PWR STEAM GENERATOR INSPECTION GUIDELINES

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REVISION 1

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FORWARD

This document was prepared through an effort sponsored by the Steam Generator Owners Group (SGOG) with significant input, participation and review by the SGOG NDE Subcommittee. The members of the Subcommittee were:

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In addition, the draft of this document was reviewed and commented on by the SGOG Technical Advisory Committee and US NSSS and ISI inspection vendors, with all formal comments addressed, resolved and responded to by the NDE Subcommittee.

This document is a report to the members of the Steam Generator Owners Group and is provided for their individual use. It has not been endorsed by the membership of the Steam Generator Owners Group. The report provides a basis for a utility operating a PWR to establish an effective steam generator inspection program, and it is intended that the Guidelines will be revised and updated as experience with their use is gained and as steam generator inservice inspection (ISI) and NDE technology advance. Application of the details of these guidelines as a regulatory requirement rather than as guidance is far beyond the reports intended purpose.

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Section 1

INTRODUCTION

Periodic nondestructive examination (NDE) provides valuable information about the condition and expected performance of pressurized water reactor (PWR) steam generators. An effective NDE program detects and monitors the progression of steam generator tube wall degradation and damage precursors. The inspection results in turn are used to implement appropriate plant corrective actions. This helps utilities avoid costly unscheduled outages.

This document provides guidelines for the inservice inspection of pressurized water reactor steam generator internals. The guidelines are recommendations and are intended to satisfy utility company objectives of meeting mandated safety inspection requirements and increasing plant availability. The recommended actions are based on:

- NRC regulations
- Plant operating experience
- Work sponsored by the Steam Generator Owners Group and the Electric Power Research Institute (EPRI).

The document also describes NDE equipment and instrumentation, PWR steam generator operating history, and NDE experience with various tube wall damage forms and damage precursors.

Section 2

SCOPE

The guidelines cover recommended nondestructive examination methods for determining tube integrity and for monitoring tube damage precursors.

The guidelines are applicable to Westinghouse, Westinghouse licensees and Combustion Engineering recirculating steam generators (RSGs), and Babcock & Wilcox once-through steam generators (OTSGs).

The guidelines document provides:

- An overview of steam generator NDE objectives
- NDE guidelines, designed to help utilities implement a steam generator inservice inspection (ISI) program
- A survey of available remote positioning, data acquisition, data analysis equipment and data base management systems
- A survey of available technology for identifying and monitoring tube damage precursors
- A summary of adverse operating experience which documents damage forms, vulnerable locations within the steam generator, and NDE experience.

The NDE guidelines provide specific recommendations for:

- NDE equipment for detecting and monitoring tube integrity and damage precursors
- Probe designs, instrumentation, and signal interpretation methods appropriate for particular forms of degradation at various locations within the generator
- Increased surveillance of regions within the generator that, historically, have been prone to degradation.

Section 3 of the guidelines document provides recommendations for implementing a steam generator ISI program. Recommendations point

to areas of the generator in need of increased inspection surveillance and describe NDE methods for monitoring tube integrity and damage precursors. The basis for the recommendations in Section 3 are discussed in detail in Sections 4 through 6, which consider, respectively, steam generator NDE equipment and instrumentation, steam generator operating experience and NDE experience with various damage forms. For convenience, Appendix A contains a list of definitions of terms used throughout the guidelines which may be referenced as required. Eddy current inspection is the most common testing method for most steam generator examinations. Accordingly, Appendix B considers the basics of eddy current inspection and presents background information with regard to test design.

Section 3

INSERVICE INSPECTION GUIDELINES

3.1 INTRODUCTION

The purpose of a PWR steam generator inservice inspection (ISI) program is to provide information about the condition and expected performance of a plant's steam generators. An effective inspection program detects and monitors 1) the progression of steam generator tube degradation, and 2) damage precursors. This document is intended to help utilities establish or improve NDE programs by providing inspection program recommendations, information on materials and equipment, representative NDE experience, and recommended inspection methods for the various damage forms and damage precursors.

The recommendations are presented as a set of options which should be considered by a utility when undertaking a program to optimize PWR steam generator reliability. Those options that are appropriate for the needs of a particular power plant should be adopted. It is emphasized that a particular plant's needs are based on many considerations such as: plant size and equipment; plant age and operating history; site characteristics; and, utility management structure, resource allocation priorities, cost-benefit methodology, support staff size, and Public Utilities Commission interactions.

In designing an ISI program, utility company objectives are to satisfy safety requirements and maximize plant availability. To ensure that the safety goal is met, the recommendations provided in this section satisfy the current safety-oriented guidelines for steam generator ISI developed by the NRC and outlined in the plant technical specification. Also, because unscheduled outage costs are much higher than incremental inservice inspection costs, this guideline sometimes suggests a more thorough examination than required by NRC regulations.

This section provides guidelines for the inservice inspection of PWR steam generator internals. The recommendations are based on:

- NRC Regulatory Guide 1.183 (1)
- Plant Technical Specifications (2,3,4)
- Plant operating experience
- The judgment of personnel at EPRI and the EPRI NDE Center.

The recommendations vary according to:

- Manufacturer (Westinghouse, Combustion Engineering, or Babcock & Wilcox)
- Model number and design
- Operating history
- Suspected type of degradation

Section 3.2 contains a summary of the recommendations for steam generator inspection. Section 3.3 contains recommendations for preservice inspection and suggestions for good inspection practices. Section 3.4 presents information for steam generator inspection plan development. Section 3.5 discusses NDE recommendations for monitoring tube wall degradation and damage precursors. Section 3.6 presents recommendations for post-inspection actions.

To facilitate use of the guideline document, a branching approach is used to provide the reader with information to the desired level of detail. Additional sections of the guidelines are referenced within Sections 3.3 to 3.6 where applicable which the reader may refer to if desired.

3.2 SUMMARY OF RECOMMENDATIONS

Category	Summary of Recommendations	Where Discussed
Preservice and General Inspection	• Choose an ISI vendor on the basis of experience and technical capabilities	3.3
	• Perform a baseline inspection of all steam generators	3.3
	• Inspect all steam generators during every scheduled steam generator outage	3.4

Category		Summary of Recommendations	Where Discussed
Preservice and General Inspection	•	Provide protected storage for tapes, stripcharts, and films containing NDE data analysis results	3.3
	•	Lay up steam generators properly during inspection	3.3
	•	Implement an equipment maintenance program	3.3
	•	Conduct visual inspection after performing any secondary side maintenance	3.3
	•	Use tracer gas leak detection methods for steam generator leak detection	3.3
	•	Use a no-jump eddy current probe manipulator	3.5
Steam Generator Inspection Plan Development	•	Assess steam generator tube integrity by selecting a sample of tubes which satisfy plant "tech spec" requirements	3.4.1
	•	Monitor additional regions of the steam generator based on operating experience of the unit and those of similar design and chemistry	3.4.2
	•	Monitor tube damage precursors	3.4.3
Nondestructive Examination	•	Use multifrequency eddy current examination	3.5
	•	Choose probe designs, instrument settings, and signal interpretation methods that are appropriate for the steam generator design and expected damage forms	3.5
	•	Analyze all data collected; document all degradation and anomalous signals	3.5
	•	Conduct an independent review of all eddy current data acquired during an outage	3.5
	•	Examine support plate signals for evidence of magnetite in the plate crevice gap if the unit is not dented	3.5
	•	Monitor continued denting by observing an increase in the number of dented support plate intersections	3.5

Category		Summary of Recommendations	Where Discussed
Nondestructive Examination	•	Assess dent growth using profilometry. Plug dented tubes based on strain criterion.	3.5
	•	Look for support plate ligament cracking in extensively dented units	3.5
	•	Confirm suspected support plate cracking with optical methods or radiography	3.5
	•	Develop a basis for not plugging tubes with low signal-to-noise ratio indications	3.5
Post-Inspection Actions	•	Classify tubes as degraded or defective based on eddy current testing. Mark degraded tubes for reinspection during subsequent ISI's.	3.6
	•	Utilize steam generator data base management systems to assess overall steam generator condition	3.6
	•	Take corrective actions to prevent further damage progression.	3.6

3.3 PRESERVICE AND GENERAL RECOMMENDATIONS

This section contains general recommendations for good inspection practices.

RECOMMENDATION: Choose an experienced ISI vendor.

Because of the complex nature and critical importance of this task, selection of an ISI vendor should emphasize the experience and technical capabilities of the organization and the qualifications and experience of individual data analysts. The utility should review data analysis practices of their ISI vendor to assure that a sequential signal detection and analysis practice is being followed. See Table 3-3 and Appendix B.2. Prior to analyzing data from a current outage, the ISI vendor should review data from a previous outage in order to get accustomed to the particular plant. As a general rule, the analysis practices in interpreting eddy current signals should be reviewed for consistency in estimating signal phase angles.

RECOMMENDATION: Perform a baseline inspection of all steam generators.

A preservice inspection provides a basis (a baseline) for comparison with subsequent inservice inspection results. In particular, it enables a utility to positvely separate degradation which is associated with the manufacture of the steam generator from that which is attributable to operation. Past baseline inspections have uncovered a variety of preservice problems, including obstructed tubes, loose parts, and unexpanded tubes. It is good practice, therefore, to inspect 100% of the tubes at full length, in all steam generators before commencing powered operation. For the same reasons, a thorough visual inspection of the steam generator secondary side should also be performed.

RECOMMENDATION: Inspect all steam generators during each planned steam generator outage.

After the first inservice inspection, NRC regulations permit the inspection of steam generators on a rotating basis, with one or more steam generators inspected during each ISI. However, inspection results from one steam generator are not always reliable indicators of the condition of the other steam generators in the plant. Since the incremental cost of inspecting additional steam generators is small compared with the cost of a forced outage, all steam generators should be inspected during each planned ISI.

RECOMMENDATION: Provide protected storage for tapes, stripcharts, and films containing NDE data and analyses in a format that enables rapid retrievability.

Tapes, stripcharts, films, and other NDE records should be dated, identified, and stored carefully to ensure the availability of background and reference information for future examinations in a short interval to minimize decision-making time. These data also provide feedback for management decisions on steam generator inspection.

RECOMMENDATION: Lay up steam generators properly during inspection.

Impurities accumulated on the secondary side during operation can cause corrosion to progress during a shutdown period. For example, chlorides, copper, and copper oxides can cause pitting in an oxygenated environment. Therefore, the steam generators should be in a proper layup condition during the inspection period. Recommendations for steam generator layup are provided in (5).

RECOMMENDATION: Implement an equipment maintenance program.

Electronic and mechanical equipment used for steam generator inspection is subjected to intensive use during an outage. Therefore, simple, easy-to-repair equipment is recommended, and it should be thoroughly checked prior to the start of an outage. Spare parts for components prone to failure or whose failure could affect the outage schedule should be kept available on-site. Eddy current probe pusher/pullers should be rebuilt between outages to assure reliable performance during an inservice inspection. During the outage, pusher/puller belts should be changed frequently to assure proper operation. Remote instrumentation extension cables should be stretched prior to routing to facilitate cable lay-out.

RECOMMENDATION: Conduct visual inspection after performing any secondary side maintenance.

Foreign objects left in generators after secondary side maintenance have caused leaker outages. Therefore, a secondary side visual inspection should be made to make sure that no loose parts or other foreign objects are left behind which could cause tube damage during operation. A one time visual inspection of the secondary side of a steam generator is a reasonable method for finding loose parts or foreign objects, providing the following points are recognized.

1) There are differences in steam generator geometry and access; therefore, the scope and type of visual inspection must be tailored to the specific steam generator design.

2) Inspection should be balanced with awareness of the potential for tube corrosion when a steam generator is drained.

Subsequent visual inspections of the secondary sides of steam generators should be performed only when the specific situation warrants, e.g., when nondestructive examination suggests the presence of a foreign object or when QA/QC or cleanliness procedures employed during maintenance are judged to have been insufficient. When conducted, such a subsequent inspection should be restricted in scope and duration to the minimum required to resolve the specific question that prompted it.

RECOMMENDATION: Use tracer gas leak-detection methods for steam generator leak detection.

Experience has shown that helium leak detection methods are more sensitive than hydrotesting, resulting in the capability to locate smaller leaks. Sulfur hexafluoride has been proposed for use as a tracer gas, however no steam generator field experience presently exists. The higher sensitivity and simplicity of sulfur hexaflouride chemical analysis equipment may offer the potential for locating smaller leaks than with helium. Also, a significant reduction in tracer gas costs may be realized due to the reduction in gas concentration required because of the greater sensitivity of the sulfur hexaflouride analysis equipment.

3.4 STEAM GENERATOR INSPECTION PLANNING

This section considers factors important for the development of a steam generator inspection program. The NRC steam generator sampling requirements for assessing tube integrity are reviewed; additional recommendations are made based on operating experience. Suggested inspection programs for the monitoring of damage precursors are also presented.

3.4.1 NRC Requirements For Steam Generator Inspection

RECOMMENDATION: Select tubes based on NRC sampling requirements.

Nondestructive examination of a steam generator begins with selection of a sample of tubes for testing. If, as recommended in these guidelines, each steam generator is inspected, then the NRC typically requires that the sample include:

- At least 3% of the total number of tubes in all steam generators - randomly selected
- All nonplugged tubes that previously had estimated tube wall penetrations greater than 20%.

For RSGs, the NRC defines a tube inspection as an inspection of the steam generator tube from the point of entry (hot leg side) completely around the U-bend to the top support of the cold leg. For OTSGs, inspect each steam generator tube from the point of entry completely to the point of exit.

Inspections should be carried out according to NRC guidelines as outlined in the plant technical specification. The required procedure follows these four steps:

- Select and examine an initial random sample of tubes from the steam generator
- Classify the results of the tube examination according to NRC regulations. Classification is based on the number of degraded and defective tubes found in the steam generator (see below)
- If a sample contains defective tubes, or if at least 5% of the tubes inspected are degraded, inspect additional tubes from this steam generator. If more than 10% of the tubes inspected are degraded, or more than 1% of the inspected tubes are defective, notify the NRC and inspect additional tubes from this and other steam generators
- Classify the steam generator based on the total number of degraded and defective tubes found. If more than 10% of the tubes are degraded or more than 1% of the inspected tubes are defective, promptly notify the NRC.

Figure 3-1 shows the general sequence of actions delineated by the regulatory guide for steam generator inservice inspection. The Standard Technical Specification (2,3,4) define the classifications shown in Figure 3-1 as follows:

- Class C1 --- Less than 5% of the tubes inspected are degraded, and none of the inspected tubes are defective
- Class C2 --- Between 5% and 10% of the tubes inspected are degraded, or at least 1 tube, but not more than 1% of the tubes inspected, is defective

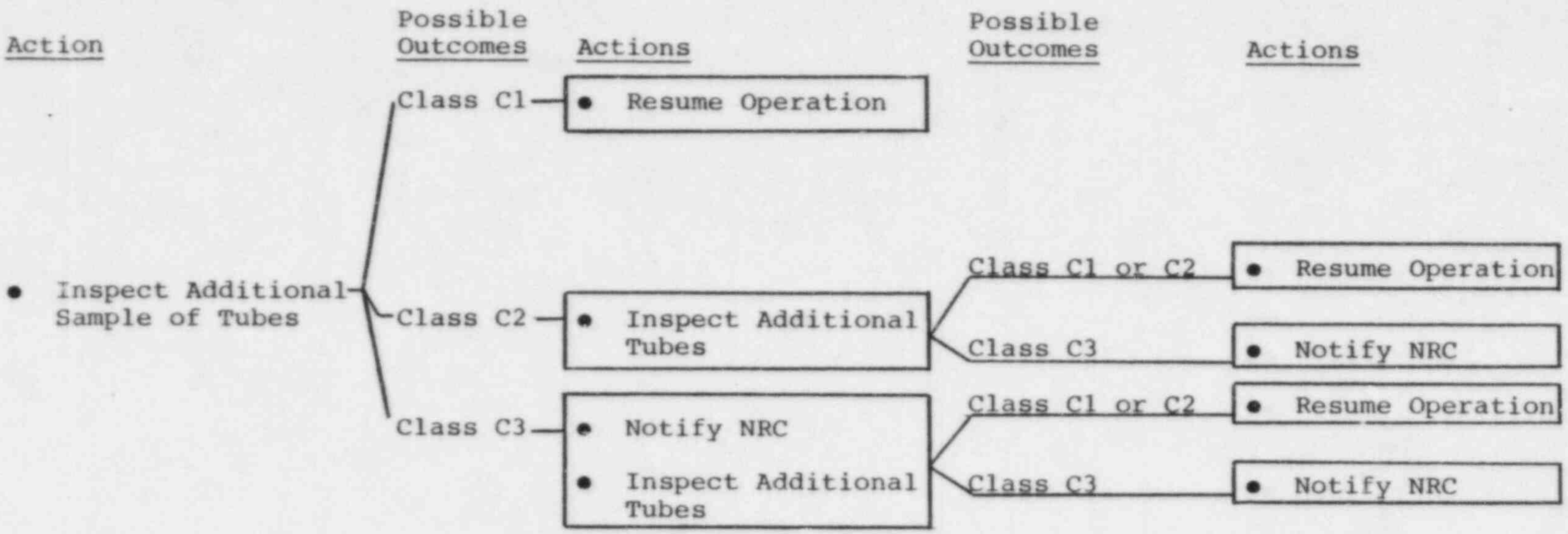


Figure 3-1. General Sequence of Testing Actions and Outcomes for Steam Generator Inservice Inspection

- Class C3 --- More than 10% of the tubes inspected are degraded, or more than 1% of the inspected tubes are defective.

A tube is defective according to the NRC definition if it has an imperfection of such severity that it is unacceptable for continued service. At the conclusion of an inspection, all defective tubes should either be plugged or sleeved.

A tube is degraded according to NRC definitions if it has a previously unreported tube wall penetration of more than 20% or if a previously detected degradation in the tube exhibits more than 10% additional wall penetration.

Depending on the extent of the degradation found during the inspection described above, additional tubes may have to be inspected. Typical NRC requirements for additional sample sizes are provided in Table 3-1. The regulations also indicate that these secondary inspections should concentrate in the areas where imperfections were found.

3.4.2 Additional Sampling Requirements

RECOMMENDATION: Include additional tubes in the inspection program.

Each steam generator design exhibits characteristic problem areas, i.e., regions in which degradation is more likely to occur. In order to increase the chances of detecting degradation, inspection should concentrate on these regions. This is known as stratified sampling. Although NRC regulations acknowledge the need for stratified tube sampling, they are not explicit about the location of characteristic problem regions. Ideally, stratified sampling plans should be developed on an individual basis for each plant, based on the operating history of that plant and similar units. For information on statistical methods to analyze and choose specific sampling plans, see Easterling (6).

Table 3-1

NRC STEAM GENERATOR SAMPLE INSPECTION REQUIREMENTS

SAMPLE SIZE	RESULT	ACTION REQUIRED	RESULT	ACTION REQUIRED	RESULT	ACTION REQUIRED
A minimum of S Tubes per SG	C-1	None	N/A	N/A	N/A	N/A
	C-2	Plug defective tubes and inspect additional 2S tubes in this S.G.	C-1	None	N/A	N/A
			C-2	Plug defective tubec and inspect additional 4S tubes in this SG	C-1 C-2	None Plug additional tubes
					C-3	Perform action for C-3 result of first sample
			C-3	Perform action C-3 result of first sample	N/A	N/A
	C-3	Inspect all tubes in this SG, plug defective tubes and inspect 2S tubes in each other SG	All other SG are C-1	None	N/A	N/A
			Some SG C-2 but no additional SG are C-3	Perform action for C-2 result of second sarple	N/A	N/A
		Prompt notification to NRC	Additional SG is C-3	Inspect all tubes in each SG and plug defective tubes- Prompt notification to NRC	N/A	N/A

S=3 N/n % where N is the number of steam generators in the unit, and n is the number of steam generators inspected during an inspection

The remainder of this section makes recommendations for additional tube inspections. Special regions within the steam generator are identified for more intensive inspection. If eddy current indications are detected within these regions then the inspection program is expanded within these regions. The areas for additional inspection and the percentage of tubes inspected depend on operating history, steam generator design, specific tube damage forms, uncertainties in degradation growth rates and difficulties associated with the NDE methods.

Guidelines for inspection plan development that are specific to Westinghouse, Combustion Engineering, and Babcock & Wilcox steam generators are given below. The suggested inspection plan includes NRC requirements plus additional tubes based on steam generator operating experience. Damage precursor monitoring recommendations are discussed in Section 3.4.3.

Recommendations for Westinghouse steam generators. Each scheduled steam generator inspection should include:

"Tech Spec" Requirements

- All nonplugged tubes that previously had tube wall penetrations greater than 20%
- An additional 3% of the tubes, randomly selected.

Additional Regions

- The tubes specified in Table 3-2

Table 3-2 is based on the Westinghouse operating experience summarized in Section 5.3; the recommendations in the table and the supporting experience are restated briefly in the following paragraphs.

- Inspect the hot leg side - Units with an open tube sheet crevice should inspect 100% of the steam generator if there is a history of tube sheet crevice region IGA or SCC. Inspect to the first support plate.
- Westinghouse Model 51s are susceptible to fretting at the AVB's (see Section 5.3.6). The fretting mechanism is believed to have an initiation time of five effective full power years.

Table 3-2

RECOMMENDED ADDITIONAL ISI TUBE SAMPLE FOR WESTINGHOUSE STEAM GENERATORS

PERCENTAGE	TUBE LOCATION	STEAM GENERATOR MODEL NUMBER			
		24, 27, 33	44	51	D,E
100%	of the hot leg side if there is a history of IGA or SCC (1,3)	X	X	X	
3%	of the AVB's (5)			X	
100%	of the outer three rows of preheater section				X
100%	of Rows 1 and 2			X(4)	X(4)
100%	of the outer two rows of the periphery			X(2)	

(1) To first support plate.

(2) Cold leg side to upper support plate. Outer periphery region is outer 10 rows.

(3) Plants with open crevices only.

(4) Plants manufactured in 1971 or 1972 with W SMD tubing only.

(5) 100% baseline on Row 5 and beyond AVB tubes should be done on units after five effective full power years of operation.

An initial 100% baseline inspection should be conducted on all tubes beyond Row 5 which intersect the AVBs for those units which have been operating for more than five effective full power years.

During outages subsequent to the baseline, tubes beyond Row 5 which intersect the AVBs should be inspected using the normal NRC 3% sample size. If indications are detected, then the inspection program should be expanded in this region only using NRC guidelines.

- Inspect 100% of the outer two rows of the cold leg section in preheater models. The preheater section is prone to fretting wear (see Section 5.3.6). If fretting is observed, expand the inspection inward until there are no additional indications.

- Inspect 100% of Rows 1 and 2 in Model units manufactured in the 1971-1972 time frame that have Westinghouse SMD tubing. Primary side SCC has been observed in the Row 1 bends. See Section 5.3.4. One Model D3 steam generator (Summer 1) has experienced Row 1 cracking; however it is not clear whether this incident is unique to this particular plant or indicative of a possible generic occurrence within Model D steam generators.

- Inspect 100% of the outer two rows of the cold leg periphery region in Model 51s. Inspect up to the cold leg top support. This region may experience thinning (see Section 5.3.2). If thinning at the support plate is observed, expand the inspection inward until there are no additional indications.

<u>Recommendations for Combustion Engineering steam generators</u>. Each scheduled steam generator inspection should include:

"Tech Spec" Requirements

- All nonplugged tubes that previously had estimated tube wall penetrations greater than 20%

- An additional 3% of the tubes, randomly selected.

Additional Regions

- 20% of the tubes within the kidney region

- Selected tubes within Rows 5-14. Randomly inspect 50% of susceptible tubes. These are generally within Rows 5-14. However, the utility should contact the NSSS vendor for exact locations. If eddy current indications are identified in the U-bend within the specific rows, then the inspection should be expanded to 100% of the tubes in the specific rows. The U-bend region of tubes in these rows has experienced pitting

or cracking (see Section 5.4.3). This recommendation is not applicable to C-E steam generator models 34-10 or System 80 steam generators.

Recommendations for Babcock & Wilcox steam generators. Each scheduled steam generator inspection should include:

"Tech Spec" Requirements

- All nonplugged tubes that previously had tube wall penetrations greater than 20%
- An additional 3% of the tubes in each steam generator, randomly selected.

Additional Regions

- Inspection of the lane region - This region at the upper support plates and tube sheet is prone to corrosion-assisted high-cycle fatigue cracking and fretting (see Sections 5.5.5 and 5.5.6).

  Inspect 20% of the lane region if unit has not experienced high-cycle fatigue cracking; inspect 100% of the lane region if unit has experienced high-cycle fatigue cracking or an eddy current indication is identified during the 20% sample size inspection. Inspection should be from the 14th support plate up through the upper tube sheet. The lane region is prone to environmentally assisted high-cycle fatigue cracking (see Section 5.5.5). See Section 5.3 for additional information.

- Owners with steam generators experiencing impingement damage should concentrate their inspections in the area of suspected damage, typically the outer periphery. See Figure 5-9 and Section 5.5.7). The recommended sample size for units with impingement damage is 6% of the tubes randomly selected.
- Units which have experienced cracking in the wedge area (see Figure 5-9) or the upper tube sheet region should inspect 100% of these regions from the 15th support up through the upper tube sheet.

3.4.3 Damage Precursors

RECOMMENDATION: Monitor damage precursors within a steam generator. Take corrective actions to minimize their impact on tube integrity.

Damage precursors are conditions within a steam generator which can impact tube integrity. Currently recognized damage precursors include

sludge, copper deposits, magnetite within the support plate crevice gap, and denting. See Section 6.3.8.

Sludge. Sludge is the accumulation of corrosion products from the condensate-feedwater system and the condenser. It tends to accumulate on the tubesheet in low flow velocity regions within the steam generator. A top-view of the sludge pile is typically kidney-shaped; tubes within this "kidney region" are susceptible to corrosion attack because of the retention of corrosion products within the sludge pile.

Sludge profiling using eddy current is typically done during an outage to determine the height and extent of the sludge. A tube sample matrix is constructed which covers the tubesheet. The matrix can be somewhat coarse in its sampling i.e., every fifth to tenth tube, with the tubes inspected to the first support plate (see Section 6.3.8 and Figure 6-57).

Copper. The primary source of copper in steam generators is due to the corrosion of copper-based materials within the balance-of-plant heat exchangers. Not all units have copper-based materials in their system hence its potential impact will be plant specific. The adverse effects of copper with the appropriate faulted secondary side chemistry include the promotion of denting, the formation of stress corrosion cracking and pitting. Metallic copper is readily detectable using eddy currents and typically occurs within the sludge pile and the tube sheet crevice region.

A separate inspection program, in the context of additional tubes, is not recommended for units with copper in their system. The presence and location of copper signals should be noted during the course of the steam generator inspection for future reference. However, if small amplitude eddy current signals suggestive of pitting are detected in the presence of copper above the tube sheet, then the inspection program should be expanded to include 100% of the steam generator (see Section 5.3.3).

Denting. A rationale for developing an inspection program to assess denting in a steam generator is now considered. Denting results from the corrosion of carbon steel support structures within the steam

generator i.e., support plates, eggcrates and the tube sheet. The corroded carbon steel undergoes a phase change to magnetite which has approximately twice the volume as the original source material. Continued growth of the corrosion product fills the gap between the tube and its support structure and eventually dents the tube. Continued denting can result in cracked tubes and support plate ligaments. Tube cracking can cause an unscheduled outage whereas ligament cracking represents a potential source of loose parts and subsequent foreign object damage.

Events of interest in the scenario described above can be time ordered as follows:

- Magnetite formation
- Dent initiation
- Dent growth
- Tube cracking
- Plate ligament cracking

The steam generator inspection plan and appropriate NDE methods will in general depend on where the steam generator is in the denting sequence. Possible plant corrective actions will also have this dependency. In general, the earlier a condition of interest is detected, the more lead time a utility has to plan and initiate corrective actions. As an example, the detection of denting in its incipient stage by noting the formation of magnetite within the gap between the tube and its support structure might allow the utility to modify secondary side chemistry at an early stage and possibly avoid the actual denting of tubes.

If a unit is not dented, then the appropriate conditions of interest to be looked for during an inspection are 1) magnetite formation within the tube/support structure or 2) dent signals. Both of these conditions can be detected using appropriate NDE methods (see Section 6.3.8). Again, approach 1) offers advantages over 2) in that the condition is detected at an earlier stage giving the utility more reaction time.

If the unit is dented, then evidence for continued denting and dent growth is important. Continued denting can be monitored by noting an increase in the number of dented support plate intersections when compared with previous outage results. The assessment of dent growth can only be reliably accomplished using profilometry. See Section 6.3.8.

Dents can grow by changes in their shape, minimum diameter or both. The controlling factor with regards to the integrity of a dented tube is the tube strain. In general, there is little correlation between tube strain and minimum diameter.

Dent shape generally controls tube strain which in turn determines the susceptibility of a tube to stress corrosion cracking. The present inspection philosophy is to remove a tube from service if its strain value exceeds some threshold: 17-25% are values that have been used by several utilities. This approach avoids the tedious inspection of dented tubes for cracking and has increased plant availability. Profilometry is the only reliable approach for detecting changes in dent size and shape (see Section 6.3.8).

Specific recommendations for monitoring damage precursors are now presented.

<u>Recommendations for Westinghouse steam generators</u>. Each scheduled steam generator inspection should include:

- A sludge inspection program. The hot leg and cold leg side of the steam generator should be examined. See Section 6.3.8. In general, the test should be conducted before sludge lancing.
- A support plate crevice gap inspection program. Non-dented steam generators with carbon steel drilled support plates should be examined for the formation of magnetite within the support plate crevice gap. This should be done on the hot leg side in the area of the generator where T(hot) is greatest, typically in the interior of the bundle above the kidney region.
- Units with active denting should have a dent inspection program. Units in the early stages of denting should monitor for dent growth by noting the percentage increase in the number of dented support plate intersections.

A sample of dented tubes should also be selected for monitoring using profilometry techniques. This same sample of tubes should be monitored during subsequent ISI's in order to assess dent growth.

A stress analysis program should be conducted to determine the likely areas of high support plate strain and tube strain. Tube strain criterion for plugging dented tubes should be developed.

- A support plate ligament inspection program. Dented units which are susceptible to support plate ligament cracking should inspect the high strain areas of the support plates for ligament cracking.

Recommendations for Combustion Engineering steam generators. Each scheduled steam generator outage should include:

- A sludge inspection program. The hot and cold leg side of the steam generator should be examined before sludge lancing.

- A support plate crevice gap inspection program. Non-dented steam generators with carbon steel partial support plates should be examined for the formation of magnetite within the support plate crevice gap.

- A dent inspection program. Units in the early stages of denting can monitor the status of continued denting by noting the percentage increase in the number of dented support plate intersections.

  A sample of dented tubes should also be selected for monitoring using profilometry techniques. This same sample of tubes should be monitored during subsequent ISI's in order to assess dent growth.

  A stress analysis program should be conducted to determine the likely areas of high support plate strain and tube strain. Tube strain criterion for plugging dented tubes should be developed.

- A support plate ligament inspection program. Dented units which are susceptible to support plate ligament cracking should inspect the high strain areas of the support plates for ligament cracking.

Recommendations for Babcock & Wilcox steam generators. Each scheduled steam generator inspection should include:

- A tube distortion program. Areas of tubes with inner diameter distortions (dings) should be evaluated using eddy current and profilometry techniques. Attention should be paid to numbers of tubes, amount of distortion, and patterns.

3.5 NONDESTRUCTIVE EXAMINATION

RECOMMENDATION: Use a no-jump eddy current probe manipulator.

No-jump probe manipulators are now available which can be installed without entering the steam generator channel head. Use of these devices for inservice inspection can significantly reduce radiation exposure.

RECOMMENDATION: Use multifrequency/multiparameter eddy current instrumentation to perform inspections.

Multifrequency/multiparameter eddy current systems provide greater inspection reliability in the presence of extraneous variables such as denting, support plate intersections, tube sheets, and metallic deposits on the tube wall (see Appendix B). In addition, lower frequencies are useful for monitoring tube damage precursors. (See Section 6.3.8.) Although these inspection systems increase both equipment costs and work load on data analysts, the extra expense is justified by the increase in data reliability.

RECOMMENDATION: Choose eddy current probe designs, instrument settings, and signal interpretation methods that are appropriate for the steam generator design and the suspected type of degradation.

The reliability of multifrequency eddy current test results depends not only on data analysis but also on the type of eddy current probe used and the frequencies chosen. The remainder of this section recommends eddy current test procedures as a function of probe design and frequency, steam generator NSSS vendor, design, and operating history.

Probe Design. In general, eddy current testing should be performed with an annular-shaped bobbin coil. However, if special damage forms or extraneous variables are present or postulated, testing should be performed with probes of alternative designs.

RECOMMENDATION: In the presence of special conditions, choose the following probe designs or coil modes:

- IGA/SCC. Units with open tube sheet crevices should acquire absolute bobbin coil eddy current data for analysis in conjunction with normal differential bobbin coil data.

- Copper deposits. If pitting is suspected in the presence of copper, use a focused differential bobbin coil (.030" winding width and .060" coil spacing) for more reliable defect depth estimation (see Section 6.3.2).

- Environmentally-assisted high-cycle fatigue cracking in OTSGs. Tubes in the lane region at the upper support plate and tube sheet are prone to circumferentially oriented high-cycle fatigue cracking. In one unit, a partial through-wall crack was detected using a pancake array coil whereas the same crack was not detected using a conventional bobbin coil. See Section 6.3.6.

  Tubes in the lane region should be examined using a pancake array coil down to the upper support plate. All eddy current indications in the vicinity of the upper support plates which exhibit a fast rise-time and have an apparent axial length of about twice the coil diameter should be plugged without regard to the eddy current estimated depth.

- Fretting at the AVBs and baffle plates. Use an absolute bobbin coil with signal amplitude sizing criterion to characterize fretting in RSGs. Standard differential bobbin coil testing tends to overestimate the depth of a defect under these conditions resulting in the unnecessary plugging of tubes (see Section 6.3.5).

The basis and auxiliary frequencies recommended in Table 3-3 emphasize the sequential detection and measurement of tube wall degradation. Detection is accomplished using the lower basis frequency, whereas measurement may be performed using the higher auxiliary frequency. In the presence of excessive tube noise due to tube pilgering or other tube manufacturing processes, the basis frequency may have to be lowered to approximately 100 KHz. See Appendix B for a complete discussion of frequency selection.

Frequency Selection. Appropriate frequencies should be selected to monitor both tube integrity and tube damage precursors such as accumulation of magnetite in the support plate crevice gap, denting, tube support plate cracking, and sludge accumulation.

Table 3-3

GENERAL GUIDELINES FOR EDDY CURRENT FREQUENCY SELECTION

NSSS VENDOR	SG MODEL #	FREQUENCIES		
		Basis (1) (Differential Coil)	Auxiliary (2) (Absolute & Differential)	Tube Exterior (3) (Absolute)
Westinghouse	27	170 KHz	100 KHz Abs. & 340 KHz Diff.	10-40 KHz
	24,33,44,51	200 KHz	100 KHz Abs. & 400 KHz Diff.	10-40 KHz
	D & E	225 KHz	100 KHz Abs. & 550 KHz Diff.	10-40 KHz
Combustion Engineering	All	200 KHz	100 KHz Abs. & 400 KHz Diff.	10-40 KHz
Babcock & Wilcox	All	400 KHz	100 KHz Abs. & 200 KHz Diff.	10-40 KHz

(1) The basis frequency is the frequency that should be monitored for detecting tube wall degradation.

(2) Auxiliary frequency or frequencies are used as an additional aid in monitoring tube wall integrity and as mixing frequencies to suppress extraneous variables. The higher auxiliary frequency combined with the basis frequency is recommended for support plate/tube sheet suppression.

(3) A frequency in the range 10-40 KHz will provide information on damage precursors (e.g., sludge accumulation, foreign objects, etc.).

RECOMMENDATION: Assuming no special conditions are present, use the basis and auxiliary frequencies recommended in Table 3-3. The basis frequency eddy current data should be reviewed for evidence of tube wall degradation.

RECOMMENDATION: In the presence of special conditions, perform bobbin coil tests using the following frequencies:

- IGA/SCC in the tube sheet crevice region -- (100 x 200) KHz mix, absolute mode is recommended for confirming tube wall degradation reported off the single frequency absolute channels

- Fretting in Westinghouse preheaters and at the AVBs of Model 51s -- (100 x 300) KHz mix, absolute mode.

- Row 1 U-bend cracking -- 100 KHz, absolute and differential modes.

- Copper deposits, in conjunction with pitting or other degradation -- (600 x 250) KHz mix, differential mode for reliable sizing.

RECOMMENDATION: Analyze all data collected; document all degradation and anomalous signals.

There is historical evidence (7) that eddy current data have been collected but not fully reviewed. Multifrequency eddy current inspection represents a defense-in-depth approach to steam generator inspection; it is effective only if all the data is reviewed. The utility should budget additional time or manpower for the necessary data review.

RECOMMENDATION: Conduct an independent review of all eddy current data.

There are numerous examples of unscheduled shutdowns which have been attributed to missed eddy current indications by a data analyst. The task of reviewing and analyzing data is extremely tedious and is normally done under considerable time pressures; any single individual is vulnerable to a missed indication. All eddy current data should be independently reviewed by at least two analysts, preferably from separate organizations or companies. This recommendation is particularly important for units which have

experienced intergranular attack or stress corrosion cracking.

RECOMMENDATION: If the unit is not dented, monitor the 10-40 KHz absolute mode data for evidence of support plate corrosion and magnetite packing of the crevice region, which would indicate incipient dent formation.

RECOMMENDATION: If the unit is dented, monitor dent progression by determining the increase in dented support plate intersections. In RSGs monitor the higher auxiliary frequency for dent signals; in OTSGs monitor the basis frequency (see Table 3-3).

RECOMMENDATION: Monitor changes in dent size with profilometry. Eddy current bobbin coil methods do not provide a reliable estimate of dent size or changes in dent size. Profilometry methods must be used to reliably assess dented tube integrity. Plug dented tubes based on strain criterion.

RECOMMENDATION: In extensively dented units, monitor appropriate regions of the steam generator for support plate ligament cracking. Use differential eddy current bobbin coil at 10-40 KHz.

RECOMMENDATION: Confirm any eddy current indication of support plate cracking.

Support plate inspection methods, in order of increasing cost, are:

- Visual inspection (restricted to the outer periphery of the steam generator near the access openings)
- Fiber optics or TV (restricted to within a few rows of the outer periphery or along the tube lanes)
- Radiography (no access restrictions, but expensive)

RECOMMENDATION: Develop a basis for not plugging tubes with low signal-to-noise ratio eddy current indications.

Low signal-to-noise ratio eddy current signals may be encountered during an inservice inspection. This is particularly true when multiparameter methods are used for extraneous variable suppression. For signal-to-noise ratios less than 5-10 at the mixed channel output

eddy current depth estimates may be extremely conservative and unreliable leading to unnecessary plugging of tubes. If a technically sound basis can be found for stating that the source of the eddy current indication is either not crack-related or cannot impact plant safety or availability, then merely note the presence of the indication and do not initiate plugging action. The basis could be established by pulling several tubes to confirm the damage mechanism or additional flaw characterization using specialized eddy current probes, e.g., a rotating pancake coil or array coils. Tubes found to have low signal-to-noise indications should be monitored during subsequent outages.

3.6 POST-INSPECTION ACTIONS

RECOMMENDATION: Review inspection results from all steam generators.

After the steam generator has been inspected, each tube should be classified as degraded or defective based on the eddy current test results. The total number of degraded and defective tubes found during the inspection determines the NRC classification for this steam generator. If the classification is Class C3, promptly report to the NRC.

The NRC requires utilities to remove all defective steam generator tubes from service. The plugging limit, or point beyond which a tube is considered unsuitable for continued service, is included in the technical specifications for each plant. The utility must decide whether to plug or to sleeve these defective tubes.

Degraded tubes should be marked for reinspection during the next ISI. For this purpose, a tube is considered degraded if it has a tube wall penetration of more than 20%.

RECOMMENDATION: Utilize steam generator data base management systems to assess the overall health of steam generators.

A wealth of data can be produced during a steam generator inservice inspection. Data from the current inspection and analysis results from previous inspections must be compared for the identification of trends and regions of the generator requiring special attention.

The sheer volume of the data requires the use of computer data base management systems.

RECOMMENDATION: Consider sleeving defective tubes in any area of the steam generator experiencing extensive wall damage below the first support plate and in the interior of the tube bundle.

If sleeving seems appropriate, plan to sleeve the damaged area during the next scheduled outage. See (8) for a discussion of the relative merits of sleeving and plugging in various situations.

RECOMMENDATION: Take corrective actions to prevent further damage progression.

Indications of tube degradation or tube damage precursors should not be ignored. In general, utilities should respond to such indications with corrective actions designed to solve the problem rather than merely to treat the symptom. Examples of corrective actions that may be required are:

- Preventive removal of undamaged tubes from service. In some cases, it may even be appropriate to plug or sleeve undamaged tubes. For example, Westinghouse recommends removing from service all Row 1 tubes if the unit has or can expect 1 cm of hourglassing within the next cycle.

- Changes in water chemistry, air inleakage control, balance-of-plant hardware, or operating and maintenance procedures. Any of these actions may be appropriate for dealing with particular forms of degradation or tube damage precursors.

Section 4

PWR STEAM GENERATOR NDE EQUIPMENT AND INSTRUMENTATION

4.1 INTRODUCTION

The nondestructive examination of a steam generator has two objectives:

- To determine the integrity of the tubing in the primary system pressure boundary
- To detect and characterize tube damage precursors.

Some types of secondary side conditions initially are not detrimental to the integrity of the pressure boundary, but if allowed to progress they may influence tube integrity. Sludge and debris, copper deposits, crevice gap magnetite packing, support plate cracking, and denting are all considered tube damage precursors; their detection and characterization can provide early warning of potential tube damage.

Eddy current data acquisition is relatively fast and simple. For this reason, eddy current inspection is the method most commonly used to determine tube wall integrity and to identify damage precursors.

Proper application of the eddy current method requires an understanding of the test objectives and the limitations of the method. Once these are clear, appropriate NDE equipment, instrumentation, and data analysis techniques can be chosen.

Section 4.2 provides an overview of commercially available eddy current data acquisition equipment, including remote positioning equipment, probes, and instrumentation. Section 4.3 gives a survey of eddy current data analysis equipment, while Section 4.4 presents an overview of other NDE methods and equipment capable of damage precursor evaluation and specialized tube integrity applications. Section 4.5 discusses data base management systems. Appendix B discusses the fundamentals of the eddy current method and a philosophy for

designing eddy current tests to evaluate steam generator tube integrity and damage precursors.

4.2 EDDY CURRENT DATA ACQUISITION EQUIPMENT

Initially, eddy current methods were used only to determine tube wall integrity. However, steam generator operating experience over the past few years has demonstrated the need for characterizing damage precursors as well. Recent advances in eddy current instrumentation and probe design have enhanced the capability of eddy current methods to detect diverse tube damage forms and to monitor damage precursors including sludge, crevice packing, and cracked plate ligaments.

Eddy current testing typically is divided into two phases: data acquisition and data analysis. A typical data acquisition system with mechanical positioning equipment is shown schematically in Figure 4-1. The eddy current probe and probe positioning equipment (manipulator and pusher/puller) are located within the channel head and outside the manway. To reduce operator radiation exposure, the data station typically is located outside of containment in a clean area or in a van. Data analysis is conducted either in the instrumentation van or off-site.

In selecting eddy current test probes and instrumentation, the inspector must try to minimize both inspection time and operator radiation exposure.

4.2.1 Remote Positioning Equipment

The steam generator channel head is an area with high radiation levels (more than 10 R/hr in older operating units). Consequently, remote mechanical probe positioning equipment is utilized to gain access to tubes. The positioning equipment moves the eddy current probe from tube to tube, as directed by the operator from a remote location. After the probe has been positioned, a pusher/puller propels it through the selected tube to gather inspection data.

The two general types of remote positioning equipment are manipulators and finger-walkers.

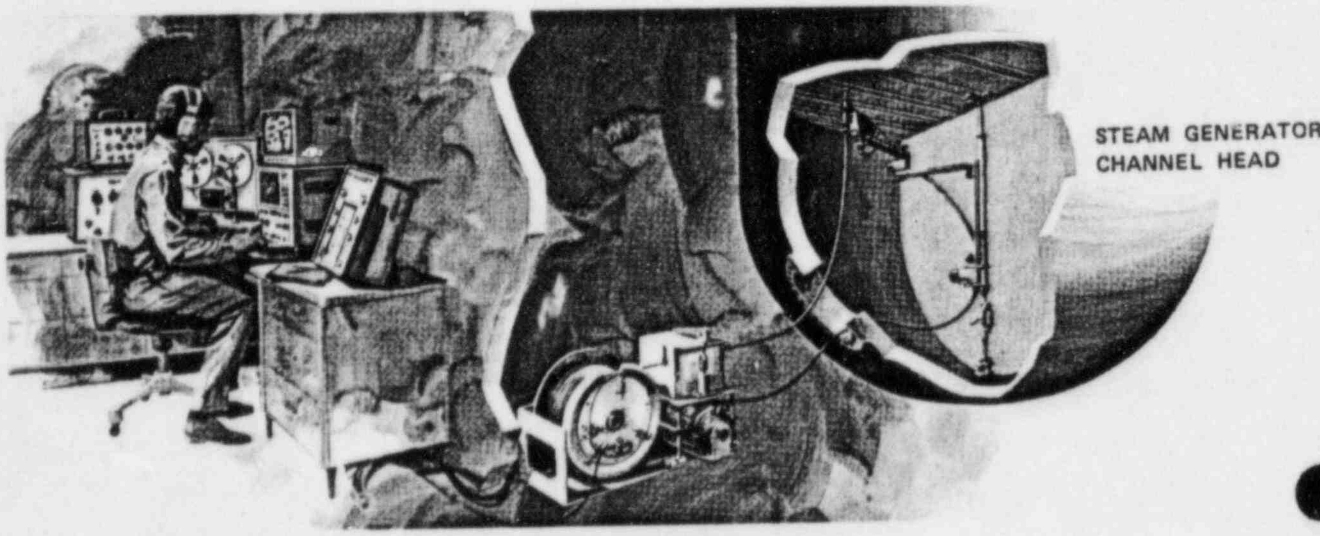


Figure 4-1. Typical Steam Generator Eddy Current Data Acquisition System (Zetec)

Manipulators. Typical manually installed manipulator configurations for RSG and OTSG channel heads are shown in Figure 4-2. Figure 4-2(a) illustrates the channel head components of the Zetec SM-4 system for RSGs. The components installed in the channel head typically include:

- Numbered templates for tube sheet positioning referencing
- A closed-circuit TV camera
- The manipulator fixture
- The probe conduit with an in-line calibration standard.

A fixture control box and TV monitor are kept at the remote equipment site. The operator uses the TV monitor to select the manipulator position.

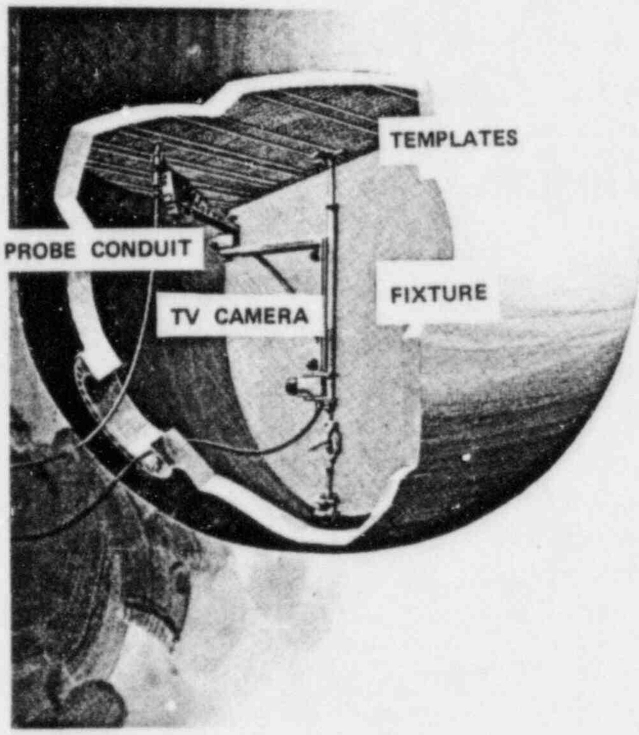
Figure 4-2(b) shows an OTSG manipulator developed by Babcock & Wilcox. This computer-controlled manipulator operates without templates. Installed channel head equipment includes:

- A closed-circuit TV camera
- The manipulator fixture
- The probe conduit with an in-line calibration standard.

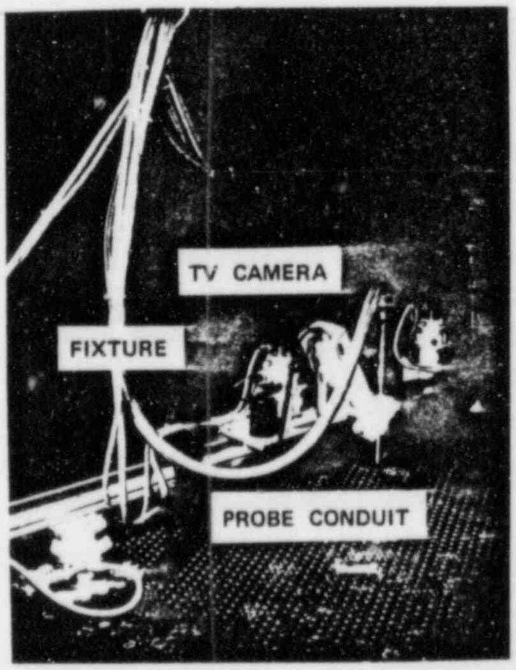
Remote equipment includes a TV monitor and encoder for tube positioning/entry information. Zetec offers a manually controlled manipulator (SM-3) for OTSG channel heads that uses templates for tube identification.

Full entry into the channel head is required for installing these manipulators. Installation time varies from one to four minutes, depending on whether or not tube sheet templates are used. Some utilities prior to operation have stamped tube identification numbers directly onto the tubesheet primary side, thereby eliminating the need to install templates.

Computer-controlled remotely installed positioning devices have recently been introduced. B&W offers a manipulator for Remotely Operated Generator Examination and Repair (ROGER). This is an all-purpose no-jump manipulator designed for both recirculating and



(a) Zetec SM-4 manipulator for RSG's



(b) B&W manipulator for OTSG's

Figure 4-2. Manually Installed Probe Manipulators (Zetec and Babcock & Wilcox)

once-through steam generator work. The device has multiple applications including eddy current and profilometry, mechanical plug installation, remote tube pulling, machining of damaged tube ends or plugs, and remote plug welding. ROGER is shown in Figure 4-3.

Its installation and removal from a steam generator can be accomplished from the manway without entering the steam generator. A typical installation sequence for an RSG unit is shown in Figure 4-4. Computer control eliminates the need for tubesheet templates. After initial installation, this one device will handle all necessary inspections and repairs, from start to finish, in the steam generator.

ROGER has been used in numerous plants as of this writing. Experience with the device has been positive. Installation time from the manway has ranged from 5 to 13 minutes with a total installation radiation exposure of approximately 550 mr. Radiation exposure associated with tube plugging operations have been reduced by a factor of two.

Zetec has also introduced a no-jump computer-controlled manipulator. This device, the SM-10, (see Figure 4-5(a)) is used only for eddy current inspection. The device is attached to the steam generator manway as shown in Figure 4-5(b) and is controlled using an HP-9836 computer. Plant experience with the Zetec manipulator has been good.

Westinghouse has a Remotely Operated Service Arm (ROSA) which can be used for repair and maintenance applications in high radiation locations. The device is shown in Figure 4-6. After placement on the manway opening, ROSA attaches itself to the tubesheet without hands-on assistance. Repositioning operations of ORSA on the tubesheet are accomplished remotely.

Brown Boveri offers a remotely controlled manipulator for the inspection and repair of recirculating and once-through steam generators shown in Figure 4-7. The device has the following applications;

Inspection of steam generator tubes

- Eddy current inspection

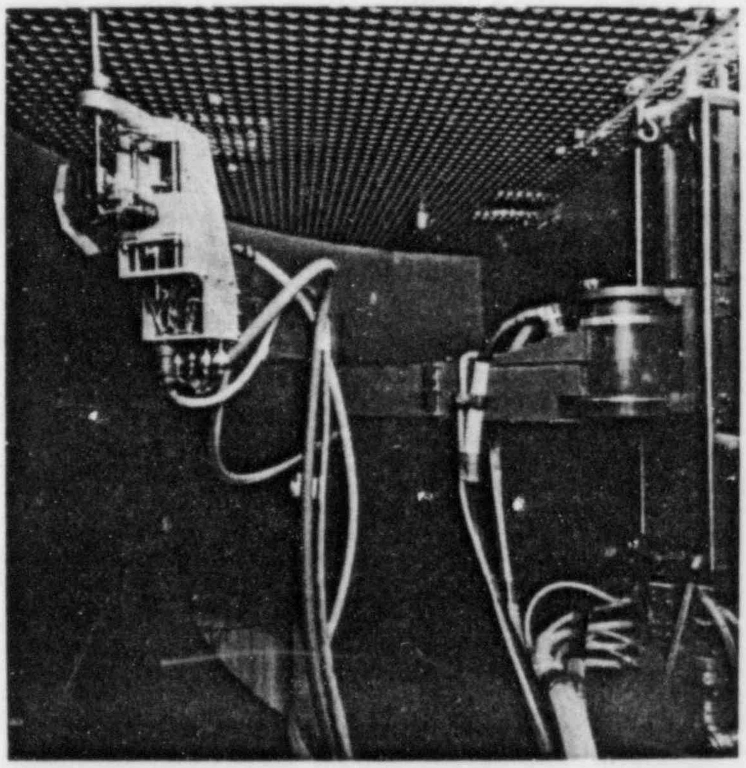


Figure 4-3. Babcock & Wilcox No-Jump Channel Head Examination and Repair Service Tool (ROGER)

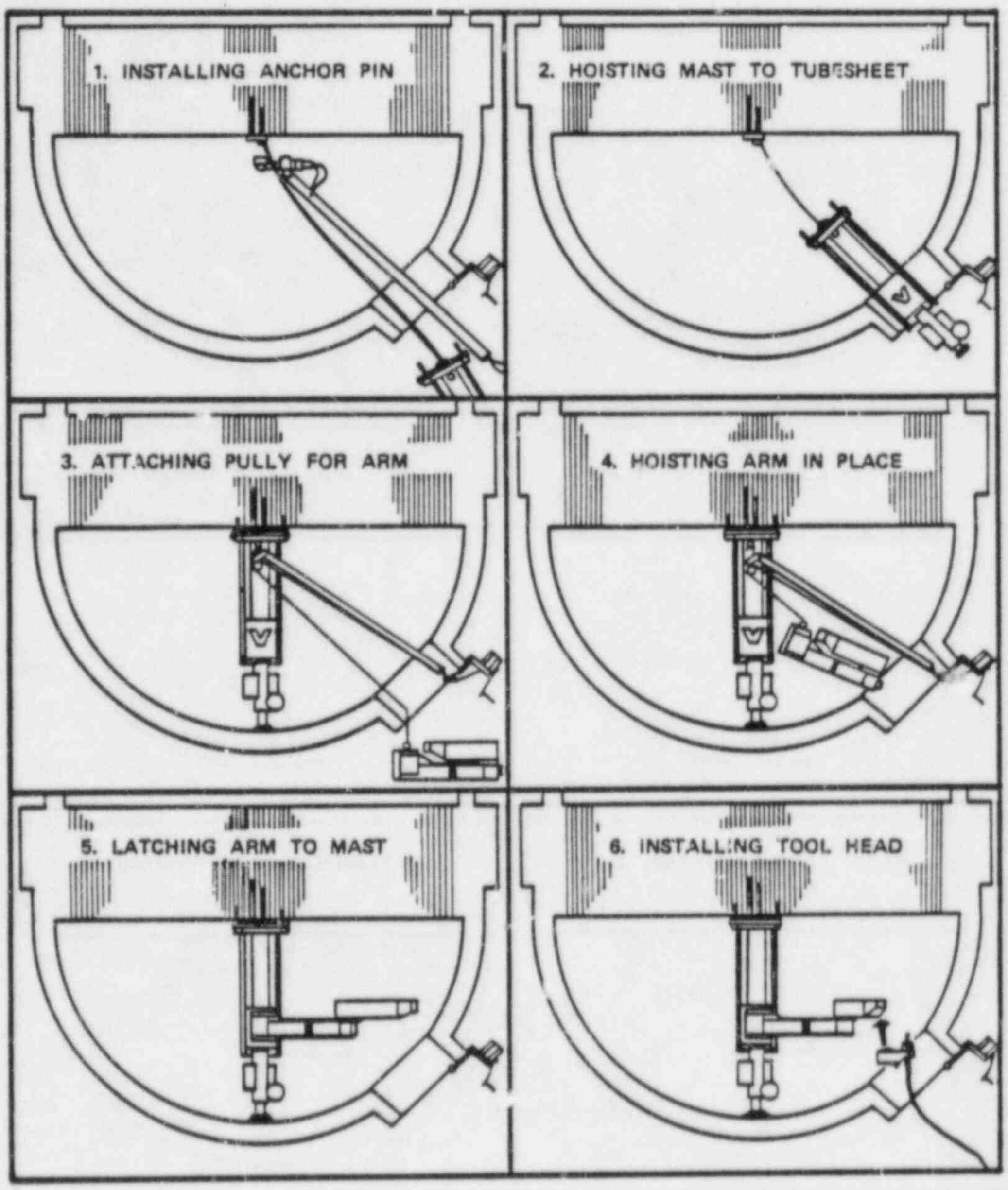
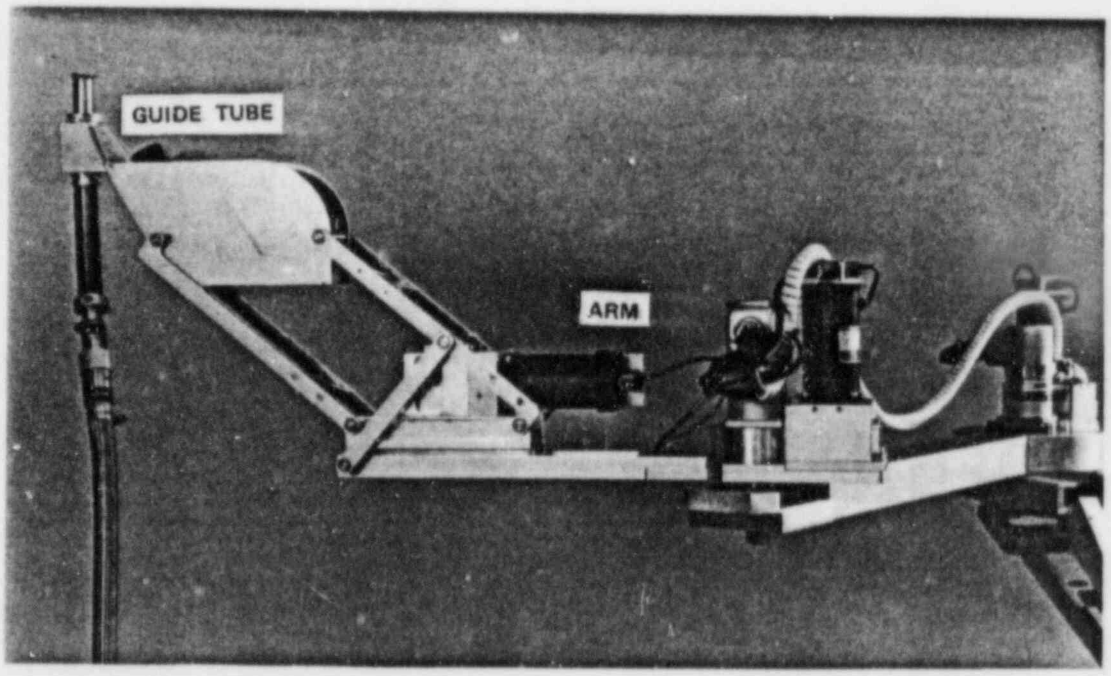
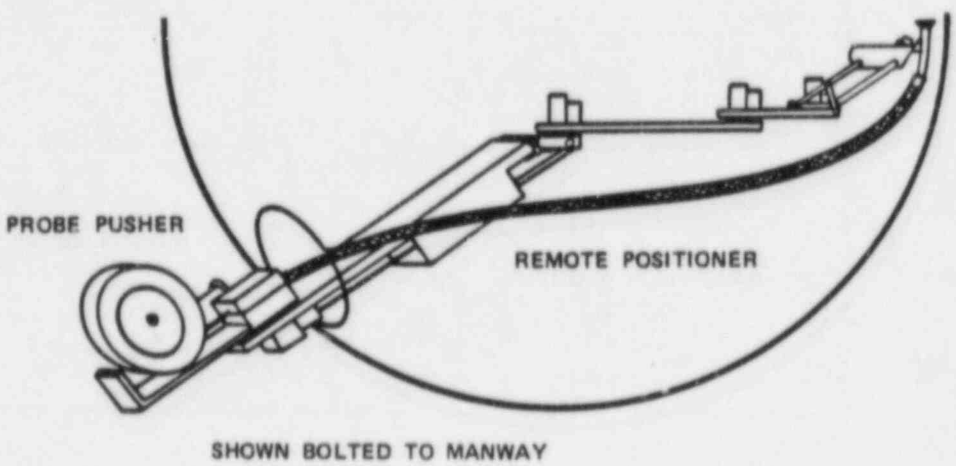


Figure 4-4. Typical Installation Sequence For ROGER



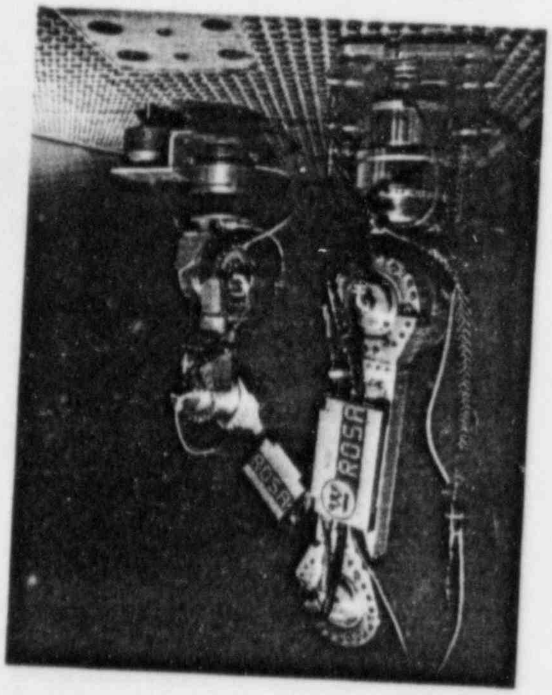
(a)



(b)

Figure 4-5. Zetec No-Jump Eddy Current Manipulator

TOOL HEAD MAST



CHANGING TOOL HEAD CONFIGURATION

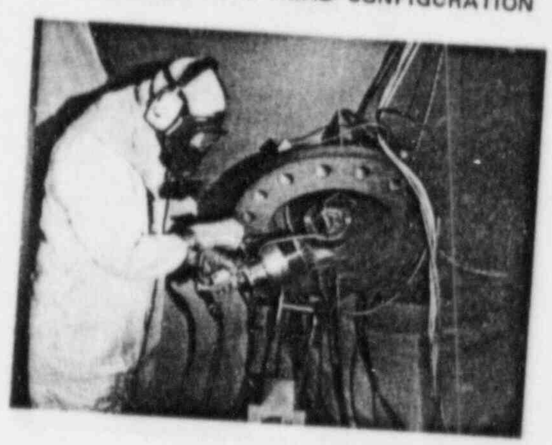


Figure 4-6. Westinghouse No-Jump Remotely Operated Service Arm (ROSA)

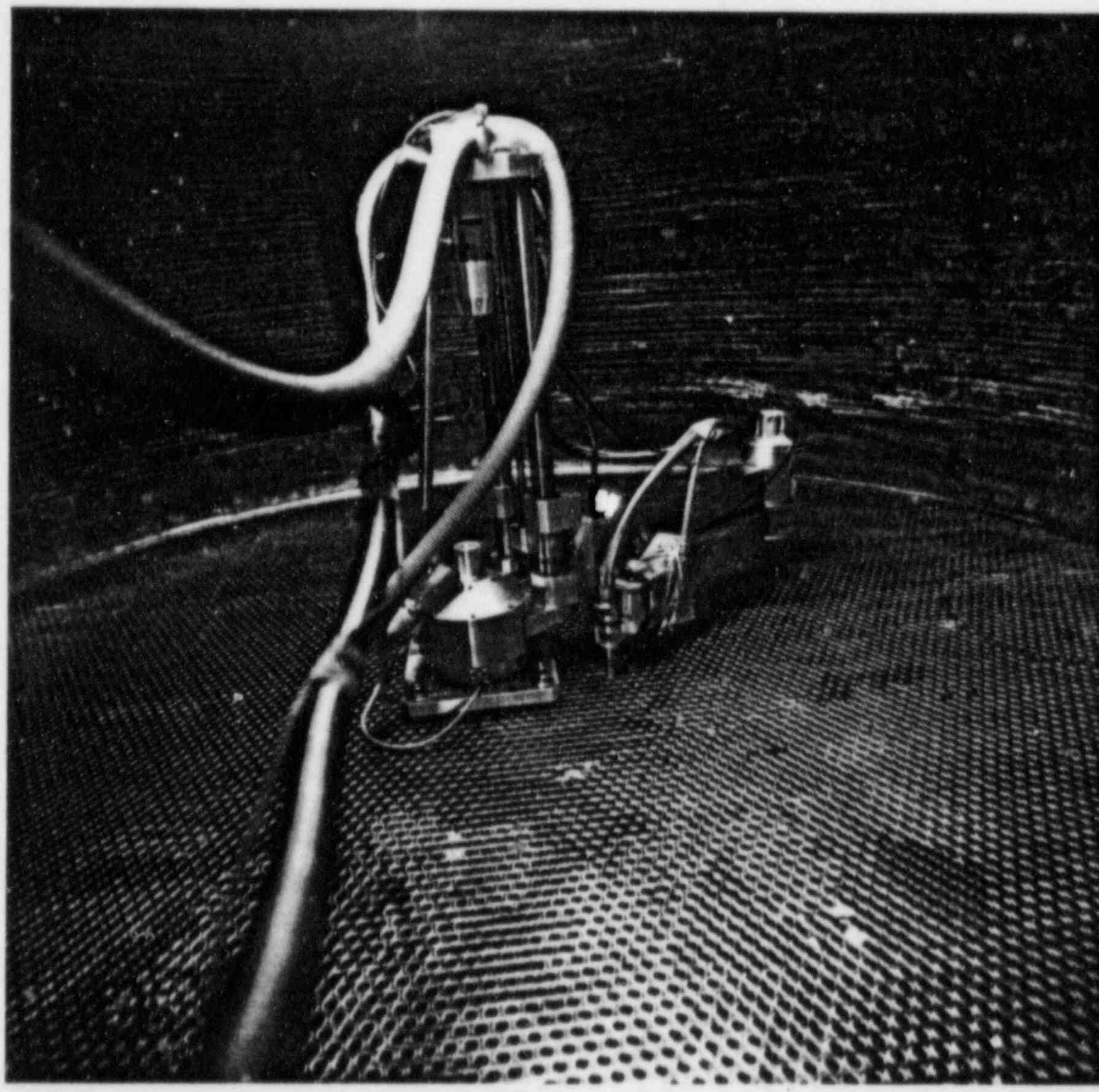


Figure 4-7. Brown-Boveri No-Jump Manipulator

- Ultrasonic inspection
- Visual inspection

Tube repair

- Tube pulling
- Tube plugging
- Sleeving
- Tube end repair

Installation is from outside the manway without manway entry. The device has high positioning accuracy and access to 100% of the tube-sheet surface. Positioning of the arm is rapid for both random and systematic 100% inspection of the steam generator.

Finger-walkers. Finger-walker probe positioning devices developed by Combustion Engineering (C-E) and Intercontrole are shown in Figures 4-8 and 4-9, respectively. The finger-walker is installed in the channel head and monitored by a TV camera in the channel head manway. No tube sheet templates are required. The probe conduit with an in-line standard runs directly to the probe pusher/puller. Remote equipment includes a TV monitor and controller units for positioning.

Partial entry into the channel head is standard practice for installing finger-walkers (see Figure 4-9). Installation time is typically less than 30 seconds. Therefore, typical worker radiation exposures for installing finger-walkers are lower than for installing manipulators.

Recently, Intercontrole has developed remote installation capability for their finger-walker. C-E has developed a similar capability but their plant studies have not shown a reduction in man-rem exposure when using this remote installation mode (9).

Finger-walker usage within the channel head may be restricted by tube plugs. In general, tube sheet access time is relatively slow with a finger-walker for inspection programs that require a lot of movement around the tube sheet.

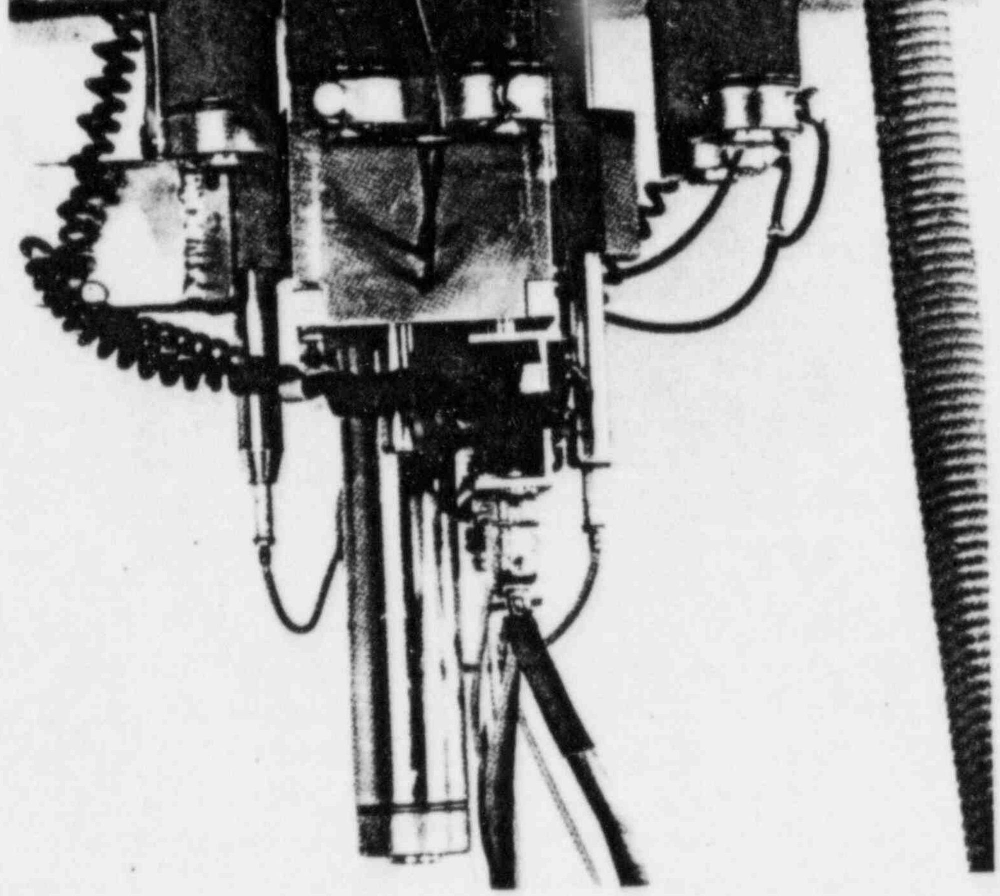


Figure 4-8. Combustion Engineering Finger Walker

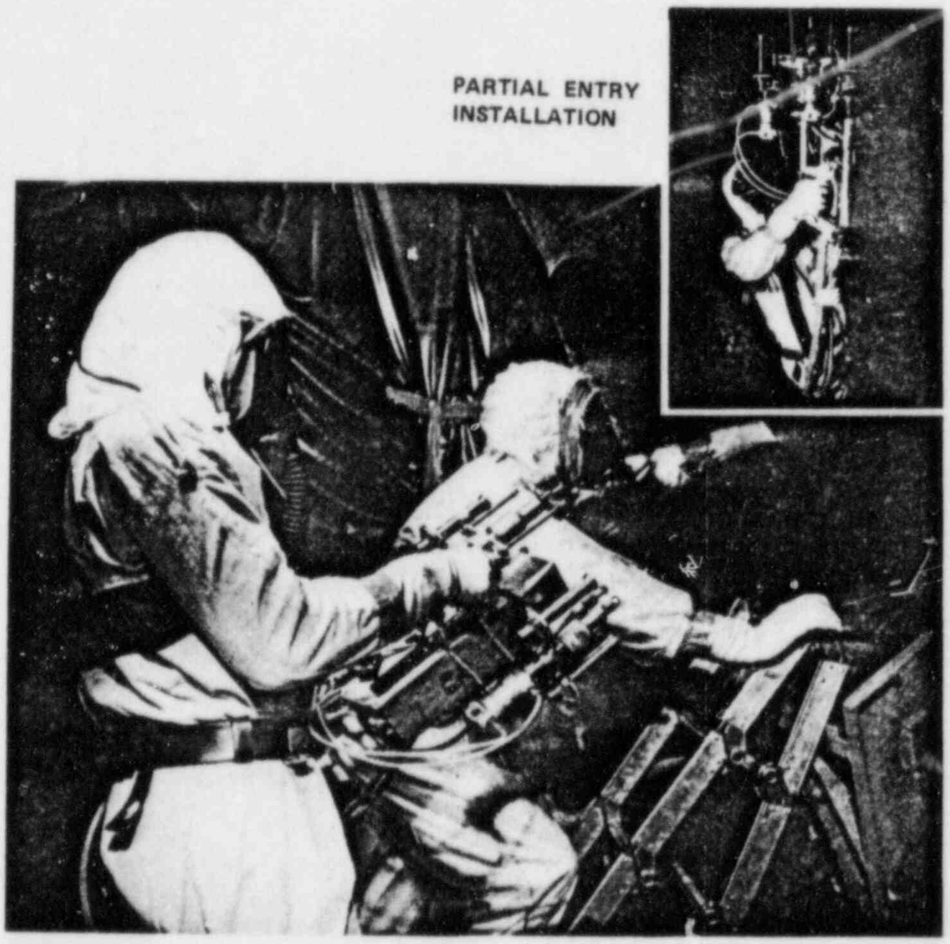


Figure 4-9. Intercontrole Finger Walker

Pusher/pullers. As shown in Figure 4-10, probe translation through the tube is achieved by using a rotary drum pusher/puller. Pusher/pullers typically push the probe into the tube at a constant rate of 36 inches/second and retract the probe at a rate of 12 inches/second. No tooling is required to change drive belts or the probe. The probe is usually pre-wound on a quick-disconnect drum for rapid changes.

Figure 4-11 illustrates a pusher/puller marketed by Intercontrole. The pusher/puller is connected to a finger-walker or manipulator by a flexible probe guide conduit. A multi-wheel probe drive gear box controls probe speed and direction. A probe speed security encoder provides feedback to the pusher/puller control unit, which shuts off the pusher/puller if the probe insertion speed deviates from its preset level. This feature can prevent probe damage caused by tube obstructions.

Figure 4-12 shows a four wheel drive gear box modification developed by CONAM for use on Zetec probe pusher/pullers. This modification has greatly increased probe pusher/puller durability during an outage. Complete steam generator inspections have been conducted without a change of the wheel drive assembly. The unit has sufficient driving power that a complete tube - including Row 1 U-bends - can be inspected from one side of the steam generator.

Digital encoders are now utilized to encode tube identification information directly onto magnetic tape or disc. This eliminates operator errors in tube identification and also simplifies the retrieval of eddy current data from a particular tube during the data review phase since automatic tube search and identification can be conducted.

4.2.2 Eddy Current Instrumentation

Multiple frequency eddy current instrumentation is recommended as the basic building block of a general purpose steam generator NDE data acquisition system. The benefits of multifrequency eddy current steam generator tube inspection are documented (10). They include:

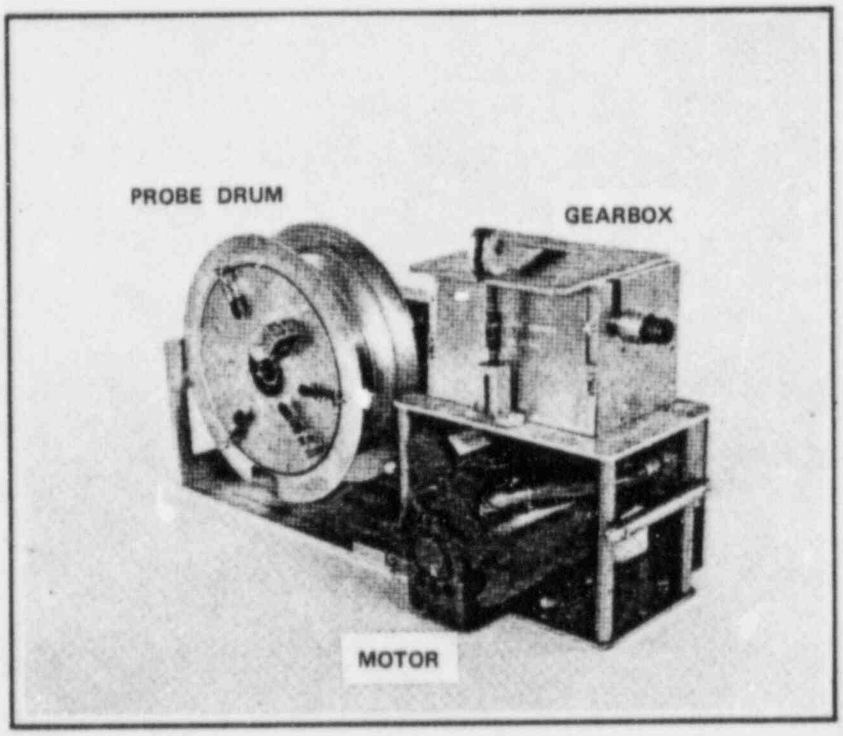
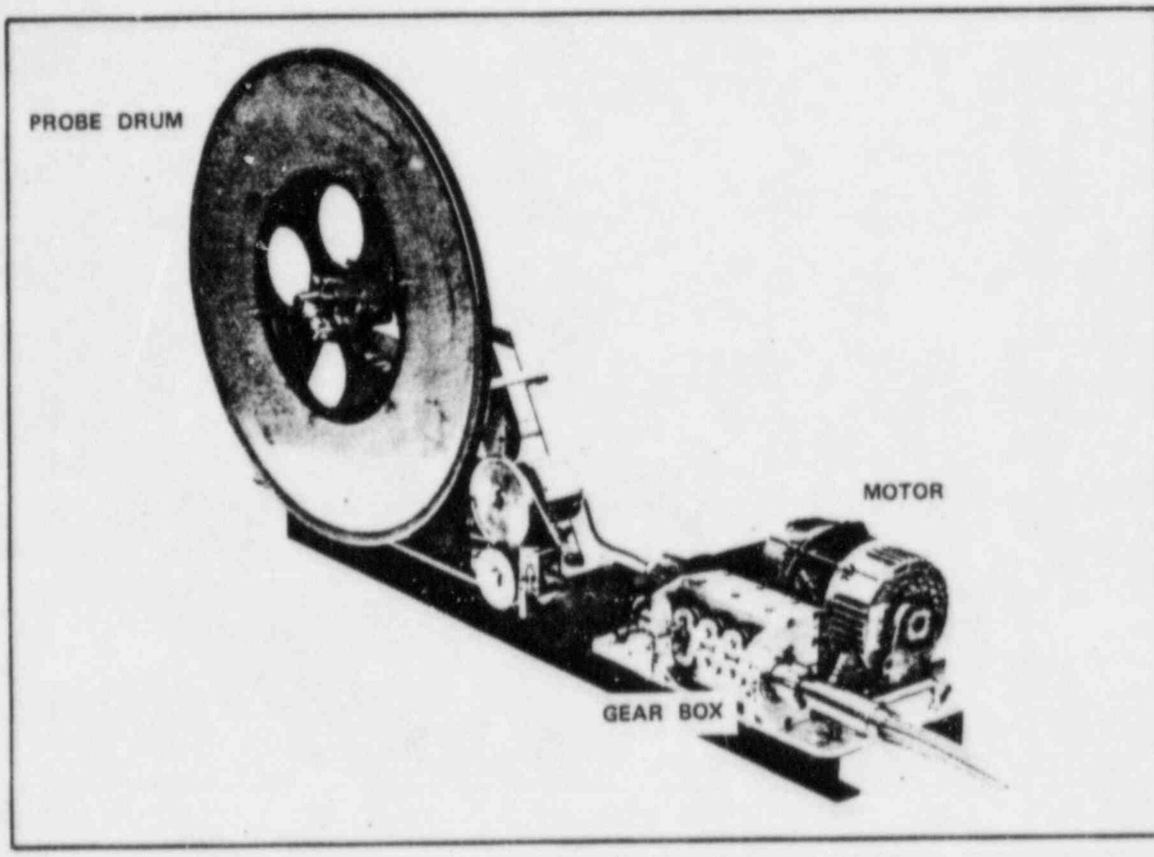


Figure 4-10. Zetec Probe Pusher/Puller



Figur^ 4-11. Intercontrole Probe Pusher/Puller

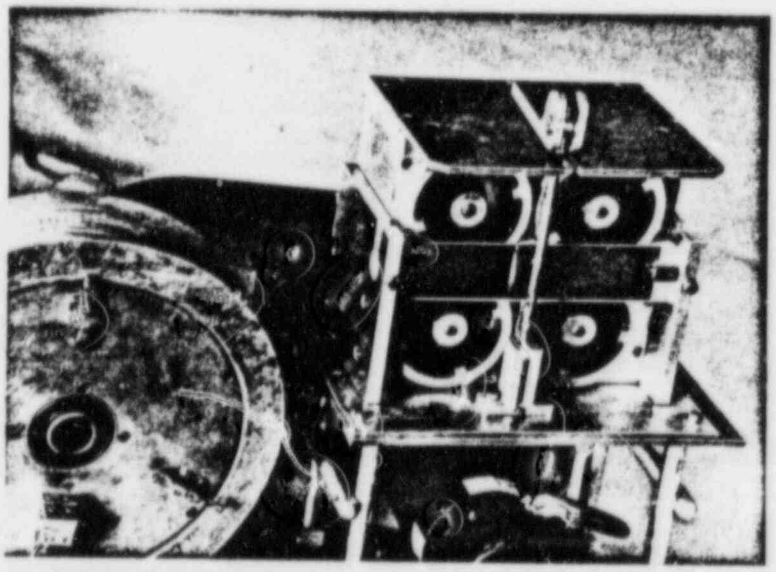


Figure 4-12. CONAM Heavy Duty Pusher/Puller.

- Reduction in data acquisition time. Determining tube integrity and detecting damage precursors generally requires separate examination frequencies. Use of a multiple frequency probe allows simultaneous testing during a single probing of the tube. This saves time and reduces operator radiation exposure, thereby reducing overall outage costs

- Signal redundancy. This increases the probability of detection and improves signal analysis.

- Extraneous variable suppression. Suppressing extraneous variables with multiparameter analysis equipment increases detection reliability and improves estimates of tube wall degradation.

Proper use of multiple frequency instrumentation requires selecting a basis frequency and auxiliary frequencies. The basis frequency is the primary analysis frequency used for monitoring tube wall integrity. Auxiliary frequencies are used to:

- Monitor for the presence of damage precursors

- Suppress extraneous test variables (in combination with the basis frequency)

- Provide backup data channels that improve detection reliability and facilitate analysis of complex signals.

Appendix B presents detailed procedures for selecting frequencies. The guidelines in Section 3 recommend specific basis and auxiliary frequencies for Westinghouse, C-E, and B&W steam generators under normal circumstances and in the presence of special damage forms or extraneous variables.

Figure 4-13 illustrates a multiple frequency eddy current instrumentation package based on Zetec technology. The package contains the MIZ-12 four frequency eddy current instrument and display, an 8-channel magnetic tape recorder and a 2-channel strip chart recorder for data storage, a communications system that provides voice contact for remote operations, and an OMB-1 control console that controls the strip chart, magnetic tape recorders, and the manipulator fixture. The OMB-1 unit also has a microphone for voice recording.

During the data acquisition phase, the pusher/puller translates the eddy current probe through the tube at a constant rate. The probe

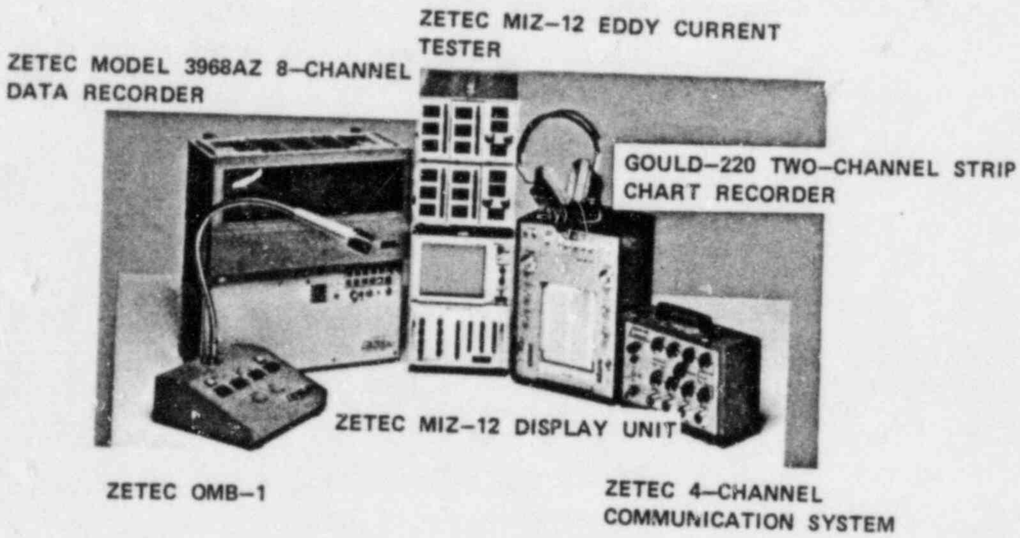


Figure 4-13. Zetec MIZ-12 Multifrequency Eddy Current Data Acquisition System

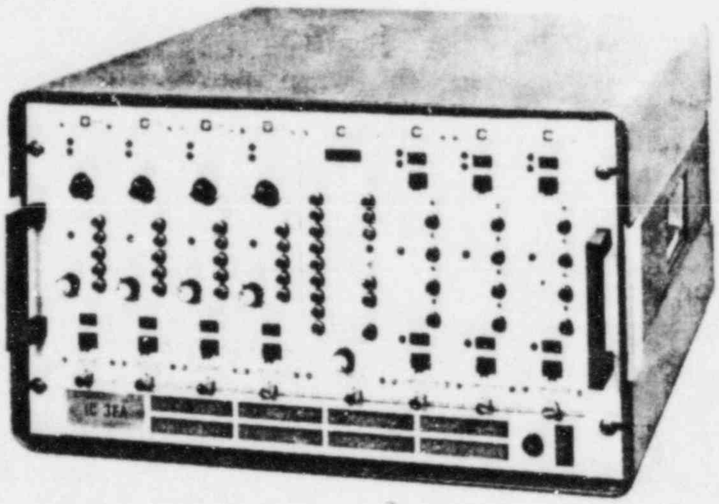
response at different frequencies is recorded on a multiple channel tape recorder for subsequent off-line analysis. Some of the data being recorded can be fed to the strip chart recorder, allowing the operator to verify that the system is operating properly. The strip chart recorder is operated at a constant speed, and this helps the analyst identify and estimate the axial location of conditions of interest within the tube. The strip chart and magnetic tape become the permanent examination record for a tube.

Other types of multiple frequency eddy current instrumentation are available commercially. For example, Figure 4-14(a) shows three-frequency instrumentation manufactured by Intercontrole. The instrument consists of three differential frequency modules, an absolute frequency module, and three mixing modules. Frequency cards are used to generate a highly stable frequency source. All frequencies are presented simultaneously to the test coil.

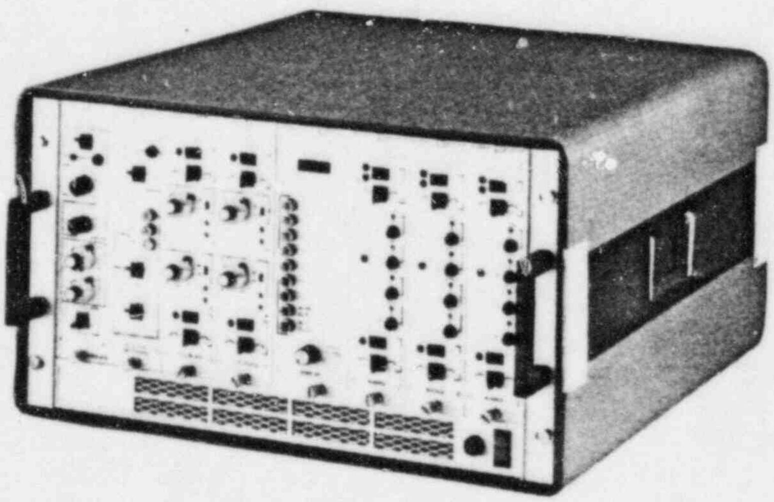
Intercontrole also offers an on-line digitizer for multiple frequency eddy current data which can be used in conjunction with an off-line analysis system. The IC4AN digitizer/analyzer is shown in Figure 4-14(b). The advantage of this approach is the elimination of the need for on-line mixing which reduces operator exposure. In addition, digital data greatly increases available dynamic range and signal-to-noise.

An Intercontrole remote digital data acquisition and analysis system is shown schematically in Figure 4-15. Data acquisition is typically done from the steam generator cold leg. The eddy current instrument, digitizer, and data link are located in close proximity to the steam generator. Eddy current data is transmitted outside of containment to an interface unit and subsequent recording on a digital recorder. The data link eliminates the need for a direct penetration into containment. During data analysis, analog data is recreated from the digital tapes for processing on the analyzer and generation of strip chart data. As the data is analyzed results are entered into a mini-computer for automatic report generation.

Eddy Current Technology, Inc. offers a line of versatile eddy current instrumentation for heat exchanger applications. The ECT 3000 series



(a) Eddy current instrumentation



(b) Analyzer

Figure 4-14. Intercontrole Multifrequency Eddy Current Instrumentation and Signal Analysis Equipment

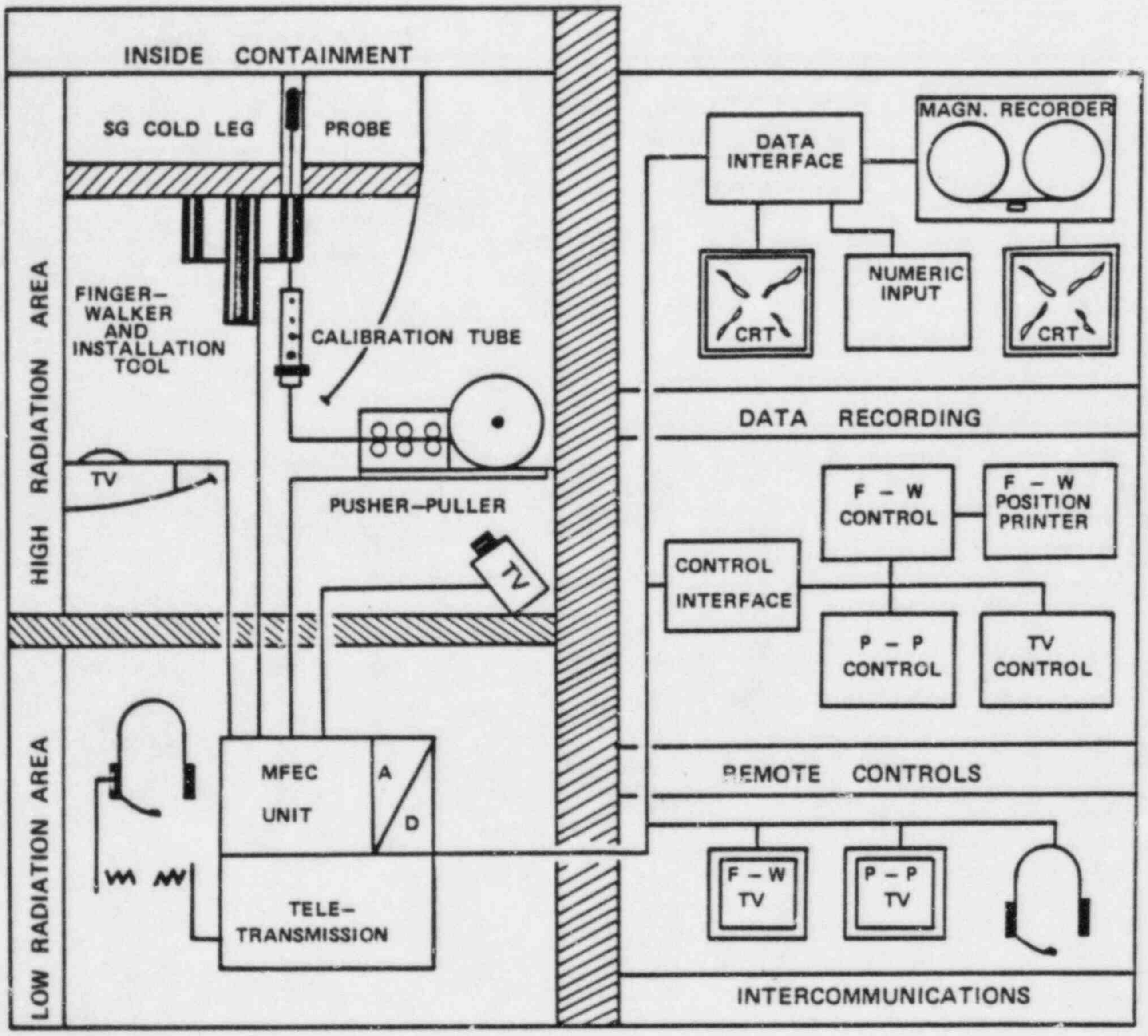


Figure 4-15. Intercontrole Remote Digital Eddy Current Data Acquisition System

can be configured in a multiple frequency package with as many as three mixing modules. Simultaneous multiple frequency coil excitation is utilized which means mixing results are independent of probe speed. The instrument is shown in Figure 4-16. Frequency range is from 1 KHz to 750 KHz with all frequencies crystal controlled for stability.

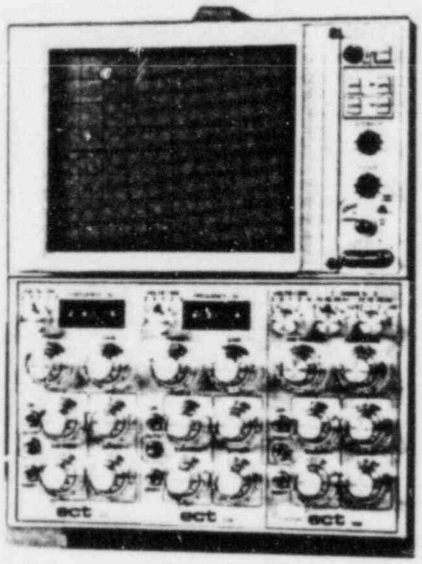
Hocking Electronics, Ltd. has recently introduced a four-frequency multifrequency unit. The Vector S904DV is shown in Figure 4-17 and consists of the following components:

- Four frequency generators, adjustable from 1 KHz to 1 MHz with variable drive power to the test coil, auto-calibration facility and bandpass filtering
- Four channel modules with controls for gain, phase and instantaneous electronic auto balance, absolute or differential mode
- Four mixer modules with independent input control of gain and phase and output control of gain and weighting of mixed signals
- Two storage scope displays with choice of impedance plane or timebase presentation.

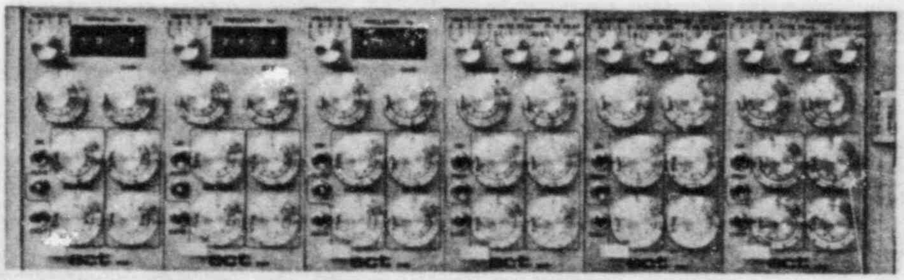
The entire system is housed in a dustproof rackmount enclosure as can be seen in the figure.

Zetec has recently introduced the first digital eddy current data acquisition system which is identified as the MIZ-18. The system provides for a significant increase in dynamic range and signal-to-noise ratio. The MIZ-18 consists of a remote acquisition unit and a local controller/recording unit interconnected with a digital data link. The system is shown in Figure 4-18.

Contained within a sealed enclosure, the remote acquisition unit comprises a frequency synthesizer, an analog processor with two 16-bit analog-to-digital converters, and an input/output controller. Frequency range is 10 KHz to 1 MHz. The local controller unit incorporates the HP-9836 computer, an interface between an internal HPIB port and the MIZ-18 remote cable, and the HCD-75Z digital data cartridge recorder. Digital data is recorded on the cartridge recorder for analysis and permanent storage.



TWO FREQUENCIES WITH ONE MIXER



THREE FREQUENCIES WITH MIXERS

Figure 4-16. Eddy Current Technology Multifrequency Eddy Current Instrumentation

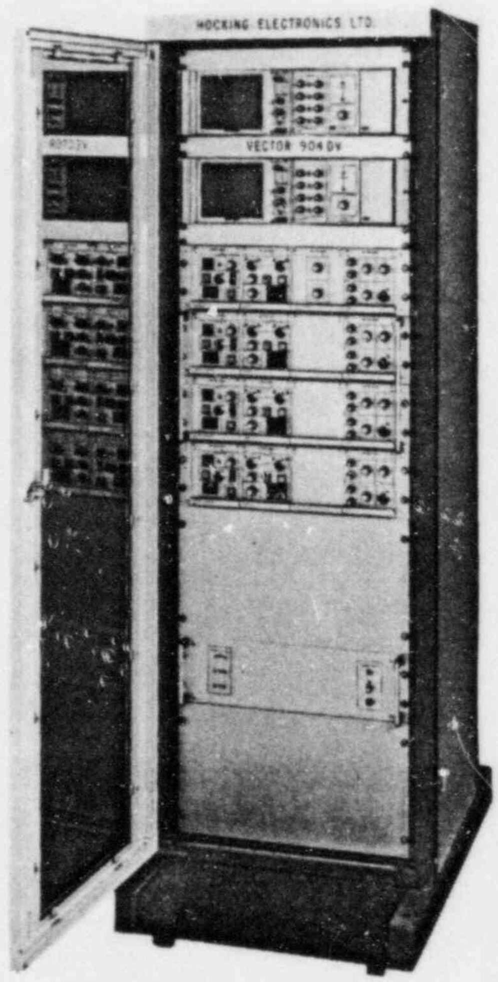


Figure 4-17. Hocking Electronics Multifrequency Eddy Current Instrumentation

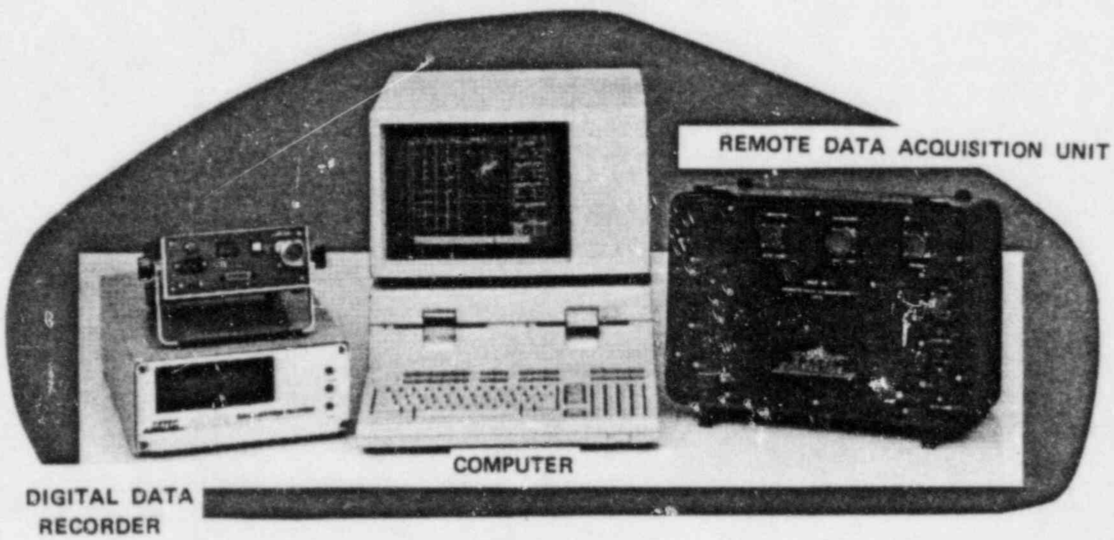


Figure 4-18. Zetec MIZ-18 Eddy Current Digital Data Acquisition System

Most eddy current data acquisition equipment is operated remotely, typically in dedicated instrumentation trailers. This has reduced operator radiation exposure, has increased data acquisition efficiency, and has raised operator morale. Figure 4-19 illustrates a typical remote equipment trailer installation. NRC approval is necessary for routing remote instrumentation cables through the containment equipment hatch if there are not already existing penetrations.

Another typical mobile data acquisition and analysis van as used by CONAM is shown in Figure 4-20. The unit contains multiple data acquisition stations and data analysis station. The trailer contains steam generator mockups which are useful for training purposes.

Eddy Current Technology, Inc. has developed a 3D dual frequency eddy current instrument which utilizes special coils for applications which require a capability to detect both circumferential and axial cracking in the presence of test variables which exhibit axisymmetry, i.e., roll expansion or roll transition. The instrument consists of the mainframe shown in Figure 4-16 with special plug in modules. The instrument has demonstrated a significant improvement in detecting cracking in the roll expansion when compared with conventional bobbin coil multifrequency technology. Specific examples of its capability are discussed in Section 6.

4.2.3 Eddy Current Probes

An important element of the data acquisition package is the eddy current test probe or coil. For optimum defect detection, the probe windings should be orthogonal to the expected defect plane.

Bobbin Coils. The bobbin coil is the most commonly used probe because of its rapid inspection speed and high mechanical reliability. A differential bobbin coil is pictured in Figure 4-21(a). Figure 4-21(b) shows the eddy current test coil and the direction of current flow in the tubing. Since the coil windings are in the circumferential direction about the tube axis, the probe is most sensitive to volumetric (three-dimensional) and linear tube wall discontinuities oriented parallel with the tube axis. Wastage, and axially oriented stress corrosion cracking, are examples of volumetric and linear tube

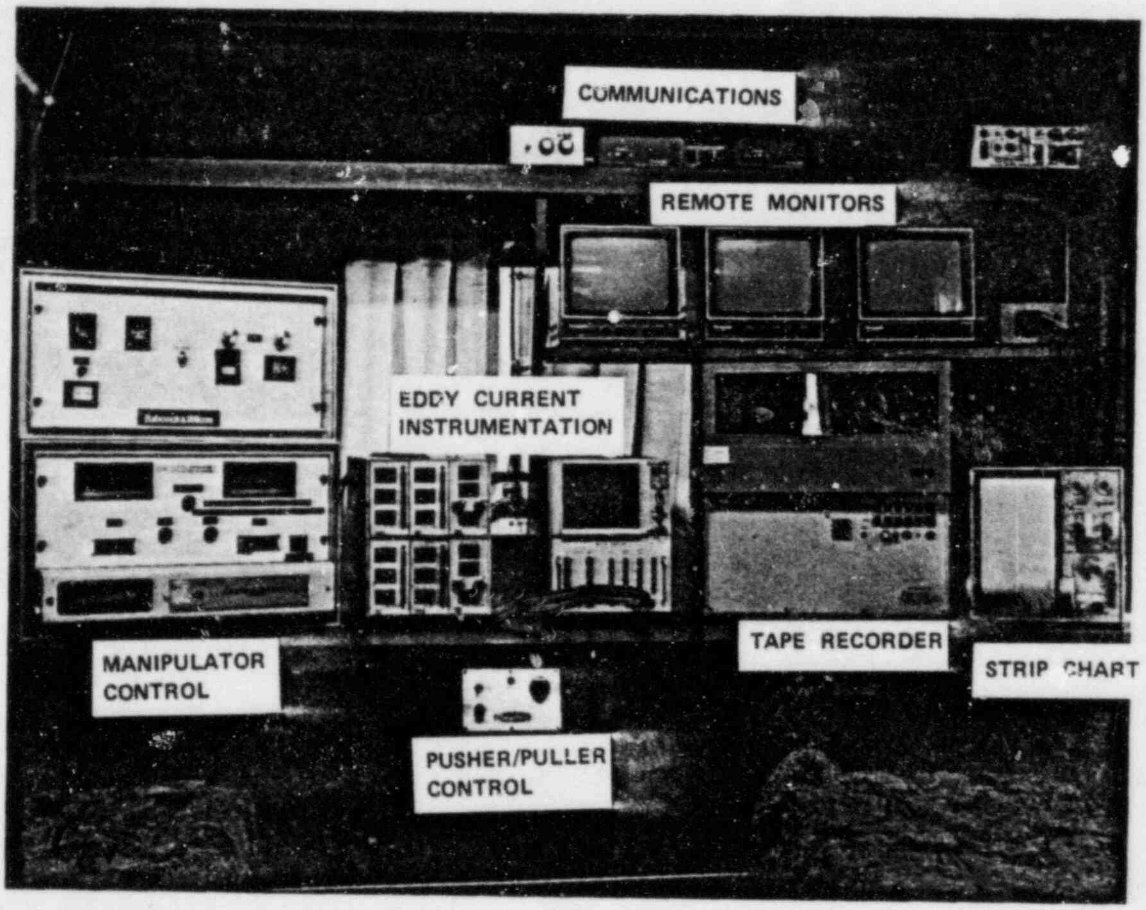


Figure 4-19. Typical Remote Eddy Current Data Acquisition Instrumentation (Babcock & Wilcox)

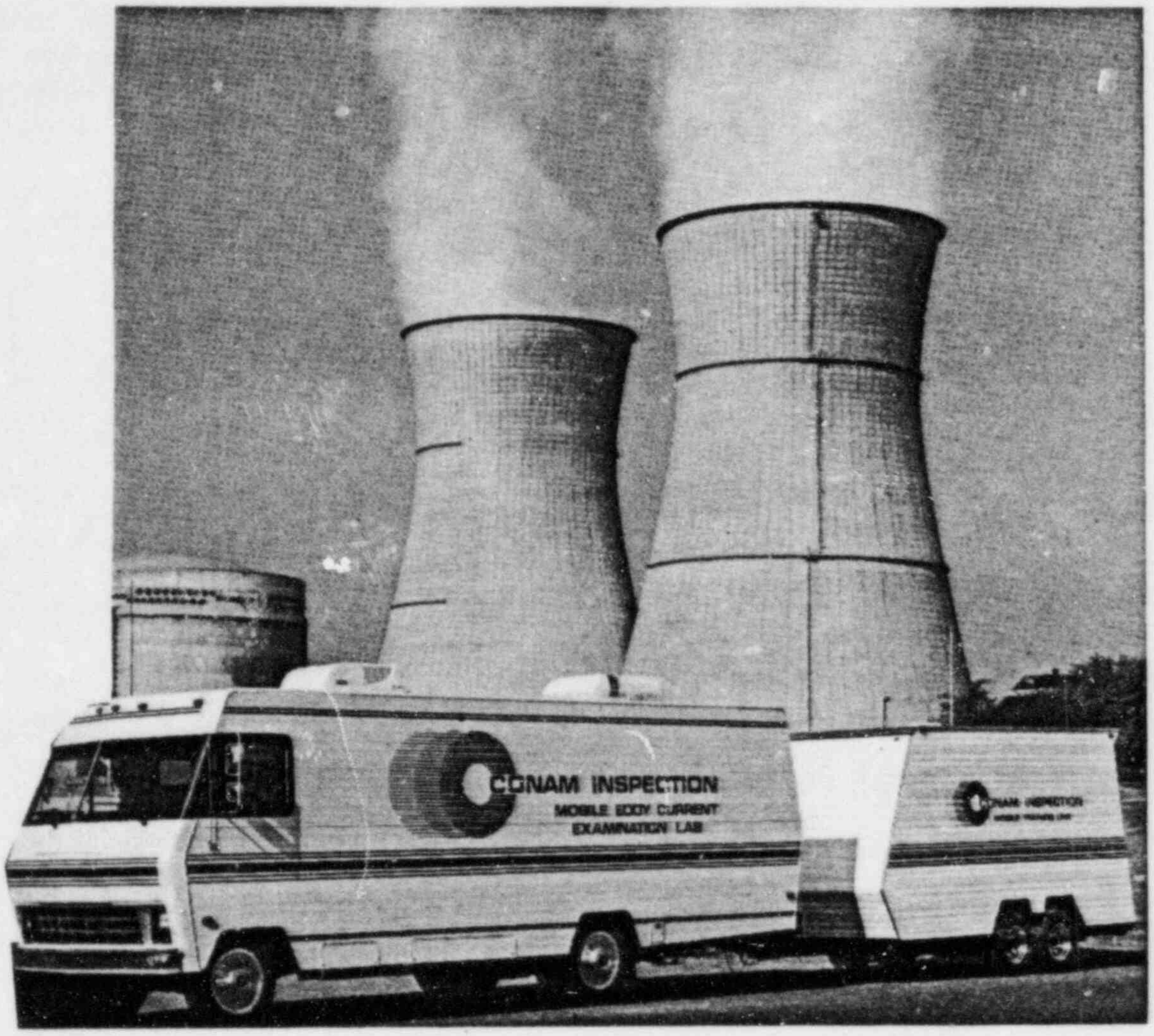
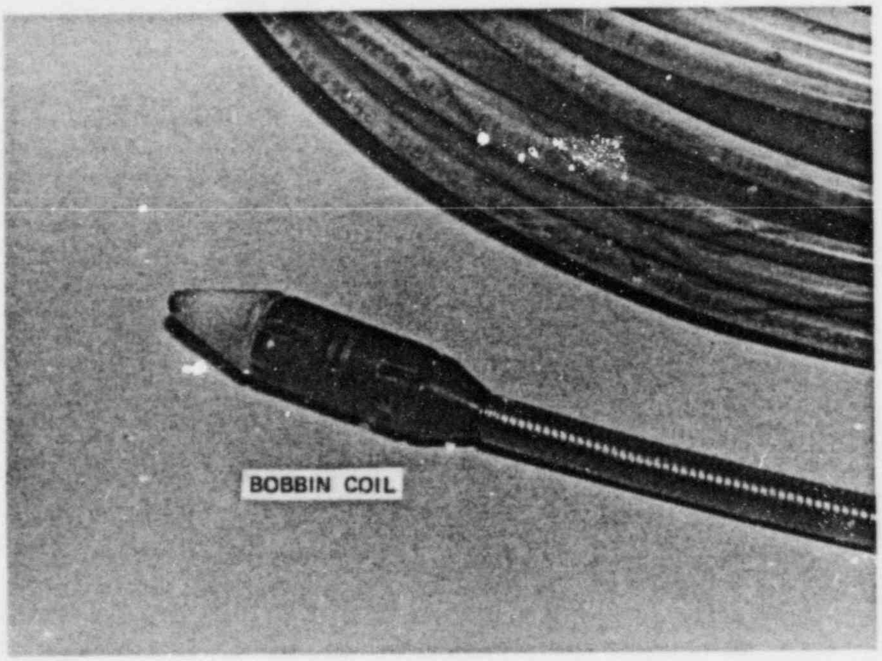
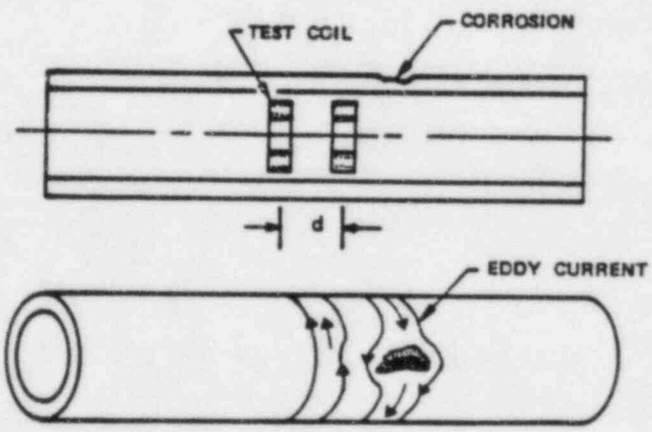


Figure 4-20. CONAM Mobile Van



(a) Differential bobbin coil



(b) Eddy current flow in tube

Figure 4-21. Typical Differential ID Bobbin Coil

wall discontinuities, respectively.

The differential bobbin coil provides an output voltage proportional to variations in the tube wall. This is achieved by winding the two coils in series opposition. This winding pattern tends to enhance detection of localized discontinuities and to suppress long-range variations in material properties, e.g., conductivity changes or gradual wall thinning. In addition, the effects of temperature variations and probe motion (wobble) are reduced.

The bobbin probe can also be operated in absolute mode, using the measurements obtained by one of the two coils. In this mode, the coil is sensitive to tapered discontinuities in the tube wall such as fretting, thinning, and volumetric intergranular attack; these tapered discontinuities tend to be suppressed in the differential mode. The absolute and differential coil measurements are achieved simultaneously by appropriate electronic operation of the coils shown in the figure.

Bobbin coils are flexible in accommodating to different regions of the steam generator. Large fill-factor probes are used where possible. Smaller fill-factor probes may be required in the presence of restrictions such as dents, dings, or tube-end seal welds.

The geometry of inner row U-bends in RSGs necessitates the use of special probe designs. To achieve desirable field penetration into the tube wall in this case, the winding width is increased and the operating frequency is lowered; this compensates for the relatively small fill-factor of the bobbin coil. Figure 4-22 shows a Row 1 U-bend probe manufactured by Zetec.

Axially oriented, stress assisted tube damage forms, such as stress corrosion cracking and intergranular attack, tend to occur where hoop stresses predominate. Denting may modify the normal stresses in the tube in such a manner that circumferentially oriented damage mechanisms result. The conventional bobbin coil may not reliably detect these damage forms for the following two reasons:

- The orientation of the induced eddy current flow is not orthogonal to the expected defect direction

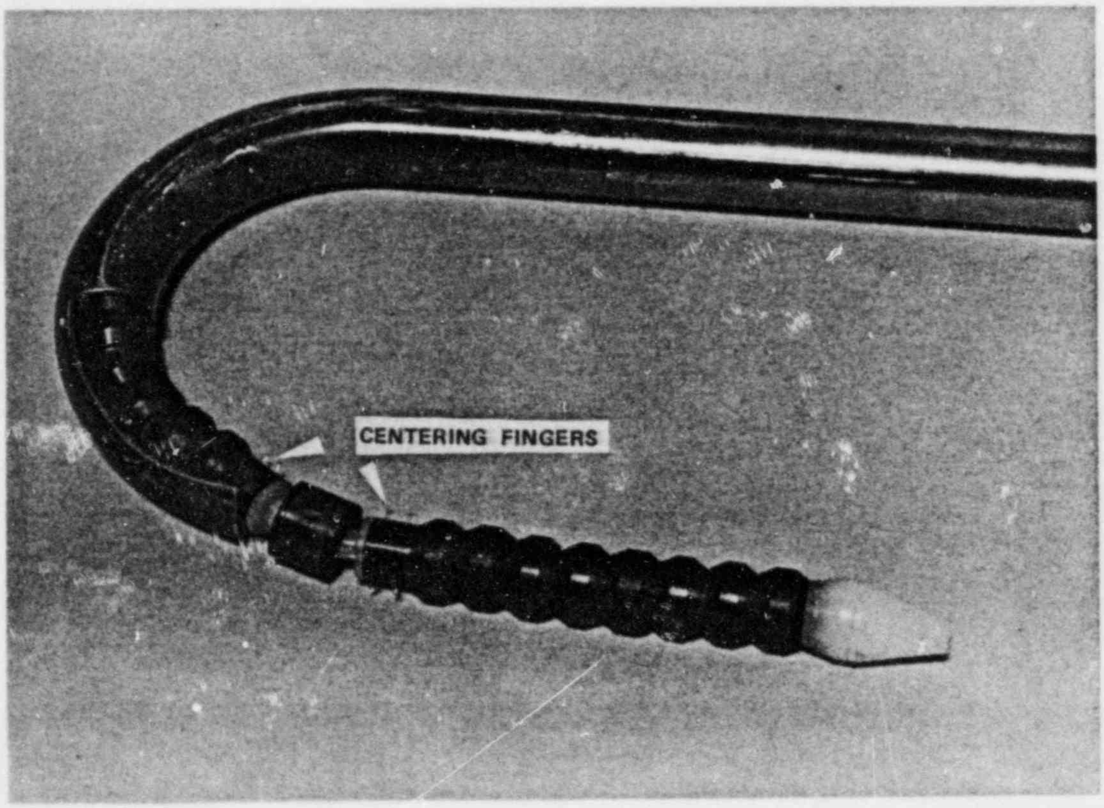


Figure 4-22. Typical Inner Row U-bend Probe

- The dent causes a large variation in bobbin coil fill factor, which produces a large amplitude extraneous signal that masks the tube wall degradation signals.

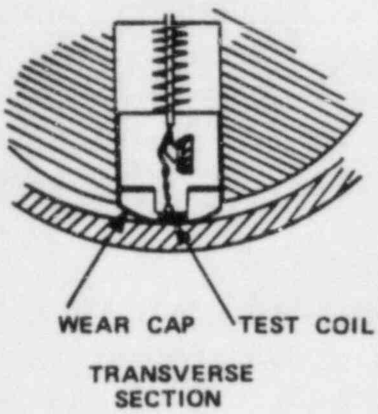
Probe Coils. Spring-loaded probe coils can improve inspection capabilities in the presence of either circumferentially oriented tube wall degradation or variations in tube wall geometry caused by dented support plate/tube sheet intersections or roll transition regions. The probe axis of symmetry is typically along the radius of the tube, with the coil windings parallel to the inner surface of the tube.

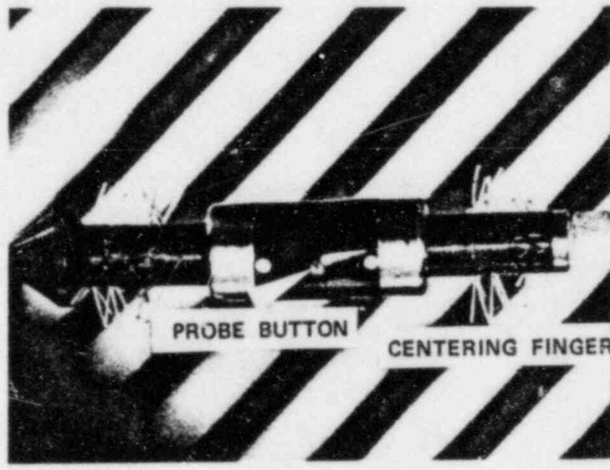
Since the induced eddy current flow is circular, the coil is equally sensitive to axially and circumferentially oriented discontinuities. Figure 4-23(a) illustrates a typical probe coil configuration. The probe button is spring-loaded to reduce coil lift-off effects. Nylon fingers keep the probe head centered in the tube.

For this device, the probe coil's field of view of typically one to two coil diameters (one diameter is approximately 0.187"). Therefore, the probe must be translated axially and rotated circumferentially in order to achieve full inspection coverage within the tube. This is achieved by using special pusher/puller equipment such as the Zetec SM-6 shown in Figure 4-23(b). To rotate the probe, the pusher/puller rotary drum is mounted on an axis of rotation; translation is achieved by using multiple friction drive wheels.

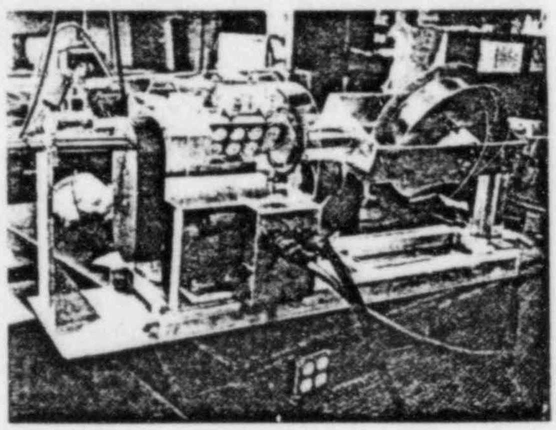
The SM-6 system can provide an inspection capability where none previously existed. However, the inspection rate is relatively slow and, historically, constant attention and equipment maintenance has been required. Radiation exposure and inspection time using this device are high.

Intercontrole has developed a rotating probe system to inspect the roll expansion at the top of the tube sheet in French units with fully expanded crevices. The rotating probe mechanical drive system and control unit are shown in Figure 4-24. The mechanical unit sets in front of the steam generator manway and is designed to feed the probe to a finger-walker. Slip rings are used to eliminate the need for mechanical rotation of the probe head. The system has been used extensively in France without significant problems.





(a) Spring-loaded probe coil configuration



(b) Zetec SM-6 pusher/puller

Figure 4-1[illegible]. Zetec Rotating Pancake Coil Technology

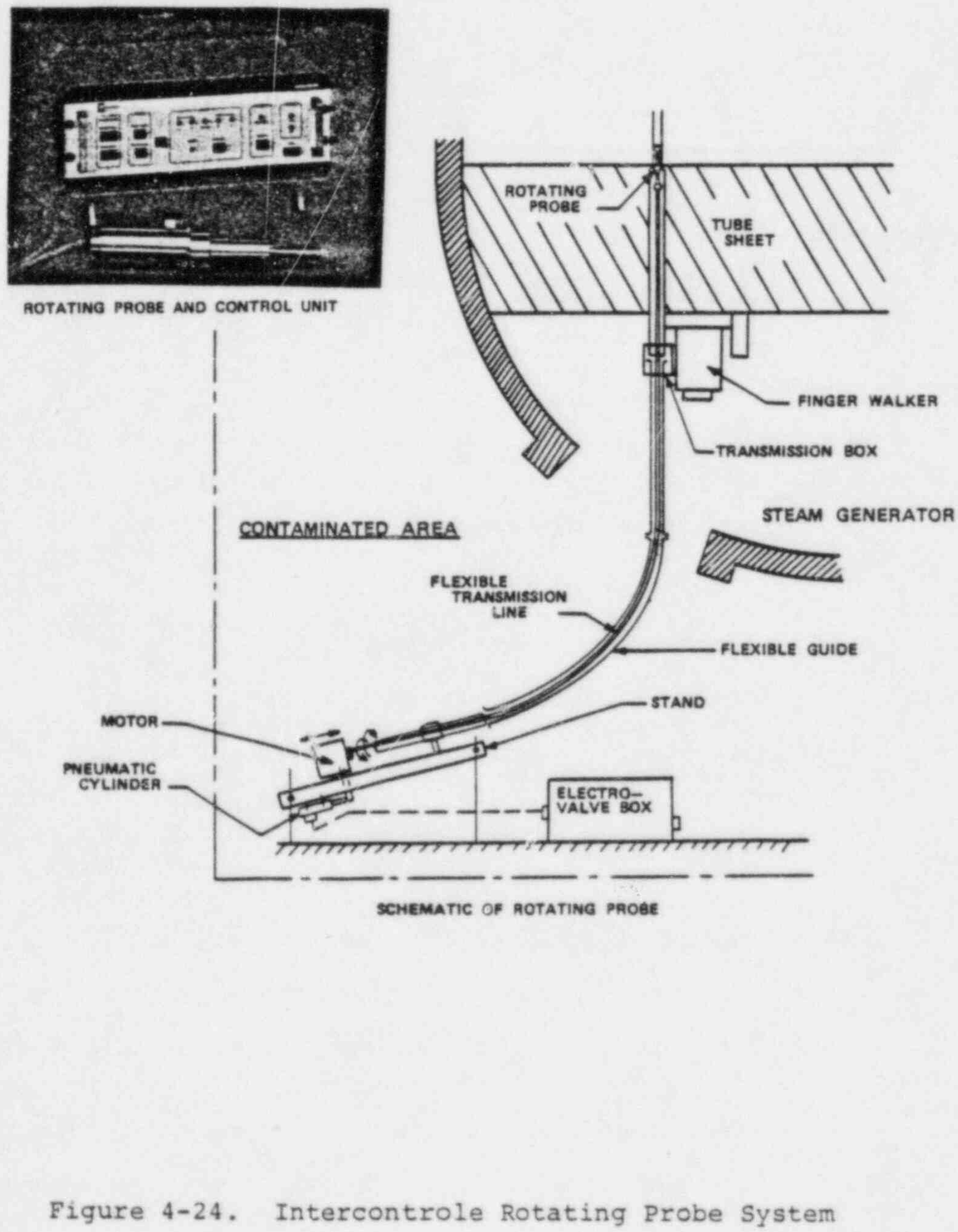


Figure 4-24. Intercontrole Rotating Probe System

Laborelec has developed a rotating probe system for the inspection for cracking in expanded tube sheets. The system has had extensive field experience in Belgian units. The inspection rate for a tube sheet hole is less than 55 seconds. A key feature of the system is its graphics display capability from which the detailed morphology of a crack can be determined. This capability has proven to be very useful in identifying critical crack geometries and monitoring crack growth rate. Figure 4-25 shows the Laborelec rotating probe and an exampl of a graphics plot of eddy current data obtained from a calibration standard.

Array Coils. Surface-riding array coil probes have been used for selected steam generator inspection problems. A typical array coil probe consists of eight coils, located about the circumference of the probe head. As shown in Figure 4-26, the coils may be in the same transverse plane or may be staggered axially. Since a single coil has a limited field of view, multiple coils are required to achieve full tube coverage. The coils are typically spring-loaded to minimize coil lift-off effects. Advantages of array coil technology include:

- Equal sensitivity to axially or circumferentially oriented tube wall discontinuities
- Spring-loaded coils that suppress tube geometry changes (mechanical suppression of tube geometry changes is generally better than changes made through an instrumentation approach)
- Full coverage of the tube wall by the array coil, eliminating the need for an SM-6 positioner.

Disadvantages of array coil technology include:

- Increased complexity and cost compared to the bobbin coil
- Duplication of eddy current instrumentation to accommodate the multiple coils
- Increased time required to analyze data from multiple coils
- Decreased reliability cuased by short array coil lifetime.

Eddy Current Profilometry. Non-contact array coil probes have also been used to profile dents. The shape of the dent is estimated by fitting a curve to eight sample points around the tube circumference.

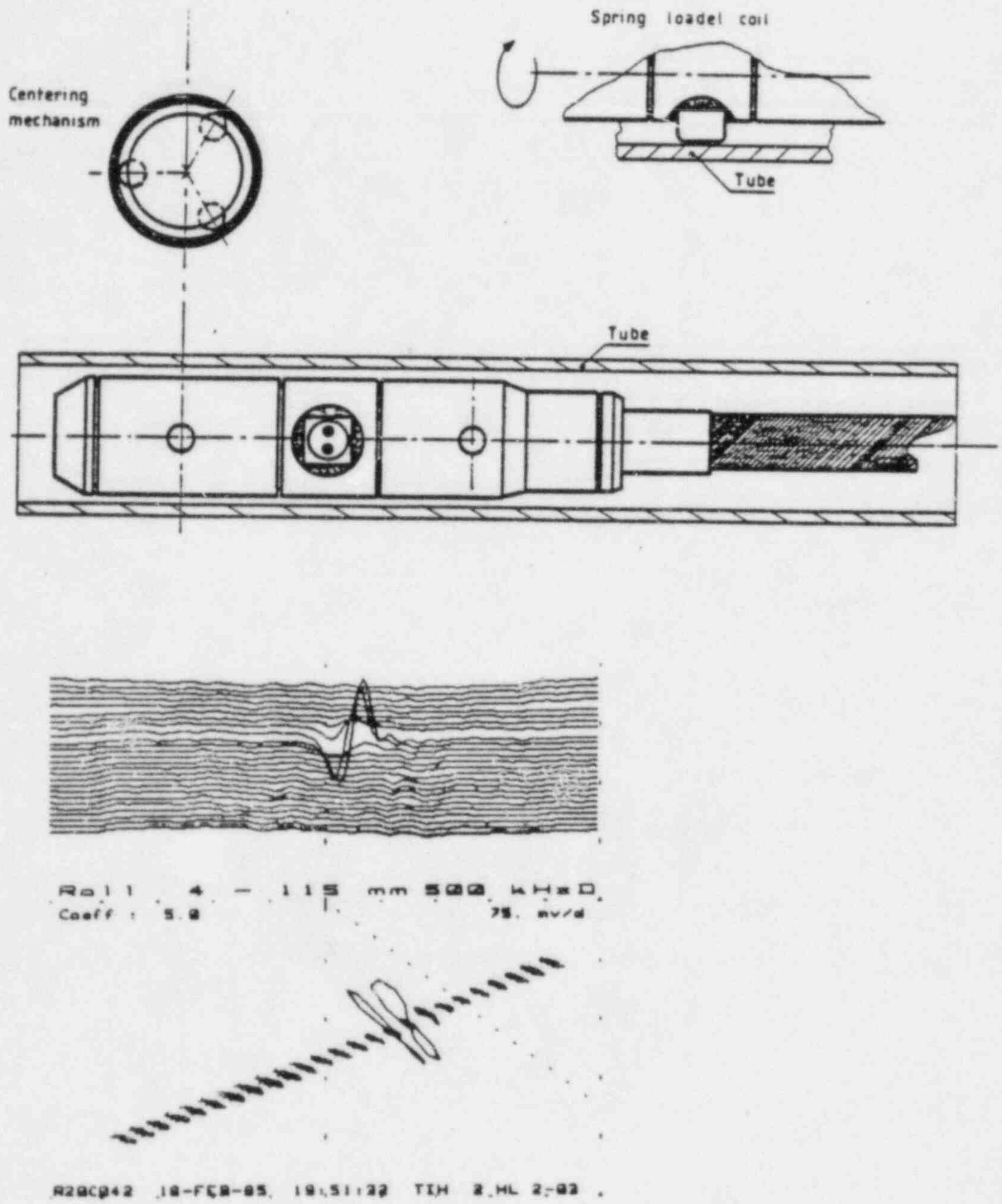
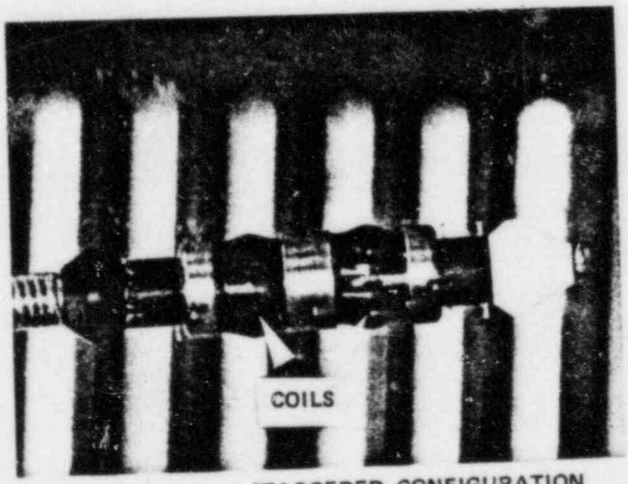


Figure 4-25. Laborelec Rotating Probe-Graphics Display

8x1 CONFIGURATION



STAGGERED CONFIGURATION

Figure 4-26. Array Coil Technology

Strain information is then calculated from the profile. Using established strain criteria as a basis for judgment, the tube may be plugged in order to prevent stress corrosion cracking, leaking dents, and unscheduled outages. Figure 4-27 illustrates a typical eddy current profilometry probe. The probe is multiplexed by using Zetec MIZ-18 digital eddy current instrumentation (see Figure 4-18).

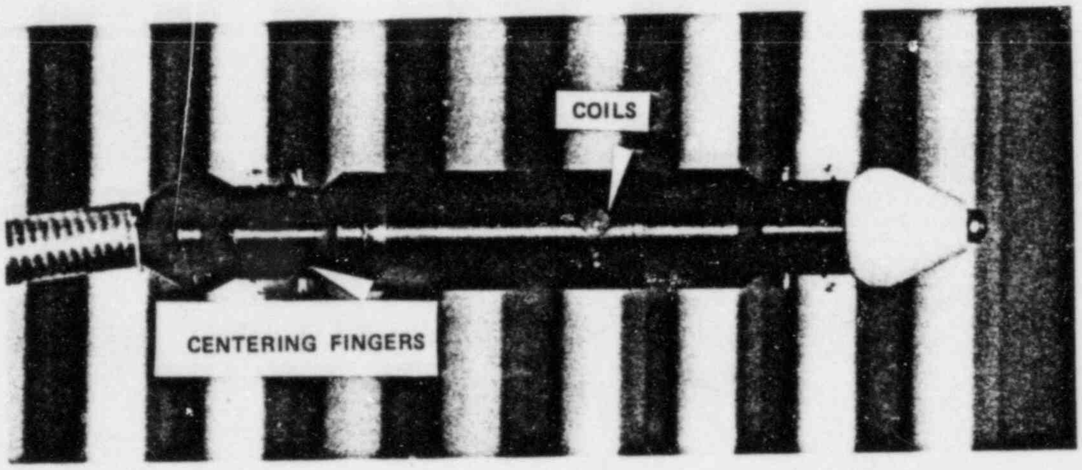
4.3 EDDY CURRENT DATA ANALYSIS

The condition of a steam generator tube is assessed by analyzing the eddy current inspection data. In some cases, extraneous test variables perturb the eddy current data and thereby inhibit reliable detection and characterization of tube wall degradation. In particular, the electromagnetic field of the probe is affected by conductive and magnetic materials near the tube wall and, depending on probe type, it may be affected by geometry changes in the tube. Typical extraneous variables are summarized in Table 4-1. The variables have been divided into two classes: those attributable to variations in the tube diameter, and those due to material property variations (resistivity or permeability) within or near the tube wall.

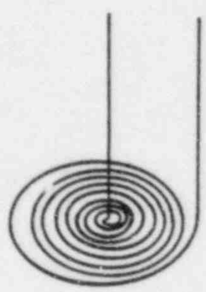
Table 4-1

EXTRANEOUS VARIABLES

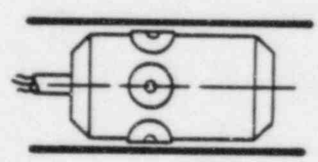
Property Variations	Geometry Changes
• Tube structural supports (tube support plate, tube sheet, eggcrates, AVBs)	• Denting
	• Roll transition
• Metallic deposits (copper)	• Roll expansion
• Magnetite deposits (sludge)	• U-bend transition
• Tube wall permeability changes	• ID noise
• Tube sheet noise	• Dings



PROBE HEAD



SINGLE COIL



SIDE-VIEW OF ARRAY PROBE

Figure 4-27. Eddy Current Profilometry Probe

The two general approaches that have been used to mitigate the effects of extraneous variables are electronic and test coil suppression methods.

4.3.1 Test Coil Suppression Methods

Test coil suppression methods seek to reduce sensitivity to the extraneous variable directly at the test coil. Use of a surface-riding probe (see Figure 4-26) can reduce the effects of the variations in geometry listed in Table 4-1 with the exception of ID noise. Saturating coils can reduce magnetic property variations within the tube wall. Typical saturating coils are bobbin coils that use permanent magnets or a dc magnetic field to produce a saturation field.

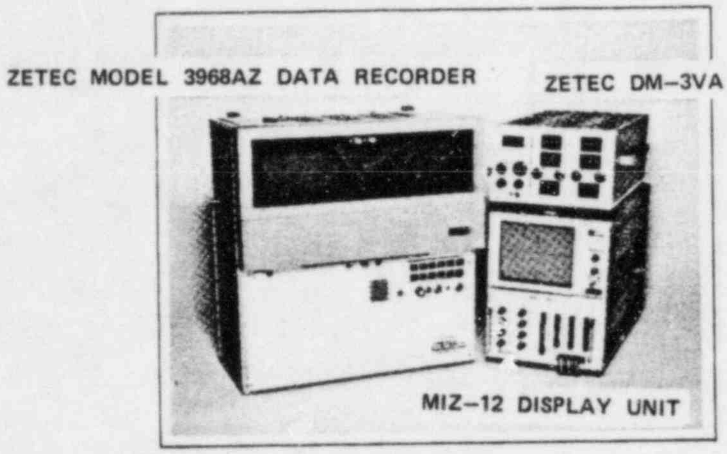
4.3.2 Electronic Suppression Methods

Electronic suppression methods use either multiparameter or signal subtraction data analysis equipment. Multiparameter approaches sample the extraneous variable at two or more frequencies and produce a weighted linear combination of input data that minimizes the effect of the extraneous variable. The signals are combined in analog computers called mixers or with digital data analysis systems, the mixing is done numerically. The process is referred to as mixing. Appendix B discusses mixing in more detail.

Figure 4-28(a) shows a representative example of multiparameter analysis equipment. The analysis package consists of an 8-channel magnetic tape recorder for data replay and tube identification, and an X-Y storage scope for viewing and measuring signals of interest. Multiparameter manipulations and analysis of the multifrequency eddy current data are accomplished using the DM-3VA data mixing system.

Single frequency eddy current data which is perturbed by an extraneous variable can be analyzed using signal subtraction methods. In this approach, a non-distorted reference signal (e.g., of a support plate or tube sheet) is subtracted from the perturbed signal.

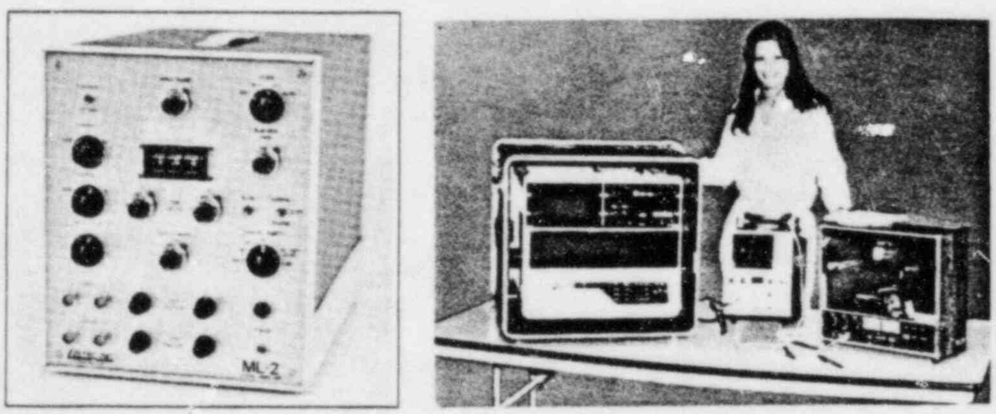
Figure 4-28(b) illustrates signal subtraction equipment. Analog data replay and viewing is accomplished by using a tape recorder and storage scope as described for the multiparameter approach. A minicomputer



(a) Multiparameter data analysis equipment

ML-2

CECA



ZETEC

BABCOCK & WILCOX

(b) Signal subtraction equipment

Figure 4-28. Eddy Current Signal Analysis Equipment

(B&W CECA) or digital shift registers (Zetec ML-2) performs the vector subtraction operation.

In general, signal subtraction approaches do not accommodate either multiple simultaneous extraneous variables or as wide a range of extraneous variables as do multiparameter methods. The overall analysis time is also slower than for multiparameter approaches (10).

Zetec has recently introduced the first digital data analysis system. The system is shown in Figure 4-29. It consists of an A/D-8 analog to digital converter, an HP-9836 computer with 1.048 megabytes of RAM and Zetec-developed software. The data analysis system is best described as a computer-assisted manual analysis system. The computer stores all analysis parameters, user-selected data segments and descriptive information to allow the analyst to later re-create analysis conditions. A complete report can also be stored. The thermal printer plots the graphic display and final report on hard copy for permanent records.

The digital analysis system has been used extensively in numerous plants and user acceptance has proven to be very satisfactory. Improvements to the software are currently being assessed based on user feedback. Some of these improvements include:

- Data disk information transfer to an identical digital system via a modem and telephone line
- Data transfer to other data base management systems
- Data screening during data input.

4.4 OTHER NDE METHODS FOR SPECIALIZED TUBE INTEGRITY APPLICATIONS AND FOR MONITORING DAMAGE PRECURSORS

Other steam generator NDE methods have been developed for special tube integrity applications and monitoring damage precursors. The detection and characterization of steam generator damage precursors can provide an early warning of potential tube damage. This enables the utility to implement corrective actions in an orderly fashion and to monitor their effectiveness. Recognized damage precursors include:

- Sludge or debris, a possible precursor to tube wall

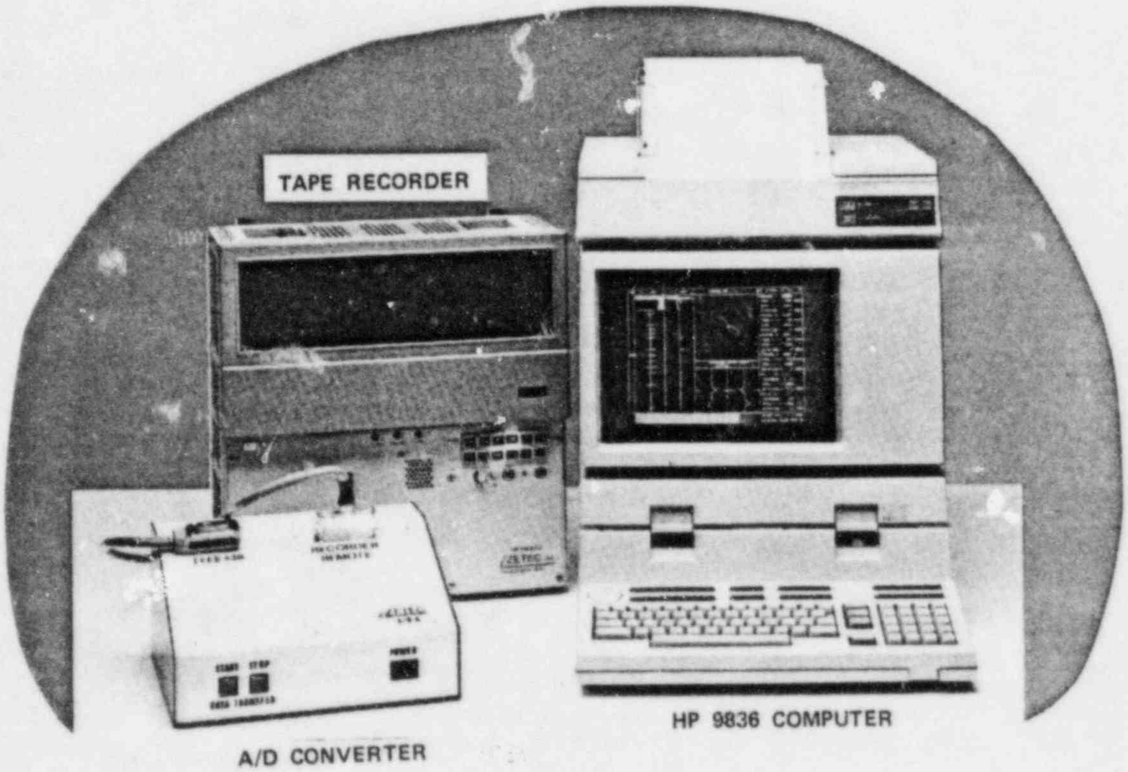


Figure 4-29. Zetec Digital Data Analysis System

corrosion

- Crevice gap magnetite packing, a step in denting evolution
- Support plate cracking, a consequence of denting that is detrimental only if plate elements are released and cause foreign object damage
- Dented tubes, which can crack, causing leakage and hence unscheduled outages.

4.4.1 Ultrasonic Methods

Kraftwerk Union has developed a computer controlled rotating dual eddy current ultrasonic probe for the evaluation and characterization tube wall degradation. The combined head is shown in Figure 4-30. A focussed ultrasonic beam is rotated around the tube circumference as the probe is translated through the region of interest. After reaching the test starting point, coupling medium (demineralized water) is fed through a tube situated inside the probe pusher/puller. A ring seal is used to maintain couplant within the tube. Axial inspection rate is 10 mm/sec.

Westinghouse has also developed an ultrasonic inspection system for steam generator inspection applications. The system consists of a precision 360 degree scanner, a high resolution ultrasonic transducer, and computerized data reduction with pseudo-isometric mapping. The system has been used in the field to characterize fretting tube damage and performed quite well. System resolution is on the order of one mil.

4.4.2 Radiography

Inspection for cracks in drilled support plates in Combustion Engineering and Westinghouse steam generators can be accomplished by using a radiographic technique (11). A gamma-ray source is placed within a tube at a given support level, while film cassettes are positioned in six surrounding tubes to radiograph the interposed support ligaments (see Figure 4-31). The mechanical delivery system has been verified in an operating plant.

The cracked ligament detection capabilities of radiography and eddy current approaches have not been compared. The inspection rate for

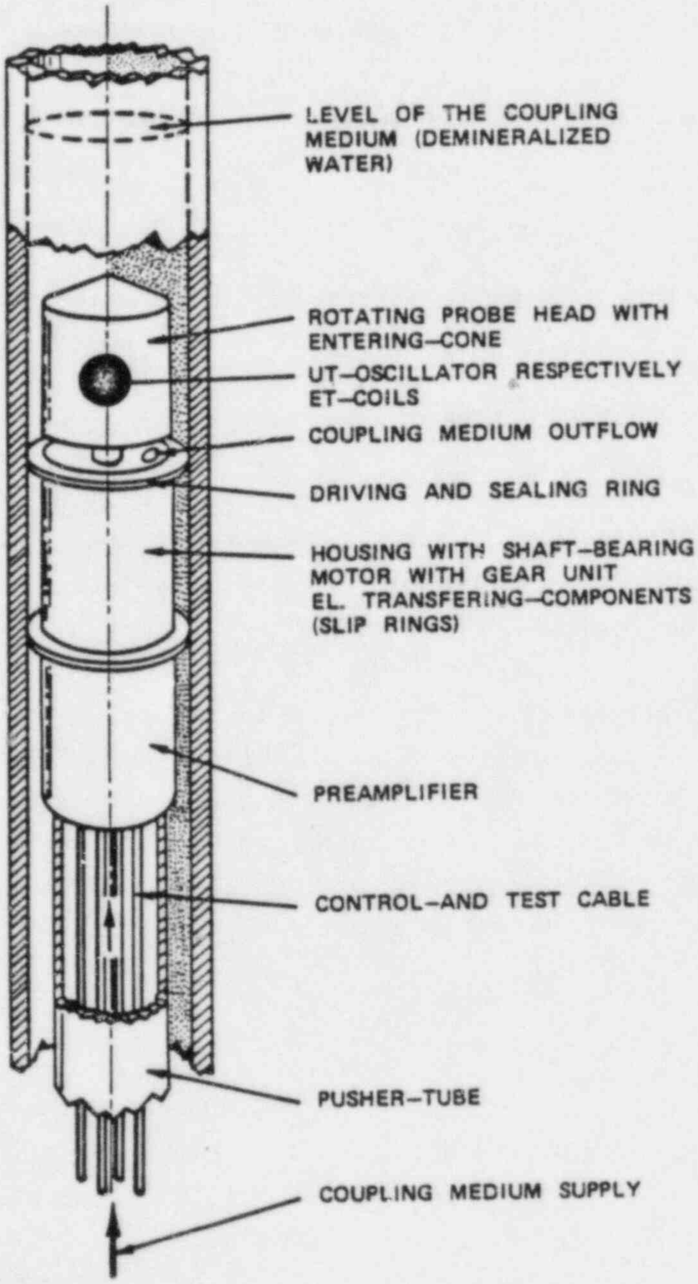
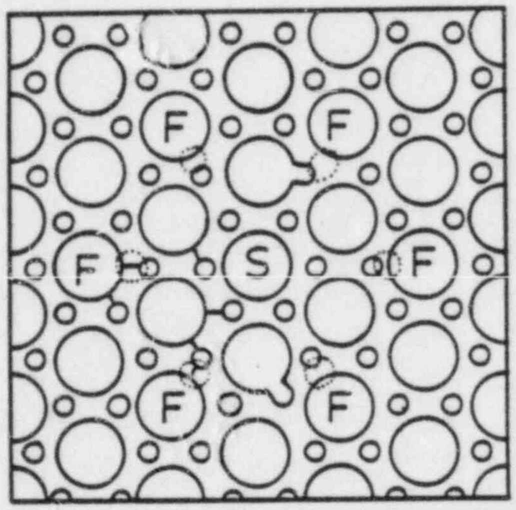
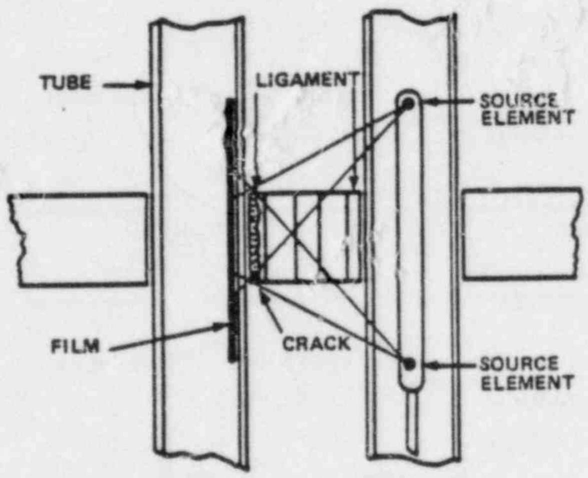


Figure 4-30. Kraftwerk Union Ultrasonic Probe Head For Steam Generator Tube Examination



PLACEMENT OF SOURCE (S) AND FILMS (F) .
DOTTED CIRCLES INDICATE THE LIGAMENTS BEING INSPECTED .



DUAL SOURCE CONFIGURATION

Figure 4-31. Radiographic Support Plate Inspection

radiography is 300 intersections in a seven-day (24 hours/day) period, or approximately 2 intersections per hour (11). The eddy current inspection rate is on the order of 72 intersections per hour.

Although radiography is slower than eddy current testing, it can fulfill needs not met by the eddy current approach. For example, distinguishing between cracked support plate ligaments and misaligned drilled flow holes that intersect the tube hole is impractical with eddy current testing. This misalignment is unique to certain Combustion Engineering steam generators. In laboratory and model boiler tests, radiography has also been very successful at detecting cracked plate ligaments and recognizing mis-drilled flow holes (11).

Preliminary laboratory studies indicate that radiographic testing may also be able to detect tube sheet cracking (12).

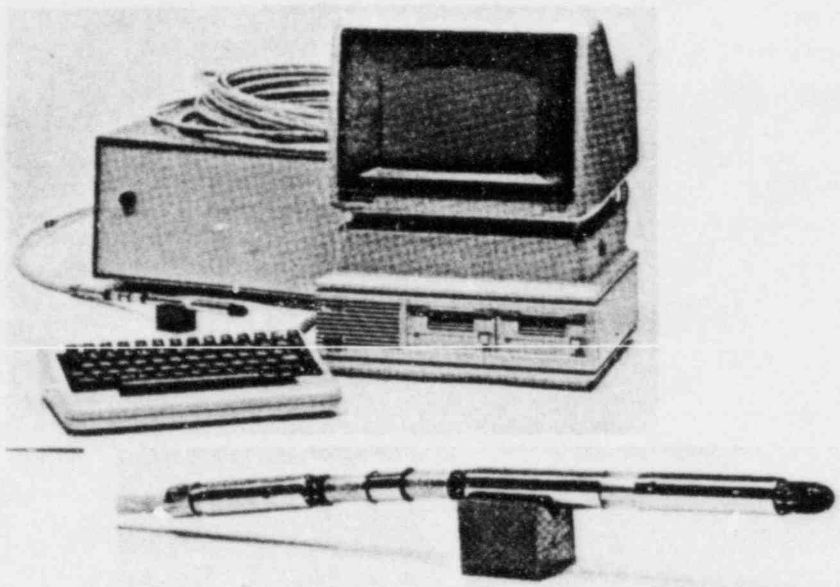
4.4.3 Visual/Optical Methods

Visual examination methods have been used to monitor sludge height, debris, crevice gap packing, support plate cracking, and flow slot distortion. Visual examination may be direct, via a camera, or indirect, via fiber optics.

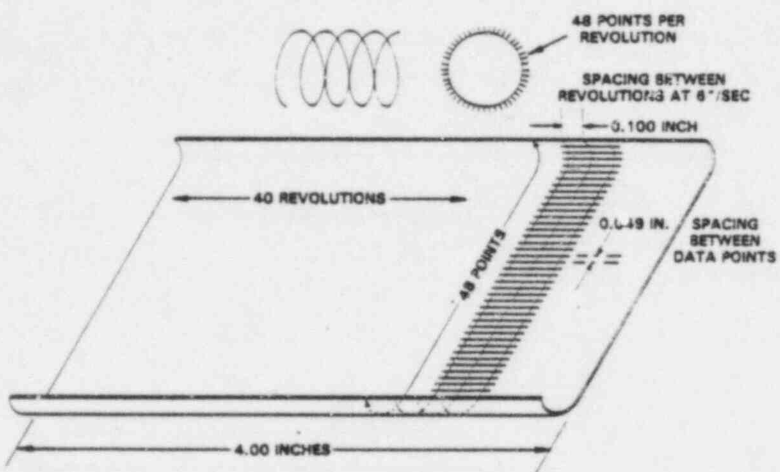
A fiber optics system has been developed by using commercially available optics and a delivery system configured for OTSG applications (13). Fiber optic devices with bundle extensions 30 to 100 feet in length are available commercially (14).

An optical profilometry system has also been investigated (15). The system consists of an optical sensor/rotating mirror assembly for sampling a dented support plate intersection, and a computer data acquisition system. Figure 4-32 illustrates the overall system and the probe sampling scheme. Many samples can be acquired in order to measure the dent profile accurately. The system was developed by Sigma Research under initial SGOG funding.

The optical profilometer system includes a noncontacting probe, signal conditioning/data acquisition microprocessor, and control computer with CRT. The probe housing is stainless steel except for the optics section, which is encased in a 360-degree clear, polycarbonate window



PROFILOMETRY DATA ACQUISITION INSTRUMENTATION AND PROBE



TUBE SAMPLING SCHEME

Figure 4-32. Sigma Research Optical Profilometry System

with a scratch-resistant coating. Two sets of nylon fingers on centering spiders hold the probe in position.

In an evaluation at the EPRI NDE Center, the optical profilometry system performed well. Its capabilities have been compared with eddy current and strain gage approaches to dent profiling. Results are discussed in Section 6. The system has not been used in an operating steam generator.

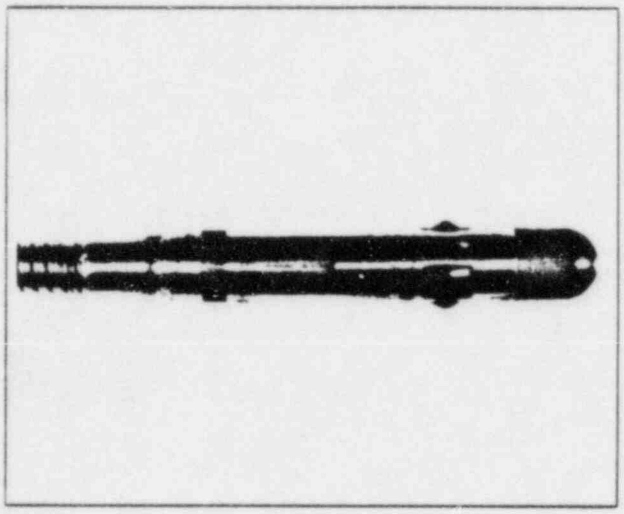
4.4.4 Electro-Mechanical Profilometry

Strain gage methods using multiple sensor probes have been developed for profiling dents. Figure 4-33(a) depicts a typical commercial eight finger strain gage probe head. Figure 4-33(b) shows the reconstruction of the dented support plate intersections based on the probe outputs. Computerized data acquisition and processing equipment are shown in Figure 4-34. The system has been used extensively in the field.

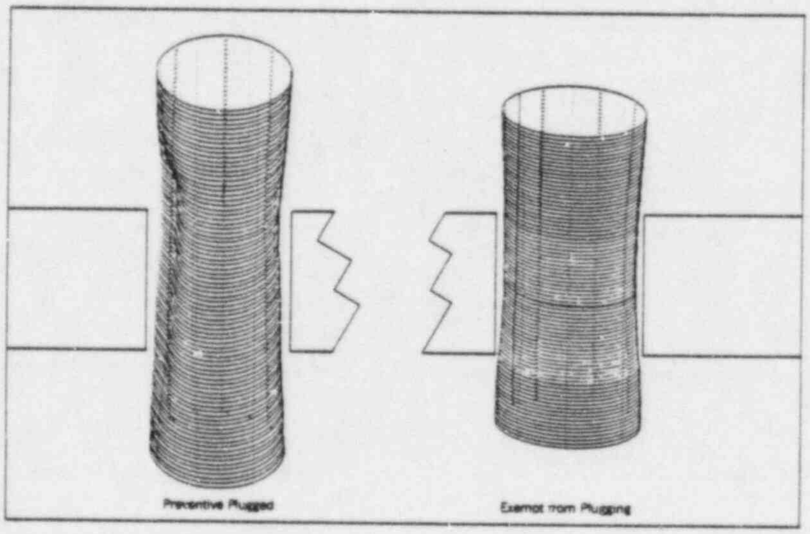
For symmetrical dents, strain gage profilometry is accurate to within about 2 mils (16). However, the eight samples provided by the method may be inadequate for characterizing distorted or non-symmetrical dents. The extent of this performance limitation is discussed in Section 6.

Consolidated Edison has developed a single point rotating profilometer for examining dented steam generator tubes at Indian Point 3. Because this rotating device uses a large number of sample points, it characterizes distorted or non-symmetrical dents more completely than eight finger strain gage profilometers. The system has been evaluated at the EPRI NDE Center as part of a dent characterization round robin program. Results are discussed in Section 6. The system has been licensed to Babcock & Wilcox for commercial applications. The probe head is shown in Figure 4-35.

The rotating probe system has been used at Indian Point 2 and North Anna. At Indian Point, over 350 tubes in four steam generators were examined. The system performance and the results obtained were quite satisfactory. Previous practice by Consolidated Edison on Westinghouse Type 44 steam gneerators was to plug tubes that failed to pass a



(a) Probe side-view showing "fingers"



(b) Dent profiles constructed using probe outputs

Figure 4-33. Babcock & Wilcox Eight-Finger Strain Gage Profilometry

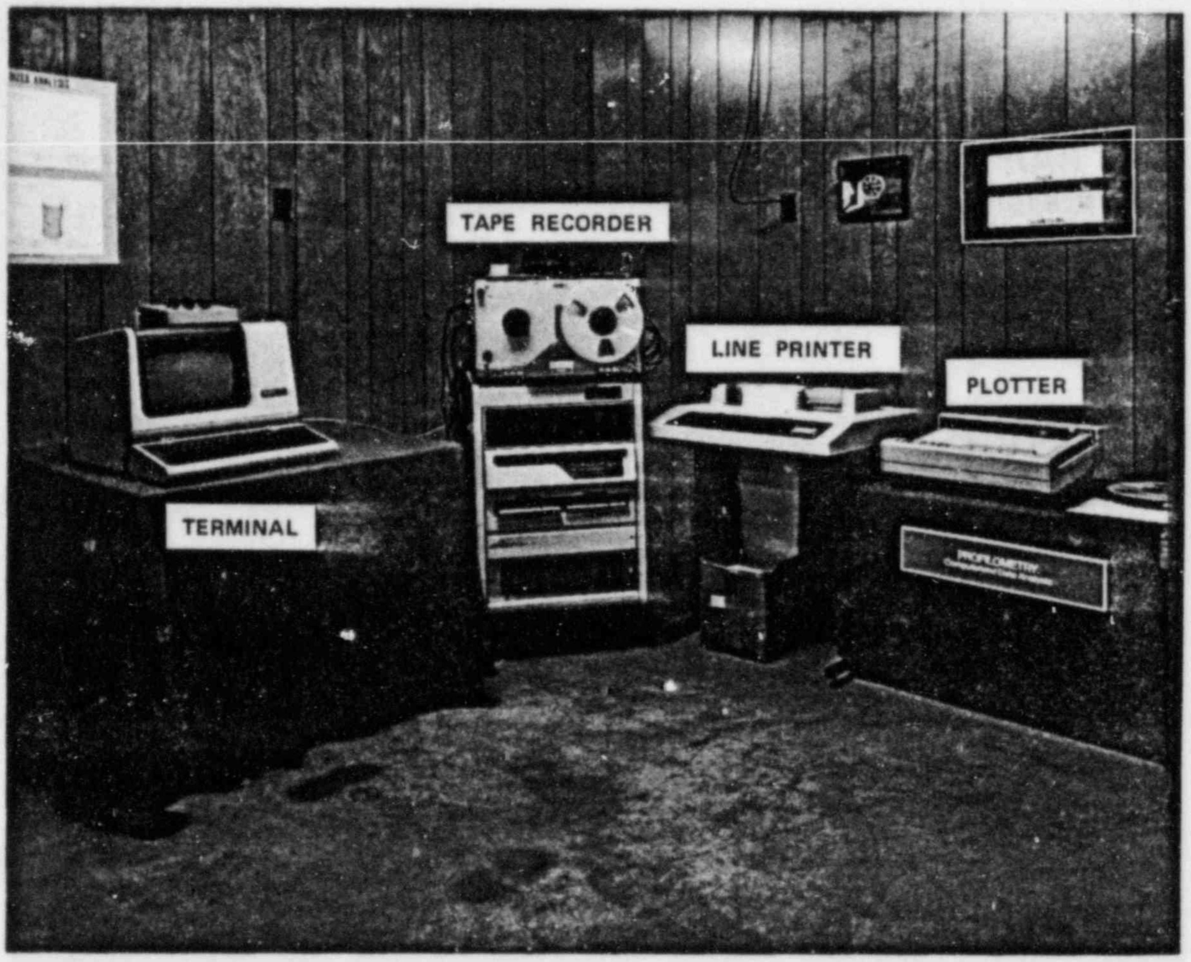
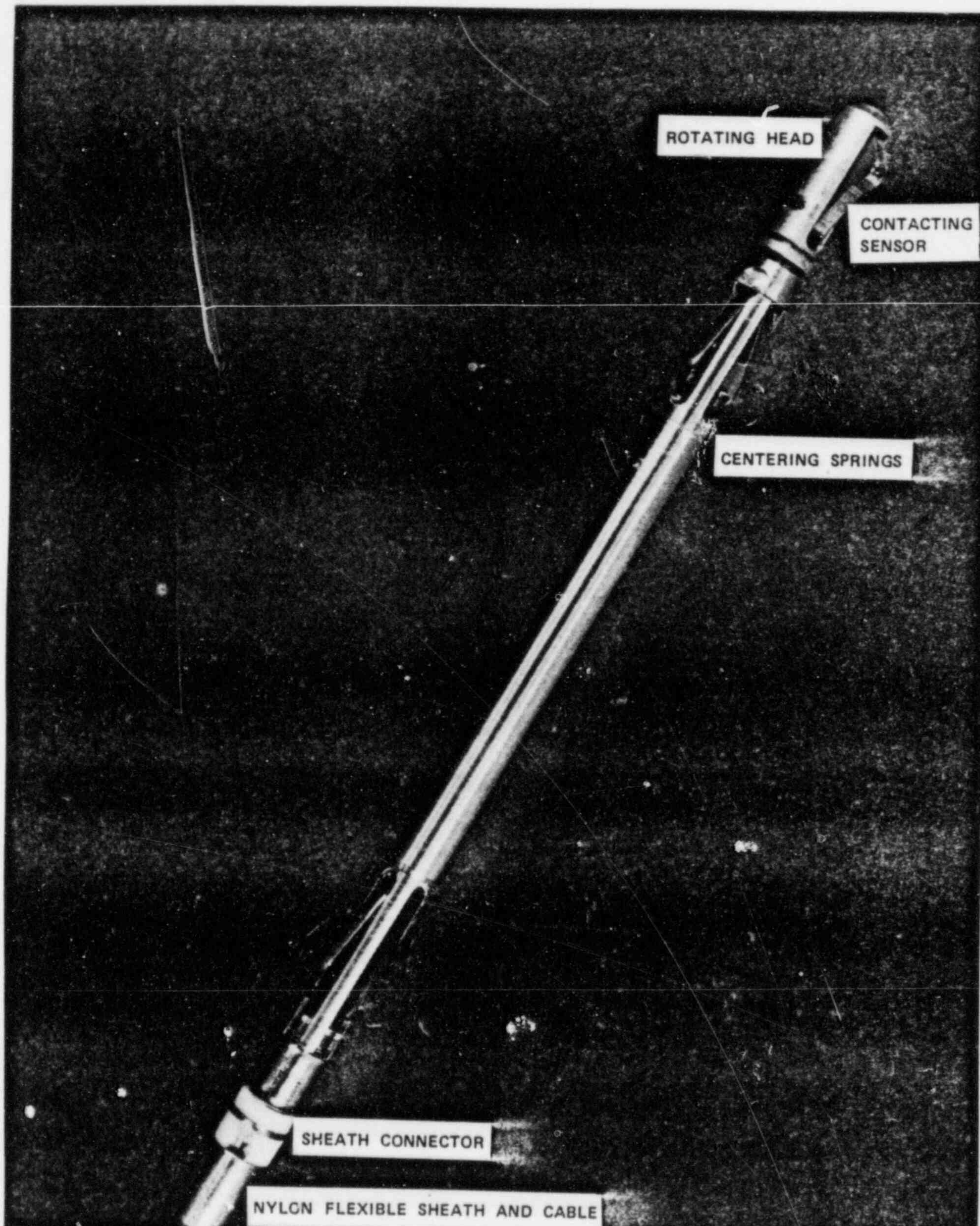


Figure 4-34. Babcock & Wilcox Profilometry Data Analysis System


ROTATING HEAD
CONTACTING
SENSOR
CENTERING SPRINGS
SHEATH CONNECTOR
NYLON FLEXIBLE SHEATH AND CABLE

0.610" diameter eddy current probe. Forty of these tubes that were examined by the rotating probe system failed to pass this criteria. In twenty of these tubes, the strain and stress levels were low enough to leave them in service. Another twenty tubes were plugged preventively. By avoiding unnecessary tube plugging, not only are the plugging costs and delays avoided, but the generator life is extended. Accurate measurements of dents also allow the establishment of a data base for tracking dent growth and monitoring the effectiveness of denting mitigation programs.

4.4.5 Induced Vibration

Induced vibration methods developed by ANCO Engineering, Inc. estimate tube vibrational signatures. Applications for this method include both monitoring the effectiveness of chemical cleaning agents designed to remove magnetite from the crevice region and confirming tube vibration frequencies. The latter is particularly helpful in inspecting Westinghouse units that are prone to flow-induced vibration in the preheater section. The system is also capable of distinguishing between locked and unlocked tubes in a support plate.

The system consists of a probe containing an eccentric rotating mass, a probe clamping mechanism, and signal monitoring/recording equipment. Figure 4-36 provides a schematic illustration of this probe. The system has been used to evaluate support plate alignment before and after post-weld heat treatment (Ontario Hydro), and measure tube support plate clearances at Ringhals 3 & 4 (Swedish State Power Board). An attempt to use the system at McGuire 1 proved unsuccessful due to problems with the probe - too large a diameter - and probe delivery system. Additional effort is required to demonstrate a workable remote probe delivery system for contaminated steam generators.

4.5 DATA BASE MANAGEMENT SYSTEMS

A large amount of data is typically generated during a steam generator inspection. This data must be readily and rapidly retrievable in order to assess the condition of the steam generator. Data base management systems are utilized to perform this task.

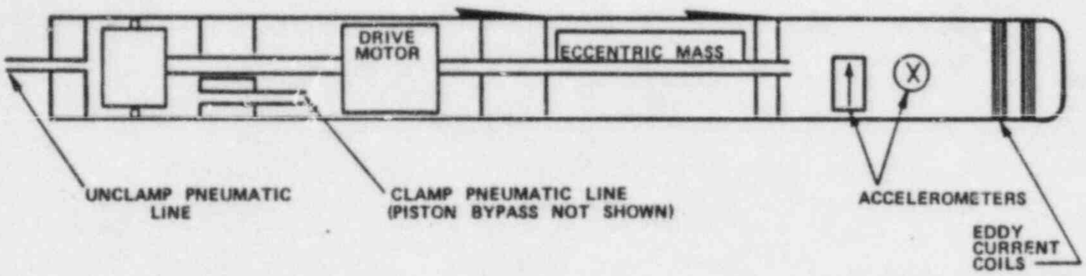


Figure 4-36. Induced Vibration Probe Schematic

Westinghouse has introduced Supertubin which is a computerized data management system. The system stores all analyzed eddy current data on magnetic discs, and provides for the generation of timely status reports as the inspection proceeds. It also prepares standardized computer printouts for the final report, and provides for the electronic transmission of data back to the main analyzed eddy current data base in Pittsburgh. Computer generated mathematical analyses, graphic presentations of indication distributions, and indication growth calculations can be provided.

As the inspection progresses, the Supertubin data base provides the information required for daily progress reports and various indication listings. As the inspection nears completion, the computer generates re-test lists as required, to ensure that all originally scheduled and subsequently added tubes have been inspected and evaluated to the required extent. The system is shown in Figure 4-37.

Figure 4-37. Westinghouse SUPERTUBIN Data Base Management System

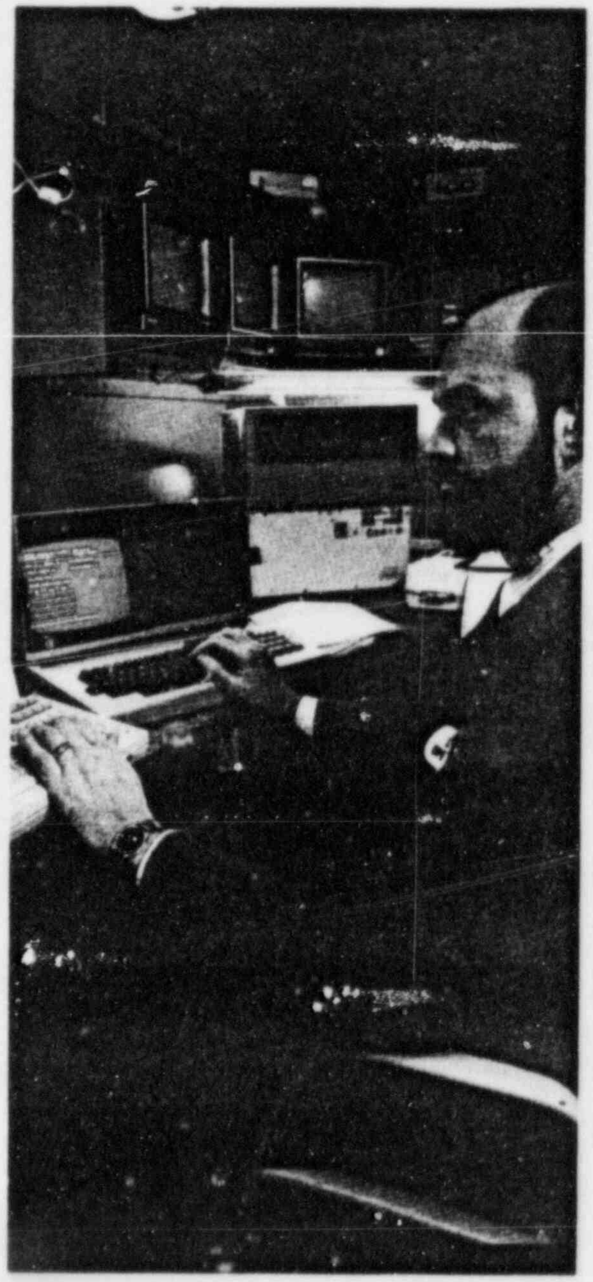
Babcock & Wilcox has introduced TUBAN which is a comprehensive eddy current data management system for storing and reporting historical steam generator inspection results. In addition, a computerized system called DECIDE processes eddy current inspection results into inspection summaries and status reports for daily plant staff outage meetings. This enables timely decisions during the outage to minimize inspection activities on "critical path." The DECIDE system is used to both record inspection results (electronic data sheet), and in the data acquisition mode, as the central control for the eddy current manipulator.

TUBAN can be used for assessing the current condition of the steam generator, trending the past and projecting it's future health. Typical applications include:

- Pre-outage planning - preparation of tube inspection lists which include tubes with special past inspection results, tubes in special regions of the steam generator, and random tube lists
- In-outage support - Rapid access to historical data recorded on any tube(s) for quick defect/indication growth comparisons
- Post-outage reporting - Concise management summaries of current inspection results and ability to trend the steam generator condition between inspection outages.

The TUBAN and DECIDE systems are shown in Figure 4-38.

TUBAN



DECIDE

Figure 4-38. Babcock & Wilcox TUBAN and DECIDE Data Base Management Systems

Section 5

PWR STEAM GENERATOR OPERATING EXPERIENCE

5.1 INTRODUCTION

Developing a rational steam generator inspection program requires awareness of industry experience with tube degradation and damage precursors, and their location within a steam generator. The choice of inspection method and proper interpretation of data can depend on the type of degradation suspected. In addition, the guidelines presented in Section 2 recommend increased surveillance of regions within the generator that, historically, have been prone to degradation. These potential problem areas for each type of steam generator can be identified by examining the operating experience presented in this section.

Section 5.2 presents an overview of steam generator operating experience. Sections 5.3, 5.4, and 5.5 provide more detailed discussions on a plant-by-plant basis for Westinghouse, Combustion Engineering, Babcock & Wilcox and Framatome steam generators, respectively.

5.2 SUMMARY OF PWR STEAM GENERATOR OPERATING EXPERIENCE

Table 5-1 provides a summary of operating experiences for domestic and foreign steam generator units. Denting affects the largest percentage of the units. As of August 1984, 36 out of 112 units had reported denting at the tube support plate, tube sheet, or eggcrates. Tube corrosion and mechanical degradation are also significant, although fewer units experience these forms of degradation. Tubing corrosion can take the form of tube wall thinning, pitting, primary side stress corrosion cracking, or secondary side intergranular attack/stress corrosion cracking (IGA/SCC). Mechanical degradation can take the form of fretting, mechanical wear, fatigue cracking, or impingement effects.

Although 40 of the 112 units have experienced none of the problems

Table 5-1

STEAM GENERATOR EXPERIENCE SUMMARY - AUGUST 1982

PROBLEMS	ONCE-THROUGH STEAM GENERATORS	RECIRCULATING STEAM GENERATORS					TOTAL PWR UNITS
	B&W (9)	C-E (11)	W* (48)	W** (7)	KWU (9)	F/C (28)	(112)
Denting							
Tube support corrosion	0	9	26	1	0	0	36
Tubesheet corrosion	0	2	12	0	0	0	14
Eggcrate corrosion	N/A	2	N/A	N/A	N/A	N/A	2
Tubing corrosion							
Thinning	0	2	22	0	7	0	31
Pitting	1	3	2	0	0	0	6
Primary side cracking	1	0	24	1	1	2	29
Secondary side IGA/SCC	2	2	29	0	2	3	38
Mechanical degradation							
Fretting and wear	4	0	14	4	0	0	22
Fatigue cracking	5	0	0	0	0	0	5
Impingement effects	2	0	0	0	0	0	2
No problems (more than 5 years operation)	2	0	0	0	1	3	6
No problems (all)	2	2	14	2	2	20	42

* Units without preheaters
** Units with preheaters
W = Westinghouse units

B&W = Babcock & Wilcox units
C-E = Combustion Engineering units
KWU = Kraftwerk Union units

F/C = Framatome units (similar to W units)

listed in Table 5-1, only 4 units that have been operating for at least 5 years have had none of these problems.

It is possible to make some generalizations about the types of degradation encountered by steam generators with particular designs or operating histories. A few of these are provided for Westinghouse (W), Combustion Engineering (C-E), and Babcock & Wilcox (B&W) steam generators. For detailed discussions of damage forms, their locations within the steam generator, and inspection methods, see Sections 5.3-5.5.

Westinghouse units

- Most older W units exhibit some degree of denting. The damaging consequences are most pronounced in the outer periphery wedge and flow slot area
- Units that use or have used all solids (phosphate) secondary side water chemistry tend to experience thinning attack. It occurs on both the hot leg and cold leg sides, at and above the top of the tube sheet, within the sludge pile
- Units with open tube sheet crevices are prone to IGA/SCC within the crevice region
- Models 51 and 51 A/M are susceptible to primary side cracking at inner row U-bends and at the roll transition
- Models 24, 27, 33 and 51 experience fretting wear at the anti-vibration bars (AVBs).
- Preheater units can experience fretting wear at the preheater baffle plates on the outer periphery near the inlet nozzle.

Combustion Engineering units

- Denting occurs at drilled plates and eggcrates
- Plants that use phosphate chemistry and have drilled-hole support plates for most of their tubing supporting structures are subject to thinning
- Pitting is a potential problem
- Secondary side stress corrosion cracking has occurred on the horizontal section of square U-bends near AVB straps.

Babcock & Wilcox units

- High-cycle fatigue cracking, the primary cause of leaker outages in OTSGs, is limited to the lane region at elevations between the 15th support plate and upper tube sheet
- Fretting can occur in the lane region at upper support plate elevations
- Impingement damage occurs in the outer periphery region.

5.3 WESTINGHOUSE OPERATING EXPERIENCE

Tables 5-2 through 5-6 summarize the operating experience for plants designed or licensed by Westinghouse. Table 5-2 displays Model 24, 27, and 33 experience. Tables 5-3, 5-4, 5-5, and 5-6 exhibit Model 44, Model 51, Model 51 A/M (Framatome/Creusot Loire), and preheater steam generator experience, respectively.

According to the experience cited in these tables, degradation in non-preheater Westinghouse units is predominantly corrosion in the tube and tube support structures. Known corrosion forms include denting, thinning, pitting, primary side stress corrosion cracking (SCC), and secondary side intergranular attack (IGA) and SCC.

Most of the older Westinghouse units exhibit some degree of denting, ranging from minor denting to extensive denting with some tube leakage. Units that have used a solids (phosphate) secondary side water chemistry tend to experience wastage attack on both legs of the generator; one unit has been affected at the AVBs. Units with open tube sheet crevices are prone to IGA/SCC. In the extreme, this can cause leaker outages and force the utility to plug hundreds of tubes. Models 51 and 51 A/M are also suscepible to primary side cracking at inner row U-bends and at the roll transition.

In non-preheater units, mechanical degradation occurs in the form of fretting wear at the AVBs in Models 24, 27, 33, and 51.

Most of the adverse experience with Westinghouse preheater units has been mechanical degradation caused by fretting wear at the preheater baffle plates. One unit is dented and one unit recently had a leaker outage due to a Row 1 U-bend crack.

Table 5-2

OPERATING EXPERIENCE SUMMARY - WESTINGHOUSE MODEL 24, 27 AND 33 STEAM GENERATORS

Unit (1)	Model	# of Steam Generators	OL Issued	Secondary Water Chemistry	Thinning	Fretting	Secondary Side IGA/SCC	Primary Side SCC	Pitting	Denting
San Onofre 1	27	3	3/67	PO4	X	X(2)	X(3,4)			Extensive
Zorita (Jose Cabrera)	24	1	8/69	PO4	X	X(2)	X(3,5)	X(3)		
Beznau 1	33	2	12/69	AVT*	X	X(2)	X(3)			
Beznau 2	33	2	3/72	AVT*	X	X(2)	X(3)			Minor
Haddam Neck	27	4	12/68	AVT*	X	X(2)	X			Minor

* Previous PO4 chemistry.
(1) All units have steam gneerators with open tube sheet crevices
(2) At AVBs.
(3) Tube sheet crevice hot leg.
(4) 6508 Sleeves installed in three steam generators because of extensive IGA
(5) Hot leg, 1st support

Table 5-3

OPERATING EXPERIENCE SUMMARY - WESTINGHOUSE MODEL 44 STEAM GENERATORS

Unit	# of Steam Generators	OL Issued	Secondary Water Chemistry	Thinning	Fretting	Secondary Side IGA/SCC	Primary Side SCC	Pitting	Denting
Ginna	2	9/69	AVT*	X		X(2,11)			Minor
Robinson 2 (pre)	-	9/70	PO4	X(8)		X(2)			Minor
Robinson 2 (post)	3		AVT						
Point Beach 1 (pre)	-	10/70	AVT*	X		X(2)			Moderate
Point Beach 1 (post)	2		AVT						
Point Beach 2	2	11/71	AVT*	X		X(2,9)			Moderate
Mihama 2	2	7/72	AVT*	X		X(2)			
Turkey Point 3 (pre)	-	7/72	AVT*	X			X(3)		Extensive (4,7)
Turkey Point 3 (post)	3	5/82	AVT						
Turkey Point 4 (pre)	-	4/73	AVT*	X			X(3)		Extensive (4,7)
Turkey Point 4 (post)	3	5/83	AVT						
Indian Point 2	4	9/73	AVT*	X		X(2)	X(4)	X(12)	Extensive (4,7)
Doel 1	2	2/75	AVT*						Minor
Doel 2	2	2/75	AVT			X(2)	X(5,6)		Minor
Indian Point 3	4	12/75	AVT			X	X(4)	X	Extensive (4,7)

Table 5-4
OPERATING EXPERIENCE SUMMARY - WESTINGHOUSE MODEL 51 STEAM GENERATORS
(Including Westinghouse Licensees)

Unit (1)	# of Steam Generators	OL Issued	Secondary Water Chemistry	Thinning	Fretting	Secondary Side IGA/SCC	Primary Side SCC	Denting
Surry 1 (pre)	-	5/72	AVT*	X			X(3,6)	Extensive (6)
Surry 1 (post)	3	7/81	AVT					
Surry 2 (pre)	-	1/73	AVT*	X			X(3,6)	Extensive (6)
Surry 2 (post)	3	9/80	AVT					
Zion 1**	4	4/73	AVT*	X	X	X(2)	X(4)	Minor
Prairie Island 1**	2	8/73	AVT*	X	X	X(2)		
Kewaunee 1**	2	12/73	AVT*	X	X	X(2)		Minor
Zion 2**	4	11/73	AVT*	X	X	X(2)		Minor
Prairie Island 2**	2	10/74	AVT	X	X	X(2)		
D.C. Cook 1**	4	10/74	AVT			X(2)	X(4)	Minor
Takahama 1**	3	11/74	AVT	X		X(2)	X(4)	
Ringhals 2**	3	5/75	AVT*			X(2)	X(4,5)	Moderate
Tihange 1**	3	9/75	AVT			X		Minor
Genkai 1**	2	10/75	AVT		X	X		
Trojan 1	4	11/75	AVT			X(4)		
Takahama 2**	3	11/75	AVT			X		
Beaver Valley 1	3	1/76	AVT					Minor
Salem 1	4	8/76	AVT	X	X			Minor
Mihama 3**	3	12/76	AVT					
Farley 1	3	6/77	AVT		X	X(4)	X(4)	
Ko-Ri 1	2	6/77	AVT					Minor
Ikata 1	2	9/77	AVT			X(5)		

* Previous PO4 water chemistry
(1) Units identified with ** have open tube sheet crevices.
(2) Tube sheet crevice hot leg.
(3) U-bend cracking - denting assisted.
(4) U-bend cracking - non-denting assisted
(5) Roll transition
(6) Leaking dents

Table 5-5

OPERATING EXPERIENCE SUMMARY - WESTINGHOUSE MODEL 51 STEAM GENERATORS
(Including Westinghouse Licensees)

Unit (1)	# of Steam Generators	OL Issued	Secondary Water Chemistry	Thinning	Fretting	Secondary Side IGA/SCC	Primary Side SCC	Denting
North Anna 1	3	11/77	AVT				X(4)	Minor
D.C. Cook	4	12/77	AVT		X	X(2)	X(4)	
OHI 1	4	3/79	AVT			X(2)	X(5)	
OHI 2	4	12/79	AVT					
North Anna 2	3	8/80	AVT					
Sequoyah 1	4	9/80	AVT					Minor
Salem 2	4	4/80	AVT		X			
Farley 2	3	10/80	AVT					
Genkai 2	2	3/81	AVT					
Sequoyah 2	4	9/81	AVT					
Diablo Canyon 1	4	9/81	AVT					
Ikata 2	2	3/82	AVT					

* Previous PO4 water chemistry
(1) Units identified with ** have open tube sheet crevices
(2) Tube sheet crevice hot leg
(3) U-bend cracking, denting assisted
(4) U-bend cracking
(5) Roll transition
(6) Leaking dents

Table 5-6

OPERATING EXPERIENCE SUMMARY - WESTINGHOUSE PREHEATER STEAM GENERATORS

Unit (1)	# of Steam Generators	OL Issued	Secondary Water Chemistry	Thinning	Fretting	Secondary Side IGA/SCC	Primary Side SCC	Pitting	Denting
Almaraz 1	3	12/79	AVT		X				Minor
Ringhals 3	3	7/80	AVT		X				
McGuire 1	4	7/81	AVT		X				
Krsko	2	12/81	AVT		X				
Almaraz 2	3	10/83	AVT						
Ringhals 4	3	1[illegible]/83	AVT						
VC Summer	3	10/83	AVT				X(2)		
McGuire 2	4	3/84	AVT						

(1) All units have fully expanded tube sheet crevices
(2) Row 1 U-bend

Details of Westinghouse plant experience are provided in the remainder of this section.

5.3.1 Denting

In some cases, steam generator tube denting has had a significant impact on plant availability. Nine units have experienced leaking dents. Steam generator replacements at Surry 1 & 2 and Turkey Point 3 & 4 are the results of denting-related damage.

Denting can occur at many different locations within the steam generator; Figure 5-1 displays some of these locations. Although denting has been observed on both the hot leg and cold leg sides of the generator, it tends to initiate on the hot leg side. The consequences of denting are more pronounced in regions of the steam generator that have hard spots, e.g., the outer periphery wedge areas and the flow slot areas. For this reason, the guidelines presented in Section 6 recommend increased monitoring of these areas in Westinghouse steam generators.

Extreme consequences of denting include flow slot closure and hourglassing, cracked support plate ligaments ovalized and cracked inner row U-bends, and tube cracking at dented support plate intersections (see Figure 5-1).

5.3.2 Thinning

Phosphate wastage attack (tube wall thinning) tends to occur in units that have used an all-solids (PO4) secondary side water chemistry control program during their operating history (see Tables 5-2 through 5-4). Thinning has been observed on both the steam generator hot leg and the cold leg sides, at and above the top of the tube sheet, within the sludge pile.

Thinning-like attack has been confirmed at the 1st and 2nd support plate intersections on the cold leg side at Prairie Island 2. From examination of a removed cold leg tube, the problem is described as wall thinning resulting from an unidentified corrodent (17). Vibration assisted corrosion is a postulated mechanism. The affected tube was located on the periphery of the bundle at R34C79.

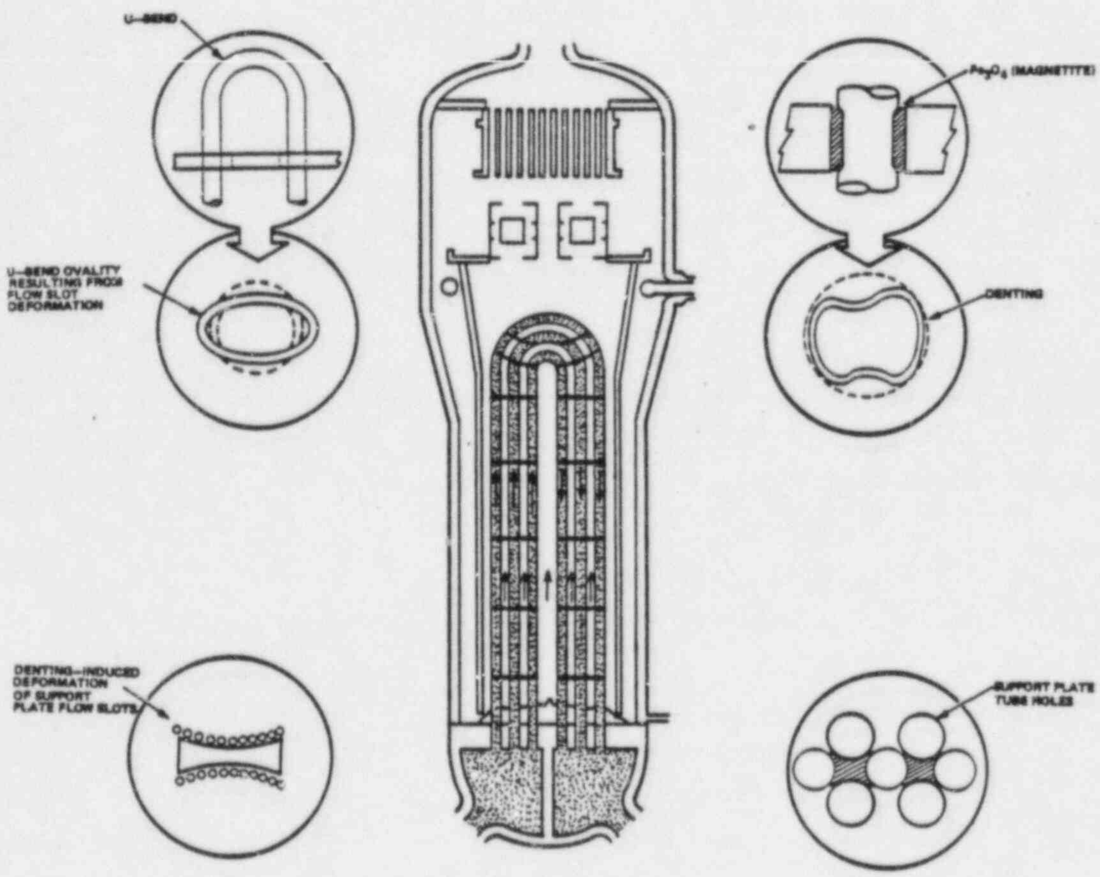


Figure 5-1. Denting Related Degradation In Westinghouse Steam Generators

Zion 1 and Salem 1 have reported similar eddy current indications confined to within a five-tube radius of the outer periphery.

Areas prone to thinning-related tube degradation or wastage are illustrated in Figure 5-2.

5.3.3 Pitting

Extensive secondary side pitting attack coupled with copper deposits has been observed at Indian Point 3. The attack was observed mainly in the region between the tube sheet and 1st support, on the cold leg side of the generator (see Figure 5-3). Although the cause of the attack is not fully understood, it is believed to be related to severe oxygen ingress through continuous condenser inleakage and to the presence of copper on the secondary side. Four affected steam generators have been sleeved to extend their lives.

Small amplitude eddy current signals, suggestive of pitting in the presence of secondary side copper, have recently been reported at Indian Point 2. Confirmation of the suspected pitting by tube removal is planned for a future outage.

5.3.4 Primary Side Cracking

Primary side stress corrosion cracking (SCC) may be denting or non-denting related. Surry (original tubing), Turkey Point (original tubing), and Indian Point 2 and 3 have had extensive denting with tube leaks at support plate intersections. Primary side cracking unrelated to denting has been observed at the roll-transition at Doel 2, and Ringhals 2, and in the inner row U-bends at Trojan, Farley 1, Cook 1 & 2, Zion, Doel 2, Fessenheim 1 and Bugey 2 & 3. At the expanded region at the top of the tube sheet units affected include Fessenheim 1, Bugey 3 & 5, Dampierre 1 & 2, Blayais 1, Ikata 1, and OHI 1. Figure 5-4 summarizes these primary side crack locations.

Inner row U-bend cracking. Cracking occurs predomenantly in Westinghouse Blairsville tubed Series 51 steam generators manufactured between 1971-1972. The majority of the Cracking occurs in Row 1 bends at one of the bend-to-straight section transitions. Some cracking has been observed near the bend apex at Trojan. Cracking

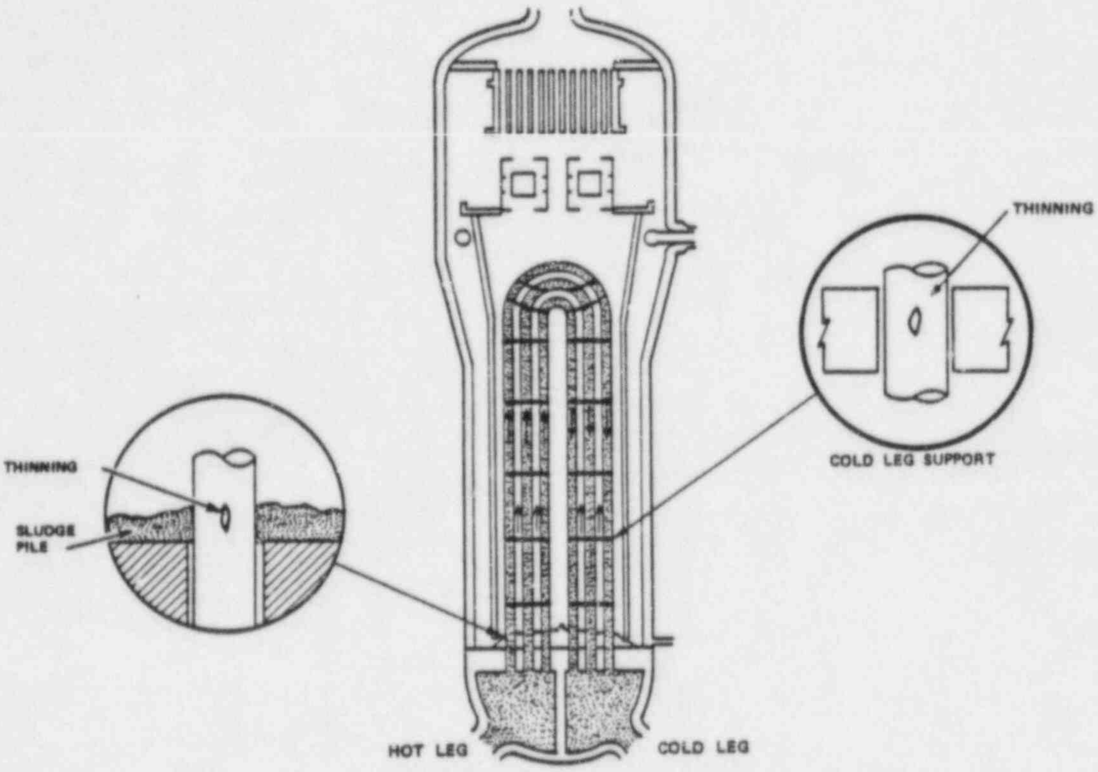


Figure 5-2. Thinning Locations in Westinghouse Steam Generators

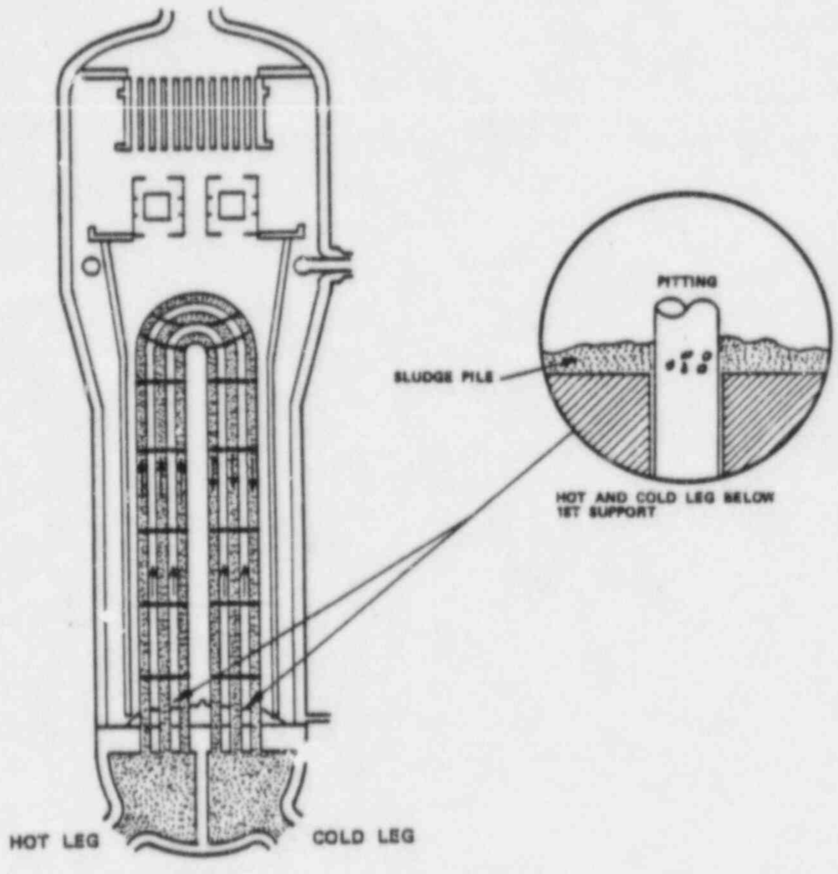


Figure 5-3. Pitting Locations in Westinghouse Steam Generators

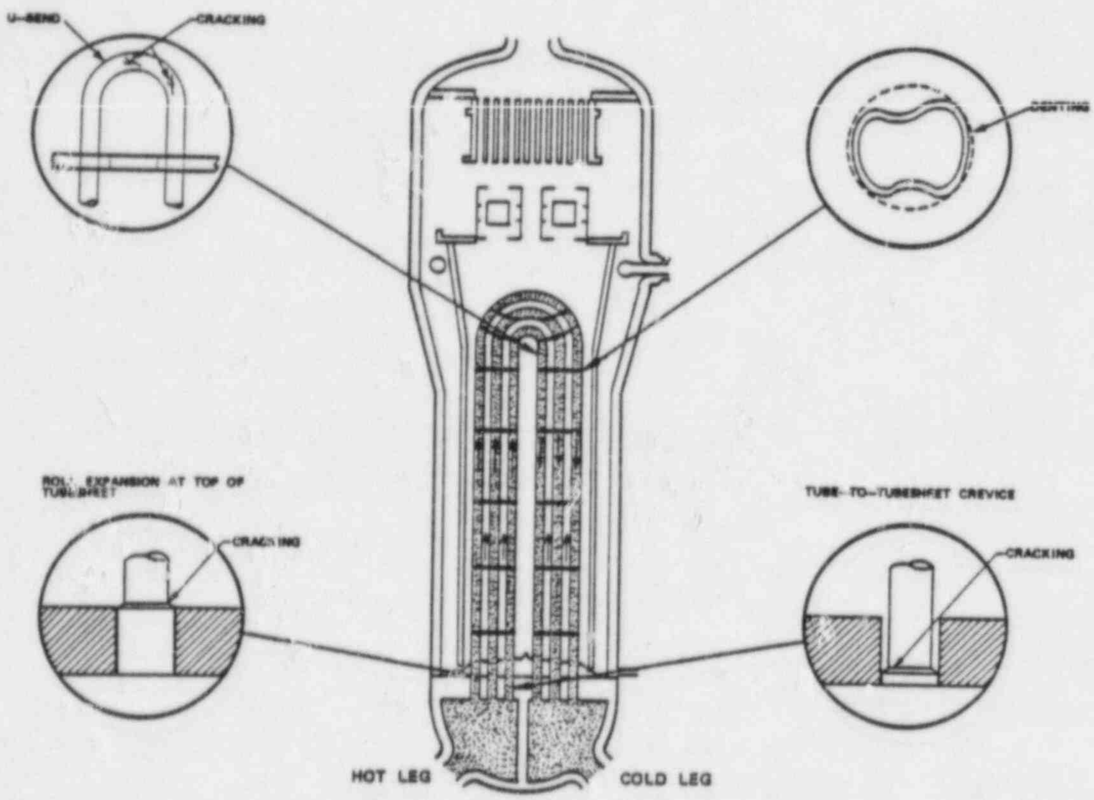


Figure 5-4. Primary Side Stress Corrosion Cracking Locations in Westinghouse Steam Generators

has also been identified in Row 2 bends and in one instance, (Zion 1), was detected at both U-bend transitions (18). One preheater steam generator (Summer) has recently experienced a Row 1 U-bend leak.

Numberous leaker outages are attributable to U-bend cracking. Trojan, Ringhals 2, Farley, and North Anna 1 have plugged all Row 1 U-bends to eliminate this source of leaker outages.

Primary side SCC at dented support plate intersections. See the discussion on this subject in Section 5.3.1.

Primary side SCC at the roll transition. Primary side cracking at the roll transition has been confirmed on a tube removed from Ringhals 2. Doel 2 has also experienced primary side cracking at the roll transition. Extensive tube plugging, re-roll operations and sleeving have been used to accommodate the cracking at Doel.

Roll expansion cracking. Numerous French units have encountered cracking at the roll expansion at the top of the tube sheet in units with fully expanded crevices.

5.3.5 Secondary Side IGA/SCC

Secondary side SCC occurs at dented support plate and tube sheet intersections. IGA has also occurred within an extensive sludge pile (height approximately 30-40") at San Onofre 1. IGA in conjunction with dented tube sheet intersections can result in extensive circumferential SCC at the top of the tube sheet. Other units with little or no existing sludge, but with open tube sheet crevices, have experienced IGA and SCC within the crevice region (Ginna, Point Beach 1 (original tubing) & 2, and Robinson 2 (original tubing), Zion 1, and Ringhals 2). Genkai 1, OHI 1, Takahama 2 and Zorita have reported IGA/SCC at or near the 1st support plate. An illustration of SCC and IGA/SCC locations is provided in Figure 5-5.

At San Onofre, IGA is confined to a band several inches above the top of the tube sheet; denting also exists at the tube sheet. In this case, IGA in conjunction with denting led to the preferential formation of circumferential stress-assisted cracking. (Out of sixteen pulled tubes with tube sheet crevice region IGA, only one deep-crevice

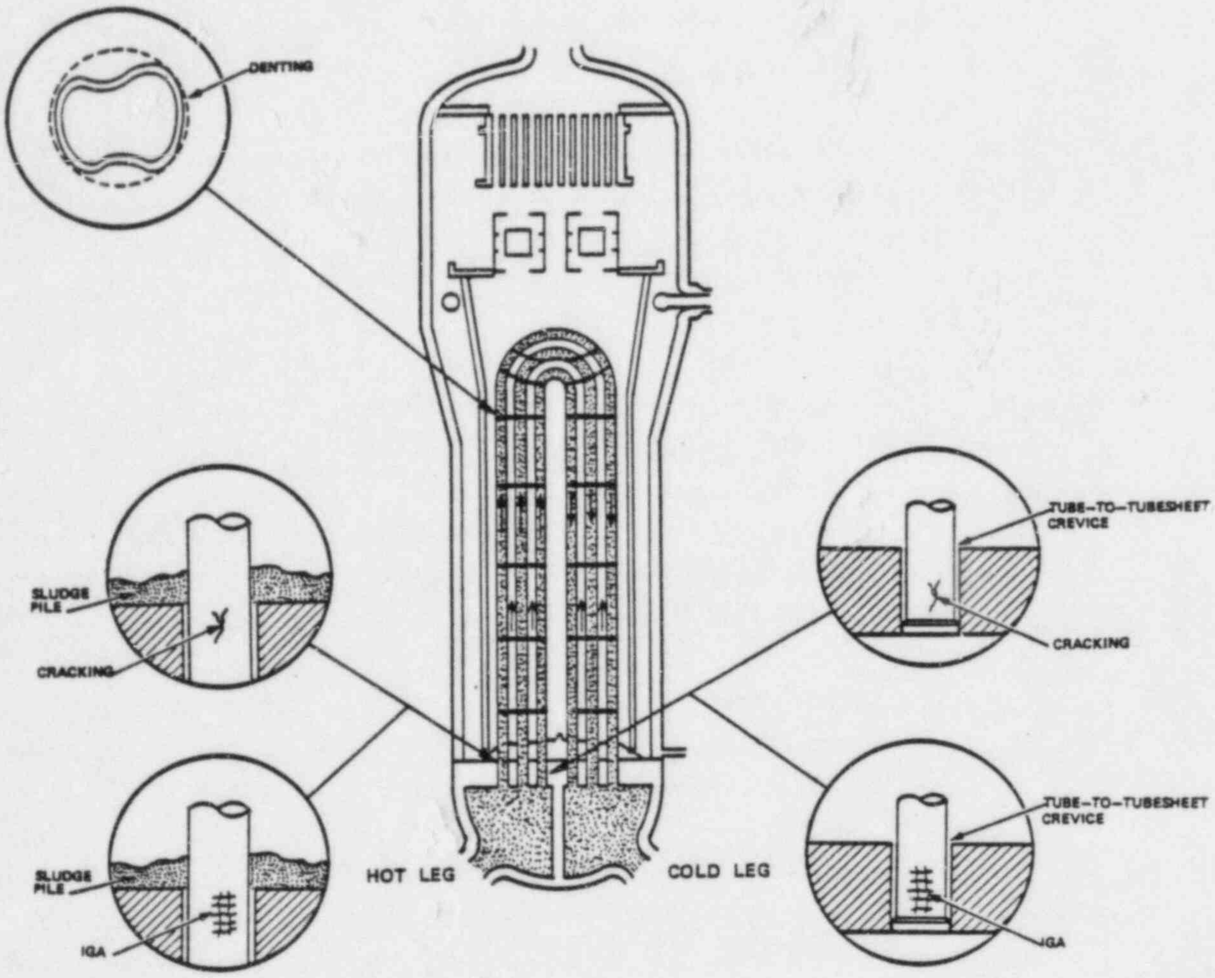


Figure 5-5. Secondary Side Intergranular Attack and Stress Corrosion Cracking Locations in Westinghouse Steam Generators

indication of axial stress corrosion cracking was found. During San Onofre's 1980 outage, 4958 tubes were inspected from the hot leg side in three steam generators. Of these, 854 showed eddy current indications of greater than 50% through-wall defects. A 1980 review of prior eddy current data showed the presence of degradation during past inspections.

The remainder of this section provides additional IGA/SCC case histories. These are included to emphasize the importance of carefully analyzing eddy current data from the tube sheet crevice region. Particular attention should be given to eddy current data in the absolute coil mode.

Point Beach. Point Beach Unit 1 first reported attack in the tube sheet crevice region in October 1977. During the February 1980 outage, Point Beach Unit 2 observed indications of attack. Eight tubes removed from Units 1 and 2 showed IGA and SCC in the tube sheet crevice region. Unit 1 steam generators have since been replaced because of extensive IGA and SCC whereas Unit 2 has been sleeved.

Ginna. Indications of attack were first noted at Ginna during the March 1979 refueling outage. Metallography on seven removed tubes revealed IGA and SCC within the tube sheet crevice region. Ginna has had excellent success in detecting IGA within the tube sheet crevice. This success has been attributed to careful analysis of both absolute and differential bobbin coil data. Ginna has not experienced a leaker outage attributable to crevice region IGA. A sleeving program has been implemented to allow degraded tubes to remain in service.

Ringhals. In April 1982, Ringhals Unit 2 was shut down two weeks prematurely because of a leak in steam generator 3. Eddy current inspection showed multiple defects within the tube sheet crevice region, extending from 7 to 10" above the tube end. Examination of prior inspection data on one affected tube (R4C56) showed no eddy current indications. Metallographic examination of this tube identified the damage as secondary side SCC associated with axial score marks on the tube; this latter phenomena has also been observed on tubes removed from Point Beach. Eddy current tests in 1982 produced seventeen indications of crevice region defects, four of which were

present in the 1981 data set.

5.3.6 Fretting

In the mid 1970's, tubes at San Onofre Unit 1 and Haddam Neck experienced fretting wear at the AVB supports located in the U-bend region (see Figure 5-6). This particular problem occurs in Models 24, 27 and 33; subsequent designs minimize the problem by incorporating AVBs with a square cross section.

Signals that are believed to be fretting related have been observed at the AVBs of numerous plants including Zion 1 & 2, Prairie Island 1 & 2, Salem 1 & 2, Cook 2, and Farley 2. Using secondary side fiber optic inspection methods to examine the AVB intersections, Prairie Island was unable to confirm the damage mechanism (19). Zion has since conducted a secondary side tube removal and confirmed the presence of fretting. In February 1984, 21 tubes with wear at the AVBs were identified in Farley Unit 1. There were a total of forty-four indications in one steam generator; nine tubes were plugged.

Westinghouse Model D2/D3 steam generators have experienced fretting wear at tube baffle plate intersections in the preheater section. Figure 5-6 also illustrates the preheater section of a Model D2 generator and the location of the wear phenomenon. The tube wear typically assumes the shape of the baffle plate hole; due to the preheater flow velocity distribution, the wear is not necessarily symmetrical around the tube.

This form of degradation was first observed at Ringhals 3 during 1981. Review of the plant's eddy current data clearly showed evidence of tube degradation at the baffle plates (20). This fretting wear led to a subsequent leaker outage. Almaraz 1 and McGuire 1 and Krsko have also experienced fretting wear in the preheater section.

5.4 COMBUSTION ENGINEERING PLANT EXPERIENCE

Table 5-7 summarizes operating experience for Combustion Engineering (C-E) steam generators. Degradation in these generators, limited to the secondary side, includes denting, thinning, IGA/SCC, and

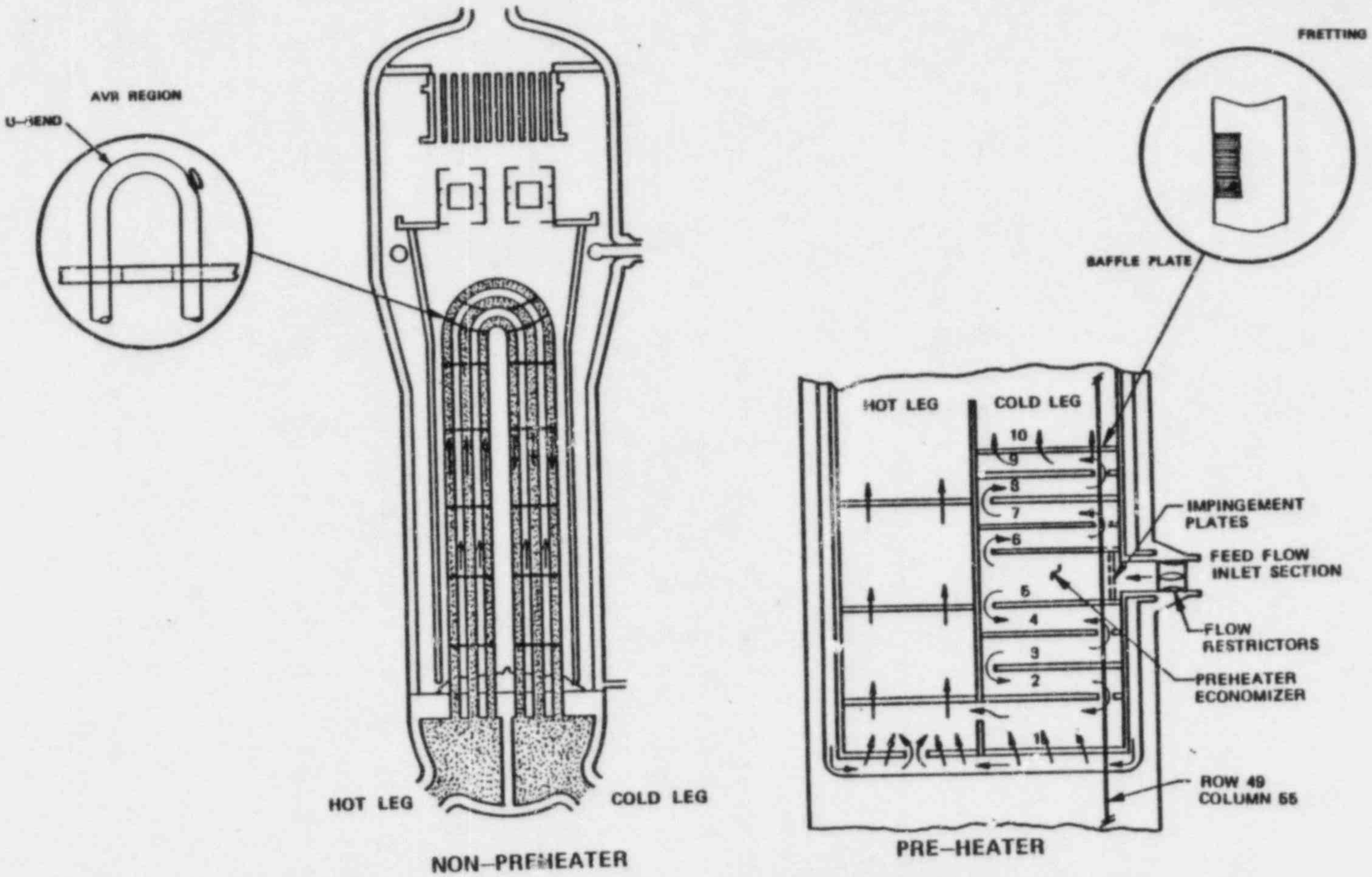


Figure 5-6. Fretting Locations in Westinghouse Steam Generators

Table 5-7

OPERATING EXPERIENCE SUMMARY - COMBUSTION ENGINEERING STEAM GENERATORS

Unit (1)	# of Steam Generators	OL Issued	Secondary Water Chemistry	Thinning	Pitting	Secondary Side IGA/SCC	Denting
Mihama 1	2	11/70	AVT*	X			
Palisades	2	3/71	AVT*	X	X	X	Moderate
Maine Yankee	3	9/72	AVT				Minor
Ft. Calhoun 1	2	5/73	AVT*	X(2)		X(4)	Minor
Calvert Cliffs 1 (3)	2	8/74	AVT				Minor
Millstone 2	2	8/75	AVT		X		Extensive
St. Lucie 1 (3,6)	2	3/76	AVT		X(5)		Minor
Calvert Cliffs 2 (3)	2	8/76	AVT				Minor
Arkansas 2	2	9/78	AVT				Minor
San Onofre 2	2	8/83	AVT				
San Onofre 3	2	1/84	AVT				

* Previous PO 4 water chemistry.
(1) All units have a full depth tube expansion in tube sheet crevice.
(2) Probable manufacturing defect.
(3) Numerous moderate amplitude mid-span eddy current signals have been observed in these units. The exact damage mechanism has not been identified.
(4) Crack located in Line 89 Row 24 - Horizontal section of U-bend.
(5) Linear eddy current indication in horizontal section of U-bend; believed to be multiple pitting or cracking.
(6) Eddy current signals have been detected at the partial support plates which indicate some sort of secondary side tube degradation.

pitting. Denting is the most prevalent problem. Plants that have used phosphate chemistry are subject to thinning. IGA/SCC has been confirmed at two plants (Palisades and Ft. Calhoun) and is suspected at one other unit (St. Lucie). Pitting has been positively confirmed at Millstone 2 and Palisades.

Figure 5-7 illustrates the locations of these forms of degradation in C-E steam generators.

5.4.1 Denting

In C-E steam generators, drilled plates and eggcrates provide structural support for tubes. With the exception of Palisades and Mihama, the drilled plates are two partial-span plates located near the top of the bundle. U-bend support is provided by vertical and horizontal carbon steel straps placed within the tube bundle. Figure 5-7 illustrates denting at eggcrates, support plates, and the U-bend antivibration strips.

Denting has occurred at drilled plates in all units. Eggcrate denting has been observed at Millstone 2 and Maine Yankee; Maine Yankee has also reported dent-like signals at the U-bend antivibration strips. Magnetite formation has been visually confirmed at the U-bend strip structure at Millstone (21).

Support plate ligament cracking occurred at Millstone 2 in the upper two partial support plates, near the plate support lugs (hard spots) which are attached to the tube bundle shroud. In addition, plate rotation has caused deformation of some tubes near the outer periphery. Plate shearing stresses have been relieved by cutting the plate lugs.

5.4.2 Thinning

Extensive wastage attack has occurred at support plates, eggcrates, and antivibration strips at Palisades and Mihama. These are the only C-E units that have significant operating experience with phosphate solids water chemistry. In addition, drilled-hole support plates are used for a majority of the tubing support structures (fourteen plates plus two eggcrates). The absence of flow holes in

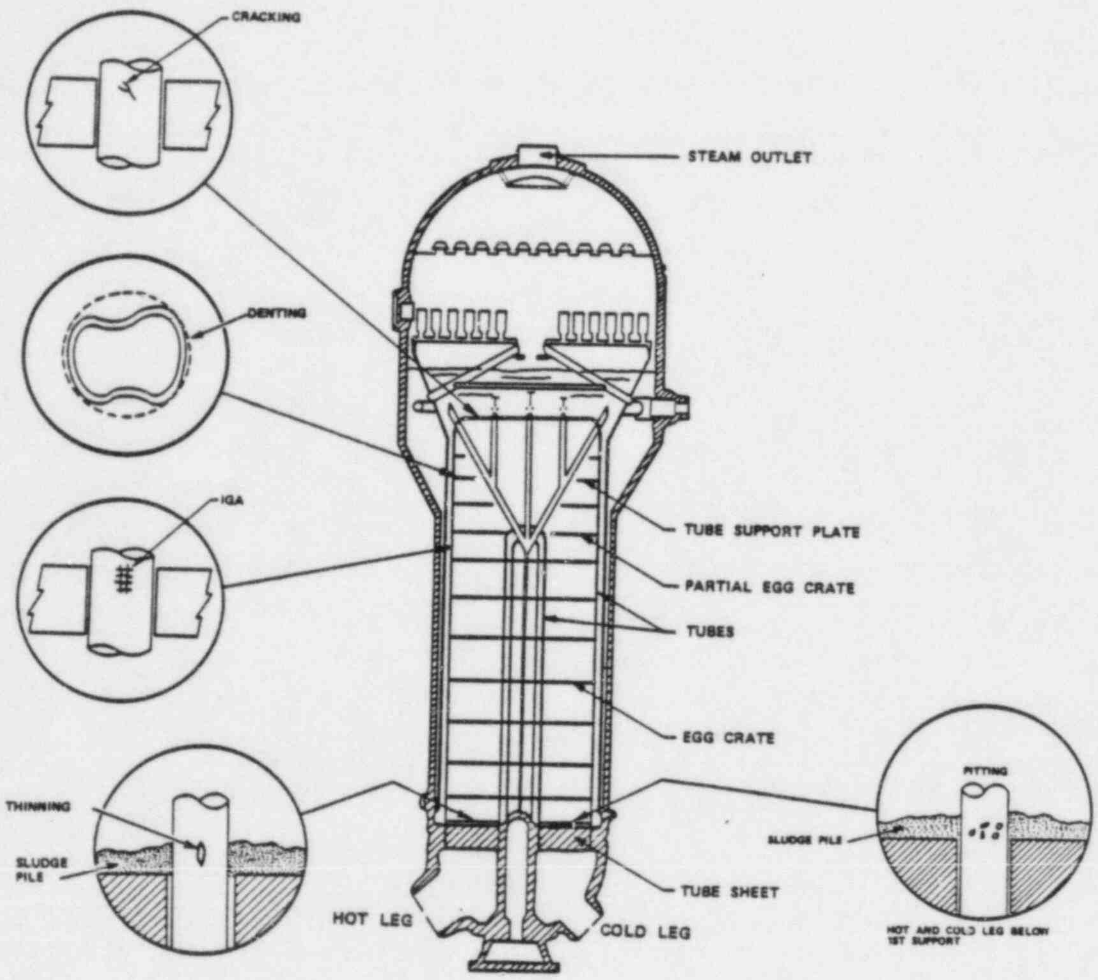


Figure 5-7. Summary of Tube Degradation Locations in Combustion Engineering Steam Generators

some support plates contributes to sludge buildup on the plates, which then results in phosphate wastage attack on the tubes.

Fort Calhoun has reported a secondary side indication 1/4" below a support plate. The mechanism for the attack has not been positively confirmed but it is believed to be a manufacturing defect (22).

With the exception of Palisades, Mihama, and possibly Fort Calhoun, no other C-E units have reported thinning-related indications.

See Figure 5-7 for a summary of the locations of thinning attack in C-E steam generators.

5.4.3 Pitting

Secondary side pitting attack has been confirmed in Palisades and Millstone 2.

Millstone 2 has had extensive pitting attack in association with secondary side copper deposits. The pitting attack occurred predominantly on the cold leg side of the steam generators, although the hot leg side contained a small number of tubes with small volume flaws. Sleeving of 2022 tubes, with the flaws exceeding the plugging limit, has been performed on the cold leg side of the steam generators.

A linear multiple eddy current indication on the intrados side of a U-bend at St. Lucie is believed to be multiple pitting or cracking as a result of steam blanketing. Mid-span eddy current signals reported at Calvert Cliffs 2 are believed to result from pitting (23).

Figure 5-7 summarizes pitting locations in C-E steam generators.

5.4.4 Intergranular Attack/Stress Corrosion Cracking

Palisades and Ft. Calhoun are the only C-E units which have confirmed IGA or SCC. IGA was first discovered at Palisades in 1974 on tubes removed from the A steam generator. The attack occurs in the upper

region of the tube bundle. It probably began as a result of steam generator layup conditions during an extended outage (sulfate/sulfite attack).

Circumferential SCC has been postulated as the initiator of a leaker outage at Palisades during early 1982. The degradation has been characterized by using pancake array coil technology specifically configured for the outage. Two crack signals were identified; one was located at a dented support plate while the other was observed in the horizontal run of a square U-bend at a support strap (24). Review of the eddy current data from previous outages shows that one of the two crack signals had been present for some time.

In late 1983, numerous tubes were removed from the Palisades A and B steam generators in order to identify the source of eddy current signals that were encountered during inservice inspection. SCC and IGA were identified during subsequent metallography. The IGA is believed to be due to the original sulfate/sulfite attack present since 1974. Most of the cracking was at dented support plates and is believed to be denting related.

Ft. Calhoun came down for inspection during mid-1984. At the completion of the outage during hydrotest of the steam generators a large leak was discovered. The leak was traced to the horizontal section of a square U-bend. Secondary side visual examination showed the leak to be due to a crack-like discontinuity which had burst. Review of the eddy current data from the recently completed inspection showed the presence of a large indication that had been missed.

Figure 5-7 summarizes IGA/SCC locations in C-E steam generators.

5.5 BABCOCK & WILCOX PLANT EXPERIENCE

Table 5-8 summarizes the operating experience for Babcock & Wilcox (B&W) steam generators. Corrosion damage in B&W once-through steam generators is secondary side initiated, with the exception of the damage at TMI-1. Secondary side corrosion damage includes stress corrosion cracking, pitting, and possibly denting. Tube degradation attributable to mechanical phenomena includes fretting, corrosion-

Table 5-8

OPERATING EXPERIENCE SUMMARY - BABCOCK & WILCOX STEAM GENERATORS

Unit (1)	# of Steam Generators	OL Issued	Secondary Water Chemistry	Pitting	Secondary Side IGA/SCC	Primary Side SCC	Fretting	High-Cycle Fatigue	Impingement
Oconee 1	2	2/73	AVT	X	X		X	X	X
Oconee 2	2	10/73	AVT				X	X	
Oconee 3	2	7/74	AVT				X	X	X
Arkansas 1	2	5/74	AVT		X			X	
Rancho Seco 1	2	8/74	AVT				X	X	
Three Mile Island 1	2	4/74	AVT			X			
Crystal River 3	2	12/76	AVT						
Davis Besse 1	2	4/77	AVT						
Three Mile Island 2	2	2/78	(License suspended)						

(1) All units have open tube sheet crevices.

assisted high-cycle fatigue cracking and flow-associated debris impingement.

A rank ordering of the Babcock & Wilcox operating plant problems by importance is as follows:

- Environmentally assisted high-cycle fatigue cracking - This mechanism has resulted in the most number of tube leaks
- Primary side stress corrosion cracking - This mechanism has resulted in the most number of plugged tubes. However, this condition has occurred at only one plant (TMI-1) under non-typical operating conditions.
- Secondary side intergranular attack - This mechanism is second in the number of plugged tubes.
- Impingement damage - This mechanism is third in number of tubes plugged.

Concerning the other mechanisms listed:

- Pitting - No tubes have been plugged because of pitting although it has been observed on several pulled tubes
- Denting - No tubes have leaked as a result of tube distortions. A few tubes, spproximately 50, have been plugged as a result of not passing a standard eddy current probe.
- Fretting - Approximately 20 tubes have been plugged due to this mechanism and another 24 tubes are being tracked for indications. Only a few tubes are involved and there appears to be no trend of increasing fretting.

Typical elevational locations for OTSG tube wall degradation are given in Figure 5-8.

5.5.1 Environmentally-Assisted High-Cycle Fatigue Cracking

High-cycle fatigue cracking is the primary cause of leaker outages in OTSGs. The cracking is limited to the lane region at elevations between the 14th support plate and the upper tube sheet. The cracking is believed to be corrosion assisted initiating at under-deposit corrosion sites.

Until recently, no crack precursor or initiator had been identified,

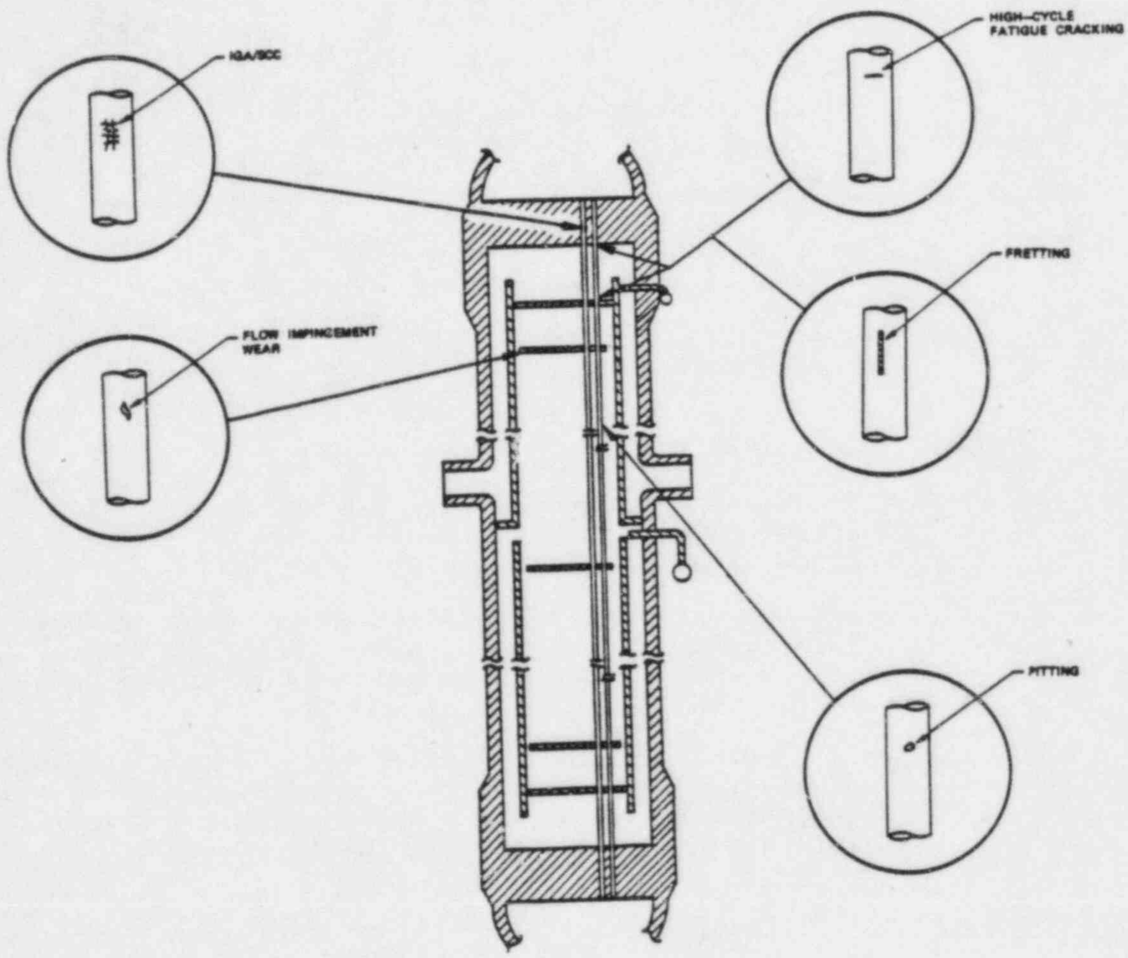


Figure 5-8. Summary of Tube Degradation Locations in Babcock and Wilcox Steam Generators

i.e., the crack was either non-existent or 100% through-wall. Oconee experienced a leaker outage late in 1982 involving five tubes in proximity to the lane region. One pulled tube had an eddy current indication of less than 100% through-wall; in-plant examination of the tube surface showed a circumferential crack-like discontinuity. Subsequent laboratory examination showed the crack to be spproximately 60% throughwall. The crack was not detected with conventional bobbin coil technology but was found with an array coil.

5.5.2 Secondary Side IGA/SCC

In a tube (77-17) removed from the lane region during 1977, Arkansas 1 found SCC in the upper tube sheet region, and a crack at the upper tube sheet characteristic of lane region high-cycle fatigue cracking (see Section 5.5.6). Subsequently, they found other upper tube sheet crevice eddy current indications. The damage is attributed to corrosion product transport up the lane region into the upper tube sheet; it is believed to be confined to the wedge area.

Figure 5-9 displays the location of the lane region and various other areas in an OTSG.

5.5.3 Fretting

Fretting damage is flow-related and is limited to the lane region at the upper support plate elevations. Numerous OTSGs have been affected as can be seen from Table 5-8. Approximately 20 tubes have been plugged due to this mechanism and another 24 tubes are being monitored for indications. Only a small percentage of tubes from the total steam generator population are affected and there appears to be no trend in increasing tube fretting.

5.5.4 Impingement Wear

It is speculated that secondary side solids transported by fluid flow are the source of impingement damage (25). Impingement wear occurs within the outer periphery of the generator; it is bounded approximately by the annulus formed by the circumferential band of support plate tie rods (see Figure 5-9). Other descriptors for this damage form include erosion-corrosion of "14th support plate defects." The latter name arises because the damage occurs more often at the 14th support

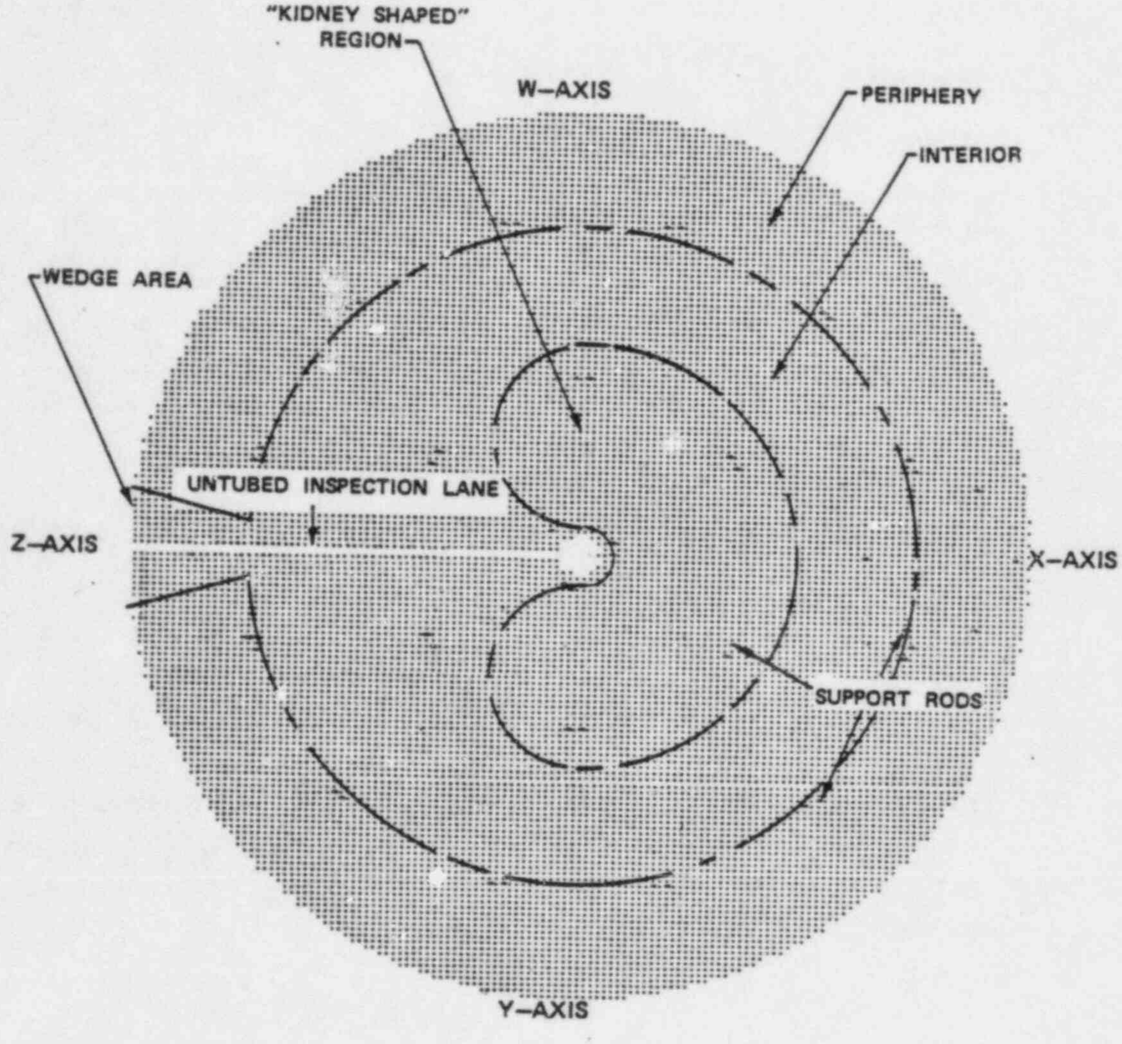


Figure 5-9. Tube Sheet Map for Babcock & Wilcox Units Showing Distribution of Tube Wall Degradation

plate.

5.5.5 Primary Side Stress Corrosion Cracking

TMI-1 is the only unit that has experienced primary side SCC. The cracking has been attributed to the accidental intrusion of sulfur compounds into the primary loop. Most of the cracking is confined to the upper tube sheet.

5.5.6 Pitting

Pitting under the 15th broached support plate has been confirmed on one tube removed from Oconee 2. Pit diameter was approximately 15 mils, with a maximum depth of 6 mils (about 17% of the tube wall). The pitting was not detected during the outage prior to tube removal; pit-like degradation probably can not be detected until the volume of removed metal approaches that equivalent to 40 mils diameter by 40% through-wall depth.

5.5.7 Denting

OTSGs use carbon steel broached support plates, with trefoil land contact, for the first fourteen support plates. The fifteenth support plate also contains a number of drilled holes in the outer three to four rows. As in RSGs, drilled holes are prone to denting; a broached hole may not be as susceptible.

Dent-like signals, termed dings, have been observed in OTSGs at the 9th and 10th support plates and within the kidney region at the lower tube sheet. Some of the ding signals are attributable to installation practices during the tubing of the steam generator or tube vibration that occurs during steam generator operation.

The ding signals in the lower tube sheet kidney region have a strong association with lower tube sheet banana signals (LTS banana) in some units. The LTS banana signals can spread from the interior region of the tube bundle into the periphery. They have been duplicated in the laboratory by placing high density magnetite around the tube at the tube sheet face. Although there is a high probability that the lower tube sheet ding signals are related to denting, denting has not been positively identified in removed tubes.

5.5.8 Distorted Upper Tube Sheet Entry Signals

Distorted upper tube sheet entry signals, classified as C1, C2, or C3 type indications, depending on signal formation, have been observed for a number of years in OTSGs. Examinations of pulled tubes with C type indications show a depression of approximately 2 mils at the lower face of the upper tube sheet, probably caused by corrosion. No correlation has been established between the severity of tube degradation and the numerical value of the C type indication.

Section 6

STEAM GENERATOR NDE EXPERIENCE

6.1 INTRODUCTION

This section considers NDE experience with known damage forms based on a review of pulled tube and in-plant eddy current data. In addition, recommended inspection methods for various damage forms are also discussed based on pulled tube experience, laboratory, and in-generator experiments. Prior to discussing specific experience, general background information on the inspection of steam generator internals is presented.

6.2 TUBE INTEGRITY INSPECTION REQUIREMENTS

Inspection equipment and procedures for steam generator examination are defined in the plant technical specification. With regard to the specifics of the eddy current examination, the plant technical specification may reference one of two documents. These are:

- NRC Regulatory Guide 1.83 - Inservice Inspection of Pressurized Water Reactor Steam Generator Tubes
- ASME Code Section 11 - Rules for Inservice Inspection of Nuclear Power Plant Components (Various Editions).

Section C.2 of the Regulatory Guide lists some nine paragraphs of which the following three are discussed in some detail.

C.2.a - "Inservice inspection should include nondestructive examination by eddy current testing or equivalent techniques. The equipment should be capable of locating and identifying stress corrosion cracks and tube wall thinning. . ."

Eddy current examination is the primary inspection method because it is fast and simple. However, other NDE methods can be used if an equivalent inspection capability can be demonstrated. The use of the word "identifying" in the quoted paragraph should not be understood in the context of being able to recognize the various types of tube

wall damage from their eddy current signature.

> C.2.b - "The inspection equipment should be sensitive enough to detect imperfections 20% or more through the tube wall."

In general, detectability is a strong function of the geometry of the defect, its location with respect to extraneous influences, the type of eddy current coil used for inspection, and orientation of the defect with respect to eddy current flow within the tube wall. The above requirement is impossible to satisfy for all defect types and test conditions. The fact that an inservice inspection has resulted in no reportable indications does not necessarily mean that there is no degradation occuring within the steam generator or that it is less than 20% through wall.

> C.2.e - "Standards consisting of similar as-manufactured steam generator tubing with known imperfections should be used to establish sensitivity and to calibrate the equipment. Where practical, these standards should include reference flaws that simulate the length, depth, and shape of actual imperfections that are characteristic of past experience."

This is a key paragraph of the NRC Regulatory Guide 1.83 document. The words "and location" should be inserted within the last sentence after "actual imperfections" since tube wall degradation can occur in proximity to extraneous test variables which can influence detection and sizing capability. The essence of paragraph C.2.e is the demonstration of capability of the proposed inspection method.

Another point of the subject paragraph is that an inspection is performed based on past experience. An eddy current test cannot be designed for the unknown; however, it is possible to design a test in which the number of assumptions are minimized. New damage mechanisms can be encountered during an inservice inspection which are not reliably detected or sized because of non-optimal inspection procedures for the specific flaw type, location, and orientation. Past experience should be understood in the broader context of the experience of sister units of similar design or similar chemistry. If older units are experiencing particular problems then the inspection practices of newer units should reflect that experience in terms of steam generator

sampling plans and optimization of the eddy current test.

The best thing a utility can do to identify the limitations and capabilities of an eddy current inspection for its steam generators is to implement paragraph C.2.e for expected flaw types, geometries and locations as a part of the inspection bid package.

ASME Code requirements are specified in Appendix IV of Section XI. Technical requirements are stated within the appendix or are referenced back to Article 8 Appendix 1 of Section V depending on the date of the document. For purposes of discussion, the summer 1983 edition is utilized.

> I-21(f). "The ET system shall be capable of detecting and recording flaws originating on either tube wall surface and extending to a depth of 20% or more..."

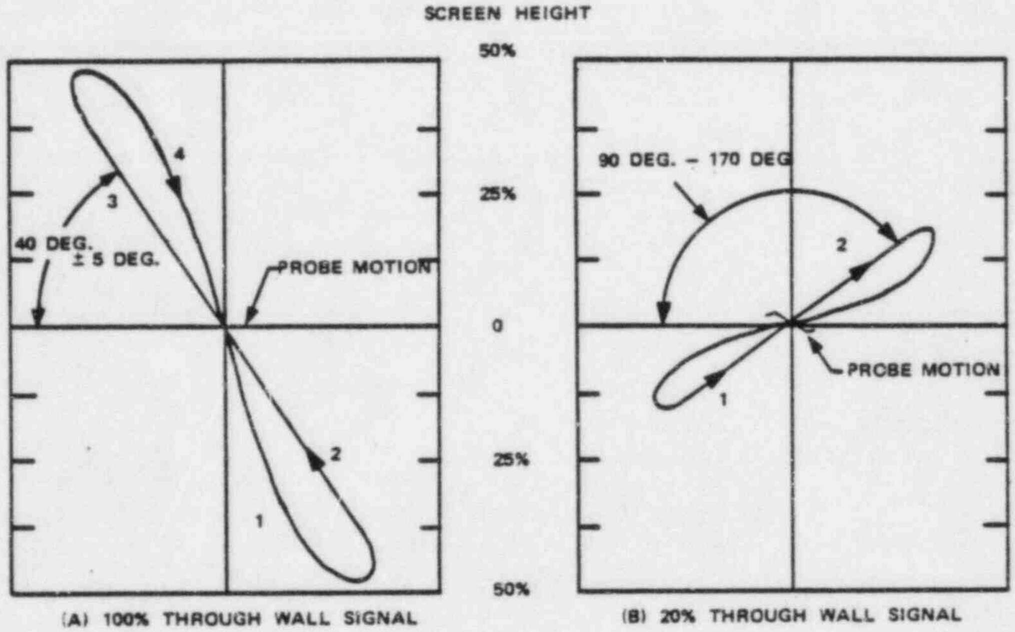
Generally not possible for the same reasons discussed in response to C.2.b of the NRC Regulatory Guide 1.83.

More general comments with regard to the code are as follows:

- Test coil selection - The code does not require the use of an ID bobbin coil for tube inspection. Other coil configurations are allowed. Bobbin coils are generally the preferred approach since they are mechanically reliable and offer a rapid inspection capability.

- Calibration standard - The ASME code standard is designed to verify consistent eddy current system response. It does not establish optimum working sensitivity in all cases nor does it provide for the best estimation of the depth of tube wall discontinuities under all circumstances. Use of the ASME standard in estimating flaw depth may result in conservative or nonconservative estimates depending on characteristics of the particular flaw.

- Frequency selection - The selection of operating frequency is based on the phase angle response obtained from the 100% and 20% through wall holes. After setting the signal from the 100% hole at 40 degrees plus or minus 5 degrees, the signal from the 20% through wall hole must be between 90 degrees and 170 degrees as measured from the negative x-axis in a clockwise direction. (See Figure 6-1.) In 0.050" wall tubing, the larger phase spread corresponds to a test frequency of 400 KHz whereas the smaller phase spread corresponds to a frequency of approximately 100 KHz.



NOTES:

(1) ANGLES AND SIGNALS ARE APPROXIMATE

(2) ARROWS AND NUMBERS DENOTE CRT TRACE MOTION AS PROBE IS WITHDRAWN PAST CALIBRATION DISCONTINUITY

Figure 6-1. Typical Signals From a Properly Calibrated Eddy Current Differential Probe Coil System

Frequencies which give the smaller phase spread are generally better for detection; higher frequencies are generally better for measurement in the presence of secondary side extraneous test variables. However, probe motion effects and noise due to tube ID variations may preclude the use of the higher frequencies. This is particularly true in thinner walled tube (0.034" - 0.043") where the "thinness" may necessitate frequencies between 550 KHz and 650 KHz to satisfy the larger phase spread requirements of the code.

- Sensitivity setting - The code requires that the sensitivity shall be sufficient to produce a response from the through-the-wall hole with an amplitude minimum of 50% of the full CRT screen height. There are several problems with this requirement. First of all, the statement ". . .an amplitude 50% of the full screen height" is ambiguous. It is not clear whether one measures the peak-to-peak vector magnitude or its projection onto the vertical axis. (See Figure 6-1.) Second, the sensitivity established using the ASME standard may not be applicable under all conditions within a steam generator. As a general rule, the sensitivity should be established using standards which duplicate the expected flaw geometries and locations similar to that described in NRC Reg. Guide 1.83.

  The use of the 100% through wall hole to establish a sensitivity setting also causes significant problems. The hole is not axisymmetric; consequently, the eddy current response obtained using smaller fill-factor probes can vary significantly depending on how the probe is aligned with respect to the hole. The scatter in true sensitivity setting as measured using a axisymmetric reference can vary by a factor of two or more.

6.3 NDE EXPERIENCE WITH SPECIFIC TUBE WALL DEGRADATION

This section discusses NDE experience with specific damage mechanisms. In most cases, the experience reflects the use of conventional bobbin coil technology and ASME code procedures. Where there are exceptions, they are so stated.

There are presently two general classes of tube wall damage; 1) corrosion induced and 2) mechanical degradation. The former class includes thinning, pitting, and cracking (primary and secondary side), whereas the latter includes fretting wear, environmentally-assisted fatigue cracking, and flow impingement damage. As a general rule, corrosion damage predominates in recirculating steam generators while mechanical damage is more common in once-through steam generators.

Present eddy current analysis practices are not always capable of distinguishing the various damage forms. Eddy current signal analysis can generally distinguish between tube wall damage, whether it is primary or secondary side initiated, and conditions external or internal to the tube wall which are not indicative of tube wall damage, e.g., deposits, support structures, etc. In most cases, the different forms of tube wall degradation tend to occur at given locations within the steam generator. "Recognition" of a particular type of degradation tends to be based on its location within the steam generator.

ASME code phase angle sizing techniques are typically used to estimate the depth of tube wall degradation. Exceptions include wear at AVBs and preheater steam generator baffle plates. In these cases, the tube wall damage tends to exhibit some regularity in its geometry and eddy current signal amplitude sizing is generally used. The use of signal amplitude has advantages in low signal-to-noise situations where it is less affected by extraneous test variables than signal phase angle.

The use of the ASME standard to generate a calibration curve from which signals are assigned a depth can result in conservative or nonconservative depth estimates depending on the morphology of the tube wall damage. Improvements in depth measurement accuracy can generally be realized if the geometry of the degradation can be measured and eddy current standards which duplicate the geometry are used to establish a calibration curve. Measurement of flaw geometry cannot be done with conventional bobbin coil because of coil averaging effects. Alternate coil configurations must be utilized.

Most of the adverse experience associated with sizing tube wall discontinuities has been with stress corrosion cracking and intergranular attack. This factor coupled with uncertainties in growth rates has resulted in the practice of removing from service any tube believed to be cracked or have intergranular attack. Most cracking and intergranular attack occur within the tube sheet crevice region; all indications are plugged without regard to the eddy current estimated depth.

Detailed NDE experience with the various forms of tube wall degradation is now considered.

6.3.1 Thinning

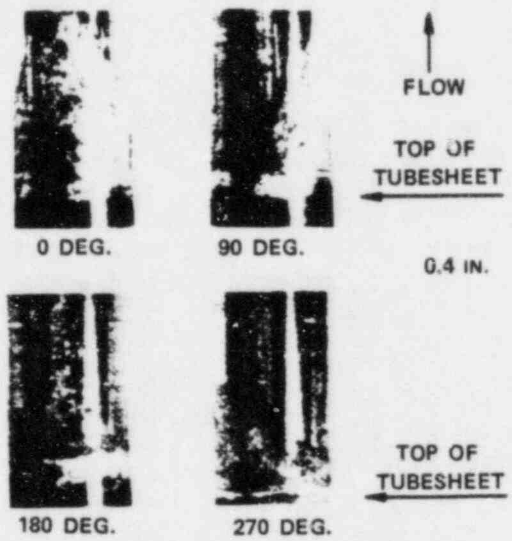
Thinning which results from phosphate attack is called wastage. Figure 6-2(a) shows several views of wastage as it occurs on a tube at the top of the tube sheet. The tapered condition of the wastage geometry is apparent in the figure. Specific locations for wastage are determined by the extent of the fludge pile within the steam generator.

Wastage has also occurred at tube support plate intersections in steam generators which do not have flow holes in the support plate. It's occurrence is attributed to sludge buildup on the support plate. See Figure 6-2(b).

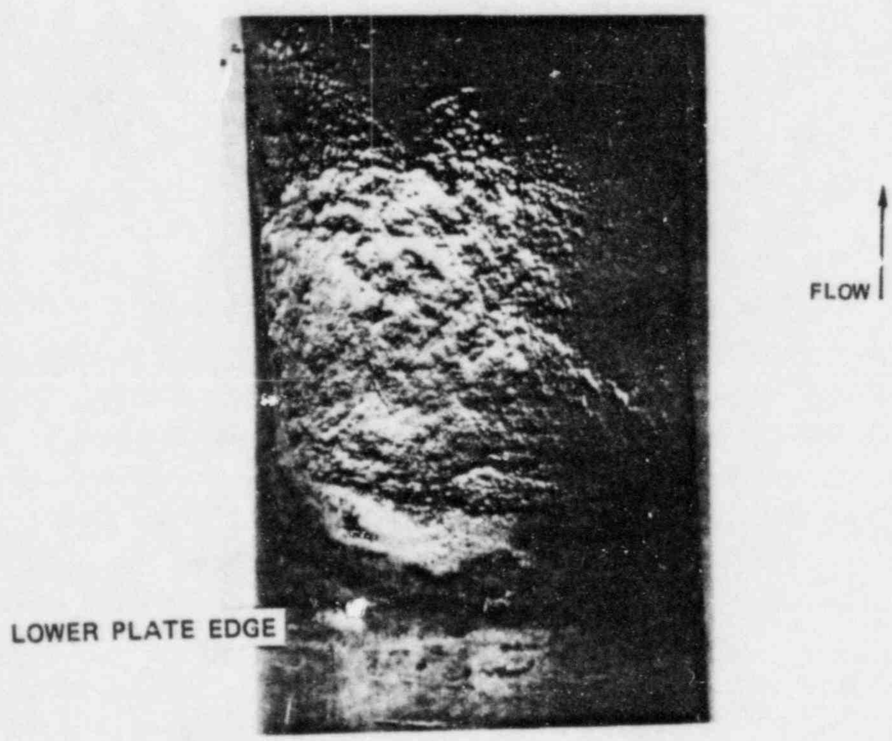
Eddy current detection of non-tapered tube wall thinning is quite reliable. Differential bobbin coil modes typically detect 20% through-wall depths and greater. With the coil operating in the absolute mode and use of lower coil excitation frequencies (100-200 KHz for 0.050" wall tubing), detection can be achieved at less than 10% through-wall penetration.

Depth estimation has been statistically conservative (26). The range of error is approximately +20% to -5% with, on the average, a conservative bias.

A thinning defect above the tube sheet, attributed to fretting by an adjacent plugged tube which had severed due to foreign object damage, did result in a tube burst at Ginna. Post burst review of eddy current data acquired from the previous outage showed an indication clearly present on the absolute coil channel which had not been analyzed due to an oversight. The differential data channels which were analyzed did not indicate anything of significance. Examination of the burst tube after removal showed the fretting to be very gradual which explains why there was little response with the differential coil. The latter coil mode is more sensitive to sharp discontinuities within the tube wall. This is an example of why all eddy current data should be analyzed.



(a) Wastage at tubesheet



(b) Wastage at a support plate

Figure 6-2. Examples of Wastage

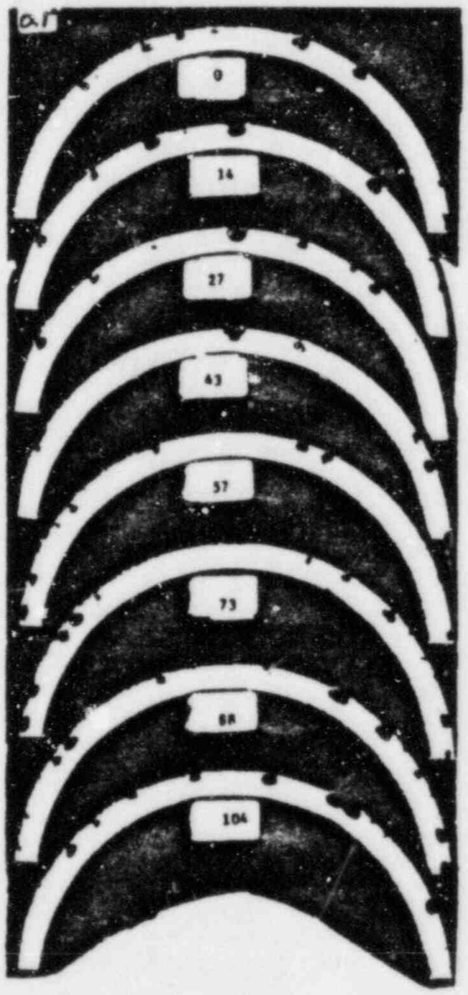
6.3.2 Pitting

Figure 6-3 illustrates multiple pitting with a series of transverse cross sections taken axially at 0.015" intervals through a section of removed tubing. The pitting has been attributed to the presence of copper on the secondary side tube surface in a highly oxygenated environment. The pitting is typically re-entrant in cross section with oxide deposits and metallic copper present within the pits.

Pitting in association with secondary-side copper deposits represents a difficult inspection problem. Initial attempts to detect and size pitting in the presence of copper employed a multiparameter (100x400 KHz) differential bobbin coil mix. However, comparisons of field eddy current data with the measurements obtained from removed tubes revealed large discrepancies. For example, a tube actually containing 40% through-wall pitting was classified as having no detectable degradation; a tube actually containing 66% through-wall degradation was classified as a possible indication (27).

Improvements in measurement capability have been achieved by increasing the eddy current mixing and basis frequencies to 250x600 KHz, and by decreasing the focus of the bobbin coil (reducing coil winding width). These changes improve the quality of the data by reducing the effects of the copper deposits. Figure 6-4 shows a differential bobbin coil with a decreased focus for characterizing pitting in the presence of copper. Depths estimated from eddy current data obtained with this method agreed to within 5% with depths determined destructively from two pulled tubes (28).

Detection studies of pitting in the presence of copper have also been conducted in the laboratory. Various combinations of hole diameters and depths ranging from 0.010" - 0.125" in diameter and 50%-100% throughwall respectively were used. Based on these studies, reliable detection of pitting in the presence of copper has been estimated at 0.050" diameter and 50% throughwall (0.050" wall tubing). Pitting with a lesser volume i.e., shallower depth but larger diameter or greater depth but smaller diameter, may not be detectable in the presence of copper (29).



TRANSVERSE CROSS SECTIONS
OF TUBE AT 0.015 IN. INTERVALS

MAGNIFIED VIEW SHOWING
LAYERS OF OXIDE AND
COPPER WITHIN PIT

Figure 6-3. Pitting-Copper Attack Morphology

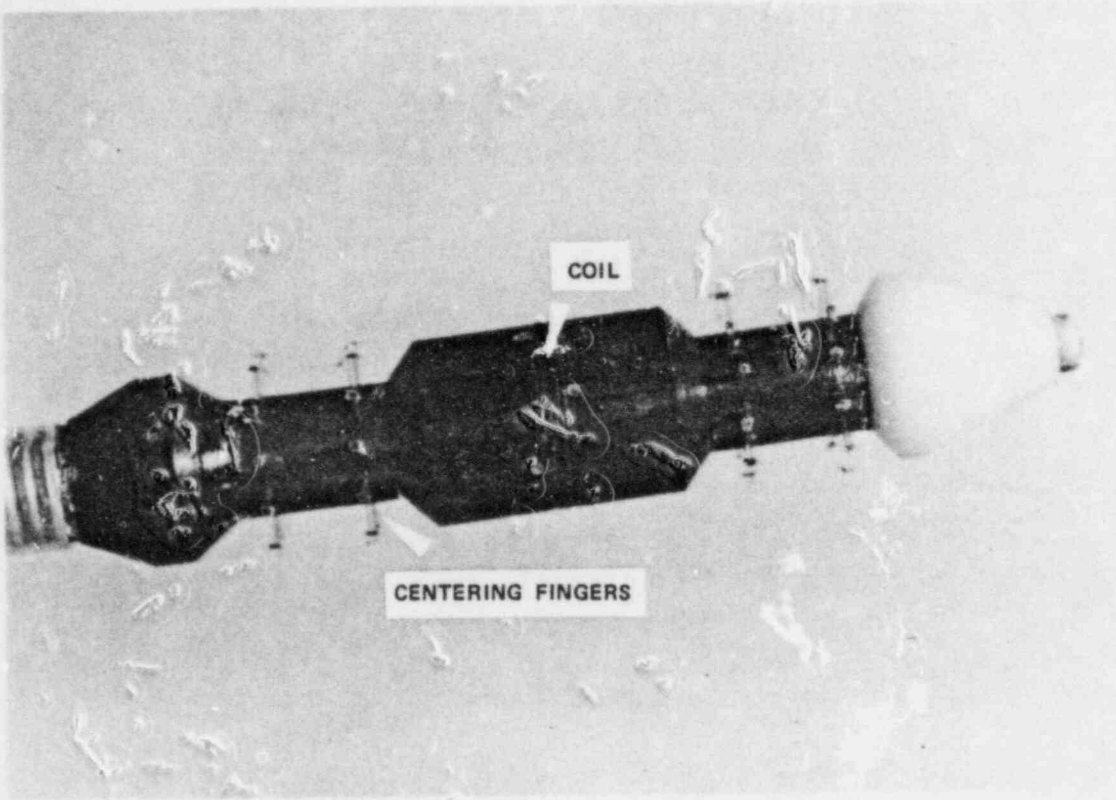


Figure 6-4. Reduced Focus Differential Coil
(Combustion Engineering)

6.3.3 Primary Side Stress Corrosion Cracking

Dented Tube Cracking. As shown in Figure 6-5, a dented tube is often severely distorted. Cracking initiates where tensile strains dominate and can initiate from either the primary or secondary side. Inspection of dented tubes for cracking is accomplished using a spring-loaded pancake coil, which rides the tube inner surface, driven by the Zetec SM-6 positioner (see Figure 4-23). The inspection procedure is extremely tedious and time consuming. A single tube support plate intersection may require many minutes to inspect. Crack sizing is not attempted; all indications are plugged, regardless of eddy current indicated depth. Crack depth detection is on the order of 40% through wall (30).

Dented tubes presently are not routinely inspected for cracking. Rather, profilometry techniques are used to estimate tube strain at dented support plate intersections. The tube is removed from service at a strain level, typically 17%-25% total strain, below which cracking would be expected. The capabilities of commercial profilometry methods in providing estimates of dent shape from which tube strain is derived are discussed in Section 6.3.8.

Roll Transition Cracking. Numerous units have experienced primary side cracking within partially rolled tube sheet crevices. Most of the cracking has been experienced in European and Japanese units although there is no known reason why US domestic units should be excluded from this mechanism. Indeed, recent tube pulls from Cook 2, have confirmed the presence of shallow (less than 20%) primary side cracking at the roll transition.

The detection of primary side cracking at the roll transition using a bobbin coil requires paying careful attention to the shape and rotation of the roll transition signal. It is especially important to review bobbin coil eddy current data at an intermediate frequency. Evidence of roll transition cracking is provided indirectly by loop opening or rotation of the normal roll transition signal, or is provided directly by distinct crack signals. This open loop structure has been confirmed in the laboratory using cracked roll transition speciments and from pulled tubes (31). Figure 6-6 shows metallographic and in-plant eddy current data from a pulled tube

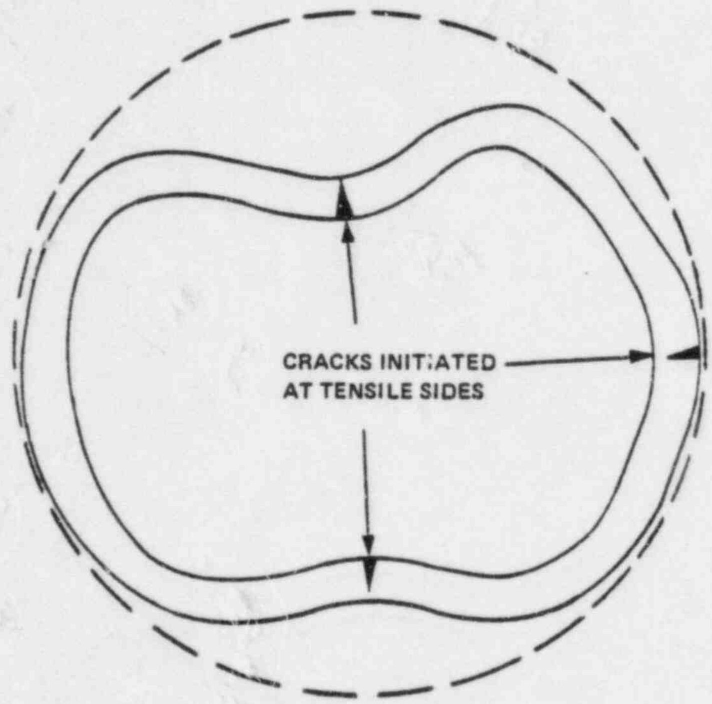
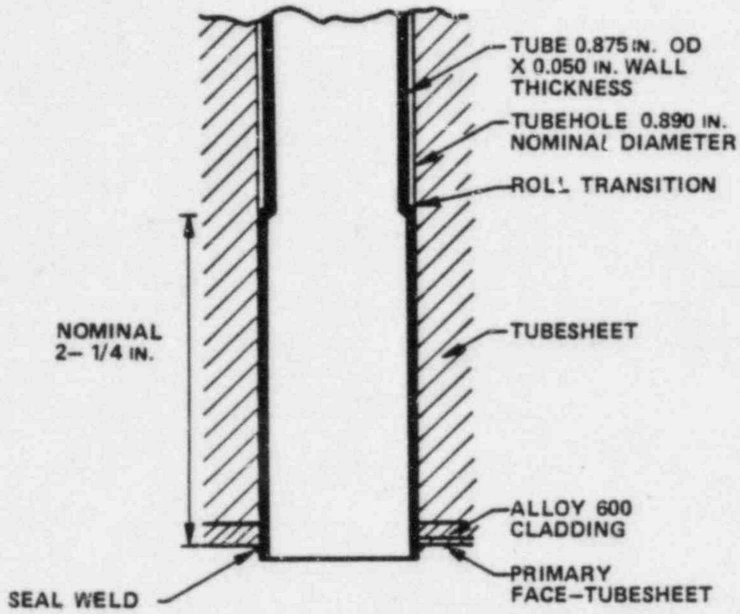
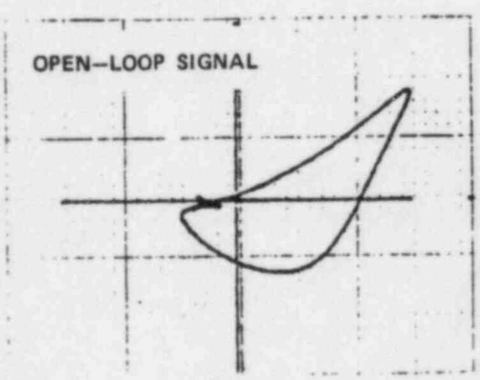
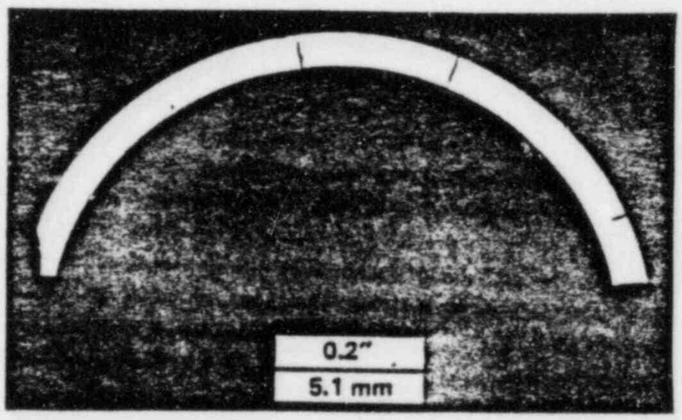


Figure 6-5. Denting Assisted Tube Cracking



(a) Tubesheet roll transition geometry





(b) Roll transition eddy current signal

Figure 6-6. Roll Transition Primary Side Cracking - Typical Signal

which was cracked at the roll transition. Notice the loop opening and rotation in the roll transition signal caused by the multiple cracking.

Laborelec has conducted in-plant studies in which the detection capabilities of a conventional bobbin coil and a rotating pancake coil were compared for roll transition inspection. In general, only transitions which had multiple extensive cracking could be identified with the bobbin coil. Thus, the presence or the extent of roll transition cracking can be grossly underestimated based on eddy current bobbin coil data.

Roll Expansion Cracking. Numerous units have had tubes expanded in the sheet crevice in order to eliminate the crevice as a potential sink for the accumulation of secondary side corrodents. Mechanical, hydraulic, and explosive tube expansion methods have been used. Several units have experienced primary side cracking within expanded tube sheet crevices. As with roll transition cracking, most of the adverse experience has been with European and Japanese units, although results from recent inspections in US plants have shown primary side eddy current indications within the expanded region.

French (Intercontrole) and Belgian (Laborelec) ISI groups have developed rotating probe systems for the inspection of expanded tubes within the tube sheet crevice (see Figures 4-24 and 4-25). These systems can provide detailed information on crack length, depth, and orientation. Inspection rate is approximately 40 tubes per hour (full length inspection of the crevice region) for the Laborelec system. Both systems have had extensive field experience with very good performance. Laboratory detectability studies using electro-discharge machine notches is approximately 20-40% through wall with a one millimeter notch length.

Laborelec has conducted very detailed in-plant studies comparing the detectability of primary side cracking using conventional bobbin coil and rotating probe technology. The percentage of tubes sampled which were cracked based on the rotating probe results has ranged from approximately 4% to 40%. With the bobbin coil, the percentage has never exceeded about 0.5%. (32)

Inner Row U-bend Cracking. Eddy current examination of inner row U-bends is presently conducted using 100 KHz absolute and differential bobbin coil techniques. Eddy current indications are typically not reported until the crack approaches 60-100% through wall. Distorted U-bend transition signals are also observed which are probably indicative of cracking in close proximity to the transition.

Figure 6-7 shows a Row 1 U-bend removed from Trojan. A through wall axial crack is visible in the extrados view. Most of the cracking has occurred at the opposite side transition just above the extrados transition. Some cracking has occurred near the apex and at the smooth side transition.

Figure 6-8 shows eddy current data from a cracked Row 1 bend from Zion 1. The overall signal structure from a U-bend can be somewhat complex. The U-bend shown in the figure was scanned from the opposite-side transition to the smooth-side transition. In time, the opposite-side intrados signal develops first (number 1 in the figure) followed by the opposite-side extrados transition (number 2 in the figure), the crack signal (number 3 in the figure), and finally the smooth-side intrados transition signal (number 4 in the figure). The crack signal forms after the opposite side extrados transition signal; hence the crack is located just above the extrados transition.

Of interest is the magnitude of the crack signal in comparison with the transition signals. For the data shown in the figure, the transition signals are larger than the crack signal. Depending on the location of the crack relative to the transition, the latter may overwhelm and mask the crack signal resulting in unreliable detection. For the example under discussion, the crack signal occurs in time separate from the larger transition signals allowing for its detection.

Figure 6-9 shows eddy current data from another U-bend. For this example the crack signal is larger than the signals from either of the two transitions, allowing for reliable detection. Figure 6-10 shows eddy current data from two consecutive outages on a Row 1 bend from Zion 1. The earlier data shows a somewhat flat loop structure; the composite signal is rotated clockwise relative to the later data. This rotation is probably attributable to differences in the absolute

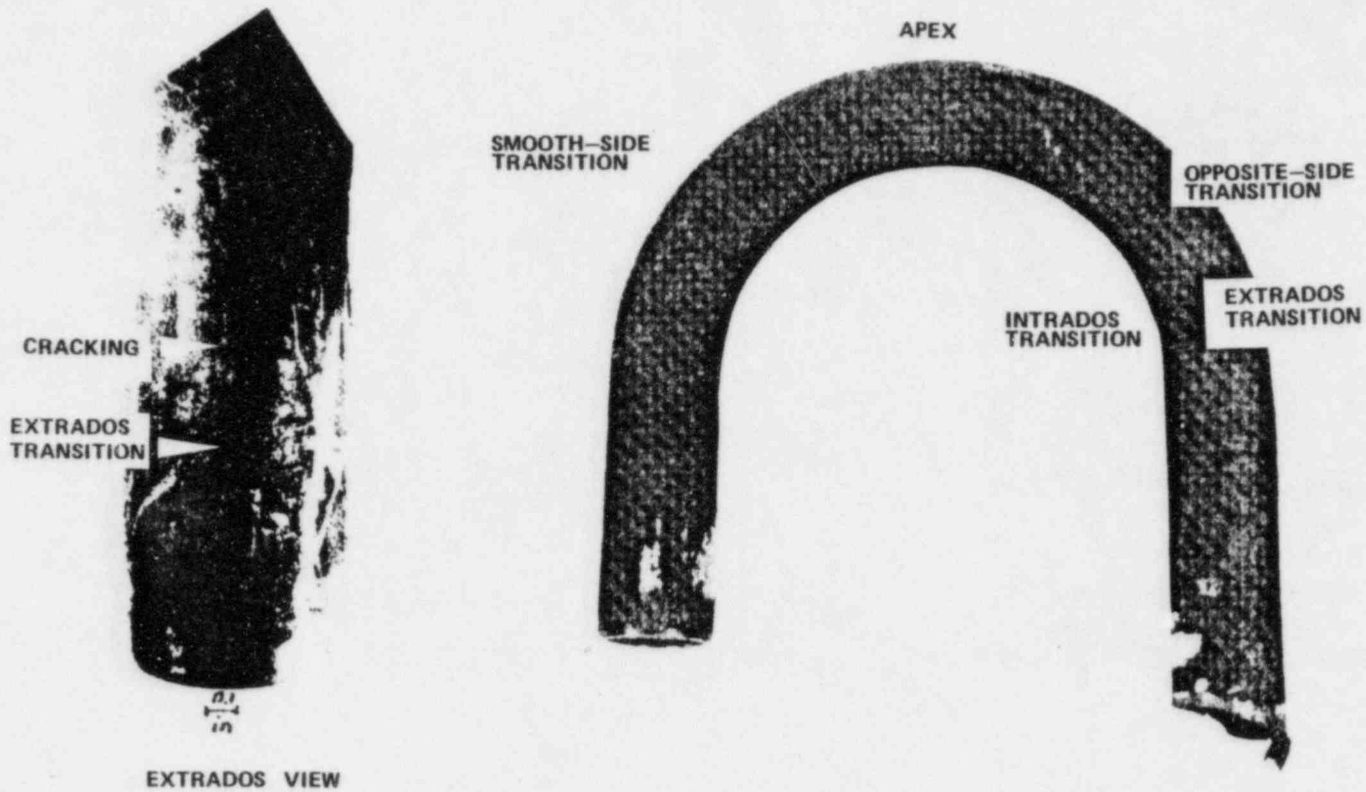


Figure 6-7. Trojan Row 1 U-bend - Cracked at Opposite Side Transition

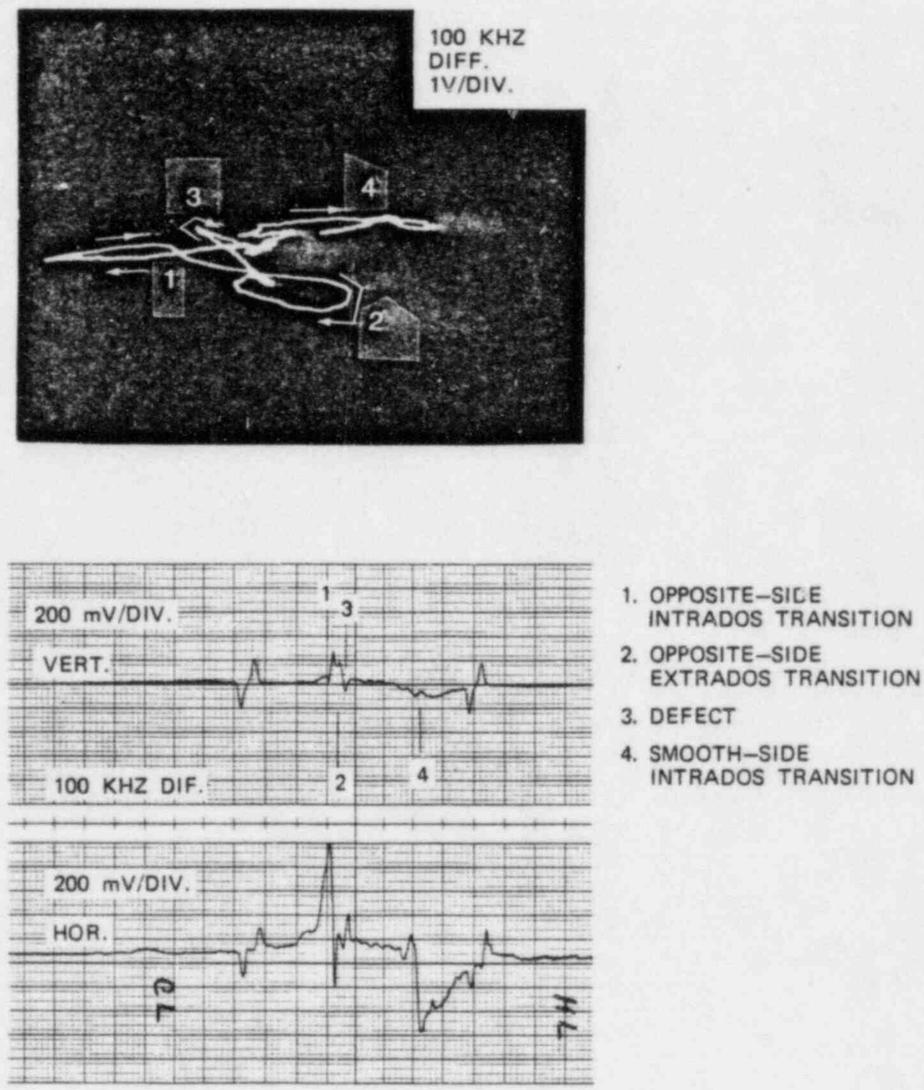


Figure 6-8. Row 1 Tangent Point Cracking - Zion 1

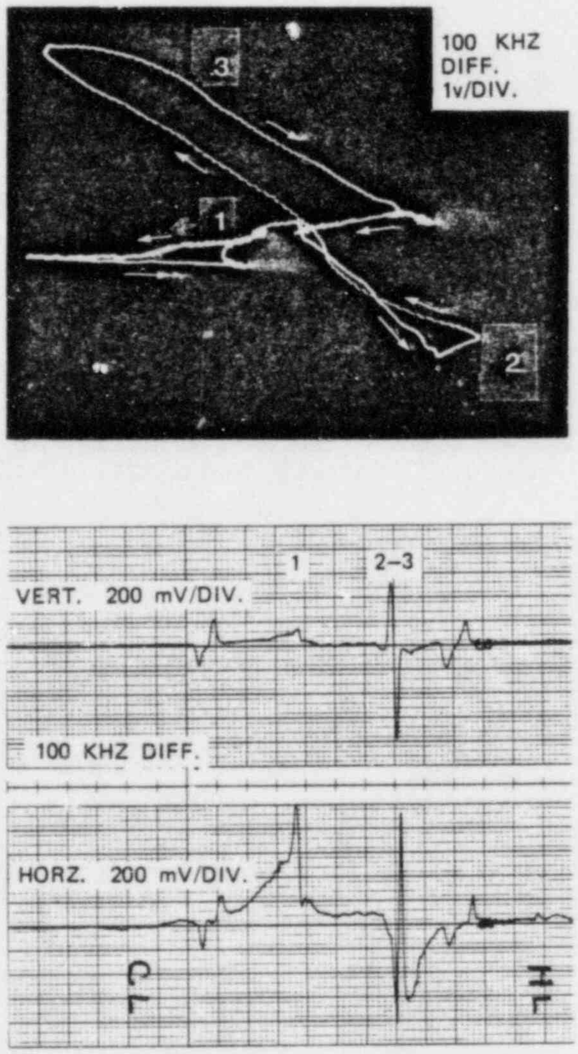
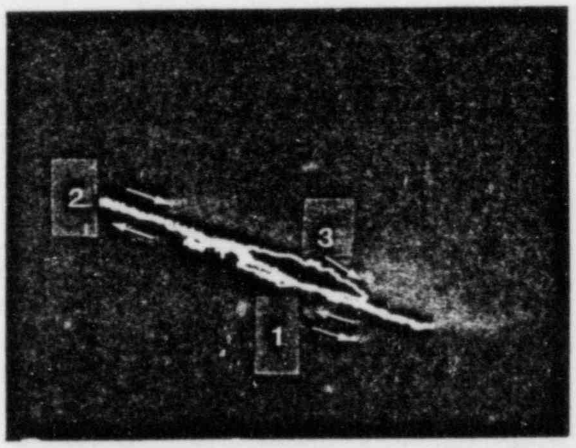
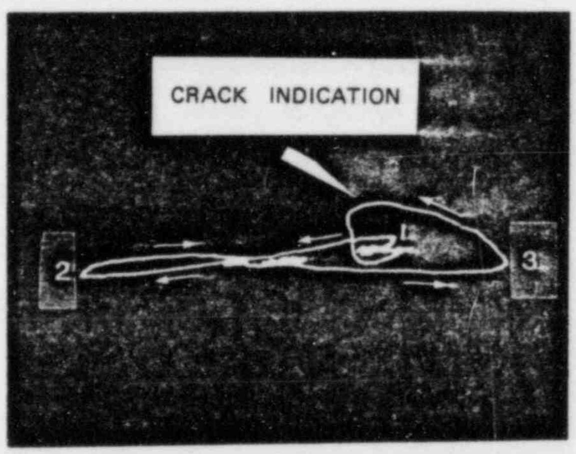


Figure 6-9. Row 1 Tangent Point Cracking - Zion 1



JAN. '81

100 KHZ
DIFF.
1v/DIV.



FEB. '82

Figure 6-10. Row 1 Tangent Point Cracking - Zion 1

phase settings for the two different inspections. Of significance is the opening of the loop structure shown in the bottom photograph. This signal structure is indicative of a crack in close priximity to the transition. The crack length or depth (or both) is small which accounts for the relatively small amplitude. The crack signal distorts the transition signal providing a basis for detection. U-bend transition signals should be closely monitored and compared with previous data for evidence of transition signal distortion.

Both absolute and differential bobbin coil modes should be used to inspect inner row U-bends. As a general rule, the U-bends should be inspected from both sides of the bend. Laboratory studies on removed tubes have shown that probe dynamics as affected by probe pull direction can significantly alter the signal structure obtained from a suspect U-bend transition (33).

It has been speculated that U-bend ovality at the opposite-side transition may be related to the susceptability of a tube to develop primary side cracking (34). This is inconsistent with evidence presented in reference (33) which is based on numerous tubes removed from the Trojan 1 unit.

In (34) it is also claimed that U-bend ovality can be measured from bobbin coil signal amplitude. This is not consistent with evidence presented in (35). In general, nothing quantitative can be said about a particular U-bend transition based on bobbin coil measurements.

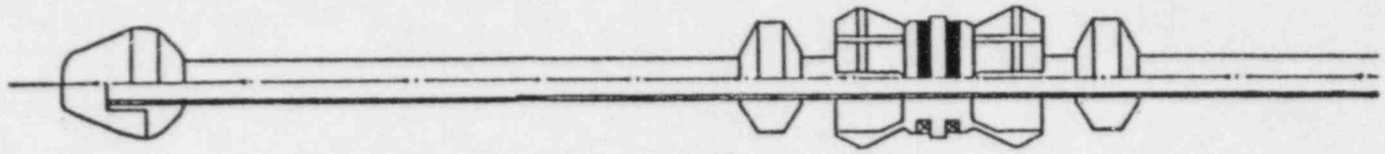
The reliability of inspecting U-bends with bobbin coil technology has been questioned based on numerous leaker outages which have been experienced. Some plants which have excess design margin have plugged all their Row 1 bends in order to increase plant availability. It should be pointed out that primary side crack growth rates can be quite high. Thus the crack can initiate during operation and rapidly propagate to failure, causing a leaker outage. Because of the rapid growth rate, improvements in crack detection capability might not necessarily offer any significant benefit.

Various groups have nevertheless proposed alternate coil designs with the intent of improving signal-to-noise and hence inspection reliability at the U-bend tangent point. In (35), a pancake array coil designed for traversing Row 1 U-bends was evaluated using U-bends containing various EDM notches at different depths and lengths. When compared with conventional bobbin coil data, an improvement in inspection capability was noted. However, additional work was required to field harden the array coil. Mitsubishi Heavy Industries has developed and field tested a Row 1 U-bend probe shown in Figure 6-11(a). The probe is basically a bobbin coil which is mounted on a strap which can bend in one direction. The strap keeps the probe centered within the bend during the pull improving probe dynamics. No data is available as to the improvements offered by this approach. Figure 6-11(b) shows a "tongue depressor" probe developed by Combustion Engineering. The coils are spring-loaded and are designed to ride the extrados side of the U-bend which is the expected location of the cracking. As with the Japanese probe, no data is available with regards to improvements offered in inspection reliability.

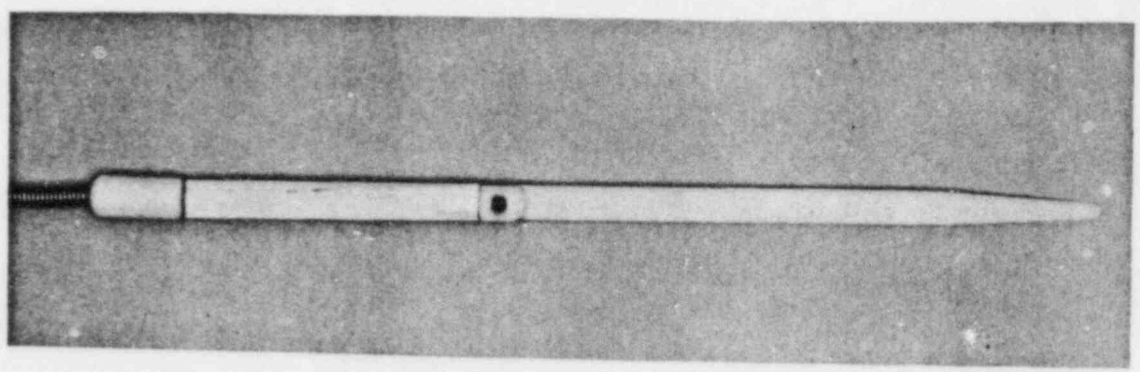
6.3.4 Secondary Side Intergranular Attack/Stress Corrosion Cracking

Secondary side intergranular attack and stress corrosion cracking have caused numerous leaker outages. Most of the corrosion attack has been confined to the tube sheet crevice in units which have an open crevice. Some units have experienced IGA/SCC within the sludge pile and at the first support plates in RSG's , and at the upper support plates in OTSG's.

An example of SCC is shown in Figure 6-12(a). Crack lengths have ranged from a fraction of an inch to tens of inches, the longer length cracks being confined to the tube sheet crevice region (36). Examples of intergranular attack are shown in Figure 6-12(b). IGA does not necessarily cause tube wall loss; instead grain boundary dissolution modifies the conductivity of a region or layer within the tube. The attack can be volumetric with no preferred growth direction or can grow with stress assistance in preferred directions (see Figure 6-12(b)). Typically, IGA initiates volumetrically followed by intergranular penetrations with subsequent stress corrosion cracking and tube leakage.

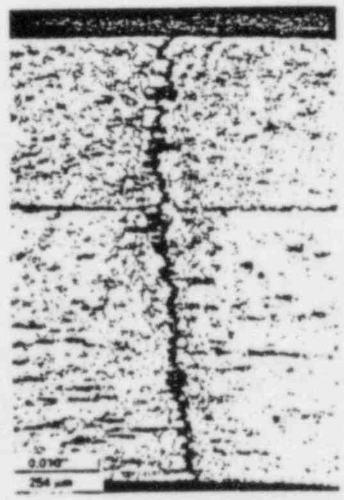


(a) Japanese U-bend probe

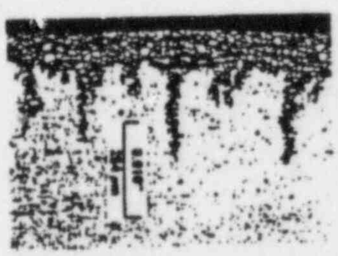


(b) Combustion Engineering U-bend probe

Figure 6-11. Eddy Current Probes for U-bend Inspection



(a) Stress corrosion cracking



VOLUMETRIC WITH PENETRATIONS

VOLUMETRIC

(b) Intergranular attack

Figure 6-12. Intergranular Attack - Stress Corrosion Cracking Morphology

A review of in-plant eddy current data and metallographic results on removed tubes has identified several factors which have contributed to unscheduled plant outages. Key factors include:

- Rapid growth rate of IGA/SCC
- Eddy current data analysis practices
- Limitations of conventional eddy current bobbin coil technology.

Some tubes which have developed leaks showed no evidence of tube wall degradation during the previous inspection. This may suggest a rapid through wall growth rate. Rapid growth rates can be accommodated by more sensitive inspection methods or shorter inspection cycles although economics would tend to disfavor the latter alternative.

Eddy current data analysis practices are an important consideration in reducing the probability of a leaker outage. In numerous instances, indications have simply been missed by the analyst. Unscheduled shutdowns have occurred at the following plants as a result of missed eddy current indications:

- Point Beach 2
- Zion 1
- Robinson 2
- Millstone 2
- Ginna
- Fort Calhoun
- Farley 2

Eddy current signals were clearly present in the acquired data set. It is important to analyze all eddy current data and conduct two independent analyses of all acquired data.

Figure 6-13 shows an example of a stress corrosion crack that resulted in an unscheduled outage. The crack and its eddy current signal are shown at the top of the figure. Review of the eddy current data from the previous outage shown in the lower part of the figure clearly showed the presence of an indication. The estimated depth of the crack was 80% through wall. A practical near term solution to this

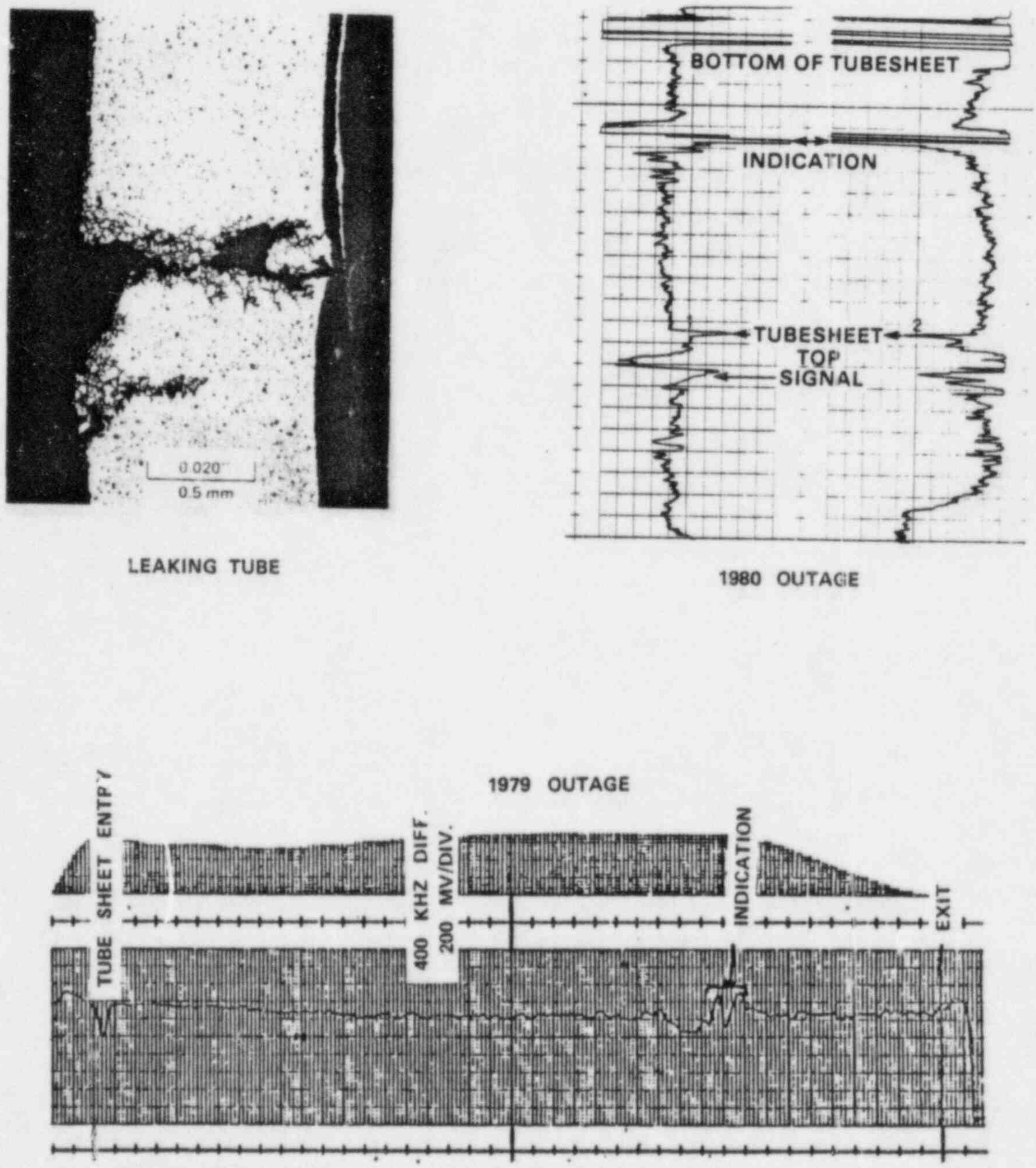


Figure 6-13. Data Analyst Reliability - Missed Indication

problem is to implement an independent analysis of all eddy current data. Each analysis group may still miss some indications but the probability of each group missing the same indication is reduced. Cross checking of both data sets will establish a composite analysis set. The incremental costs associated with the hiring of additional analysts is small when compared with the costs of an unscheduled outage.

Another important factor is the analysis of all eddy current data. Multifrequency eddy current data is routinely acquired during most inspections. The multiple data sets can be viewed as a defense-in-depth approach to the unexpected with data redundancy increasing detection probability and characterization capability. However, all data must be reviewed which has not always been the case. Figure 6-14 shows an example of a tube which was judged to be okay based on an analysis of the "Code" eddy current data (400 KHz - 0.050" wall tubing). The tube was found to contain IGA penetrations 60% through wall just above the roll transition. Examination of the 400 KHz strip chart data shown in the figure shows no indications above the roll transition. However, review of the 100 KHz eddy current data clearly shows indications which were not analyzed which correspond to the location of the IGA identified during the metallographic examination.

Not all eddy current data is analyzed. This results from two reasons; 1) prejudice on the part of the data analyst as to what data is judged to be important or 2) lack of time. The utility must provide the analysis agency with sufficient time to analyze all the necessary eddy current data. Multifrequency eddy current data will take longer to analyze than single frequency eata sets because of a greater number of channels that have to be reviewed. The utility has the responsibility to assure that all data is being analyzed to by conducting an independent audit directly or assigning that responsibility to a second party.

The eddy current test coil mode has also been shown to be an important factor in detecting IGA. Figure 6-15 shows an axial cross section of a tube containing volumetric IGA on the order of 40% through wall located just above the top of the tube sheet. Also shown is the in-

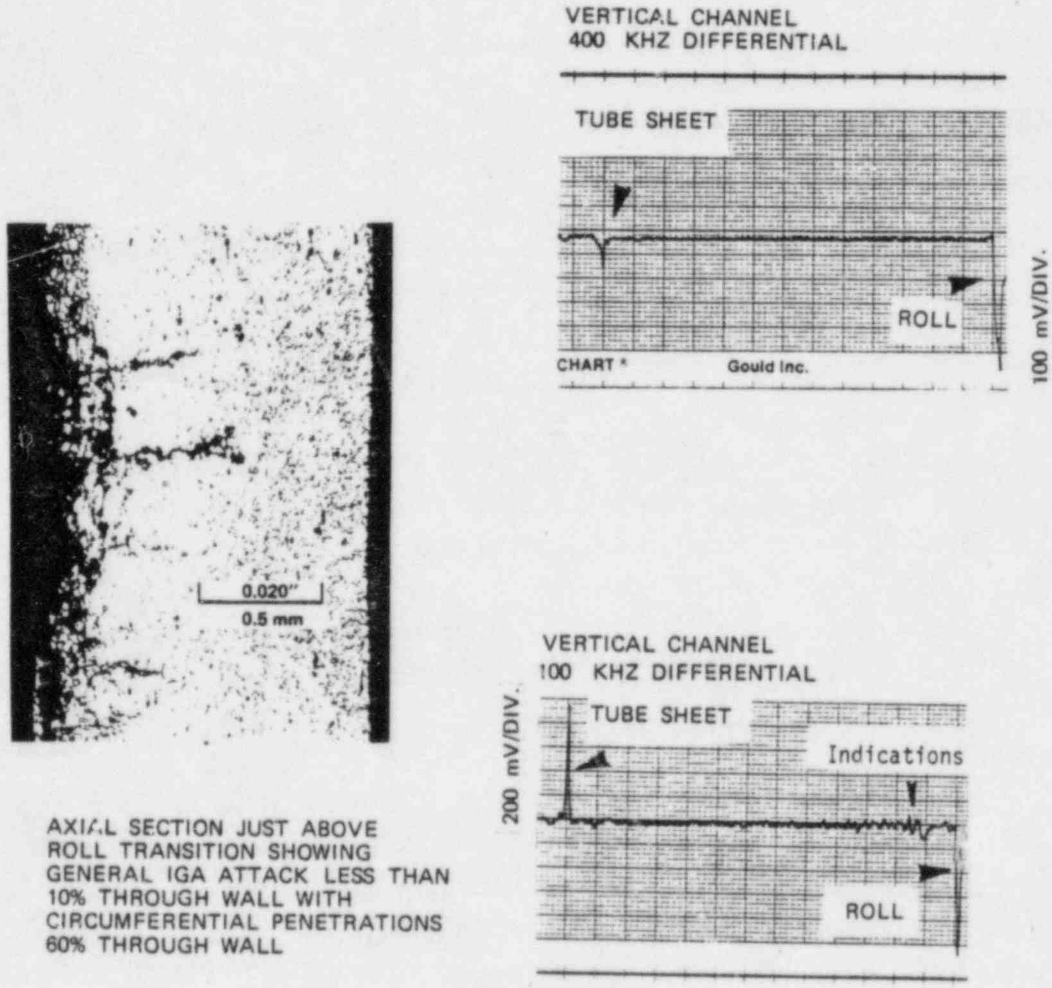


Figure 6-14. Data Analyst Reliability - Analyze Available Data

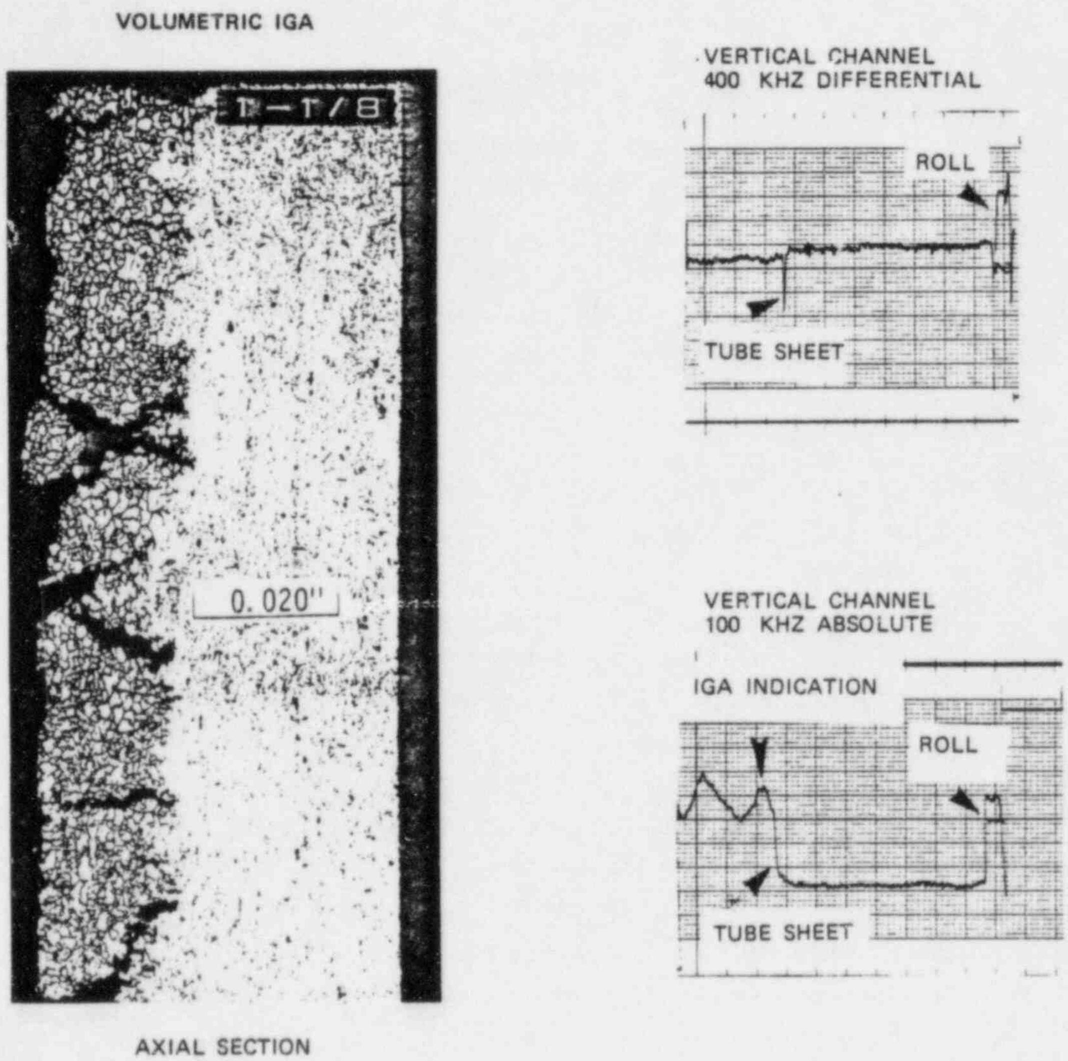


Figure 6-15. Importance of Absolute Coil

plant eddy current data acquired prior to tube removal. The conventional 400 KHz differential coil data set shows the tube sheet entry signal with no evidence of the IGA above the tube sheet. The absolute coil data set shows an indication which corresponds to the location of the IGA. Hence, in this case, the absolute coil mode is necessary for IGA detection.

Another example of the importance of the absolute coil is shown in Figure 6-16. Shown is a transverse cross section of a tube containing IGA penetrations 60%-80% through wall. The in-plant eddy current strip charts for the 400 KHz differential and the 100 KHz absolute are also shown. The differential data does not show any obvious indications whereas the absolute shows a general drift which has been shown to be characteristic of IGA within the tube sheet crevice region.

In summary, the acquisition and analysis of multifrequency, multiple coil mode (differential and absolute) eddy current data cannot be overemphasized for the effective monitoring of IGA and SCC.

We now discuss what is known about detecting and sizing SCC and IGA. The discussion is based on results from pulled steam generator tubes and laboratory studies.

Battelle-Northwest Laboratories has recently concluded a round-robin program in which ten stress corrosion crack samples were given to various groups for sizing (37). Four independent data sets were acquired based on differential bobbin coil ASME code procedures; two independent data sets were acquired using absolute pancake coil technology. The tubes were sectioned metallographically in order to determine the actual depth of the cracking for comparison with eddy current estimated depths. Maximum crack depth and an average crack depth based on the average of three axial sections through what was believed to the deepest part of the crack were established. Figure 6-17 shows a typical transverse cross section through a cracked tube. In general, multiple cracks existed within the tube as can be seen in the figure.

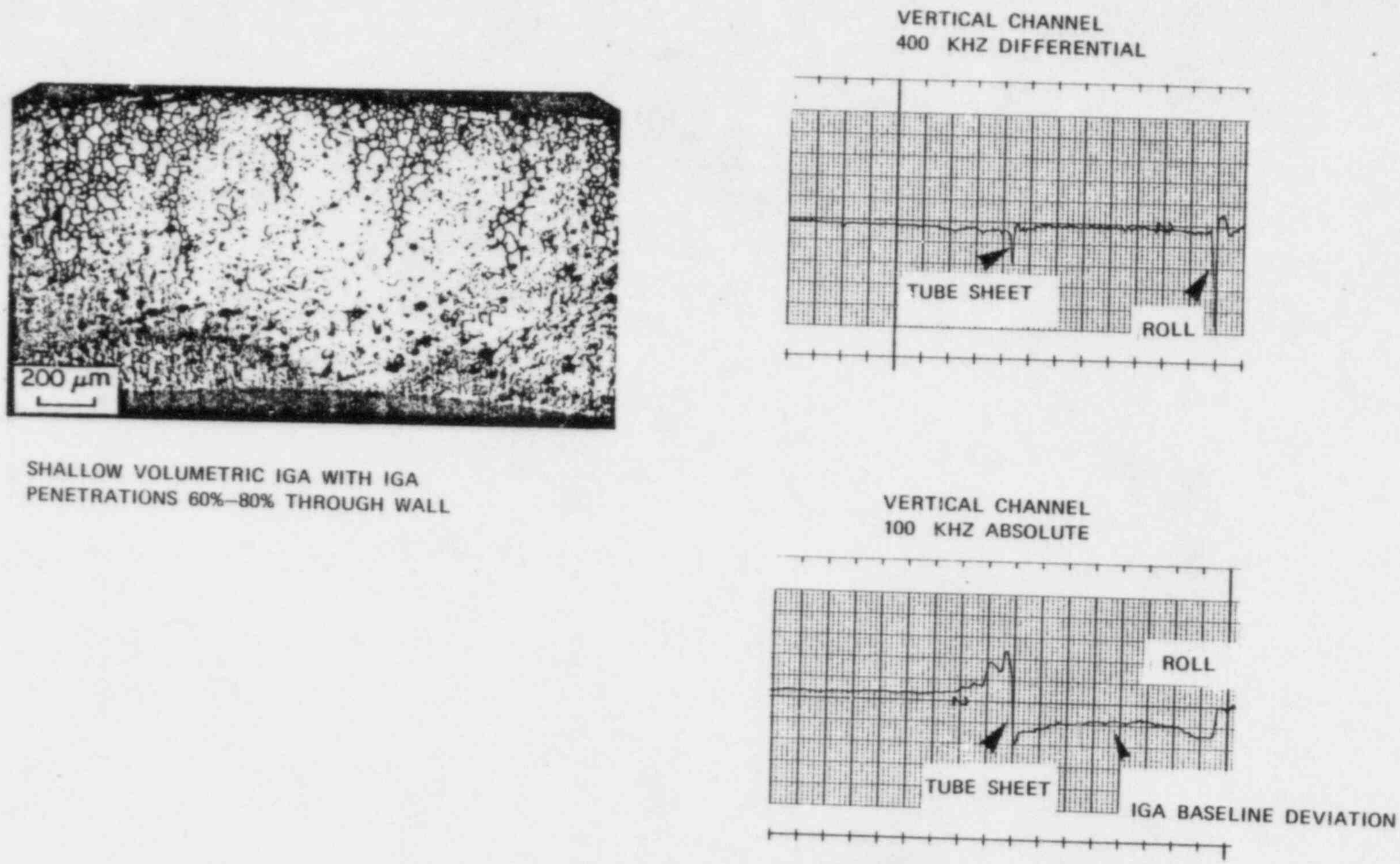


Figure 6-16. Bobbin Coil Averaging Effects

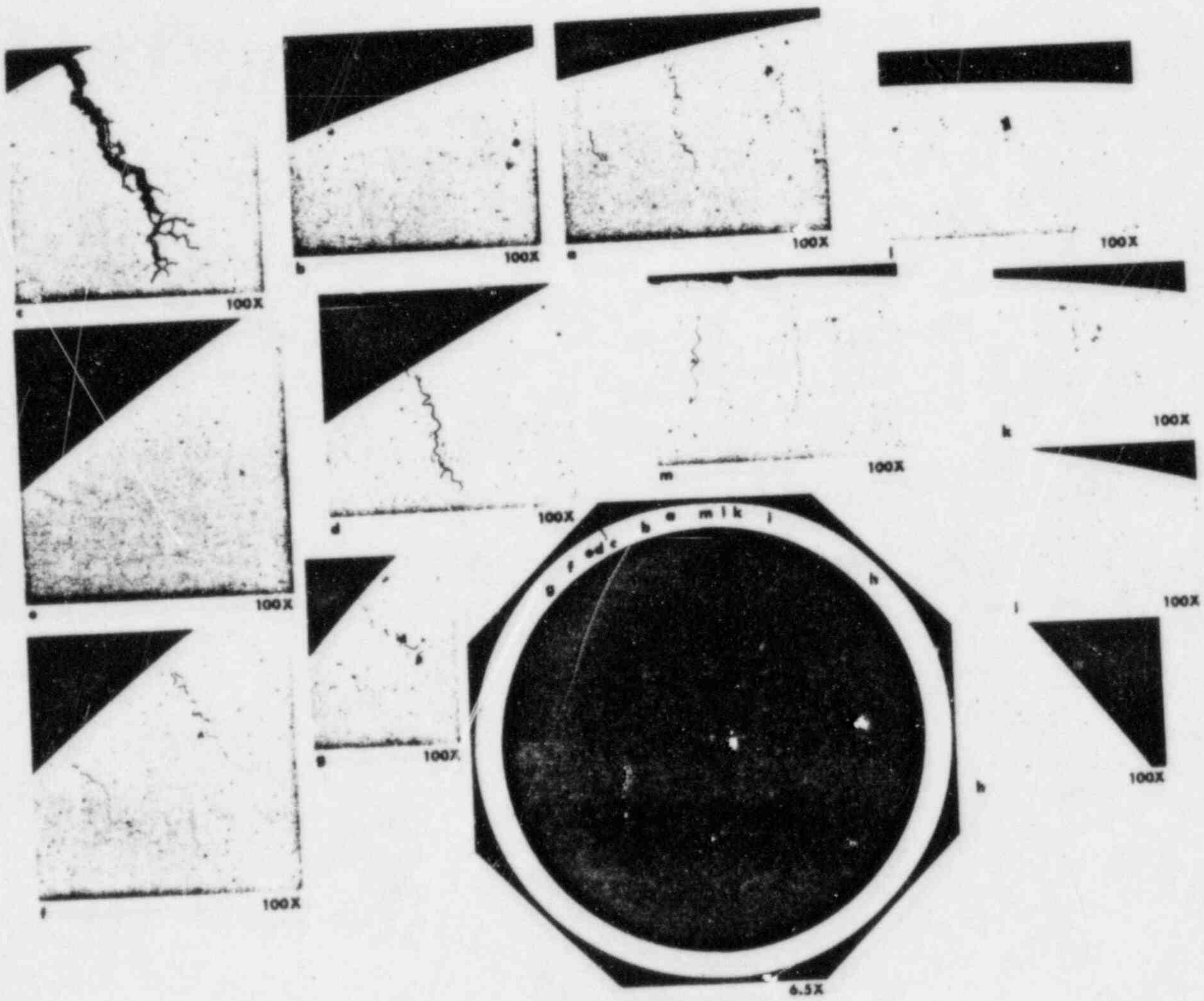


Figure 6-17. Multiple Stress Corrosion Cracking

The relationship between actual maximum crack depth and average crack depth is shown in Figure 6-18. As can be seen, there is a strong correlation between average and maximum depths for all the samples except for one specimen. With the exception of the one data point, the data is very systematic with the maximum depth 5%-7% greater than the average depth.

A scatter plot of eddy current estimated depths versus actual maximum crack depth is shown in Figure 6-19. Again, the data represents the results from five teams using procedures based on the ASME code. There is a tendency towards underestimation of crack depth with considerable scatter in the overall results. Of the data presented in the figure, 71% of the data points are within a ±20% error band which is a figure that has been used in the past for eddy current measurement error allowance.

The same crack specimens were also sized using an alternate technique based on acquiring eddy current data with a pancake coil and using an EDM notch to establish a calibration curve. All of the SCC specimens contained multiple cracks; the use of a pancake coil reduces averaging effects allowing for individual crack depths to be identified. Conventional bobbin coil technology averages over the full circumference of the tube. Results for the two teams that used pancake coils are shown in Figure 6-20. There is a much greater consistency in the depth estimates. Most of the data is within ±15% of the true depth.

In-plant NDE experience with intergranular attack is now considered. Overall, the experience is somewhat mixed or inconsistent. Figure 6-21 illustrates a tube removed from a recirculating steam generator which has IGA within the crevice region. Initial in-plant depth estimates for the IGA were 30%-40% through wall. As can be seen from the figure, localized IGA penetrations are present with a maximum depth of 80% through wall. The eddy current depth estimate was based on the signal amplitude derived from the absolute bobbin coil with the assumption that the IGA was volumetric in its extent. Eddy current data from tubes which had been pulled during previous outages were used as a source for calibration information. The underestimation of depth in this case is probably due to the averaging effects of the bobbin coil and the presence of the IGA penetrations. Differential

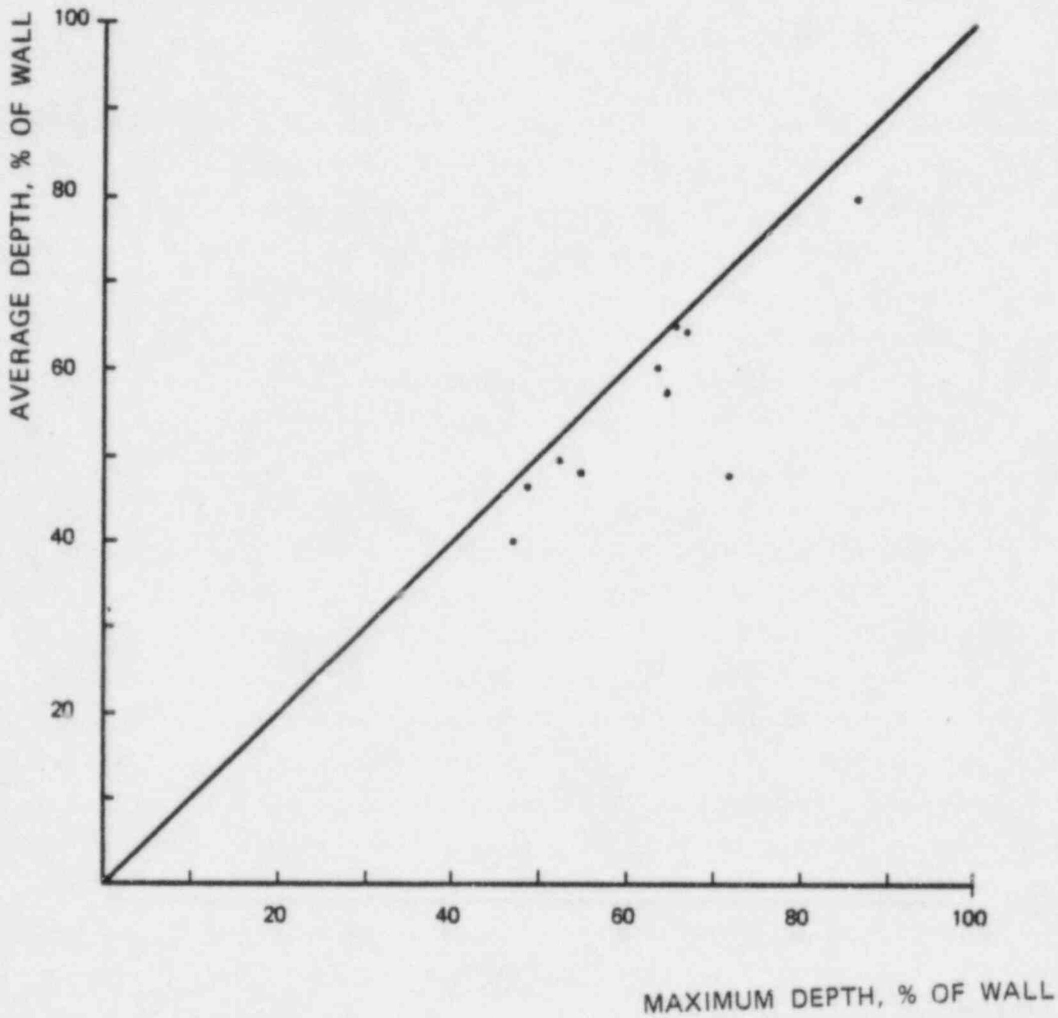


Figure 6-18. Scatter Plot of Average and Maximum Crack Depth

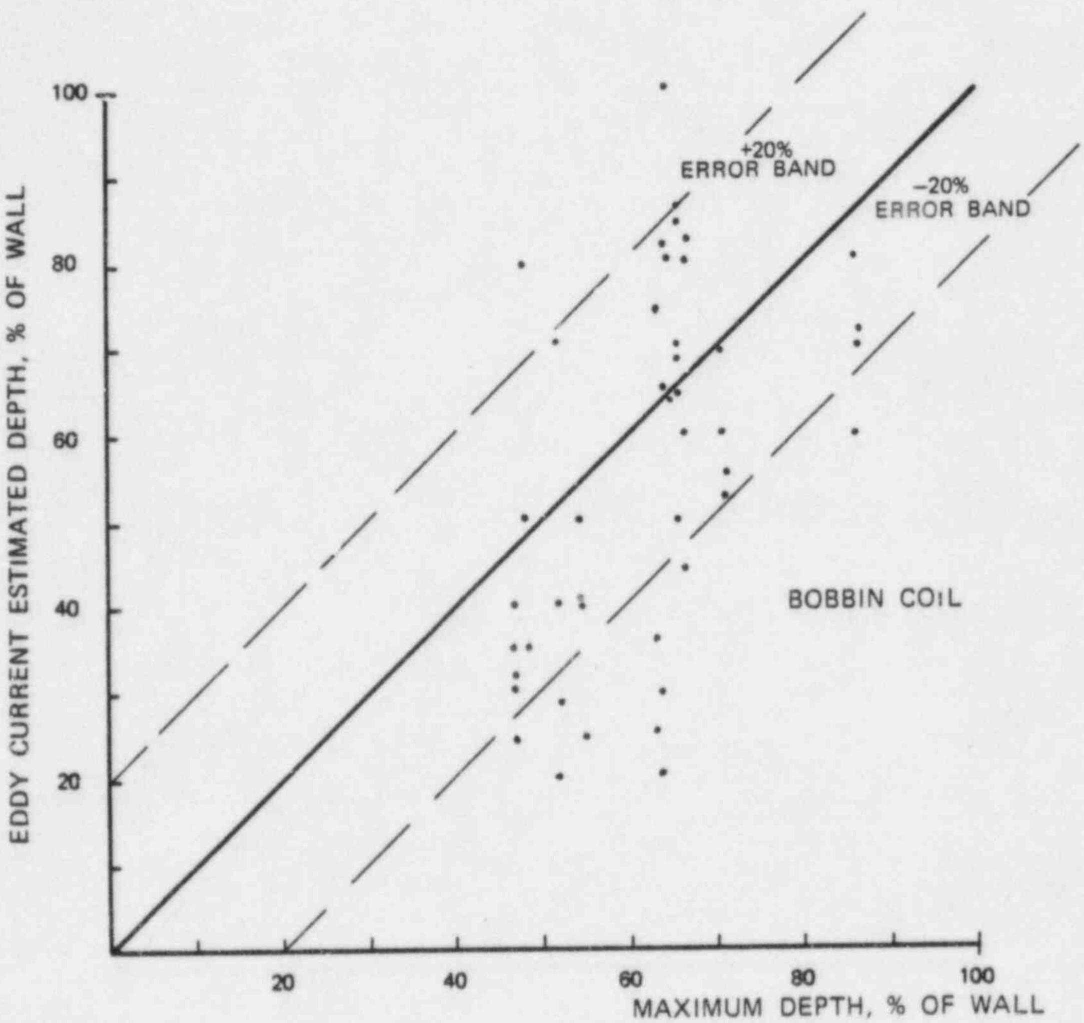
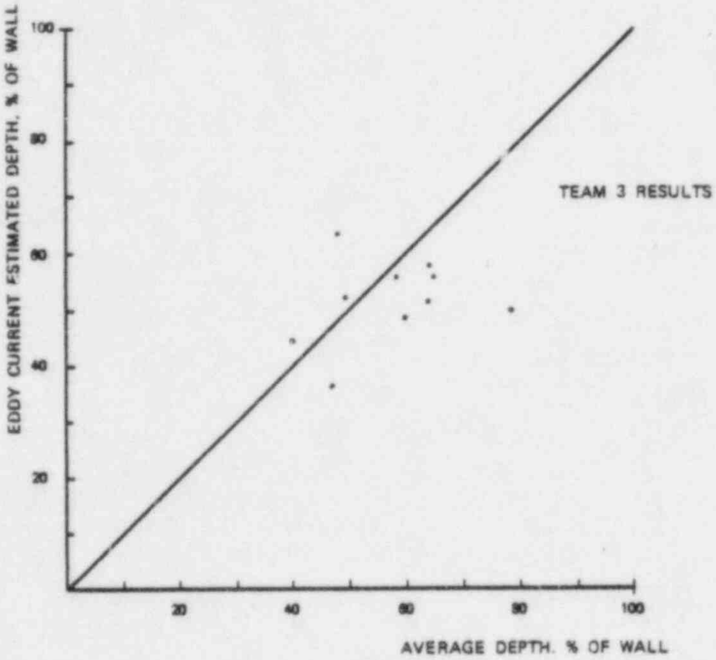


Figure 6-19. Scatter Plot of Bobbin Coil Estimated and Actual Crack Depths



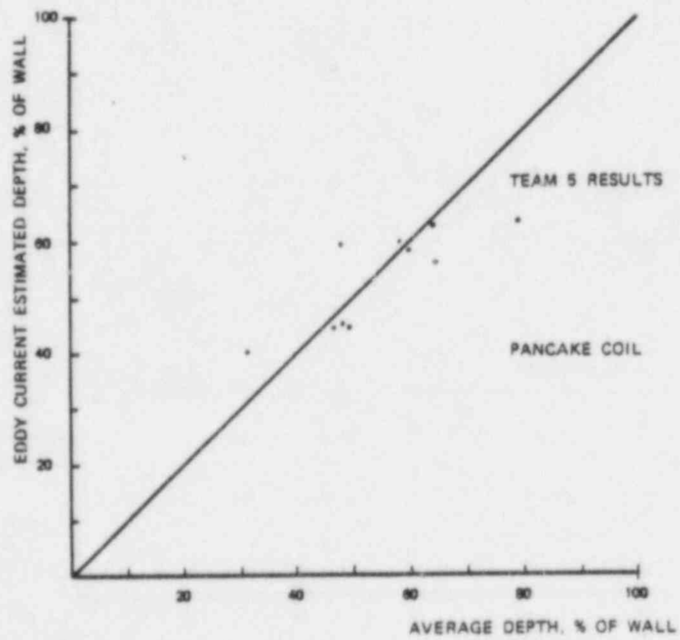


Figure 6-20. Scatter Plot of Pancake Coil Estimated and Actual Crack Depths

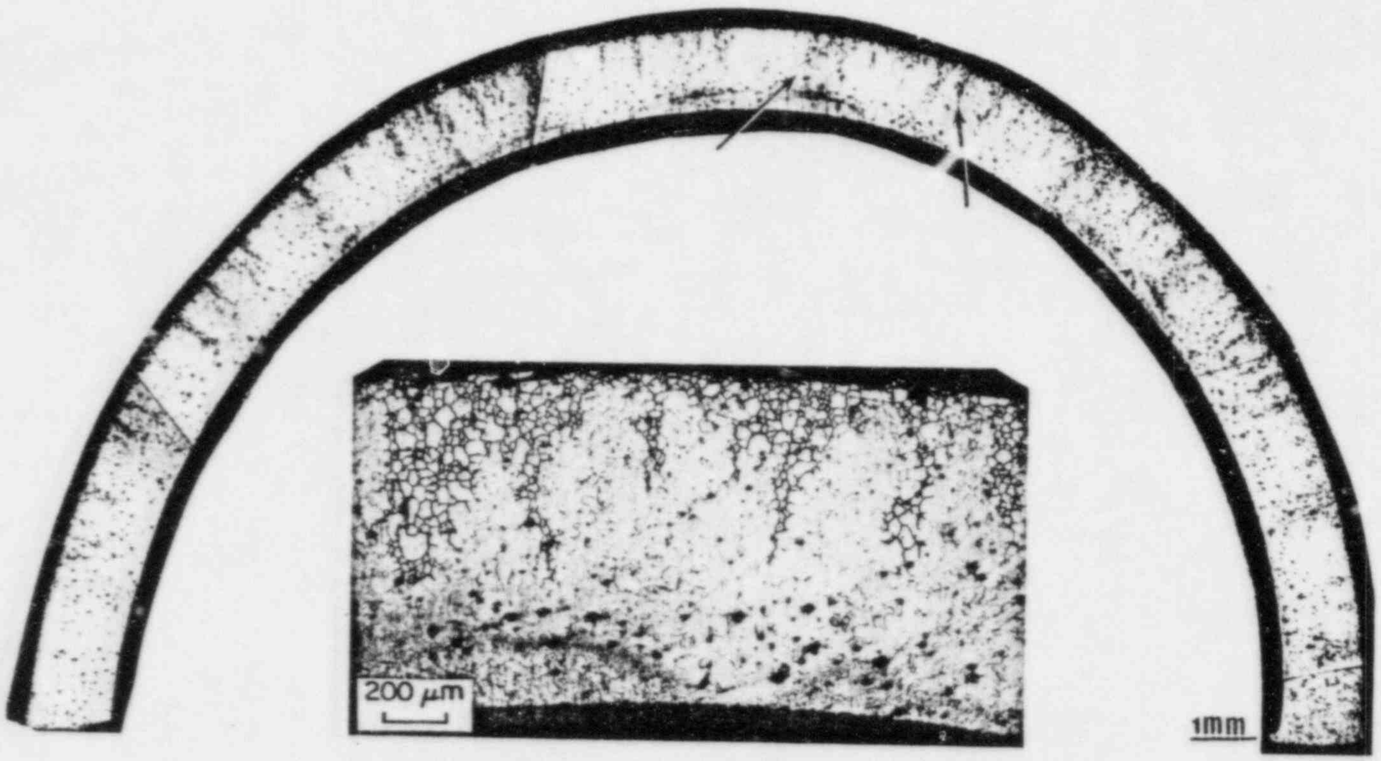


Figure 6-21. Intergranular Attack - Finger Penetrations - Poor Sizing

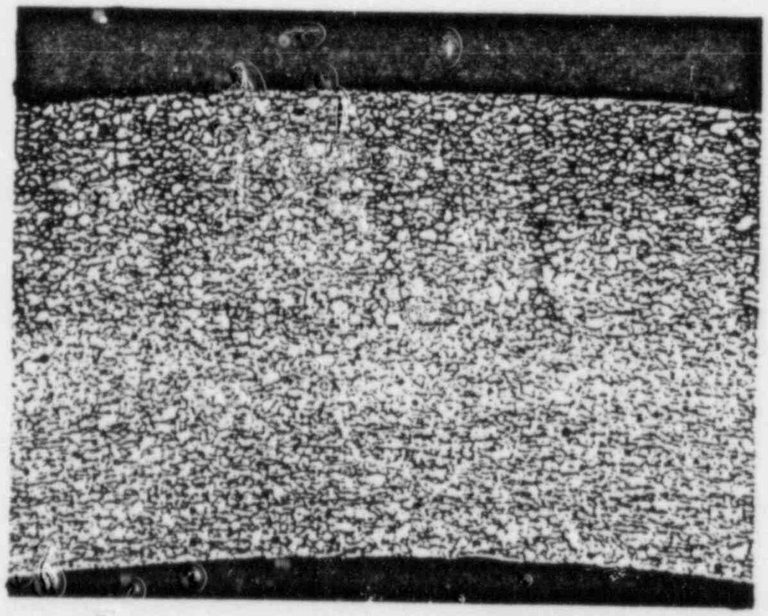
coil data for this particular tube did not show any indications.

Figure 6-22 shows a transverse section through a tube containing axial IGA penetrations. The maximum depth observed metallographically was 65% through wall. Eddy current bobbin coil depth estimate for this tube was 60% through wall which agrees quite well with the actual maximum depth.

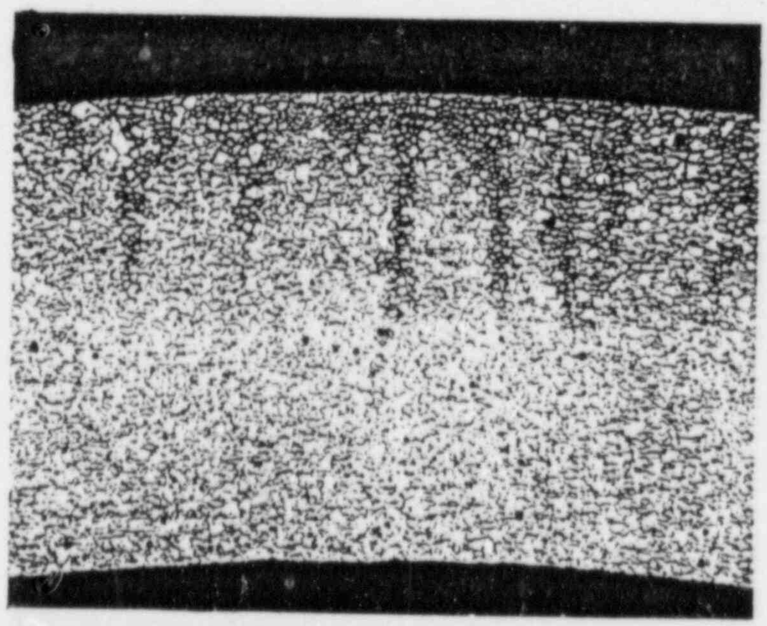
Figure 6-23 shows a section of tubing removed from an OTSG which has experienced IGA within the upper tube sheet crevice and in the vicinity of the 15th support plate. Several tubes were removed; a comparison of in-plant eddy current depth estimates with actual depths determined destructively are listed in the figure. The average error is approximately 26% through wall in the non-conservatibe direction. ASME code procedures using a differential bobbin coil were used to establish the in-plant depth estimates.

Well over one hundred tubes have been removed from numerous units in order to confirm the presence of IGA/SCC tube wall degradation and to assess eddy current inspection capability. A scatter plot of predicted eddy current and metallographically estimated depths is shown in Figure 6-24. As can be seen, there is considerable scatter in the data.

Improvements in detecting localized SCC/IGA penetrations can be realized using eddy current pancake coil technology. The eddy current distribution within a tube for a conventional bobbin coil is shown in Figure 6-25(a). The coil averages over the entire tube circumference and over an axial extent determined by the diameter of the bobbin coil, e.g., typically on the order of 0.720" for 7/8" diameter tubing. The influence of extraneous variables on the secondary side of the tube and the impact on signal-to-noise ratio are illustrated in Figure 6-25(b). Illustrated are absolute bobbin coil signals from a stress corrosion crack 50% through wall and the tube sheet entry signal at three different frequencies. The ratio of the crack signal to the tube sheet entry signal is much less than unity. As the coil excitation frequency is increased, the ratio increases slightly. The ratio of the crack signal to the tube sheet entry signal is a measure of the signal-to-noise ratic. The higner the ratio, the

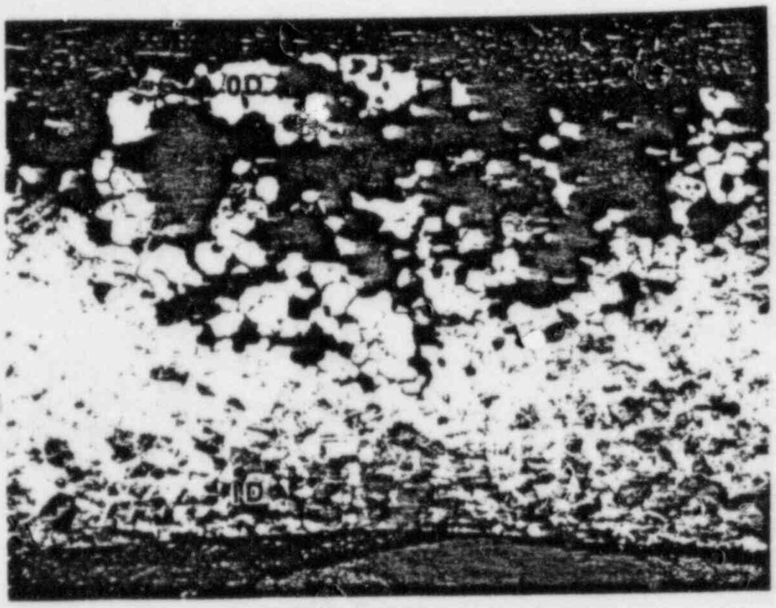


50X



50X

Figure 6-22. Intergranular Attack - Finger Penetrations - Good Sizing



VOLUMETRIC IGA

IN-PLANT EDDY CURRENT	METALOGRAPHY
84%	100%
60%	100%
36%	70%
84%	100%

AVERAGE ERROR
-26%

Figure 6-23. Intergranular Attack - OTSG

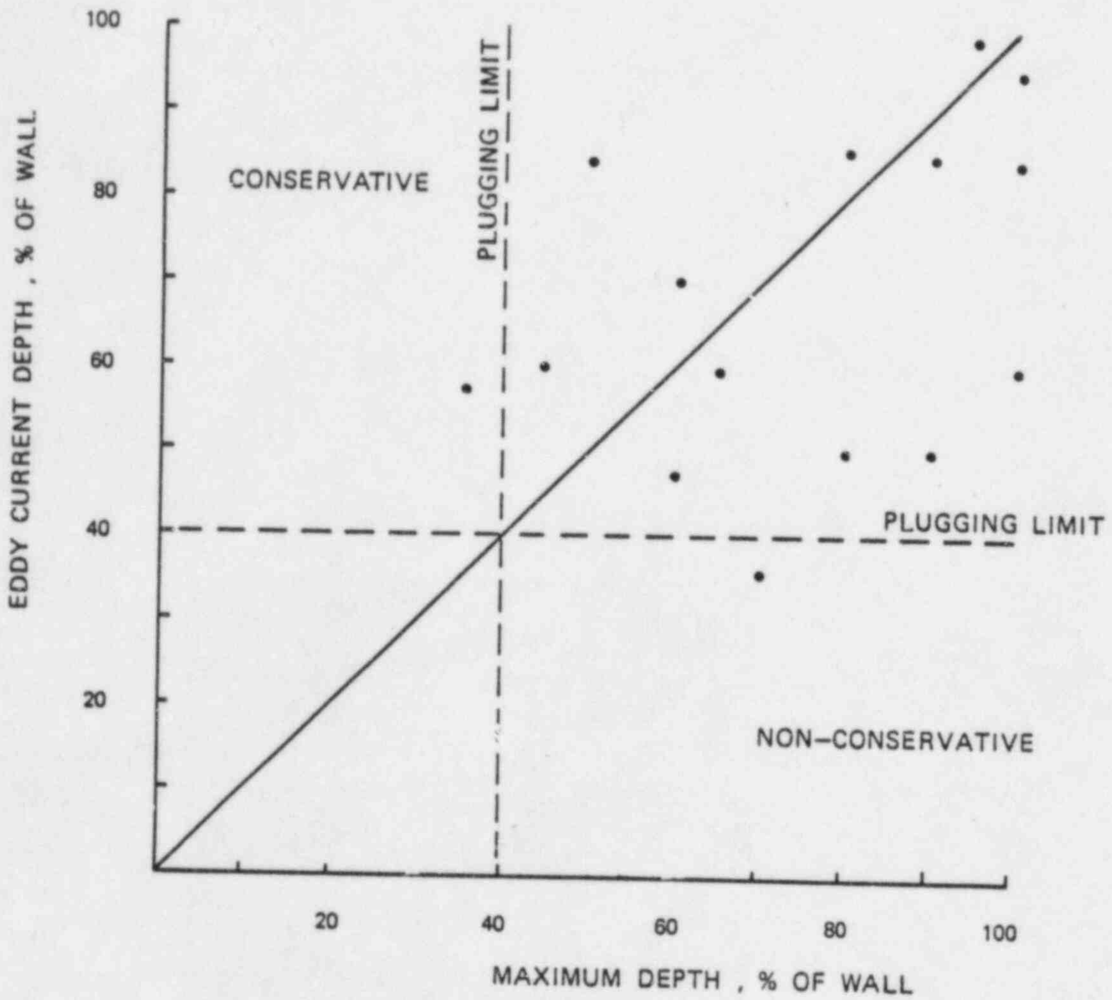
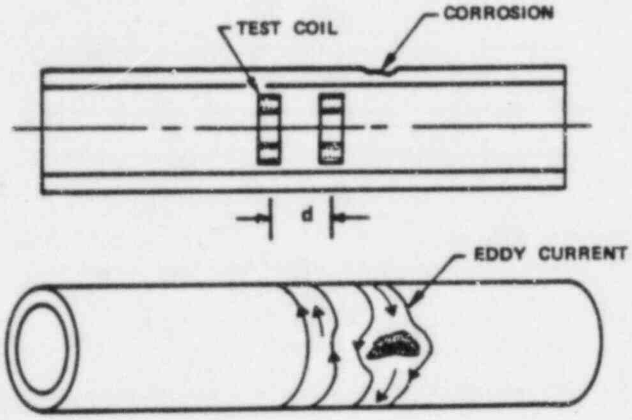
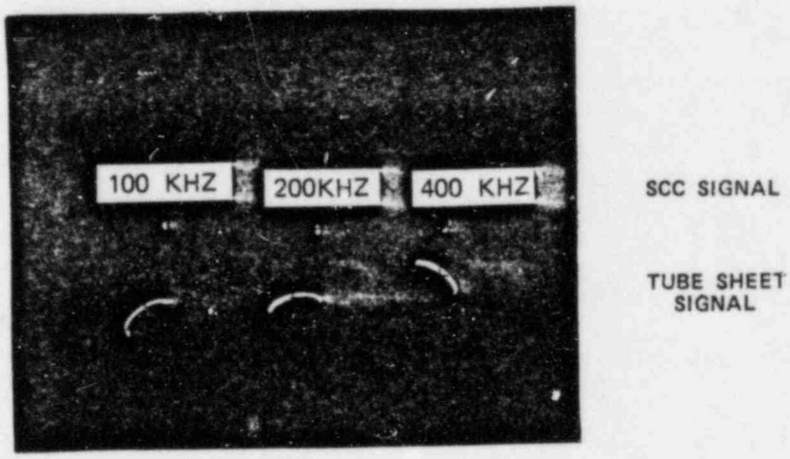


Figure 6-24. Intergranular Attack/Stress Corrosion Cracking - Scatter Plot of Predicted and Actual Depths



- AVERAGES OVER TOTAL TUBE CIRCUMFERENCE
- TENDS TO ENHANCE AXISYMMETRIC EXTRANEOUS VARIABLES (COPPER, TUBE SHEET)
- REDUCES S/N

(A)



(B)

Figure 6-25. Bobbin Coil Signal-to-Noise Ratio Averaging Effects

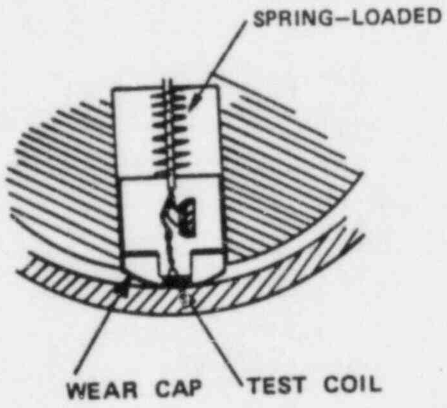
more likely the crack is expected to be detected.

Figure 6-26(a) shows the configuration of a pancake coil. The coil is typically spring-loaded to reduce the lift-off. Eddy current flow within the tube wall is such that the coil is responsive to both axial and circumferentially oriented discontinuities. The bobbin coil responds primarily to volumetric or axially oriented discontinuities with a lesser response to circumferentially oriented discontinuities. Use of a pancake coil for inspection is thus less dependent on assumptions about the expected direction of discontinuities within the tube wall. The coil typically has a diameter of 0.1"-0.2" and must be scanned to achieve complete inspection of the tube wall.

A pancake coil in general provides an improved signal-to-noise ratio in detecting discontinuities within the tube wall. This is illustrated with data shown in Figure 6-26(b). Shown are pancake probe eddy current signals from the same stress corrosion crack and tube sheet entry used in Figure 6-25(b). Data at three frequencies is shown. As the eddy current test frequency is increased, the ratio of the crack signal to the tube sheet entry signal increases significantly. At 400 KHz, the ratio is greater than one and is much greater than the case for the bobbin coil. Again, an increase in signal-to-noise ratio will improve the reliability of the inspection process.

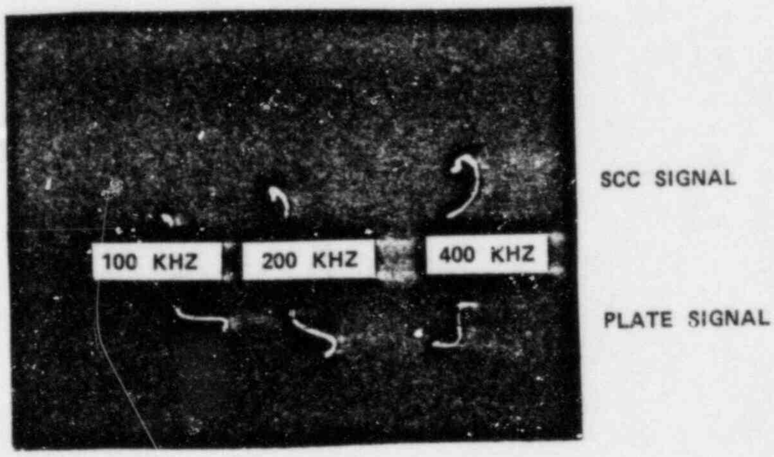
Pancake coil inspection of tubing is somewhat inefficient in terms of inspection time. Array coils represent a concept in which the sensitivity of a pancake coil is retained while maintaining an inspection speed comparable to the conventional bobbin coil. Eight pancake probes operating in parallel form the elements of the array. The array is typically operated with the Zetec MIZ-18 instrumentation or a dual MIZ-12 setup.

Each coil has a limited field of view; the coils are staggered circumferentially in order to obtain complete coverage of the tube wall. Complete coverage of the tube can be measured by translating the array through an axial EDM notch; between each scan, the notch is rotated. During each scan the amplitude of the signal obtained from



- AVERAGES OVER COIL DIAMETER
- PROVIDES IMPROVED S/N

(A)



(B)

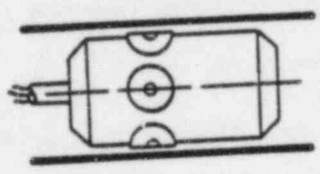
Figure 6-26. Pancake Coil Signal-to-Noise Ratio Improvements

the notch is measured. A plot of signal amplitude versus rotation is then made. A typical plot of amplitude versus angular rotation is shown in Figure 6-27. The basic pancake probe response is repeated eight times since eight coils are used in the array in order to achieve coverage over the tube circumference.

Figure 6-27 illustrates several important points in using array coils. The response pattern of a given pancake coil within the array is non-uniform. Complete coverage of the tube wall is achieved by staggering the coils such that the individual coil responses overlap. There is a gap in the array coil coverage between coil 3 and coil 4 due to misalignment of coil 3. Hence, the complete tube circumference would not be examined with this particular array coil. All array coils should be profiled prior to their use during a tube examination to confirm adequate tube wall coverage.

An example of the improvement in signal-to-noise that can be obtained using an array coil is shown in Figure 6-28. Illustrated are bobbin and array coil eddy current data for the same tube from a plant known to have IGA within the tube sheet crevice region. Absolute bobbin coil data (100 KHz) is shown in the top of the figure. Signals from the 1st support plate, thinning above the tube sheet and the roll transition are identified. In addition, a signal attributed to IGA within the tube sheet crevice is shown. Of interest is the ratio of the amplitude of this signal to the signal from the support plate. The support plate signal represents a secondary side extraneous variable. The ratio is such less than unity.

Array coil data from one channel for the same tube is shown in the lower part of the figure. Again we see signals from the 1st support plate, thinning above the tube sheet, the tube sheet entry signal and a small signal from the roll transition. The roll transition signal from the array coil is reduced as compared with the same signal from the bobbin coil because the array coil rides the tube inner surface which suppresses the transition mechanically. Notice the signal attributed to IGA within the crevice region and its ratio with the 1st support plate signal. This ratio is much greater than unity demonstrating an improved signal-to-noise from the array coil.



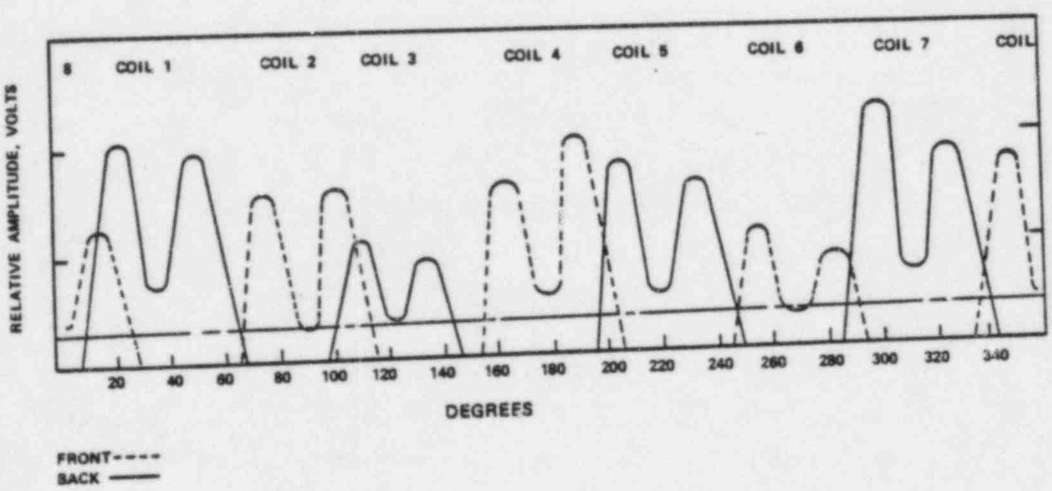


Figure 6-27. Array Coil Tube Wall Coverage

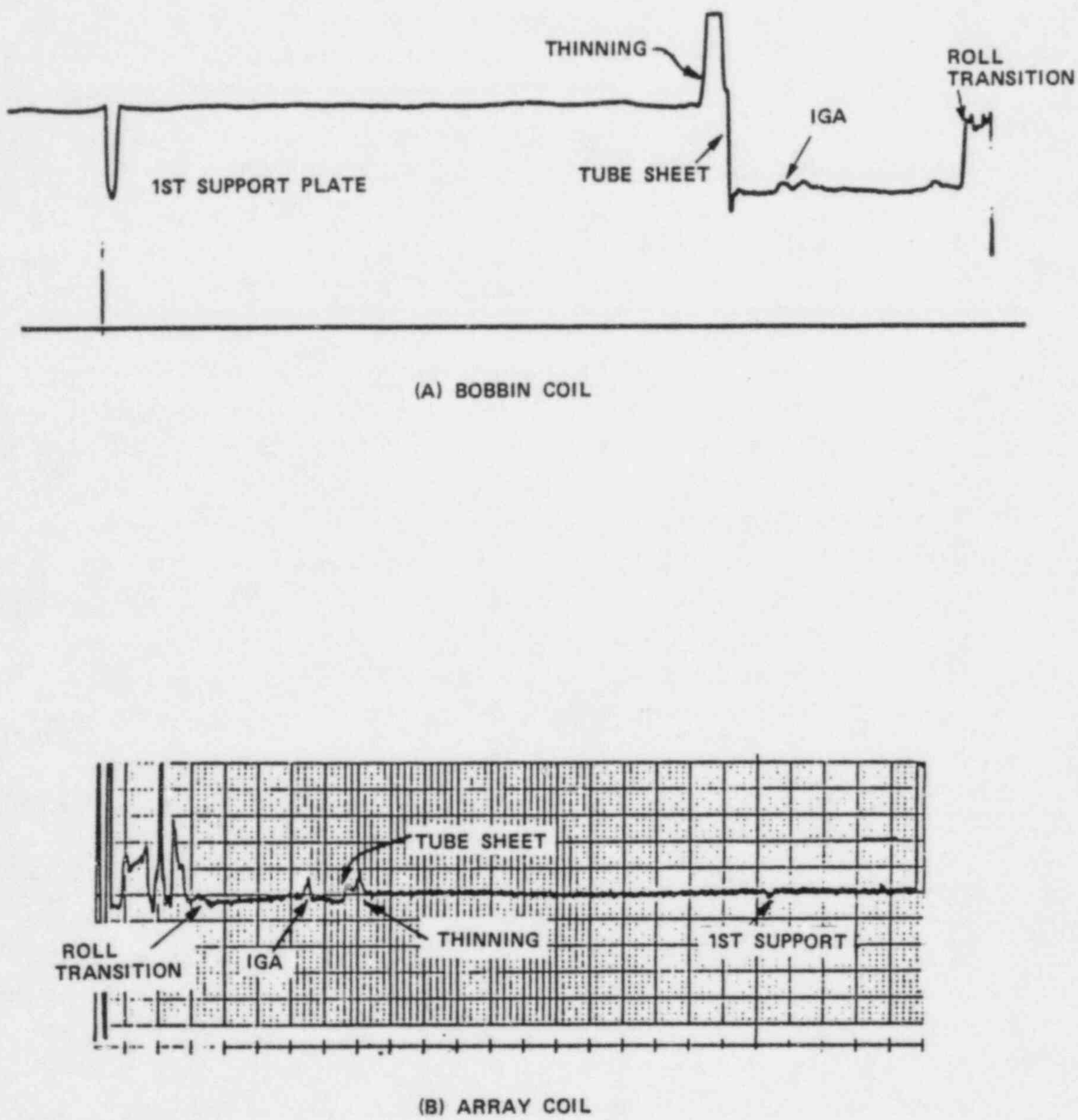
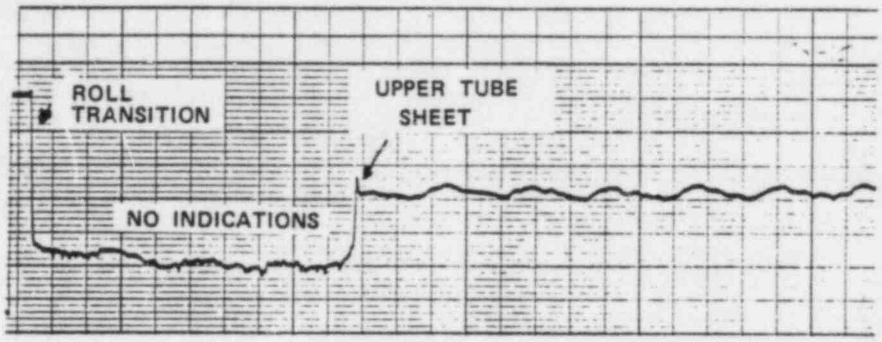


Figure 6-28. Array Coil Signal-to-Noise Improvement

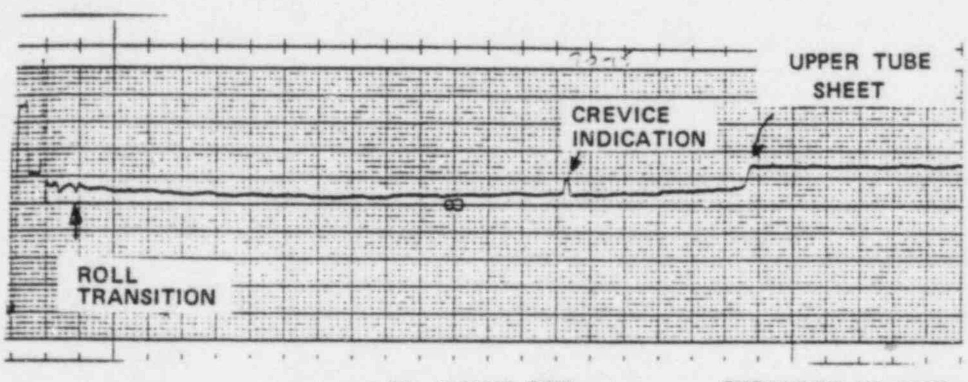
Improvements in signal-to-noise obtained with the array coil would allow for the more reliable detection of a condition within the tube wall. This is illustrated with data shown in Figure 6-29. Again we show data from a common tube for both a bobbin and array coil. Review of the bobbin coil data shows a general noise-like signature; no obvious signal indicative of tube wall loss is apparent. The array coil data has a much quieter baseline and clearly shows a signal indicative of tube wall loss.

Another application of array coil technology is recognizing the existence of finger-like IGA or SCC penetrations. These kind of conditions within the tube wall can lead to complete tube wall penetration and a possible leaker outage. Figure 6-30 illustrates a tube which has both volumetric IGA and IGA penetrations. Bobbin coil eddy current data from a tube with this condition would show a composite signal given by the summation of responses to both the volumetric and localized IGA fingers because the bobbin coil averages over the full circumference of the tube wall. With an array coil, localized penetrations can be recognized. Figure 6-30 shows the output of three channels of an array coil. The region of interest is the tube sheet crevice which is bounded by the tube sheet entry signal and the roll transition signal. Channel 5 shows a quiescent baseline suggesting no detectable degradation within the coil 5 field of view. Channel 2 shows a signal which exhibits a gradual rise and fall as the probe traverses the tube sheet crevice, indicative of a volumetric tube wall loss condition. Channel 1 shows a gradual signal similar to channel 2 with an additional superimposed fast rise time signal. This latter signal suggests the presence of a localized discontinuity within the tube wall. The particular plant where this data was acquired has a history of IGA within the tube sheet crevice region. The signal structure shown in Figure 6-30 can be interpreted as due to volumetric IGA within the tube sheet crevice with axial IGA penetrations. Since there are uncertainties in estimating the depth of the IGA penetrations and the IGA growth rate, a decision to sleeve or remove the tube from service could be made based of the presence of the "finger-like" signals.

The problem of sizing volumetric IGA is now considered. Figure 6-31 shows a section of steam generator tubing in which volumetric IGA



(A) BOBBIN COIL



(B) ARRAY COIL

EXPANDED IN TIME AS COMPARED WITH (A)

Figure 6-29. Improved Detectability with Array Coil

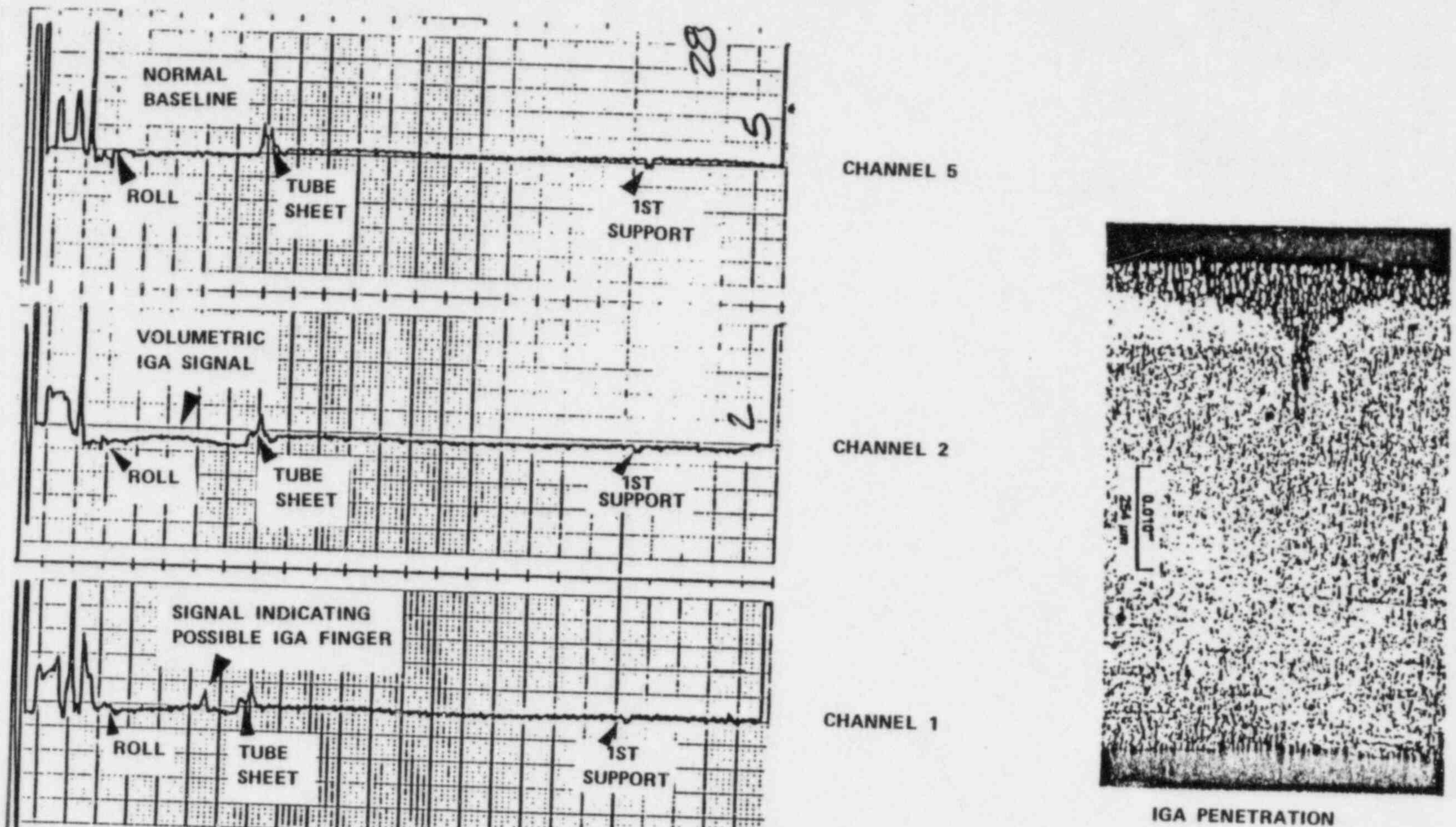
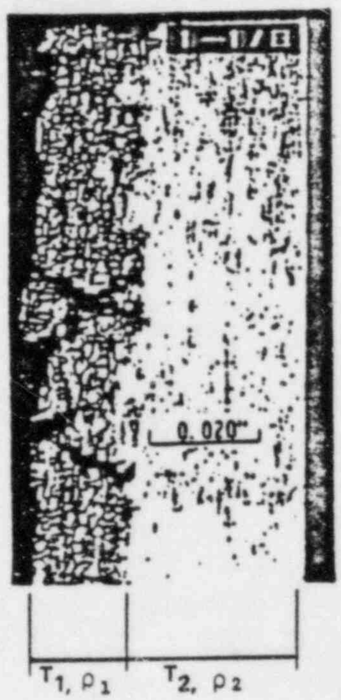


Figure 6-30. Array Coil Characterization of Crevice Indications



$T_1 + T_2$ = WALL THICKNESS

$R = \rho_1 / \rho_2$

T = THICKNESS

ρ = CONDUCTIVITY

Figure 6-31. Volumetric Intergranular Attack

extends to a depth of approximately 40% through wall. Normally, with IGA, there is no change in tube wall thickness. Rather, the region within the tube undergoes grain boundary dissolution which in turn modifies it's conductivity. The IGA layer has a thickness t1 and conductivity sigma 1 while the remaining Inconel thickness is t2 with conductivity sigma 2. With the exception of the extreme in which grain boundary dropout occurs, the total wall thickness T remains constant with T = (t1 + t2). The ratio of the conductivity of the IGA layer to the nominal Inconel value is R = sigma 1/sigma 2.

A tube which has undergone severe IGA is shown in Figure 6-32. Extensive grain boundary dissolution has occurred; the individual metal grains have separated and a condition known as grain boundary dropout has resulted. IGA to this extent can be viewed as a form of wall thinning. In terms of our model discussed in the previous paragraph, the thickness of the IGA layer is t1, with a conductivity equal to that of air (sigma 1=0) which makes the ratio R equal to zero.

During the early stages of IGA, the conductivity of the effected layer will be close to the nominal Inconel value. Hence, the R value will be close to unity. As the attack progresses, the R value will assume a continuum of values between one and zero. The significant item affecting IGA detectability will be the ratio of the two values of conductivity. Variations in conductivity within the IGA layer coupled with an unknown thickness make the measurement of thickness non-unique if a single feature of the eddy current signal e.g., amplitude or phase, is correlated with depth.

The fabrication of IGA specimens with controlled variations in thickness and conductivity has not been accomplished as yet. Two dimensional finite element computer codes have been used to compute eddy current signals for various test conditions of interest. Figure 6-33 shows computed absolute bobbin coil eddy current signals for 40% IGA in which the R value was varied between 1.09 and zero. The latter case corresponds to the case of grain boundary drop out and is also equivalent to wall thinning. The R value equal to 1.09 represents the case in which the conductivity of the IGA layer differs from the nominal Inconel value by 9%. As can be seen, a significant variation in signal amplitude occurs. Signal phase angle variations also occur but are not apparent in the figure.

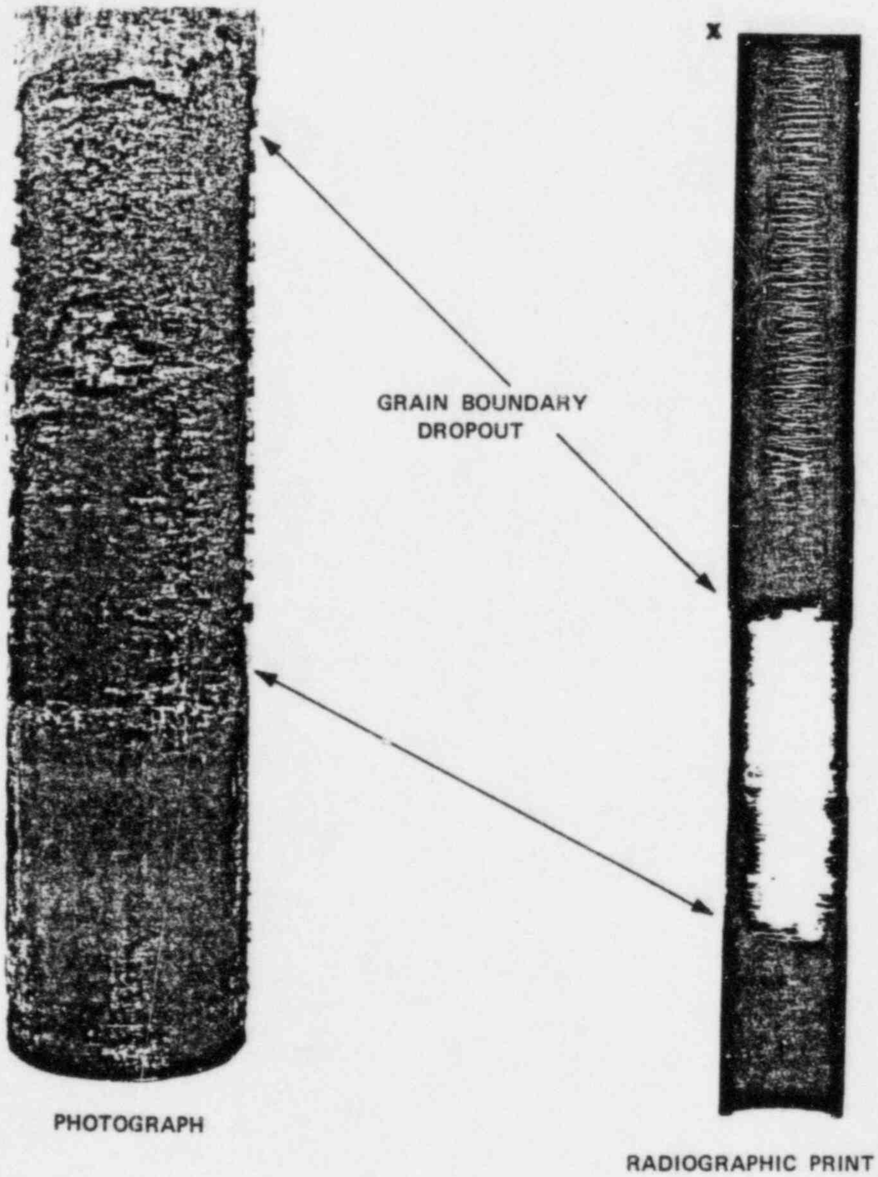


Figure 6-32. Volumetric Intergranular Attack - Grain Boundary Drop Out

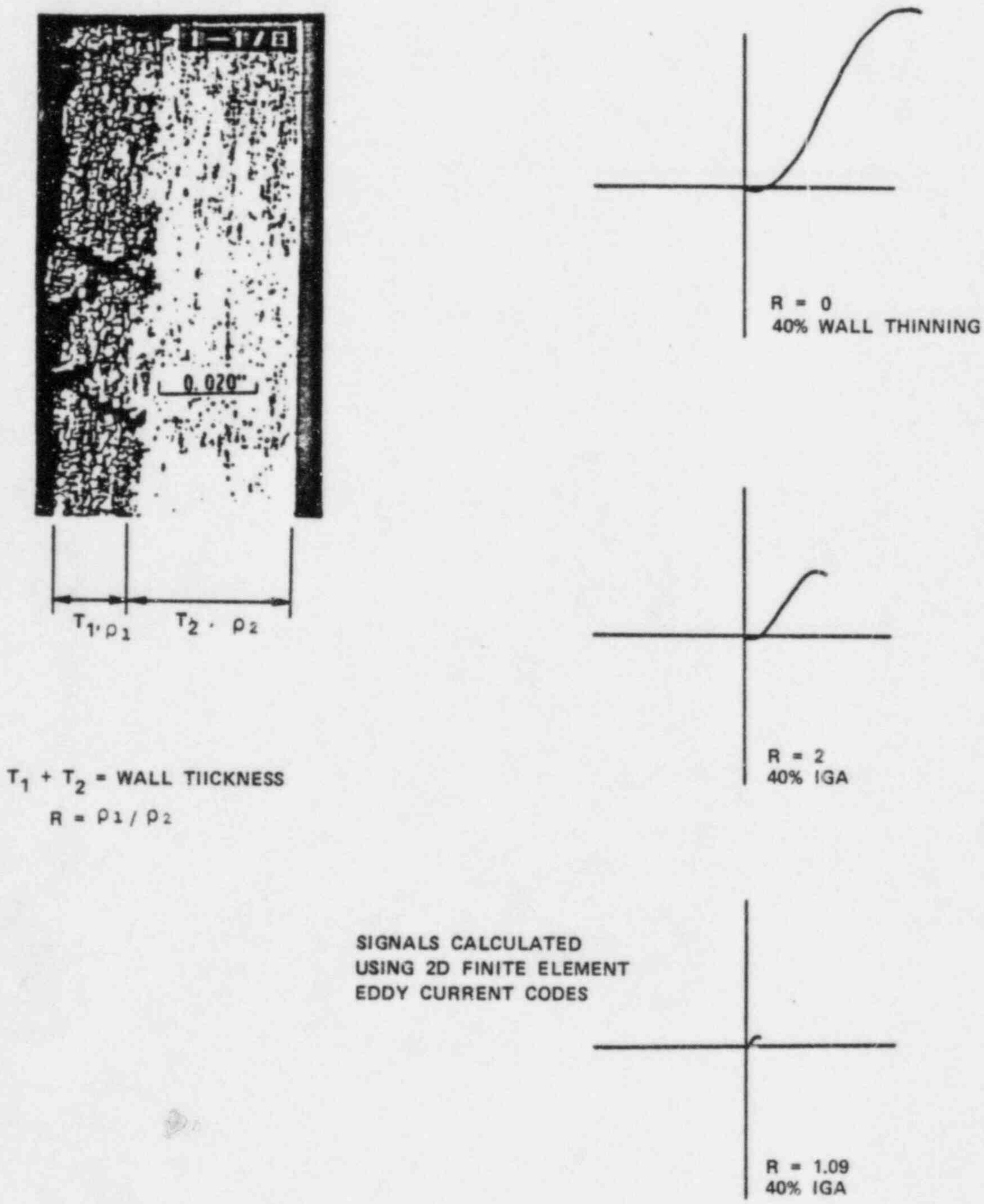


Figure 6-33. Effect of Intergranular Attack Conductivity Variations on Eddy Current Signal

Figure 6-34 shows a plot of eddy current signal magnitude and phase for three depths of wall thinning and IGA. For a given thickness of IGA, the value of its conductivity has been allowed to vary over some range. As the ratio of the two conductivities approach unity, the IGA signal magnitudes and phase angles approach the values assumed by wall thinning. The signal magnitudes and phase angle together for IGA describe a unique locus of points in the magnitude-phase angle plane allowing for the unique measurement of thickness. The use of either magnitude or phase to determine IGA depth results in nonconservative estimates if a wall thinning curve is used as a basis for calibration. The underestimation can be significant depending on the ratio of conductivities of the IGA and the nominal Inconel value.

Figure 6-35 shows experimental eddy current data acquired from volumetric IGA specimens and a wall thinning standard. IGA depths were estimated by sectioning the end of the tube for a particular specimen. Signal amplitude and phase angle is plotted for three different depths of wall thinning and IGA. The IGA depths have been extrapolated back to their equivalent wall thinning depths. The experimental data in Figure 6-35 is in good agreement with the two dimensional finite element code predictions shown in Figure 6-34. The magnitude and phase angle values for a given depth of IGA are less than the equivalent wall thinning depth. Thus a wall thinning standard provides a nonconservative estimate of depth. The estimation of IGA depth using either amplitude or phase angle can be in error by a factor of two which is comparable to in-plant experience.

The results of Figure 6-35 also show that it is possible to distinguish between wall thinning and volumetric IGA. The locus of points assumed by different thicknesses of IGA lie below the wall thinning calibration curve allowing for its recognition. The data shown in the figure was acquired using conventional eddy current instrumentation and a pancake probe. The use of a pancake probe is essential in order to minimize the coil averaging area.

In practice, the generation of a calibration curve would proceed as follows. The locus of points assumed by a fixed thickness of IGA assumes a straight line in the amplitude-phase angle plane when the

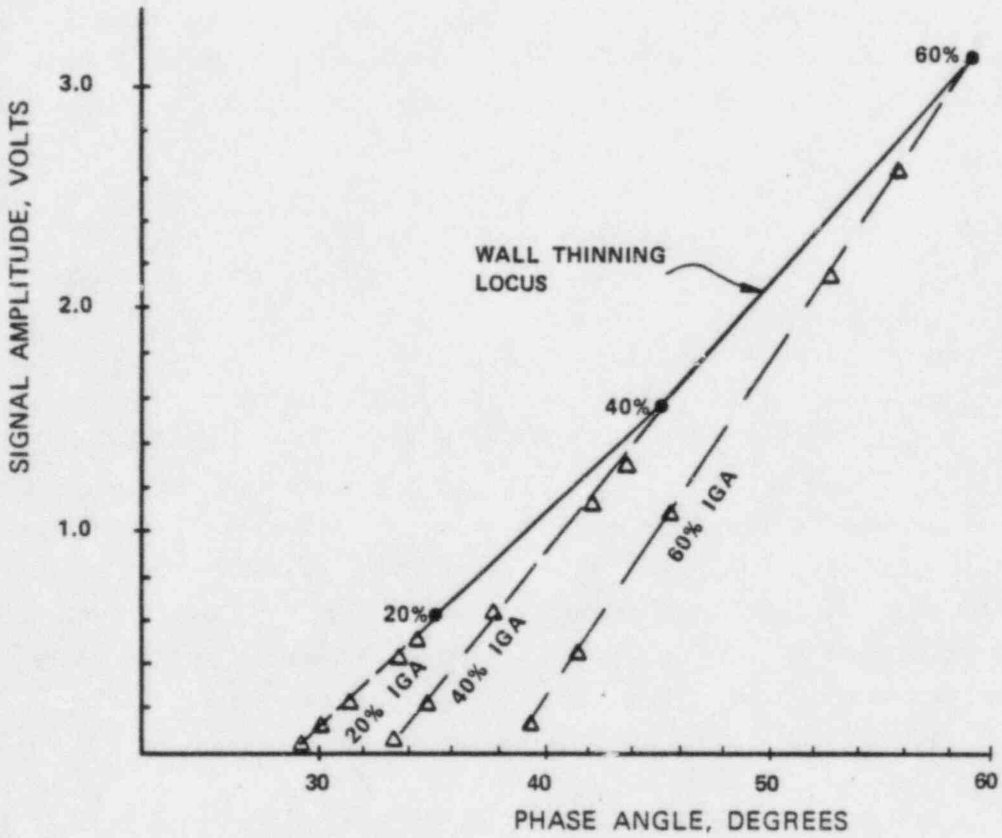


Figure 6-34. Eddy Current Signal Magnitude - Phase Angle Variation for Wall Thinning and Intergranular Attack (Computer Prediction)

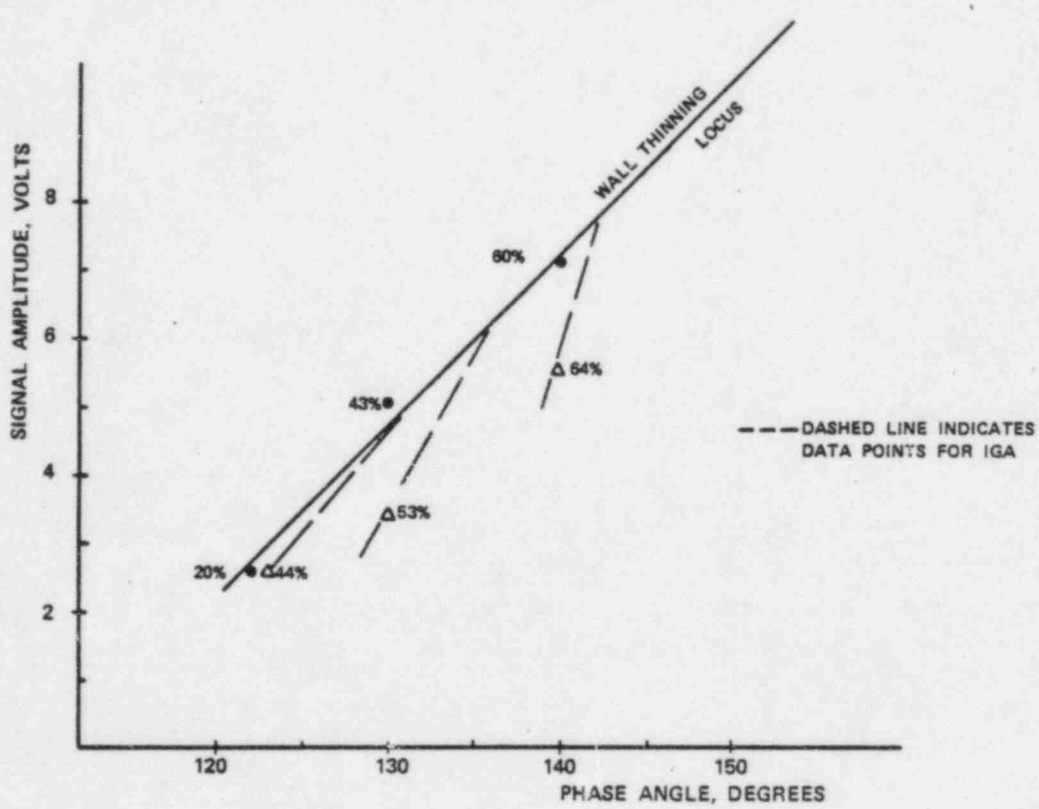


Figure 6-35. Eddy Current Signal Magnitude - Phase Angle Variation for Wall Thinning and Intergranular Attack (Experimental)

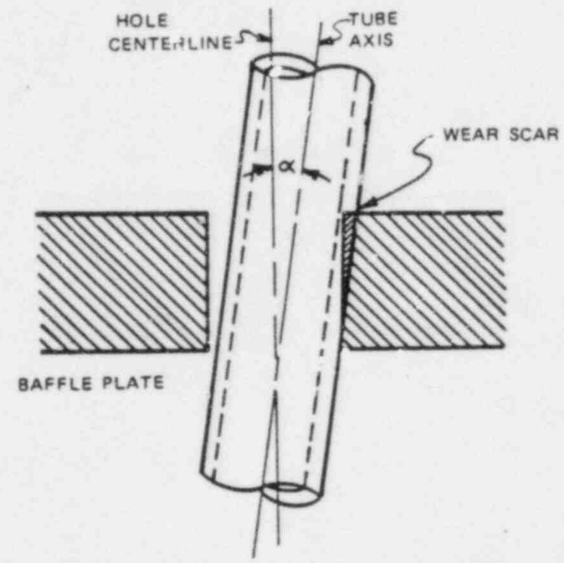
conductivity of the IGA is varied. Calibrations standards of known thicknesses of IGA and wall thinning are fabricated. Signal magnitude and phase angle data is acquired from the wall thinning standard and a calibration curve is constructed. Similar data is acquired from the IGA standards. If the IGA standard measured depths are not equal to the wall thinning depths, the equivalent wall thinning depth is interpolated on the wall thinning calibration curve. Eddy current signal amplitude and phase angle data is acquired from one of the IGA specimens; this point is entered at the appropriate position in the signal amplitude-phase angle plane. A line is drawn through the two points determined by the IGA datum point and its equivalent wall thinning point on the wall thinning calibration standard. For a fixed thickness of IGA, variations in IGA conductivity will occur along this constant thickness line. Hence, only two points are necessary to determine this line, i.e., the wall thinning data point and one IGA data point. This procedure is repeated for different thicknesses of IGA until the desired calibration curves are obtained.

6.3.5 Fretting

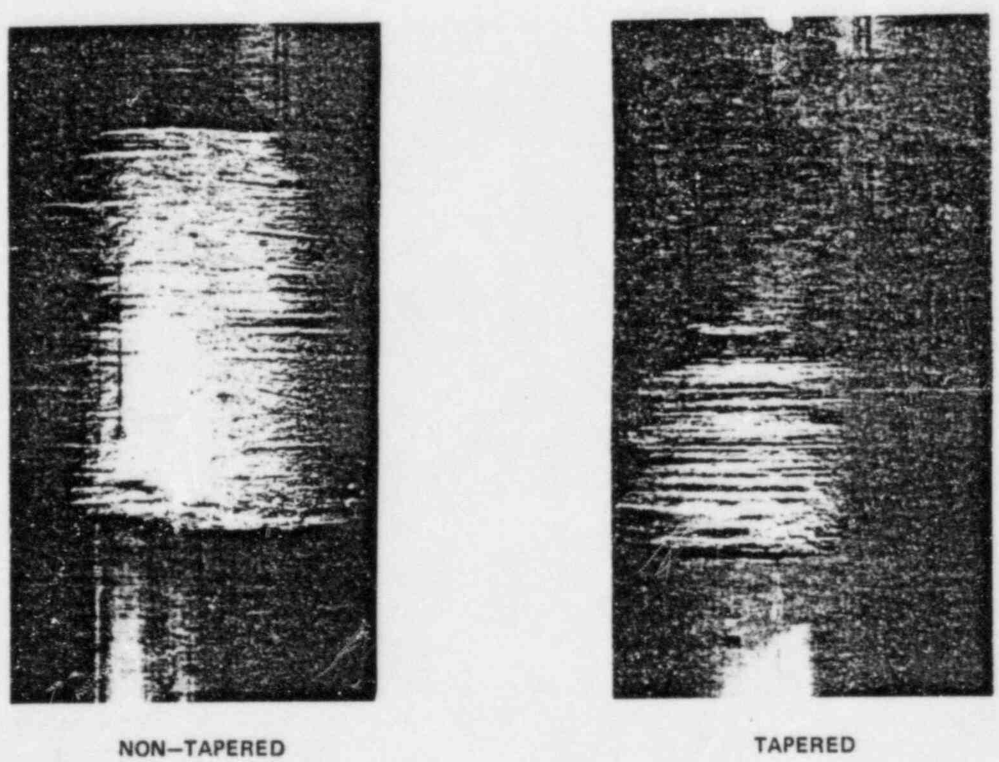
Experience with eddy current inspection for fretting in preheaters at baffle plates is documented in (38). Some eleven tubes have been removed from the Almaraz 1 and Ringhals 3 steam generators to characterize the fretting or wear scar geometry and to develop and qualify improved sizing techniques.

The tube within a baffle plate is typically inclined at some angle, alpha, which varies between zero and two degrees. This variation in inclination angle results in two general classes of wear scar geometries, i.e., flat and tapered, which are illustrated in Figure 6-36.

Initial sizing using signal amplitude derived from a flat wear scar standard resulted in statistically nonconservative depth estimates. Most of the bias has been removed using a tapered wear scar standard. The relationship between wear scar depth and removed metal volume is shown in Figure 6-37 for various inclination angles. Since eddy current signal amplitude is proportional to removed metal volume, the curves relate wear scar depth to signal amplitude.



(a) Tube inclined within baffle plate



(b) Wear scar geometries

Figure 6-36. Preheater Tube Fretting

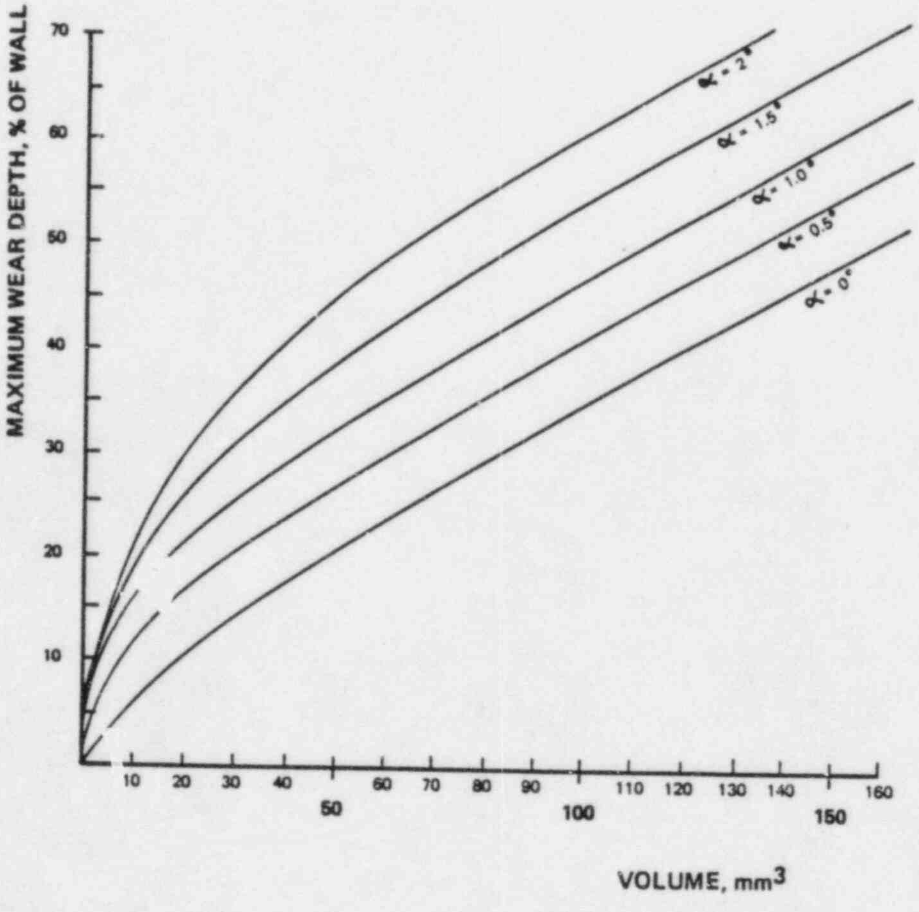


Figure 6-37. Relationship Between Wear Depth and Wear Volume For Various Tube Inclination Angles

Figure 6-37 shows that a calibration curve based on a tapered standard conservatively bounds flat or non-tapered wear scars. A two degree inclination angle has been selected based on experiments with removed tubes. A scatter plot showing eddy current estimated depth with actual wear scar depth on tubes removed from Ringhals 3 steam generators is shown in Figure 6-38. A least squares fit of the data is conservative with a scatter of plus and minus five percent.

Eddy current data acquisition is accomplished using an absolute bobbin coil with a (100x300) KHz mix for baffle plate suppression. In practice two approaches are used for sizing. At Almaraz 1, a tapered scar standard with a two degree inclination angle is used directly to generate a calibration curve relating signal amplitude to depth. At Ringhals 3 a transformed flat wear scar curve is used which is now explained in more detail.

Although the tapered scar standard results in more conservative depth estimates, it is difficult to fabricate. In addition, a large eddy current data base already exists derived from the flat wear scar standard. For these reasons, Swedish State Power Board staff have derived a sizing approach based on a transformation of the flat wear scar calibration curve.

The curves shown in Figure 6-37 can be approximated by an equation of the form

$$\log W = C + 0.5\,[\mathrm{Vol} - \mathrm{Vol}(50\%)] \qquad \text{Equation (1)}$$

where

Vol(50%) is the volume of the zero degree 50% depth flat wear scar which from Figure 6-37 is about 157 cubic millimeters.

Vol are the volumes of other wear scars at various depths again derived from the zero degree curve.

W is the corresponding maximum wear depth in percent of wall for each of the selected wear scar volumes.

C is a constant which depends on the particular curve being fit.

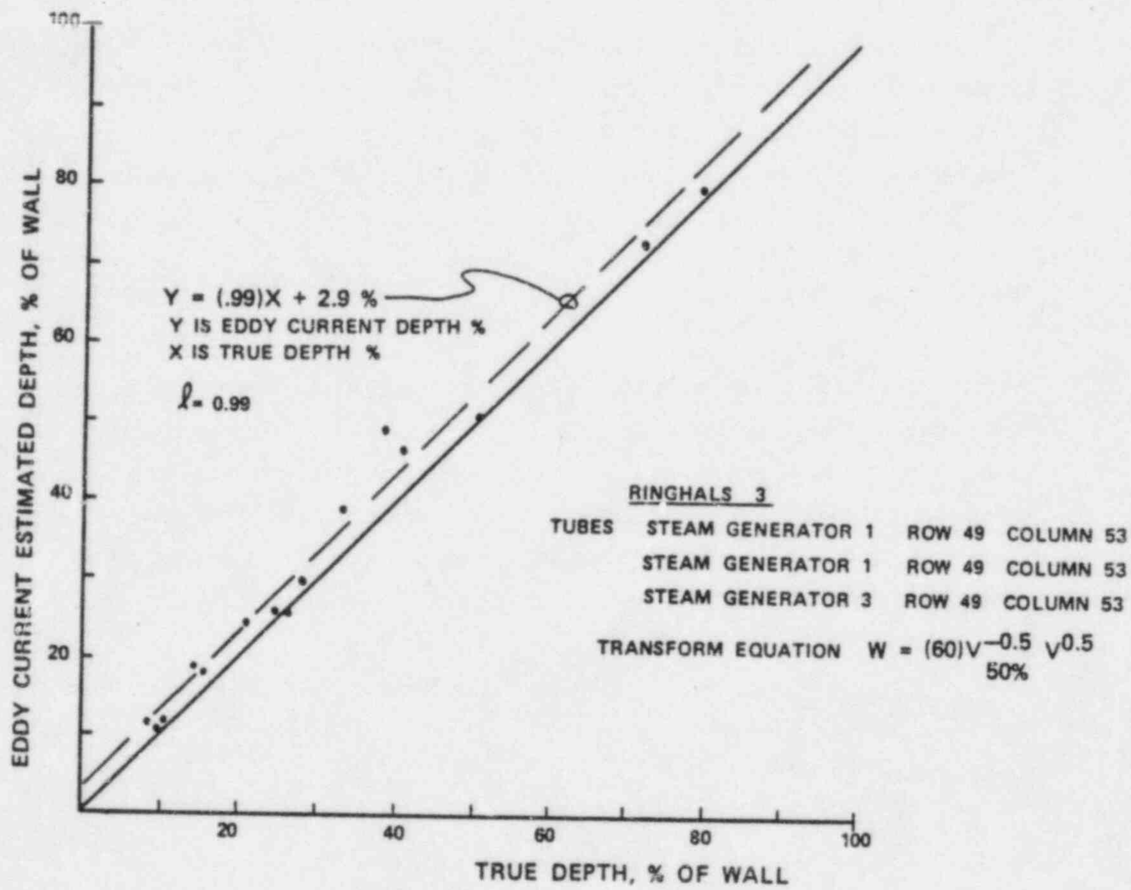


Figure 6-38. Wear Scar Estimated Depth Versus Actual Depth

Since wear scar volume and eddy current absolute bobbin coil signal amplitude are proportional, the volume dependency in Eq. (1) can be replaced by wear scar standard (alpha = zero degrees) signal amplitudes. Thus,

$$\log W = C + 0.5\ [V - V\ (50\%)] \qquad \text{Equation (2)}$$

where

V(50%) is the signal amplitude obtained from the 50% through wall flat wear scar standard.

V are the voltages obtained from the remaining wear scars on the flat wear scar standard.

C is a constant whose value is determined from the graphs in Figure 6-37

W is the maximum wear depth in percent of wall for each of the wear scars from the flat wear scar standard.

SSPB staff have used the equation

$$\log W = 60 + 0.5\ [V - V(50\%)] \qquad \text{Equation (3)}$$

to estimate wear scar depths on three tubes from Ringhals 3. Scar depth estimates using this curve were presented earlier in Figure 6-38. The SSPB transformation approach has been compared directly with the Tecnatom tapered standard and the two agree to within five percent. The two curves are shown in Figure 6-39.

Fretting wear at AVBs in Westinghouse RSGs present special interpretation problems which are now considered. Tube fretting occurs as the result of tube vibration against an adjacent AVB. One or two AVBs can be in proximity to the tube depending on the location of the tube in the generator. Also, round AVBs were used in earlier Model 27 steam generators whereas square AVBs are used in later models.

Tube fretting eddy current signals can have relatively small amplitudes which are strongly influenced by the AVB. Conventional phase angle analysis of the fretting eddy current signal can result in a significant overestimation of fretting depth. Signal amplitude sizing techniques derived from appropriate standards can be used to provide a better estimation of depth.

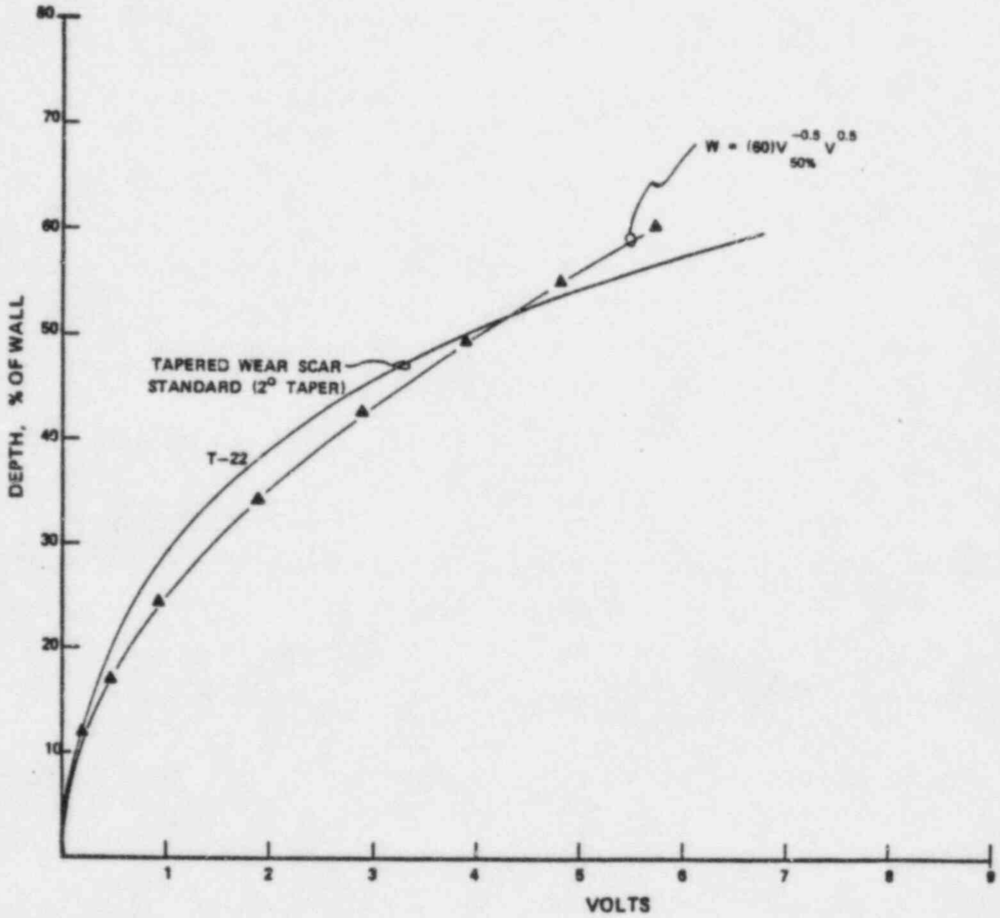


Figure 6-39. Comparison of Tapered Wear Scar and Transformed Flat Wear Scar Calibration Curves

AVB wear standards are typically constructed as shown in Figure 6-40. One and two-sided standards at various depths are utilized. Square or round wear cross-section geometries are used depending on the steam generator model. A calibration curve relating signal amplitude to depth is generated for data interpretation.

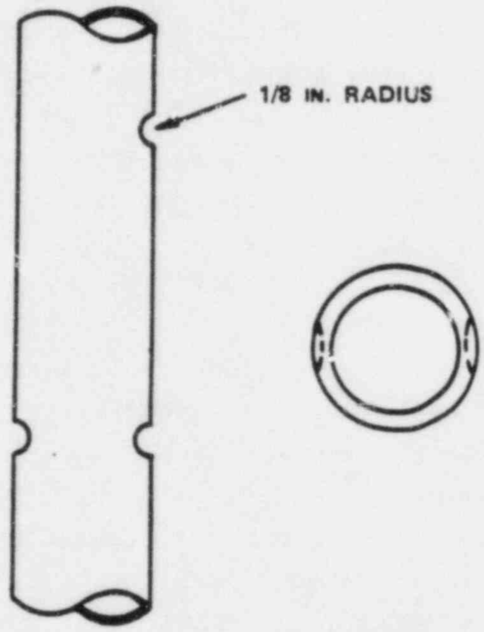
Certain assumptions have to be made to conservatively size wear in tubes that have AVBs on two sides. For these tubes it does not necessarily follow that wear occurs on both sides or that it occurs to equal depths. Since the eddy current signal amplitude response to wear on each side is additive, a conservative depth estimate is provided if the single-sided standard is used. Array coil technology could be used to discriminate between single and double sided wear allowing for more accurate depth estimates.

Fretting in OTSGs is the result of cross-flow induced tube vibration within the upper region of the steam generator. The degradation is limited to the lane region at elevations between the 14th support plate and upper tube sheet. Figure 6-41 shows fretting on a tube removed from Oconee. The tube can made contact with the broached support plate land contact areas (LCA) of which there are three. The tube wear tends to assume the rectangular geometry of the LCA.

The tube wear can be tapered which suggests that an eddy current absolute coil mode is the preferred choice for inspection. Only one example is known where the in-plant eddy current depth estimate has been compared with metallographic results on a pulled tube. In this case, the in-plant signal subtraction analysis method estimated 60%-90% through wall depth whereas the actual depth was approximately 15% through wall. This significant over estimation has been attributed to poor eddy current signal-to-noise ratio and the choice of calibration standard.

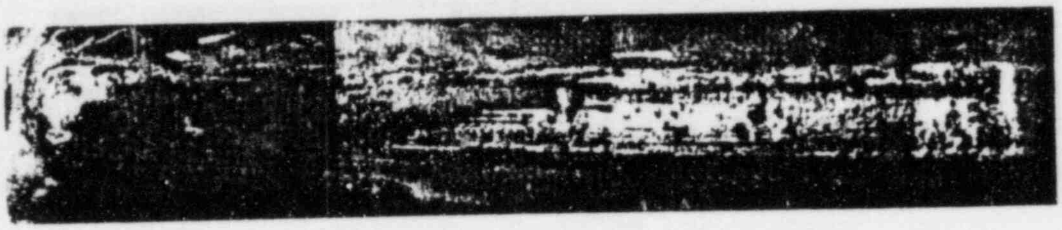
6.3.6 High-Cycle Fatigue Cracking

High-cycle fatigue cracking is the primary cause of leaker outages in OTSGs. The cracking is circumferential; a typical crack is shown in cross section in Figure 6-42(a).

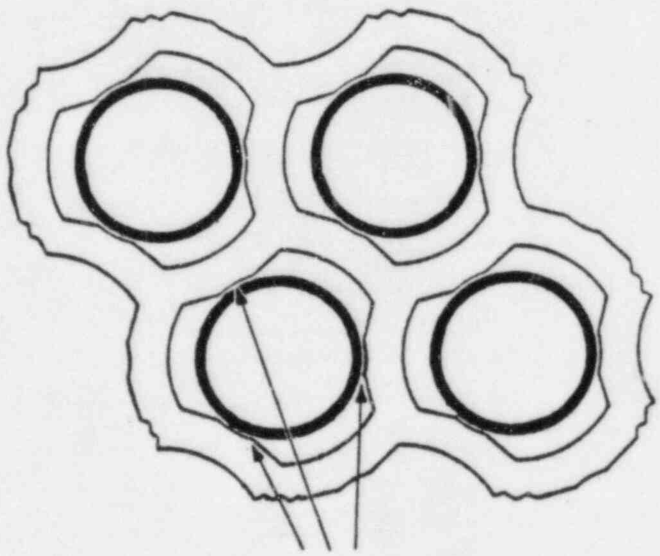


- SINGLE AND DOUBLE SIDED STANDARDS
- VARIOUS DEPTHS
- WEAR CROSS-SECTION CONFORMS TO AVB GEOMETRY

Figure 6-40. Antivibration Bar Wear Calibration Standards - One and Two Sided



(a) Fretting at land contact area



(b) Broached support plates (top view)

Figure 6-41. Fretting at Broached Support Plate Land Contact Areas

(a) Through wall crack

(b) Partial through wall crack

Figure 6-42. High Cycle Fatigue Cracking

Until recently, no crack precursor or initiator had been identified, i.e., the crack was either non-existent or 100% through wall. Oconee experienced a leaker outage late in 1982 involving five tubes in proximity to the lane region. Conventional bobbin coil and 8x1 array coil technology were used to inspect tubes in the vicinity of the leak in order to identify candidates for tube pulling. One tube (79-5) was identified that had an eddy current indication of 40% through wall using the 8x1 but no indication using the bobbin coil. The tube was removed; a photograph is shown in Figure 6-42(b). The presence of a circumferential discontinuity is clearly apparent just above a rectangular patch which is lighter than the rest of the tube. The rectangular patch is tube wear attributed to contact between the tube and the support plate land contact areas. The circumferential discontinuity was sectioned and identified as a high-cycle fatigue (HCF) crack 63% through wall. This is the first example of a partial through wall HCF crack.

6.3.7 Impingement Wear

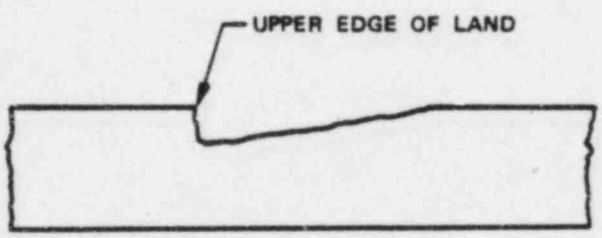
Figure 6-43 shows typical impingement wear on a tube removed from Oconee steam generators. Eddy current estimates of impingement wear depth have been nonconservative. Pulled tube results show errors ranging from -30% to -10% through wall (39). The wear geometry can be somewhat tapered which may account for underestimation.

6.3.8 Damage Precursors

Specific NDE experience with what are considered to be damage precursors is now presented. Damage precursors are important conditions to monitor in the steam generator since knowledge of their existence can provide the utility early warning of potential tube damage. Initiation of plant corrective actions can possibly remedy the situation or minimize its impact on steam gneerator availability.

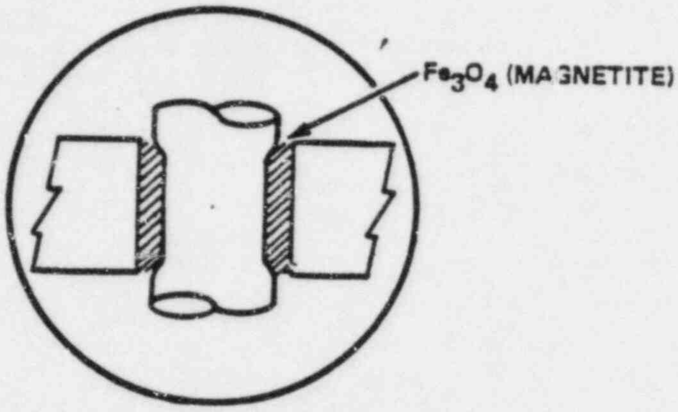
Crevice Gap Magnetite. Denting is a result of corrosion product buildup in the tube support-support plate gap. The major corrosion product is magnetite, which is derived from carbon steel support plates undergoing accelerated corrosion due to faulted secondary side water chemistry. As shown in Figure 6-44 the support plate corrodes in a non-uniform manner; it corrodes faster towards the center than at

(a) Impingement wear

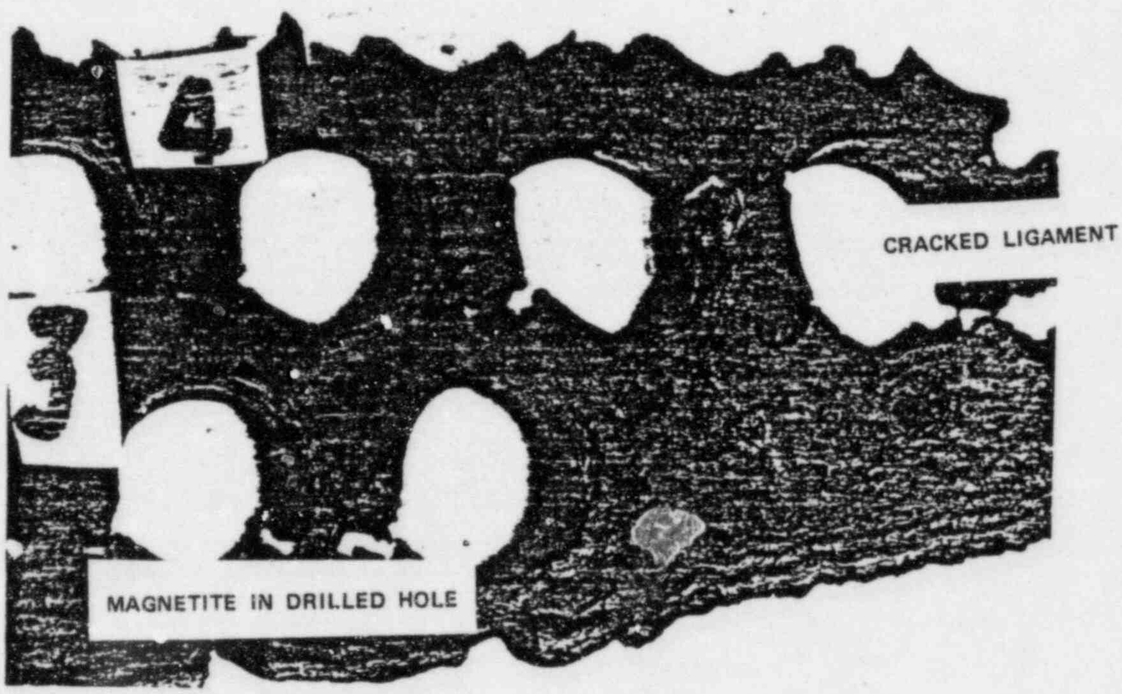


(b) Typical wear cross section

Figure 6-43. Flow Impingement Wear



(a) Magnetite packed crevice region



(b) Support plate section showing magnetite crevice region and cracked ligament

Figure 6-44. Magnetite Formation Within Support Plate Crevice Region

the plate edges. The corrosion process can be detected by changes in the support plate hole diameter and filling of the crevice gap with magnetite. Both of these conditions can be sensed with an eddy current coil.

Eddy current bobbin coils in the absolute mode have been used to monitor for evidence of support plate corrosion. The earliest plant application reported in the open literature is at Ginna during 1976 (40). References (41,42) describe the basis for the eddy current detection of magnetite.

During an extensive outage at Oconee in 1979, absolute mode bobbin coil techniques were used to detect and quantify magnetite debris on the support plates and magnetite packed within the broached support plate holes (43). The results of the eddy current examination were confirmed from the secondary side using remote fiber optics. Good correlation was reported.

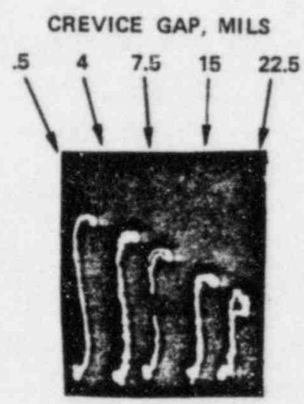
Eddy current bobbin coil examination for support plate corrosion products is accomplished using frequencies in the range of 10-40 KHz.

Eddy current array coil technology (8x1) has been used to detect and characterize magnetite within corroded carbon steel drilled support plates (44). Laboratory investigations using magnetite-packed support plate crevice standards showed that it is feasible to estimate the axial and circumferential extent of magnetite with the crevice gap. A procedure has been developed which was used to acquire data from an operating steam generator. The in-plant results were comparable to those obtained in the laboratory.

An eight element pancake coil surface-riding array coil along with MIZ-18 eddy current instrumentation is used for magnetite detection within the crevice gap. A test frequency of 100 KHz is used. A "zero gap spacing" (press fit) support plate standard is used to establish initial setup. The support plate signal is rotated onto the vertical axis of the display as shown in Figure 6-45(b).

Magnetite present in the crevice gap will be sensed as a signal with a different magnitude and phase than the support plate. Its effect

(a) Normal plate signal



(b) Signal amplitude versus lift-off

Figure 6-45. Eddy Current Pancake Coil Signal Amplitude Variation with Crevice Gap Width

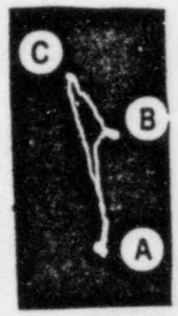
on the support plate signal will be dependent on how the magnetite is distributed with the crevice gap.

Figure 6-46(a) shows the signal obtained from a crevice gap partially packed axially with magnetite which is shown schematically in Figure 6-46(b). The probe in travelling right-to-left in the figure first encounters the support plate's leading edge and the normal support plate signal A-B forms. The probe then enters the magnetite packed region and forms the signal vector B-C. Upon exiting the support plate, the signal C-A is formed; it differs from A-B due to the presence of the magnetite at the trailing edge. Magnetite thus yields the characteristic signal B-C or distorts the plate entrance or exit signal by increasing its magnitude with a rotation in the counter-clockwise direction.

Estimation of the axial and circumferential extent of magnetite using array coil technology can be done by analysis of the strip chart data. Axial extent is estimated by observing the duration of the magnetite signal and then normalizing to the length of the support plate. The circumferential extent is estimated by noting the numbers of coils that have a magnetite signal. Each coil field-of-view is 45 degrees which is then multiplied by the numbers of coils on which the magnetite was detected.

Figure 6-47 shows array coil eddy current signals from a support plate crevice gap which contains magnetite over a 120 degree sector. There are eight signals; one from each of the pancake coils which form the array. The signals from coils 4 through 8 appear as normal support plate signals; they are on the vertical axis of the display with minor variations in amplitude which indicate small variations in spacing between the tube and the support plate. The signals from coils 1 through 3 are similar to what was shown in Figure 6-47 indicative of magnetite within the crevice gap. Each coil has a field of view of 45 degrees so that the estimated circumferential extent of the magnetite is 130 degrees.

The procedure for estimating the axial extent of the magnetite from strip chart data is shown in Figure 6-48. The ratio of the magnetite signal width (l) to the width of a normal plate signal width (L) gives



MAGNETITE IN CREVICE

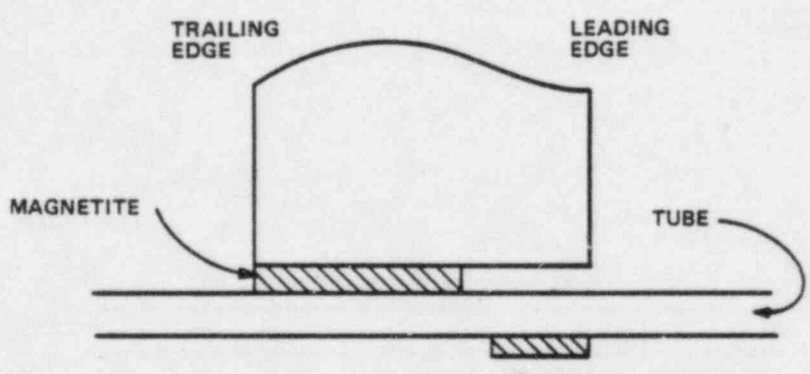
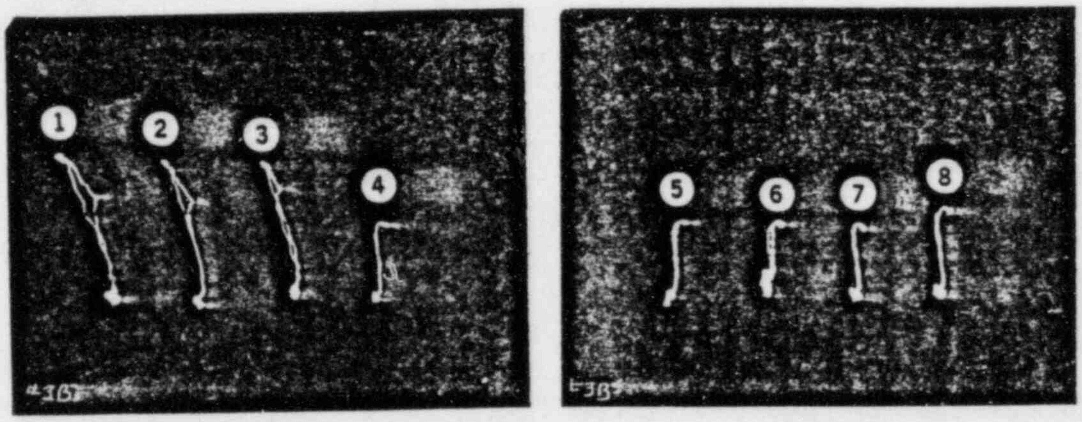


Figure 6-46. Pancake Coil Response To Support Plate Crevice Gap Magnetite



ARRAY COIL SIGNALS

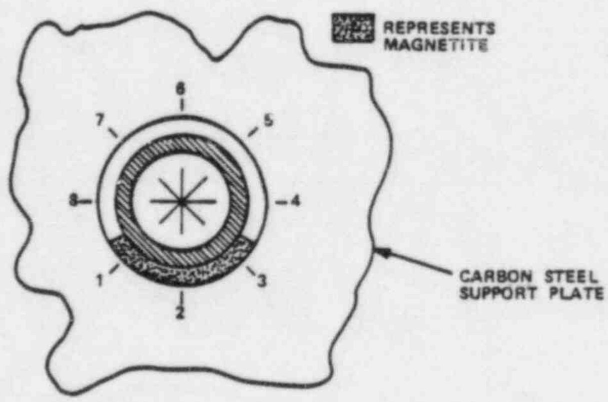


Figure 6-47. Array Coil Signals From a Tube Containing Magnetite

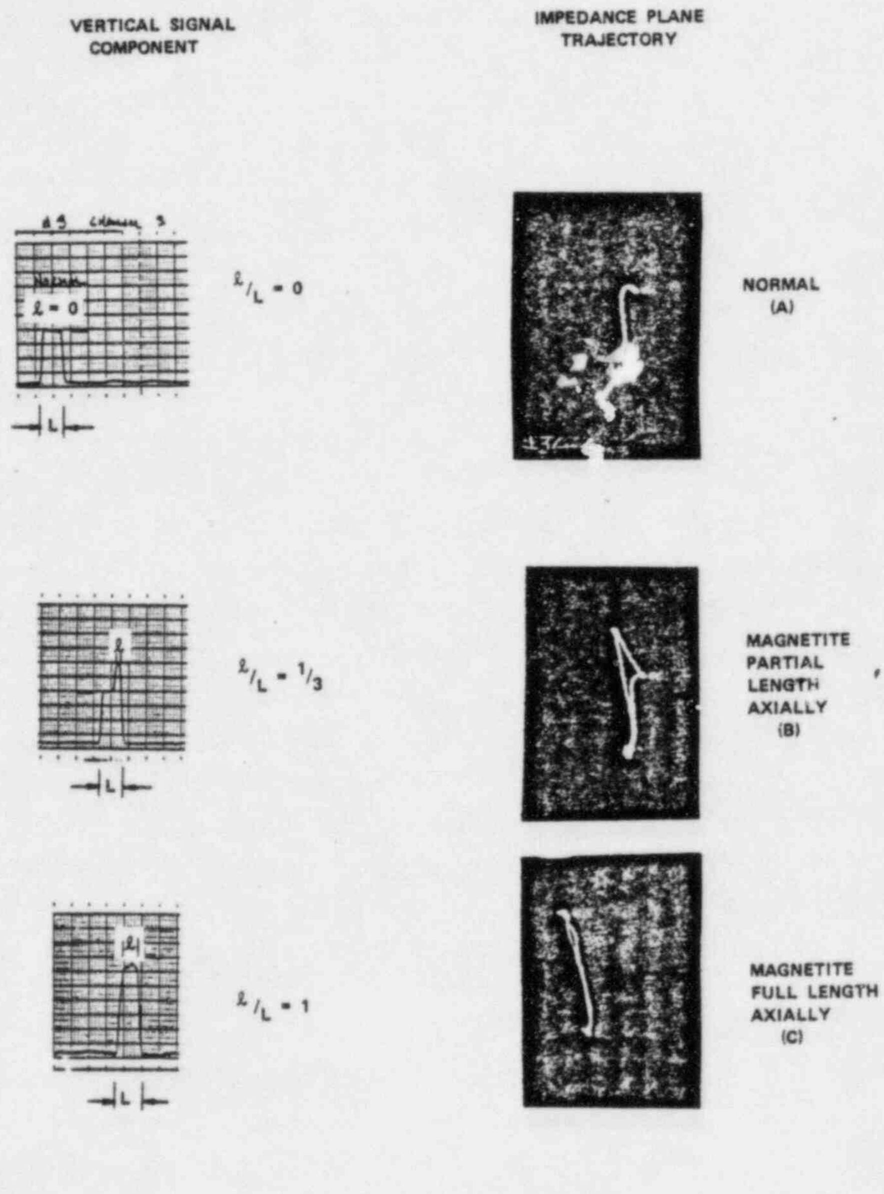


Figure 6-48. Array Coil Signals For Various Amounts of Magnetite Within the Crevice Gap

the axial fraction of the crevice packed with magnetite.

Denting. It has been mentioned in an earlier section that the inspection of dented tube support plate intersection for cracking is time consuming and difficult. The current philosophy is to estimate the profile of the dent from which tube strain information can be deduced. The tube is removed from service only if its strain value exceeds some threshold. Tubes with a strain value greater than the threshold are susceptible to stress assisted cracking. This allows for a greater safety margin and an improvement in unit availability.

Before considering dent profiling methods in more detail, alternate techniques which are in present use are discussed. Go/no-go gaging methods using mechanical probes of various diameters have been used to measure tube restriction. However, this approach does not provide a direct measure of tube strain and is extremely conservative resulting in the unnecessary plugging of tubes (45).

Eddy current methods are very sensitive to variations in spacing between the coil and surface of interest. A bobbin coil will respond to denting as a variation in fill-factor and provide an output signal which in certain circumstances is proportional to variations in tube diameter. Unfortunately, the necessary circumstances, i.e., axisymmetric denting, can not be counted on to occur within a steam generator with any regularity. Thus eddy current bobbin coil approaches can generally detect a dent but cannot be used to reliably estimate dent size or shape. Reference (45) documents a case in which a conventional bobbin coil had indicated the presence of a dent 3-5 mils diametral. Actual measurement of the dent showed it to be on the order of 60 mils.

The problems of estimating dent size and shape is illustrated with the aid of Figure 6-49 where we show a nondented tube, an ovalized dented tube, and an irregularly dented tube. A completely axisymmetric dent would assume the shape of the nondented tube but would have variations in tube diameter. If steam generator denting occurred in this fashion then eddy current bobbin coils and mechanical gaging techniques could be used. More typically, denting assumes the other two shapes shown in the figure.

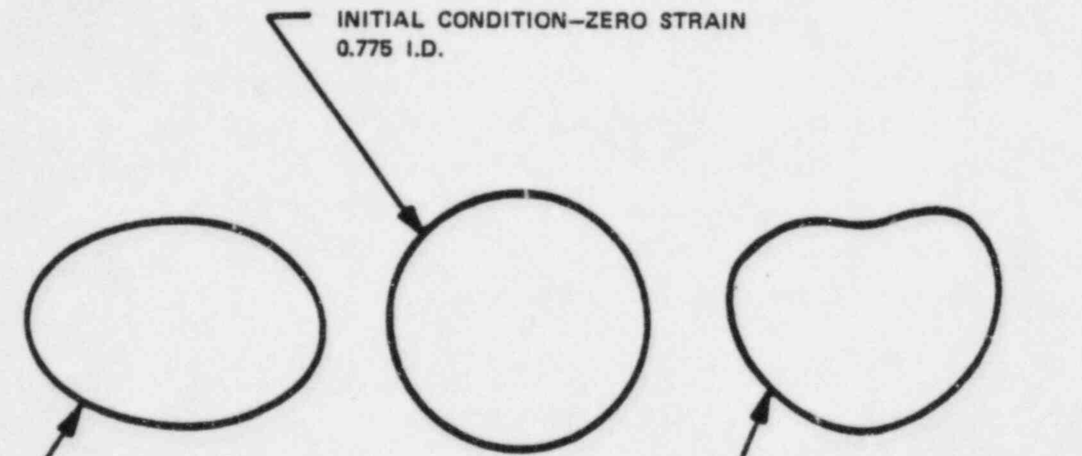


Figure 6-49. Examples of Different Dent Shapes

Present gaging criteria is to plug a tube if it does not pass a 0.610" probe. Using this criteria, the ovalized tube shown on the left with a 0.610" minor and a 3% strain value would be removed from service. The irregular dent with a 0.648" minor diameter would remain inservice even though its strain value is much higher.

Profilometry techniques are used to estimate the shape of the dent by sampling the dent contour at various angular increments around the tube inner circumference. This is illustrated with the aid of Figure 6-50 for an irregular shaped dent and eight sample points (eight radii). Curve fitting algorithms are used to reconstruct the dent contour from the sampled data. The accuracy with which a given shape is replicated will depend on the number of sample points and the choice of curve fitting equations.

With a small number of sample points, the reconstructed dent shape will depend on orientation effects of the profilometry sensor as it is scanned through the dented tube. Rotation of the eight finger probe shown in Figure 6-50 will result in a different set of radii and hence a reconstructed shape that differs from the initial estimated profile. Since strain information is derived from the sampled radii, uncertainties in estimated tube strain will occur due to finite sampling effects. Variations in strain calculations which differ by a factor of two are documented in (45). Again, this variation is attributed to the limited number of sample points.

Sampling errors may be decreased by increasing the number of sample points. In general it will depend on the shape of the dent. Figure 6-51 shows data for an axisymmetric dent. The "true" shape is shown along with estimated shapes derived from 8-point and 36-point sampling schemes. Since the dent is axisymmetric, sampling effects are not pronounced and both approaches show approximately the same shape. The 36-point sample size does give a better estimate.

Figure 6-52 shows samples data sets for a kidney-shaped dent. Again, the "truth" is shown along with 8-point and 48-point sampling. In this example the true data set shows two localized indented regions. These regions are indicated within the 48-point sample set but are significantly smoothed in the 8-point data. This particular dent shape is

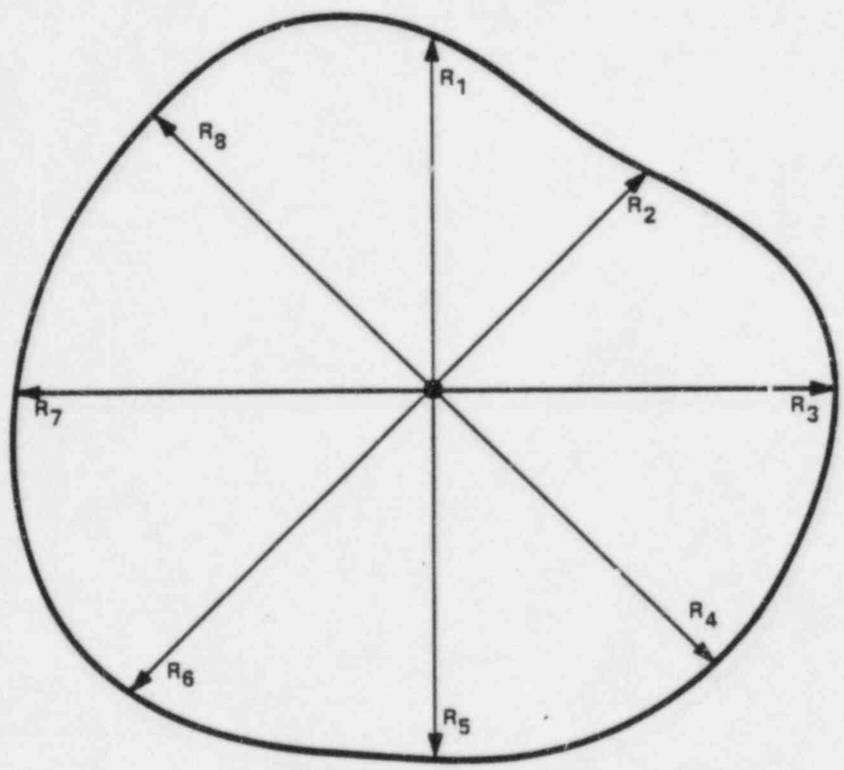
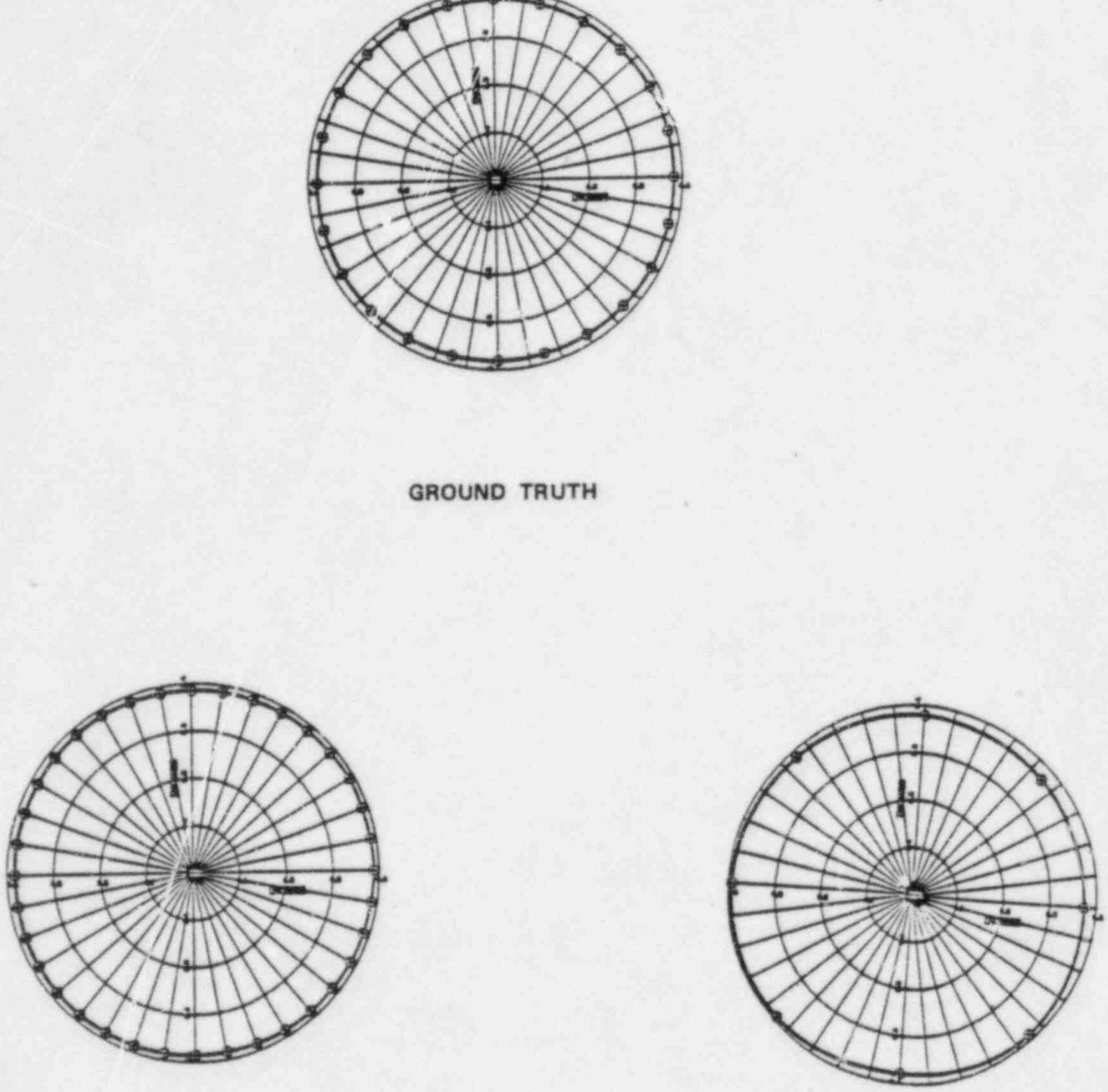


Figure 6-50. Angular Sampling of a Dent



GROUND TRUTH

36– POINT RECONSTRUCTION

8– POINT RECONSTRUCTION

Figure 6-51. Axisymmetric Dent - Effects of Sampling

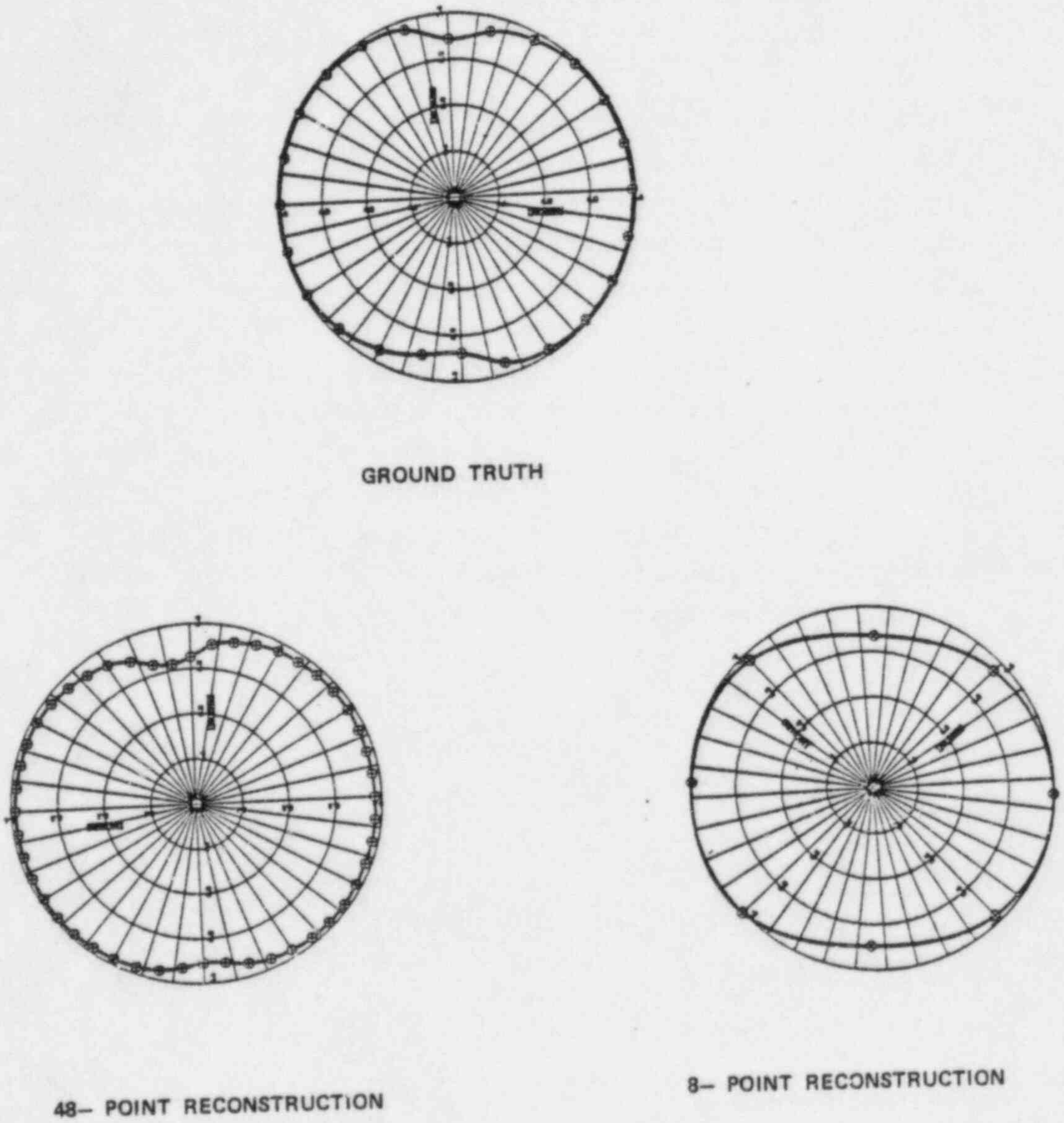


Figure 6-52. Kidney Shaped Dent - Effects of Sampling

susceptible to cracking because of higher strain values due to indentations. Quite different conclusions would probably be drawn as to the integrity of this tube from the two data sets. Again, the larger sample size reconstruction is in better agreement with the truth than the smaller sample set.

There are presently five techniques that are commercially available for use in characterizing the inner diameter of tubing. These are listed in Table 6-1 along with the number of sample points typically acquired. Strain gage technology is available from Babcock & Wilcox (see Figure 4-33) and Combustion Engineering; eddy current bobbin and array coil technology is available from Zetec (see Figures 4-21(a) and 4-27) or vendors who use Zetec equipment. The optical profilometry system was developed under EPRI Steam Generator Owners Group funding by Sigma Research (see Figure 4-32) while the electromechanical profilometry sensor was developed by Consolidated Edison and is being marketed as a service by Babcock & Wilcox (see Figure 4-35). With the exception of the optical system, all of the methods listed in Table 6-1 have been used in the field.

Table 6-1

Method	Number of Sample Points
• Eddy Current Bobbin Coil	1
• Strain Gage	8
• Eddy Current Array Coil	8
• Optical	48
• Electromechanical	36

Steam generator applications for the listed technology include (1) dent detection and characterization, (2) measuring preheater expansions at baffle plates, (3) measuring sleeve expansions and, (4) measuring tube diameters in the tube sheet crevice after expansion or sleeving.

Application areas (2), (3) and (4) utilize processes which tend to result in axisymmetric geometries. Hence, eight-point profilometry methods (eddy current array coil and strain gage) are probably adequate for these applications.

The use of an eddy current bobbin coil in detecting denting is certainly well documented. However, under certain circumstances, the bobbin coil is vulnerable. Denting at eggcrates in CE units has gone undetected because of its ovalized shape and averaging effects of the bobbin coil. The recommended approach in detecting denting would be to monitor the presence of magnetite within the gap between the tube and its supporting structure (see Section 6.3.8 Crevice Gap Magnetite).

The bobbin coil cannot be used to reliably estimate dent size or shape because of coil averaging effects. Continued denting in a plant is generally monitored by noting the increase in the number of dented support plate intersections. The severity of the denting and its impact on tube strain and potential support plate cracking cannot be monitored using an eddy current bobbin.

Profilometry techniques must be used to assess dented tube integrity. In general, the greater the number of profilometry sample points, the more reliable is the estimate of tube strain. Eight-point sampling schemes (strain gage or eddy current array coil) are vulnerable to assumptions made about the expected dent shape. Techniques which have a greater number of samples (electromechanical or optical) are less vulnerable to dent shape assumptions and are the recommended approach.

Support Plate Ligament Cracking. One of the extreme consequences of denting is support plate cracking. Extensive denting can severely deform the support plates resulting in flow slot hourglassing and cracked support plates. See Figure 6-53. The figure shows the bottom surface of the first support plate (looking upwards). Closure of the flow slot is apparent along with a cracked support plate section. This particular steam generator is no longer in service. Extensive cracking of this sort can create the potential for loose parts, e.g., sections of the support plate, and subsequent foreign object damage.

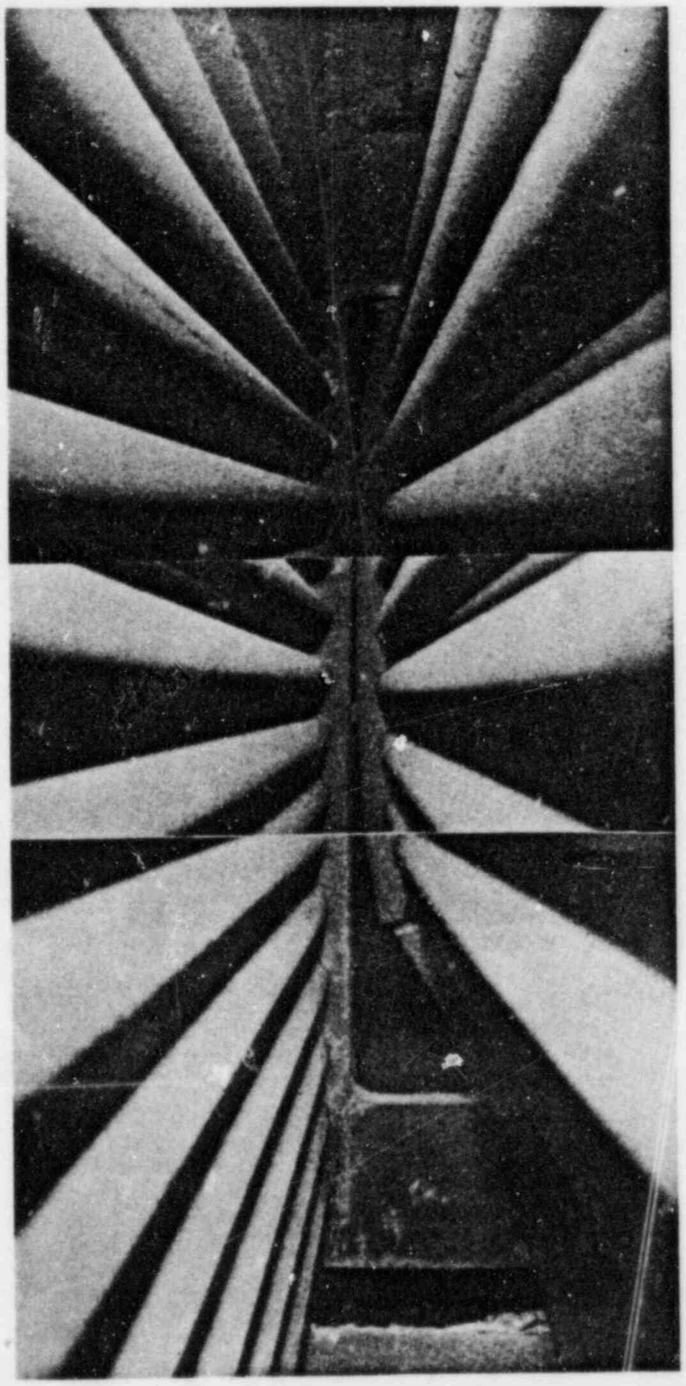


Figure 6-53. Flow Slot Closure - Support Plate Cracking from Extensive Denting

See Figure 6-54.

Current field eddy current procedures have been evaluated for detecting and characterizing support plate ligament cracking (46). Conventional bobbin coil technology was used with coil excitation frequencies in the range of 10 KHz - 40 KHz. In evaluating the eddy current bobbin coil approach, a cracked support plate standard was constructed which had various percentages of ligament cross section wall loss. The standard is shown in Figure 6-55 along with the range of ligament cracking which was considered.

Differential bobbin coil signals for various degrees of ligament cracking are shown in Figure 6-56. Comparison of the impedance plane signal structure for the two extremes of no cracking and complete ligament loss (A and H of Figure 6-56) shows that the loop structure collapses for a completely cracked ligament (the horizontal signal component is reduced). Partial ligament cracking is evidenced by a collapsing of the lower part of the impedance plane trajectory. This is more evident for cases in which 50% or greater ligament cracking exists (Signals E, F, and G of Figure 6-56) than for cases in which the percent ligament loss is less than approximately 50% (Signals B, C, and D of Figure 6-56).

The cracked plate standard shown in Figure 6-55 did not contain magnetite within the tube support plate hole crevice gap which is not a realistic situation. The placement of magnetite within the gap introduces additional complications which were first discussed in (38,39). Under this condition it is found that magnetite alone within the crevice gap results in bobbin coil signals which are similar to partial ligament cracking signals and that the two conditions are not distinguishable. Complete ligament cracking is however still detectable.

Partial ligament cracking 50% and greater can be distinguished from magnetite within the crevice gap by using an alternate test coil first described in (41) and confirmed in (46). In a normal denting sequence, magnetite formation would initiate first followed by denting and, if the denting is extensive, plate ligament cracking. Hence magnetite-partial ligament cracking signal ambiguity may or may not exist

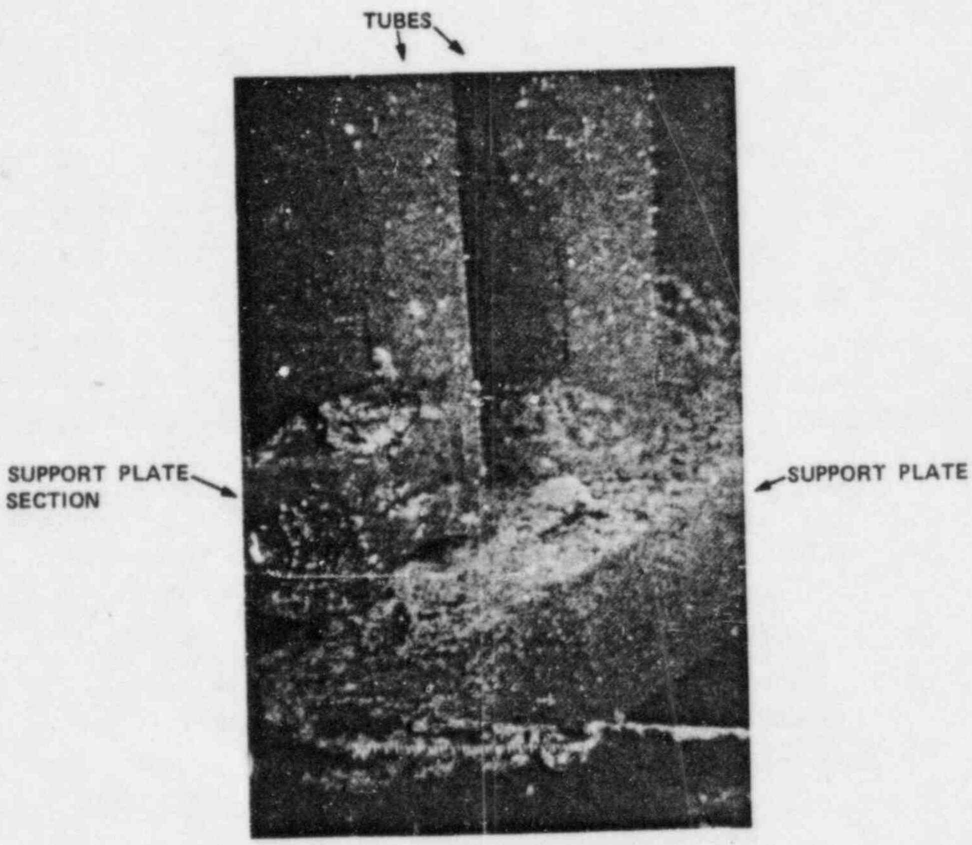
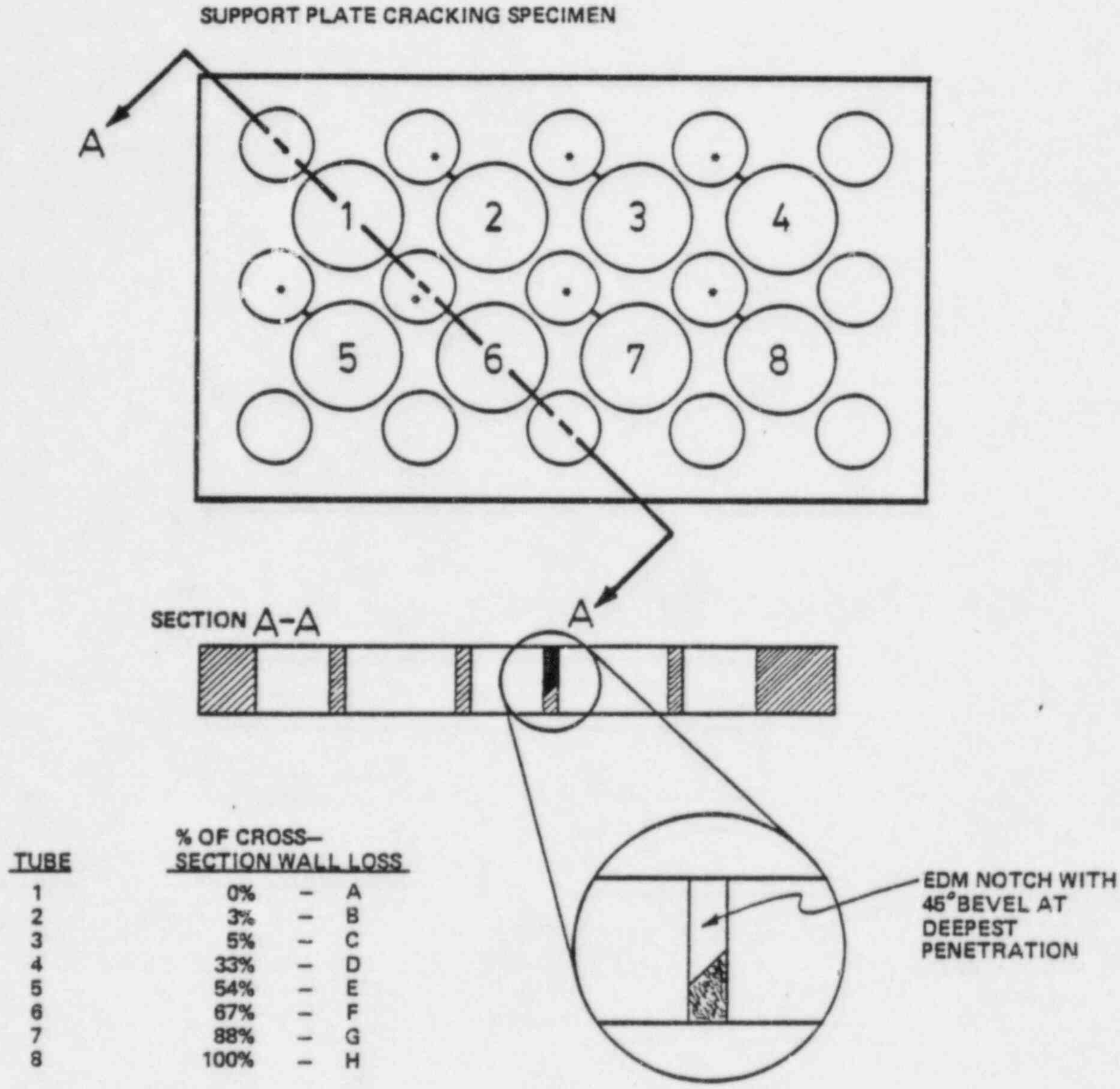


Figure 6-54. Loose Support Plate Section



TUBE	% OF CROSS-SECTION WALL LOSS		
1	0%	–	A
2	3%	–	B
3	5%	–	C
4	33%	–	D
5	54%	–	E
6	67%	–	F
7	88%	–	G
8	100%	–	H

* INDICATES GENERAL AREA OF CRACK

Figure 6-55. Support Plate Cracked Ligament Standard

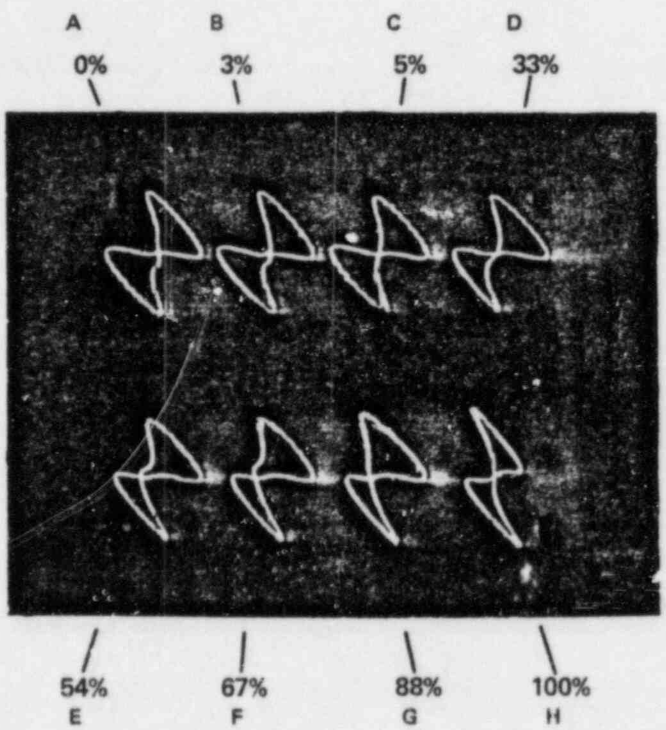


Figure 6-56. Normal and Cracked Support Plate Ligament Eddy Current Signals

depending on the extent of the denting.

Radiography can also be used to detect and quantify support plate ligament cracking (see Figure 4-31). The system is probably best utilized as a confirmatory tool to substantiate possible ligament cracking evidenced by eddy current results. There are two CE units that have misdrilled flow holes in their support plates which in some cases intersect the tube hole. This condition is not distinguishable from ligament cracking by eddy current; radiography could be used to recognize this condition.

Sludge Profiling. Magnetic deposits (sludge or debris) external to the tube wall are routinely detected and measured using eddy current bobbin coils in the absolute mode. Typical coil excitation frequencies range from 10 KHz to 40 KHz depending on the preference of the inspecting agency. The effects of sludge may also be noticeable at higher frequencies (e.g., 200 KHz to 400 KHz), but are more pronounced at frequencies below 100 KHz.

Sludge is a mixture of corrosion products from the condensate/feedwater system components, condenser in-leakage products, and secondary side water chemistry additives. Magnetite is a major constituent of sludge; it is magnetic and will perturb the eddy current coil field which provides a basis for sludge height measurement. Sludge height is measured by translating the eddy current probe through the tube at constant speed and recording the duration of the sludge signal on a strip chart.

The accuracy of eddy current sludge height measurements is not known, but some utilities record sludge height to the nearest tenth of an inch (47). Eddy current sludge profile results have been compared with secondary side observations. The correlation between the two data sets has been described as "rather good" although no specific numbers are quoted (48).

Visual or fiber optic methods probably represent the most reliable indicator of sludge extent within the steam generator. This inspection approach would be limited by access constraints within the inner region of the tube bundle and inspection speed. Eddy current methods

in general cannot distinguish between sludge and magnetic deposits on or near the tube wall. Hence, the eddy current method may tend to give a conservative estimate of sludge extent. Water balance methods have also been used for sludge monitoring. The method has not proven to be reliable in practice because of assumptions that are made during the test and measurement accuracies (49).

The sludge pile in a steam generator is three dimensional; both its lateral extent and its height must be estimated in order to identify regions susceptible to corrosion attack. Hydraulic conditions within the steam gneerator determine sludge pile extent, with the sludge tending to accumulate in low flow regions. The boundary can be determined using a tube sample matrix from the central region of the tube bundle. Figure 6-57 shows a typical sludge height inspection program for a Westinghouse Series 51 steam generator.

The height of sludge piles in operating units has ranged from fractions of an inch to over forty inches.

Eddy current measurement of sludge height should be made before and after sludge lancing to monitor the effectiveness of sludge removal.

6.3.9 Sleeve Inspection

Sleeving consists of installing a smaller diameter tube (sleeve) into the original damaged steam generator tube in order to create a new pressure boundary. Thus rather than removing a damaged tube from service by plugging, the tube is sleeved and can remain in service. Numerous plants have used sleeving as an alternative to steam generator replacement. A listing of plants which have sleeved steam generators, and the reason for sleeving is given in Table 6-2. The sleeving at Palisades was done in tubes which had wastage at the support plate intersections. In general, the sleeves are relatively short and span the plate intersection. Doel 2 utilizes mini-sleeves to accommodate primary side stress corrosion cracking at the roll transition. All of the other listed units use a longer sleeve which generally extends the length of the tube sheet crevice or to some distance above the top of the tube sheet.

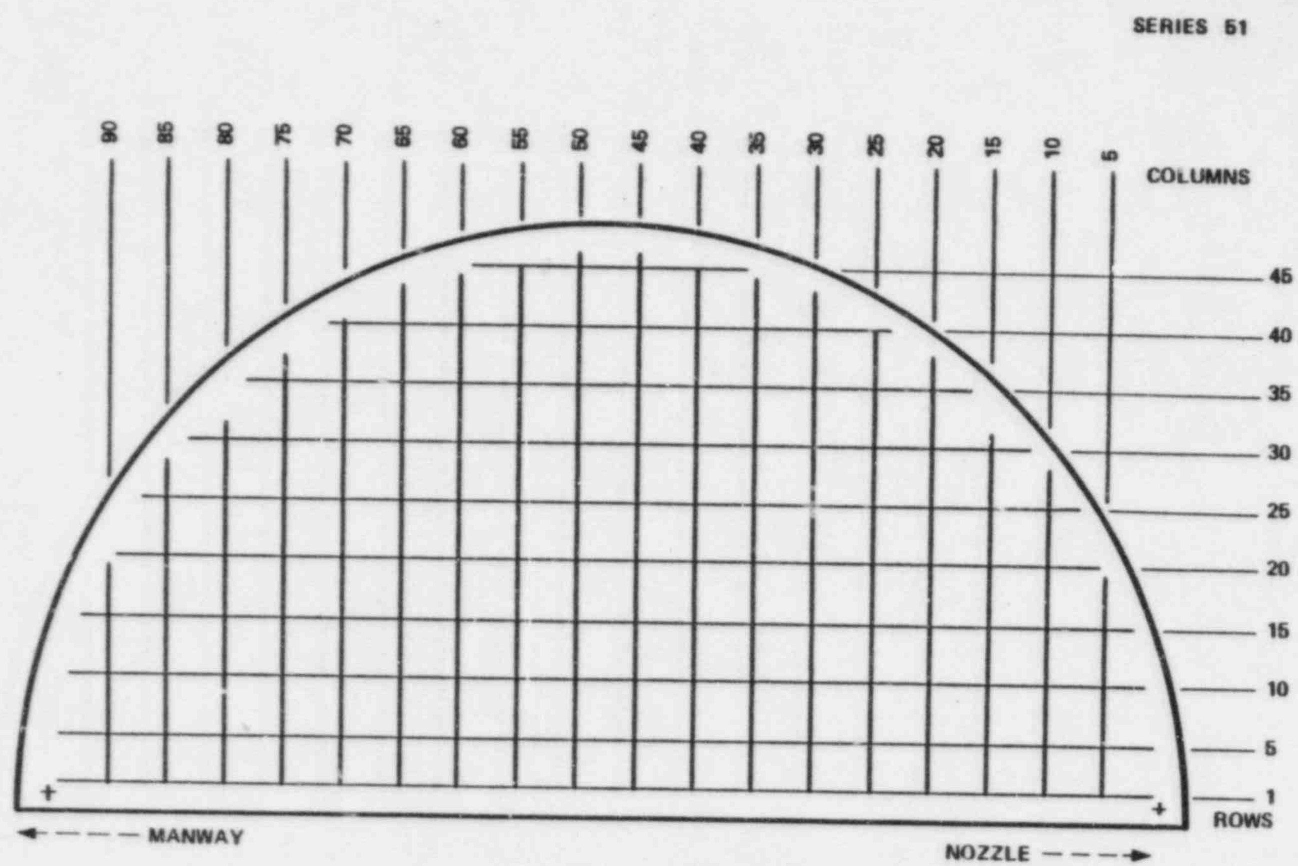


Figure 6-57. Typical Sludge Hieght Sampling Matrix

Table 6-2

Plant	Number of Sleeves	Reason for Sleeving
San Onofre 1	6929	IGA
Indian Point 3	2971	Pitting
Point Beach 2	3000	IGA
Millstone 2	2022	Pitting
Ginna	99	IGA
Doel 2	185	SCC
Palisades	14	Wastage

Sleeve configurations can vary somewhat depending on specific plant needs. A composite sleeve configuration is shown in Figure 6-58 which incorporates various features of the different designs. Depending on the specific sleeve design, the ends or total length of the sleeve are expanded and sealed to provide both a seal and redundant load carrying path. As shown in the figure, the sleeve may be clad or unclad. The purpose of the cladding is to increase corrosion resistance in particular operating environments. The upper end of the sleeve can be expanded and rolled; brazed; or welded to the original tube. The lower end of the sleeve is typically expanded and rolled or welded to the parent tube.

Sleeving NDE related activities generally fall into two categories; 1) those associated with the installation of the sleeve and 2) subsequent inservice inspection.

Specific NDE requirements conducted during sleeve installation include;

- Verification that the parent tube inner surface is clean. This can be accomplished using boreside visual inspection methods.
- Verification of parent tube inner diameter and expansion of sleeve after installation. Tube and sleeve dimensional information can be obtained using profilometry techniques. Some parent tubes have been found to be dented which prevented the use of sleeves.

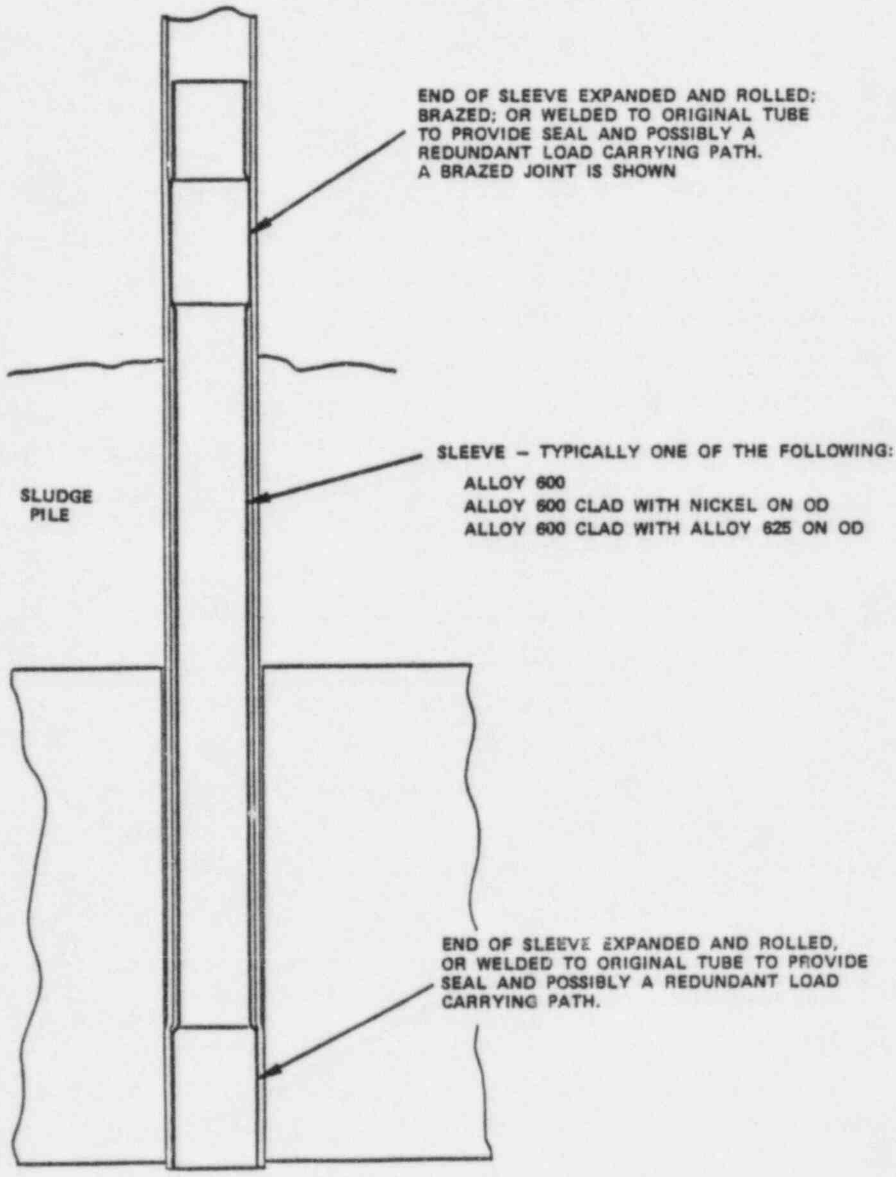


Figure 6-58. Sleeve Configuration

- Verification of braze bond quality. Ultrasonic inspection methods are used to assess the integrity of the brazed region. Welded joints have been inspected using both eddy current and ultrasonic techniques.

- Acquire baseline eddy current data from installed sleeves using techniques to be used during inservice inspection. Acquiring baseline data will allow for detection of changes that occur during steam generator operation.

Inservice inspection requirements for sleeved tubes are comparable to those for the original tubing. Sleeving does however introduce special inspection problems which must be addressed. The upper sleeve end (see Figure 6-58) presents a special challenge because of the abrupt change in apparent tube diameter. Conventional bobbin coil technology detects this condition as a large change in fill factor; an extraneous signal is generated which may override eddy current signals from parent tube degradation occuring near the upper end of the sleeve. Dual cross-wound eddy current probes are currently used to reduce tube end effects.

A dual cross-wound probe consists of two pairs of coils; each pair is wound so that tube conditions that exhibit axisymmetry are suppressed. Each coil pair covers approximately 180 degrees of the tube wall; hence complete coverage is obtained by using two pairs which are rotated 90 degrees with respect to each other. A typical example of the response pattern of a dual cross-wound probe is shown in Figure 6-59. The response of each of the coil pairs has a null which is compensated by a peak in the other coil pair. It is important that the coverage of cross-wound coils that are to be used for inservice inspection be verified.

The expanded regions of a sleeve are also axisymmetric; hence, a cross-wound probe will also suppress this condition. The success of the cross-wound coil in suppressing sleeve tube end effects and expanded regions will depend on the actual symmetry obtained during sleeving and the inherent electrical balance obtained during manufacture of the coils. In general, there will be some residual signal due to coil imbalance or because axisymmetry is violated. This residual typically is suppressed further using signal processing, i.e., multiparameter or regression methods (digital mixing).

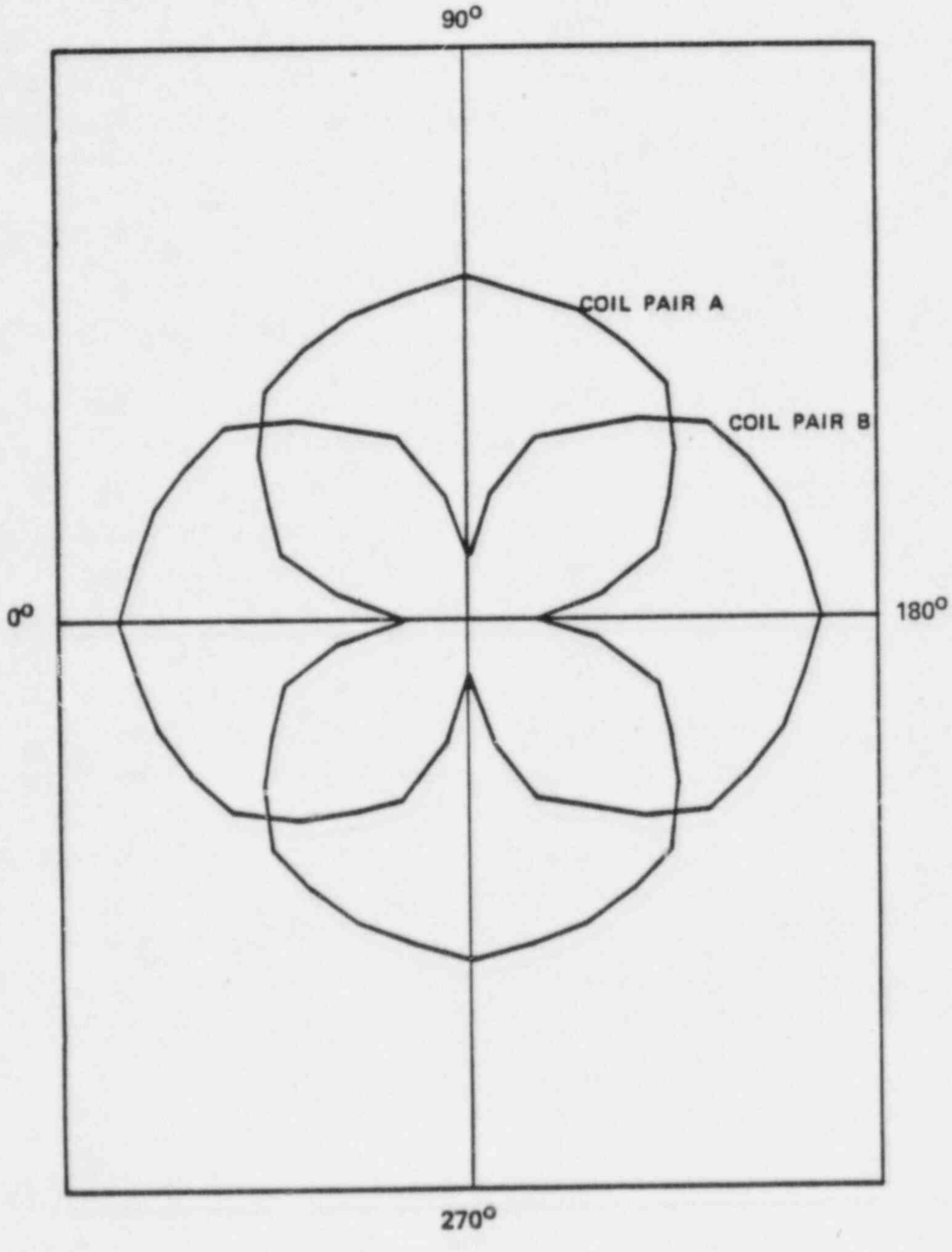


Figure 6-59. Dual Cross-Wound Probe Response

Bimetallic sleeve designs which utilize nickel as the clad material introduce an additional problem. Nickel is ferromagnetic which decreases eddy current penetration within the parent tube wall. Variations in the nickel cladding thickness and permeability will introduce extraneous signals which will reduce inspection capability as compared with a non-ferrogmagnetic clad material. The latter problem can be mitigated somewhat by using magnetic saturation techniques in connection with the eddy current inspection.

Qualification of the proposed inservice inspection method should be done as a general rule. The plant technical specification will determine minimum inspection requirements. In addition, it is recommended that postulated sleeve-parent tube failure modes be identified. This would allow for the fabrication of appropriate defect geometries, depths and locations with respect to extraneous test variables, e.g., tube end, expansion area, etc. A demonstrated capability of the inservice inspection method could then be identified.

As mentioned previously, in-plant baseline eddy current data should be acquired on all sleeved tubes. This will provide for a data base for comparison with subsequent inservice inspection data. Some units with sleeved tubes have experienced problems with primary side magnetite accumulating within the gap between the sleeve and parent tube above the upper expansion. This has resulted in distorted eddy current signals which were duplicated experimentally in the laboratory and also verified destructively. Service related sleeved tube eddy current signal distortion should be carefully monitored during subsequent ISI's and explained.

Section 7

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Appendix A

DEFINITIONS

The following definitions are povided to ensure a uniform understanding of terms used in this guideline:

Absolute Mode Bobbin Coil

A large diameter multi-turned multi-planar winding internal to a tube, mounted so that its axis is parallel to the tube longitudinal axis (see Appendix B, Figure B-1). Current flow in the test object parallels the coil's windings.

Anti-Vibration Bars (Straps)

Mechanical restraints placed in the upper part of the tube bundle to inhibit flow-induced tube vibrations.

Array Coil

Multiple, radially aligned coils configured onto a common shaft in order to achieve complete inspection coverage of the tube wall (see Figure 4-26).

ASME Calibration Standard

A section of steam generator tubing containing specified artificial discontinuities which is used for eddy current system calibration.

Auxiliary Frequencies

Eddy current test frequencies used in addition to the basis frequency for measuring conditions internal or external to the tube wall and for suppressing extraneous variables.

Basis Frequency

The frequency normally used for examination of the tube wall. The value of the basis frequency is a function of the tube wall thickness and the resistivity for non-ferromagnetic tubing.

C-Type Indications

Anomalous eddy current signals occurring at the upper and lower tube sheet in OTSGs. C1, C2, and C3 are specific classifications of the general C-type indication; the numbering does not necessarily reflect the severity of the indication.

Damage Precursor

A condition existing within a steam generator whose detection and characterization may provide early warning of changes in tubing integrity. Recognized tube damage precursors include sludge, debris, copper, denting, packed magnetite crevices, and cracked support plate ligaments.

Debris

Solidified material of high iron content which appears in OTSGs as deposit buildup at tube support plates, on tubes, and on the secondary side of the upper tube sheet. Pieces of debris may also appear scattered throughout the steam generator.

Denting

Plastic deformation of tubes resulting from the buildup of corrosion products (magnetite) in the tube-to-tube support structure annuli.

Differential Bobbin Coil

Two bobbin coils connected in series-opposition and separated by some distance d so that their respective fields overlap a common region (see Figure 4-21). This coil configuration responds more strongly to localized axial changes in tubing geometry such as cracking than to gradual or tapered changes such as thinning.

Dings

Tube diameter reductions caused by manufacturing, support plate shifting, vibration, or other mechanical means.

Eddy Currents

Electron current flow in a conductive object resulting from a time-dependent magnetic field in proximity to the test object.

Eggcrate

Intersecting strips of metal used to provide restraint of tubes in lieu of drilled support plates (found in Combustion Engineering steam generators).

Erosion-Corrosion

The combined effect of corrosion and erosion caused by thermal-hydraulic conditions and the impingement of fluids containing suspended particles or highly reactive chemicals.

Extraneous Test Variable

A source of noise that tends to obscure test results of interest.

Fatigue

Material failure resulting from the initiation and/or propagation of cracks due to cyclic loads.

Fill-Factor

A measure of the degree to which a bobbin coil fills a tube. Specifically, the square of the ratio of bobbin coil outside diameter to tube inner diameter.

Flow Slots

Rectangular holes within the support plate between the hot and cold leg inner row U-bends of Westinghouse units.

Fretting

The loss of tube material caused by excessive rubbing of the tube against its support structure.

Gamma-Ray Radiography

An NDE method that uses high-energy electromagnetic radiation to shadow image a test object onto photographic film plates.

Gauging

A technique that estimates the degree of restriction or minimum diameter or a tube by passing probes of various sizes through the tube.

Hard Spots

Areas of the tube support plate located near the edges of flow slots and the support plate periphery, which do not have flow holes.

Hourglassing

Deformation of the flow slots as a result of denting. The parallel flow slot walls become narrower in the center than at the ends.

ID Noise

Noise due to variations in the tube wall inner diameter (ID). An annular bobbin coil senses this as a variation in fill-factor.

Interior

The inner region of an OTSG tube bundle. Its boundary is approximately defined by the circular orientation of a series of support plate tie rods (see Figure 5-9).

Intergranular Attack (IGA)

Corrosion attack of grain boundaries in Inconel 600.

Kidney Region

A region of the tube sheet in which the sludge height is a half-inch or greater. For Westinghouse units it is typically the interior region of the tube bundle bounded by columns 20-70 and Rows 2-20. The kidney region for OTSGs is illustrated in Figure 5-9; it is approximately defined by a "Kidney-shaped" pattern of support plate tie rods.

Lane

An untubed inspection lane in OTSGs. In the lane, a row of tubes stretching halfway across the tube bundle is omitted in order to facilitate access to the tube bundle. (See Figure 5-9.)

Lane Region

Groups of tubes in an OTSG within three rows of the untubed inspection lane from the 15th support plate to the upper tube sheet (see Figure 5-9).

Lift-Off

The distance between a pancake or probe coil and the test object surface. Variations in lift-off cause variations in the output signal.

LTS Banana

An anomalous eddy current signal distortion, shaped like a banana, occurring at the lower tube sheet in OTSGs. The signal has been duplicated experimentally by placing magnetite around the tube near the tube sheet edge.

Mixer

An analog signal processing device for eddy current data consisting of summing amplifiers, weighting resistors, and phase rotators. A mixer has multiple input dual ports and a single output dual port.

Multiple Frequency Eddy Current

The application of more than one frequency to a test coil. The frequencies may be applied simultaneously or multiplexed.

Multiparameter Eddy Current

A signal processing method that combined multiple frequency eddy current data in order to suppress extraneous test variables.

Multiplexing

The time-sharing of an information source with a common output.

Noise

An unwanted addition to a signal.

Off Lane

A location in an OTSG tube bundle not in the lane region.

Ovalization

A tube condition in which a transverse cross section departs from a circular section, i.e., tube diameters measured at different angular positions are not equal. Ovalization can occur as a consequence of extreme denting or from tube bending practices.

Pancake Coil

A small diameter winding, mounted so that its axis is perpendicular to the test object surface (see Figure 4-23). The windings are in a single plane, wound with increasing radii. This coil type is extremely sensitive to lift-off; it may be used in a multiplexed array configuration for profiling dents.

Periphery Region

The outer region of an OTSG tube bundle. Its boundary is approximately defined by the circular orientation of a series of support plate tie rods (see Figure 5-9).

Phase Angle

The angle subtended by an eddy current signal vector as measured from the horizontal axis of the signal display. For a differential bobbin coil, the angle is typically measured at the transition or crossover region between the response of the two coils (see Figure 6-1). For an absolute coil, the angle is measured at the signal peak (see Figure B-2).

Pitting

Localized corrosion attack on tubing.

Primary Side Stress Corrosion Cracking

Stress corrosion cracking on the reactor coolant side (inside) of steam generator tubes.

Probe Coil

A small diameter multi-turned multi-planar winding, mounted so that its axis is perpendicular to the test object surface (see Figure 4-23). Current flow in the test object parallels the coil windings in a

direction opposite to the current flow in the winding.

Probe Wobble

The tilting or off-center movement of a bobbin coil within a tube. This motion gives rise to a "wobble signal" which is normally linear and is rotated onto the horizontal axis of the eddy current signal display.

Profilometry

The process by which a transverse cross-section of a dent is determined. From the profile information, tube strain can be estimated.

Secondary Side Stress Corrosion Cracking (SCC)

Stress corrosion cracking on the outsides of the steam generator tubes.

Single Frequency Eddy Current

The application of one frequency to a test coil.

Signal Subtraction

A single frequency signal processing method in which a reference signal is subtracted from a distorted signal in order to identify the nature of the distortion. Typically the distorted signal is a support plate or tube sheet signal perturbed by a signal from partial through-wall degradation. The reference signal in this case would be an undistorted support plate or tube sheet signal.

Sludge Pile

An accumulation of particulate matter, typically confined to low flow areas of the steam generator on the tube sheet or, in some cases, support plates. Since sludge is typically ferromagnetic, it gives a strong response to an eddy current probe.

Sludge Profiling

Measuring the extent of the sludge pile.

Strain Gage

An electromechanical device that provides an electrical output signal proportional to the displacement of a mechanical arm.

Stress Corrosion Cracking (SCC)

Intergranular cracking of stressed tubes without reference to a causative chemical agent.

Surface-Riding Coils

Eddy current coils that are mechanically loaded to ride the tube surface in order to reduce lift-off effects.

Thinning

Loss of tube wall thickness as the result of corrosion.

Wastage

A localized secondary side corrosion of Inconel 600 caused by chemical attack from acid phosphate residues concentrated in low flow areas.

Appendix B

EDDY CURRENT INSPECTION OF STEAM GENERATORS

B.1 STEAM GENERATOR EDDY CURRENT TEST DESIGN

Eddy current examination methods play an important role in steam generator inspection. This section reviews basic material for the reader unfamiliar with its basic principles and provides background information related to test frequency selection.

B.1.1 Eddy Current Fundamentals

If a test coil is excited by an alternating current source, a time varying primary magnetic field is generated which in turn induces current flow (eddy currents) in a conductor intercepting the coil's magnetic field. From Lenz's Law, the eddy currents create an opposing secondary magnetic field that is superimposed on the test coil primary magnetic field, decreasing the coil flux which in turn modifies the coil voltage. See Figure B-1.

The orientation of the coil windings and the direction of current flow within the windings determine the direction of the eddy current flow in the neighboring conductor. In general, eddy current flow is parallel to the coil windings. Discontinuities within the tube wall which have a component perpendicular to the eddy current flow will perturb the flow modifying the coil voltage. The coil voltage is displayed and monitored on a storage scope for further analysis.

During steam generator tube inspection, the coil is translated through the tube from the primary side. If a region of the tube contains variations in wall thickness, a time-dependent signal will be generated as the coil scans through the discontinuity. This is illustrated with the aid of Figure B-2.

Coil positions A · ıd C represent regions of the tube that do not exhibit degradation. For this condition, a quiescent coil voltage will

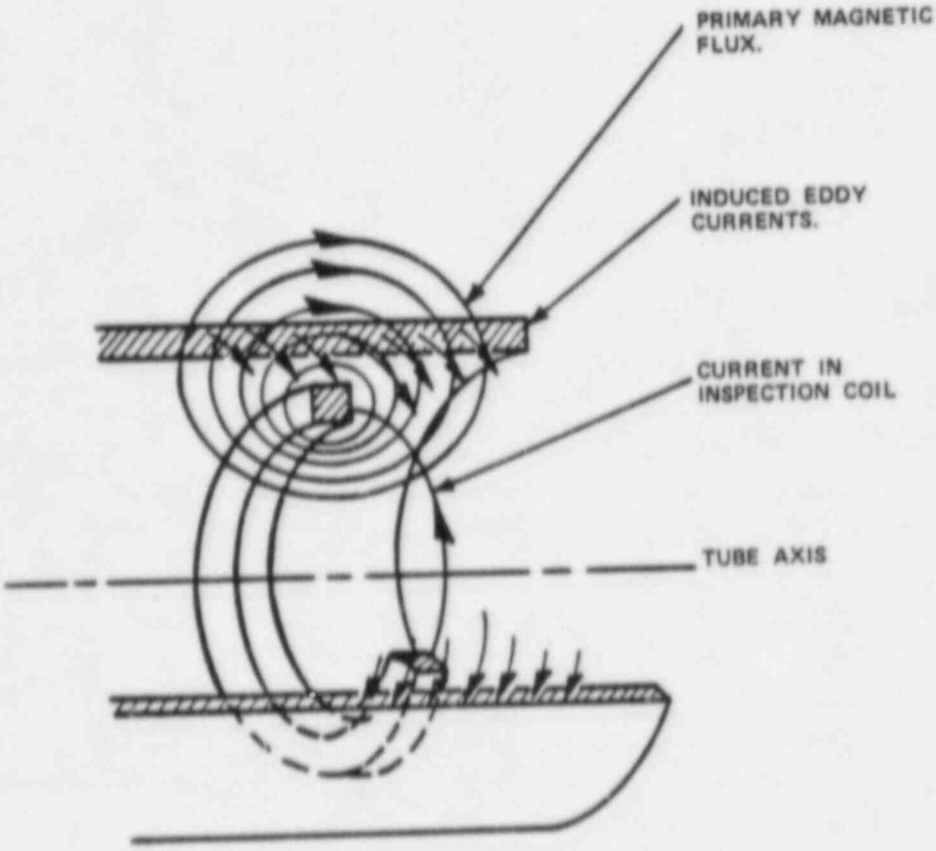
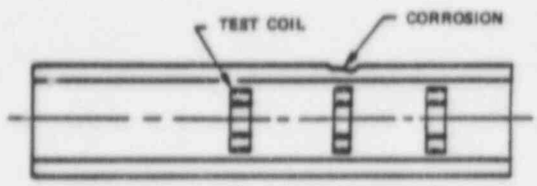
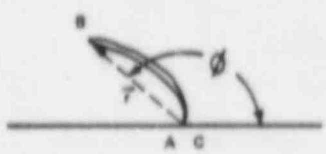


Figure B-1. Eddy Current Bobbin Coil Tube Inspection (CEGB)

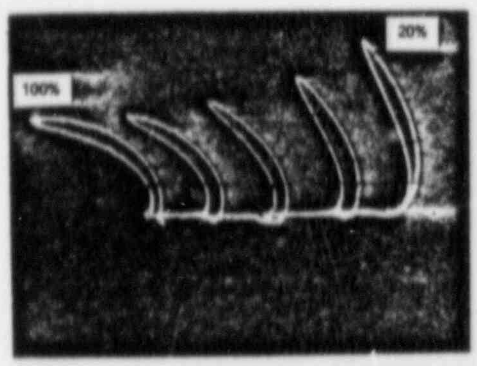


(A) BOBBIN COIL STEPPED THROUGH A CORRODED REGION OF A TUBE

LENGTH OF VECTOR $\vec{AB}$ IS ITS MAGNITUDE. Ø IS THE ANGULAR POSITION RELATIVE TO THE HORIZONTAL AXIS.



A,B,C DENOTE COIL POSITION IN TUBE SHOWN IN FIGURE (A).



SIGNALS FROM A SERIES OF HOLES IN A TUBE. HOLE DEPTHS FROM LEFT TO RIGHT ARE NOMINALLY 100%, 80%, 60%, 40%, AND 20%.

(B) EDDY CURRENT SIGNAL DYNAMICS.

Figure B-2. Bobbin Coil Detection of Tube Wall Degradation

be displayed on the storage scope. As the coil is translated past position B, which has some tube wall loss, the eddy current flow in the tube is perturbed, modifying the coil output voltage. Thus the coil voltage will trace a signal from A to B with a return to A as the coil is moved along the tube from position A to C (see Figure B-2).

The signal described by the locus of points A-B can be modeled as a vector which is characterized by a magnitude and phase angle. The magnitude of the vector is determined by the distance from A to B, whereas the angle phi describes the orientation of the vector relative to the horizontal axis of the storage scope. By measuring vector magnitude and/or angle, an estimate the tube wall loss as position B can be made.

Figure B-2 illustrates absolute mode bobbin coil signals obtained by scanning a series of flat-bottomed holes ranging in depth from 20% to 100% of the tube wall thickness. As can be seen, the phase angle decreases monotonically with increasing hole depth. A calibration curve is then generated which relates phase angle to hole depth. During an inspection, the phase angle of the signal from a discontinuity is measured. This angle in conjunction with the calibration curve is then used to estimate the depth of the actual discontinuity in the tube wall.

The accuracy is estimating the depth of a discontinuity within the tube wall will be controlled by the geometry of the discontinuities in the calibration standard. The closer the correspondence between the discontinuities in the standard and the actual degradation in the tube, the better the depth estimate. The measurement error can be conservative or nonconservative depending on geometry differences between discontinuities in the standard and the actual tube wall.

As can be seen from Figure B-1, the test coil primary magnetic field or flux penetrates beyond the tube wall. Penetration of the magnetic field through the tube is controlled by frequency for a given coil and tube material property values. Magnetic or conductive objects near the tube wall that intercept the test coil primary magnetic field also induce eddy currents affecting the test coil output voltage.

This can be advantageous or detrimental depending on the test objectives.

Typical secondary side conditions which can affect eddy current coil response include sludge and debris, support plates, and tube sheet, antivibration bars (AVBs), and copper deposits. Some of these conditions are of interest from a detection-measurement standpoint i.e., sludge, debris, while other conditions can interfere with the measurement of tube wall degradation i.e., tube sheet, support plate, and copper. These latter conditions interfere with the measurement of tube wall degradation by creating extraneous signals which in general must be suppressed.

The test coil is also extremely sensitive to spacing variations between the coil outside diameter and the tube inside diameter. Therefore, variations in tube geometry caused by denting, dings, roll transition, and ID noise can cause extraneous signals that affect the measurement of tube wall degradation.

The effects of the extraneous variables discussed previously can to some extent be controlled by the proper selection of frequencies. The introduction of multifrequency eddy current instrumentation has provided the capability to efficiently acquire data at different frequencies during a single probing of the tube. Eddy current data at the different frequencies can be reviewed for an assessment of tube wall integrity, for conditions of interest external and internal to the tube wall, and the suppression of extraneous signals.

B.1.2 Multifrequency Eddy Current Testing

Eddy current testing objectives of a steam generator are 1) to detect and measure tube wall integrity and 2) monitor damage precursors. These objectives are achieved by selecting several test coil excitation frequencies, each of which is sensitive to a particular condition of interest. This is called multiple-frequency or multifrequency examination. During the analysis phase, the appropriate test frequencies are reviewed individually for tube wall degradation and damage precursors.

With multifrequency eddy current instrumentation, the coil is excited at several frequencies. An advantage of multifrequency eddy current instrumentation is that signals associated with tube wall degradation can be distinguished from signals due to other conditions. By selecting appropriate frequencies, conditions external, within, and internal to the tube wall can be assessed. In addition, multifrequency eddy current data can be analyzed using special signal processing equipment to reduce the influence of extraneous signals resulting in the more reliable assessment of tube wall degradation.

Extraneous variables are suppressed by the appropriate vectorial combination of the multifrequency eddy current data. This can be accomplished using analog hardware such as the Zetec MIZ-12 or DM3-VA, or in software using the Zetec DDA-4. The former devices are called mixers, whereas the latter approach using software is called digital mixing.

Multiparameter signal analysis is the general term used to describe extraneous signal suppression. Since it relies on eddy current data from different frequencies, multifrequency eddy current data is required for multiparameter signal analysis. It is possible however to conduct a multifrequency examination without doing multiparameter analysis.

B.1.3 Eddy Current Frequency Selection

This section provides general background information to assist in eddy current frequency selection using a bobbin coil.

Determining tube wall integrity is of primary interest in steam generator examination. Other conditions in close proximity to the tube wall may or may not be of interest. Typical steam generator conditions that can be encountered in a section of a tube are summarized in Figure B-3(a).

To establish test frequencies for multifrequency examination, a intermediate frequency is selected for monitoring tube wall integrity; this is termed the basis frequency. Auxiliary frequencies are then selected to monitor other conditions of interest. A lower auxiliary frequency is selected for monitoring sludge height and/or support plate cracking,

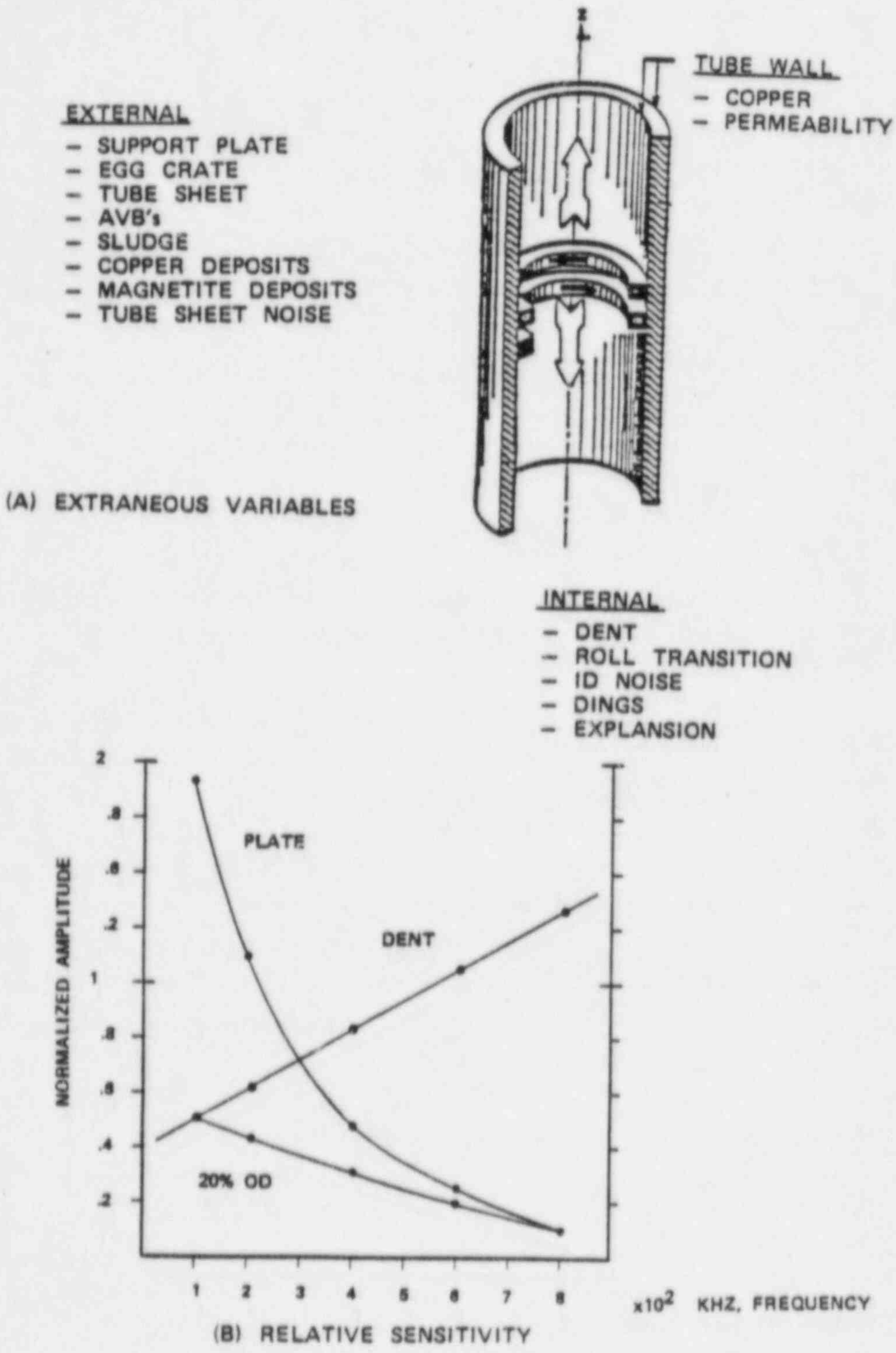


Figure B-3. Tube Wall Test Variables - Relative Sensitivity at Different Frequencies

while a higher auxiliary frequency might be selected for monitoring conditions inside a tube i.e., detecting denting.

Frequency selection for the various test applications is based on differences in relative sensitivity. Lower frequencies are more sensitive to conditions external to the tube wall whereas higher frequencies will be more sensitive to conditions internal to the tube wall. Intermediate frequencies will be sensitive to variations within the tube wall with some sensitivity to both external and internal tube wall conditions. This is illustrated with data shown in Figure B-3(b).

Normalized signal amplitudes from a support plate, a 20% through-wall hole, and a dent are plotted against frequency in Figure B-3(b). These signals are associated with external, through-wall, and internal tube conditions respectively. On a normalized basis, lower frequencies are more sensitive to external tube wall conditions; higher frequencies are more sensitive to internal tube wall conditions.

Figure B-3(b) also implies that test frequencies can be selected to enhance a particular variable of interest while reducing a second variable. For example, consider the detection of support plate ligament cracking. Since this typically will occur at dented support plate intersections, the analyst must contend with two signals: the dent signal and the support plate signal. As frequency is lowered, plate signals increase while dent signals diminish (see Figure B-3(b)). Thus, by selecting an appropriately low frequency, the effects of the dent signal on the support plate ligament signal can be reduced.

Another example of simultaneous test variables occurs when monitoring a tube sheet roll transition region for evidence of cracking. At a higher frequency, the roll transition signal caused by the change in internal geometry may overwhelm signals associated with cracking. Review of an intermediate auxiliary frequency will decrease the effects of the roll transition signal and will improve the detection of tube wall degradation.

Denting provides a final example of the need for proper auxiliary frequency selection. Denting, which is an internal tube wall condition,

can occur at support plate, eggcrate, or tube sheet intersections. A high auxiliary frequency will emphasize the dent signal at the expense of the external structural support signal. Hence, in reviewing eddy current data for evidence of denting, the higher auxiliary frequency data should be examined.

To summarize, steam generator examination requires low, intermediate, and high frequencies. Factors which affect the selection of actual frequency values are now addressed.

B.2 FREQUENCY SELECTION

B.2.1 Basis Frequency

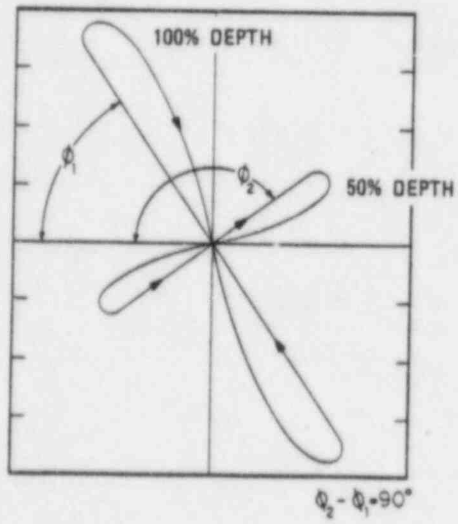
The test coil frequency that is used to monitor tube wall integrity in the absence of extraneous variables is called the basis frequency. When extraneous variables are present, auxiliary frequencies of multi-parameter channels are also reviewed during data analysis.

Initial criteria for selecting a basis frequency value are based on work documented in (50). Significant factors which were investigated included:

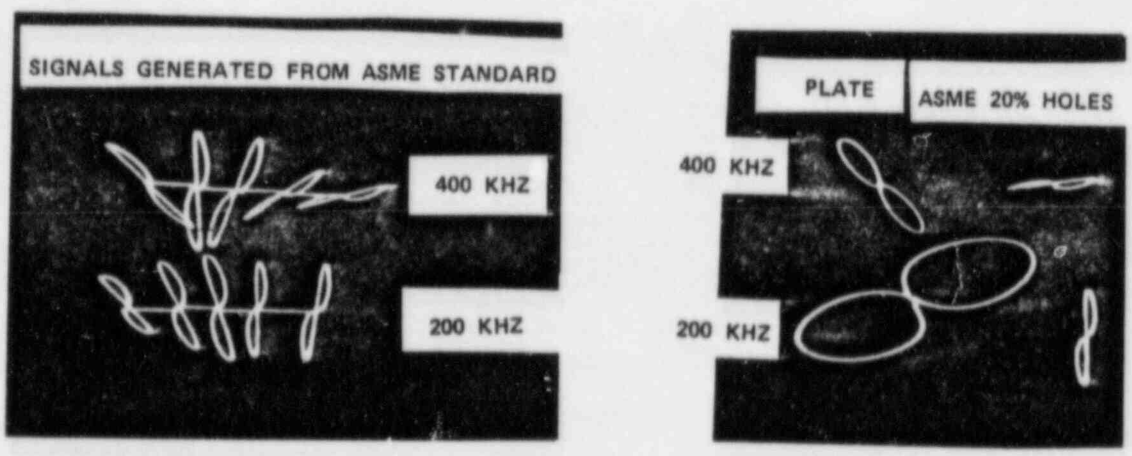
- Minimizing the effects of probe motion (wobble)
- Compromising between phase angle separation and sensitivity to tube wall degradation
- Reducing the effects of the support plate and tube sheet.

These various criteria for selecting an optimum basis frequency can be expressed in a single rule: the optimum choice for basis frequency is that which results in a ninety-degree phase angle difference between a 100% and 50% through wall hole (50). This criterion is illustrated in Figure B-4. The actual frequency value is experimentally determined; for Alloy 600 steam generator tubing, the frequency value is primarily determined by the tube wall thickness. For 0.050" wall tubing, a frequency of 400 KHz satisfies the phase angle criteria.

Equation B-1, which is based on the classical skin-depth relationship for a plane electromagnetic wave penetrating a conducting medium, has been used to numerically estimate an optimum basis frequency based on the phase angle separation criterion mentioned previously (51).



(A) BASIC FREQUENCY DEFINITION BASED ON PHASE ANGLE DIFFERENCE



PHASE ANGLE DIFFERENCE AT TWO FREQUENCIES

EFFECT OF A SUPPORT PLATE SIGNAL AT TWO FREQUENCIES

(B) FACTORS AFFECTING FREQUENCY SELECTION

Figure B-4. Criteria Effecting Selection of Basis Frequency

$$f = \frac{10r}{t^2} \qquad \text{B-1}$$

where

r is the resistivity of the tubing in micro-ohm-cm
t is the tubing wall thickness in inches
f is the optimum frequency in Hertz.

For Inconel 600 tubing, the nominal resistivity is 100 micro-ohm-cm. The second column in Table B-1 lists the basis frequency calculated from Equation B-1 for various ranges of steam generator tube wall thicknesses. As the tube wall thickness decreases, the frequency required to achieve the desired phase angle spread increases.

Table B-1

FREQUENCIES TO ACHIEVE 90° PHASE ANGLE DIFFERENCE AND FREQUENCIES RECOMMENDED FOR DETECTION OF TUBE WALL DEGRADATION

Nominal Tube Wall Thickness	90° Phase Angle Optimum Frequency (See Equation B-1)	Recommended Detection Basis Frequency*
.055"	340 KHz	170 KHz
.048-.050"	430-400 KHz	200 KHz
.043"	540 KHz	225 KHz
.038"	690 KHz	400 KHz

*Note: Frequencies are approximate and may have to be modified modified depending on circumstances.

The basis frequency definition provided by Equation B-1 is not universally accepted. The major point of disagreement derives from the fact that the phase spread criterion results in a relatively high choice of frequency. A high frequency is especially undesirable in thinner walled tubing (0.043" or less), where tube ID noise and probe motion have a stronger impact on detection and measurement capability. Tube ID noise is particularly prevalent in some Combustion Engineering System 80s and some Westinghouse preheater units, due to

tube manufacturing practices.

Detection of tube wall degradation must logically precede measurement or estimation of the depth of degradation. The 90° phase angle criterion for selecting a basis frequency attempts to optimize simultaneous detection and measurement using one frequency. Sequential optimization of the eddy current test identifies separate frequencies to provide optimum detection and optimum measurement. This is the approach recommended in this document.

The third column of Table B-1 summarizes the recommended basis frequencies for detection of tube wall degradation. These frequencies are lower than those based on the phase angle criterion. After tube wall degradation has been detected, higher auxiliary frequencies may be used to estimate through-wall depth is desired.

The remainder of this section discusses the reasons underlying the frequency recommendations shown in Table B-1.

Detection of tube wall degradation is achieved by monitoring for the presence of a signal. As frequency is increased, the signals associated with through-wall degradation rotate in a clockwise direction towards the horizontal axis of the display (see Figure B-4, which shows eddy current signals for a range of through-wall depths at 400 KHz and 200 KHz). At 400 KHz, most of the signal component for through-wall hole depths of 20-40% is on the horizontal axis. At 200 KHz, little rotation is observed with depth; essentially all of the signal is on the vertical axis.

Probe motion, tube geometry changes, and tube ID noise occur on the horizontal channel. A higher signal-to-noise ratio can be achieved using the lower frequency of 200 KHz than can be obtained using 400 KHz because of the larger signal on the low noise vertical channel. Since higher signal-to-noise ratios result in improved detection reliability, frequencies lower than those calculated using Equation B-1 are better for detection of tube wall degradation.

Tube support plate and tube sheet signals are more pronounced at lower frequencies (see Figure B-4), reducing the signal-to-noise ratio.

Therefore, for tube wall degradation occurring in proximity to the support plate or tube sheet, single frequency eddy current methods will produce less reliable results at the lower frequency. This was one of the original reasons for adopting the phase angle criterion defined by Equation B-1. However, multifrequency/multiparameter eddy current instrumentation can reduce the effects of the extraneous support plate signal, which then becomes a less important factor in the selection of a basis frequency.

In addition to detecting tube wall degradation, the inspection should produce an estimate of its depth. The measurement error associated with the depth estimate is purportedly related to the eddy current signal phase spread. Phase spread is defined as the phase angle difference between the 100% and 20% through-wall holes. From Figure B-4 it can be seen that the phase spread is greater at 400 KHz than at 200 KHz. If phase angle is plotted versus depth for the two frequencies, the lower frequency will result in a curve with a greater slope than the higher frequency. Assuming a constant ±5 degree phase angle uncertainty independent of frequency, there will be a greater depth uncertainty at 200 KHz than at 400 KHz because of the differences in the slopes of the two curves. Under this assumption, 400 KHz represents a better measurement frequency.

The assumption of constant phase angle uncertainty, independent of frequency, has not been demonstrated. It should also be noted that this definition of measurement error is an estimate of the precision of the measurement process; it does not consider systematic errors caused by geometrical differences between the discontinuities in the calibration standard and those encountered during steam generator inspection. The latter source of error may be quite small or may be on the order of many tens of a percent through-wall.

In conclusion, since signal detection must occur before any measurement, and since there is no strong evidence favoring the choice of the frequency calculated in Equation B-1 as a "best" measurement frequency for tube wall degradation isolated from extraneous test variables, the frequencies listed in the last column of Table B-1 are recommended as basis frequencies. Again, the basis frequency is that frequency which is normally reviewed for detecting tube wall degradation.

B.2.2 Auxiliary Frequencies for Extraneous Variable Suppression

Auxiliary frequencies for extraneous test variable suppression depend on the location of the variable to be suppressed, i.e., internal or external to the tube wall. The auxiliary frequency is combined with the basis frequency; the latters numerical value is a function of the tube wall thickness as shown in Table B-1.

Frequencies higher than the basis frequency are preferable for internal extraneous variable suppression. For external extraneous variable suppression auxiliary frequencies higher than the basis frequency are preferable in RSGs; for OTSGs an auxiliary frequency lower than the basis frequency is recommended. This difference is discussed in a subsequent paragraph. In addition, certain basis frequency/auxiliary frequency combinations are recommended because they provide better signal-to-noise ratios.

Mixing. The purpose of mixing is to reduce the effects of extraneous test variables so that conditions of interest can be more reliably detected and characterized. Complete suppression of an extraneous variable is never achieved. Accordingly, the signal-to-noise ratio in the mixed channel output is an important consideration.

The noise level is generally determined by the care in establishing the mixer settings; to some extent it can be controlled. The signal level is determined by the size of the defect, which may vary over a large dynamic range. Flaw depth estimates derived from the mixed channel are reliable only when the signal-to-noise ratio is on the order of 5-10. The larger signal-to-noise ratio value is for the condition in which the defect signal is strongly influenced by an extraneous variable, such as when a defect is located near the support plate edge.

Figure B-5 shows examples of the mixed channel output for tube wall degradation at a support. Data from the same support plate intersection is illustrated taken during two separate outages four months apart. The earlier data has a vary small signal-to-noise ratio; the estimated depth based on phase angle analysis is approximately 60% through wall. Data from the later outage shows a much greater signal-to-noise; the estimated depth is less than the earlier depth estimate.

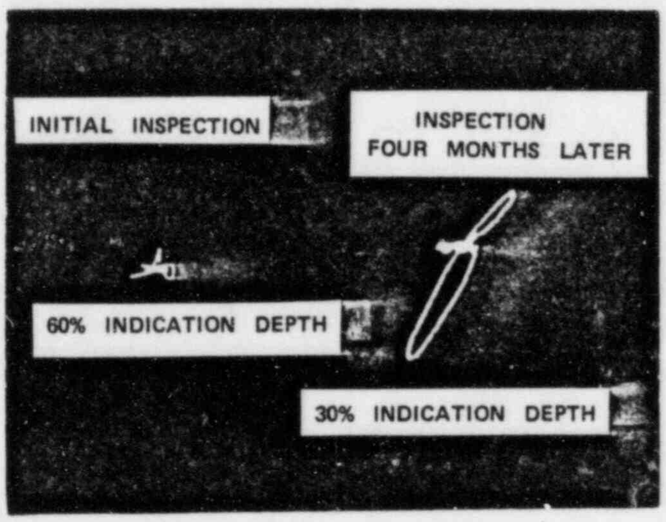


Figure B-5. Illustration of Poor Signal-To-Noise in Mixed Channel Output

This discrepancy in sizing is attributed to low signal-to-noise.

Sizing of low signal-to-noise ratio signals can result in the unnecessary plugging of tubes. Tubes with a low ratio should not be removed from service unless there is evidence the suspect signal is a crack which might impact plant availability. The low signal-to-noise ratio should be monitored during subsequent outages.

Mixing is accomplished by using analog computers called mixers. As shown in Figure B-6(a), a mixer has two inputs and one output. The extraneous variable is sampled at two frequencies f1 and f2. The in-phase and quadrature components of the input signals are weighted (scaled) in order to produce a niminal residual output in the difference (f1-f2) for the extraneous variable. Thus the mixing process is basically a vector subtraction operation.

Frequency f2 is typically the basis frequency. The auxiliary mixing frequency f1 can be higher or lower than this, depending on whether the extraneous variable is internal or external to the tube wall. To get an adequate sample of the extraneous variable, the variable is selectively favored by using frequency as a weighting device (see Figure B-3).

Since the mixing operation is a vector subtraction, the frequencies f1 and f2 must not approach each other, or the output (f1-f2) becomes zero for all inputs, including tube wall degradation. As the mixing frequency approaches the basis frequency, a loss in signal amplitude in the mixed channel output occurs. This is called mixing loss. The reduction in signal amplitude can be compensated somewhat by increasing the gain in the mixed channel output.

A general rule of thumb is that the auxiliary mixing frequency should be no greater than half the basis frequency for external extraneous variables and no less than twice the basis frequency for internal extraneous variables.

The preceding discussion addresses the suppression of a single extraneous variable, either external or internal to the tube wall. In steam generator inspection, multiple extraneous variables can be present

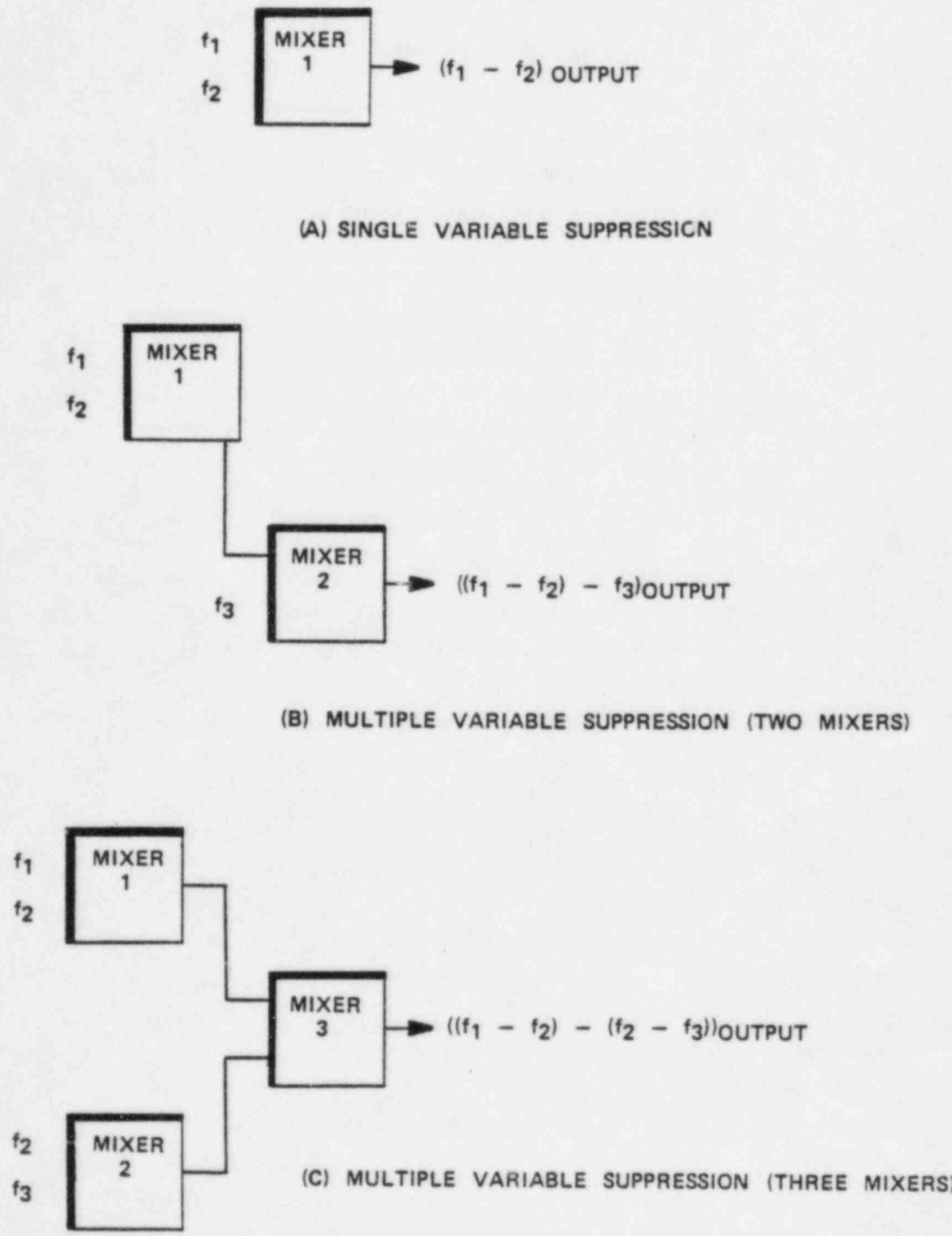


Figure B-6. Mixer Configurations

simultaneously. For example, denting (an internal variable) may occur at a support plate or at the roll expanded region at the top of the tube sheet (external variable). With the mixing configuration of Figure B-6(a), only one of the two variables can be suppressed.

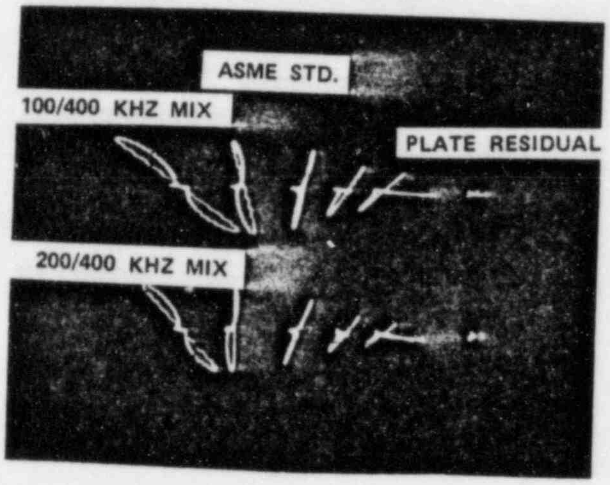
Mixing approaches for multiple simultaneous variable suppression shown in Figure B-6(b) and (c) rely on appropriate mixer sequencing. In Figure B-6(b), the external extraneous variable is suppressed in the first mixing stage; the output is then fed to a second mixer and combined with a higher mixing frequency f3, which is sensitive only to tube ID effects. In practice f3 should be on the order of 1.6 MHz for two stage mixing. Zetec MIZ-12 and Intercontrole IC3FA instrumentation have an upper limit of approximately 600 to 900 KHz. At these frequencies, the f3 support plate signal may be the limiting factor in the mixed output channel signal-to-noise ratio.

Work documented in (10) has found a way around this high frequency limitation. As illustrated in Figure B-6(c), three mixers are required. Mixers 1 and 2 achieve a double elimination of the external extraneous variable using a basis frequency f2 in conjunction with auxiliary mixing frequencies f1 and f3. Frequency f1 is between f2/4 and f2/2. Frequency f3 is typically 1.5 f2. The outputs of Mixer 1 and Mixer 2 contain only the internal extraneous variable, which is then suppressed in Mixer 3.

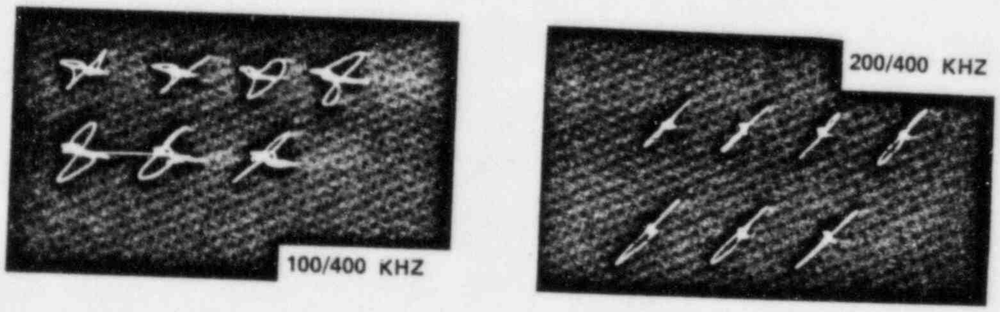
Specific mixing approaches for extraneous variable suppression are now considered.

Support Plate Suppression. Two differential bobbin coil mixing approaches have been utilized for support plate suppression. In the following discussion, the two approaches are compared for Westinghouse 0.050" wall tubing.

The two approaches utilize the same auxiliary mixing frequency (400 KHz), but differ in their selection of basis frequency (100 KHz versus 200 KHz). Figure B-7(a) shows the response of the two mixing approaches to an ASME calibration standard and shows the support plate residual.



(A) SUPPORT PLATE SUPPRESSION USING TWO DIFFERENT BASIS/AUXILLIARY FREQUENCY COMBINATIONS



(B) PLATE RESIDUAL DISTORTION OF A 20% ASME HOLE AS IT IS STEPPED THROUGH A SUPPORT PLATE EDGE

Figure B-7. Support Plate Suppression Using Different Basis-Auxiliary Frequency Combinations

The (100x400) KHz combination has a larger phase spread and greater amplitude. However, the (200x400) KHz combination has a better signal-to-noise ratio, as can be seen by comparing the magnitude of plate residual with the ASME calibration standard eddy current signals. The (200x400) KHz is believed to have less statistical precision than the (100x400) KHz because of phase angle compression.

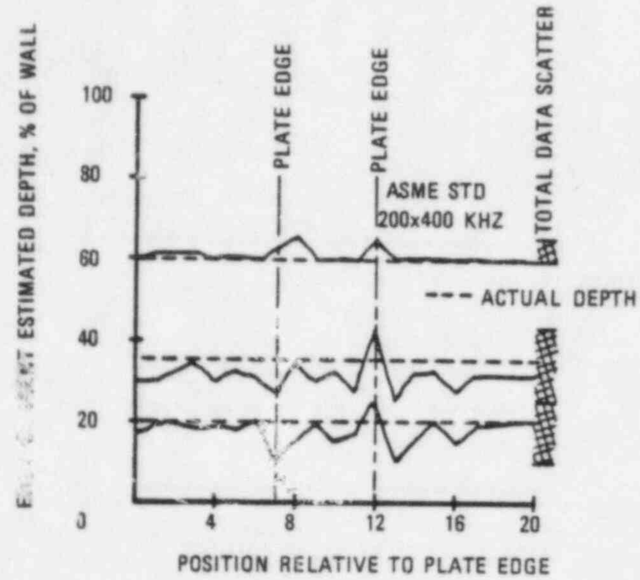
The signal-to-noise ratio advantage of the (200x400) KHz approach has been compared with the (100x400) KHz phase spread advantage. Figure B-7(b) shows signals from an ASME calibration standard as it was stepped through the edge of a support plate. The (200x400) KHz combination exhibits a better signal-to-noise ratio, with less signal distortion; the output of the mixed channel is essentially a straight line. The (100x400) KHz combination shows a poorer signal-to-noise ratio, with considerable signal distortion. This distortion reduces the reliability of phase angle measurements, which are necessary for depth estimation.

The ultimate comparison involves the depth estimate error shown in Figure B-8. The error in estimated depth is less for (200x400) KHz combination than for the (100x400) KHz combination. Therefore, signal-to-noise ratio is a more fundamental quantity than phase angle spread.

The (200x400) KHz mixing approach for plate support suppression in 0.050" wall tubing can be translated to other tube wall thicknesses by frequency scaling. For 0.055" wall thickness, the equivalent frequencies are 170x340 KHz.

For 0.038" and 0.043" wall tubing, an auxiliary mixing frequency which is greater than the 400 KHz basis frequency is subject to tube ID noise effects and results in an inadequate sample of the support plate. In order to reduce the effects of mixing loss, the auxiliary mixing frequency is lowered to 200 KHz. The net result is that a (200x400) KHz combination is recommended for all wall thicknesses less than 0.050" for support plate and tube sheet suppression.

Copper Suppression. The mixing rules should be modified in the presence of copper, which can be external or within the tube wall and which may occur in conjunction with pitting. For wall thicknesses of



NOTICE LESS SCATTER
IN DATA FOR 200/400 KHZ
COMBINATION.

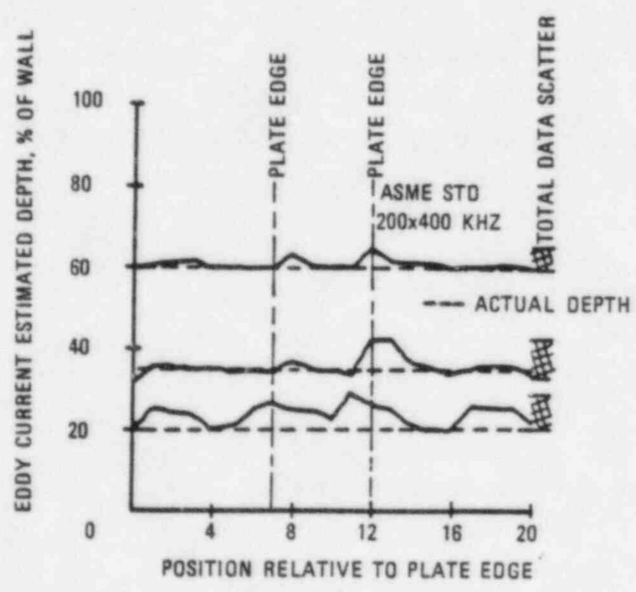


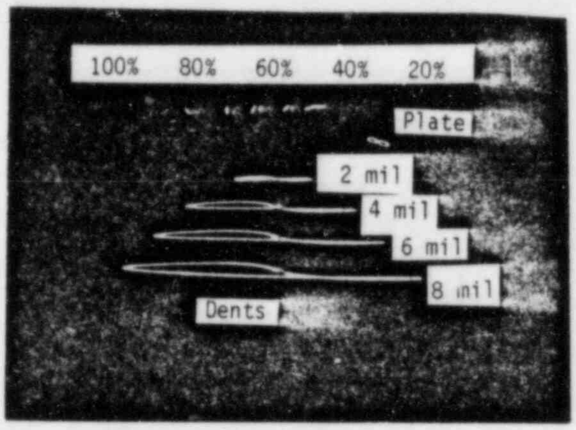
Figure B-8. Mixing Error for Different Basis-Auxiliary Frequency Combinations

0.050", the 200 KHz basis frequency is retained, but the mixing frequency is raised to 600 KHz in order to decrease the depth of penetration of the basis frequency. Higher mixing frequencies and modifications decreasing probe focus have been shown to be effective in suppressing extraneous signals associated with copper deposits (29).

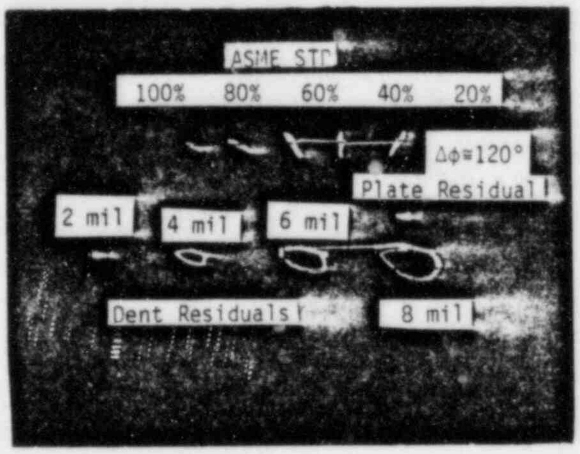
Internal Variable Suppression. The mixer configuration shown in B-6(a) is recommended for single internal variable suppression, i.e., for suppression of ID noise and roll transition effects.

Tube ID noise, which is a result of certain manufacturing practices (e.g., pilgering), has been successfully suppressed using mixing approaches. Using an auxiliary mixing frequency twice the basis frequency i.e., 800 MHz and 400 KHz respectively (0.043" wall tubing), the uncertainty in sizing tube wall degradation in the presence of ID noise was estimated at ±5% through wall (52).

Mixing approaches for dent suppression have typically utilized the mixer configuration shown in Figure B-6(c). Field experience with this mixing approach is documented in (10). Dent suppression capability is shown in Figure B-9. Shown are input and output signal-to-noise ratios using dents of various diameters and the ASME standard as a source for the wall degradation signals. Figure B-10 shows field data taken from a plant with extensive denting at support plates. Single frequency and mixed channel data are shown for comparison. The significant improvement in signal-to-noise ratio in the mixed channel output is obvious.

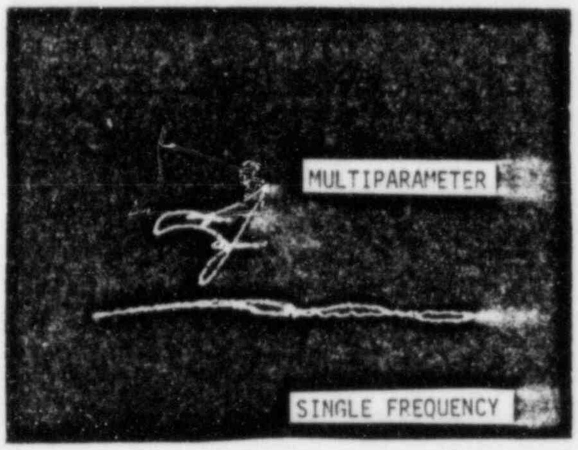


Dent Signal Input Signal-to Noise Ratio



Dent Signal Suppression - Output Signal-to-Noise

Figure B-9. Dent Signal Suppression



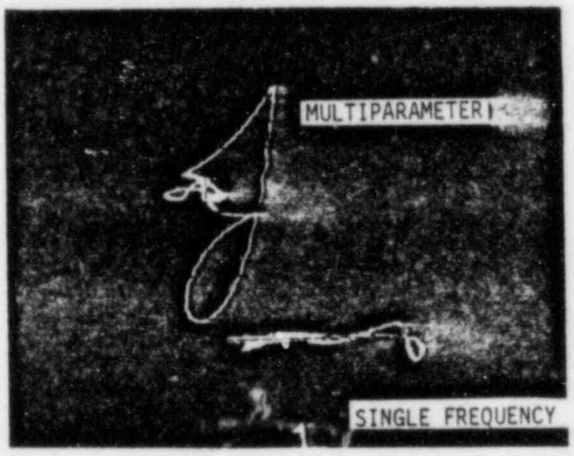


Figure B-10. Field Data Showing Improvements in Signal-to-Noise