Casing design (temperature-base) of the K well in ‘NPY’ geothermal field - Indonesia

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Abstract. This study explains the casing design for the K well in geothermal field, that involve high temperature of wellbore about 200 °C – 300 °C. In the wellbore, elevated temperature generates stress that occurs in the casing material, cause casing installed in the wellbore to expand and shrink, and ultimately failure at a certain temperature conditions point. This failure will change the production casing in length, as well as the well integrity. The casing design for geothermal well must consider high temperature first, because the thermal effect on the casing strength, resistance and burst, that cause the maximum joint strength of the casing decreases, and leads to the collapse of the well. This study concludes that the design of geothermal well casing configuration which is suitable for the K well are casing grade L80 for surface section, casing grade S95 for production section, and grade S95 for slotted liner section. which agreed with the design factors for the temperature maximum of plastic deformation i.e. 599.26 F, 667.6 F, and 852.36 F for respectively sections: surface, production, and liner depths. This study also gives a benefit, i.e. recommendation for the field similar characteristics with the K well – Indonesia. Pore and fracture or overburden pressure gradients, is a determinant in casing shoe depth selection, the depth where temperature variation, play role in decreasing the strength of casing material. It must be a major concern. Author suggest a reservoir geomechanics studies on pore and fracture pressures gradient on the reference geothermal well, may provide a comparison in casing depth selection based on resistivity logs analysis besides BPCD.

1. Introduction
By any change in temperature to a material, a thermal stress is created. Geothermal wellbore temperatures in high temperature field, with reservoir temperature of 250 – 300 °C and high enthalpy 1000 – 2800 kJ/kg [1], not only causes the decrease of casing materials yield strength, but also leads to the change of casing materials elastic modulus and coefficient of thermal expansion. Casing materials modulus of elasticity decreases linearly with the rise of temperature, while its thermal expansion coefficient increases with the rise of temperature [2]. Besides calculating the value of the load parameters that occur in each section of the casing to be installed in the well, it is also necessary to consider the influence of temperature variation on the above parameters, so that the design is safe against loads, and the influence of high temperatures. An example is the high temperature geothermal well with the highest wellhead temperature measured was 450°C [3] at pressure around 144 bar [4], has caused the production casing was severely damaged by multiple coupling failures and casing collapse. This concluded the elevated wellbore temperature will increase the load on the casings.

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2. Methods
This study aims to determine the grade of the casing strength, safe from the loads and temperatures. Thermal effect on casing design of geothermal well, based on thermally induced axial and radial stress, and plastics deformation. The data used are hydrostatics or pore and fracture or overburden pressure gradients of the reference well in the NPY geothermal field. There are 6 (six) steps of work in this study.

First, determining the casing shoes depth based on hydrostatic and overburden pressures gradient. Minimum depth of casing (according to the New Zealand code of practice 1991 [5]), is determined by the way of extending the hydrostatic pressure up the well until it intersects the overburden pressure line. This is commonly called BPDC (boiling point-depth curve) approach. By repeating the procedure, then casings depth for conductor, surface, production and liner can be determined. Second, plastic deformation analysis: finding the maximum temperature for plastic deformation obtained from the intersection of the yield strength and thermal stress lines at formation’s temperature range. The maximum temperature for plastic deformation, i.e. conditions of plastic deformation when thermal load no longer caused a strain process after passing this temperature. The material has exceeded its yield strength maximum, and at the same time its compressive stress value remain constant, although the temperature continues to increase effectively [6,7]. Third, calculating the percentage of yield strength reduction at formation's temperature for the each casing sections. Forth, Design Factor (DF) analysis i.e. Yield Strength Reduction divided by Adjusted Loads, to find the casing strength which has been in plastic deformation condition (reduction yield strength). Fifth, calculating the thermal stress of the casing which has been in a plastic deformation condition. Sixth: casing grade selection based on the DFs.

3. Geothermal well casing configuration and casing depth selections
The initial stage in well casing design is casing configuration determination. The configuration typically is divided in three sections [8], namely surface or conductor (the largest diameter), anchor or intermediate that support success that supports successive wellhead, and production or reservoir section. The depth of each section should be chosen on the basis of the expected depths, and conditions (temperature and pressure) of production fluids. Determination of the expected depth for each section is influenced by drilling engineering, and geoscience information such as pore pressure and fracture pressure gradients, as well as the depth of the top reservoir.

![Figure 1](image1.png)
**Figure 1.** An example of pore pressure and fracture gradients used in casing depth selection [9].

![Figure 2](image2.png)
**Figure 2.** An example of pore pressure and overburden gradients used in casing depth selection by New Zealand code of practice [5].
Figure 1 and 2 are example of the selection of casing shoe depth for each section (surface, production, liner) based on pore pressure, and overburden or fracture pressures gradient.

4. Geothermal casing design (temperature base)

The major considerations in designing geothermal well casing is temperature. There are different parameter need special consideration due to elevated temperature. Aside from the yield strength reduction consideration, the two additional design criteria that need to be included are thermally induced axial stress and plastic deformation. Besides, selection of the casing connection is also critical. The connection should have the strength to withstand the compressive and tensile stresses generated when exposed to high temperature.

4.1. Thermally induced axial stress

Once the casing is cemented, thermal expansion resulting from elevated temperature is restricted because of creating axial compressive stress within the casing string. The maximum temperature change of the well occurs during throttled (killing) operations. In geothermal wells, wellbore temperatures can reach as high as about 600 °F (315.6 °C) when throttled and as low as 80 °F (26.7 °C) when killed. With the high temperature change, material properties of casing should be investigated for stress-temperature relationship to prevent casing failure.

Axial strain \( \varepsilon_z \) is introduced when casing is subjected to a change in temperature, which is related to coefficient thermal expansion. When the casing is cemented in place, the induced strain is converted to stress, which is related to Young’s modulus elasticity.

Liu Xiao-gang et al. [10] discovered that the yield strength, coefficient of thermal expansion, and modulus of elasticity of N80 change with temperature variation. Table 1 shows that under elevated temperature, casing grade N80’s yield strength and its modulus of elasticity is reduced progressively with a status of linear relationship. Noted that N80’s coefficient of thermal expansion is observably enlarged along with the temperature raising [11].

| Temperatures Degrees C | 20   | 100  | 150  | 200  | 250  | 300  |
|------------------------|------|------|------|------|------|------|
| Yield Strength (M.Pa.) | 600.46 | 583.24 | 572.48 | 561.72 | 550.96 | 540.20 |
| Elasticity Modulus (G.Pa.) | 208.09 | 287.62 | 174.82 | 162.03 | 149.23 | 136.44 |
| Thermal expansion coefficient, \((\text{m/}(\text{m}^2\text{C})\times10^-6)\) | 0.66 | 14.50 | 20.35 | 24.03 | 25.56 | 24.94 |

4.2. Yield strength reduction and casing grade selection

The weight and grade of casing to be used for each section will be dependent on the burst rating, collapse resistance, tensile strength, thermal stress, and corrosion resistance requirements dictated by the design criteria, geologic environment and operating conditions. In general, the burst rating, collapse resistance and tensile strength of casing are linearly proportional to the yield strength of the material. For certain conditions where the ratio of the pipe diameter to the wall thickness is high, the collapse rating is no longer linearly proportional to the yield strength [11]. Various casing manufacturers have their own tables for yield strength degradation due to temperature which the designer may opt to use. Casing Yield Strength Degradation provided by Grant Pride Co – TCA shown in Table 2.

4.3. Plastic deformation

The concept of plastic deformation design for casing has many applications in geothermal well design. For example, if tieback casing cemented at 100°F (37.8 °C) was subjected to flowing temperature of 550°F (287.8 °C), the theoretical thermally induced compressive stress on the casing would exceed the yield strength if L-80 casing was used. However, once the casing reaches the yield point, the
compressive stress remains constant while the temperature continues to increase effectively shortening the length of the casing. When the casing is cooled to 80°F (26.7 °C) (quenching) after yielding, the casing will be shorter that its original length and tensile stress will be generated as the temperature decreases.

| Temperature Degrees F | Standard API Casing Grade | K-55 | N-80 | L-80 | C-80 | C-95 | T-95 |
|------------------------|---------------------------|------|------|------|------|------|------|
| 300                    |                           | 0.875| 0.875| 0.875| 0.925| 0.875| 0.925|
| 400                    |                           | 0.830| 0.830| 0.830| 0.890| 0.830| 0.90  |
| 500                    |                           | 0.780| 0.780| 0.780| 0.860| 0.780| 0.860|
| 600                    |                           | 0.725| 0.725| 0.725| 0.825| 0.725| 0.825|

Table 2. Casing yield strength degradation by Grant Pride Co.

Theodoriu et.al [12] has calculated the material yield strength induces thermal stress, for common used grades of casing. The result is shown in Table 3. It concluded that the temperatures in any higher enthalpy geothermal well will cause plastic deformation even in casing strings made of high-grade steel.

Table 3. The material yield strength induces thermal stress, for common used grades of casing.

| Grade        | J-55 | N-80 | P105 | P110 |
|--------------|------|------|------|------|
| Temperature change (degrees C) | 157  | 222  | 286  | 310  |
| Temperature-corrected yield strength (MPa) | 392  | 553  | 712  | 771  |

4.4. Safety factor
There are recommended safety factors for thermally induced axial stress and plastic deformation are shown in Table 4.

Table 4. Safety factor for thermal induced stress, and plastic deformation [11].

|                          | Safety Factor |
|--------------------------|---------------|
| Thermal Induced Stress   | 1.0           |
| Plastic Deformation (Maximum Tensile Load) | 2.0 |

5. Parameters used
The parameters used for burst, collapse, tension and thermal stress calculations are derived from the characteristics of the reference well, casing material and mud properties, shown in Table 5.

Table 5. The parameters used for burst, collapse, tension, and thermal stress calculation.

| The Reference Well | Casing Material | Mud Properties |
|-------------------|-----------------|----------------|
| Gf, Fracture pressure Gradient [psi/ft] | Collapse rating, [psi] | Mud Weight, [Sg], [ppg] |
| Gob, Overburden pressure Gradient, [psi/ft] | Body Yield, [lbs] | Wu, [ppf] |
| Depth @Casing Shoe, [m] | Internal Yield pressure, [psi] | Collapse Rating, [psi] |
| Rock Formation Density (andesite), [g/cm³] | Joint Strength [lbs] | Cement Density, [ppg] |
| Rock Formation Density (granodiorite), [g/cm³] | Strength Casing, [psi] | |
| Temperature and pressure profile | OD, outer diameter, [inch] | |
| | ID, inside diameter, [inch] | |
6. Steps of the study and result

Step 1: Casing shoe depth selection for the well casing configuration, referred to hydrostatic and overburden (soil) pressure gradients of the reference well in the NPY geothermal Field [13]. The casing diameters used in this study is as follow: conductor 30”, surface 20”, production 13 3/8”, liner 10 3/4”.

The results are: casing liner shoe depth of 2100 m TVD, production casing string shoe at depth of 1200 m TVD, intermediate or anchor casing string shoes at depth of 600 m TVD.

Step 2: By referring the well temperature profile, calculating the thermal stresses due to elevating temperature ranges from: a) 200 °C to 315 °C at the casing surface casing shoe depth, b) 200 °C to 480 °C at the production casing shoe depth, c) 200 °C to 480 °C at the liner casing shoe depth.

Step 3: Finding the maximum temperature of plastic deformation ($T_{max}$) at the casing shoe depth. This study found $T_{max}$ casing are 315.14 °C at the intermediate casing shoe depth, 353.14 °C (667.6 °F) at the production casing shoe depth (Figure 3), and 455.75 °C at the liner casing shoe depth.

Step 4: Found the yield strength reduction of 31.75%, 35.30%, and 35.30% for surface, production and liner sections respectively.

Step 5: Found the Design Factor ($DF$): Burst [2.6 - 20”, 1.9 - 13 3/8”, 6.6 -10 ¾%]; Collapse [1.4 – 20”, 1.4 – 13 3/8”, 1.7 – 10 ¾”]; Tension [5.8 - 20”, 3.7 – 13 3/8”, 1.7 – 10 ¾”;] Thermal Stress [3.0 - 20”, 2.0 – 13 13/8”, 2.2 - 10 ¾”].

Step 6. Found the selected casing grade based on $DF$s: L80 for surface section, S95 for production section, S95 for slotted liner section.

![Figure 3. Finding $T_{max}$ of plastic deformation at production casing shoe depth, i.e. 667.6 OF or 353.1 OC, is a point of intersection between thermal stress line and yield strength reduction line. [Nanda Pratama Yufi, his final assignment for Petroleum undergraduate Program] [14].](image)

7. Conclusion

The suitable casing grades for the K well are L80 surface casing, S95 production casing, and S95 liner, which agreed with the design factors at temperature maximum of plastic deformation ($T_{max}$) 599.26 °F, 667.6 °F, and 852.36 °F respectively for surface section, production section, and liner depths.

8. Discussion

Since each geothermal field or reservoir has its own characteristics, this study will give a benefit, i.e. recommendation of the casing design for the field, which has similar characteristics with the NPY Field – Indonesia. Even though, the pore pressure and overburden pressures gradient, as a determinant of the casing shoe depth selection, must be a major concern. In this study, pore pressure gradient is hydrostatic pressure of the Boiling point-depth curve (BPDC) [15,16], has been used to determine minimum casing depth. While, the pore and fracture pressure gradient applicable in oil and gas industry is obtained by analysing resistivity logs and leak of test data (LOT) [9] instead of BPDC, then
the author suggests that this study need to be compared using geomechanics approach [17,18], to obtain pore and fracture pressures gradient.

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