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Eddy Current Inspection of INCONEL-600 Steam Generator Tubes at the Tube Sheet

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ABSTRACT

The ability of eddy current inspection to detect and size flaws in Inconel 600 steam generator tubing at the tube sheet was studied. Single frequency absolute, single frequency differential, and multi-frequency differential eddy current tests were conducted on small, medium, and large volume defects placed into a simulated tube sheet. Position of each defect was varied with respect to the surface of the tube sheet. Results are presented on detectability and sizing of the defects versus measurement method, location of the defect relative to the tube sheet surface, and defect volume.

SUMMARY

This laboratory investigation of flawed steam generator tubing examined three test cases: (1) Case A - flaw is positioned under the tube sheet; (2) Case B - flaw is half under the tube sheet, and (3) Case C - flaw is above tube sheet. Single-frequency differential and absolute eddy current test results are presented for each test case. The results showed that multiple-frequency eddy current testing was clearly able to detect and size medium (elliptical wastage) and large (uniform thinning) wastage flaws that were as small as 20% of the tube wall thickness (nominal 0.050 inch) in depth for each of three cases studied. Multiple-frequency eddy current results showed that electro-discharge machine (EDM) slots ($\sim$ 0.20 inch long) that were less than 30% of the wall thickness in depth were not detected for each test case. EDM slots greater than 30% of the wall thickness in depth were clearly detected and sized in depth for each test case.

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INTRODUCTION

Eddy current inspection of flawed Inconel-600 steam generator tubes was performed under laboratory conditions. Tube specimens with machine induced flaws, typical of reported service flaws, were measured using both single-frequency and multiple-frequency eddy current testing techniques. The object of this test program was to provide initial baseline measurement data that will show current flaw measurement capability for both single-frequency and multiple-frequency eddy current testing techniques about the tube sheet region in steam generators.

TUBE FLAW MATRIX

A 4 inch long section of carbon steel with a bored center section to accept the steam generator tubing was used to simulate the tube sheet. Inconel-600 tubes, with a diameter of 0.875 inches and wall thickness of 0.05 inches, were used in the program. An annulus of 0.008-0.010 inches existed between the Inconel tube and simulated tube sheet. Figure 1 shows the three types of machined flaws that were tested. Elliptical wastage is considered to be a medium volume wastage flaw, whereas uniform thinning wastage is considered to be a large volume wastage flaw. Electro-discharge machined (EDM) slots are crack type flaws and are small in volume. Because of the unavailability of a 100% throughwall EDM slot, a stress corrosion crack specimen with a 100% throughwall crack was substituted in the flaw matrix. Tables 1, 2, and 3 show flaw dimension data for elliptical wastage, uniform thinning wastage and EDM slot tubes.

TEST METHOD

In order to assess eddy current measurement capability at the tube sheet region, three test cases were considered. Figure 2 shows the three cases of interest with elliptical wastage as an example. Case A shows the flaw under the tube sheet. Case B shows the flaw position one half under the tube sheet. Case C shows the leading edge of the flaw approximately 3/16 to 1/4 inch above the tube sheet.

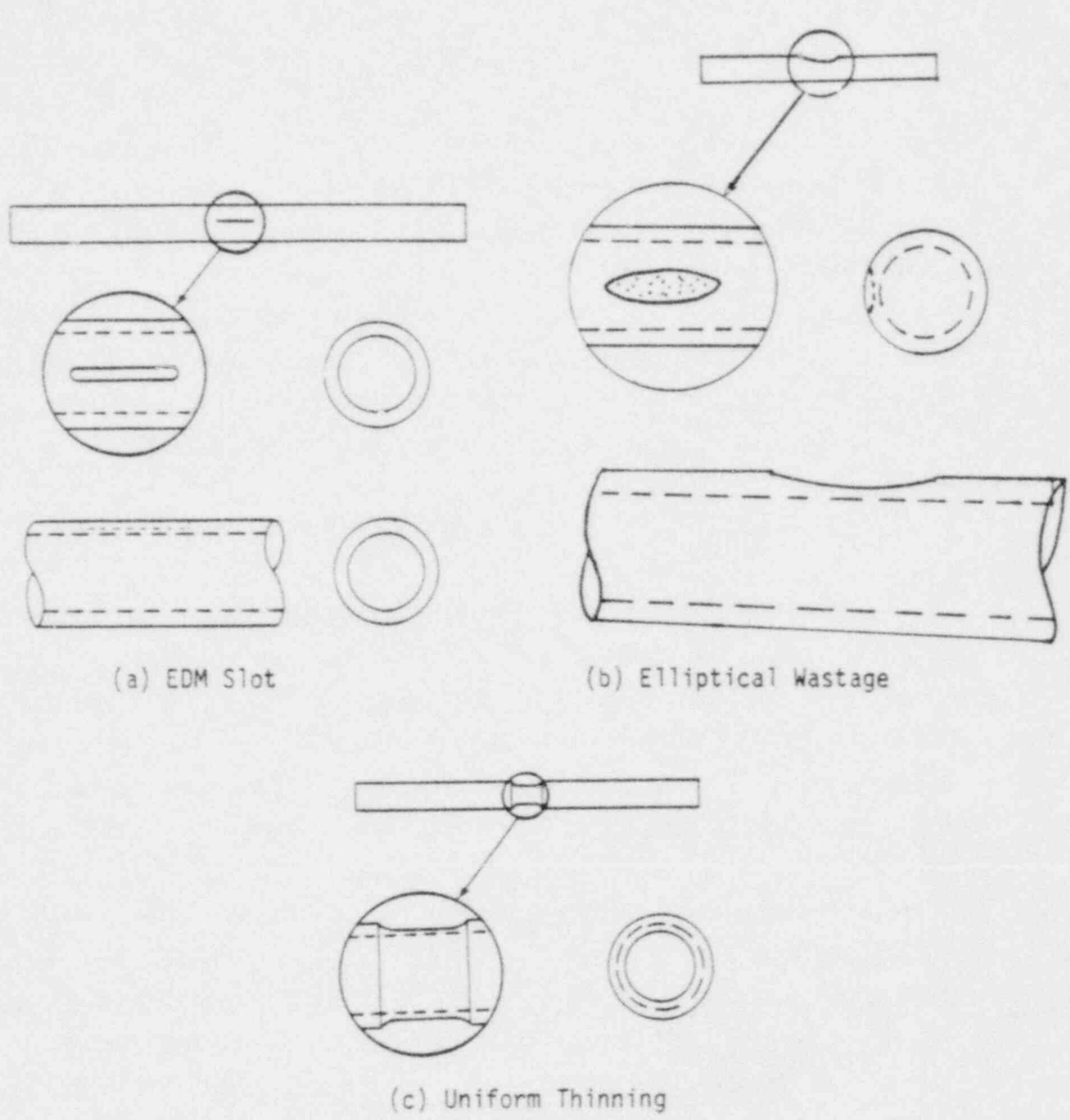


FIGURE 1. EDM Slots, Elliptical Wastage, and Uniform Thinning Wastage Flaw Specimens

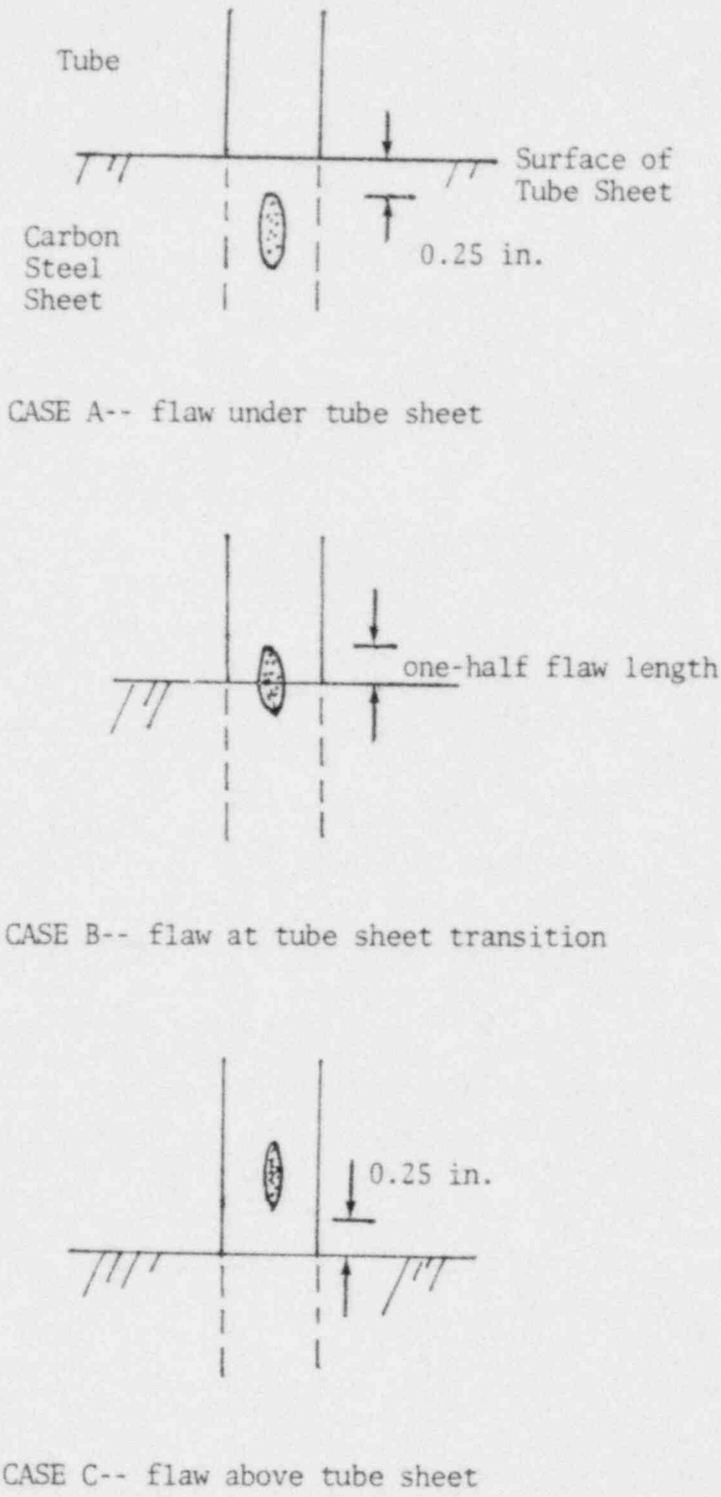


FIGURE 2. Flawed Tube Test Case A,B, and C at the Tube Sheet

TABLE 1

ELLIPTICAL WASTAGE FLAW DIMENSIONS

DEPTH (% Wall)	LENGTH (Inch)	WIDTH (Inch)
80.2	1.40	0.380
66.0	1.23	0.342
43.0	0.98	0.280
22.0	0.72	0.208

TABLE 2

UNIFORM THINNING WASTAGE FLAW DIMENSIONS

DEPTH (% Wall)	LENGTH (Inch)
80	0.280
62	0.280
41	[illegible].280
22	0.280

TABLE 3

EDM SLOT FLAW DIMENSIONS

TUBE NO.	SLOT NO.	DEPTH (% Wall)	LENGTH (Inch)	WIDTH (Inch)
PNL-1	D-3	20	0.195	0.0035
PNL-1	F-2	28	0.205	0.005
PNL-2	G-2	36	0.185	0.0035
A-21	H	50	0.250	0.010
PNL-2	H-1	63	0.190	0.011
PNL-2	I-1	71	0.190	0.005
PNL-2	J-1	80	0.180	0.007
PNL-2	M-1	92	0.210	0.016
B-46-4	SCC	100[a]	0.720	0.0015

[a] Single-frequency ECT indicates SCC crack has varying depth from 80% to 100% wall.

The American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Appendix IV (referred: ASME Code) has specific calibration and procedure requirements for the single-frequency eddy current testing of steam generator tubes. The calibration and procedure requirements dictated by the ASME Code were followed in this test program. Test results represent measurements taken by a single operator. Multi-scans were conducted to assure repeatability.

Single-frequency differential eddy current testing (SFDECT) is the current as-practiced technique for inspection of steam generator tubing. Single-frequency absolute eddy current testing (SFAECT) has also been employed in the inspection of steam generator tubing[a]. Multiple-frequency differential eddy current testing (MFDECT) is now being used on a routine basis for in-service inspection of steam generator tubing. A three frequency eddy current instrument was used in this test program. Frequencies of 200 kHz, 400 kHz, and 1.6 MHz are electronically mixed in order to cancel extraneous tube sheet/support plate signals and probe wobble (noise). The 200 kHz and 400 kHz frequencies are mixed to cancel tube sheet/support plate signals. The 1.6 MHz and 400 kHz frequencies are mixed to cancel probe wobble. The MIZ-12[b] multiple-frequency eddy current inspection system was used to inspect tubing at Point Beach. This system uses a two frequency mix. It was reported [c] that frequencies of 100 kHz and 400 kHz were used for the Point Beach inspection. It is anticipated that there is little difference in the 100 kHz versus 200 kHz mix.

EDDY CURRENT RESULTS

FLAW EVALUATION

The results of the SFDECT and SFAECT are shown in Figures 3 through 7 and Table 4. The results of the MFDECT are shown in Figures 8, 9, and 10. The single-frequency and multiple-frequency test results were analyzed and evaluated using video and analog signal data. Three distinct flaw evaluation categories were determined from the analysis.

(a) Rochester Gas and Electric Corporation, R. E. Ginna 490Mwe Plant.

(b) Zetec, Inc., Issaquah, WA.

(c) Mr. J. C. Hagood, Westinghouse Electric Corporation, Pittsburgh, PA.

The categories were (1) flaw clearly detected and sized in depth, (2) flaw detected only - unable to determine flaw depth, (3) flaw undetected. Further clarification of category (2) is in order and applies specifically to single-frequency data analysis. For the case of small and medium volume flaws located about the tube sheet region (Figure 2, Case B), the dominant effect from the tube sheet signal indication tends to mask flaw signal data. However, flaws of certain depth, length, and width can affect the tube sheet signal indication to the degree that the tube sheet signal is significantly distorted. This then becomes the means whereby skilled eddy current data interpreters would be alerted to the presence of some flaw anomally in this region of interest. Hence, if distorted sheet signals are observed, the interpreter would assume a flaw existed in the region; however, estimating flaw depth from pattern phase or analog data interpretation is difficult, if not impossible. One could make a qualitative estimate of the flaw depth based on known signal response data generated from laboratory samples or actual pulled tubes from service generators. To conclude, the interpreter is alerted to the flaw presence at the tube sheet transition region (Case B) by the distorted sheet signal.

SINGLE-FREQUENCY DIFFERENTIAL TEST RESULTS

Figure 3 shows the SFDECT results for elliptical wastage specimens for test Cases A, B, and C. The results show that elliptical wastage flaws with depths of 43% of the wall thickness (% wall) and greater were either detected or clearly detected and sized in each case. An elliptical wastage flaw 22% wall in depth went undetected for test Cases A and B. This flaw was clearly detected and sized in Case C.

Figure 4 shows the SFDECT results for uniform thinning wastage specimens for test Cases A, B, and C. The results show that uniform thinning wastage is clearly detected and sized in each case.

Figure 5 shows the SFDECT results for EDM slot specimens for test Cases A, B, and C. The results show that small EDM slots (length approximately 0.20 inch) less than 30% of the wall in depth went undetected in each case. An EDM slot that was 36% of the wall in depth was clearly

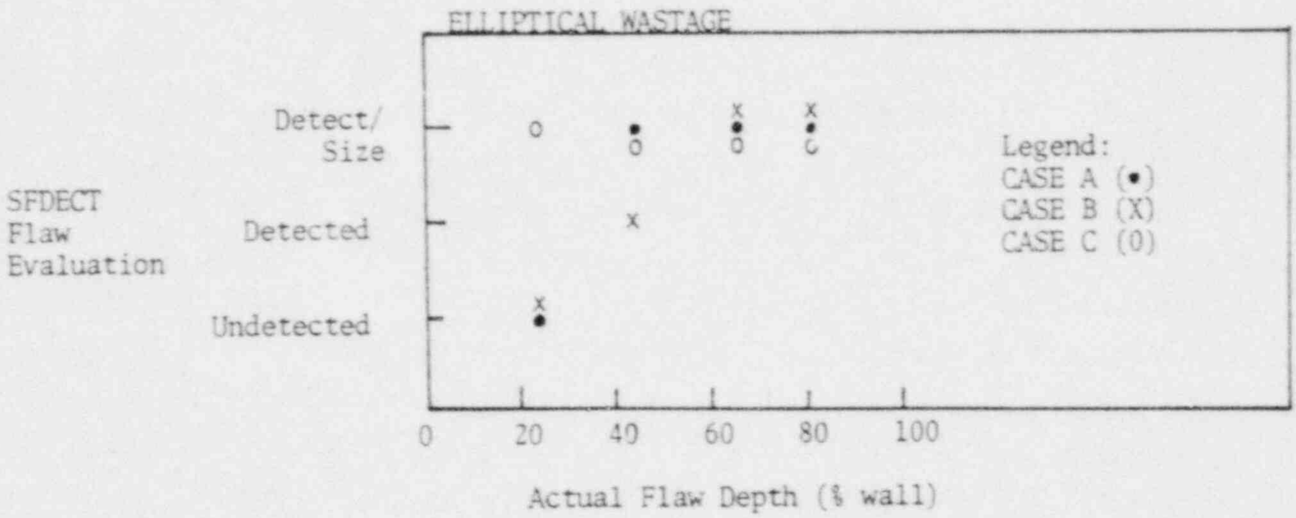


FIGURE 3. Elliptical Wastage Results for SFDECT

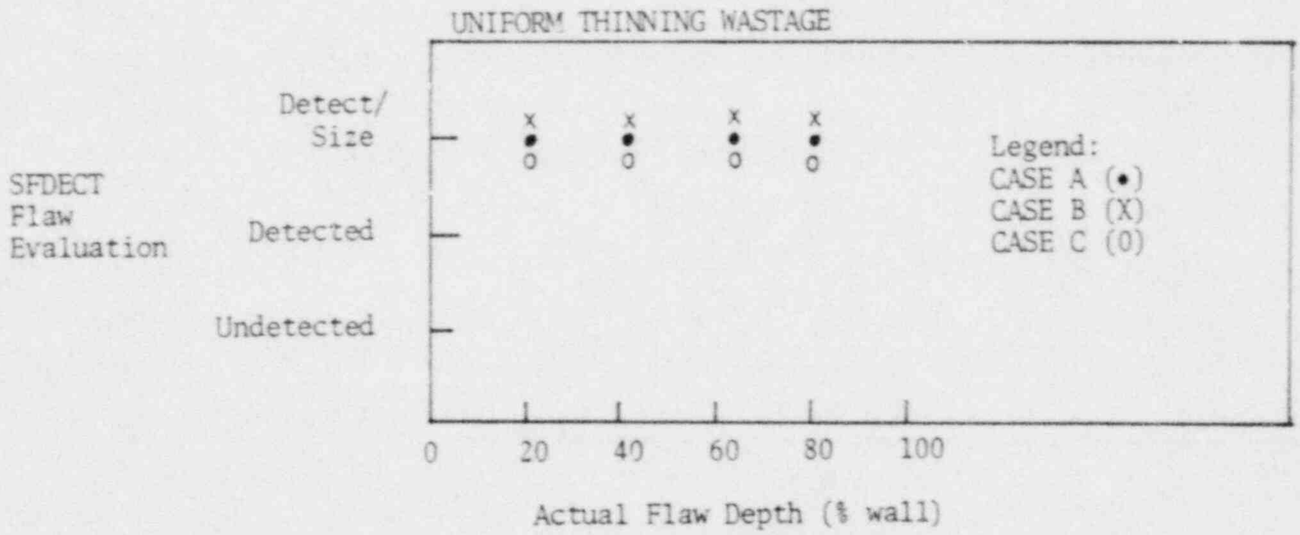


FIGURE 4. Uniform Thinning Wastage Results for SFDECT

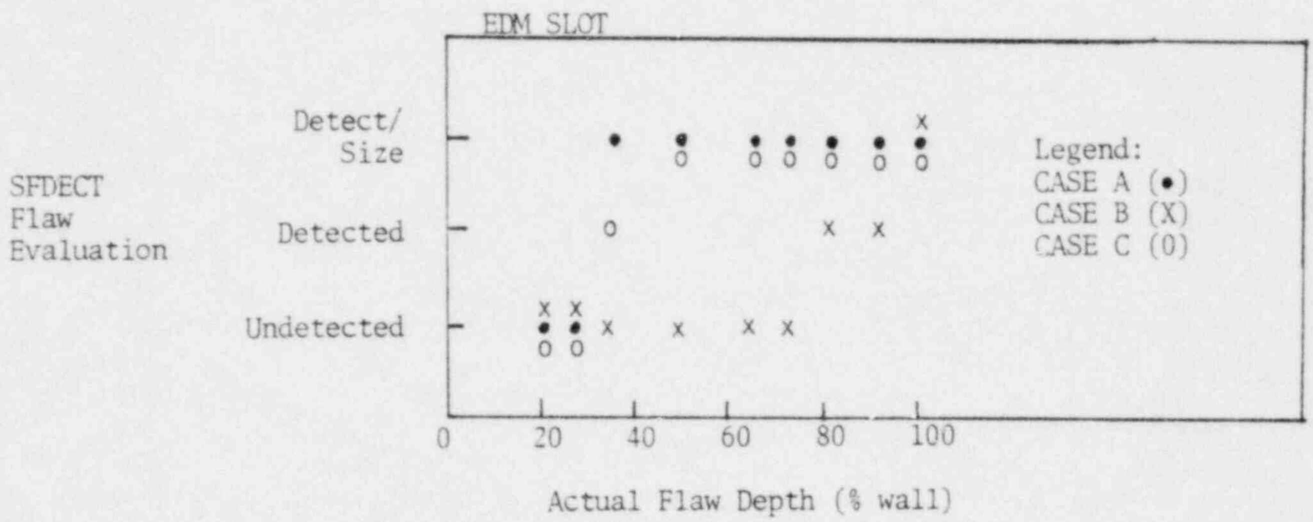


FIGURE 5. EDM Slot Results for SFDECT

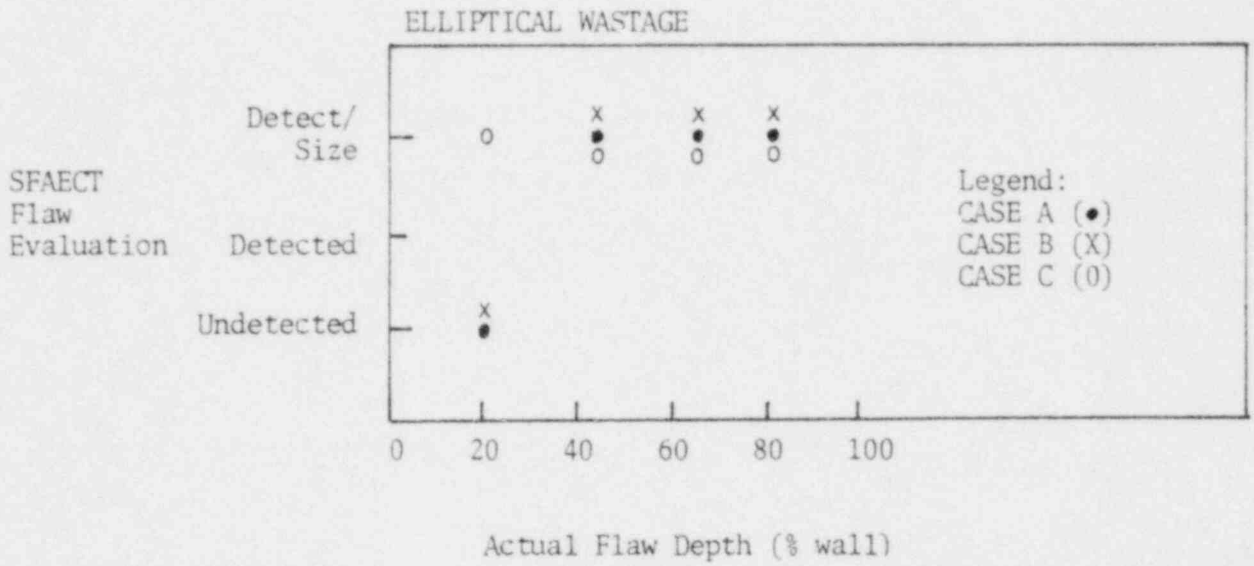


FIGURE 6. Elliptical Wastage Results for SFAECT

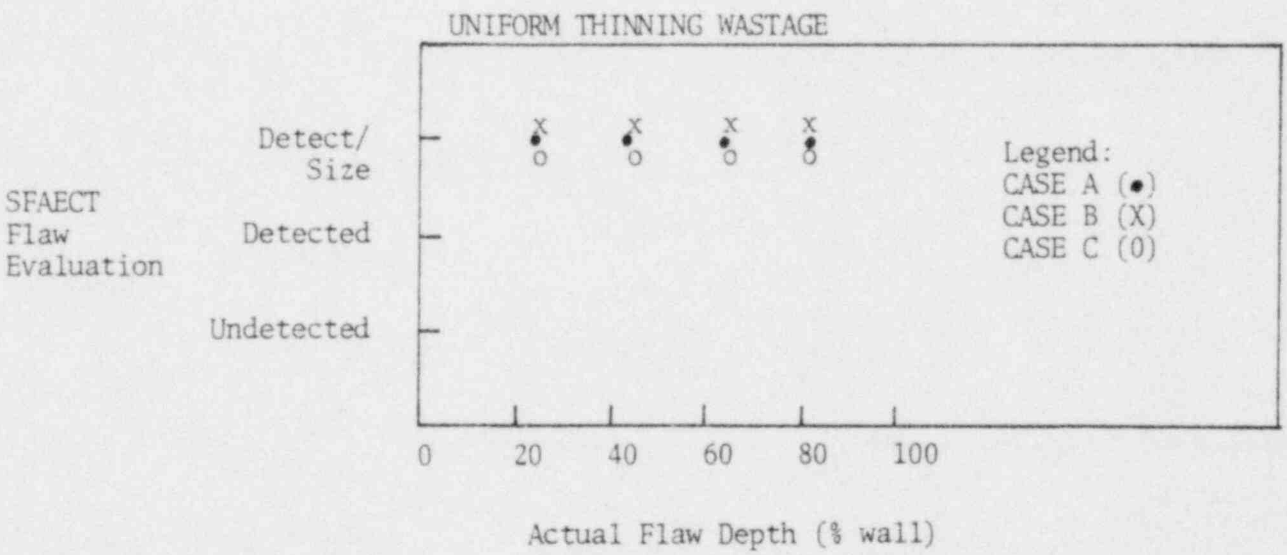
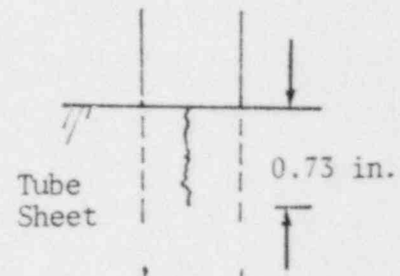
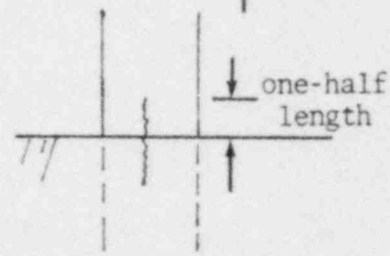
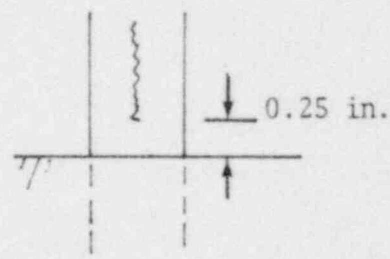


FIGURE 7. Uniform Thinning Wastage Results for SFAECT

TABLE 4. Single-Frequency Absolute Test Results for a 100% Stress Corrosion Crack Specimen (B-46-4)

FLAW EVALUATION	TEST CASE	FLAW POSITION
Detected	A	
Detected	B	
Detect/ Size	C	

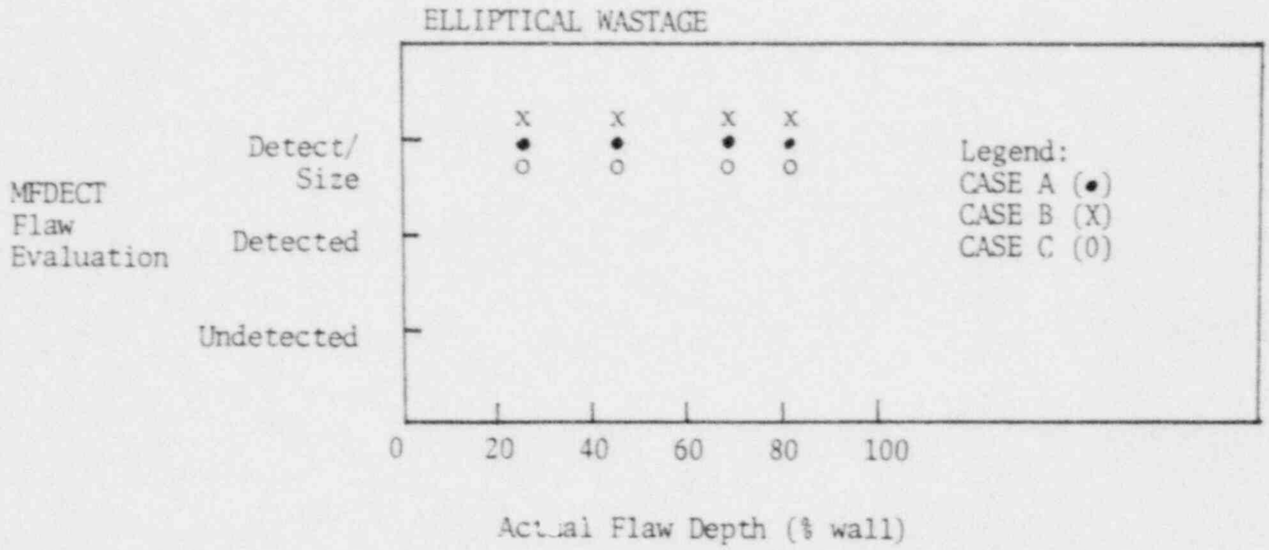


FIGURE 8. Elliptical Wastage Results for MFDECT

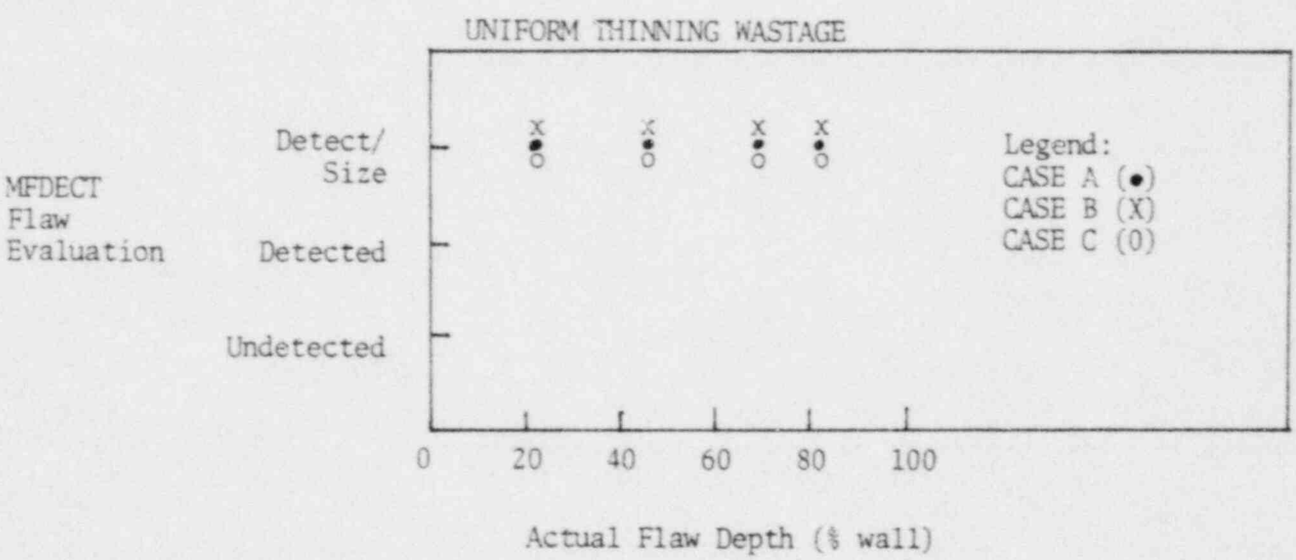


FIGURE 9. Uniform Thinning Wastage Results for MFDECT

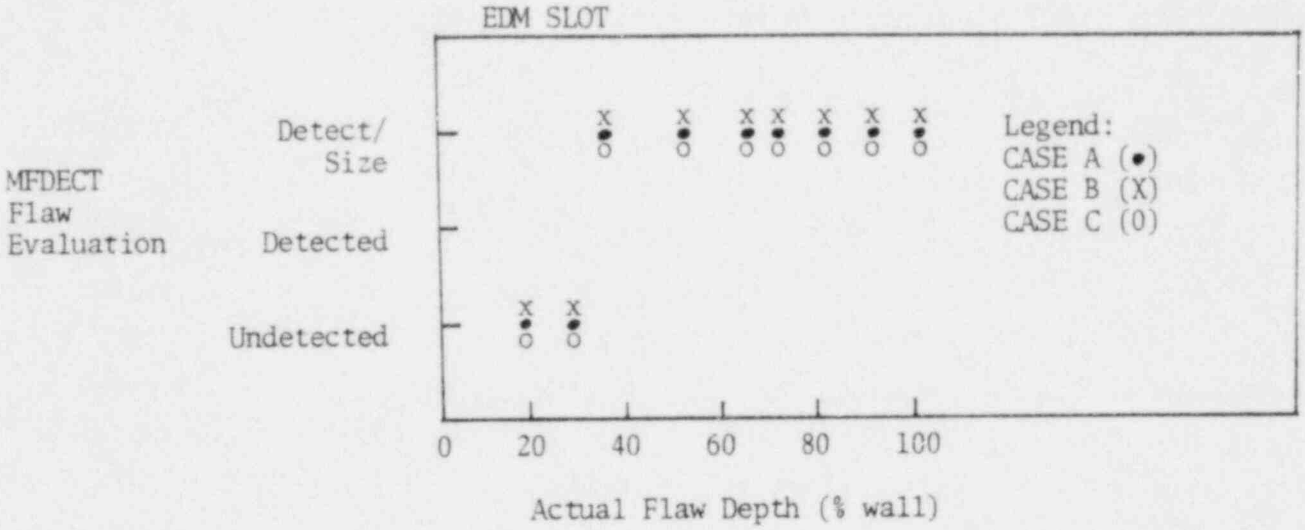


FIGURE 10. EDM Slot Results for MFDECT

detected and sized in Case A, detected in Case C, and undetected in Case B. EDM slots that were 50% of wall and greater in depth were all clearly detected and sized for Case A and Case C. EDM slots 50%, 63%, and 71% of wall were undetected for Case B. Slots 80% and 92% of wall were detected for Case B. The 100% SCC crack was clearly detected and sized in each case.

SINGLE-FREQUENCY ABSOLUTE TEST RESULTS

Figure 6 shows the SFAECT results for elliptical wastage specimens for test Cases A, B, and C. The results show that elliptical wastage flaws with depths of 43% wall and greater were clearly detected and sized in each case. An elliptical wastage flaw 22% of wall in depth went undetected for test Cases A and B; this flaw was clearly detected and sized in Case C. This data is in good agreement with the SFDECT results of Figure 3.

Figure 7 shows the SFAECT results for uniform thinning wastage specimens for test Cases A, B, and C. The results show that uniform thinning wastage is clearly detected and sized in each case. This data duplicates the uniform thinning results of Figure 4 for SFDECT.

Table 4 shows the results from the examination of a 0.72 inch axial stress corrosion crack specimen that is 80% at one end and 100% of wall in depth at the other (viz. depth gradient). This tight crack (width = 0.001 inch) was detected in Cases A and B; it was clearly detected and sized in Case C.

MULTIPLE-FREQUENCY DIFFERENTIAL TEST RESULTS

Figure 8 shows the MFDECT results for elliptical wastage specimens for test Cases A, B, and C. The results show that the elliptical wastage flaws were clearly detected and sized in each case.

Figure 9 shows that the uniform thinning wastage was clearly detected and sized in each case.

Figure 10 shows that EDM slots less than 30% of wall in depth went undetected for each case. EDM slots 36% of wall and greater were clearly detected and sized in each case.

CONCLUSION

The results of this laboratory effort show that multiple-frequency eddy current testing was clearly able to detect and size medium and large volume wastage flaws as small as 20% of the wall thickness in depth. In addition, the multiple-frequency results show that EDM slots (approximately 0.20 inch long) less than 30% of the wall thickness in depth went undetected for each test case. Slots greater than 30% of the wall in depth were clearly detected and sized for each test case.

The single-frequency differential and absolute test results show that elliptical wastage flaws less than 40% of the wall in depth were undetected in Case A (flaw under tube sheet) and Case B (flaw half under tube sheet). Elliptical wastage flaws 22% of the wall in depth were clearly detected and sized for Case C (flaw 0.25 inch above tube sheet). Uniform thinning wastage was clearly detected and sized for each test case. Only one SCC sample (approximately 100% wall) was examined using single-frequency absolute testing techniques. In Case A (flaw under tube sheet) and Case B (flaw half under tube sheet), our evaluation determined that this flaw was detected, but could not be sized. In Case C (flaw above tube sheet) the SCC crack was clearly detected and sized. On the other hand, the single-frequency differential test results showed that the SCC crack was clearly detected and sized for each case. The single-frequency differential data for EDM slots showed that slots had to be 80% of the wall in depth before they could be evaluated as being detected, or clearly detected and sized. Slots positioned half under the tube sheet (Case B) 36% wall to 71% wall in depth went undetected. Slots less than 30% of the wall in depth went undetected, regardless of position.

Many of the SCC samples that were generated during Phase II of the Steam Generator Tube Integrity Program (specifically 30% to 60% of wall thickness) were not available for this investigation (sent to Germany). Therefore, it is difficult to assess SCC flaw detectability using single-frequency absolute techniques. The one SCC specimen that was examined would indicate that the absolute technique was less sensitive than the differential technique.

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16. ABSTRACT (200 words or less)

The ability of eddy current inspection to detect and size flaws in INCONEL-600 steam generator tubing at the tube sheet was studied. Single frequency absolute, single frequency differential, and multifrequency differential eddy current tests were conducted on small, medium, and large volume defects placed into a simulated tube sheet. Position of each defect was varied with respect to the surface of the tube sheet. Results are presented on detectability and sizing of the defects versus measurement method, location of the defect relative to the tube sheet surface, and defect volume.

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