Ultrasonic Pattern Recognition Study of IGSCC in SS Piping

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Prepared by
Ultrasonics International
Churchville, Pennsylvania

ELECTRIC POWER RESEARCH INSTITUTE

Ultrasonic Pattern Recognition Study of Intergranular Stress Corrosion Cracks vs Weld Crown Reflectors in SS Piping

NP-891
Research Project 892-1

Ultrasonic System Optimization Study

Interim Report, September 1978

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EPRI PERSPECTIVE

PROJECT DESCRIPTION

The activity covered in this report is part of a continuing effort to improve the capability of inservice ultrasonic inspection to detect cracks in the vicinity of welds in nuclear reactor piping. A means of identifying the signal from a tight crack close to a weld crown is demonstrated. The method uses computerized processing of Fourier transforms of the acquired signals. The procedure is applicable to the analysis of existing test data, or it may be used to tailor improved inspection systems. Either result would be useful since correct crack identification is very difficult using present conventional testing methods.

PROJECT OBJECTIVES

This short-term project had the objective of demonstrating that computer data processing methods can be used to simplify and improve ultrasonic inspection reliability. The processing performed eliminates many of the uncertainties introduced by fabrication artificats (e.g., weld crowns).

CONCLUSIONS AND RECOMMENDATIONS

The results of this study, as well as those of parallel project RP770 (reported in NP-688, Development of Adaptive Learning Networks for Pipe Inspection by Adaptronics, Inc., McLean, Virginia) firmly indicate the value of frequency-domain signal processing to improve UT inspection capability. These results are being incorporated in RP892, which has the broad goal of improving the equipment and procedures of inservice inspection.

Another project, RP1125, Application of Nonlinear Processing to Pipe Inspection, is also under way to extend and further exploit this data processing methodology.

M.E. Lapides
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ABSTRACT

Pattern recognition techniques for discriminating between geometrical and crack reflector signals obtained during ultrasonic inspection of the weld zone in type 304 austenitic stainless steel piping have been applied to one set of data. Seven welds from four different 4-in diameter pipe specimens containing intergranular stress corrosion cracking (supplied by the GE pipe laboratory through SwRI) were examined ultrasonically. The geometrical reflectors considered in this feasibility study were crown type reflectors only, since they were readily available in the pipe specimens. The ultrasonic inspection was conducted in a pulse-echo mode using a 1.5 MHz nominal center frequency, 3/8-in diameter transducer mounted on a plexiglass shoe with a 45° refracted transverse wave. A version of the Southwest Research Institute pipe weld examination code was used for recording the data. The ultrasonic signals were digitized and stored for further analysis. One hundred fifty-five indications were recorded from seven different welds, four of which were examined from both sides, and three from only one side. The ultrasonic data were correlated with dye penetration tests and ultrasonic examination conducted by SwRI in order to obtain correct training information. The data naturally fell into two categroies, cracks and crowns (geometric reflectors). A total of 107 crown indications and 40 intergranular stress corrosion cracking (IGSCC) indications were further analyzed.* The pattern recognition analysis indicated that an IGSCC indication was discriminated from a crown indication in about 98% of the cases.

The overwhelming success of the pattern recognition algorithm employed in this study demonstrates the applicability of this technique for solving such important problems as discrimination between IGSCC and geometric reflectors in 304 stainless steel pipe welds. Additional work on other kinds of geometric reflectors is required to establish an overall confidence level in reflector classification analysis.

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*The analysis did not consider any arrival time, amplitude information, or any other time-domain feature, but was based on various Fourier transform features.

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FIGURES

TABLES

Section 1

INTRODUCTION

Background

Inspection of austenitic stainless steel piping at welded joints poses a special challenge to NDE engineers due to the complex metallurgy and structural geometry. The ultrasonic inspection problems for pipe welds are further enhanced by the presence of a rather hostile radioactive environment and limited access to the piping itself. The three basic problems that complicate ultrasonic inspection and evaluation of pipe welds are:

- Piping and weld metallurgy
- Weld configuration
- Piping counterbore adjacent to the welds

Piping and Weld Metallurgy

Various investigators mention the difficulties of inspecting austenitic stainless steel, some even label it "impossible" to inspect. The ultrasonic waves undergo tremendous attenuation during propagation through austenitic stainless steel. The following metallurgical conditions have been identified as contributing factors to such a phenomenal attenuation:

- Grain size
- Grain orientation
- Ferrite content
- Microfissure content
- Precipitates content and
- Heat treatment

Variations in any or all of the above cause variations in the attenuation and scattering characteristics of the metal. The large absorption and scattering, both of the outgoing signal and the returning echo, is responsible for the very low signal-to-noise ratio (SNR).

Weld Configuration and Piping Counterbore Adjacent to the Weld

One of the major problems in inspecting stainless steel welds is that irregularities in the root and/or crown may reflect the interrogating ultrasonic beam. It is rather difficult to pinpoint the location and nature of the ultrasonic indication. This is particularly true if the indication happens to be on the root side of the pipe, since reflection from the crown can be damped. The goal of the study is to come up with a pattern recognition algorithm which will recognize the nature of the indication; i.e., will distinguish whether a particular ultrasonic signal response is from a geometric reflector or a crack (defect) in the pipe specimen.

Section 2

DATA ACQUISITION

Four pipe specimens, four inches in diameter, namely, M7616, NDTE-5, NDTE-11, and GE#1, were acquired from the General Electric pipe laboratory at San Jose through Southwest Research Institute and are shown in Fig.-1. Seven weld zones were ultrasonically inspected; four of the welds in the M7616 pipe specimen were inspected from both sides, whereas the remaining three were examined from one side only. The data were acquired using the SwRI code for the ultrasonic examination of pipe welds. A hand-held 3/8" diameter transducer, 1.50 MHz center frequency mounted on a plexiglass shoe rated at 45° in steel was used. Fig. 2 shows the block diagram of the ultrasonic test system employed for this study. The major instrumentation components were:

- UTA-2 Pulser-Receiver
- HP 1200A Scope
- Textronix 7A12, 7704 Amplifier, Scope
- Biomation 8100 Analog to Digital Converter
- PDP 11/05 Minicomputer with Disk Drive and Floppy Unit
- Tektronix 180D Scope
- Tektronix Graphics Terminal and Hardcopy Unit

Preliminary studies determined the operating characteristics and best combinations of settings to be used in the data acquisition system. These characteristics and settings were:

1. The pulser damping control should be set to achieve maximum high-frequency signal content.
2. The gain trim control on the pulser should be set at the maximum level.
3. To achieve maximum sensitivity, voltage level range of the A/D converter should be $\pm$ .05V with no attenuation on the pulser amplifier. This would insure the maximum of quantum levels (+127 to -128) without overdriving the A/D converter.

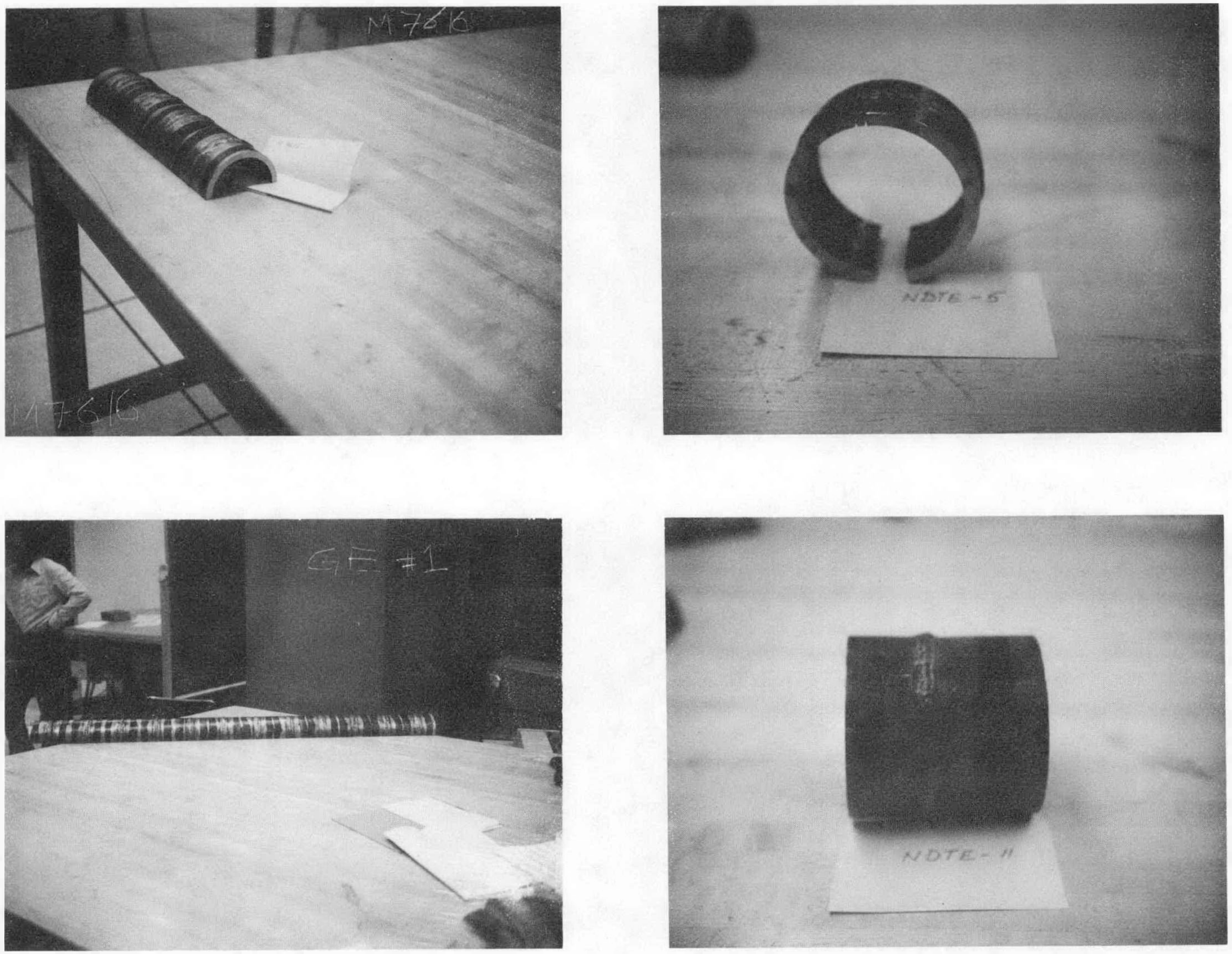


Figure 1. Pipe Specimens Used for Weld Inspection Study

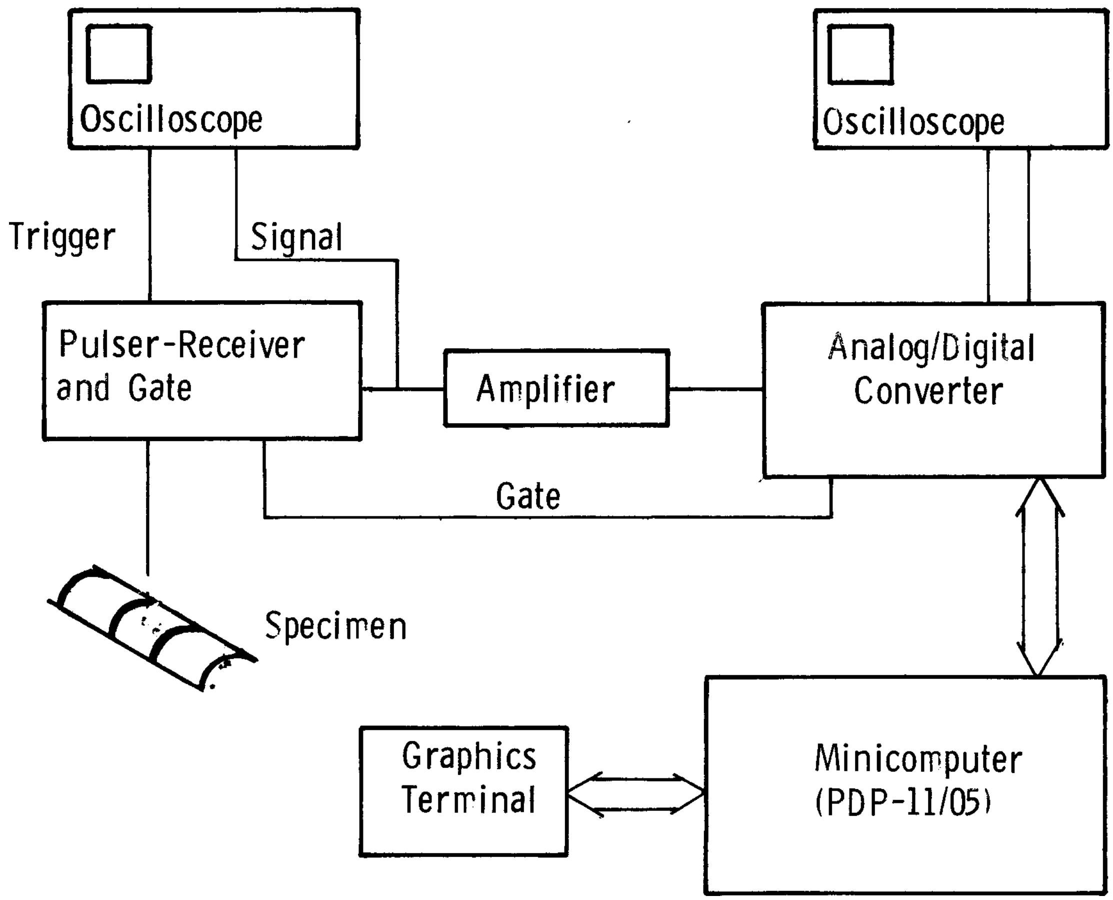


Figure 2. Block Diagram of Ultrasonic Test System

4. The ultrasonic pulse echoes received from crown indications were very low in amplitude. Therefore they were amplified using a Tektronix 7A12 amplifier before feeding the signal to the A/D converter. This step was necessary to achieve higher sensitivity in digitizing a signal. It is worthwhile mentioning that the amplifier has a 55 MHz specified bandwidth and its use resulted in a more optimum use of the A/D converter.

5. Signal averaging is necessary in order to increase the signal-to-noise ratio (SNR). A preliminary study on a typical crown signal indicated that the SNR increases as the number of times a signal is averaged. Further tests indicated that 32 times averaging is sufficient for our purposes.

6. It is a well-known fact that pattern recognition techniques are sensitive to the input signal which is further dependent on system characteristics and, in particular, on transducer characteristics. A transducer acceptance check was, therefore, made before acquiring test data on a particular day. The acceptance check involved acquiring a maximized echo from the edge of the 1" thick side of an IIW block, and comparing it with the reference echo in the time and frequency domain as shown in Fig. 3.

Typical Test Sequence

A typical test sequence consisted of a transducer and instrumentation check before acquiring data from pipe specimens. The top portion of the data sheet shown in Appendix I was filled out. The pipe and weld identification code were noted. Approximately 3/4 inch away from the centerline of the weld, the pipe specimen was scrubbed to obtain the preliminary topography of the weld. During the subsequent data recording, all indications above 20 mv level and 1/4 inch apart were recorded after obtaining the highest peak-to-peak echo. The transducer was kept as nearly parallel to the centerline of the weld as possible. It is worthwhile to note that the 20 mv amplitude level was established by converting the SwRI DAC curve to our system. A rubber band was used to hold the transducer in the approximate vicinity. Then using a metal hose clamp, the transducer was held more firmly. The transducer was repositioned to achieve the same voltage level as obtained during the hand scrubbing operation. The bolts on the metal band were then tightened with care so as not to tilt the wedge sideways. The signal of interest was then checked for the quantum levels using a computer program. If the quantum levels were small, the signal was amplified further and a check made again. The signal was then averaged 32 times using a computer program and stored on the disk or floppy for further analysis. A Polaroid picture of the signal was also obtained. All the pertinent data were

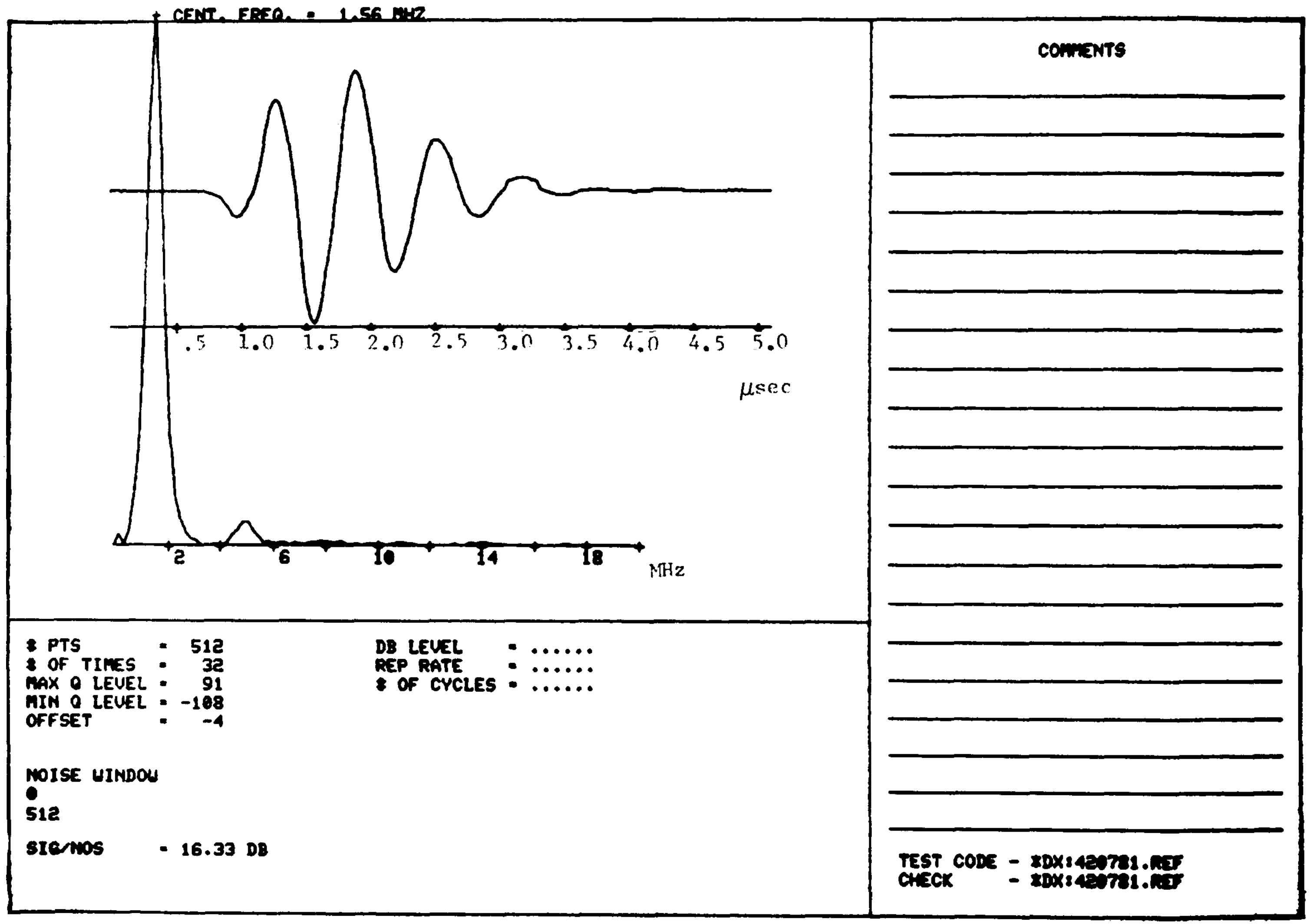


Figure 3. Typical Reference Echo Data Acquired from an IIW Block (Showing Both Amplitude vs Time and Amplitude vs Frequency Profiles)

recorded as shown in Appendix I. The sequence of the manual operation took about 30 minutes to acquire data from one location of the pipe.

A brief clarification of Appendix I data sheets is in order. Extensive data were recorded in order to evaluate the effect of various variables that may affect the classification. Search unit location coordinates are taken according to the SwRI code. These measurements are rather approximate because of unevenness of the weld and curvature of the pipe. More accurate distance measurements were made from reference lines that were marked on pipes in axial as well as radial directions. The reference lines in axial directions were marked every 1/2 inch. L dimensions would locate the beginning of the quadrant and then L'_{ref} gives exact distance. d'_{ref} is the reference distance from the beam exit point to the reference line in the radial direction. Fig 4 shows the angle beam transducer and plexiglass wedge assembly held by a metal band on the pipe specimen.

The time of arrival of the peak interface echo (plexiglass and steel) and the flaw echo (crack or crown) were recorded. Amplitude levels of peak-to-peak interface echo and amplified defect were also noted. The defect types were classified based on the ultrasonic examination data and dye penetrant data provided by SwRI. Before going into further analysis, it is deemed necessary to clarify the duration of the signal and position of the start of gate (controlled by delay) that was recorded. Both these factors were based on the physics and mechanics of the problem and practical experience gathered after considerable experimentation.

Crack indications did not pose much problem in deciding the start of the data collection point and its duration. It was, however, a totally different story for signals obtained from the crown indications. The duration of the echo and its position varied from location-to-location and pipe-specimen-to-pipe-specimen. After a careful study of the physics and mechanics of the problem, it was found that there were many variables that could affect the duration of the ultrasonic signal and its position on the time scale (for crown indications). Some of the most important variables are:

a. thickness of pipe on both sides of the counterbore

b. crown height, width and general geometry

c. crown roughness

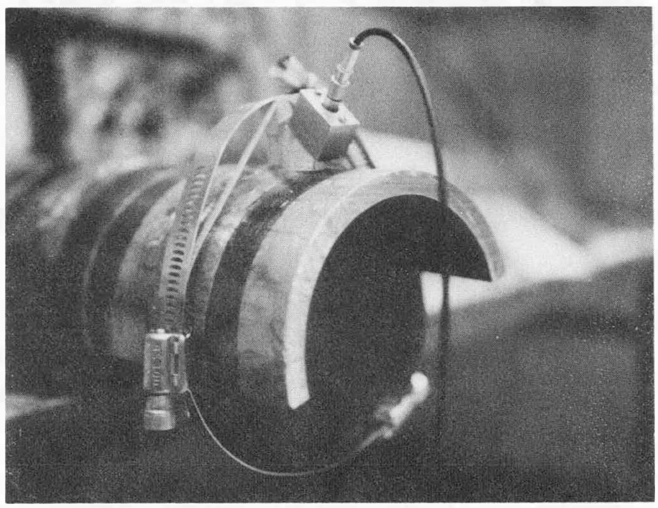


Figure 4. Data Acquisition Technique

d. sharpness of crown at leading and trailing edge

e. counterbore taper

f. wave speed in the material and material anisotropy

A preliminary analysis assuming counterbore taper angles of 14° and 45° showed that the pulse duration of the signal may change as much as 5-7 microseconds for a 3/8-inch diameter transducer, assuming that only shear waves exist in the pipe having a 0.338 in. wall thickness.

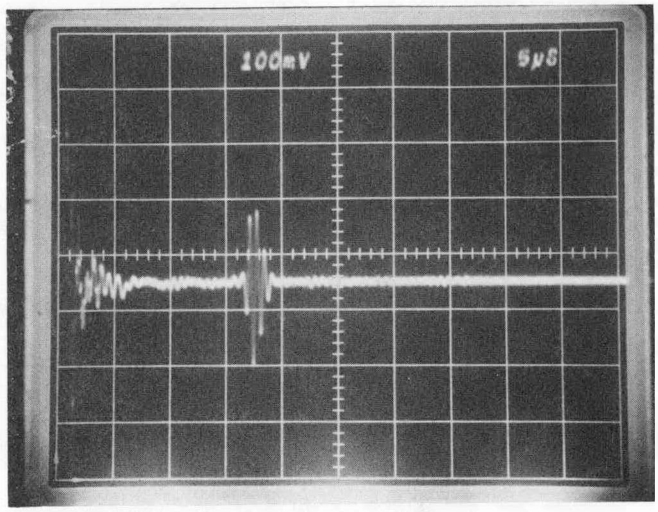
Table 1 shows the breakdown of the data after correlating with the SwRI data. The data were divided into two classes, indications from crowns (geometric reflectors) and cracks (IGSCC). A total of 155 indications were recorded. Only 147 indications were analyzed because of data transfer problems in the computer system. One hundred seven out of one hundred forty-seven indications were from geometric reflectors and forty from cracks. This classification is based on a very high degree of reliability due to various precautions taken during the course of this project. Figs. 5 and 6 show typical Polaroid pictures and the computer printout of the crack and crown indications, respectively.

Table 1

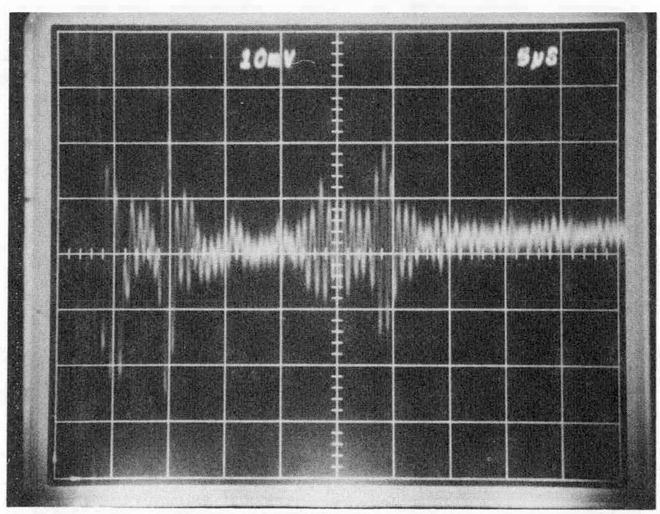
BREAKDOWN OF THE DATA ACQUIRED

Pipe Identification Code	No. of Welds/ Sides Inspected	Total No. of Indications Recorded	Crown	Crack
M7616	4 welds/2 sides	19	57	22
GE#1	1 weld/1 side	22	6	16
NDTE-5	1 weld/1 side	29	24	5
NDTE-11	1 weld/1 side	25	25	0
		155	112	45

Due to data transfer problems in the computer, only 107 crown indications and 40 crack indications were further analyzed in this study.



a) Crack - M7616, Weld D1



b) A Crown Geometric Reflector - M7616, Weld C2

Figure 5. Typical Polaroid Photographs of Ultrasonic Pulse-Echoes from 2 Reflectors

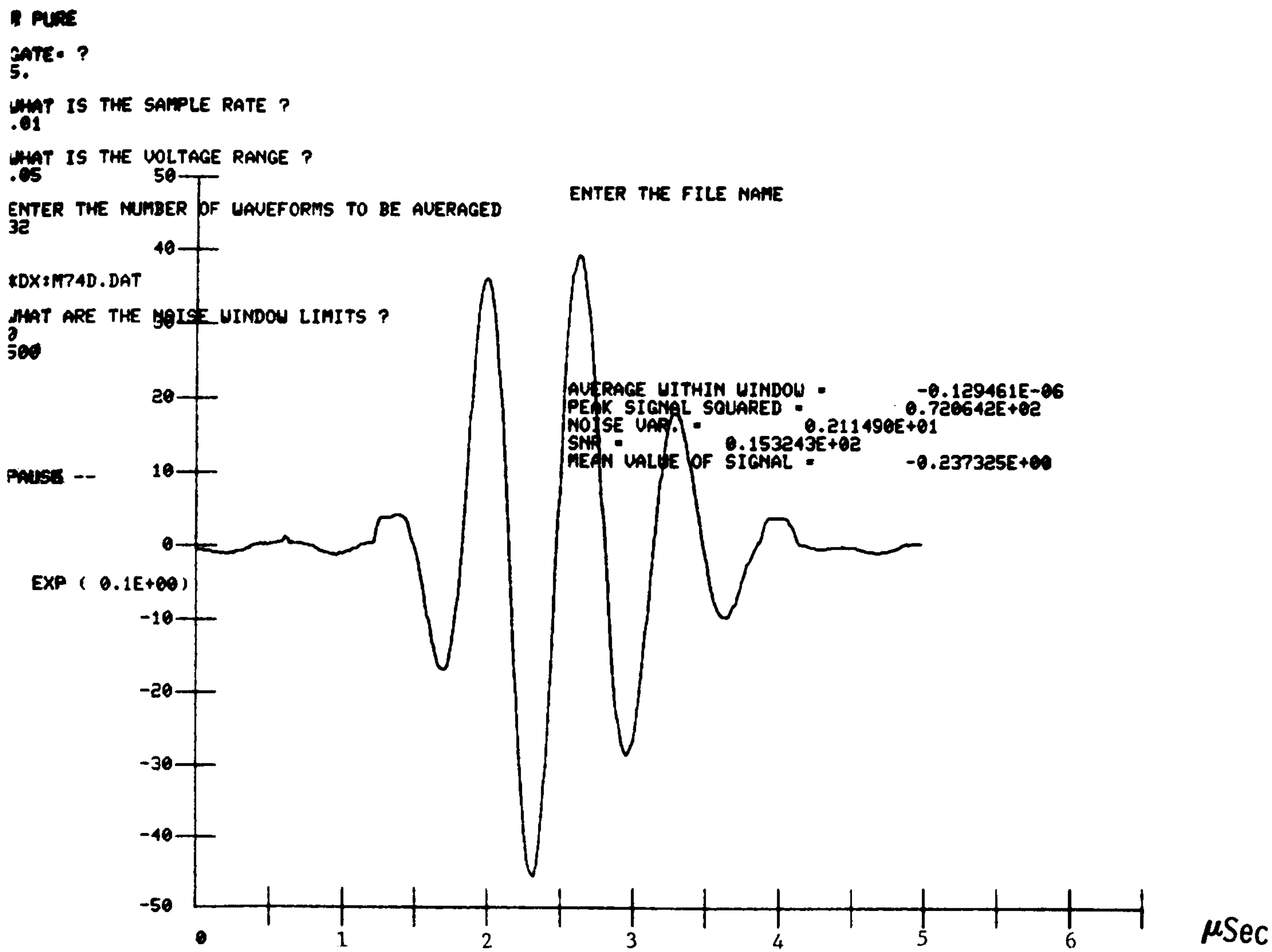


Figure 6a. Typical Ultrasonic Pulse-Echo Signal Portion for a Crack Reflector (Stored for Pattern Recognition Analysis from 5a)

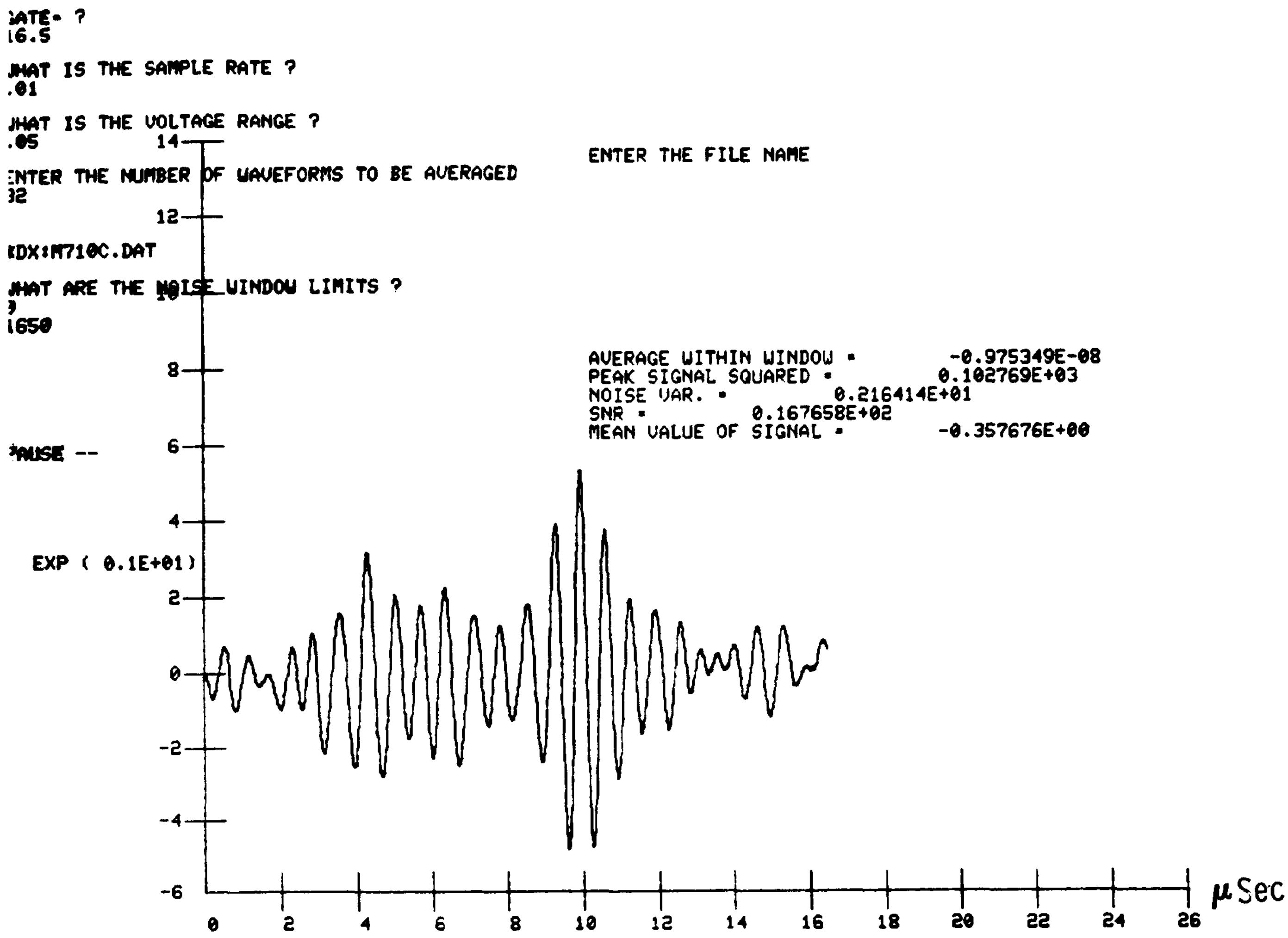


Figure 6b. Typical Ultrasonic Pulse-Echo Signal Portion for a Geometric Reflector (Stored for Pattern Recognition Analysis from 5b)

Section 3

DATA ANALYSIS

Quite often, classification of the RF signals displayed on an oscilloscope (while acquiring the data) was immediately possible by visually noting the feature of echo arrival time. Certain pulse shape characteristics also proved useful in establishing an immediate evaluation of either crack or geometry classification. In order to improve the classification reliability, however, it was decided to incorporate a computer-controlled data acquisition and decision routine. It was also decided at this time to concentrate on ultrasonic waveform characteristics specifically and to neglect the feature of arrival time and waveform amplitude. This was also due to the fact that low SNR results in the threshold selection and computer feature evaluation being quite difficult and time-consuming. Power spectrum analysis of all the 147 echoes was performed, and five features were chosen based on the physics and mechanics of the problem. Figs. 7a and 7b show typical spectrums from crack and crown. The features chosen for this analysis are explained below. Additional features were not required in this analysis because of the success level in using these features.

Feature #1 - Number of Spectral Peaks Above 20 dB. This feature was selected since the signals obtained from geometric reflectors, as well as cracks, were in many cases superpositions of several ultrasonic signals. This was especially true for the crown indications due to superposition of signals reflected from the leading edge, various discontinuities in the crown and the trailing edge of the crown. More than one peak in the spectrum was also evident for multiple crack situations. This feature by itself turned out to be an extremely useful feature. If the threshold is set at 4, all the cracks can be detected with 100% reliability, whereas one crown indication out of 107 was misclassified as a crack, giving 99.06% correct classification.

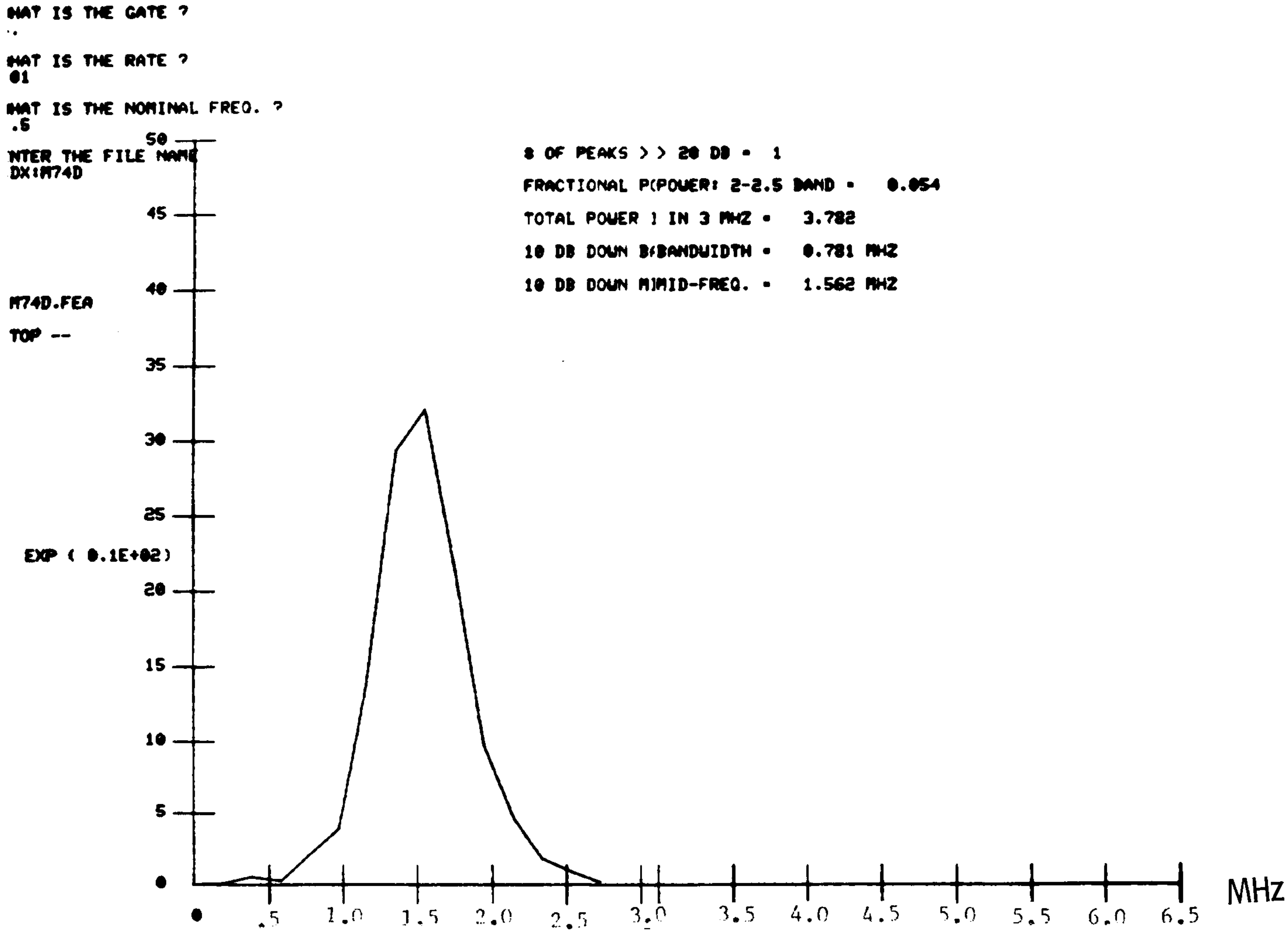


Figure 7a. Fourier Spectrum of the Signal Shown in Figure 6a (Crack)

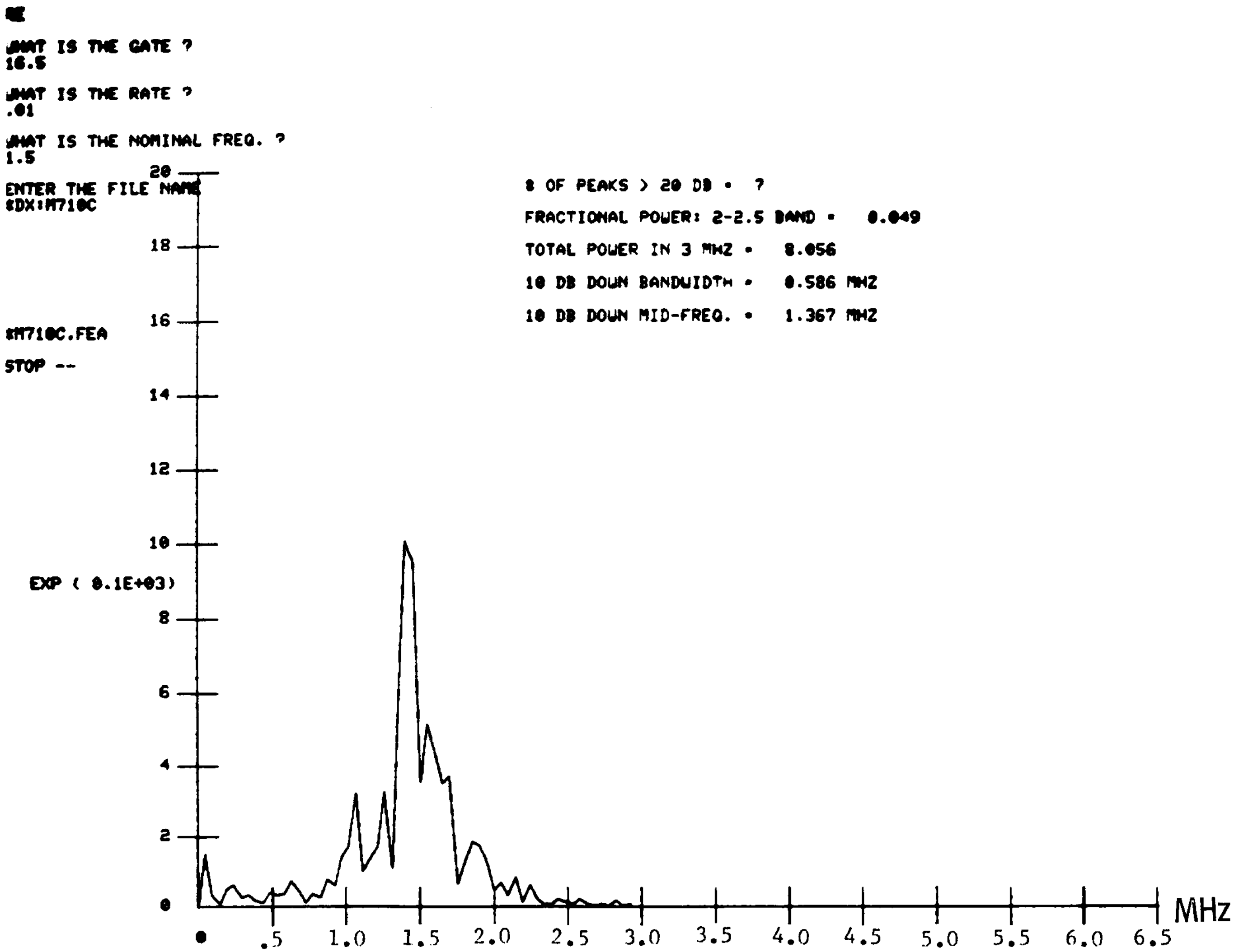


Figure 7b. Fourier Spectrum of the Signal Shown in Figure 6b (Geometry)

Feature #2 - Fractional Power Ratio 2-2.5 MHz. This feature is obtained by dividing the power in the 2-2.5 MHz region by the total power in the 0-3 MHz region. This feature was chosen since crack reflectors act as high-pass reflectors, whereas crown indications do not generally contain high-frequency content. The high-frequency content in the case of pulse ehoes is probably lost due to the longer metal path. This feature by itself did not turn out to be a very useful discriminator.

Feature #3 - Total Power in 0-3 MHz Range. This feature is another measure of spectral peaks in a frequency profile. Setting a threshold level at 8.75, all the cracks are correctly classified, whereas 10/107 crown indications are classified as cracks; i.e., cracks are classified 100% correct, whereas crowns are classified 90.65% correct. Overall index of performance is 91.8%.

Feature #4 - 10 dB down Bandwidth. This feature was selected bearing in mind the characteristic attenuation response of cracks and crowns. Setting the threshold level at .75 MHz, 2/40 cracks are misclassified, whereas 34/107 crown indications are incorrectly identified. A performance level of 95% for cracks and 68.3% for crowns is obtained. Overall index of performance is 74.1%. The reason for poor performance of this feature was determined to be the manner by which this feature was computed. The performance level can definitely be improved by changing the computation procedure.

Feature #5 - 10 dB down Mid-Frequency. This feature did not look promising to begin with, but was included in the study to see how it interacts with the further analysis. By itself, this feature did not provide any useful discrimination.

After feature selection and preliminary analysis, the goal was to partition the feature-space into two separate regions, where all the points in one region correspond to crack (0) indications, and all points in the other, correspond to geometric indications (+).

To achieve this end, a simple two-space plot between various features are shown in Figs. 8 to 17. Decision surfaces are drawn on graphs which hold some promise of classification. Fig. 8 shows 98.5% correct classification for cracks as well as crown indications. It must be pointed out that even though only relatively few indications on any curve may be visible, there are 40 crack indications and 107 crown indications plotted. Some of these indications are obviously superimposed. The results of Fig. 11 indicates that two features, namely, number of spectral peaks above 20 dB and 10 dB down mid-frequency, are sufficient to classify cracks and crowns with 100% confidence from crack recorded and analyzed. It should also be noted that other features, when combined with Feature #1, i.e., number of spectral peaks, result in very high index of performance. Figs. 12, 15, and 16 show combination of other features which are quite good discriminators.

The decision surfaces shown in some of the figures are drawn based on the conservative approach, i.e., all cracks are classified correctly, whereas a minimal degree of misclassification can be tolerated for geometry type reflectors. The decision surfaces shown can quite easily be used to program an automated decision algorithm for classification purposes.

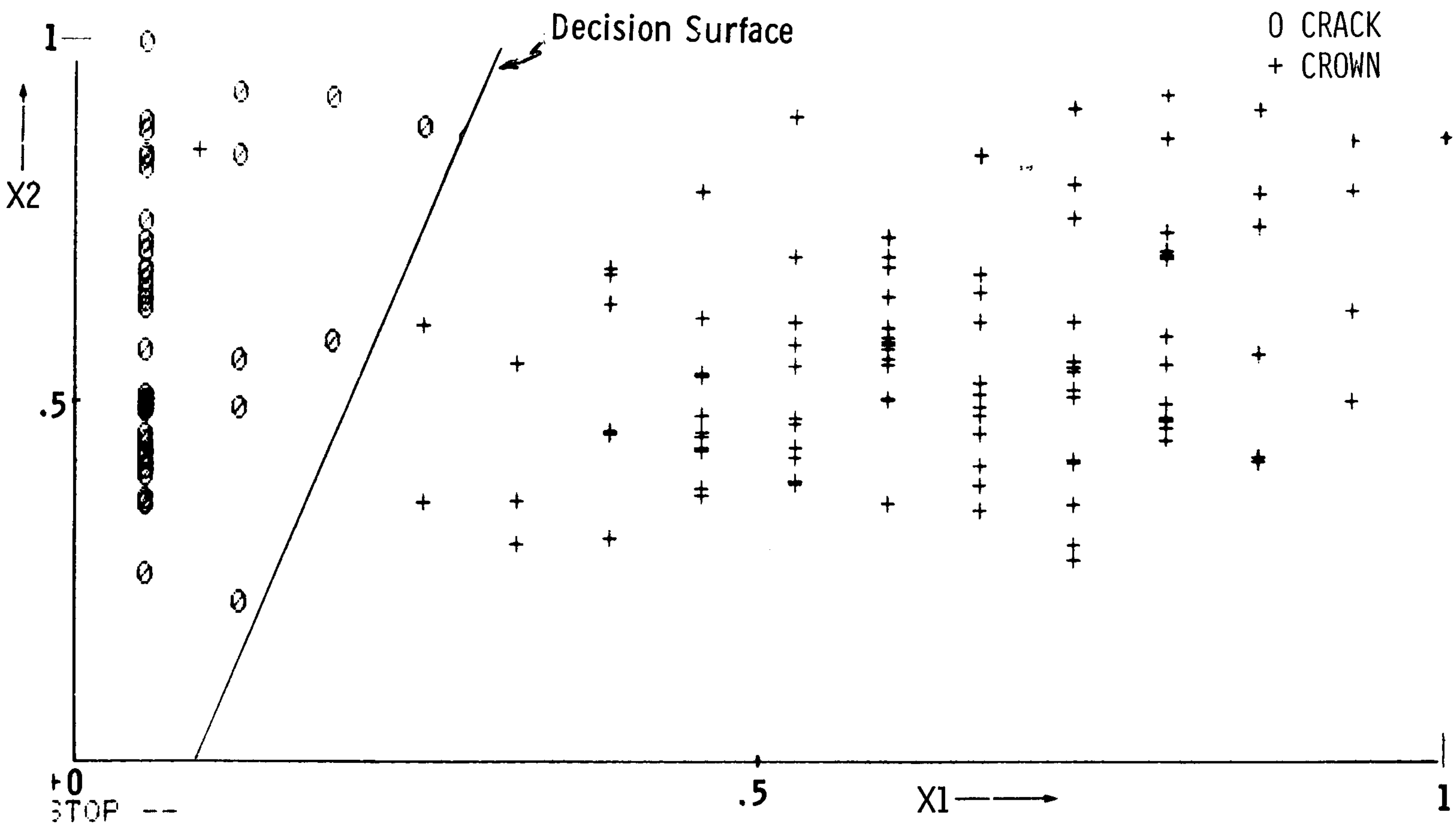


Figure 8. Two-Space Plot Between Number of Spectral Depressions Above 20 dB (X1) and Fractional Power Ratio (X2)

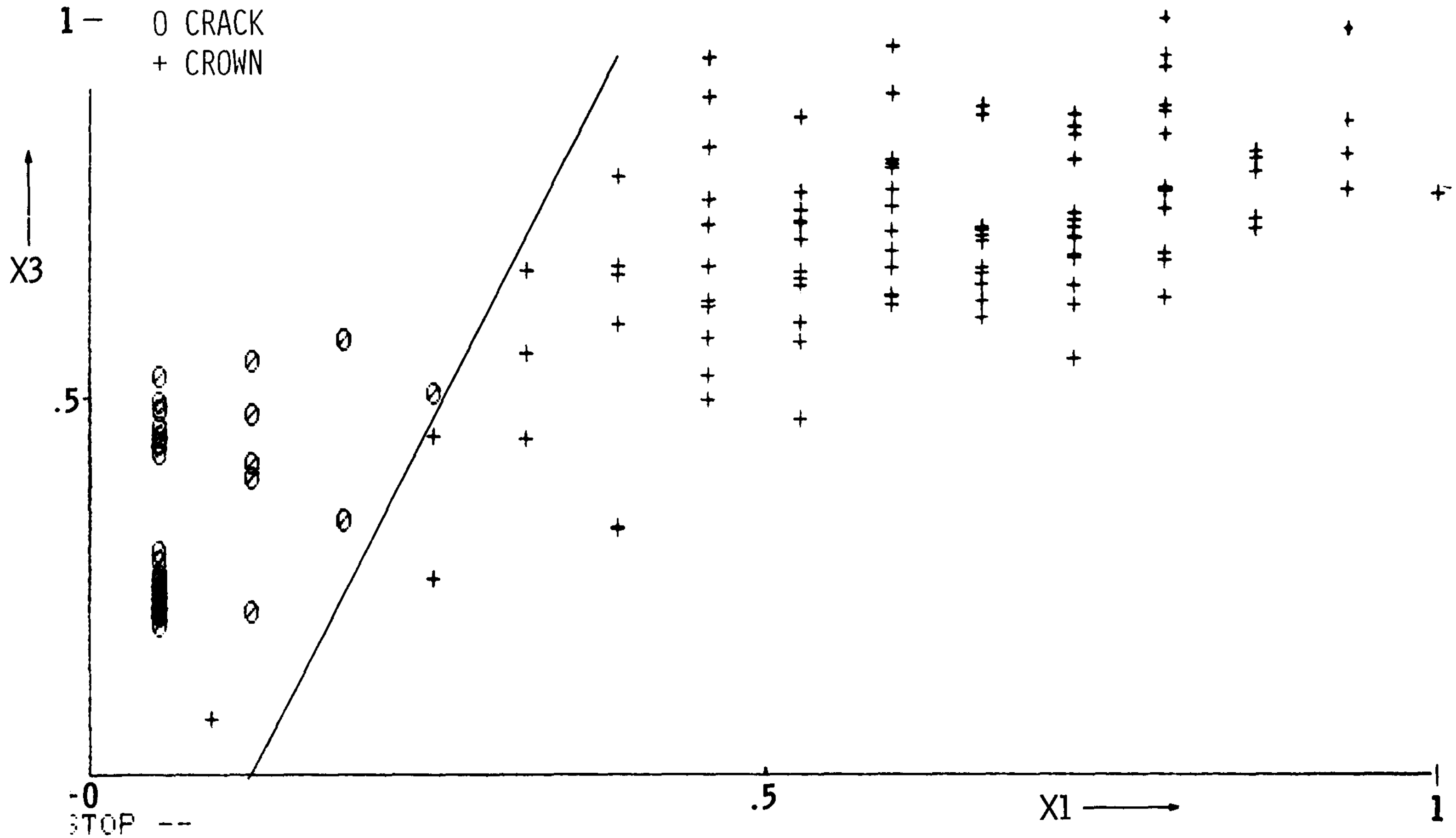


Figure 9. Two-Space Plot Between Number of Spectral Depressions Above 20 dB (X1) and Total Power in 0-3 MHz Range (X3)

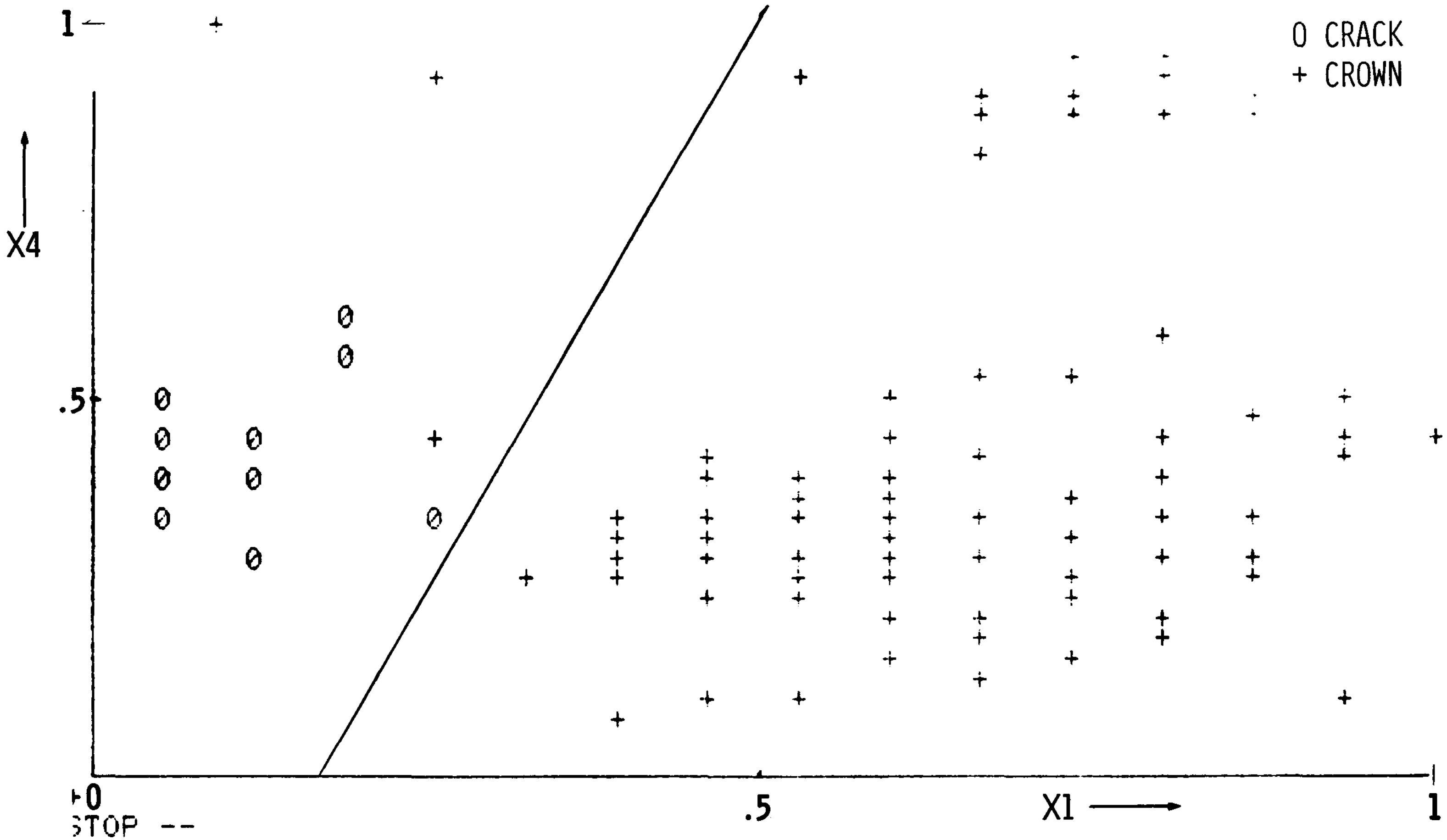


Figure 10. Two-Space Plot Between Number of Spectral Depressions Above 20 dB (X1) and 10 dB Down Bandwidth (X4)

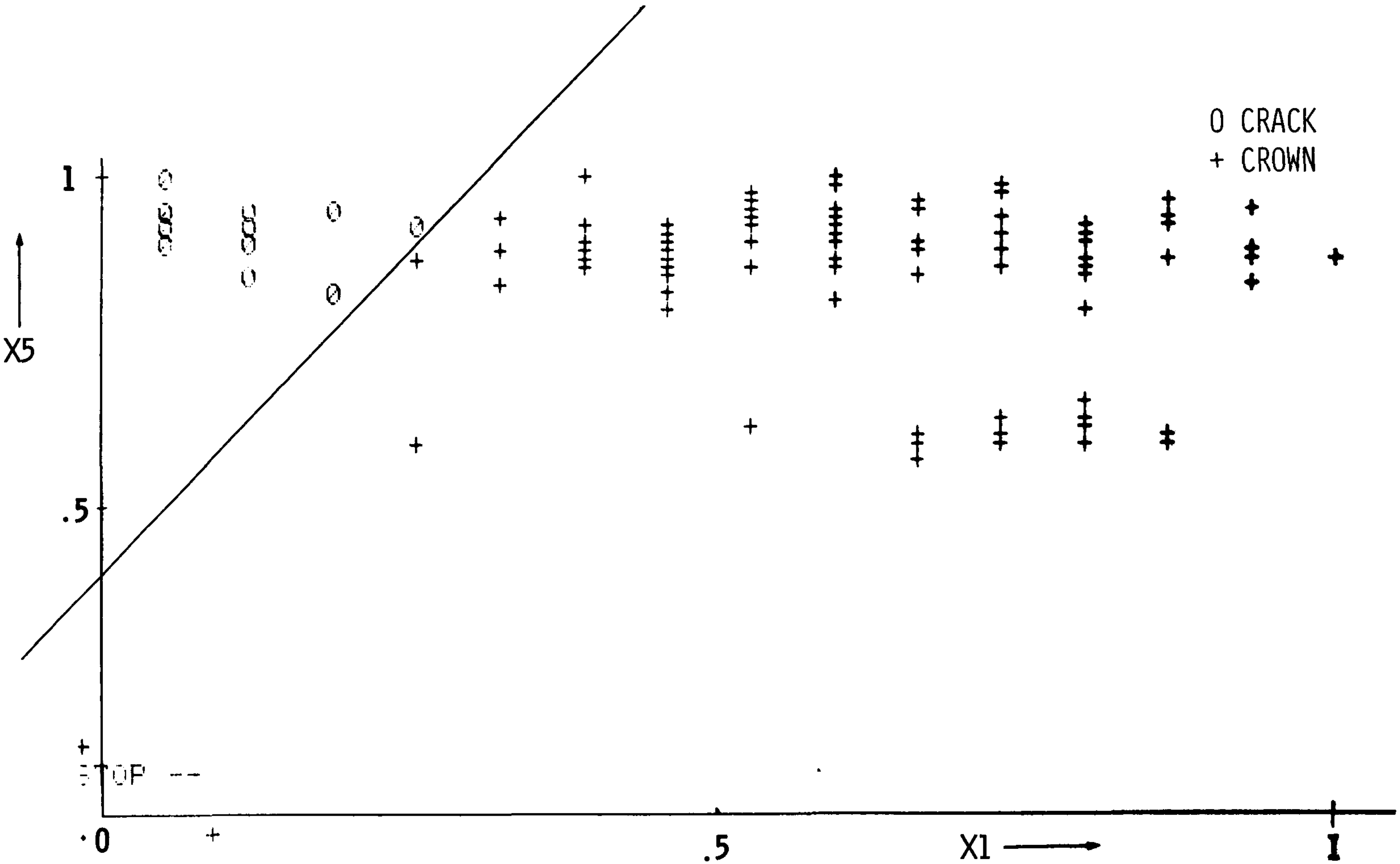


Figure 11. Two-Space Plot Between Number of Spectral Depressions Above 20 dB (X1) and 10 dB Down Mid-Frequency (X5)

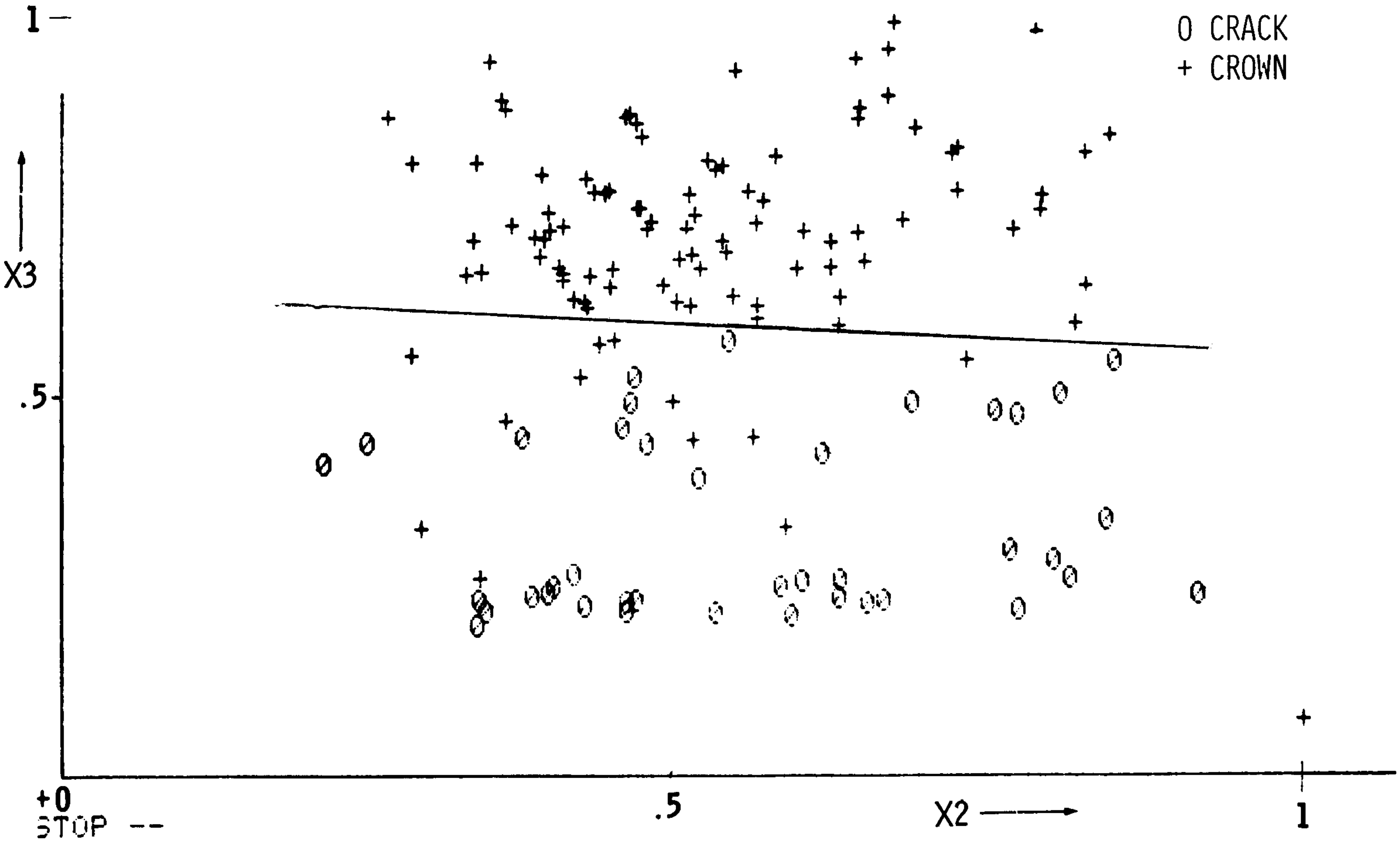


Figure 12. Two-Space Plot Between Fractional Power Ratio (X2) and Total Power in 0-3 MHz Range (X3)

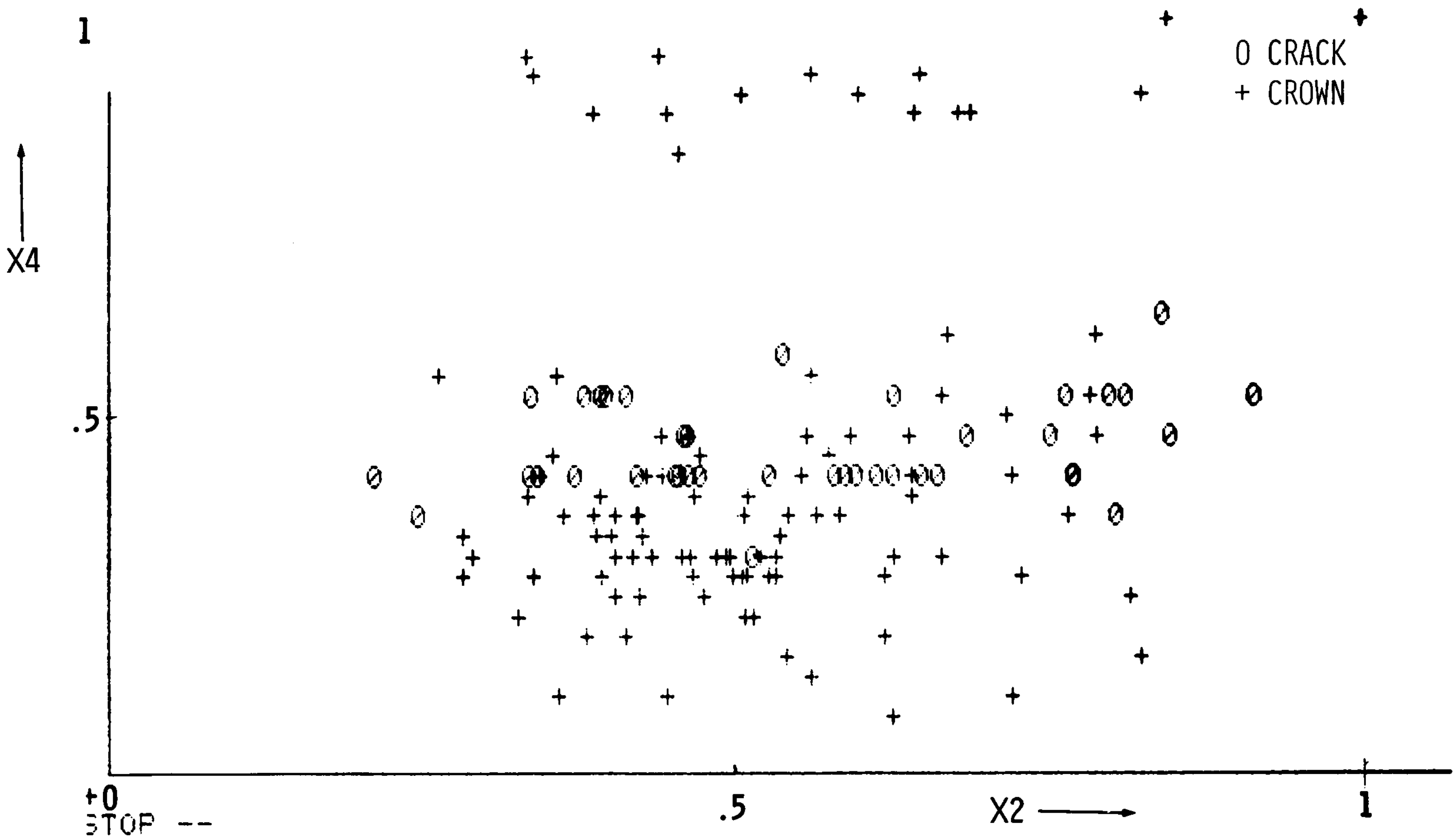


Figure 13. Two-Space Plot Between Fractional Power Ratio (X2) Between 2-2.5 MHz and 10 dB Down Bandwidth (X4)

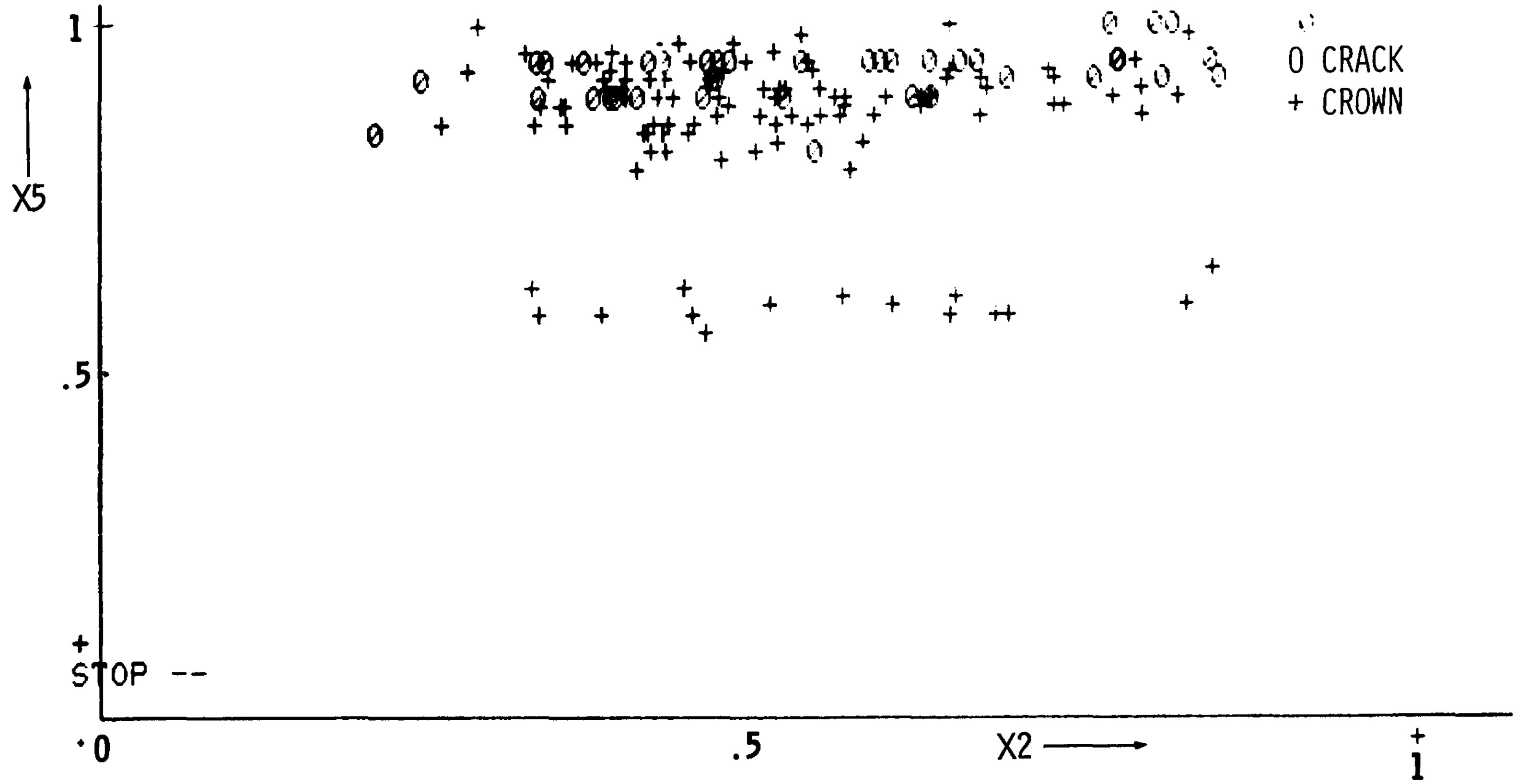


Figure 14. Two-Space Plot Between Fractional Power Ratio (X2) and 10 dB Down Mid-Frequency (X5)

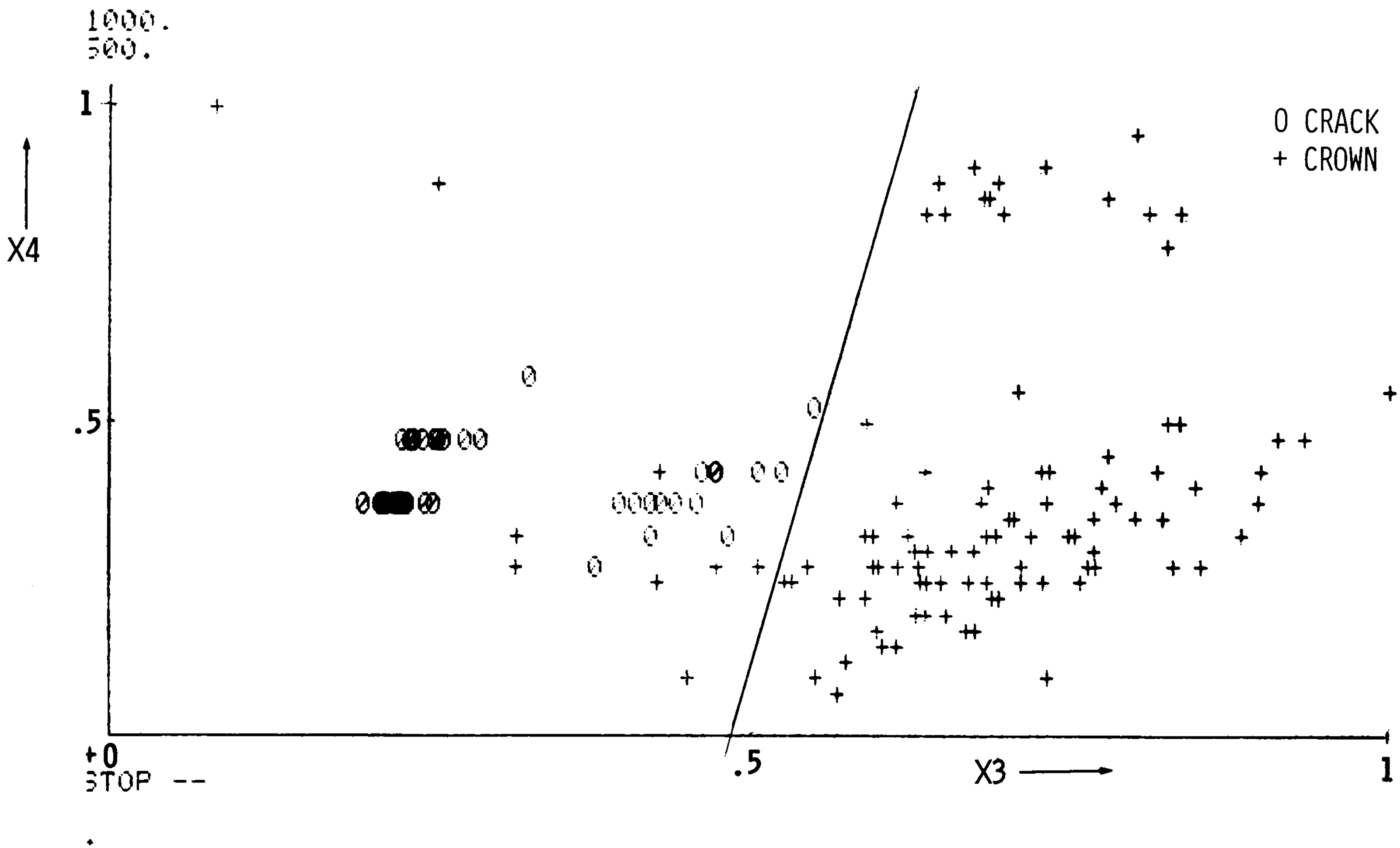


Figure 15. Two-Space Plot Between Total Power in 0-3 MHz Range (X3) and 10 dB Down Bandwidth (X1)

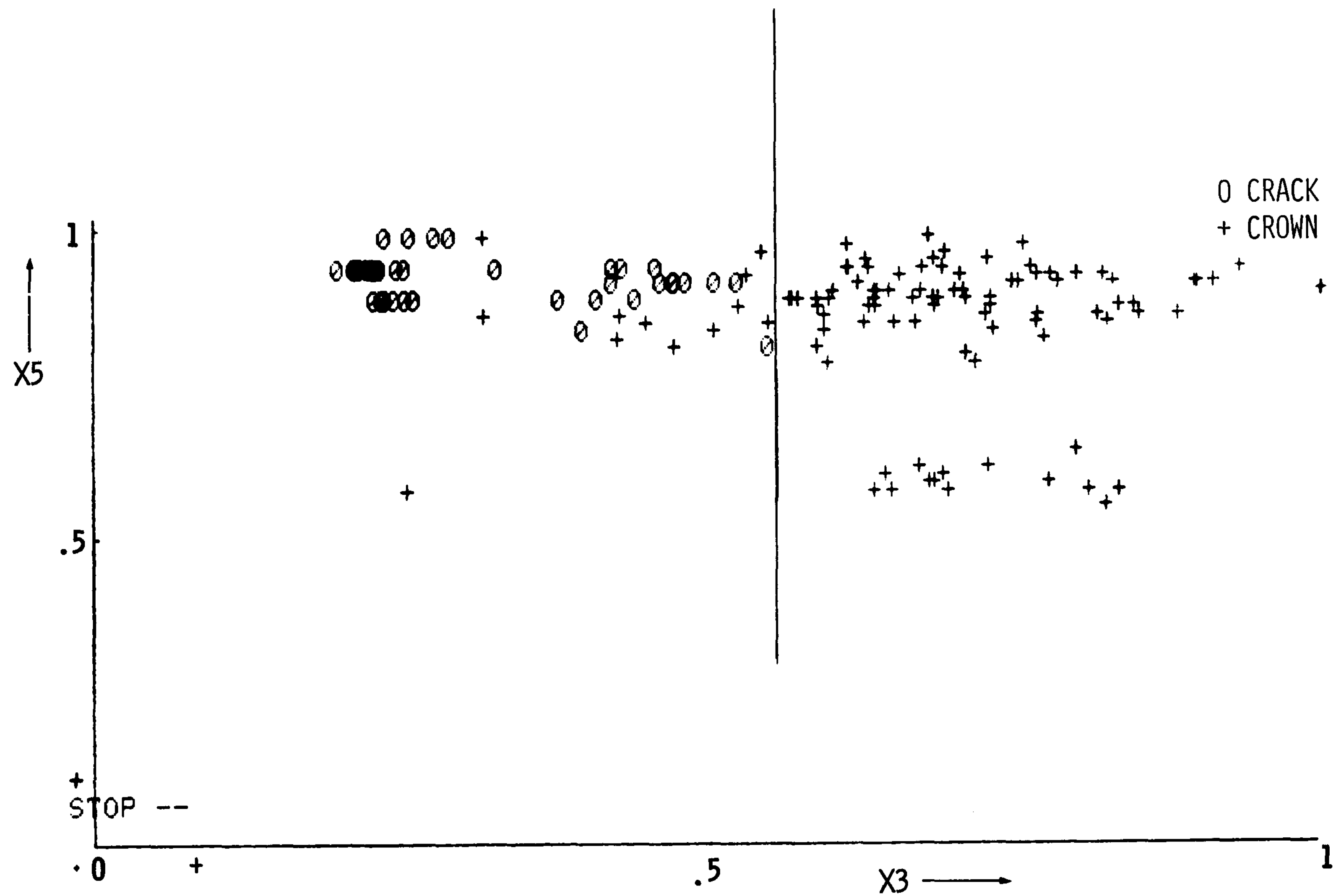


Figure 16. Two-Space Plot Between Total Power in 0-3 MHz Range (X3) and 10 dB Down Mid-Frequency (X5)

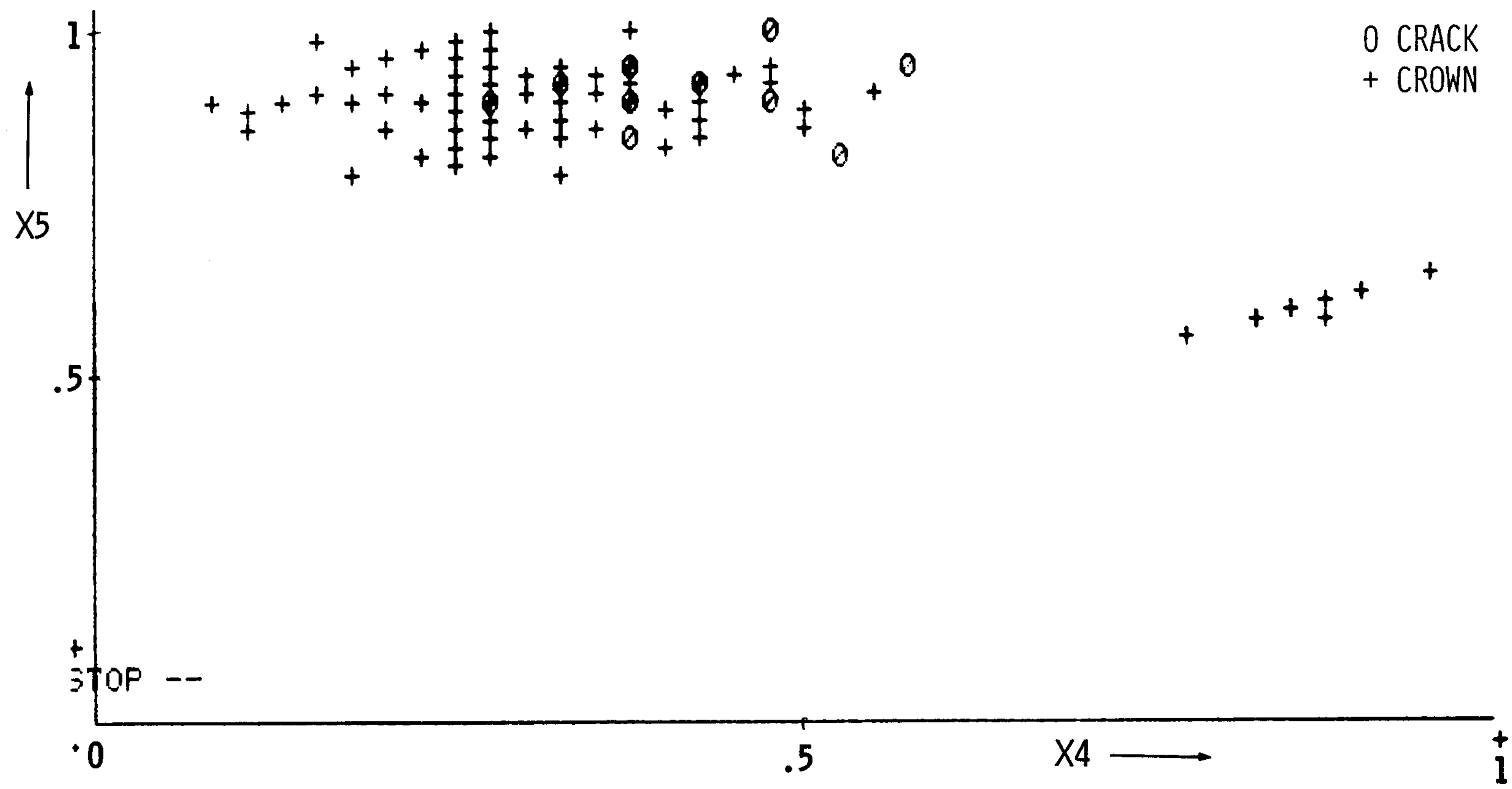


Figure 17. Two-Space Plot Between 10 dB Down Bandwidth (X4) and 10 dB Down Mid-Frequency (X5)

Section 4

CONCLUSIONS

This feasibility study has demonstrated the highest degree of applicability of pattern recognition algorithms for solving IGSCC cracking versus geometric (crown) reflector discrimination in the vicinity of welds in type 304 stainless steel pipe. It must be recognized that a 100% index of performance was achieved in cracks versus these geometric reflectors without using arrival-time analysis or any other time-domain feature. The data were obtained using a conventional transducer (3/8 inch dia, 1.5 MHz frequency) and plexiglass shoe (45^0) combination and the SwRI pipe examination code. The data were acquired from seven different welds in four different 4-inch pipe specimens. A large data set was considered in this study, a fact that provides a very high level of confidence in the results.

In summary, the problem of discriminating IGSCC versus crown reflector indications can be solved quite easily by selecting suitable portions of the amplitude versus time waveform and then carrying out an appropriate Fourier transform and feature extraction. Two of the most useful features are (1) number of spectral peaks above 20 dB and (2) power ratio in 2-2.5 MHz range. These features can be used with the decision surface shown in Fig. 8, to obtain an overall index of performance in classification of 98.5%.

Further studies on additional geometric reflectors (other than crowns) will establish the usefulness of this technique for general field application. The analysis would probably call for the use of more advanced techniques in pattern recognition than those considered in this study because of the overall increase in problem difficulty and complexity. For example, utilization of pattern recognition concepts outlined in a paper by Rose* might prove beneficial.

*Rose, J. L., "A 23 Flaw Sorting Study in Ultrasonics and Pattern Recognition," Materials Evaluation, July 1977, pp. 87-92.

APPENDIX

DATA SHEET FOR ULTRASONIC EVALUATION OF AUSTENITIC STAINLESS STEEL PIPING

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from

Original Document

DATA SHEET FOR ULTRASONIC EVALUATION OF AUSTENITIC S.S. PIPES

DATE

SEARCH UNIT #	DIAMETER	NOMINAL CENTER FREQUENCY	MEASURED CENTER FREQUENCY	SHOE #	NOMINAL ANGLE	MEASURED ANGLE	DAMPING	GAIN TRIM	REP RATE	GATE DURATION
TIME-SCALE ON HP Scope	TIME SCALE ON TEK	SAMPLING INTERVAL	TIME SCALE ON MONITORING SCOPE	INPUT RANGE A/D	LEVEL	INPUT OFFSET	PIPE THICKNESS	LONGITUDINAL WAVE VELOCITY	SHEAR WAVE VELOCITY	

PIPE IDENTIFICATION NO. :-

WELD IDENTIFICATION LETTER:-

	inches →			SU Loc.	- inches -			echo Plexi-Steel μsec	defect echo μSec	stored Signal duration μSec	Gate Starts at	delay	RP Interface Plexi-Steel		RP defect echo		damping									
No.	W	MP	L		d_{ref}	L'_{ref}	Atten						Scope	Amp	Scope	Amp		Crack	Counterbore	Root	Crown	undecided	Located by SwRI	NOT LOCATED BY SWRI	REMARKS	FILE NO.