SG-00-02-003

Assessment of Burst Pressure for ANO-2 SG B, R72C72

February 10, 2000

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1.0 Introduction

At the ANO-2 2P99 inspection in November 1999, SG B tube R72C72 was in situ tested to obtain the burst pressure and leakage potential for the indication. The maximum pressure obtained during the in situ test was 4147 psi as corrected for the pressure drop due to leakage flow in the test equipment and for instrumentation error. The in situ test was performed as a whole tube test, as contrasted to use of a localized test employing a bladder, and the maximum test pressure was limited by the flow capacity of the test equipment. The objectives of this assessment are to evaluate whether or not the in situ test resulted in a burst of the indication, and, to obtain a best estimate of the burst pressure if a burst was not obtained during the in situ test.

The assessment on whether burst was achieved during the in situ test is based on the post in situ RPC response of the indication as compared to responses for specimens known to have achieved a complete burst of the tube. The estimated burst pressure for R72C72 is obtained by evaluation of the pressure time history from the in situ test to estimate the additional pressure increase required to burst the indication. By definition, a burst requires that the test result in significant crack extension at the ends of the crack, and burst of an axial crack typically results in the crack opening resembling a fish mouth condition.

ANO-2 operates with a primary to secondary pressure differential of ΔP_{NO} = 1350 psi. For structural integrity, indications are required to maintain a burst pressure margin of $3\Delta P_{NO}$, which would be 4050 psi at operating conditions. For evaluation of room temperature tests, burst pressures must be increased by the ratio of the material properties at room temperature to that at operating temperature. For tubing in CE SGs, the operating temperature material properties are 92.7% of the room temperature material properties. The required burst margin at room temperature is then 4050/0.927 and the room temperature $3\Delta P_{NO}$ = 4369 psi or 222 psi above the in situ test pressure achieved for R72C72. The in situ test results are evaluated against the 4369 psi burst margin requirement.

2.0 In Situ Test Results for R72C72

The in situ test results obtained during the 2P99 inspection are given in Table 1. The maximum pressure differential reached in the test was 4147 psi, which is less than the burst margin requirement of 4369 psi. The test was terminated due to the leakage flow exceeding the capacity of the equipment, which prevented further increases in the test pressure. The pressure time history from the in situ test is further discussed in Section 6.

No leakage was obtained at the steam line break pressure differential, which is bounded at room temperature conditions by the pressure test at 2882 psi. This result indicates that there was no throughwall or near throughwall corrosion for the indication. The initial leakage of 0.02 gpm was obtained at 3774 psi indicating a short length break-through of a wall thickness ligament. The test results indicate increases in the break-through length at 3971 to 4147 psi. For the leak rate of about 1 gpm at 4132 psi found in the testing, a throughwall length on the order of 0.6 to 0.7 inch would be expected. This throughwall length is less than the R72C72 crack length, which tends to indicate that the crack did not burst at the test conditions.

3.0 Pre and Post In Situ RPC Response for R72C72

A RPC inspection of R72C72 was performed prior to the in situ test and after completion of the test. Figures 1 and 2 show the pancake coil terrain plots before and after in situ using 300 kHz (Figure 1) and 300/100 kHz mix (Figure 2) analyses. The mix tends to reduce the influence of the egg crates and tube deposits, which improves the signal response for sizing of the indications. The differences between the 300 kHz and mix responses are small for the post in situ test results.

The post test responses can be characterized by the dips or valleys in the circumferential direction for each rotation of the coil and by a uniform angular response from the front to back of the crack. As shown in Section 4 (Figure 4), the dips and uniform angular responses in the circumferential direction are typical of modest crack separation as also seen in RPC responses to throughwall EDM slots. The differences in the R72C72 response from that for burst tubes are further discussed in Section 4. From Figure 2, it is seen that the angle encompassed by the RPC response increased from 36° before in situ testing to 61° after testing, which also typical of modest crack opening. The 100% slot of Figure 4 shows an RPC angle of 51°, which is comparable to that from the post in situ test response.

The post in situ voltage responses of Figures 1 and 2 show 3 to 4 distinct breaks in the response at which the dips are not present and the voltage magnitude is lower than adjacent rotations. It is expected that these changes in the response are due to uncorroded ligaments in the crack face, which may span the crack opening.

Crack depth profiles for R72C72 were obtained from analysis of the 115-mil pancake coil results. The pre-test analyses (two independent analyses) used the frequency mix while the post-test analysis used the 200 kHz response. The signal response at 400 kHz was saturated for the post-test data, and crack sizing could not be performed for the mix so 200 kHz was used for the depth profile analysis. Sizing experience has indicated that analyses of the 200 kHz data tend to result in over estimates of crack depth and increased voltages, but the data can indicate the post test features of the indication. A comparison of the pre and post test depth profiles for R72C72 is shown in Figure 3. The two pre-test analyses are in good agreement over the center of the indication with one analysis (B5534) deeper at the lower voltage tails of the indication and a shorter length. Comparing the same analyst for pre and post-test conditions, the pre-test analysis shows a crack length of 1.42", maximum depth of 93% and average depth of 73.1% while the post-test shows a crack length of 1.49", maximum depth of 100% and average depth of 95%. These values suggest that the crack opening did not extend significantly beyond the NDE identified depths near 65%. The post-test results following testing up to 4147 psi indicate tearing of some of the uncorroded wall thickness ligaments with no significant difference in crack length (i.e., no crack extension from the in situ testing).

4.0 RPC Response Characteristics of Burst Tubes

This section provides burst tube RPC responses for comparison with the post-test response of R72C72. First it is appropriate to review the response from a throughwall EDM slot which is shown in Figure 4 (axial response at left side of terrain plot). It is seen that the slot shows slight voltage dips in the circumferential direction of probe rotation. Separation of the faces for the EDM slots is typically about 5 to 6 mils. The circumferential dips for the slot are similar, although smaller, than found for the 300 kHz response for R72C72 in Figure 1. The dips are typical of modest separation of the crack faces and are not present in larger openings typical of burst cracks as shown in the following discussion.

The RPC response for a very large burst opening is shown in Figure 5 for ANO-2 tube R16C60, which burst in a 1996 in situ test. The figure shows the pre and post test responses for this indication. The post-test length is about 3.5" as compared to the pre-test length of about 1.26". The large increase in length indicates extensive tearing at the crack tips during the burst test. For this long burst opening, the occurrence of a burst is obvious and the angular extent of the RPC response is about 246°, whereas the pre-test angle was about 40°. The large RPC angle is more than the expected opening and is partly attributable to the lead-in and lead-out coil effects as well as possible coil lift off due to the fish mouth opening. Across the wide part of the burst opening, the voltage response is flat without the circumferential dips. However, the circumferential dips are seen at both ends of the burst opening where the crack face separation approaches zero. The latter also supports the dips as indicative of small gaps in the crack faces. Signal noise at the separated crack faces is likely due to the RPC coil entering and leaving the crack opening. Based on this burst opening response, the signal features for a burst opening are: a flat voltage response over the widest part of the opening, dips in the response at the ends of the opening and a varying angular response from end to end of the opening with the largest angular response at the center of the fish mouth burst opening.

Further insight in the RPC response characteristics of burst openings can be obtained by examination of burst openings of various length and angular extent. Figure 6 shows burst specimens with significant differences in the length and width of the burst opening. The burst openings for the two specimens to the left of Figure 6 show little crack tip extension and would represent a lower bound to the burst pressure for these indications. Specimens PI-104-98 and PI-105-98 had 0.70" EDM notches, 80% deep. The burst pressure for PI-105-98 was 600 psi higher than that for specimen PI-104-98, which does not show a complete burst with significant crack extension. Specimen PI-098-98 had a 0.50", 80% deep notch and burst at the same pressure as the longer PI-105-98 notch, which indicates that PI-098-98 is also an incomplete burst. Specimen PI-060-98 had 5% wall thinning and burst at a burst pressure near that of undegraded tubing.

Figures 7 and 8 show the pancake coil responses for the two smallest and the two largest burst openings. The RPC data for these figures was collected with tape across the ID of the burst opening to minimize probe noise at the crack faces in order to more clearly demonstrate the flat response across a significantly wide gap. Although specimens PI-098-98 and PI-104-98 are incomplete bursts, the RPC responses shown in Figure 7 have the general features of a burst with the flat response over the widest part of the opening, a wider angular response at the center of the opening and the voltage dips at the ends of the opening. To provide pancake coil responses prototypic of a field inspection, the data for specimens PI-098-98, PI-104-98 and PI-105-98 were obtained without tape across the burst opening such that the effects at the edges of the opening are included in the responses. These responses are shown in Figure 9, which includes the PI-98-98 opening from two different angles. The similarity of the responses can be clearly seen for the complete bursts of specimen PI-105-98 in Figure 9 and that for R16C60 in Figure 5. Even the incomplete bursts of specimens PI-098-98 and PI-104-98 in Figure 9 show the features of the complete bursts for specimens PI-105-98 and R16C60. Comparing the Figure 9 responses with Figure 1 for R72C72 further supports that R72C72 had a modest crack opening that is not representative of a burst opening even for an incomplete burst. For the long crack length of R72C72, a complete burst would be expected to have a RPC response more like that found for specimens PI-105-98 in Figure 9 and ANO-2 R16C60 in Figure 5.

5.0 Conclusion on Post Test Condition of R72C72

The following conclusions can be drawn from the comparisons of the post in situ test, pancake coil response of R72C72 (Figure 1) with that of burst openings shown in Figures 5 to 8:

- The in situ test pressure of 4147 psi obtained for SG B, R72C72 does not represent a burst and the true burst pressure would exceed the maximum measured in situ test pressure.
- The post in situ test, crack face opening for R72C72 is much less than that expected for a true burst. The crack face separation likely exceeds the 5 mils typical of an EDM notch and could be the order of a few tens of mils. The crack face separation for a burst would be measured in terms of tenths of an inch, such that the separation for R72C72 is likely less than $1/10^{th}$ that expected for a burst.
- The signal features for a burst opening are: a relatively flat voltage response over the widest part of the opening, dips in the response at the ends of the opening, a varying angular response from end to end of the opening and the largest angular response at the center of the fish mouth burst opening. The features for the post in situ test response for R72C72 show only dips in the circumferential response over the length of the crack, and are typical of a crack face separation for a wide EDM notch or the crack tips of a burst opening.
- The post in situ condition of the R72C72 crack appears to be equivalent to that following tearing of the remaining wall thickness ligament to permit significant leakage, but without crack extension required for a burst. This is a common test result in performing burst tests without a bladder and ligament tearing models (see Section 6.2) have been developed to predict ligament tearing as contrasted to models for predicting burst pressures.

6.0 Estimated Burst Pressure of R72C72

6.1 Review of Time History from In Situ Test of R72C72

The purpose of this section is to evaluate the in situ pressure and leak test data obtained from testing the R72C72. The leak rate and pressure time histories are illustrated on Figure 10. The higher pressures where leakage occurred in the time history data of Figure 10 included a preliminary pressure reduction of 100 psi for leakage flow pressure drops and instrument calibrations. The final correction was 62 psi and the corrected data are used in the remaining discussion in this section. The intent of this evaluation is to determine if a reasonable estimate of the burst pressure of the tube can be obtained from an examination of the test data. A summary of the presented information is as follows:

1. There are four distinct pressure hold times or pressure plateaus apparent on the chart. These correspond to starting times of about 5, 10, 14, and 17 minutes. The pressures were held constant at about 1568, 2232, 2882, 3774 psi, respectively.
2. The pressurization rate prior to each hold time plateau was the same. Because the rate of introducing water is constant the implication is that there was no plastic deformation of the flanks of the crack.
3. At 1 minute into the fourth hold period, at a pressure of about 3870 psi, a small amount of leakage was observed, attended by a decrease in the differential pressure of about 100 psi.
4. A differential pressure of about 3774 psi was held for almost four minutes in the presence of a constant small amount of leakage. The implication is that a small radial ligament in the axial crack tore, resulting in a 100% throughwall segment.

5. At 22 minutes into the test, the pressure was increased to about 3971 psi. The leak rate started to increase and the system attempted to hold the pressure constant.
6. At 23 minutes into the test, a step increase in the leak rate occurred from about 0.2 to 0.6 gpm. The pressure in the system dropped to about 3573 psi.
7. The leak rate and pressure were constant for about 1.5 minutes, at which time the pressure was increased again in the presence of an increasing leak rate. Slope of the pressure increase matched the first four pressurization rates.
8. At 25 minutes a pressure of about 4025 psi was reached with an attendant leak rate of about 0.7 gpm.
9. Further pressurization led to erratic fluctuations of the pressure on the order of ±50 psi as the leak rate continued to increase. From about 25.5 to 26.5 minutes the mean pressure decreased slightly as the leak rate increased to 1.0 gpm.
10. At 26.5 minutes the pressure was ramped up to 4147 psi at which time the leak rate exhibited a step increase to 3.7 gpm and the pressure simultaneously dropped. At 27 minutes the pressure and leak rate were zero.
11. At about 30 minutes an attempt was made to re-pressurize the tube using a high capacity pump. This is mentioned because the record is on Figure 10, but has no bearing on this discussion.

The pressurization rates at 25.5 and 26.5 minutes were slightly smaller than the previous rates. In the absence of tooling anomalies, this implies that the flanks of the crack were deforming to increase the leakage area. The eddy current evidence conclusively indicates that the tube did not burst. The issue is how much more pressure would have been required to result in a burst if the tube had been in operation. Over the last few seconds, the curve is bending over slightly, which may be indicative of plastic deformation followed by a sudden jump in the leak rate. This may imply stretching and tearing of a ligament, which is supported by the post-test RPC response that indicates the likely presence of a few remaining ligaments. In any event, the in situ data do not contradict the conclusion from the eddy current analysis that burst did not occur.

A second plot of the data was made by adjusting the time values to shift the pressure ramp rate values to be more in line with each other, see Figure 11. Much of the hold time data was also removed for this second look at the data, creating a history of pressure values relative to effective test times. The information indicates that the pressure-time history remained rather linear until the final surge in the leak rate. This information does not provide conclusive evidence regarding the burst pressure that could have been reached if ligament tearing and significant leakage had not terminated the test.

In summary, the in situ data do not provide direct evidence regarding the magnitude of the expected burst pressure relative to the maximum pressure achieved in the test. The burst pressure exceeds the maximum test pressure of 4147 psi. However, other methods have to be applied to estimate the burst pressure as discussed in the following section.

6.2 Increase in Burst Pressure Above Onset of Significant Leakage

As noted in Section 5, the post in situ test condition of the R72C72 crack is that following ligament tearing of the remaining wall thickness ligament, but without the crack extension required for a burst. The objective of this section is to predict the pressure difference required between ligament tearing and burst. Calculation models are available for both ligament tearing and for burst such that the difference calculated between these two models represents the pressure difference to be added to the in situ pressure of 4147 psi, representing ligament tearing, to obtain the burst pressure for R72C72. An additional method to estimate the burst pressure correction for R72C72 is the difference between pressure tests of specimens that resulted in ligament tearing and tests that result in a complete burst. Both of these methods are applied in this section.

As described in Section 4, the Westinghouse model is used for burst pressure predictions in this report and the ANL model (Reference 1) is used for prediction of ligament breakthrough or tearing predictions for leakage analyses. These models can be applied to the NDE depth profiles given in Figure 3. The material properties are known only by rows in CE SGs. The properties are not known specifically for R72C72 and a flow stress of 80 ksi is assumed for this analyses based on ANO-2 pulled tubes with ODSCC at egg crate intersections having flow stresses of 80 ksi (R70C68, 1996 pulled tube) and 83.95 ksi (R16C56, 1996 pulled tube). The material properties for the pulled tubes are higher than indicated in the tube manufacturing data for these rows, which is typical for comparisons of pulled tube and material certification data. Applying the Figure 3 profile for analyst S5971, the predicted burst pressure is 4311 psi from the Westinghouse model and the predicted ligament tearing pressure is 3752 psi for a pressure difference of 559 psi. Adding this pressure difference to the in situ test pressure of 4147 psi leads to an estimated burst pressure of 4706 psi for R72C72. The predicted burst pressure for the S5971 NDE profile is conservative by nearly 400 psi relative to the estimated burst pressure. Applying the Figure 3 profile for analyst B5534, the predicted burst pressure is 3644 psi from the Westinghouse model and the predicted ligament tearing pressure is 3125 psi for a pressure difference of 519 psi. Adding this pressure difference to the in situ test pressure of 4147 psi leads to an estimated burst pressure of 4666 psi for R72C72. The predicted burst pressure for the B5534 NDE profile is very conservative compared to the estimated burst pressure indicating that this NDE analysis significantly overestimates the crack depth profile for R72C72. The correction to the in situ test pressure exceeds 500 psi for both NDE profiles.

Visual examination of the flaw opening following a burst test can be used to characterize the test result as an incomplete burst with little or no crack tip extension or a complete burst with crack tip extension. The results of such tests for burst testing of EDM notches are given in Table 2. Figure 12 shows photos of the burst openings for the specimens included in Table 2. The results of Table 2 show that the pressure differences between incomplete and complete bursts tend to increase with decreasing flaw size as would generally be expected. The results of the tests for the 0.70 inch long by 80% deep EDM notches are the most applicable to this evaluation since the notch size is close to the deep crack section of R72C72 (Figure 3). These results support a pressure difference of 400 to 600 psi between an incomplete burst with negligible crack extension and a complete burst with ligament tearing at the flaw tips. These test results support the above analytical model prediction of a 500 psi correction to the in situ test pressure in order to obtain the burst pressure for R72C72. Similar analyses for the test correction were performed using the Framatome ligament tearing model and a burst model based on a modification to the Framatome model to estimate burst pressures rather than ligament tearing. The pressure differences between ligament tearing and burst from these models are higher than given above.

7.0 Overall Conclusions on Burst Pressure of R72C72

The following conclusions can be drawn from the evaluations performed to assess the burst pressure for the egg crate intersection ODSCC flaw in R72C72:

- The in situ test pressure of 4147 psi obtained for SG B, R72C72 does not represent a complete burst and the estimated burst pressure would be about 4650 psi which exceeds the room temperature $3\Delta P_{NO}$ burst margin requirement of 4369 psi.
- The post in situ condition of the R72C72 crack appears to be equivalent to that following tearing of the remaining wall thickness ligament to permit significant leakage, but without crack extension required for a burst. This is a common test result in performing burst tests without a bladder. The correction to the R72C72 in situ test pressure in order to obtain the burst pressure can be estimated as the difference between the calculated burst pressure and the calculated ligament tearing pressure.
- The burst pressure correction to the R72C72 in situ test pressure is estimated at about 500 psi based on the calculated pressure difference between burst using the Westinghouse model and ligament tearing using the ANL model. This analytical estimate is supported by differences in the test pressures of EDM notches between specimens with complete (significant crack tip extension) and incomplete bursts (negligible crack tip extension).
- The signal features for a burst opening are: a flat voltage response over the widest part of the opening, dips in the response at the ends of the opening, a varying angular response from end to end of the opening and the largest angular response at the center of the fish mouth burst opening. The features for the post in situ test response for R72C72 show only dips in the circumferential response over the length of the crack, and are typical of the crack face separation of a wide EDM notch or the crack tips of a burst opening.

References

1. Majumdar, Saurin, "Predictions of Structural Integrity of Steam Generator Tubes Under Normal Operating, Accident, and Severe Accident Conditions," 24th Water Reactor Safety Meeting, October 21-26, 1996, Bethesda, MD (September 1996).

Table 1. In Situ Test Results for SG B, R72C72 at 2P99 Outage	
Test Pressure (psi)	**Test Results**
1568	No leakage for 2 minute hold time. Simulates normal operating pressure differential.
2232	No leakage for a 2-minute hold time.
2882	No leakage for a 2 minute hold time. Simulates MSLB pressure differential.
3737	Leakage detected
3774	Leakage = 0.02 gpm measured over 5 minute interval.
3971	Step increases in leakage with associated test pressure drop.
3573	Leakage = 0.56 gpm
4132	Leakage = 0.92 gpm
4147	Leakage = 1.16 gpm. Maximum test pressure obtained as corrected for test equipment pressure drop due to leakage flow and for instrument error.

Table 2. Burst Pressure Differences Between Incomplete and Complete Bursts				
Specimen	**EDM Notch**	**Test Pressure (psi)**	**Burst Characterization**	**Comments**
PI-104-98	0.7" by 80% deep	3600	Incomplete Burst Figure 6	Supports difference of 400 to 600 psi between incomplete and complete burst for flaw size comparable to that of the deeper part of R72C72
PI-105-98	0.7" by 80% deep	4200	Complete Burst Figure 6	
PI-106-98	0.7" by 80% deep	4000	Complete Burst	
PI-98-98	0.5" by 80% deep	4200	Incomplete Burst Figure 6	Indicates large pressure differences between complete and incomplete burst for flaws shorter than R72C72
PI-99-98	0.5" by 80% deep	5400	Complete Burst	
PI-100-98	0.5" by 80% deep	6200	Complete Burst	

Figure 1. ANO-2 R72C72 Pre and Post In Situ 115 Pancake Coil 300 kHz Response

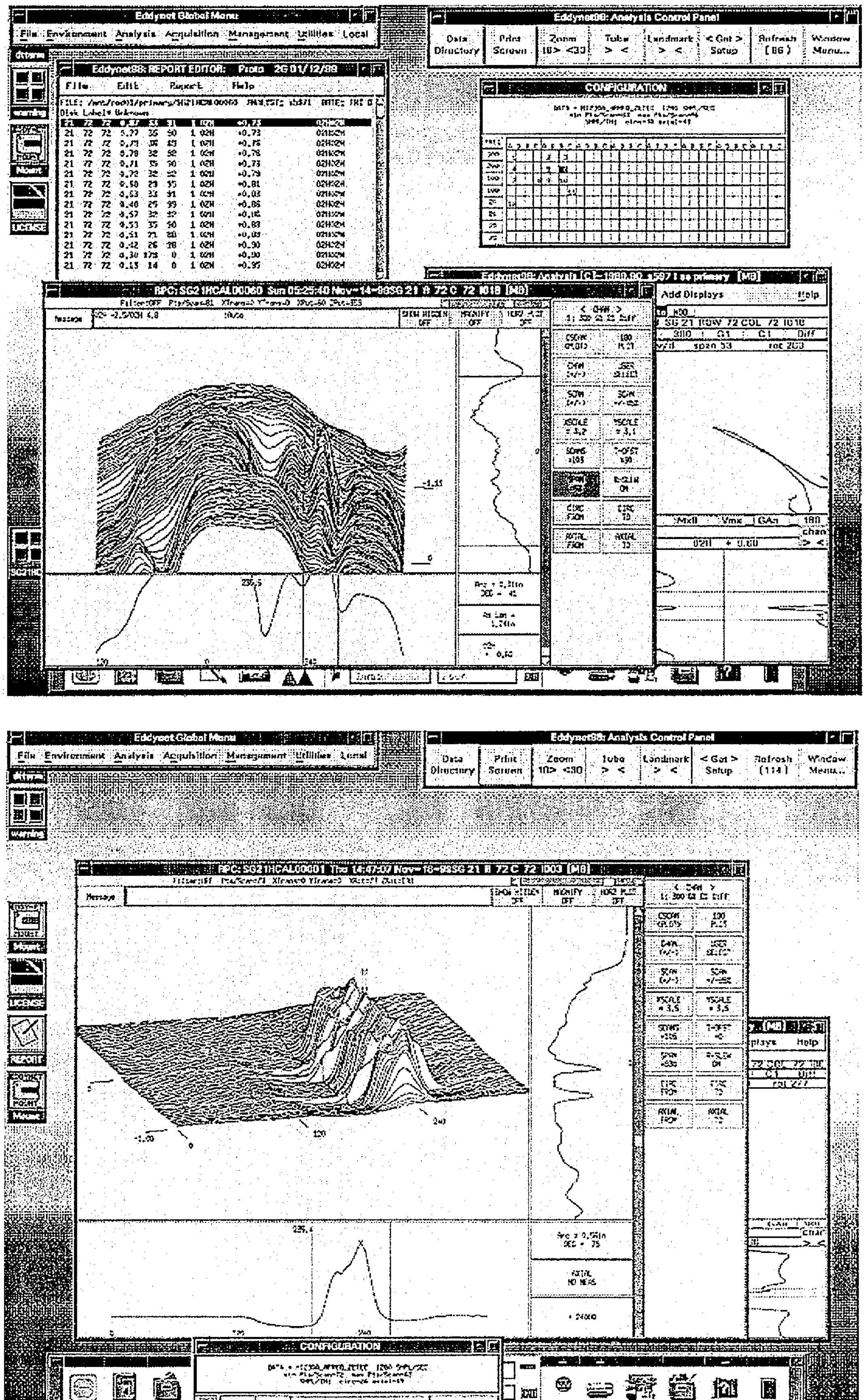


Figure 2. ANO-2 R72C72 Pre and Post In Situ 115 Pancake Coil 300/100 kHz Mix Response

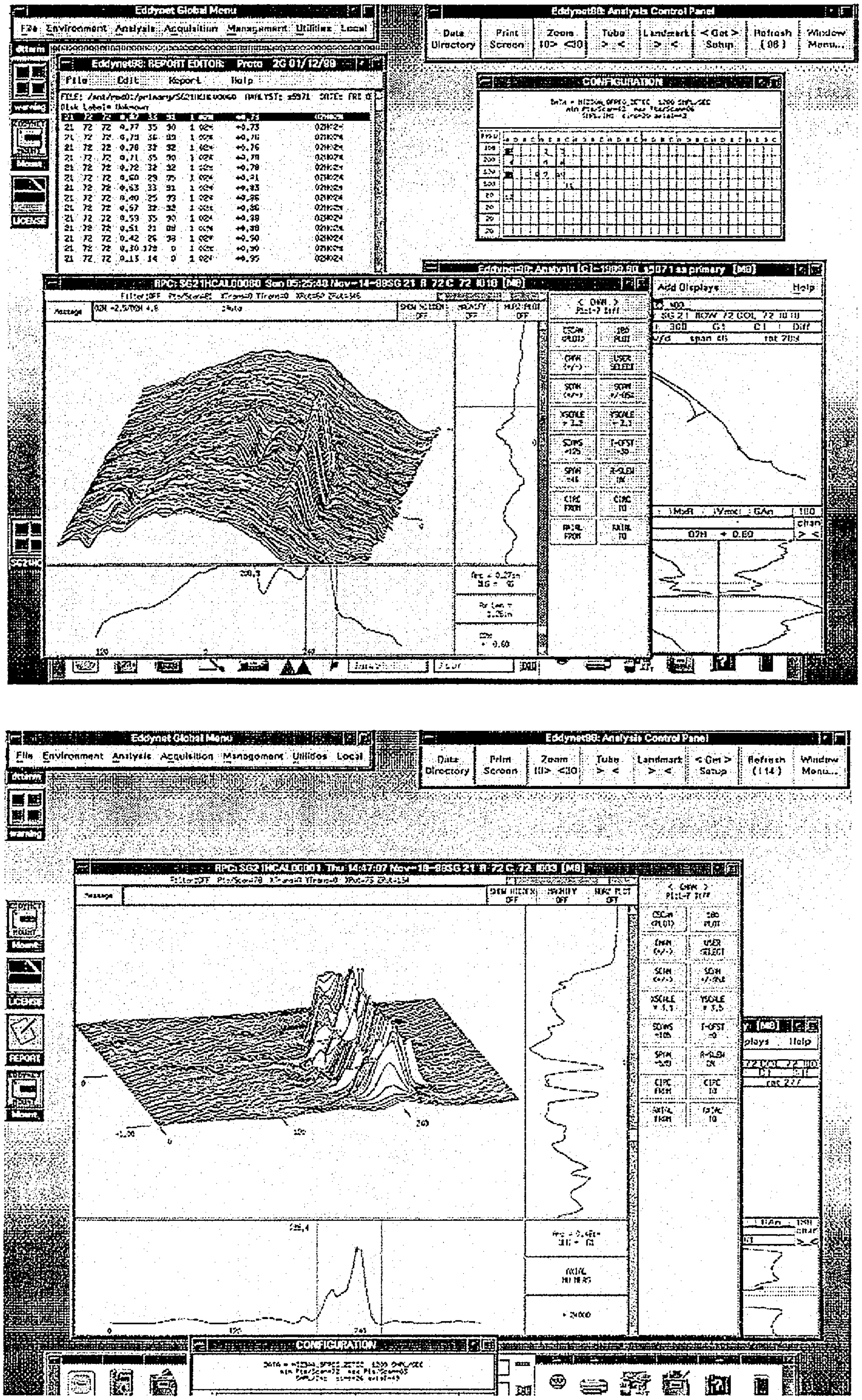
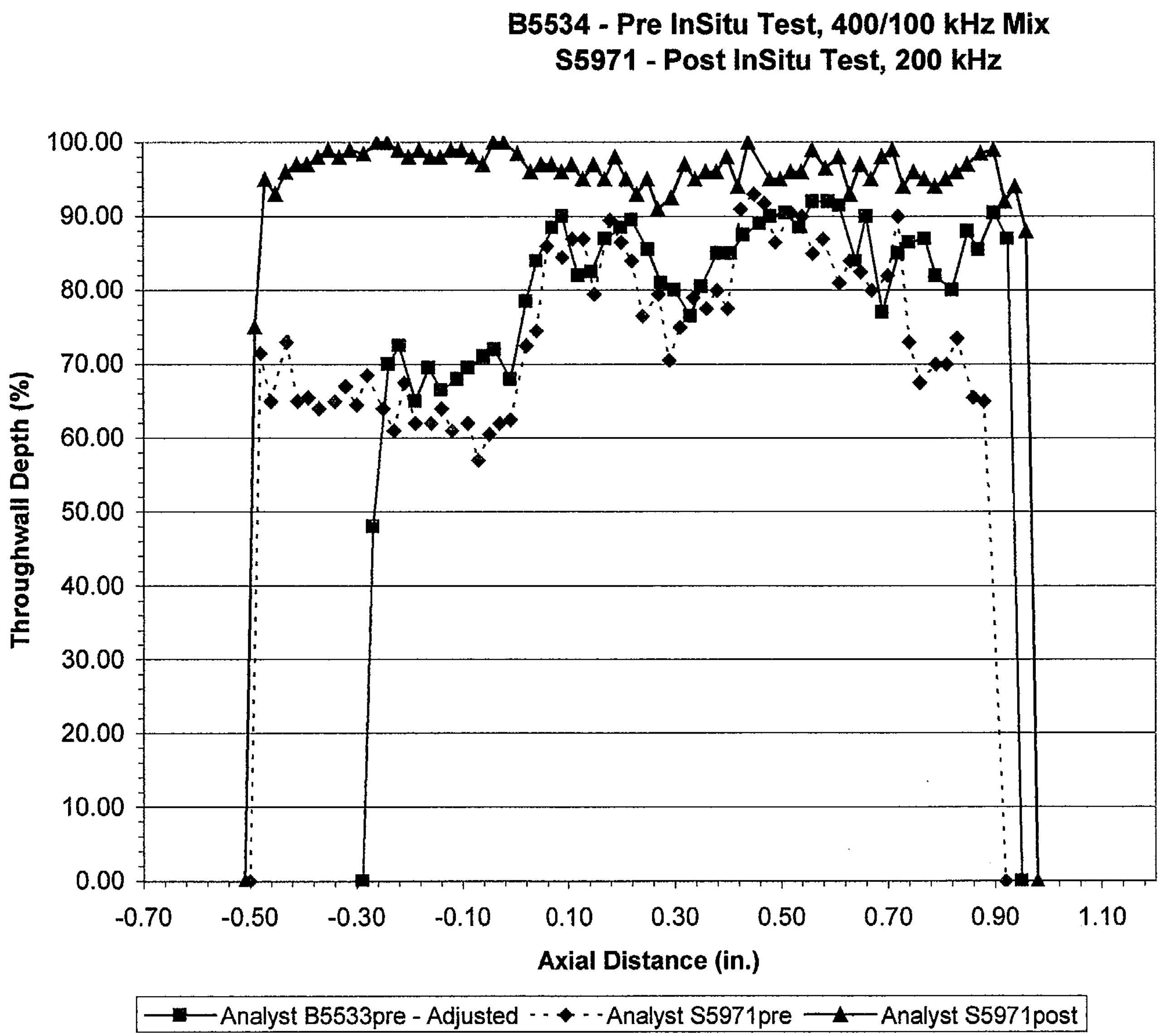


Figure 3. ANO-2 Pre and Post In Situ Depth Profiles from 300/100 kHz Mix Data



	Adjusted Pre B5534	Pre S5971	Post S5971
Length	1.24	1.42	1.49
Max. Volts	0.99	0.92	21.64
Max. Depth (%)	92.0	93.0	100.0
Avg. Depth (%)	79.9	73.1	95.0

Figure 4. Throughwall Slot 115 Pancake Coil 300 kHz Response

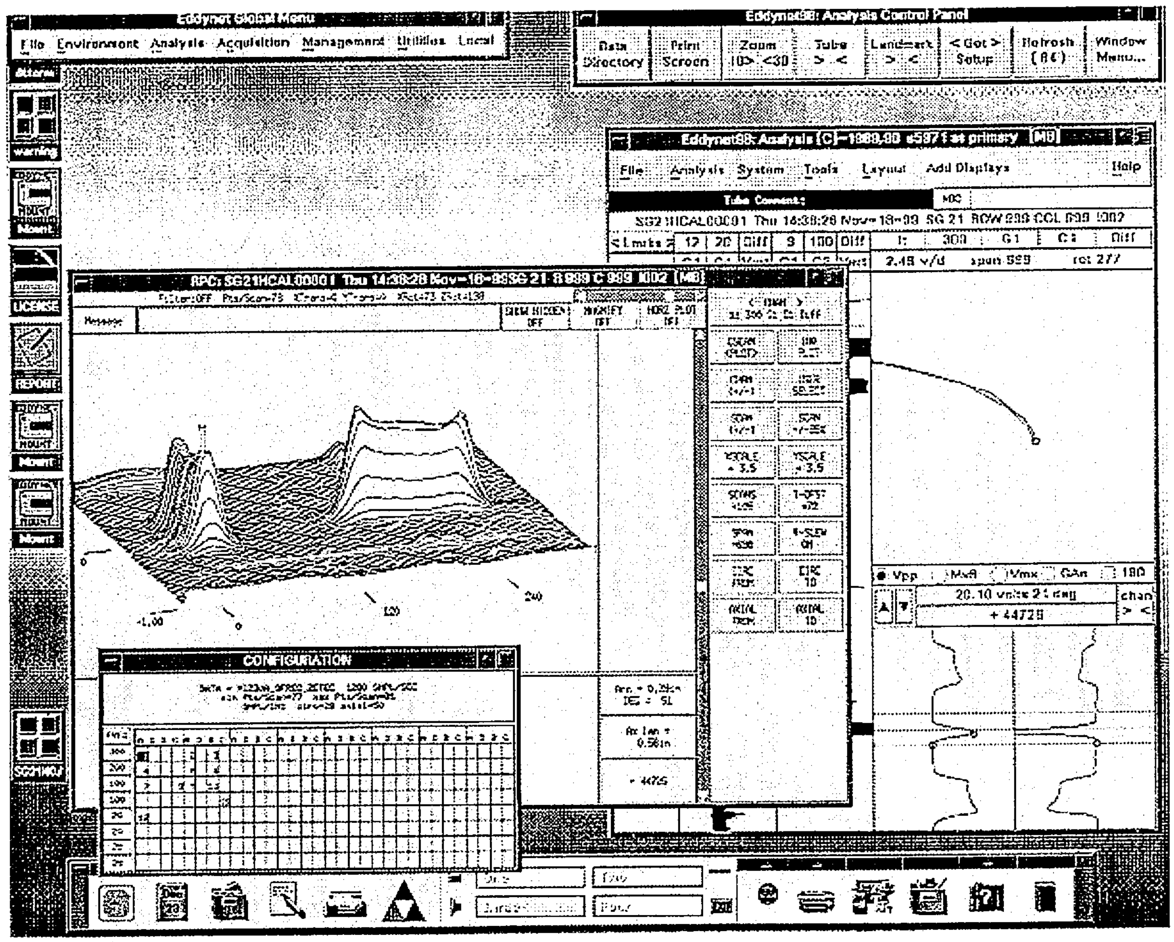


Figure 5. ANO-2 R16C60 1996 Pre and Post In Situ 115 Pancake Coil 400 kHz Response

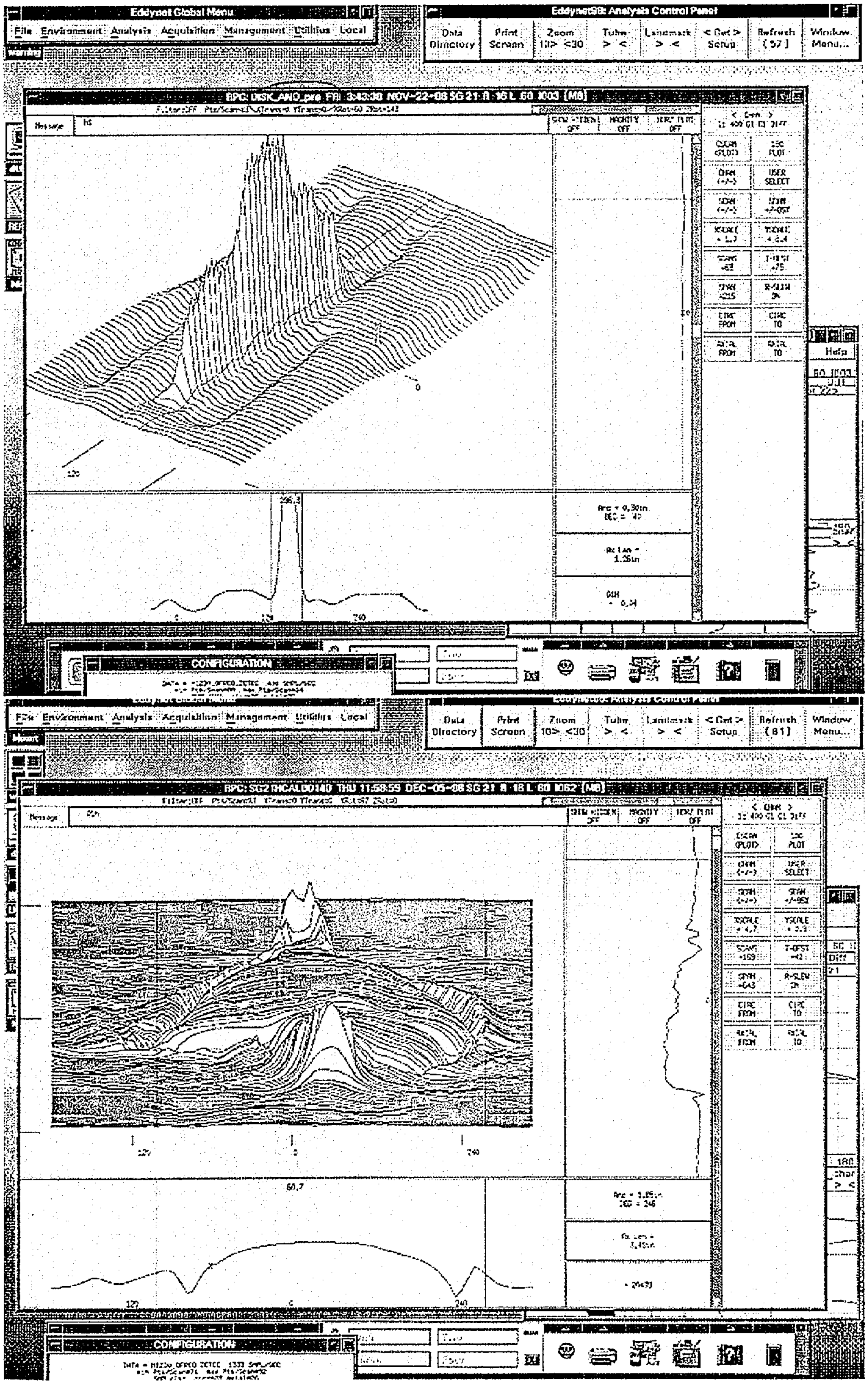


Figure 6. Post Burst Test Photo of Four Burst Openings with Varying Length and Width

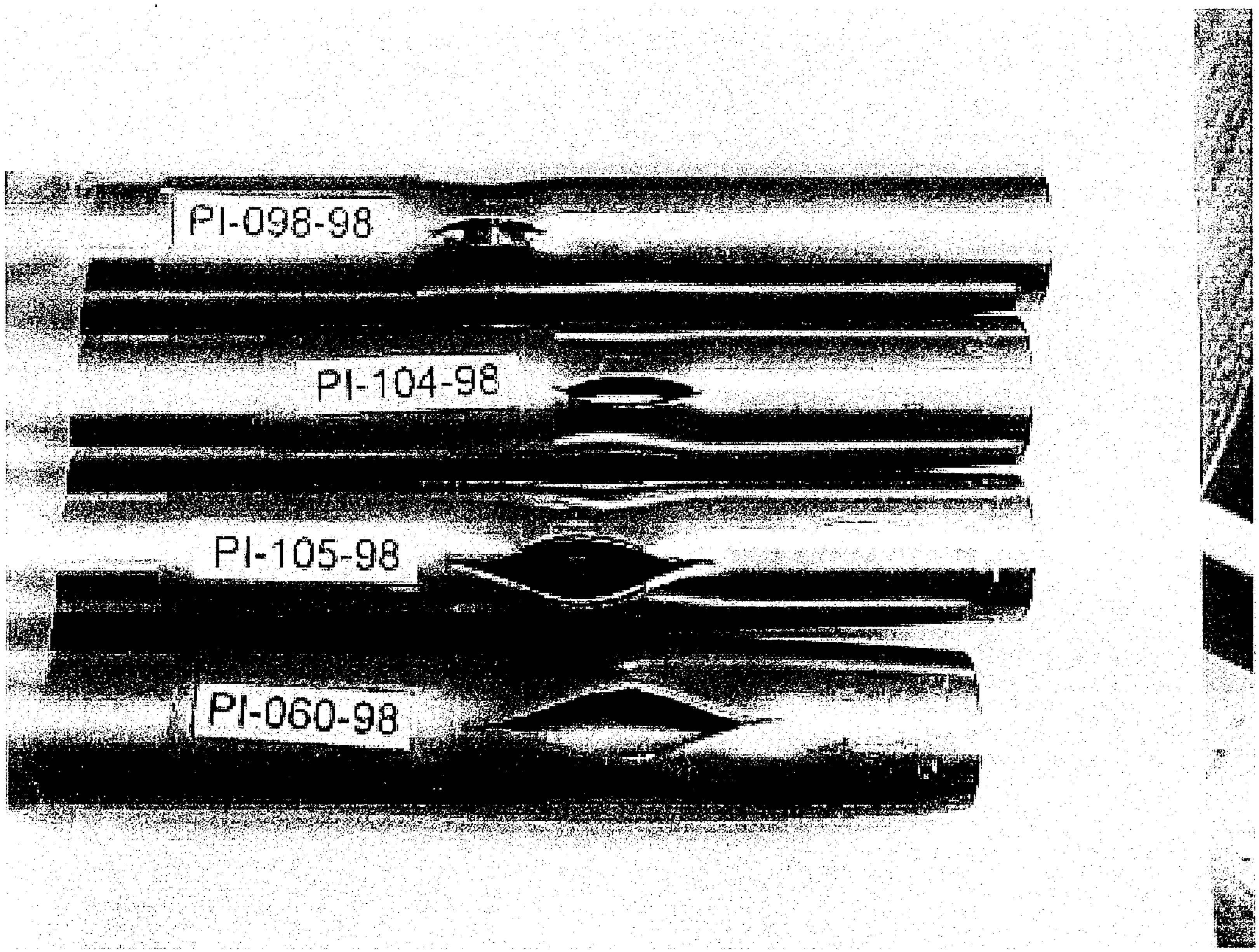
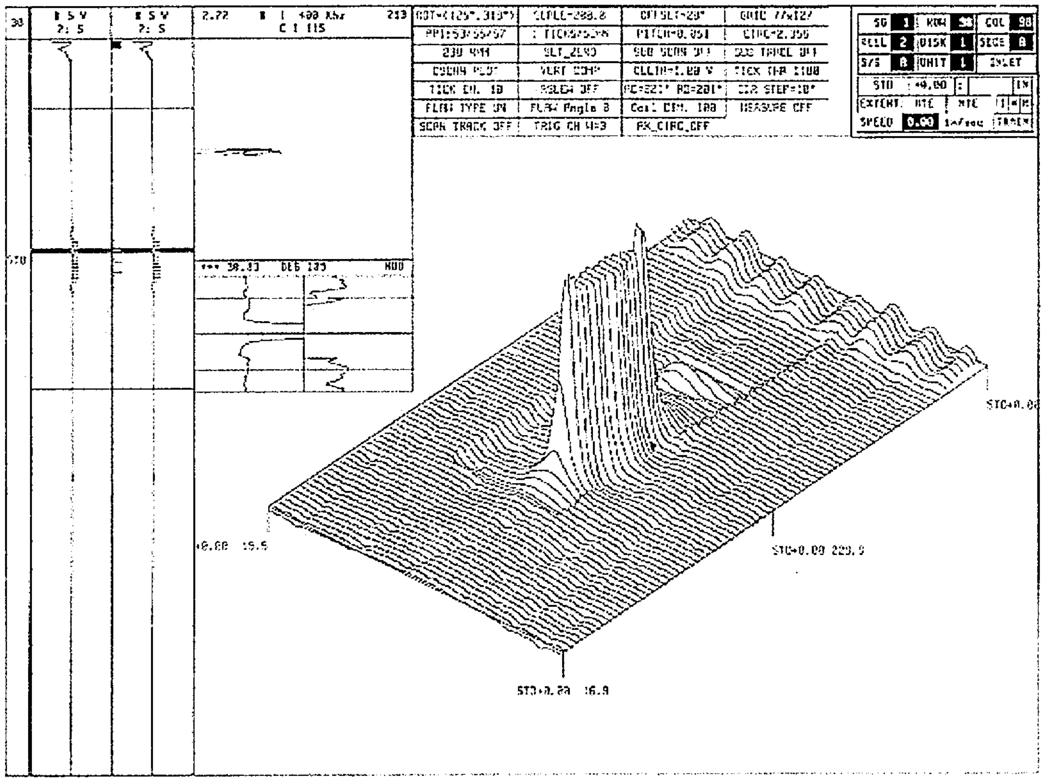


Figure 7. Specimens PI-098-98 and PI-104-98 Post Burst Test 115 Pancake Coil 400 kHz Response (Taped Opening)



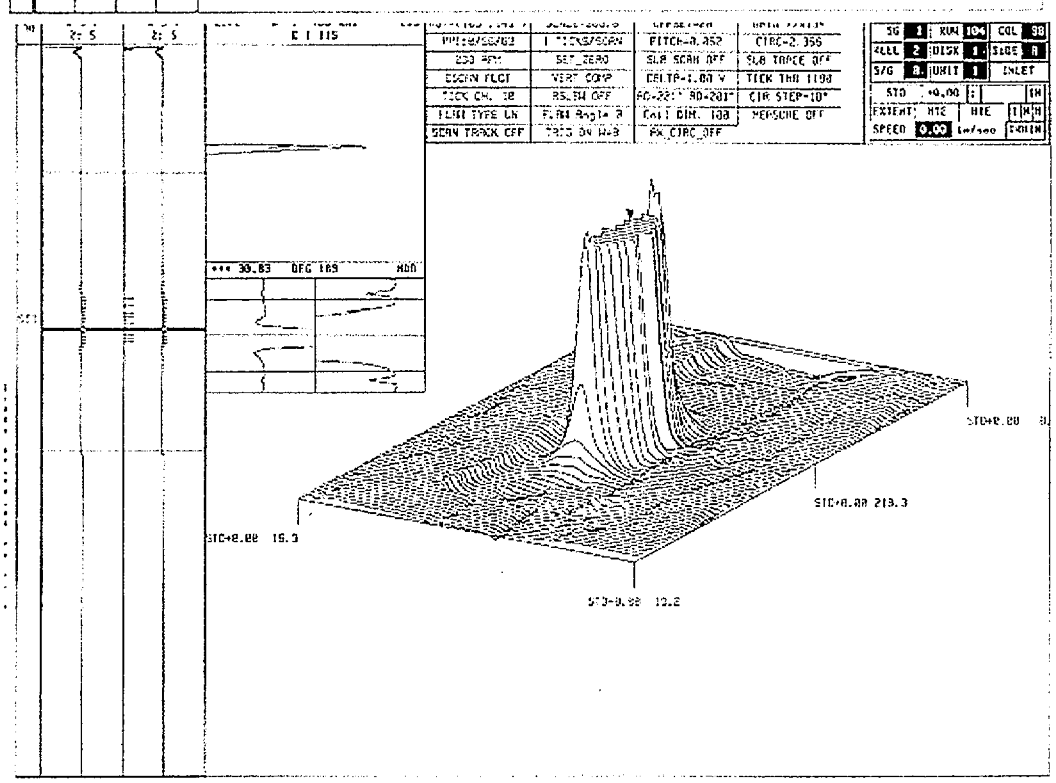
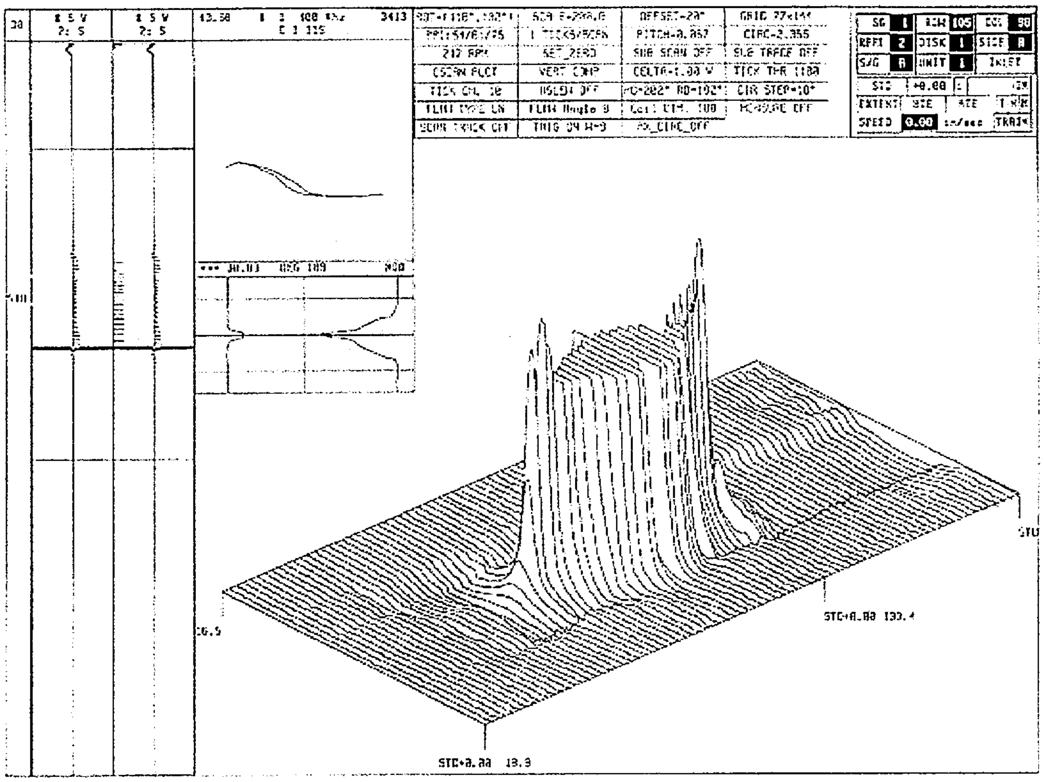


Figure 8. Specimens PI-105-98 and PI-060-98 Post Burst Test 115 Pancake Coil 400 kHz Response (Taped Opening)



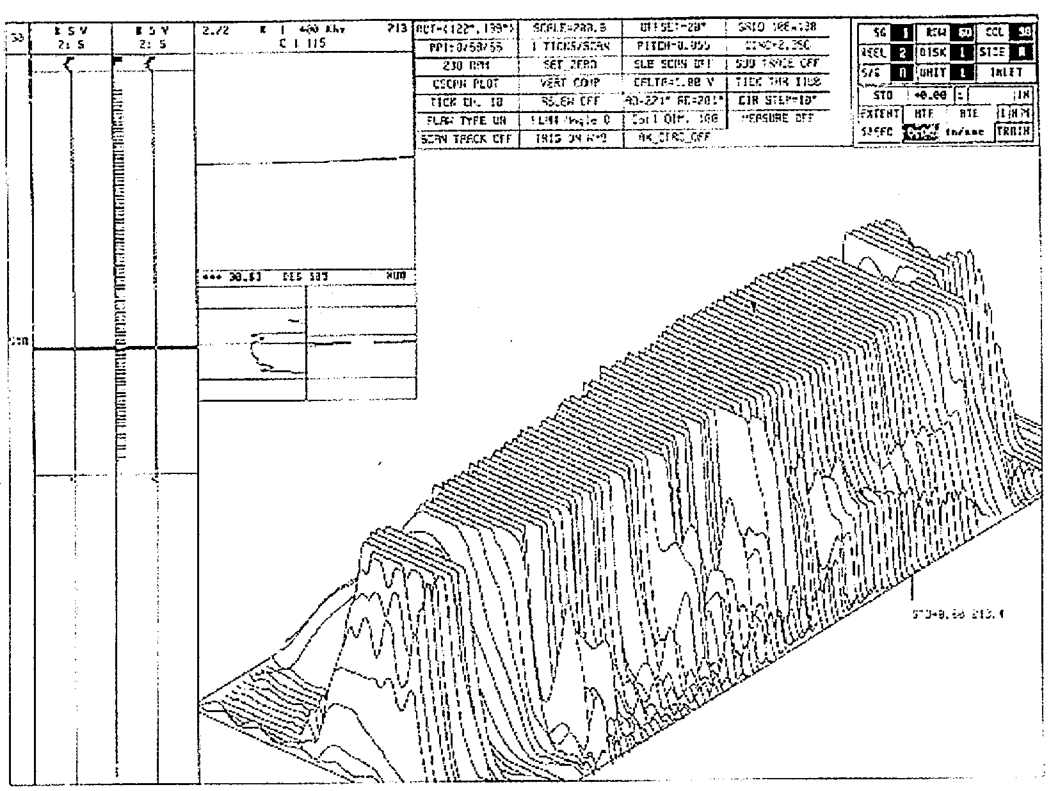
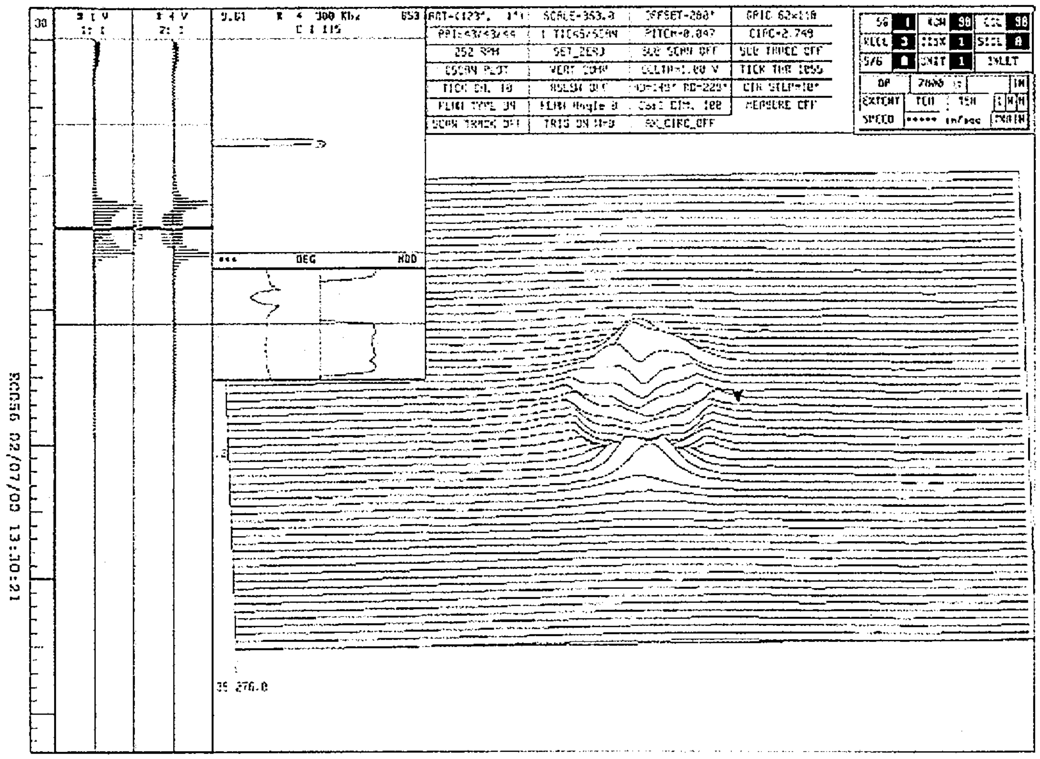


Figure 9. Specimens PI-098-98, PI-104-98 and PI-105-98 Post Burst Test 115 Pancake Coil 300 kHz Response



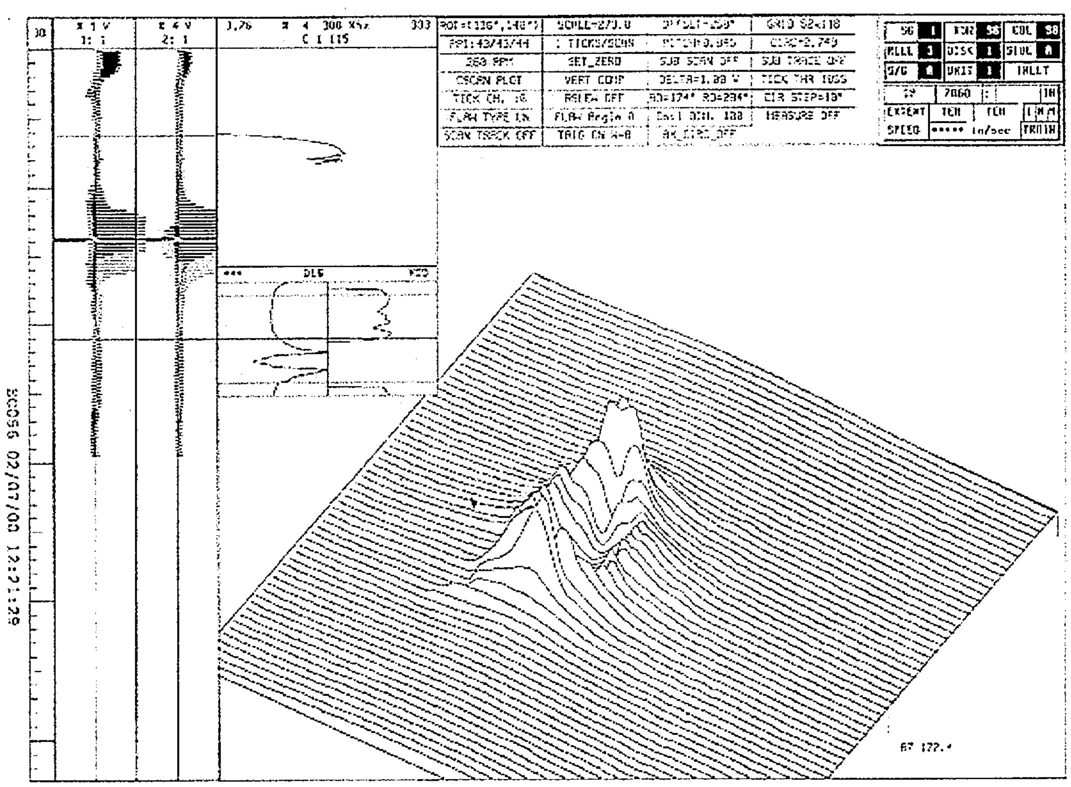
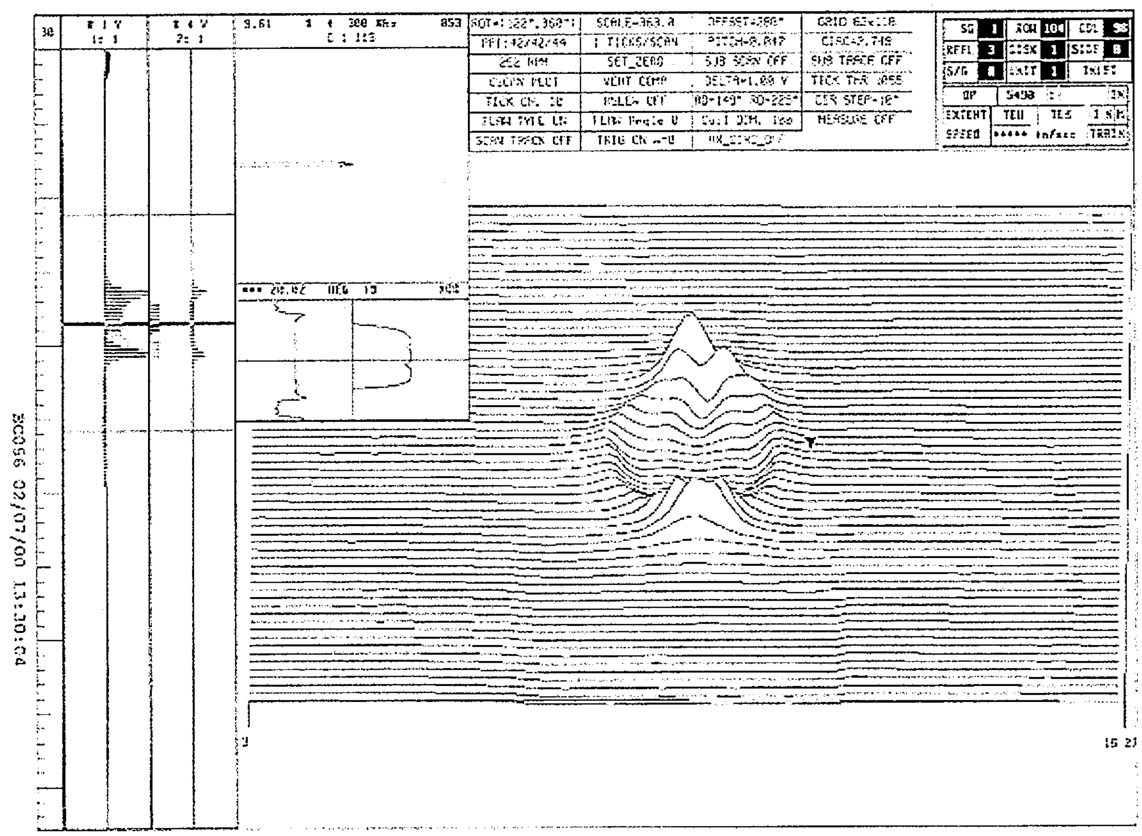
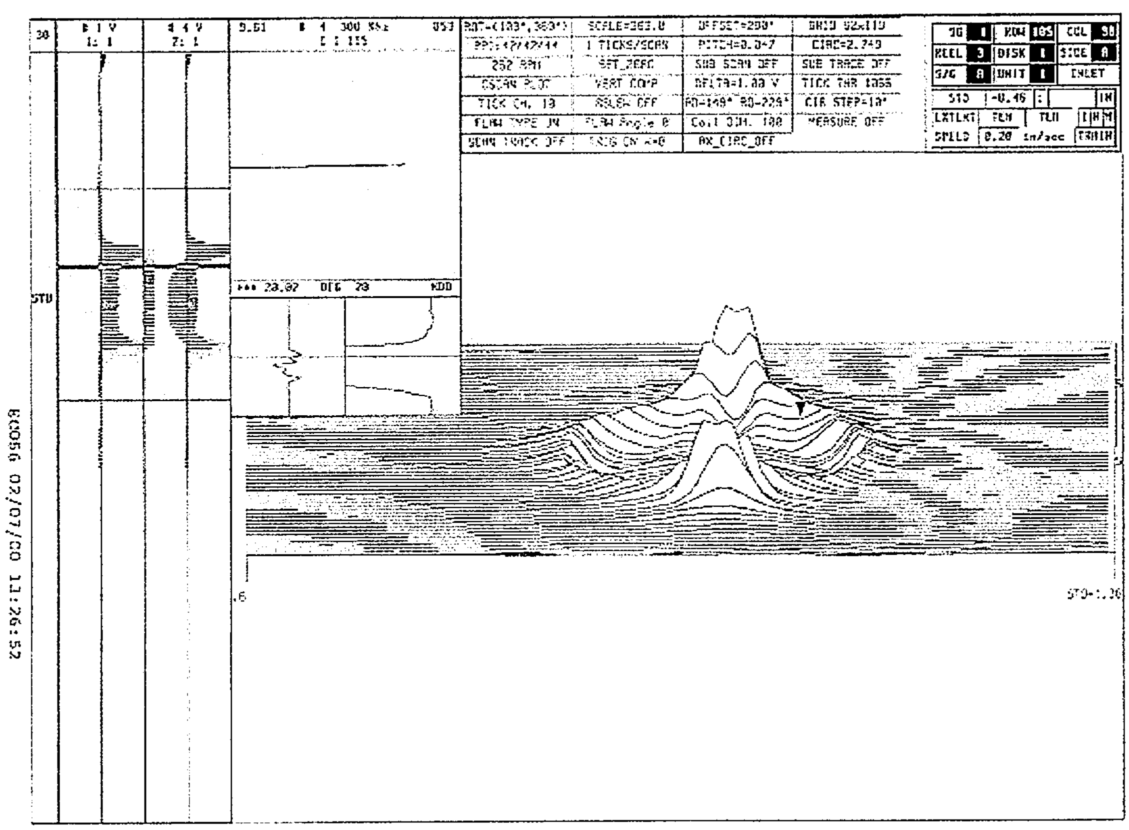


Figure 9. Specimens PI-098-98, PI-104-98 and PI-105-98 Post Burst Test 115 Pancake Coil 300 kHz Response (Continued)





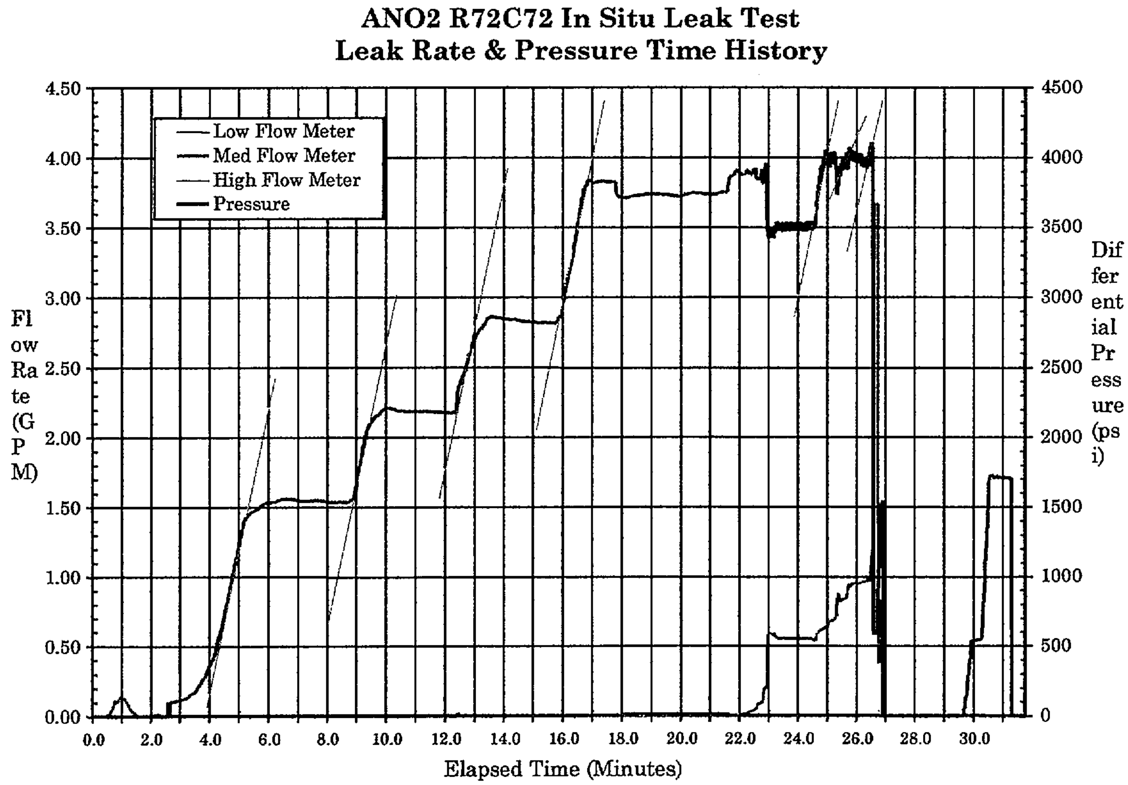


Figure 10

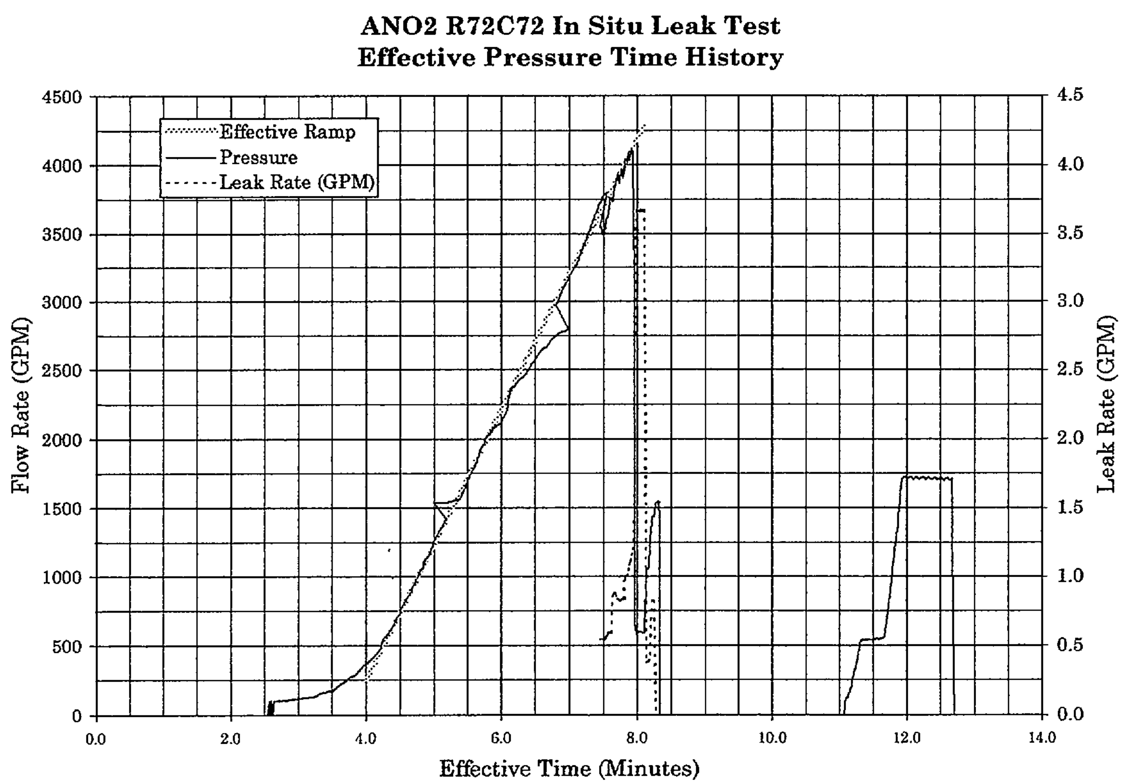


Figure 11

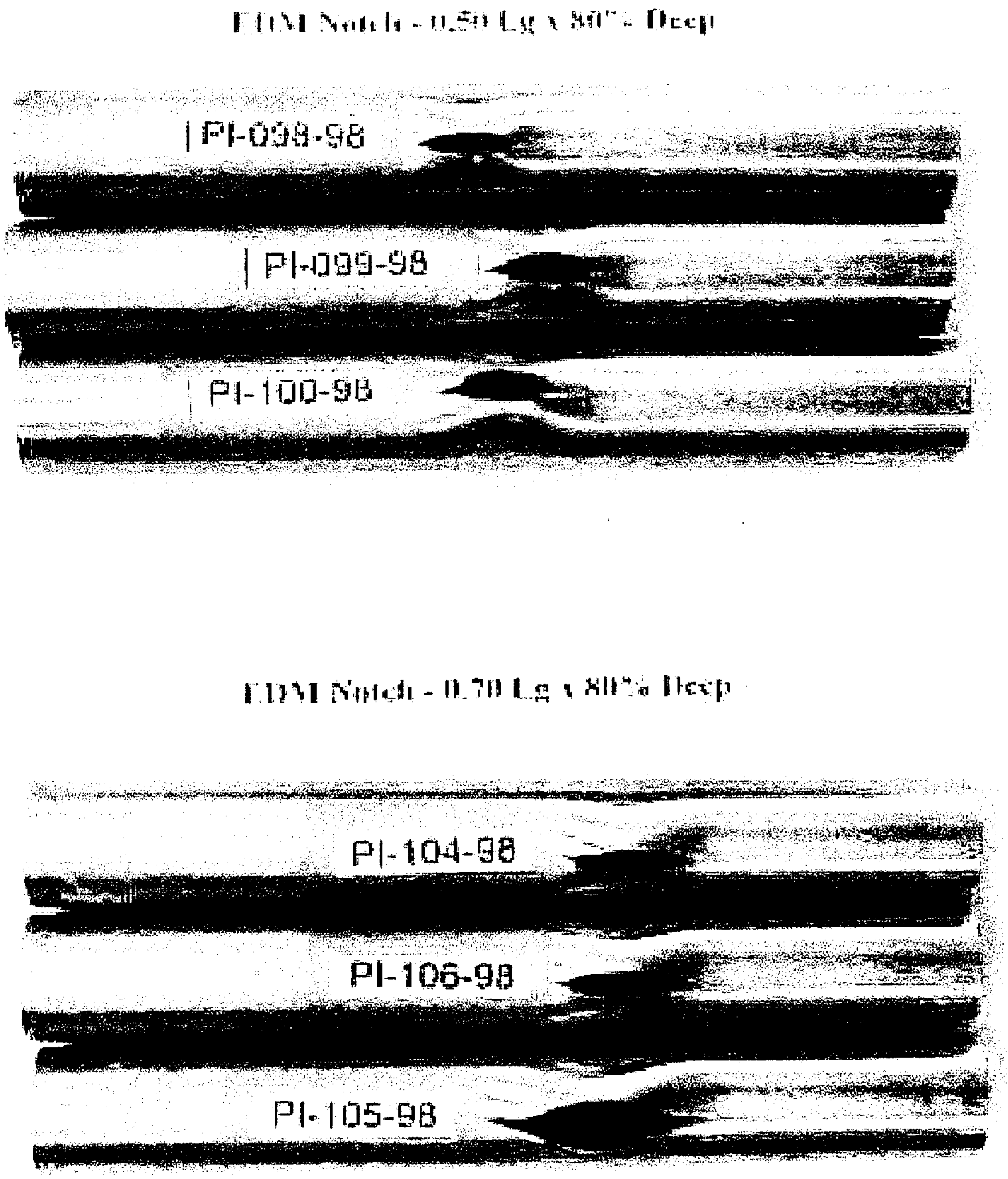


Figure 12. Photo of Burst Test Openings for Incomplete and Complete Bursts