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Geothermal Well Casing Design with High Temperature and Corrosive in Q Field

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Abstract

Casing design is the most crucial phase of drill a geothermal well. As most of problems could be prevented beforehand by having an excellent well casing design. Prior and present well problems may be assessed to enhance casing design mitigate leading causes and its relationship to well casing. This research is about geothermal well casing design by analyzing in advance the problems that the casing may encounter during drilling and production through NPT & casing damage analysis. The purpose is to construct design depth and grade of geothermal well casing from the effects of axial, hoop, and thermal stress, as well as corrosion. The method used is to analyze the NPT from the available DDR data of the wells and then analyze the damage that occurs to the production wells which then the results of these analysis' become recommendations for of the next well casing design. The results show Well FDL-33 will use tie-back system with surface casing 20" K55 133 ppf at 350 mMD with semi-premium connection, production casing 13-3/8" L80 68 ppf at 1475.8 mMD with premium connection, production tieback casing 13-3 /8" L80 68 ppf at 300 mMD with premium connection, and production liner 9-5/8" L80 40 ppf at 2695.3 mMD with semi-premium connection.

INTRODUCTION

The design process used to drill geothermal wells safely begins with identifying subsurface rocks and fluids up to required drilling tools and equipment. Most critical aspect of the design process is selection of casing, casing specification, casing shoe depth, and how the well is completed. Selection of casing depth and specification of materials weights and connections is crucial to determine success and safety of well drilling process and to the integrity and life of the well (Hole, 2008).

Casing must be able to contain any internal or external loads that are present. These loads are originated from constant factor in geothermal environment such as high temperature, hard rocks, fractured formation, corrosive fluids, and undersaturated pressure (Standards New Zealand, 2015). Consequently, in the construction process of casing depth and geothermal production well design, those factors shall be considered based on the well location conditions to guarantee casing failures do not occur.

The well to be drilled is FDL-33. This well will be a development well or an additional production well from field D. The reservoir temperature is estimated at 300-330°C with a liquid-dominated system, formation pressure is estimated to follow the water pressure gradient. The purpose of this research is to design casing well FDL-33 in Q Field by considering the effects of axial, hoop, and thermal stress, as well as corrosion.

MATERIAL AND METHODS

This research analyzes Q Field data and designs a new production well for Q Field. Q Field is one of the geothermal fields located in Central Java which has many casing problems presumably due to the high temperatures and corrosive fluids. But prior to the casing design, NPT & casing damage analysis will be taken to develop design recommendations. Recommendations will cover casing setting depth, casing configuration, and casing grade plan. During the casing grade determination, casing will be calculated by

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load scenario (burst, collapse, and tension) and chromium equivalent & thermal stress specially for production casing. Workflow for this research can be seen in Figure 1.

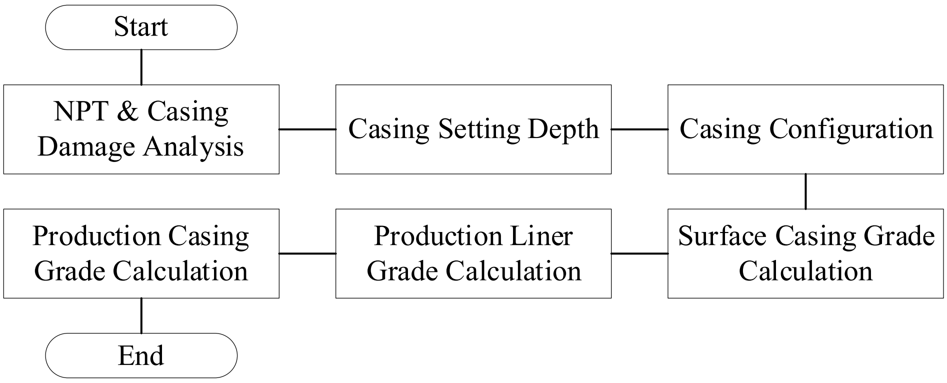


Figure 1. Research Workflow.

NPT Analysis

NPT Analysis is taken to find drilling problems that may could been corrected with better casing design. Recommendations that have been made with NPT analysis are recommendations which correlated with formation problems such as lost circulation zone isolation or tight hole prevention. NPT Analysis will classify PT and NPT based on DDR data from the offset wells. NPT will be analyzed and seen which NPT has the most influence on drilling. Then, the most influential NPT will make recommendations on casing design that focus on determining the depth and size of the hole/casing. The workflow of the NPT analysis is shown in Figure 2 below.

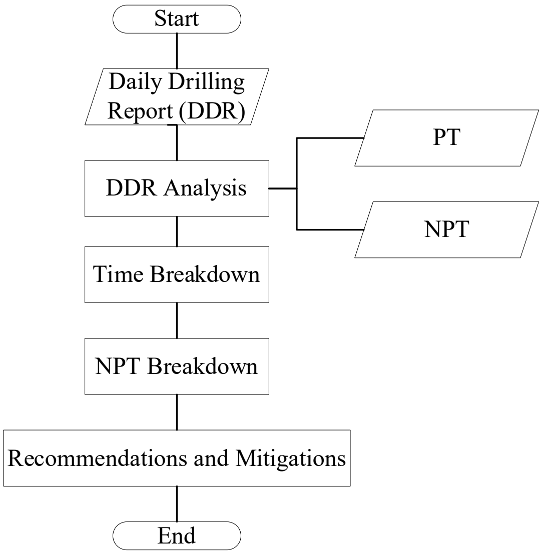


Figure 2. Workflow of the NPT analysis.

Casing Damage Analysis

Through casing damage analysis, the problems experienced by the casing during production to P&A can be identified. Therefore, casing design corrections can be made for the next well with reference to the previous casing conditions so that the problem can be resolved. Casing damage analysis will summarize the problems that occur in the casing in the wells in the geothermal field based on the casing damage report. Problems in the casing are analyzed for causes and later corrections or solutions are made for a new casing design that focuses on casing grade. The following Figure 3 is the workflow of casing damage analysis.

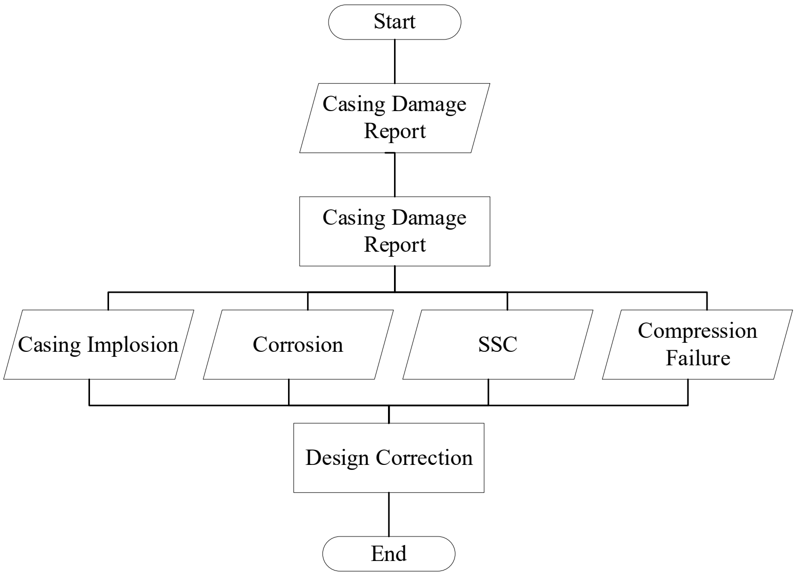


Figure 3. Workflow of Casing Damage Analysis.

Casing Grade

Following previous analysis FDL-33 casing grade calculated by estimated loads took in place while drilling process, casing corrosion resistance were also assessed. The estimated loads are hoop stress (burst & collapse), axial stress (tension), and thermal stress. As for casing corrosion, chromium equivalent analysis is performed.

Chromium equivalent

The casing grade is determined by the chromium equivalent value based on tubing material selection on corrosion rate. Corrosion rate for casing selection can be calculated by the following equation from (Ekasari & Marbun, 2015):

$$\log(\mathrm{Cr}) = 2.981 - 2.912\,(\mathrm{Cr}_{\mathrm{eq}}) - 4.532\,(\mathrm{pH})\ 25.052\left(\frac{1}{\mathrm{T}}\right)$$

Cr = corrosion rate

Cr_{eq} = Chromium equivalent

T = Temperature

Burst & Collapse

Hoop stresses are defined internal/external fluid pressures exerted radially. Burst & collapse loads are examples of these loads. Maximum loads condition occurs when cementing. Burst load design were casing full of cement.

$$\mathrm{Pb} = \mathrm{Pi} - \mathrm{Pe}$$

While collapse design were casing full of mud and annulus full of cement

$$\mathrm{Pc} = \mathrm{Pe} - \mathrm{Pi}$$

Pb = Burst load

Pc = Collapse load

Pe= External pressure by cement or mud

Pi= External pressure by cement, mud, or water

Axial stress

Tension load is generated from the weight of the casing and its maximum loads will be weight of casing minus buoyancy factor. While 100,000 lbs Margin of Overpull (MOP) were used also.

Tension = (Casing weight * BF) + MOP

For deviated section:

Tension = Wa + Bending force + MOP

Wa = (KOP*Wp) + (MD-KOP) * Cosθ

Wa = Casing weight in air

Wp = Casing nominal weight

θ = Well inclination

MD = Measured Depth

KOP = Kick off point

On production liner, load occurred are compression as terms of tension load due to uncemented:

$$\mathrm{fc} = \mathrm{Lz\ x\ Wp\ x\ g\ x}\ \left[\frac{1}{\mathrm{Ap}} + \frac{\mathrm{De}}{2\mathrm{lp}}\right]$$

fc = Total extreme fibre compressive stress due to axial & bending force

Lz = liner length

Wp= liner weight

g = acceleration of gravity

Ap = cross sectional area liner

D = OD liner

e = eccentricity (actual hole diameter minus diameter liner

lp = pipe section net moment of inertia

Thermal stress

The maximum temperature change during killing/throttling operations can reach 600°F and drop to 80°F. Therefore, further analysis is needed regarding the selection of casing materials. Thermal stress is calculated by relationship between the modulus of elasticity (E) and the coefficient of thermal expansion (α_T) from (Torres, 2014):

$$\sigma z = -E\alpha_T\Delta T$$

σz = thermal stress

E = Young Modulus of elasticity

ΔT = change of temperature

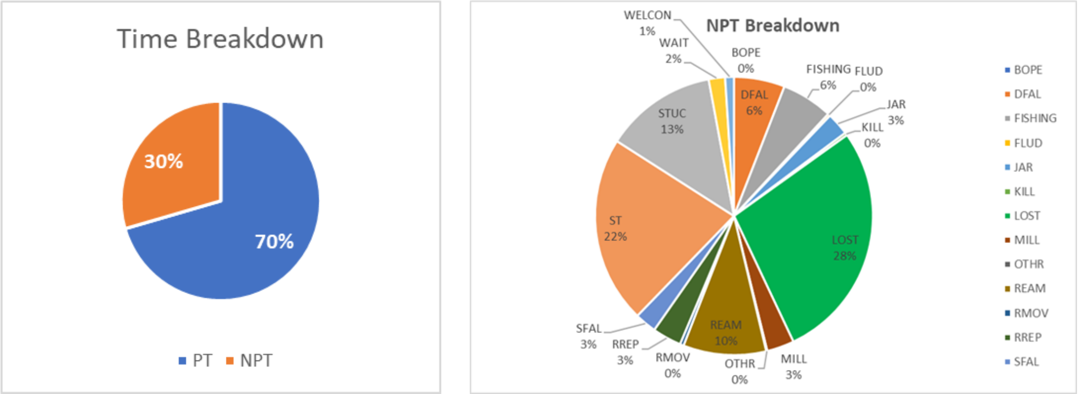
RESULTS AND DISCUSSION

Offset Wells NPT Analysis

NPT analysis analyzed 11 offset wells in the Q geothermal field. The data analyzed was obtained from the Daily Drilling Report (DDR) data for each well. Each well was analyzed by grouped each drilling activity started from the first-time drilling (spud) to completion (rig down). Out of 11 offset wells of the Q field, the total NPT that occurred was almost one-third of the total drilling duration. This shows that in the Q geothermal field, the presence of NPT greatly affects the duration of drilling and can increase drilling costs.

30 % NPT of the drilling duration of the 11 offset wells was broken down per problem to see the most influential NPT activity. The most influential NPT in the Q field was due to lost circulation (LOST) of 28%, sidetrack (ST) of 22%, stuck pipe (STUC) of 13%, and reaming (REAM) of 10%. These four NPTs are

included in the subsurface NPT category, which means that the NPT in the Q field is dominated by wellbore problems. **Error! Reference source not found.**(a) shows the effect of NPT on the total duration of drilling. Of the 11 field offset wells Q and Figure 4(b) shows the NPT per problems.



(a) (b)

Figure 4. PT and NPT breakdown (a) NPT Breakdown per problem (b)

The analysis of the four most dominant NPTs was focused on the section with the most dominant NPT, specifically section 12-1/4" to observe the relationship between the top 4 NPTs and section 12-1/4". Figure 5 showed that the top 4 NPT in the 11 offset wells in the 12-1/4" section always appeared, only in well XX-1 which did not have a top 4 NPT (no reaming).

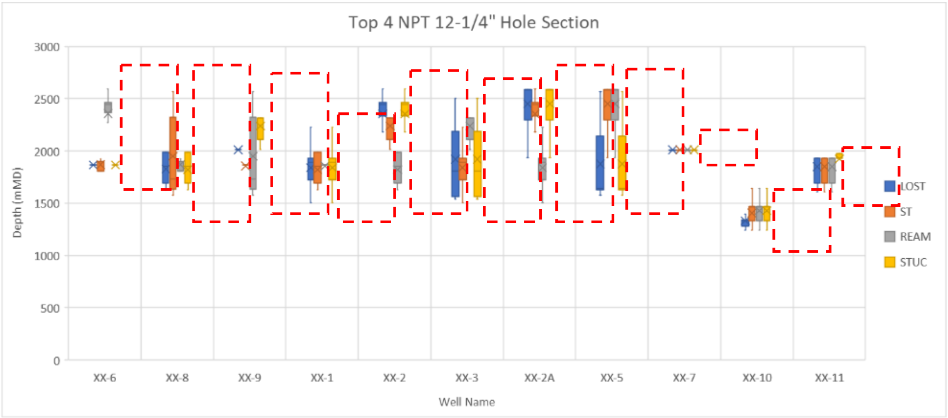


Figure 5. Top 4 NPTs in 12-1/4" section.

Further NPT analysis on section 12-1/4" in the Q field wells confirmed that section 12-1/4"(production liner zone) was highly risk without any adjustment compared to prior casing design. The potential or risks that may be experienced in drilling new production wells in Q field must be included in the planning in the form of design recommendations as this analysis will function as lesson learned analysis. NPTs associated with the casing or formation be considered to improve new well casing design and prevent later drilling problems. Based on the analysis per section, the problems that may be encountered during drilling in the Q field are related to the subsurface conditions and possibly to the well design, such as lost circulation, stuck pipes, as well as the condition of the well itself. Table 1 show recommendations on the design:

Table 1. Design recommendations based on NPT analysis on Q Field.

Problem	**Design recommendations**
Lost Circulation	Consider using a lighter density mud (<16.2 ppg) in the reservoir zone
Stuck pipe	Determination of casing depth is not on unconsolidated formation
Tight Hole	Choose a casing & wellbore size with good hole clearance
H_2S	Casing design with corrosion resistance

Production Wells Casing Damage Analysis

In Field Q consists of 45 full-size wells (regular to large-bore). These wells were drilled in sectors A and B in field Q. Based on the survey results of active wells in the Q field, most mechanical problems are related to the combined effects of external casing corrosion, thermal stress, and casing wear.

Corrosion damages both the cement and the casing, in some cases interfering with the ability of the casing to retain formation fluid in the wellbore resulting in plug and abandonment (P&A). Thermal compressive stress, especially in the first flow test of the well, causes leaks at the casing connections resulting in unwanted fluid movement between zones. The wear on the casing, which is obtained during the construction of the well, further causes a decrease in the ability of the casing to withstand corrosion and thermal stress. Other failure problems are sulfide stress cracking (SSC), casing implosion, and cracks in the casing head welds.

Increasing temperatures, corrosive fluids, and high concentrations of H_2S have resulted in many casing failures for the Q field well. At least a total of 11 wells have been plug and abandonment (P&A) in one sector. Table 2 below shows various types of casing failures in field Q based on casing damage reports:

Table 2. Q Field casing failures.

Casing failure	**Mechanism of failure**	**Total damaged wells**
Mechanical wear	Abrasive and adhesive wear from Contact load of pipe against casing; difference in hardness of materials in contact.	15 Wells
Pipe end bulge or jump off causing leak at connection	Compression failure ΔT and added heat up plus dogleg	8 Wells
Bulge in casing body	Casing Implosion- ΔT and entrapment of fluid	3 Wells
Corrosion	External corrosion from shallow acid formation (sulphate-rich).	10 Wells
Annular Leak	Consequence of external corrosion, compression failure, abrasive /adhesive wear.	5 Wells
Crack in casing and Weldment	Sulphide Stress Cracking Moist H2S environment (<80°C) and high stress areas.	6 Wells

The problems encountered in the Q field wells were related to increasing temperatures, full of gas and a corrosive H2S environment. In addition, wear of the casing due to drilling operations resulted in mechanical problems leading to the P&A of several wells. These failure findings were certain because of failure in casing design to stand high temperatures and corrosive fluids which then resulted in severe damage to production wells. Therefore, based on an analysis of the casing damage in field Q the design recommendations were made to anticipate future damage (Table 3).

Table 3. Design Correction based on casing damage analysis on Q Field

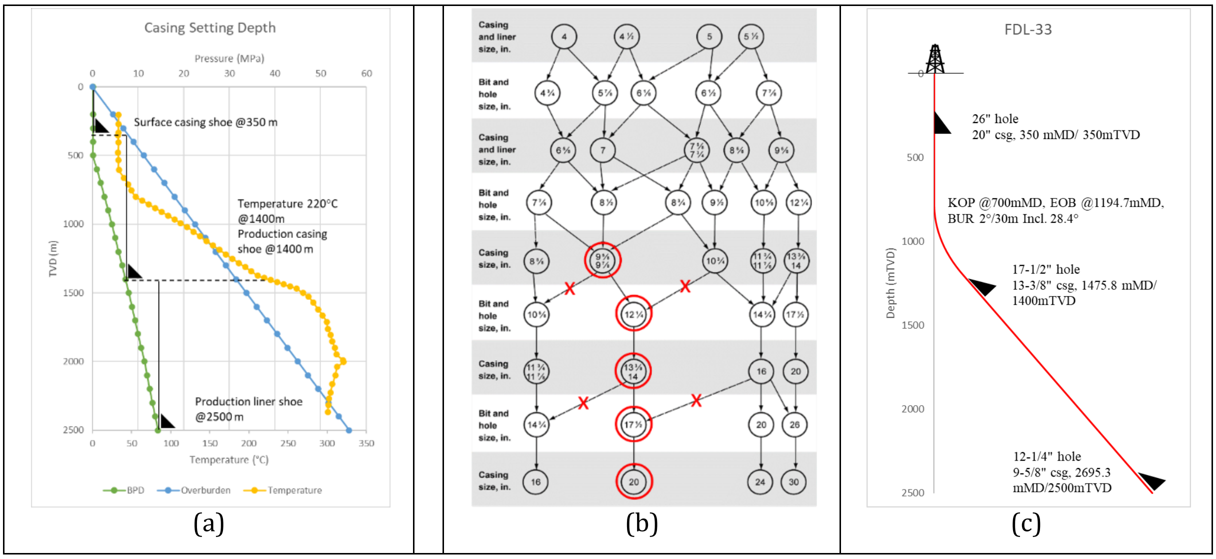
Casing failure	**Design correction**
Corrosion	-Use of thicker walled 20" (133 ppf), 13-3/8, (72ppf) casing with HRC>22 -Consider us of corrosion resistant alloy (CRA) to cover acid zones -Double or triple lining (20", 13-3/8", 9-5/8")
Bulge in casing body	-Consider tie-back cementing method over the stage cementing method -For mitigation, select thick and high-grade casing (HRC >22) for extra strength
Pipe end bulge or jump off causing leak at connection	-For 2-stage and tie-back method, pre-calculate the amount of overpull -Use premium connection and high strength casing (Grade L80) for anchor dan production casing.

Mechanical wear	-Use thick anchor and production casing (HRC>22).
	-Provide for at least 3 mm of corrosion / wear allowance
Annular Leak	-Consider tie-back system

Casing Setting Depth and Configuration

The well to be drilled is FDL-33. This well will be a development well or an additional production well from the Q field. The reservoir (307.49 °C based on offset wells) is a liquid-dominated system, formation pressure is estimated to follow the water pressure gradient, but the water level is unknown. Pore pressure data uses BPD and overburden of 0.224 MPa/m from offset well XX-3. The temperature data used is also data from offset well XX-3 based on(Marbun et al., 2019) for same referenced well due to data limitations.

Determination of the depth of the casing was by Philippines method, the production casing shoe placed on the top of the reservoir (TOR). at a minimum temperature of 220°C at 1400 mTVD. FDL-33 is a directional well so that stuckpipe during drilling and mechanical wear may occur. Therefore, the DLS as well as the size of the hole and well casing follow the considerations of NPT analysis and casing damage. The DLS from the XX-3 well data used in the FDL-33 well is 2°/30m according to the recommendation earlier (DLS <3°/30m) with KOP at 700 mMD. The size of the hole and casing also considered so that the possibility of a stuckpipe is reduced (Figure 6).



(a) (b) (c)

Figure 6. Casing setting depth (a) Determination of hole and casing size (b) and well trajectory (c).

Based on casing damage analysis, it was also recommended to use the tie-back cementing method. This is because in field Q there are numerous problems related to compression failure and annular leak which may also be caused by thermal expansion of trapped fluid. Final configuration of FDL-33 is detailed by

Table 4.

Table 4. FDL-33 Casing configuration with casing tie-back.

Hole/ casing size	Configuration	Depth interval (mMD)
36”/30”	Conductor Casing	0-20
26”/20”	Surface Casing	0-350
17-1/2”/13-3/8”	Production Tieback	0-300
17-1/2”/13-3/8”	Production Casing	300-1475.8
12-1/4”/9-5/8”	Production Liner	1425-2695.3

Casing Loads

Grade for surface, production, and production tieback casing were determined firstly by calculating burst, collapse, and tension load. Burst load scenario assumes that casing is in cementing condition where casing is full of cement and float valve is blocked (Internal pressure = cement pressure, external pressure=BPD). While collapse load scenario assumes that cement is fully pumped to annulus (Internal pressure = drilling mud pressure, external pressure=cement pressure). Then, tension load calculates amount of tension while running casing with or without bending stress presence since FDL-33 was a directional well. Specifically for production liner, burst & collapse were not calculated since liner will not be cemented but only placed at bottom therefore only tension is present.

All loads were calculated following the recommendations by previous analyses mentioned in

Table 1 and

Table 3. As per recommendations, cement density assumption used was 15.8 ppg (<16.2 ppg) except for the tieback (16.2 ppg) as tail slurry. Also, casings with HRC>22 are priorities as it's thicker to prevent casing damages in Q Field. As a result, surface casing K-55 133 ppf will be used while other casings grades need to be analyzed further. Burst, collapse, and tension load graphs for each following sections of FDL-33 are shown in Figure 7, Figure 8, Figure 9 and Figure 10.

Surface Casing

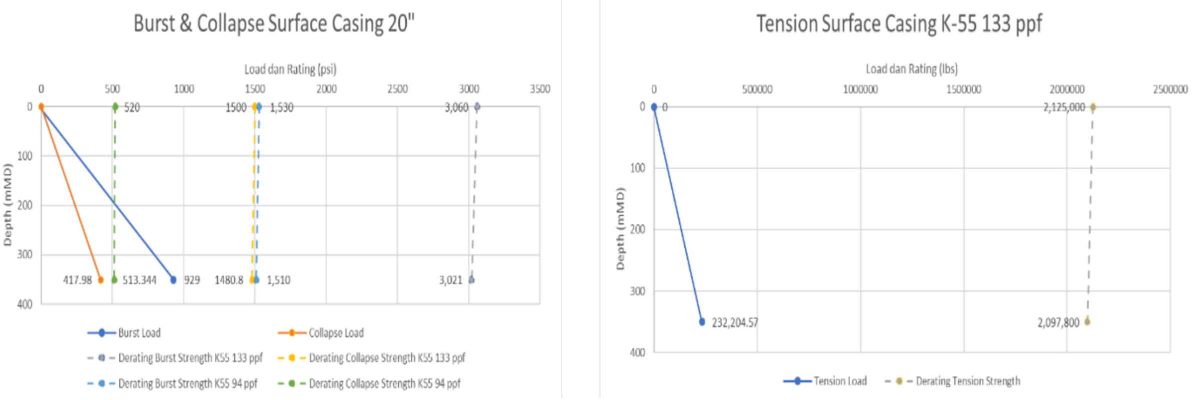


Figure 7. Burst, collapse, and tension loads of surface casing.

Production Casing

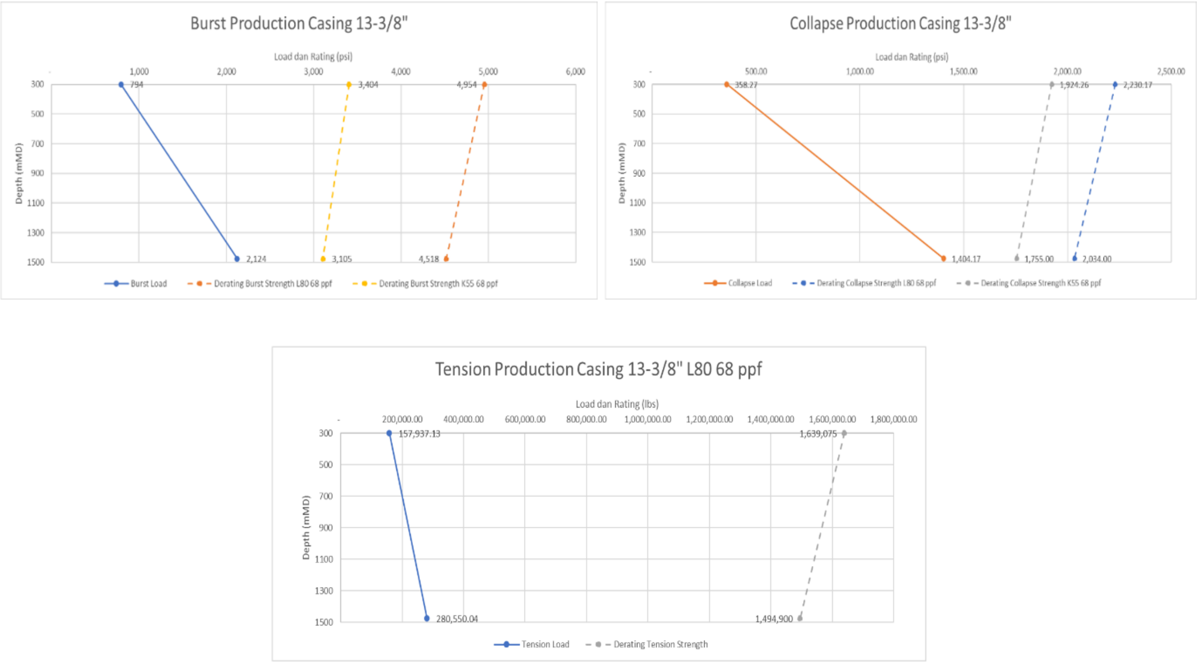


Figure 8. Burst, collapse, and tension loads of production casing.

Production Tieback Casing

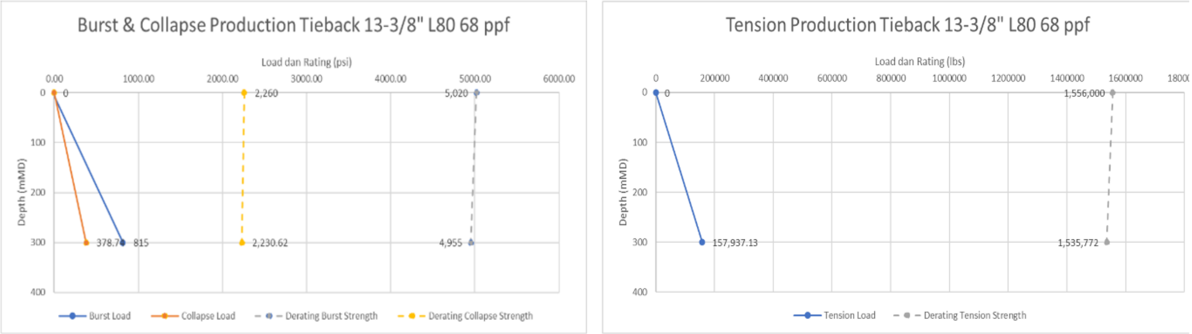


Figure 9. Burst, collapse, and tension loads of production tieback casing.

Production Liner

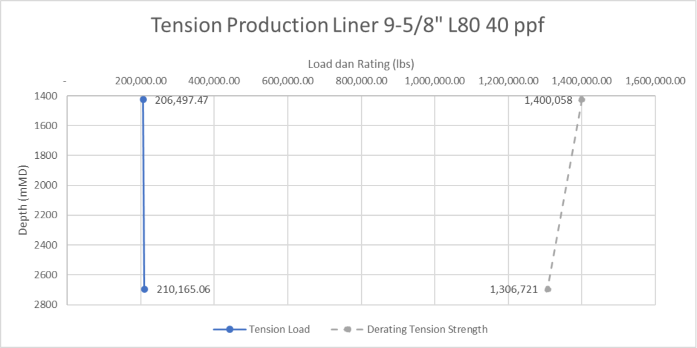


Figure 10. Tension loads of production liner.

Other loads considerations for FDL-33 were also assessed since geothermal wells are not highly affected with formation pressure but also high temperatures and corrosive fluids. Therefore, thermal stress and chromium equivalent analysis were taken for production & production tieback casing where temperature most high and corrosive fluids flow. More specific analysis is compressive stress analysis for production liner. Since production liner will not be cemented, loads for liner are its own weight and has tendency to buckling due to compressive stress.

Chromium Equivalent Analysis

Chromium equivalent (Creq) analysis were conducted following the methodology from (Ekasari & Marbun, 2015) with prior corrosion rates calculation from (Bahadori, 2017) as data it's not available. Following the recommendations from casing damage analysis, corrosion allowance (CA) 3 mm is used for a typical geothermal well life of 30 years, the maximum corrosion rate for FDL-33 is 0.1 mm/year. Then the corrosion rate of 0.1 mm/year is included in the Creq calculation with the most extreme conditions simulated (most acidic pH 4 and a maximum temperature of 307.49 °C from Q Field data). The results of the calculation analysis show in Figure 11 that the Creq value is -4.88615.

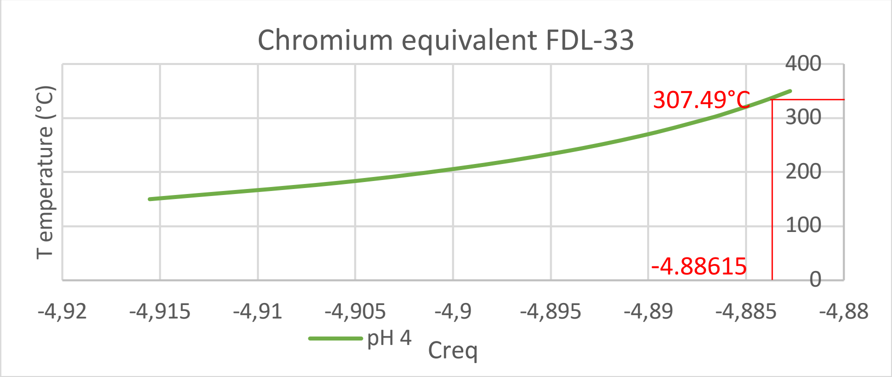


Figure 11. Graph plotting & calculation of Creq.

Through the Creq calculation, the casing grade that will be used in production casing, tie-back, and liner was obtained minimum of M65 (Creq = -5.5 to -4.3 from API 5CT). The M65 casing is included in group 2 on the API 5CT which means a special corrosion resistant casing that has HRC> 22 (recommendation of casing damage analysis). However, the M65 casing is still relatively new in API 5CT, data is less available, so the design will use a higher casing L80-1 as a replacement for the M65.

Thermal Stress Analysis

Thermal stress analysis estimates the amount of compressive stress received by production casing and tieback in the well's thermal cycle after cementing. The temperature of the well at cementing was at 80°F, then after cementing it rose to the equivalent of the maximum temperature/reservoir temperature of 585.48°F, then dropped again during the killing/quenching process to 80°F. Figures below are the thermal stress received by the L80 68 ppf casing from chromium equivalent analysis with yield strength equal to 80000 lbs in the thermal cycle of FDL-33 well. Figure 12 shows the compression stress reservoir temperature, while Figure 13 shows the amount of tensile stress will be received in a well cycle.

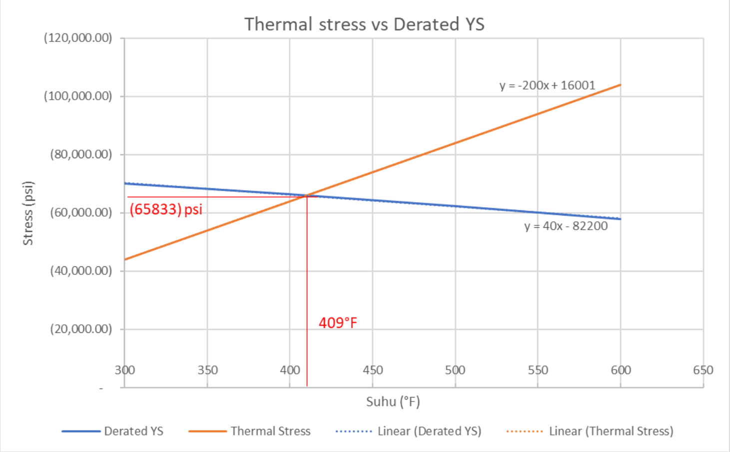


Figure 12. Thermal stress vs derated YS L80 68 ppf.

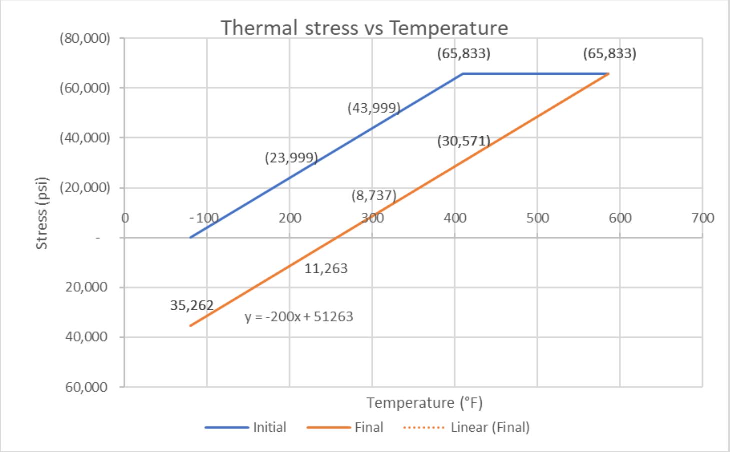


Figure 13. Thermal stress vs temperature L80 68 ppf

The result of the intersection of the derated YS curve with thermal stress shows a temperature of 409°F and a stress of -65833 psi. Thus, L80 68 ppf casing will begin to experience compression at 409°F at a constant stress of 65833 psi. As the temperature increases from 409°F, the stress will be constant while the length of the casing will shorten due to compression. When the well temperature rises from 80°F to a maximum temperature of 585.48°F and then drops back down to 80°F, a tensile stress of 35262 psi will be generated. This tensile stress is 44% of the total YS rating of the L80 casing 68 ppf or with a design factor calculation of 2.27 (minimum 2.0). Therefore, it can be concluded that the L80 68 ppf casing can be used as a production casing and tieback.

Compressive stress on uncemented liner

This calculation analyzed whether the liner 9-5/8" L80 40 ppf can withstand compressive stress as buckling effect. Based on API, the YS of L80 40 ppf is 80000 lbs. In this calculation, hole size enlargement 0.125" was used 6 times (Table 5).

Table 5. Axial compressive stress liner 9-5/8"-L80 40 ppf.

Actual hole diameter (in)	12 1/4	12 3/8	12 1/2	12 5/8	12 3/4	12 7/8
Actual hole diameter (mm)	311.2	314.3	317.5	320.7	323.9	327.0
eccentricity (mm)	66.7	69.9	73.0	76.2	79.4	82.6
Extreme fibre compressive stress (lbs)	27052	27756	28459	29163	29866	30570
Design Factor (Min. = 1.2)	**2.44**	**2.38**	**2.32**	**2.27**	**2.21**	**2.16**

Based on the enlargement of the hole by 6 times, the result shows that the liner -5/8"-L80 40 ppf is still safe from axial compressive stress. Hence, the liner 9-5/8"-L80 40 ppf with a length of 1269.5 m can be used in the FDL-33 well.

Casing Design summary

Altogether previous casing design analyses and calculations are combined to develop the final design of FDL-33 well. Regarding the casing connection, following the recommendations from the casing damage analysis for not using a BTC connection but premium, specifically in production casing. Thus, the final design for the FDL-33 well casing is as shown in

Table 6.

Table 6. FDL-33 well final casing design.

Casing	**Depth Interval (mMD)**	**Hole Size, in**	**OD, in**	**ID, in**	**Drift Diameter, in**	**Grade/ Weight**	**Connection**
Conductor Casing	0-20	36	30	-	-	X-42/ 148 ppf	Welded
Surface Casing	0-350	26	20	18.73	18.54	K55/ 133 ppf	Semi Premium
Production Tieback	0-300	17-1/2	13-3/8	12.415	-	L80/ 68 ppf	Premium
Production Casing	300-1475.8	17-1/2	13-3/8	12.415	12.259	L80/ 68 ppf	Premium
Production Liner	1425.8-2695.3	12-1/4	9-5/8	8.835	8.679	L80/ 40 ppf	Semi Premium

CONCLUSION

NPT analysis proved that drilling practice could also be related with well design as in Q Field well problems are lost circulation and stuckpipe most common due to poor hole clearance and casing setting depth. Thus, recommendations developed for the next well are to set the depth of the casing not in unconsolidated formations, use mud densities <16.2 ppg when drilling the reservoir zone, and decent hole clearance. Another suggestion that may be advance this research is to combine with lithological or subsurface data hence this analysis can reach be optimum.

Casing damage analysis on the other hand, has proven that Q Field needs developing a new well design cause severe casing damage that led to P&A. As previous research on casing damage reports, high temperatures and corrosive fluids were responsible for mechanical wear, external corrosion, casing implosion, compression failure, and annular leak in Q Field production wells. Design corrections newly developed to the casing design simply to withstand thermal stress exerted due to high temperature and conserve casing thickness from acidic yet corrosive fluids to its expected life. Therefore, new casing design use of a thicker casing (HRC>22) and corrosion resistance alloy (CRA), as well as a tieback system.

Based on design recommendations from NPT analysis & casing damage as well as calculations of burst, collapse, tension, and corrosion & thermal stress analysis, FDL-33 will use surface casing 20” K55 133 ppf, production casing & tieback 13-3/8” L80 68 ppf, and the production liner 9-5/8” L80 40 ppf.

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