APPLICATIONS AND ENHANCED PROCESSING TECHNIQUES FOR A NEW FLUX-LEAKAGE / EDDY-CURRENT PIPE INSPECTION TOOL

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Abstract

Data from field tests of a new flux-leakage/eddy-current wireline logging tool are presented. This device is used to inspect well casings in place. Images of both the inner and outer surfaces of the casing can be produced using the high resolution data provided by this tool. A real-time signal processing algorithm is available to enhance the raw data. The signal processing algorithm is described, and then several examples of applying the algorithm in different wells are given. Both conventional data presentations and images are shown. The paper gives important details about the tool and some results of testing the tool on well casings which have known artificial defect arrays.

It is shown that holes as small as 1/8 in. in diameter can be detected. Further, metal loss from as little as 10% of total wall thickness to 100% of total wall thickness can be identified by the tool. In addition to sharpening the resolution of the measurements, the enhanced signal processing algorithm can be used to classify joints of pipe as undamaged to extremely damaged; and, makes it easier to see small defects which are masked by background signal which is due to small-scale surface roughness of the non-defected pipe.

This pipe inspection device is a cost effective system for determining pipe conditions for repair, remedial workovers, or adjustments to cathodic protection systems when needed. Usage's such as determining economic value of the pipe in P&A, exact location of perforations or leaks, periodic monitoring in gas storage or injection wells, and pressure limits for well servicing operations.

Introduction

Corrosion of downhole well casings is a substantial problem for petroleum producers, and concern about it is heightened because of the large number of aging wells and because of safety and environmental concerns. Although corrosion prevention methods like chemical inhibitors, cathodic protection, and corrosion-resistant coatings are available, they are not always used, and when such methods are used, they may not be fully effective. Consequently, in-situ inspection of downhole well casings for corrosion damage can be beneficial. Visual inspection is the most reliable, however, it is not possible in a downhole environment because the borehole fluid is often opaque, and it is necessary to be able to examine the outer wall of the pipe. Among the alternate methods of inspecting downhole casing is the flux-leakage/eddy-current technique. A new device known as the Pipe Inspection Tool (PIT™) uses the flux-leakage/eddy-current technique for downhole casing inspection. Special signal processing algorithms simplify interpretation of logs generated by the PIT. This logging tool is particularly useful for detecting localized corrosion pits or cracks because PIT measurements are inherently high resolution.

This paper provides general background information about the flux-leakage/eddy-current method of nondestructive inspection. Next, high-resolution data sampling and quality control features are discussed. Examples of logs based on PIT data are discussed. To characterize the PIT's capabilities, the paper examines logs of new casings with artificial defects which have been machined into the pipe. It is shown that the PIT can detect through holes as small as 1/8 in. in diameter. A signal processing algorithm used to enhance the data is based on novel techniques, and it is shown to simplify the interpretation of the log. Images of the pipes made using PIT data are also shown.

Flux-Leakage/Eddy-Current Background

Flux-leakage and eddy-current (FL/EC) measurements are commonly used to nondestructively inspect metal goods. Both measurement methods are especially helpful if localized damage such as corrosion pits or cracks must be detected. Downhole FL/EC measurements have been used to inspect oil well casings since the late 1960's. In order to make FL measurements, a static magnetic field is set up in the test piece. Because the test piece has a finite magnetic permeability, some of the magnetic flux inside the test piece "leaks out." This leakage flux can be sensed and related to the integrity of the part. Specifically, if the surfaces are smooth and interior of the test piece is homogeneous, a constant amount of flux will leak out per unit area from the surfaces of the part. Anomalies in or on the test piece alter this pattern. Sensor measurements are indicative of the pattern, and they can be used to draw inferences about the integrity of the test piece.

Tools for inspecting downhole well casings typically use a D.C. electromagnet to magnetize the casing, and coils placed inside pads which are applied to the inner surface of the casing measure the field pattern. Because virtually static fields are used, there is no skin effect; so, even defects on the outer surface of the casing can be detected. Note that the FL method requires the test piece to be magnetic because the test piece needs to be magnetized. This requirement causes no difficulty for inspecting downhole well casings because nearly all casings are made of ferrous metal. Finally, the FL method can be used to inspect the innermost casing in a multiple string even though the outer strings reduce the amount of flux delivered to the inner string.

Electrical currents flowing through a transmitter coil are used to induce eddy-currents on the surface of the test piece in the EC method. Measurements sensitive to the eddy-current pattern are used to detect anomalies in the pattern. Such measurements are commonly the impedance of the transmitting coil or of the mutual coupling between the transmitter and other receiver coil(s). Mechanical defects in the test piece are then associated with anomalous eddy current patterns. The eddy currents tend to be concentrated near the surface of the test piece closest to the transmitter coil because of the skin effect; consequently, the EC measurement is less sensitive to defects on the far surface of the test piece than is the corresponding FL measurement. If the specimen is magnetic, the best results are obtained if it is magnetized as much as possible. Magnetic permeability variations can be mistaken for actual defects but high magnetization of the specimen reduces this variation in the specimen's permeability. Downhole casing inspection equipment typically uses coils of wire to sense the eddy currents. Frequencies of 1 kHz to 10 kHz work well on highly magnetized casings. Traditionally, the eddy-current measurement has been used in downhole casing inspection equipment to distinguish defects on the inner surface of the casing or defects on the outer surface that extend through to the inner surface from defects on the outer surface.

Pipe Inspection Tool (PIT) Details

The PIT provides FL and EC measurements from induction coil-type sensors in pads which are applied to the inner wall of the casing. As shown in Fig. 1, the pads are disposed in two staggered rings around a mandrel which contains a large DC electromagnet. The vertical resolution and sensitivity of PIT measurements are determined by the sensor and magnet design which are discussed below.

The largest practicable magnet is used to maximize the level of magnetization in the casing. The following are advantages of using such a magnet: (1) effective magnetic permeability variations which adversely impact the EC measurement are reduced; (2) flux-leakage caused by defects on the casing OD more readily passes through to the inside of the casing where it can be picked up by the sensors; and (3) demagnetization effects caused by anomalies in the casing are mitigated.

Induction coil sensors were chosen to simultaneously provide high sensitivity FL/EC measurements and full azimuthal coverage of the casing. The front view of a PIT sensor is shown in Fig. 2. The EC transmitter coil is in the middle. Above and below it are receiver coils that pick up the FL and EC signals. The receiver coils are used as a differential pair; so, the raw FL/EC data are actually the difference between the voltage across the upper and lower receiver coils. The differential receiver array minimizes sensitivity to pad standoff, provides a null output when the pipe is defect-free, and has a resolution that can be controlled by the spacing between the coils, which is denoted by the parameter d in Fig. 2. For the PIT, d has been chosen to provide a 1/4-in. vertical resolution. The other key parameter of the sensor is its width, which is denoted by w in Fig. 2. Each of the three sizes of the PIT has a sensor width chosen so that all the sensors collectively provide complete azimuthal coverage over the range of casing sizes in which the tool operates. The basic specifications for each size of the PIT is shown in *Table 1*.

The PIT is equipped with several quality-control features. A Hall probe is positioned between the magnet core and one of the pole pieces. It is used as an indicator of the amount of magnetic flux provided by the magnet; so, any abnormalities in the flux supply can be detected. There is, also, an uphole current regulator that allows the magnet to supply a constant magnetomotance regardless of the temperature. Excellent pad contact is ensured by a special mounting scheme in which dual springs (one above the sensor and one below it) allow each end of the pad to move independently.

Data Processing Algorithm & Example Logs

A new data processing technique has been developed to improve the data quality and normalize the vast array of information available from the PIT tool. This processing algorithm is available for both real-time and post-processing applications.

In this algorithm, the "cleanest" section of casing which is logged serves as a "calibration joint." Actually, only three or more feet of relatively clean casing is required. The raw data from the calibration joint are fed to specially-developed filters which compute the normalization constant and the offset for each curve. The calibration accounts for minute differences between the response of each pad, and it eliminates other variables besides casing wear that can impact the data. The calibration must be applied every run because the calibration depends on the pipe size and the specific tool that is used. If a clean section of pipe is not available, satisfactory results can be obtained by using calibration values for the same tool (both instrument and sensor section) and a pipe of similar nominal size.

Log Example 1 - The section below 90 ft. served as the calibration joint. The eddy and flux curves are plotted on the same scale range with a different offset. Notice the activity on each of the curves and that the EDDY 3 and EDDY 4 scales are closer together than the scales for the other curves. The irregularities are a result of pad tolerances and noise caused by small-scale surface roughness on the pipe. Small holes in the pipe may be masked by noise as shown by the EDDY and FLUX data around 86.5 ft.. The processed curves denoted by PEDDY and PFLUX on the right allow one to easily distinguish the holes. In fact, the very small holes just above 86 ft. show up clearly on the PFLUX curves. Notice that almost all of the noise resulting from small scale surface roughness on the raw data is eliminated by the algorithm; consequently, each pad produces the same response when it crosses a given defect. In the example shown here, the pads are expected to produce identical responses because identical defects have been machined into a gauge pipe. Further, the amplitude and extent of the deflections on the processed curves are proportional to the size of the defect in the pipe.

The example logs shown below demonstrate the applications of the signal processing algorithm on new pipes with artificial defects and on well in West Texas.

Log Example 2 - This a log contains a section of new 7.0-in., 26-lb./ft, N-80 pipe with the following defects machined from the bottom to the top of the pipe:

four through holes with 1-in. diameter, 90-degree azimuthal separation, and 3-in. vertical separation;
six through holes with 1/2-in. diameter, 60-degree azimuthal separation, and 2-in. vertical separation;
twelve through holes with a 1/4-in. diameter, 210-degree azimuthal separation, and 1-in. vertical separation;
twelve through holes with 1/8-in. diameter, 210-degree azimuthal separation, and 1-in. vertical separation.

A photograph of one side of this pipe with some of the defects pointed out is shown next to the log which was recorded in a downhole test well. The tool's response to the defects is quite evident by the amplitudes of the FL and EC signals with respect to the size and position of the defect. All defects are clearly visible with the exception of most of the EC signals in the 1/8-in. diameter holes; however, the FL signals show clear responses to these 1/8-in. defects.

Log Example 3 - Logs of a section of new 7-in., 26-lb/ft, P-110 pipe are shown here. The defects machined in this pipe from bottom to top are the following: five 1/4-in. diameter, flat-bottom pits that penetrate 100%, 80%, 40%, 20%, and 10% of the way through the pipe wall from the inside. These defects were machined on the inside of the pipe after it was cut in half. Afterwards, the pipe was put back together and tack welded on the ends to hold it together.

A photograph of one inside half of the pipe before it was welded back together is shown next to the logs. Notice that the FL amplitude is proportional to the amount of metal loss while the EC indicates that the defect is on the inside of the pipe.

Log Example 4 - This log is from a well in West Texas in 7-in., 20 lb/ft casing. The well had developed a leak in the pipe which had become difficult to locate using typical pressure test. Upon running the pipe inspection device a small hole was detected at XX73 which is evident from the large EC and FL signals. Subsequent pressure test confirmed the location of this hole and was repaired by means of a cement squeeze across the defective section.

Log Example 5A & 5B - These logs are from a well in Oklahoma in 5-1/2-in., 20-23-lb/ft, N-80 casing inside 7-5/8-in., 29.7 lb/ft, N80 casing. Two Baker packers were placed at XX737 and XX756 between the 5-1/2-in. casing and 2-3/8-in. tubing and an acid frac performed in the perforated intervals at XX956-XX968 and XX996-XY008. The well was not immediately cleaned out and put on production. After drilling out the packers and logging the pipe inspection device, it was determined that the acid which had remained inside the 5-1/2-in. tubing and eroded the pipe almost completely through.

Example 5A is a plot of the FL and EC signals with the tubular goods and downhole hardware shown in the center of the log. Note the extremely large EC signals due to the excessive corrosion on the inner portion of the pipe. Note the symmetrical patterns of FL and EC curve response across the intervals where the packers had been drilled out which is typical of mechanical damage.

Example 5B places all tubular goods, hardware and perforations in the center of the log and clearly shows the locations of the zero phase perforations across the three perforated intervals. Note the slight rotation of the tool through the perforations illustrated by the response of the FL and EC signals switching to adjacent pads on the mandrel as the tool comes uphole.

Conclusion

A new flux-leakage/eddy-current Pipe Inspection Tool (PIT) is available for downhole inspection of oil well casings. This device provides high-resolution data, and it can detect holes in pipes as small as 1/8-in. in diameter. Both conventional and image-like presentations of the data are offered. The PIT comes in three sizes, and it can inspect casings from 5-in. through 10-3/4-in. in diameter. A signal processing algorithm can be applied to the raw data to simplify log interpretation and eliminate noise on the log caused by small-scale surface roughness on the pipe.

References

Anonymous, *Corrosion Control in Petroleum Production*, published by the National Society of Corrosion Engineers, 1979.

Uhlig H. H., *Corrosion and Corrosion Control*, John Wiley and Sons, (1971).

Walters W. T., and Nagel D. D., "Magnetic Inspection Apparatus for Well Pipe Utilizing Detector Shoes with Outriggers and Magnetic Latching Means for Said Shoes," U. S. Patent No. 3,543,144, Nov. 24, 1970

Table 1
Basic information about the Pit

Logging speed: 60-ft/min	Max Temp: 350° F
Sample Rate: 0.1-in	Max Pressure: 15,000 psi
Pit is H_2S Tolerant	Nominal Length*: 185-in
Nominal Tool Size	Casing Range
5-1/2-in (8 pads)	5-0-in (11.5 lb/ft) 5-1/2-in (15.5 - 23 lb/ft)
7-0-in (12 pads)	6-5/8-in (20 -28 lb/ft) 7-0-in (17 - 38 lb/ft) 7-5/8-in (26.4 - 39 lb/ft)
8-5/8-in (12 pads)	8-5/8-in (32 - 40 lb/ft) 9-5/8-in (32.3 - 53.5 lb/ft) 10-3/4-in (32.75 - 60.7 lb/ft)

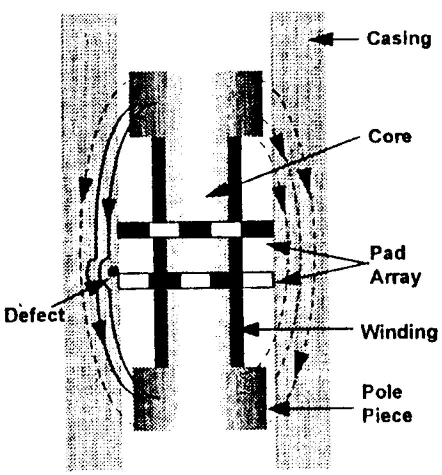


Figure 1

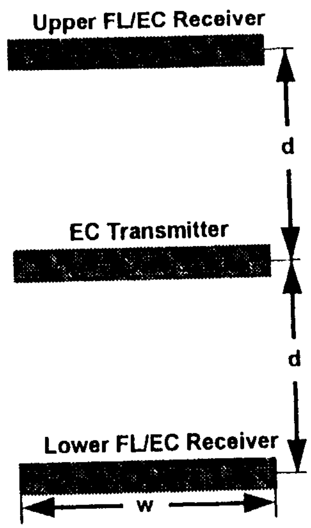
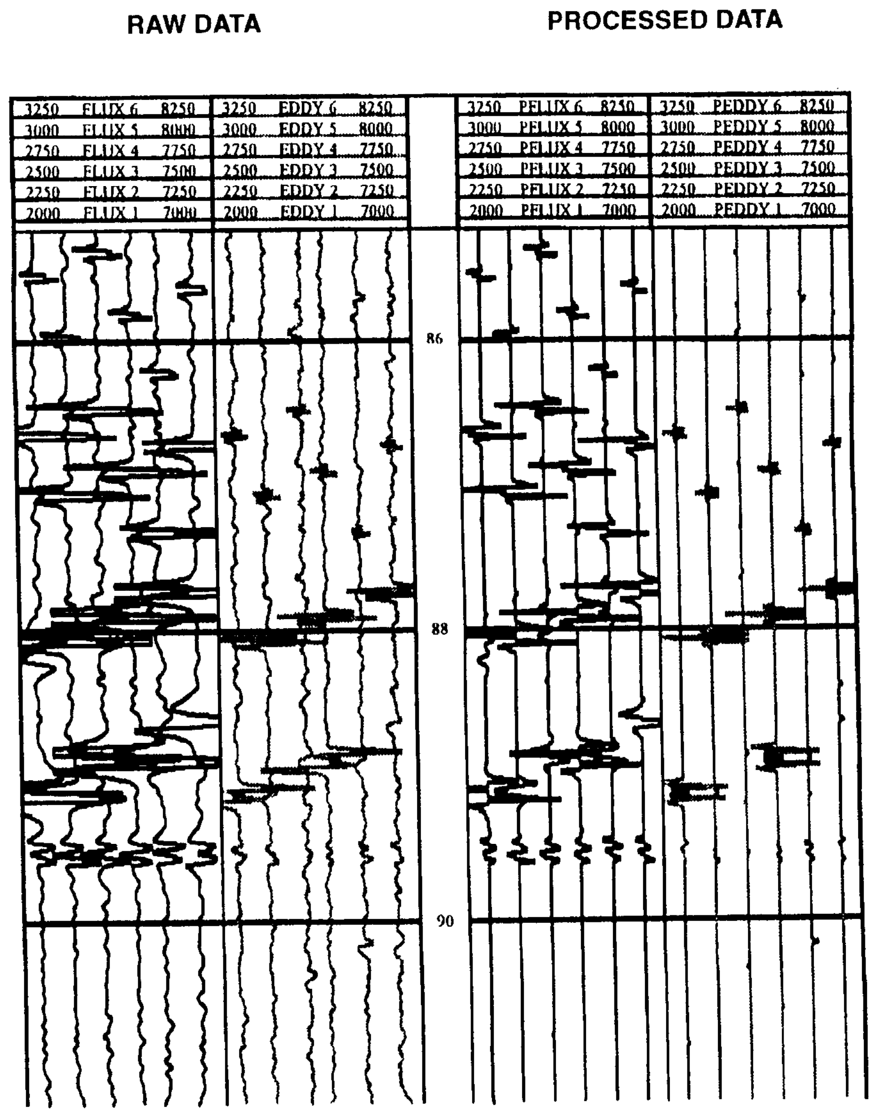
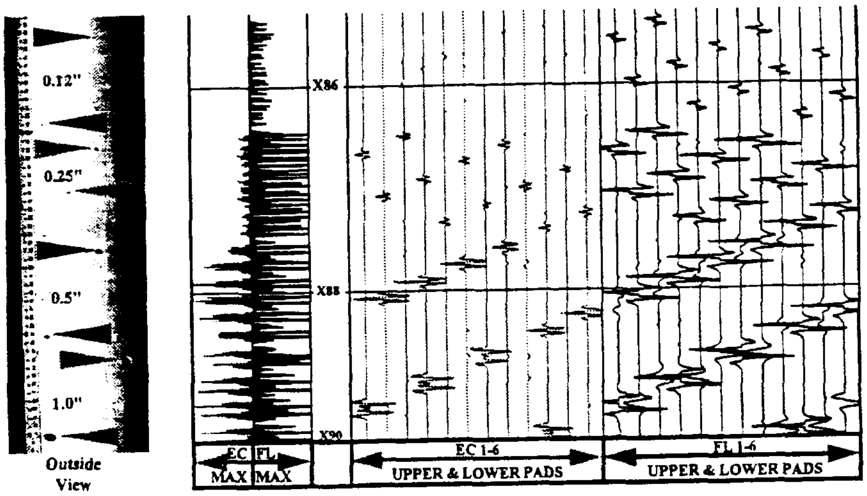


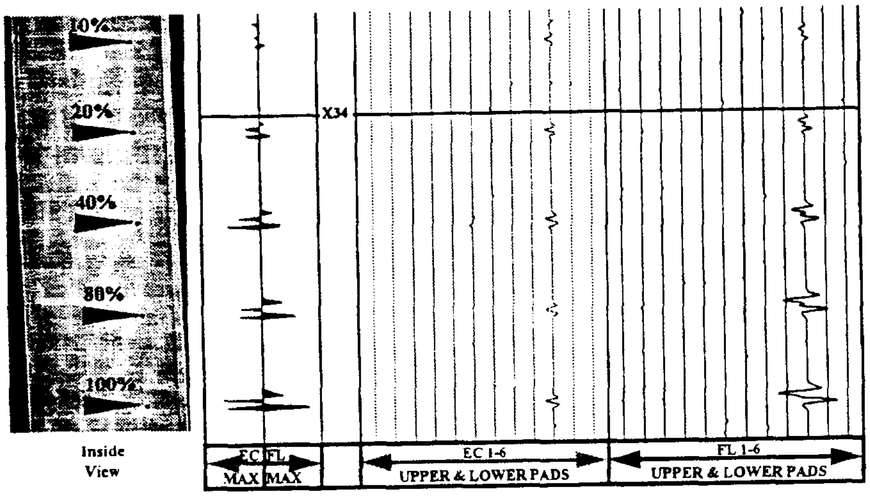
Figure 2



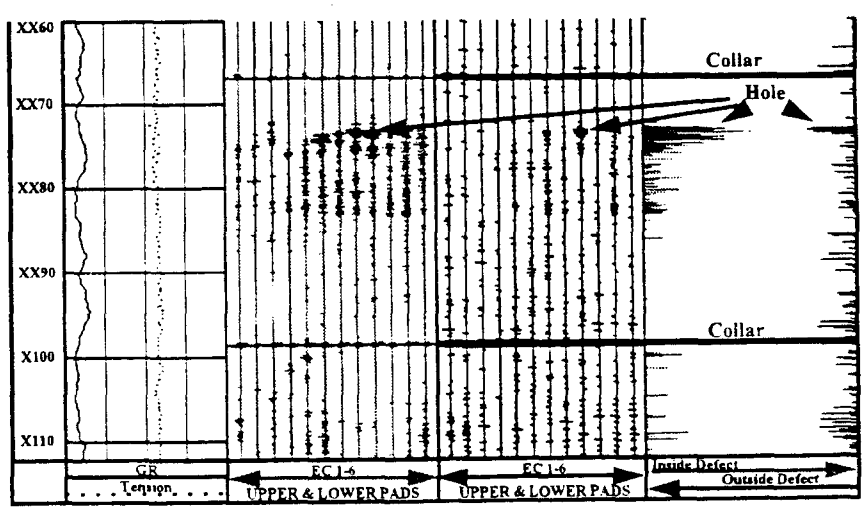
Log Example 1: This log shows the benefits of the data processing algorithm. The logs on the left are "raw data" without the normalization and offset correction while the logs on the right are corrected based on clean pipe responses. Notice that the log responses for each defect are the same and the inherent noise is eliminated from the data.



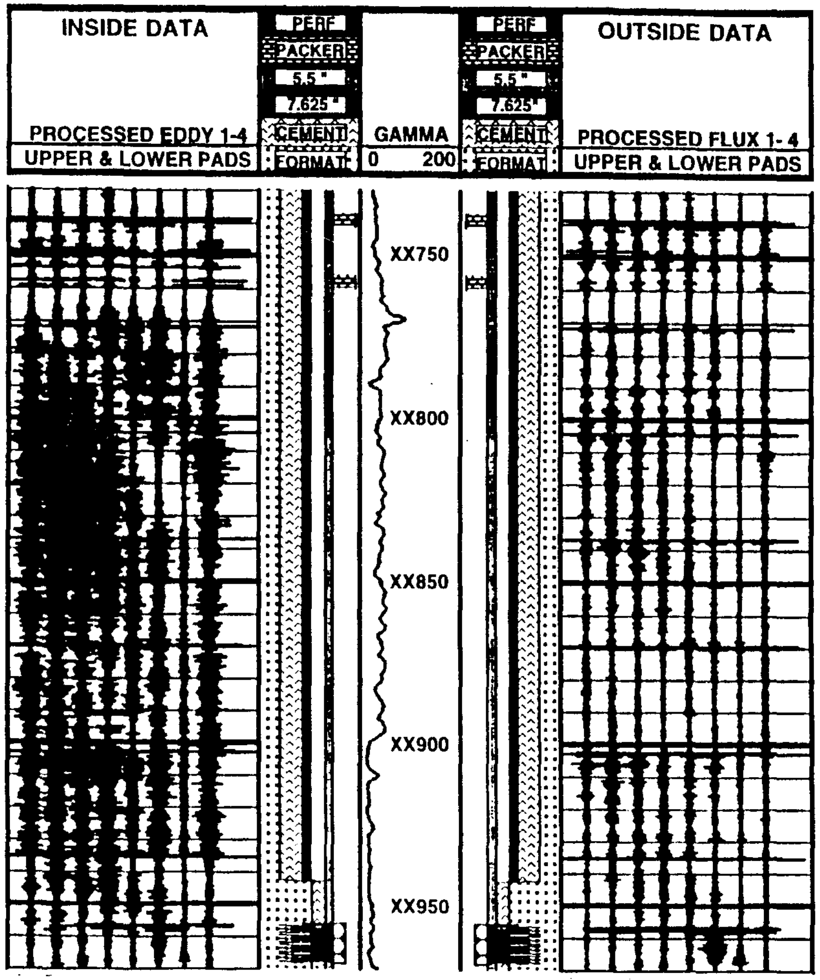
Log Example #2: The example above is from a section of test casing with man-made thru-hole defects. A photograph of the outside of the pipe is shown next to the log and scaled to match the scale of the log presentation.



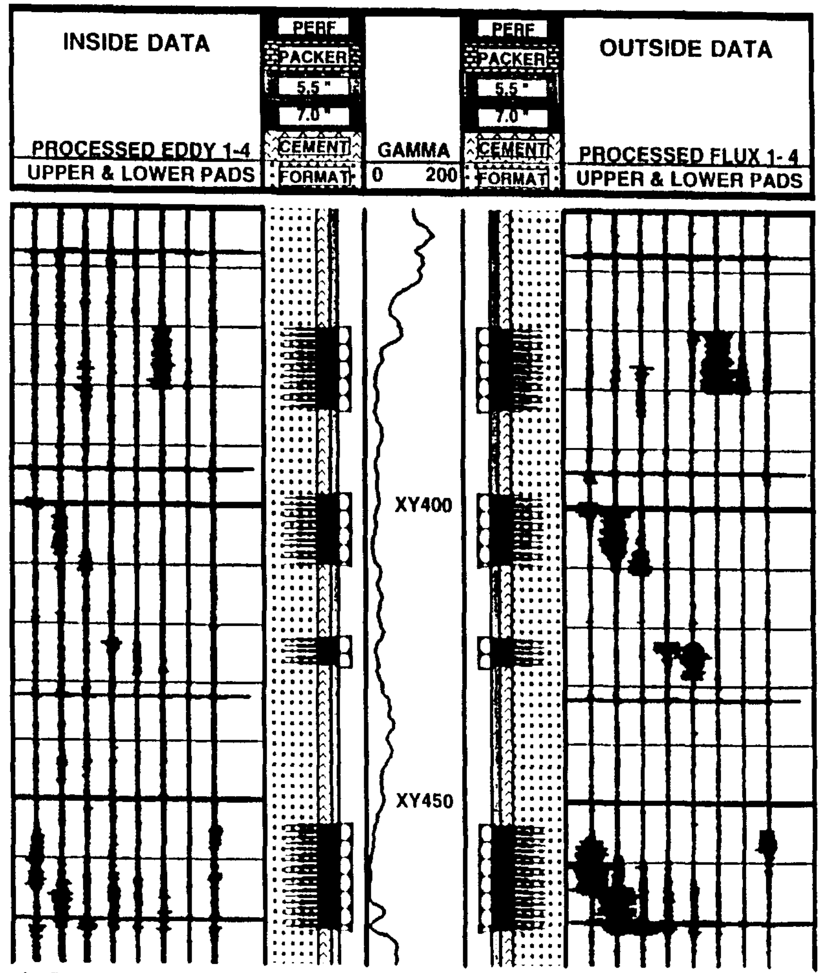
Log Example #3: The example above is from a section of test casing with man-made inside defects. A photograph taken of the pipe split open is shown next to the log and scaled to match the scale of the log presentation.



Log Example #4: The example above is from a well in West Texas in a 7.9", 20#/ft. pipe. The casing profile in the far right track is a discriminated maximum defect from the inner and outer portions of the pipe.



Log Example #5A: Oklahoma example of 5.5" casing showing acid damage. The wellbore diagram allows visualization of tubular items including packers. Notice the damage occurred by packer setting and/or removal.



Log Example # 5B:

Log Example #5B: The Same Oklahoma Example of 5.5 casing showing several perforated intervals. The Pit tool will allow determination of perforation depth and associated patterns.