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Integrated Analysis of Optimizing Casing Materials Selection of Geothermal Well by Using a Model for Calculating Corrosion Rates

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ABSTRACT

The lifetime of geothermal well can be maintained as long as possible by performing the well casing design, particularly the selection of the appropriate production casing. Due to the fact that it is the only casing that is in constant contact with the extracted geothermal fluid. Considering that the geothermal fluids often have a high salinity and contain many corrosive agents, it is not surprising that corrosion phenomena are a rather frequent occurrence in production casing resulting to thinning that can lead to failure.

This study presents a comprehensive methodology, as a pilot project of selecting production casing based on corrosion resistance in geothermal environment by using corrosion rate calculation resulting from Kurata et al. (1995) experiments and pressure drop modelling. This study has been implemented for selecting materials casing in well conditions similar to well "A" in a geothermal field in Indonesia. Based on this study, it is known that the corrosion rate equation by Kurata et al. (1995) cannot be applied in different geothermal environment directly due to the differences in data and observed area. Therefore, generation models have been made from the Kurata's corrosion rate equation to the field data using analytical software SPSS to be more applicable regarding the particular condition. It is expected that the corrosion rate equation results of this study could be developed for geothermal well conditions in Indonesia and further research about corrosion in wellbore should be pursued.

1. INTRODUCTION

There were reports regarding casing failures and one of them is in Indonesia. A geothermal field in Indonesia was drilled to depths of more than 2000 meters. The wells encountered corrosive fluids with temperatures higher than 320°C and pH value equal to 1, which destroyed cement and casing at a depth of 600 meters (Sanada, et al., 1997). Therefore, materials selection of production casing and casing design has to be done as part of mitigation of casing damage caused by corrosive and high temperature acidic geothermal fluids. It also has a significant effect on the lifetime and performance of geothermal well. Materials selection generally was approached by mechanical and corrosion resistance design. Aside from stress and load that occurs in the well, calculation of corrosion rate in production casing is also important in order to prevent failure during well operation.

Currently the study of corrosion rate calculation in geothermal environment was only been conducted in Japan from experimental data using the regression method by Kurata, et al. (1995). They did corrosion tests for materials under various geothermal conditions in several deep geothermal wells in Japan. They stated that they have built the relationship between corrosion rate results from tests on different corrosion environment using different alloy elements. The relationship has been derived to make the data and equation applicable to material selection in more general geothermal environment.

This study is intended as a pilot project to introduce a comprehensive methodology of selecting production casing in terms of corrosion resistance in geothermal using data from a geothermal field in Indonesia. The methodology was done by following Kurata's method using corrosion rate calculation and pressure drop modelling. Afterwards, the casing result was optimized by modifying the correction factor of the corrosion rate equation.

2. CORROSION IN GEOTHERMAL WELL

Geothermal fluids contain several chemical species that can be acidic and have a significant effect on the corrosion of metallic materials. General corrosion would occur on many metallic materials in these acid fluids (Sanada, et al., 1997). Review of corrosive effects of several species is reported in Ellis and Conover (1981). The species which has great contribution to general corrosion are dissolved oxygen, chloride, dissolved carbon dioxide, ammonia and hydrogen ion.

2.1 Corrosion Type

There are several types of internal corrosion, which may occur in the geothermal wells according to several studies. These are as follows:

<u>Uniform (or general) corrosion</u>

General corrosion occur due to phase inhomogeneity in steels surface that has created local electro-chemical conditions, which is often promoted by proton H^+, oxygen, chloride, CO_2, and H_2S.

One of the principal parameters, CO_2, is the most abundant gas in geothermal systems and often represents over 85% by both volume and weight of the total gas content of a discharge (Mahon, et al., 1980). The gas can be produced by thermal alteration of carbonate rocks and minerals, from the degradation of organic matter within sedimentary rocks at depth or in near-surface reaction, from solutes in meteoric waters, or even from a magmatic origin. Dissolved CO_2 due to presence of water could initiate the corrosion.

The basic reaction is as follows: $CO_2 + H_2O \rightarrow H^+ + HCO_3^-$

It leads to the increase of H^+ ions, which lowers the production water's pH and corrosion process begins. The resulting corrosion process causes the formation of iron carbonate $FeCO_3$ that precipitates on the metal surfaces. This precipitate, which is generally not very adhesive, is not enough to significantly slow down the corrosion; this deficient protection will become more pronounced as the speed of the fluids increases (erosion-corrosion).

Erosion-Corrosion

Erosion-corrosion is associated with a flow-induced mechanical removal of the protective surface film that results in a subsequent corrosion rate increase via either electrochemical or chemical processes. Erosion-corrosion may be enhanced by particles (solids or gas bubbles) and impacted by multi-phase flows. It happens due to the acceleration or increase in rate of deterioration or attack on a metal because of relative movement between a corrosive fluid and the metal surface. This movement is quite rapid and mechanical effects or abrasion is involved. Erosion-corrosion is actually the main caused of many thinning problems than general corrosion because it is a physical-chemical process, where corrosion and erosion factors are similar in magnitude and occur simultaneously (Povarov and Tomarov, 1997). In geothermal cases, erosion-corrosion is caused by high velocity fluid, droplets or particulates.

Pitting Corrosion

Pitting is a form of extremely localized attack that results in holes in metal that mostly in small diameter. It is initiated by chemical and mechanical damage to the protective film or local damage to coatings. As in geothermal environment or petroleum, the major species, responsible for pitting is chloride ion and in general, all halogen ions like sulphate and heavy metal. Pitting occurs only in the presence of oxygen. At the anodic sites, oxidation occurs as $Fe \rightarrow Fe^{2+} + 2e^-$. The anode forms the site of the pit. At the cathodic sites, reduction of oxygen takes place as $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$. Due to continued oxidation at the anode, positive ions (Fe^{2+}) are accumulated and excess positive charge is established in the pitted area. These positively charged ions attract the negative Cl^- ions present in the electrolyte in which the metal is exposed: $Fe^{2+} + Cl^- \rightarrow FeCl_2$. The pitting process is auto catalytic i.e. once it starts, it continues to accelerate with time and it only ends when the metal is perforated.

However, the tendency of pitting corrosion in geothermal well is smaller since the presence of oxygen in wellbore is quite rare, usually indicates contamination either by soil air or during the sampling procedure. In mild steel, the presence of Cl^- ion has the tendency to form general corrosion.

From the literature review above, we can conclude that the corrosion type likely to occur in geothermal well with low-grade steel (mild steel) is uniform (general corrosion) and erosion-corrosion, if the velocity of fluid in the wellbore is not controlled.

2.2 Corrosion Rate

Metals and non-metals often compared based on their corrosion resistance, even between metals group itself. To make definitive comparison, the rate of attack of each material must be expressed quantitatively (Fontana, 1986). Corrosion rates have been expressed in a variety ways such as percent weight loss, mils per year (mpy), milligrams per square centimeter per day, and grams per square inch per hour. Corrosion rate or the rate of penetration or the thinning of a structural piece can be used to predict the life of a given component. The rate of corrosion resistance for materials, particularly ferrous and nickel based alloy, are divided into several performance groups as shown in Table 1. For more expensive alloys, rates greater than 5-20 mpy are usually excessive. Rates above 200 mpy are sometimes acceptable for cheap materials with thick cross section. Corrosion rate is often used also for selecting respective materials under various environments

Table 1: Performance group relative to corrosion resistance (Fontana, 1986)

Relative to corrosion resistance	Corrosion rate	
	(mpy)	(mm/year)
Outstanding	< 1	<0.025
Excellent	1 - 5	0.025 - 0.1
Good	5 - 20	0.1 - 0.5
Fair	20 - 50	0.5 - 1.27
Poor	50 - 200	1.27 - 5.08
Unacceptable	200 ++	5.08 ++

There are various factors affecting the corrosion rate of the geothermal fluid. These are the following:

- pH and Temperature
  Corrosion rate of carbon steel increases as pH decreases and temperature increase. A high pH means a lower quantity of the oxidant H^+. Furthermore, when the pH increases, and with carbon steel, the situation can develop where passivation by oxides / hydroxides confers a certain protection. This kind of protection or the passivity of many alloys is very dependent on pH.
- Corrosive species
  Corrosive species can initiate the corrosion and higher corrosion rate if continuously present with certain concentration. Primarily on Cl^- ions that can causes the breakage of the passive layer that prevents many metals from corrosion if the

concentration is 133,500 ppm and the temperature above 150°C. By breaking this passive layer, any type of corrosion and cracking can occur.

- Salinity
  Salt (concentrations of Na, K, Cl, etc) increases the waters ability to carry electrons. These electrons take part in corrosion when oxidation and reduction occur. Since these two processes have to occur together, they are called redox reactions. Salt also is hydroscopic. This means that salt attracts water. Since water is needed for corrosion, along with oxygen, salt helps gather that water. Therefore, greater fluid salinity produces a lower pH.

3. MATERIALS SELECTIONS BASED ON CORROSION RATE CALCULATION

Extraction of geothermal fluids, which has high temperature and high salinity resulting corrosive environment, presents a materials selection challenge to handle brine, steam and brine/steam mixtures, particularly for well casings and piping. Geothermal production has borrowed on petroleum technology with regard to well casing and piping materials. However, the materials, which work well in petroleum wells, may not be suitable for all geothermal wells. According to study, corrosion inhibitors, such as amine and imidazoline types that are used extensively in petroleum production are not likely effective means of corrosion control in geothermal production because of the higher temperatures and salinities (McCright, 1980). Furthermore, geothermal wells consist of a simple-production casing followed with liner. Without an annular arrangement of tubing inside the production casing, it is difficult to inject an inhibitor into the well. The presence of Cl ion from reservoir fluid is also unavoidable considering its effect on destroying passive layer on steel surface. Therefore, the selection of down well components materials particularly casing based on corrosion resistance is important.

As for the casing grade selection in geothermal, currently these are still based on mechanical properties. The selected grade casing are investigated for their resistance by comparing the value of the biaxial load with burst rating, and then collapse, and the tension that has been modified by the correction factor (Deni Syarif, 2011). If all the value is smaller than the modified load rating of casing, then the modified collapse rating is evaluated with the biaxial load. If it turns out that the corrected collapse rating is still greater than the collapse load, then the selected casing grade is compliant. Otherwise, the examination of the higher grade is conducted.

Taking an example from the petroleum industry, the selection of tubing material in crude oil is generally based on corrosion rate of particular tubing material with respect to its environment due to many tubing failure caused by corrosion phenomenon. The most common corrosion rate equation that has been used and developed is de Waard CO_2 corrosion rate equation as shown in Equation (1). The idea of de Waard equation is to adjust all the corrosion parameters in one equation as a corrosion factor, such as the presence of protective scale, H_2S, crude oil or condensate, glycol, and inhibitor by means of multiplier on the base CO_2 corrosion rate. This particular corrosion factor has its equation to be calculated with well data and fluid properties as an input (Smith, 2005).

$$Corrosion\ rate = V_{cor} x\ F_{scale}\ x\ F_{H2S} x F_{cond} x F_{oil} x F_{inhib} x F_{glyc} \quad (1)$$

Material selection process in this study is intended to look for suitable material according to specific well conditions. This is to maintain the delivery of geothermal fluids without experiencing failure due to corrosion with the limits of corrosion allowance. The selection of grade casing in this study was conducted based on the method of Cr equivalent. This method considers the chemical composition which can increase the corrosion resistance of a material. As for some of the element composition alloy influencing the corrosion resistance of materials.

Several studies have been done in the area of deep geothermal well related with the production casing material selection. Deep geothermal resource developments might be expected to be more corrosive because of higher temperatures and higher concentrations of corrosive species transported by the well casing (Noda, 1992). One of them is the study which was done by Kurata and Sanada in Japan. Corrosion tests were initiated in 1980 in two steps of acidic environments: (1) static solution laboratory tests at pH values in the range of 1 to 5 and at temperatures in the range 100 - 300°C, (2) field tests at velocities up to 100 m/s in Onikobe geothermal well with pH values in the range of 2 to 5 (Sanada et al, 1992). From the literature review above, in geothermal industry, there is no established corrosion rate equation yet that can be generally used in all field and consider all the corrosion parameters like the de Waard equation. According to previous study in 2011 by Deni Syarif, the casing selection based on corrosion resistance is important because the highest load in the casing is during production and also considering both erosion and corrosion.

4. METHODOLOGY OF SELECTING WELL CASING MATERIALS

This study presents a comprehensive methodology of selecting well casing materials with integrated study by using corrosion rate calculation and pressure drop wellbore modeling. The modelling, as an additional analysis, is conducted in order to estimate flash point location to obtain the appropriate casing length. Work flow of the entire process can be seen in Figure (1), that has been divided into two main steps, grade and length selection. The methodology suggest that despite the selection of grade casing, it is also important to select appropriate length of casing to accommodate destruction due to corrosion. The following is a discussion of the Cr equivalent method and pressure drop modeling.

Casing materials selection in this study was conducted according to Kurata et al. (1995) experiment. Kurata et al. (1995) has made a study for predicting the corrosion rate of various materials in deep geothermal wells of geothermal field in Japan using the regression method. The objective of Kurata's study is to systematize the selection of production casing pipe material. Various tests have been conducted to evaluate material resistances against geothermal environment, whether it is laboratory or field tests. There were many kinds of materials which have been examined: carbon steels, low alloy steels, martensitic stainless steels, austenitic stainless steels, precipitation hardening stainless steel, etc. This kind of test is conducted to obtain corrosion rate of various materials under corrosive geothermal environment and the main goal is to create global equation and diagram assessment to select grade casing. The whole process of obtaining corrosion diagram assessment is shown in Figure (2).

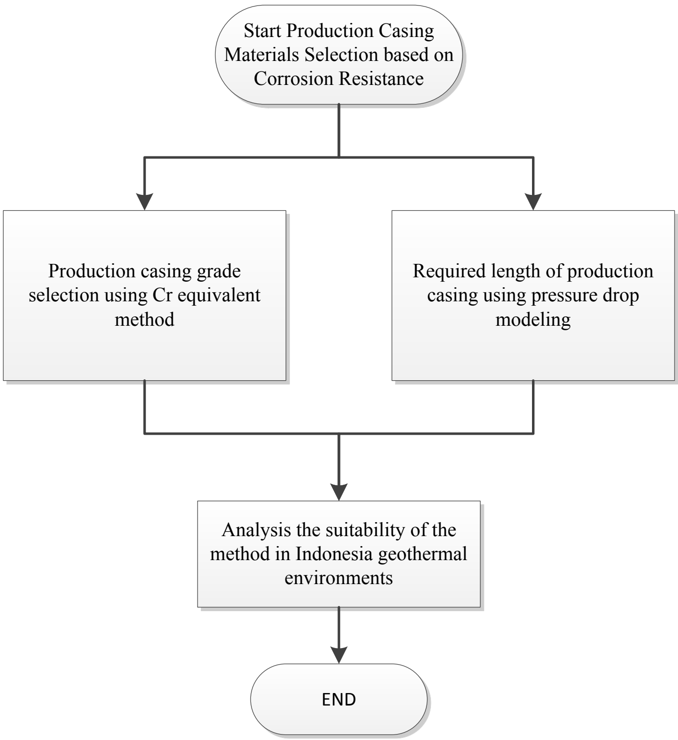


Figure 1: Flow Chart of Methodology

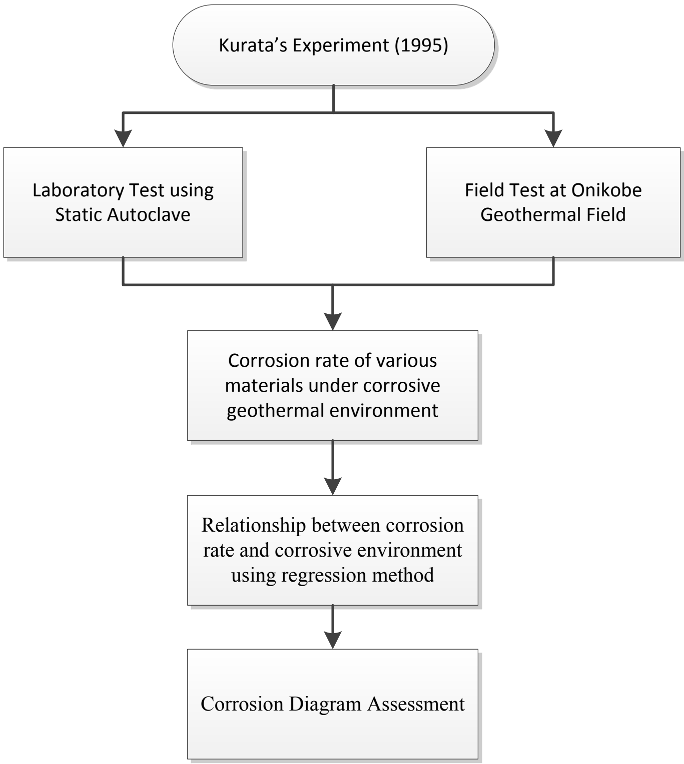


Figure 2: Flow Chart of Kurata's experiment

In order to make the experimental data applicable to materials selection process in general geothermal environment, a relationship between corrosion rate and corrosive environment has been made. The relationship was derived from experimental data using regression method resulting the idea of Cr equivalent method which the equation considering the ratio of the contribution of corrosion resistance elements as Cr, Si, Mn, Mo, S, Ni, C, P, Cu, and S.

The method of analysis based on Cr equivalent is outlined briefly as follows. It was assumed, that a corrosion rate model satisfies the following equation:

$$C.R. = K\ x\ \exp\{\frac{-E_k}{RT}\}\ x\ [H^+]^n \quad (2)$$

Where,

K - is a Constant

E_k - activation energy

$[H^-]$ - concentration of hydrogen ion

N - reaction degree of hydrogen ion

R - gas constant

C.R. - corrosion rate in mm/year

Equation (2) is actually the Arrhenius equation with the addition of pH factors, shown as H^+. Arrhenius equation expressed the influence of some factors to the rate of any chemical reaction.

Taking logarithms of Equation (2), obtained the following equations:

$$\log C.R. = log\ K\ x\ 0.4343\{\frac{E_k}{RT}\}\ x\ n\ \log[H^-] \quad (3)$$

In Equation (3), - log $[H^+]$ shows the pH, and T acted as corrosion factor. log K is a constant based on factors, which Kurata thinks would be fine if K is dependent on the material, later on called proportion of Cr eq. Activation energy and n can be derived from regression analysis of the experimental data. Alloy elements of the material are formulated by converting to Cr equivalent since Cr is the fundamental composition of corrosion resistant materials, the contributions of other elements to corrosion resistance were expressed in terms of Cr with each portion is described with B_1, B_2 and etc.

$$(Cr)_{eq} = (\%Cr) + B_O\ (\%C) + B_1\ (\%Si) + B_2\ (\%Mn) + B_3\ (\%P) + B_4\ (\%S) + B_5\ (\%Ni) + B_6\ (\%Mo) + B_7\ (\%Cu) \quad (4)$$

Therefore, the value of corrosion rate connected linearly to Cr equivalent and corrosion factors by this following equation:

$$\log(C.R) = C_O + C_1\ (Cr)_{eq} + C_2(pH) + C_3(\frac{1}{T}) \quad (5)$$

To obtain the coefficient C_O, C_1, C_2 and C_3, Kurata using the results of corrosion tests of various material and the corresponding corrosion factors. Trial and error process was carried out to obtain similar corrosion rate. The regression method results a correction factor for previous corrosion rate equation to obtain Cr equivalent value for general geothermal environment, as shown in Equation below.

$$(Cr)_{eq} = Cr - 13.73\ C + 1.598\ Si - 0.433\ Mn + 27.28\ P - 51.12\ S + 0.237\ Ni + 0.712\ Mo - 1.06\ Cu \quad (6)$$

$$\log(C.R) = 6.696 - 0.085\ (Cr_{eq}) - 0.622\ (pH) - 1930\ (\frac{1}{T}) \quad (7)$$

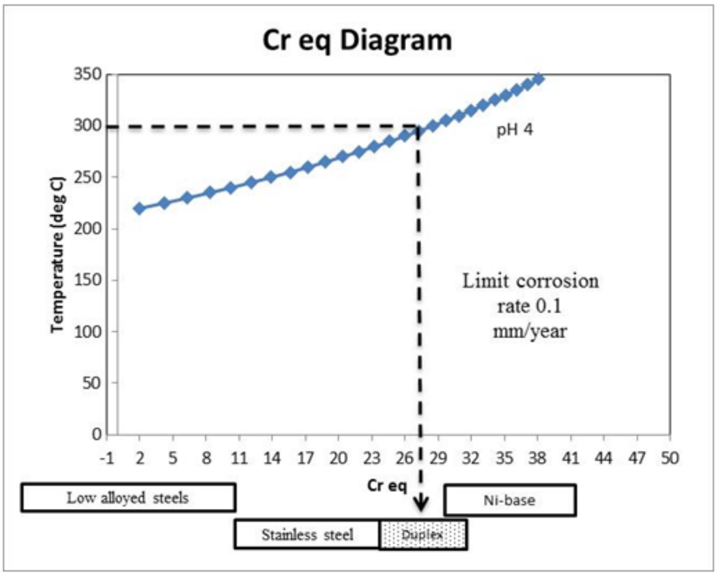


Figure 3: Diagram to assess suitable casing materials under particular pH and Temperature conditions

From the final corrosion rate above, the diagram to assess the suitability of materials for geothermal environment can be obtained. The diagram was built from Equation (6) and (7) under certain range of pH and Cr equivalent for each alloy system. Kurata et al (1995) on reference published paper used the diagram with the assumption that the lower limit for the corrosion rate of usable geothermal materials is less than 0.1 mm/ year as shown in Figure (3). As an example of using the diagrams, a suitable casing materials in geothermal well with temperature 300°C and pH 4.0 should be have more than 27 mass% of Cr equivalent, which leads to duplex stainless steel or an equivalent high Ni-based alloy.

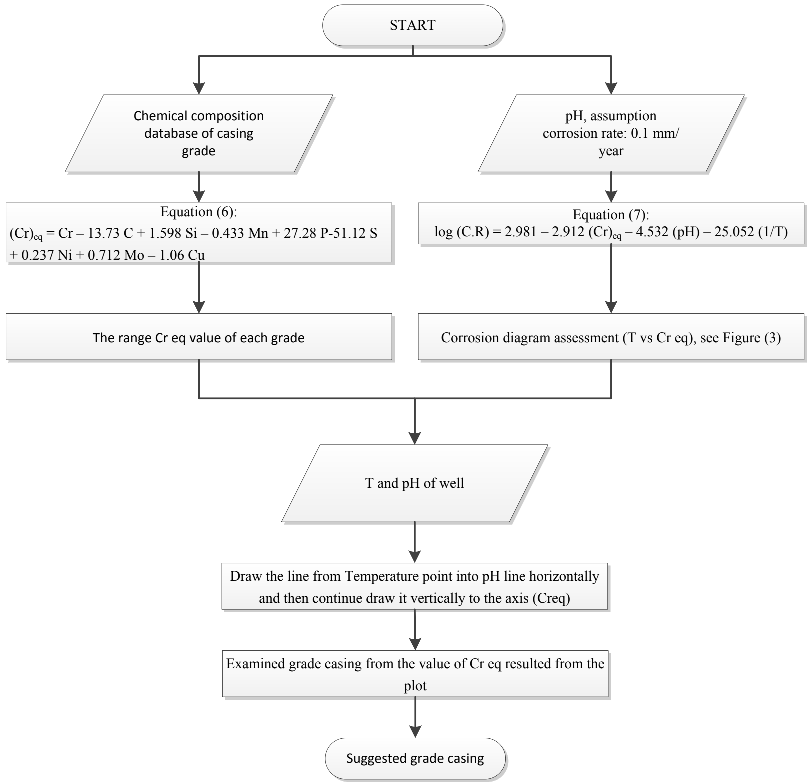


Figure 4: Flow Chart of Grade Casing Materials Selection

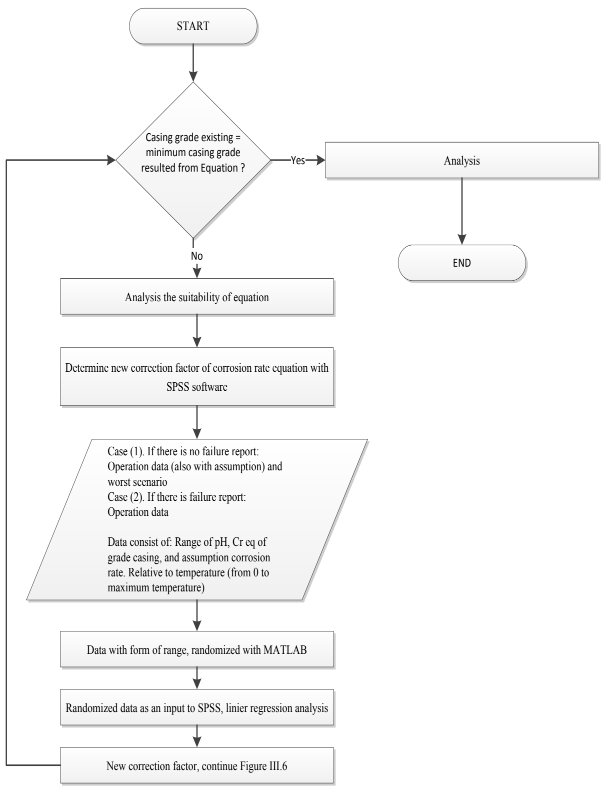


Figure 5: Flow chart of analysis and optimization process

Afterwards, the suggested grade casing is analyzed along with the whole method including the equation. The analysis is intended to applicate the original equation (Equation 5) in observed geothermal field using one of the well considering its optimization to cost.

In this study, the casing grade being evaluated is limited only to grade a casing in accordance with API-5CT classifications. In short, the flow chart for the whole analysis the suitability of the Kurata's method in observed well geothermal environment is shown in Figure 4.

Therefore, we can obtain more optimized casing with lower cost and still can accommodate casing failure due to corrosion during operation / design time. The optimization has been conducted with modify the correction factor of Equation 5 using observed well data and SPSS statistical software. The flow chart of the analysis process is shown in Figure 5.

In addition to casing materials selection as described above, according to Kurata et al experiment, the pressure drop modelling should be conducted to determine the depth of flashing point. It was intended to minimize selected casing materials usage by applying it only to the most sensitive areas.

Pressure-drop modelling was conducted using the drift-flux correlation by Hasan and Kabir (2010). Pressure drop calculations were performed by the method of bottom to top starting from the bottom of the well to the wellhead with three-meter intervals. Based on study, three meters interval will provide accurate and good results, in either forward calculation or iterative calculation (Situmorang, 2012). The results to be obtained from modelling of pressure drop in geothermal wellbore for the analysis of flashing area is dryness vs depth profile and pressure vs depth profile. The flowchart of the pressure drop modeling process is shown in Figure 6.

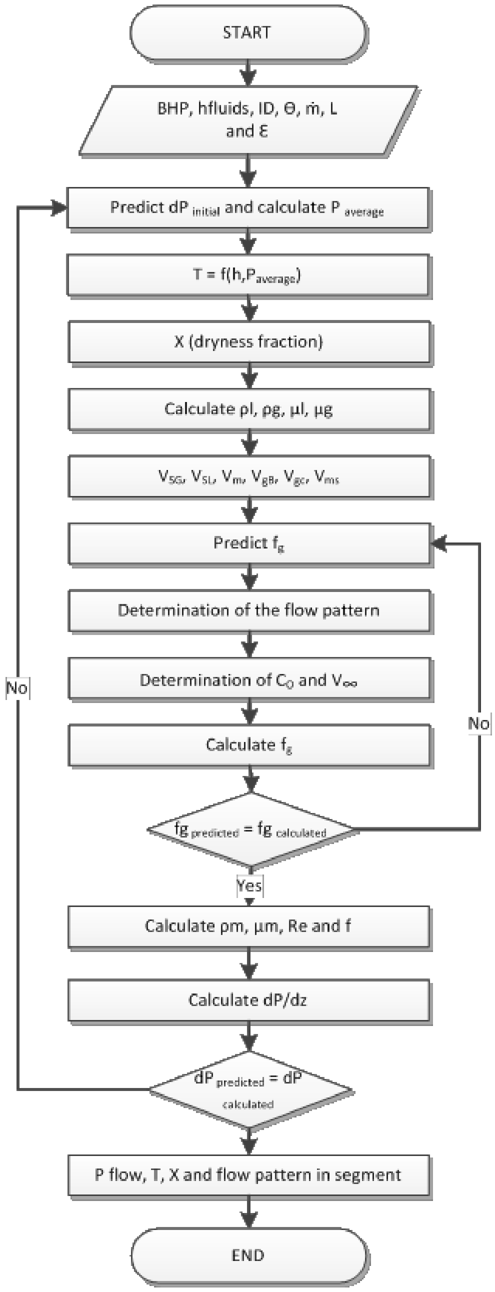


Figure 6: Flow chart of Hasan-Kabir Pressure Drop Calculation

5. CASE STUDY

The implementation of the methodology of casing materials selection will discuss by applying it in well “A” in Indonesia under certain condition. Well “A” delivers two-phase geothermal fluid and located in vapor dominated reservoir with the well completion is shown in Table (2) and Figure (7) below.

Table 2: Well completion of well “A”

Casing properties	Production casing	Perforated liner	Perforated liner
Grade	L-80	K-55	K-55
Weight (ppf)	68	40.5	26
OD (inch)	13-3/8	10-3/4	7
Depth (meter)	0 - 786	786-1081	1081-1630

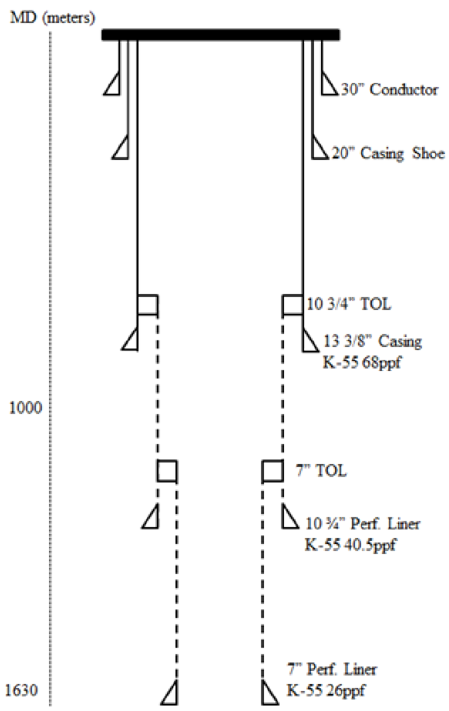


Figure 7: Wellbore diagram illustration of well “A”

Well “A” located in area where both reservoir are steam and brine. Completed in 1997, the well “A” penetrates deep brine reservoir and steam cap at shallow depth resulting two-phase geothermal fluids with temperature 250°C and mass rate 21-36 kg/s at wellhead pressure 18-20 bar. The top of reservoir of well “A” area lies between depth 780 - 880 meters. This explain why the production casing shoe of well “A” installed at 827 m. The well configuration itself, as shown in Figure 7 is vertical wells with total measured depth 1630 m.

6. RESULTS AND DISCUSSIONS

6.1 Results of Grade Casing Selection with Cr equivalent method

Fluid sampling in well "A" routinely performed from 2001 to 2012 with an average pH of the sampling is at 5.34 at a WHP=16 bar. At grade selection process, the value of pH 5 is used as the input and the maximum temperature is used to follow a bottom hole temperature of 250°C by assuming that both conditions are severe conditions for well "A". Another assumption that has been used is the design value of corrosion rate. A value of 0.1 mm / year was taken, as this value is used as a basic common design practice that meet the corrosion rate with respect to the corrosion allowance for material pipe or casing that is designed to operate for 30 years. If the corrosion rate value is higher than 0.1 mm / year, it takes a greater thickness of material or higher-grade material to meet the corrosion allowance value and this can cause a significant increase in cost. The corrosion diagram assessment can be obtained as shown in Figure 8.

From Figure 8, if well "A" delivers fluid at a temperature of 250°C and pH of 5, the Cr equivalent obtained are in the low alloyed steel area. It can also be seen that if the fluid temperature rises, the casing grade needed will be higher.

Afterwards, the results of the assessment, which is low alloyed steel area, further are subdivided into casing grade group based on API 5CT as shown in Figure 9.

As can be seen from the Figure (9) above, with the environments similar to well "A", based on Cr equivalent method, a suitable material should have Cr equivalent more than 11% Cr mass, which correspondents exactly to grade L80-9Cr.

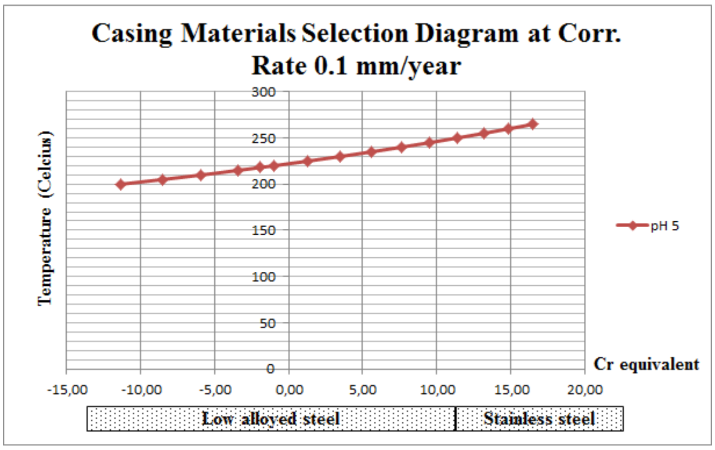


Figure 8: Diagram to assess the suitability of casing for geothermal environment

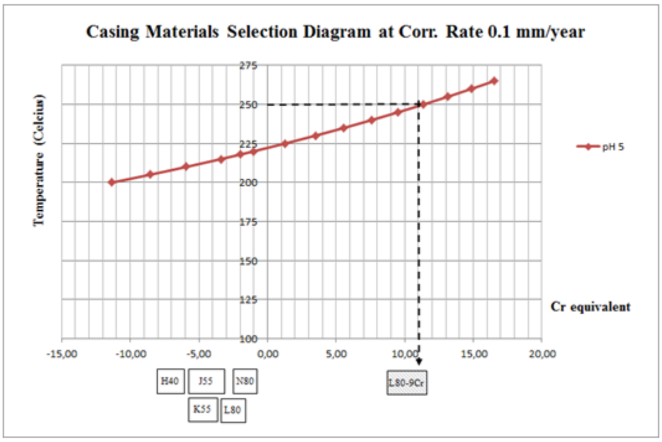


Figure 9: Casing materials selection, case geothermal environment: well "A"

6.2 Results of Pressure Drop Modelling

Pressure drop-modeling results of well "A" produce a pressure and dryness profile as shown in Figure (10). The results of modeling generates large number of wellhead pressure, 20 bar with the dryness at the wellhead is 0.1. At the depth of 1630 meters to 1260 meters, geothermal fluid flow is in a compressed liquid state. From the depth of 1258 meters to surface, geothermal fluid flow in the form of slug resulting vapor fraction increases two-phase flow. From the modeling results, it is estimated that flashing occurs at a depth of about 1258 meters.

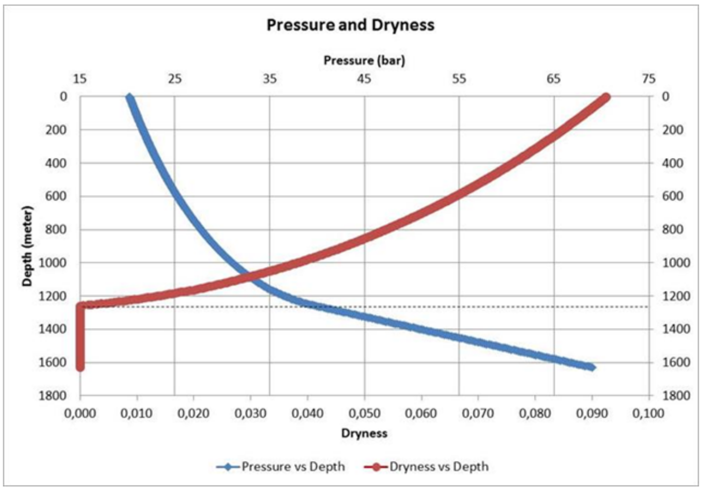


Figure 10: Pressure drop modelling results vs Dryness

As shown in Figure 10 above, the pressure profile when the flow is compressed liquid follows the hydrostatic pressure gradient. Then after flashing, vapor phase separated from the liquid phase so that the profile is no longer hydrostatic pressure but follow the two-phase pressure profile.

6.3 Analysis

According to the Cr equivalent method, it is known that the production casing which suitable with the condition of well "A" is grade L80-9Cr as can be seen in Figure 10. It also can be seen that the value of Cr equivalent for each grade in the form of range. The value will change depending on the respective of manufacturing that will produce the minimum and maximum range of the Cr equivalent, as shown in Table 3.

Table 3: Range of Cr equivalent value using Equation 6

Range of Cr equivalent value			
Grade casing (API 5CT)		Min	Max
Group 1	H40	-8,5	-7,5
	J55	-6	-5,4
	K55	-6	-5
	N80-1	-2	-1,5
	N80Q	-2	-1,5
Group 2	M65	-5,5	-4,3
	L80-1	-2,4	-1,8
	L80-9Cr	10	11,5
	L80-13Cr	11	12

Actual data shows that well "A" used grade K55 as production casing and the liner. This can mean two things, whether the casing material selection process conducted by Kurata using Cr equivalent method is too conservative therefore cannot be done directly in well “A”, considering well “A” is still using low grade production casing and there is no report of failure or the selection process in the well "A” is somewhat still arguable. In the opinion of the authors, the tendency of the incompatibility of the use of the method is high due to the main study that has been experimented by Kurata is the deep geothermal wells conditions in various geothermal field in Japan. So the method is made for the most severe condition of the geothermal well with very high fluid temperatures (>300°C) and the pH of the fluid is relatively acidic (less than 5), while in the observed data, the well were drilled generally at shallow depths (1.6 - 2 km) with the fluid condition is not too severe. Differences in data surely will also affect the existing corrosion rate equation. In addition, the authors think that Kurata et al set the bar too high with the assumption that the casing material will not be corroded within the production time. Therefore, the Kurata’s equation results very high grade, which not applicable yet in most cases in Indonesia due to the high cost.

Regarding to equation that has been made by Kurata, in the opinion of the authors, the approach taken in corrosion rate equation is still arguable particularly when the equation plots into a graph under various pH as shown in Figure 11.

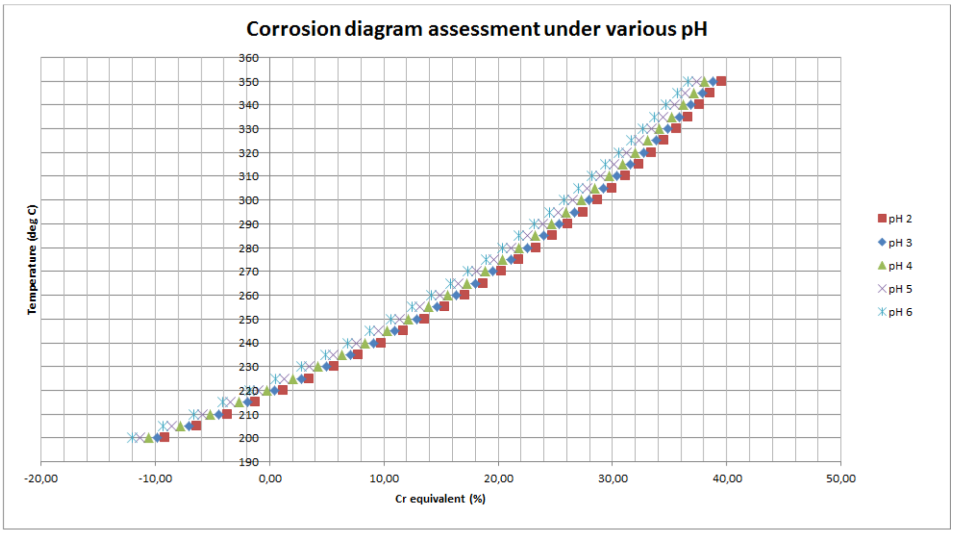


Figure 11: Corrosion diagram assessment under various pH

As we can see in the Figure 11 above, it shows that the pH has less effect on the selection of casing. Meanwhile, according to several studies, the lower the pH level, the higher the rate of corrosion. It is suspected that Kurata has been generalized all the corrosion rate test resulted from pH 1-7. However, the effect of pH to corrosion process cannot be generalized from one pH value to other. The corrosion process has a tendency to produce protective layer as corrosion product in pH 5-7 which can also decrease the corrosion rate while at extreme pH from 1 to 4, the corrosion can attack aggressively and the corrosion product are not protective. Therefore, it is suggested that the equation should be modified and divided into two groups based on pH value: extreme (1-4) and normal or safe condition (5-7).

In order to make the corrosion rate equation model more applicable, the equation from Kurata experiment results has been modified to suit the geothermal well condition in Indonesia, particularly in well “A” environment. The new correction factor of the corrosion rate equation has been made using SPSS statistical analysis software. By using the basic equations as in Equation 5, we will get generation models such as linear regression equation with correlation coefficient and begins with randomization of the data. This was carried out due to the lack of field data so that the data and assumptions used is in the form of arange. Furthermore, since there is no report of failure in well “A”, the form range of data is composed of operation data with worst scenario condition added. The data were randomized as follows:

- Measured pH of well "A" from 2001-2012 range from 4 to 6.
- Percent assumed equivalent mass of Cr in two conditions, the existing grade that used in well "A", K-55 grade (mass% Cr range: -6 to -5), and starts at 150°C, taking the worst scenario which is the most severe condition where Cl ions can destroys the passive layer of iron, grade L-80 is chosen (mass% Cr range: -2.4 to -1.8).
- Corrosion rate is assumed between 0 - 0.1 mm / year

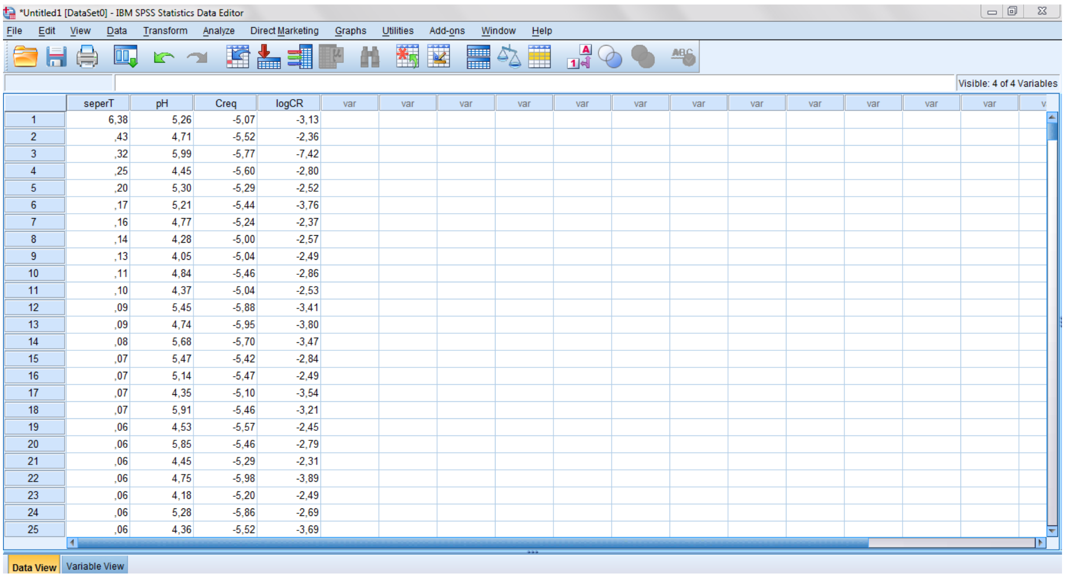
The first thing that was done is the randomization of the three data sets above relative to temperature using MATLAB. Temperatures were made sequentially from zero up to 300°C. Corrosion rate plays a role here as the dependent variable or primary data, while pH, T and Cr eq referred to as secondary data and acts as free variables. Table (4) is the data and initial range value to be randomized in MATLAB.

Table 4: Initial range data for making generation model

T	pH		Cr eq		C.R (mm/year)	
(°C)	Min	Max	Min	Max	Min	Max
0.01	4	6	-6	-5	0	0.1
10	4	6	-6	-5	0	0.1
20	4	6	-6	-5	0	0.1
30	4	6	-6	-5	0	0.1
40	4	6	-6	-5	0	0.1
50	4	6	-6	-5	0	0.1
60	4	6	-6	-5	0	0.1
70	4	6	-6	-5	0	0.1
80	4	6	-6	-5	0	0.1
90	4	6	-6	-5	0	0.1
100	4	6	-6	-5	0	0.1
110	4	6	-6	-5	0	0.1
120	4	6	-6	-5	0	0.1
130	4	6	-6	-5	0	0.1
140	4	6	-6	-5	0	0.1
150	4	6	-2.4	-1.8	0	0.1
160	4	6	-2.4	-1.8	0	0.1
170	4	6	-2.4	-1.8	0	0.1
180	4	6	-2.4	-1.8	0	0.1
190	4	6	-2.4	-1.8	0	0.1
200	4	6	-2.4	-1.8	0	0.1
210	4	6	-2.4	-1.8	0	0.1
220	4	6	-2.4	-1.8	0	0.1
230	4	6	-2.4	-1.8	0	0.1
240	4	6	-2.4	-1.8	0	0.1
250	4	6	-2.4	-1.8	0	0.1
260	4	6	-2.4	-1.8	0	0.1
270	4	6	-2.4	-1.8	0	0.1
280	4	6	-2.4	-1.8	0	0.1
290	4	6	-2.4	-1.8	0	0.1
300	4	6	-2.4	-1.8	0	0.1

In order to look for a new correction factor for Equation 5, the variable T changed into 1/T, and CR into log CR. Within the temperature range data (0-300°C), we breakdown the data into 500 pairs with dT = 2°C. Afterwards, the data is randomized in MATLAB. The random data from MATLAB are then be used as an input in SPSS software, as shown in Figure (12).

Using SPSS software, random variables that are then analyzed using a linear regression correlation coefficient. The result is shown in Table 5 below.



*Untitled1 [DataSet0] - IBM SPSS Statistics Data Editor

	seperT	pH	Creq	logCR
1	6,38	5,26	-5,07	-3,13
2	,43	4,71	-5,52	-2,36
3	,32	5,99	-5,77	-7,42
4	,25	4,45	-5,60	-2,80
5	,20	5,30	-5,29	-2,52
6	,17	5,21	-5,44	-3,76
7	,16	4,77	-5,24	-2,37
8	,14	4,28	-5,00	-2,57
9	,13	4,05	-5,04	-2,49
10	,11	4,84	-5,46	-2,86
11	,10	4,37	-5,04	-2,53
12	,09	5,45	-5,88	-3,41
13	,09	4,74	-5,95	-3,80
14	,08	5,68	-5,70	-3,47
15	,07	5,47	-5,42	-2,84
16	,07	5,14	-5,47	-2,49
17	,07	4,35	-5,10	-3,54
18	,07	5,91	-5,46	-3,21
19	,06	4,53	-5,57	-2,45
20	,06	5,85	-5,46	-2,79
21	,06	4,45	-5,29	-2,31
22	,06	4,75	-5,98	-3,89
23	,06	4,18	-5,20	-2,49
24	,06	5,28	-5,86	-2,69
25	,06	4,36	-5,52	-3,69

Figure 12: Display of random data as an input in SPSS software

Table 5: Results of SPSS Software

Coefficients					
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std Error	Beta		
(Constant)	2,981	0,724		-6,622	0
seperT	-25,052	0,267	-0,072	-1,614	0,107
pH	-4,532	0,136	0,037	0,83	0,407
Creq	-2,912	0,076	0,074	-1,668	0,096

From the SPSS software, we obtain the correction factor. For Equation (5), the new correction factor is C_0= 2.981; C_1= -2,912; C_2= -4,532; C_3=-25.052. The corrosion rate equation for geothermal condition similar to well "A" become this following equation.

$$\log(C.R) = 2.981 - 2.912\,(Cr)_{eq} - 4.532(pH) - 25.052(\frac{1}{T}) \quad (8)$$

Afterwards, at the temperature of 250°C and pH = 5, the new correction factor given the value of Cr eq at -6, corresponds to grade K-55. According to the new equation, for the similar condition to well "A", grade casing minimum to accommodate corrosion failure is K-55, as shown in Figure 13 below.

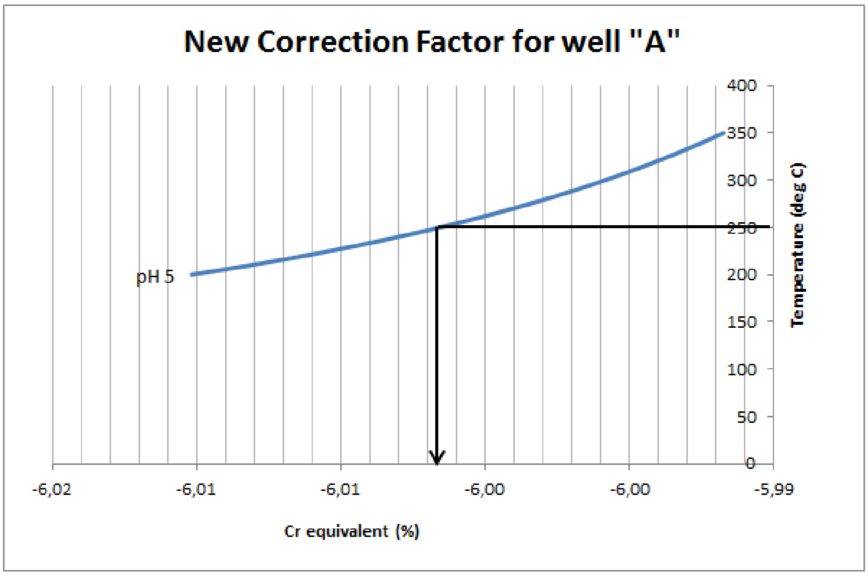


Figure 13: Corrosion diagram assessment for well "A" using new correction factor with T= 250°C and pH 5

Given that the current wells used in Indonesia are still shallow wells where corrosion is not the main problem, the use of low-alloyed steel, such as K-55, J-55 and L-80 were deemed to able to accommodate the corrosion allowance for wells with a design life of 30 years. This is applicable if the chemistry of the wells does not change significantly. However, the new correction factor needs to be developed considering that assumption data is still not giving the worst case scenario such as the lower pH. Further studies related to the corrosion rate equation model will be needed when deep wells drilling becomes widely practiced in Indonesia.

It is noted from the pressure drop modeling, that the flow pattern starts to change from compressed liquid to bubble flow at a depth of 1258 meters and turn into slug flow from 1090 meter up to surface. Assuming the flashing is along 300 meters, the flashing area is estimated from depth of 1258 meters - 958 meters.

Therefore, the appropriate length of L80-9Cr production casing in geothermal environments similar to well "A" is estimated at depth 1258 meters for optimum corrosion resistance at minimal cost in order to minimize its usage by applying it only to the most sensitive areas. The flashing is believed to be the area where the erosion-corrosion damage occurs. This erosion-corrosion aggravates the decomposition of metals due to mechanical process caused by the rising of fluid velocity and the corrosion reaction itself. However, in two-phase geothermal well, the erosion corrosion can be controlled since it started to occur when fluids moves rapidly (more than 100 m/s) and when the flow pattern is turbulent.

Moreover, the corrosion factor that has been used by Kurata is still very simple and needs further development. Taking as an example the calculation of corrosion rate in existing petroleum, de Waard in his well-known models for corrosion rate in crude petroleum, taking into account some parameters as a corrosion factor. Some of them can be taken into account for the calculation in geothermal well since its presence also affects the corrosion rates in wells, such as Cl^- concentration, partial pressure of CO_2 and H_2S. However, the development of these models also needs to be adapted to the general or other well condition in Indonesia.

7. CONCLUSIONS AND RECOMMENDATION

7.1 Conclusions

Some hypotheses were proposed to predict the suitability the corrosion rate equation by Kurata et al (1995) in order to select appropriate production casing grade. The idea of using Cr equivalent as a corrosion factor in corrosion rate calculation for production casing selection process in the opinion of the authors is quite a huge step for the next development considering there is still few studies that study the corrosion rate calculation in production casing in geothermal environments. From the study with the observed environment is well 'A', we may conclude that:

- The type of corrosion that likely to occur in geothermal wellbore is general (uniform) corrosion and in particular case, erosion-corrosion
- Methodology of selecting production casing in terms of corrosion resistance in geothermal had been introduced using corrosion rate equation to obtain grade casing and pressure drop modelling to obtain casing length.
- Suggested grade and length production casing to accommodate corrosion failure according to Kurata's method is L80-9Cr and length of 1258 meters.
- Corrosion rate equation by Kurata et al cannot be applied in another geothermal environment directly due to the differences in data and the severity level of geothermal condition.

Generation models, with new correction factor have been made from the Kurata's corrosion rate equation to the data field in well "A" using analytical software SPSS and only can be applied in a similar environment.

7.2 Recommendation

The following is some of the suggestions for further studies:

- Further studies related to the corrosion rate equation will be needed when deep wells drilling becomes widely practiced in Indonesia including conduct of materials test under various environment, in particular taking account of some corrosion parameter, such as Cl- concentration, partial pressure of CO_2 and H_2S.
- For selecting production casing in similar wellbore environment with well "A", the flow chart below can be follow.
- Generation model and correction factor resulted from the study should be calibrated and modified with field data, in particular the most severe data (extreme value of pH). The step for modification follows Figure 14.
- Study related to cementing is also important to prevent external corrosion.

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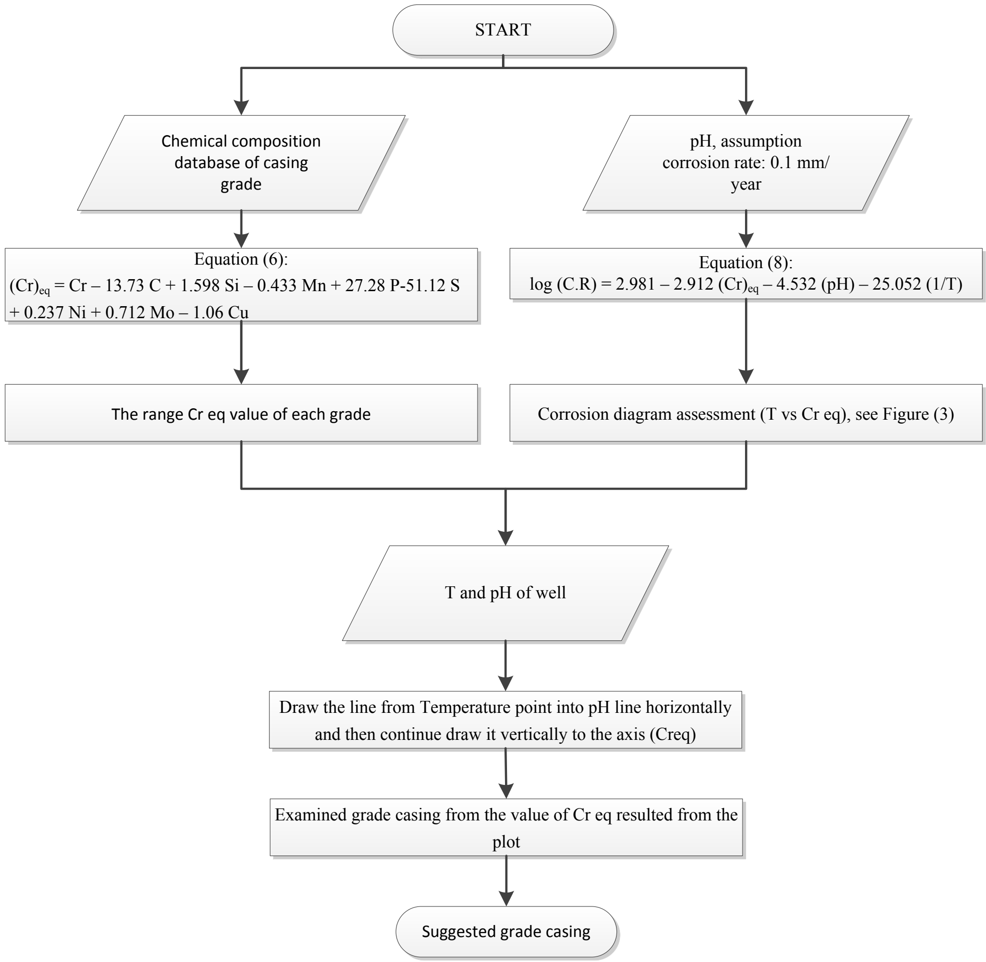

Figure 14: Flow chart to select grade casing in similar environment with well "A"