Quantitative Phase Analysis of HTCC EM Logs

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ABSTRACT

Quantitative Phase Analysis (QPA) provides a way to report quantitative thickness measurements of HTCC-EM logs in wellbore casing. Without QPA, thickness measurements are reported qualitatively. QPA analyses the reduction in thickness of particular defects and eliminates certain errors. Any areas that have no defects are deemed to have no thickness loss. The result is a quantitative report for the whole log.

1. INTRODUCTION

MB Century's High Temperature Casing Condition – Electromagnetic (HTCC-EM) tools assess wellbore casing thickness along with the internal diameter and roughness/cracking of the inside of the casing. The HTCC-EM can operate up to 280°C allowing measurements to be made without the need to quench the well. The HTCC-EM uses three electromagnetic (EM) instruments to perform these assessments: Phase to assess casing thickness, Caliper to assess internal diameter and RI to assess roughness and cracking. The assessments tend to be qualitative because of a range of effects that cannot easily be quantified. Bore field operators prefer quantitative reports of defects in their wells. Quantitative results are easier for making judgements on casing condition and are not influenced by inherent variation in human interpretation.

QPA was developed to turn the qualitative metal loss from HTCC-EM logs into quantitative metal loss to satisfy customers' needs.

QPA is limited to the Phase instrument of the HTCC-EM log. It does not consider or attempt to calibrate Caliper or RI instruments.

QPA follows on from research dating back to 2011, where some work was done to quantify the Phase instrument. This was used to provide quantitative thickness of casing defects in some specially commissioned reports. These reports were used to help customers manage their fields and have been used for example to prioritize workover activity.

Recently a customer had a requirement to report quantitative casing thickness over the whole log. This was achieved by extending the QPA concept – perform QPA of each defect in the well and combine the QPA minimum casing thickness values into a table that formed part of the report.

This paper details how QPA works, the accuracy that can be achieved, and the assumptions made.

2. PHASE MEASUREMENT

The Phase instrument measures a quantity that is linearly related to casing thickness and obeys the formula in Equation 1.

$$\phi = t\sqrt{2\omega\mu\sigma}$$

Equation 1: Phase response to Casing Thickness

Where;

Ø	is the phase shift
ω	is the angular frequency of the excitation
μ	is the magnetic permeability of the pipe
σ	is the electrical conductivity of the pipe
t	is the pipe thickness

The Phase instrument relies on the Remote Field Eddy Current (RFEC) technique to be able to work in large steel pipe. This technique uses two coils to separate the transmission and reception of EM waves. The technique will only work if the coils are separated by at least 2.5x the ID of the pipe being inspected.

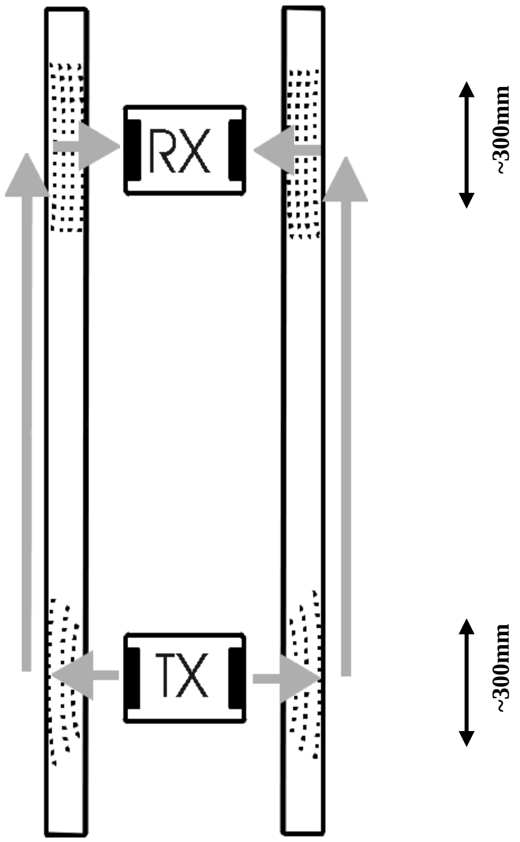

Figure 1: Cross section view of Phase transmit (Tx) and receive (Rx) coils in casing.

3. MEASUREMENT ERRORS

3.1 Errors Due to Ghosting

The effect of using two coils (Rx and Tx) introduces a ghosting effect, i.e., thickness is measured in two places at once (Figure 1).

The contribution of the ghosting effect cannot easily be determined by eye. In some cases, where metal loss occurs in isolation, it is straight forward to estimate the ghost position and make allowances for it. In other cases where there is a complex (messy) phase response, it is not obvious. The effect of the ghost can halve the phase response depending on the vertical length of the anomaly. An anomaly that is shorter than the distance between the coils will have half the phase response as an anomaly that is longer than the distance between the coils. The thickness estimation can be out by a factor of two because of this.

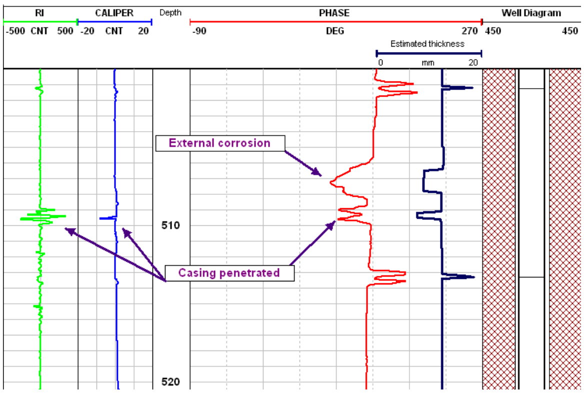

Figure 2: HTCC log showing two defects

In Figure 2, the estimated thickness log (dark blue) was manually created to account for the ghosting of the two coils. The anomalies at 507 m and 509 m show larger and smaller phase responses respectively, but these relate to smaller and larger loss in thicknesses respectively. If the Phase were calibrated in clean pipe the large response at 507 m would be correct but the small vertical anomaly at 509 m will respond by only 50%. A trained interpreter must double the response manually.

QPA removes the ghosting effect, but it only works over short sections of a log, i.e., over a particular defect.

3.2 Errors Due Averaging

If the vertical length of the anomaly is less than the band of EM response of a particular coil (about 300 mm), the response will be the average of not only the anomaly, but the good pipe (pipe in nearly new condition) above and below the anomaly.

The phase is also averaged circumferentially, so it is difficult to tell the difference between a large thickness reduction in one place (i.e. a hole) and a small amount of metal loss spread around the circumference. Other EM tools in the oil and gas market use multiple receiver coils to be able to detect metal loss that is localised around the circumference, but the HTCC-EM does not. All EM tools have an averaging effect, but manufactures do not mention it in their documentation.

In Figure 2 at 509 m, the estimated thickness is 0.31 in, however the Caliper and RI suggest that the casing has been penetrated. This suggests that the anomaly response has been averaged along with good pipe. Either the anomaly extends less than 300 m vertically or the anomaly does not extend around the circumference (e.g., there is a hole on one side of the casing).

The only way to deal with the averaging effect with the current technology is to make it clear that the reported casing thickness is the average thickness, not the minimum thickness.

3.3 Errors Due to Geometry

The MB Century 13-3/8" test casing for the HTCC-EM has been analysed with respect to Phase response and a calibration has been determined. A graphical depiction of the test piece and associated log is shown in Figure 4.

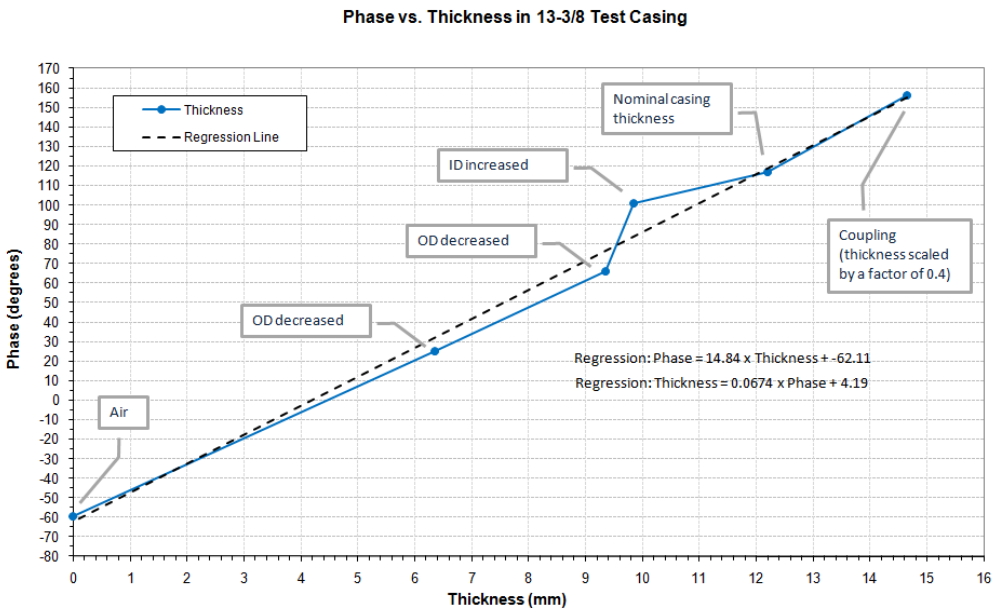

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Figure 3: Phase calibration of test piece

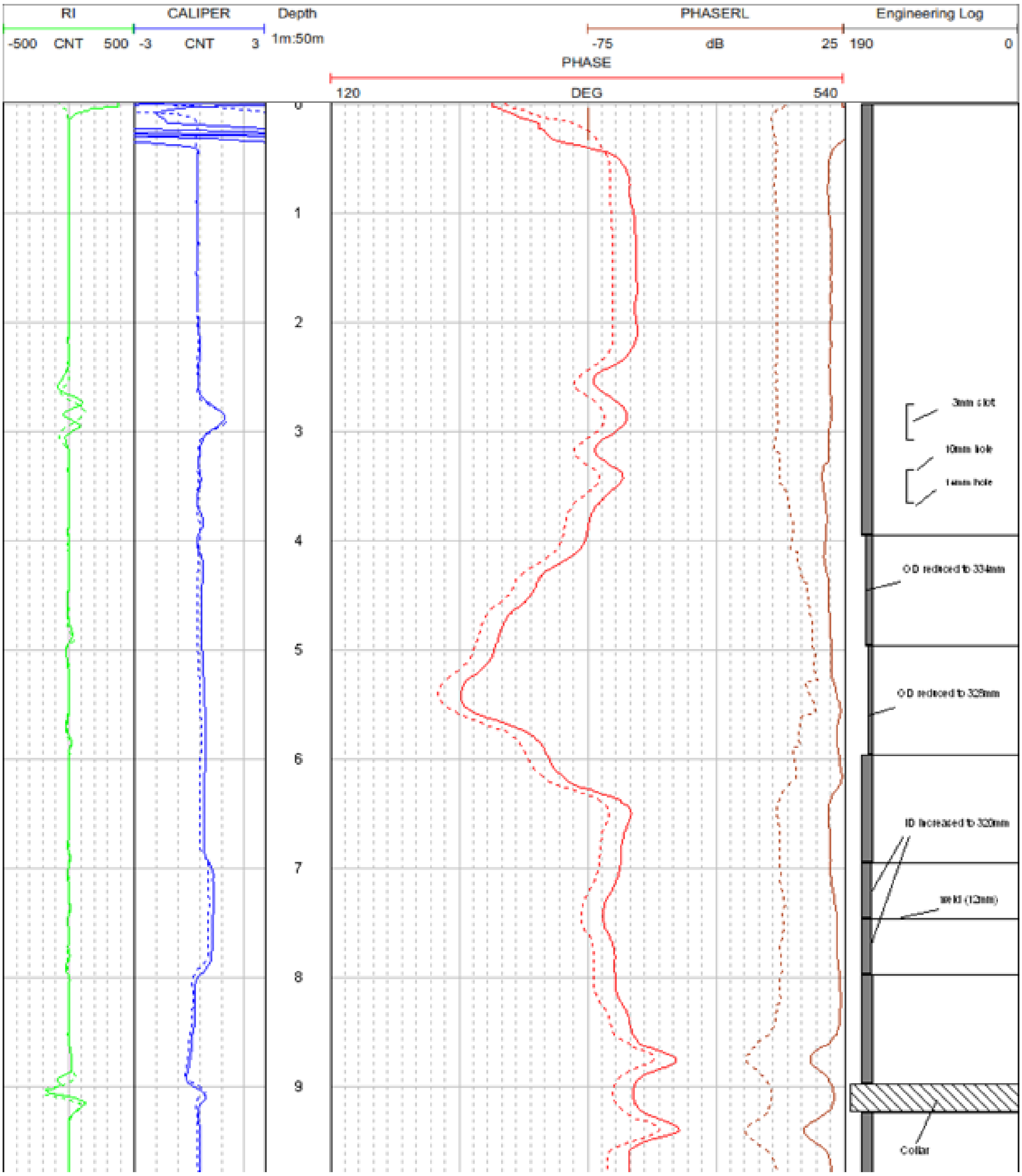


Figure 4: HTCC log of 13-3/8" test piece

Phase response in Air represents 0 mm thickness, and this can be used along with the measurement from good pipe to establish a linear relationship.

Figure 3 shows that the HTCC-EM tool Phase calibration for the 13-3/8” test piece is 377 °/in. Maximum error is 0.04 in (or 8 % of the nominal thickness of 0.48 in).

The coupling can be expected to give approximately half the response of the longer defects since it is shorter than the distance between the coils. In practice, a scale factor of 0.4 appears to be a good fit.

When calibrating old HTCC logs, the phase reading in air may not be known which may make it difficult to achieve an accurate scale factor. It may be possible to use the coupling heights instead.

3.4 Errors Due to Magnetic and Temperature Effects

Changes in magnetic properties of the casing material (in particular magnetic permeability) will add errors to the calculated thickness. Some temperature effects will cause the phase line to drift. These effects tend to vary slowly and can be identified by a trained eye, but to the untrained they may be interpreted as thickness changes.

A survey of some common logs reveals that these effects can vary from 5 ° to 40 ° (see Figure 5). For the test piece response (381 °/in) this represents an error of up to 0.1 in (or 20 % of the casing thickness).

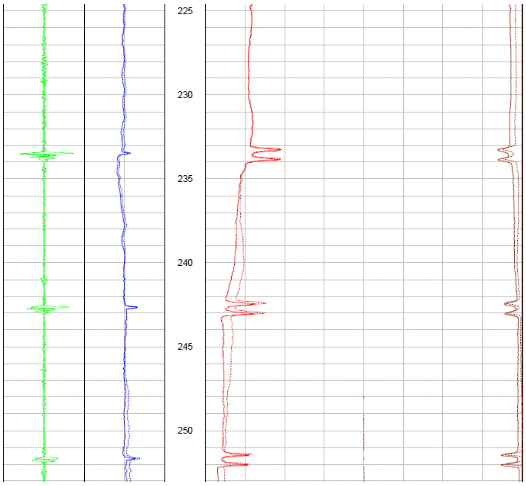


Figure 5: Variation of phase angle with changing conditions

The temperature effects will cause offset and scale errors while the magnetic effects will cause a scale error. For the purpose of this analysis these errors have been lumped together.

These errors tend to be slowly changing and cause a baseline shift of the Phase measurement. They can be eliminated by using a trained eye to look for relative changes in Phase rather than absolute changes. The Phase difference between good pipe and the defect is used to assess metal loss. QPA uses the good pipe starting point to calculate metal loss and thus eliminates this error.

4. QUANTITATIVE PHASE ANALYSIS

QPA is a process that identifies anomalies, applies an algorithm that corrects for ghosting, magnetic and temperature effects, and outputs thickness data in a tabular format.

4.1 The Algorithm

QPA assumes that the starting point is good pipe and that both coils see zero thickness loss. It is important that the analysist picks a suitable start point in the log for this assumption to be valid. Assuming downward travel of the tool, the start point will be the upper most depth value. As we travel down the well, any initial phase response must be due to the Tx (bottom) coil alone. When the Rx (top) coil reaches the starting point of the Tx coil, its response will a delayed version of the Tx coil. The algorithm can be described as a difference equation (Equation 2).

$$y_{qpd}(d) = Tx(d) + Rx(d - sp)$$

Equation 2: QPA difference equation

Where $y_{qpd(d)}$ is the corrected phase angle with respect to depth (d), Tx and Rx are the transmit and receive coil phases, and *sp* is the spacing between the coils.

QPA was verified using a 13-3/8” test casing. Figure 6 shows the correlation between the test casing (grey) and QPA output (blue). It was found that the accuracy was within 0.06 in.

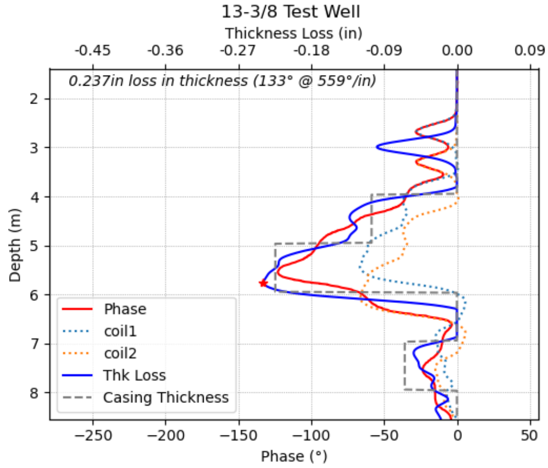
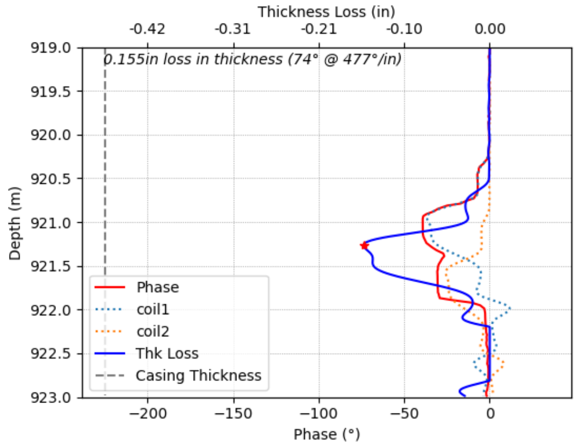


Figure 6: QPA of test casing

4.2 Example QPA of defects

Figure 7 shows the results of QPA done on two casing defects in different parts of a well. The red line is the Phase measurement, and the blue line is the output of the QPA algorithm. The two plots highlight how QPA is superior to human interpretation of defects. The thickness loss at 921.2 m in Figure 7 could have been underestimated by a human interpreter.



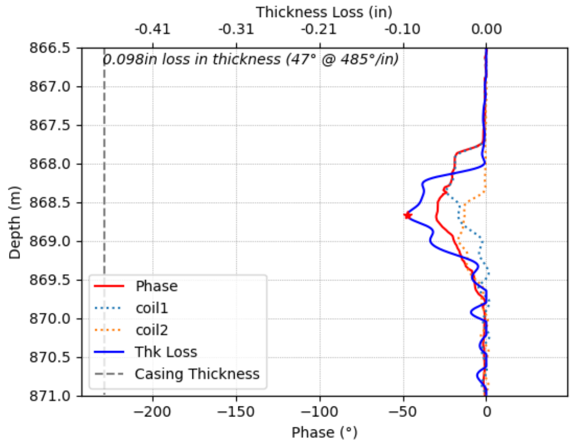


Figure 7: QPA of two defects in a well

The defects in Figure 7 were recorded while logging a 270 °C geothermal well with known external corrosion issues. QPA estimated metal losses of 0.155 in and 0.089 in at 921.2 m and 868.6 m respectively.

Joint	Top (m)	Bottom (m)	Length (m)	Nom. Thickness (in)	Avg. Thickness (in)	Max. Depth (m)	Metal Loss	Comment
1	0.00	11.80	11.80	0.472	0.472		0.0%	Caliper decentralised
…	…	…	…	…	…	…	…	…
27	323.24	336.38	13.14	0.472	0.467	334.50	1.0%	Internal metal loss
28	336.38	349.50	13.12	0.472	0.426	341.88	9.7%	Internal metal loss
29	349.50	361.16	11.66	0.472	0.406	351.60	14.1%	Internal metal loss
30	361.16	373.38	12.22	0.472	0.472		0.0%	
31	373.38	386.32	12.94	0.472	0.472		0.0%	
32	386.32	399.72	13.40	0.472	0.472		0.0%	
33	399.72	412.42	12.70	0.472	0.472		0.0%	
34	412.42	425.20	12.78	0.472	0.436	418.84	7.6%	External metal loss
35	425.20	438.84	13.64	0.472	0.4406	428.44	6.7%	External metal loss
36	438.84	451.50	12.66	0.472	0.472		0.0%	
37	451.50	463.96	12.46	0.472	0.472		0.0%	
38	463.96	477.00	13.04	0.472	0.472		0.0%	
39	477.00	489.72	12.72	0.472	0.457	485.58	3.2%	External metal loss
40	489.72	502.36	12.64	0.472	0.442	495.90	6.3%	External metal loss
41	502.36	516.32	13.96	0.472	0.419	504.28	11.3%	External metal loss
42	516.32	529.16	12.84	0.472	0.472		0.0%	

43	529.16	542.14	12.98	0.472	0.472		0.0%	
44	542.14	555.12	12.98	0.472	0.472		0.0%	
45	555.12	567.46	12.34	0.472	0.472		0.0%	
46	567.46	579.82	12.36	0.472	0.427	571.90	9.6%	External metal loss
47	579.82	592.68	12.86	0.472	0.434	591.12	8.1%	External metal loss
48	592.68	605.66	12.98	0.472	0.472		0.0%	
49	605.66	618.16	12.50	0.472	0.431	610.26	8.6%	External metal loss
50	618.16	631.86	13.70	0.472	0.385	619.84	18.5%	External metal loss
51	631.86	643.26	11.40	0.472	0.472		0.0%	
52	643.26	656.98	13.72	0.472	0.472		0.0%	
53	656.98	669.34	12.36	0.472	0.464	667.70	1.6%	External metal loss
54	669.34	682.22	12.88	0.472	0.461	677.24	2.3%	External metal loss
55	682.22	695.26	13.04	0.472	0.472		0.0%	
56	695.26	707.96	12.70	0.472	0.426	705.96	9.8%	External metal loss

Table 1 – Sample of QPA processed defect table

4.3 Temperature Compensation

Temperature effects are compensated for by using the value of the starting point as a measure of the temperature drift in the system.

The effect of temperature on the QPA measurement was checked by measuring casing couplings' thickness using the QPA algorithm at various points in a well. Figure 8 plots measured thickness with the coil temperature (the coil temperature follows the well temperature with some lag).

The result was that there is no correlation between the coupling thickness measurements and the temperature in the well. This suggests that QPA measurements are not influenced by temperature.

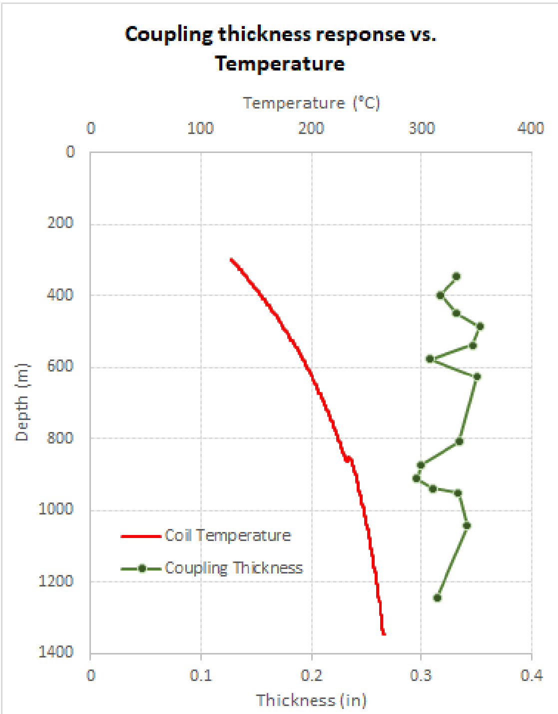


Figure 8: Temperature Compensation Check

4.4 Example QPA report

The process of data preparation is unchanged with QPA, however the presentation is different. QPA replaces the original table in the HTCC-EM log (Table 2) with a joint table similar to those used in some service companies' Multi-Finger Caliper reports (Table 1). The log is initially processed the original way; the analyst notes the depths of defects and comments are made on the nature of the defects.

Depth(m)	Type	Comments	Action
0-7	Observed	Caliper decentralized	No concern
59, 82-86, 91-94,	Minor	Internal metal loss	Monitor for changes

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323-326, 332-335,	Minor	Internal metal loss	
340-354	Moderate	Internal metal loss	Monitor for changes
419, 427, 486, 495, 572, 591, 610, 619-624, 668, 677, 706	Minor	External metal loss	Monitor for changes

Table 2 – Sample of Original HTCC-EM report defect table

With QPA, the data undergoes further processing. The depths of each casing joint are found, and each defect is individually processed to determine the average thickness (and metal loss percentage). This data is presented in a joint table along with the original analysts' comments. If multiple defects are found in one joint, the worst-case metal loss values are used in the associated row in the table.

4.5 Estimate of Error

The following disclaimer is included in every report;

Using Phase Simulation Analysis, we are able to account for some but not all of the errors inherent in the HTCC-EM phase measurement. Using our Test Casing we found that the maximum measured error was 0.06 in. The modelling error in the test casing was 10 % which translates to approximately 0.05 in of thickness. Some other errors are not so easy to predict, and the error margin is given along with some assumptions and limitations.

- *The thickness measurement is averaged around the circumference and approximately 300 mm vertically.*
- *It is not known if magnetic permeability changes within the depth boundaries of an anomaly. It is assumed that it does not.*
- *The estimate of error is the combination of the estimate and modelling errors (above) which is 0.11 in and is subject to the assumptions (above).*

5. CONCLUSION

QPA can eliminate the ghost effect of the two-coil Phase instrument. A linear relationship can be used to calculate metal loss from the QPA processed data. Limited testing shows that an error of about 0.04 in (or 8 %) can be expected in the linear relationship.

Phase drift due to temperature and magnetic effects can add errors of approximately 0.12" into thickness measurements. A trained eye can account for these errors and exclude them. The QPA can be used to account for these errors, but it requires a human step to identify the baseline of each defect.

The averaging effect when defects are smaller than 300mm long (vertically), and when defects are not spread around the circumference, causes the phase response to underestimate the loss in thickness by an unknown amount. In these cases, the Caliper and RI measurements may be able to provide more information, such as highlight that casing penetration has occurred even when the Phase indicates that it has not. The circumferential distribution of a defect does not matter when the cross-sectional area of the casing is being estimated.

If the Phase log were converted to an absolute scale, you can expect measurement errors of 0.16 in (33 % in 13-3/8" 68 lb/ft casing) ignoring averaging errors. A more accurate assessment of casing thickness can be made if QPA is used to eliminate ghosting errors and relative measurements are made between localised regions of good pipe and bad pipe. This cannot easily be transformed into a log, but it can be tabulated.

If QPA is applied selectively to the defects in a well, it should be possible to measure average thickness with about 0.04 in error (about 8 % in 13-3/8" 68 lb/ft casing), but it must be noted that this is the average thickness not the minimum thickness.

Currently the disclaimer assumes a measurement error of 0.04 in and a modelling error of up to 0.05 in to give a combined error of 0.11 in. With recent improvements in the QPA algorithm, the modelling error is likely to be much smaller than this. More work is required to reduce the error margin in QPA analysis.

The combination of HTCC-EM and QPA provides quantitative thickness measurements of casing in high temperature geothermal wells.

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