

IPTC.16997

Successful Application of a New Electromagnetic Corrosion Tool for Well Integrity Evaluation in Old Wells Completed with Reduced Diameter Tubular

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This paper was prepared for presentation at the International Petroleum Technology Conference held in Beijing, China, 26–28 March 2013.

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Abstract

As the number of aging wells grows in the oil and gas industry, there is a recurrent need for monitoring the health of these wells over their productive life and providing assurance of the integrity of the well barriers that isolate them from uncontrolled formation pressure and fluids. Tubing and casing condition evaluation is a crucial aspect of this evaluation. The industry utilizes a number of conventional technologies for evaluation of tubing and casing integrity, such as internal mechanical calipers, electromagnetic and ultrasonic thickness (UT) tools, which are generally quite satisfactory for the evaluation of the inner casing but are often affected by internal tubular diameters in terms of their application. Most conventional tubular evaluation tools are unable to evaluate multiple concentric barriers. When combined with the low diameter production tubing completions the options for evaluating the production and outer casings become very limited, necessitating the need to pull the inner casing by performing a workover at a considerable expense and inspect the outer casing with conventional technology. A new electromagnetic casing corrosion evaluation technology was applied in a group of critical wells completed with small diameter tubing. The technology utilizes electromagnetic pulsed transient eddy currents to simultaneously inspect tubing and the casing behind it and provide quantifiably segregated measurements of thickness in the tubing and the first concentric casing as well as qualitatively characterized by a third casing string. This slim tool with a diameter of 1-11/16" allows measurements through slim production tubing. The objective of the study was to assess the integrity of a group of mature wells completed with small diameter restrictions, near populated areas and associated with high H₂S environment. This study includes the candidate generation, field application, results evaluation and general recommendations for the well integrity program. The results exhibited that the data obtained from the tool is reliable. A quantifiable assessment of the metal loss of casing behind the tubing could be made, which made a mitigation strategy possible to prevent casing leaks, which in these wells are critical due to their population sensitive location.

Introduction

Damage to the well tubular is a major cause of high risk well integrity problems. Monitoring the corrosion of both the primary (production tubing) and secondary barriers (casing) is a critical aspect of well integrity. In some cases corrosion spreads from the outer casings (primary barriers) to the inner tubing or casing. Measuring corrosion in the casing in the presence of the production tubing or evaluation of corrosion of concentric casing barriers is a difficult challenge but, if overcome, can bring that much needed early stage information about the potential for well integrity issues (Wheeler et al, 1998).

The wells in this study are located in an oil field that was developed in the 1940s. The wells were drilled originally as vertical oil producers, but with the advance of horizontal drilling have been reassigned as observation wells for reservoir monitoring.

The main facilitating conditions for corrosion in these wells are high H₂S environment, salinity of the water injection and the characteristics of the aquifer behind the casing.

The main drivers for monitoring the corrosion in these wells are:

1. Identify wells that are in need of immediate attention so as to plan specialized, low footprint intervention for that specific well.
2. Establish a trend for the zones of corrosions and infer any kind of association with formation, depth or other external factors.
3. Arrive at workable estimates for annual rate of loss of metal due to corrosion in the specific zones in casing behind the tubing.

Description of the Technology Deployed

The electromagnetic defecto-scope technology was utilized to evaluate corrosion. The tool employs an electromagnetic transmitter and receiver coils to induce transient or pulsed eddy currents in the cross section of the tubulars being evaluated and measure the decaying electromagnetic response generated from the induced signal with the receiver coils. The resulting signal is processed to extract individual metal thickness measurements from multiple concentric strings of tubing and casing (Riaz-ud-Din et al, 2011).

The working principle is based on Faraday's laws of electromagnetic induction. When a time varying power is supplied to the emitting coil in the tool, a transient electromagnetic flux is induced in the surrounding tubing and or casing which further induces eddy currents in the cross sections of the concentric tubular sections (**Fig. 1**) (Xingfu et al, 2007).

$$\varepsilon = -\frac{d\Phi}{dt} \quad d\Phi = S \cdot dB, \text{ then, } \varepsilon = -\frac{S \cdot dB}{dt} \quad (1)$$

Where,

ε is Electrical field induced by the changing magnetic field

Φ is magnetic flux act on receiving coil

S is sectional area of receiving coil

B is the intensity of magnetic field generated by transmitting coil

These eddy current loops produce time varying magnetic fields, which induce electromotive voltage in the receiver loop in the tool. When a pulsed signal is supplied to the transmitter coil, the transient eddy current response produced progress in a radial pattern around the tool with a radius that increases with time and eventually dissipating at the outer limits of the tool signal to noise ratio (SNR). The response of the receiver signal induced by the pulsed eddy currents from the transmitter is manifested as a convolution of time decay signal with each increasing radius circular shell of metal corresponding to a "time window" in the decay. The ability of the tool to separate the signals coming from the concentric cylindrical shells of eddy currents in time domain provides the unique capability to differentially determine the thickness of the different strings of tubing and casings present in the well completion.

When the thickness of the tubing or the casing changes, there is a corresponding, measurable change induced in the transient eddy current pattern, which can be detected in the change of the time domain decay spectrum. The measurement is precise enough to detect small changes of thickness in the concentric tubulars.

With a diameter of 1-11/16" (42 mm), the tool can be run through most of the commonly used tubing sizes and used to inspect casing conditions through the tubing by calculating both tubing and casing thicknesses and areas of corrosion. This allows for greatly reduced operating costs and time to evaluate the tubing and casing behind it without the need to pull-out the tubing string to evaluate the casing condition.

When combined with multi-finger caliper (MFC) imaging tools, both the inner and outer wall conditions are determined. Different sensors within the instrument have different depths of investigation. During interpretation, specific empirical relations between the decay response and the tubular thickness are used to estimate the specific tubular thickness.

As an estimated measurement, the tool provides an average thickness over a cross section of the tubular being evaluated at each depth.

Area of Deployment

Six wells were selected for field deployment. The objectives of the campaign were to:

- Outline well conditions and provide information for future abandonment and recompletion plans.
- Identify zones of significant corrosion and perform a risk assessment. Evaluate the possibility of prioritizing workover operations based on the integrity profile of each well.
- Establish the applicability of the technology for through tubing multi-string tubular inspection.
- Correlate the results of the corrosion log with well history and past cement bonding quality evaluate correlation with outside casing corrosion.

A brief description of the wells is provided below (**Figs. 2 to 4**).

Well-A

This well was originally drilled in 1948 as an oil producer. The last workover was performed in 1995 to convert it from an oil producer to naphtha injector. Currently the well is used as an observation well. The well was last completed with a 3½” tubing and a minimum internal diameter (ID) of 2.2” at the nipple and a 2⅞” tailpipe (Fig. 2a).

Well-B

This well was drilled in 1949 and completed as an Arab-C and -D oil producer. The well was completed with 4½” tubing and 3½” tailpipe with a minimum ID of 2.635” at nipple XN. In 1980 a casing leak was found in the 7” casing at 2,760 ft, which was squeezed with cement. Over the years there has been significant development of farms, roads and shops. Accessibility to the well is challenging and concerns for the safety of the neighboring inhabitants. Currently the well is suspended with mechanical through tubing bridge plug (MTTBP) and it is planned for plug and abandon (P&A) (Fig. 2b).

Well-C

This well was drilled in 1950 and completed as an Arab-C producer. The well was completed with 2⅝” tubing on 5” casing with a minimum ID of 1.76”. The well is located in proximity of farms and city areas. The well was confirmed with a downhole communication problem. The well is currently killed and secured with a downhole plug and it is planned for workover to eliminate the high tubing-casing annulus (TCA) pressure and to be converted to an observation well (Fig. 3a).

Well-D

The well was drilled in 1967 as dual oil producer. It was completed with 3½” tubing on 7” liner with a minimum ID of 2.697”. The liner was extended to surface to provide additional protection to the production tubing. The well is planned for workover to be converted to an observation well with downhole pressure monitoring gauges (Fig. 3b).

Well-E

This well was drilled in 1979 to access the Arab-C reservoir. It was completed with 2⅞” tubing and 4½” liner. The minimum ID of the tubing is 2.205” at nipple. In 1980 the well was found to have communication behind the pipe, which was repaired by squeezing off entire Arab-C, re-perforated and completed as Arab-C. The well is planned for workover to be converted to an observation well with downhole pressure monitoring system (Fig. 4a).

Well-F

This well was drilled in 2002 as horizontal open-hole salt water disposal. The well was completed with 7” x 4½” tubing inside the 9⅝” casing and 7” liner. In 2010 high TCA was shown indicating down-hole communication. The well is pending for workover to fix the down-hole communication and restart as a water disposal (Fig. 4b).

Typical salinity tests on the produced water from these wells shows chlorides in the range 90,000 ppm and dissolved solids in the range of 147,000 ppm.

Field Test Results for Benchmarking

Before deploying the tool in the field under evaluation, the tool was field tested in another field with a specific objective of benchmarking the tool response against an established measurement of the ultrasonic thickness (UT) tool, which was deployed during a workover operation. The ultrasonic caliper was run to evaluate the casing after the tubing was removed from the well. After the circumferential acoustic scanning log was run, the 4.5” tubing was run in again and the electro-magnetic (EM) tool was logged again with the tubing in the same well. The results showed an excellent match, with the thickness from the EM and the acoustic scanning log. Additionally, a number of localized zones of major corrosion were detected by both tools. The percentage of metal loss in these zones was within the 2% agreement between the two measurements. **Figure 5** displays segments of the tool thickness comparison across an extended zone. A localized section of

corrosion damaged zone logged with both the tools is shown in the lower part of the **Fig. 6**, where the metal loss measurements are within a metal loss value of 1.5%.

Results and Key Outcomes

The technology was deployed in the field after qualification and revealed varying levels of corrosion in different wells across the area. The data acquired in the selected wells across the field was repeatable and of good quality. In some cases the EM was run with a MFC, which provided a good benchmark to compare and qualify the measurement using the newly deployed technology (EM tool). The MFC data processing includes centralization to eliminate the effects of eccentricity, and editing to correct any point or finger readings that appear not to correlate. All the data were depth correlated before processing. Additionally, the patterns of corrosion were analyzed and compared with the quality of cement bonding conditions across the zones evaluated to establish useful trends. Four of the six wells logged in this evaluation had low to medium corrosion; the other two wells had corrosion at relatively higher levels that would necessitate further well intervention. The results are described in more details in the sections below.

Processing and Analysis Results

The data from the EM is processed using empirical relationships established over extensive data collected for varying combinations of well completion profiles, normalized and presented as a thickness map along with a visual representation of the normalized decay curves. A well schematic is represented with specific intervals flagged for collars, which are also evident in the variable-density log (VDL) of the decay curves, as well as flags for corroded intervals. A typical map is shown in **Fig. 10**. When combined with the MFC log presented the technology provides a comprehensive diagnostic service for multiple strings of casing.

Metal Loss Evaluation Over Different Wells with Cement Bond Logs

A comparison of metal loss was done against the cement bond log over different wells. The goal was to study the effect of presence or absence of cement on the degree and magnitude of corrosion. **Fig. 7** shows this comparison over interval 6,500 ft to 7,000 ft in the 7" liner. The results demonstrate high degree of correlation between the metal loss and cement bond.

On the other hand in Well-A, there is excellent cement bond across the zone analyzed, with minimal corrosion (< 4%) from the EM log (**Fig. 8**).

Indications of significant localized corrosion possibly with penetration in the first joint in the 4½" liner 3,847 ft to 3,888 ft interval) in Well-F (**Figs. 9 and 10**) was observed. This well is also known to have TCA communication.

Effectiveness of Evaluation

By deploying this multi-barrier casing and tubing evaluation technology and combining it with the well history, available information and other measurements made in the well, meaningful evaluation of the condition of the casing behind the tubing could be performed. The integrity of the production casing could be correlated with the cement evaluation results available. Metal loss tended to increase in zones of poorly cemented pipe and was minimal or absent in zones of good cement bond. This trend was identified across different wells as well as different zones within single wells. Additionally, in zones of significant corrosion, a corrosion rate of metal loss per year could be established and will serve as a reference for establishing future trends in certain zones in this field.

The results have enabled the prioritization of the workover program for these wells. The workovers will also enable the further direct and detailed evaluation of the casing and physically verify the results of this campaign and forego some of the scheduled workovers. With a high cost of each workover, there is a potential to save significant unnecessary remedial cost across the field.

Recommendations and Future Proposed Work

The current technology is able to quantify the thickness of the first and the second strings, which includes the tubing and the first casing behind the tubing. There is also the ability to qualitatively evaluate the third string of casing. Further improvements in signal to noise ratios in the measurement could enable the quantitative evaluation of the thickness of the third casing. The physics of the measurement indicate this is possible. At the same time it is essential to implement a program of evaluation of cement bond logs in the third tubular, generally 9⅝" casing and the 13⅝" casing.

Measurement of corrosion in multiple tubulars and inferring metal loss from these measurements is a complex task with several variables. To reduce the uncertainties it is recommended that a multi-pronged approach be taken to evaluating the integrity of the well:

1. **Multisensor measurements for corrosion:** Since the physics of the measurement is different for different tools a combination of two measurements can provide a less uncertain picture of the barrier integrity. For example the MFC can provide a radial profile of the internal radius but unable to measure thickness. The EM does a good job of providing the thickness measurement over the same interval, complementing and completing the evaluation for the inner tubular.
2. **Cement, CBL logs and remedial action:** A fair to good correlation was observed the corrosion metal loss in the casing and the quality of cement bond behind casing. External corrosion due to exposure to formation fluids spreads from the outside to the inner casings. Further evaluation of cement logs for the casing sections for the production as well as the outer casings is recommended, which will conduct to possible remedial action to isolate the metal from the corrosive formation fluids.
3. **Time-lapse measurement of casing thickness:** Whereas the threshold for measurement of corrosion behind the tubing, in the casing is around 3% metal loss, as has been the experience with MFCs, the time-lapse measurements of casing corrosion can be a powerful method for evaluating the progression of corrosion in concentric tubulars, before it reaches the inner production tubing.
4. **Correlation of corrosion measurements with other measurements and information:** Additional measurements can provide valuable clues for the source of corrosion in tubulars:
 - Temperature logs provide useful information about possible movement of fluids in the annulus and formation, which could be possible agents for corrosion.
 - Advanced noise logging for localization and characterization of cross flow and leak detection could be used for finding zones where corrosion is suspected to cause a leak.
 - Past recorded CBL logs to determine isolation can identify potential exposure issues in the tubular, which could be related to corrosion.
 - Past PLT records if any.
 - Production history and reservoir depth correlation with zones.
5. **Well integrity surveillance corrosion monitoring frequency:** Casing inspection logs should be run based on criteria set up according to different factors such as well type, fluids, pressure, temperature, etc., to calculate the remaining life of the well. Inspection frequency according the corrosion class, rate and remaining life of the production casing is another factor.

Acknowledgments

The authors wish to thank Saudi Aramco and Halliburton for permission to publish this paper. Special thanks go to Khalid I. Al-Omaireen, Faisal M. Al-Dossary and Redha H. Al-Nasser for their support in writing this paper.

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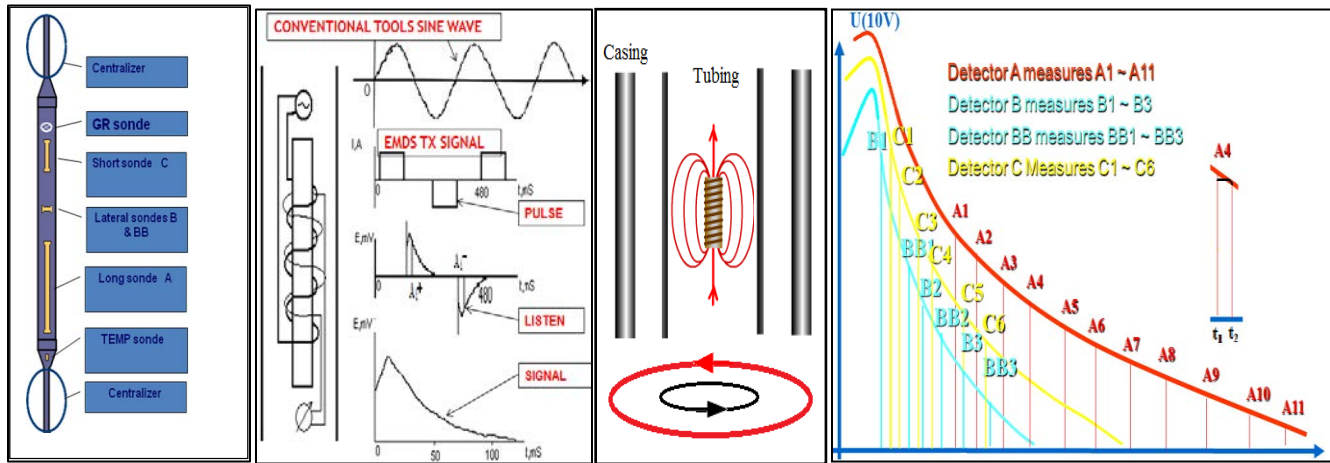


Fig. 1. Principle of the EMDS tool.

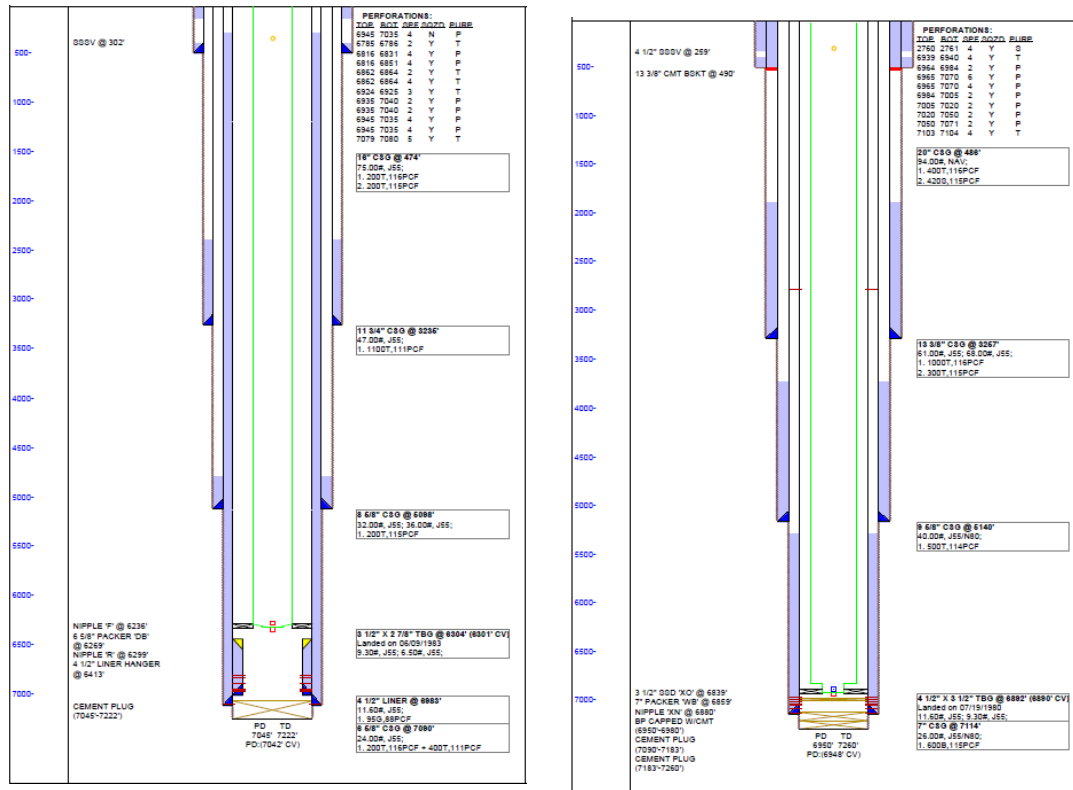


Fig. 2a and 2b. Wells A and B cross section.

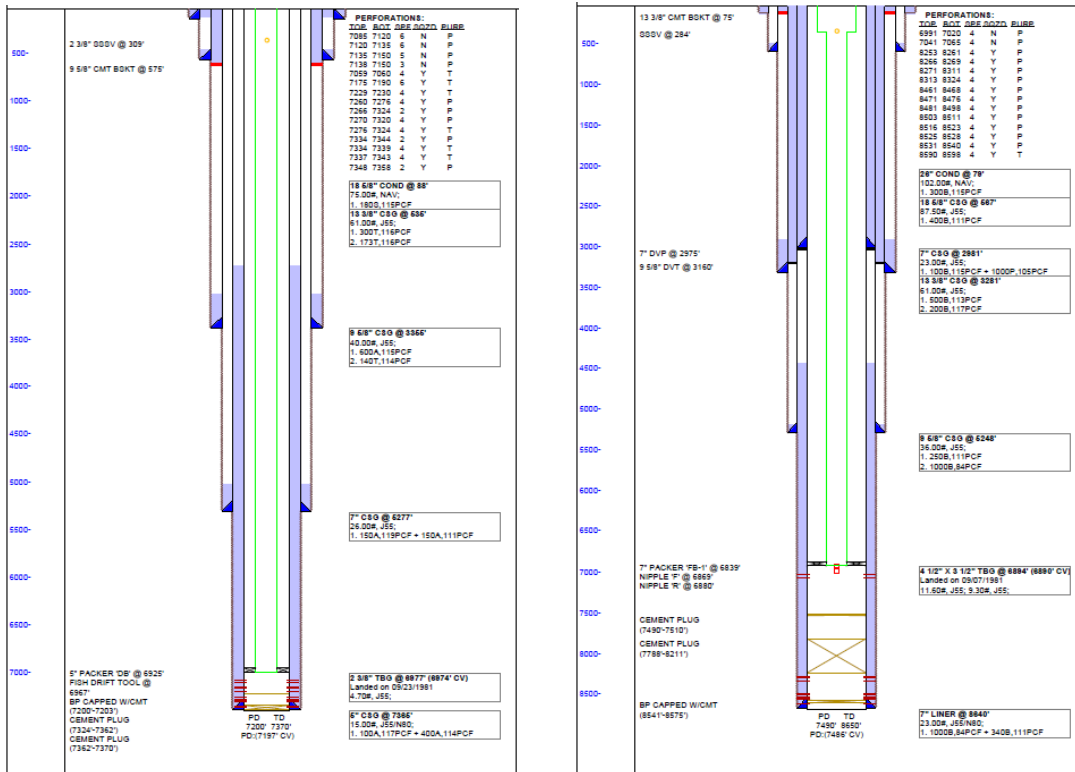


Fig. 3a and 3b. Wells C and D cross section.

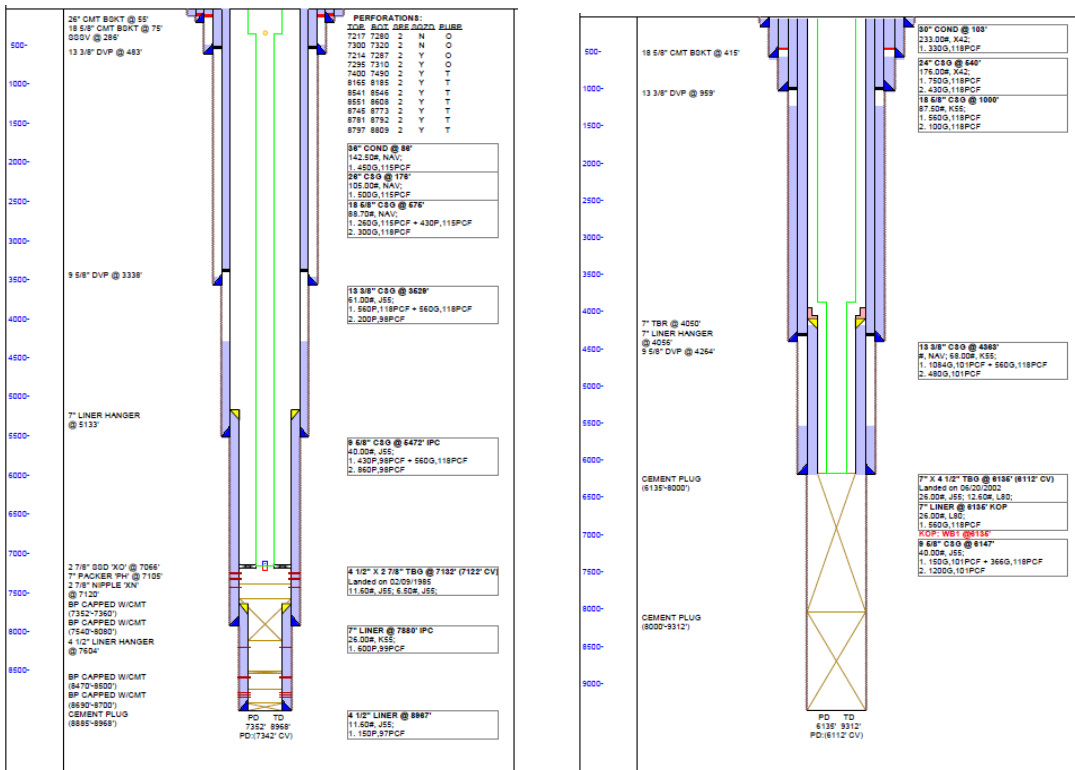


Fig. 4a and 4b. Wells E and F cross section.

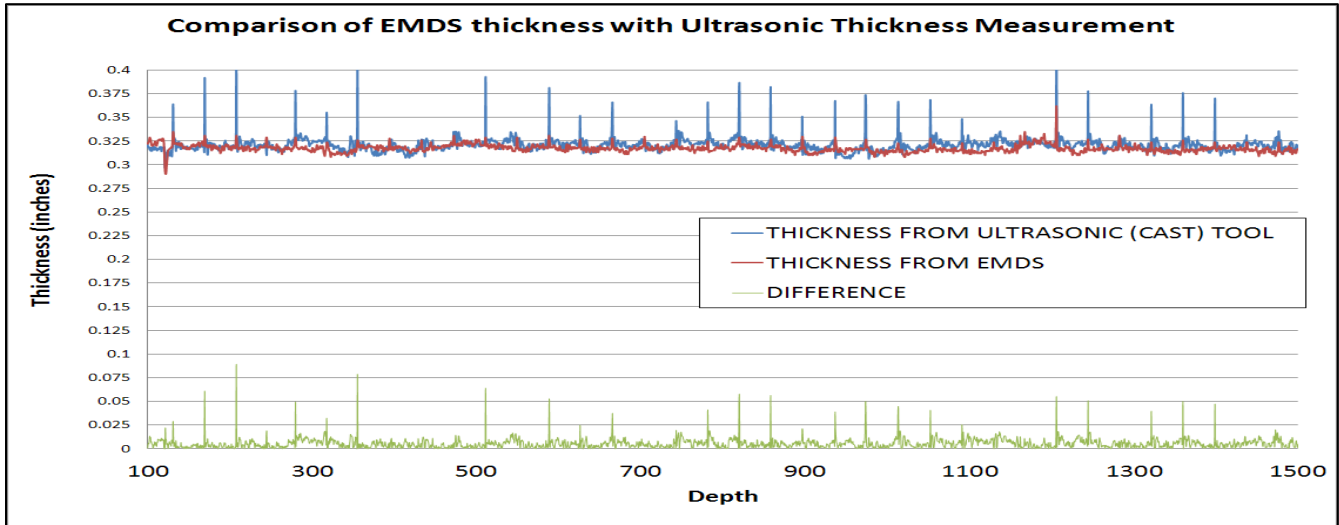


Fig. 5. Field qualification of EMDS vs. the CAST (UT tool) for thickness measurement.

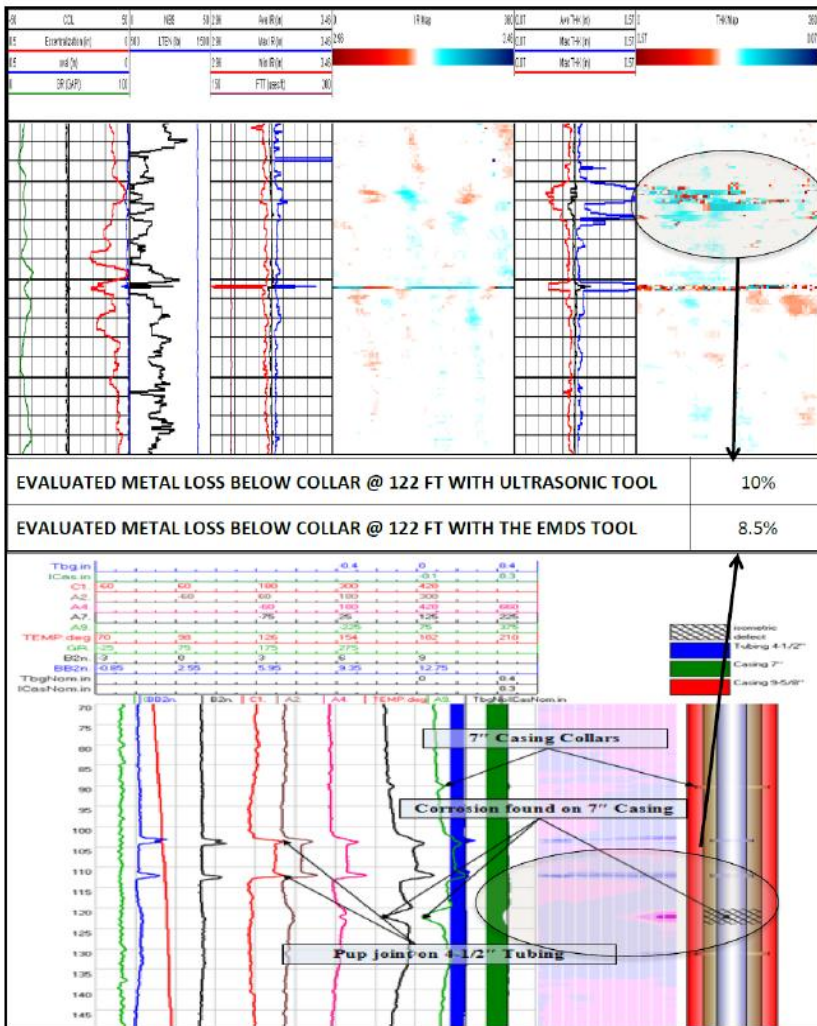


Fig. 6. Localized measurement of corrosion EMDS vs. the CAST (UT tool) for metal loss estimation.

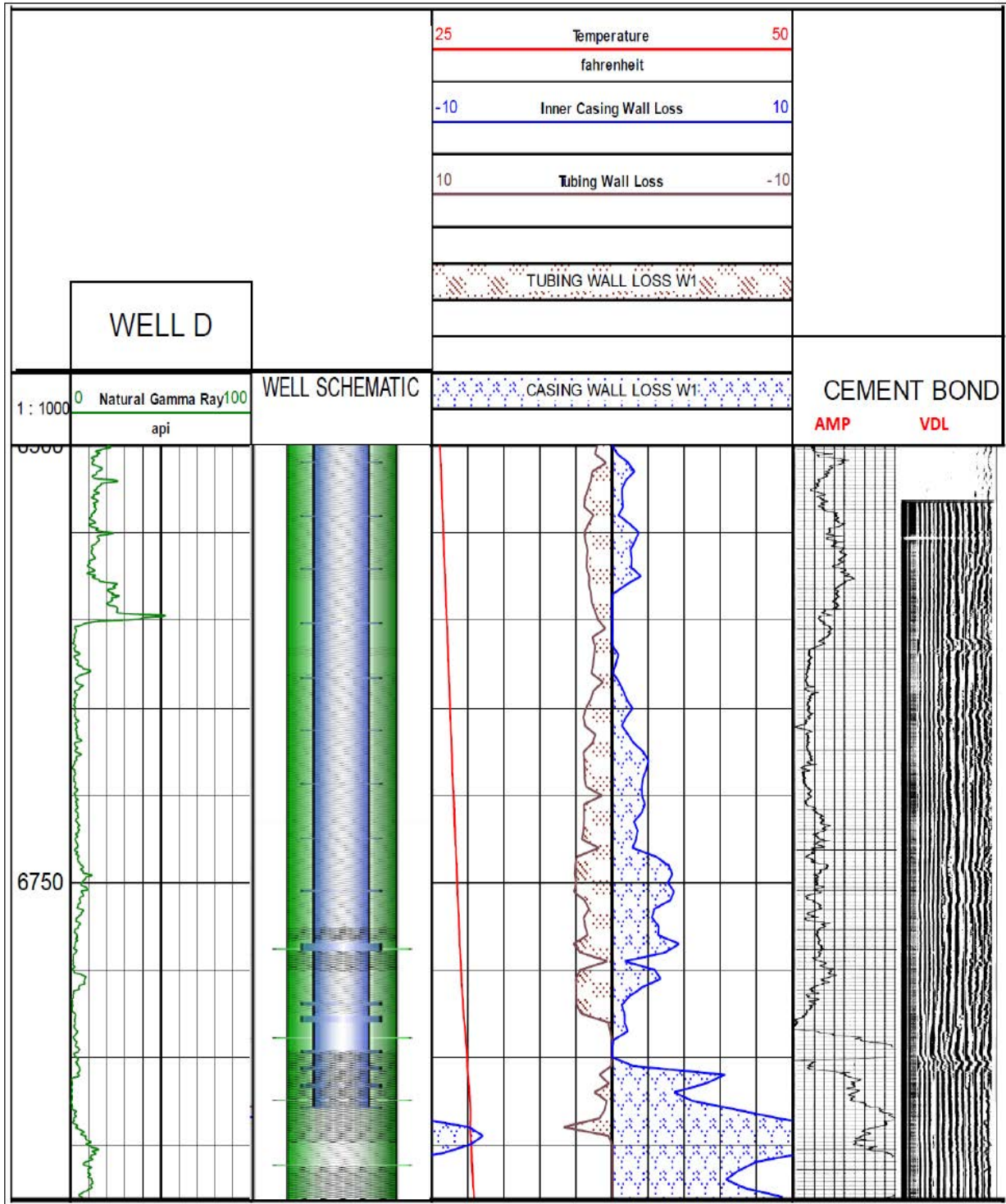


Fig. 7. Well-D correlation of metal loss in the casing with the cement bond log against the same interval (6500 ft to 7000 ft).

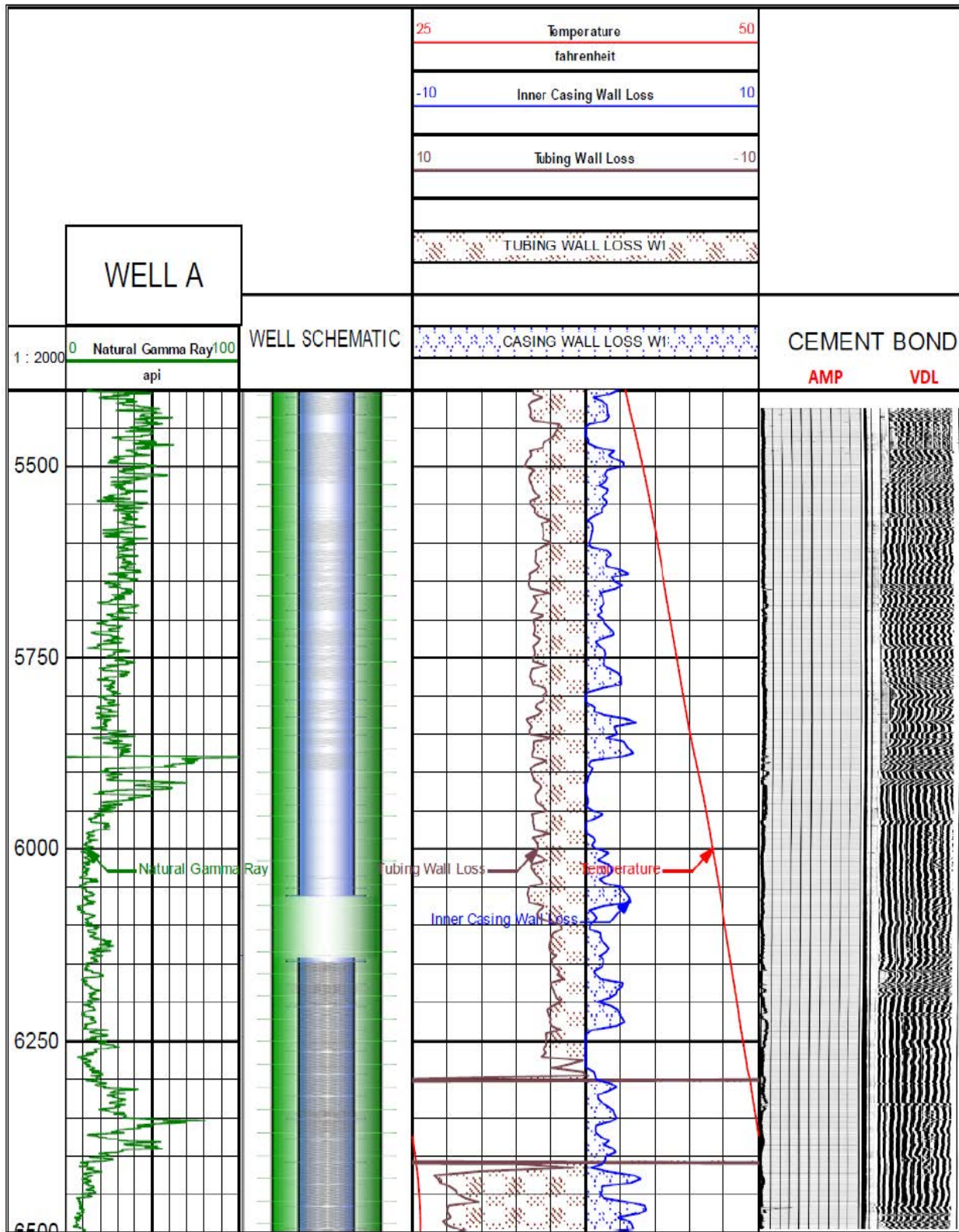
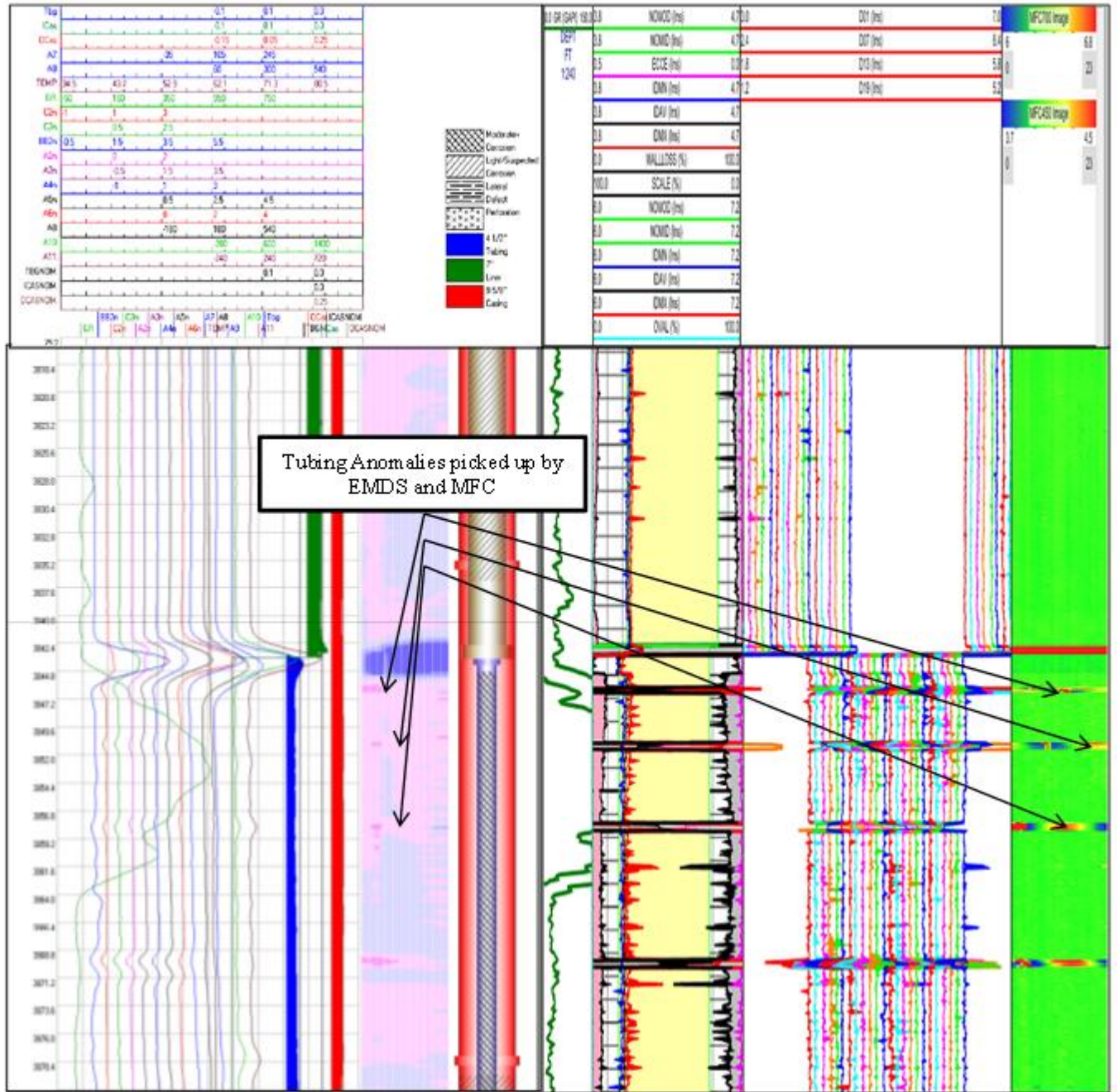


Fig. 8. Well-A minimal corrosion found on casing in well bonded cement zone. (The gap in the inner tubular is due to an upper 4.5" tubing string and a lower 4.5" liner string)



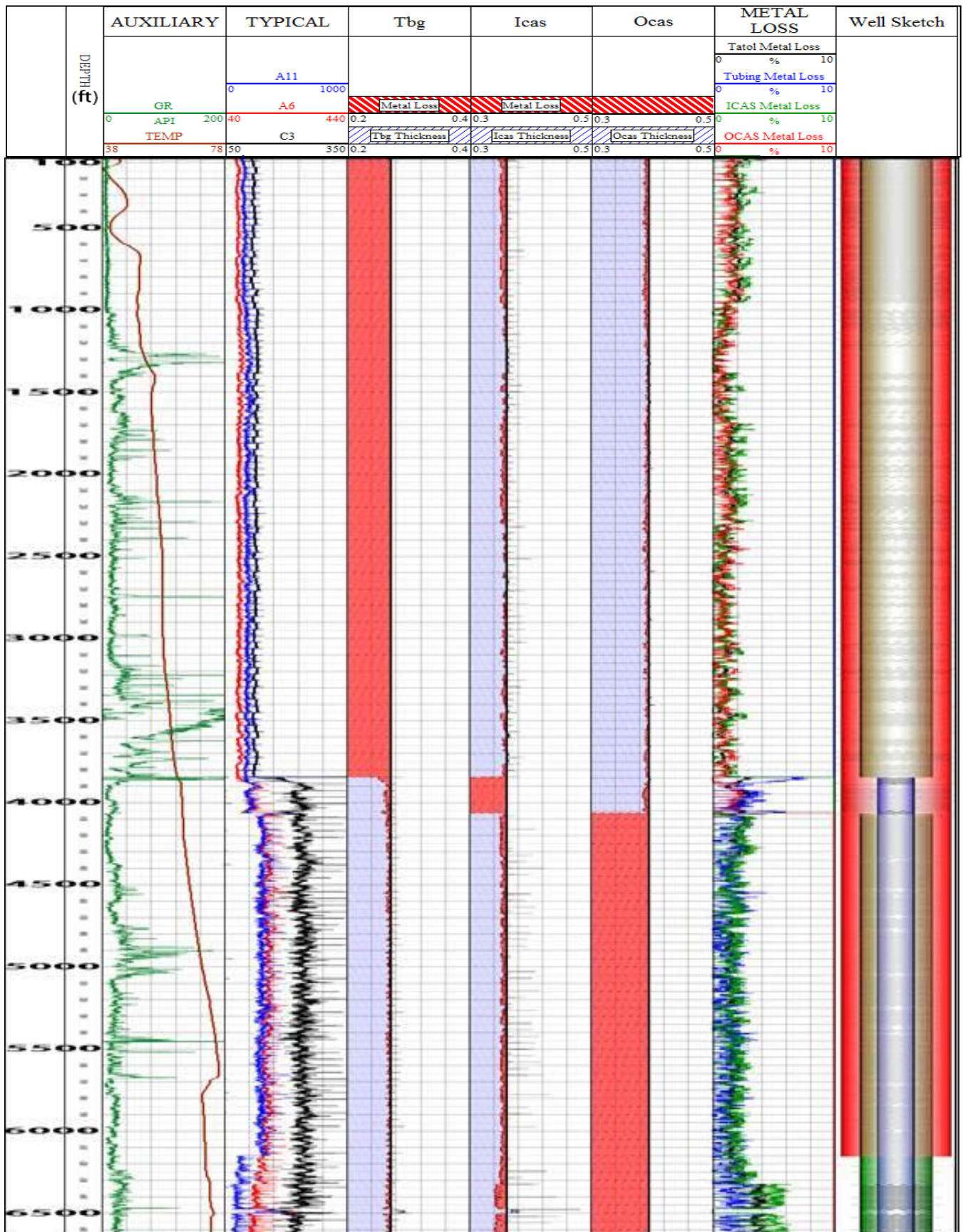


Fig. 10. Typical EMDS corrosion map for Well-F.