	0.1021	4,053	2.174	0.0666
-155	3.356	0.1047	4,204	2.188	0.0683
-160	3.375	0.1072	4,356	2.201	0.0700

-170	3.412	0.1123	4,660	2.231	0.0734
-180	3.449	0.1173	4,966	2.261	0.0769

Source: Bourgoyne Jr., Millheim, Chenevert, & Young Jr., 1986

Table 6. Suggested C Factor for Erosional Velocity Calculation American Petroleum Institute 1991

Fluid		Suggested C-factor	
		Continuous Service	Intermittent Service
Solids-free	Non-corrosive Corrosive + inhibitor Corrosive + CRA	150 - 200	250
	Corrosive	100	125
With Solids		Determine from specific application studies	

Source: American Petroleum Institute, 1991

Table 7. Casing and Tubing Specification American Petroleum Institute 2011

Tubular, Grade	OD (inch)	ID (inch)	Weight (lb_m /ft)	Wall Thickness (inch)
Surface Casing, N-80	9.625	8.755	43.5	0.870
Production Liner, N-80	7	6.276	26	0.724
Production Tubing, L-80	3.5	3.246	9.3	0.254

Source: American Petroleum Institute, 1991

Table 8. Production Tubing Data

Production Tubing Data	Value
Production Tubing Grade	L-80
Type of Connection	EUE
Weight of Production Tubing, lb_m /ft	9.3
Production Tubing OD, inch	3.5
Production Tubing ID, inch	3.246
Wall thickness, inch	0.254
Minimum Yield Pressure, psi	80,000

Table 9. Chemical Composition of L-80 Tubing Grade in Mass Fraction (%) American Petroleum Institute 2011

Grade	Type	C		Mn		Mo		Cr		Ni	Cu	P	S	Si
		min	max	Min	max	min	max	min	max	max	max	max	max	max
L80	1	-	0.43	-	1.9	-	-	-	-	0.25	0.35	0.03	0.03	0.45
L80	9Cr	-	0.15	0.3	0.6	0.9	1.1	8	10	0.5	0.25	0.02	0.01	1
L80	13Cr	0.15	0.22	0.25	1	-	-	12	14	0.5	0.25	0.02	0.01	1

Source: American Petroleum Institute, 2011

Table 10. Erosional Velocity Calculation Input Data

Properties	Value
Wellhead Pressure, psia	160
Bottomhole Pressure, psia	681
Temperature at Wellhead, ˚F	77
Temperature at Bottomhole, ˚F	193
CO_2 Composition, %	0
H_2S Composition, ppm	0
Water Salinity, ppm	0
Oil API Gravity, ˚API	40.3
Crude Oil Rate, BOPD	69
Gas Rate, MMSCFD	0.028
Water Rate at Wellhead, BWPD	931
Measured Depth, ft	4,603
OD, inch	3.5
Wall Thickness, inch	0.254

Table 11. Input Data for Production Tubing Load Calculation

Properties	Value
Depth of Production Tubing, ft	4,603
ESP Discharge Pressure, psi	2,500
Pore Pressure Gradient, psi/ft	0.465
Weight of Production Tubing, lb_m /ft	9.3
Burst Load Safety Factor	1.2
Collapse Load Safety Factor	1.2
Tension Load Safety Factor	1.6

Table 12. Burst Pressure Calculation

Depth (ft)	Internal Pressure (psi)	External Pressure (psi)	Burst Pressure (psi)	Burst Design (psi)
0	160	0	160	192
4,603	2,500	2,140.395	359.605	431.526

Table 13. Collapse Pressure Calculation

Depth (ft)	Internal Pressure (psi)	External Pressure (psi)	Collapse Pressure (psi)	Collapse Design (psi)
0	0	0	0	192
4,603	0	2,140.395	2,140.395	2,568.474

Table 14. Tension Load Calculation

Depth (ft)	Tubing Weight (lb_m/ft)	Tension Load (lb_f)	Tension Design (lb_f)
0	9.3	42,807.90	68,492.64
4,603	9.3	0	0