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Full Well Corrosion Insight – Case Studies in the Added Value of Electromagnetic Thickness Measurements During Well Interventions

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Abstract

Monitoring pipe corrosion is one of the critical aspects in the well intervention. Such analysis is used to evaluate and justify any remedial actions, to prolong the longevity of the well. Typical corrosion evaluation methods of tubulars consist of multifinger caliper tools that provide high-resolution measurements of the internal condition of the pipe. Routinely, this data is then analyzed and interpreted with respect to the manufacture's nominal specification for each tubular. However, this requires assumptions on the outer diameter of the tubular may add uncertainty, and incorrectly calculate the true metal thicknesses. This paper will highlight cases where the integration of such tool and electromagnetic (EM) thickness data adds value in discovering the true condition of both the first tubular and outer casings.

These case studies demonstrate the use of a multireceiver, multitransmitter electromagnetic (EM) metal thickness tool operating at multiple simultaneous frequencies. It is used to measure the individual wall thickness across multiple strings (up to five) and operates continuously, making measurements in the frequency domain. This tool was combined with a multifinger caliper to provide a complete and efficient single-trip diagnosis of the tubing and casing integrity. The combination of multifinger caliper and EM metal thickness tool results gives both internal and external corrosion as well as metal thickness of first and outer tubular strings.

The paper highlights multiple case studies including; i) successfully detecting several areas of metal loss (up to greater than 32%) on the outer string, which correlated to areas of the mobile salt formation, ii) overlapping defects in two tubulars and, iii) cases where a multifinger caliper alone doesn't provide an accurate indication of the true wall thickness. The final case highlights the advantages of integrating multiple tubular integrity tools when determining the condition of the casing wall.

Metal thickness tools operating on EM principles benefit from a slim outer diameter design that allows the tools to pass through restrictions which typically would prevent ultrasonic scanning thickness tools. Additionally, EM tools are unaffected by the type of fluid in the wellbore and not affected by any non-ferrous scale buildup that may present in the inside of the tubular wall. Combinability between complementary multifinger caliper technology and EM thickness results in two independent sensors to provide a complete assessment of the well architecture.

Introduction

Monitoring the well integrity from pipe corrosion is one of the critical aspects in maintaining the longevity of the well as corrosion can start from internally (inner most pipe), externally (outer most pipe) and a combination of both.

As an example, corrosive defects that are left untreated can be one of the sources of excess water production (Wijaya & Bagir, 2018). Which economically, may cost more than 40 million USD for water treatment alone. Assessing each and all pipes condition are not only needed to assure its integrity through the lifetime of the well but also to ensure the well is managed in the most economic fashion.

Many traditional technologies are available to evaluate the tubular condition in the well. Each technology has its advantages, but typically share a common weakness – they only measure the condition of inner most tubular. Among other tools, Multifinger calipers (MFC) tools and Ultrasonic scanning tools are among the most frequently utilized tools in the evaluation of wear and corrosion over the lifetime of a well. These high-resolution measurements can provide an excellent quantitative understanding of the internal surface of the pipe as well as inferences on the geometry of the inner most tubular.

The MFC tool measures the first-string internal wall condition and can operate in gas filled wellbores unlike ultrasonic technology which requires an acceptable hydrostatic pressure and fluid fill. However, the pipe integrity assessment using wall thickness from an MFC tool requires a knowledge of external pipe condition, which is often assumed and would induce uncertainty.

The ultrasonic scanning tools on the other hand, has the benefit of simultaneously measures the inner and outer tubular condition. Providing a direct measurement of the pipe wall thickness with 360-degrees high-resolution azimuthal coverage. However, like MFC tool, it can only measure the first-string condition.

To evaluate multiple tubulars integrity, electromagnetic (EM) is the only technology capable of the in-situ evaluation of multiple nested casing (San Martin et al. 2017). The EM-based tools measurement is unaffected by non-ferrous annular fill, coatings or fluid type within the borehole and provides an average wall thickness measurement of each casing in up to five nested tubulars.

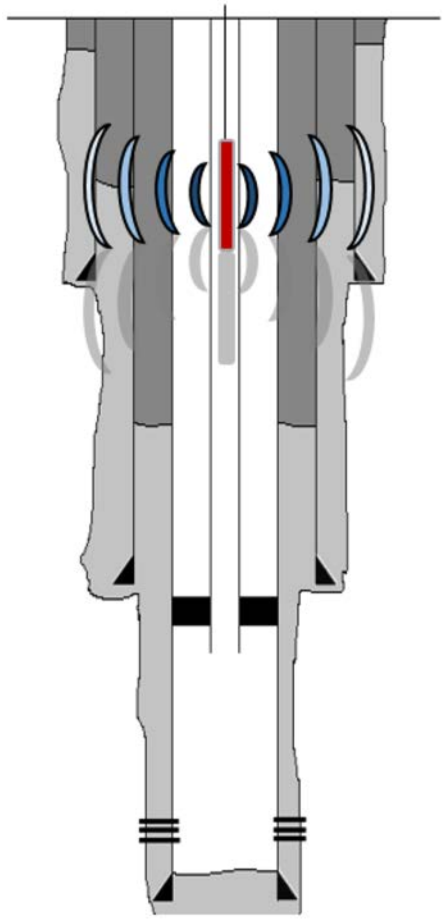

Figure 1—Well Diagram Illustration

History of EM Casing Inspection Technology

The use of electromagnetic eddy-current approaches to pipe corrosion detection can be dated back to the 1960's. Edwards & Stround (1963) published a paper which explains the basic principle of operation and its interpretation use cases both from laboratory and field experiences. During those early years, the tool consisted of two simple radial coils, one as an exciter (transmitter) and the other one as a receiver coil.

At that time, the basic principles technique of examining the casing integrity was based on the phase-shift from the attenuated eddy currents which were measured by the receiver coil. This phase-shift is a function of casing wall thickness, frequency, magnetic permeability, and resistivity of the metal as shown at the following equation (figure 2).

$$\phi = 2\pi D \sqrt{\frac{F\mu}{\rho \times 10^{9}}}$$

where ϕ = phase shift,
D = depth,
μ = magnetic permeability,
ρ = resistivity in micro-ohm cm, and
F = frequency in cycles/sec.

Figure 2—Equation to calculate the wall thickness based on phase-shift (Edwards and Stround, 1963).

The unknown parameters (magnetic permeability and resistivity) are minimized through calibration at a known joint interval. The reference joint acts as a form of "baseline" from which the zero percent metal loss is calculated. Some examples from Edwards & Stround are displayed in the below figure.

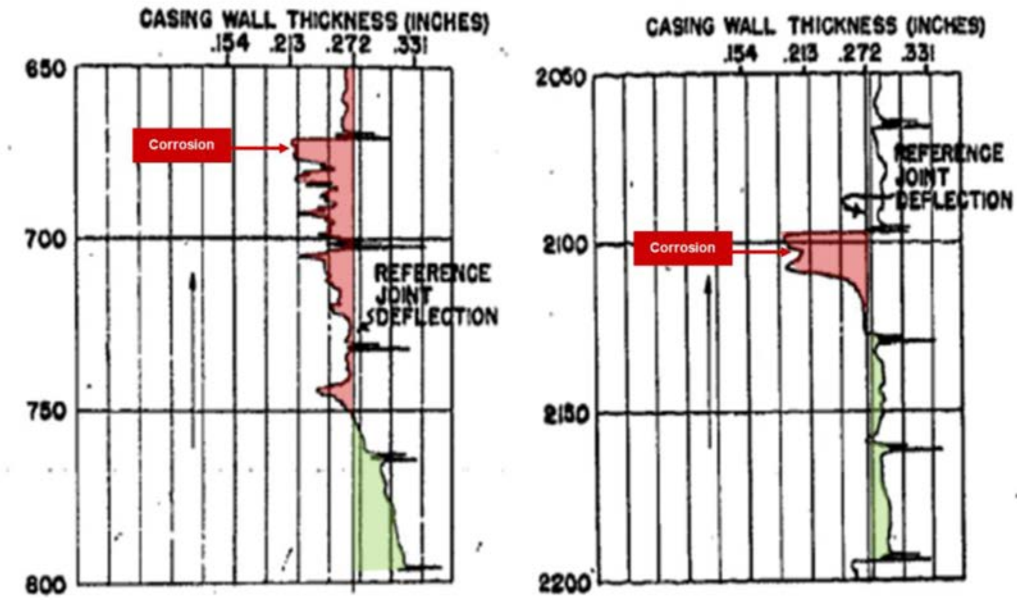

Figure 3—Examples of corroded pipe (Edwards and Stround, 1963 with modification).

The challenge with this early tool was the accuracy and the number of pipes that can be evaluated. The accuracy suffers from the dependency of a reference joint and that the properties are assumed to be nominal. The casing evaluation can only be done in the first tubular and limited to steel-type (non-alloy) pipe.

Advanced Tool Theory and Tool Physics

In general, the advancement of EM technology has allowed the industry to evaluate multiple tubular wall thicknesses. Published studies indicate that newly available EM tools can detect metal loss, even with only 5% metal loss (Schieber and Graham, 2020).

The EM tool outlined in these case studies utilizes High-Definition Frequency (HDF) technology to analyze up to 5 concentric pipes. As a frequency domain corrosion detection tool, the EM tool exploits an array of recievers and transmitted frequencies to evaluate multiple nested tubulars. High frequencies can be used for inner most pipe inspections and low frequencies for outer most pipe inspection. Figure 2 provides an illustrative example of how defects in the far-field are more dominant on receivers that have a greater depth of investigation.

The EM tool generates and transmits a set of low-frequency sinusoidal EM waves from the primary and high-resolution antennas (figure 5), therefore the EM tool is comprised of two sections (Fouda et al. 2020):

- The high-resolution section consists transmitter and two receivers closely spaced
- The primary section consists of a longer transmitter and six receivers.

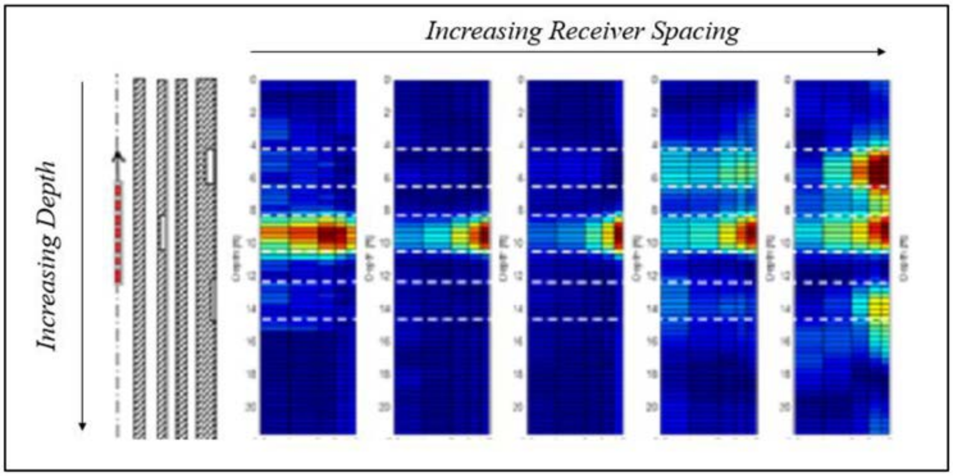

Figure 4—Illustrative Multi-Receiver response against various defects on multiple strings

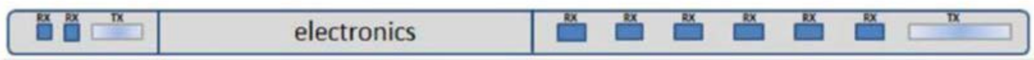

Figure 5—EM tool configuration: two transmitters and eight receivers. Transmitter with high frequency and two receivers are located at the high-resolution section and another transmitter with lower frequency and six receivers are located at the primary section.

The transmitted EM waves induce a strong magnetic flux field extending into the concentric sets of pipes. Within each of the pipes, the induced magnetic flux field lines generate eddy currents, which in turn generate a secondary EM field that can be measured by receiver antennas. The secondary EM field can be measured at each receiver antenna as a real-valued receiver voltage.

The magnitude and relative phase of the secondary EM fields at each frequency is determined by the frequency and magnitude of the transmitted EM signal, the position at which the secondary field is measured, and by the amount of metal (and its properties) that is present at different radial distances from the transmit antenna. Based upon this principle, the EM tool uses a diverse parameter set of frequencies and receiver antenna positioning from which to extract information about the amount of metal present in each pipe. The controlled test indicates that the inversion model showed a good correlation to defects, even at overlapping area (figure 7).

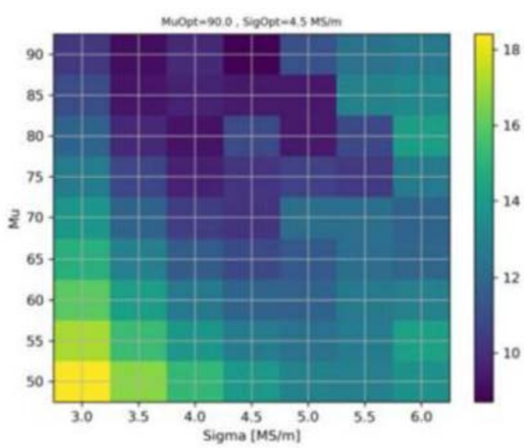

Figure 6—Misfit Map for Mu/Sigma parameter (San Martin et al, 2017)

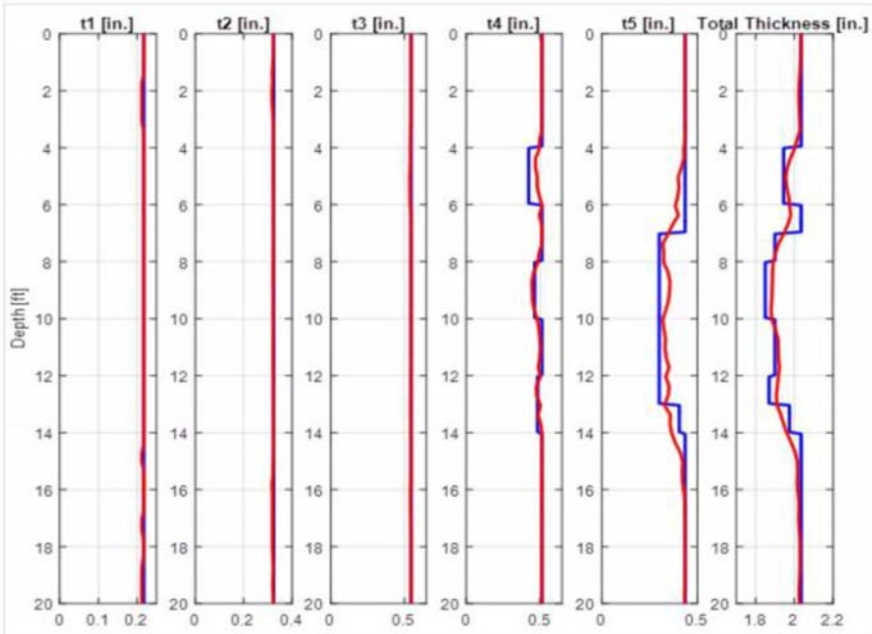

Figure 7—Inversion result across five concentric pipes. Blue is the actual thickness, red is the inversion result (San Martin et al, 2017).

Processing of the acquired data produces a log of the thickness of each pipe from voltage logs recorded with different receivers and at different frequencies. The number of pipes, their outer diameters, and nominal thickness are the inputs required for the processing of the data. Also, a rough estimate of the conductivity of the pipes is assumed to be available. Inversion works on finding the optimum thickness and relative permeability of each pipe that minimize the misfit between measurements and synthetic data generated using a radial one-dimensional (R1D) model that assumes air core coils. The accuracy of the model is enhanced by using adjusted hyperparameter through cost function algorithm. A misfit map (figure 6) is generated to illustrate a better view on the modeled mu/sigma parameter from the processing. Further detailed discussions on the principles and algorithms are presented within San Martin et al 2017.

Tool String

The design of the multifinger caliper tool and EM thickness tool allows combinability in a single run which helps reduce risks related to interventions as well as reduce time required to acquire the data which makes it an optimal solution for cost reduction and efficient interventions.

Both tools are able to operate on a real time platform such as electric line, fiber optic fusion cables, realtime coil tubing or digital slickline, this allows realtime monitoring of the data and ability to broadcast the information to onshore support offices when a realtime decision is required. The tools are also capable of operating on memory platforms utilizing various available intervention solutions including slickline, coil tubing and pipe conveyance which allows flexible field deployment independent of conveyance type.

The combinability and flexible operating platforms allow intervention in any well trajectory from vertical shallow wells to highly deviated and horizontal deep wells. The flexibility of conveyance also helps conduct surveys in any well environment including sour harsh conditions. Today, the technology is actively being used to monitor the longevity of all types of wells including oil & gas, geothermal, gas storage and carbon capture wells.

The figure 8 shows the typical toolstring configuration for combining both measurements in one run for realtime as well as memory. With an outer diameter of 1-11/16-in the EM tool can deploy through completion restrictions and small tubing sizes, however with appropriate centralization the tool can evaluate large casing sizes in the absence of completion tubulars.

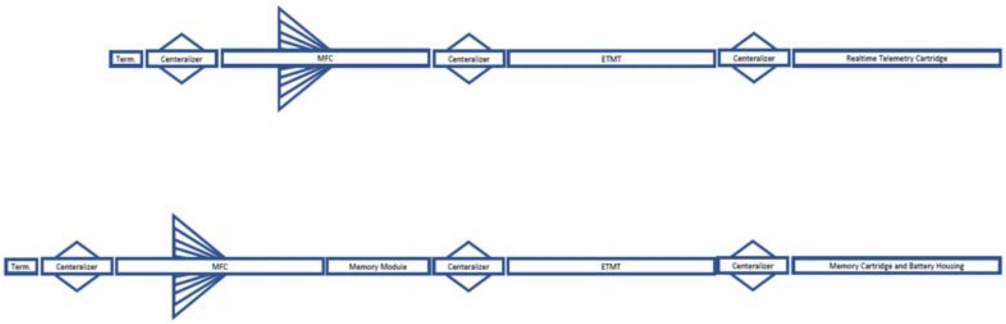

Figure 8—Tool String Diagrams. (Upper, realtime MFC and EM toolstring. Lower, memory configured MFC and EM toolstring)

Well A

The first case study consists of three tubulars: 4.5-in tubing, 7-5/8-in liner, and 9-5/8-in casing as indicated in figure 9. The EM tool was run in combination with the MFC tool, to evaluate the tubing and liner integrity. Notably, this well penetrates a series of halite formations that are mobile by nature and present additional well integrity hazards.

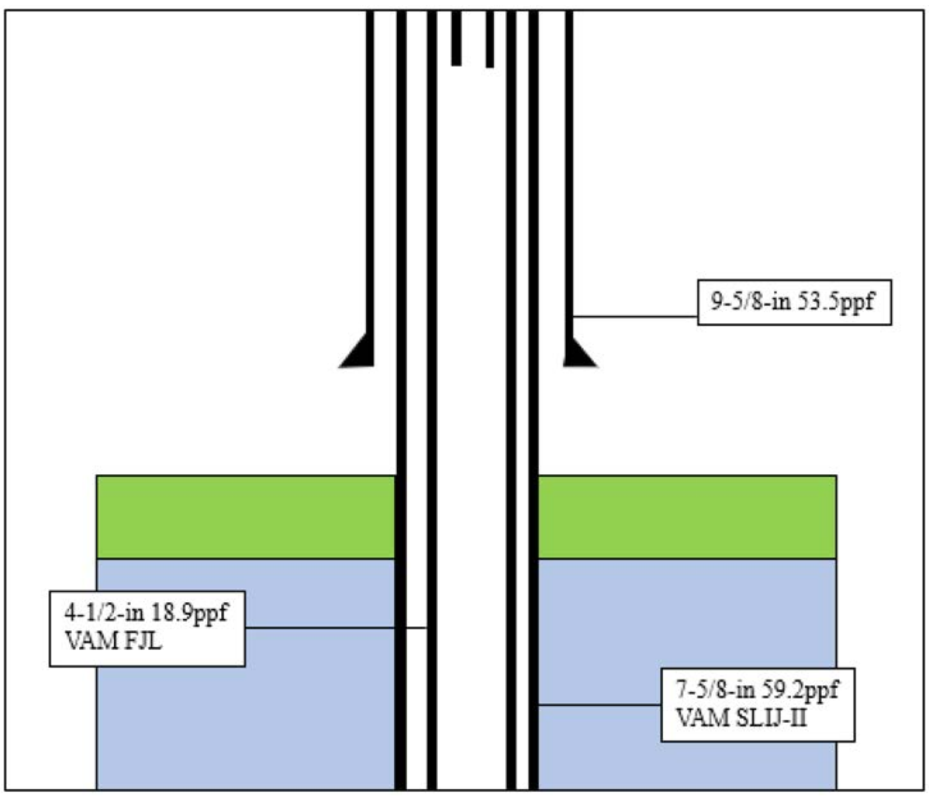

Figure 9—Case Study Well A Diagram

The processed MFC data is shown in figure 10. Maximum wall penetration is low throughout the interval. The PRADN image in track 6 is shaded white, indicating that the measured radius falls close the nominal internal radius of the 4.5-in tubing. The raw caliper data features an anomaly across an interval highlighted in figure 10. The feature repeats across two passes within this area and is interpreted to represent a disturbance in the geometry of the 4.5-inch tubing (e.g. buckling or shape changes which can occur across the halites).

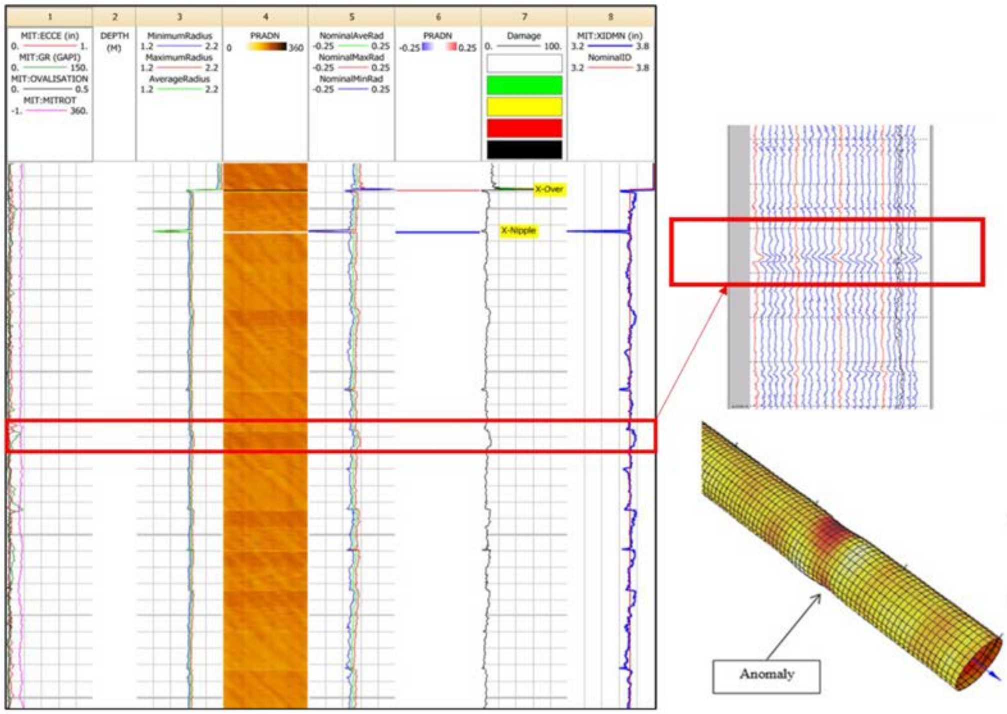

Figure 10—Well A Multifinger Caliper Data (Left: eccentricity corrected, Right: raw un centralized data)

The processed EM thickness tool indicates multiple anomalies across second tubular (7-5/8-in), with metal loss up to 32% (figure 11). Furthermore, temperature data was acquired in combination with the EM thickness tool and indicates changes in temperature towards lower values (cooling effect) near the anomalies.

The integrated plot (figure 12) shows that the MFC tool indicates that the inner wall condition of the 4.5-in tubing (tubular-1) is in good condition which shows low metal loss values. The MFC result (PEML – Track 6) is in a good agreement with the EM metal loss reading (DeltaPThk – Track 6).

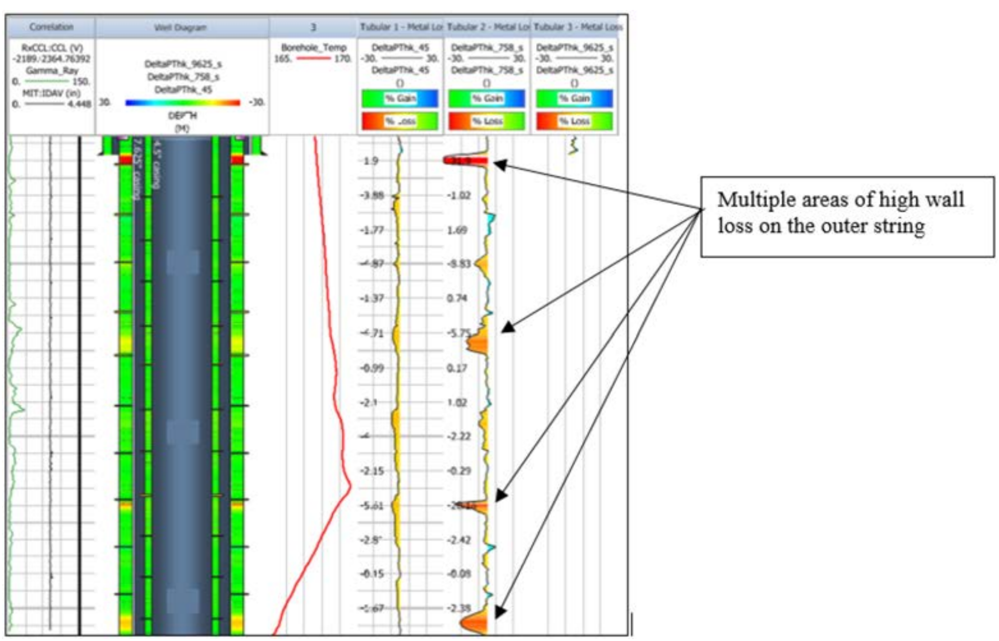

Figure 11—Well A EM tool processed data

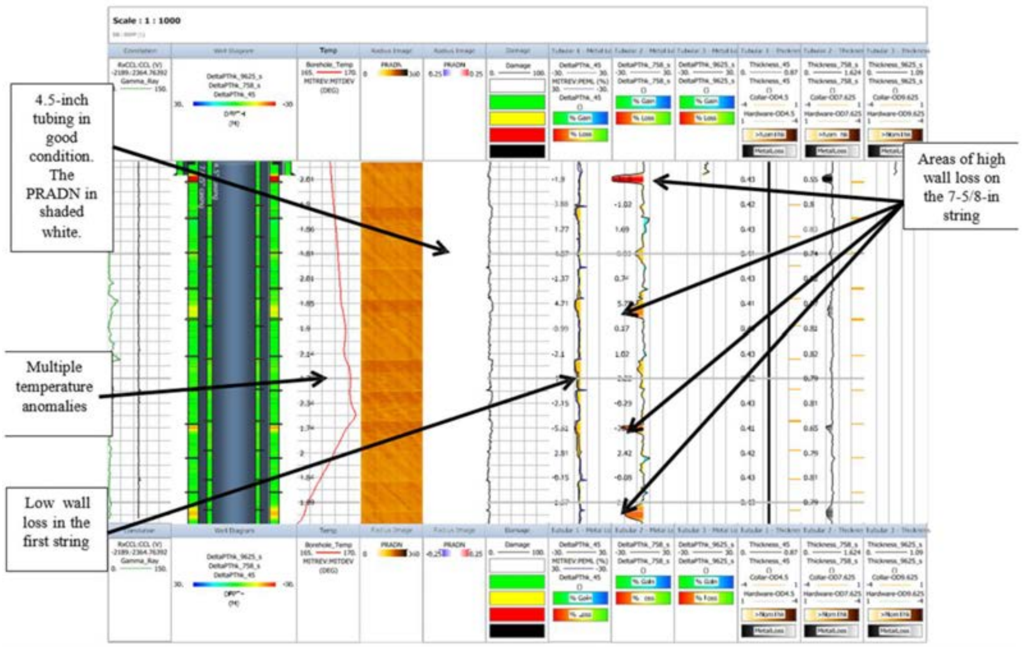

Figure 12—Well A Integrated Log Plot

Across the second tubular however, the EM metal thickness reading indicates a high metal loss with up to 32%. This outer string is interpretted to be damaged by the mobile salt formation that was common in this locality. In this case without the EM tool, one can only determine the first tubular integrity based on measurements of the internal radius, and might be missing the high metal loss across several intervals in the second tubular (7-5/8-in). By using the combination of MFC and EM tools reading, a full understanding of the tubing and liner condition can be achieved.

Well B

While the previous case study highlighted the capabilities of detecting damage on outer casing strings, EM technology adds value and is beneficial on interventions that require a measurement of only a single string.

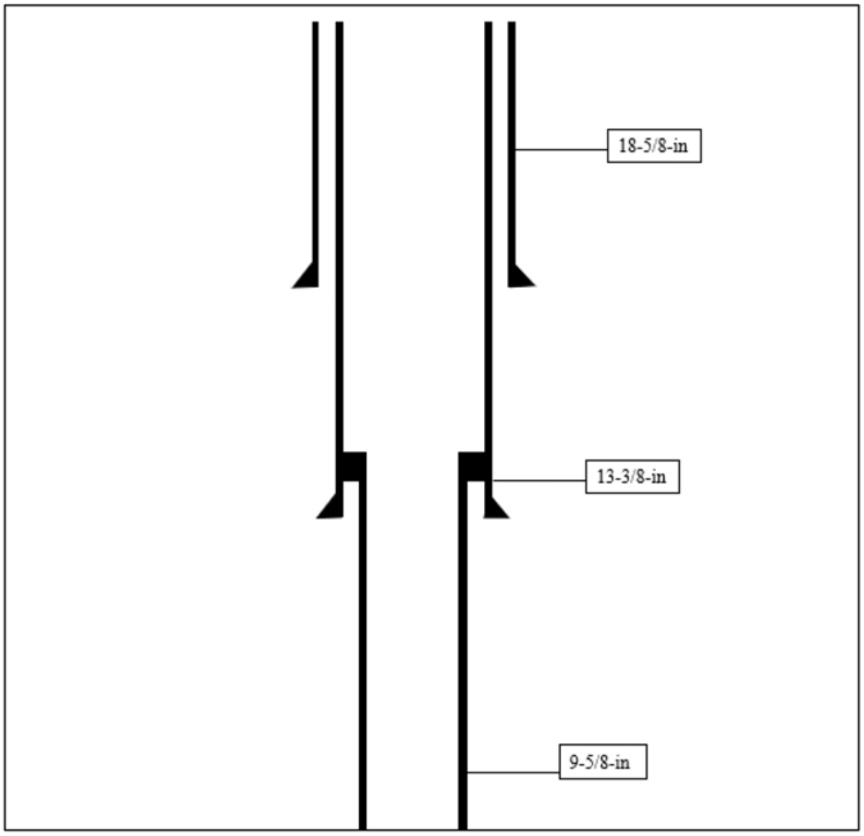

Figure 13—Case Study Well B Well Diagram

The objective of the second case study was to perform a time-lapse survey within a geothermal well across the 9-5/8-in and 13-3/8-in casing. This case study combines data collected from the electromagnetic tool and a high resolution multifinger caliper.

Both tools were combined into a single toolstring and conveyed on slickline while recording the data to a memory module. In a geothermal setting the multifinger caliper is routinely run for monitoring the remaining wall condition. What is obvious from this approach is that calculations on wall thickness or wall loss from a caliper alone will carry an assumption on i) the original baseline radii measurement and ii) the outer diameter. As the EM tool is measuring the average wall thickness it's measurement is not complicated by subtle changes in the shape of the pipe in the same manor as the multifinger caliper tool. In this case the tubulars were observed to feature ovalisation since the original baseline survey, this is highlighted within figure 14 where the PRADN image reveals the classic indicators of ovality where an increase in radius is measured along one axis, thus, maximum wall penetration and wall loss results increase through the ovalised zone.

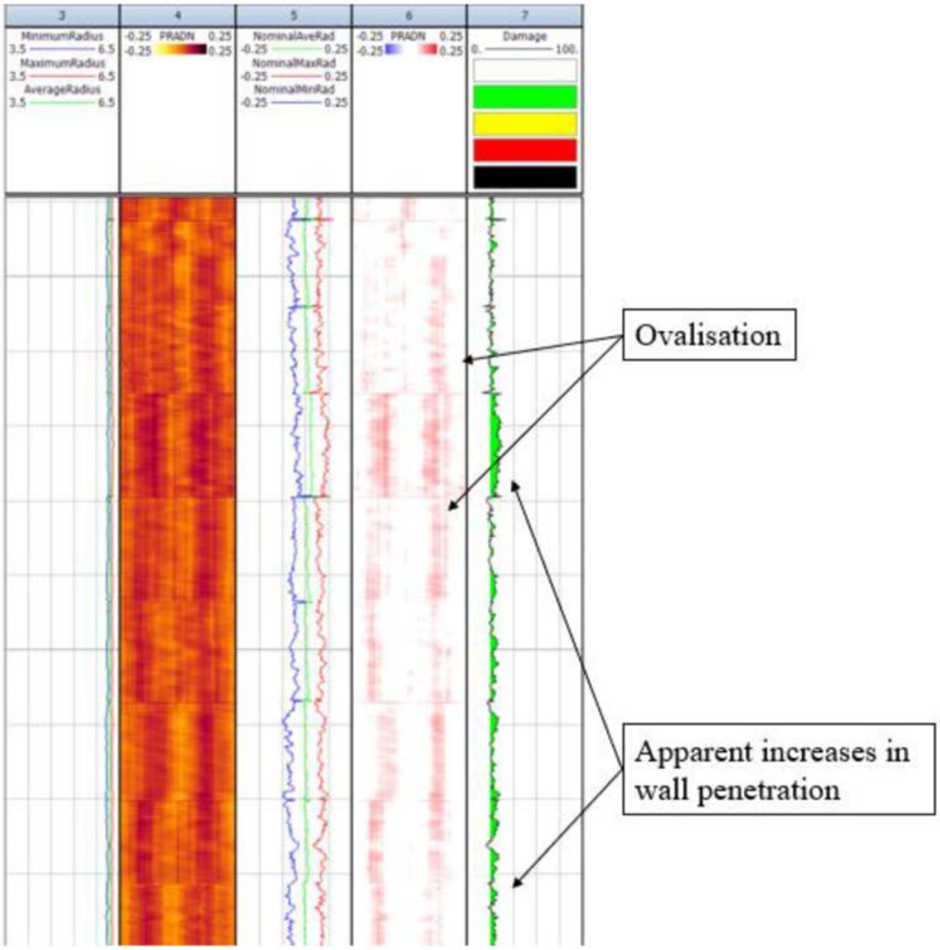

Figure 14—Multifinger Caliper data showing ovality

Figure 15 presents a chart of the mean wall loss across the 9-5/8-in and 13-3/8-in casing strings calculated from three sets of data. The blue series shows the wall loss calculated from a multifinger caliper two years prior to the latest survey. The red series shows the mean wall loss calculated from the most recent multifinger caliper data set. Finally, the green data is the mean wall loss calculated from electromagentic wall thickness measuremnets. What is apparent from the multifinger caliper data is that the wall loss over time is largely negligble over the upper part of the well, with both the red, blue green series trending close to each other. Moving into the deeper 9-5/8-inch area a shift is apparent with the latest suvey indicating 5% change in metal loss according to the latest MFC survey.

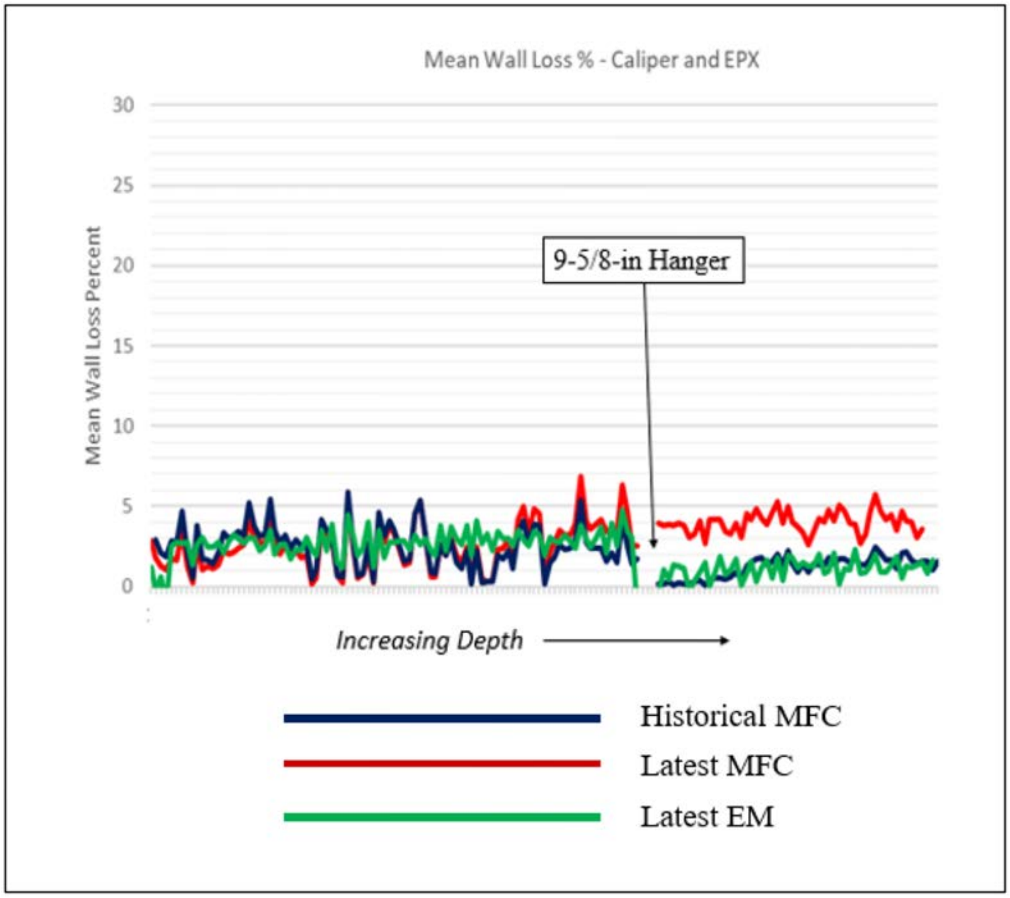

Figure 15—Timelapse comparison of wall loss % data within Well B

However, as stated previously, the caliper derived metal loss carries assumptions on the outer diamter – assuming it is exactly the baseline outer diameter. When ovalisation of the tubular occurs, the shape of the casing changes but the metal volume remains constant. As highlighted in figure 15, the EM wall thickness (green curve) trends closer to the baseline wall thickness (blue curve), while the most recent MFC calculated wall loss (red curve) reads higher by around 5%. Particularly through the deeper section, MFC data alone would result in an overestimation of the year-by-year wall loss occuring in this well.

The cross section in figure 16 summarizes an example of how subtle geometry related changes in the pipe (such as ovalistion) can result in an over-estimate of the wall loss in a given tubular. In the case of Well B the EM tool added value by confirming that the rate of metal loss within the 9-5/8-in interval was not as high as estimated by the MFC data alone. The well operator factored the EM results into a planned future workover of the well.

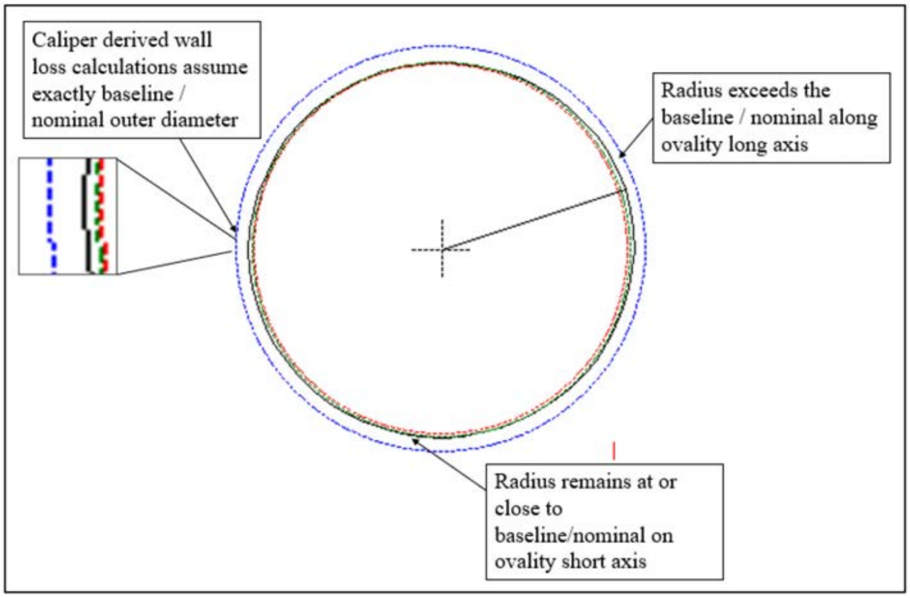

Figure 16—Example of casing ovality and resulting wall loss % computations

Well C

As discussed, the EM tools measure the total metal loss across all tubulars. Although each tubular's metal loss can be calculated from EM data alone, combining an EM tool with MFC or an ultrasonic scanning tool can reduce uncertainty in the interpretation. The below case highlights the advantages of combining an EM tool with a MFC when determining the condition of both the inner casing wall and outer string. In this well the outer casing damage overlaps with a deformity within the inner string.

Well C consists of three tubulars: 11.75-in casing, 16-in casing, and 24.5-in conductor casing as indicated in figure 17.

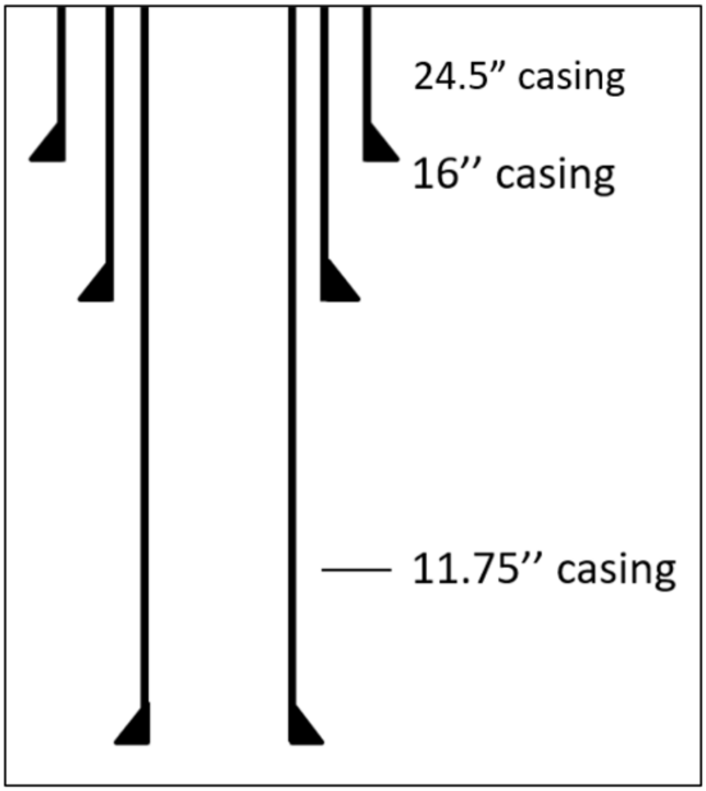

Figure 17—Case Study Well C Well Diagram

The main objective was to evaluate the condition for the 11.75-inch inner string and 16-inch outer string after multiple deformations were apparent in a MFC log preformed in the previous year. The MFC tool data indicates that the inner 11.75-inch casing features deformities, raising questions on the condition of the outer 16-inch string. The EM tool was used to confirm the MFC findings and evaluate the external metal loss across the 11.75-inch casing, and finally the condition of the 16-inch casing.

The average metal loss across the 11.75-inch and 16-inch string were 4% and 11%, respectively. An area of interest was identified in the 16-inch section with increased metal loss in comparison to the rest of string (figure 18). Notably this was occuring parallel to the deformities within the inner string (overlapping defects).

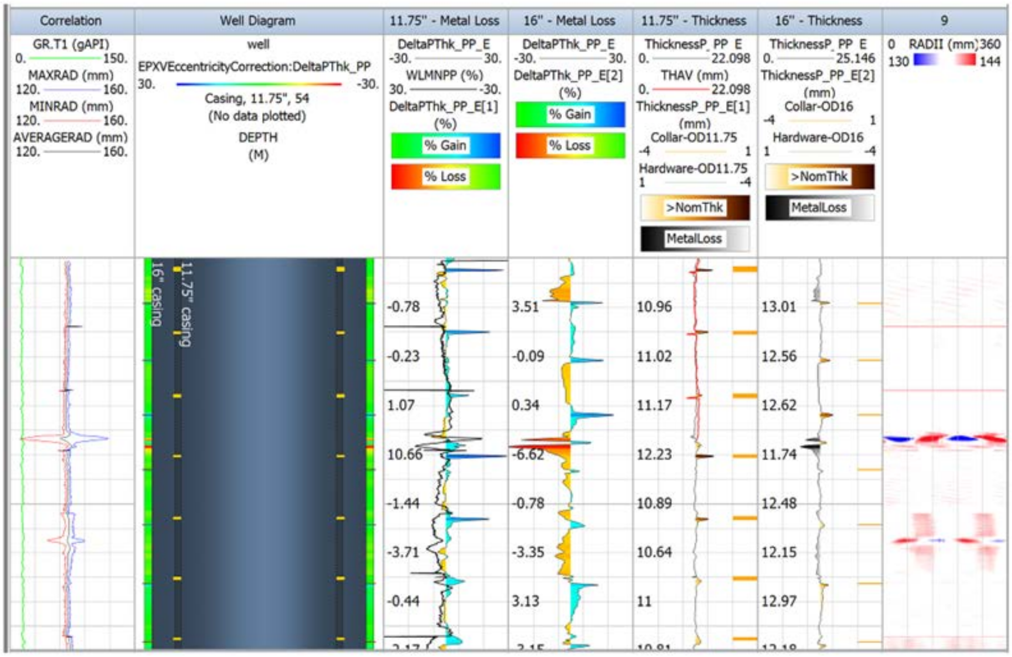

Figure 18—Comparison of the results from MFC and EM tools in first 11.75-inch tubing. Metal loss from MFC is presented in third track from left: WLMNPP. Metal loss in the outer 16-inch casing calculated only from EM tool.

On the final plot (figure 18) metal loss in the 11.75-inch casing (track 3) is in good correlation between the EM and MFC tools. This leads to the conclusion that no external corrosion is observed in the first pipe. Metal loss is observed on 16-inch pipe to be slightly higher in comparison to the rest of the string, with a maximum metal loss of 31.87%. As a further confirmation of the measurement, the EM result of the 11.75-inch casing is compared in track 5 to a previously available ultrasonic thickness log with good correlation.

This final case study illustrated the ability of EM thickness tools to identify outer casing string damage across overlapping defects within the well structure.

Conclusions

This paper gave three case studies where EM wall thickness measurements add value during well interventions and routine well integrity monitoring. The case studies show that EM data is beneficial for the detection of defects beyond the first tubular and when integrated with multifinger caliper results it can provide a comprehensive picture of the state of the tubulars. Chiefly, the main benefits of integrating electromagnetic thickness data with routine well inspections can be summarized as:

- Gain a complete understanding of the well condition by gathering wall thickness measurements in multiple nested tubulars
- Generate a more accurate picture of metal loss within the first tubular by integrating caliper and thickness data together. This allows for better understanding of the geometry of the tubular and its impact on caliper derived wall loss.
- Diagnose specific well integrity issues such as suspected outer casing string breaches by using the only technology suitable for the in-situ evaluation of outer casing strings.
- Gather wall thickness measurements and internal radius measurements in gas filled tubulars where ultrasonic technology can not function.
- The slim design of EM and MFC tools allows for their deployment through narrow restrictions that typically prevent the deployment of ultrasonic scanning tools.
- Gain wall thickness measurements through coated pipe and gas rich wellbore fluids, with no effect from non-ferrous scales.

- The combination of EM and MFC tools allows for a detailed time-lapse analysis and calculation of metal-loss rate as part of proactive well integrity monitoring

Abbreviations

MFC – Multifinger Caliper
EM – Electromagnetic
WT – Wall Thickness
ID – Internal Diameter
OD – Outer Diameter
HDF – High Definition Frequency
PRADN – Pipe Radius Normalised Image
PEML - Pipe Metal Loss % Average

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