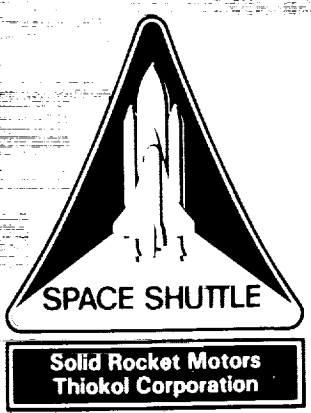


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Early Focus Development Effort, Ultrasonic Inspection of Fixed Housing Metal-to-Adhesive Bondline Final Report

March 1991

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**Early Focus Development Effort,
Ultrasonic Inspection of Fixed Housing
Metal-to-Adhesive Bondline
Final Report**

March 1991

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ABBREVIATIONS AND ACRONYMS

μ sec	microseconds
CL	confidence level
deg	degree
FSH	full-scale height
ft	foot
ID	inside diameter
in.	inch
in. ²	square inch
KSC	Kennedy Space Center
MDF	minimum detectable flaw
MHz	megahertz
mil	0.001 inch
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
POD	probability of detection
ppm	parts per million
RMS	root mean square
RSRM	redesigned solid rocket motor

INTRODUCTION

This report and the testing discussed herein were initiated as a direct result of the TEM-7 fixed housing bondline failure. Specifically, the metal housing-to-adhesive bondline. Questions about the integrity of other flight ready fixed housing bondlines began to arise as a result of the TEM-7 failure. A request was made by NASA/Marshall Space Flight Center (MSFC) to begin development of an ultrasonic inspection for this region. NASA/MSFC required that a short term development effort be tailored to support inspection of flight hardware stacked at Kennedy Space Center (KSC) (Flight 15 in particular).

The development effort, because it was set to an aggressive time line, focused only on the detection of metal-to-adhesive unbonds. The approach that was taken for development was heavily customized to the requirement that the inspection be capable of scanning a stacked configuration. If the ultrasonic inspection were to be used as an in-process examination (long term effort), several changes would be recommended to make the inspection more compatible with the manufacturing environment. These suggestions are discussed in Section 5.

OBJECTIVE

The goals of this effort, again with reference to a stacked configuration, were to:

- 1) identify a transducer couplant, 2) identify/develop a couplant application method,
- 3) identify/develop ultrasonic equipment, an automated ultrasonic scanner, and ultrasonic transducer, 4) identify, develop, and optimize data acquisition, signal processing techniques, and a scan protocol conducive to the fixed housing metal-to-adhesive bondline, and 5) perform a probability of detection (POD) study to determine the minimum detectable flaw (MDF) size at a 90 percent POD and 95 percent confidence level (CL).

SUMMARY

This section contains a summary of the key results from the testing. As stated in the introduction, this effort was developed upon the premise that this inspection would be performed on a stacked motor configuration at KSC. Additional information and details can be found in Section 6.

The couplant that best suited a vertical scan was the Echo Laboratories, GEL 3000. Its characteristics of good adherence to the part's surface, sound transmission qualities, and safety to operators and equipment made it the top selection.

A paint roller (medium nap) was developed as the primary means by which to apply couplant. It applied the couplant in a uniform manner as required, and also contained a low enough profile to maneuver in the stacked configuration working envelope.

An ABB Amdata 3010, Low Profile Ultrasonic scanner was selected as the means by which to perform the ultrasonic scan. It provided an automated scan of a defined region and was compatible with existing equipment at Thiokol (thus a large cost was avoided). Transducer selection was based on surface quality of the metal housing, coupling effects, and minimum detectable flaw size. With this taken into account, a 2.25 Mhz, 0.5 in. diameter transducer was selected.

Two basic forms of signal processing were used in the technique development. Peak detection of the highest rectified signal amplitude with in the electronic gate, and a summing technique by where the data points of the rectified signal with in the gate are summed. The peak detection C-scan was used as the primary display during data acquisition.

The scan protocol was developed to minimize the number of moves the scanner assembly (scanner, guide track, cabling, tether) needed to make while still providing maximum coverage of the bondline. Currently, three axial moves would be required

to scan one 3-ft circumferential region. With a modified guide track and scanner assembly, the only move required shall be in the circumferential direction.

In determining the MDF size, the requirement of a 90 percent POD at a 95 percent CL was applied. A 1.0 in. diameter unbond was the MDF size based on the POD requirement. In addition, various portions of several fixed housings were scanned to determine the signal variability from place to place, and also to compare the variability from fixed housing to fixed housing.

CONCLUSIONS

An ultrasonic technique has been developed for the fixed housing metal-to-adhesive bondline that will support the Flight 15 time frame and subsequent motors. The technique has the capability to detect a 1.0-in. diameter unbond with a 90 percent POD at a 95 percent confidence level. The technique and support equipment will perform within the working envelope dictated by a stacked motor configuration.

RECOMMENDATIONS

Due to the successful completion of the given task, the following recommendations are made:

- a. The inspection should not be applied to Flight 15 or any other hardware until critical flaw size criteria is produced by the Nozzle Design group. The ultrasonic inspection, sooner or later will detect an unbond, and with no criteria existing other than "none allowed", we (NASA/Thiokol) will be presented with questions that have no answers.
- b. Flaw size criteria, based on component performance, needs to be established by the Thiokol Nozzle Design group prior to qualification.
- c. An engineering change proposal should be submitted to NASA/MSFC recommending that a more detailed development effort be pursued, with the effort ultimately producing an inspection fully qualified for in-process examination. In general, the development effort would encompass further refinement of the inspection, incorporation of improved scanner tooling, water-based couplant, calibration standard fabrication, and specific technique development. This effort would be documented in a program plan.

DISCUSSION

6.1 OPTIMIZATION OF INSPECTION PARAMETERS

It was determined at the outset of this development effort that automated scanning of the metal housing should be pursued. This is an important factor in reducing signal amplitude variability on bonded regions as it removes the instability caused by the transducer operator, which can be very subjective in this type of an application. Bearing in mind the aggressive time line that was established for the development of this inspection, several decisions were made to expedite its progress. The most significant decision was to use the Amdata Intraspsect-98 Volumetric Inspection System. This qualified system is currently used on-line for the automated scanning of the clevis, tang, and membrane portions of the RSRM. Use of this system also enabled the use of the current qualified bondline inspection techniques as a baseline.

The requirements for the scanner necessary to perform this inspection are: 1) it had to be of a low enough profile to fit into the work space, 2) it had to be able to scan in an inverted position, and 3) it must be easy for the operator to position. With the possibility of performing the inspection on stacked flight hardware, a low profile 3010 scanner developed by ABB Amdata was identified for use. This scanner met the minimum conditions noted previously and was compatible with the I-98 equipment previously mentioned. This scanner is shown in Figure 1. The method chosen to attach the scanner to the metal housing was a metal track using suction cups powered by a vacuum pump. Amdata had in their possession a 3-ft flat section of track. This section was used for the development effort. However, when the track was attached to the conical ID of the housing, it traced out a slight arc on the ID surface.

A scan protocol was developed to minimize the number of moves the scanner assembly (scanner, guide track, cabling, tether) needed to make while still providing



Figure 1. Low Profile Scanner Assembly Interfaced to Fixed Housing

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maximum coverage of the bondline. Currently, three axial moves are required to scan a 3-ft circumferential region. The first two axial moves support down hill scanning with the transducer saddle in the down hill position. This scanning covers approximately 80 percent of the inspectable bondline. The third and final axial move supports down hill scanning of the last 20 percent of the inspectable bondline. With this scan sequence, the transducer saddle is rotated 180 deg. This allows for inspection of the upper most portion of the fixed housing.

Amdata and Thiokol personnel have defined a track configuration which will remedy the arc problem as well as only requiring one track position to scan the entire axial length. This will be accomplished by using angulated extensions between the track and the suction cups. This will allow the track to flex to the configuration of the housing, without causing distortion of the track.

During ultrasonic inspection, a liquid couplant was used to aid in the transmission of the sound energy from the transducer into the specimen under inspection. In the case of the D6AC steel fixed housing, the roughness is such that couplant selection becomes a significant factor. It is significant because when using a signal amplitude technique, a consistent level of sound energy must be transmitted into the specimen. In this case, it also becomes important that a couplant be of a high enough viscosity to remain in place on the vertically-oriented fixed housing without dripping onto and contaminating the adjacent components. The couplant must conversely be of a low enough viscosity as to allow for even application and prevent buildup on the transducer.

Numerous types and viscosities of couplants were tested for use on this project. The following is a partial listing of the couplants tested: Echo laboratories Gel 3000, and Ultrigel II, Sonotech Soundclear formulations, and glycerine.

These couplants were tested individually and with water as a diluent. The dilution ratios (couplant:water) were 1:1, 2:1, and 3:1. The couplants ability to adhere to the part, sound transmission characteristics, and overall cleanliness was monitored.

At the completion of testing, Echo Laboratories Gel 3000, diluted with water at a 3:1 ratio, was selected.

Gel 3000 possesses unique bridging properties which are particularly significant in eliminating the spurious noise generated by mode conversion and refraction of the sound beam when rough surface finishes are encountered. This gel is a nonflammable, biodegradable non-ionic surfactant based couplant, which does not contain petroleum products. Total halogens, sulfur, lead, phosphorus, and mercury are less than 50 ppm.

Application of the couplant was attempted using a 2-in. foam paint brush and a medium nap paint roller applicator. The best results were obtained using the medium nap roller with the couplant applied in the circumferential direction. This application method proved significant in resolving the dilemma relating to the advantages of using high and low viscosity couplants. The application method is shown on Figure 2. In addition, several transducer shoe configurations were tested. The shoe fits onto the base of the transducer which allows a consistent thickness of couplant to be maintained. This thickness was 0.015 mil. It was found no shoe was necessary because of the exceptional qualities provided by the couplant.

Minimizing variations in ultrasonic signal response due to surface roughness and other couplant-related effects was the dominant factor in the transducer frequency selection. Data obtained during the development of the RSRM field joint bondline inspection showed that the 2.25 MHz frequency was more immune to the above mentioned effects than the 5.0 MHz frequency. Preliminary testing on postfired fixed housings confirmed this data. The only 2.25 MHz transducers available were 0.5 in. diameter. It was felt that this was a reasonable aperture size to begin with since no flaw size criteria existed.

6.2 DATA COLLECTION AND ANALYSIS

Once the inspection parameters for the fixed housing were defined, testing was done to determine the overall capability of the system for detecting unbonds. This involved

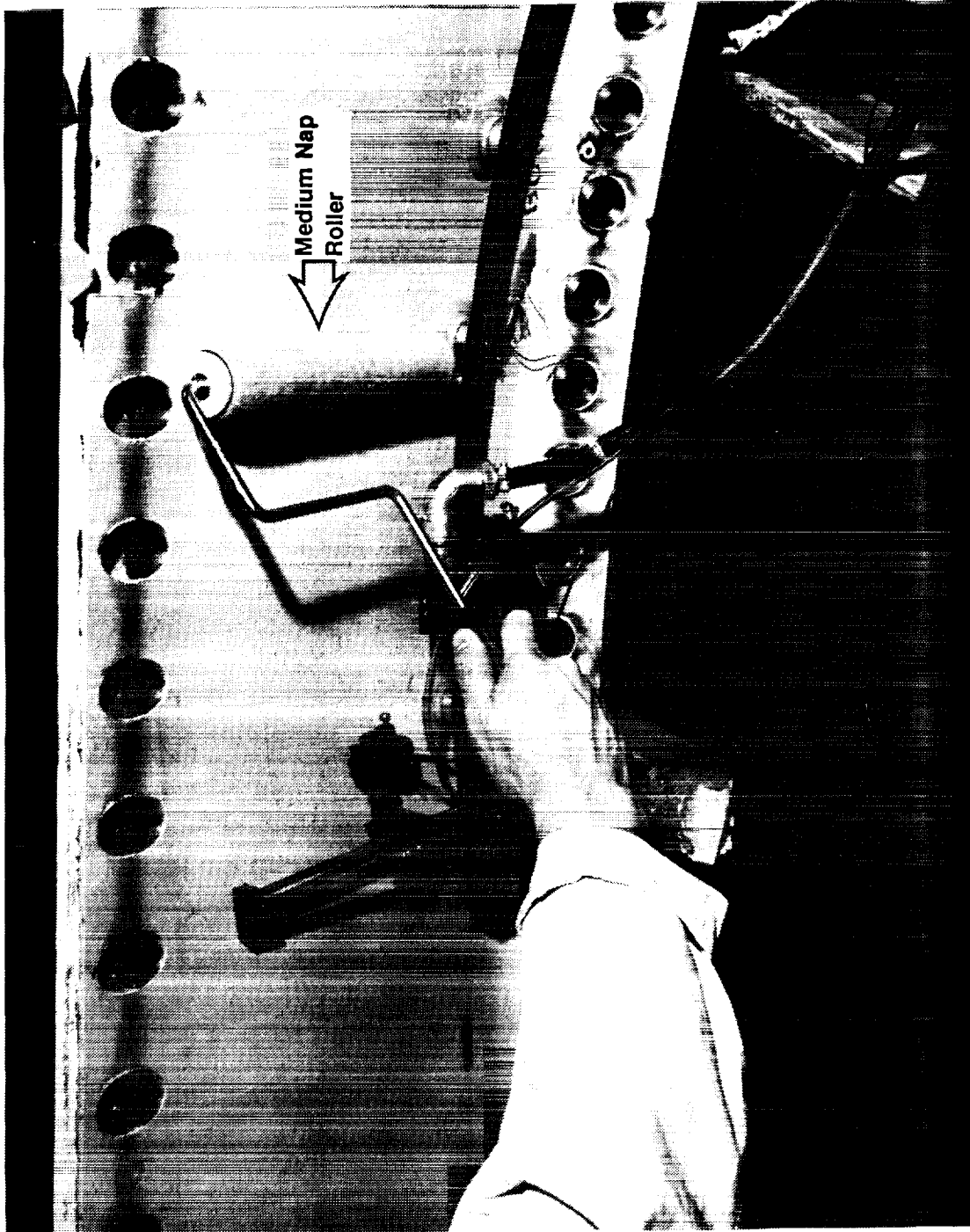


Figure 2. Couplant Application Method

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finding the probability of detecting unbonds of different sizes and determining if unbonded signals could consistently be distinguished from bonded (or background) signals. Distinguishing unbonds from bonds becomes more difficult as the inherent variability of the inspection increases, which is what happens when an ultrasonic gel is used in place of water as a couplant. Three postfired fixed housings (11A, 11B, and 12B) were available for testing.

The logic here was that the more fixed housings that could be inspected, the better the part to part variability could be understood. On two of the fixed housings, a large section of carbon phenolic was removed from the glass phenolic (Figure 3). Holes of various diameters (ranging from 0.25 to 1.5 in.) were then drilled into the glass down to the D6AC steel. Fixed housing 11A contained 24 holes (eight diameters, three holes per diameter), while fixed housing 11B contained 32 holes (eight diameters, four holes per diameter) as shown in Figures 1, 2, and 3. Due to certain physical and time constraints, not all of the holes were used for the POD study.

A reference calibration scan was performed periodically throughout the testing. This reference scan was done on a 3 by 3 in. portion of an early RSRM fixed housing prototype, which was used in the initial design stages of the fixed housing, and was a precursor to the present design used on the RSRM. The area inspected on the reference standard contained a 1-in. diameter circular unbond. The inspection surface of this standard was somewhat rougher than those seen on the actual hardware. This made the reference scan less repeatable than desired. The reference calibration essentially served as a safeguard against any gross, repeatable changes in the equipment response.

The ultrasonic inspection was done in a pulse-echo mode using a 2.25 MHz, broadband transducer with an alumina-oxide wearface, made by Combustion Engineering. The scanning index was 0.25 inch. This was chosen with the intent of satisfying both the desire for higher resolution (finer index) and practical inspection times (coarser index). Only a portion of the wavetrain, known as the C-gate, was used for analysis. The C-gate started at 58 μ sec into the wavetrain and extended out

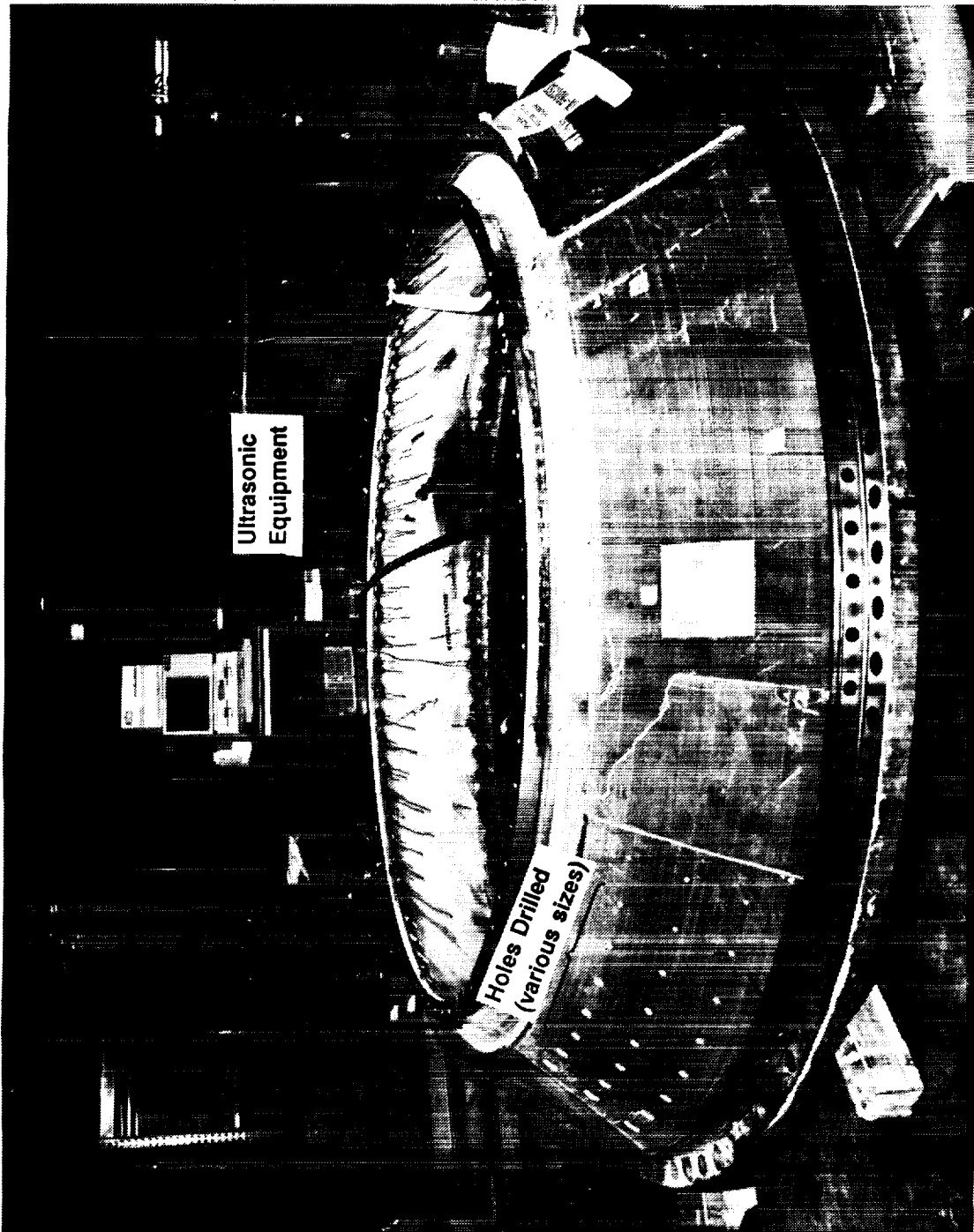


Figure 3. POD Test Sample

to 82 μ sec. Although the thickness of the fixed housing varied almost 90 mil from the forward end to the aft end, the C-gate was positioned so that the 10th to 13th echos were usually within the gate. Thus, the peak amplitude value was almost always taken from the 10th echo. The choice of the C-gate location was not an arbitrary decision, but arose from both experimental and theoretical testing. The objective was to place the gate far enough out in time in order to enhance the unbond-to-bond response ratio, and yet not too far out so as to degrade the signal-to-noise ratio. The choice of 58 to 84 μ sec was not rigidly determined, but did seem to optimize these two factors.

Two features were extracted from each wavetrain and used as indicators of bond condition. These features were: 1) the peak (or largest) absolute amplitude value (data point) in the C-gate, and 2) the sum of all the data points making up the rectified waveform in the C-gate. The peak amplitude value almost always came from the first echo in the C-gate, which was usually the 10th echo as mentioned previously. The summed value is essentially proportional to the overall energy being returned to the transducer and is similar mathematically to the root mean square (RMS) of the signal. There are sometimes advantages to using one feature over the other for unbond detection. For the most part, however, the two features will respond in a similar manner to unbonds.

As well as inspecting some of the circular unbonds from fixed housings 11A and 11B, portions of bonded regions from fixed housings 11A, 11B, and 12B were also inspected. Figures 4 and 5 show the ultrasonic response to the various unbonds on 11A and 11B. The x-axis on these plots is the unbond size (diameter) in inches, and the y-axis is the response value (either peak amplitude or summed C-gate). Some of the data points represent multiple scans of the same unbond. It can be seen from these figures that both the peak amplitude and the summed C-gate correlate with unbond size, but with a large amount of scatter. This is primarily due to the inherent variability in coupling ultrasound into the case and the case to case variations in surface condition. The inspections showed that the unbonds on 11B consistently gave a lower response than those on 11A. It can also be seen that the response also

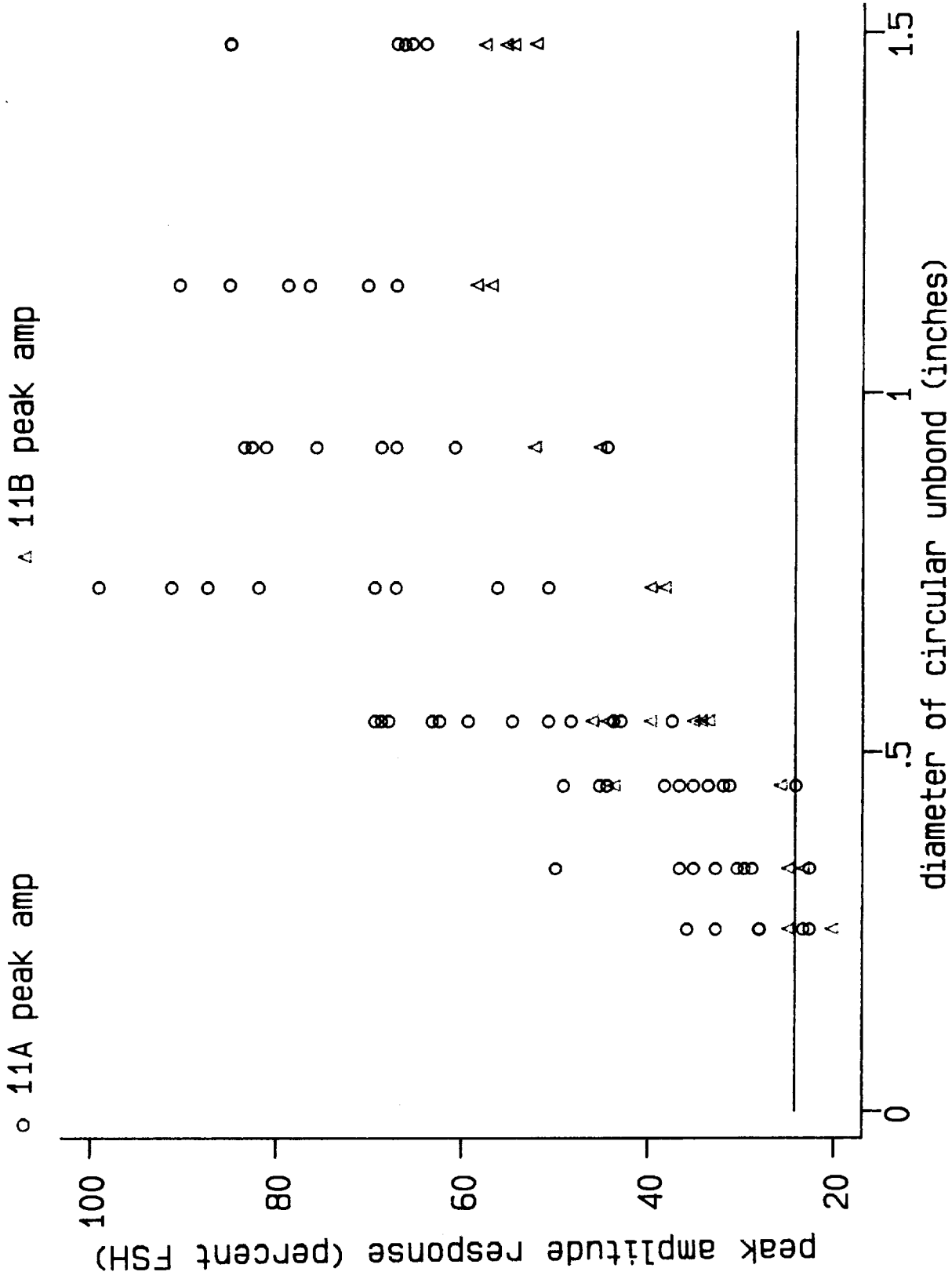


Figure 4. Debond Detection in Fixed Housings 11A and 11B

o 11A
A 11B

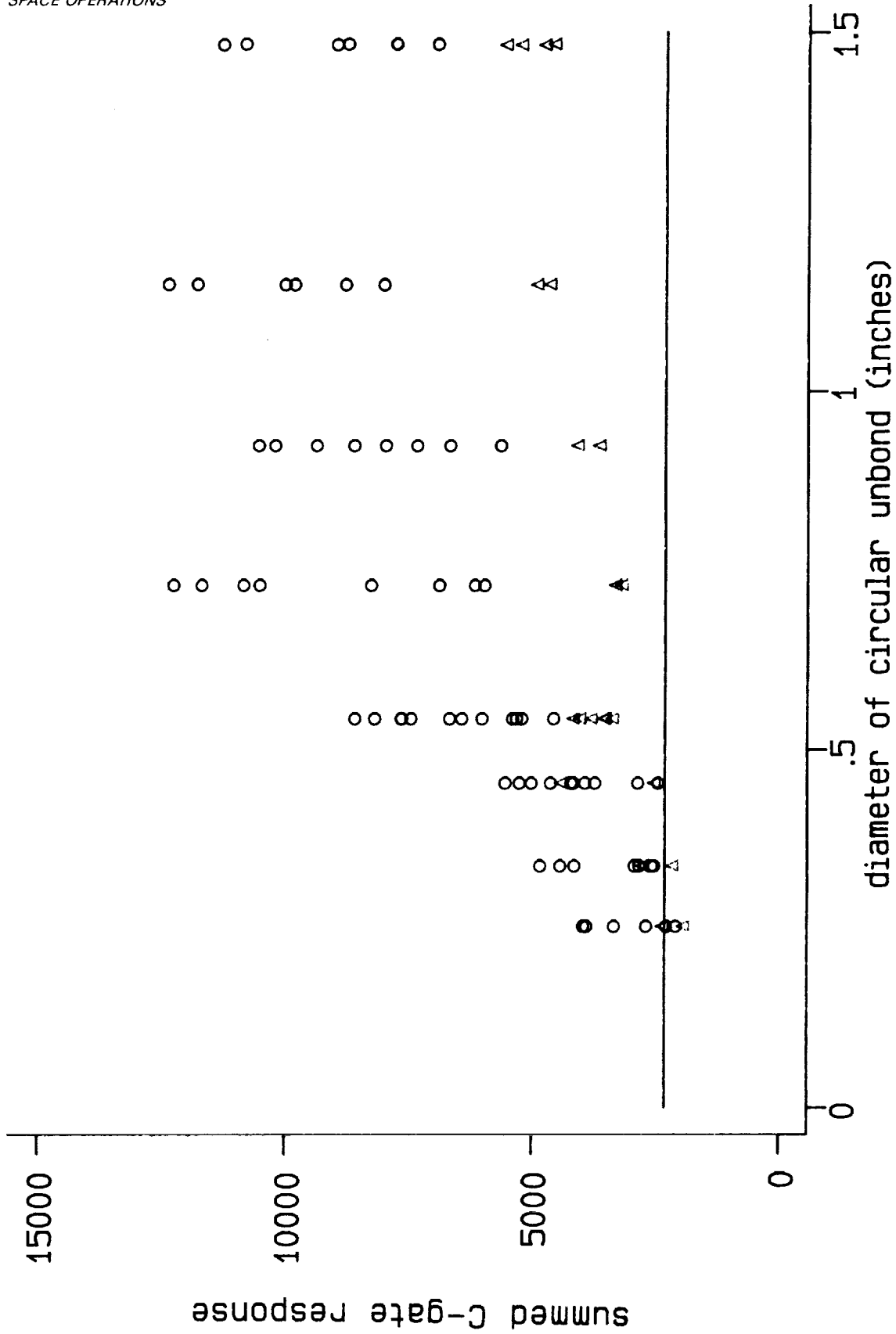


Figure 5. Debond Detection in Fixed Housings 11A and 11B

flattens out as the diameter exceeds 1 inch. This is simply because the transducer only inspects approximately a 0.5 in. diameter of circular area on the bondline at a given moment in time. A larger area unbond does not increase or contribute to the response of the 0.5 in. area that is being inspected, but it does mean that a larger number of pixels (or wavetrains) will occur over an unbonded area, therefore increasing the probability of a higher response. For all practical purposes, however, the response should level out for unbonds larger than 1 in. diameter when a 0.5 in. diameter transducer and 0.25 in. scanning index is used.

The horizontal lines near the bottom of the plots represent the upper edge (average + 5σ) of the background, or bonded, signal distributions. Figures 6 and 7 show these distributions for both peak amplitude and summed C-gate data. The distributions are not the actual background data, but are synthetic normal distributions with mean and standard deviation equal to those of the raw background data. The background data itself was collected from six separate scans of Fixed Housings 11A, 11B, and 12B. Each scan contained between 900 and 1,000 pixels (response values). The average maximum value of the six scans was less than the average + 5σ value from the synthetic normal distribution.

The final step in the analysis was to determine an amplitude (peak amplitude or summed C-gate) threshold, or alarm, that will reliably discriminate between a bonded and unbonded condition of a certain size. In other words, choose a threshold so that unbonds larger than a defined area will produce an amplitude response greater than the threshold 90 percent of the time (and thus trigger the alarm), and bonded areas will produce a response that falls consistently below the threshold. In order to determine this threshold level, d versus a POD analysis was performed on the unbond data. This analysis generates a POD curve calculated at the 95 percent CL. From this curve, a MDF size can be found. The MDF is usually defined as the smallest flaw (or unbond) that can be found with a 90 percent POD. Figure 8 shows the 95 percent CL POD curve for a peak amplitude inspection with the alarm threshold set at 40 percent full-scale height (FSH). The 90 percent POD value occurs at an unbond

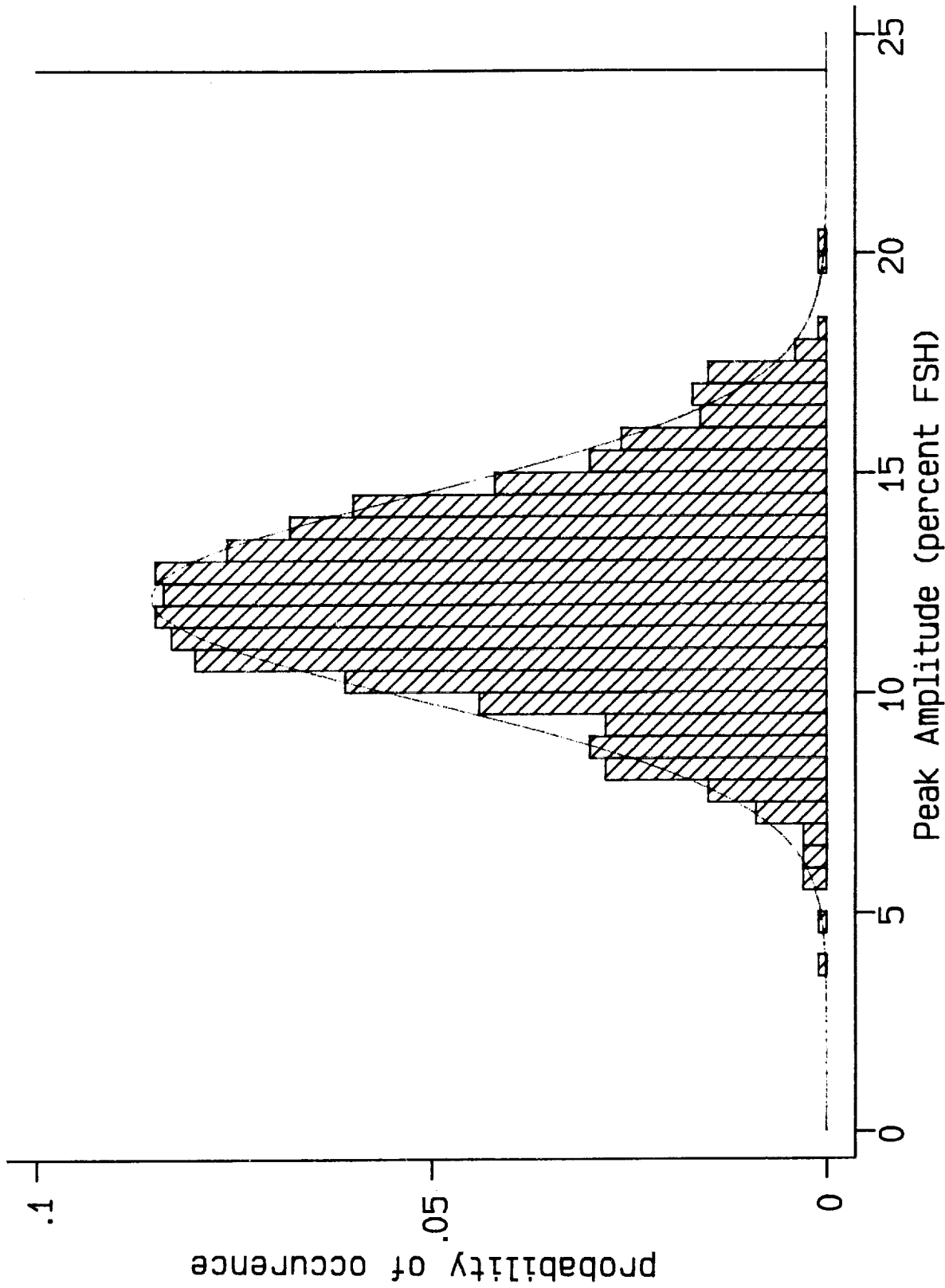


Figure 6. Background From 11A, 11B, and 12B (average + 5σ = 24.15)

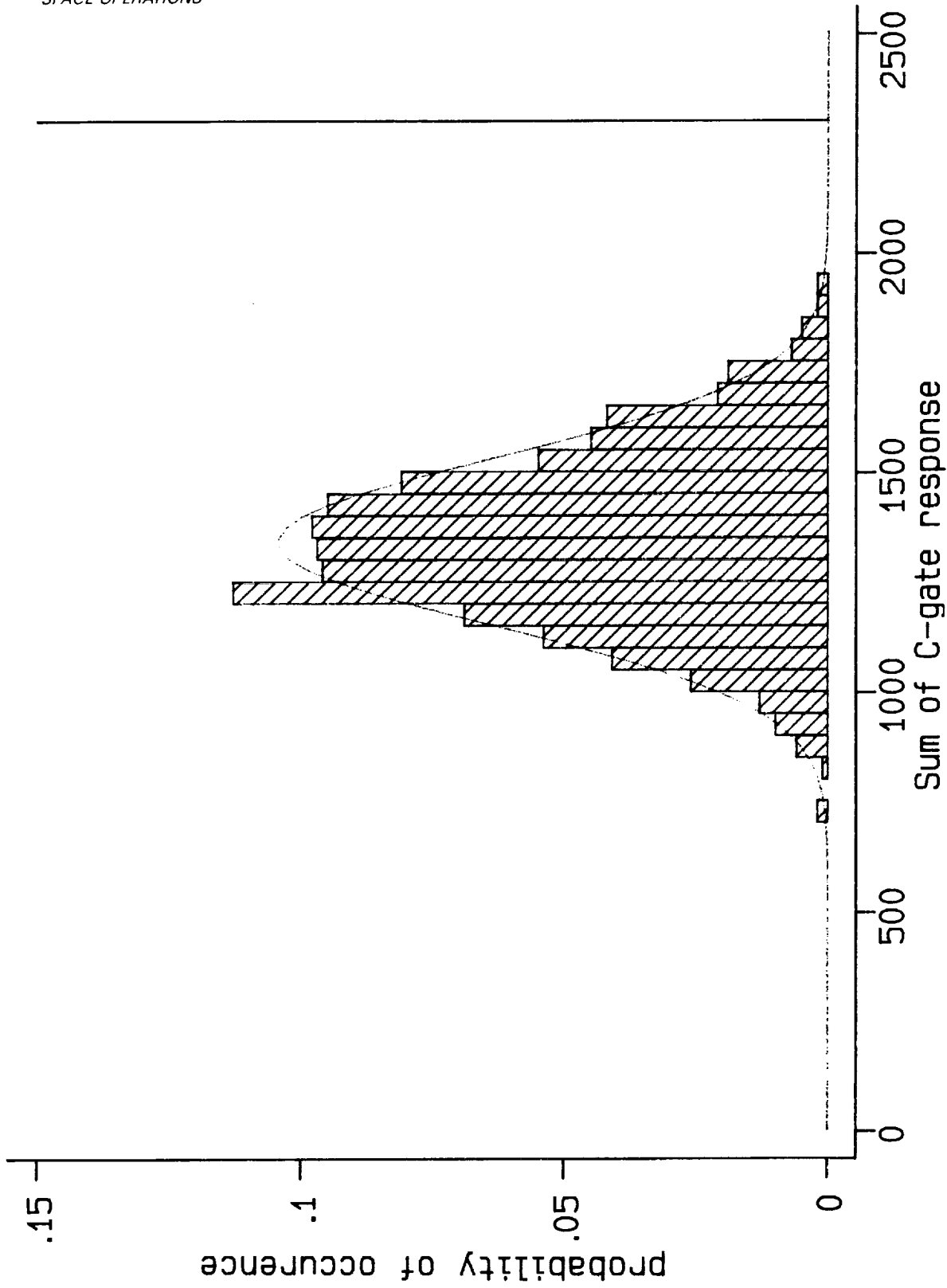


Figure 7. Background From 11A, 11B, and 12B (average + 5σ = 2,300)

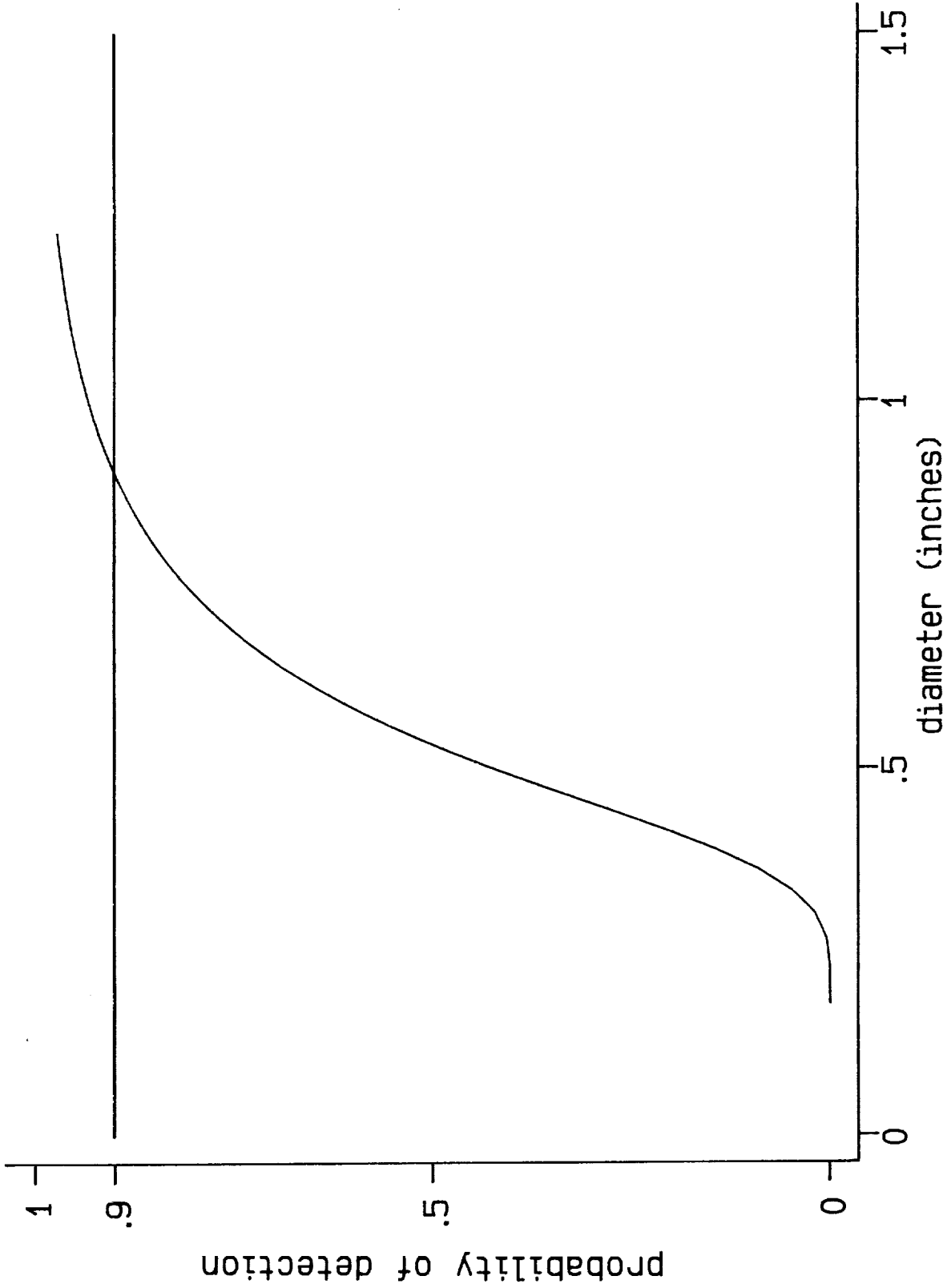


Figure 8. POD Curve With Peak Amplitude Threshold = 40 Percent

size of 0.63 in.² (or 0.9-in. diameter circular unbond). Our MDF would thus be a 0.9-in. diameter circular unbond for this inspection when our alarm threshold is set at 40 percent FSH. Figure 6 shows that the background noise, or bonded signal, is safely below this 40 percent level. This means that unbonds of approximately 1 in. diameter or greater can confidently be detected without the risk of false alarms (bonded areas appearing as unbonds). Of course, sensitivity to unbonds can always be increased by lowering the alarm threshold, but this would also increase the risk of false alarm. Figure 9 shows the 95 percent CL POD curve for the summed C-gate inspection when the alarm threshold is set at a value of 3,250. The MDF for this inspection is also approximately a 0.9-in. diameter circular unbond.

The \hat{d} versus α analysis program was run for several alarm thresholds. The MDF corresponding to each threshold is listed in Table 1. It appears that a peak amplitude threshold close to 40 percent FSH is near optimum for this inspection. It should be emphasized that the sensitivity of this inspection would improve if a more stable couplant is used (such as water). Also, the efficiency of the inspection will increase when the improved scanner and track are purchased. It is recommended that another POD study be performed on postfired fixed housings when this new equipment arrives.

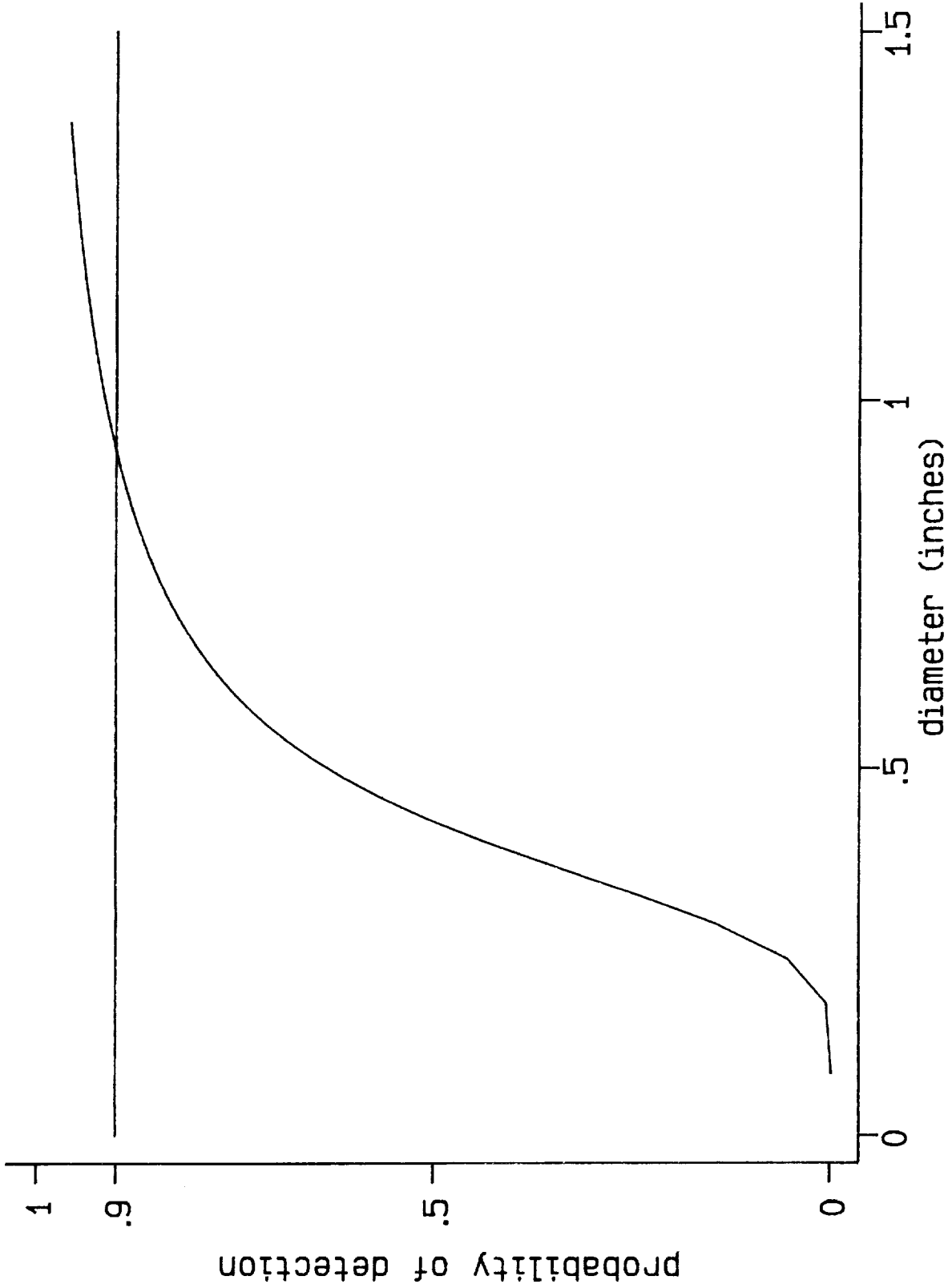


Figure 9. POD Curve With Summed C-gate Threshold = 3,250

Table 1. Minimum Detectable Debond Sizes for Various Inspection Thresholds

Inspection Threshold	Minimum Detectable Circular Unbond at 90 Percent POD, 95 Percent CL
Peak Amplitude FSH (%)	Diameter (in.)
50.0	1.30
45.0	1.09
40.0	0.90
35.0	0.73
30.0	0.59
Summed C-gate	
5,000	2.23
4,500	1.77
4,000	1.38
3,500	1.06
3,000	0.80

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