



ASSESSMENT OF SCALING FORMATION IN STEAM PIPELINE OF PRODUCTION WELL KMJ-67 IN KAMOJANG GEOTHERMAL FIELD, WEST JAVA, INDONESIA

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ABSTRACT

Kamojang, the first Indonesian operating geothermal field, has been producing electricity since 1983. The total installed capacity is 140 MWe and 1100 tons/h steam are produced from 33 production wells. Condensate is injected into five injection wells. Although only apparently dry steam is produced from the wells, scaling has been observed in the pipeline from one of the production wells. The scale builds up on the pipe walls, especially near the tee connection of steam transmission line, about 18-22 m from the wellhead. The scales were discovered during an annual maintenance shut down. X-ray diffraction and Scanning Electron Microscopy, including backscatter imaging and energy dispersive spectroscopy, demonstrate that the scale consists of well crystallized quartz with minor impurities. Scale morphology indicates that they formed by precipitation from aqueous solution. Observed temperature-pressure conditions in the surface pipeline were used to evaluate the water fraction in the steam. The resulting water fraction was equal to 0.43%. Observed static pressure as a function of depth in the well are inconsistent with the presence of dry steam only but are in good agreement with a water fraction of about 0.5% in the steam. Mass balance calculations based on observed amounts of scales, estimated silica concentration in the water fraction and steam flow-rate indicate that the water fraction is equal to only 0.05%. The apparent discrepancy between these methods indicates that either the concentration of silica in the water fraction is much lower than assumed in mass balance calculations or that only 10% of the available silica is deposited in the pipeline. If the latter is true, 90% of the dissolved silica in the water fraction is carried through the steam pipeline, as dust. In order to solve the scaling problem in the pipeline of well KMJ-67, at least 126 g/s of water need to be injected into the steam line. This amount of water is needed to keep the steam wet all the way to the turbine.

1. INTRODUCTION

The Kamojang field is the first developed geothermal field in Indonesia. It lies in the western part of Java Island, about 40 km to the southeast of Bandung, the capital of West Java Province. An overview of the field is shown in Figure 1. The initial 30 MWe unit came online in 1983, and in 1987 the capacity was increased to 140 MWe. A further increase to 200 MWe is planned for the end of 2006.

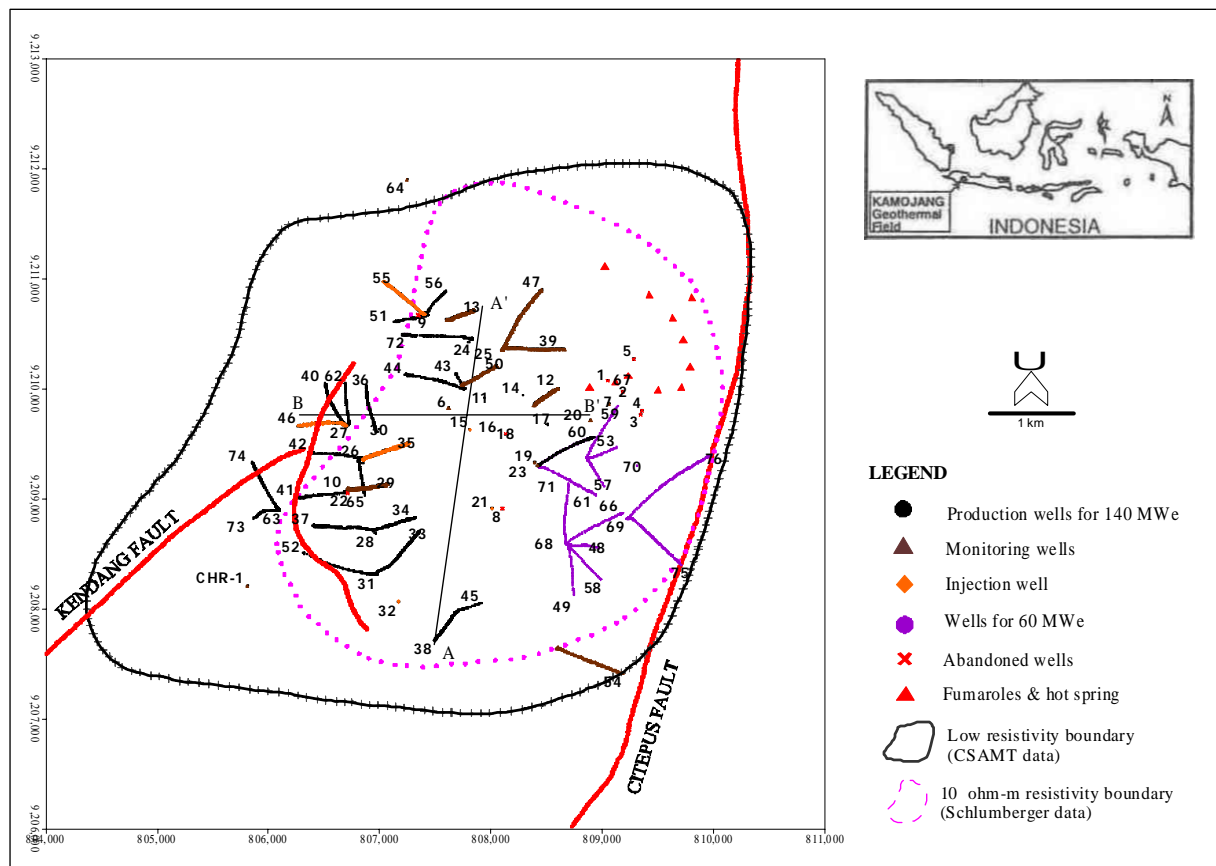


FIGURE 1: An overview of the Kamojang geothermal field showing location of wells and main geological structures

The field lies on the Rakutak-Guntur volcanic chain, 1500 m above sea level. The surface manifestations, which consist of hot pools, fumaroles, mud pools, and hot springs, are located in the so called Kawah Kamojang area, northeast of Kamojang reservoir. The chemical analyses of the hot water manifestations in Kamojang show a low content of chlorine. The gas content in the steam is approximately 2% by weight, mostly CO_2 and H_2S . The major lithology in the studied wells includes andesite ash, andesite lava, andesite breccia, and andesite tuff.

Preliminary studies in Kamojang were commenced in 1926 to 1929 by the Volcanological Survey of the Netherlands East Indies, which drilled five slim holes to depth ranging between 66 and 128 m (Robert, 1988). Only one of these is still active and discharges dry steam. New investigations were initiated in 1971 by the cooperative work between the Government of Indonesia and the Government of New Zealand. A geological map was established, chemical analyses were carried out as well as Schlumberger resistivity mapping that delineated the boundaries of the field.

Geothermal drilling in the Kamojang area was initiated in 1974 to 1975 when five exploration wells were drilled down to 700 m throughout the area. Two of these are productive, producing dry steam from shallow feed zones with a temperature of 232°C at about 600 m depth (Sudarman et al., 1995). To date, 77 wells have been drilled in the Kamojang geothermal field. The 33 current production wells are connected to four main steam transmission lines that lead to the power plant. Most of the production wells produce dry steam.

Although production wells produce dry steam, scales have been encountered in the pipeline from one of the production wells. The scales formed on the pipe walls, especially about 18-22 m from the wellhead near the tee connection to steam transmission line. The scales were discovered during an annual maintenance shut down. One of the gate valves of the steam pipeline was stuck due to scale formation.

The objective of this report was to find the most appropriate solution to the scaling problem in well KMJ-67. This involved characterization of the scaling phases and an analysis of the conditions that lead to the formation of the scales, specifically analyses of the water saturation conditions in the steam.

2. KAMOJANG GEOTHERMAL FIELD

2.1 Geology and reservoir characteristics

The Kamojang geothermal field is a two-phase steam-dominated system, associated with 400,000 year old Quaternary volcanic products of Pangkalan and Gandapura volcanic centres. It appears to occupy a volcanic depression created by the Pangkalan caldera rim inside the NE-SW trending graben formed by the Kendang fault in the west and Citepus fault in the east (Sudarman et al., 1995). The Pangkalan caldera rim, the Citepus fault and a W-E trending fault system in the northern part of the field are associated with high steam productivity. Two low-permeability barriers are assumed to exist in the Kamojang field, striking NW-SE and SW-NE. The SW-NE permeability barrier is interpreted as a "shear zone" from normal faulting observed in the area (Robert, 1988).

A reservoir area of 14 km² has been estimated from DC-Schlumberger soundings (Hochstein, 1975) and a further field delineation of up to 21 km² has been determined from CSAMT studies (Sudarman et al., 1990). Reservoir assessment of the Kamojang geothermal field was prepared by Brian Barnett (1988) with all well measurement and well testing data integrated in order to produce a physical picture of the field. Figure 2 shows a projection of most deep wells onto a S-N trending cross-section. The productive aquifer in the cross-section is at the greatest depth in the south rising to the north. Its thickness is variable but appears to range from 100 to about 500 m.

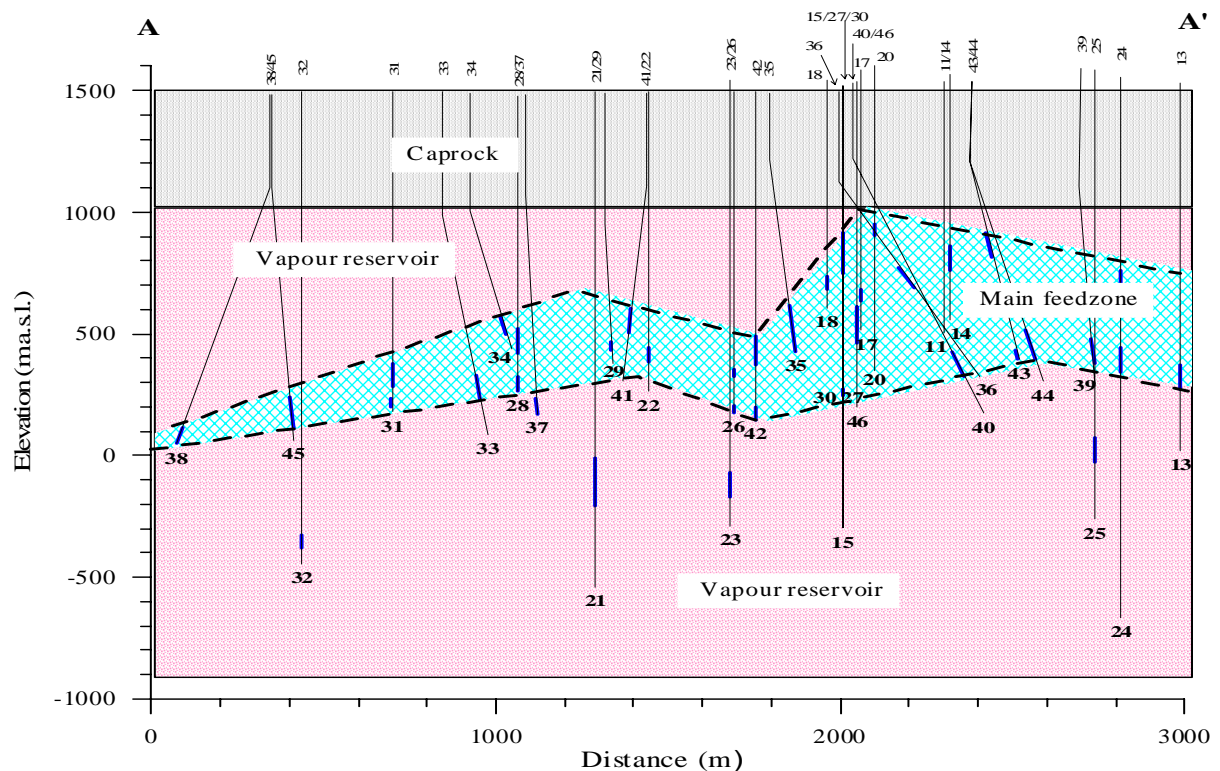


FIGURE 2: Kamojang well feed zone locations on a S-N cross-section, showing caprock, main feedzone and vapour reservoir (adapted from Barnett, 1988)

2.2 Hydrothermal alteration and reservoir structure

The primary minerals present in the Kamojang subsurface rocks are mainly feldspar (andesite-labradorite), pyroxene (hypersthene and augite) and olivine (forsterite). The subsurface rocks are mostly intensely or very intensely altered. Alteration minerals occur both as direct precipitates from solution and as replacements of primary minerals. The hydrothermal minerals present are quartz, feldspar, calc-silicates, zeolites, carbonates, iron oxides, and iron sulphides, sulphates and clay group minerals. Interlayered clays are common in Kamojang but they do not vary systematically downwell (Pri Utami, 2000).

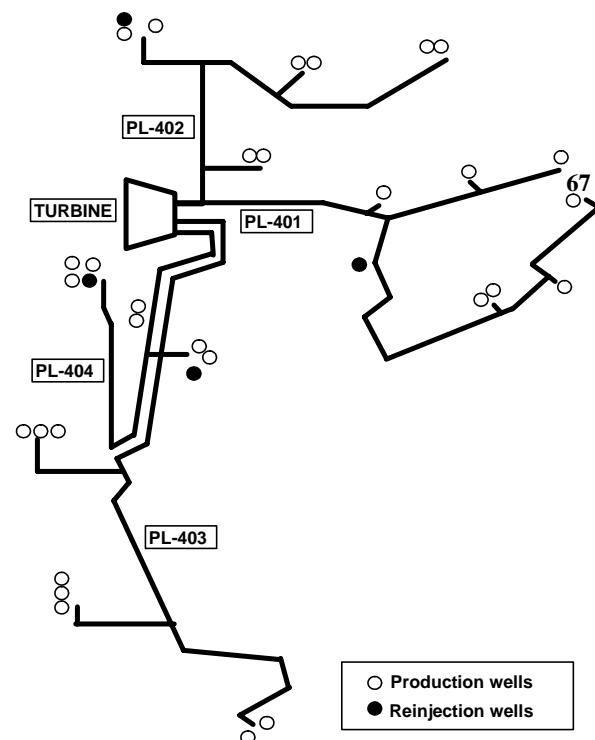
There are two distinct hydrothermal mineral assemblages at Kamojang, namely the “acid” and the “neutral” assemblages, which occur at shallower and deeper levels, respectively. The “acid” assemblage in the shallower level of the system (from near surface down to 100-300 m), is characterised by the presence of kaolin with or without smectite, alunite, quartz, cristobalite, and pyrite (Pri Utami, 2000). The deeper, “neutral” assemblage comprises quartz, adularia, albite, epidote, titanite, wairakite, laumontite, calcite, siderite, titanohematite, pyrite, anhydrite, smectite, chlorite, illite, and interlayered clays. Both assemblages indicate that the altering fluid was liquid.

The presence of two distinctive hydrothermal mineral assemblages can also be utilized to help characterise the possible hydrological structure of the reservoir at the time of their formation, e.g. the depth of the boundary between the steam-condensate layer and the deep reservoir fluid and the maximum depth of the sulphate-rich water penetration.

2.3 Steam field, production and injection wells

The steam mass flow is about 1,100 tons/h delivered to the existing 140 MWe power plant from 33 production wells with an average wellhead pressure of 11.8-14.8 bar. There is a strong correlation between steam flow and wellhead pressure. In a dry well steam, the maximum wellhead pressure is when the well is closed. When a well is open, the steam production pressure drops with increasing steam production.

The steam is delivered through four main pipelines, PL-401, PL-402, PL-403 and PL-404 (Figure 3). Each pipeline (PL) gathers the steam from several wells (5-12 wells). The total pipe length is about 4,000 m. Five injection wells are in the centre of the production zone to maintain reservoir pressure and steam field management.



2.4 Scale formation in well KMJ-67

FIGURE 3: Kamojang steam transmission lines

Scaling deposits were found in the pipeline from the KMJ-67 production well during an annual maintenance shutdown. The scales formed on the pipe walls, especially at a location 18-22 m from the wellhead, near the tee connection of the steam transmission line. The scale deposits have an

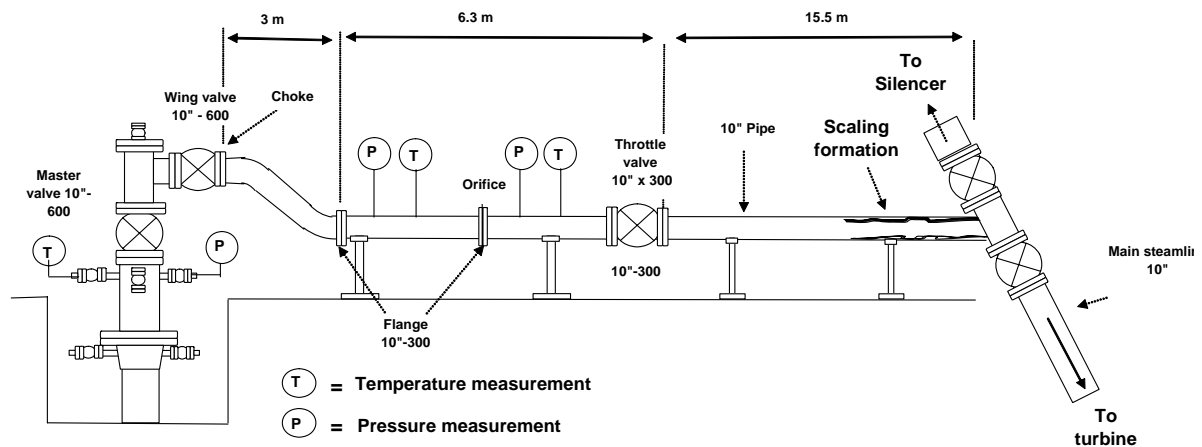


FIGURE 4: Pipeline installation of production well KMJ-67

average thickness of 1.5 cm and their occurrence is limited to approximately 3 m in the pipeline. The location of the scale deposits is shown in Figure 4, which shows the design of the wellhead of KMJ-67 and the surface pipelines connected to it.

Well KMJ-67 is located at the end of one of two branches of the PL-401 steam transmission line, and as a result there are no wells connected to this line upstream from KMJ-67 as shown in Figure 3. This well is one of the production wells that has produced steam since 1997. During operation, it produces 53 tons/h of steam at a wellhead pressure of 18.9 bar-a and temperature of 195°C.

3. SCALE CHARACTERIZATION

3.1 Optical examination and physical description of scale

Scale deposits from well KMJ-67 are grey coloured. The scale form is semi-parallel, 1-2 mm thick intergrown strings. The surface of the scale strings is covered by small crystals that are rough to the touch. The scale strings formed along the direction of the steam flow. Figure 5 is a photograph of scale samples from KMJ-67.

3.2 X-ray diffraction analysis

One scale sample from the steam pipeline was analysed in the ÍSOR laboratory in Iceland using an X-ray diffractometer (XRD). The crystal structure of the sample was identified from the diffraction pattern with the help of a computer program by locating in the file of known patterns one which exactly matched the pattern of the unknown sample.



FIGURE 5: Photograph showing scales from KMJ-67

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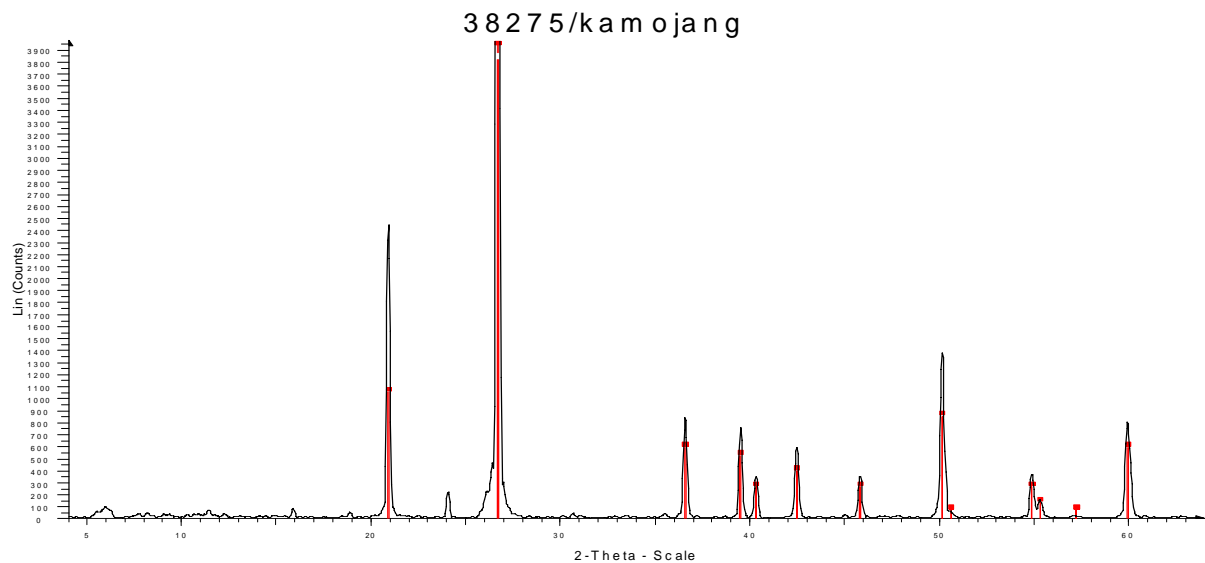


FIGURE 6: XRD pattern of scale sample from well KMJ-67 and quartz library pattern reflections

The results of the X-ray diffraction analysis indicate that scale deposits from the pipeline of well KMJ-67 contain almost pure quartz (SiO_2). The XRD pattern of the scale sample is shown in Figure 6. Also shown in Figure 6 is the library pattern reflections of quartz (red). It can be seen that all the peaks in the sample pattern, with the exception of one minor peak at $\sim 24^\circ$ 2θ , correspond to reflections in the quartz library pattern. The peak at $\sim 24^\circ$ 2θ could not be identified, but it represents some minor impurities in the sample. Flat background indicates that the sample does not contain significant amounts of amorphous materials.

3.3 SEM investigation of scale morphology

The Scanning Electron Microscopy (SEM) investigation of scale deposits was conducted to investigate the morphology of the scales, to study their composition and their chemical homogeneity. A scale sample was mounted in epoxy, polished and coated with gold before it was placed in the SEM. The operation conditions were 20 kV accelerating voltage and 60 μm aperture size. Backscatter images were collected to investigate the chemical homogeneity of the sample. The different shades of grey indicate different chemical composition. Figure 7 shows that the sample is fairly homogeneous, most of the sample is in one shade of grey with only a few spots that are brighter and few that are slightly darker. Figure 7B shows small but euhedral quartz crystals (grey) growing into open space (black). The crystals are angular, that means that they have not been transported after they formed. This is a good indication that the crystals form by precipitation in situ.

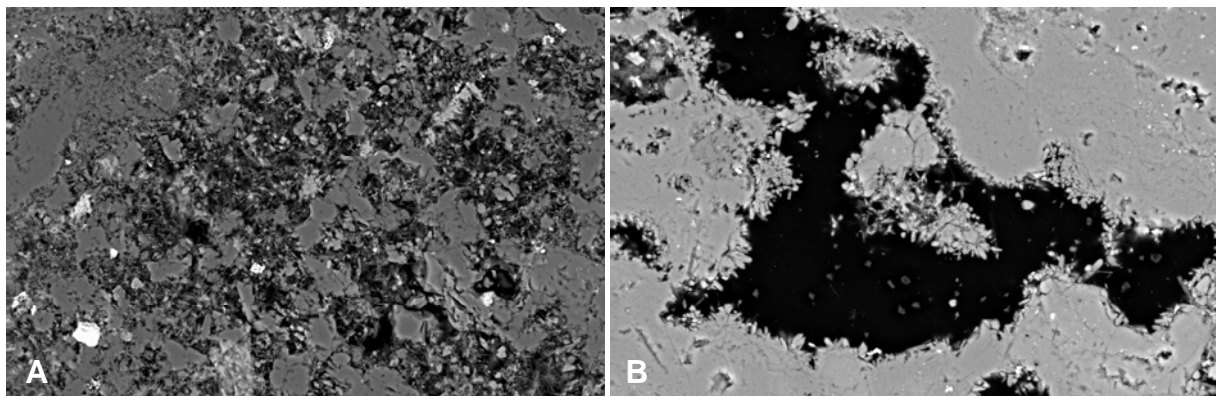


FIGURE 7: SEM analysis of scale morphology

3.4 SEM investigation of scale composition

The SEM is equipped with an energy dispersive spectrometer (EDS) that was used to do several EDS spot analyses. The EDS analyses are semi-quantitative i.e. they give an idea of what elements are present in the sample but do not quantify their concentration. The EDS analyses (Figure 8) demonstrated that the majority of the sample consists of only Si and O, consistent with quartz. The few bright spots were iron-oxide and iron-sulfides. The few grains that were slightly darker than the bulk of the sample contained Al, Na, K, Ca and O, consistent with feldspar composition.

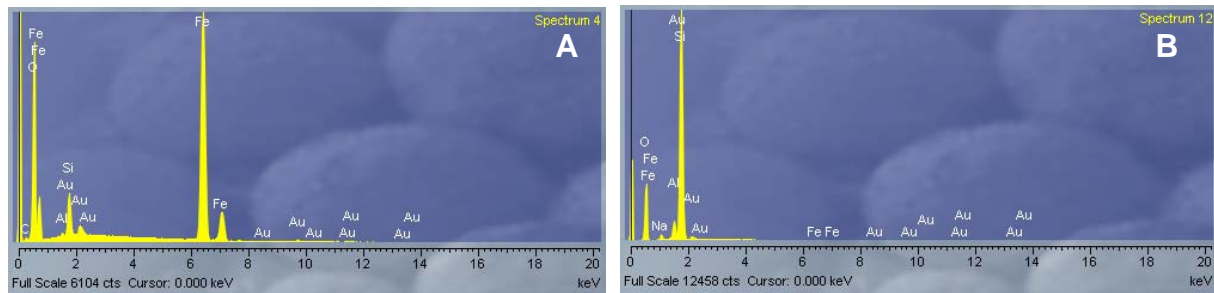


FIGURE 8: SEM analysis of scale composition

4. ASSESSMENT OF WATER FRACTION

The XRD and SEM investigations demonstrated that the scales in the pipeline from KMJ-67 consist of almost pure quartz. The observation that the crystals are euhedral and angular strongly indicate that the quartz scales formed by precipitation in situ. If the scales had been composed of quartz dust the grains would have been more rounded. Silica cannot be transported by vapour but is quite soluble in liquid water. The discovery of the scales in the pipeline from KMJ-67 does, therefore, conclusively demonstrate the presence of liquid water in the steam coming from the well and the scales most likely formed because of the drying out of this water. In order to understand the conditions that lead to the formation of scales in KMJ-67 pipeline, it is necessary to assess the water fraction in the steam from the well. Furthermore, an understanding of the conditions that lead to the scale formation in KMJ-67, in terms of pressure, temperature, and water fraction, will allow a relatively straightforward solution of the scaling problem. The solution of the problem involves injecting the appropriate amount of water (condensate) into the steam line in order to prevent drying out. Observed pressure-temperature conditions in surface pipelines at the wellhead were used to evaluate the water fraction in the steam. The resulting water fraction was further constrained by observed down-hole pressures in the well and by mass balance calculations.

4.1 P-T conditions and water saturation in surface pipelines by wellhead

Steam flows from the well pass through a master valve before choking. The choke is used for restriction of flowing steam from the well. After passing the choke, steam flows through an orifice plate as a flowing measurement device. Consequently, there are three locations in the surface pipeline where three different pressure and temperature conditions prevail (see Figure 4). Table 1 gives a list of the observed pressures and temperatures at the three locations in the surface pipeline, as well as the saturation temperature for the given pressure.

The measurements shown in Table 1 were made on 15 November 2004. The pressure/temperature conditions of three locations in the surface pipeline are fairly stable, i.e. they do not vary significantly with time. Inspection of Table 1 shows that the steam is very close to saturation downstream from the orifice. It is assumed, for the sake of these calculations that the steam completely dries out approximately at the downstream station. The presence of the quartz scales a few meters from the

TABLE 1: P-T conditions at surface

	Pressure (bar-a)	Temperature (° C)	Sat. temp. (°C)
Wellhead	18.9	195	209
Up stream from orifice	14.6	195	197
Down stream from orifice	14.0	194	195

downstream station supports this assumption. It is also assumed that at 18.9 bar-a there is a water fraction present and that the phases change between the wellhead and the downstream station area adiabatically. The assumption of adiabatic conditions means that there is not a net change in enthalpy of the system between the wellhead and the downstream station, i.e.:

$$\Delta H = H_{Total}^{14.0} - H_{Total}^{18.9} = 0 \quad (1)$$

where ΔH refers to the enthalpy change of the system (kJ/kg); and $H_{Total}^{14.0}$ and $H_{Total}^{18.9}$ refers to the total enthalpy at downstream station and at the wellhead (kJ/kg), respectively.

Rearranging Equation 1 yields:

$$H_{Total}^{18.9} = H_{Total}^{14.0} \quad (2)$$

As noted above, it is assumed that at the downstream station only dry steam is present but at the wellhead, both steam and water coexist. The steam and water fractions at the wellhead are referred to as x and y , respectively, and:

$$y + x = 1 \quad (3)$$

Consequently, the enthalpy of the system at 14.0 bar is equal to the enthalpy of steam at those conditions but at 18.9 bar the enthalpy of the system is equal to the enthalpy of both steam and water in the appropriate proportions. This can be described by:

$$H_{14.0}^s = x H_{18.9}^s + (1 - x) H_{18.9}^w \quad (4)$$

where the superscripts s and w refer to steam and water, respectively.

Equation 4 can be rearranged to determine the steam fraction at 18.9 bars by:

$$x = \frac{H_{14.0}^s - H_{18.9}^w}{H_{18.9}^s - H_{18.9}^w} \quad (5)$$

Taking the enthalpy for steam at 14.0 and 18.9 bar and water at 18.9 bar from steam tables, we get a steam fraction of 99.57%. Consequently, the water fraction at wellhead conditions is equal to 0.43%.

4.2 Downhole measurements and steam saturation

Static down-hole pressure and temperature measurements provide an opportunity to evaluate the water fraction in the steam well KMJ-67. Pressure/depth profiles are very sensitive to steam/water ratio in the well. This is because pressure is a sensitive function of the average density of fluid in the well.

The relationship between pressure, density and depth is given by:

$$P = \rho g h \quad (6)$$

where P = Pressure (bar);
 ρ = Density (g/cm^3);
 g = Acceleration of gravity in (m/s^2); and
 h = Depth in m.

At 232°C the density of liquid water is $824.6 \text{ kg}/\text{m}^3$, whereas the density of saturated steam at this temperature is only $14.5 \text{ kg}/\text{m}^3$. Consequently, even a small fraction of liquid water will significantly increase the average density of the two-phase fluid in the well and thus the observed pressure at a given depth. The relationship between the density of the two-phase fluid and steam fraction is described in Equation 7:

$$\rho = x \rho_s + (1 - x) \rho_w \quad (7)$$

where ρ_s = Density of steam at given temperature (g/cm^3);
 ρ_w = Density of water at given temperature (g/cm^3); and
 x = Steam fraction.

Substituting Equation 7 into Equation 6 gives

$$P = [x \rho_s + (1 - x) \rho_w] g h \quad (8)$$

which allows calculation of the pressure of a two-phase fluid as a function of depth at a given temperature.

Figure 9 shows the observed pressure in the well as a function of depth on 15 December, 2004. The Excel plugin software STEAM TAB was used to calculate the down-hole pressure for dry steam (shown in Figure 9 by filled rectangles). Figure 9 shows that the dry steam conditions do not fit the observed pressure profile in the well because the pressure in the well rises more steeply with depth than it would if there was only dry steam in the well. However, the pressure depth profile, calculated assuming a water fraction of 0.43% gives a better fit, particularly for the upper part of the profile. The conclusion from this is that the down-hole measurements indicate that there must be approximately 0.5% of water in the steam at least in the uppermost part of the well. From 600 m to bottom, the water fraction seems to decrease with depth.

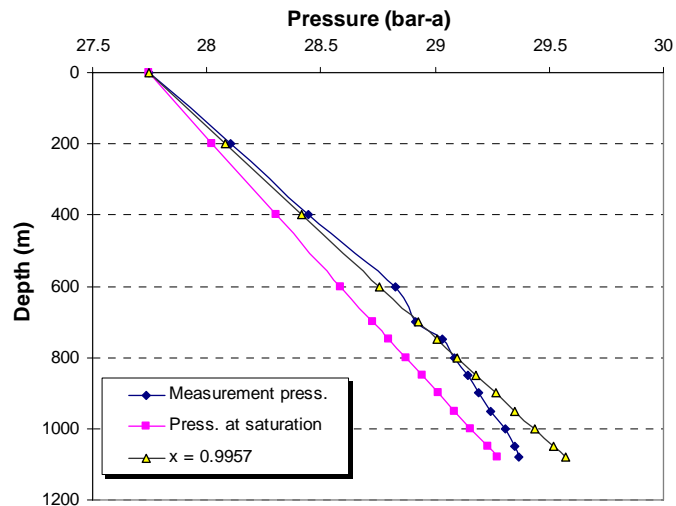


FIGURE 9: Graph of static pressure down-hole measurement in KMJ-67 and calculated pressure graphs

4.3 Scaling mass balance

It has been shown in the previous section that the scales in KMJ-67 must have been precipitated in situ from aqueous solution. Scale mass balance calculations were carried out to evaluate the amount of water needed to form the scales. For the purpose of these calculations two assumptions were made:

1. The silica concentration in the water is controlled by equilibrium with quartz at 230°C; and
2. All the silica was deposited at 18-21 m away from the wellhead.

The concentration of silica in water in equilibrium with quartz at 230°C was found to be 306 ppm (SiO₂) using the SUPCRT92 code (Johnsson et al., 1992). As noted above, the scales were confined to an interval of about 3 m (l), their average thickness was equal to 1.5 cm (h_{scale}), and the radius of the pipe is 12.7 cm (r_p). This allows the calculation of the volume of the scales (V_{scales}) by:

$$V_{scale} = \pi l (h_{scale}^2 - 2r_p h_{scale}) \quad (9)$$

The mass of scales (m_{scale}) can be calculated from the volume assuming that the density of the scales, ρ , is somewhere between that of pure quartz (2560 kg/m³) and 1800 kg/m³ (to account for open space between the scales):

$$m_{scale} = \frac{V_{scale}}{\rho} \quad (10)$$

Using the above observations and Equations 9 and 10 it can be shown that the mass of silica deposited in the pipelines is between 61 to 89.5 kg.

Assuming that the concentration of SiO₂ in the water is equal to 306 ppm the amount of water (m_{water}) needed to transport the above amount of silica into the pipeline can be calculated by:

$$m_{water} = \frac{m_{scales}}{C_{SiO_2}} \quad (11)$$

where C_{SiO_2} = Concentration of aqueous silica (in this case 306 ppm).

Accordingly, the amount of water needed to bring the silica that was deposited in the pipeline is equal to 2.0×10^5 to 2.9×10^5 kg. Since the time of scale deposition is unknown it is assumed that the time is one year. Well KMJ-67 produces 53 tons of steam per hour of 4.6×10^8 kg in a year. Therefore, the water fraction in steam that formed scale in pipeline is approximately 0.04-0.06%. This result gives the minimum water fraction for KMJ-67. The apparent discrepancy between the mass balance method and the calculations based on wellhead conditions indicates that either the concentration of silica in the water fraction is much lower than anticipated or that only 10% of the available silica is deposited in the pipeline. If the latter is true, 90% of the dissolved silica in the water fraction are carried through the steam pipeline, most likely as dust.

5. DISCUSSION

According to XRD analysis, the scale mostly contains pure quartz with minor impurities. This result was also affirmed by SEM investigation, showing that the scale is fairly homogenous. The angularity of the crystals indicates that the scale formed by precipitation from solution and formation in situ. In order to prevent scale formation at the wellhead of KMJ-67 it is necessary to prevent the dry-out of the water in the pipe, between the wellhead and the separator. This can be done by injecting water (condensate) into the pipe by the wellhead. The necessary rate of water injection is determined below by calculating the water fraction needed at the wellhead in order to keep the steam wet all the way to the separator.

Two calculations, based on independent data sets, indicate that there is about 0.43% water in the steam at the wellhead. If the separator pressure of the turbine is 7.2 bar-a, and adiabatic conditions are

assumed in the pipeline, i.e. that there is no net change in enthalpy of the system between the well head and the separator of turbine, then, similar to what was shown in Section 4.1:

$$\Delta H = H_{Total}^{7.2} - H_{Total}^{18.9} = 0 \quad (12)$$

where ΔH refers to the enthalpy change (kJ/kg) of the system, and $H_{Total}^{7.2}$ and $H_{Total}^{18.9}$ are to the total enthalpy (kJ/kg) at the separator station of turbine and at the well head, respectively.

Rearranging Equation 12 yields:

$$H_{Total}^{18.9} = H_{Total}^{7.2} \quad (13)$$

As noted above, in this calculation it is assumed that at the separator station only dry steam is present but at the well head, both steam and water coexist. As before, the steam and water fractions at the well head are referred to as x and y , respectively, and:

$$y + x = 1 \quad (14)$$

Consequently, the enthalpy of the system at 7.2 bar is equal to the enthalpy of steam at those conditions but at 18.9 bar the enthalpy of the system is equal to the enthalpy of both steam and water in the appropriate proportions. This can be described by

$$H_{7.2}^s = x H_{18.9}^s + (1 - x) H_{18.9}^w \quad (15)$$

Equation 15 can be rearranged to determine the steam fraction at 18.9 bars by:

$$x = \frac{H_{7.2}^s - H_{18.9}^w}{H_{18.9}^s - H_{18.9}^w} \quad (16)$$

Taking the enthalpy for steam at 7.2 bar and 18.9 bar and water at 18.9 bar from the steam tables, we get a steam fraction as 98.73. Consequently, the water fraction at the wellhead conditions must be 1.27%. The wellhead condition has a water fraction of 0.43%, hence the water that needs to be injected is 0.84%. As noted above the average production from KMJ-67 is equal to 53 tons/h or 14.7 kg/s. Consequently, the condensate needs to be injected at a rate of 126 g/s in order to keep the steam wet all the way to the separator.

6. CONCLUSIONS

1. Scale deposition formed in the steam pipeline of production well KMJ-67 is mostly quartz with minor impurities, according to analyses by XRD and SEM.
2. As quartz or silica is only soluble in the liquid phase, the silica concentration equilibrium at the bottom hole temperature 230°C is 306 ppm. Well KMJ-67 has a water fraction of approximately 0.43%, analysed by pressure-temperature surface conditions and static down-hole measurements.
3. The scale formed at a T-connection, as the pressure drops from 18.9 to 14.0 bar-a.
4. In order to keep the steam wet all the way to the turbine, 126 g/s of water need to be injected into the steam flow line at wellhead conditions.

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