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AUSTENITIC STAINLESS STEEL WELD INSPECTION

MASTER

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This paper describes analytical techniques applied to ultrasonic waveforms obtained from inspection of austenitic stainless steel welds. Experimental results obtained from a variety of geometric and defect reflectors are presented. Specifically, frequency analyses parameters, such as simple moments of the power spectrum, cross-correlation techniques, and adaptive learning network analysis, all represent improvements over conventional time domain analysis of ultrasonic waveforms. Results for each of these methods are presented, and the overall inspection difficulties of austenitic stainless steel welds are discussed.

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INTRODUCTION

This paper reports on progress in remote ultrasonic pre-service and in-service inspection of piping welds in liquid-metal-cooled reactors. Specifically, the paper discusses problems and possible solutions involved in inspecting weldments in Schedule 40 austenitic stainless steel piping.

Problems associated with ultrasonic inspection of austenitic stainless steel welds have previously been well documented[1]. Serious efforts are being made to understand the structures contributing to the attenuative and beam-scattering properties of austenitic weldments that obscure rejectable defects[2,3].

In light-water reactor coolant lines, areas with a high probability of developing stress-corrosion cracks can be predicted and monitored with some accuracy. This is not true of liquid-metal-cooled reactors, however, because the preferred locations of defect formation in these environments are not yet known. The challenge for in-service ultrasonic inspection, therefore, is to develop an inspection system that will allow the entire volume of the weld to be inspected in a liquid-metal-cooled reactor.

While a variety of inspection techniques is available to inspect welds pre-service, radiation and temperature preclude the use of many of these techniques after the first power cycle. Ultrasonic inspection appears to be the most viable of the possible solutions.

One problem with using ultrasonic techniques for in-service inspection, however, is that an ultrasonic scanner would have to be re-positioned to within 0.127-cm (±0.05-in.) of its former position relative to a weld in order to achieve meaningful comparisons between the scanner's assessment of the weld's pre-service condition and its in-service condition, or condition at the time of inspection.

Since such close re-positioning is clearly not obtainable manually, especially on piping that will move slightly during the lifetime of the reactor, an alternate plan was developed to record baseline data during pre-service inspection and use the recorded data to re-position the scanner during subsequent in-service inspection. Given enough pre-service data about the surface and internal characteristics of a given specimen, it was felt a computer could re-position the scanner more repeatably relative to a point on the weld than manual re-positioning could.

The remainder of this paper will report on this and related work. We will also discuss methods of improving upon pre-service inspection data analysis, and ways to use pre-service data for maximum benefit during in-service inspection

The data included in this paper were acquired using conventional ultrasonic pulser-receiver electronics, commercially-available transducers, digitally-controlled scanning mechanisms, and a high-speed transient digitizer. A minicomputer was employed for data acquisition and archival data storage, scanner control and data analysis.

EXPERIMENTAL PROCEDURE

An "as-received" 8-inch Schedule 40 stainless steel piping weld sample with electro-discharge machined (EDM) notches on the inside diameter (as shown in Figure 1) was examined with a single circumferential scan of 500 equally-spaced angular positions. The transducer was a wideband (80 percent bandwidth), 3-MHz transducer containing dual elements with approximately 10-degree cross-beam focus in a 60-degree longitudinal mode. Inspection data were stored as digital records of the original ungated RF waveform obtained at each point of examination. During the analysis phase of this project, these original waveforms would be used to evaluate the analytical method being considered.

Subsequent to the initial pipe section examination, a sector of a 25.4-cm (10-in.) diameter, 1.016-cm (0.4-in.) wall, stainless steel pipe weldment was prepared, with two reflectors that remained unchanged between successive scans, and one reflector enlarged in 0.038-cm (0.015-in.) increments between scans, as shown in Figure 2. In this examination, the transducer was a dual element 4-MHz unit, operating in a pitch-catch mode, and set to generate a 45-degree shear wave. The 0.076-cm (0.03-in.) wavelength used compares with 0.178-cm (0.07-in.) for the refracted longitudinal 3-MHz previously used, and was selected to give sufficient sensitivity to detect the 0.038-cm (0.015-in.) changes in notch depth. The effective diameter of the inspection beam at the focal point was estimated to be 0.1016-cm (0.04-in.). This focal point was mechanically adjusted to a depth of 0.127-cm (0.04-in.) by employing the 0.254-cm (0.1-in.) deep stationary notch as a reference target.

Between scans, the pipe section was removed from the scanner, the "growing" EDM notch was enlarged, and the sample re-inserted into the scanner. Data obtained on successive scans were digitally recorded on magnetic discs for later retrieval and analysis.

To demonstrate the practicality of this method of detecting small changes in reflectors, it was necessary to devise a technique that would permit the remote scanning mechanism to be removed and re-installed without unreasonable mechanical tolerances, yet produce effective scan replication within 0.127-cm (0.05-in.). The last test addressed this problem.

The configuration for this test consisted of a pipe section with a pattern of fiducial marks approximately 5.08-cm (2 in.) apart, as shown in Figure 3. These marks become reference points for realignment of the scanning unit during in-service inspection. During the initial scan, the surface was profiled with an additional small focused transducer, servo-controlled normal to the pipe surface. The position of these surface marks was cataloged, together with the ultrasonic examination data. On three successive tests, the pipe specimen was physically re-positioned several inches away from its last position, then relocated by the profiling transducer. Once the surface and the reference marks were relocated, the positional data relative to the reference marks was stored, along with the ultrasonic scan data. Later this data was employed to reposition all of the data scans such that these later scans were mechanically reproduced within 0.127-cm (0.05-in.) at the focal point.

DATA ANALYSIS TECHNIQUES

Digitized time domain waveforms (RF) were processed by three computational methods: amplitude detection, cross correlation, and transformation to the frequency domain using a fast fourier transform (FFT) algorithm. Simple moments of the power spectral density of the frequency domain information were calculated as:

$$M_K(i) = \sum_{j=1}^{i} J^K p_j ,$$

where i is the frequency index and P_j is the discrete analog of the power spectral density,

$$p(\omega) = (A_\omega^2 + B_\omega^2)^{1/2} .$$

These techniques and their results, as applied to the pipe section shown in Figure 1, are more fully described in Reference 4, while the results are summarized in Figure 4.

The data resulting from the aforementioned techniques were employed as input vectors for an adaptive learning network (ALN) model[5]. Twenty of the 500 examination points were used for training the model, while another 20 were used for testing it. The remaining 460 points of the 500-point data set were subjected to the model created by the network, with the results as illustrated in Figure 5.

Two techniques, single- and multiple-pass, were used to analyze the growing notch test series data. Each technique was based on a different premise. Single-pass techniques assume no archival data, and reflect the pre-service inspection situation. Multiple-pass techniques assume archival data are available, such as in the in-service inspection situation. The single-pass technique employed both the amplitude detection method and the second moment of the power spectral density, M_2, which proved to be the most successful single-pass indicator of rejectable defects. Results of these analyses are shown in Figure 6.

Multiple-pass techniques were developed utilizing prior (baseline) data to enhance those features that change between examinations, while suppressing those that are unchanging. This would be a simple model of a defect that developed after the baseline examination. The first multiple-pass technique cross-correlated a baseline waveform with a corresponding waveform taken during a subsequent examination. These waveforms were then aligned in time, as indicated by this cross-correlation. The resulting waveform differences, indicated as E_1, are illustrated in Figures 7 and 8.

The second of the multiple-pass techniques not only minimized the time skew error, E_1, but also scaled the amplitude of the baseline data to produce a least-squared error in amplitude. The resulting error, E_2, was then both time- and amplitude-corrected before the waveforms were subtracted.

Profile data were taken curing the baseline examination to accurately catalog the location of the reference marks and the profile of the local surface. During subsequent examination, these data were used to determine the mechanical alignment changes that would permit analysis of waveforms obtained during different scans. Once the mechanical alignments are made, any or all of the previously-mentioned techniques are viable.

RESULTS AND DISCUSSION

Digital time-domain records of wideband, ungated ultrasonic waveforms can be processed to produce outputs similar to conventional ultrasonic testing (UT) techniques. Synthetically, one can gate and/or bandwidth limit the signal. Similarily, A-scans or amplitude detection, B-scans and C-scans can be produced.

In addition to the conventional UT data, processes such as the second moment algorithm, M_2, the best single analysis process to date, can be used with significant improvement over conventional techniques. Further, multiple data sets can be generated from a set of single scan records and analyzed as a composite in a process such as regression analysis, producing results superior to any of the individual data sets.

Techniques have been developed that capitalize on the fact that detailed historical information exists for the entire volume being examined. The time-domain algorithms that generate the waveform differences, E_2, utilize prior information to minimize both the time skew and sensitivity changes caused by a change in acoustic path length. Simple waveform subtraction clearly reveals the small changes in the presence of large stationary reflections.

The analysis technique, E_2, as shown in Figure 8, demonstrates the ability to detect a 0.038-cm (0.015-in.) change in defect depth. The resulting defect indicator is significantly larger than the stationary background, even though the background contains a stationary defect of approximately twice the depth. The enlarging notch is detected between 0.076-cm (0.03-in.) and 0.114-cm (0.045-in.) depth because of the size and location of the focal point, as previously described. Similarly, at depths greater than 0.114-cm (0.045-in.) the indicator shows no significant improvement because the entire inspection beam is intercepted by only the shallowest portion of the notch.

For data generated after the baseline inspection to be usable in the manner just described, absolute mechanical repeatability on the order of 0.127-cm (0.05-in.) must be realized at the focal point. This, obviously, is an unreasonable requirement to place on a mechanical system over the life span of a reactor. Utilization of fiducial marks, historical profile data, and coordinate transformation permit this requirement to be met.

Providing the mechanical scanning system has better than 0.0127-cm (0.005-in.) reproducibility and 0.0025-cm (0.001-in.) resolution within the surface defined by a set of reference marks, waveform replication can be expected, as shown in Figure 9. It is worth noting that the magnitude of the resulting waveform differences between successive scans relative to a single waveform is of the same order of magnitude as the data obtained during the growing notch series. Thus, the alignment and differencing scheme, E_2, if used here, should be sufficient to resolve the same 5-10 percent change in defect size determined earlier.

CONCLUSIONS

Analytical techniques have been developed and demonstrated that improve on conventional UT pre-service and in-service inspection processes. Utilization of frequency domain information, specifically the M_2 algorithm, produces a better single process defect indicator than time-domain information. Combinations of both time and frequency domain information in an adaptive learning network produced results superior to any single process.

Multiple-pass analytical techniques, utilizing detailed archival records of ultrasonic waveforms have been shown to be useful in detecting small changes in the presence of large stationary signals. These techniques could be applied during in-service inspection by utilizing the baseline data.

Reference marks and local profile data have been utilized to demonstrate that UT in-service examination may be performed with the accuracies mandated by the analysis techniques.

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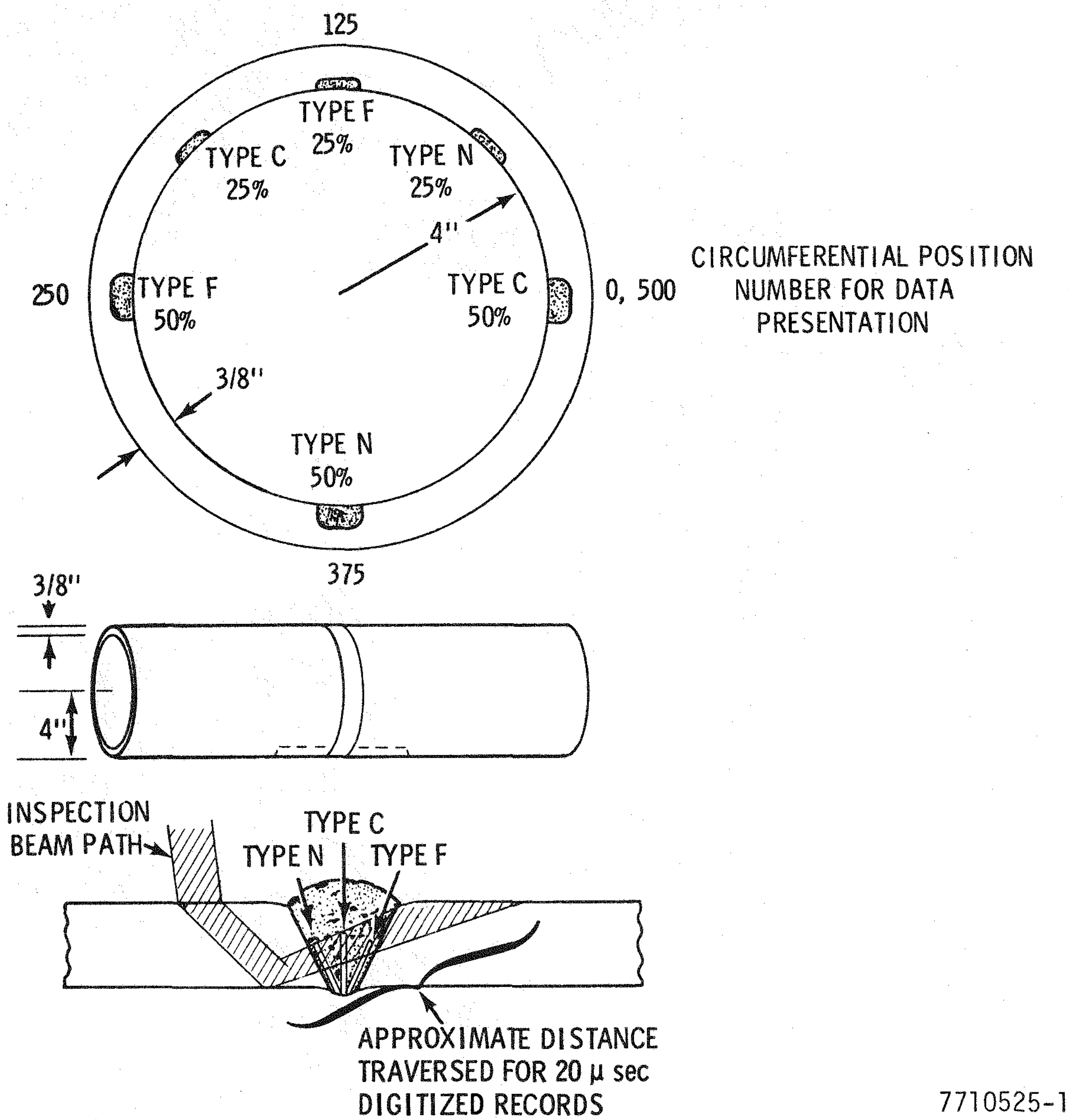

FIGURE 1. Inspection Beam Path and Notch Locations.

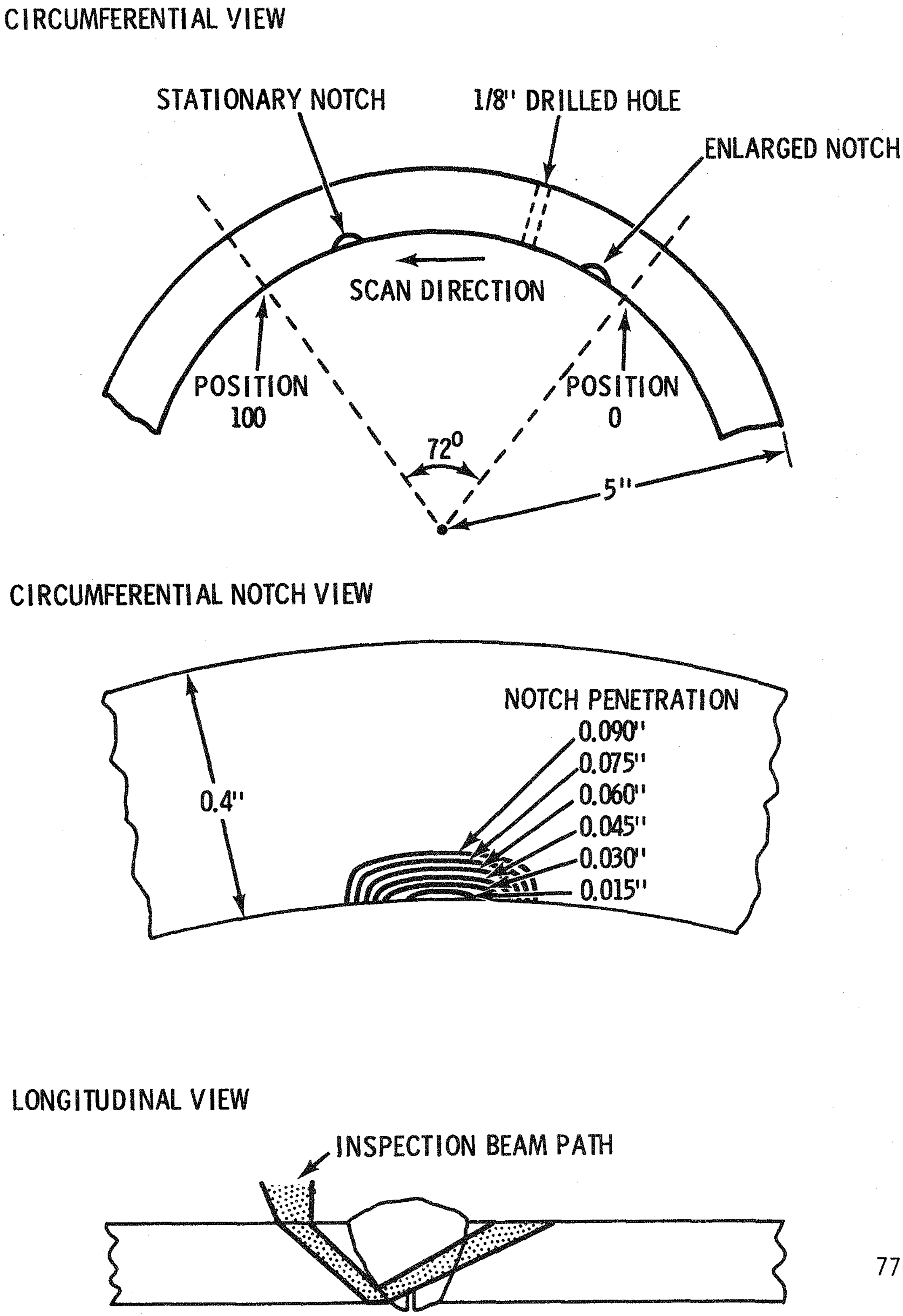

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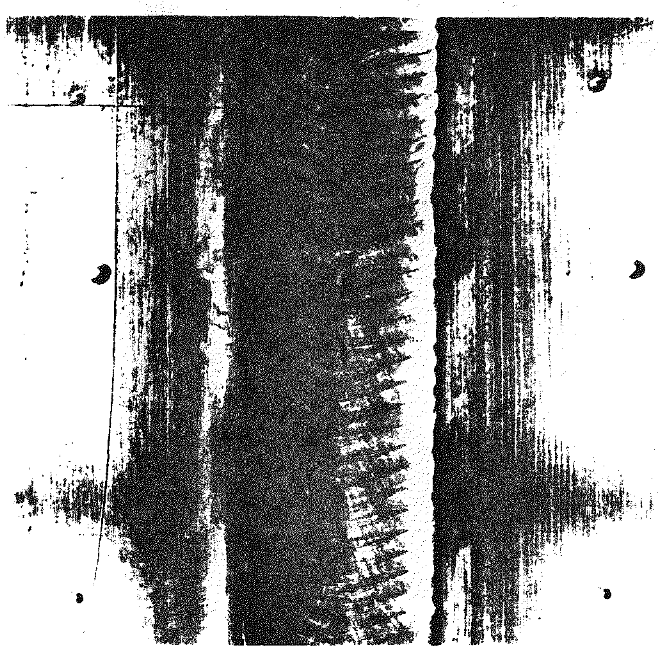
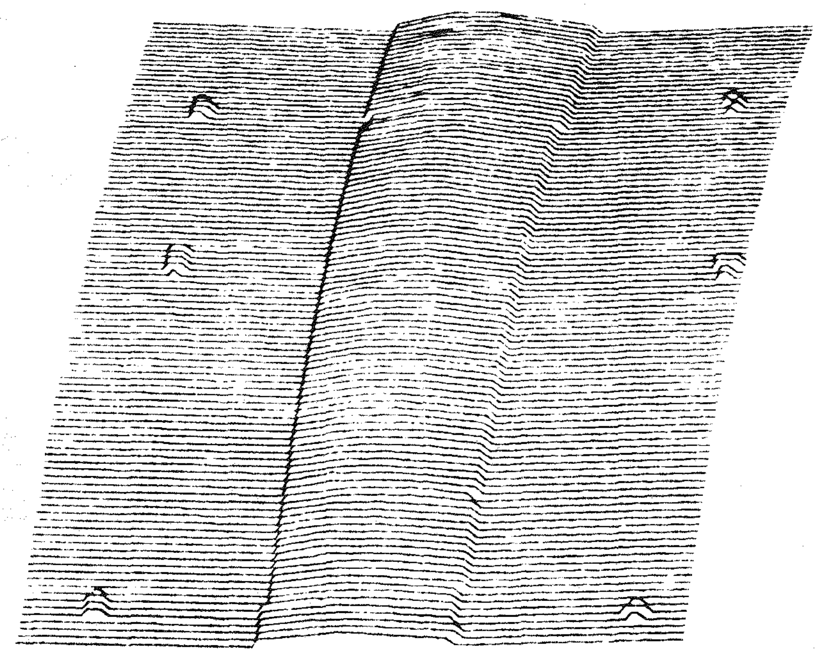
FIGURE 2. "Growing Notch" Test Specimen Geometry.



ACTUAL PHOTOGRAPH OF PIPE SURFACE



ULTRASONIC SCAN OF PIPE SURFACE

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FIGURE 3. Pipe Section Profile Results. Note these surface marks are drilled and punched indents.

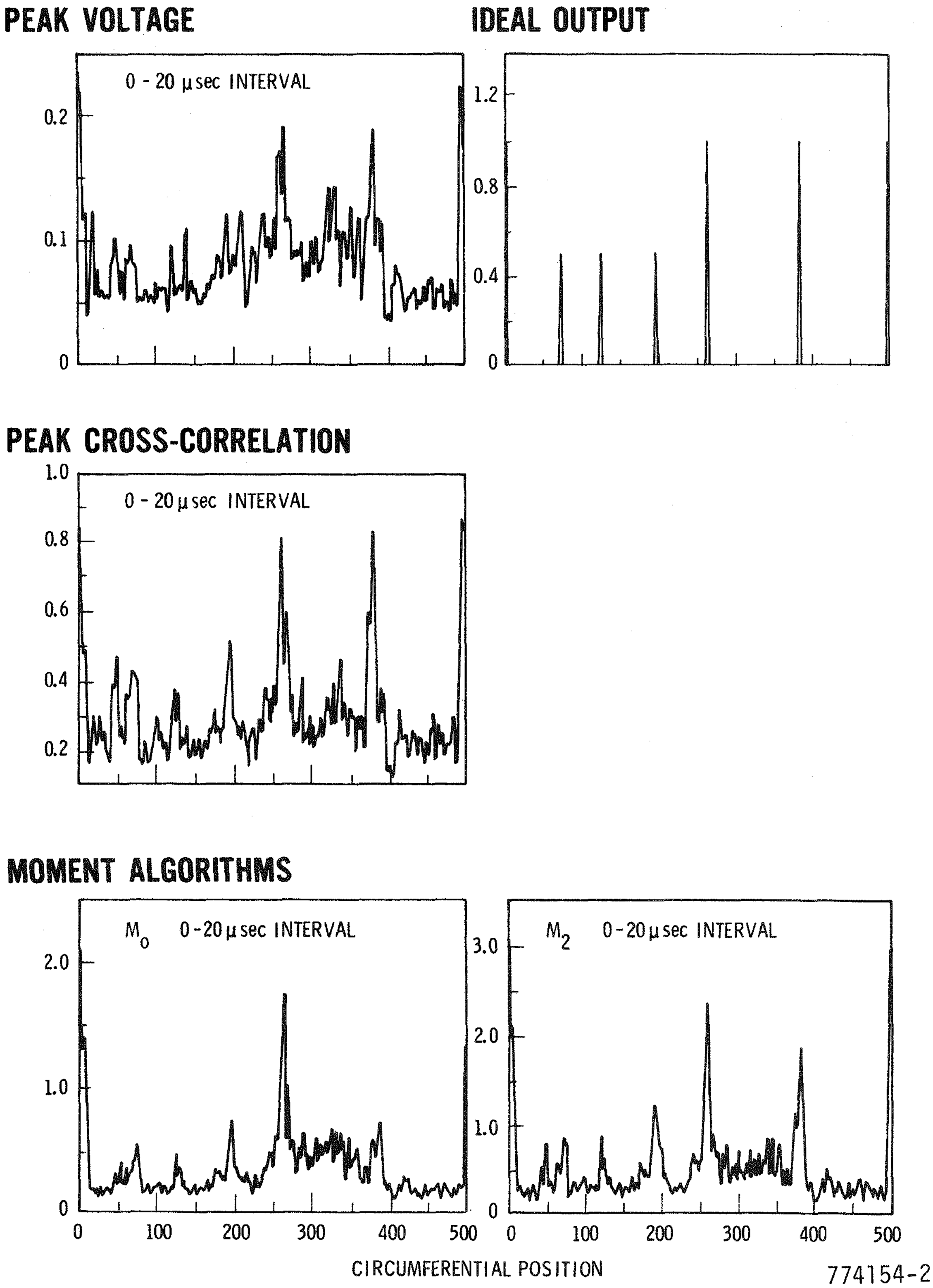

FIGURE 4. Peak Voltage, Total Power M_0, and Moment M_2 for 60° Refracted Longitudinal Inspection.

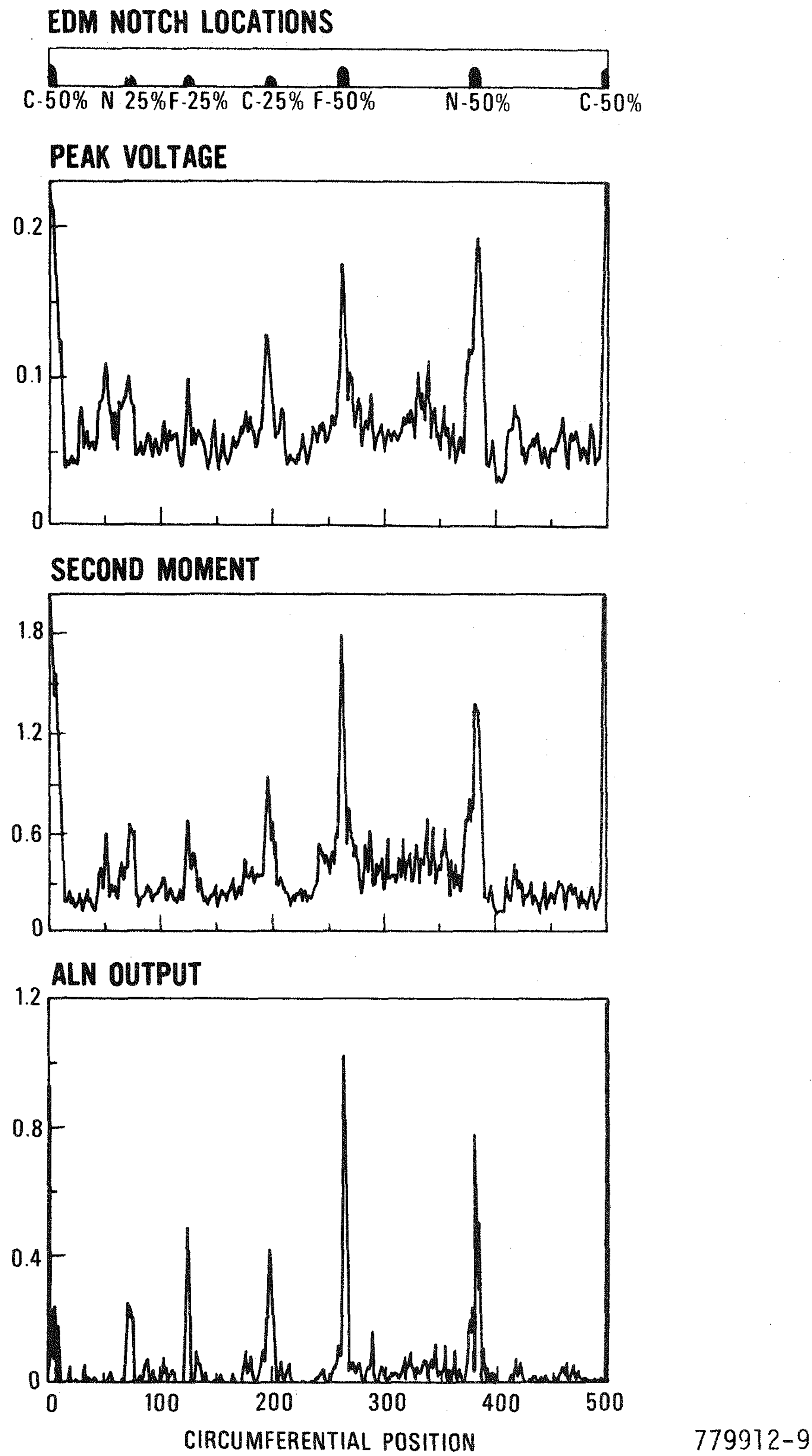

FIGURE 5. Comparison of Peak Voltage, Second Moment, and ALN.

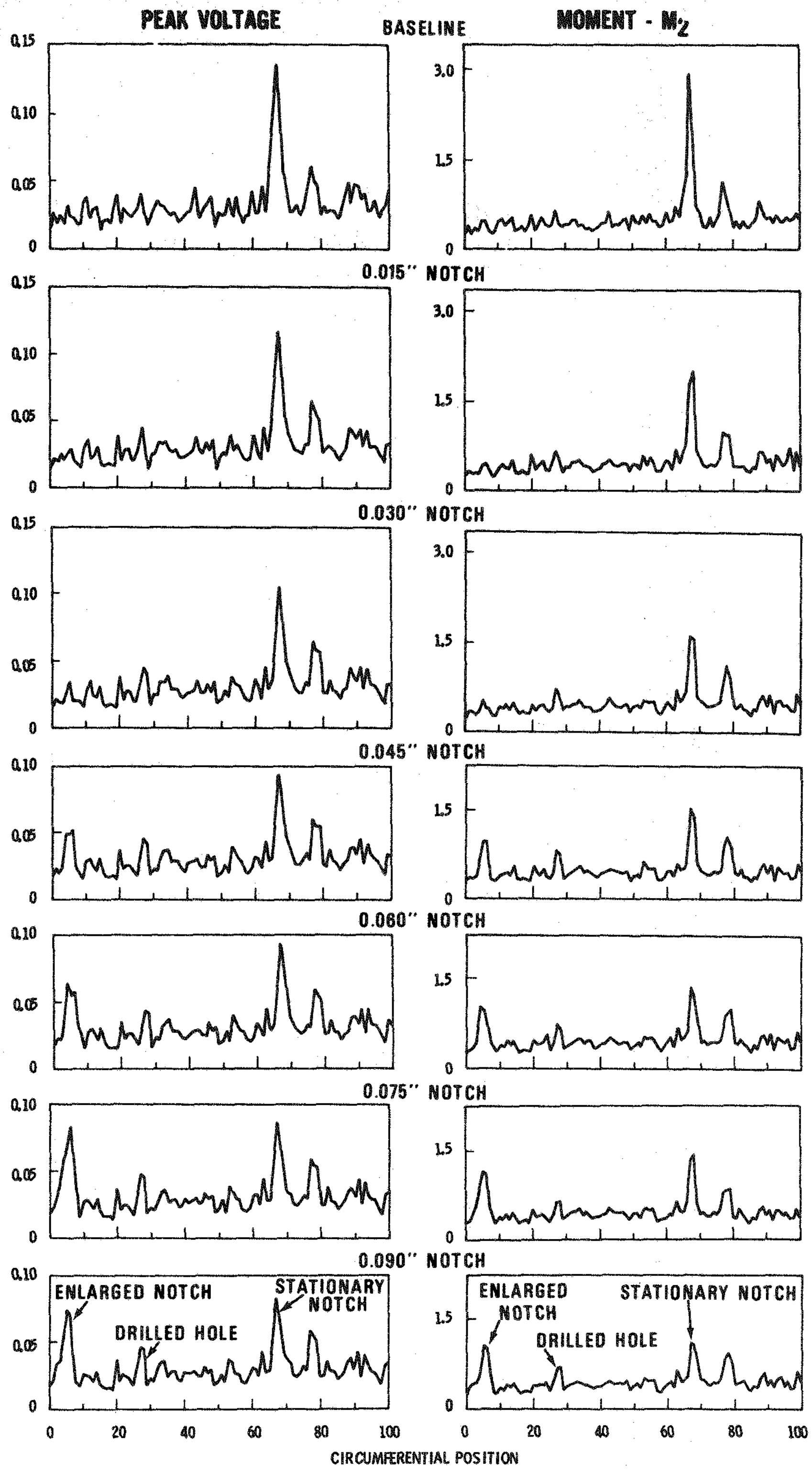

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FIGURE 6. Peak Voltage and Moment Results.

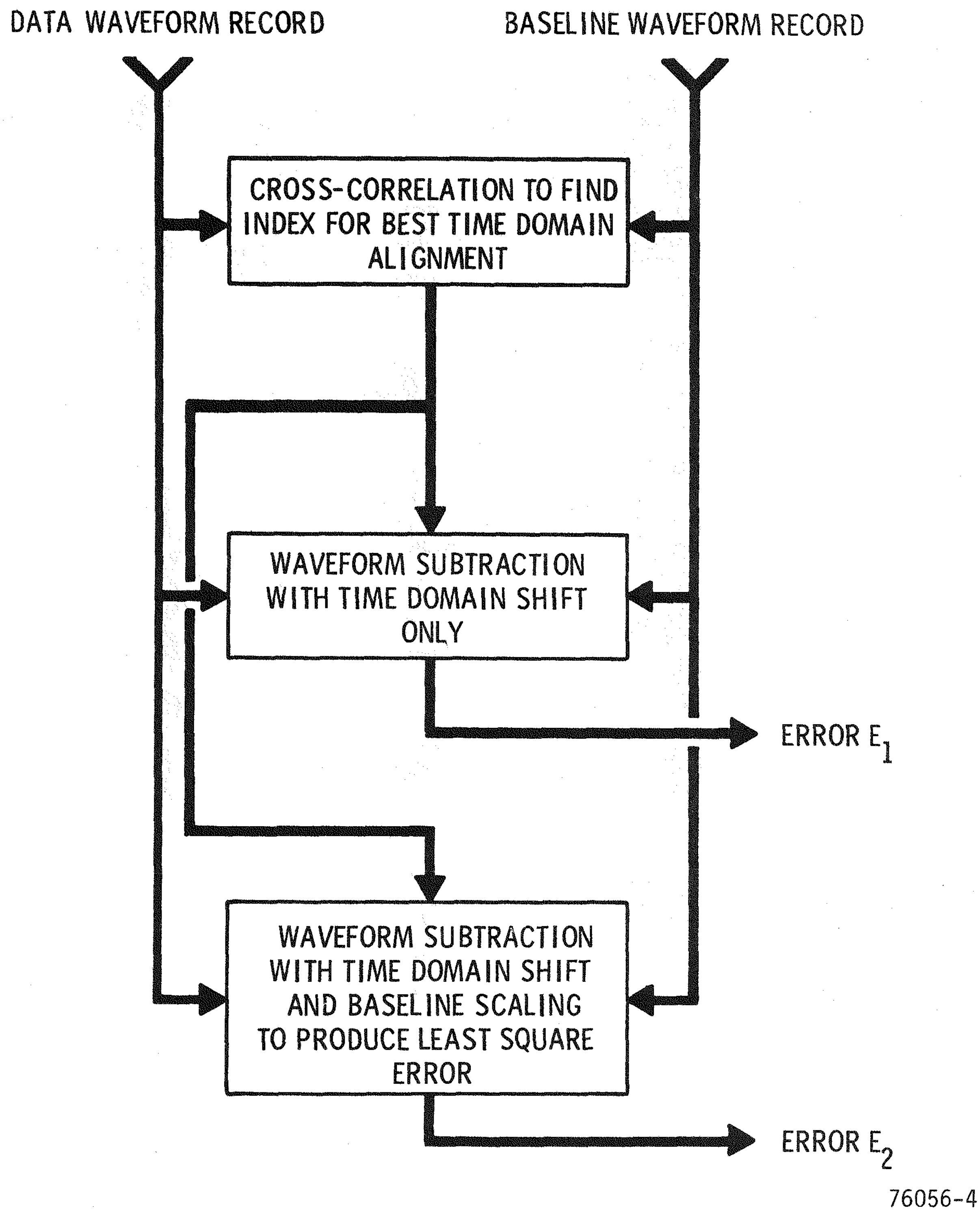

FIGURE 7. Numerical Analysis Differencing Schemes.

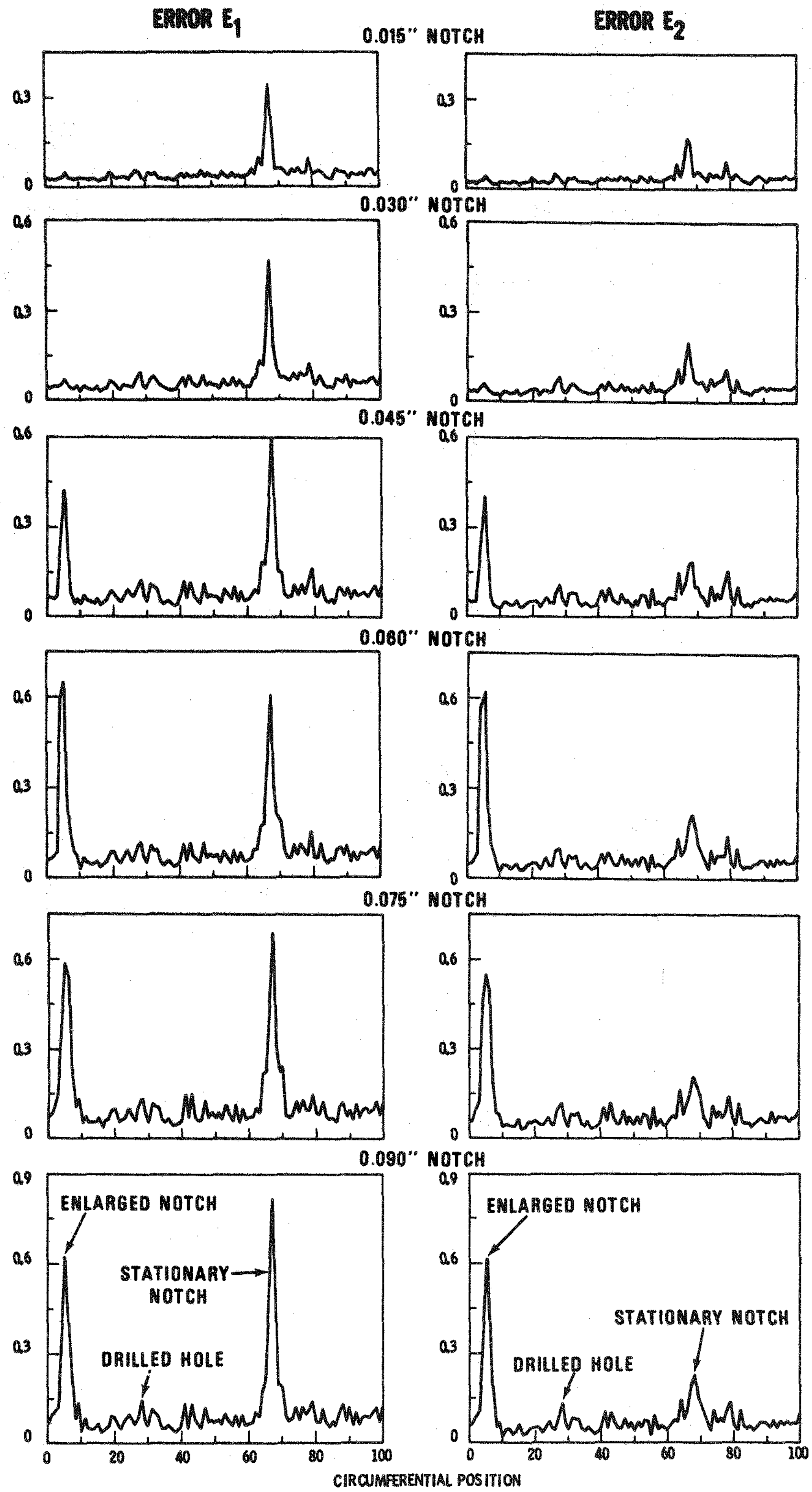

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FIGURE 8. Results of Differencing Algorithms.

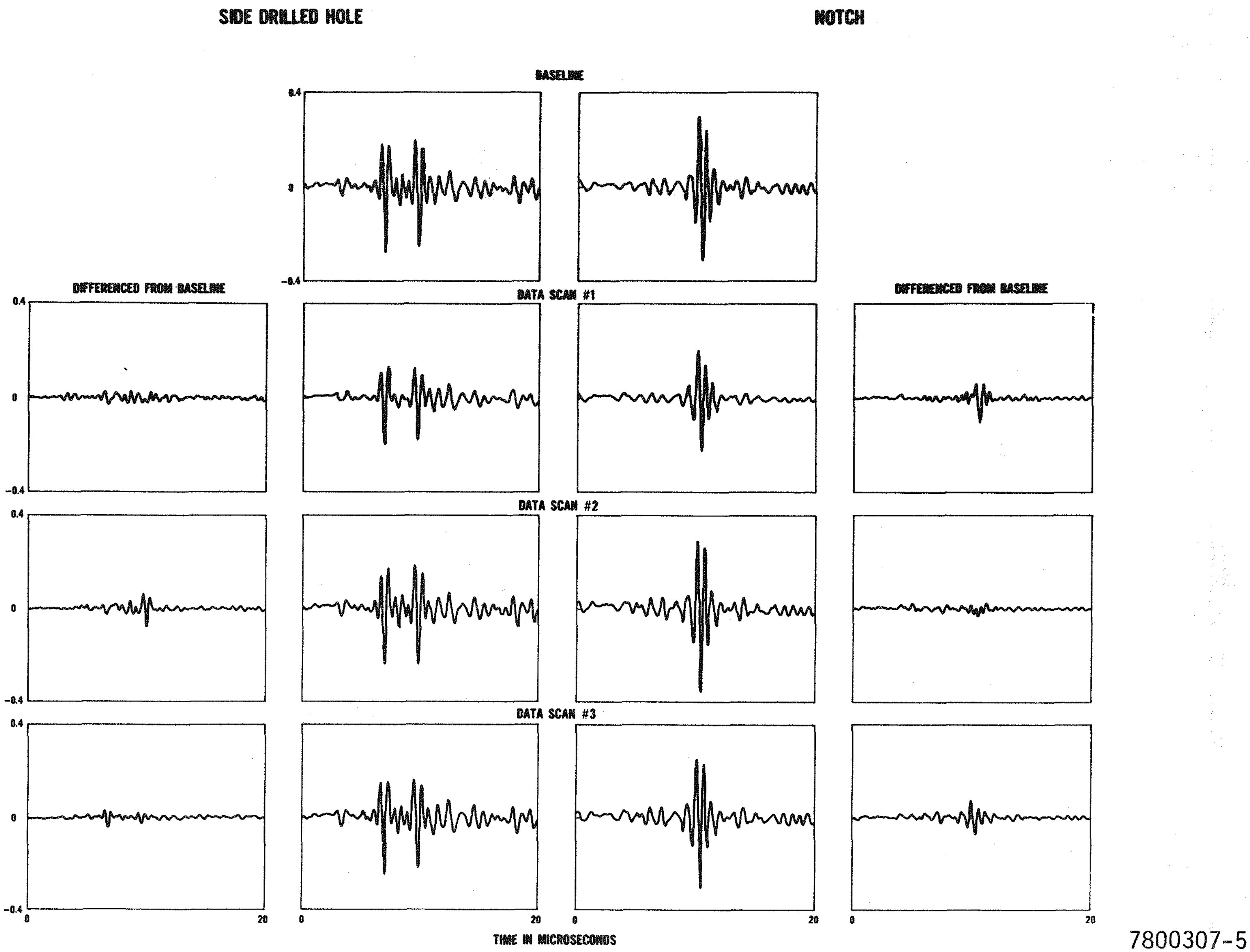

FIGURE 9. Scan Waveforms and Differences from Baseline for Side-Drilled Hole and Notch Signals.