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Well Integrity Assessment by EM Wireline Logging in Acidic Geothermal Production Well: Case Study of the Hatchobaru Geothermal Field, Japan

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ABSTRACT

Well integrity assessment is very important for maintaining the well activity through the entire well lifecycle. If the well integrity is not compliant, a catastrophic incident may potentially be triggered, such as blowout or formation fluid seepage to surface. This study introduces a case study of the assessment by wireline logging in the Hatchobaru geothermal field located on Kyushu Island, Japan.

Sidetracking was planned in one of the production wells, which had produced hot acidic fluid for more than 10 years, and a substantial amount of metal debris of casing conveyed from downhole had been observed. Well integrity was one of the major concerns when planning sidetracking, and it was decided to conduct a casing corrosion assessment by wireline logging. Typically, five logging technologies are available for the casing pipe corrosion evaluation: 1) a mechanical caliper measurement, which is a robust measurement of the inner diameter of a casing string, 2) an ultrasonic measurement requiring a fluid-filled borehole, which enables measurement of casing ID and the thickness of the inner casing string, 3) an electromagnetic (EM) eddy current evaluation measurement, which is sensitive not only to thickness of the inner casing string but also to that of the outer casing strings in a multiple-string configuration, 4) a magnetic flux leakage (MFL) measurement, 5) a downhole camera. In the case of this particular well, the casing section of interest was filled with air and the static borehole temperature exceeded the operating temperature limits of logging tools. Under these environmental constraints, the EM eddy current evaluation measurement was selected because it would suit the client's needs. The temperature limitation could be overcome by injecting water during the logging survey to lower the borehole temperature.

The data processing and interpretation was conducted after implementing strict QC on the acquisition data. The acquired EM signal exhibited a good signal-to-noise ratio and enabled further processing. Integrating the EM data with the auxiliary log data, the downhole condition of the production well was interpreted as follows: 1) Downhole temperature was sufficiently reduced by the injection water. 2) The flow regime of the injection water was probably a mist flow interpreted by the pressure log. 3) Precipitation of casing scale was indicated by high gamma-ray count at the shallower section. 4) Casing thickness tends to get thinner as it goes deeper. 5) Metal loss mainly occurred inside the casing, which was most likely caused by general corrosion.

Based on the well integrity condition interpreted by the logging data, the operator managed to optimize the remedial workover program.

1. INTRODUCTION

A compromised well integrity may lead to catastrophic incidents during well operation. This is applicable not only to the oil and gas industry, but also to the geothermal industry, where production wells produce. The production fluids of a geothermal field can be at a very high temperature and acidic, which may cause an accelerated corrosion of steel in the well during the production life cycle. In this case, an assessment of casing corrosion is important to ensure the casing integrity for maintaining production operation or during a workover operation. In this study, we demonstrate casing corrosion monitoring logging for casing integrity assessment in the acidic hot water production well located in the Hatchobaru geothermal field.

The Hatchobaru geothermal field is located in the eastern part of the Kyushu Island in Japan. Kyushu Electric Power Co., Inc. (hereinafter referred to as KEPCO) has engaged in the geothermal development in this field since the 1960s and the first geothermal power plant there was inaugurated in 1977. In 1990, the second unit started its operation and a binary cycle unit was added later. Currently its total capacity is 112 MW comprising two steam turbine units of 55 MW each and one binary cycle unit of 2 MW, which makes it a largest geothermal power plant in Japan.

A sidetrack drilling workover operation was planned in the production well in the Hatchobaru geothermal field. The concerned well was drilled in 2002 and produced neutral geothermal fluid in the beginning. The pH of the fluid had gradually declined, and eventually the well started producing acidic fluid with a pH of around 3. Although it remained one of the main steam producers in the Hatchobaru geothermal power plant, a lot of metal debris of casing conveyed from downhole was observed at surface. This metal debris indicated serious damage of the casing pipe downhole. The situation worsened to a point where KEPCO decided to consider an option for sidetracking from the cased hole section. A sidetracking workover operation was planned to use a whipstock. The casing integrity had to be ensured prior to starting the actual sidetracking drilling operation. Thus, KEPCO decided to conduct a casing corrosion assessment by an appropriate wireline logging technology.

2. CASING DIAGRAM AND CORROSION MONITORING LOGGING

Figure 1 shows the casing program of the concerned well. Regarding the planning of the wireline operation, the key conditions were as follows.

- There was a total of four casing sizes installed, including 20-in casing, 13⅜-in casing, 9⅝-in casing, and 7-in liner.
- The zone of interest of corrosion monitoring for the sidetrack drilling operation was from 10 m to 1,250 m, i.e., mostly a single 9⅝-in casing section with a multiple casing sections at shallower depths.
- The borehole deviation was vertical with less than 3° inclination in the zone of interest.
- The borehole was filled by air in the zone of interest under well shut-in condition.
- The free water level in well shut-in condition was below the top of liner (1,265.89 m) as observed by a previous pressure and temperature wireline logging in 2014.
- The pressure and temperature data indicated that the maximum static temperature at the casing section of interest was 222 degC.

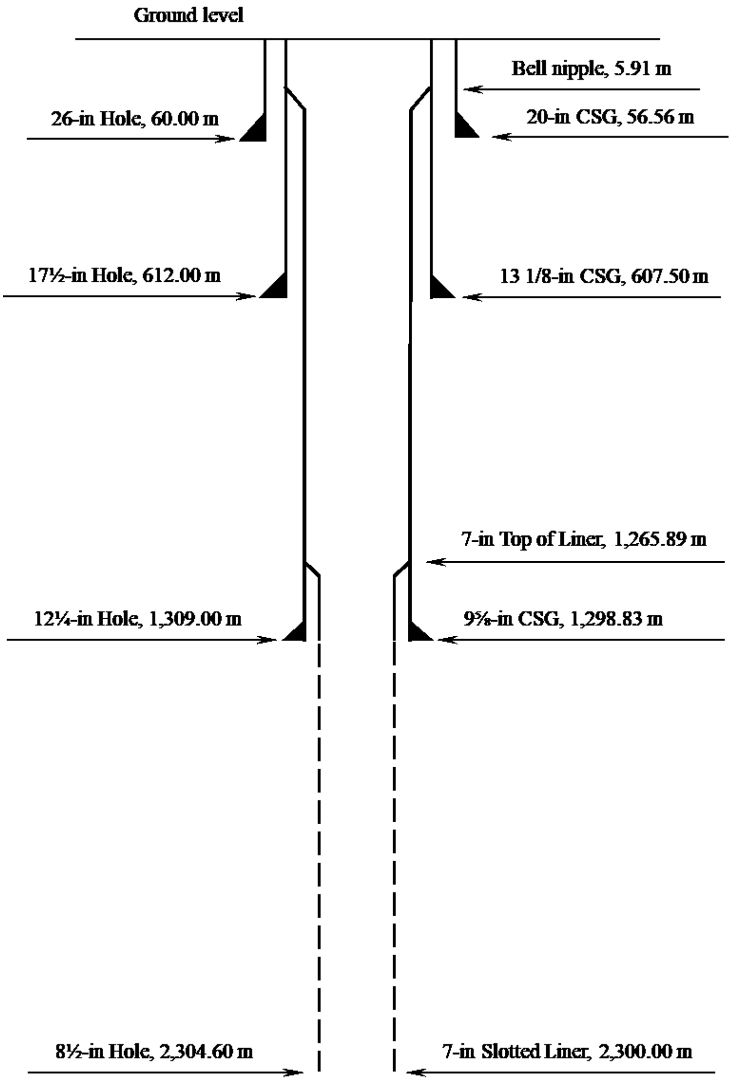

Figure 1: Casing program of the well subjected to corrosion evaluation in the Hatchobaru geothermal field, Kyushu, Japan

Typically, five logging technologies are available for casing corrosion monitoring (Acuña et al., 2010). 1) A multifinger mechanical caliper measurement is a well-established logging technology for evaluating internal pipe problems, but it provides no data about external corrosion and is affected by scale deposited inside the casing. 2) An ultrasonic measurement is an excellent pipe thickness measurement in a single casing string and has superior azimuthal resolution. However, ultrasonic logging measurements are unable to operate in a borehole containing gas. 3) An electromagnetic (EM) eddy current evaluation measurement, which is sensitive not only to thickness of the inner casing string but also to that of the outer casing strings in a multiple-string configuration. 4) a magnetic flux leakage (MFL) measurement 5) Downhole cameras can also be used for corrosion monitoring, if the borehole is filled with gas or another clear fluid, but it is not suitable for quantifying the thickness of casing.

The production well in this study was filled with air. Thus, an ultrasonic measurement was not suitable because it requires the logging interval to be fluid-filled. Setting a packer might have enabled filling the borehole with water injected from the surface, however, the borehole temperature was expected to exceed the tool hardware limitations because the static borehole temperature was recorded 222 degC by the previous wireline logging without water injection. A downhole camera or a multifingered mechanical caliper were also possible choices, however, quantification of casing thickness was required, which is not achievable by either of these techniques. Given the technical limitations of each corrosion monitoring logging technology, we proposed EM eddy current evaluation measurements to KEPCO, as it would fulfill the client's needs while the hardware temperature limitation issue could be overcome by cooling down borehole temperatures using the continuous injected water from surface during logging operation. KEPCO accepted that proposal.

In the actual operation, a junk basket with a gauge ring of 8⅛-in was conducted prior to the corrosion monitoring logging as dummy run. Logging tools were stopped at 564.4 m (near the 13⅜-in casing shoe depth) where a mechanical obstruction was expected. Thus, the actual measured section was determined to be from 550.0 m for corrosion monitoring logging.

3. EM-TYPE CORROSION MONITORING LOGGING

Two common EM-type corrosion monitoring logging measurement techniques are magnetic flux leakage and electromagnetic eddy current inspection. A flux leakage logging tool uses a permanent- or electromagnet to magnetize the pipe to near saturation. Magnetic flux leaks out of the pipe at locations of a hole or a corrosion patch. Coils mounted on pads of the logging tool detect that leaked flux, a measurement sensitive to the defects on the inside or outside of a pipe. This flux leakage inspection technique performs well for measuring sudden thickness changes, but it is not effective if the corrosion is constant or varies slowly over a whole section of pipe (Acuña et al., 2010).

For the pipe inspection of the well discussed in this study, an EM remote field eddy current (RFEC) evaluation logging was conducted (Brill et al., 2011). This method uses a transmitter solenoid excited by an alternating current at a given frequency. The associated EM field and secondary field from induced eddy currents in the surrounding conductive pipes induce a voltage in a separate (remote) receiver coil. The tool response can be compared to a poorly coupled and lossy transformer where the pipe acts as coupling between primary (transmitter) and secondary (receiver) coils. Unlike a typical transformer, there is no mutual magnetic core to guide the magnetic flux between transmitter and receiver. Instead, the casing acts as a guide of the flux. This flux guide is, however, quite lossy due to the eddy-currents induced in the casing metal. The losses associated with phase shifts between transmitter current and receiver voltage relative to those in air are measured to determine geometrical and electromagnetic properties of the casing.

Corrosion monitoring of casings is based on evaluating the thickness of metal. The thickness is calculated by determining how an EM field is affected by penetrating casings. The eddy currents induced in the metal create a secondary magnetic field, which opposes the primary alternating magnetic field, causing phase shifts and attenuation as the field penetrates the metal. This effect is the skin depth attenuation where one skin depth is the distance of metal traversed at which the amplitude is attenuated by 1/e with a corresponding phase shift of 1 radian. A measurement of the phase shift combined with appropriate calibrations enables the thickness determination. By deploying a sufficiently large spacing between transmitter and remote receiver, this RFEC technique leads to a sensitivity to the total metal thickness of casings between the coils. The very large contrast in electrical conductivity between the pipe and either the wellbore fluid or the background formation ensures that at low frequency only the metal is contributing to the phase delay.

Additionally, high-resolution images were measured by eighteen pad sensors. There were two types of high-resolution images available. 1) Images using the same low-frequency transmitter as the average (mandrel coil) EM thickness measurement. The low-frequency pad measurement determines the total metal loss in all strings. The sensitivity is lower with increasing radial distance from the pad sensors. The metal thickness is derived from the impedance phase shifts. A normalized 2D depth image log is typically presented by subtracting the average of all 18 pad measurements at each depth to enhance azimuthal variations. (Brill et al., 2011). 2) Images using high-frequency signals that barely penetrate into the metal of the pipe. The inner surface of the innermost pipe determines the near-field signal response immediately adjacent to the pads. Hence, this image measurement is good at detecting internal defects of the pipe. A normalized high-frequency 2D discrimination image is typically presented by subtracting the azimuthal average.

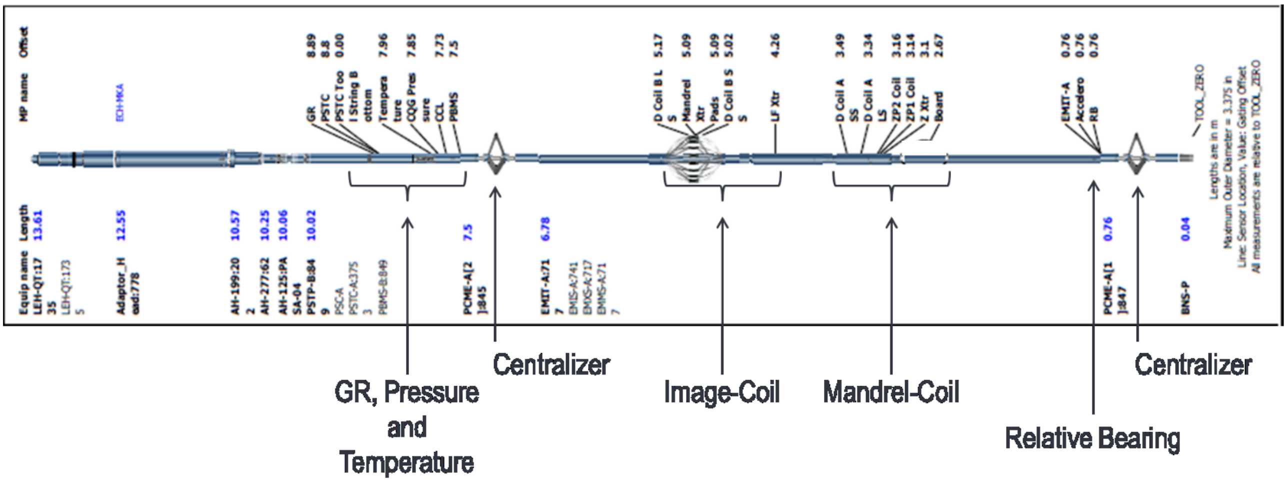

Figure 2 Wireline logging toolstring

The wireline logging toolstring was arranged to measure good quality data by the EM eddy current pipe inspection. Figure 2 shows the toolstring sketch used for the pipe inspection logging in this study. Two centralizers were put below and above the EM pipe inspection sonde to centralize the toolstring in the borehole. The accelerometer measurement below the mandrel coils measured 3-axes acceleration, which determined the toolface azimuth versus the gravity vector. The natural gamma-ray log, borehole pressure, and temperature sonde were arranged above the EM pipe inspection sonde.

The high downhole temperature—expected at 222 degC based on previous wireline logs—was higher than the tool hardware temperature limitation (150 degC). Therefore, a borehole cooling was required to run the logging tools. Fresh water from the nearest river was injected at the wellhead while the wireline tools were downhole. A dummy run prior to EM-type corrosion monitoring logging confirmed a sufficiently reduced borehole temperature. The injected water was not filling up to the logging interval. The fluid probably leaked to the formation in the openhole section below the logging interval.

The operating parameters of the EM-type corrosion monitoring log were determined by the prejob toolplanner simulation targeting the dual casing section with 9⅝-in inner casing and 13⅜-in outer casing. The operating EM excitation frequency of the main transmitter coil was set to 8.75 Hz and logging speed was arranged at 500 ft/h.

4. ACQUISITION DATA QC AND PROCESSING

Prior to data processing and interpretation, the quality of the acquisition data and the borehole condition were checked. Figure 3 shows the auxiliary logs acquired together with the EM type corrosion monitoring logging. There was no over pulling cable indicated by the tension log, which implied a smooth tool motion during logging downhole. Temperature measurements showed values between 21.8 degC and 18.8 degC, indicating borehole temperatures lower than the hardware limitation (150 degC). The injected water actually leaked to the formation from the 7-in slotted liner section deeper than the corrosion logging interval and did not fill the borehole. Thus, it appeared to generate a mist flow (the gas phase being distributed as bubbles through the liquid phase) regime downhole, which was interpreted by the pressure log data. High natural gamma-ray counts were observed at the interval shallower than 85 m, where scale was probably deposited in the casing. EM remote field eddy current type corrosion monitoring logs are not affected by the presence of nonconductive scale due to the measurement principle.

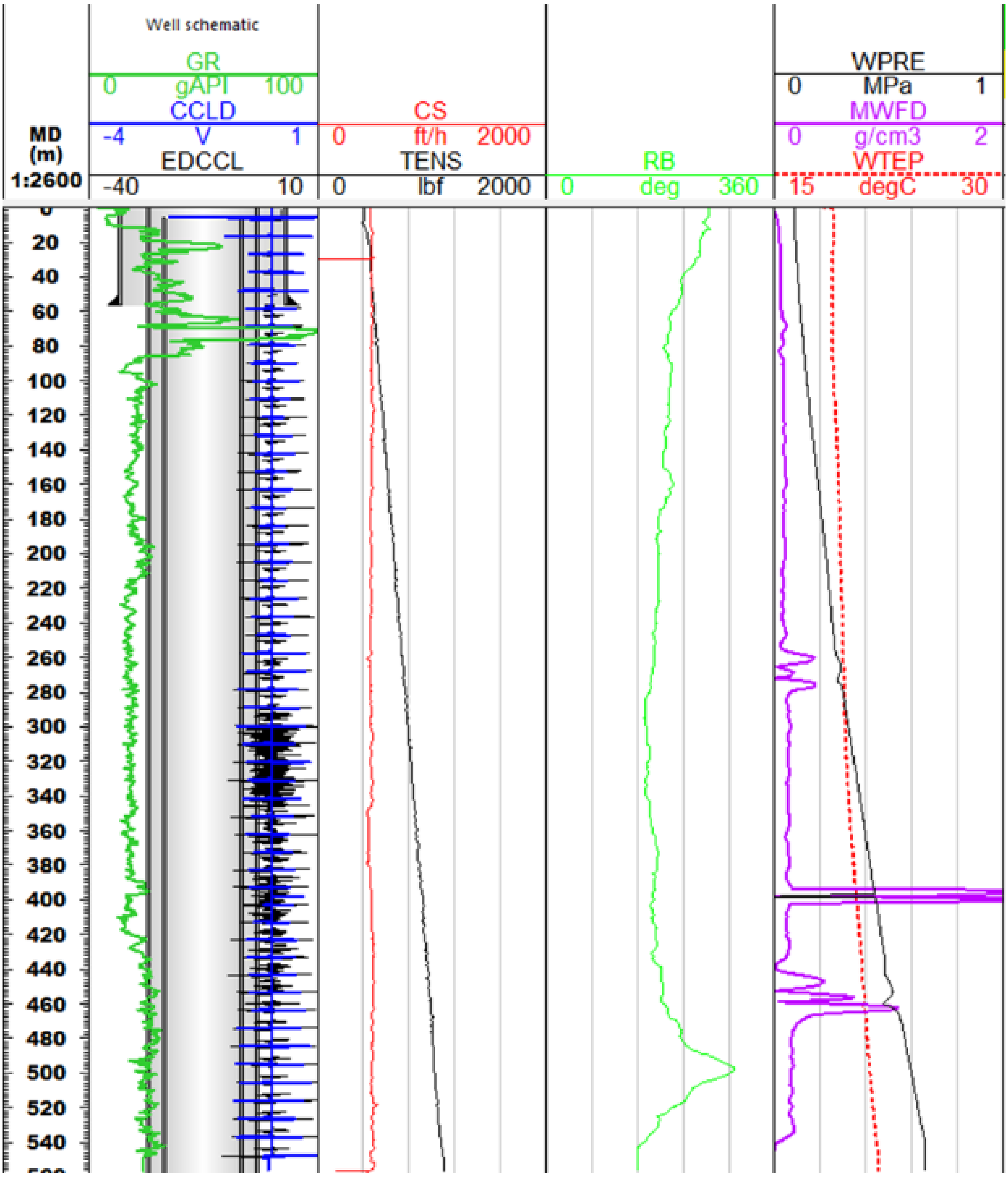

Figure 3 Auxiliary log data acquired together with corrosion inspection log

Log repeatability was validated by the comparison of data between main pass and repeat pass, which was acquired from 550 m to 476 m. Figure 4 compares the log data between main pass and repeat pass. Both amplitude and phase of EM fields measured by short and long spacing coils showed very good repeatability. In addition, good repeatability of natural gamma-ray log and casing collar locator log were also validated.

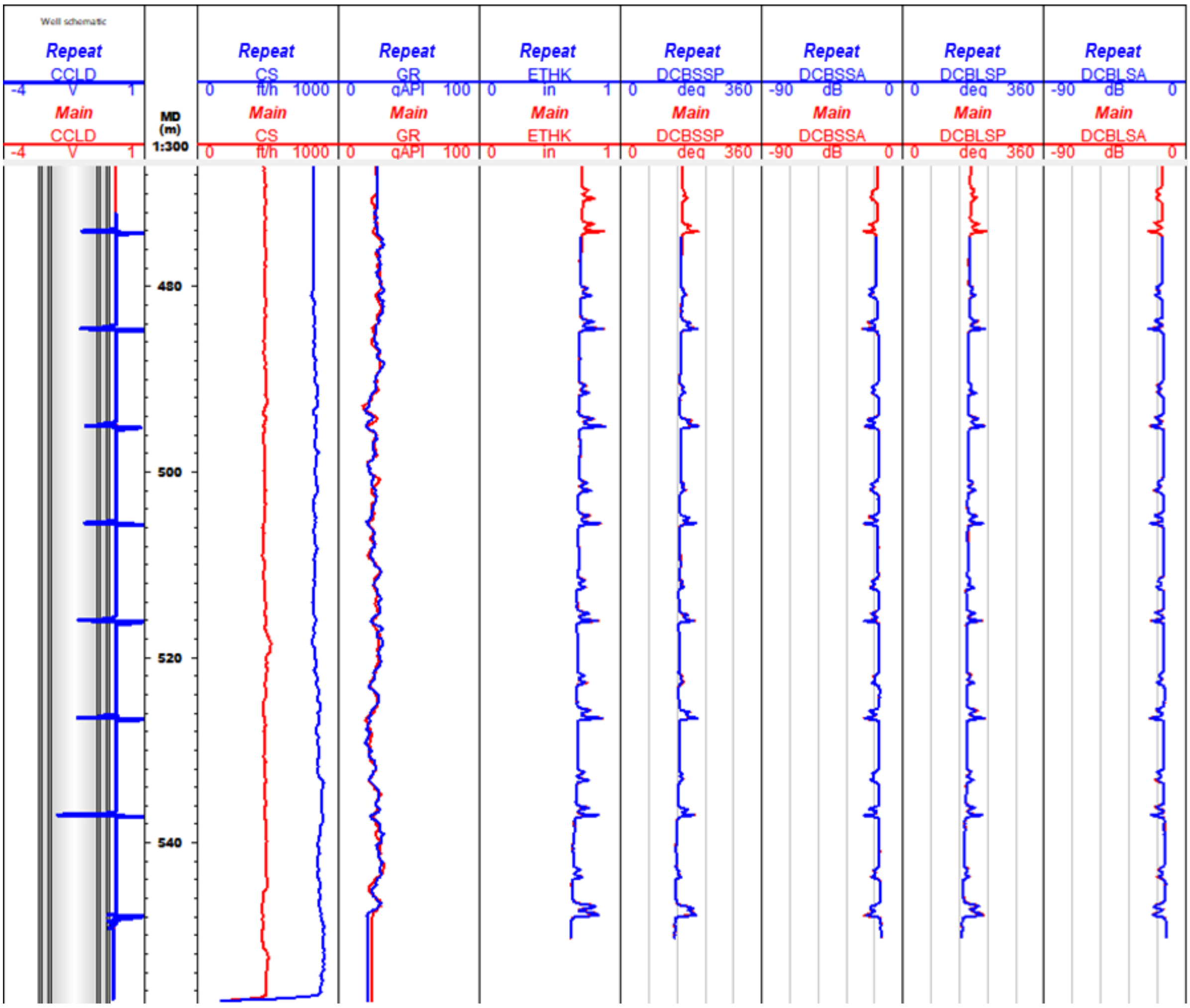

Figure 4 Log data repeatability, comparison of main pass (red) and repeat pass (blue) data.

The signal level of raw EM field measurements is important to qualitatively evaluate the casing thickness by EM-type corrosion monitoring logs. Figure 5 shows the raw EM field measurement logs of phase and amplitude data by short spacing (DSBSS) and long spacing (DCBLS) mandrel coils near the 20-in casing shoe, where the casing layers changed from dual to triple. The measured phase (P) and amplitude (A) logs showed a baseline change at 56.5 m, corresponding to the transition between dual and triple casing sections. The EM field is affected by the total thickness of metal layers surrounding the logging tool, thus that baseline change of the measured log data is reasonable. In addition, the largest variations of both phase and amplitude were repeatedly observed approximately every 10 m, which indicate the casing collars of the innermost casing, 9⅝-in casing. That is confirmed by the agreement with casing collar locator log results. In the dual casing section, there were additional repeated features observed on the amplitude and phase logs, which indicate the casing collars of the outer casing (13⅜-in casing). Moreover, another repeated feature appeared in the triple casing section, which was caused by the casing collars of the outermost 20-in casing.

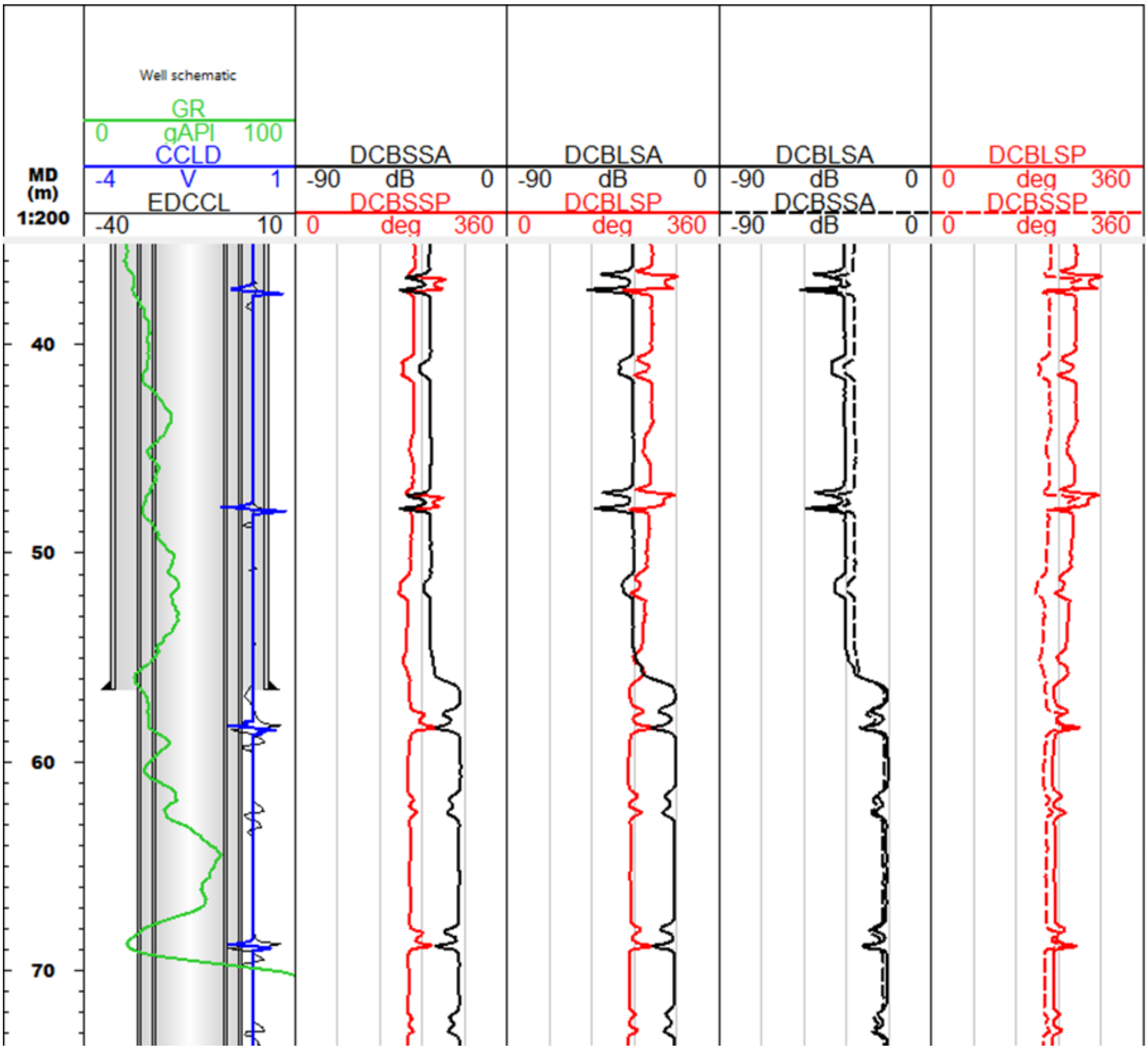

Figure 5 Raw amplitude (A) and phase (P) measurements of electromagnetic field by different receiver coils (SS: short spacing, LS: long spacing) of the corrosion monitoring log

With the above mentioned acquisition log QCs, a reasonable EM corrosion monitoring log response was validated prior to further processing. A calibration using the electromagnetic tool response in the absence of metal surrounding the tools was applied using the tool master calibration data. The calibration was performed in the tool maintenance shop prior to mobilizing the tools. Furthermore, a zero metal loss calibration point is determined from the measured data. In this study, zero metal loss was assumed at 64.2 m, close to the 20-in casing shoe. With that calibration, the thickness of casing was calculated from the measured EM field data and metal loss was calculated using the following equation:

$$ML = \frac{MLTH - ETHK}{MLTH} \times 100 \quad (3)$$

where ML is metal loss (%), MLTH (in) is the sum of nominal casing thickness, ETHK (in) is measured total metal thickness. Because the main coils are of mandrel type, the associated EM eddy current measurements are azimuthally averaged. Thus, the computed thickness and metal loss represent the average for the casings surrounding the logging tool, i.e., the computation results do not discriminate the nested casings in this study.

5. RESULT AND DISCUSSION

The average casing thickness was computed only in the dual casing section, i.e., from 56.5 m to 550 m, because the outermost 20 in casing was too large to quantitively determine the casing thickness using the EM-type corrosion monitoring logging tool specifically used in this study. Figure 6 shows the resulting casing thickness and metal loss in the dual casing section.

The computed casing thickness showed overall an increase from the deeper section to the shallower section. The same overall thickness trend was also detected by the pad image measurements. Using the thickness determined by the mandrel coil measurements, the metal loss was computed. As a result, the largest metal loss was found to be 26 % at 550 m (the deeper section of the logging interval). The metal loss reduced in the shallower section.

Because the borehole temperature was reduced to 21.8 degC–18.8 degC by the injected water during the wireline operation, it was expected that the temperature of inner casing was also cooled down to that range of temperature. On the other hand, since the outer casing was adjacent to the formation through the cement, a reduction of temperature at the outer casing could not be ascertained. If the temperature of the outer casing was still dominated by the formation static temperature, the casing conductivity decreases with the depth and accounts for a nonnegligible effect on the EM corrosion monitoring log. Assuming that the outer casing temperature was dominated by the formation temperature, the resulting effect was estimated to be a few percent in apparent metal loss, which suggests the possibility of an overestimated metal loss result. However, the overall trend of metal loss with increasing depth was still valid.

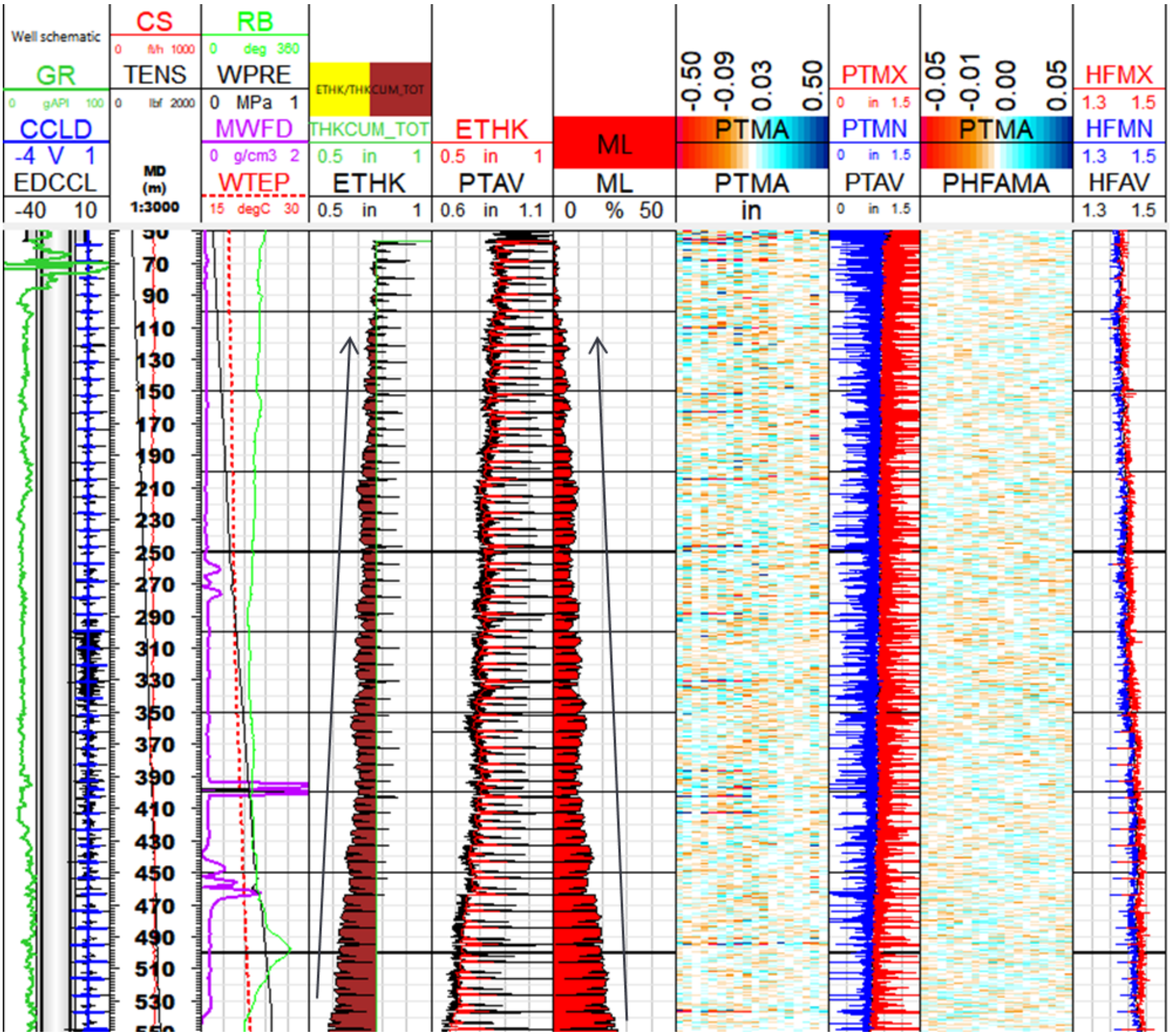

Figure 6 The result of computed casing thickness and metal loss from the EM-type corrosion monitoring log data in this study

Figure 7 shows the computed average casing thickness and metal loss results together with results for both high-resolution low-frequency image and high-frequency image from pad sensors. Both images show the residual relative to the average on Figure 7, thus, they are more sensitive to the local anomalies of casings, i.e., sudden changes of casing thickness. The low-frequency image represents the localized casing thickness variation and the high-frequency image provides the status of internal casing defects, which helps to discriminate between defects on the inner or outer wall of single casing strings. In this dataset, the low-frequency image shows smooth features and no local anomaly was observed. The high-frequency image also shows smooth features and no obvious casing defect features on the image logs. With those observation on image logs, the type of metal loss was interpreted as a general corrosion homogeneously occurring inside the pipe, probably related to the long production history of the acidic hot water (170–200 degC) production. A multifinger mechanical caliper logging in the future will be helpful to validate the results from EM measurements in this study.

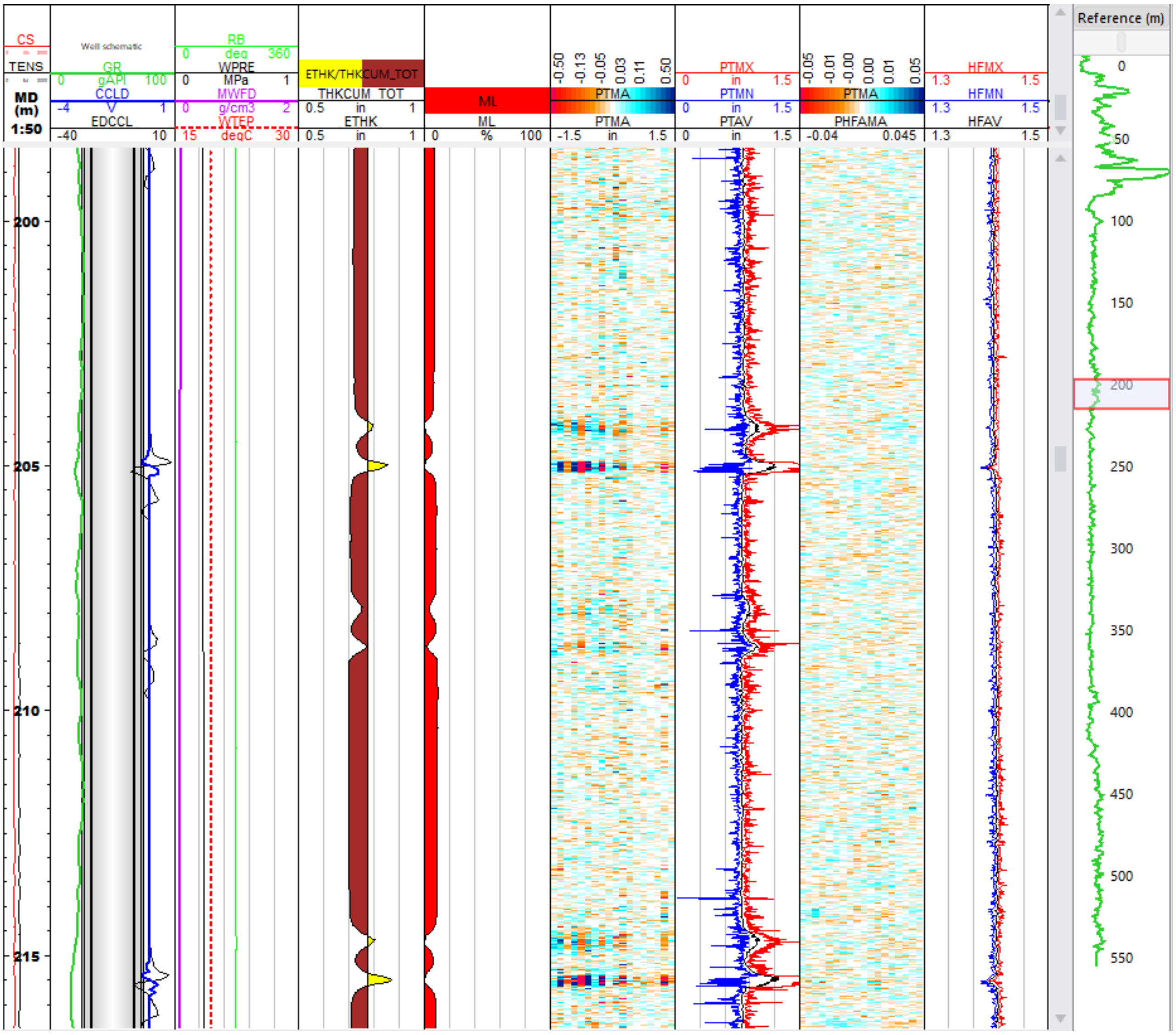

Figure 7 Computed casing thickness and metal loss with pad image logs from 197 m to 217 m

6. CONCLUSION

In this study, casing corrosion monitoring logs were performed to assess the well integrity prior to sidetracking the well, which has produced acidic hot water for more than 10 years in the Hatchobaru geothermal field in Japan. Due to an air-filled borehole, a wireline EM remote field eddy current corrosion monitoring log was conducted. To reduce the downhole temperature below the tool temperature rating, freshwater was injected during logging. As a result, highly repeatable log data with low noise levels was acquired successfully. The measured EM data was processed to compute the average total casing thickness in the dual casing interval with a 9⅝-in inner casing and a 13⅜-in outer casing assuming zero metal loss at the top of the dual casing section. The computed casing thickness increases from deeper to shallower depth, and the largest metal loss was estimated as 26 % at the deepest depth of the logging interval. Since the outer casing temperature was uncertain during logging, the estimated metal loss was potentially overestimated by a few percent. By observing smooth features on the EM pad image measurements, the majority of metal loss was interpreted to occur inside the 9⅝-in casing due to a general corrosion of steel, which is probably related to the acidic hot water production history of the well.

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NOMENCLATURE

CCLD *Casing collar locator*

CS *Cable speed (ft/h)*

DCBLSA Double coil B long spacing amplitude (dB)

DCBLSP Double coil B long spacing phase (deg)

DCBSSA Double coil B short spacing amplitude (dB)

DCBSSP *Double coil B short spacing phase (deg)*

ETHK *Electromagnetic computed thickness (in)*

GR *Gamma-ray (gAPI)*

HFAV *High frequency pad amplitude average*

HFMN *High frequency pad amplitude minimum*

HFMX *High frequency pad amplitude maximum*

ML *Metal loss (%)*

MWFD *Well downhole fluid density (g/cm3)*

PHFAMAPads high frequency amplitude minus average

PTAV *Pad thickness average (in)*

PTMA *Pads thickness minus average (in)*

PTMN *Pad thickness minimum (in)*

PTMX *Pad thickness maximum (in)*

RB *Relative bearing, tool face azimuth against the gravity vector inversed (deg)*

TENS *Cable tension (lbf)*

WPRE *Well downhole pressure (MPa)*

WTEP *Well downhole temperature (*degC*)*

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