REPORT SUMMARY

PWR Steam Generator Examination Guidelines: Revision 3

In work sponsored by the steam generator reliability project, a committee of experienced industry personnel has revised the PWR Steam Generator Examination Guidelines. On the basis of plant experiences, new research data, and lessons learned from implementing the original guidelines, this revised document will allow utilities to achieve the maximum benefit from periodic steam generator examination.

INTEREST CATEGORIES

Nuclear component reliability
Nuclear plant operations and maintenance
Nuclear plant corrosion control

KEYWORDS

Nuclear steam generators
In-service inspection
Eddy currents
Tubes
PWR

BACKGROUND PWR steam generator tubing has experienced damage from a wide variety of corrosion and mechanical mechanisms. During the early 1980s, EPRI and the Steam Generator Owners Group informally issued nondestructive evaluation (NDE) guidelines (the 1981 original and a 1984 revision) for the utility community. The purpose of these guidelines was to provide reliable NDE strategies for this diversity of damage mechanisms. With additional industry experience, increased understanding, and the emergence of new NDE technologies, an updated formal release of the guidelines was published in 1988. This revision incorporates guidelines on eddy-current performance demonstration and new information on interpretation of degradation signals at tube support plates.

OBJECTIVE To establish the recommended practice for the nondestructive examination of PWR steam generators that reflects utility operating experience.

APPROACH A committee of industry experts—utility staff, in-service inspection vendors, nuclear steam supply vendor representatives, and consultants—reviewed NDE research data, plant operating experiences, and industrywide NDE plant experience. The committee then established consensus recommendations to improve the reliability of steam generator NDE.

RESULTS The revised document consists of five chapters, eight appendixes, and one supplement. The main sections concisely present management and technical responsibilities as well as provide a recommended practice for steam generator examination. The appendixes offer additional detail on industry steam generator operating experiences, technical bases for developing random and augmented steam generator sampling plans, and industrywide steam generator NDE experiences with various damage mechanisms. The report also includes sample eddy-current data analysis guidelines and a typical bid specification for steam generator NDE. The newest version adds information on qualification of examination personnel, performance demonstration, and disposition of bobbin coil indications attributable to stress corrosion cracks at tube support plates.

EPRI PERSPECTIVE The establishment of a committee of industry experts who are knowledgeable about emerging technologies and plant needs provides an efficient means for translating laboratory research results into practice. The PWR

Steam Generator Examination Guidelines established by such a committee are of interest to generation, in-service inspection, and maintenance engineers.

PROJECT

RPS404
Project Manager: M. M. Behravesh
Nuclear Power Division

For further information on EPRI research programs, call EPRI Technical Information Specialists (415) 855-2411.

PWR Steam Generator Examination Guidelines: Revision 3

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Prepared for
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

EPRI Project Manager
M. Behravesh

Steam Generator Reliability Program
Nuclear Power Division

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EPRI FOREWORD TO REVISION 3

Revision 3 of this Guideline was prepared to incorporate the newly developed documents, Appendices G&H, on eddy current performance demonstration and Supplement I on resolution of bobbin coil indications attributable to ODSCC at tube support plates. These documents were prepared by the ISI Guidelines Committee whose members in 1991-1992 were:

Jim Benson	NORTHEAST UTILITIES
Gustavo Bollini	TECNATOM, SA
Gary Boyers	FLORIDA POWER AND LIGHT
Paul Brown	YANKEE ATOMIC ELECTRIC
Steve Brown	EPRI CONSULTANT
Blaine Curtis	ALLEN NUCLEAR ASSOCIATES
Dan Dobbeni	LABORELEC
Robert Dolansky	NEW YORK POWER AUTHORITY
Doug Harris	ANACAPA SCIENCES INC.
Gary Henry	EPRI NDE CENTER
Guy Holmes	WISCONSIN PUB. SERVICE CORP.
Howard Houserman	ZETEC INC.
Ron Ingraham	WESTINGHOUSE
Jeffrey Landrum	SIEMENS NUCLEAR PWR. SERVICES
Randy Lewis	WOLF CREEK NUCL. OP. CORP.
Dan Malinowski	WESTINGHOUSE
Dick Marlow	CONAM NUCLEAR
Rick Maurer	ABB COMBUSTION ENGINEERING
Dan Mayes	DUKE POWER
Scott Redner	NORTHERN STATES POWER
Todd Richards	B&W NUCLEAR SERVICES CO.
Mike Sears	COMMONWEALTH EDISON
Tom Smith	SOUTHERN COMPANY SERVICES
Mark Torborg	GPU NUCLEAR
Bob Vollmer	ZETEC INC.
Kevin Wachter	ROCHESTER GAS & ELECTRIC
Clayton Webber	TVA
Chairman, Mohamad Behravesh	EPRI

Appendices G&H and Supplement I have been reviewed and approved by the Technical Advisory Group and the Senior Representatives of the SGRP. An industry effort to develop capability for decentralized implementation of Appendices G&H has been underway at the EPRI NDE Center and will be available in 1993.

Mohamad M. Behravesh, Program Manager
Nuclear Power Division

EPRI FOREWORD TO REVISION 2

This document was prepared by a committee of industry representatives (the Steam generator ISI Guidelines Committee) under the auspices of EPRI and the Steam Generator Reliability Project (SGRP). The following were members of the committee:

Utilities :	A. Curtis	Rochester Gas & Electric
	D. Mayes	Duke Power
	J. Benson	Northeast Utilities
	S. Redner	Northern States Power
	A. Matheny	Southern California Edison
	J. Abramovici	GPU Nuclear
	G. Boyers	Florida Power & Light
	D. Sessler	TVA
	M. Madigan	Commonwealth Edison
Vendors:	M. Gallagher	Babcock & Wilcox
	R. Brown	Combustion Engineering
	R. Marlow	Conam Inspection
	K. Huffman	Westinghouse
	C. Denton	Zetec
	D. Dobbeni	Laborelec
Non-voting:	D. Dow	Energy management Services
	S. Brown	Consultant
	K. Krzywosz	EPRI Nondestructive Evaluation Center
	C. Welty, (Coordinator)	EPRI
	S. Green, Chairman	EPRI

The final draft of this document was reviewed and commented on by the SGRP Steering Committee, the SGRP Nondestructive Evaluation (NDE) Subcommittee, and U.S. nuclear steam supply system and in-service inspection(ISI) vendors. All formal comments were addressed, resolved, and responded to by the ISI Guidelines Committee.

This document is a report to the members of EPRI and is provided for their individual use. The senior representatives of the SGRP Steering Committee endorse this document and encourage member utilities to adopt the guidelines contained herein. The report provides a sound basis for a utility operating a PWR to establish an effective steam generator examination program. It is intended that the guidelines be revised and updated as additional experience with their use is gained and as steam generator in-service examination and NDE technology continue to advance.

S.J. Green, Director of Steam Generator Project Office
Nuclear Power Division

ACKNOWLEDGMENTS

The initial version of this document was prepared principally by Steve Brown of the EPRI NDE Center. Preparation of Revision 2 was coordinated by EPRI Project Manager, Chuck Welty. Much of the information and data contained in Revision 2 and retained in the current Revision 3 were provided by Westinghouse Electric, Babcock & Wilcox, Combustion Engineering, Zetec, Conam, Laborelec, and numerous utilities. Development of technical consensus documents such as this are at best difficult and this one owes its existence to the dedication, patience, and good judgment of the members of the ISI Guidelines Committee. Their volunteer contributions are gratefully acknowledged.

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Section 1

INTRODUCTION

1.1 PURPOSE

The purpose of this revision is to provide specific guidelines and recommendations, based on research results and plant experience, that will allow utilities to achieve the maximum benefit from periodic steam generator examination. This will also help minimize the likelihood of forced outages due to tube leaks during each operating cycle, assure that established regulatory requirements are met, and minimize unnecessary tube plugging and sleeving.

PWR steam generators have experienced tube degradation by a variety of corrosion and mechanical mechanisms. These problems have resulted in steam generator replacement at seven power plants, planned replacement at four more power plants, major repair evolutions at three plants, six tube rupture events, and numerous unscheduled outages due to leaking tubes. In the years 1980-1984, the average loss in capacity factor in the United States due to steam generator problems was 5.7%. In 1985 and 1986, the average capacity factor loss was only 1.7% (1). Contributing factors to this improvement were dedicated efforts by the utilities and vendors to improve steam generator performance, and a major program sponsored by the Steam Generator Owners Group (SGOG) and EPRI to improve steam generator availability. This program included 1) developing a basic understanding of the various damage mechanisms; 2) developing guidelines on water chemistry purity requirements and improved operating and maintenance procedures; and 3) providing recommendations for design improvements in new and replacement steam generators.

A major element in achieving improved steam generator availability is the performance of the inservice examination process, and the associated reliability of the nondestructive examination (NDE) system. Recognizing this, the Steam Generator Owners Group initially issued the "PWR Steam Generator Examination Guidelines" in 1981. These guidelines were revised in 1984 and are being revised again in response to comments on the original documents, and to reflect evolving experiences in steam generator performance and examination.

1.2 BASES

While there have been no tube rupture events attributed to deficiencies in the examination process, experience has shown a number of other problems directly related to process deficiencies. These problems have included missed indications which have resulted in tube leaks during the subsequent operating cycle and the ambiguous interpretation of indications which has resulted in either excessive plant down time or in unnecessary tube repair. Furthermore, existing regulations (10 CFR 50, Regulatory Guides 1.83 and 1.121) and codes (ASME Sections V and XI) were developed during the 1970's prior to the recognition that there are a variety of damage forms which can cause tube damage, and they provide only the broadest guidance for conducting steam generator examination. The "PWR Steam Generator Examination Guidelines" were developed to provide more specific guidance.

In a related water chemistry area, the nuclear industry has developed a protocol and established a precedence for providing guidance to upgrade industry-wide plant performance by assembling an ad-hoc committee of experts in the field to review all available data (e.g., past and current research results, recent plant experience, etc.) and to develop consensus guidelines on how to effectively deal with the issue. This same approach has been taken with this revision of these Guidelines.

1.3 CONCERNS

The major concern, alluded to above, is to assure that the steam generator examination identifies those tubes that are required to be removed from service either to prevent a forced outage due to tube leakage or to assure that a tube rupture is unlikely to occur either during normal operation or under postulated accident conditions, but does not result in the excessive plugging or sleeving of tubes.

While these guidelines do not directly address tube plugging and sleeving, it is recognized that steam generator examination is intimately related to technical specification requirements. That is, improved NDE methods which are used to prevent tube-leak outages can identify tube degradation which does not affect reliability or safety, but which exceed technical specification limits for plugging and sleeving "defective" tubes. This particular issue is being dealt with separately from these Guidelines. It is the position of the Guidelines Committee that the optimum examination be employed to assure that tube-leak outages are not likely to occur, and that the matter of dealing with certain types of flaws be dealt with on a case-by-case basis. Regulatory interaction may be required on a plant specific basis to adjust technical specifications to address these conditions.

1.4 SCOPE

The Guidelines cover recommended practices for steam generator examination. The main body of the document addresses steam generator sampling strategies or examination programs, recommended nondestructive examination, and data analyst performance demonstrations. The appendices provide much of the background for the recommendations and describe steam generator operating experience, NDE experience with various damage forms and other background information.

The Guidelines are applicable to steam generators manufactured by Westinghouse, Westinghouse licensees, Combustion Engineering and Babcock & Wilcox. Portions of these guidelines may be applicable to steam generators built by other manufacturers.

The guidelines document provides:

- An overview of steam generator NDE objectives.
- General recommendations which are designed to help utilities implement a steam generator examination program.
- A recommended practice for steam generator examination.
- A summary of steam generator operating experience which documents damage mechanisms, vulnerable locations within the steam generator based on past experience, and NDE experience.
- A survey of leaker outages on an industry-wide basis in which specific causes are identified.

Specific recommendations are provided for:

- Random tube sampling strategies for general steam generator surveillance supplemented with additional augmented sampling for units with active damage mechanisms.
- Methods for monitoring tube integrity and damage precursors.
- Establishing an eddy current data analyst performance demonstration program.

Section 1 presents a general introduction and defines the scope of the document. Section 2 describes the responsibilities of various utility personnel to insure that appropriate management and technical commitments are identified in achieving the spirit and goals of the document. Section 3 provides a summary of recommendations for implementing a steam generator examination program. Section 4 presents a recommended practice for steam generator examination and addresses key issues involving sampling plans, data acquisition and analysis, and analyst performance demonstrations.

The appendices provide much of the background and supporting data for the recommendations. Appendix A provides a survey of steam generator operating experiences. Appendix B describes the bases for steam generator sampling plans. Appendix C provides an overview of steam generator NDE experience associated with tube wall degradation. The next two Appendices, D and E, provide respectively outlines of a data analysis guideline and a steam generator NDE bid specification. Finally, Appendix F presents a list of terms used throughout the guidelines which may be referenced as required.

Section 2

RESPONSIBILITY

2.1 INTRODUCTION

The responsibility for steam generator examination rests with the utility operating the unit. The objective of this section is to provide a suggested framework of responsibilities for assuring that examination activities achieve their full potential to enhance steam generator availability. It is emphasized that management commitment and a clear communication of that commitment is necessary to achieve a consistently successful ISI program. Although there is great variability in the details of individual utility organizations, there are functions which are common to all utilities. This section addresses the general role of those functions and is not intended to specify any particular organization or approach. The timely application of an optimum examination plan is vital to enhance the reliability, lifetime, and overall economic viability of steam generators. The philosophy and responsibilities discussed reflect the desirability of operating in an anticipative mode rather than a reactive mode.

2.2 MANAGEMENT RESPONSIBILITY

2.2.1 Background

Nuclear station management periodically must compromise between minimizing the impact of steam generator examination on outage budgets or critical path schedules and performing supplemental nondestructive examination to ensure that potential problem areas are identified at their onset and fully characterized with state-of-the-art technology.

Thorough examination data provides the basis for mitigating actions and corrective repairs. It is important that all levels of utility management understand the benefits of detecting and characterizing problems at an early stage.

In order for these guidelines to be effective, management must support them both in principle and practice. These guidelines recommend an approach to steam generator examination which is intended to provide the following results:

- Extend the reliable, cost effective, operating life of the steam generators.
- Maximize the cumulative availability of the unit.
- Provide an acceptable level of immediate availability.

2.2.2 Specific Management Responsibilities

Nuclear station management is responsible for providing sufficient resources and attention to steam generator examination efforts to preclude avoidable tube leaks, costly repairs, and premature replacement. A generic guide for management execution of this function is discussed below:

- Appreciate the need for, and establish a policy for steam generator examination consistent with these guidelines. A strong statement of policy can be made simply by providing full support for implementation of these guidelines.
- Ensure that appropriate Nuclear Technical Supervisors and Outage Scheduling Supervisors are aware of the need for support of steam generator examination activities consistent with these guidelines.
- Develop a knowledgeable steam generator examination engineering organization. Provide this organization sufficient responsibility, authority, and resources to implement these guidelines.
- Ensure that areas of steam generator technical responsibility have been clearly assigned to either a single organization with coordination authority, or to multiple organizations with an effective coordination and interface mechanism. Steam generator examination activities cannot be conducted in an anticipatory manner unless they are integrated in a coherently effective steam generator program. This program would normally include chemistry, materials, examination, regulatory interface (licensing), and maintenance/repair/modifications of both the steam generators and the steam turbine cycle components that affect the steam generator environment. A steam generator reliability committee is one way to assure proper coordination among all these disciplines and areas of responsibility. This committee should be chaired by management or by someone having direct access to management in order to be able to resolve promptly the technical, operational or planning issues on a concerted basis.
- Support establishment of basic training prerequisites for steam generator examination engineers. The experience of many utilities is that the typical experienced nuclear production engineer requires significant specific on-the-job experience and formal training to be able to accomplish the functions detailed in these guidelines.

- Encourage continuity within the steam generator examination engineering organization. Engineering personnel need a detailed familiarity with both unit-specific and industry problems.

- Encourage and support utilization of steam generator training from outside sources. Recognize that formal NDE training and certification efforts require resource commitment. It is vital that the steam generator examination organization be an "educated customer" of contracted services. It can also be useful for auditors to have a basic understanding of state-of-the-art eddy current technology.

- Encourage initiative and long-term perspective within the steam generator examination engineering organization. This encouragement is helpful for an organization operating in an anticipative mode with the goals of identifying and assessing developing problems before their impact is significant. Also, continuing initiative is necessary to ensure that optimum, state-of-the-art equipment, techniques, practices, and personnel are being used.

- Encourage and support frequent and open interchange of experience and technology with other utilities, NSSS suppliers, examination vendors, and with appropriate industry research and regulatory organizations.

- Establish coordination interfaces between design organizations and steam generator examination engineering to ensure that:

    - Plant modifications do not unduly hinder access to examination platforms; and

    - Site modifications do not unduly hinder access to locations near containment penetrations for mobile NDE testing facilities and tracer gas containers for steam generator leak testing.

- Provide independent and knowledgeable auditing organizations. Numerous steam generator examination regulatory requirements exist with which full and meaningful compliance should be periodically verified.

- Encourage real-time surveillance and audit of critical aspects of the steam generator examination process and ensuing repairs. The goal of real-time surveillance is to provide assurance of preclusion of operational periods during which all requirements inadvertently have not been met.

2.3 EXAMINATION ENGINEERING RESPONSIBILITY

The responsibilities of Steam Generator Examination Engineering personnel include planning, directing and evaluating steam generator examination activities. Steam Generator Examination Engineering personnel provide a central control for steam generator examination and should participate on the Steam Generator Reliability Committee to assure integration of examination needs and requirements.

Specific planning responsibilities include the following:

- Know the plant's steam generator operating history and chemistry experience.
- Review similar plants' generator experiences and examination results.
- Review the secondary chemistry operation during each cycle with plant chemistry personnel.
- Communicate with plants' Nuclear Steam Supply System Engineering Staff.
- Implement PWR Steam Generator Examination Guidelines.
- Develop an upper internal examination program for recirculating steam generators.
- Develop eddy current examination specifications to include with the bid package.
- Develop an eddy current data analysis procedure, guideline or instruction for the plant along with a plant specific proficiency demonstration test for all data analysts.
- Plan for supplemental methods and techniques to be utilized for indication resolution and characterization, if needed.
- Plan for tube repair, if needed, which may include tube plugging or tube sleeving.
- Plan for tube pulls if new or significantly changed indications occur.
- Develop a plan to assure that examination results have been dispositioned in accordance with established criteria.
- Plan for a secondary side tube sheet visual examination.
- Plan to develop and maintain a data base management system.
- Maintain or have access to modification records, drawings and a Steam Generator Technical Manual.
- Maintain management involvement and endorsement and participate with other responsible individuals involved with the plant's steam generator reliability program.

Specific evaluation responsibilities include the following:

- Develop a final report that documents complete examination and evaluation of results.
- Define tube repair needs.

- Communicate results to other plants, vendors, EPRI and the NDE Center.

2.4 INSPECTOR RESPONSIBILITY

Steam generator examination is a major programmatic effort with requirements established from several sources including the U.S. Nuclear Regulatory Commission and the American Society of Mechanical Engineers (ASME Boiler and Pressure Vessel Code).

Inspector personnel are normally part of the utility's Quality Assurance organization or an authorized inspection agency. Inspector staff personnel should be encouraged to become involved in the steam generator examination process. Such involvement might include the following:

- Provide suggestions for improving or reinforcing programmatic measures that enhance compliance capabilities.
- Attend eddy current NDE training which is available from industry sources in a format tailored for auditing personnel. This may enhance appreciation and awareness of the most significant aspects of the overall eddy current examination process.
- Maximize real-time surveillance of critical aspects of the steam generator examination and repair process to preclude unplanned outages and damage to industry credibility. Examples of critical aspects are:
    - Identification and completion of all regulatory tube examinations
    - Processing of examination results to determine defective tubes for which plugging is required
    - Verification of the actual completion of plugging of correctly identified tube ends
    - Evaluation of secondary side visual examination data to ensure that all significant loose parts/debris have been identified and removed

2.5 RESPONSIBILITY SUMMARY

In order to achieve a successful steam generator examination program, the responsibilities for this work need to be clearly defined and communicated. Management must take the lead in emphasizing the importance of the examination activities and provide the necessary training and support for groups performing the examination.

Section 3

GUIDELINES SUMMARY

3.1 INTRODUCTION

The Guidelines document is structured to assist utilities in establishing or improving their steam generator examination program. Steam generator sampling strategies, recommended examination methods for various tube damage forms and damage precursors, steam generator NDE experience, and recommendations for data analyst performance demonstrations are addressed.

This section of the Guidelines presents in summary fashion a listing of recommended practices which should be considered for use by a utility. In general, the recommendations have their basis in experience and have contributed to improved steam generator examination and increased availability.

In designing a steam generator inservice examination program, utility company objectives are twofold--to satisfy regulatory requirements and improve plant availability. To ensure that the regulatory goal is met, the recommendations provided in this section exceed minimum requirements for steam generator examination as outlined in the plant technical specification. In addition, there are strong economic incentives for implementing a more stringent examination program than those which are legally mandated. With unscheduled outage costs being much higher than incremental examination costs, this guideline sometimes suggests a more thorough examination than that required by regulation. Increased examinations can provide a better estimate of steam generator condition and also reduce the risk of an unscheduled outage.

An effective examination program detects and monitors 1) the initial formation and progression of steam generator tube degradation, and 2) damage precursors. The information derived from an examination is used in an anticipatory manner to assess steam generator condition, expected performance during the next operating cycle, identify the need for plant corrective actions (e.g., water chemistry modifications), and monitoring the success of previously implemented corrective actions. The identification of conditions within the steam generator detrimental to tube integrity at an early stage allows for the more orderly and timely implementation of plant corrective actions.

The remainder of this section provides guidelines for the inservice examination of PWR steam generator internals, e.g., tubing and their support structures. The recommendations are based on:

- NRC Regulatory Guide 1.83 (2)
- Plant Operating Experience
- Industry experts from the EPRI SGRP, Utilities and ISI Vendors.

The recommendations vary according to:

- Steam Generator Manufacturer (Westinghouse and Westinghouse Licensees, Combustion Engineering, or Babcock & Wilcox)
- Steam generator model number and design
- Operating history
- Suspected type of degradation

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

3.2 SUMMARY OF RECOMMENDATIONS

Category	Summary of Recommendations	Where Discussed
General Examination	• Choose an experienced ISI vendor	3.3
	• Establish plant specific written eddy current data analysis guidelines	3.3
	• Conduct plant-specific performance demonstrations for data analysts and computer data screening systems	3.3
	Perform a 100% full-length preservice examination on all new and replacement steam generators	3.3
	• Provide protected storage for recording media containing eddy current data	3.3
	• Lay up steam generators properly during examination	3.3
	• Implement an equipment maintenance program	3.3
	• Conduct visual examination for loose parts	3.3
	• Use leak detection methods appropriate for the problem at hand	3.3
	• Use limited entry remote manipulators for steam generator channel head access	3.3
Steam Generator Examination Strategies	• Conduct a production examination of all steam generators during scheduled outages	3.4
	• Develop an examination plan consisting of a programmed random element and, where appropriate, an additional augmented element	3.4
	• Be prepared to and expand the basic sample plan during an examination as appropriate	3.4
	• Use appropriate NDE diagnostic methods to characterize new, distorted, or undefined indications	3.4
	• Monitor tube damage precursors	3.4
Nondestructive Examination	• Use digital multifrequency eddy current instrumentation	3.5
	• Choose appropriate frequencies for production bobbin coil testing	3.5

	• Conduct additional examinations to bridge old and new technology	3.5
	• Establish criteria for "noisy data" and monitor data quality during collection	3.5
	• Use appropriate data acquisition and analysis methods	3.5
	• Analyze all appropriate eddy current data	3.5
	• Conduct an independent review of all eddy current data	3.5
	• Utilize data base management systems to assess overall steam generator condition	3.5
Post-Examination Actions	• Take corrective actions to prevent further damage progression	3.6
	• Conduct a post-outage critique	3.6
	• Conduct leaker outage preplanning	3.6

3.3 GENERAL RECOMMENDATIONS

This section contains general recommendations for good examination 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.

RECOMMENDATION: Establish plant specific written eddy current data analysis guidelines.

Written data analysis guidelines should be prepared and made available to all analysts prior to the start of a job. The guidelines should address the operating experience of the particular generator and units similar in design. The guidelines should also address analysis procedures to be used in reviewing data and in sizing, the review of previous data, and procedures for resolving discrepancies between independent analysis. See Section 4.4.

RECOMMENDATION: Conduct plant-specific performance demonstrations for data analysts and computer data screening systems.

The data analyst's comprehension of the plant-specific analysis guidelines should be demonstrated prior to the production analysis of plant eddy current data. This should be accomplished by the passing of a practical examination consisting of the analysis of eddy current data from previous outages. The data selected should be such that analysis requirements specified in the guidelines are demonstrable. See Section 4.5.

Typical computer data screening systems are designed to be utilized in conjunction with a data analyst whose task is to assure the correct disposition of all indications identified during the screening process. When such systems are utilized, their capabilities and limitations should be established in a manner independent of the data analyst. See Section 4.4.4.

RECOMMENDATION: Perform a 100% full-length preservice examination of all new and replacement steam generators.

A preservice examination provides a basis for comparison with subsequent inservice examination results. In particular, it enables a utility to positively separate signals - and hence conditions - associated with the manufacture, transportation, or installation of the steam generator from those which are attributable to operation. Past preservice examinations have uncovered a variety of problems, including obstructed tubes, loose parts and unexpanded tubes.

RECOMMENDATION: Provide protected storage for recording media containing eddy current data.

Recording media should be dated, identified, and stored carefully to ensure the availability and retrievability of background and reference information in a short interval to minimize decision-making time. These data also provide feedback for management decisions on steam generator examination.

RECOMMENDATION: Lay up steam generators properly during examination.

Impurities accumulated on the secondary side during operation can cause corrosion to progress during a shutdown period. For examples, chlorides, copper, and copper oxides can cause pitting in an oxygenated environment. Therefore, the steam generators should be in a proper lay-up condition during the examination period.

Recommendations for steam generator lay-up are provided in other guidelines (3).

RECOMMENDATION: Implement an equipment maintenance program.

Electronic and mechanical equipment used for steam generator examination 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 equipment should be refurbished as required between outages to assure reliable performance during an inservice examination.

RECOMMENDATION: Conduct visual examinations for loose parts.

Foreign objects left in generators after secondary side maintenance have caused forced outages. Therefore, a secondary side visual examination 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 visual examination 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 examination must be tailored to the specific steam generator design.

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

Subsequent visual examinations of the secondary sides of steam generators should be performed when the specific situation warrants, e.g., when primary side eddy current 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 examination should be restricted in scope and duration to the minimum required to resolve the specific question that prompted it.

RECOMMENDATION: Use leak testing methods appropriate for the problem at hand.

Primary-to-secondary tube leakage location can be accomplished using several methods with a range in simplicity, cost and sensitivity. A secondary side hydrotest is the simplest approach and can quickly identify suspect leaking tubes. Its sensitivity is less than alternate tracer gas approaches. Experience has shown that helium leak detection methods are more sensitive than hydrotesting, resulting in the capability to locate smaller leaks.

RECOMMENDATION: Use limited entry remote manipulators for steam generator channel head access.

Many types of limited entry probe manipulators are available, some of which can be installed without entering the steam generator channel head. Remote plugging can also be accomplished using appropriate end effectors. Use of these devices during an outage can significantly reduce radiation exposure.

3.4 STEAM GENERATOR EXAMINATION STRATEGIES

RECOMMENDATION: Conduct a production examination of all steam generators during scheduled outages.

The examination results from one steam generator are not always reliable indicators of the condition of other steam generators in the plant. Since the incremental cost of examining additional steam generators is small compared with the cost of a forced outage, all steam generators should be examined during each scheduled steam generator outage. If a plant can demonstrate that all steam generators have similar operating experience and examination results, this recommendation can be modified within the constraint of the recommendation that all tubes be examined over their full length during a specific interval and that known damage mechanisms be monitored at each periodic inservice examination.

RECOMMENDATION: Develop an examination sampling plan consisting of a programmed random element and, where appropriate, an additional augmented element.

For all steam generators, the programmed random element is developed such that 100% of the tubes in the plant are examined over their full length during five consecutive cycles, and such that no less than 20% of the tubes in any steam generator are examined during each refueling outage. Tubes in this plan are examined tube end to tube end, and should be randomly selected over the entire area of the examined steam generator(s).

The programmed random examination should be supplemented by an augmented examination in each steam generator based on steam generator operating experience, previously identified degraded tubes, and additional tubes that are directed to be inspected by either the NRC or the NSSS vendor. See Section 4.2 for specific recommendations on sampling plan considerations.

RECOMMENDATION: Be prepared to expand the sampling plan during an examination as appropriate.

The 20% sample size random sample program should be expanded utilizing the augmented plan described in Tables 4-1, 4-2, or 4-3 when reportable indications (20% through wall or greater based on current plant technical specification requirements) are reported which exceed a specified threshold level. Threshold expansion criteria are as follows; 1) more than one pluggable tube , or 2) if at least 5% of the sampled tubes are degraded.

For indications that do not fall into the categories specified by the previously mentioned tables, expand the sampling plan to bound the problem. The tubes examined should be examined full length unless there is a logic to support their isolated occurrence in the vertical plane, i.e., tube sheet, sludge pile, U-bend, or AVB/batwing regions. Following bounding by the expansion process discussed above, consideration should be given to supplemental examination as discussed in the following recommendation.

RECOMMENDATION: Use appropriate NDE diagnostic methods to characterize new, distorted, or undefined indications.

Certain indications reported during an examination may initially be identified as undefined or non-quantifiable at the analyst level. Such signals must be resolved to either a repairable or non-repairable tube condition prior to a return-to-power condition. Specific recommendations are discussed in Section 4.6.

RECOMMENDATION: Monitor tube damage precursors.

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; and tube geometry changes, e.g., dents, expansions, and roll transitions. Monitoring of these conditions or regions for change at an early stage may buy the utility time in implementing remedial actions.

3.5 NONDESTRUCTIVE EXAMINATION

RECOMMENDATION: Use digital multifrequency eddy current instrumentation.

Multiple frequency eddy current examination provides a defense-in-depth approach for signal detection and analysis with its inherent signal redundancy. In addition, digital multifrequency/multiparameter eddy current instrumentation provides improved examination reliability in the presence of extraneous test variables, increased dynamic range and resolution, greater flexibility in data manipulation, and significant improvements in final report preparation. See Section 4.3.

RECOMMENDATION: Choose appropriate frequencies for production bobbin coil testing.

Eddy current examination reliability depends not only on data analysis approaches but also on the type of probe used and the frequencies selected for initial data acquisition. General production testing is conducted using an annular-shaped bobbin coil. Appropriate frequencies should be selected to monitor both tube wall integrity and tube damage precursors, and for mixing purposes. Recommended frequency ranges are provided in Section 4.3 Table 4-4.

RECOMMENDATION: Conduct additional examinations to bridge old and new technology.

When new technology is employed which negates the usefulness of baseline or previous examination results, the utility should plan for additional examinations using both the old and new technology. These additional examinations should include a sample of all previously reported indications as determined by the inservice examination engineer to ensure correlation between the examination results of the old and new technology.

RECOMMENDATION: Establish criteria for "noisy data" and monitor data quality during collection.

Data quality can significantly impact overall outage schedules since retests may have to be conducted because of poor data. It is important that data collectors have the necessary training, written criteria or examples of poor data, so that data quality can be monitored during acquisition.

RECOMMENDATION: Use appropriate data acquisition and analysis methods

Special eddy current data acquisition and analysis methods have been developed for various forms of tube wall degradation. In recirculating steam generators these include wear at preheater baffle plates, antivibration bars, and bat wings; pitting in the presence of copper; intergranular attack/stress corrosion cracking; and inner row U-bend cracking. In once-through units, damage mechanisms include fatigue cracking and wear at support plate lands. See Section 4.4.3 for additional information.

RECOMMENDATION: Analyze all appropriate eddy current data.

There is historical evidence that eddy current data have been collected but not fully reviewed (4). Multifrequency eddy current examination represents a defense-in-depth approach to steam generator examination; it is effective only if all relevant 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 (see Appendix C Section 4). The task of reviewing and analyzing data is extremely tedious and is normally accomplished under considerable time pressures; any individual analyst is vulnerable to a missed indication. One must bear in mind that hundreds of thousands of signals may be reviewed and dispositioned during an outage.

To reduce the chances of a missed indication, it is recommended that two independent analyses be conducted for all eddy current data. A suggested analysis structure is discussed in Section 4.4.1. Formal data review and discrepancy resolution procedures should be established utilizing data base management systems to assure that all differences are resolved.

RECOMMENDATION: Utilize steam generator data base management systems to assess overall steam generator condition.

A voluminous amount of data can be produced during a steam generator outage. Data from the current examination and analysis results from previous examinations should be compared for the identification of trends and regions of the generator requiring special attention during subsequent outages. Degraded tubes identified during the current outage should be identified for re-examination during the next scheduled outage. For this purpose, a tube is considered degraded if it has a tube wall penetration of 20% through wall or greater.

3.6 POST-EXAMINATION ACTIONS

RECOMMENDATION: Take corrective actions to prevent further damage progression.

Indications of tube degradation or the active continuation of 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 treat the symptom. Examples of remedial measures which might be considered for implementation include:

- Changes in secondary side water chemistry, air inleakage control, balance-of-plant hardware, or operating and maintenance procedures.
- Maintenance of an effective sludge lancing program.
- Implementation of crevice flushing procedures in units with open tube sheet crevices.
- Expanding tubes within tube support plates to control vibration related degradation - cold leg thinning and preheater wear.
- Control of loose parts.
- Application of inner row U-bend heat treatment, rotopeening, or shot peening of tubes to reduce the probability of primary side stress corrosion cracking initiation or growth.

RECOMMENDATION: Conduct a post-outage critique.

Outages are intensive activities in which many things must be accomplished in a short time. The success of an outage depends upon many factors including appropriate training, delegation of responsibility, establishing the necessary lines of communication and preplanning activities. Each outage should be critiqued in detail so that improvements can be identified and implemented during subsequent outages.

RECOMMENDATION: Conduct leaker outage preplanning activities.

Unscheduled steam generator outages as the result of tube leakage can by definition occur at any time. Accordingly, the utility should conduct appropriate planning so that in the event of a leaker outage, minimum time is lost in getting into the generator.

Section 4

STEAM GENERATOR EXAMINATION RECOMMENDED PRACTICE

4.1 INTRODUCTION

This section presents general recommendations for steam generator examination. The recommendations are intended for general guidance and must be viewed with the proper perspective and appropriate rationality. It is not practical to define a rigid series of steps that will cover all situations or circumstances that can be encountered during a steam generator examination. However, it is believed that the adoption of these general guidelines will lead to improved steam generator availability within the context of an improved and more reliable examination, and better knowledge of steam generator conditions. Information acquired at an early stage would allow for the tactical implementation of appropriate remedial measures or assist in the strategic planning process for steam generator replacement.

Five main areas of the examination process are addressed:

- Steam Generator Sampling Plan
- Eddy Current Data Acquisition
- Data Analysis
- Analyst Performance Demonstrations
- Supplemental NDE Diagnostic Methods

Material in this section is concisely presented. Additional supporting data and supplemental information is referenced accordingly, and is contained in the appendices for reference as required.

4.2 SAMPLING PLAN CONSIDERATIONS

Steam generator examination planning logically begins with the selection of tubes for routine production inspection - defining the sample plan. As testing progresses, conditions may be encountered which may require an increase in the size of the initial sample. This section provides specific recommendations on: (1) the basic sample plan; and (2) conditions which dictate an increase in the basic sample plan as the examination progresses.

The recommended sampling plan consists of two elements: a programmed random sample for all steam generators supplemented by an augmented sample for those steam generators with active damage mechanisms. The primary objective of the random sample program is to monitor the general condition of the steam generator by detecting the onset of new or the recurrence of previously experienced widespread damage; a secondary objective is to insure that the full length of all steam generator tubes is examined over some periodic time interval consistent with ASME Section XI requirements for other primary pressure boundary components. This is accomplished by using a rotating random sample selection. Tubes randomly sampled during one examination are excluded from subsequent random sample sets, e.g., sampling without replacement. The objective of the augmented sample is to insure that the condition of suspect regions of the steam generator is known prior to return to power, and to insure that those tubes requiring repair (plugging or sleeving) are identified. All tubes are examined over a five cycle interval. The recommended minimum size of the augmented sample has been developed based on industry experience and is related to specific generator types and damage mechanisms. It ranges between 20% and 100% of the region of interest depending on the risk associated with a particular damage mechanism.

The programmed random plan should be supplemented by the augmented plan in each steam generator based on (1) identified damage in that steam generator per Table 4-1 (for Westinghouse design steam generators), Table 4-2 (for Combustion Engineering steam generators) or Table 4-3 (for Babcock & Wilcox steam generators); (2) tubes that were degraded (a reportable indication 20% through wall or greater) during the previous examination (these tubes can be exempted in future examinations if there is no damage progression); and (3) special interest tubes that are directed to be examined by either the NRC or the NSSS vendor.

The augmented sample is experienced based and is applicable to those units with active damage mechanisms. Active degradation is defined as the presence of new indications attributable to operation, or growth of previous indications in excess of 10% through-wall during one operating cycle.

The sampling should be expanded when reportable indications in excess of some threshold value are observed in tubes examined as part of the programmed random

Table 4-1

RECOMMENDED AUGMENTED SAMPLE FOR WESTINGHOUSE STEAM GENERATORS
(Applicable only to those units with an active damage mechanism)

Sample Size and Tube Location		Steam Generator Model				
		24,27,33	44	51	D,E	F Types
	IGA/SCC					
100%	of the hot leg side tube sheet crevice region	X	X	X		
100%	of the hot leg side supports down to the lowest support elevation on the cold leg side for which indications diagnosed as IGA/ODSCC have been reported	X	X	X	X	
	PWSCC					
100%	of the U-bend region of Rows 1 & 2			X(1)	X(1)	
100%	of the tube sheet expanded area	X		X	X	
100%	of the hot and cold leg support plates			X		
	PITTING					
100%	of the central region of the tube bundle on applicable sides of the steam generator	X	X	X		
	WEAR					
20%	of the tubes in the region where AVB wear has occurred	X(2)	X(2)	X(2)	X(2)	X(2)
20%	of the tubes on the outer periphery - two rows deep				X(2)	
	COLD LEG THINNING					
20%	of the tubes on the outer periphery - five rows deep			X(2)		

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(1) Should be examined using rotating pancake coil or other appropriate technology with equivalent capability.

(2) Randomly selected on a rotating basis.

Table 4-2

RECOMMENDED AUGMENTED SAMPLE FOR COMBUSTION ENGINEERING STEAM GENERATORS
(Applicable only to those units with an active damage mechanism)

Sample Size	Location	Steam Generator Model 67	Steam Generator Model 3410	Steam Generator Model S80
	IGA/SCC			
100%	of the hot leg side bounded by the sludge pile	X		
100%	of the tubes within the U-bend region susceptible to steam blanketing	X		
	PITTING			
100%	of the central region of the tube bundle on applicable sides of the steam generator	X		
	WEAR			
100%	of the tubes bounding the region susceptible to diagonal strap wear		X	
20%	of the tube susceptible to vertical support strap wear	X	X	
100%	of the tubes in the preheater section susceptible to wear			X

Table 4-3

RECOMMENDED AUGMENTED SAMPLE FOR ONCE-THROUGH STEAM GENERATORS
(Applicable only to those units with an active damage mechanism)

Sample Size	Location
	Corrosion Fatigue
100%	of the lane and wedge region (1,2)
	Fretting
100%	of the lane region (2)
	IGA/SCC
100%	of the wedge region (3)
	Flow Impingement
100%	of the outer periphery region (4)

---

(1) Should be examined with (8x1) array coil technology.

(2) Examine from 14th TSP through Upper Tube Sheet.

(3) Examine from the 15th TSP through Upper Tube Sheet.

(4) Examine tubes in the affected region.

examination plan. See Appendix B for a detailed discussion of threshold criteria.

For new indications that are considered indicative of damage mechanisms that could be expected based on experience in other steam generators in the particular plant or similar steam generators in other plants, the expansion may be per Tables 4-1, 4-2, or 4-3 as applicable. For indications that do not fall into the above categories, expand the production examination to bound the problem. The tubes examined in the expansion should be examined full length unless there is a logic to support their isolated occurrence in the vertical plane, i.e., tube sheet, sludge pile, U-bend, etc.

Guidelines for sample plan development that are specific to Westinghouse, Westinghouse licensees , Combustion Engineering, and Babcock & Wilcox steam generators are given below. Additional material relative to sampling which should be reviewed is presented in detail in Appendix B.

4.2.1 Westinghouse Steam Generators

Each scheduled steam generator outage should include:

Random Sample

- 20% of the tubes full length in all steam generators with all tubes being examined over a 5 cycle interval

Augmented Sample

- The tubes specified in Table 4-1
- All degraded tubes with eddy current indications 20% through-wall or greater

4.2.2 Combustion Engineering Steam Generators

Each scheduled steam generator inspection should include:

Random Sample

- 20% of the tubes full length in all steam generators with all tubes being examined over a 5 cycle interval

Augmented Sample

- The tubes specified in Table 4-2
- All degraded tubes with eddy current indications 20% through wall and greater

4.2.3 Babcock & Wilcox Steam Generators

Each scheduled steam generator inspection should include:

Random

- 20% of the tubes full length in all steam generators with all tubes being examined over a 5 cycle interval

Augmented Sample

- The tubes specified in Table 4-3.
- All degraded tubes with eddy current indications 20% through wall or greater

4.3 DATA ACQUISITION

4.3.1 Eddy Current Instrumentation

The volumetric examination of thin walled tubing can be accomplished using eddy currents. Eddy current testing is also relatively fast and simple. The latter is important when one considers that there may be many miles of tubing examined during a steam generator outage. For these reasons, eddy current inspection is the method most commonly employed for steam generator tube examination.

Multiple-frequency eddy current instrumentation with a digital recording system is recommended as the basic building block for steam generator data acquisition. The instrumentation should be broadband with the capability of generating at least three frequencies over a range of approximately 10KHz to 1MHz. The electronic dynamic bandwidth should be greater than 12.5 Hz per inch of coil surface scanning speed. System dynamic range (defined from the probe to system output) should be at least 12 bits or 72 db. The system noise (electronic and slip rings) should be below 72 db. Digitizing rate, which is a function of sampling rate and probe speed, should provide at least 30 samples per inch of examined tubing. Although digitizing rates as low as 25 samples per inch are adequate for detection, greater rates may be necessary for specialized signal characterization.

The benefits of multifrequency eddy current steam generator tube inspection are well documented (5). They include:

- 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. Signal redundancy provides a defense-in-depth approach in tube examination. This increases the probability of properly dispositioning indications by providing additional data channels and facilitates the analysis of complex signals.
- 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 an appropriate range of frequencies. These frequencies are used to:

- Monitor tube wall integrity.
- Monitor for the presence of damage precursors.
- Suppress extraneous test variables.
- Provide backup data channels for improved detection and analysis reliability.
- Locate secondary side support members.

Recommended frequency ranges for multiple frequency tube examination are given in Table 4-4. For alloy 600 and 690 tubing, the recommended frequency ranges are a function of tube wall thickness. Frequencies in the medium range are typically used to establish overall system calibration and for tube wall examination in the absence of extraneous test variables; those in the low and high ranges may be used as mixing frequencies for extraneous variable suppression and also for supplemental tube wall examination. The fourth or optional data channel is typically used as a support member locator channel and for debris-sludge detection.

Table 4-4

BOBBIN COIL RECOMMENDED FREQUENCY RANGES
- Inconel 600 & 690 Tubing -

Wall Thickness, inches	Frequency Range, KHz Low	Medium	High	Optional
0.034-0.038	100-400	200-700	600-1000	10-1000
0.040-0.043	100-400	200-700	500-1000	10-1000
0.048-0.050	100-300	200-500	400-1000	10-1000
0.055-0.060	100-300	200-500	300-1000	10-1000

Notes:

Frequencies in the medium range are normally used to verify system performance, and for tube wall examination in the absence of extraneous test variables.

Frequencies in the low and high range are used as mixing frequencies and also for tube wall examination.

The optional frequency range is normally used as a locator channel for the purpose of identifying secondary side support members and also for measuring sludge height.

4.3.2 Test Coils

An important element of the data acquisition package is the eddy current test coil. For optimum detection of tube wall degradation, the coil windings should be orthogonal to the expected defect plane with lift-off or fill factor variations between the coil and test surface kept to a minimum. Although there are innumerable designs or configurations, three principal classes of eddy current coils are used for steam generator tube examination. These include the bobbin coil, rotating pancake coil (RPC) and array coil. Their use generally represents a compromise between inspection rate, defect geometry, minimizing extraneous test variables and test objectives.

4.3.2.1 Bobbin Coil

The bobbin coil is the most commonly used probe during production examination because of its rapid inspection speed and high mechanical reliability. The coil windings are in a circumferential direction about the tube axis; accordingly the probe is most sensitive to volumetric (three-dimensional) and linear tube wall discontinuities aligned parallel with the tube axis. Bobbin coil inspection speeds are quite fast, ranging from 12 to 40 inches per second depending on instrumentation bandwidth and sampling rates.

4.3.2.2 Rotating Pancake Coil

Spring-loaded pancake coils provide improved examination capabilities in the presence of either circumferentially oriented tube wall degradation or variations in tube wall geometry caused by dented support plate or 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 linear discontinuities independent of orientation. Mechanical methods, e.g., spring loading, are used to suppress lift-off effects directly.

Rotating pancake technology can provide an inspection capability not available from a bobbin coil. These probes have demonstrated their ability to reliably detect and characterize certain types of tube wall degradation which could not be adequately characterized with standard bobbin coil technology. Data acquisition rates are significantly slower than those for bobbin coil (typically 0.2" per second versus 40" per second) since the probe must be translated axially and rotated circumferentially in order to achieve complete coverage of the tube wall. In addition, detailed analysis of the RPC data can be time consuming.

4.3.2.3 Array Coils

Surface-riding array coil probes have been used for selected steam generator examination problems. A typical array coil probe consists of eight individual pancake coils located about the circumference of the probe head. Since each individual coil has a limited field of view, multiple coils are used in an attempt to achieve full tube wall coverage. Each of the coils are typically spring-loaded to minimize lift-off effects.

Array coil probes have typically been used in situations where the expected tube damage mechanism is circumferentially oriented and numerous tubes have to be examined. It has also been used in diagnostic applications to determine the presence of multiple-side wear at AVB's and for improved sizing of wear scars.

4.3.2.4 Recommended Applications

A general guide for probe selection is given in Table 4-5. The two primary test variables mentioned previously, e.g., lift-off and eddy current flow relative to expected defect morphology, are related to practical situations encountered during a steam generator examination. The bobbin coil (differential and absolute modes) is applicable to the majority of the conditions encountered during testing. The differential mode tends to enhance localized degradation as typified by thinning in the form of wastage, axial cracking, pitting, and flow impingement damage. Use of the absolute mode is preferred in situations where the degradation is volumetric and can assume a tapered or gradual morphology such as thinning and wear. In the presence of significant fill factor variations as exemplified by U-bend bulging, tube expansion geometries, and denting, use of the bobbin will, in general, only provide evidence of gross tube wall degradation. A bobbin coil used in the absolute mode will generally provide simpler and more reliable detection of axial cracking (at or near roll expansions and transitions) and denting (Table 4-5 footnote 2). However, the degradation must usually be somewhat significant. Use of alternate test probes, e.g., (8x1) or RPC, can provide improved test reliability and better characterize tube wall degradation. For expanded or bulged regions of tubing, use of the (8x1) is recommended where circumferential cracking is expected (Table 4-5 footnote 3), whereas for axial cracking, the use of RPC technology is preferred (Table 4-5 footnote 4). Use of the (8x1) as a supplemental examination can also

Table 4-5

RECOMMENDED TEST COILS

Mechanism/Location	Bobbin (6)		(8x1)	RPC
	Differential	Absolute		
• Thinning	X	X		
• IGA/SCC	X	X		X(4)
• Pitting	X			
• Wear				
- AVB's		X(5)	X(1)	
- Preheater Baffle Plates		X(5)		
- Lane Region		X	X(1)	
• PWSCC				
- U-bend				X(4)
- Roll Expansion	X	X(2)	X(3)	X(4)
- Roll Transitions	X	X(2)	X(3)	X(4)
- Dents	X	X(2)	X(3)	X(4)
• Corrosion Fatigue				
- Lane Region			X	
• Impingement				
	X			

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(1) Use of (8x1) and appropriate standards can provide improved sizing.

(2) Use of absolute coil mode will in general provide improved detection as compared with differential coil mode.

(3) Recommended when circumferential cracking is expected. Calibration normally established using groove standard.

(4) Will provide best detection capability. Normally calibrated with EDM notch standards.

(5) Wear scar standards normally used for sizing.

(6) ASME standard should be used for all bobbin coil examination. Other standards may be used for supplemental information.

provide information for improved sizing for wear geometries at AVB's and at broached support plate lands (Table 4-5 footnote 1). As a general rule, the bobbin coil and (8x1) are used in production situations where numerous tubes have to be examined; whereas rotating pancake coils tend to be used for diagnostic purposes. However, for characterization of cracking at roll expansions - where crack length and orientation are important - rotating pancake coil technology should be used in a production mode.

4.3.3 Standards

Calibration standards are used for several functions including; 1) providing a basis for verifying overall system performance; 2) establishing data analysis working sensitivities and allowing for signal amplitude voltage normalization and 3) providing data from which a series of calibration curves can be generated allowing for the estimation of flaw parameters of interest.

The ASME standard consists of a section of tubing drilled with flat bottomed holes of various depths and diameters. In addition to the drilled holes, a support plate ring typically encircles the tube. This standard configuration is typically used to verify overall system performance during normal bobbin coil production examination, to establish normalized voltage settings, and to determine mixing coefficients.

AVB and wear scar standards are designed to duplicate the expected geometry of wear at antivibration bars and preheater baffle plates respectively. They are typically used as supplemental standards during a bobbin coil examination. The AVB standard may be one or two sided whereas the preheater wear scar standard may consist of flat or tapered wear scar geometries. The choice of specific standard geometry is related to conservatism, historical data and plant preference. See Appendix A Section A.3.2 for additional details.

Groove and wall thinning standards are constructed using axisymmetric discontinuities and are used to establish setup parameters for the (8x1) coil. The choice of an axisymmetric standard allows for the independent setup of each of the array coil elements without the concern for rotational effects between the coil element and the standard discontinuity.

EDM notch standards are typically used to establish setup conditions for rotating probe technology. The notches may be axial or circumferential, and of different lengths and depths. In addition, multiple closely-spaced notches are sometimes used to demonstrate system resolution capability.

In test situations which involve the use of the bobbin coil, the ASME standard should always be used. Other standards can then be used to acquire supplemental data for specific calibration purposes. The types of standards typically used with a particular test coil are also summarized in Table 4-5.

4.4 DATA ANALYSIS

The use of multiple-frequency instrumentation - with its numerous possible analysis channels - coupled with the diversity of flaw types which can be encountered during a steam generator examination has necessitated the use of a highly structured approach towards data evaluation. This is necessary to ensure that the most appropriate analysis practices are used for a given flaw type and that data is analyzed in a consistent and reliable manner.

Important elements of the data analysis process include:

- Establishing independent analysis teams
- Written analysis guidelines
- Analysis methods

4.4.1 Independent Analysis Teams

It is not unusual for many hundreds of thousands of signals to be encountered during a steam generator examination. Each signal must be detected and correctly dispositioned; the consequences of a single missed indication or one incorrectly analyzed is a possible unscheduled shutdown. In order to reduce the likelihood of this event, independent data analysis teams should be established to review all plant eddy current data. To maintain independence, the primary and secondary analyses should be done separately and not as a joint effort. Each of the two teams should report its analysis results to data base management personnel where the two sets of results can then be reviewed for the existence of discrepancies.

The benefit of an independent analysis team structure is illustrated with data illustrated in Figure 4-1. Given two independent events a and b, the probability that either or both of these two events occur is given by

$$P(a + b) = P(a) + P(b) - P(a)P(b) \qquad \text{(Equation 4-1)}$$

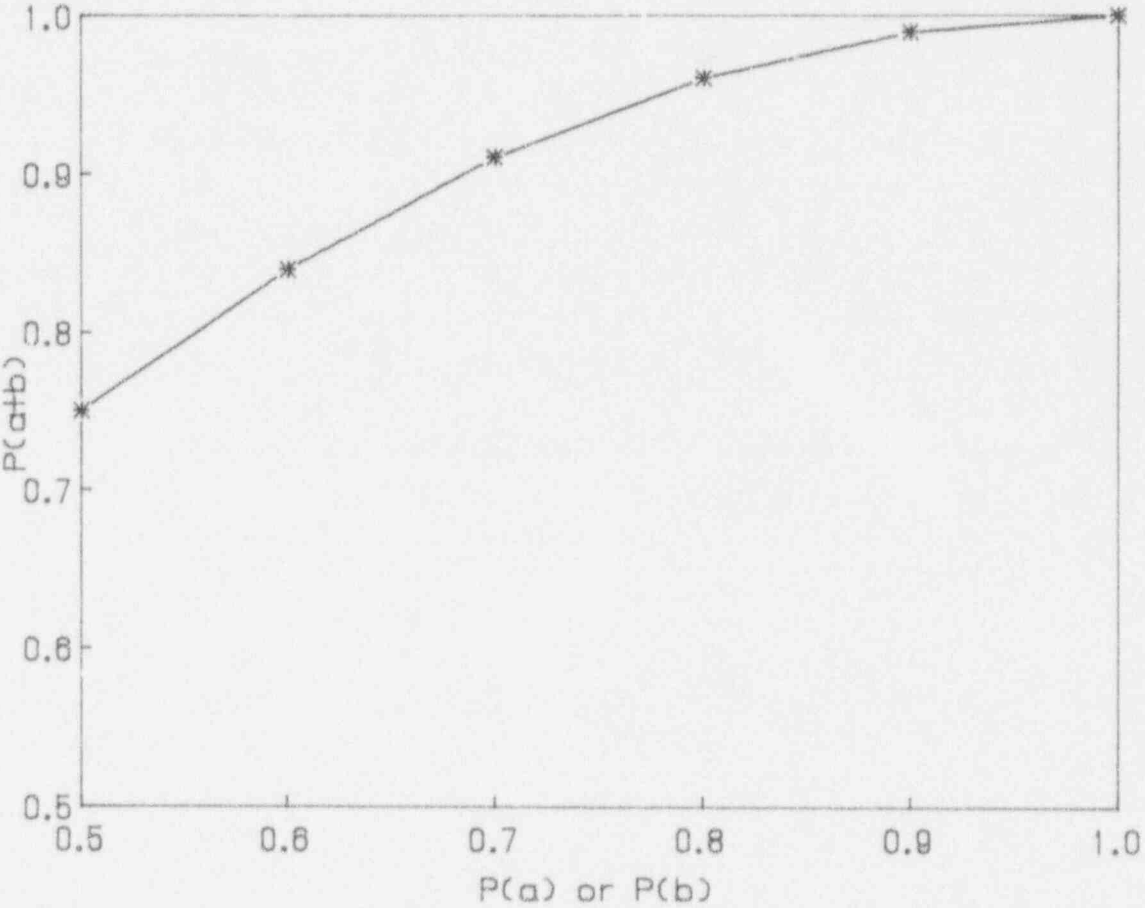


Figure 4-1. Independent Two-Party Analysis - Detection Probability

If P(a) and P(b) represents the detection probabilities of the two individual analysts, then the probability that either of the two analysts or both detect a given indication is given by Equation (1). This can be viewed as a system detection probability. For values of P(a) and P(b) both equal to 0.8, then Equation (1) assumes the value of P(a + b) = 0.96 (plotted parametrically in Figure 4-1 for P(a) or P(b) - assumed to be equal - ranging from 0.5 to 1.0) which represents a significant improvement in overall system analysis reliability illustrating the benefit of the independent review process. If the analysis is not done independently, e.g., communi between the analysts during analysis, then the system value will approach th r value of the individual analyst.

While the specific organization of the analysis teams may vary with a particular plant, a common structure typically utilized is illustrated with the aid of Figure 4-2. In this case there are two analysis t ns (Teams A & B); one designated as primary and the other secondary. The ind analysis results from each of the two teams are fed to the data base management system where discrepancy conditions are identified. Typical discrepancy conditions are summarized in Table 4-6. It is important that there be an appropriate delineation of analyst responsibilities, clear definitions of discrepancy conditions, and a well-defined process for discrepancy resolution. Discrepancies between the primary and secondary analysts are typically resolved among themselves, by the shift lead analysts, senior analysts or other designated individuals.

An extremely important consideration is the deletion of a call requiring a tube repair by either of the two analysis teams. If either of the two analysis results meets the criteria for tube repair, then at least two analysts (not from the same team) must concur before the analysis result is modified and the tube is dispositioned as not requiring repair. Additional diagnostic testing may be required to accomplish this resolution.

4.4.2 Written Analysis Guidelines

The preparation of written analysis guidelines should be done with extreme care and detail since it will basically control the tenor and overall integrity of the analysis process. It should be emphasized that the purpose of an analysis guideline is to provide structure to the analysis process and improve analysis reliability. It is not intended to restrict the analyst in situations where new conditions are encountered or situations where the analyst feels uncomfortable. In these circumstances, the analyst should alert the lead or senior analyst for the

```
              Eddy Current
      |---------- Data ---------|
      |                         |
      |                         |
|-------------|         |-------------|
|  Primary    |         |  Secondary  |
|  Analysis   |         |  Analysis   |
|  (Team A)   |         |  (Team B)   |
|-------------|         |-------------|
      |                         |
      |--------         ---------|
              \|/     \|/
           |---------------|
           |   Data Base   |
           |   Management  |
           |    System     |
           |---------------|
                   |
                   |
                  \ /

       Discrepancy Identification
```

Figure 4-2. Independent Analysis Process

Table 4-6

TYPICAL DISCREPANCY CONDITIONS

- Sizing estimates for the same indication differ by more than 10% through wall
- Location estimates for the same indication differ by more than one inch
- Reported test extents are not in agreement
- One analyst reports a tube not reported by the other analyst
- One analyst reports a reportable indication not reported by the other analyst
- The reported steam generator identifications are not in agreement
- The reported tape identifications are not in agreement
- The reported flaw location is beyond the reported extent of test
- Reported probe entry sides not in agreement
- Tubes reported as restricted which do not have a corresponding extent of test
- Missing probe size or tape identification
- Use of a three-letter code with no established definition
- Test extents and flaw elevations do not conform with the number of antivibration bars and support members in the steam generator

appropriate analysis guidelines modification or discuss the specific analysis issues.

Subject material which should be included within the analysis guidelines is given in Table 4-7. An outline for a typical plant specific analysis guideline is provided in Appendix D.

4.4.3 Analysis Methods

Data analysis criteria or "analysis rules" are typically established on a plant specific basis. Although the generic occurrence of specific damage mechanisms do occur on an industry-wide basis, cause and effect action and consequences on how indications associated with the different mechanisms at a particular plant must ultimately be dispositioned are not necessarily generic.

Plant-specific analysis rules may consist of the use of particular data channels to analyze given regions of a tube or the use of specific amplitude or phase angle thresholding criteria in terms of reporting and dispositioning an indication. In some situations, mere detection is a sufficient condition for initiating the repair of a tube; no sizing is attempted.

In most cases, a calibration curve derived using the ASME standard is used to provide a depth estimate of tube wall degradation. For some forms of tube wall degradation, special data acquisition and analysis methods have been developed for more reliable detection and or sizing. These include:

> IGA/SCC. Units with open tube sheet crevices should review both absolute and differential bobbin coil data. See Appendix C Section C.4.1.4.1 for additional information.
>
> Pitting. The use of a narrow field differential bobbin coil has provided for improved detection and sizing for pitting in the presence of copper. See Appendix C Section C.4.1.2 for further details.
>
> AVB Wear. Units with AVB wear may want to consider the use of appropriate supplemental AVB standards and (8x1) array probes for better characterization. See Appendix C Section C.4.1.3 for specifics.
>
> Wear at Preheater Baffle Plates. Absolute bobbin coil data acquisition methods and the use of wear scar standards or transform methods for sizing are recommended. See Appendix C Section C.4.1.3.1 for additional information.

Table 4-7

ANALYSIS GUIDELINES

SCOPE

- Defines the method and technique for which the analysis guidelines are applicable

RESPONSIBILITIES

- Defines the analyst hierarchy and analyst responsibilities

PERSONNEL QUALIFICATIONS

- Defines minimum analyst qualification and certification requirements, and supplemental performance demonstration

CALIBRATION

- Establishes mixing channels, voltage normalization settings, rotation and span settings, and calibration curve generation

REPORTING REQUIREMENTS

- Test extent and minimum reporting levels for tube wall degradation and damage precursors

EVALUATION

- Establishes requirement for independent analysis
- Determines analysis span settings, strip chart settings, and Lissajous viewing window channel requirements for initial data review
- Specifies channels to be used for evaluation in different regions of the tube and evaluation method
- Analyst Performance Demonstrations
- Specifies how phase angles are to be assigned and how signal amplitudes are to be measured
- Specifies how location is to be determined
- Specifies which of the two analyses stands if there are no discrepancies and defines discrepancy conditions

RECORDING

- Defines requirements for which signals are to be recorded during calibration, hard copy printouts for reportable indications and information to be included in the final report and summary section

RESOLUTION

- Determines the conditions for resolution, the formalities for resolving discrepancies, and documentation of the resolution process

Wear at Broached Support Plate Lands. Units with wear at support plate lands may want to consider the use of (8x1) array probes for improved sizing. See Appendix C Section C.4.1.3 for further information.

Corrosion-Fatigue. B&W units with corrosion fatigue should examine the lane region from the 15th support plate through the upper tube sheet with (8x1) probes. See Appendix C Section C.4.2.1 for further information.

Inner Row U-Bend Cracking. Westinghouse units with a site history of PWSCC should examine all Row 1 and Row 2 U-bends with rotating pancake technology. See Appendix C Section C.4.1.5.1 for additional information.

4.4.4 Computer Data Screening and Analysis Systems

Computerized screening and analysis of eddy current data is achieved by incorporating a detection-analysis rule base in software and allowing that rule base to interact with eddy current data. These systems are typically used in two ways:

- Interactive mode in which the analyst reviews the calls identified by the computer and compares with his own analysis of a tube before the computer results are accepted.
- Fully automated mode in which the computer analysis results are accepted with no direct independent confirmation by the analyst of the raw eddy current data.

In addition to distinguishing between interactive and automated screening-analysis modes, a further distinction can be made between data screening and analysis. Data screening is defined as a process in which a computer is used to select signals - generally those exceeding some threshold voltage - present in the data set for subsequent analysis. Data analysis is defined as the task of estimating additional features of a signal in order to make some judgment as to its significance.

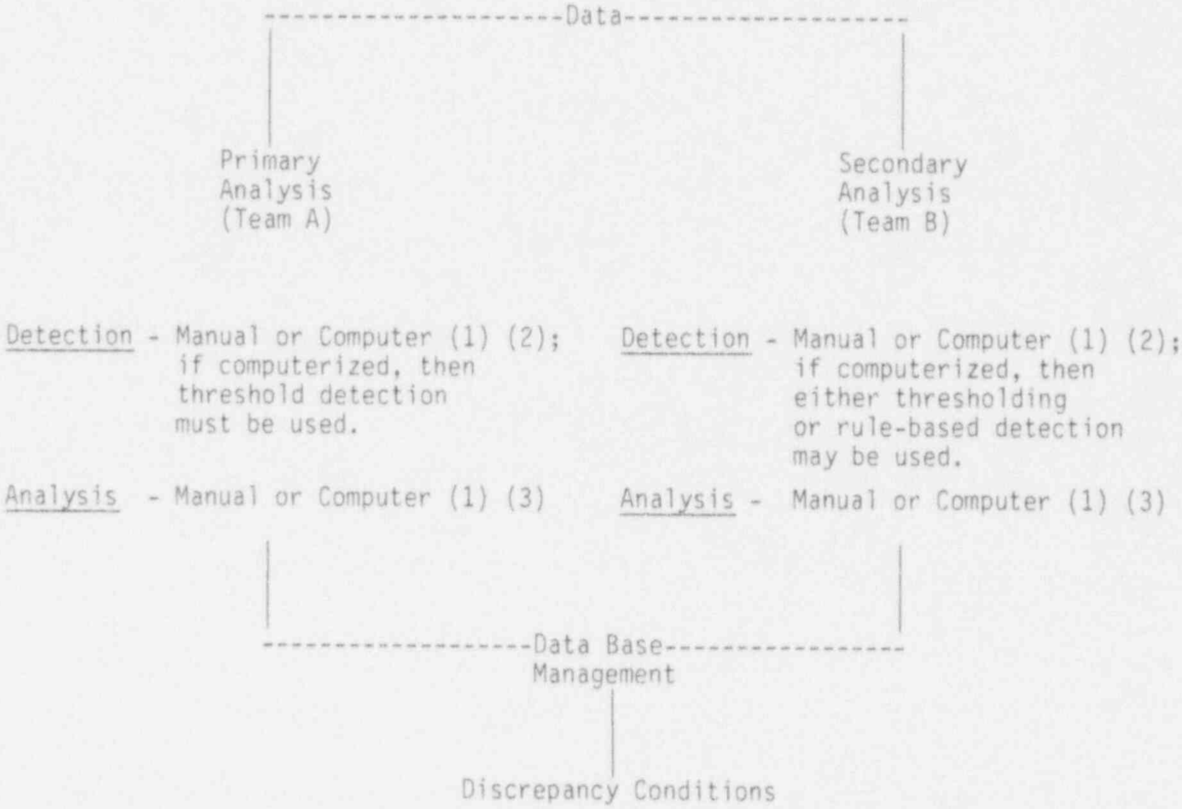
Data screening can be accomplished using various levels of sophistication. Simple "threshold" data screening is defined as a detection mode in which all signals which exceed a certain pre-established voltage level are automatically reported by the computer system for subsequent analysis. This process allows for a time-independent detection capability compensating for boredom, errors, or fatigue, characteristic of manual detection schemes. Because of the vectorial nature of an eddy current signal, this threshold typically involves both in-phase and quadrature signal components such that if a threshold is exceeded in either of the two channels, the signal is reported by the computer. The threshold voltages may assume different values in each of the two channels. In addition, the threshold level may be 1) constant, 2) dynamic e.g., varying with the local noise level present in the data or 3) context related e.g., assume different values depending on the position of the probe in the tube. More sophisticated data screening schemes may utilize "rule-based" thresholding in which the measurement of additional signal descriptors is accomplished before the signal is accepted for further processing. In a sense it represents a low-level form of analysis whose primary objective is to reduce the overall analysis data rate. The use of a "rule-based" threshold imposes additional constraints on what is expected from the data. It is experienced based and accordingly, the logic may be vulnerable to conditions for which the system has not been trained to recognize.

Once detected by either of the two schemes described above, a signal is then accepted by the computer for further analysis. In the "analysis" mode, additional features of a signal are automatically measured. The computer may assign a signal amplitude, phase angle, estimated depth, or attempt to specify the origin of the signal, e.g., support plate signal, OD indication, etc.

As a general rule, an extensive training base may be required to cover all of the subtleties associated with the automated processing of eddy current data. While the introduction of this technology is a positive step towards addressing issues associated with missed indications, or indications incorrectly assessed, its use in the fully automated mode should proceed with appropriate caution. Qualification of computer data screening-analysis systems should be conducted. This can be accomplished by conducting a performance demonstration program similar to that given to the analyst with similar acceptance criteria. This should be done with the system in both the interactive and fully automated modes so that the analysts' contributions to overall system performance can be isolated. System "training data" should not be used for qualification purposes. Independent data sets not "seen" by the system should form the bases for qualification.

If the system is used for production analysis in the fully automated mode, its performance should be audited throughout the course of the outage to assure proper system performance. This is particularly important in plants with high risk damage mechanisms, i.e., generally cracking related phenomena, or complicated analysis rule bases.

Recommended integration of the computer into the independent data analysis process as first described in Figure 4-2 is shown schematically in Figure 4-3. Key points



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(1) Computer detection and/or analysis may be used when demonstrated, by the plant specific performance demonstration, to be of equivalent or better reliability than manual methods. (See Text for details for performance demonstration and audit requirements.)

(2) If both teams use automated detection, at least one team should review all data manually if there is any question of equivalent performance.

(3) If both teams use automated analysis, then at least one of the two teams must review the automated analysis results manually.

Figure 4-3. Computer Assisted Data Analysis Process to be observed are as follows:

- Both teams may use some form of computer-assisted data screening. However, one of the two systems must use simple thresholding for signal detection. The other system may utilize either thresholding or rule-based detection logic.

- Both teams may use automated analysis. However, the automated analysis results must be verified manually by at least one of the two teams.

- Both teams A & B (including analyst and computer) must successfully complete a plant-specific analysis performance demonstration. It is recommended that the capabilities of the computer and the individual analyst be measured separately.

- Concurrence of individuals from two independent teams (or from a third team if agreement is not reached) is required to eliminate a pluggable or repair condition initially identified by one of the two teams during primary/secondary analysis.

4.5 ANALYST PERFORMANCE DEMONSTRATION

It is imperative that each analyst have a proper working understanding of the analysis rules and demonstrate this comprehension by passing a practical examination. This is warranted because data from a particular plant is typically reviewed at time intervals on the order of the refueling cycle; in addition, analysts typically come to a plant from another outage. In either case, it is to the utility's advantage for the analyst to reorient and refresh himself to the current plant for which the analysis is being conducted and to demonstrate his analysis skills.

This section provides general criteria for establishing a plant-specific performance demonstration program. Each utility should establish a plant specific program to implement these performance demonstration recommendations.

4.5.1 Performance Demonstration Process

Each analyst is assumed to already have basic Level IIA or higher analyst skills and working knowledge of the analysis equipment and typical minimum training and experience requirements based on ASNT's SNT-TC-1A. To assist the analyst in successfully completing the practical performance demonstration, the basic SNT-TC-1A training requirements are supplemented with plant-specific knowledge and skills presented in a lecture and laboratory session. All individuals who will be involved in the production analysis of plant data, or its resolution and dispositioning should be required to participate in the formal performance demonstration process. Exceptions to this practice, e.g., grandfathering, should not be permitted. Demonstration of the knowledge and skills acquired during the lecture and laboratory sessions is accomplished by requiring all analysts to successfully complete a practical examination. This should consist of analyzing a data tape which contains plant indications of interest with sufficient variety so that the analysis guidelines rule base is covered and in sufficient numbers such that the desired statistical confidence levels are established. An additional supplemental written examination may be warranted to cover additional points in the guidelines that are not readily demonstrated with the analysis practice tape.

The actual preparation and administration of the analyst demonstration program should be approved by the utility with assistance from the ISI vendor, another vendor not involved in the steam generator examination, or other qualified individuals. It is important that strict rules be established during the initial preparation and future maintenance and updating of the performance demonstration so that the overall integrity of the program is maintained. Those individuals directly involved in the preparation of a given demonstration practical examination should not be qualified for plant analysis using that same test material. A separate examination should be prepared to establish their analysis capabilities. For units with limited operating experience, reliance should be placed on information from similar plants with an operating history.

4.5.2 Lecture and Laboratory Session

The lecture session should be led by a knowledgeable individual working from a prepared instructor's guide. The session should include 1) lecture material in which the necessary plant-specific material is reviewed and 2) a laboratory session in which the instructor works individually with the analysts demonstrating the plant-specific analysis rules. The laboratory session should be led by a qualified analyst. Sufficient laboratory time should be allocated for analysts to become familiar with the plant data and practice their understanding of the analysis rules. Typical time allocation for the lecture, laboratory and practical examination is on the order of two to three days. It should be scheduled to commence just prior to the start of outage. It is strongly advised to have all analysts on hand at the beginning of the job in order to minimize the logistics associated with individual analyst performance demonstrations.

Suggested minimum lecture course material which should be presented to the analyst includes:

- Steam Generator Description
- Steam Generator Operating Experience
- Analysis Guidelines
- Examples of Reportable Indications

This material should be given to each analyst in the form of a reference manual which can then be referred to throughout the course of the lecture and outage as required. Specific topics which should be covered under each of the major categories presented above are given in Table 4-8.

The section on analysis guidelines is one of the most important within the reference manual. Because of its importance it is expanded upon in further detail and presented in Appendix D.

4.5.3 Practical Examination Content

The practical examination should be developed using data from previous examinations or data from similar steam generators. Examination "truth" should be established using the independent analysis results of at least two analysts. At least two independent tests should be prepared to cover retest situations.

The signal content of the analysis practical exam should consist of examples of indications which cover the extremes of the analysis logic base. Reportable and nonreportable indications should be included. Examples for all flaw types - postulated or known - for a given plant should be represented. The practical examination may be taken utilizing the prepared reference manual which includes the data analysis procedure.

4.5.4 Acceptance Criteria

Judgment must be used in establishing minimum acceptance criteria for the practical examination based on the plant being examined and the type of defects included. However, as a general recommendation the following is provided:

- Minimum acceptable test score is 80%.

Table 4-8

PERFORMANCE DEMONSTRATION COURSE OUTLINE

- Steam Generator Description Experience
    - Manufacturer & Model Number
    - Number of Steam Generators
    - Number of Tubes
    - Tube Material & Dimensions
    - Support Structure Locations
    - Tubesheet Expansion Geometry
    - Steam Generator Remedial Measures
- Analysis Guidelines
    - Scope
    - Personnel Qualifications
    - Responsibilities
    - Calibration
    - Reporting Requirements
    - Evaluation
    - Recording Requirements
    - Discrepancy Resolution
- Steam Generator Operating Experience
    - Baseline Inspection Results
    - Examination Chronologies
    - Postulated Damage Mechanisms
    - Damage Precursor Distribution
    - Number of Repaired Tubes
    - Other Industry Experience
    - Tube Sheet Maps
- Examples of Reportable Indications
    - Various Flaw Types
    - Damage Precursors

- At least 90% of all pluggable indications must be detected. A 90% lower bound detection probability as applied to an individual analyst equates to a 0.99 system detection probability (See Figure 4-1).
- All detected pluggable indications must be correctly dispositioned with site specific sizing requirements.

Grading schemes should address 1) proper detection, 2) correct classification, 3) false calls, and 4) administrative errors. Weighted grading should be utilized with emphasis on detection and correct classification of indications attributable to tube wall degradation. The operating implication of the indication types included in the exam should be reflected in test score weighting.

4.5.5 Reexamination

Analysts who do not successfully pass the initial practical examination should be required to undertake additional laboratory work under the direction of the instructor using practice tapes focusing on areas in which there were demonstrated deficiencies. Additional review of the reference manual may also be warranted. An additional practical exam should then be taken (retake of original exam or a separate exam). If the individual fails a second time, then analysis at that particular plant by the analyst in question should not be allowed.

4.5.6 Requalification

Individuals who have successfully completed the training and practical examination requirements of this Analyst Performance Demonstration may be requalified at a later date. This requalification shall include, at a minimum, a practical examination using current analysis guidelines and actual data representative of the conditions known or postulated to exist. Requalification is required for inspections subsequent to that associated with the initial analyst qualification. Concurrent inspections which utilize a common qualification program may be considered as a single qualification event.

4.5.7 Documentation

A permanent record of the individuals who have successfully completed the analysis performance demonstration and their test scores should be maintained on file by the utility.

4.6 DIAGNOSTIC METHODS

Diagnostic NDE methods have been used in many applications during a steam generator examination. Examples include:

- Providing clarification of signals identified during the production bobbin coil examination.
- Providing a measure of bobbin coil inspection reliability.
- Developing or confirming an analysis rule base established using the bobbin coil.
- Inferring damage mechanisms in lieu of a tube pull.

The most commonly used diagnostic method is rotating pancake coil eddy current technology. Rotation and translation of a probe coil through the region of the tube of interest allows for the acquisition of data from which, by the use of appropriate display algorithms, the definition of defect morphology and its orientation can generally be inferred. Ultrasonic technology has also been used in a similar fashion; its use is not as popular as eddy current because of the need for a fluid couplant which complicates the delivery system.

4.6.1 Characterization of Distorted Indications and Undefined Signals

During a bobbin coil examination, it is not unusual for analysts to report distorted indications or undefined signals whose classification is not covered by existing analysis guidelines. As a general rule, an extremely conservative position should be adopted with these types of indications during resolution. Specifically, tubes with these types of indications should be recommended for plugging unless other supporting data exists (tube pulls or previous NDE diagnostic data) or is developed during the course of the outage, which justifies their retention as active tubes.

Distortions to bobbin coil signals typically occur as the result of their proximity to tube diameter changes due to denting, roll expansions, etc., or the presence of secondary side deposits or support members. In either case, the use of appropriate diagnostic methods may generally provide an improved signal-to-noise ratio for better characterization of the significance of the indication(s) in question.

The position recommended herein is that lead or senior analysts should be authorized by the utility to request retests of tubes with indications in question using appropriate supplemental diagnostic NDE methods.

4.6.2 Alternative Techniques

NDE methods other than eddy current have been developed for supplementary examination of steam generator tubes. Steam generator engineering examination personnel should be aware of the limitations of eddy current examination techniques and the capabilities of alternative procedures.

Section 5

REFERENCES

(1) *Nuclear Unit Operating Experience: 1985 - 1986 Update*. S. M. Stoller Corporation, December 1987.

(2) *Inservice Inspection of Pressurized Water Reactor Steam Generator Tubes*. U.S. Nuclear Regulatory Commission, Regulatory Guide 1.83, Revision 1, July 1975.

(3) *Design Guidelines for Lay-up of PWR Steam Generators*. Dominion Engineering, Inc., December 1986.

(4) *Eddy Current NDE for Intergranular Attack*. EPRI Report NP-2962, February 1983.

(5) *Field Experience with Multifrequency-Multiparameter Eddy Current Technology*. EPRI Report NP-2299, January 1983.

Appendix A

STEAM GENERATOR OPERATING EXPERIENCE

A.1 INTRODUCTION

Developing a rational steam generator examination program requires awareness of industry experience with tube degradation and its location within a steam generator. The choice of inspection method, data interpretation, and action taken can depend on the type of degradation suspected. In addition, the guidelines presented in Section 3 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 A.2 presents an industry overview of steam generator operating experience. Sections A.3, A.4, and A.5 provide more detailed discussions on a plant-by-plant basis for Westinghouse and Westinghouse licensees (Framatome and Mitsubishi), Combustion Engineering, and Babcock & Wilcox respectively.

A.2 PWR STEAM GENERATOR OPERATING EXPERIENCE OVERVIEW

Table A-1 provides a summary of industry-wide steam generator operating experience. Tubing corrosion mechanisms include wall thinning, pitting, and primary/secondary side stress corrosion cracking. Mechanical degradation can take the form of wear, fatigue cracking, and flow impingement effects. Denting is considered a potential tube damage precursor and is associated with the corrosion of carbon steel support members (e.g., support plates, eggcrates). In recirculating units, primary side stress corrosion cracking affects the largest percentage units with 61 plants or 41% of the total steam generator population experiencing primary side cracking of one form or another. Primary side cracking has typically occurred in inner row U-bends and at roll transition areas in units with both open and closed crevices. Mechanical wear or fretting at AVB's is the second most common form of tube wall degradation followed by intergranular attack-stress corrosion cracking and thinning. In once-through steam generators, mechanical degradation in the form of wear at lane-region broached support plates and corrosion-assisted fatigue are the dominant

TABLE A-1
STEAM GENERATOR OPERATING EXPERIENCE OVERVIEW

	Once-Through Steam Generators	Recirculating Steam Generators				Total Units
	B&W	CE	W	F	M	
Number of Units	(8)	(15)	(75)	(46)	(12)	(156)
Mechanism						
• Denting	0	9	28	2	0	39
• Tubing Corrosion						
Thinning	0	5	27	0	1	33
Pitting	2	2	6	0	0	10
IGA/SCC	4	7	24	1	3	39
Primary Side Cracking	1	1	30	25	4	61
• Mechanical Degradation						
Wear	4	7	29	10	2	52
Fatigue Cracking	5	0	1	0	0	6
Impingement	2	0	0	0	0	2

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damage mechanisms.

A.3 WESTINGHOUSE OPERATING EXPERIENCE

Tables A-2 through A-8 summarize operating experience for plants designed or licensed by Westinghouse. Table A-2 displays Model 24, 27, and 33 experience whereas Model 44 experience is given in Table A-3. Model 51, preheater Models D2/D3/D4 & E, and Model F experience is summarized in Tables A-4 through A-6. Framatome and Mitsubishi operating experience is given in Tables A-7 and A-8 respectively.

Based on experience cited in these tables, corrosion is the predominant tube degradation mechanism within and above the tube sheet crevice, and at support plates. Known corrosion mechanisms include thinning, secondary side stress corrosion cracking-intergranular attack, pitting, primary side stress corrosion cracking, and denting. Mechanical wear related degradation is restricted to fretting at antivibration bars and at baffle plates in preheater models.

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

A.3.1 Thinning

Phosphate wastage attack or thinning has occurred in units that have used an all-solids (PO4) secondary side water chemistry control program during their operating history. Affected steam generators include Models 24, 27, 33, 44, and 51 (see Tables A-2 through A-4 and Table A-8). Wastage has been observed on both the steam generator hot leg and cold leg in the sludge pile region (see Figure A-1). Very few leaker outages have been attributed to wastage. Known examples of leaker outages in Westinghouse units include incidences at Ginna, Point Beach 2 and Robinson 2. With the shift to an AVT chemistry during the mid-1970's, the progression and significance of wastage has diminished. One unit, Indian Point 3, has recently experienced significant localized thinning evcn though it has always been on AVT chemistry control. Wastage is no longer considered a serious industry-wide problem.

Cold leg thinning at the lower support plate elevations was first observed on tubes removed at Prairie Island 1 and Salem during the early 1980's. The mechanism is described as wall thinning resulting from an unidentified corrodent. Vibration assisted corrosion is a postulated mechanism (1). Eddy current signals attributable

TABLE A-2
OPERATING EXPERIENCE SUMMARY
WESTINGHOUSE MODEL 24, 27 and 33 STEAM GENERATORS

Unit (1)	Model	No. of Steam Generators	Commercial Operation	Chemistry	Thinning	Wear	IGA/SCC	PWSCC	Pitting	Denting
San Onofre 1	27	3	1967	P04	X	X(6)	X (2)	X(5)	X(4)	Extensive
Connecticut Yankee	27	4	1968	P04>AVT	X	X(6)	X (2)	X(5)	X	Moderate
Zorita	24	1	1969	P04	X	X(6)	X (2,3)	X(5)		
Beznau 1	33	2	1969	P04>AVT	X	X(6)	X (2)			
Beznau 2	33	2	1972	P04>AVT	X	X(6)	X (2)			Minor

---

(1) Units have open tube sheet crevices

(2) Tube sheet crevice hot leg

(3) Hot leg, 1st support

(4) Minor pitting has been observed in U-Bends

(5) Roll transition

(6) At AVB's

TABLE A-3
OPERATING EXPERIENCE SUMMARY
WESTINGHOUSE MODEL 44 STEAM GENERATORS

Unit (1)	No. of Steam Generators	Commercial Operation	Chemistry	Thinning	Wear	IGA/SCC	PWSCC	Pitting	Denting
Ginna	2	1969	PO4>AVT	X		X (2)			Minor
Robinson 2*	-	1970	PO4	X	X	X (2)			Minor
Point Beach 1*	-	1970	PO4>AVT	X		X (2)			Moderate
Point Beach 2	2	1971	PO4>AVT	X		X (2)			Moderate
Turkey Point 3*	-	1972	PO4>AVT	X			X (3)		Extensive
Turkey Point 4*	-	1973	PO4>AVT	X			X (3)		Extensive
Indian Point 2	4	1973	PO4>AVT					X	Extensive
Doel 1**	2	1975	PO4>AVT						Minor
Doel 2**	2	1975	AVT			X (2)	X (4)		Minor
Indian Point 3	4	1976	AVT	X		X	X (3)	X	Extensive

---

* Units have been replaced with Model 44F's - see Table A-5
** Manufactured by Cockerill
(1) Units have open tube sheet crevices
(2) Tube sheet crevice
(3) Denting assisted
(4) Roll transitions

TABLE A-4
OPERATING EXPERIENCE SUMMARY
WESTINGHOUSE MODEL 51* STEAM GENERATORS

Unit	No. of Steam Generators	Commercial Operation	Chemistry	Thinning	Wear	IGA/SCC	PWSCC	Pitting	Denting
Surry 1**	-	1972	PO4>AVT	X					Extensive
Surry 2**	-	1973	PO4>AVT	X					Extensive
Zion 1	4	1973	PO4>AVT	X (1)	X (7)	X (6)	X (2,3)		Minor
Prairie Island 1	2	1973	PO4>AVT	X (1)	X (7)	X (6)	X (2)		
Kewaunee 1	2	1973	PO4>AVT	X (1)	X (7)	X (6)	X (2)		Minor
Zion 2	4	1973	PO4>AVT	X (1)	X (7)	X (6)	X (2)		Minor
Prairie Island 2	2	1974	AVT	X (1)	X (7)	X (6)			
D. C. Cook 1	4	1974	AVT	X (1)	X (7)	X (5,6)	X (2,3)		Minor
Takahama 1	3	1974	AVT	X		X (5,6)	X (3,4)		
Ringhals 2	3	1975	PO4>AVT	X (1)	X (7)	X	X (2,3)		Moderate
Tihange 1***	3	1975	AVT		X (7)	X (5)			Minor
Trojan 1	4	1975	AVT			X (4)	X (2)	X	Minor
Beaver Valley 1	3	1976	AVT	X (1)	X (7)	X (4)			Minor
Salem 1	4	1976	AVT	X (1)	X (7)	X (4)			Minor
Farley 1	3	1977	AVT		X (7)	X (4)	X (2)		
Kori 1	2	1977	AVT			X (4)	X (2)	X	Minor

---

* All units have open tube sheet crevice except where noted

** Units have been replaced with Model 51F's - see Table A-5

*** Manufactured by Cockerill

(1) Cold leg at lower supports

(2) Row 1/2 U-Bends

(3) Roll transition

(4) Fully expanded crevice

(5) Hot leg support plates

(6) Tube sheet crevice

(7) AVB's

TABLE A-4 (Cont.)
OPERATING EXPERIENCE SUMMARY
WESTINGHOUSE MODEL 51* STEAM GENERATORS

Unit	No. of Steam Generators	Commercial Operation	Secondary Water Chemistry	Thinning	Wear	IGA/SCC	PWSCC	Pitting	Denting
North Anna 1	3	1977	AVT		X (8)	X (4,2)	X (2,5)		Minor
D. C. Cook 2	4	1977	AVT	X (1)	X (8)	X (6)	X (2,3)		Minor
OHI 1	4	1979	AVT			X (4,7)	X (2,3)		Minor
North Anna 2	3	1980	AVT	X (1)	X (8)		X (2)		Minor
Sequoyah 1	4	1980	AVT				X (2)		Minor
Salem 2	4	1980	AVT	X (1)	X (8)				
Farley 2	3	1980	AVT		X (8)	X (4)	X (7)		
Sequoyah 2	4	1981	AVT				X (2)		
Diablo Canyon 1	4	1981	AVT						
Diablo Canyon 2	4	1985	AVT						
Beaver Valley 2	3	1986	AVT						

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* All units have full depth expansion except for Cook 2
(1) Cold leg at lower supports
(2) Row 1/2 U-Bends
(3) Roll transition
(4) Hot leg support plates
(5) Hot and cold leg support plates
(6) Tube sheet crevice - open crevice
(7) Full depth tube sheet expansion
(8) AVB's

TABLE A-5
OPERATING EXPERIENCE SUMMARY
WESTINGHOUSE MODEL F STEAM GENERATORS

Unit (1)	Steam Generator Type	Commercial Operation	No. of Steam Generators	Chemistry	Thinning	Wear	IGA/SCC	PWSCC	Denting
Surry 2	51F	1980	3	AVT					
Surry 1	51F	1981	3	AVT					
Turkey Point 3	44F	1982	3	AVT					
Kori 2	F	1983	2	AVT		X (2)			
Turkey Point 4	44F	1983	3	AVT					
Maanshan 1	F	1984	3	AVT					
Point Beach 1	44F	1984	2	AVT					
Takahama 3	51F	1984	3	AVT					
Takahama 4	51F	1984	3	AVT					
Callaway 1	F	1984	4	AVT		X (2)			
Kori 5	F	1985	3	AVT		X (2)			
Maanshan 2	F	1985	3	AVT					
Robinson 2	44F	1985	3	AVT					
Sendai 2	51F	1985	3	AVT					
Wolf Creek 1	F	1985	4	AVT		X (2)			
Kori 6	F	1985	3	AVT					
Kori 7	F	1986	3	AVT					
Millstone 3	F	1986	4	AVT		X (2)			
Tsuruga 2	51F	1986	3	AVT					

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(1) All units have fully expanded crevices
(2) AVB's

TABLE A-6
OPERATING EXPERIENCE SUMMARY
WESTINGHOUSE PREHEATER MODEL STEAM GENERATORS

Unit*	Model	No. of Steam Generators	Commercial Operation	Chemistry	Thinning	Wear	IGA/SCC	PWSCC	Denting
Ringhals 3	D3	3	1980	AVT		X (1,6)		X (2)	
Almaraz 1	D3	3	1981	AVT		X (1,6)	X (4)	X (2)	
McGuire 1	D2	4	1981	AVT		X (1,6)		X (2)	
Krsko	D4	2	1981	AVT		X (1,6)	X (3)	X (2)	
Angra 1	D3	2	1982	AVT					Minor
Ringhals 4	D3	3	1982	AVT		X (6)		X (2)	
Summer 1	D3	3	1982	AVT				X (2,5)	
McGuire 2	D3	4	1983	AVT				X (2,5)	
Asco 1	D3	2	1983	AVT				X (2)	Minor
Almaraz 2	D3	3	1983	AVT				X (2)	Minor
Watts Bar 1	D3	4		AVT					
Byron 1	D4	4	1985	AVT					
Doel 4	E1**	3	1985	AVT		X (1)		X (2)	
Tihange 3	E1**	3	1985	AVT		X (1)		X (2)	
Asco 2	D3	2	1985	AVT					
Commanche Peak 1	D4	4	1985	AVT					
Catawba 1	D3	4	1985	AVT					
Shearon Harris	D4	3	1986	AVT					
Watts Bar 2	D3	4		AVT					
Catawba 2	D5	4	1986	AVT					

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* All units have full depth crevice expansion

** Manufactured by Cockerill

(1) Preheater section baffle plates

(2) Roll transition

(3) Hot leg tube sheet within sludge pile

(4) Hot leg support plate

(5) Row 1 U-Bends

(6) AVB's

TABLE A-7
OPERATING EXPERIENCE SUMMARY
FRAMATOME STEAM GENERATORS

Unit*	No. of Steam Generators	Commercial Operation	Chemistry	Thinning	Wear	IGA/SCC	PWSCC	Pitting	Denting
Fessenheim 1**	3	1977	AVT		X (5)	X (1,2)	X (3,4)		
Fessenheim 2**	3	1977	AVT		X (5)		X (4)		
Bugey 2***	3	1978	AVT		X (5)		X (3)		
Bugey 3***	3	1978	AVT		X (5)		X (1,4)		
Bugey 4***	3	1979	AVT		X (5)		X (3,4)		
Bugey 5	3	1979	AVT		X (5)		X (3,4)		
Gravelines 1	3	1980	AVT		X (5)		X (3)		
Dampierre 1	3	1980	AVT		X (5)		X (3,4)		
Tricastin 2	3	1980	AVT		X (5)		X (3,4)		
Gravelines 2	3	1980	AVT						
Tricastin 3	3	1980	AVT		X (5)		X (3)		
Gravelines 3	3	1980	AVT				X (3,4)		
Dampierre 2	3	1980	AVT				X (3,4)		
Tricastin 1	3	1981	AVT				X (4)		
Dampierre 3	3	1981	AVT				X (4)		
St. Laurent B2	3	1981	AVT				X (4)		
Le Blayais 2	3	1981	AVT				X (4)		
Gravelines 4	3	1981	AVT				X (3,4)		
Tricastin 4	3	1981	AVT				X (4)		
Dampierre 4	3	1981	AVT				X (3,4)		
St. Laurent B1	3	1981	AVT			X (2)	X (3)		
Le Blayais 2	3	1982	AVT				X (4)		

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* All units have crevice rolled full depth with DAM (kiss) roll except where noted

** Full depth explosive expansion

*** Full depth roll without DAM (kiss roll)

(1) Within sludge pile, top of tube sheet

(2) Hot leg support plates

(3) Row 1 U-Bends

(4) At kiss roll

(5) AVB's

TABLE A-7 (CONT.)
OPERATING EXPERIENCE SUMMARY
FRAMATOME STEAM GENERATORS

Unit*	No. of Steam Generators	Commercial Operation	Chemistry	Thinning	Wear	IGA/SCC	PWSCC	Pitting	Denting
Chinon B1	3	1984	AVT						
Doel 3**	2	1982	AVT				X (1)		Minor
Cruas 1	3	1984	AVT						
Le Blayais 4	3	1983	AVT				X (1)		
Le Blayais 3	3	1983	AVT				X (1)		
Chinon B2	3	1984	AVT						
Tihange 2**	3	1983	AVT				X (1)		Minor
Gravelines 5	3	1985	AVT						
Cruas 3	3	1984	AVT						
Paluel 1	4	1985	AVT						
Cruas 2	3	1985	AVT						
Paluel 2	4	1985	AVT						
Cruas 4	3	1985	AVT						
Koeberg 1	3	1984	AVT						
Gravelines 6	3	1985	AVT						
St. Alban 1	4	1986	AVT						
Paluel 3	4	1986	AVT						
Flamanville 1	4	1986	AVT						
Koeberg 2	3	1985	AVT						
Paluel 4	4	1986	AVT						
St. Alban 2	4	1987	AVT						
Flamanville 2	4	1987	AVT						
Chinon B3	3	1987	AVT						
Cattanom 1	4	1987	AVT						

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* All units have crevice rolled full depth with DAM (kiss) roll

** Manufactured by Cockerill

(1) At kiss roll

TABLE A-8
OPERATING EXPERIENCE SUMMARY
MITSUBISHI STEAM GENERATORS

Unit*	Model*	No. of Steam Generators	Commercial Operation	Chemistry	Thinning	Wear	IGA/SCC	PWSCC	Denting
Mihama 2 **	44	2	1972	PO4>AVT	X(1)		X(2,[illegible])	X(4)	
Takahama 2**	51	3	1974	AVT			X(3)		
Genkai 1**	51	2	1975	AVT			X(3)		
Mihama 3	51	3	1976	AVT		X(5)		X(4)	
Ikata 1	51	2	1977	AVT		X(5)		X(4)	Minor
Ohi 2	51A	4	1978	AVT				X(4)	
Genkai 2	51M	2	1980	AVT					
Ikata 2	51M	2	1981	AVT					
Sendai 1	51M	3	1983	AVT					
Takahama 3	51F	3	1984	AVT					
Takahama 4	51F	3	1984	AVT					
Sendai 2	51F	3	1985	AVT					

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* All units have full depth crevice expansion except where noted

** Expanded to within 50 mm of top of tube sheet after operation

(1) Support plates

(2) Tube sheet crevice - hot leg

(3) Hot leg support plates

(4) Roll transition

(5) AVB's

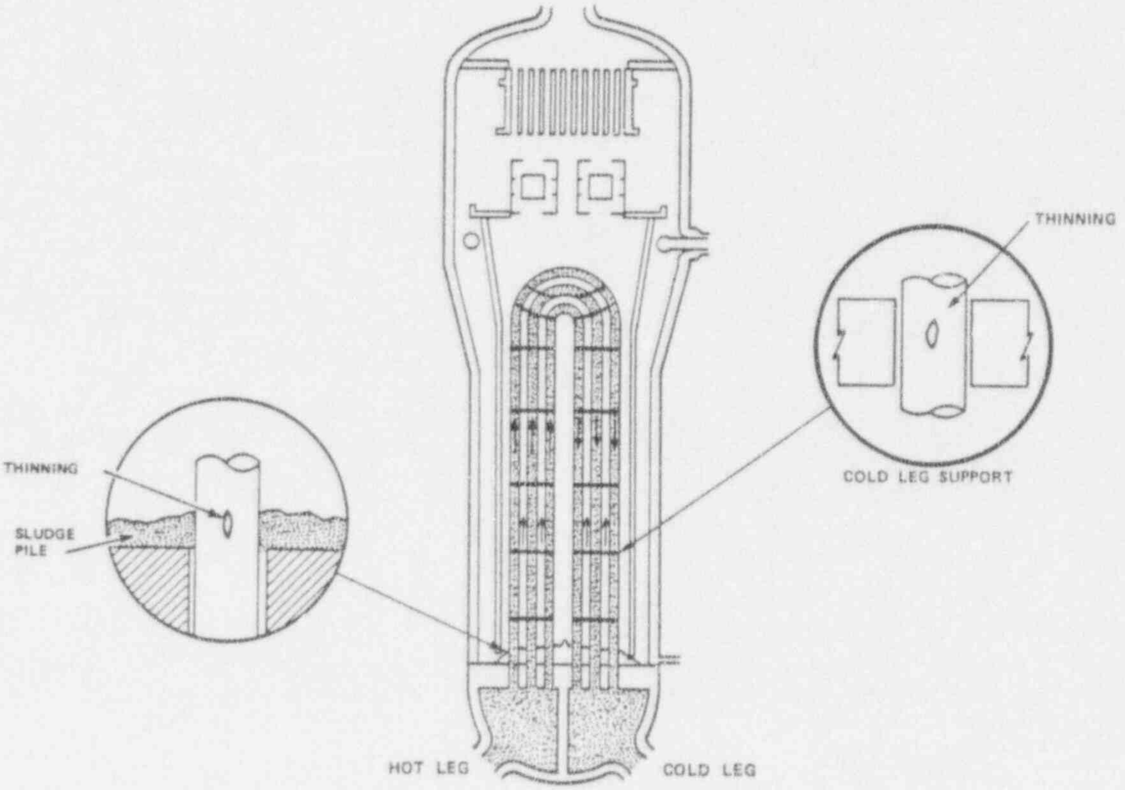

Figure A-1. Thinning Locations in Westinghouse Steam Generators to this damage mechanism have also been reported in other Model 51 steam generators (see Table A-4). The degradation is basically confined to the outer periphery of Model 51 steam generators at the 1st and 2nd support plate elevations. No leaker outages have occurred as the result of cold leg thinning.

A.3.2 Wear

In the mid 1970's, Model 27 steam generators at San Onofre Unit 1 and Connecticut Yankee experienced wear at AVB's located within the U-bend region (see Figure A-2). This particular damage mechanism has since been observed in Model 24, and 33 steam generators (See Table A-2). These units originally had AVB's with a round cross-section; antivibration bars with a square cross section, installed as part of a modification program in two of the units (San Onofre 1 and Beznau 1), have tended to reduce the propensity of AVB wear.

Eddy current signals attributable to wear at AVB's have also been reported in numerous Model 51 steam generators (See Table A-4). Using secondary side fiber optic inspection methods to examine the AVB intersections, Prairie Island 1 was able to confirm the damage mechanism. Zion 1 has conducted a secondary side tube removal and confirmed the presence of fretting (2). AVB modifications have since been implemented at several Model 51 units and are scheduled at numerous other units. It is believed that this corrective action will retard or inhibit further wear at the AVB's.

Eddy current signals at AVB's have also been reported during inspections of some Model F steam generators (See Table A-5). In some cases, the signals were observed after the first fuel cycle. As with the Model 51's, an AVB modification is being considered in order to mitigate this wear problem.

Several forced shutdowns have been attributed to wear at AVB's. Tihange 1 had a forced shutdown in 1984 due to tube wear at AVB's. The leaking tube progressed from no detectable degradation to a 100% through wall in two years. An adjacent tube had a 20% wear indication that did not change over the same period of time.

Some Westinghouse Model D2/D3 steam generators experienced wear at support plate intersections within the preheater section during their initial operation. Figure A-2 illustrates the preheater section of a Model D2 generator and the location of the wear phenomenon. The wear has typically occurred on the outer periphery opposite the feedwater inlet. The tube wear typically assumes the shape of the

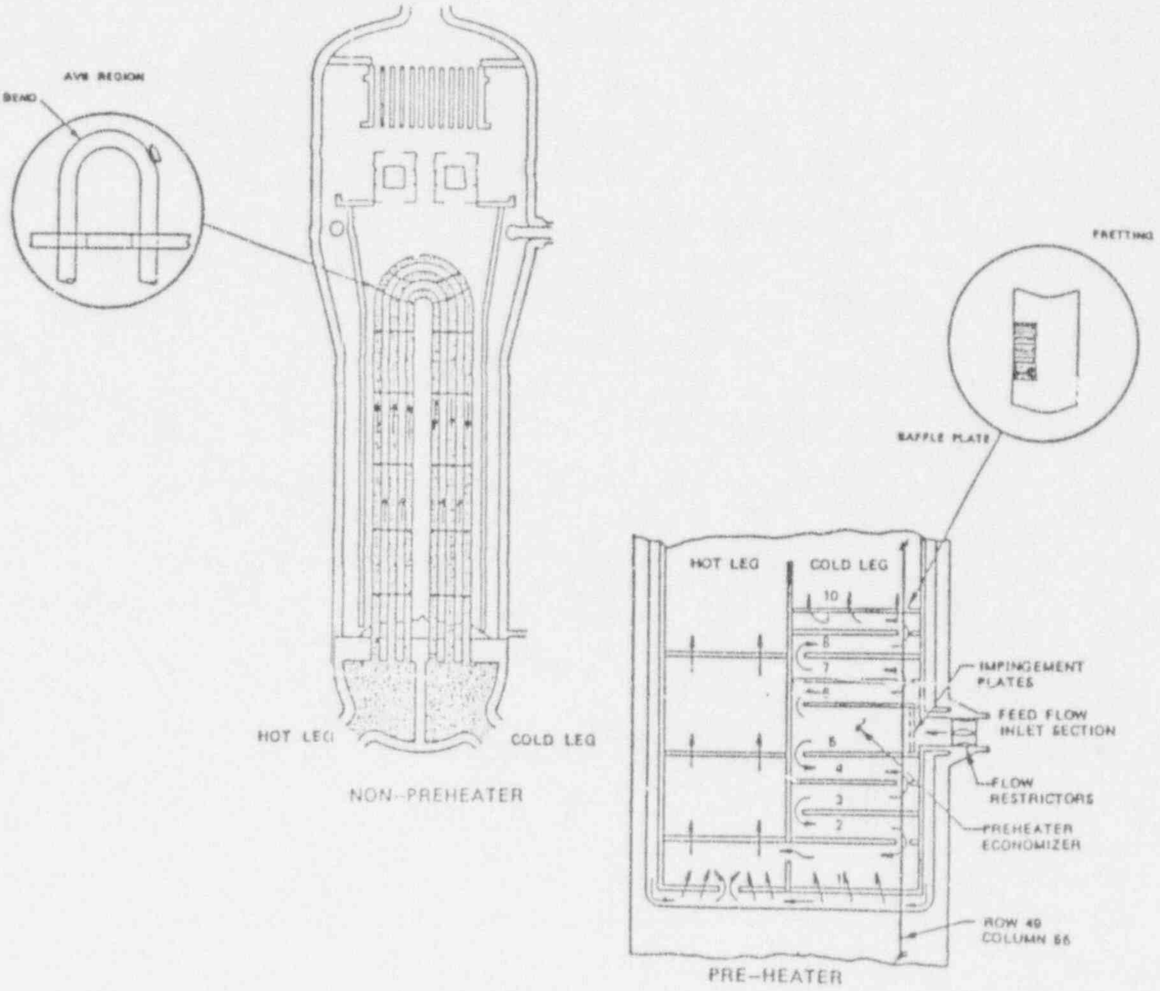

Figure A-2. Wear Locations in Westinghouse Steam Generators baffle plate hole; due to the preheater flow velocity distribution, the wear is not necessarily symmetrical around the tube. This form of wear was first observed at Ringhals 3 during 1981. Review of the plant's eddy current data clearly showed evidence of tube wall degradation at the baffle plates (3). This wear led to a subsequent leaker outage. Almaraz 1, McGuire 1, and Krsko have also experienced wear within the preheater section. Steam generator modifications have since been implemented in preheater units in order to retard tube wear at baffle plates. No significant amount of tube wear at baffle plates has been reported since modifications were made to preheater steam generators.

A.3.3 Secondary Side Intergranular Attack-Stress Corrosion Cracking

Secondary side intergranular attack and stress corrosion cracking has occurred in numerous Westinghouse steam generators with some thirty-three plants affected. In some instances, steam generators have had to be replaced (Point Beach 1) or extensively sleeved (San Onofre 1 and Point Beach 2) because of these damage mechanisms. Within the steam generator, intergranular attack and stress corrosion cracking have been found in a variety of locations including the sludge pile, tube sheet crevice region and within support plate crevices. See Figure A-3.

Caustic stress corrosion cracking was first experienced during the early 1970's in Model 27 (Connecticut Yankee), Model 33 (Beznau 1&2) and Model 44 (Point Beach, Ginna, and Robinson) steam generators (see Tables A-2 & A-3). A hybrid combination of IGA/SCC within the tubesheet crevice first became prominent in the late 1970's in some Model 44 steam generators (Point Beach 1 and Ginna). Since then it has been identified in other Model 27, 44, and 51 steam generators (See Tables A-2 through A-4). Composite tube sheet maps from various plants show that the IGA/SCC is randomly distributed throughout the hot leg side of the generator. Numerous leaker outages have been attributed to this damage mechanism. In a few instances, leaker outages have occurred subsequent to a 100% inspection of regions of the generator in which IGA/SCC is known to be active. The advent of fully expanded or rolled tube sheet crevices in later steam generator models has eliminated the crevice as a hideout region for aggressive chemical species which can contribute to the formation of IGA/SCC.

IGA/SCC at hot leg tube support plates has been identified on tubes removed from Zorita (Model 33), and numerous Model 51 steam generators (D.C. Cook 2, Farley 2, Takahama 1 & 2, Mihama 2, Genkai 1, and Fessenheim 1). Its presence has also been recently confirmed at a hot leg support plate using rotating probe eddy current

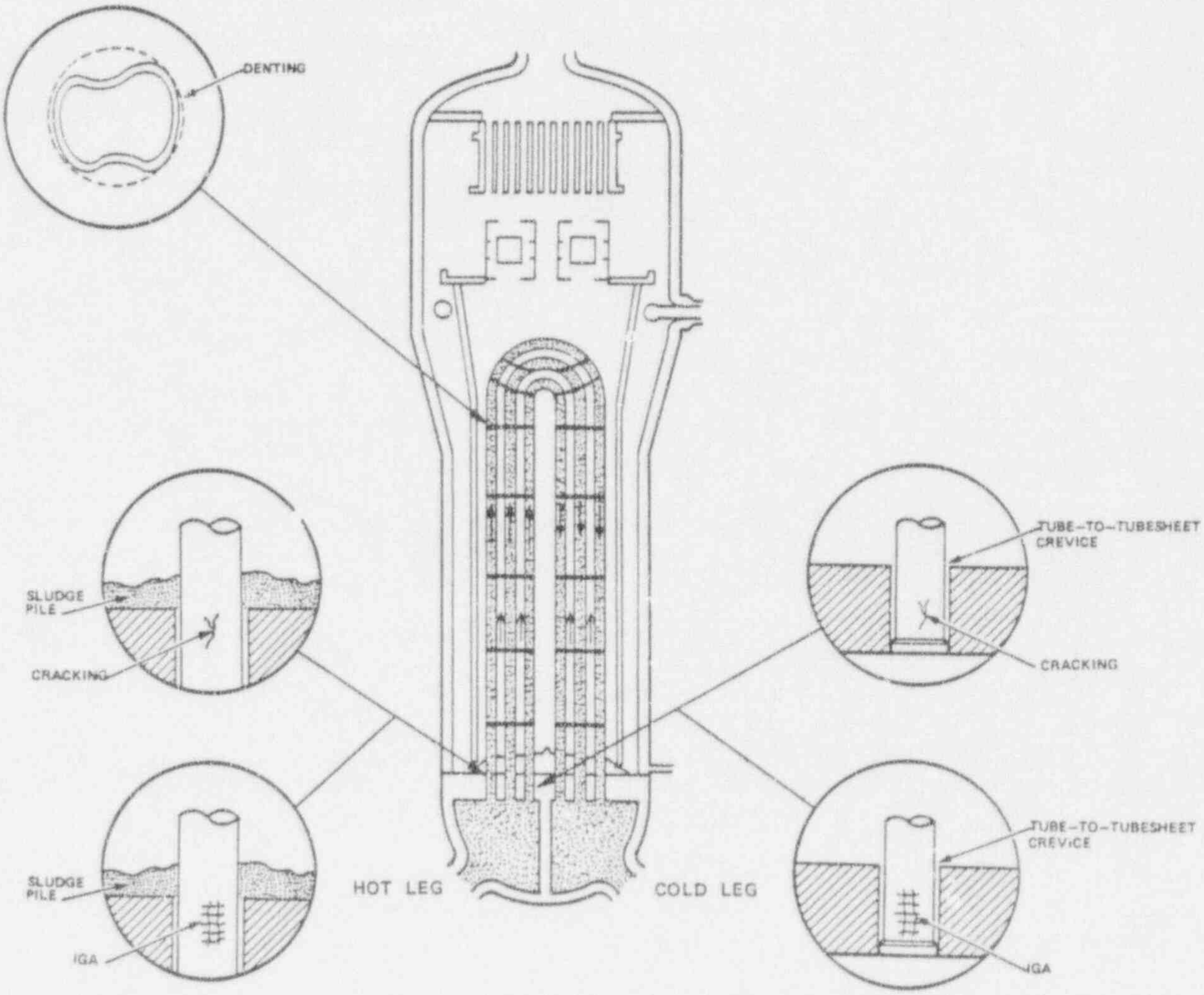

Figure A-3. Secondary Side Intergranular Attack - Stress Corrosion Cracking Locations in Westinghouse Steam Generators technology at Almaraz 1 which has Model D preheater steam generators. No leaker outages have been identified which are attributable to non-denting assisted IGA/SCC at support plates.

A.3.4 Primary Side Stress Corrosion Cracking

Non-denting assisted primary side stress corrosion cracking has been limited to steam generators fabricated by Westinghouse or its licensees (i.e., Cockerill, Framatome, Mitsubishi) from non thermally treated alloy 600 tube material. For susceptible material, such cracking can be related to inner-row U-bend fabrication processes or tube sheet expansion fabrication processes.

Fabrication details known to produce more severe cracking in susceptible tubing include:

- First and second row U-bends formed using the Westinghouse Blairsville ball mandrel bending process
- First and second row U-bends with more than 10% ovality
- Out of tolerance tube sheet expansions including; oversize holes in the tube sheet, incomplete expansion in the tube sheet (skip rolls, incomplete roll overlap), over expansion in the DAM (kiss roll) area, etc..
- Tube sheet expansion process which produces high residual stresses such as by roller expansion.

Regions of the steam generator which have been affected are shown in Figure A-4. Plant corrective actions introduced in order to reduce the chances of continued primary side stress corrosion cracking include heat treating, shot peening, and rotopeening.

Numerous leaker outages are attributable to U-bend cracking. Experience to date with U-bend cracks has been that the leakage is low (0.05 to 0.1 gpm) and increases gradually over a long period of time (i.e., months or years). The single exception has been the sudden rupture of a Doel 2 tube (135 gpm leak rate) with U-bend apex cracking resulting from high ovality.

For the case of expansion transitions and expanded areas within the tube sheet, leakage has also been relatively low (e.g., 0.005 -0.05 gpm) and has increased gradually over long periods of time. Leakage has been experienced at nine European and six Japanese units. In a few cases where the cause of the cracking has been identified (roll overexpansions or overexpanded tubes within oversize tube sheet holes), the approach has been to inspect the tubes for the condition believed to be associated with the cracking and plug affected tubes on a preventative basis. Where a large number of tubes are affected, the approach has been to accept low levels of leakage while awaiting implementation of plant remedial measures (e.g., peening or sleeving). The occurrence of primary side stress corrosion was a contributing factor in the decision to replace the Ringhals 2 steam generators.

Inner Row U-bend Cracking

U-bend tangent point cracking has occurred in numerous Westinghouse and Westinghouse licensee steam generators (see Tables A-4, A-6 & A-7). The majority of the cracking has been observed in Row-1 bends at one of the bend-to-straight section transitions; cracking in Row-2 bends has also been reported. Inner row U-bend eddy current indications attributable to cracking typically occur at one of the U-bend tangent points on either the hot or cold side of the bend. In one instance (Zion 1), eddy current indications were observed in a Row 2 U-bend at both tangent points. In some instances, cracking has also been observed near the U-bend apex. U-bend cracking has also been experienced in some preheater model steam generators. Affected plants include V.C. Summer and McGuire 2.

Remedial action has been to plug the leaking tubes, and in many cases to plug all of the Row 1 tubes on a preventative basis. Trojan, Ringhals 2, Farley, North Anna 1, and McGuire 1 have plugged all Row 1 U-bends to eliminate this source of leaker outage. An inner row U-bend in-situ stress relief process using electrical resistance heating has recently been introduced as an alternative remedial measure in order to save tubes.

Tube Sheet Roll Transition Cracking

Roll transition cracking has occurred in numerous units with partially rolled and fully expanded tube sheet crevices. See Figure A-4. Partially rolled units with roll transition cracking include two Model 27 units (Zorita & Connecticut Yankee), two Model 44 Units (Doel 2 & Mihama 2), and several Model 51 units (Zion 1, Cook 1&2, Ringhals 2, Takahama 1). See Tables A-2 through A-4. In some steam generators (see Table A-4), tubes with an initial partial mechanical roll were subsequently expanded through the thickness of the tube sheet using a explosive expansion process. Two units (Fessenheim 1 & North Anna 1) have since experienced

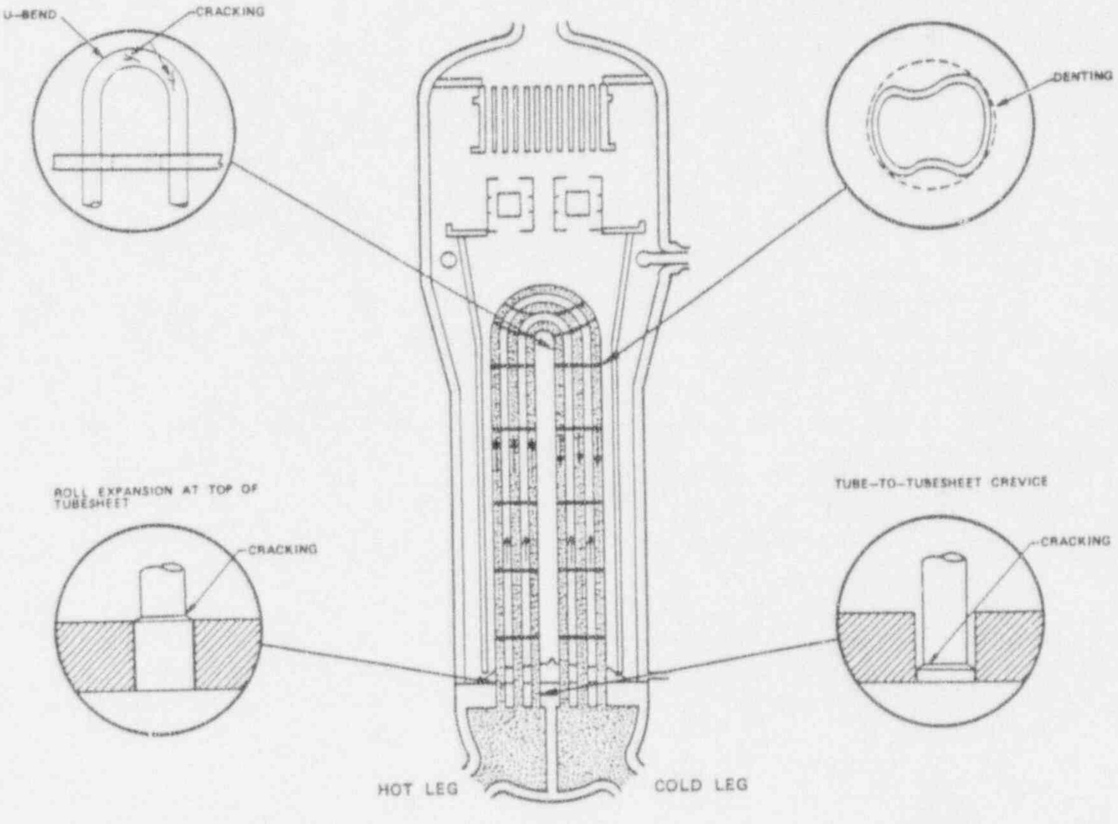

Figure A-4. Primary Side Stress Corrosion Cracking Locations in Westinghouse Steam Generators circumferential cracking at the upper expansion transition. In the case of Fessenheim, the cracking has been both ID and OD initiated and was first detected in 1981. The cracks have occurred in the sludge pile of the hot leg side of one of three steam generators. The axial location of the cracks has ranged from about 1/2" above to 3/4" below the top of the tube sheet. Leak rates have been limited to about 0.2 gpm or less. The occurrence of circumferential cracking at Fessenheim has been attributed to abnormalities associated with the explosive expansion process. Specific causative factors for the circumferential cracking at North Anna 1 have yet to be identified.

Numerous Framatome Model 51 steam generators (See Tables A-7) have experienced primary side axial cracking at the upper roll transitions with and without a "kiss" or DAM roll. Bugey 3 and Bugey 5 are the lead plants with this particular experience. Short longitudinal cracks have occurred in the top roll transition at Bugey 3. At Bugey 5, short longitudinal cracks have occurred above and below the top main roll. The upper group of cracks is located at the transition between the top main roll and the DAM roll. No circumferential cracking has been observed. Leak rates have been less than 0.25 gph.

Dampierre 1 has tubes which were rolled for the full depth of the tube sheet with a DAM roll at the top of the tube sheet. During 1984, upon removing a tube, a circumferential crack was found in the roll transition of the tube. It was determined to be a 75-90% through-wall circumferential crack around the tube located in the overlap area between the last main roll and the DAM roll. EdF evaluation of this condition indicates that it was the result of the upper main roll being too high and the DAM roll having too large an expansion. These conditions are detectable using eddy current inspection methods and EdF has plugged tubes judged to be susceptible to this problem.

Tube Sheet Expanded Area Cracking

In some steam generators, tubes were expanded over the full tubesheet height by progressive mechanical rolling. Cracking has been reported over the full height of the tube sheet with cracking generally attributed to residual stress produced during this progressive rolling. In some instances, the tubes were rolled into holes which were out of tolerance to the extent that there was no contact between the expanded tube and the hole after rolling.

Doel 3 and Tihange 2 Model 51 steam generator tubes were rolled for the full depth of the tube sheet. Skip rolls were noted prior to operation and re-rolling was performed in the field to correct this situation. Numerous leaks and primary side eddy current indications have occurred in the rolled areas. During the first fuel cycle, it appeared that most of the cracking occurred in the expanded region of tubes with oversized tube sheet holes. However, after what could be considered as the crack initiation time, cracking appeared generally at the top of the tube sheet with or without oversized holes. The indications are mostly longitudinal with a length between 1 mm and 22 mm (1987 leak). One pulled tube removed in 1986 showed two small circumferential cracks.

A.3.5 Pitting

Minor pitting attack has been observed on tubes removed from Beznau 1, San Onofre 1, and Surry 1. For San Onofre 1, the pitting was near the U-bend apex; for the other units, the attack was at or near the top of the tube sheet within the sludge pile.

Extensive secondary side pitting attack coupled with copper deposits was first reported at Indian Point 3. The pitting was observed mainly on the cold leg side of the generator between the tube sheet and 1st support plate. See Figure A-5. 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. Indian Point 3 has sleeved four steam generators in order to extend their life.

Small amplitude eddy current signals, suggestive of pitting in the presence of secondary side copper, have been reported from Indian Point 2 and Kori 2. Recent tube pulls from Connecticut Yankee and Trojan steam generators have also confirmed the presence of pitting in association with copper.

Leaker outages attributable to pitting or a hybrid combination of pitting and stress corrosion cracking between adjacent pit ligaments are believed to have occurred at several plants.

A.3.6 Denting

Some thirty six units have experienced some form of denting. In most of the units, the extent of the denting is minor. Some ten units (nine of which are extensively dented) have experienced leaking dents. In some cases, units with extensive denting have had significant plant availability problems. During the mid to late 1970's, some forty-four unscheduled or preventative plugging outages occurred at four units

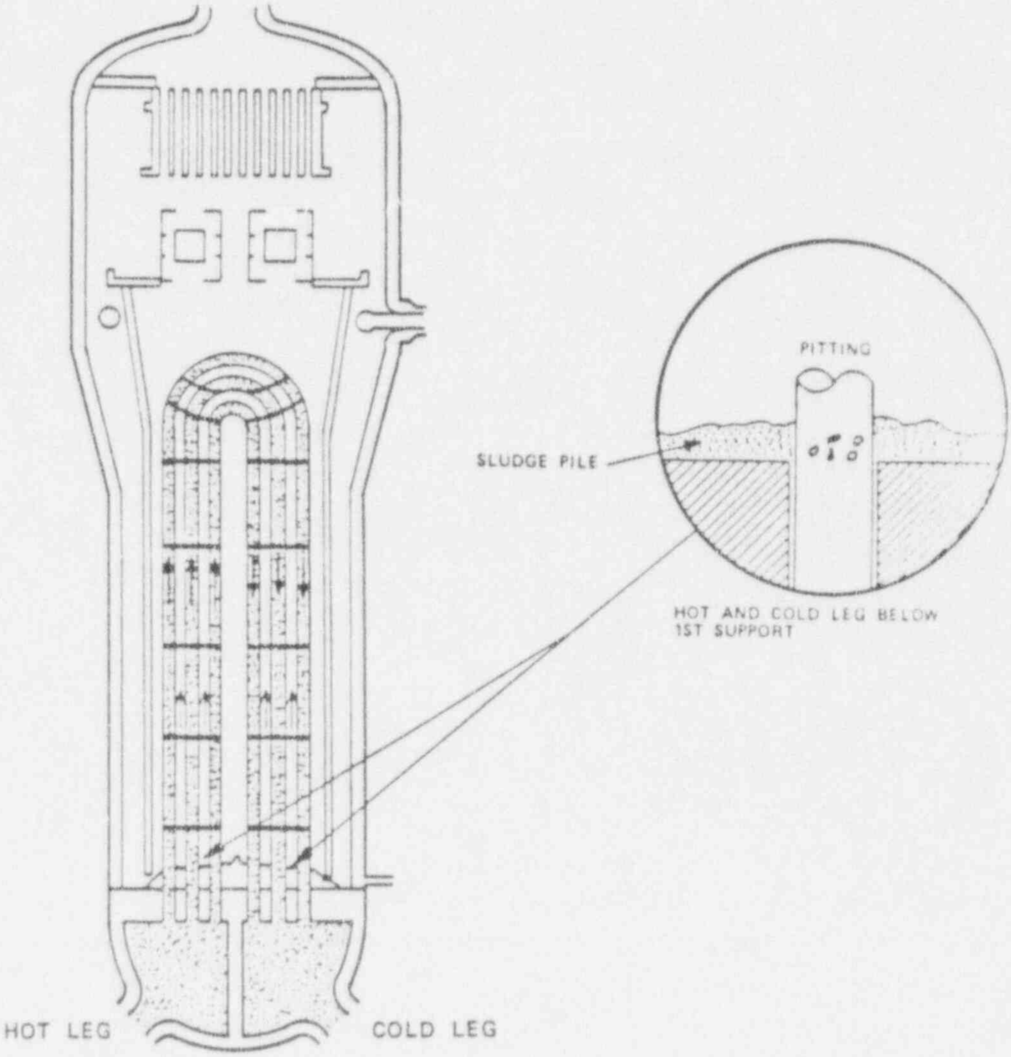

Figure A-5. Pitting Locations in Westinghouse Steam Generators as a result of extreme denting. Most of the extensively dented units (those susceptible to leakage) have been replaced or are scheduled to be replaced in the near future. Steam generator replacements at Surry 1 & 2 and Turkey Point 3 & 4 are the result of denting-related damage.

Denting and denting related damage can occur at many different locations within the steam generator; Figure A-6 illustrates some of these locations. Although denting has been observed on both the hot 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. Extreme consequences of denting include flow slot closure and hourglassing, cracked support plate ligaments, ovalized and cracked inner row U-bends, and stress corrosion cracking at dented support plate intersections.

A.4 COMBUSTION ENGINEERING PLANT EXPERIENCE

Table A-9 summarizes operating experience for Combustion Engineering steam generators. Degradation in these units, limited to the secondary side, includes thinning, intergranular attack/stress corrosion cracking, pitting and denting. Denting is the most prevalent problem. Plants that have used phosphate chemistry are subject to thinning. Intergranular attack has been experienced at numerous units whereas pitting has been positively confirmed at several units. Figure A-7 illustrates the locations of these damage mechanisms in CE steam generators.

A.4.1 Thinning

Extensive wastage attack has occurred at support plates, eggcrates, and anti-vibration straps 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 members. The absence of flow holes in some support plates contributes to sludge buildup on the plates, which then results in phosphate wastage attack on the tubes.

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

A.4.2 Pitting

Millstone 2 has had extensive pitting attack in association with secondary side

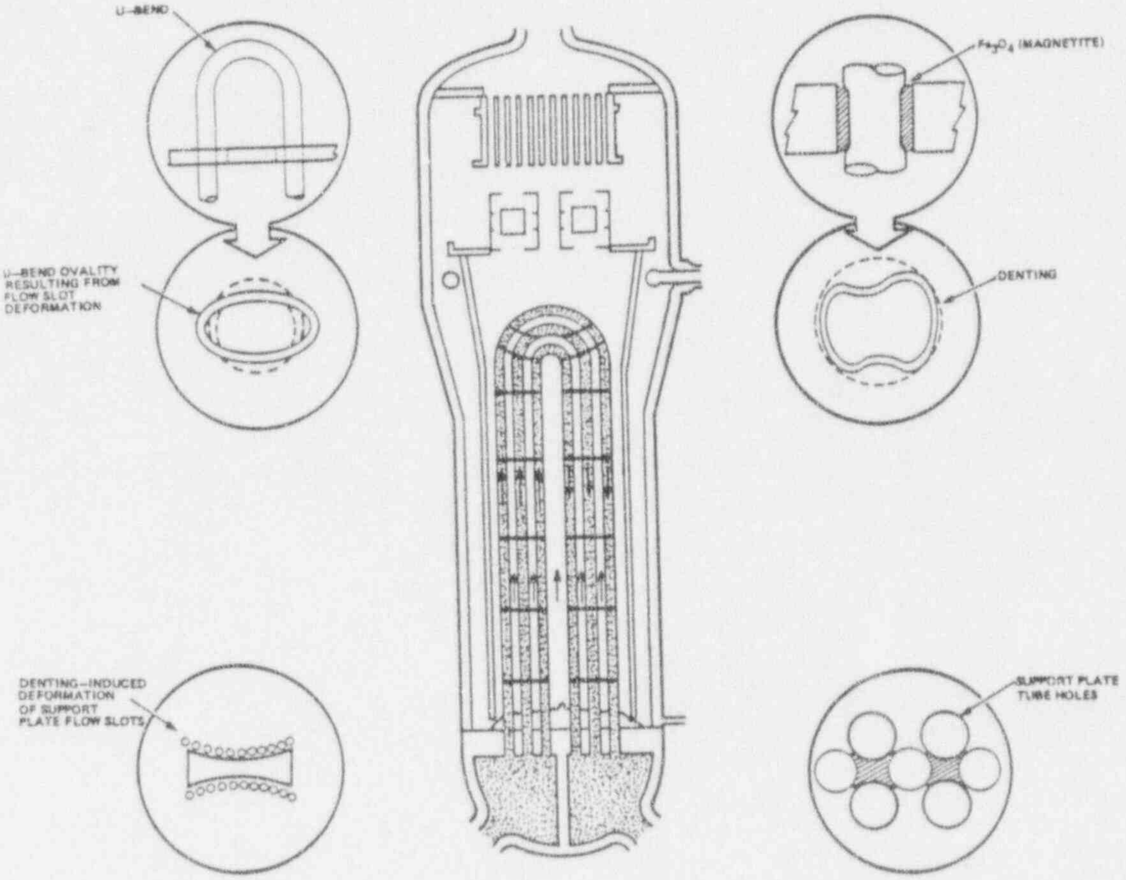

Figure A-6. Denting Related Degradation in Westinghouse Steam Generators

TABLE A-9
OPERATING EXPERIENCE SUMMARY
COMBUSTION ENGINEERING STEAM GENERATORS

Unit (1)	Number of Steam Generators	Commercial Operation	Secondary Water Chemistry	Thinning	Wear	Pitting	IGA/SCC	Denting
Mihama 1	2	11/70	AVT*	X			X	Minor
Palisades	2	12/71	AVT*	X		X	X	Moderate
Main Yankee	3	12/72	AVT					Minor (2)
Ft. Calhoun 1	2	9/73	AVT				X	Moderate (2)
Calvert Cliffs 1	2	5/75	AVT		X		X	Minor
Millstone 2	2	12/75	AVT	X		X	X	Extensive (2)
St. Lucie 1	2	12/76	AVT				X	Minor
St. Lucie 2	2	8/83	AVT		X (3)			
Calvert Cliffs 2	2	4/77	AVT				X	Minor
Arkansas 2	2	3/80	AVT					Minor
San Onofre 2	2	8/83	AVT		X (3)			
San Onofre 3	2	4/84	AVT		X (3)			
Waterford 3	2	9/85	AVT		X (3)			
Palo Verde 1	2	2/86	AVT		X (4)			
Palo Verde 2	2	9/86	AVT		X (4)			
Palo Verde 3	2	9/87	AVT					

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* Previous PO4 water chemistry.

(1) All units have a full depth tube expansion in tube sheet crevice.
(2) Denting in vertical U-bend supports and partial drilled supports.
(3) Wear at support straps.
(4) Wear at eggcrate supports in preheater section.

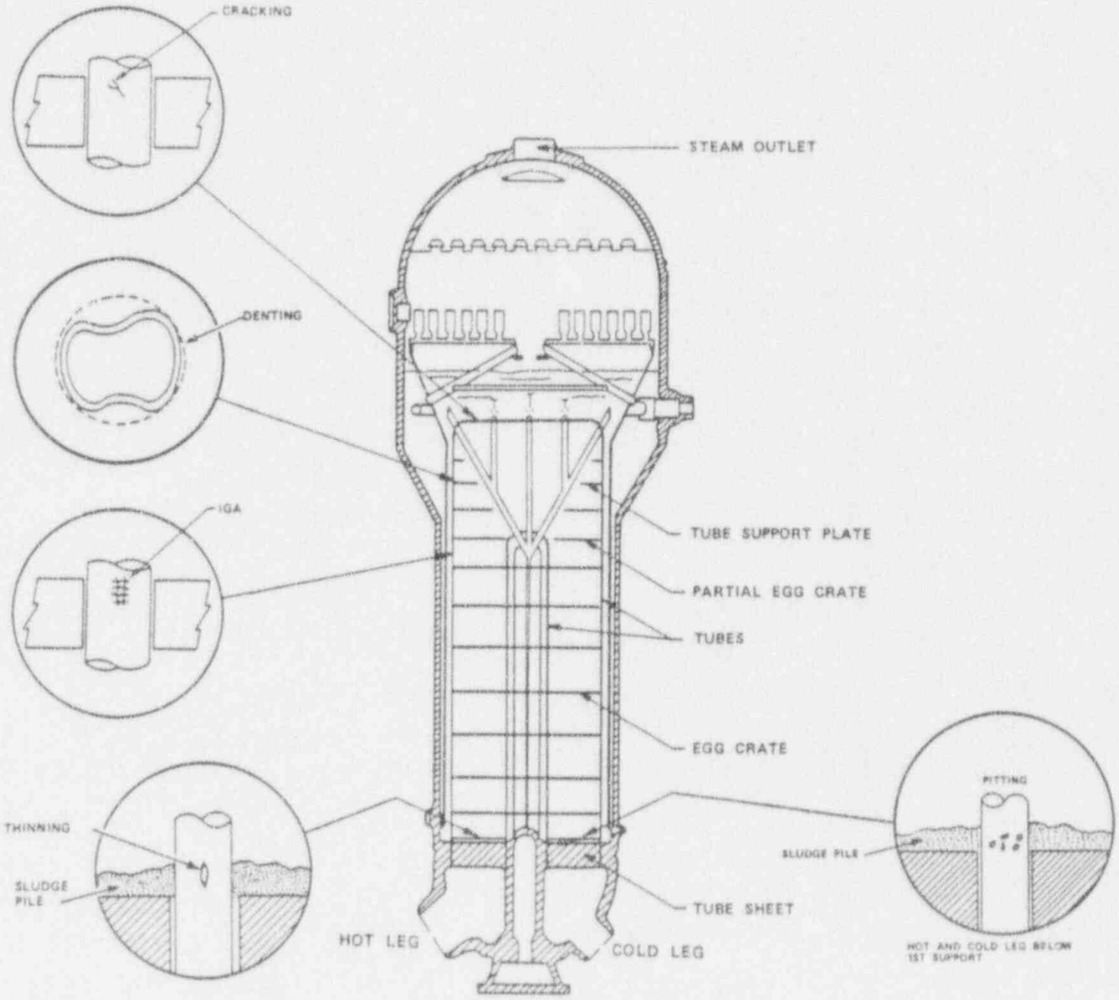

Figure A-7. Summary of Tube Degradation Locations in Combustion Engineering Steam Generators copper deposits above the top of the tubesheet. Isolated pits were observed on the cold leg side of the generators whereas shallow circumferential bands of pitting were observed on the hot leg side. Approximately 5,000 tube ends have been sleeved in order to keep tubes in service. Chemical cleaning of the secondary side of the steam generator along with improved water chemistry has reduced the progression rate of pitting to near zero. Figure A-7 summarizes pitting locations in C-E steam generators.

A.4.3 Intergranular attack - stress corrosion cracking

Intergranular attack has been confirmed at Palisades, St. Lucie 1, Calvert Cliffs 1, and Millstone 2. At Palisades, intergranular attack was first discovered in 1974 on tubes removed from the A steam generator. The attack occurred in the upper region of the tube bundle and probably began as a result of steam generator lay-up conditions during an extended outage (sulfate/sulfite attack). At St. Lucie 1, intergranular attack has been identified on pulled tubes from within the sludge pile region and at the egg crate support members. Calvert Cliffs 1 has also recently removed tubes from within the sludge pile region - on the hot leg side of the generator - where the presence of intergranular attack was subsequently confirmed. Minor amounts of attack have also been observed on tubes removed from Millstone 2.

Corrosion on the intrados of the U-bends has been observed at Mihama, Palisades, St. Lucie 1, and Maine Yankee. This corrosion is thought to be caused by steam blanketing of the tubes in this region. The specific corrosion mechanism has yet to be positively confirmed but is believed to be intergranular attack.

Denting assisted stress corrosion cracking has been experienced at Palisades and Fort Calhoun. Circumferential stress corrosion cracking has been postulated as the initiator of a leaker outage at Palisades during early 1982. The degradation was characterized using array coil technology specifically configured for the outage. Two crack indications 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. Review of the eddy current data from previous outages showed that one of the two indications 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 had been encountered during the steam generator examination. Stress corrosion cracking and intergranular attack were identified during subsequent metallography. The intergranular attack is believed to be due to the original sulfate/sulfite attack present since 1974. Most of the stress corrosion cracking was at dented support plates and is believed to be denting related.

Ft. Calhoun came down for a steam generator examination 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 and a subsequent tube pull showed the leak to be due to a stress corrosion crack which had burst. Review of the eddy current data from the recently completed examination showed the presence of a large indication that had been missed.

Figure A-7 summarizes intergranular attack/stress corrosion cracking locations in C-E steam generators.

A.4.4 Wear

Three regions of wear have been reported in the newer C-E plant designs. Batwing wear has occurred just below the square bends in tubes in the vicinity of the central cavity (stay cylinder) at San Onofre 2 and 3, St. Lucie 2, and Waterford 3. Wear adjacent to vertical straps has occurred at St. Lucie 2 and Calvert Cliffs 1. Wear in a limited region of the economizer baffle has been reported at Palo Verde 1 and 2.

A.4.5 Denting

In early C-E steam generators, drilled plates and eggcrates provide structural support for tubes. With the exception of Palisades, Fort Calhoun and Mihama, the drilled plates are two partial-span plates located near the top of the bundle. In recent C-E steam generators, eggcrates provide structural support for tubes and no drilled plates exist. U-bend support is provided by vertical and diagonal carbon steel straps placed within the tube bundle. Figure A-7 illustrates denting at eggcrates, support plates, and the U-bend antivibration straps.

Denting has occurred at drilled plates in all units so configured. Eggcrate denting has been observed at Millstone 2, Palisades, Maine Yankee, and St. Lucie 1. Maine Yankee has also reported dent-like signals at the U-bend lower support structures whereas magnetite formation has been visually confirmed at the U-bend strip structure at Millstone 2.

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.

A.5 BABCOCK & WILCOX PLANT EXPERIENCE

Table A-10 summarizes operating experience for Babcock & Wilcox (B&W) steam generators. Corrosion damage in B&W once-through steam generators is for the most part secondary side initiated. The exception is the tube wall degradation experienced at TMI-1. Secondary side corrosion damage includes intergranular attack-stress corrosion cracking, pitting, and possibly denting. Tube degradation attributable to mechanical phenomena includes wear, corrosion-assisted high-cycle fatigue cracking and flow-associated debris impingement.

A rank ordering of B&W operating plant problems by importance is as follows:

- Corrosion-assisted high-cycle fatigue cracking - This mechanism has resulted in the largest number of tube leaks.
- Primary side stress corrosion cracking - This mechanism has resulted in the largest number of plugged tubes. However, this condition has occurred at only one plant (TMI-1) under non-typical lay-up conditions. It is not expected to occur at other plants of this design.
- Intergranular attack-stress corrosion cracking - This mechanism is second in terms of the number of plugged tubes.
- Impingement damage - This mechanism is third in the number of plugged tubes.

Concerning the other damage mechanisms listed:

- Pitting - No tubes have been plugged because of pitting although it has been observed on several pulled tubes.
- Wear - Approximately 20 tubes have been plugged due to this mechanism and another 24 tubes are being monitored for indications. Only a few tubes are involved and there appears to be no trend towards increasing wear.
- Denting - No tubes have leaked as a result of tube distortion. A few tubes, less than 10, have been plugged as a result of not passing a standard eddy current probe.

TABLE A-10
OPERATING EXPERIENCE SUMMARY
BABCOCK & WILCOX STEAM GENERATORS

Unit (1)	Number of Steam Generators	OL Issued	Secondary Water Chemistry	Pitting	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	X
Arkansas 1	2	5/74	AVT		X			X	
Rancho Seco 1	2	8/74	AVT		X		X	X	
Three Mile Island 1	2	4/74	AVT			X (2)			
Crystal River 3	2	12/76	AVT						
Davis Besse 1	2	4/77	AVT						

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(1) All units have open tube sheet crevices.

(2) TMI-1 has experienced sulfur induced primary side stress corrosion cracking; its occurrence is not a result of service related conditions.

Typical elevational locations for once-through steam generator tube wall degradation are shown in Figure A-8.

A.5.1 Corrosion-assisted fatigue cracking

Corrosion-assisted high-cycle fatigue cracking is the primary cause of leaker outages in OTSGs. It was first confirmed on tubes removed from Oconee 1 and has been identified at other once-through units. The cracking is limited to the lane and wedge regions (See Figure A-9) 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.

A.5.2 Intergranular attack - stress corrosion cracking

Secondary side intergranular attack - stress corrosion cracking was first confirmed in a once-through steam generator at Arkansas 1 during a 1977 tube pull and subsequently identified during tube pulls conducted during 1984. In the first observation, the mechanism was limited to the upper tube sheet crevice whereas in the second case, intergranular attack was seen within the upper tube sheet crevice as well as at the 15th support plate. The damage is attributed to corrosion product transport up the lane region into the upper tube sheet; based on the occurrence of eddy current indications, it is believed to be confined to the wedge area of the generator.

Minor intergranular attack has also been observed on a tube removed from Oconee 1. The attack was less than 20% through wall and was confined to a region of the tube at the lower tube sheet.

A.5.3 Wear

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

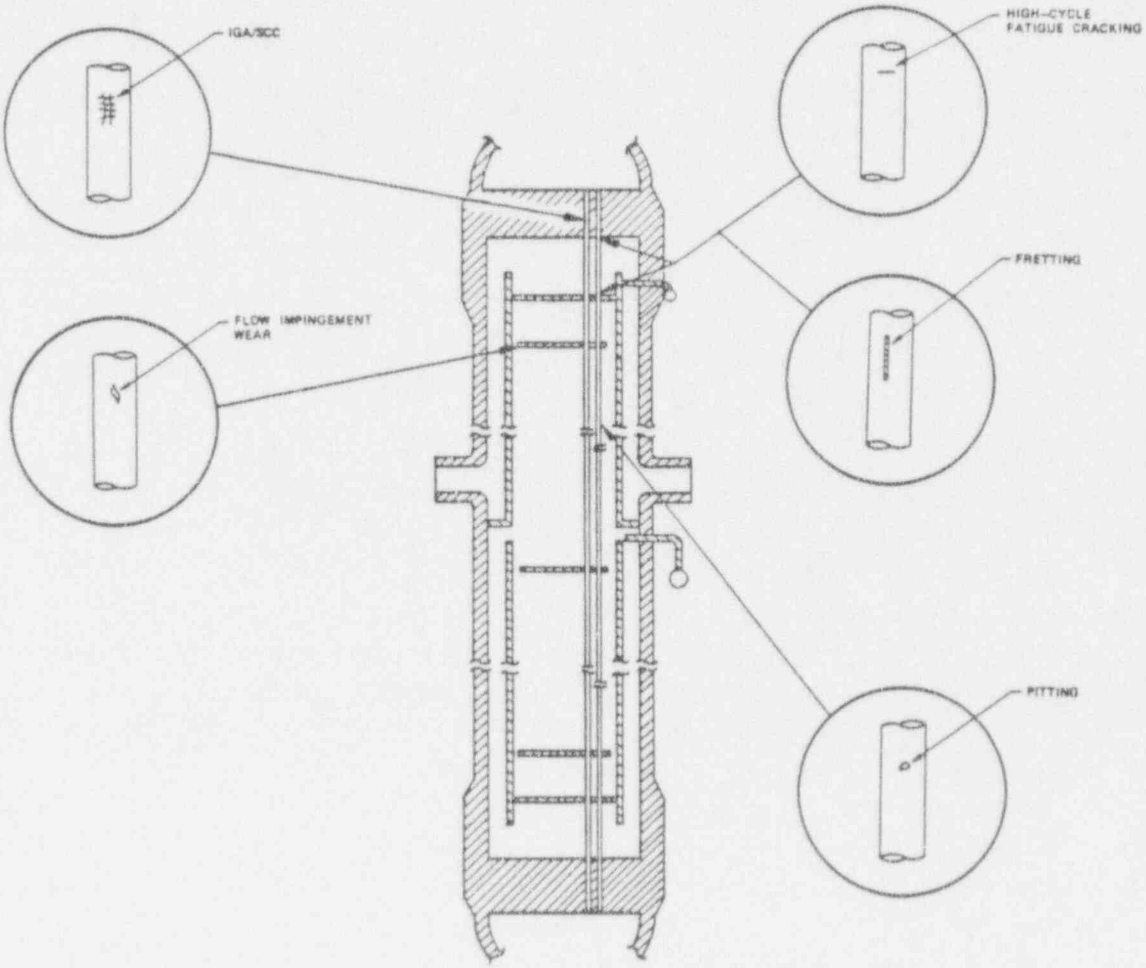

Figure A-8. Summary of Tube Degradation Locations in Babcock and Wilcox Steam Generators

A.5.4 Impingement

Secondary side solids transported by fluid flow are the postulated source of impingement damage. It typically occurs within the outer periphery of the steam generator; it is bounded approximately by the annulus formed by the circumferential band of support plate tie rods (see Figure A-9). Other descriptors for this damage mechanism include erosion-corrosion or "14th support plate defects." The latter name arises because of the preponderance of indications at the 14th support plate. In recent examinations, this phenomenon has been observed in increasing amounts from the 9th to the 14th support plates, and appears to be moving inwards towards the interior of the tube bundle.

A.5.5 Pitting

Minor pitting has been observed on several tubes removed from once-through units. In one case it was located in a region of the tube at the 15th broached support plate while in two other instances, it was located within the upper and lower tube sheet region.

A.5.6 Primary side stress corrosion cracking

TMI-1 is the only once-through unit that has experienced primary side stress corrosion cracking. The cracking has been attributed to the accidental intrusion of sulfur compounds into the primary system during shutdown. Most of the cracking is confined to the upper tube sheet.

A.5.7 Denting

Once-through steam generators 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 with recirculating steam generators, drilled holes are prone to denting; a broached hole may not be as susceptible.

Dent-like signals have been observed in once-through units at the 9th and 10th support plates and within the kidney region - see Figure A-9 - at the lower tube sheet. Some of the signals are attributable to installation practices during the tubing of the steam generator.

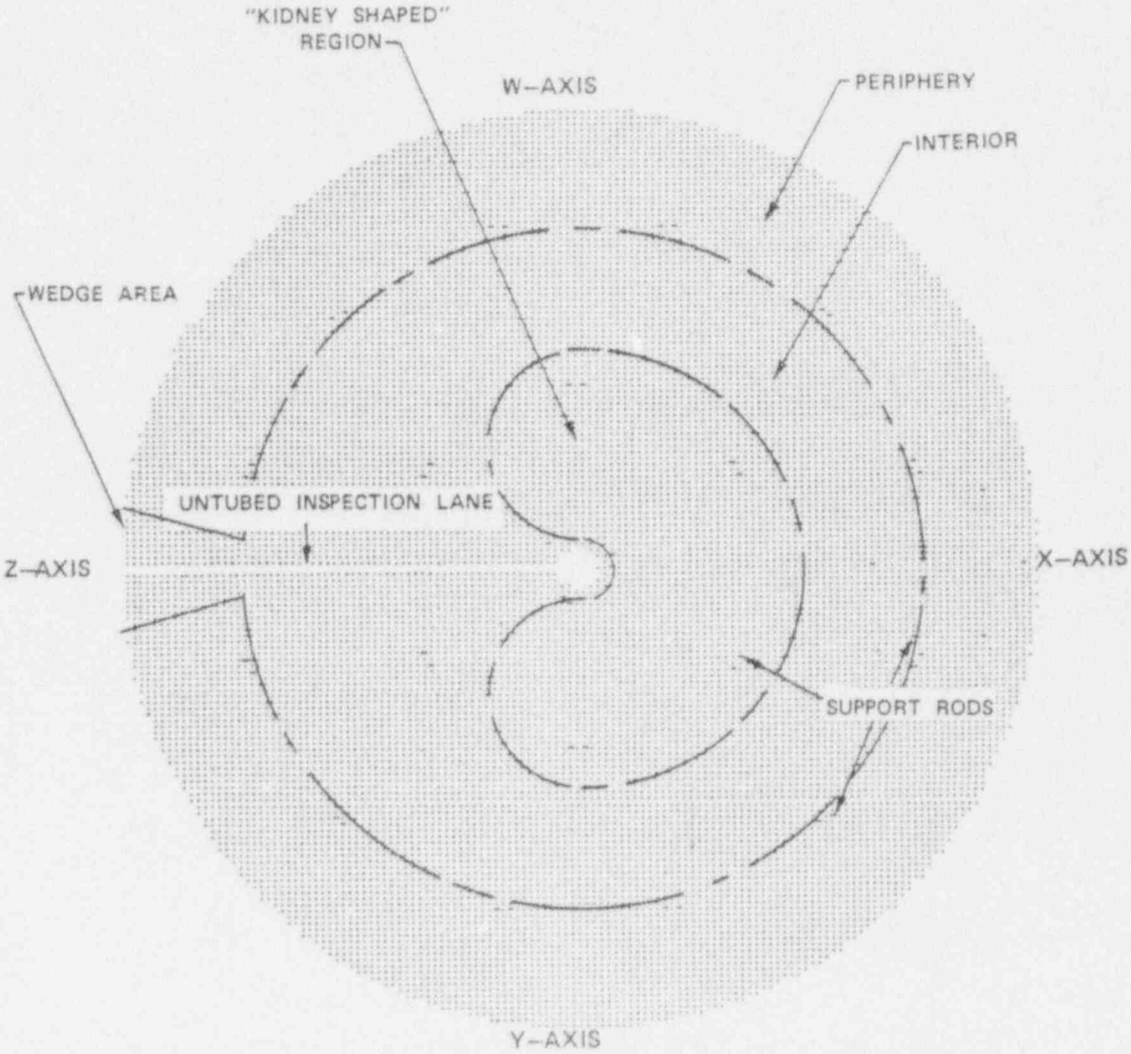

Figure A-9. Tube Sheet Map for Babcock & Wilcox Units Showing Distribution of Tube Wall Degradation

Dent signals in the lower tube sheet kidney region have a strong association with signals attributable to magnetite in some units. These magnetite signals (referred to as lower tube sheet "banana" signals) have been observed to spread from the interior region of the tube bundle outwards towards the periphery. Although there is a high probability that the lower tube sheet dent signals are related to classical magnetite denting as experienced in recirculating units, denting has not been directly confirmed on removed tubes.

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(1) EPRI NP-5140. Steam Generator Cold-Leg Thinning in Operating Plants. April 1987.

(2) EPRI NP-4375-LD. Destructive Examination of Zion Unit 1 Tube and Antivibration Bar Samples. December 1985.

(3) "New Type of Steam Generator Fails in First Year of Operation", Nuclear Safety, Vol. 23, No. 3, May-June 1982.

Appendix B

BASES FOR RECOMMENDED STEAM GENERATOR EXAMINATION PROGRAM

B.1 INTRODUCTION

Sampling programs form an important element in the overall steam generator examination process. In sampling, a fraction of tubes is examined; based on the results of this examination, the condition of the steam generator is either accepted for continued operation or the sample program is expanded. Sampling by its very nature involves some risk on the part of the user. However, this risk is to a certain extent controllable and can be established using statistical design criteria drawn from sampling theory. This section provides the engineering bases for sampling plan recommendations presented in summary fashion in Section 4.

Two types of plans are considered; 1) a programmed random examination and 2) an augmented examination. Taken together they constitute the basic steam generator examination strategy - the production examination. The random element of the production examination makes no prior assumptions about the expected location of tube wall degradation whereas the augmented examination is experienced based and is applicable to those units with active damage mechanisms.

B.2 SUMMARY

This appendix considers in some detail the bases for recommended random and augmented sampling strategies. Section B.3 provides an overview of the production, i.e., random plus augmented, examination. It is presented first, since questions raised on first reading may hopefully be answered and justified by the sections which follow.

In Section B.4, general factors important in the design of a random sampling program are considered. Random sampling of a steam generator is modeled using the binomial distribution derived from basic sampling theory. The model is approximate in that it assumes an infinite tube population e.g., sampling with replacement. In practical sampling programs in which finite populations exist, sampling is done without replacement. The correct mathematical model in this case relies on the use of the hypergeometric distribution. Numerical differences in calculated probabilities using either model are insignificant from an engineering standpoint. It is found that the required number of tubes examined or the sample size in percent is basically a function of the number of tubes of interest assumed to be present in the generator and a reliability index both of which must be specified by the user. The tubes of interest may be considered to be degraded or defective. The specific condition of the sampled object is immaterial; however, for ease in discussion, degraded tube conditions are initially assumed. Parametric studies of the sampling equation are presented in order to identify key equation parameters. Existing regulatory examination requirements are interpreted in light of the sampling equation; it is found that at a 90% confidence level, the minimum required 3% sample size is adequate for finding degraded tubes present in quantities on the order of 75 or so in a given steam generator. Performance estimates of expanded examination programs for the same confidence level based on sampling percentages of 20% are also given. The primary benefit in increasing the sample size to 20% is an approximate six-fold increase in detection sensitivity e.g., the minimum number of degraded tubes required in the population for observation of one degraded tube, is reduced from approximately seventy-five to a value on the order of twelve.

In developing sample size requirements it is important to recognize that not all sampled degraded tubes are detected because of uncertainties in the basic detection process related either to the technology, the analyst, or both. Allowances must be made for this deficiency. Two approaches are investigated in accounting for imperfect detection; 1) increasing the initial sample size and 2) relaxing or increasing the minimum number of allowed degraded tubes. The former approach is highly inefficient beyond an initial sample size of 20% whereas a relaxation in the number of allowable degraded tubes allows for the same initial sample size to be maintained at the expense of a slight increase in the degraded tube density. The general random sampling principles are then applied to the practical case of steam generator examination in Section B.5. Assumptions utilized are explicitly identified and specific sampling recommendations are established. For an initial degraded tube population of approximately 12 tubes per steam generator, a 20% sample size is viewed as a practical upper bound in sample size requirements for the sampling of at least one degraded tube at a 90% confidence level. When realistic values for detection probability are incorporated into the sampling model it is found that for a 20% sample size, the minimum number of degraded tubes present in the population for detection at a 90% confidence level increases from 12 to approximately 20. Acceptance criteria are established for sample program expansion. Here a distinction is made between a degraded or defective tube population. If in the initial 20% sample two or more tubes with pluggable indications are reported, then the sample program is expanded. The acceptance criterion for degraded tubes is 5% of the sampled tubes; this is the present limit defined in plant standard technical specifications. If either of these numbers are exceeded then sample program expansion is required. No expansion percentage is specified. Rather, the sample program is expanded to bound the extent and number of new indications.

Augmented sampling plan recommendations are presented in Section B.6. They have their basis in steam generator operating experience. Specific recommendations presented herein are derived from distributions of tube wall degradation that have been experienced in steam generators of different NSSS vendors, steam generator models, and for different forms of tube wall degradation. The percentages examined within a given region are generally a function of the risk associated with a particular damage mechanism and the probable number of degraded tubes which exist within the region of interest. The augmented examination sampling strategy is to reduce the chances of an unscheduled shutdown by focusing the examination on high-risk regions of the steam generator. In some units, the augmented sample may not be required; hence only random sampling is conducted.

B.3 RECOMMENDED PRODUCTION EXAMINATION PROGRAM - OVERVIEW

In general, the recommended production examination program is the summation of two examinations - a programmed random examination plus an augmented examination. The programmed random examination is applicable to all steam generators and is the minimum required examination. The augmented examination is applicable to those steam generators units with active damage mechanisms or those with previous indications.

The programmed random 20% sample is intended to monitor the general condition of the steam generator. All tubes in all steam generators should be examined full length over a five cycle interval. Threshold values are established for sample program expansion such that when indications are observed during the random sample in excess of some k2 threshold value, the program is expanded to bound the new phenomenon. For reportable indications 20% through wall or greater but less than the plugging limit, the value of k2 is 5% of the number of tubes examined; for pluggable indications, the value of k2 = 1. Once a new phenomenon is diagnosed and its extent is bounded, the affected tubes are then placed within the augmented program during subsequent examinations.

Tubes selected for the random sample set are randomly selected from active tubes throughout the steam generator. If these tubes include those which would also be scheduled for the augmented examination, then expected indications from regions of the tube for which the augmented examination is being conducted are not applicable towards the random examination threshold value. Thus the results of the examination of a tube may be included within both the random and augmented examinations. Again, the purpose of the random examination is to identify the occurrence of new degradation in regions of the steam generator where it has not been experienced. Once a tube has been included within the random sample, it is excluded when future random sample sets are formed - sampling without replacement - over the examination interval. Thus over a period of five examination cycles, all active tubes will have been examined at least once using the random sample program.

The augmented sample is experienced based and is applicable to those units with active damage mechanisms. Active degradation is defined as the presence of new indications attributable to operation, or growth of previous indications in excess of 10% through wall during one operating cycle. The purpose of the augmented sampling is twofold; 1) to monitor tubes with previous indications and 2) to remove tubes from service from known regions which may have a high probability of causing an unscheduled shutdown or may have inadequate plugging margin during the subsequent operating interval. Specific regions within the tube bundle or sections of the tube are examined; the percentage examined from a given region is a function of the risk associated with a particular damage mechanism.

A logic diagram for the overall production examination is given in Figure B-1. Two parallel paths are shown for each of the random and augmented examinations. Again, it is possible for a given tube to satisfy both legs of the overall examination. In following the random examination logic path, it is initiated with a 20% sample size. If indications are identified during the random sample program, they are first compared with previous operating experience in other units. If applicable, an augmented examination is then conducted. If the indications represent a first time occurrence, then the program is expanded to bound the phenomenon. Once bounded, the tubes are then placed in the augmented program during subsequent examinations.

During the augmented examination, tubes with previous indications and regions of the steam generator in which indications can be expected based on past site experience are examined. The percentage examined of a given region is fixed and is primarily a function of the risk associated with a particular damage mechanism.

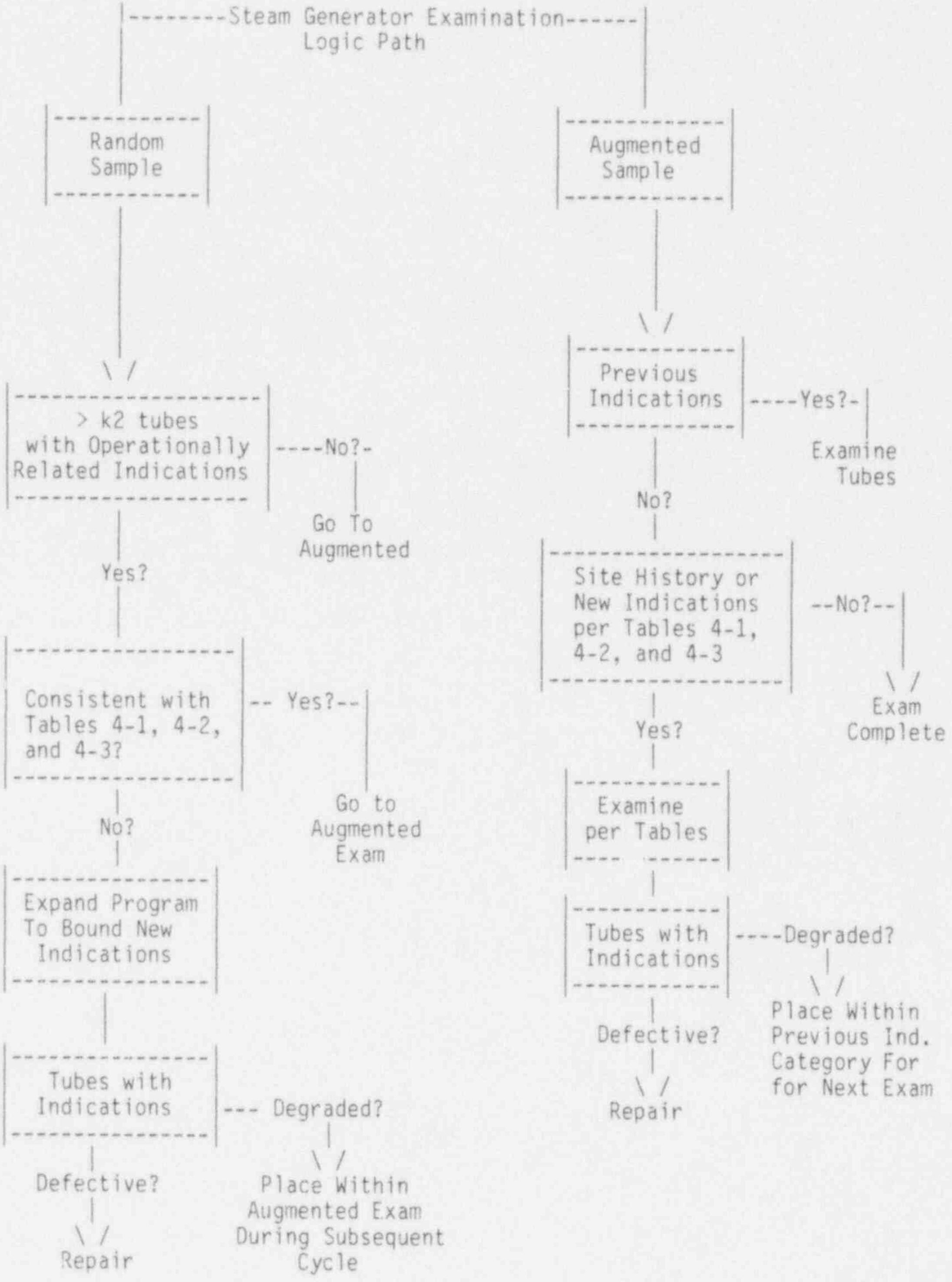


Figure B-1. Steam Generator Examination Logic Path

B.4 RANDOM SAMPLING

A random sample or selection of tubes is examined in order to monitor steam generator quality by observing the presence of operationally related tube wall degradation. Tubes are selected at random because in this mode of sampling no prior assumptions are made about the expected location of tube wall degradation. Sampling strategies in which assumptions are made about the most likely occurrence of degraded tubes fall within the augmented plan and are discussed in Section B.6.

A certain percentage of tubes is sampled in a generator since this is less expensive than doing a 100% examination. Steam generator condition is inferred based on the results of the sample examination. Depending on the outcome of the initial sample, the sample program is expanded or the condition of the steam generator is accepted. The trigger point for expansion is typically the observance of a certain number of degraded or defective tubes in excess of some threshold value e.g., more than k2 tubes. This value of k2 is referred to as the acceptance value c in quality control circles. Both degraded and defective tubes can be present in the tube population. The condition of the sampled object is immaterial as far as sampling strategies are concerned. However, different acceptance levels are typically used depending on whether the observed tubes are defective or degraded. When degradation is assumed to be randomly distributed throughout the generator in multiple tubes, an efficient sampling strategy is to choose an approach such that at least one degraded tube is likely to be sampled since this can act as a trigger point for sample program expansion. Since only a fraction of the tubes in a population is sampled, there is some chance that a degraded tube - even though present - is not sampled. This risk can be controlled by choosing the sample size sufficiently large within the constraints determined by some desired reliability index.

B.4.1 Model Sampling Equation

The probability of sampling at least one degraded tube from a population of N tubes containing a fraction of p degraded tubes is modeled approximately using the binomial distribution as follows:

$$P(k \geq 1) = 1 - (1-p)^n \qquad \text{Equation (B-1)}$$

where

p is the probability that a single sampled tube is degraded. For n' degraded tubes present in the sampled population, p is simply the ratio

n'/N where N is the total number of tubes in the sampled population.
n is the number of tubes examined or the sample size;
and $P(k \geq 1)$ is a performance measure or reliability index.

The exact model for sampling from a finite population is the hypergeometric distribution. Both models predict the probability of sampling at least one degraded tube as a function of the percent of tubes sampled. The binomial model assumes sampling with replacement whereas the hypergeometric model assumes sampling without replacement. The former is utilized here since its predictive equation is easier to evaluate and manipulate. This approximation is sufficiently accurate for engineering applications considered herein.

The derivation of Equation (5-1) is as follows. The single trial probability of sampling a degraded tube is p whereas the single trial probability of not sampling a degraded tube is q. Since in sampling, one of the two events must occur - we either sample a degraded tube or we don't - it follows that $(p+q)=1$. The probability of drawing a particular sequence of degraded and non-degraded tubes in n trials or samples is then given by the product ppqpq... since each of the trials is independent; again, p and q are the single trial success and failure probabilities. Three basic types of sequences are possible. Written in general form they are:

(1) pppppp... all n tubes are degraded

(2) ppqpqq... n tubes which contain a mixture of degraded and nondegraded; there are k degraded and (n-k) nondegraded for a total of k + (n-k) or n tubes

(3) qqqqqq... all n tubes are not degraded.

The first and last sequences can occur in only one way; the probability of their occurrence is $(p)^n$, and $(q)^n$. In general, there are numerous ways for sequence (2) to occur; the probability of occurrence for a particular sequence is determined by the product of $p^k q^{(n-k)}$ and a number called the binomial coefficient, which gives the number of ways in which the sequence can occur. The simplest approach in arriving at the desired answer is to recognize that the probability of sampling at least one degraded tube $P(k \geq 1)$ is one minus the probability of sampling no degraded tubes since sequences (1) and (2) each contain at least one degraded tube. This is simply one minus the probability of obtaining sequence (3) since the total probabilities sum to unity. Thus

$$P(k \geq 1) = 1 - (q)^n \qquad \text{Equation (B-2)}$$

Since for single trial events, $(p + q) = 1$, we have $q = (1 - p)$. Substituting for q in Equation (B-2), Equation (B-1) is obtained.

Figure B-2 shows a plot of Equation (B-1) for an initial 1% degraded tube density present in the population (p=1%). Plotted is the probability or "odds" of sampling at least one degraded tube as a function of the absolute number of tubes sampled. As can be seen, if roughly 70 tubes are sampled, the odds are the same as flipping a fair coin e.g., P=0.5, that a least one degraded tube will be sampled. However, if 500 tubes are sampled, then the odds are almost certain e.g., P = 1.0, that at least one degraded tube - if present at a 1% density or greater - will be sampled. If no degraded tubes are encountered with the 500 tube sample size, then it can be inferred that if degraded tubes are present, their density is most likely less than 1%.

Practical implications of Equation B-1 are shown with data presented in Figure B-3 which show parametric plots of sampling probability versus percent sampled for various initial p values (initial percentages of degraded tubes). The data is for a Westinghouse Series 51 steam generator with a total tube population of N = 3388 tubes. It is seen that for some fixed sample size (say 10%) - assuming a performance index of P = 0.9 (horizontal line in the figure) - degraded tubes present in the population on the order of 0.3% are not likely to be sampled at least once e.g., $P < 0.9$; when the percentage p equals 1%, P just exceeds a value of 0.9 and at least one tube is very likely to be sampled. For a p value of 10%, P assumes a value near unity so that with a 10% sample size, the sampling of at least one tube is almost certain.

For a fixed sampling probability (horizontal solid line in Figure B-3), the number of tubes which must be sampled varies inversely with the percentage of degraded tubes present e.g., if fewer degraded tubes are present, then a greater percentage must be sampled for the same confidence level. Conversely, for a fixed number of tubes sampled, the number of degraded tubes must exceed some threshold value before at least one will be most likely sampled. In practice, if degraded tubes are present in the steam generator in some small number, the degradation must continue to spread until it is likely to be sampled. Early recognition can be guaranteed by doing a 100% steam generator examination. Early recognition can almost be guaranteed by choosing a sufficiently large sample size for steam generator examination since in this case the sampling probability will be approximately one.

Herein lies the dichotomy between the costs associated with a 100% examination - in

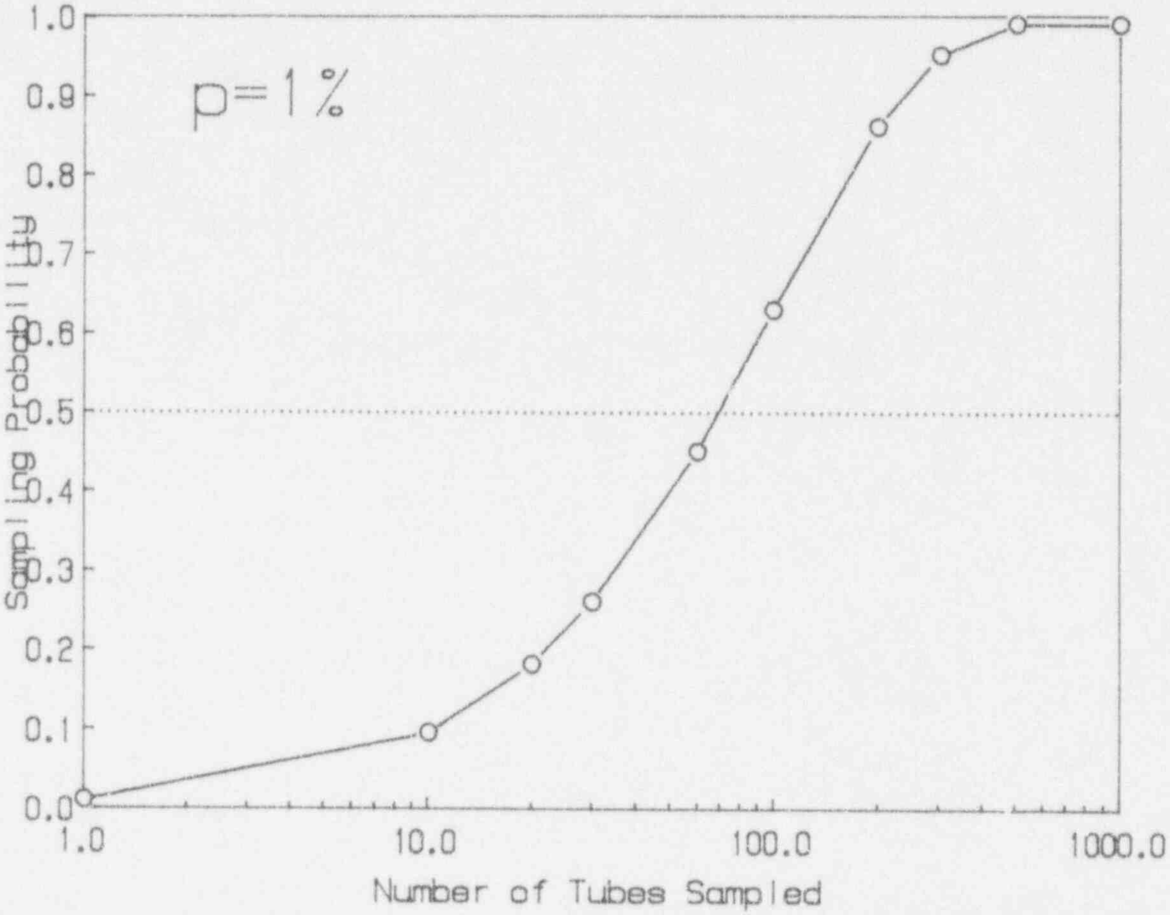


Figure B-2. Probability of Sampling at Least One Degraded Tube

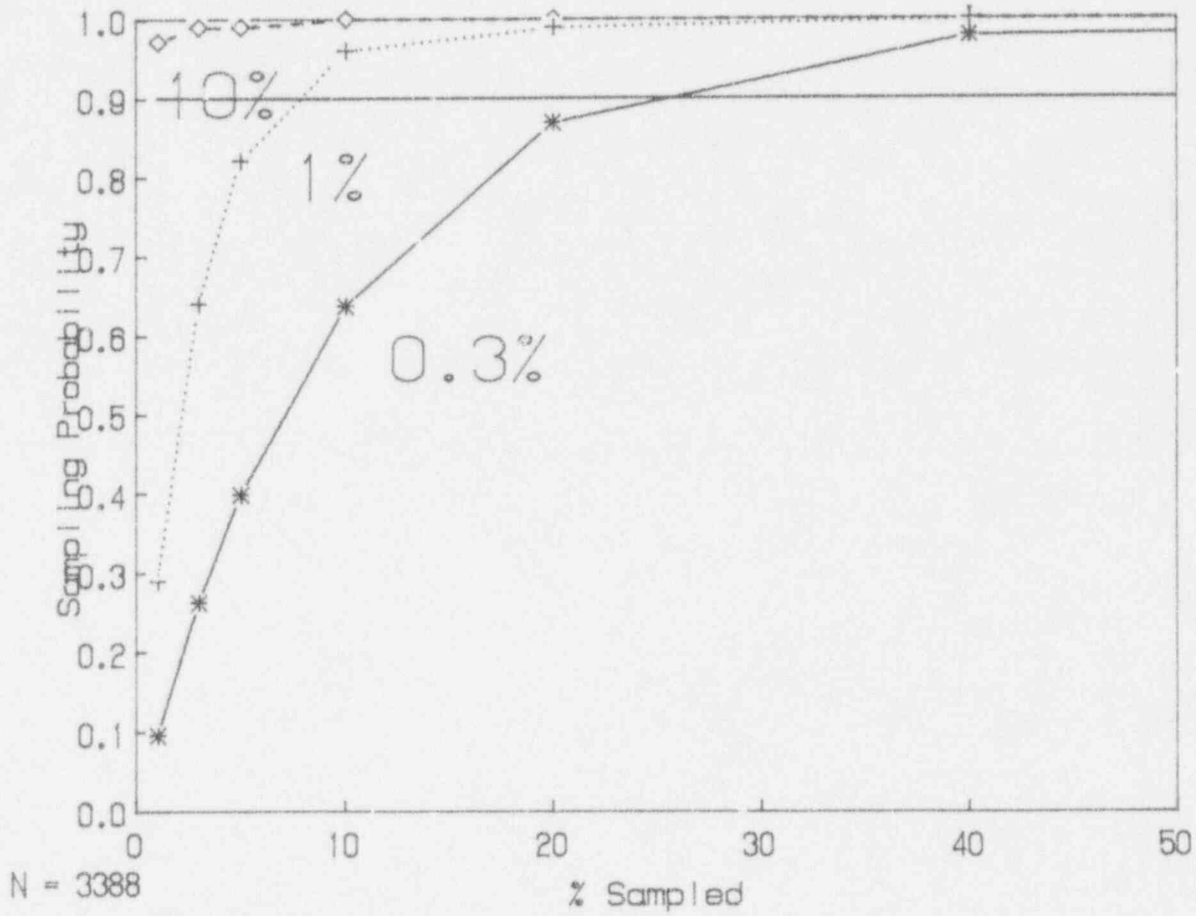


Figure B-3. Probability of Sampling at Least One Tube - Percent Degraded Variable which certain knowledge is obtained during each examination - and the risks which result from partial examinations in which incomplete knowledge is obtained. From an engineering viewpoint, the discussion in the previous paragraph represents the crux of the issue in specifying a sampling program. Two parameters must be defined in order to estimate the required sample size n or the percent of tubes n/N examined within the steam generator. These are 1) the expected number of tubes initially degraded e.g., specification of p, and 2) an acceptable statistical confidence level or reliability index e.g., specification of P.

Clearly there is no direct control over the number of degraded tubes n' present in the generator - it will be whatever it is after first discovery. However, the sample size n can be chosen large enough so that an assumed initial distribution of affected tubes - if present - are likely to be found. If for the moment defective tubes are assumed to be present, then this number n' should be driven by safety considerations; however, if degraded tube conditions are assumed, then steam generator reliability considerations might be a driving factor. For now, the numerical value of n' is left undefined. The statistical reliability index P is some number between zero and one. A value close to unity is desirable since it is preferable to have the event of sampling at least one degraded tube almost guaranteed. Typical engineering practice is to select a number 0.9 or greater for a reliable examination.

B.4.2 Sample Size Considerations

Selected properties of Equation (B-1) can be investigated by solving for n as follows:

$$n = \log (1-P)/ \log (1-p) \qquad \text{Equation (B-3)}$$

As discussed in the previous section, the number of tubes n which must be sampled is a function of the two numbers P and p. The desired reliability is specified by requiring that P be equal to or greater than 0.9. Attention is now focused on p which relates to the initial amount of degraded (or defective tubes) desired to be discovered by sampling.

B.4.2.1 Minimum Tube Density Considerations - Absolute or Relative Sense Definition

In Equation (B-3), p is defined as a ratio; it is the ratio of n'/N where again, n' is the number of degraded tubes in a total population of N tubes. If the detection of tube damage (degraded or defective tubes) is defined as some minimum percentage of tubes then this criterion is independent of tube population size. This in turn implies that the absolute number of tubes n' which must be found varies with the size of the tube population e.g., the number of tubes in a steam generator. A 1% degradation level in a Westinghouse 51 steam generator is 34 tubes whereas in a once-through unit, the number is approximately 150 tubes. If however, the absolute number of tubes n' which must be located by sampling is controlled, then n (the number of tubes sampled) is independent of the available tube population. As an example, choosing p equal to 0.01 (1% initial degradation), then for P=0.9, solution of Equation (B-3) for n gives 229 tubes. Thus, the absolute sample size n is the same for all steam generators. However, the percentage examined n/N varies since for fixed n, N varies with steam generator model. In fact, the sampled percentage increases with decreasing tube population. However, if some minimum absolute number of degraded tubes n' are to be recognized - independent of the population size - then p effectively varies with N. Since p = n'/N, for fixed n', the effective p will depend on the available tube population.

The two possible definitions discussed in the previous paragraph are now illustrated as follows. Equation (B-3) is plotted in Figure B-4 for p equal to a constant (p=1% in this case) showing that the percentage examined is dependent on tube population although n is fixed (n = 229). For constant p, the number of tubes sampled was fixed and independent of the population size. The sampled percentage increases with decreasing population size because n is fixed and N decreases. For constant n' (number of degraded tubes), the percentage of tubes which must be sampled is independent of the population size; however, the absolute number sampled increases with larger populations. Equation (B-3) is also plotted in Figure B-4 for n'= constant = 150 tubes. In this case, a fixed percentage of tubes, e.g., 1.5%, of the population must be examined. The absolute number of tubes examined however, varies with population size.

The observation that if a constant percentage of tubes is examined in tube populations of various sizes results in a comparable examination capability is illustrated with the following example. In using the binomial distribution as a sampling model, it can be shown that the most probable number of sampled degraded tubes - for a given sample size and degraded tube density - is given by the product (np) where n is the number of tubes sampled and p is the initial degraded tube density. The most probable number is readily calculated and is given by

Most Probable # = (np) Equation (B-4)

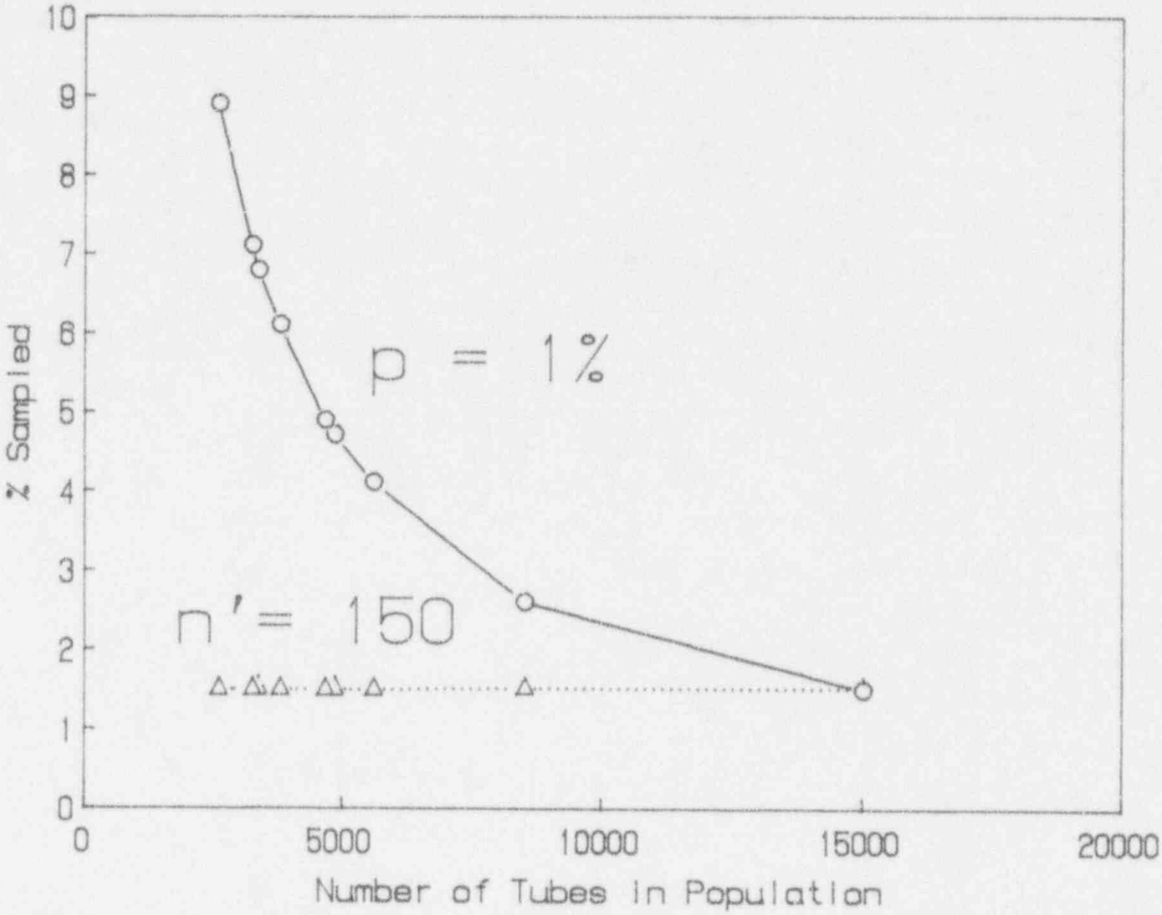


Figure B-4. Sample Size Requirements - Constant p and n'

Since p = n'/N and n = (%sampled/100)N, Equation (B-4) can be rewritten as follows

Most Probable # = (%sampled/100) x n'   Equation (B-5)

which is the fraction of tubes sampled times the initial number of degraded tubes present in the population. In other words, the probable number of degraded tubes expected on sampling is the total number of degraded tubes present in the population multiplied by the fraction of tubes sampled. As can be seen, Equation (B-5) is independent of the total tube population size. In addition, it should also be apparent that if more tubes are sampled, more degraded tubes are likely to be sampled for a given degraded tube density.

It was previously mentioned that the choice of sample size is based on some minimum degraded tube density present in the sampled population. Since, the absolute number of tubes n' which must be found is independent of population size, then for fixed n', p - the effective degraded tube density - varies with the overall tube population N. This variation is shown in Figure B-5 for various tube population extremes which cover existing commercial steam generators. Curves are shown for n' = 74, and n' = 12 which correspond respectively to minimum detectable degraded tube densities for 3% and 20% sample sizes assuming perfect detection. For a typical Westinghouse Model 51 with N = 3388 tubes, the p values range from 2.6% to 0.35% whereas for a Babcock & Wilcox unit with 15,531 tubes, the effective p values range from 0.58% to 0.07%.

Equivalence in examination capability is also demonstrated with data presented in Table B-1 which lists the probable number (np) of degraded tubes for various steam generator tube populations assuming an initial degraded tube density of n'= 74 and a 3% sample size. It is noted from the table that for fixed n' = 74, the single trial success probability p decreases with increasing tube population N. When multiplied by 100, this is also the initial degraded tube density p in percent. For a fixed sampling percentage of 3%, the number of tubes n sampled increases with tube population. It is observed however that the product (np) assumes approximately the same value for all steam generators (within the limits of calculator round-off error). That (np) remains constant implies that the expected number of sampled degraded tubes is the same for all tube populations for a fixed sample size and the same initial number of degraded tubes present in the population. If the sample size or the absolute number of degraded tubes is increased, the product (np) increases but again remains the same for all steam generator tube populations.

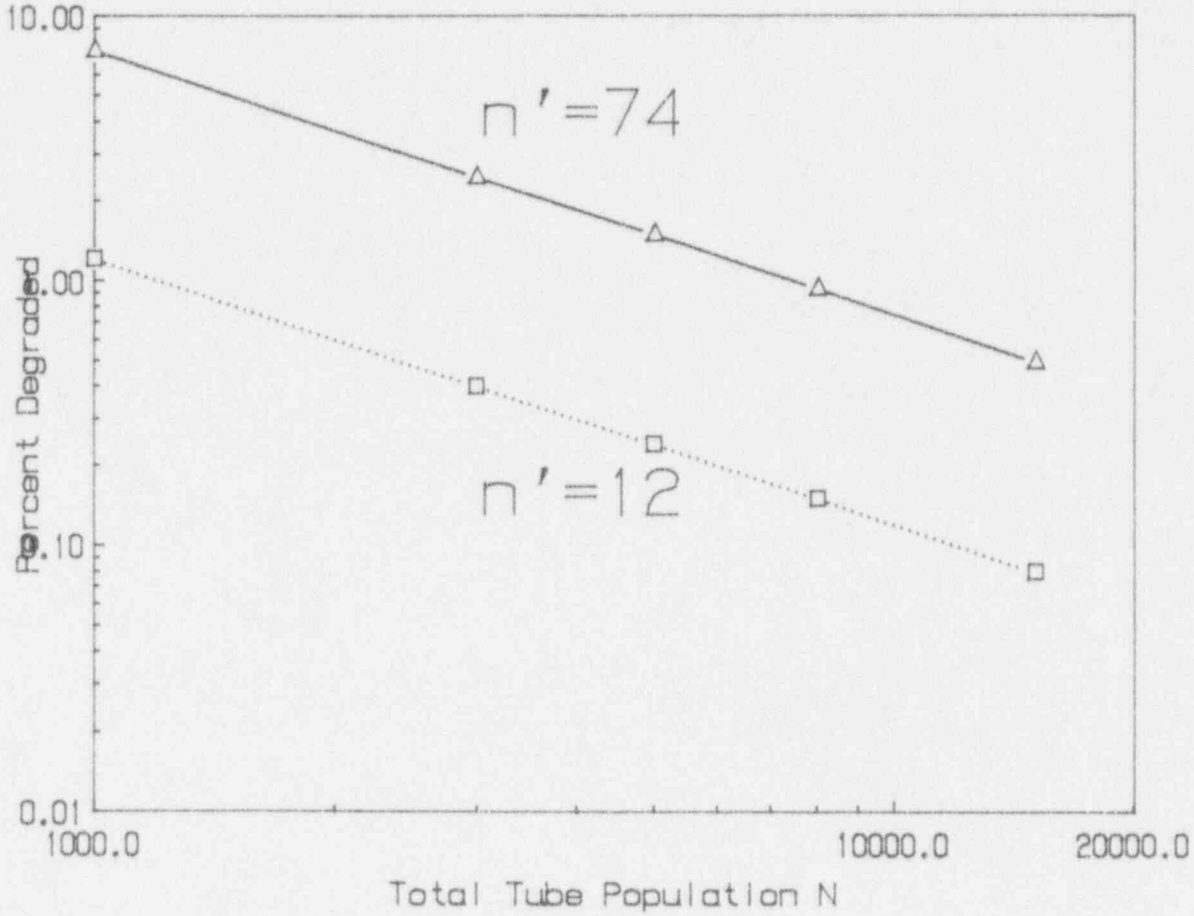


Figure B-5. Percent Degraded for Various Steam Generator Tube Populations

Table B-1

EXPECTED NUMBER OF DEGRADED TUBES (np) FOR VARIOUS STEAM GENERATORS
- 3% Sample Size & n'= 74 Tubes -

NSSS VENDOR	N	p	n	(np)
Westinghouse				
Series 24	2604	0.0284	78.1	2.22
Series 44	3260	0.0226	97.8	2.21
Series 51	3388	0.0218	101.6	2.21
Series 27	3794	0.0195	113.8	2.21
Model D	4674	0.0158	140.2	2.21
Model E	4851	0.0152	145.5	2.21
Model F	5626	0.0131	168.8	2.21
Combustion Engineering	8519	0.0086	255.5	2.20
Babcock & Wilcox	15531	0.0047	465.9	2.19

Note: Column Headings are as defined for Equation (1).

The implication of Equation (B-1) in light of existing Regulatory Guide 1.83 and plant technical specifications is briefly considered. These documents specify a minimum sample size on a percentage basis - typically 3%. Since sample size requirements are defined on a percentage basis, the implicit definition of a minimum degraded tube density is within the context of some absolute number of tubes. This observation follows from Figure B-4 where a line of constant percent sampled is for n' = constant where again n' is the number of degraded tubes.

In summary, if a minimum degraded tube density is defined on an absolute basis, e.g., some minimum number of tubes, then all units must examine the same percentage of tubes. However, if it is defined in a relative sense, then all units must examine some minimum number of tubes. In either case, the "early" recognition of widespread degradation means that both p and n' will necessarily be small.

B.4.2.2 Sampling Equation - Parametric Form

Equation (B-3) can be used to develop a graph suitable for engineering purposes relating the percent of tubes examined as a function of the number of degraded tubes assumed to be present in the total tube population for various reliability indices P. This is shown in Figure B-6 for P values ranging from 0.5 to 0.95. As an example, if the percent sampled is 3%, the number of degraded tubes which can be reliably found (defined as P = 0.9) is given where the 3% sample size intersects the appropriate curve in Figure B-6. This intersection occurs at a value of n' equal to approximately 74 tubes. Thus a 3% sample size is designed to reliably sample at least one degraded tube given that at least n'= 74 degraded tubes are present in the sampled population. It is emphasized that 3% of the tube population must be examined e.g., 3% of one steam generator or 3% of the plant tube population irrespective of the population size N. It follows that present examination requirements are uniform on an industry wide basis in the sense that some minimum absolute number of degraded tubes must be identified in all steam generators independent of tube population.

The curves presented in Figure B-6 can also be used as a basis for identifying benefits from increased sampling percentages. As shown previously, a minimum 3% sample size can reliably determine the presence of tube wall degradation in a steam generator if the number of degraded tubes exceeds approximately 74. By extending a line of constant percent sampled at a value of 20%, it is noted from Figure B-6 that reliable detection occurs with as few as 12 degraded tubes - an approximate six-fold improvement in detection sensitivity. Further examination shows that sample

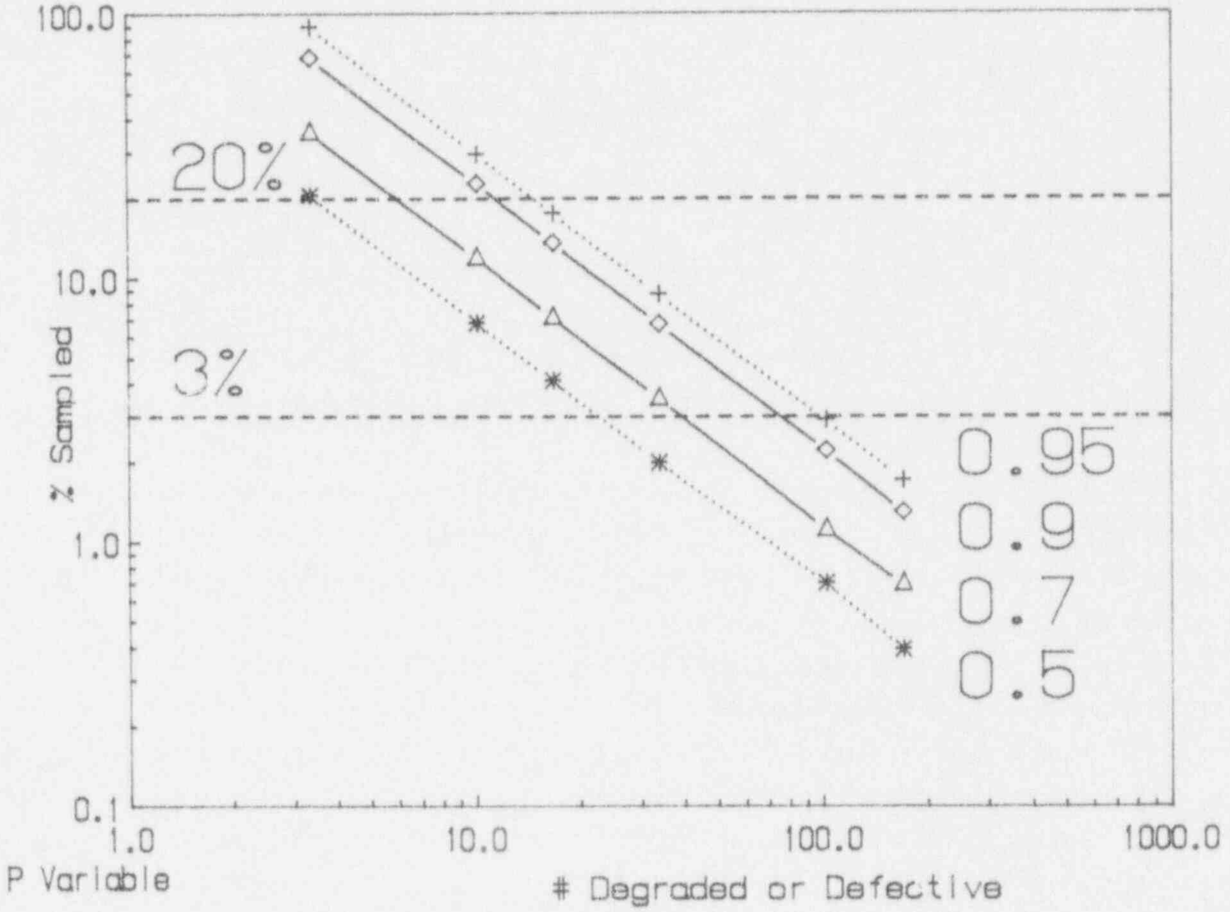


Figure B-6. Sample Size Requirements, Reliability Index and Degraded Tube Density Variable percentages approaching 100% are needed to detect the nearly degradation-free condition of only 2 or 3 degraded tubes.

In summary, a 3% sample size can determine the presence of tube degradation when the number of degraded tubes is on the order of 74 or so; a six-fold improvement in detection sensitivity is achieved when the sample size is increased to 20%. No further significant statistical improvement is achieved by increasing our sampling percentage beyond this point in the sense that essentially a complete steam generator examination is required to find singularly degraded tubes; 100% examinations no longer involve sampling. If a steam generator examination sampling strategy is going to be adopted, then a 20% sample size is roughly the upper bound in terms of realizable benefits within the context of sampling some reasonable number of tubes.

B.4.3 Sampling Plan Acceptance Criteria

The present regulatory basis for accepting or rejecting the continued operation of a steam generator is probabilistic and typically involves establishing acceptance criteria e.g., some number of defective or degraded tubes c' and c'' respectively, which if exceeded during sampling, then the sample program is expanded. If not, the generator is accepted for continued operation. It is important to recognize at the outset that the observation of no degraded or defective tubes during sampling does not imply that the steam generator is free of degraded or defective tubes. This is only true in a statistical sense.

Historically, in quality control circles, the effects of acceptance value and sample size have been evaluated using the concept of an operating characteristic (OC) curve. This curve plots the probability of accepting the lot, i.e., the entire tube population, versus the lot fraction defective. Thus, the OC curve displays the discriminatory power of the sampling plan. It is advantageous to use since it integrates the effects of sample size, acceptance criteria and lot fraction defective into a single equation which can be readily evaluated. The acceptance probability is defined as

$$Pa = BI(k2,n,p) \qquad \text{(Equation B-6)}$$

where

BI(k2,n,p) is the cumulative binomial distribution
k2 is a threshold number or acceptance value c

n is the number of tubes sampled;
p is the fraction of degraded/defective tubes; and
Pa is the probability that the number of degraded
or defective tubes is less than the acceptance value.

For fixed values of k2 and n, Equation B-6 is evaluated with p as the parameter of interest. Since p is the degraded or defective tube density, solutions to Equation B-6 result in a curve which provides a statistical measure of how well the chosen values of n and k2 perform over a range of degraded or defective tube densities which in turn control steam generator quality level.

Figure B-7 shows the operating characteristic curve for a 20% sample size and an acceptance level of k2 = c'= 0 defective tubes. For a given fraction defective p in a steam generator, the curve shows the probability P that the steam generator will be accepted for continued operation using the given sampling plan and acceptance level. Acceptance is defined within the context of not expanding the sample program. If one defective tube is sampled, then the sample program is expanded. If no defective tubes are sampled, then with 90% confidence (solid horizontal line shown in the figure), the defective tube p density is less than approximately 0.0025. Notice that this latter number is not zero which illustrates the point that it is possible to have a defective tube density less than some critical value. On the other hand, it is highly unlikely ($P < 0.1$ - dashed line in the figure) that defective tube populations with density p exceeding 0.0025 are accepted. Operating characteristic curves are of great pragmatic interest since their acceptance properties can be controlled by selecting appropriate values of sample size and k2.

Examples of operating characteristic curves for 3% and 20% sample sizes - showing the effects of various acceptance levels - are given in Figure B-8. A Westinghouse Series 51 steam generator is assumed with a total tube population of N = 3388 tubes; a 20% sample size corresponds to n - 678 whereas for a 3% sample, n = 102. The 3% sample size operating characteristic curve with zero defective tubes observed during the initial sample corresponds to standard technical specification C-1 category acceptance limits (shown as the dashed line curve in Figure B-8). This curve should be compared with the 20% sample size characteristic curves with acceptance limits of 0, 1, and 2 defective tubes (shown as solid line curves in Figure B-8). Comparison is achieved by choosing an acceptance probability, say P = 0.1, and observing the fraction defective value at this point. The 20% sample size operating characteristic curves are shifted to the left - achieve the same acceptance

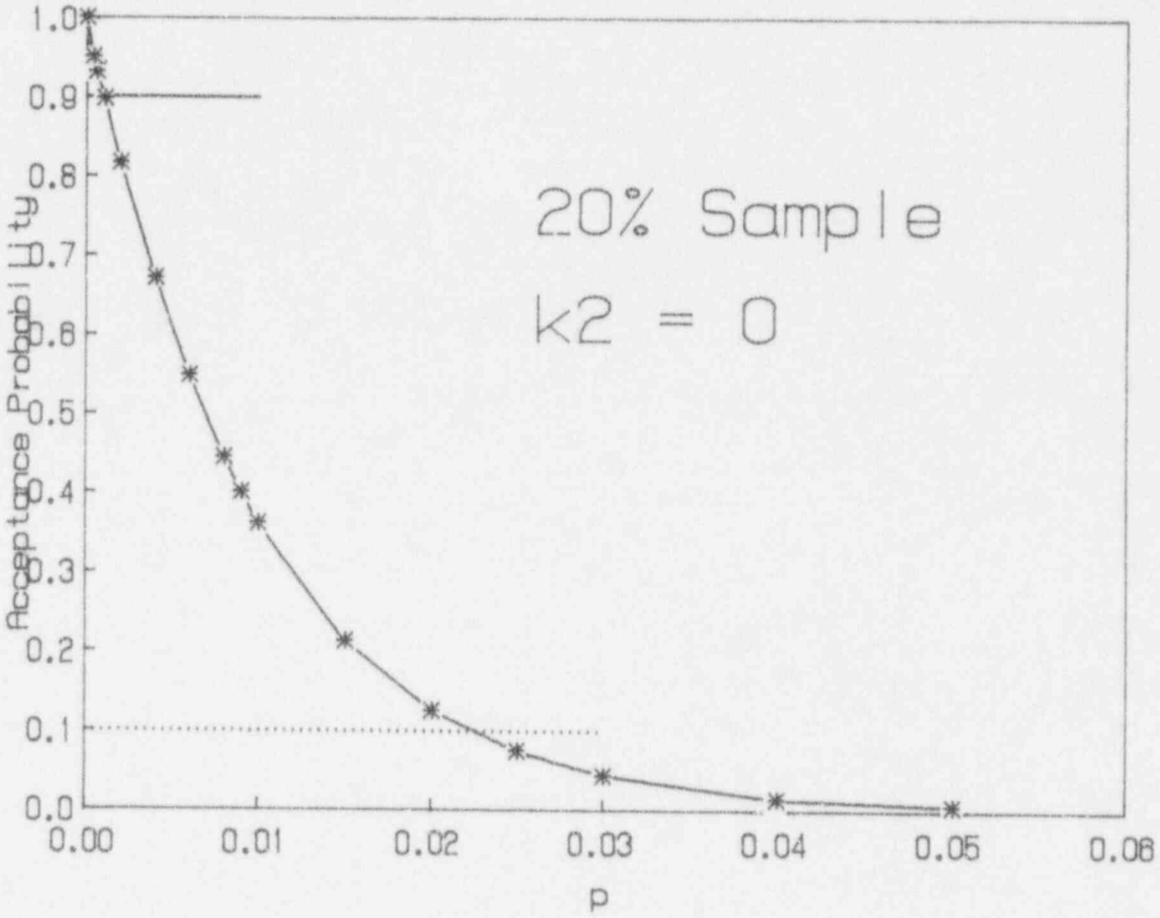


Figure B-7. Operating Characteristic Curve - 20% Sample Size

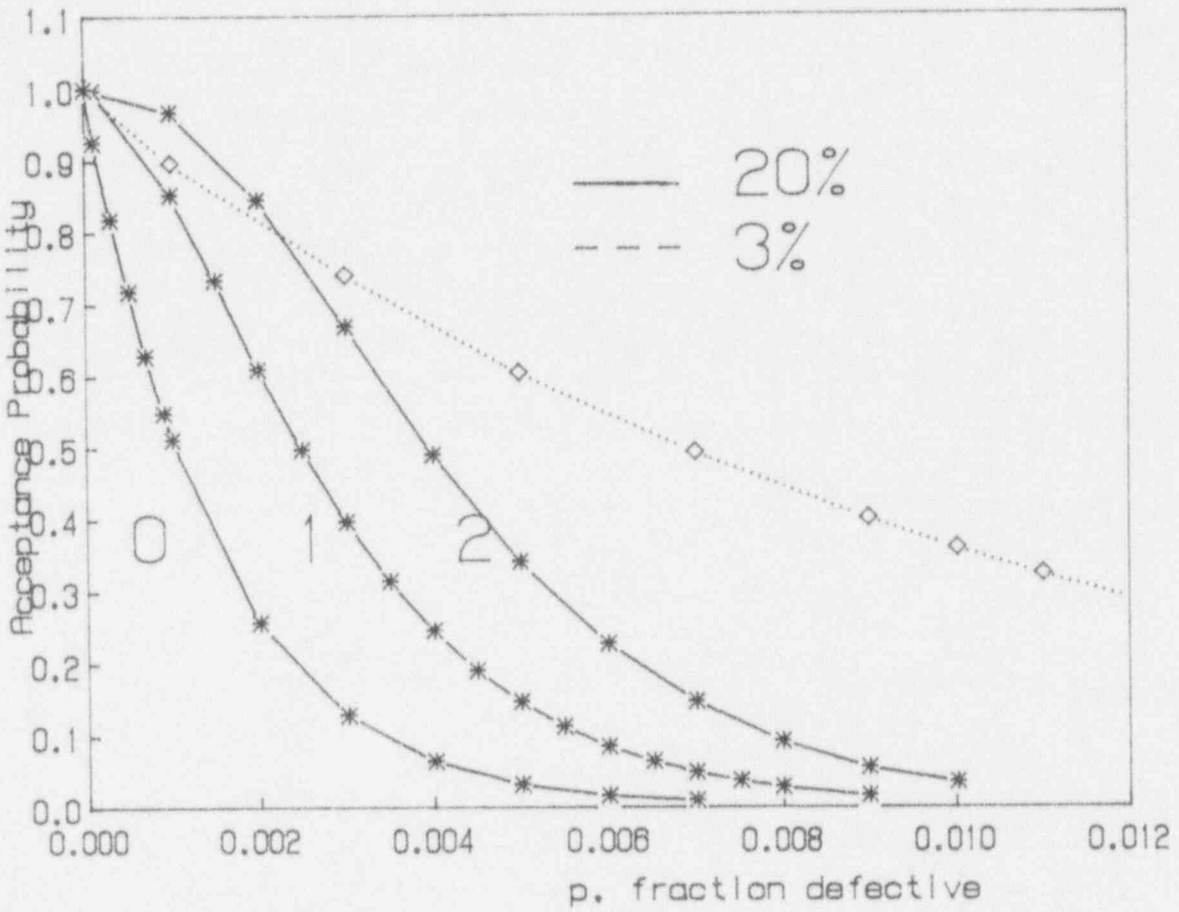


Figure B-8. Operating Characteristic Curves -
3% and 20% Sample Size

probability at a lower fraction defective - and become more selective in their cutoff features i.e., the slopes of the characteristic curves increase, as the number of allowable defective tubes is decreased.

For purposes of discussion, assume that our critical fraction defective value is $p = 0.008$. It is desired to reject steam generator tube populations with a fraction defective equal to or greater than this p value with high probability. Rejection is defined within the context of requiring an expanded sample program. As can be seen from the figure, this can be achieved using a 3% sample size with an acceptance probability of 0.5. This same success rate could be achieved by flipping a fair coin rather than examining the steam generator. On the other hand, a 20% sample size with an acceptance level of no more than two defective tubes can reject steam generator tube populations with high probability, i.e., $P < 0.1$. Even lower acceptance probabilities or lower fraction defective tube populations can be rejected by choosing a lower acceptance value, e.g., a smaller number of allowed defectives in the sample size.

B.4.4 Compensation for Imperfect Detection

A limitation of the previous analysis is that it assumes a 100% detection probability, i.e., all degraded tubes which are sampled will be observed and reported as such by the data analyst. The effects of imperfect detection can be modeled by recognizing that the events of sampling and detection are independent. Accordingly,

$$P_{obs} = P_s \times P_d \qquad \text{(Equation B-7)}$$

where

Pobs is the probability a sampled tube is observed,
and Pd is the detection probability.

It should be noted that since the sampling and detection probabilities are generally less than unity, the product of the two probabilities will be less than the lower of the two values.

Parametric variations in Ps and Pd are now considered in order to establish what overall values are achievable. From Equation B-1, Ps is a function of two variables, the sample size n and the degraded tube density n'. The probability of sampling and detecting at least one degraded tube as a function of sample size is given in Figure B-9 for an initial degraded tube density of n' = 12 tubes and various detection probabilities. For detection probabilities less than unity, Pobs is simply the sampling probability scaled downwards by the detection probability. Increasing sample size increases the value of Pobs; however, beyond an approximate 20% sample size, the incremental numerical improvement varies extremely slowly with an increase in sample size. For a detection probability of 0.9, essentially a 100% sample size is necessary to achieve a 0.9 probability of observing at least one degraded tube given that n'= 12 degraded tubes are present in the sampled population. A reasonable conclusion is that increasing sample size beyond 20% to compensate for imperfect detection is not an efficient examination strategy in that sample sizes on the order of 100% are rapidly approached.

An alternate strategy is to consider a relaxation in the initial degraded tube density n'. The probability of sampling more than k2 tubes is shown in Figure B-10 for various degraded tube densities assuming a 20% sample size. For a value of P(k>k2) = 0.9 (dashed line in the figure), k2 assumes values greater than one for n' greater than 20. Values of k2 for P > 0.9 derived from the figure are in turn plotted in Figure B-10 as a function of n', i.e., the number of degraded tubes, for various detection probabilities. At least one sampled tube must be detected (for observation) in order to act as a trigger point for expansion. The fraction of sampled tubes that will be observed is simply the number likely to be sampled with probability 0.9 multiplied by the detection probability. Again, for an observation to occur, these curves should exceed the value of one (horizontal dashed line). This in fact occurs for n' equal to a minimum value of 20. Thus, by relaxing the minimum degraded tube density from n'= 12 to n'= 20, adequate compensation for detection probability is achieved while maintaining a high probability that at least one tube is both sampled and detected utilizing a 20% sample size.

B.5 RANDOM SAMPLE PLAN RECOMMENDATIONS

Standard plant technical specifications which address steam generator sampling plan requirements exhibit three general features; 1) definition of a minimum sample size (typically 3%), 2) a requirement for sample program expansion based on observing a certain number of defective tubes (as few as one), and 3) a similar expansion requirement when a certain number of degraded tubes (typically > 5% of the sampled tubes) are observed. Implicit technical specification sampling goals are twofold; 1) to prevent the continued operation of a steam generator in an unsafe condition - addressed by controlling the number of defective tubes - and; 2) to recognize at an early stage the onset of "widespread" tube degradation possibly impacting steam

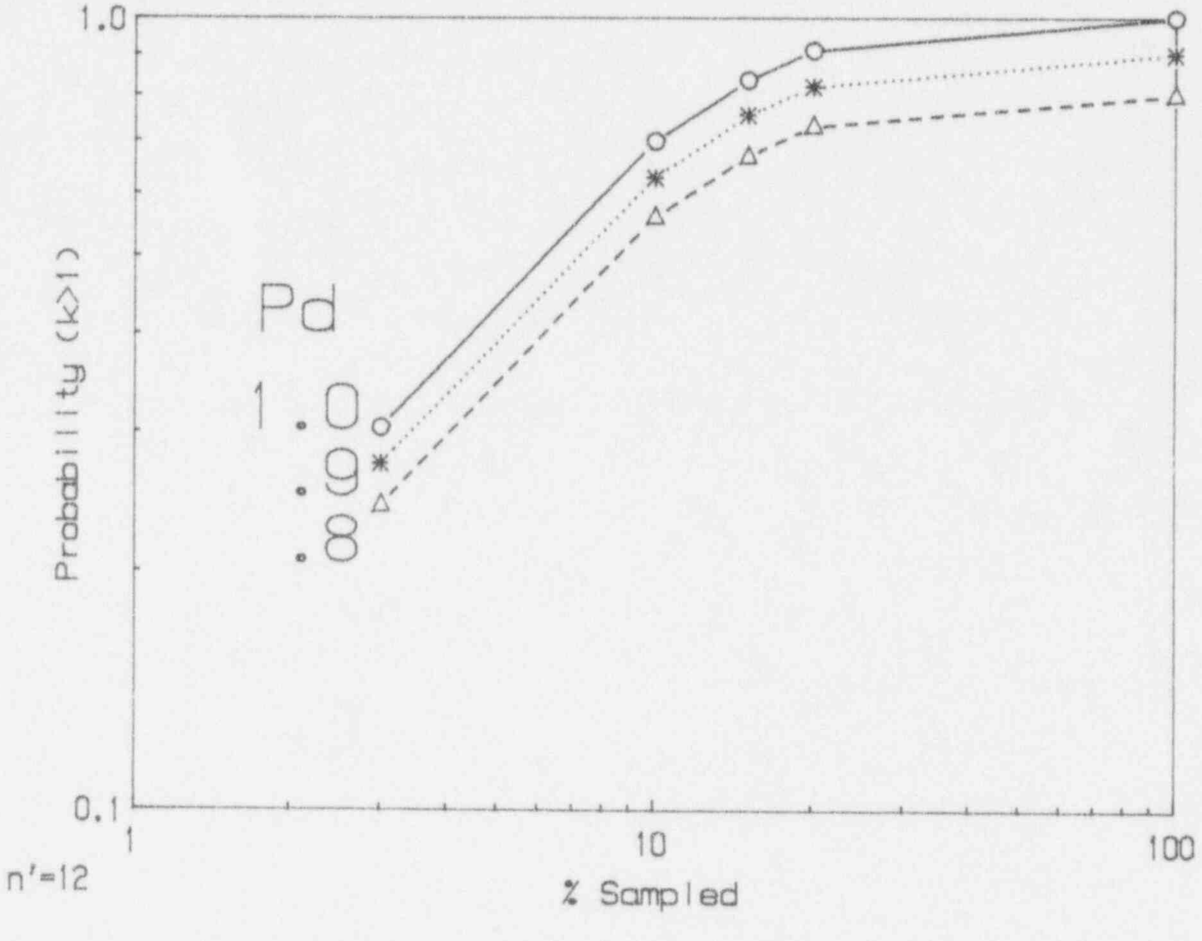


Figure B-9. The Effects of Imperfect Detection on Sampling Probability

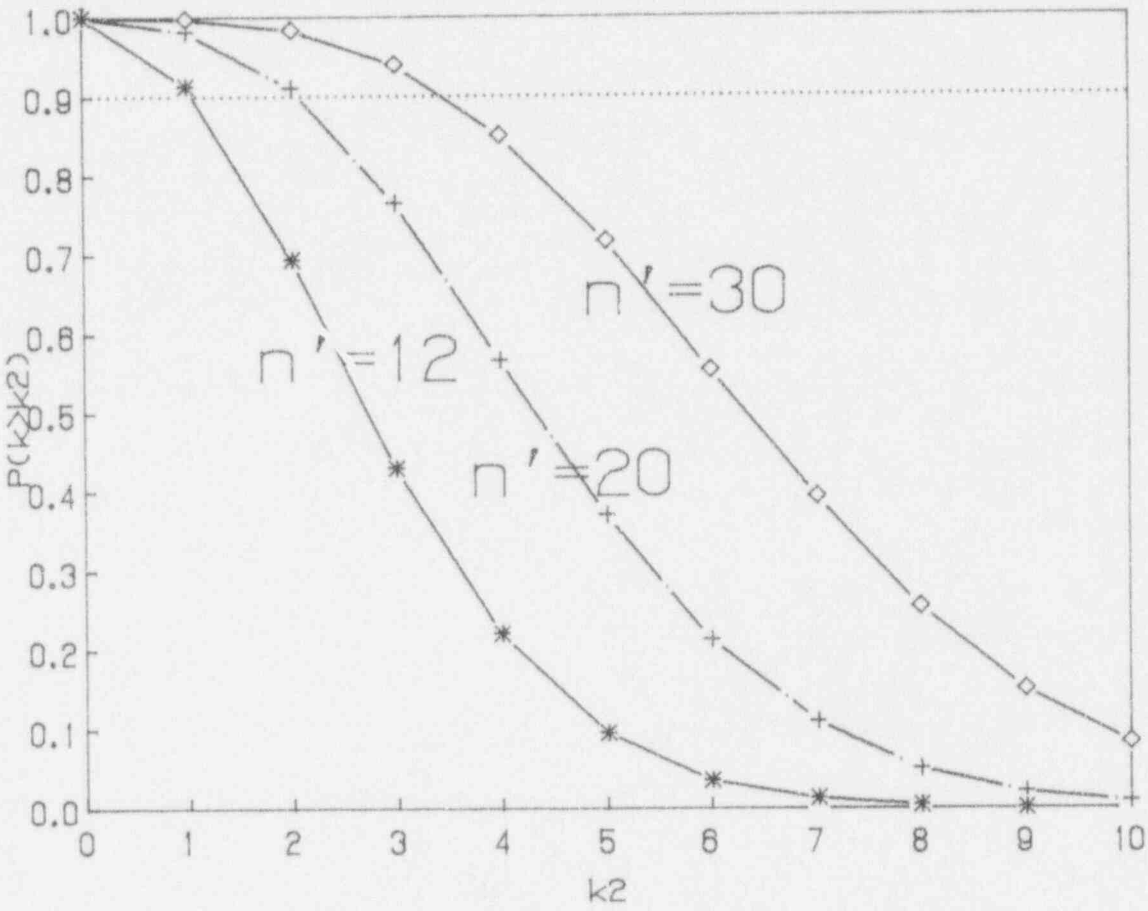


Figure B-10. Probability of Sampling k2 or More Tubes for Various Degraded Tube Densities generator reliability - addressed by controlling the number of degraded tubes. Both goals are assumed to be adequately accomplished starting with a minimum 3% random sample followed by specified expansion rules.

The previous section considered general factors important in the design of a steam generator sampling program. The following key concepts were discussed:

- Initial Degraded Tube Density
- Sampling Reliability Index
- Compensation for Imperfect Detection
- Sampling Plan Acceptance Criteria

Attention is now focused on each of these items; assumptions are explicitly stated with the objective of specifying a recommended steam generator sampling program.

B.5.1 Initial Degraded Tube Density

The most critical number in specifying sample size is the minimum number of tubes which must be discovered e.g., the initial degraded or defective tube density. Implicit in this specification is the concept that for densities less than some critical value, the condition of the generator is deemed acceptable. In other words, some minimum number of tubes - whose condition is immaterial - are allowed to remain in the generator.

As mentioned previously, existing regulatory criteria for an acceptable steam generator condition and sample program expansion are probabilistic based. However, as pointed out in (1), there is no quantitative basis relating tube rupture probability to existing examination requirements. Present steam generator examination requirements were first developed during the mid-1970's primarily on the basis of experience and engineering judgment. While risk analyses of single and multiple tube failures have since been conducted, the rigorous application of a probabilistic basis relating tube failure to steam generator sampling program requirements has been judged to be economically unjustified. Therefore, there is no attempt in this document to justify acceptable probabilities related to single or multiple tube rupture events or couple tube failure probabilities to sampling requirements. Rather, the focus is on insuring that a large enough sample is used to reliably detect the onset of "widespread" tube degradation, and showing that the incremental improvement beyond a recommended sample size of 20% is insignificant up to and including a 100% examination. Comparison of recommended sample size capabilities with existing technical specification recommendations are, however, made.

Analyses presented previously have determined - using order of magnitude estimates - that degraded or defective tube subpopulations on the order of 74 tubes can be reliably found ($P_s > 0.9$) with an existing technical specification minimum sample size of 3%. A 20% sample size is necessary to reliably discover smaller subpopulations on the order of 12 to 20 tubes - this range being controlled by detection probability - whereas a 100% examination is essentially required to find less than ten tubes of interest i.e., one or several tubes. These results follow from basic sampling theory in which the sampling probability exhibits a saturation point at approximately a 20% sample size. Little incremental benefit in sampling probability is achieved beyond a 20% sample size.

B.5.2 Sampling and Detection Reliability Indices

Assuming a minimum degraded tube density of $n' = 20$ tubes per steam generator, a value of $P(k) = 0.9$ for sampling at least one tube is taken as a measure of a reliable sampling program. The physical significance of this reliability measure is as follows. For an initial degraded tube density of $n' = 20$ tubes randomly distributed throughout the steam generator, they are likely to be discovered using a 20% sample size 90% of the time. In other words, for every ten steam generator examinations with this tube population, one examination is likely to pass as an acceptable steam generator condition.

In conjunction with detection probability considerations presented in Figure B-11, this sampling reliability constraint provides for high confidence that at least one tube will be sampled and observed. The detection probability ranges assume that appropriate examination technology e.g., multifrequency instrumentation and proper test coils, are used for the expected degradation mechanism and location within the steam generator. Using data presented in Appendix C, the average detection probability for four different damage mechanisms (thinning, pitting, IGA/SCC, and wear) at a true flaw depth of 40% through wall is $P_d(\text{avg.}) = 0.8625$. This probability is analogous to a "recording probability" and reflects the capability of the technology. The effects of analyst performance are considered as follows. Using the independent data review process, the system detection probability is given as

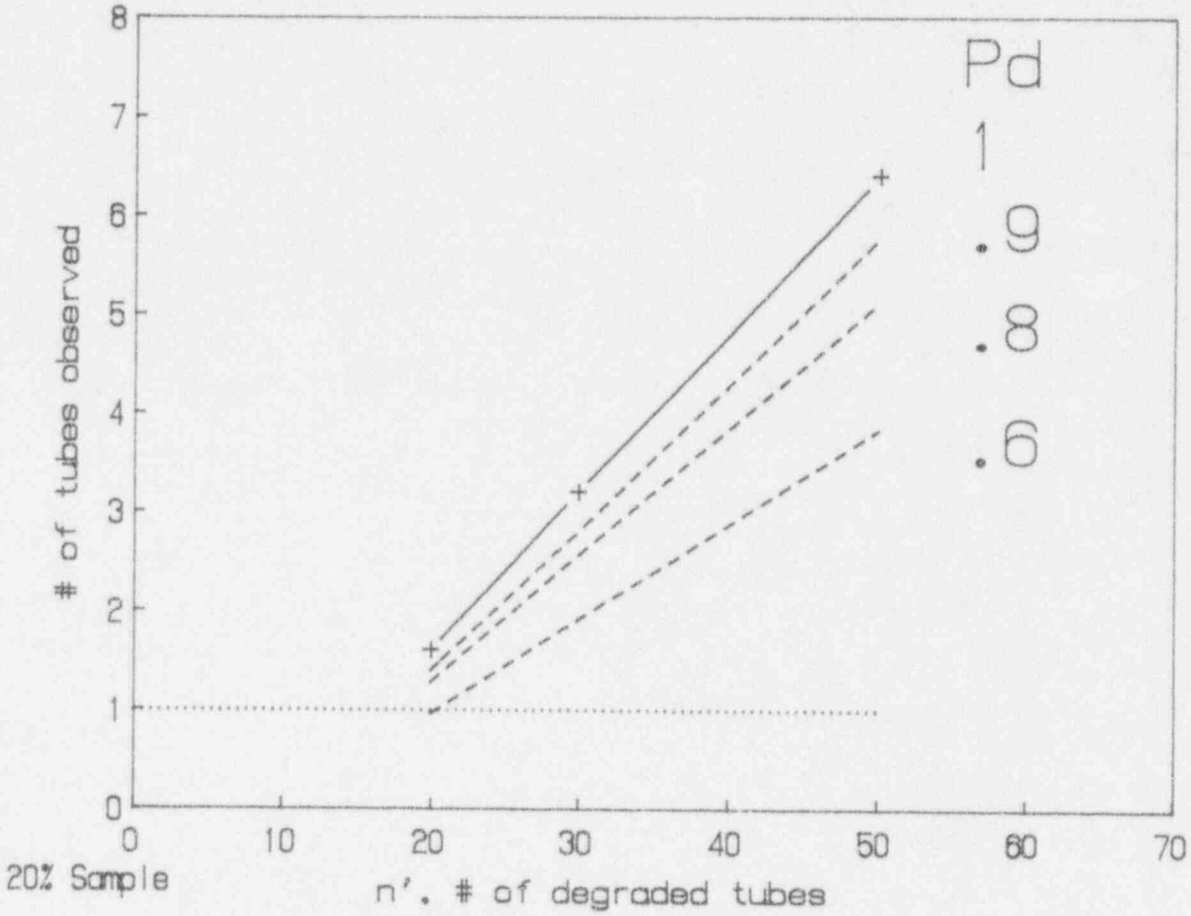


Figure B-11. Number of Tubes Observed for Various Detection Probabilities

P(system) = Pd(avg.) P(a + b)   (Equation B-8)

where

Pd(avg.) is the average recording probability,
P(a + b) is the probability that analyst a or b
or both report the signal.

Data analyst performance demonstrations require that individual analysts perform with a reporting probability of P = 0.9. This value in turn equates to a value of 0.99 for P(a + b). Multiplying this by the estimate of Pd(avg.) gives a P(system) value of 0.85. Again, from Figure B-11, using this value as a performance measure assures that given multiple sampled degraded tubes at least one is likely to be observed.

B.5.3 Sample Plan Acceptance Criteria

The basic sampling sensitivity using a 20% sample size is a defective or degraded tube density of approximately twenty tubes. This equates to a critical fraction defective limit p for a Westinghouse Model 51 of approximately 0.006 i.e., 20 divided by 3388. An ideal operating characteristic curve (shown as a rectangle in Figure B-12) would accept all steam generators with a fraction defective less than 0.006 and reject all those with a fraction defective greater than this value. This can be achieved in principle by doing a 100% steam generator examination assuming perfect detection and sizing. As can be seen from the 3% OC curve in Figure B-12, existing technical specification C1 acceptance criterion meets this upper fraction defective limit with an acceptance probability of approximately 0.5. Significantly improved acceptance performance is achieved using a 20% sample size with an acceptance number of k2 = 1 defective tube as shown in Figure B-12. At a p fraction defective of 0.006, a rejection criterion of more than one defective i.e., accept for k2 = 1 defective tube or less, reduces the acceptance probability to less than 0.1. A similar OC curve has been constructed for once-through steam generators and is shown in Figure B-13.

B.5.4 Expanded Program

Once the acceptance value is exceeded there are several logic paths that can be taken. If during the random sample program, reportable degraded indications - attributable to operation - are reported in excess of the threshold value k2, (> 5%

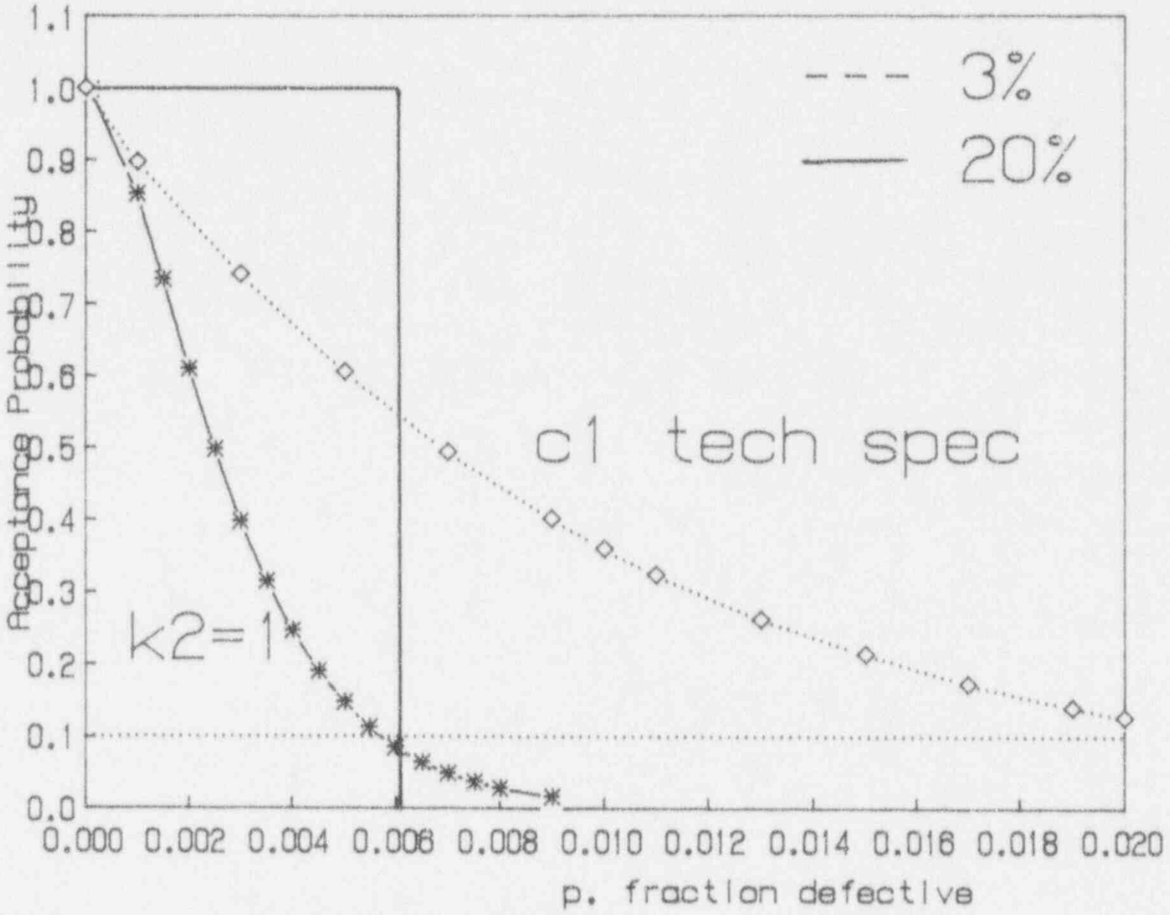


Figure B-12. Operating Characteristic Curves - Westinghouse Model 51 Steam Generators

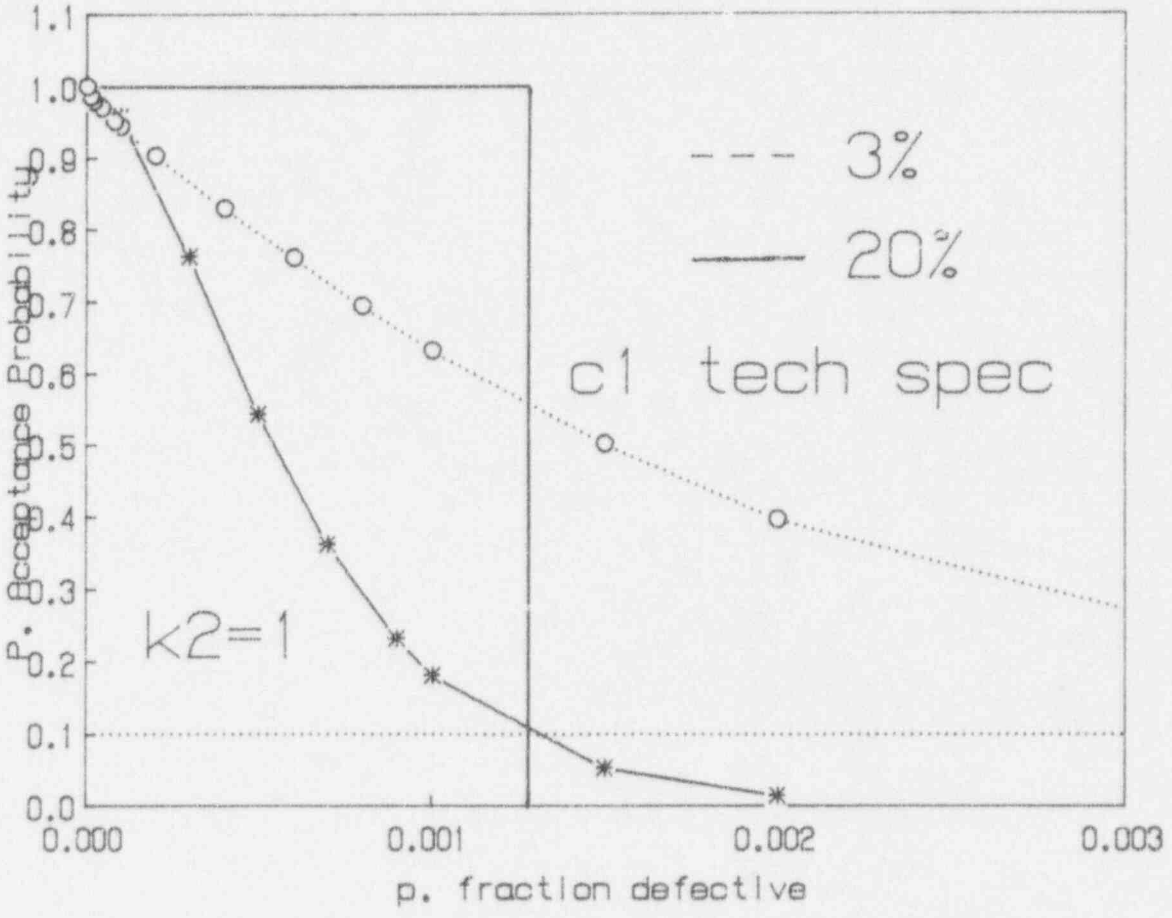


Figure B-13. Operating Characteristic Curve - Babcock and Wilcox Once-Through Steam Generator of the sampled tubes) their locations should first be compared with the experience summarized in Tables 4-1 through 4-3. If the new indications are consistent with the tabulated experience, then an augmented examination should be conducted per the applicable tables.

If the new indications are not consistent with the tabulated experience then the random sample program should be expanded to bound the new phenomenon. No particular expansion percentage is specified; however it should be done with sufficient completeness such that all probable locations are examined - this may involve a 100% examination of the suspect region. Every effort should be made to develop a supporting logic providing a basis for isolating the new indications to a specific region of the generator. This should be supported by eddy current data acquired from the steam generator from regions where the indications are and are not expected. Supplemental diagnostic NDE methods e.g., generally eddy current RPC, should be used on a selected number of these new indications to identify their probable morphology from which it may be possible to infer the nature of the damage mechanism. Tube pulls may be warranted in case the results from NDE diagnostics are inconclusive.

B.6 AUGMENTED SAMPLE PLAN RECOMMENDATIONS

As stated previously, the augmented sample plan is experienced based and addresses the examination of those regions of the steam generator in which tube wall degradation is known or expected to occur. This section presents a detailed overview of operating experience summarized in Tables 4-1, 4-2, and 4-3 (presented in Section 4) for steam generators designed by Babcock & Wilcox, Combustion Engineering, and Westinghouse. Specific regions within a steam generator are highlighted for the purposes of augmented sample planning. It is emphasized that over 98% of the forced outages that have occurred have been because of tube failures in the regions highlighted below. Appropriate examination of these regions during scheduled outages can reduce the propensity for an unscheduled outage.

B.6.1 Babcock & Wilcox Units

Tube wall degradation experience in Babcock & Wilcox units has consisted of four principal classes of damage mechanisms. These include corrosion-fatigue, wear, IGA/SCC, and flow impingement damage. One unit has experienced primary side stress corrosion as the result of sulphate intrusion during lay-up; this experience is considered atypical and is not discussed. Corrosion-fatigue and wear have occurred within the lane region in several units (Oconee 1,2,3, Arkansas 1, and Rancho Seco) whereas IGA/SCC has occurred within the upper tube sheet crevice and wedge region in one unit (Arkansas 1). Flow impingement damage has been limited to three units (Oconee 1, 2, 3) and tends to be confined to the outer periphery region of the steam generator. These various regions of interest are shown in Figure B-14.

Some 47 forced outages have occurred in once-through steam generators as a result of tube wall degradation. Thirty one of these outages were due to corrosion fatigue with the majority having occurred at the three Oconee units. Arkansas 1 and Rancho Seco have also had forced outages due to corrosion fatigue. Four outages have occurred as the result of IGA/SCC in one unit (Arkansas 1), whereas flow impingement damage has contributed to three unscheduled shutdowns (Oconee 1 & 3). The remainder of the forced outages were due to loose parts or other problems. No forced outages have occurred as the result of wear.

Tubes within the lane region of two units - Oconee 1 and Rancho Seco - have recently been sleeved in order to increase tube stiffness. This is expected to reduce the susceptibility lane region tubes to vibration and hence reduce the chances for a fatigue related failure.

B.6.1.1 Lane Region

The open lane in a once-through steam generator is an untubed region of the generator in which a single row (Row 76) was left untubed during manufacturing for purposes of visual examination at some later date. In Oconee 3 steam generator A, an additional two rows were only partially tubed (Rows 75 & 77). The "lane region" in most cases is defined to be the region within +/- 3 rows adjacent to Row 76. See Figure B-15. Tube failures within this region of the generator have accounted for 77% of the forced outages in once-through units.

Tubes along the open lane at the upper region of the steam generator have been susceptible to flow related tube degradation e.g., corrosion-fatigue and wear, and intergranular attack. Corrosion-fatigue is a hybrid damage mechanism in which very small secondary side corrosion sites are postulated to act as initiators for subsequent through wall circumferential fatigue failure. Failures have been observed primarily at the 15th support plate and at the lower edge of the upper tube sheet. Fatigue failure occurs over an extremely short time frame e.g., less than 24 hours, propagating from extremely small initiation sites whose detection is beyond the capabilities of production NDE methods. In a sense, the examination of a tube

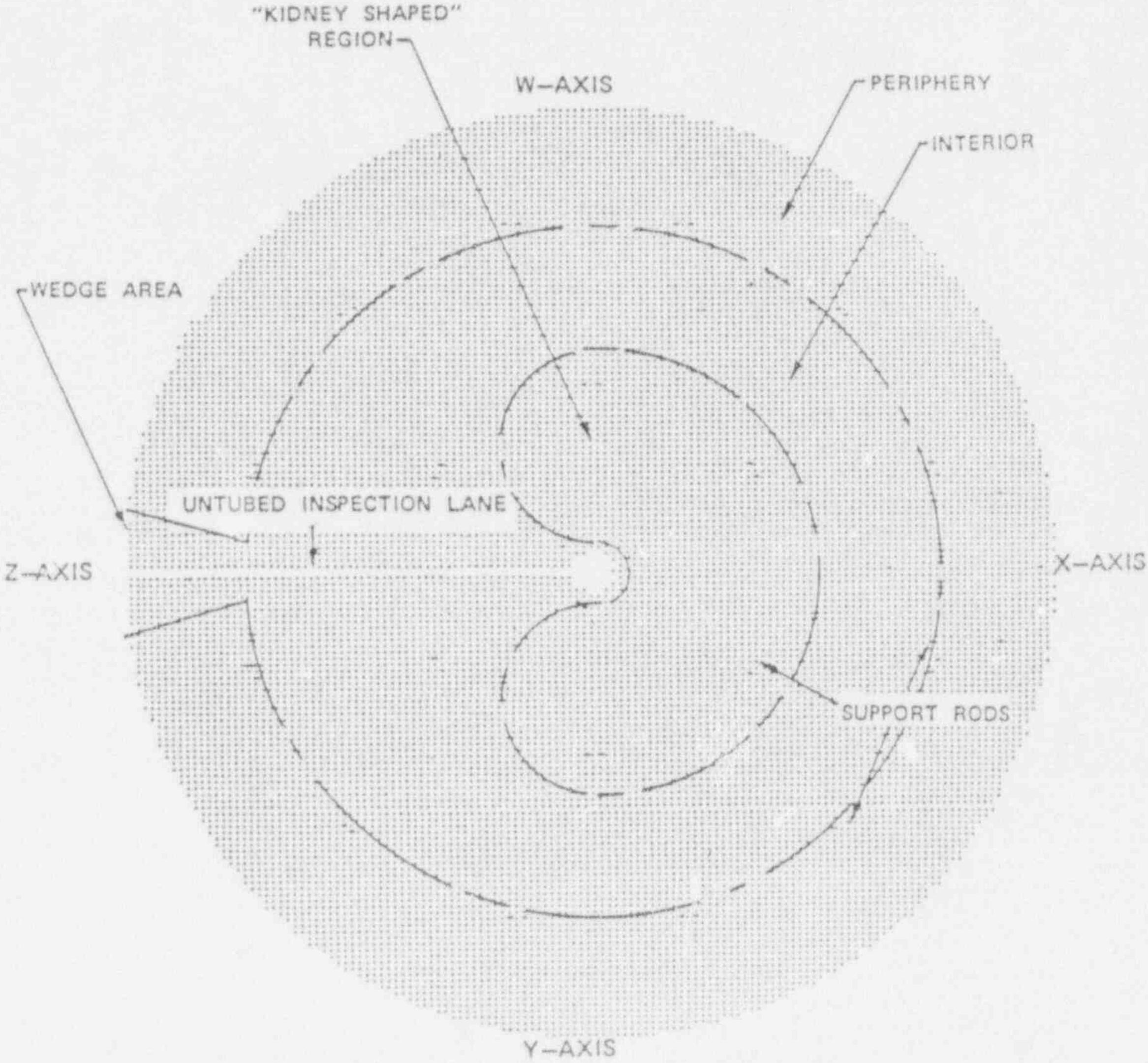


Figure B-14. Once-Through Steam Generator Tube Sheet Map Showing Various Regions of Interest

OTSG

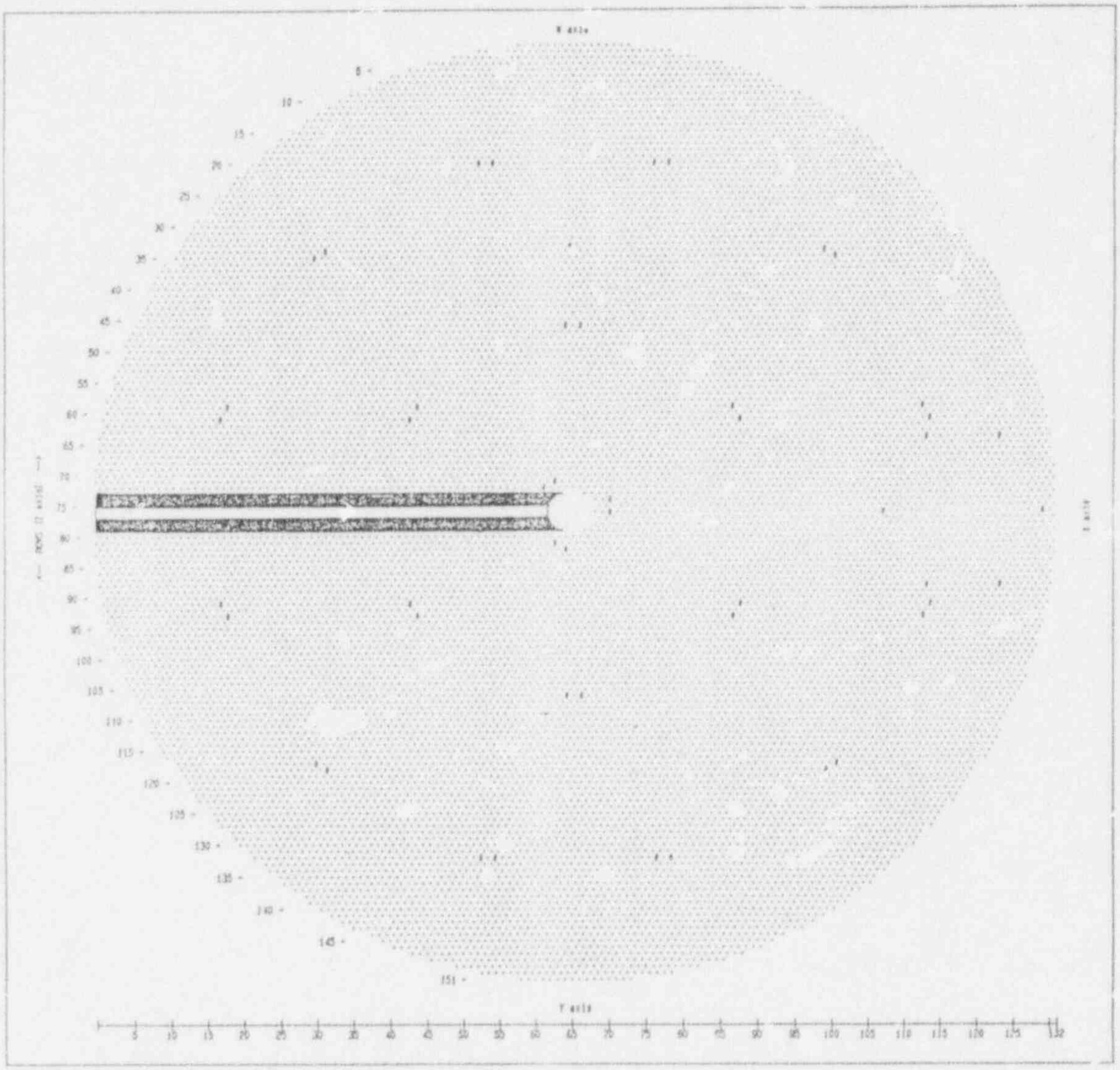


Figure B-15. Once-Through Steam Generator "Lane Region" for fatigue damage is not an NDE issue because of the short failure time. Examination of a steam generator for this damage mechanism will not necessarily reduce the chances of an unscheduled outage. Leaker outages due to fatigue are something that have been begrudgingly anticipated and accommodated.

Wear at the broached support plate land contact region has occurred within the same region of the generator. It has been observed as low as the fourteenth support plate. Very few tubes in the OTSG total tube population have been affected by wear - a total of twenty tubes in eight units e.g., twenty tubes out of roughly 240,000 tubes.

Lane region tubes removed from Arkansas 1 have also shown the presence of intergranular attack. This form of tube wall degradation has been observed at the upper support plates and within the upper tube sheet crevice. It is also believed to be the source of eddy current indications within the so-called wedge region discussed in the next section.

Because of its circumferential nature, tubes susceptible to fatigue damage should be examined for fatigue using (8x1) array coil technology. See Appendix C Section C.4.2.1 for further information. Recommended examination strategies for fatigue consist of a 100% examination of the "lane region" from the 14th support plate up through the upper tube sheet. Since broached support plate wear occurs within the same region, its presence can also be determined using the same examination plan.

B.6.1.2 Wedge Region

Several lane region tubes have been removed from the Arkansas 1 steam generators confirming the presence of intergranular attack. Degradation was observed at the 15th support plate and within the upper tube sheet as mentioned previously. Extensive eddy current examinations at Arkansas 1 have shown that indications attributed to intergranular attack are distributed throughout the entire region of the upper tube sheet with a tendency to concentrate in a wedge-shaped region near the lane region outer periphery. The wedge region was shown previously in Figure B-14; it is located along the open tube lane with the base of the wedge at the periphery of the bundle on the Z-axis of the generator. Figure B-16 shows the concentration of indications within the wedge region at Arkansas 1. A similar concentration appears to be in an early stage of development at two other units - Rancho Seco and Oconee 2.

ANO-1 OTSGs

TUBES WITH PLUGGABLE INDICATIONS

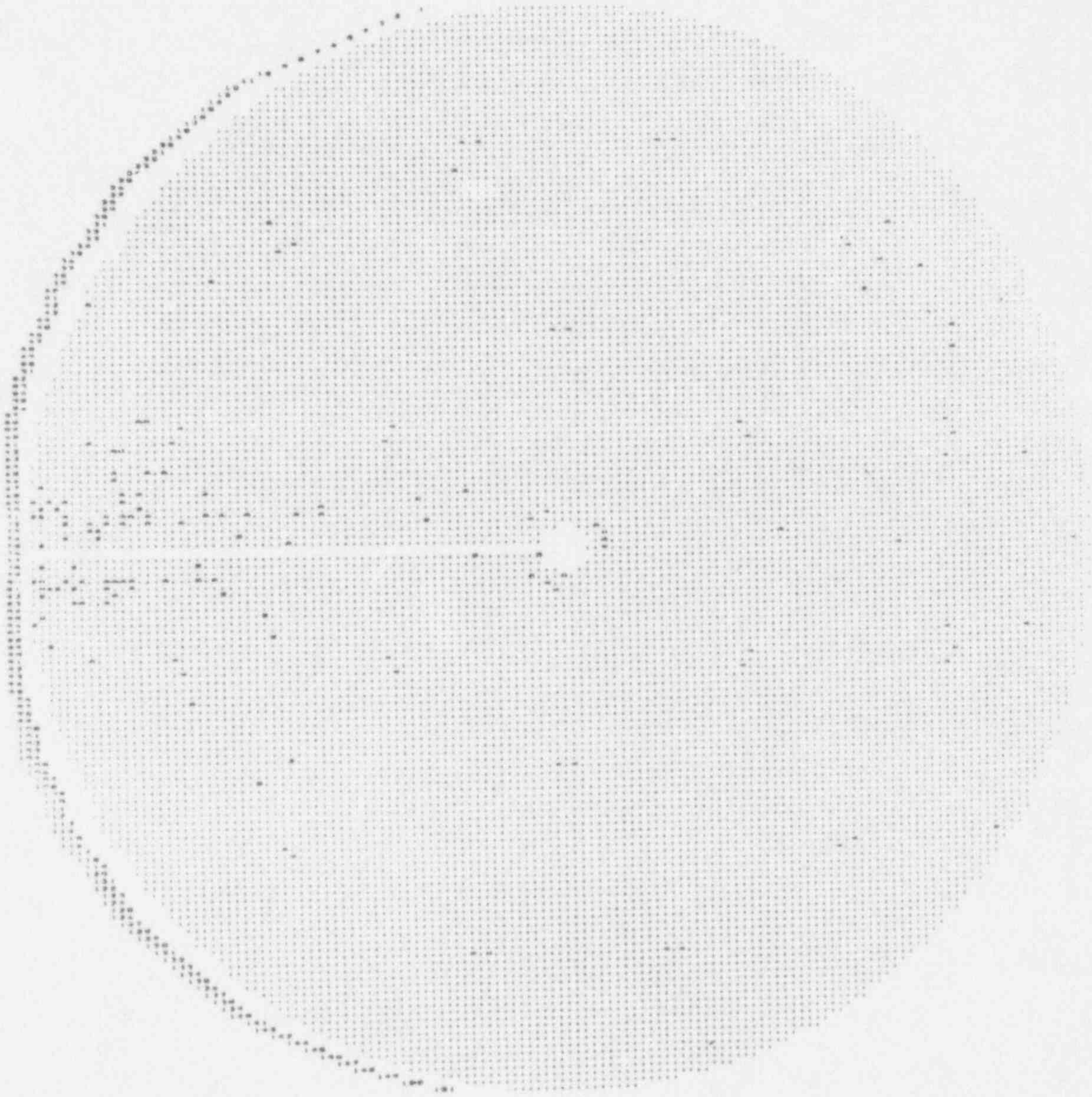


Figure B-16. Wedge Area Indications - Arkansas Nuclear One

Because of the high-risk nature of this damage mechanism - several leaker outages have occurred - 100% examination of the wedge region from the 15th support plate through the upper tube sheet is recommended. The extent of the wedge region may vary on a plant-to-plant basis; its extent will have to be determined using bounding examination strategies.

B.6.1.3 Outer Periphery

Tubes within the outer periphery region of three units (Oconee 1, 2, 3) have been susceptible to flow impingement damage with more than 90% of the indications reported at Oconee 1. The outer periphery region is defined as the circular region bounded by the outermost support rods and the outer periphery of the steam generator. See Figure B-14. Tubes within this region represent approximately 44% of the total steam generator tube population. Flow impingement damage has occurred throughout this region although there is a tendency for it to occur on the half of generator towards the Z-axis. Units with steam generators susceptible to flow impingement damage which have a history of high growth rates should examine 100% of the outer periphery region.

B.6.2 Combustion Engineering

Combustion Engineering steam generators have experienced several forms of tube wall degradation including thinning, pitting, IGA/SCC, and wear. Tube failure as a result of these mechanisms has resulted in a total of eleven forced outages. Two of the outages were due to wear related damage mechanisms (St. Lucie 2, Palo Verde 1); two of the outages were attributed to early phosphate wastage or thinning problems in one unit (Palisades); two were due to stress corrosion cracking at dented vertical support strips (Ft. Calhoun and Palisades); three were due to improper heat treatment of the tubing (San Onofre 2 & 3); one was due to pitting (Millstone 2), and one was due to stress corrosion cracking near one of the stay rods (Millstone 2). Thinning or wastage is no longer considered an active damage mechanism in the two Combustion units in which it has occurred (Palisades and Mihama) so specific regions in which it has been observed are not presented. Remaining areas of interest within a steam generator relevant to examination planning include the sludge pile, support plates-eggcrates, the central stay cylinder area, stay rod region, batwings, and inner row U-bends.

B.6.2.1 Sludge Pile Region

Pitting in association with copper has been experienced in one unit (Millstone 2) on both the hot and cold leg sides of the steam generator. It is confined to the central region of the steam generator within the sludge pile. Figure B-17 illustrates a sludge map from the steam generator cold leg side showing three levels of sludge height; 0"-3", 3"-8", and greater than 8". As can be seen, most of the sludge is concentrated within the central interior of the steam generator with heights ranging from 3"-8". Figure B-18 shows a tube sheet map of pitting indications from within the same region of the generator; thousands of tubes are affected. We see that there is a strong correlation between the location of pitting and the areal extent of the sludge pile. A similar correlation exists for pitting on the steam generator hot leg side. The recommended minimum examination is 100% of all tubes up to the 1st eggcrate within the confines of the sludge pile on applicable sides of the steam generator. Sludge pile extent can generally be determined using low frequency eddy current. An alternative plan would be to consider examining the entire generator up to the 1st eggcrate - this would eliminate the need to determine the extent of the sludge pile.

Eddy current indications due to IGA/SCC have been confirmed within the sludge pile region of two units (St. Lucie 1, and Calvert Cliffs 1) on both legs of the steam generator. The indications are distributed randomly within the sludge pile. Recommended examination practice is to first bound the areal extent of the indications within the sludge pile and then examine 100% of the affected region. This practice is shown in Figure B-19 where a central region of the steam generator has been blocked out for 100% examination.

B.6.2.2 Eggcrate-Support Plates

Numerous eddy current indications at eggcrates and support plates have been reported in one unit (St. Lucie 1). Based on information derived from the removal of three tubes, the indications have been shown to be due to a combination of intergranular attack and stress corrosion cracking. St. Lucie 1 is a Combustion Engineering Model 67 steam generator with six full eggcrates (H1-H6), two partial eggcrates (H7-H8), and two partial support plates (H9-H 10). In addition, there are five batwing assemblies; DH and DC are the two diagonal bars whereas VH, VM, and VC are the three vertical bars. See Figure B-20. Distribution of eddy current indications believed attributable to intergranular attack in elevation are as follows:

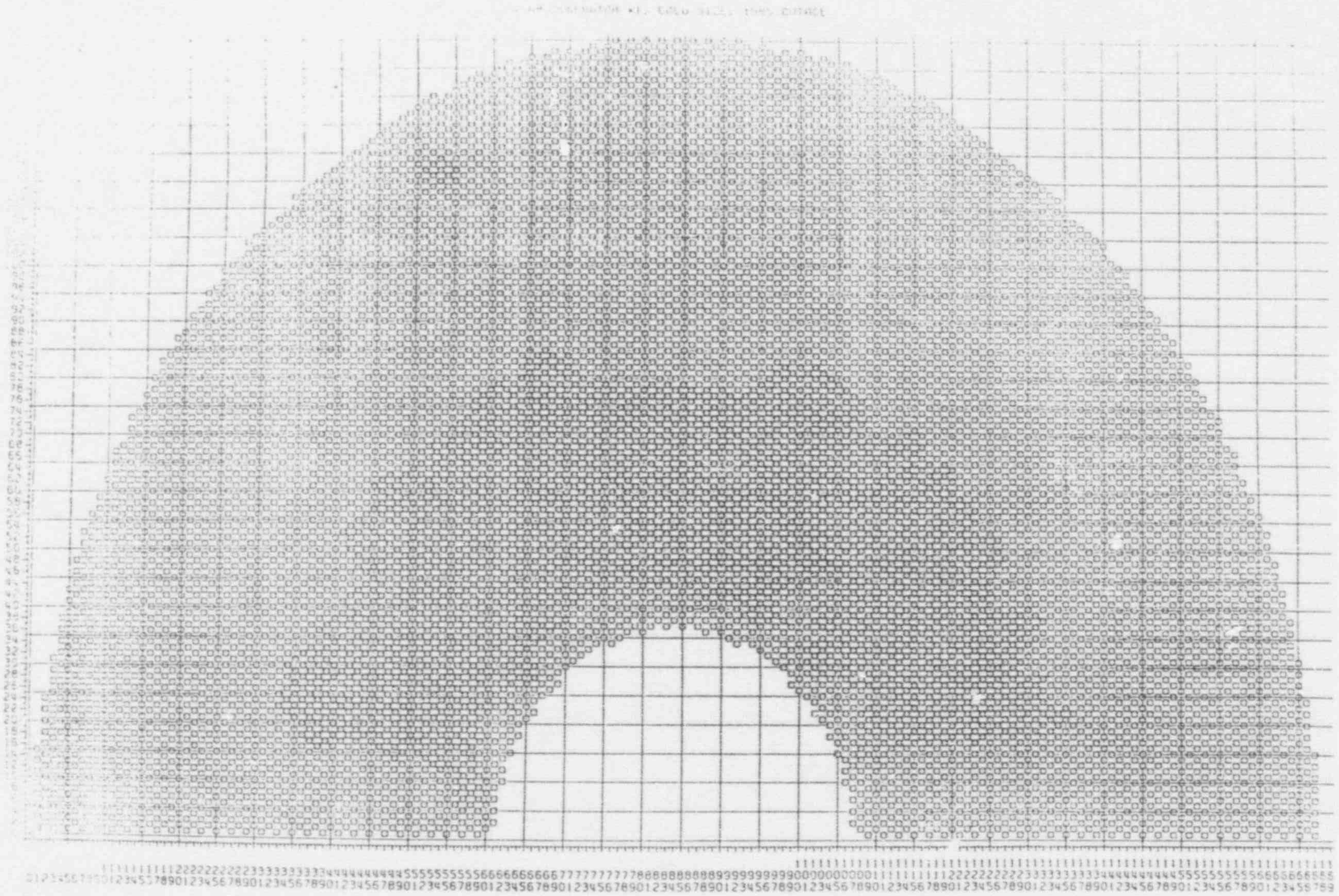


Figure B-17. Sludge Profile Map - Millstone 2

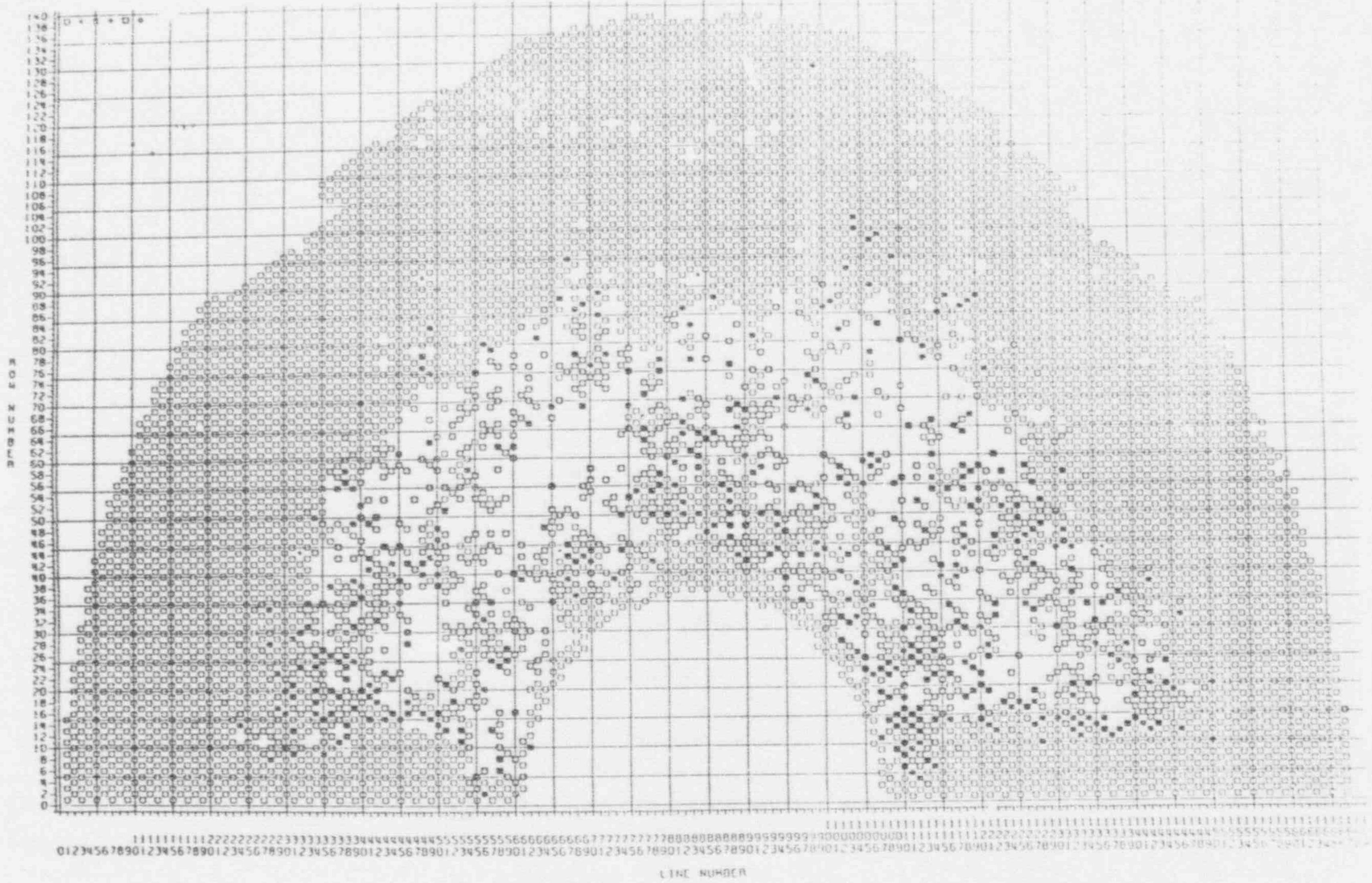


Figure B-18. Millstone 2 - Pitting Distribution

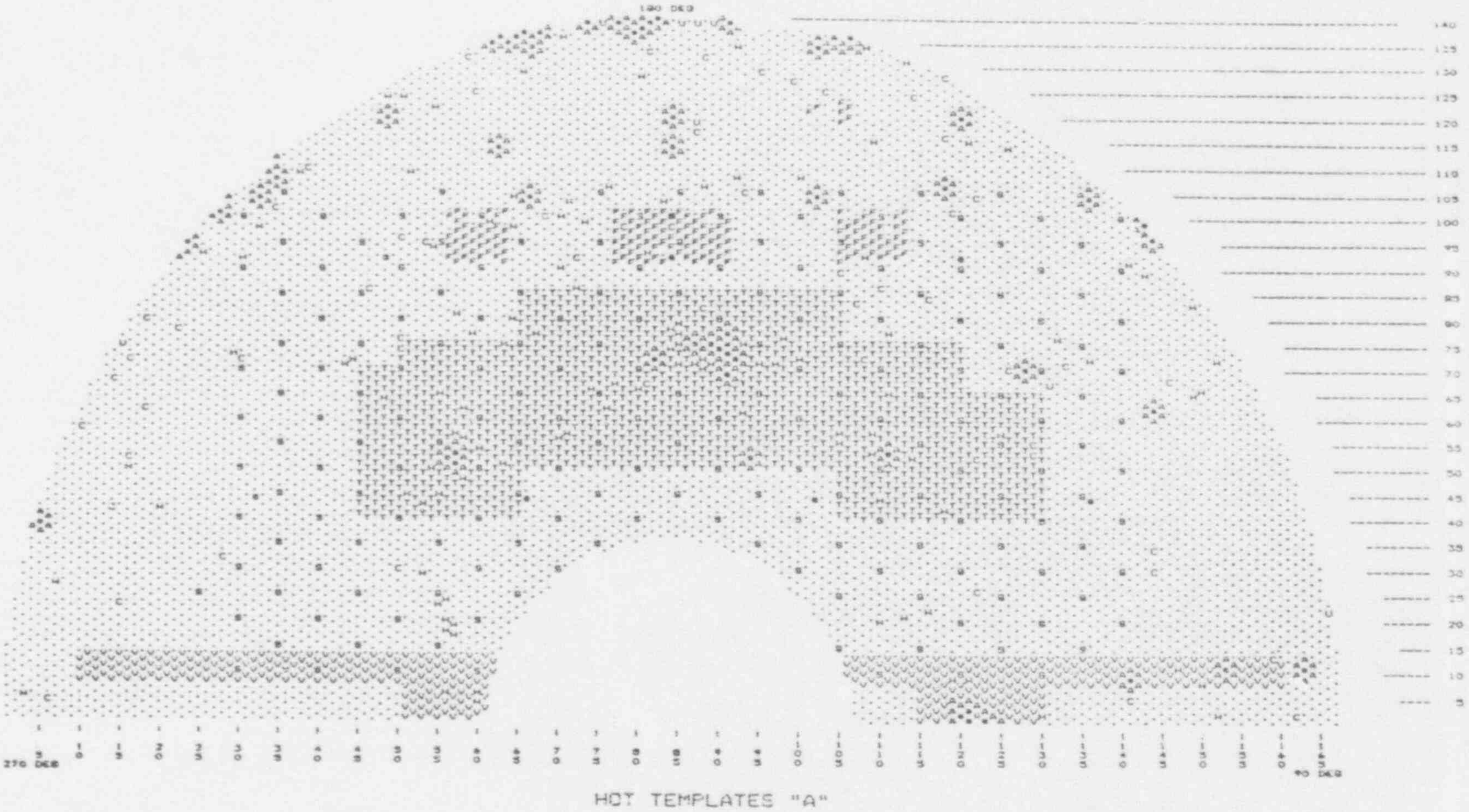
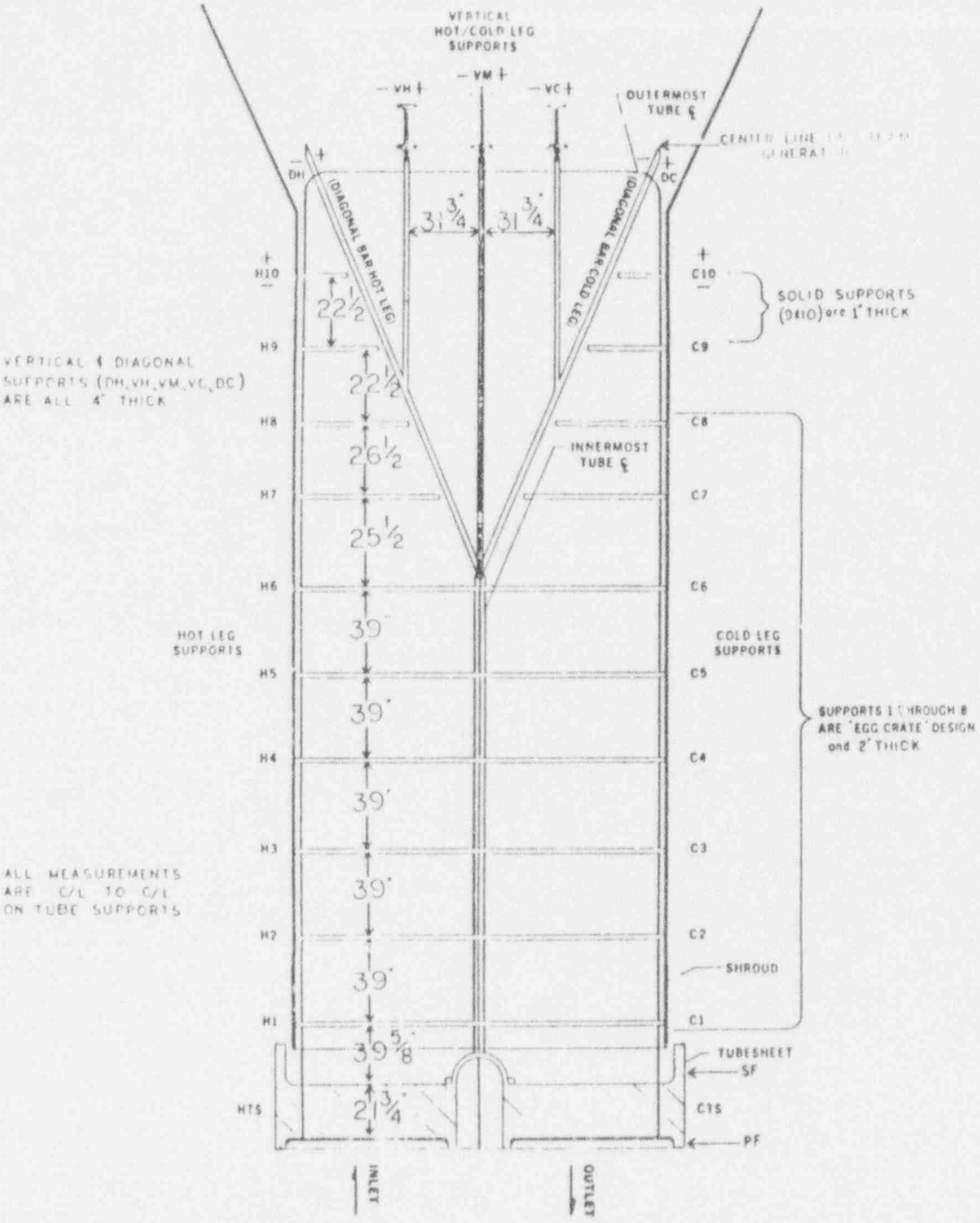


Figure B-19. Central Region of Bundle Examined for Intergranular Attack - Calvert Cliffs



Rows Contacting Supports Above 6th TS

ROWS	NO OF SUPPORTS	SUPPORT DESIGNATIONS
1-9	1	VM
10-35	3	DH, VM, DC
36-65	5	H7, DH, VM, DC, C7
66-73	7	H8, H7, DH, VM, DC, C7, C8
74-89	9	VH, H8, H7, DH, VM, DC, C7, C8, VC
90-115	11	H9, VH, H8, H7, DH, VM, DC, C7, C8, VC, C9
116-140	13	H10, H9, VH, H8, H7, DH, VM, DC, C7, C8, VC, C9, C10

Figure B-20. Series 67 Steam Generator Support Members

Location	# Indications
TSH	460
1H-8H	122
9H-10H	70
10C-9C	60
1C-8C	11
TSC	216

We see that a majority are concentrated on both the hot leg and cold side of the generator above the top of the tube sheet with other concentrations at the hot leg eggcrates and at the upper hot leg and cold leg support plates. A review of the appropriate tube sheet maps show the indications randomly distributed throughout the generator within the confines of a given support structure (partial or full eggcrate or partial support plate).

The only rational approach for this situation is basically a 100% examination of the generator because of the wide distribution of the indications. This could be continued over several examination cycles in order to verify that the condition has stabilized. If stabilization is achieved, then one could possibly consider 100% examination of the hot leg and cold leg up to the first support plate - or possibly just within the sludge pile - along with other degraded tubes which have indications at eggcrates or support plates.

B.6.2.3 U-Bend Steam Blanketing

Four units have reported U-bend indications in a region of the generator in which steam blanketing occurs (Maine Yankee, St. Lucie 1, Calvert Cliffs 1 & 2). Using special eddy current examination methods, these indications have been shown to be on the intrados side of the U-bend. IGA has been postulated as a likely damage mechanism candidate; no tube pulls have been made to confirm the hypothesis because of access problems. The region of steam blanketing is bounded by Rows 8 through 11 and runs across the entire diameter of the steam generator from Line 1 through Line 167 as shown in Figure B-21. 100% of this region should be examined for U-bend indications.

B.6.2.4 Batwing - Vertical Support Strips

Tube wear in Combustion units has been caused by vibration of the diagonal or vertical support strips. See Figure B-22.

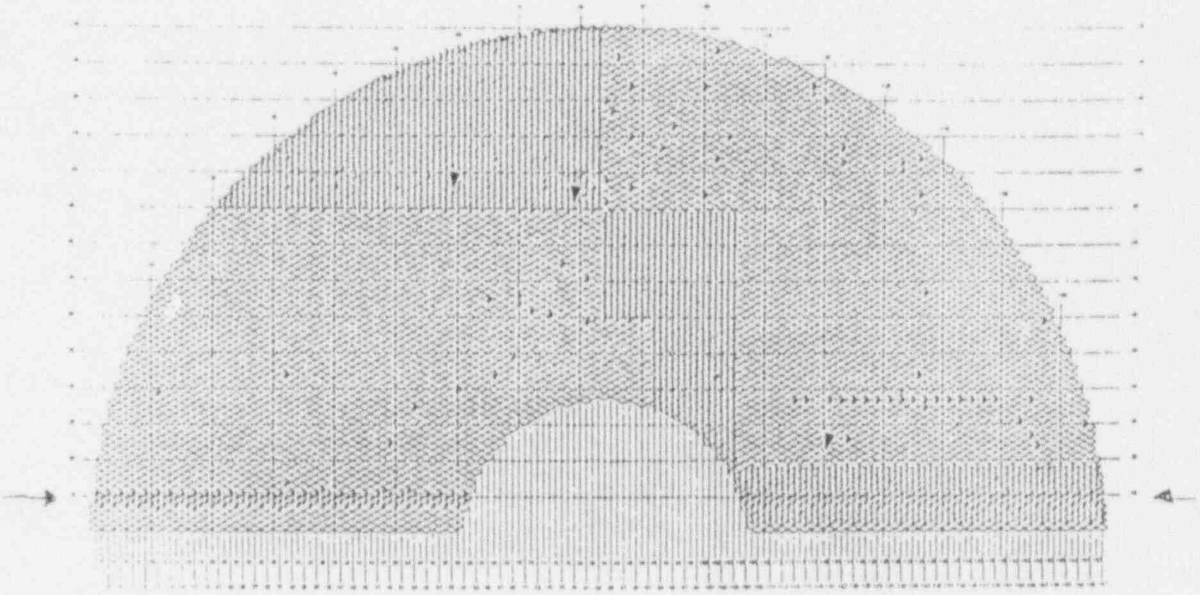


Figure B-21. Steam Blanketing Region in Series 67 Steam Generator

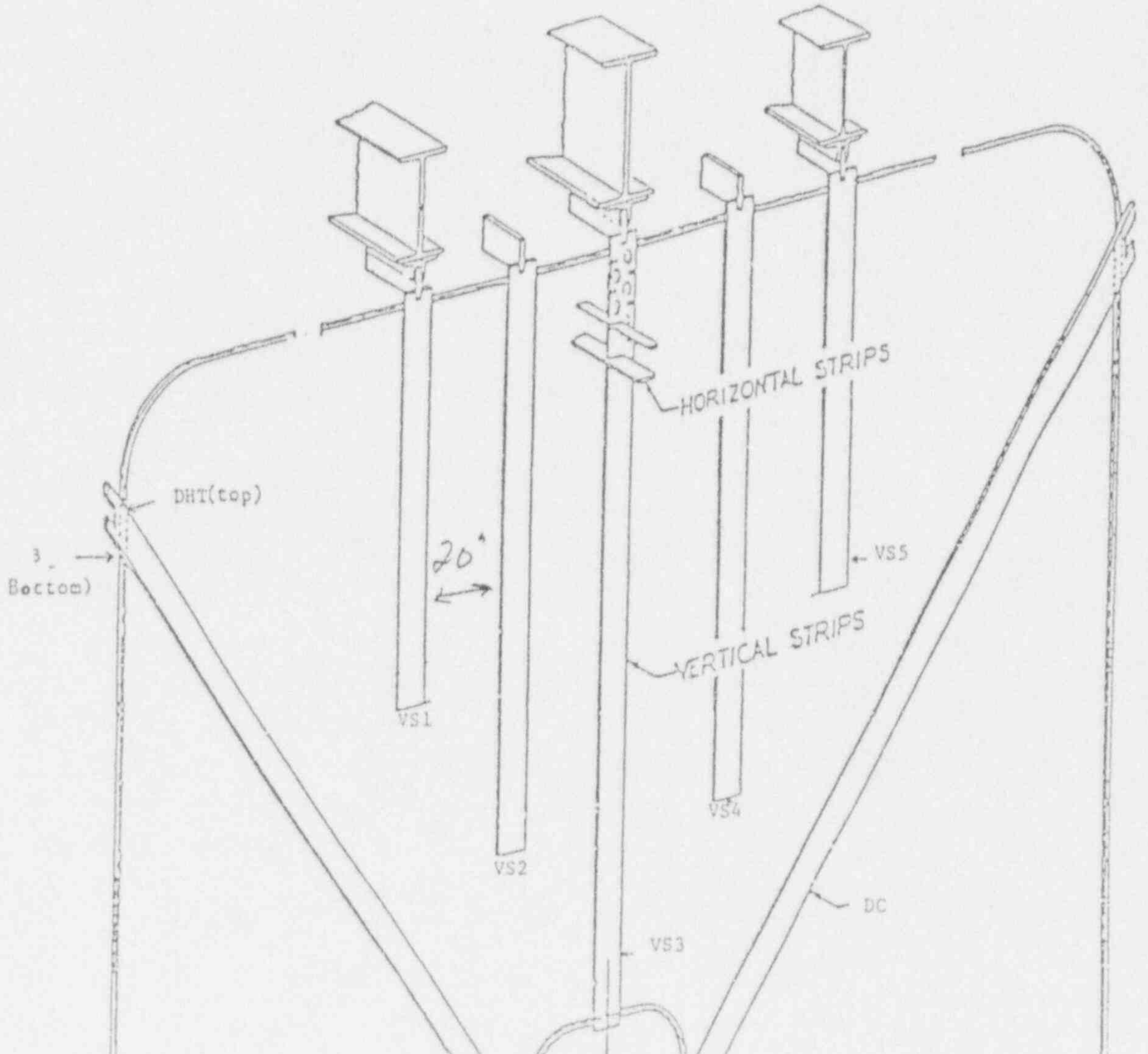


Figure B-22. Diagonal and Vertical Support Members - Series 67 Steam Generators

Wear at the diagonal batwing supports has been observed in tubes in close proximity to the central stay cylinder cavity. Units affected include San Onofre 2 & 3, and Waterford 3, which are Combustion Engineering Model 3410 plants. The diagonal bars have a fairly long span; most of the bar vibration is occurring between the seventh and eighth eggcrate which when projected downwards onto the tube sheet is in a region near the central stay cylinder. See Figure B-23. The susceptible wear region starts at Row 24 and is concentrated between Columns 80 and 96 which contains the longest diagonal support span. A tube sheet map of the region of interest in shown in See Figure B-24.

Wear indications at the vertical support strips have also been observed in Combustion Engineering steam generators (Calvert Cliffs 1 and St. Lucie 2). At Calvert Cliffs 1, a tube was destructively examined that was removed from the periphery of the tube bundle. A wear indication at the vertical middle support was confirmed. At Calvert Cliffs, the wear susceptible region is located near the divider plate and runs almost the full diameter of the steam generator. See Figure B-25. At St. Lucie, the region of interest is near the central stay cylinder, bounded approximately by Rows 20 to 68 and Columns 65 to 113. See Figure B-26. Regions within a steam generator in which tube wear can occur or be expected should be bounded using appropriate examination strategies. Wear growth rates should be estimated with all tubes in the region examined over some period of time. The examination interval and the percentage of tubes examined will in general be determined by the expected growth rate. This may vary from some small percentage up to possibly 100% of the region if the wear rate is quite rapid.

Stress corrosion cracking in tubing at dented vertical and horizontal support strips have in two instances (Palisades and Ft. Calhoun) led two forced outages. In both instances, eddy current indications were present but missed by the analyst. If a unit has dented support strips, particular caution should be used in the review and analysis of eddy current data from this region.

B.6.2.5 Stay Rod Inspection

At one unit (Millstone 2), distortion of tubes near one of the support plate stay rods has been identified as a possible culprit contributing to the occurrence of a forced outage. The locations of these stay rods are shown in Figure B-27. It is recommended that the nearest neighbor tubes around all stay rods be examined for evidence of tube wall degradation.

CE MODEL 3410 TUBE SUPPORT DRAWING

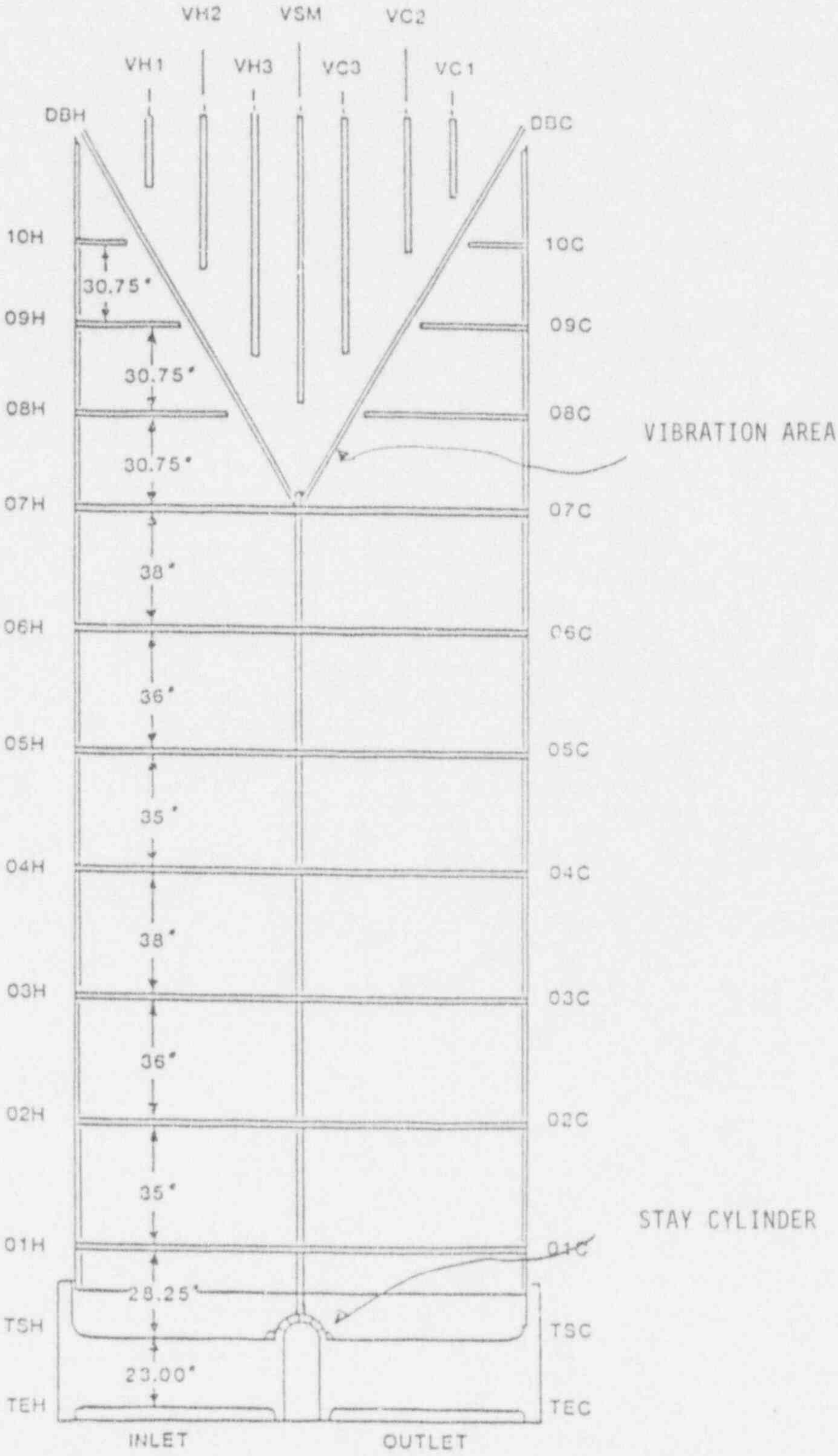


Figure B-23. Support Members - CE Model 3410

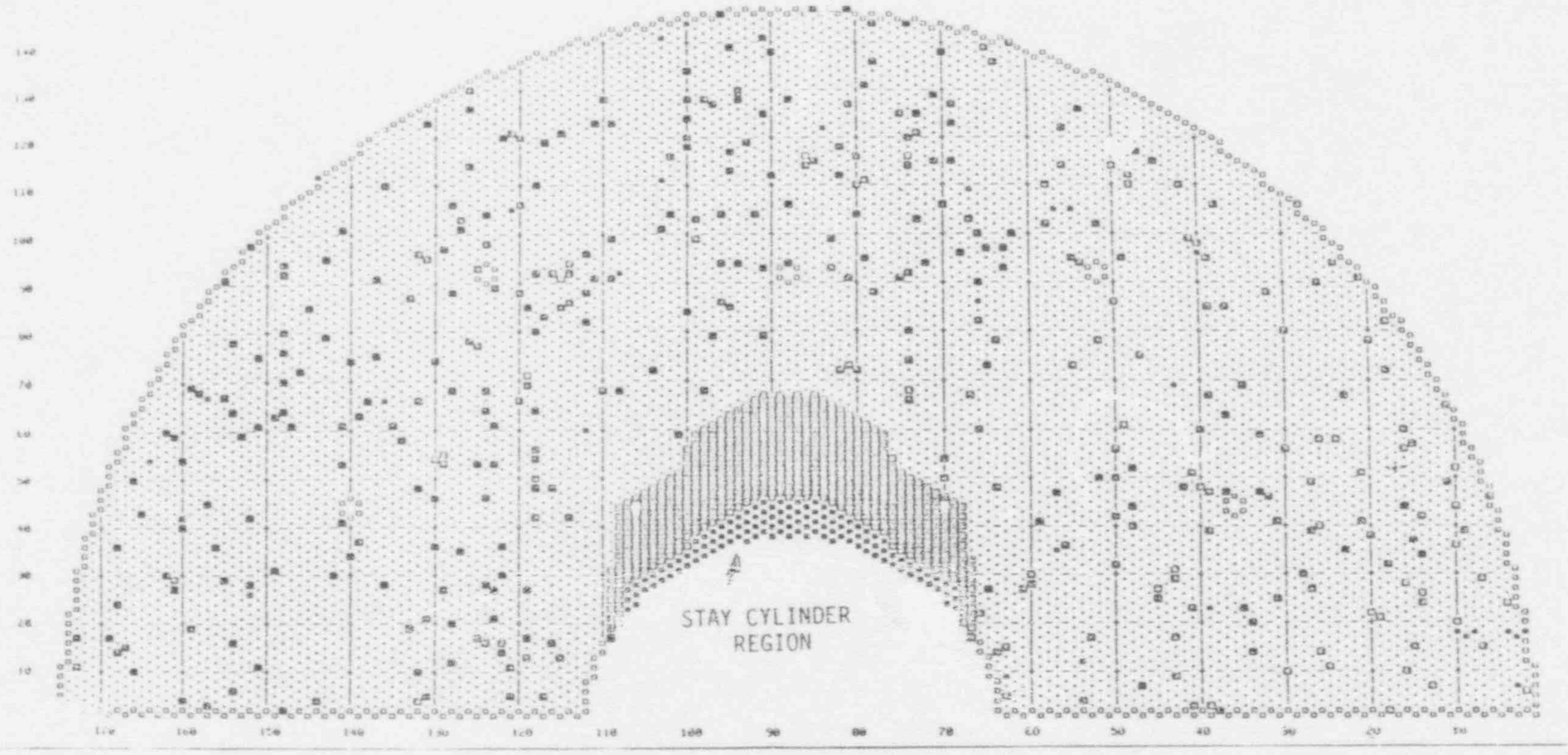


Figure B-24. Wear Region in Model 3410 Steam Generators

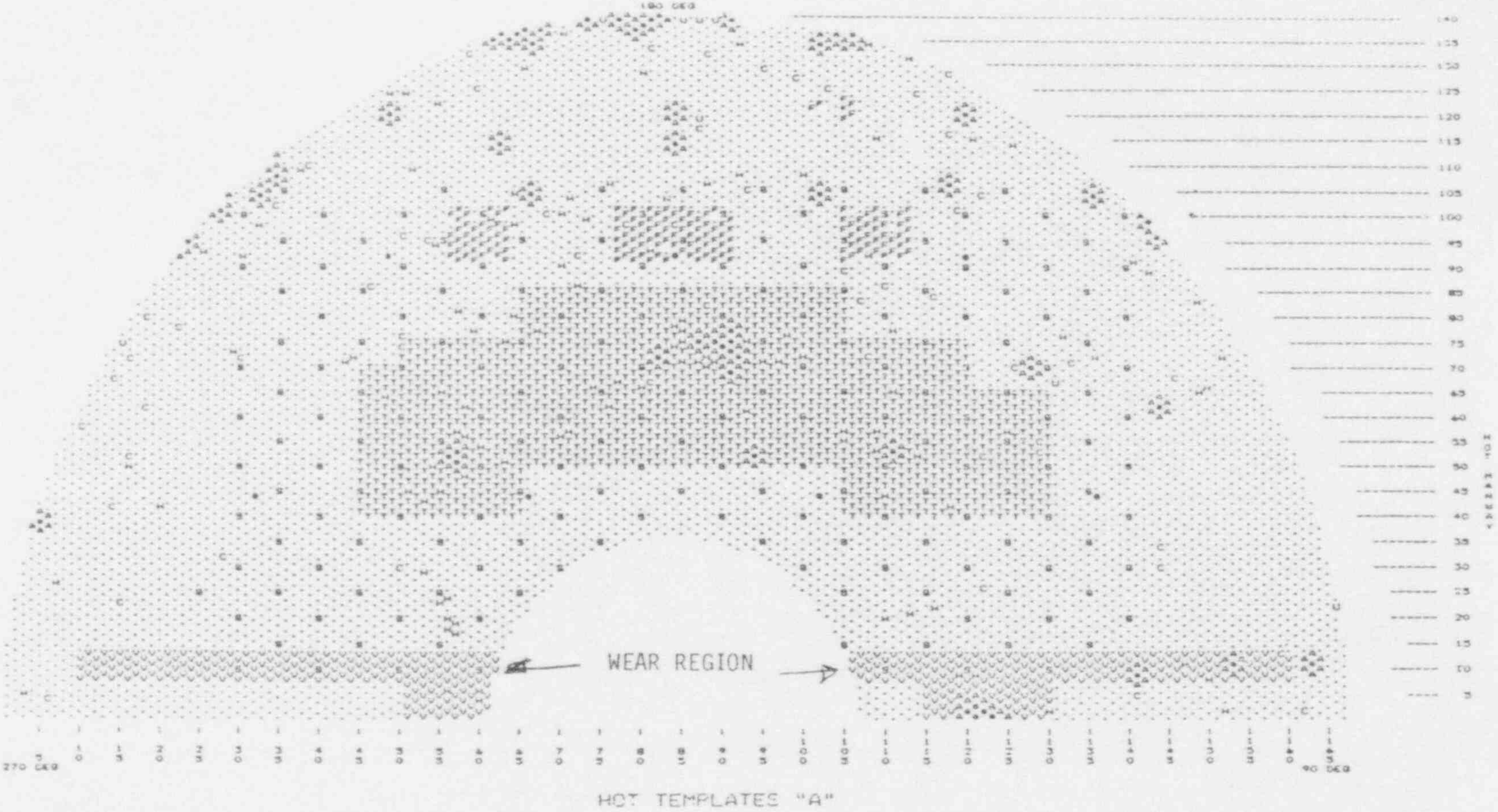
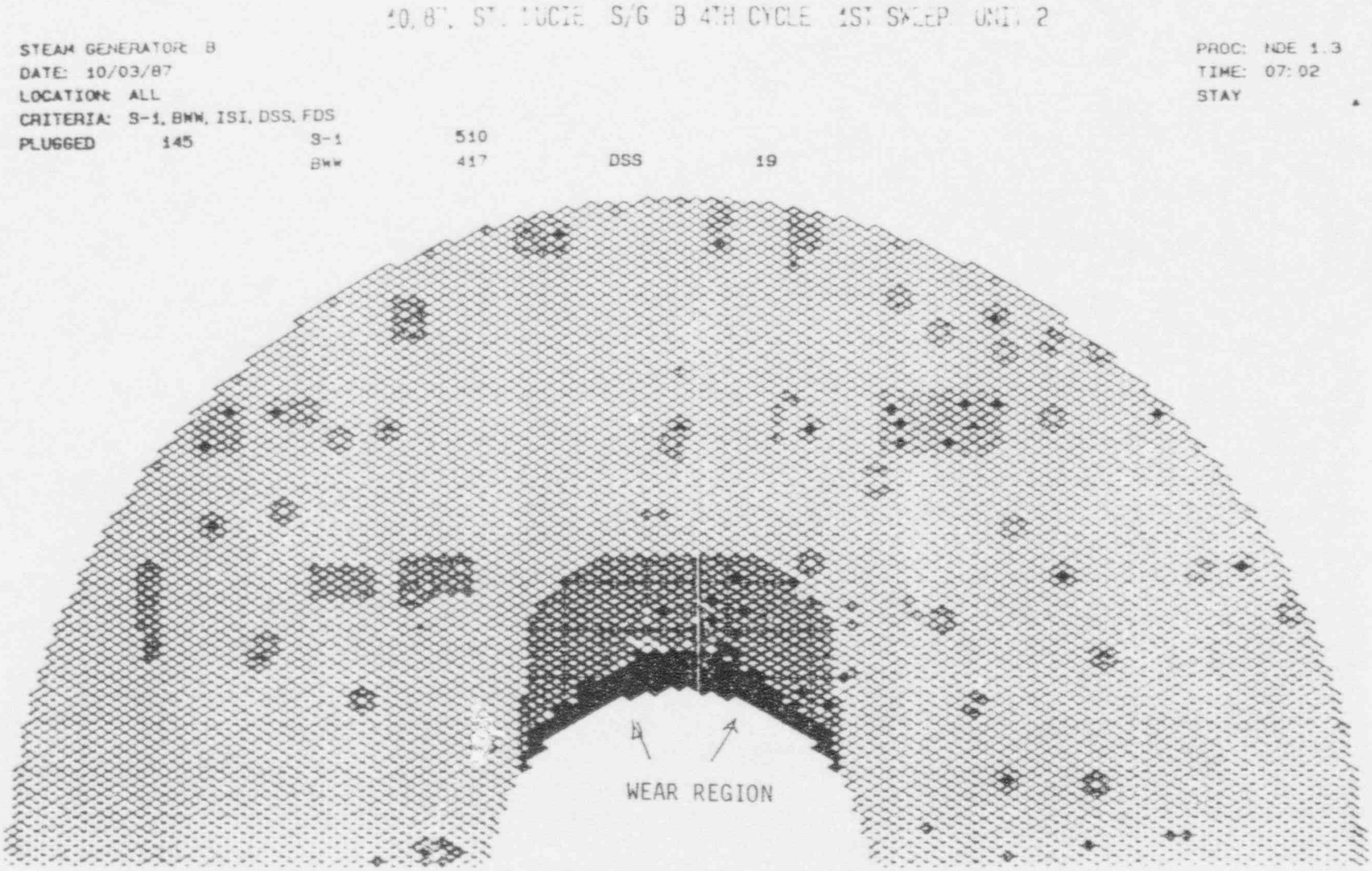


Figure B-25. Wear Region in Series 67 Steam Generator - Near Divider Plate



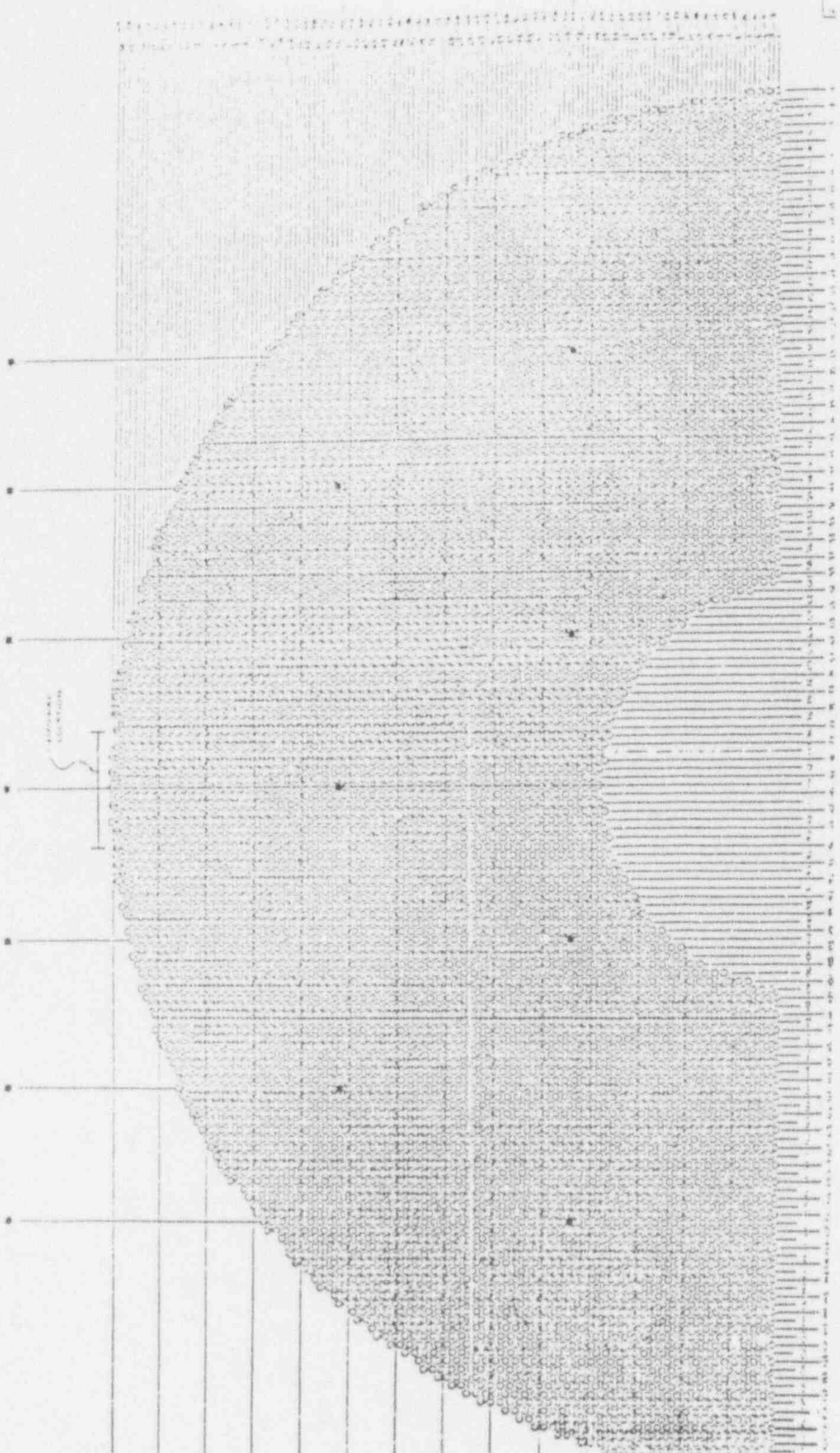


Figure B-27. Stay Rods in Series 67 Steam Generator

B.6.3 Westinghouse Units

Westinghouse and their licensees (Framatome, Mitsubishi, & Cockerill) steam generators have experienced diverse forms of tube wall degradation including thinning, pitting, intergranular attack-stress corrosion cracking, fatigue, denting side effects, and primary side stress corrosion cracking. Tube failure as a result of these mechanisms has resulted in at least 157 forced outages; fifty-one were the result of denting related side effects most of which occurred during the late 1970's at four plants whose steam generators have since been replaced; forty-two were due to stress corrosion cracking or intergranular attack while a total of twenty-seven were the result of primary side stress corrosion cracking with twenty-three of these due to Row 1 U-bend leakage. Five are attributable to early wastage problems, three due to pitting, and two due to wear and one recent event due to fatigue. Some eighteen outages have been attributed to loose parts. The balance of eight outages forced outages are due to miscellaneous (leaking plugs) or unknown causes.

Steam generator examination regions of interest for the purposes of augmented sample planning are varied and depend on steam generator model. Since there are numerous models, specific regions of interest are discussed as a function of model number

The bulk of the experience reflects an all-volatile (AVT) secondary side water chemistry. Only two units have remained on phosphate (San Onofre 1 and Zorita). Early problems with wastage are not discussed since it is no longer considered a significant nor widespread industry issue.

B.6.3.1 Cold Leg Outer Periphery (Model 51 Units)

Cold leg thinning was first reported during the early 1980's and has since been identified in twelve plants and some twenty-nine Model 51 steam generators. A total of two tubes have been removed with this damage mechanism (Salem 1 and Prairie Island 2) with no definitive cause established for the degradation - it exhibits features of both wear and corrosion. One unit (Beaver Valley 1) has recently expanded some fifty tubes at the cold leg support plates in order to establish whether this remedial measure retards further progression.

A majority of the eddy current indications attributable to cold leg thinning are confined to the outer periphery region at the first two cold leg support plates. Figures B-28 and B-29 show cumulative tube sheet maps of reported eddy current indications at the first and second support plates (twenty-nine steam generators in

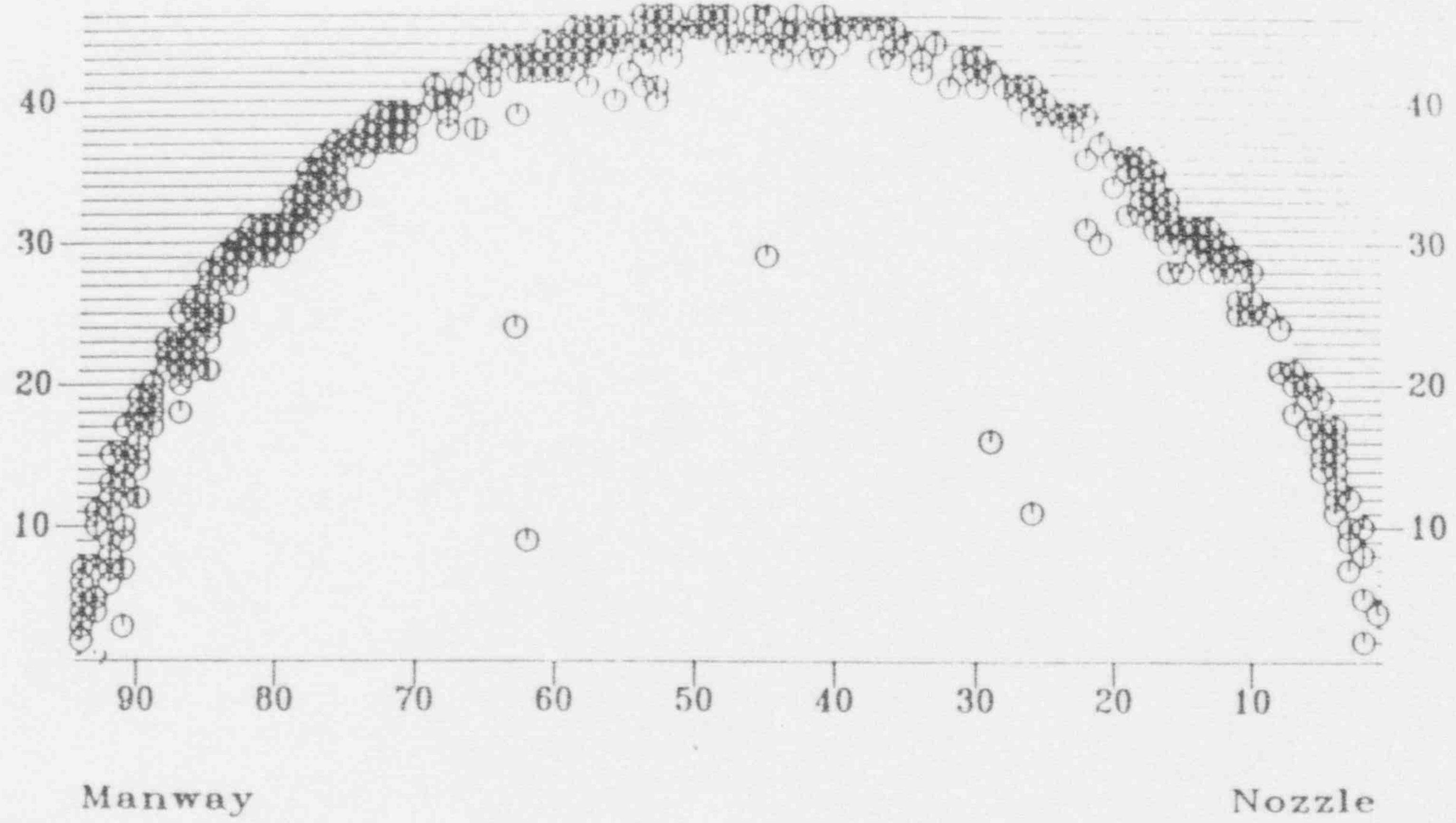


Figure B-28. Model 51 Cold Leg Thinning - First Support Plate

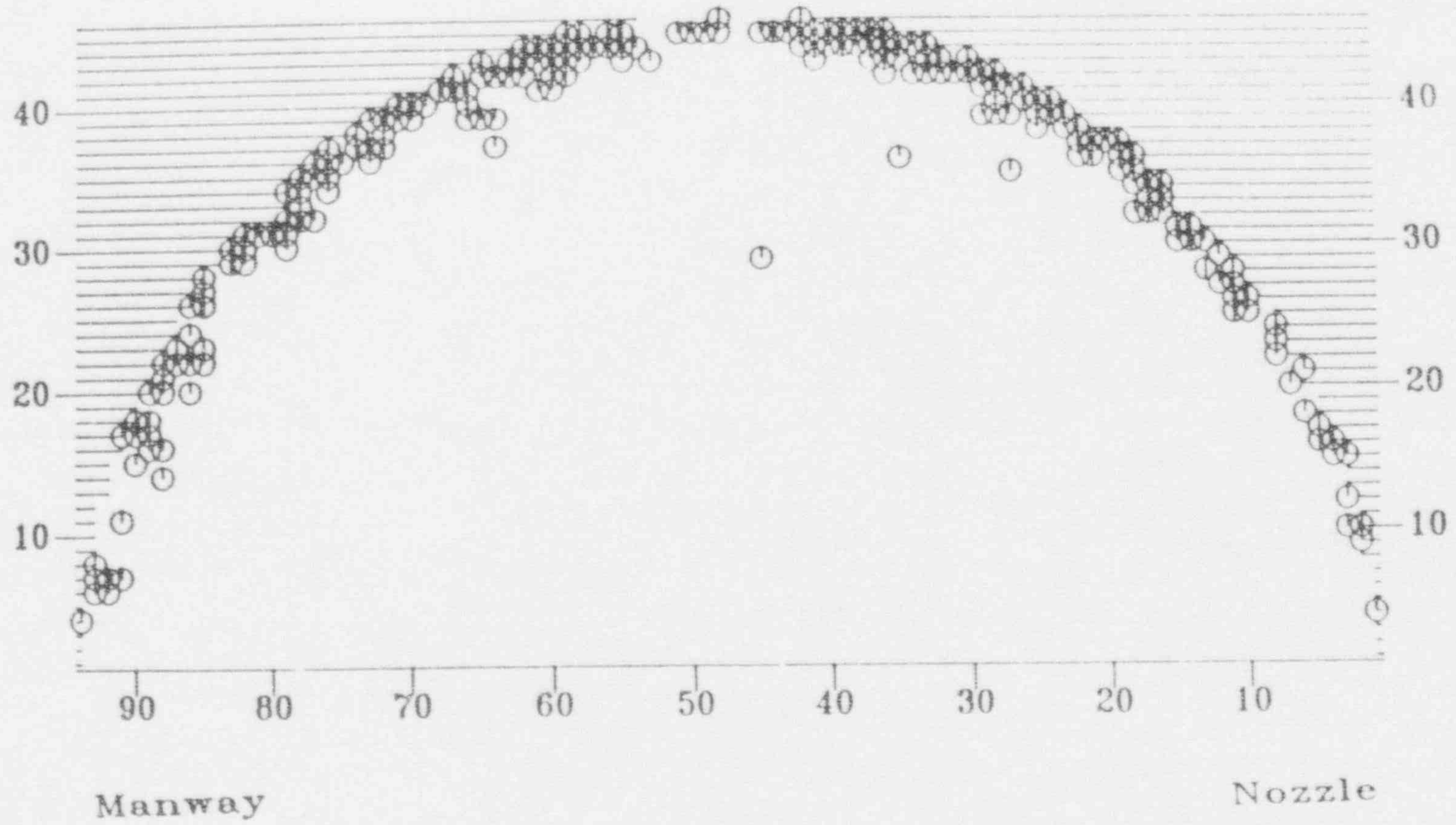


Figure B-29. Model 51 Cold Leg Thinning - Second Support Plate twelve plants). As can be seen, the bulk of the indications are confined to a region within five rows or columns of the outer periphery. Typical numbers of affected tubes range from less than ten on the lower end to more than thirty on the upper end. The time to first observation for cold leg thinning in a Model 51 steam generator has ranged anywhere from two to eleven years of operation with a median of approximately seven years. Average growth rate estimated from eddy current data is on the order of 6% per effective full power year. No forced outages have occurred as the result of cold leg thinning.

The mechanism is considered low-risk because of its slow growth rate and the relative ease with which it is detected. The thinning is volumetric with an estimated lower bound on reliable detection of approximately 20% through wall. Recommended examination strategy is to partially exam the outer periphery region over a period of time. Tubes in the outer five rows or columns in a Model 51 steam generator in which cold leg thinning total has been observed total approximately 570 in number which constitutes approximately 17% of the total tube population. It is recommended that the outer periphery region in which it occurs be monitored on a periodic basis with 20% of the tubes in the region (approximately 3.4% of the total tube population) examined at any one time with the complete periphery region examined over a five year interval.

B.6.3.2 Baffle Plate Wear (Preheater Units; Model D & E)

Some preheater Model D steam generators (Ringhals 3, Almaraz 1, & McGuire 1) experienced significant wear at the cold leg baffle plates near the feedwater inlet during the early 1980's. This time frame represents the early days of operation of the preheater model units. Only one forced outage has occurred (Ringhals 3); this was the result of eddy current indications which were not dispositioned properly. Since then, modifications to these and other units have been performed which have significantly retarded wear progression. It should be pointed out that these modifications are not expected to prohibit wear but rather retard or slow its rate of progression estimated to be less than 1% per effective full power month.

The affected region lies on the outer periphery of the steam generator near the feedwater inlet. See Figure B-30. The minimum recommended examination practice is to conduct a partial examination of the outer two rows (Rows 48 & 49) over a fixed time period - rotating 20% sample size (sampling without replacement) from the outer two rows over a five year period. There are a total of 110 tubes in the region of interest which is approximately 2% of the total tube population.

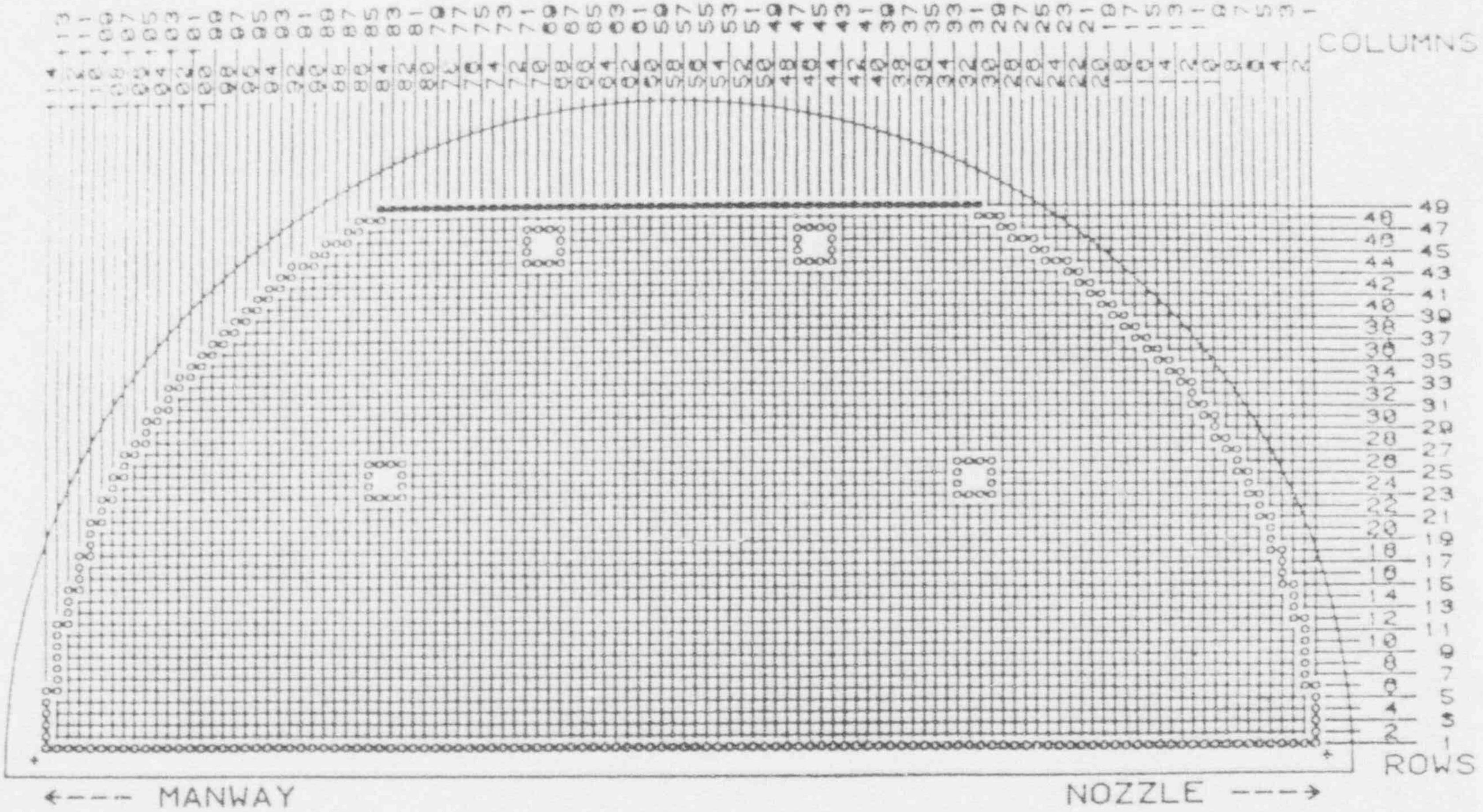


Figure B-30. Wear in Preheater Steam Generators

B.6.3.3 Antivibration Bars (All Models)

Tube wear at antivibration bars has occurred to some extent in all Westinghouse model steam generators. It has become somewhat of a generic design issue with Model 51 steam generators and may become a similar issue with Model F designs since numerous eddy current indications in some units have been reported during the first operating cycle. AVB repairs in the form of newly designed and installed AVB's have been performed in eight plants to date. These include Beznau 1, San Onofre 1, Farley 1&2, Prairie Island 1&2, Tihange 1, and Zion 2. No forced outages have occurred as the result of tube wear at the AVB's although in the case of one Model 51, numerous near-through wall eddy current indications were identified during a recent outage. The occurrence of this event has been attributed to inadequate steam generator sampling during previous examinations rather that rapid growth rate. It is important that this region of the steam generator be adequately monitored so that the existence of this damage mechanism is recognized at an early stage. Estimates of the initiation time of tube wear at AVB in Model 51's is shown in Figure B-31. The figure shows the range in the total number of tubes per generator with tube wear at AVB's as a function of the number of years of operation.

In Model 51's, AVB's one and four are designed to contact tubes at Row 11 whereas AVB's two and three contact tubes at Row 15. Tube wear at AVB's has shown a tendency to initiate near the center of the tube bundle as shown in Figure B-32. Total numbers of affected tubes by generator for a four-loop plant over several examination cycles (100% examination from 3/83 onward) are shown in Figure B-33. The data shows roughly a two to one variation in the numbers of affected tubes between the different steam generators.

Eddy current wear indications at AVB's with depths estimated to be less than 20% through wall are shown in Figure B-34 for a steam generator of Model F design. Wear distribution patterns are shown for two steam generators. Distributions of indications with depths estimate to be greater than 20% through wall are shown in Figure B-35 for two steam generators. As can be seen, there is a tendency for the wear to concentrate towards the outer periphery.

Estimated growth rates for AVB wear range from 5% to 15% per effective full power year. Tubes which contact AVB's represent a large fraction of the steam generator tube population - in a Model 51 they constitute approximately 69% of the population. Once the existence of wear in a steam generator has been established it is important bound its extent and identify the regions of high wear progression. This can be

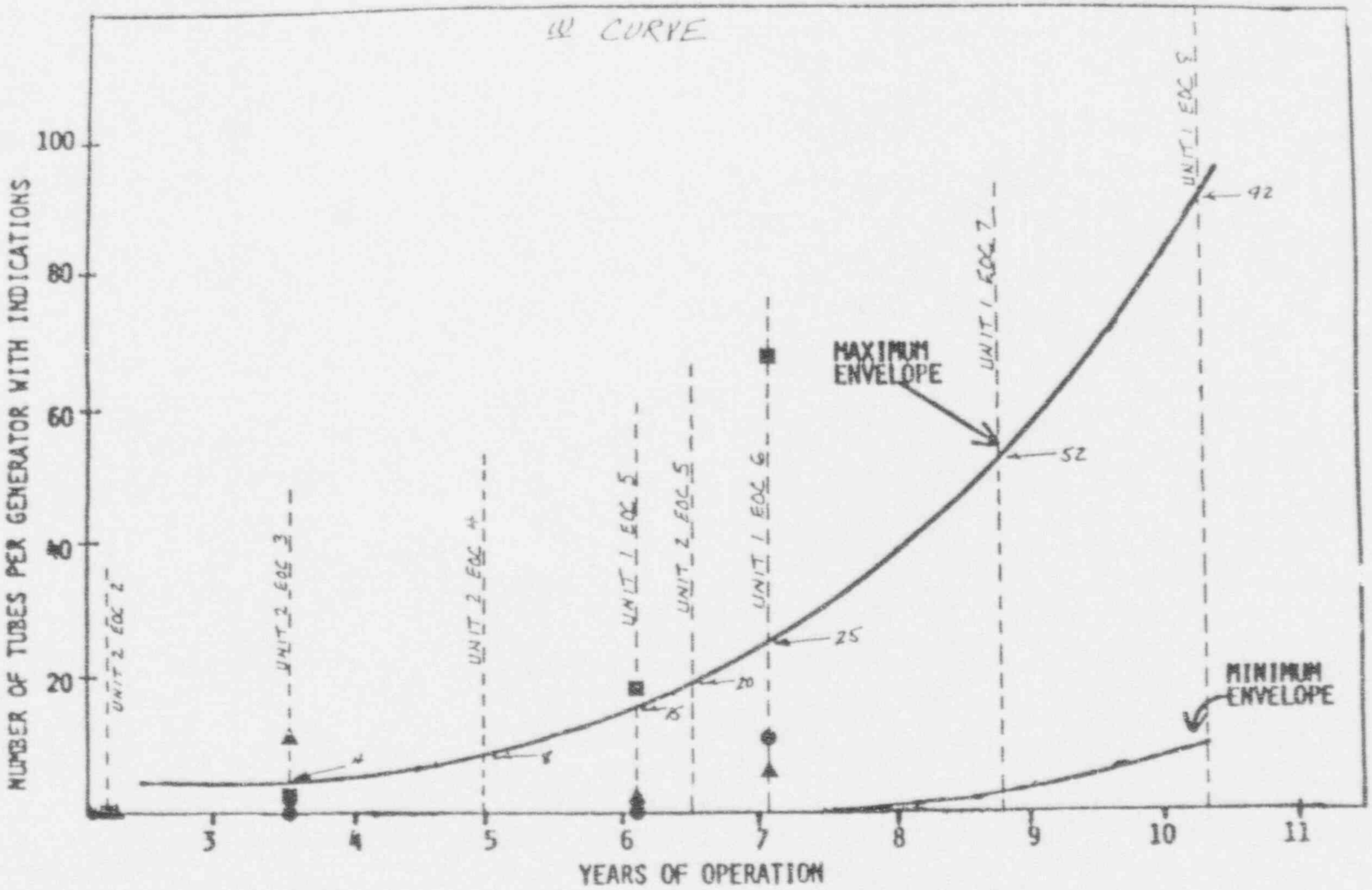
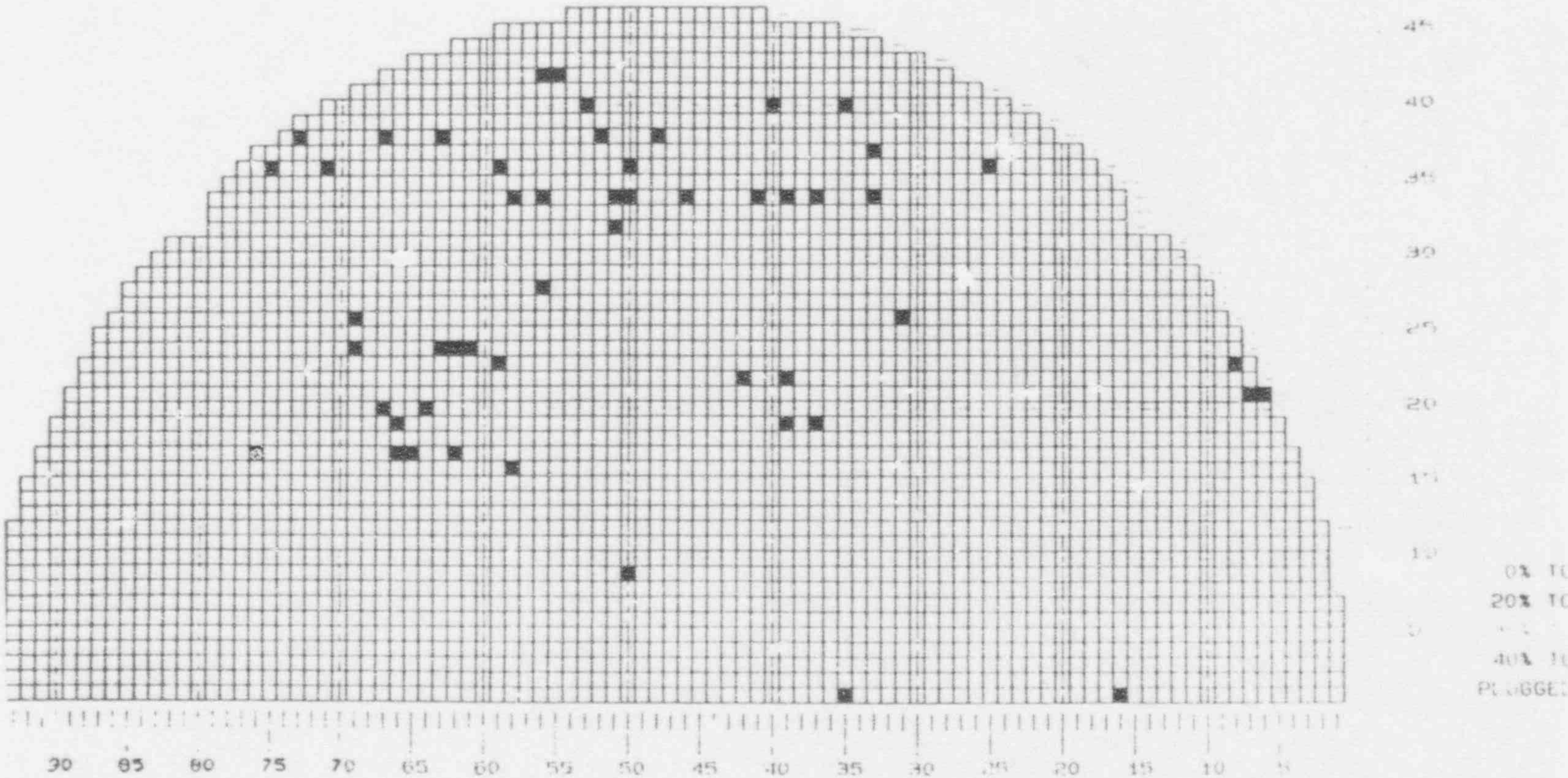


Figure B-31. AVB Indications: Last Time Without Indications & Cumulative Indications at Last Inspection -Model 51

STEAM GENERATOR: C
INDICATION LOCATION: AV1 TO AV4
INDICATION RANGE : 0% TO 100%

PROC: 42-EC-099
DATE: 03/17/86
TIME: 14: 36



CONAM INSPECTION 660 S. 31ST STREET RICHMOND, CALIFORNIA 94804 (415) 233-9668 TELEX 337676

Figure B-32. AVB Wear in Model 51 Steam Generators

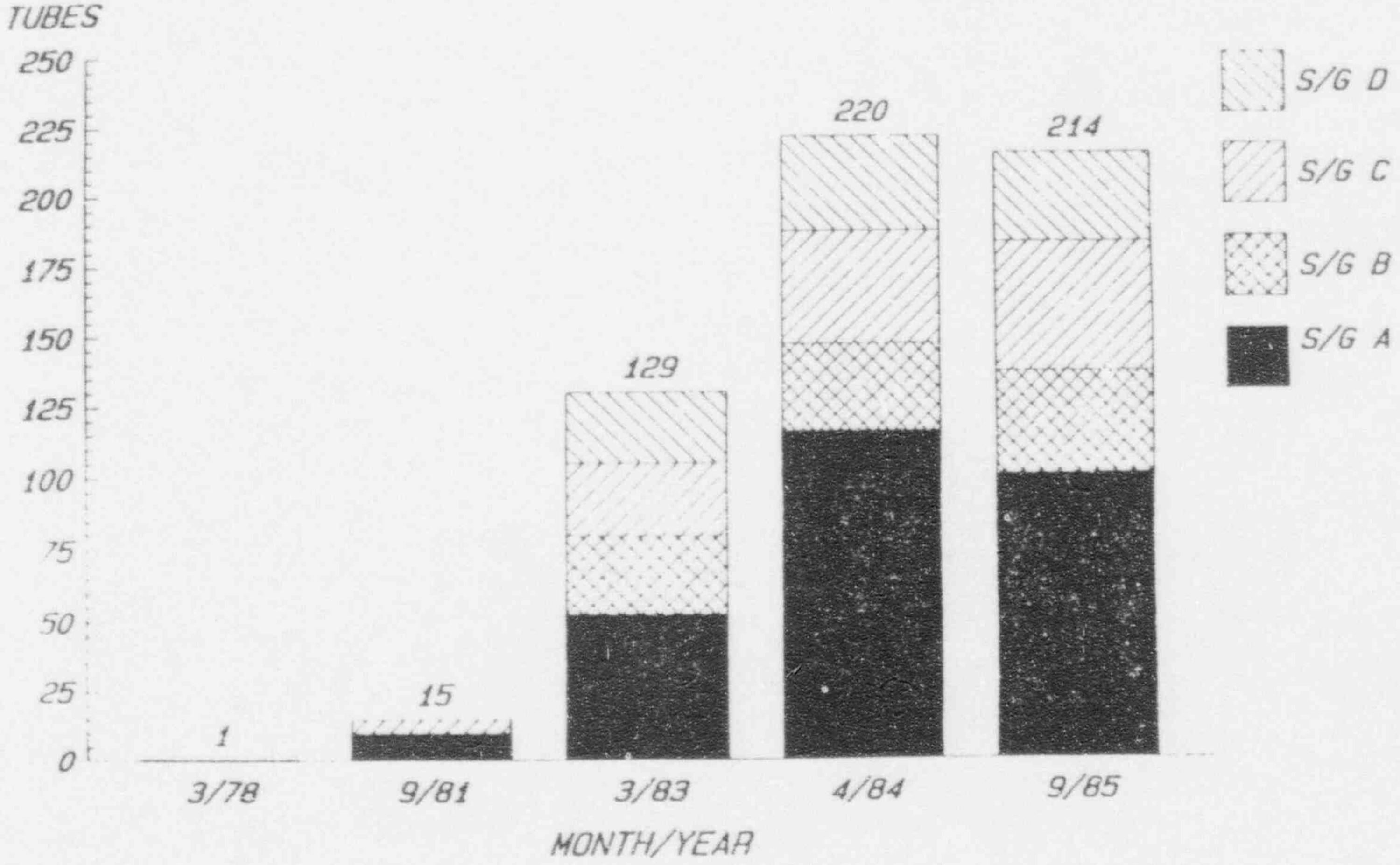


Figure B-33. AVB Wear in Different Steam Generators

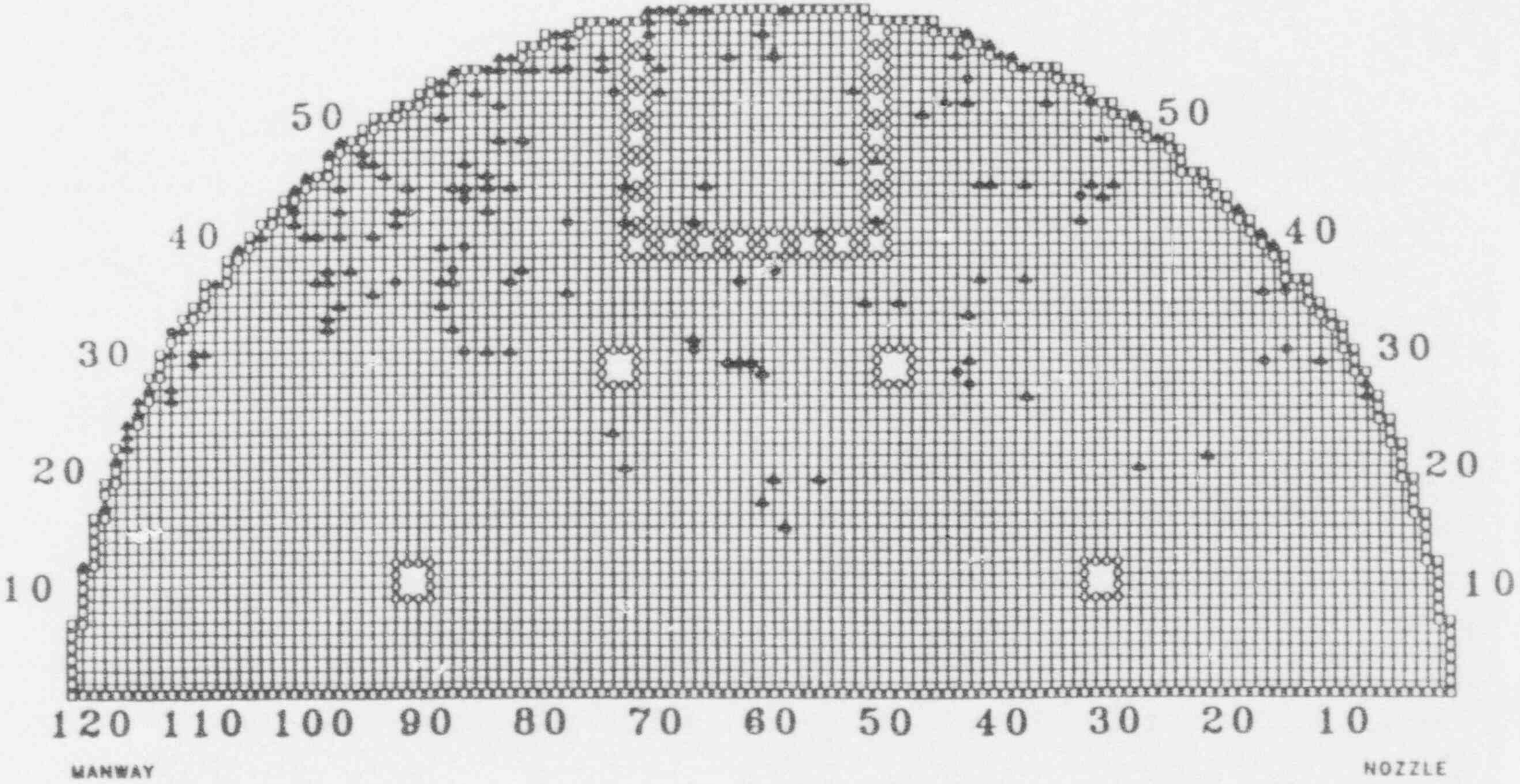


Figure B-34. Model F AVB Wear - <20% Through Wall

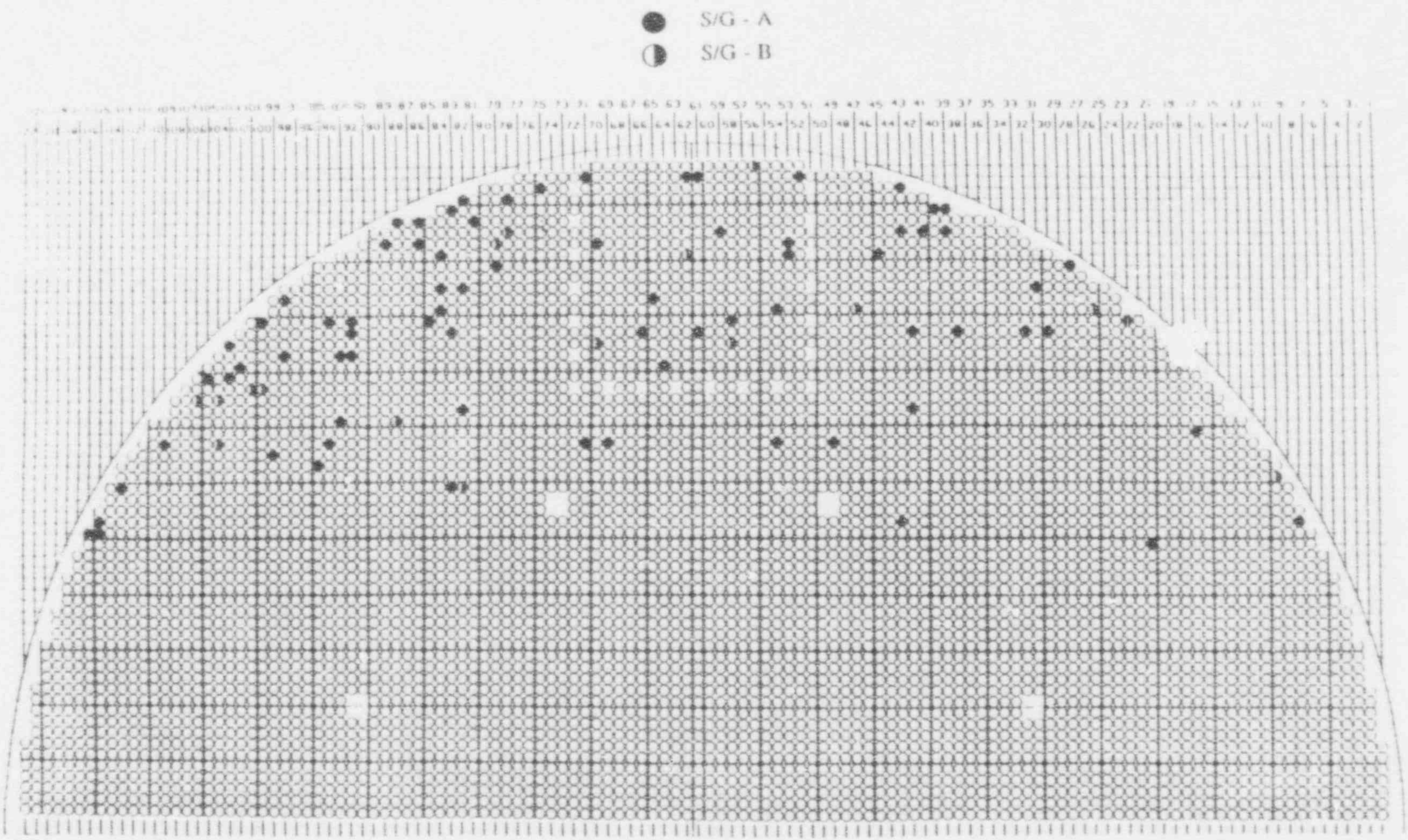


Figure B-35. Model F AVB Wear Indications - >20% Through Wall accomplished by conducting a 100% baseline after wear is detected. A reasonable follow-on examination strategy is to sample 20% of the tubes which contact AVB's on a rotating basis (about 14% of the total tube population) with a 100% of the tubes from the region examined over a minimum period of five years.

B.6.3.4 Tube Sheet Crevice Region (Models 33,44,51)

Approximately 98% of all the forced outages due to tube sheet crevice region intergranular attack-stress corrosion cracking have occurred in Model 33,44, & 51 steam generators with more than half of these occurring in Model 51's. Intergranular attack and stress corrosion cracking have been diagnosed or confirmed in all Model 51 steam generators with open tube sheet crevices.

The number of tubes with indications in a steam generator can vary from several to many tens. This small a number of tubes - which determines the initial tube density - coupled with relatively high growth rates necessitates the 100% examination of the region of interest. Cumulative distributions of tube sheet crevice indications for Model 51 and Model 44 steam generators are shown in Figures B-36 and B-37 respectively. As can be seen, the indications are randomly distributed over the entire extent of the tube sheet. A 100% examination of the generator up to the first support plate is recommended in units with a site history of crevice indications because of the high risk of a forced outage.

Numerous units with open tube sheet crevices have also been diagnosed as having primary side stress corrosion cracking at roll transitions. This has been confirmed in several instances with tube pulls. Units with this damage mechanism are also typically examined for secondary side initiated intergranular attack and stress corrosion cracking so that the same 100% examination plan will cover both damage mechanisms. However, particular attention should be given to distorted roll transition signals.

B.6.3.5 Support Plates (Model 51 and Model D Preheaters)

Numerous Model 51 steam generators (Mihama 2, Ohi 1&2, Takahama 1&2, Genkai 1, Cook 1, Farley 2, Fessenheim 1) have experienced non-denting related secondary side initiated stress corrosion cracking at hot leg support plates. This mechanism - in its advanced stages - can be quite extensive with a distribution over the entire tube bundle. It is more pronounced on the hot leg side of the steam generator at the lower support plate elevations. Distribution of eddy current indications

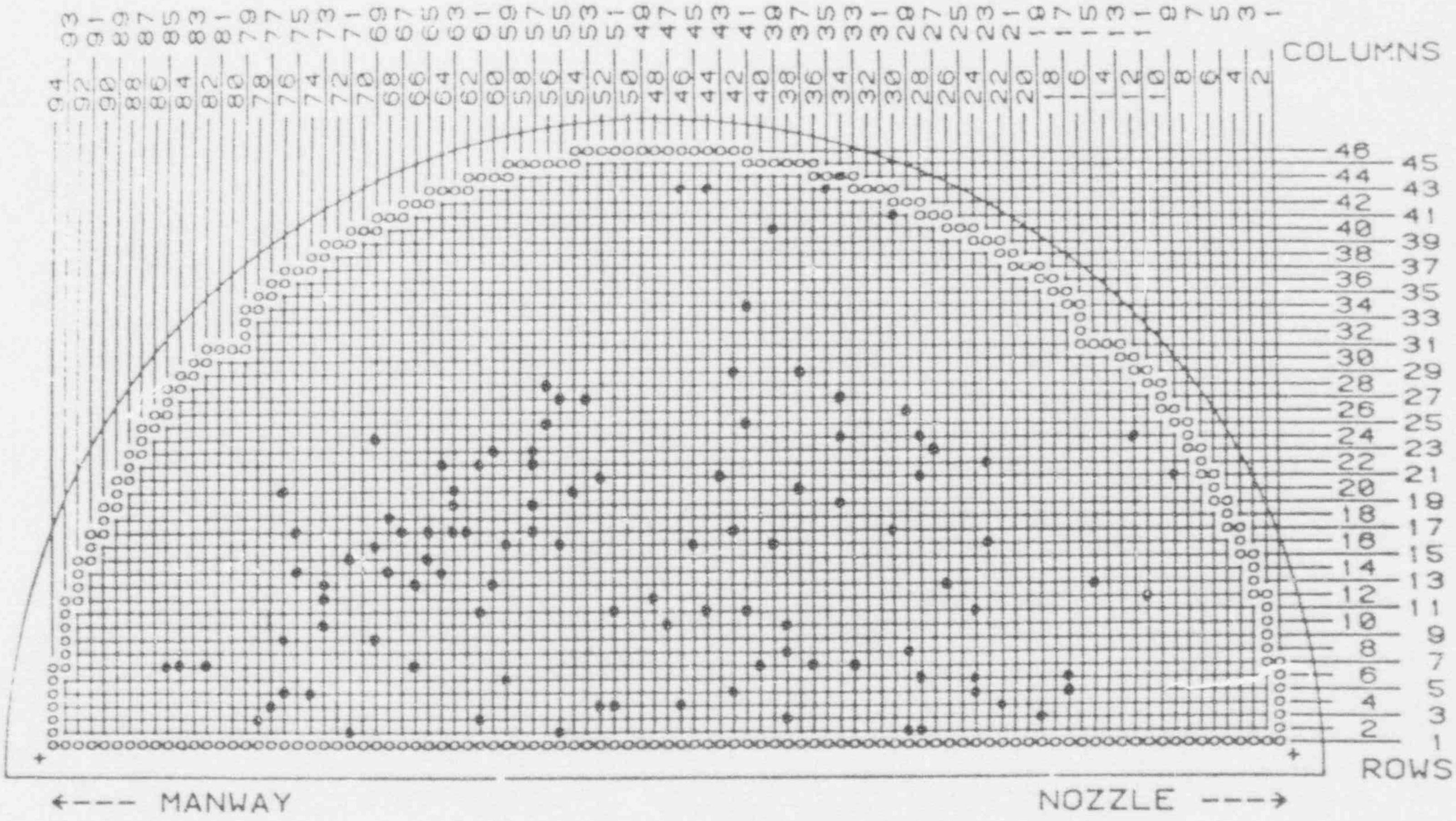


Figure B-36. Model 51 Tube Sheet Crevice Indications

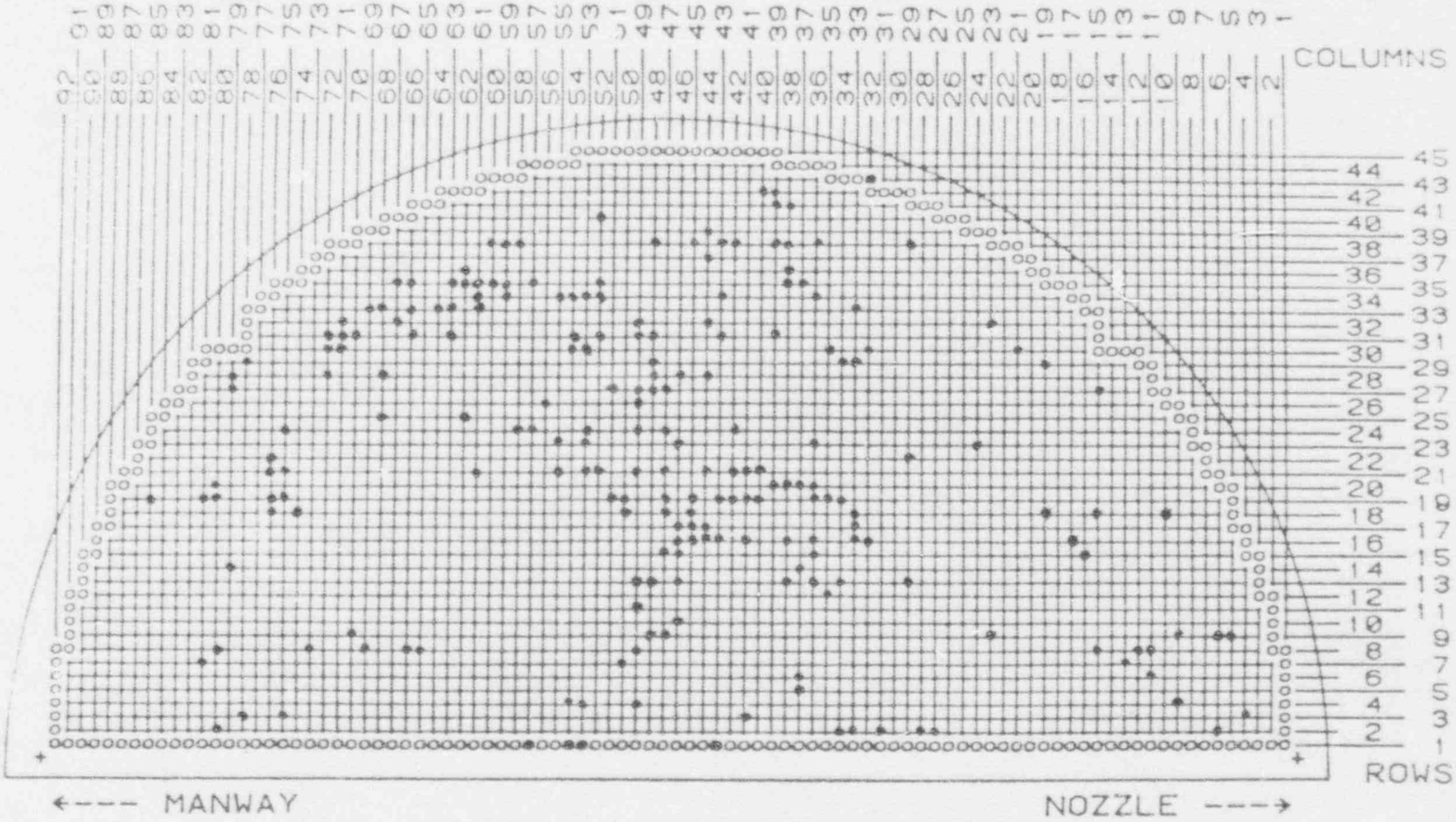


Figure B-37. Model 44 Tube Sheet Crevice Indications attributed to this damage mechanism are shown in Figure B-38. Two preheater steam generators have recently reported isolated occurrences of eddy current indications at hot leg support plates (Almarez 1 & Ringhals 3). While no tube pulls have been conducted, rotating pancake coil eddy current results suggest a morphology that is characteristic of axial stress corrosion cracking. It remains to be established whether this is the beginning of a more generic occurrence within Model D steam generators.

No steam generator leakage has occurred as a result of cracking at support plates. Rotating pancake coil eddy current data and destructive examination on numerous pulled tubes have shown that the cracking is confined to within the support plate. Burst testing has shown adequate margin in burst strength. Growth rates are relatively small. The recommended examination strategy is to conduct a complete examination of the affected region - typically 100% of the hot leg side of the steam generator up through the seventh support plate. Special eddy current analysis rules established for this damage mechanism are discussed in Appendix C. During the late '70's four extensively dented units - since replaced - experienced numerous forced outages as the result of denting assisted cracking at support plates. One Model 51 unit (North Anna 1) has experienced several forced outages; subsequent examination of pulled tubes has confirmed the presence of axial primary side stress corrosion cracking at dented support plate intersections. The plant is considered to have minor denting - strains less than 10% - which initiated during the early days of operation and was then stopped. The occurrence of cracking may represent a situation in which susceptible tubing with an initial strain is prone to cracking when operated at higher T(hot) temperatures. Eddy current indications have been observed on both the hot leg and cold leg sides of the steam generator up to the seventh support plate. The indications are distributed randomly across the generator as shown in Figure B-39. A 100% bobbin coil examination of the steam generator is recommended using special eddy current analysis rules which are discussed in Appendix C.

B.6.3.6 Inner Row U-Bends (Model 51 & Model D Preheater Units)

Non-denting assisted primary side stress corrosion cracking in inner row U-bends has been most prevalent in Model 51 steam generators (See Table A-4). However, there have been recent Row-1 leakage incidents in preheater Model D steam generators (Summer and McGuire 1) and one isolated Row-1 tube plugging incident (no leakage) in a Series 33 steam generator (Beznau 1). Most of the eddy current indications have occurred at the U-bend tangent point on either the hot leg or cold leg side of the

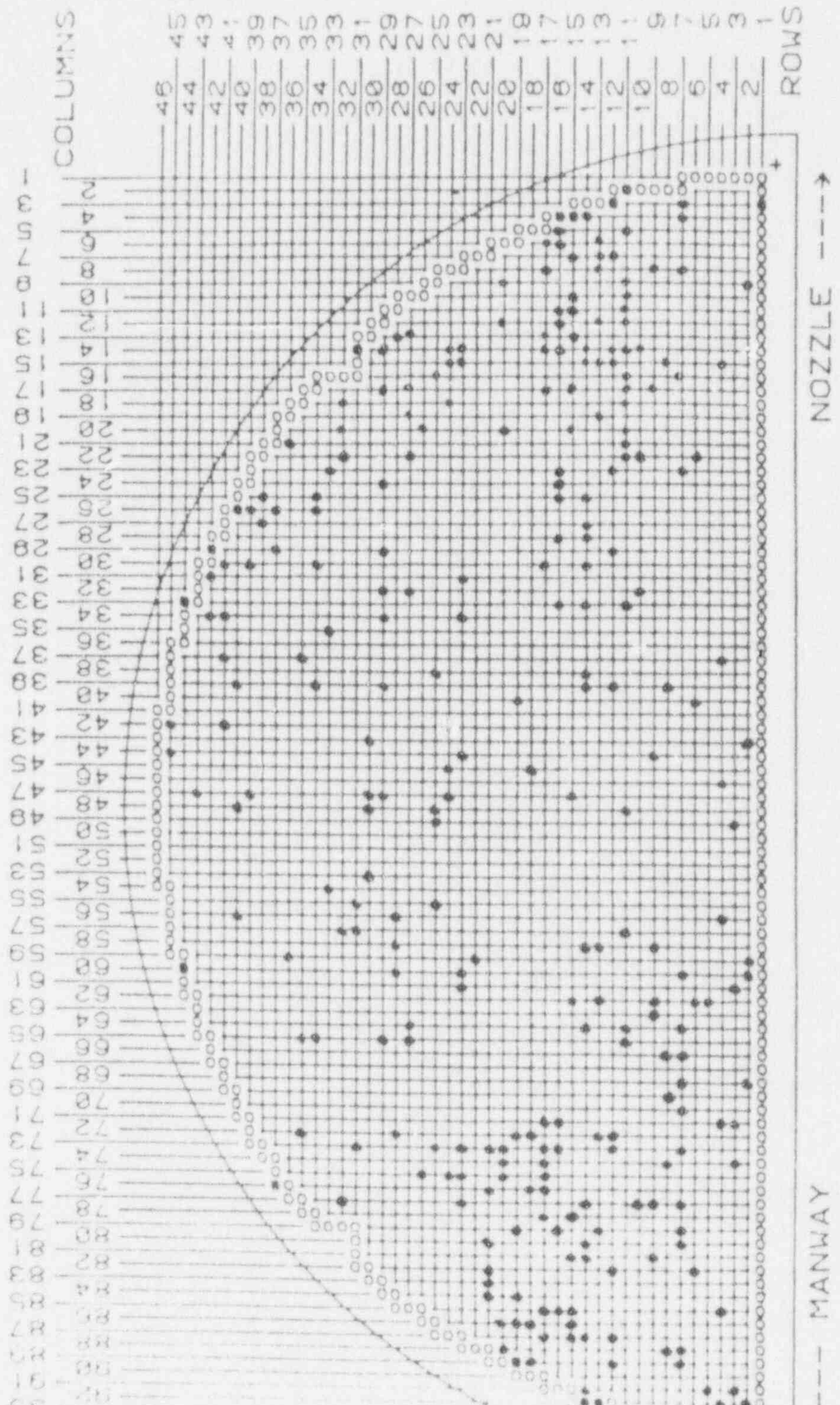


Figure B-38. Model 51 Support Plate Indications Attributed to SCC

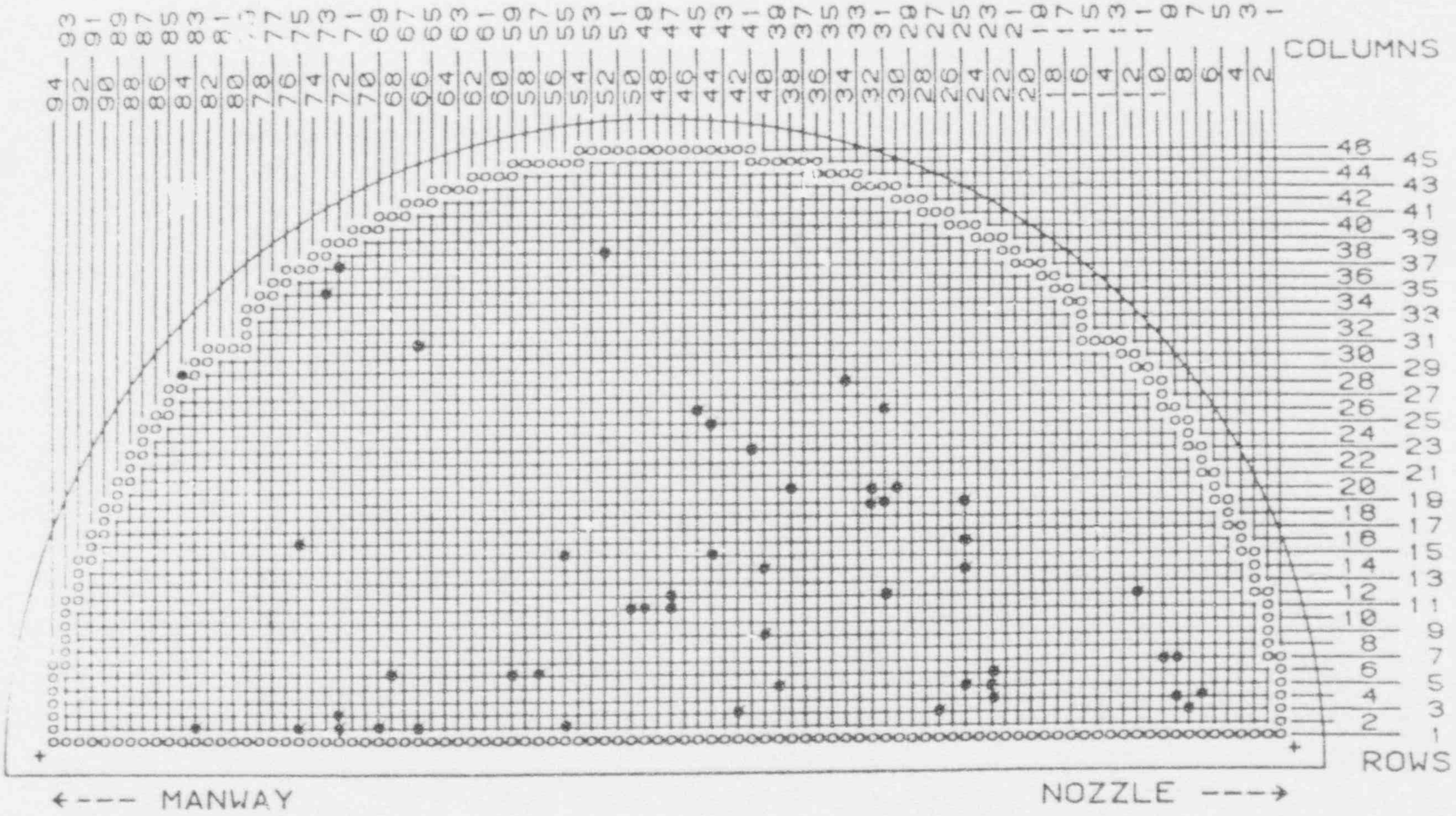


Figure B-39. Model 51 Support Plate Indications Attributed to PWSCC steam generator. There are some instances where apex indications - not related to denting - have been observed (Trojan, & North Anna 2). In one case (Zion 1) eddy current indications were reported at both tangent points in a Row 2 U-bend. Some twenty-three forced outages have occurred as a result of inner row U-bend leakage. A tube sheet map of effected tubes shows that the are occur anywhere throughout the inner row bends. See Figure B-40. Inner row U-bend PWSCC is considered a high-risk damage mechanism in the context of growth rate uncertainties and difficulties in detecting the condition. Recommended examination strategy is 100% of both Row 1 and Row 2 U-bends with rotating pancake coil technology. The use of conventional bobbin coil technology for examination of this region is inadequate because of geometry changes associated with the tube bending process. Numerous plants have elected to preventatively plug their Row-1 bends for economic reasons.

B.6.3.7 Full Depth Rolled Tube Sheet Crevices (Late Model 51's, Model D's)

Westinghouse modified their manufacturing process in later model steam generators electing to expand tubes within the tube sheet in order to eliminate the tube sheet crevice. Tubes were expanded using several methods including mechanical rolling, explosive expansion (Wextex), and hydraulic means. Several forced outages or leaking tubes identified during shutdown have occurred in units with full-depth rolled steam generators (Dampierre 1, Fessenheim 1, Bugey 2&3, Doel 3, McGuire 2).

Units with full depth rolled crevices should conduct an initial profilometry examination of the steam generator in order to identify regions of abnormal rolling within the tube sheet crevice and the existence of over roll conditions above the top of the tube sheet. In addition, units with a site history of leakage should do a 100% bobbin coil examination of the tube sheet region up to the first support plate. Distorted bobbin coil signals at or near the top of the tube sheet should be examined with rotating pancake coil to confirm the presence of tube wall degradation.

One Wextex expanded unit (North Anna 1) has experienced circumferential primary side stress corrosion cracking at the top of the tube sheet. Crack orientation was predicted with rotating pancake coil eddy current data and subsequently confirmed by tube pull. Three steam generators are affected; a tube sheet map showing the distribution of eddy current indications is given in Figure B-41. (8x1) eddy current data acquisition and analysis followed by confirmatory rotating pancake coil on all reported (8x1) indications is recommended Because of the wide distribution of indications, a 100% examination of the tube sheet is necessary.

SERIES 51

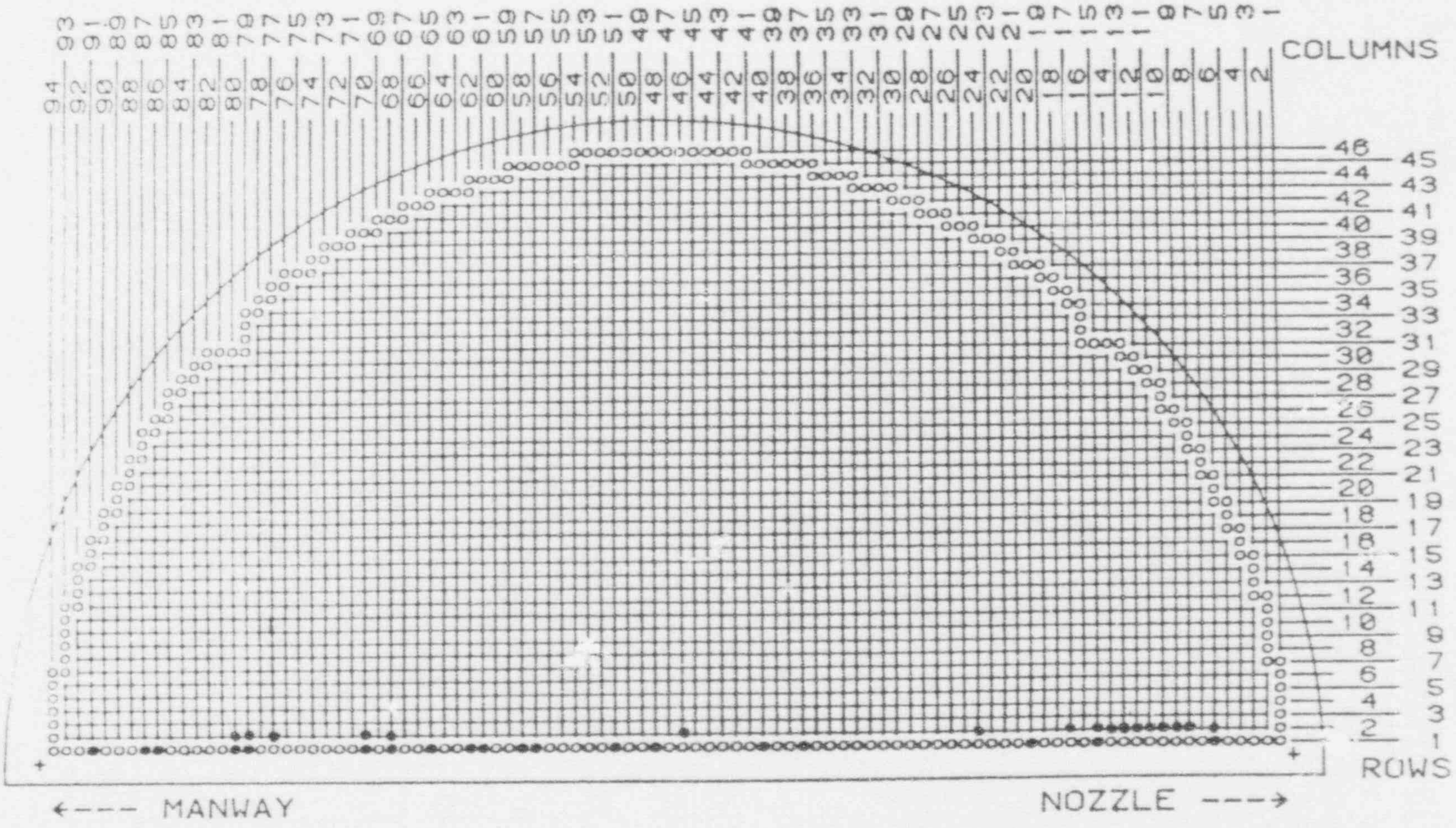


Figure B-40. Inner Row U-Bend PWSCC Indications

SERIES 51

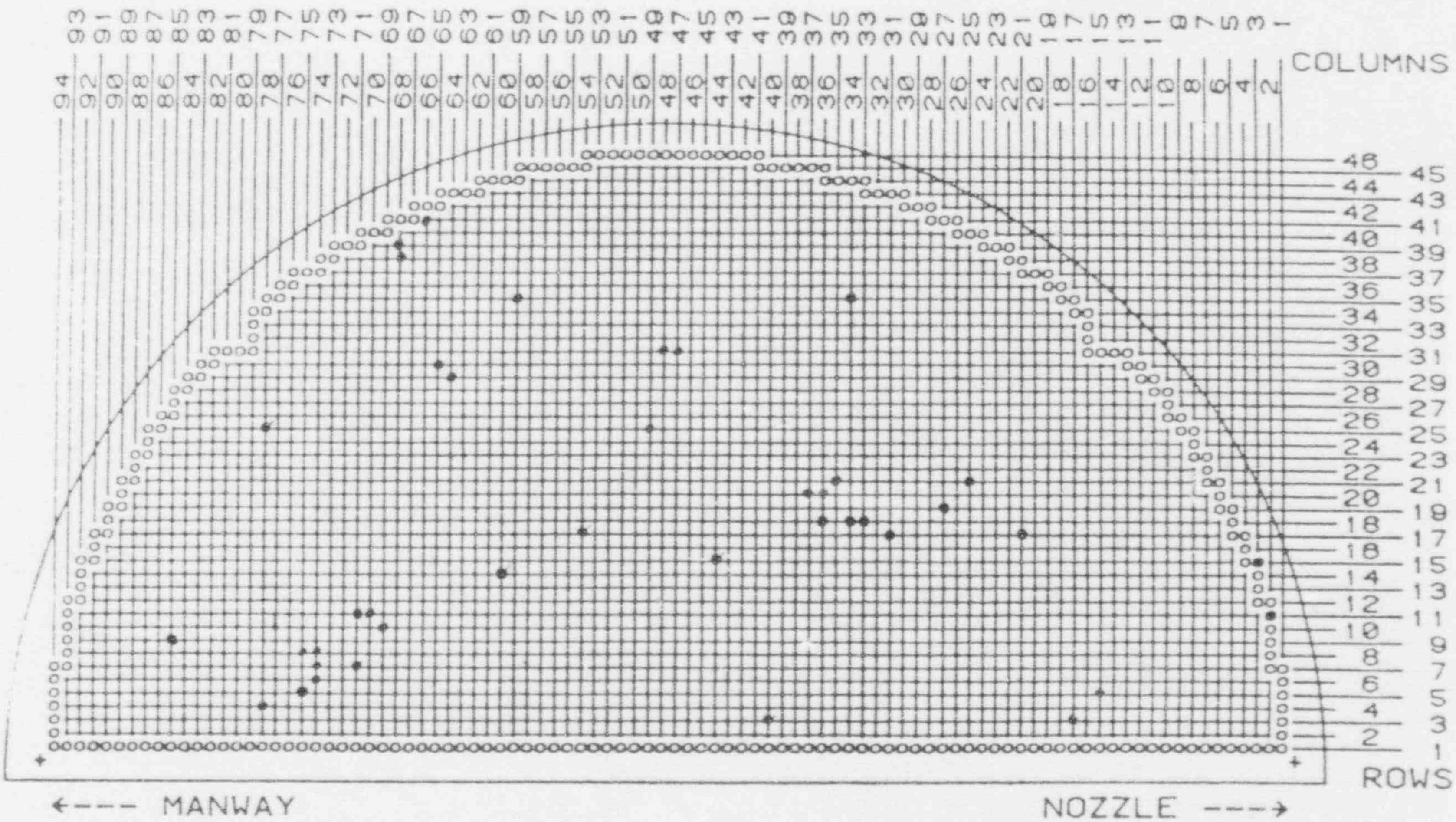


Figure B-41. Model 51 - Eddy Current Indications at Wextex Expansion (Three Steam Generators)

B.6.3.8 Sludge Pile Region (Model 27, 33, 44, 51, D)

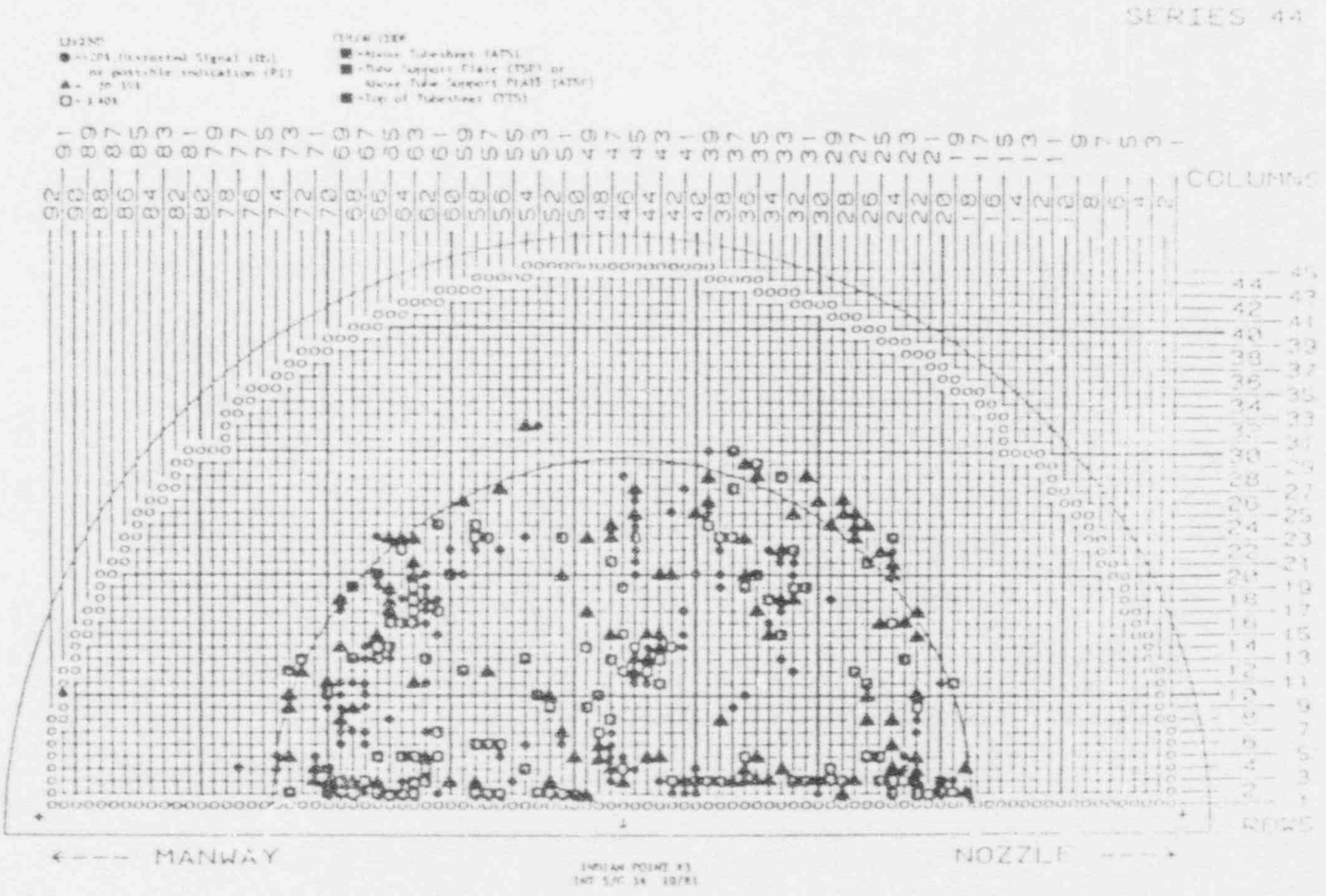
Two Model 44's (Indian Point 2 & 3) and two Model 51 (Trojan & Kori 1) have been diagnosed as having copper assisted pitting within the sludge pile. This has been confirmed by tube pulls in two of the four plants (Indian Point 3 and Trojan). As a general rule, hundreds or thousands of tubes can be affected with the extent of the indications typically bounded by the sludge pile below the first support plate. See Figure B-42. Two forced outages have occurred in Westinghouse units as a result of this damage mechanism.

Two units (Krsko - Model D and North Anna 1 - Model 51) are known to have experienced secondary side axial stress corrosion cracking above the top of the tube sheet within the sludge pile. This has been confirmed with a tube pull in one case (Krsko) and rotating pancake coil eddy current data in the case of North Anna 1.

Units with a site history of these mechanisms should conduct a 100% examination of the region bounded by the sludge pile.

REFERENCES

(1) NUREG/CR-5016. Compendium and Comparison of International Practice for Plugging, Repair, and Inspection of Steam Generator Tubing. April 1988.



a) Indian Point

Figure B-42. Model 44 - Eddy Current Indications Attributed to Pitting

Appendix C

STEAM GENERATOR NDE EXPERIENCE

C.1 INTRODUCTION

Knowledge concerning the reliability of the steam generator examination process has historically been derived from three sources. These include forced outages, tubes removed from operating steam generators, and experiments conducted on degraded tubes. In the past, much of this information has been assessed on a piecemeal basis, sometimes compartmentalized, and generally not available to the industry as a whole. Taken together, these sources can provide valuable insights into the strengths and weaknesses of the examination process.

Steam generator forced outages caused by tube failures provide a very direct and simple measure of NDE effectiveness. However, proper identification of the failure cause requires a careful systems analysis of the examination process. The latter must typically be broken down into its basic elements e.g., steam generator sampling strategies, technology limitations, and human factors contributions before a proper causal assignment of the failure can be established. Review of forced outage occurrences in pressurized water reactor steam generators and the establishment of their causes can thus be expected to provide useful insights into reliability issues.

Tubes removed from steam generators are an invaluable resource in estimating technology performance capability. A comparison of the condition of the tube as predicted by in-plant eddy current analysis results with that determined destructively can be used as a basis for quantifying eddy current performance. The analyst's field calls, the ready retrievability of the original field data with the ability for its re-analysis, and the relative ease with which tubes can be removed for destructive analysis, constitute a unique data package not readily available for other power plant components.

A third source of information are experiments conducted on degraded tubes. This can include in-generator experiments conducted on tubes allowed to remain in service - to see what happens - or experiments conducted on supposed replica tubes in which the particular damage mechanism has been "duplicated" in the laboratory. In-generator experiments are a valuable and necessary activity in determining strategies for handling specific damage mechanisms. Two key issues questioning laboratory experimental validity are eliminated by in-generator experiments; these include 1) duplication of the tube secondary side environment, which often is impossible to even know let alone simulate under laboratory conditions, and 2) the extent to which the in-generator flaw condition has been replicated. This latter point is particularly important for corrosion mechanisms for which it is not always possible to fabricate specimens which have the material property values or the degree of difficulty possessed by "real" flaws. The issue of flaw physical parameters and morphology, their impact on eddy current signal formation, and our knowledge of flaw statistics based on limited tube pull data is not something to be casually ignored. Some caution in extrapolating conclusions drawn from laboratory experiments is generally necessary as they relate to in-generator NDE performance capability.

This appendix presents an integrated perspective of steam generator NDE reliability issues. Section C.2 presents an overview of forced outage occurrences attributed to steam generator tube failures. Weaknesses in the examination process - technology versus process related - are identified. Section C.3 provides an overview of the pulled tube data base - which consists of approximately 650 tubes removed to date - from which performance estimates are derived. Section C.4 provides estimates of eddy current technology performance capability for specific damage mechanisms in recirculating and once-through steam generators. Performance parameters consist of estimates of detection probability and measurement accuracy for each of the various damage mechanisms. In most cases, this experience reflects the use of conventional bobbin coil technology and ASME code procedures. Where there are exceptions, they are so stated. In addition, recommended data acquisition and analysis procedures for various damage forms are also discussed based on pulled tube experience, in-generator experiments, and laboratory studies.

C.2 LEAKER OUTAGE OVERVIEW

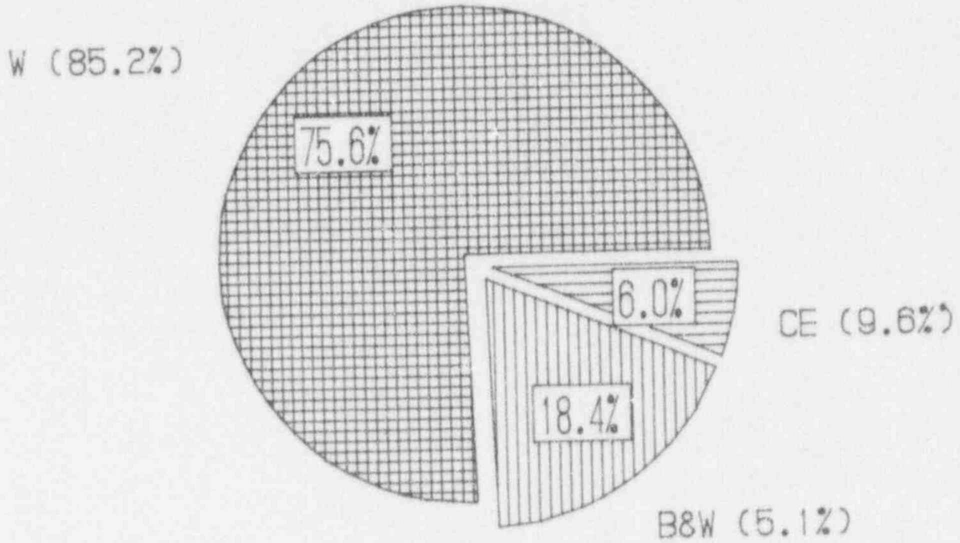
Since large scale pressurized water reactors first went into commercial operation during the late 1960's, there have been 247 identified unscheduled shutdowns (worldwide) attributable to steam generator tubes in plants designed by Westinghouse, Combustion Engineering, and Babcock & Wilcox over this thirty-year period. Analysis of the causes of forced outages is important in that it can identify weaknesses in the examination process, technology limitations, and provide insight in defining R&D needs.

Distribution of the 250 forced outages by NSSS vendor is shown in Figure C-1. The percentage figures shown in parenthesis represent the fraction of the operating plant population for a particular vendor. As a first approximation, the percentage of forced outages might be expected to track the fraction of operating plants since with more units the probability of a forced outage would be greater. Applying this logic it is seen that forced outages in recirculating units are disproportionately smaller than those that have occurred in once-through units. This difference is attributed to design-related failures in once-through units i.e., the lane region, in which a high incidence of tube failures have occurred as the result of corrosion-assisted high-cycle fatigue.

A breakdown of forced outages in Westinghouse designed units by cause is shown in Figure C-2. Four prominent causes are apparent. These include 1) denting related side effects 2) intergranular attack-stress corrosion cracking 3) primary side stress corrosion cracking and 4) loose parts. A similar breakdown for Combustion Engineering Units is shown in Figure C-3. In this case, three causes stand out; 1) tube wear, 2) denting related side effects, and 3) thinning. Figure C-4 shows a breakdown of Babcock & Wilcox unit forced outages. The most significant contributor in this case is lane region corrosion-fatigue.

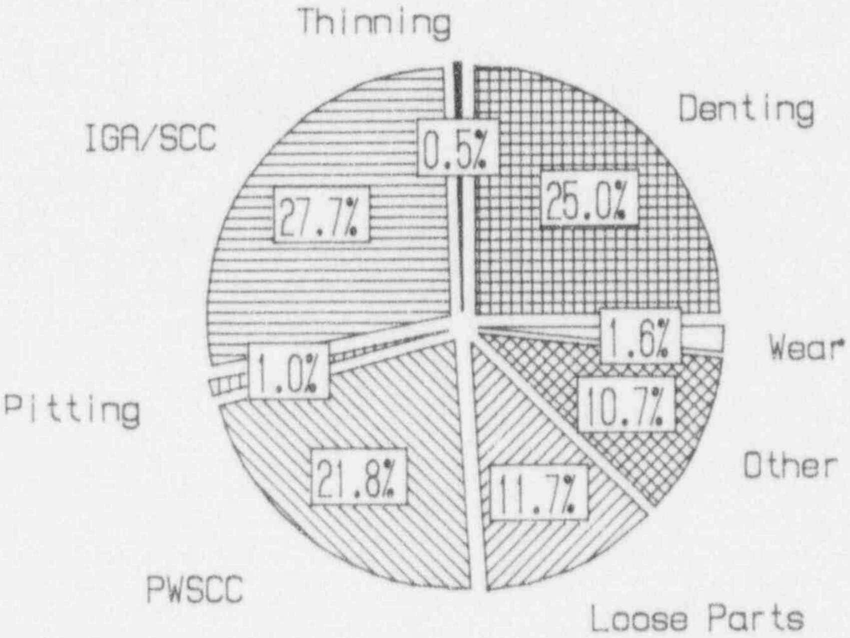
Denting related side effects account for a total of 25% of the forced or preventative outages that have occurred in Westinghouse and Combustion Engineering recirculating steam generators. Eighty-two percent of the denting related outages have occurred in four extensively dented plants (Surry 1 & 2, and Turkey Point 3 & 4) - all during the mid to late 1970's. These units have since been replaced. Two other extensively dented units (Indian Point 2 & 3) account for 8% of these outages - replacement steam generators for these units are currently being manufactured. Two Combustion Engineering Units (Palisades and Fort Calhoun) account for 6% of the outages while the remaining 4% have occurred at North Anna 1. The forced outages at Palisades and Fort Calhoun both occurred as the result of missed eddy current indications by individual analysts (single party analysis) and were not the result of technology limitations. Denting related outages at North Anna 1 have occurred as late as 1986 and are considered to be due to inadequacies in the analysis rule base which has since been rectified.

Denting as a tube plugging issue reached its peak in 1977 and has basically subsided since 1981. See Figure C-5. This is attributed to a basic understanding of the



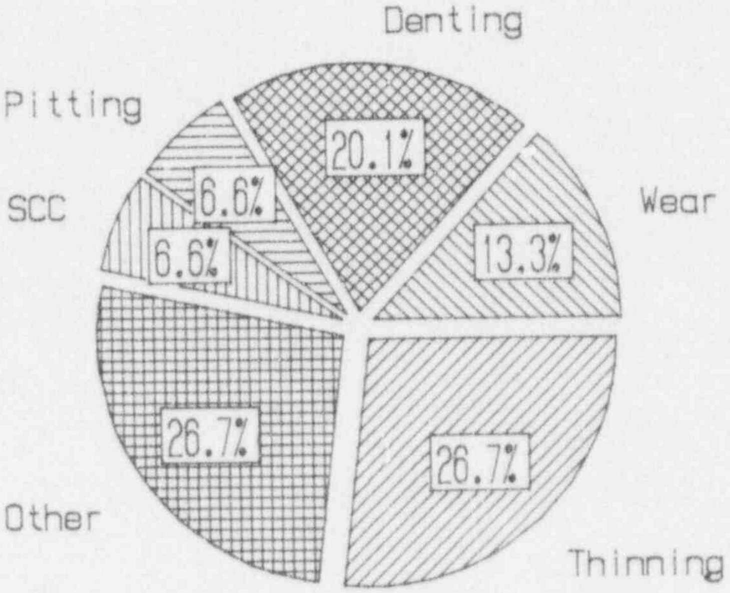
250 Total Outages

Figure C-1. Steam Generator Forced Outages Due to Tube Leaks (Note: Numbers in parentheses denote percentage of operating plants.)



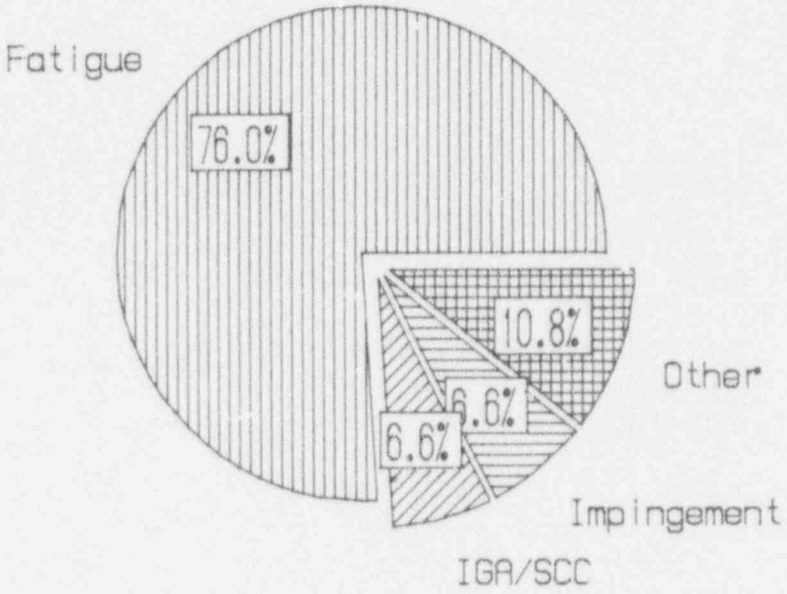
189 Total Outages

Figure C-2. Westinghouse Forced Outages Due to Tube Leaks



15 Total Outages

Figure C-3. Combustion Engineering Forced Outages Due to Tube Leaks



46 Total Outages

Figure C-4. Babcock and Wilcox Forced Outages Due to Tube Leaks

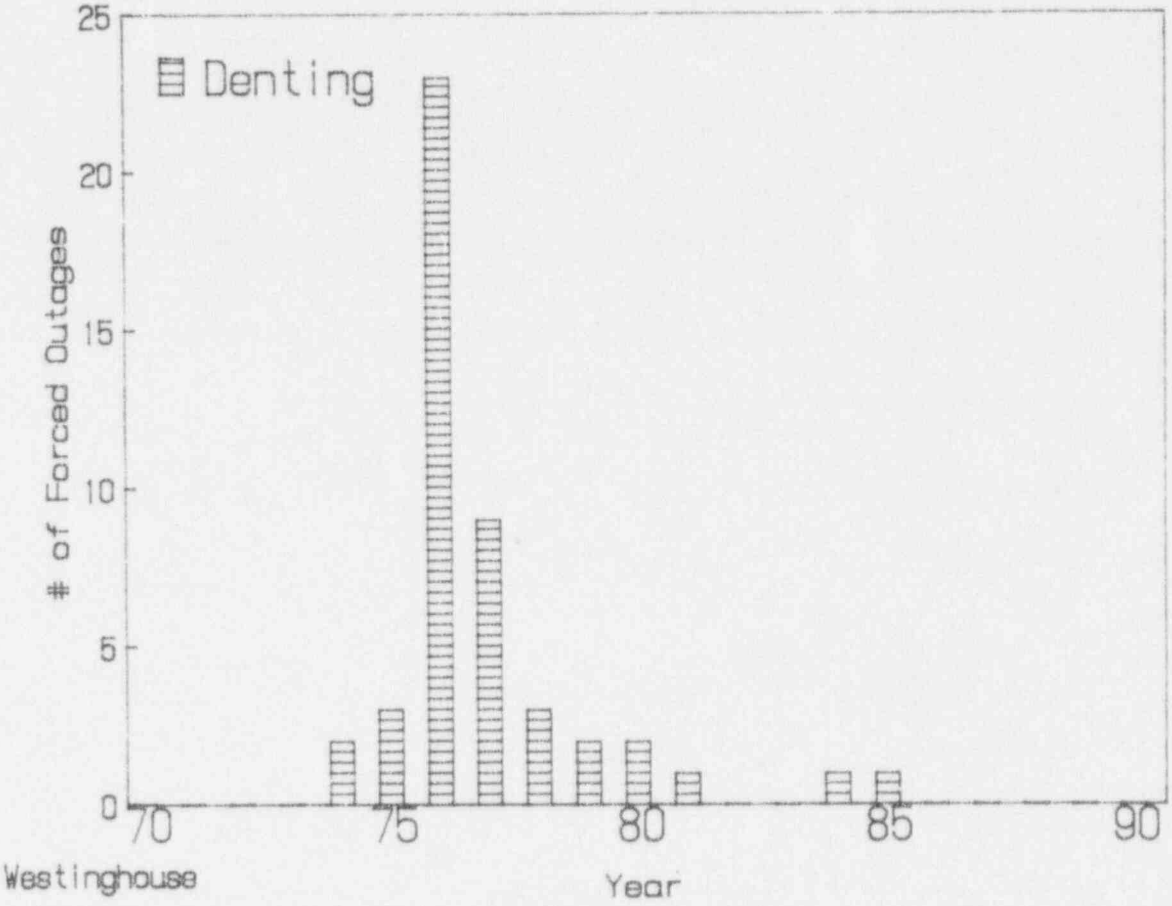


Figure C-5. Denting Related Forced Outages - Recirculating Units denting mechanism developed during SGOG I and the implementation of appropriate secondary side water chemistry guidelines. Technology limitations were the largest single contributor to forced outages and were due to inadequacies of bobbin coil examination e.g., coil fill-factor effects. NDE technology improvements in two areas have since been developed which offer an improved examination capability. Preventative plugging strategies have been implemented at several units which rely on plant-specific strain criteria (1). The tube is removed from service before it is likely to develop cracking in the dented region. Tube strain is derived from profilometry data acquired using mechanical or eddy current sensors (2-3). Improved rotating pancake coil eddy current technology has also been developed for the examination of dented support plate intersections for cracking. None of this technology was available when denting was at its zenith.

A breakdown of PWSCC caused outages in Westinghouse units is shown in Figure C-6. A majority (66%) are the direct result of non-denting assisted inner row U-bend cracking at the tangent point. The bulk of these outages have occurred in Model 51 steam generators with isolated occurrences in several Model D steam generators. Many utilities have elected to plug their Row 1 bends where there is excess tube plugging capacity because of economic reasons. Technology limitations have clearly contributed to U-bend related forced outages. Bobbin coil examination of the U-bend region is not considered reliable because of fill factor variations which occur at the tangent point. The recent introduction of rotating pancake coil technology for the U-bend region does provide an improved examination reliability when compared with the conventional bobbin coil. However, it is not clear whether improved examination will eliminate U-bend related forced outages. There still remain uncertainties in growth rates and the potential for incipient cracking - below the detectable limits of the improved technology - to rapidly propagate through wall. Direct preventative measures have been taken at some plants in the form of a U-bend heat treat process intended to reduce residual stresses in the bend region.

Forced outages attributable to intergranular attack or stress corrosion cracking in Westinghouse units are shown in Figure C-7. Several other stress corrosion cracking related outages have occurred in once-through units (Arkansas 1) and in Combustion Engineering Units (Millstone 2). Most of the forced outages have occurred in units of Westinghouse design. In these units, most have occurred in Model 51 and 44 steam generators at four plants (Point Beach 1, Robinson 2 and D.C. Cook 1, and Ringhals 2). Two of these plants have since replaced their steam generators (Point Beach 1 and Robinson 2) whereas the Cook 1 and Ringhals 2 generators are scheduled for replacement during the late 1980's. Inadequate steam generator sampling, technology

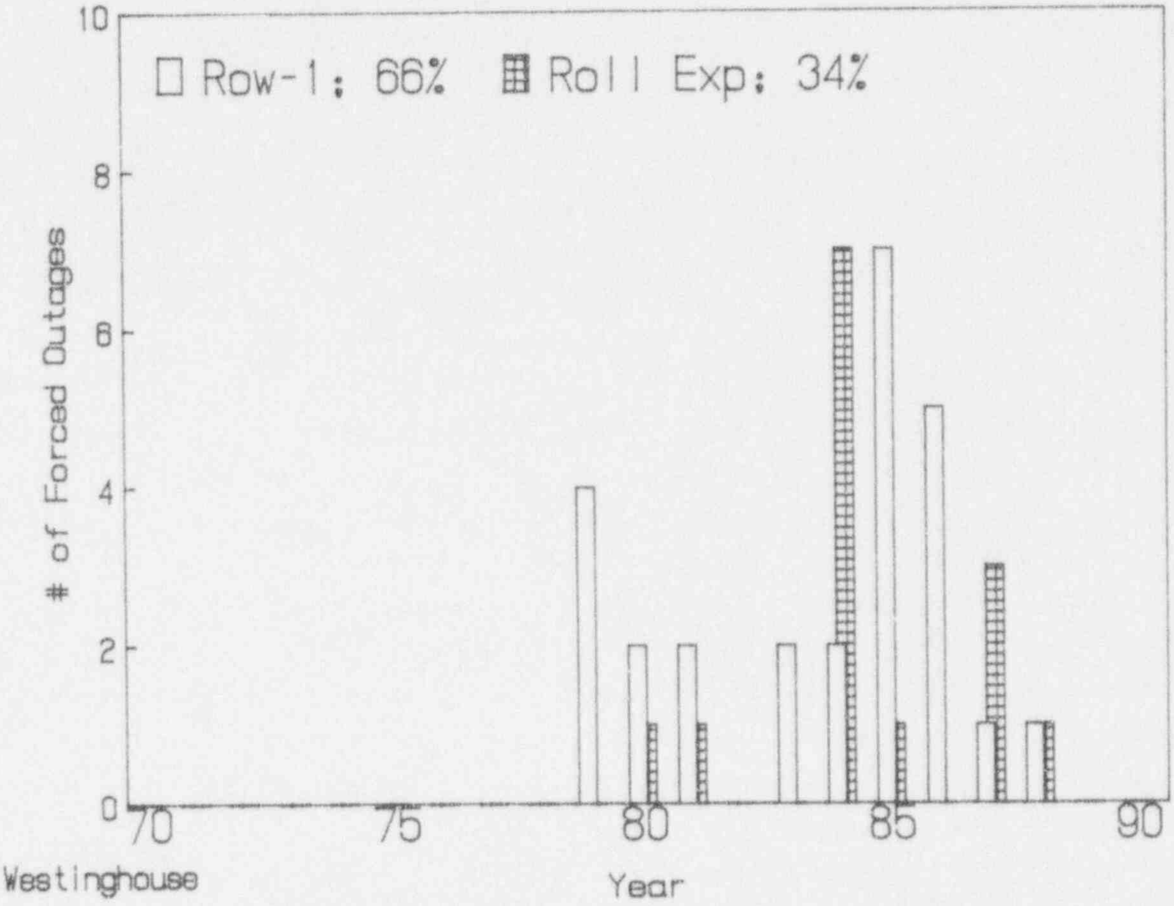


Figure C-6. Steam Generator Forced Outages - PWSCC

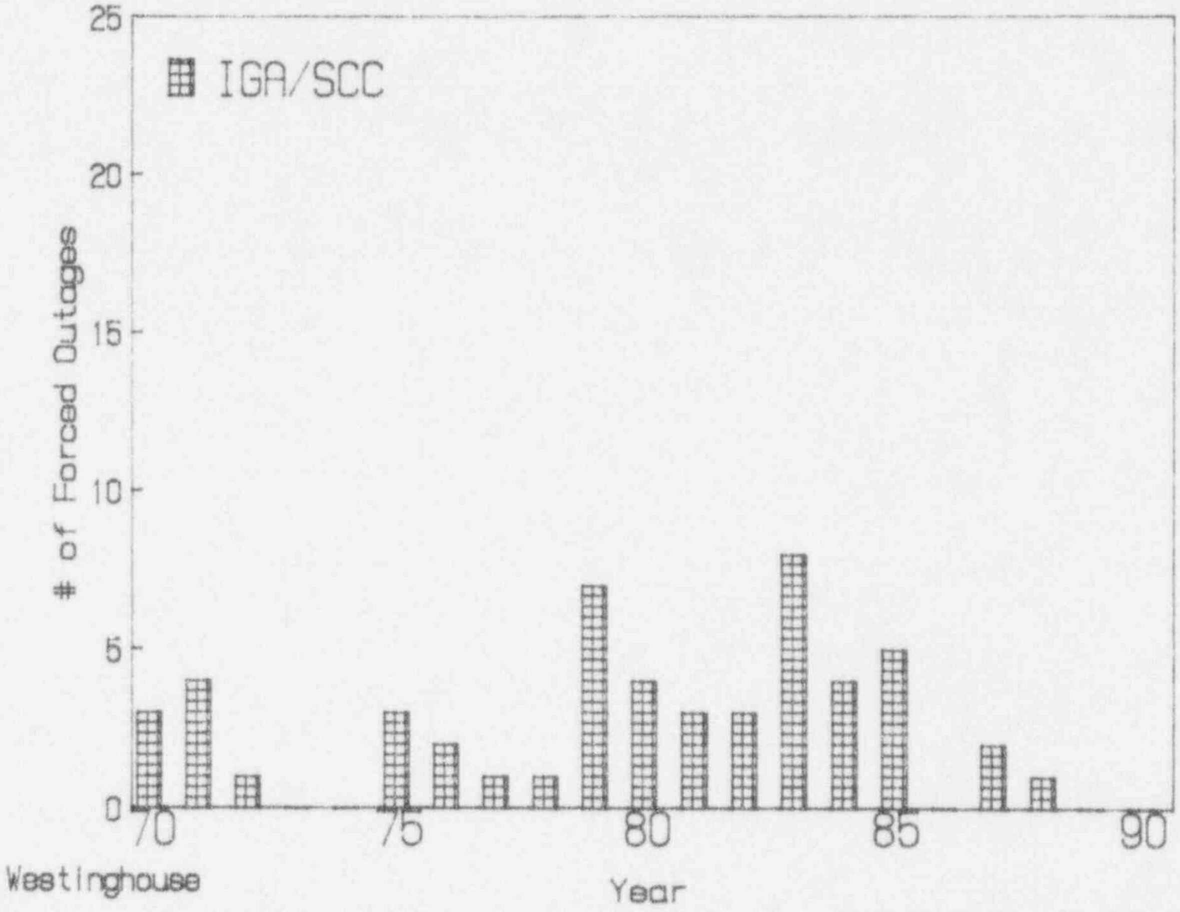


Figure C-7. Steam Generator Forced Outages - IGA/SCC limitations, and human factor elements have all contributed to IGA/SCC forced outages. Some units have attempted to implement minimum sampling strategies as defined by plant technical specifications (3% plus expansion program) and suffered leakage on start-up; other units have conducted 100% examinations of the tube sheet crevice region and still have had forced outages during the subsequent operating cycle; finally, numerous units which have implemented single party analysis procedures have had forced outages because of missed indications.

At least 16 outages - which represents 7% of the total known forced outages in recirculating and once-through units - have been the result of missed or incorrectly diagnosed eddy current indications. All of these have occurred in recirculating units. Two outages attributed to wear have occurred at Ringhals 3 and Ginna. The former involved the initial discovery of preheater wear in which eddy current signals at the baffle plates were not correctly dispositioned whereas the latter case had to do with an indication incorrectly diagnosed as thinning. The two dent related forced outages occurred at Fort Calhoun and Palisades and have already been discussed in a previous paragraph. The bulk of the forced outages due to IGA/SCC have occurred in Westinghouse units (Robinson 2, Zion 1, Cook 1, Point Beach 1, Ringhals 2) with one recent incident occurring at a Combustion unit (Millstone 2) in which an indication was incorrectly dispositioned. The importance of eddy current data two-party review and the need for a 100% examination of the tubesheet crevice region cannot be overemphasized in units with a site history of IGA/SCC. The issue of missed or incorrectly diagnosed eddy current indications has been addressed head-on with the introduction of computer data screening and analysis systems. However, it should be emphasized that some units have still experienced forced outages even with the implementation of two-party analysis and 100% steam generator examination. This implies basic technology limitations, rapid growth rates, or both.

Other significant contributors to forced outages include loose parts, thinning, and pitting in recirculating steam generators, and corrosion fatigue and impingement damage in once-through units. Lane region corrosion-fatigue cracking prevalent in once-through units is not considered to be an examination issue although it is a significant contributor to forced outages. See Figure C-8. The cracking initiates at extremely small precursor sites rapidly propagating through wall in a time frame estimated at less than twenty-four hours. Array coil (8x1) eddy current technology has been successful in inspecting for a fatigue crack condition present during an outage. However, initiation and rapid failure during subsequent operating intervals has still occurred. A more direct measure such as lane region preventative sleeving has been recently implemented in several units in order to increase tube stiffness

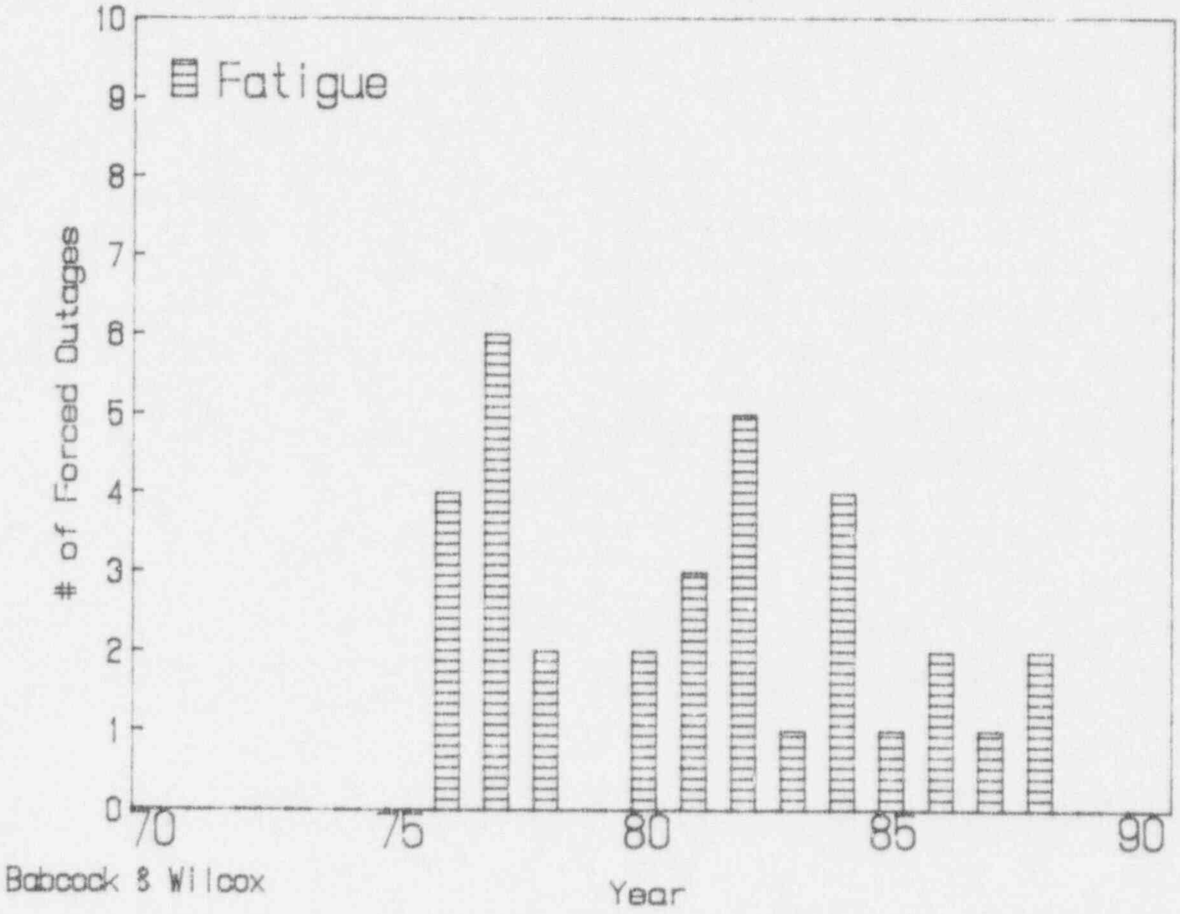


Figure C-8. Corrosion - Fatigue Forced Outages - Babcock and Wilcox Units reducing the susceptibility of a tube to vibration. Impingement damage forced outages have occurred in two units (Oconee 1 & 3) and were basically the result of inadequate sampling of the outer periphery region of the steam generator. Increased sampling percentages within this region of the generator have reduced the occurrence of forced outages. Loose part forced outages have occurred in numerous units (Prairie Island 1, Farley 1, Beaver Valley 1). Regular secondary side visual examination of the steam generator can reduce the occurrence of forced outages as the result of loose parts; this can be supplemented by a primary side eddy current examination of the outer periphery of the steam generator when a loose parts condition is suspected. Forced outages as the result of thinning have occurred at several plants (Palisades, Turkey Point 3, and Mihama 1). In general, these occurrences have been attributed to inadequate sampling strategies rather than technology limitations.

C.3 PULLED TUBE DATA BASE OVERVIEW

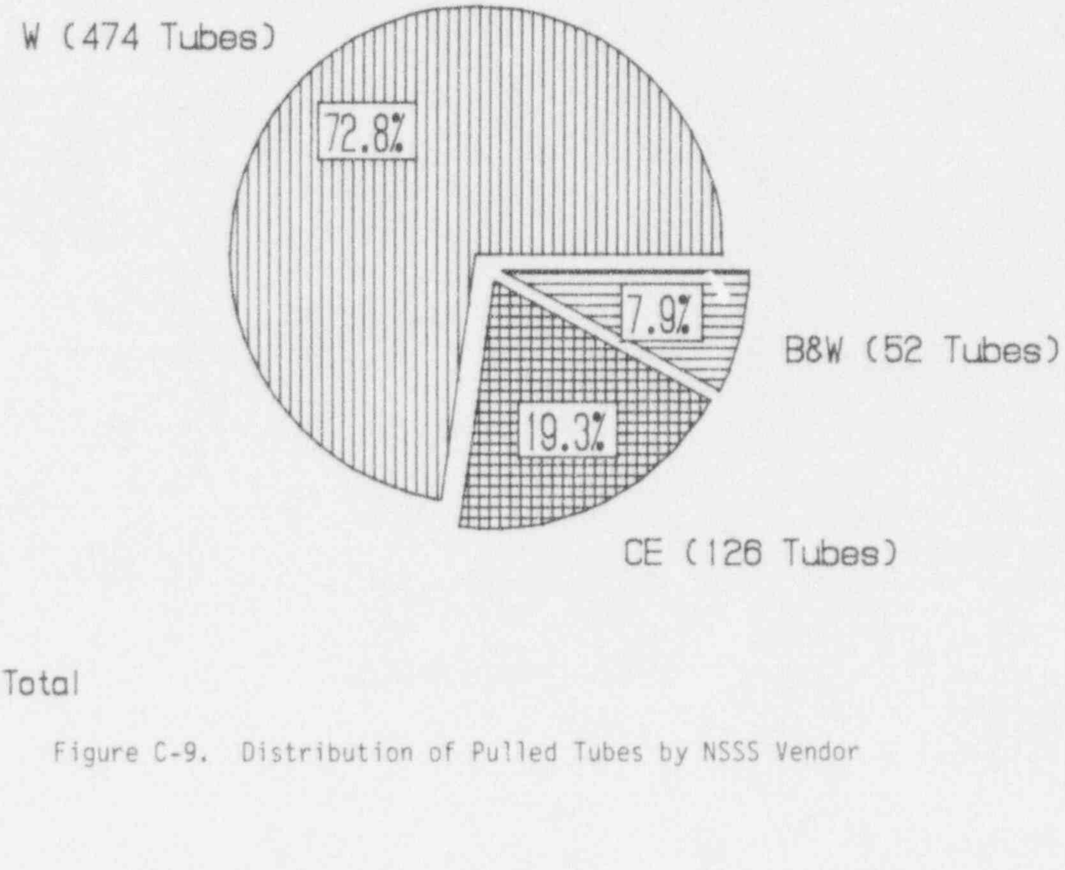
Tubes removed from operating plants represent an invaluable resource from which much can be deduced about the effectiveness of the eddy current examination process. A comparison of the original in-plant analysis results or a detailed review of the eddy current data under laboratory conditions with results obtained from destructive metallography can provide valuable insights in determining the capability of existing technology and provide guidance for procedure or technology improvements.

The first tubes removed from a commercial pressurized water reactor steam generator were from Connecticut Yankee (Haddem Neck) during 1970. The total estimated number of removed tubes currently stands at 652. Tubes are normally removed from a steam generator in order to identify damage mechanisms and their causes so that appropriate plant remedial actions can be initiated. The confirmation and validation of eddy current detection and measurement capability has historically played a secondary role. Because of the nature of the tube pulling process, the available data base is widely dispersed in both time and space. Utilities throughout the world have removed tubes over the past thirty years with no central repository for the resulting data. In many instances, the information derived from a tube pull has limited distribution (it is often proprietary) and has not always been incorporated in data analyst guidelines to assist analysts in their analysis process. The analyst must continue to evaluate data - tube end to tube end - with no contextural information. This section provides an overview of the pulled tube data base derived from three major sources; 1) Westinghouse and their licensees, 2) Combustion Engineering, and 3) Babcock & Wilcox. An initial breakdown of pulled tubes by NSSS vendor is given in Figure C-9. As might be expected, most tubes have been removed from Westinghouse designed units since they and their licensees have the largest percentage of operating plants.

A breakdown of tubes removed from once-through units is shown in Figure C-10. The largest percentage of removed tubes is because of primary-side stress corrosion cracking which occurred as the result of an unusual primary-side chemical intrusion in one unit (TMI-1). If these tubes are excluded from the population then relatively few tubes (approximately 20) have been pulled from once-through units. The remaining tubes are roughly equally distributed among the major damage mechanisms that have plagued once-through units e.g., wear, IGA/SCC, corrosion-fatigue, and impingement damage.

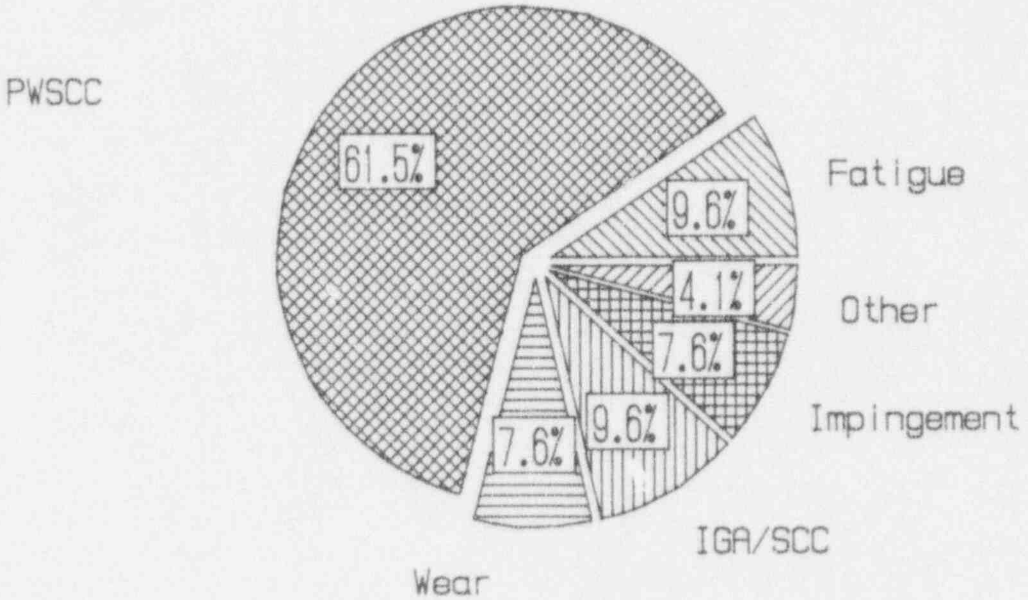
The distribution of tubes pulled from Combustion Engineering units is shown in Figure C-11. The majority of tubes that have been removed are for "other" reasons which include 1) access tubes removed to get to tubes of interest (secondary side tube removal at Palisades), 2) tubes removed with no degradation, and 3) tubes removed with manufacturing defects e.g., improper heat treat and buff marks (Calvert Cliffs and San Onofre 2). Of the remaining tubes, the next two largest categories are for denting and thinning. These were all removed from Millstone 2, Palisades and Fort Calhoun. Tubes with IGA/SCC have been removed from four units (Millstone 2, St. Lucie 2, Palisades, and Calvert Cliffs 1). Only one tube with wear has been removed (Calvert Cliffs 1).

Tubes removed from Westinghouse designed units are shown in Figure C-12. The largest percentage have been removed for non-denting related PWSCC with the bulk of these from Framatome units. Most of the PWSCC tubes have been removed for stress corrosion cracking in expanded tubes. Only three tubes have been removed with U-bend tangent point cracking. Denting related tube pulls are the next largest percentage with the majority of these coming from six plants (Surry 1 & 2, Turkey Point 3 & 4, Indian Point 2, and Ringhals 2). IGA/SCC tube pulls follow with the bulk coming from eight units (Ginna, Point Beach 1, San Onofre 1, Ringhals 2, Cook 1, Robinson 2, Takahama 2, and Ohi 1). Tubes with thinning constitute the next largest percentage followed by wear and pitting. Most of the significant tubes pulled for pitting have come from three units (Indian Point 2, Connecticut Yankee, and Trojan); tubes with wear have been pulled from six units (AVB wear - San Onofre 1, Robinson 2, Zion 1, and preheater baffle plate wear - Almaraz 1, Ringhals 3 and Krsko).



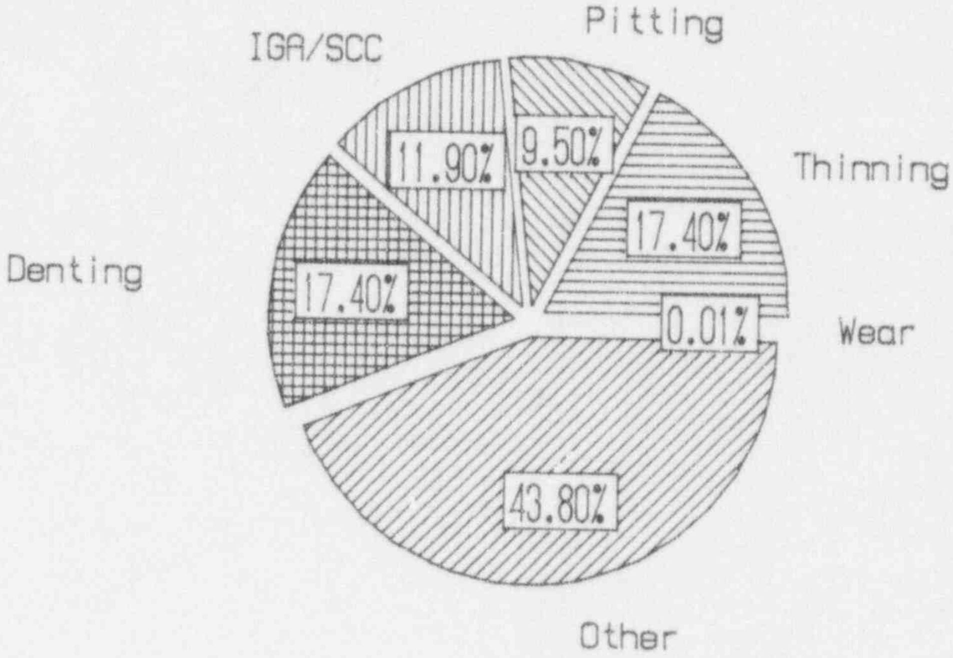
652 Tubes Total

Figure C-9. Distribution of Pulled Tubes by NSSS Vendor



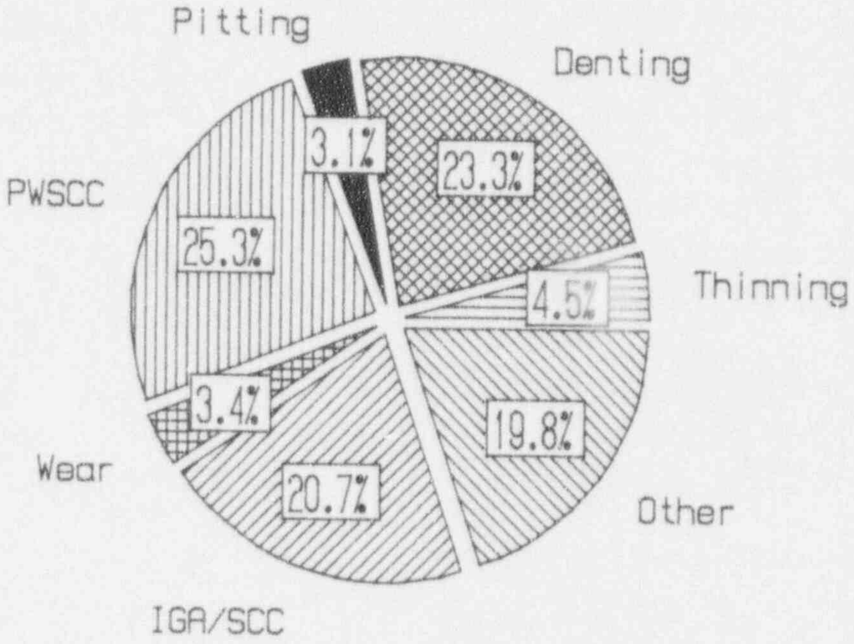
52 Tubes Total

Figure C-10. Babcock and Wilcox Pulled Tubes



126 Tubes Total

Figure C-11. Combustion Engineering Pulled Tubes



474 Tubes Total

Figure C-12. Westinghouse Pulled Tubes

C.4 EDDY CURRENT TECHNOLOGY PERFORMANCE CAPABILITY ESTIMATES

This section presents NDE experience with specific damage mechanisms derived from tubes removed from operating steam generators. Information derived from pulled tube reports is used to construct two types of data presentations which are then used as an objective measure of eddy current technology performance capability. This is done individually for all damage mechanisms which have been observed in recirculating and once-through steam generators. Data presentations include; 1) a scatter plot of measured defect depth versus eddy current predicted depth - this is used to assess measurement error; and 2) an estimate of detection probability as a function of defect depth which is a measure of how reliable a condition can be found. To provide some context for detection and measurement error performance estimates, reliable detection is defined to be that depth at which the detection probability assumes a value of 0.9 whereas for measurement error, a value of +/- 10% is what is generally assumed for the purpose of calculating plugging limits. Recirculating steam generator experience is presented in Section C.4.1 followed by once-through experience in Section C.4.2.

C.4.1 Recirculating Units

Eddy current performance capability as derived from pulled tube experience is now presented for recirculating steam generators. Damage mechanisms considered include thinning, pitting, wear, intergranular attack and stress corrosion cracking, and primary side cracking.

C.4.1.1 Thinning

Thinning is a generic term used to describe the volumetric loss of tube material. It is a surface attack which proceeds by the dissolution of tube material into the localized steam generator coolant. Localized coolant conditions are emphasized since aggressive impurity chemical species must be concentrated before corrosion will occur. The resultant morphology cuts across the microstructure without evidence that grain boundaries are preferentially corroded (4).

Thinning which occurred as the result of phosphate attack during the period in which sodium phosphate secondary side water chemistry treatment was utilized is called wastage. Potential locations for wastage occurrence are generally determined by the extent of the sludge pile in the steam generator and has been observed on both the hot and cold leg side of the generator. Wastage has also occurred at support plate intersections in some Combustion Engineering steam generators (Mihama 1, Palisades) as the result of sludge buildup because of inadequate flow. Typical wastage morphology as it occurred on a tube at the top of the tube sheet (Beznau 1) is shown in Figure C-13. An example of wastage at a support plate intersection (Palisades) is shown in Figure C-14. The latter example illustrates the rather large volume of metal loss that can occur with extensive wastage attack.

Several forced outages have occurred as the result of wastage (Palisades, Turkey Point 4). A review of the circumstances associated with these outages shows the cause to have been related to inadequate sampling of the steam generator or rapid growth during lay-up rather than technology limitations. With the switch to an all-volatile water chemistry by all but two units (San Onofre 1 and Zorita), wastage has ceased being a significant industry issue. At Zorita, progression has been slowly continuing whereas at San Onofre 1, it has been arrested based on eddy current results.

Another form of thinning has been experienced in Model 51 steam generators. It occurs on the cold leg side outer periphery at the lower two support plates and is referred to as "cold-leg" thinning. Two tubes have been removed with this damage mechanism from Salem 1 and Prairie Island 2. No definitive cause has been established; it exhibits features of both wear and corrosion and may represent a hybrid combination of the two mechanisms. It is confined to within the support plates as shown in Figure C-15.

Measurement accuracy and detection probability estimates for thinning as derived from pulled tube data are shown in Figures C-16 and C-17. All of the original in-plant eddy current data was acquired using a differential bobbin coil at a test frequency of 400 KHz. The dashed line in Figure C-16 is a least squares fit to the experimental data and gives a measure of the systematic error. The data is described by the equation $y = (0.81)x + 13.87$ with a correlation coefficient of 0.90. The systematic error - as measured by the least squares fit - is conservative over the range of normal plugging limits. Detection probability estimates given in Figure C-17 show no significant reliability issues.

C.4.1.2 Pitting

Pitting is a form of general corrosion in which degradation is driven by local galvanic differences in the tubing. As with thinning, pitting occurs by dissolution of surface material with no preferential grain boundary attack. Because pitting is

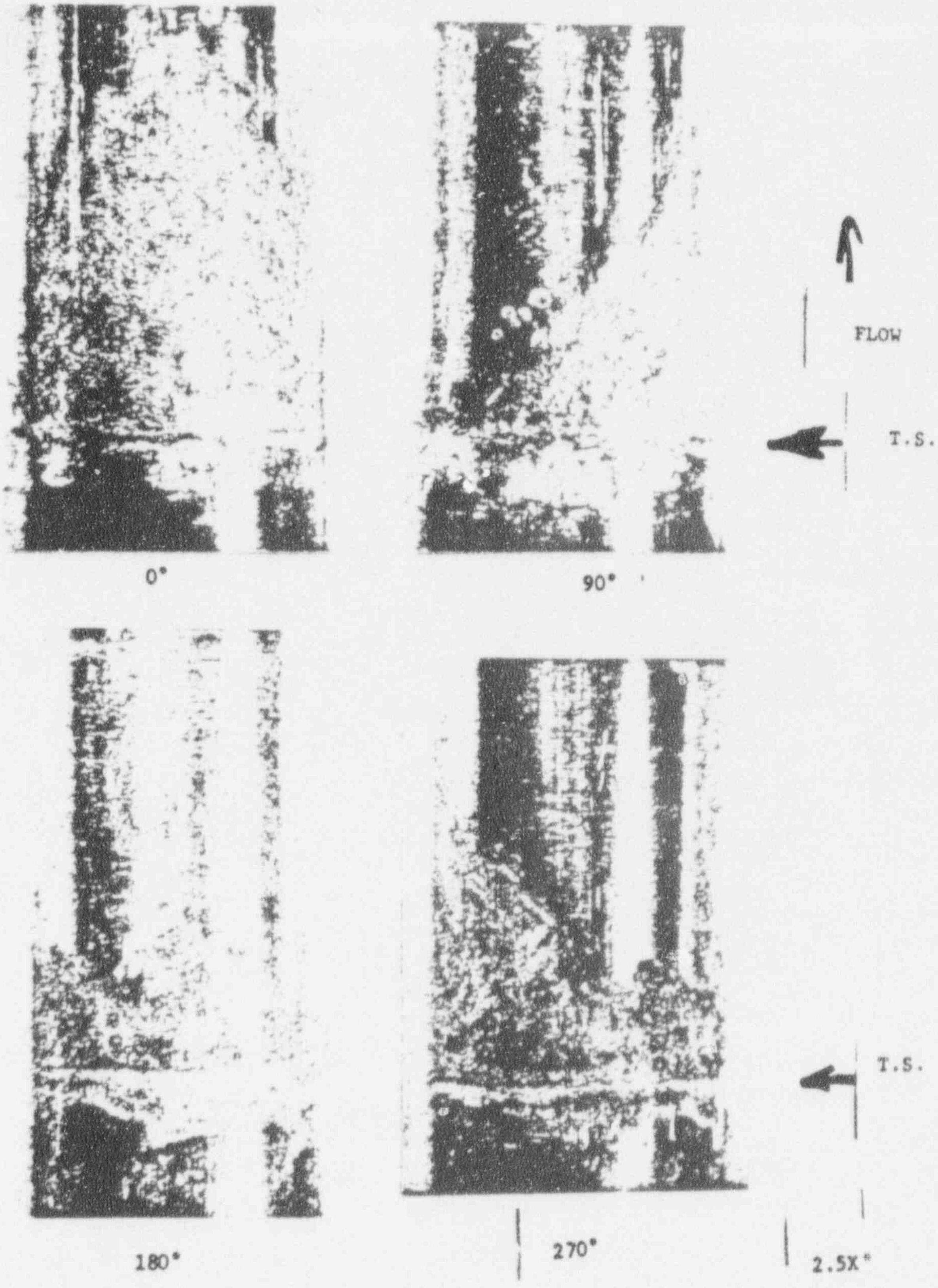


Figure C-13. Wastage at Top of Tube Sheet (Beznau 1)

* Please note that the illustration(s) on this page has been reduced 10% in printing.

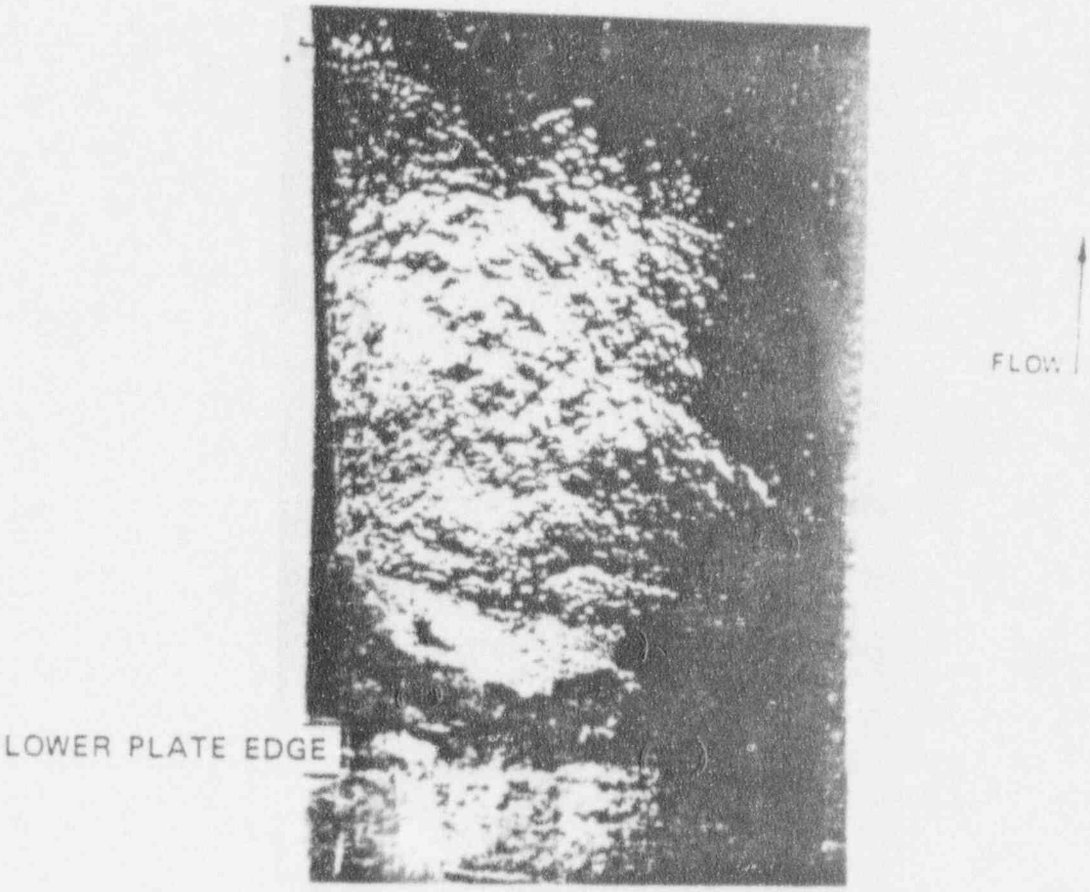


Figure C-14. Wastage at Support Plate (Palisades)

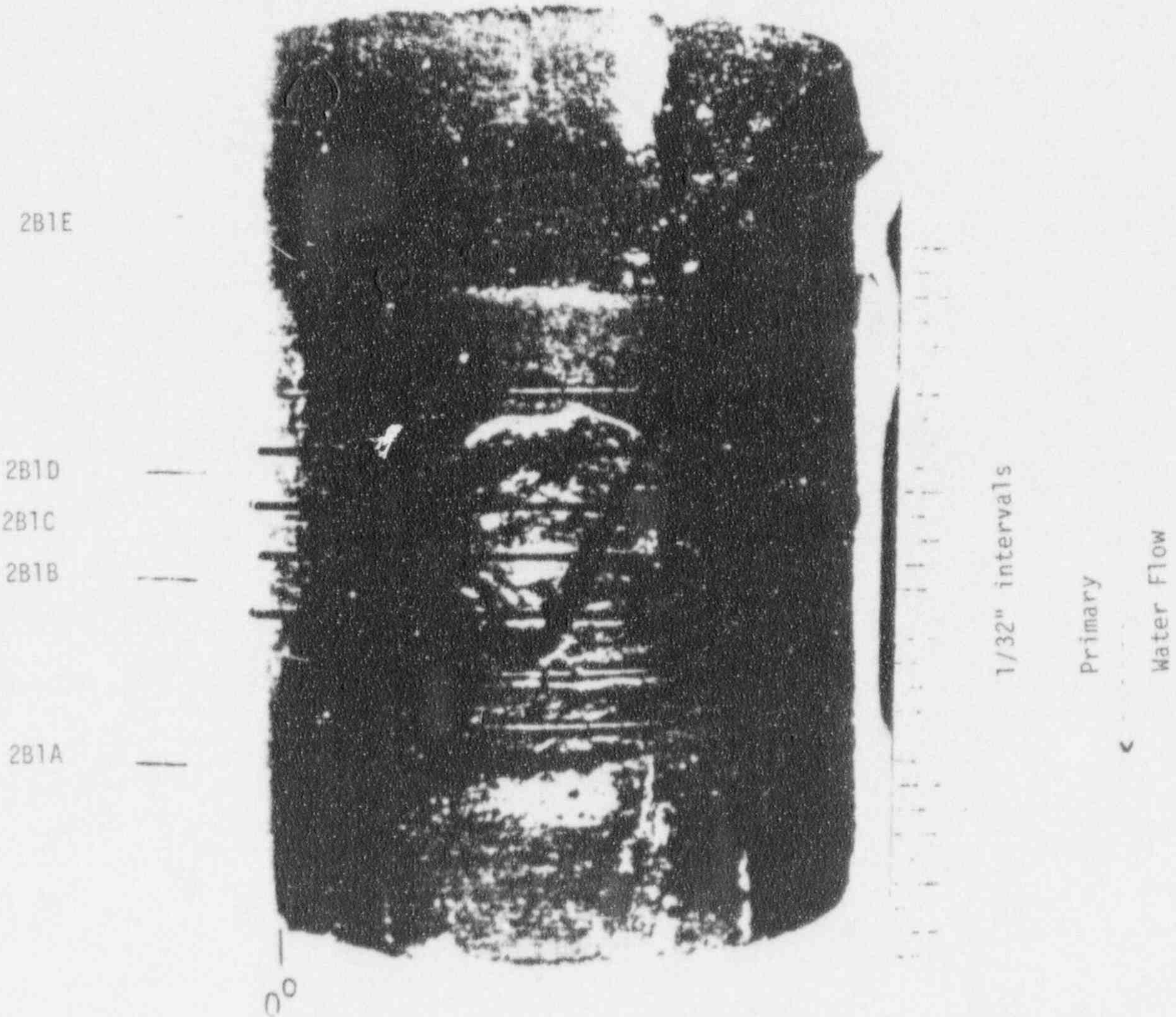


Figure C-15. Cold Leg Thinning - 2nd Support Plate (Prairie Island 2)

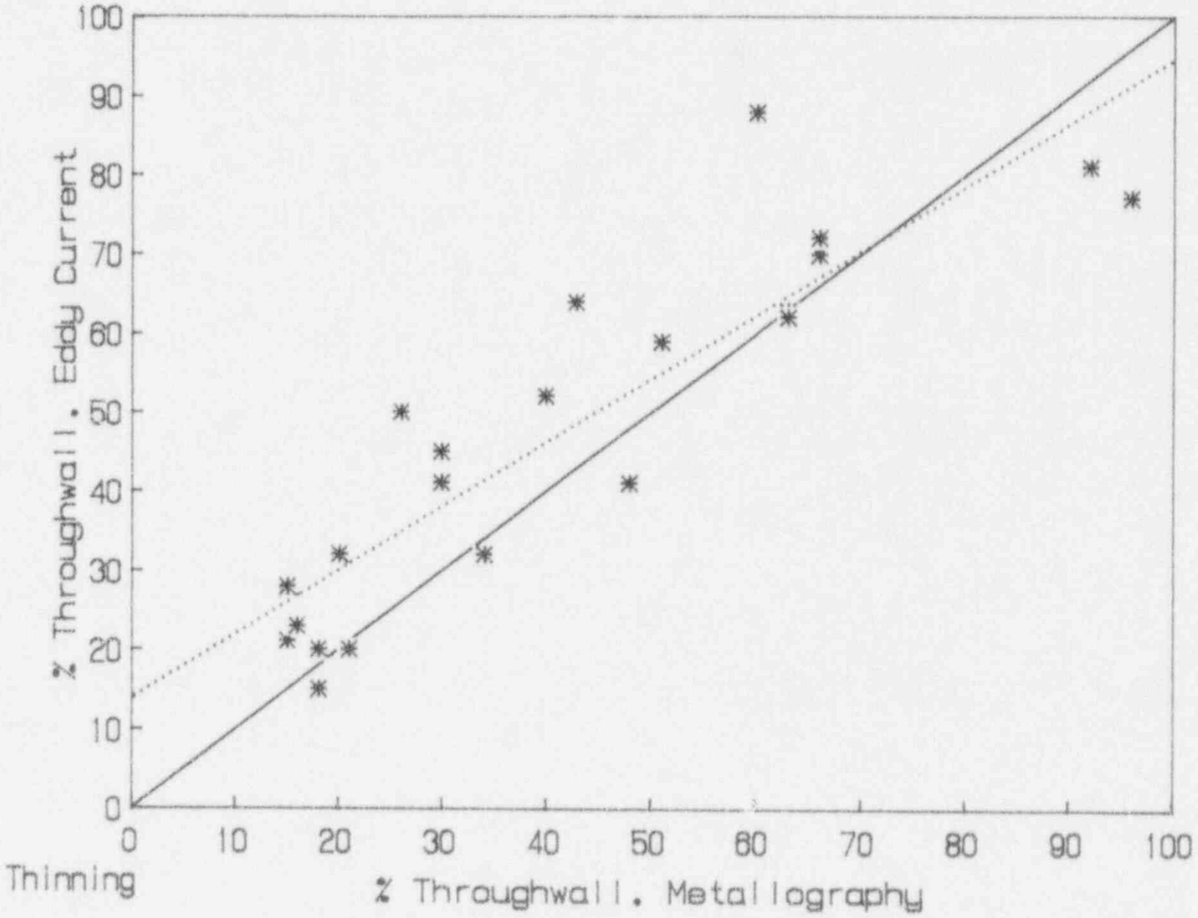


Figure C-16. Measurement Accuracy - Thinning

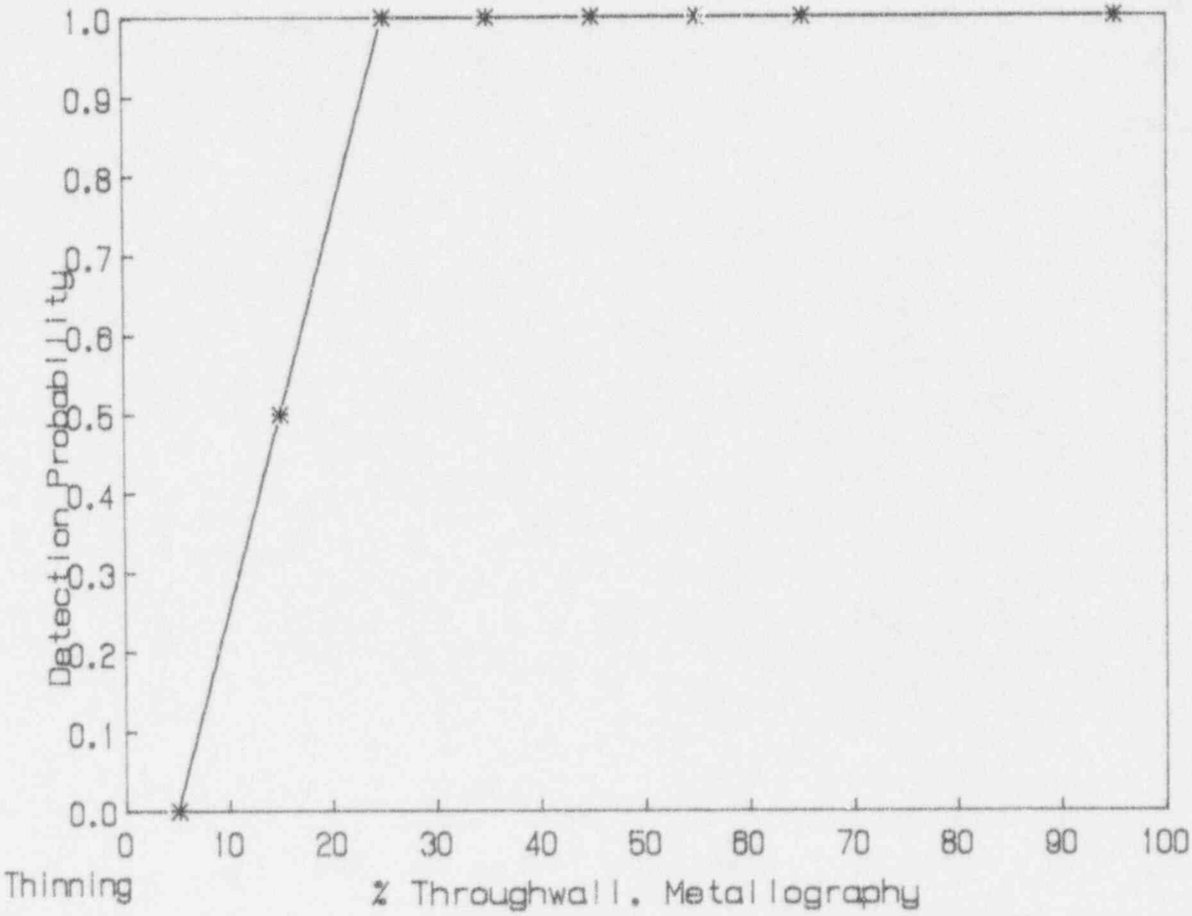


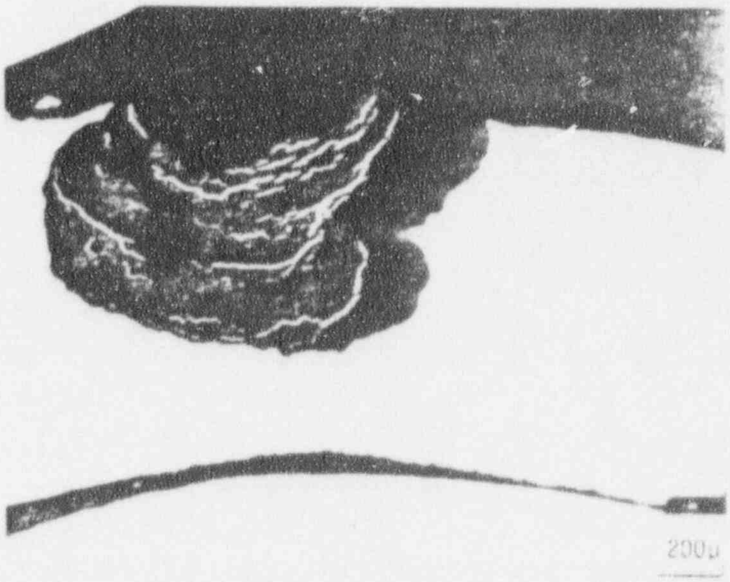
Figure C-17. Detection Probability - Thinning driven by small and localized galvanic differences, a given pit does not tend to grow to the large volumes characteristic of thinning (4). Pitting morphology as a form of corrosion in recirculating units was first observed superficially on tubes removed from Beznau 1, San Onofre 1, and Palisades during the 1970's. It became significant as a cause for tube plugging in 1981 when it was discovered on tubes removed from Indian Point 3 and Millstone 2. Its discovery at Indian Point 3 occurred during September 1981 when a leak was detected during a primary-to-secondary hydrotest of the No. 31 steam generator (5). Subsequent eddy current examination revealed numerous indications on the cold leg side of each of the four steam generators between the tubesheet and first support plate.

Destructive examination of tubes removed from Indian Point 3 steam generators identified pitting as the source of the eddy current indications. At Millstone 2 in December, 1981, multiple eddy current indications were reported on both the hot leg and cold leg side of each steam generator located between the tubesheet and the first eggcrate support during a 100% examination of both steam generators. Subsequent destructive examination of tubes removed from the unit identified pitting similar to that found at Indian Point 3 as the cause of the eddy current indications. It has since been diagnosed or confirmed at four other plants which include Indian Point 2, Connecticut Yankee, Kori 2, and Trojan.

Pitting morphology on tubes removed from Indian Point 3 and Millstone 2 assumes a re-entrant or undercut geometry with layers of an intermittent magnetite oxide corrosion product and metallic copper laminations as shown in Figure C-18. The lighter colored layered feature within each of the pits shown in the figure is metallic copper. The pitting tends to form clusters in a region of the tube between the top of the tube sheet and the first support member as shown in Figure C-19 which shows a radiographic print of a tube segment removed from Indian Point 3 at a location approximately 18 " above the top of the tube sheet. In the figure, one can observe the light colored circular features indicative of pitting attack. Multiple pitting tends to occur around the tube circumference and along the tube axis as shown in Figure C-20 which shows transverse cross-sections of a tube at approximately 15 mil increments. The undercut pitting geometry is shown in some detail in the montage shown in Figure C-21. Finally, external views of a pitted tube are shown in Figure C-22; the dark corrosion product, scabs or carbuncles within the pits, is apparent.

The analysis of eddy current data from pitted tubes in the presence of secondary side copper deposits can be complicated by the occurrence of multiple pitting and

a. Indian Point 3 Tube R12C66 (1)



b. Millstone 2 Tube 68/88 (3)

Figure C-18. Pitting/Copper (Indian Point 3 and Millstone 2)

LOCATION
~19 inch above tubesheet

Figure C-19. Print of Radiograph Showing Pit Clusters (Indian Point 3)

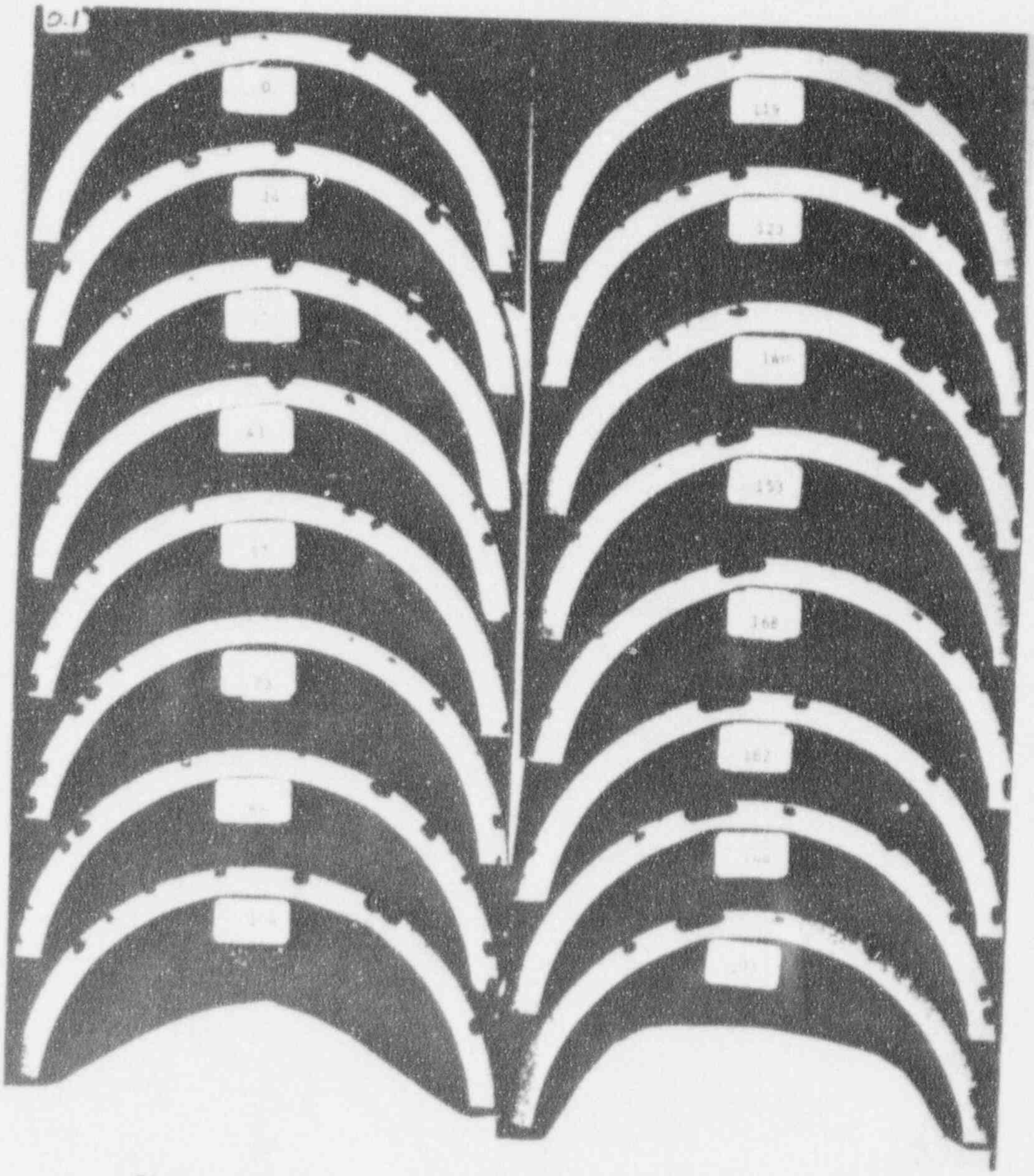


Figure C-20. Transverse Cross-Sections of Pitted Tube at 15 Mil Intervals (Indian Point 3)

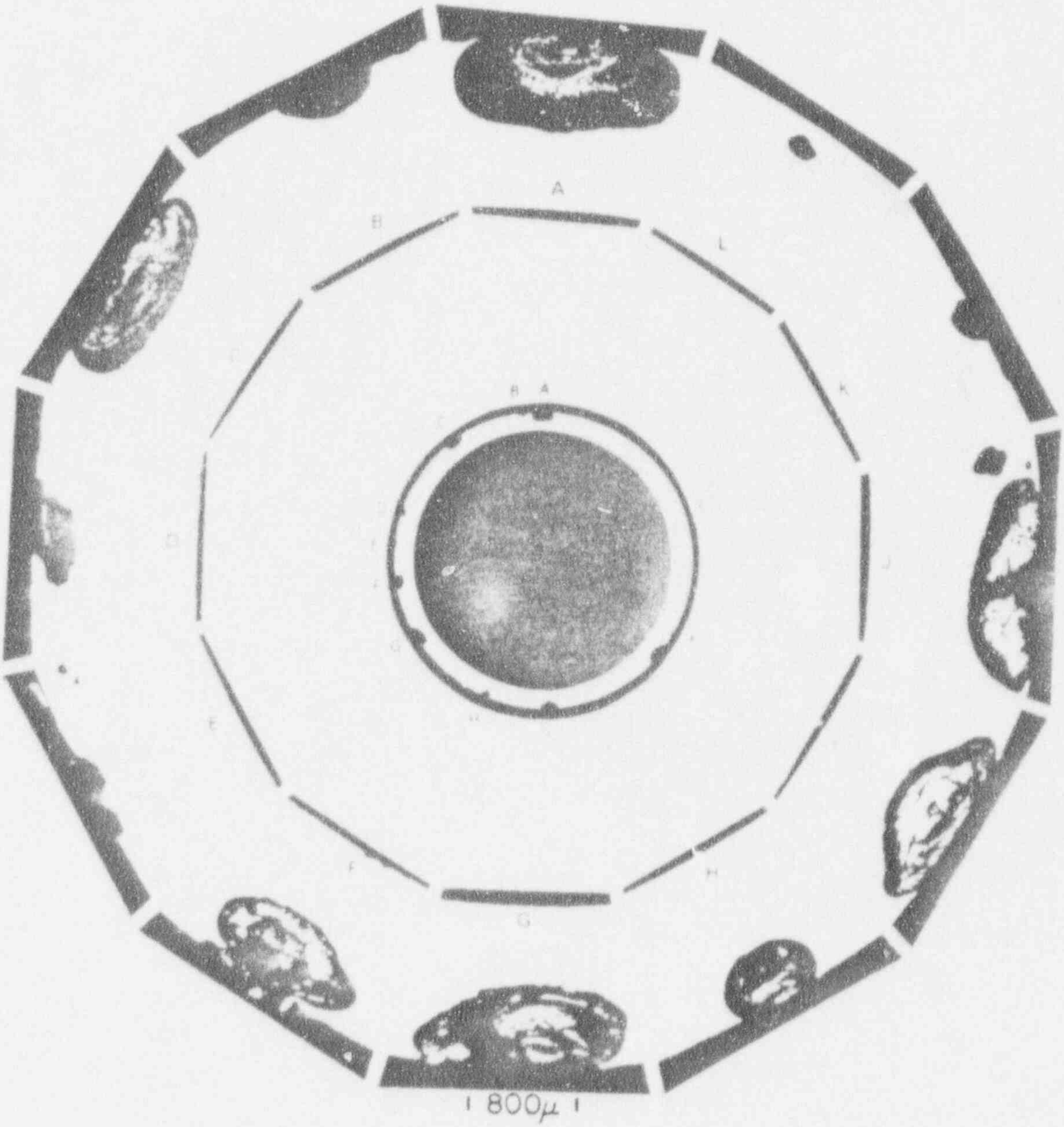
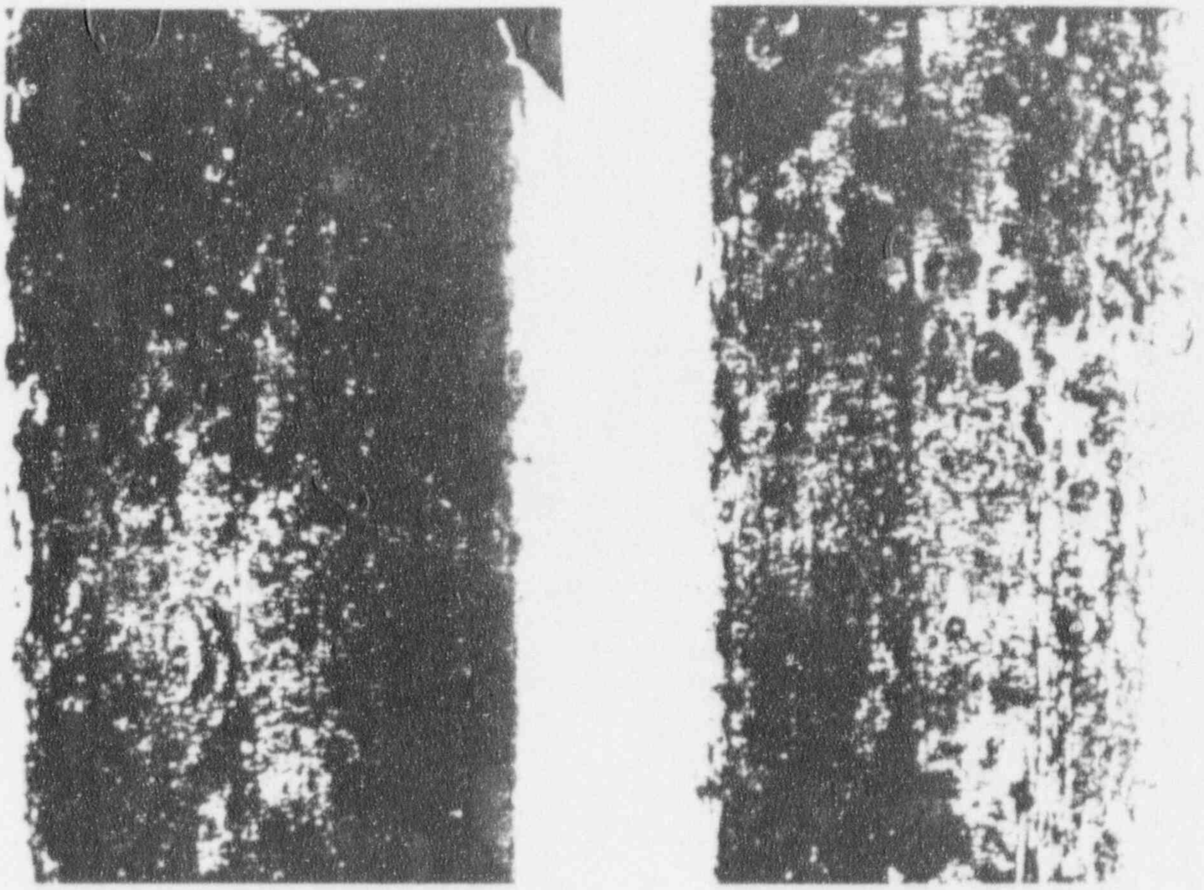


Figure C-21. Montage of Pitted Tube Showing Re-Entrant Pitting Geometry (Indian Point 3)


∿3X*

∿3X*

Figure C-22. Closeup Views of Pitted Tube Surface (Indian Point 3)

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* Please note that the illustration(s) on this page has been reduced 10% in printing.

copper deposition. These factors contribute to the formation of complex signal structures generally in the presence of a mix residual. Laboratory qualification studies directed towards optimizing eddy current data acquisition and analysis procedures were first reported in (6) for application at Indian Point 3 and Millstone 2. The program was conducted using pitting specimens fabricated electrochemically and plated with copper in order to simulate the generator environment. Experimental variables included various combinations of primary-mixing frequencies, coil spacing and winding width. Evaluation criteria included signal quality, signal-to-noise ratio, axial resolution, detection capability, and measurement accuracy. Key conclusions derived from these studies included:

- Differential bobbin coil focusing coupled with higher mixing and primary frequencies can provide improved axial resolution and signal-to-noise ratio. Focusing is achieved by decreasing coil winding length; preferred primary-mixing frequencies were determined to be (250 x 600) KHz.
- Special high frequency probes with a fill-factor greater than 80% are recommended.
- Pits with diameters greater than 0.050" and depths 50% through wall or greater are detectable in the presence of copper. Pitting with a lesser volume i.e., shallower depth but larger diameter or greater depth but smaller diameter, may not be detectable.
- Measurement accuracy was estimated to be +/- 10% through wall.

Initial laboratory specimen design was based on a detailed analysis of pit morphology observed on tubes removed from Indian Point 3 (7). Figure C-23 shows a scatter plot of measured pit diameter versus depth on two tubes. There is a reasonable correlation between diameter and depth; aspect ratio (diameter/depth ratio) is greater than one in most cases e.g., pits tend to increase in diameter as they corrode through the tube wall. Single pits at a depth of 40% through wall (20 mils) have an expected diameter of approximately 38 mils whereas for a through wall depth of 65% (32.5 mils), the expected diameter is 60 mils. Estimates of the performance capability of eddy current technology in detecting and measuring pitting in the presence of copper as derived from pulled tube data is shown in Figures C-24 and C-25. Figure C-24 shows estimated detection probability derived by comparing reported field eddy current analysis results with results determined destructively from metallography. Plotted is the fraction of pits reported as a function of pit depth. Twenty-seven data points were used to compile the results shown in the figure with the data quantized by depth in 10% increments. In general, the results are comparable with the laboratory studies in that reliable detection is achieved at depths on the order of 50% through wall. An estimate of measurement accuracy -

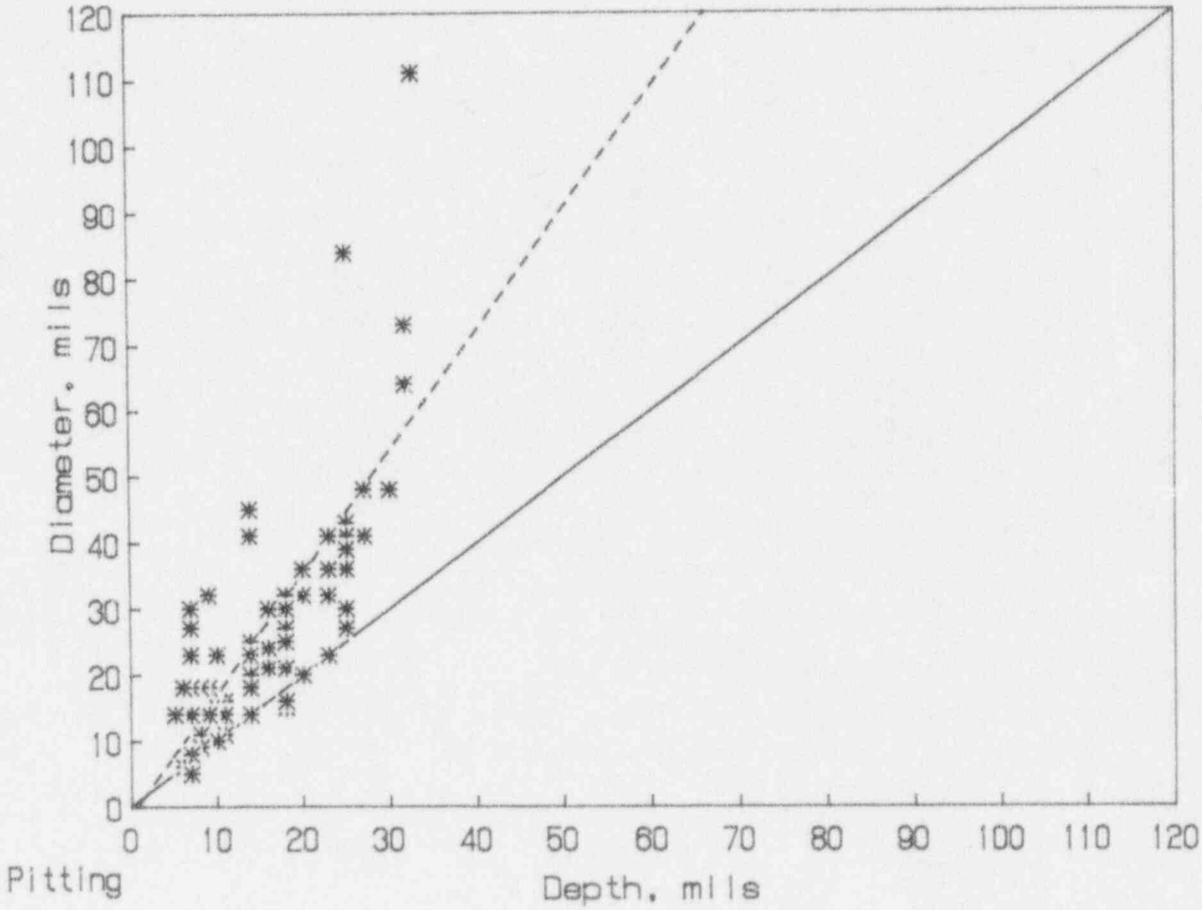


Figure C-23. Pit Depth - Diameter Correlation (Indian Point 3)

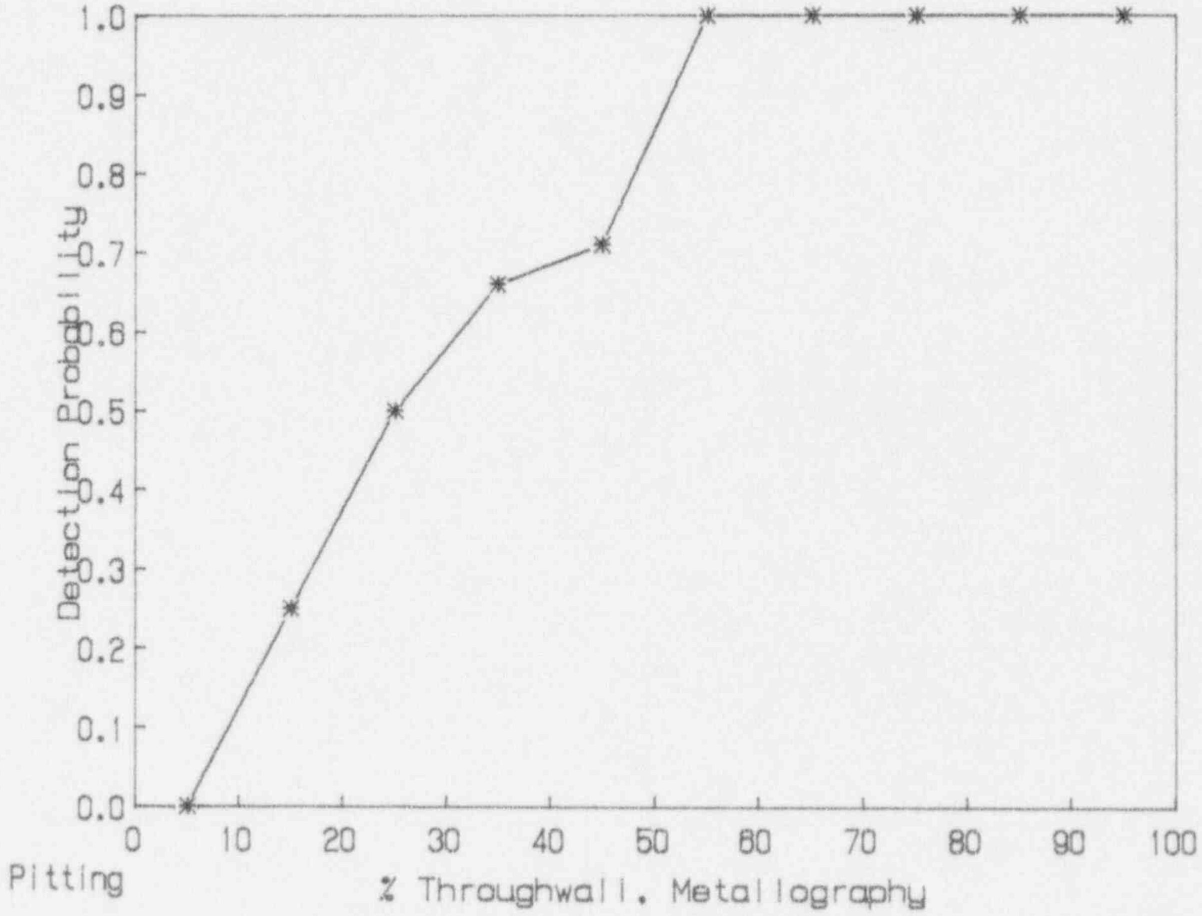


Figure C-24. Detection Probability - Pitting

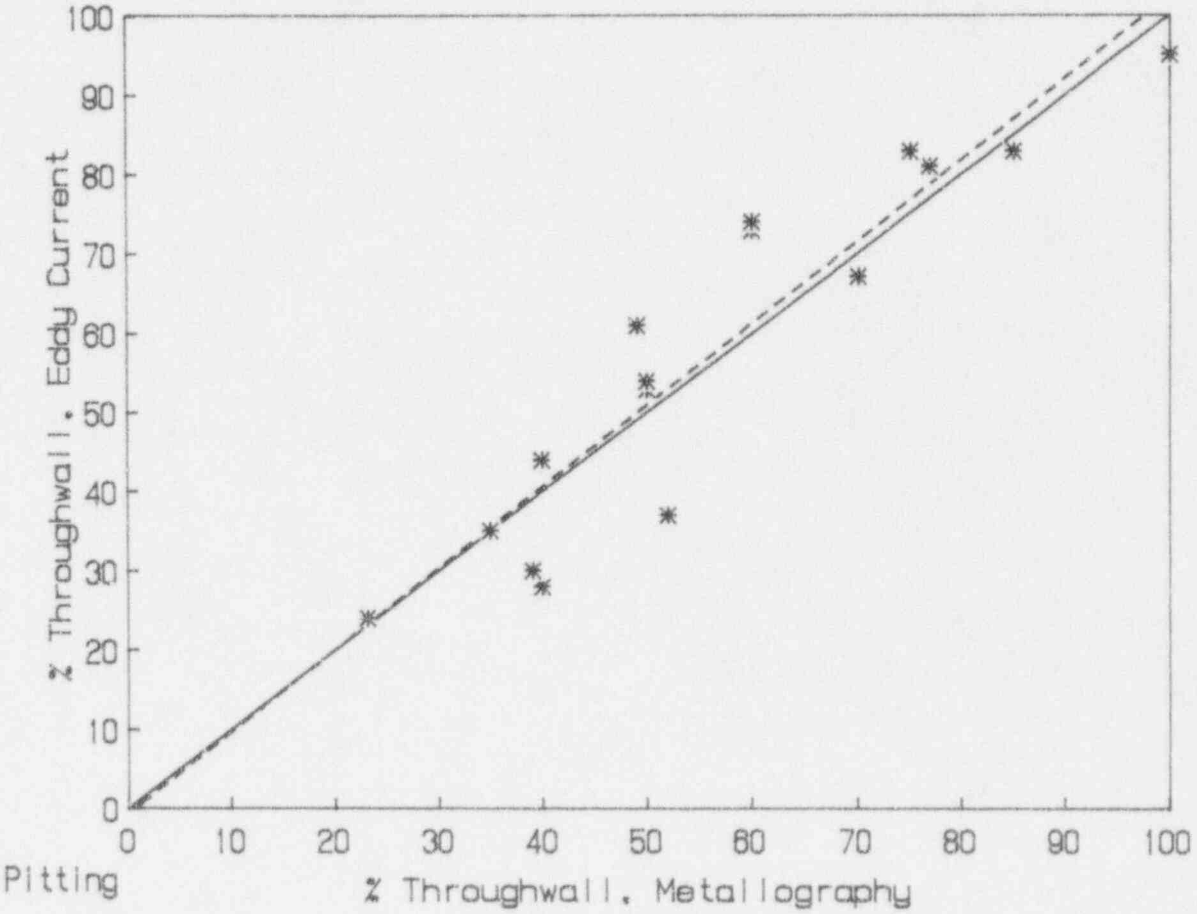


Figure C-25. Measurement Accuracy - Pitting again derived from pulled tube data - is given in Figure C-25 which shows a scatter plot of predicted eddy current depths versus depths determined destructively. The data is described by the equation $y = (1.03)x - 0.71$, with a correlation coefficient of 0.94. The bulk of the data is bounded by a +/- 10% error band which is comparable to the laboratory prediction.

C.4.1.3 Wear

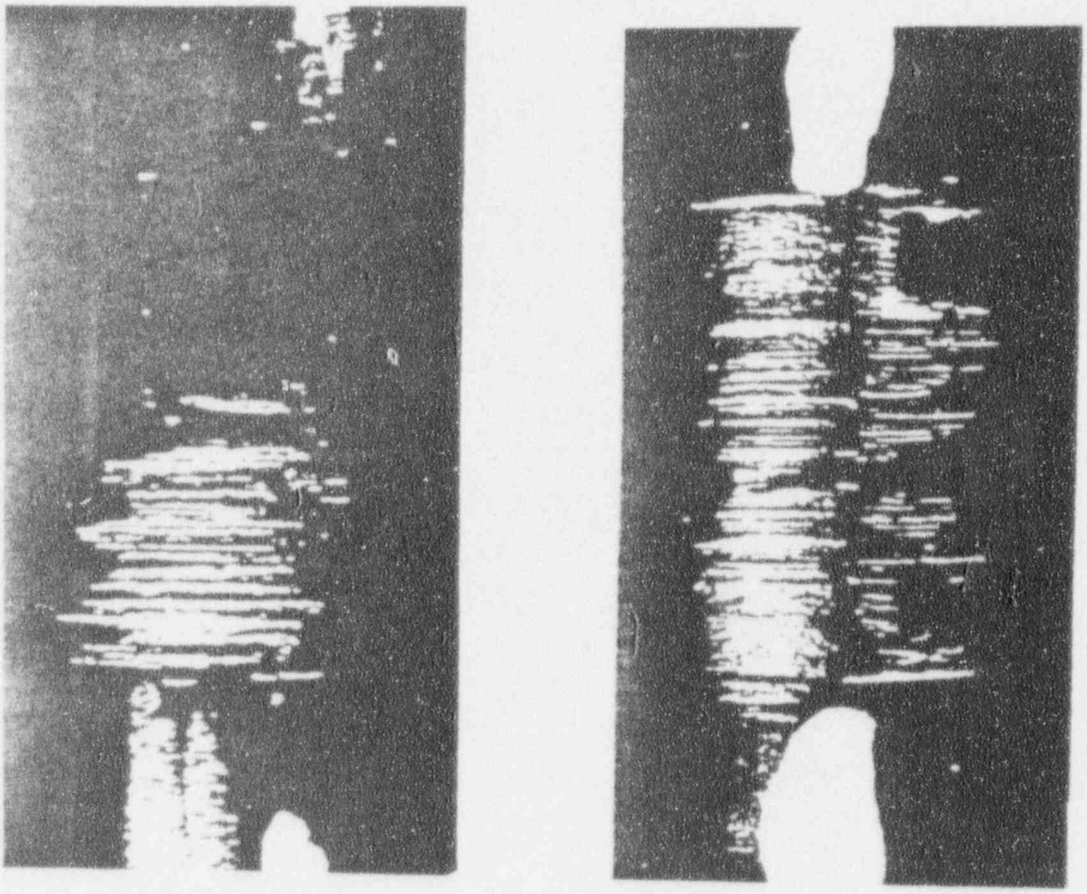
Wear is defined as the volumetric removal of material caused by the mechanical action of one material in contact with another. Wear cuts across grains nondiscriminately leaving a surface similar in appearance to one formed by general corrosion (4). Tube wear has occurred in steam generators designed by Westinghouse (preheater models at cold leg baffle plates and non-preheater models at the AVB's) and Combustion Engineering (diagonal and vertical support plate strips).

C.4.1.3.1 Wear at Preheater Baffle Plates

Experience with eddy current inspection for wear at preheaters baffle plates is summarized in (8). Some eleven tubes have been removed from Almaraz 1, Ringhals 3, and Krsko steam generators in order to characterize wear scar geometry and to develop and qualify improved sizing procedures.

Depth sizing was initially attempted using conventional mixed channel phase angle analysis in conjunction with the ASME eddy current standard. Comparison of eddy current predicted depths with depths determined metallographically showed extreme conservatism. This conservatism would result in plugging an excessive number of tubes and was attributed to poor signal-to-noise ratio. The mixed residual adds vectorially with the small amplitude wear scar signal in a conservative direction. To improve accuracy, signal amplitude sizing techniques were developed using wear scar calibration standards.

Design of wear scar calibration standards was based on a review of wear scar morphologies on pulled tubes with two basic geometries identified i.e., flat and tapered, as shown in Figure C-26. Which of the two geometries occurs depends on how the tube is aligned within the baffle plate. As shown in Figure C-27 the tube within a baffle plate can be inclined at some angle alpha which varies between zero and two degrees. This variation in inclination angle results in the two extremes of wear scar geometries, i.e., flat - in which the inclination angle is zero - and tapered - in which the angle assumes a non-zero value.



Flat

$\alpha = 0°$

Tapered

$\alpha \neq 0°$

Figure C-26. Preheater Wear Scar Geometries (Almaraz 1)

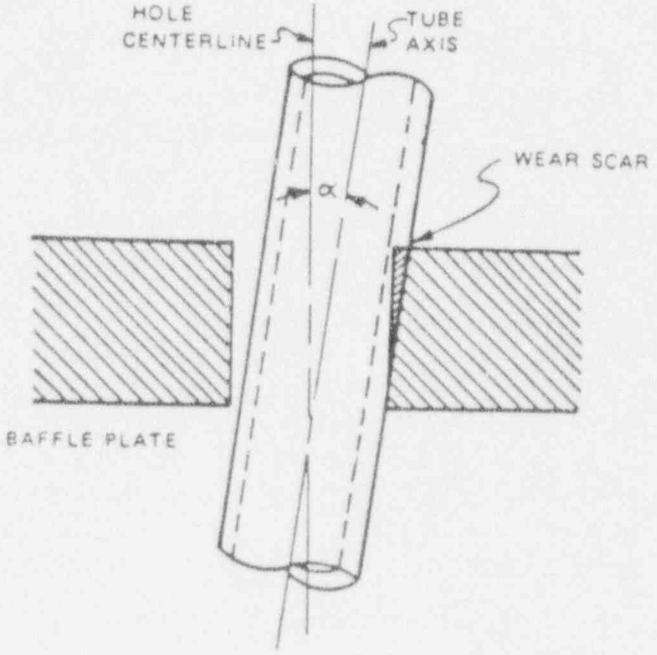


Figure C-27. Tube Inclined Within Baffle Plate Hole

An analytical model has been developed which relates wear scar depth to removed metal volume (8). This relationship is a function of the inclination angle and is shown in Figure C-28 for various angles. Measured data derived from pulled tubes is superimposed on the analytical predictions of Figure C-28. The scatter in the data is attributed to variations in inclination angle. As can be seen, essentially all of the measured data is bounded by the two-degree curve. A conservative estimate of depth is provided by the two-degree wear scar curve; however, an accurate fitting to all the data by a single curve is not possible because the inclination angle of a given wear scar is not known beforehand. Since eddy current signal amplitude is proportional to the removed metal volume, for a given wear scar inclination angle, signal amplitude can also be related to the maximum depth.

Both flat and tapered wear scar standards are used for sizing. Although the tapered scar standard results in a more conservative depth estimate, it is more difficult to fabricate. In addition, since a large eddy current data base already exists derived from a flat wear scar standard, it is advantageous to maintain historical continuity with past records. Accordingly, sizing approaches based on using a tapered wear scar standard directly and one which utilizes a transformation of the flat wear scar calibration curve have been developed. In both cases, eddy current data acquisition is accomplished using an absolute bobbin coil with a (100 x 300) KHz mix for baffle plate suppression. 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 calibration curve is used which is now explained in more detail.

The curves shown in Figure C-28 can be approximated by an equation of the form

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

where

Vol(50%) is the volume of the zero degree 50% depth flat wear scar which from Figure C-28 is about 157 cubic millimeters.

Vol are the volumes of other wear scars at various depths 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.

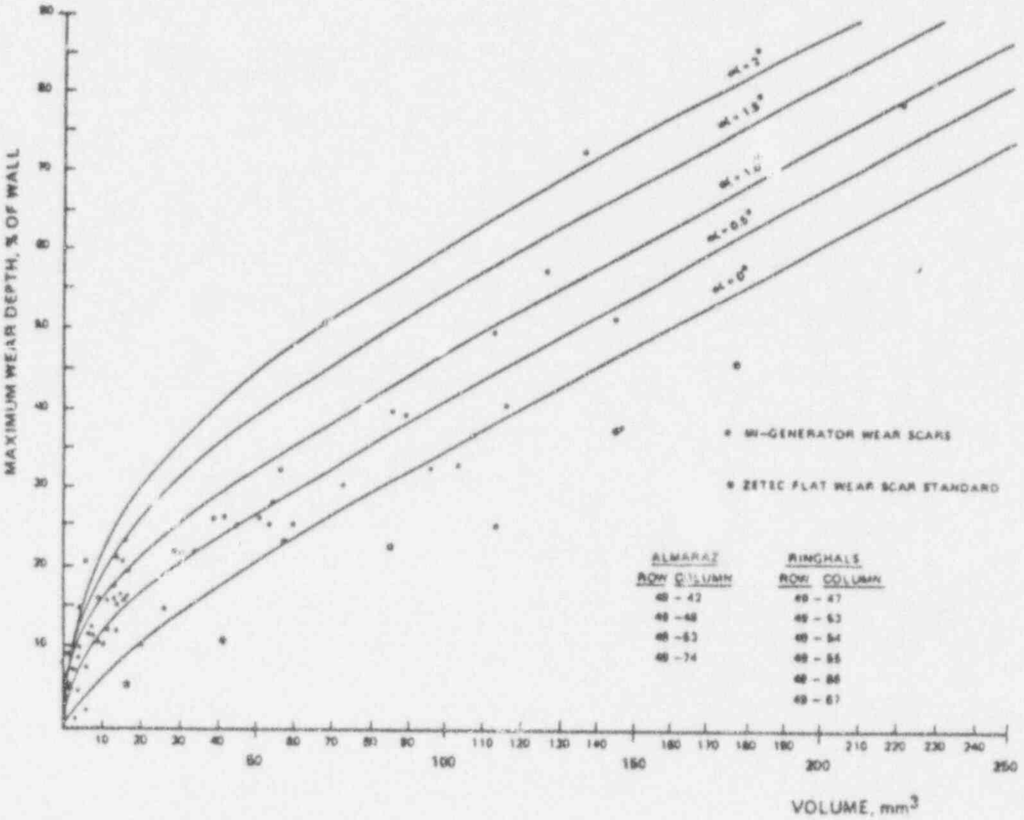


Figure C-28. Wear Scar Volume Versus Maximum Depth - Various Tube Inclination Angles

Since wear scar volume and eddy current signal amplitude are proportional, the volume dependency in Eq. (C-1) can be replaced by wear scar standard (alpha = zero degrees) signal amplitudes. Swedish State Power Board engineering staff have also determined empirically from pulled tubes that a best choice for C is a value of 60. Accordingly, we have

$$\log W = 60 + 0.5 \{V - V(50\%)\} \qquad \text{Equation (C-2)}$$

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.

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

This transformation approach has been compared directly with results using the tapered standard and the two agree to within five percent.

A scatter plot showing eddy current predicted depth with measured wear scar depth for tubes removed from Ringhals 3 steam generators is shown in Figure C-29. A least squares fit of the data is conservative and is described by the equation $y = .95x + 4.65$. The correlation coefficient has a value of 0.98. Estimated detection probability is shown in Figure C-30. As with thinning, there is no evidence of a reliability problem.

C.4.1.3.2 Tube Wear at AVB's and Support Straps

Tube wear at antivibration support members (bars in Westinghouse units or straps in Combustion Engineering units) can be one or two sided depending on the displacement amplitude of adjacent supports. Eddy current signals from shallow wear can have relatively small amplitudes which are strongly influenced by the antivibration support member. Conventional phase angle analysis of wear signals can result in a significant overestimation of depth. As with preheater wear scars, signal amplitude sizing techniques using appropriate standards can be used to provide a better estimation of depth.

Antivibration bar or strip wear standards are typically constructed to duplicate the geometry of the vibrating member. Since tube wear can be one or two sided, certain assumptions have to be made in order to assure a conservative estimate of depth. A

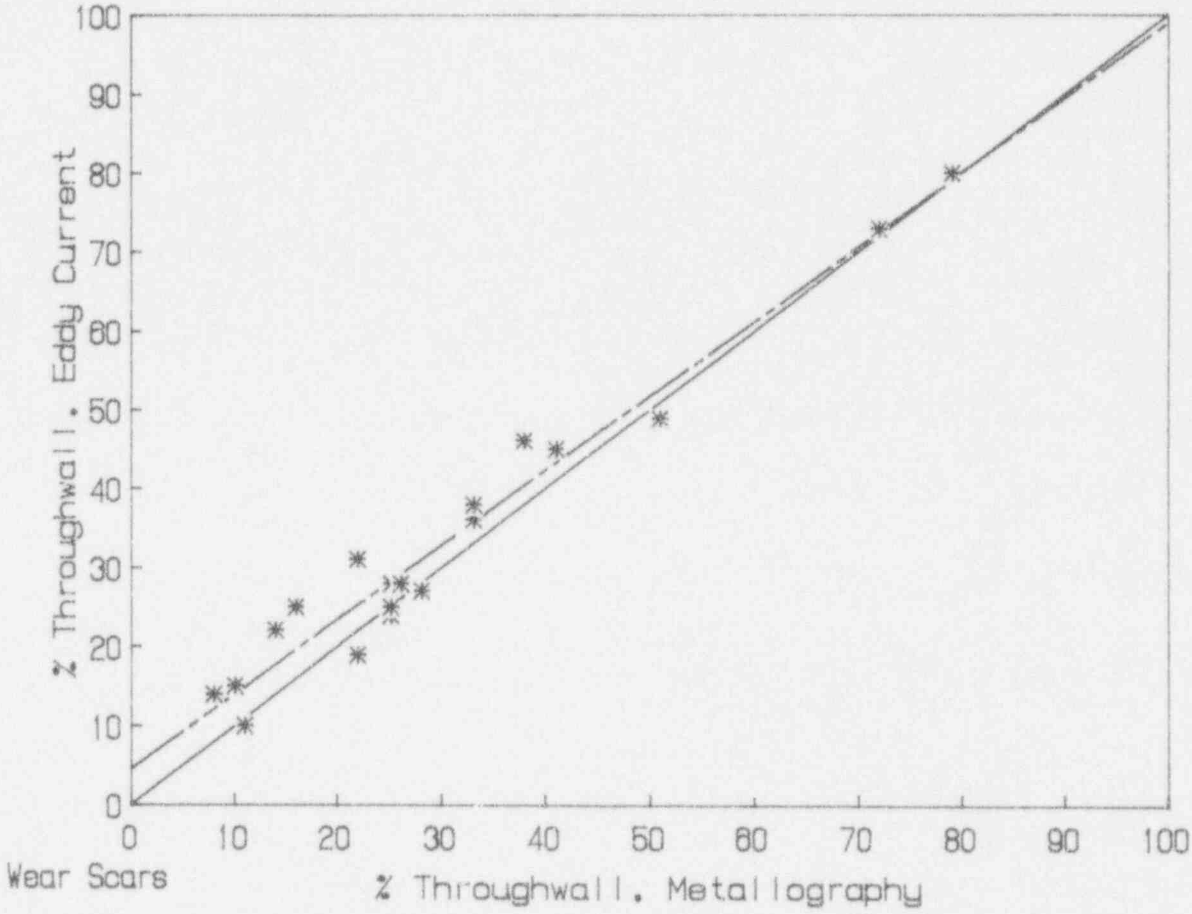


Figure C-29. Measurement Accuracy - Preheater Wear Scars

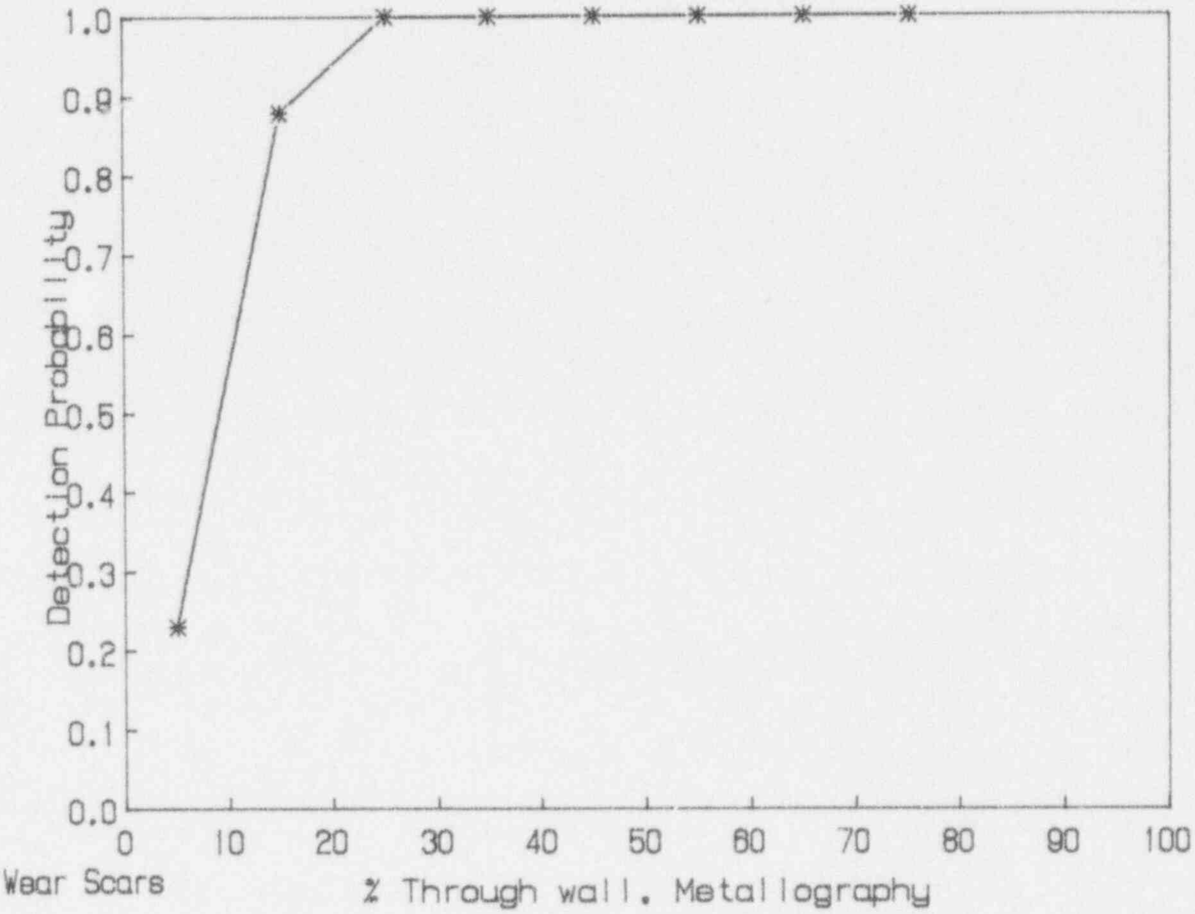
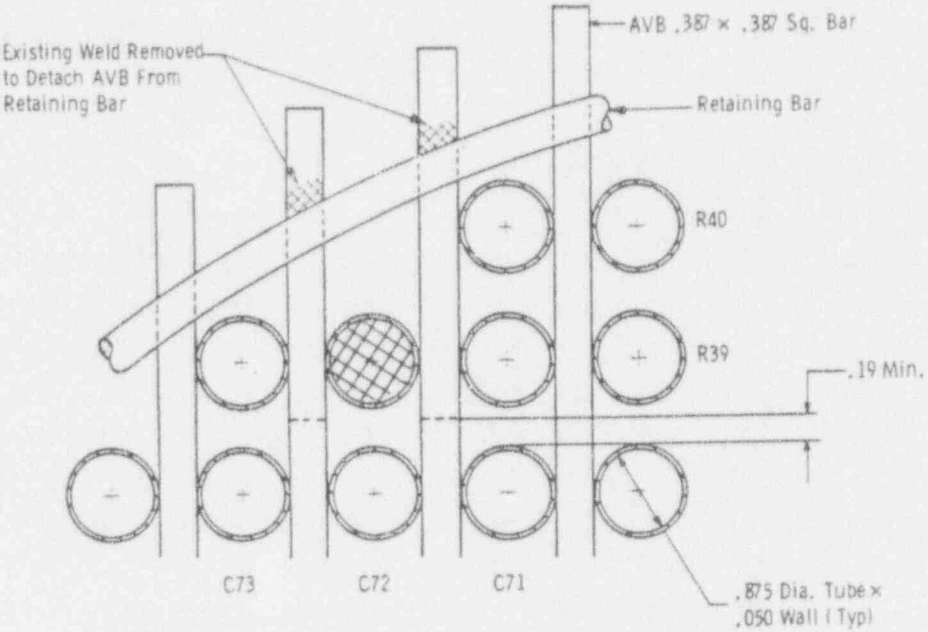


Figure C-30. Detection Probability - Preheater Wear Scars conservative depth estimate is provided if a single-sided standard is used since the eddy current signal amplitude response is proportional to the total removed metal volume. Array coil or segmented bobbin coil technology can be used to distinguish between one and two sided wear. If this is done then further conservatism in depth sizing can be reduced. Calibration curves are generated using single-sided wear scar standards.

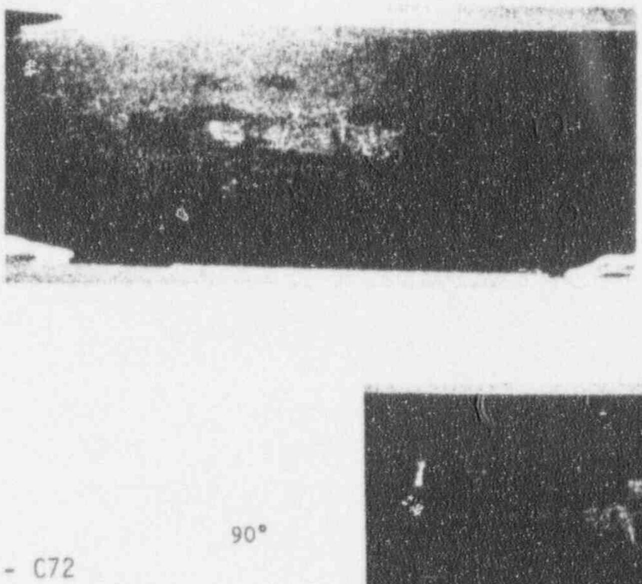
Since eddy current signal amplitude is proportional to the removed metal volume, for a given wear scar inclination angle, signal amplitude can also be related to the maximum depth. Very little well documented data is available from the pulled tube data base to provide estimates of measurement accuracy and detection probability. Figure C-31 shows a wear scar removed from Zion 1 and the location of the removed tube within a Model 51 steam generator tube bundle. The antivibration bars and their retaining bar are also shown in the figure. The original field eddy current analysis estimated the depth of the wear scar at 44% through wall using conventional phase angle analysis with the ASME standard. Destructive examination of the tube showed two-side wear to be present with a depth of 20% on one side of the tube and 8% through wall on the opposing side. The excessive conservatism resulting from phase angle analysis is apparent.

Laboratory studies of this tube using one and two-sided wear scar standards are now considered. Figure C-32 shows calibration curves generated using one and two-sided wear scar standards. Measured signal amplitude from the pulled tube wear scar with the antivibration bar in place using a (100 x 400) KHz differential mix was approximately 7.4 volts as indicated by the horizontal dashed line in the figure. Estimated depth using the single wear scar calibration curve is approximately 14 mils or 28% through wall whereas using the two-sided wear scar calibration curve, the estimated depth is 16% through wall. Again, the maximum actual depth was 20% through wall. The predicted depth derived using signal amplitude more closely approximates the true depth than that predicted from phase angle analysis. The conservative predictions of the single-sided standard as compared with the two-sided standard is also apparent.

Extensive laboratory data has been generated using simulated single-sided and two-side wear scar standards. Experimental results basically confirm the extreme conservatism associated with the conventional phase angle analysis and improved sizing capability using appropriate wear scar standards. Figure C-33 shows a scatter plot of predicted eddy current depth versus maximum true depth for double-sided wear scars. The initial calibration curve was established using a single-



270°



90°

R39 - C72
(Two Views)

Figure C-31. AVB Wear - Zion 1

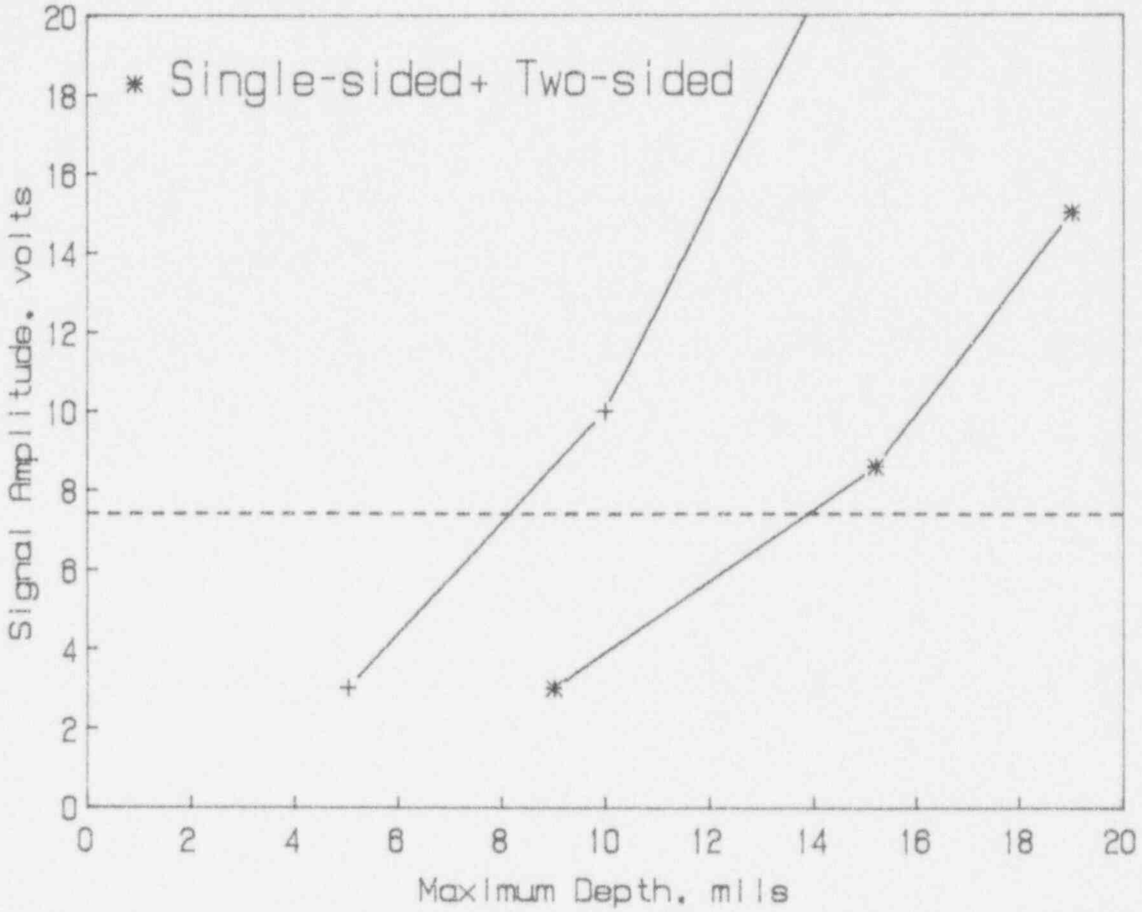


Fig e C-32. AVB Wear Calibration Curves - Single and Two-Sided Wear

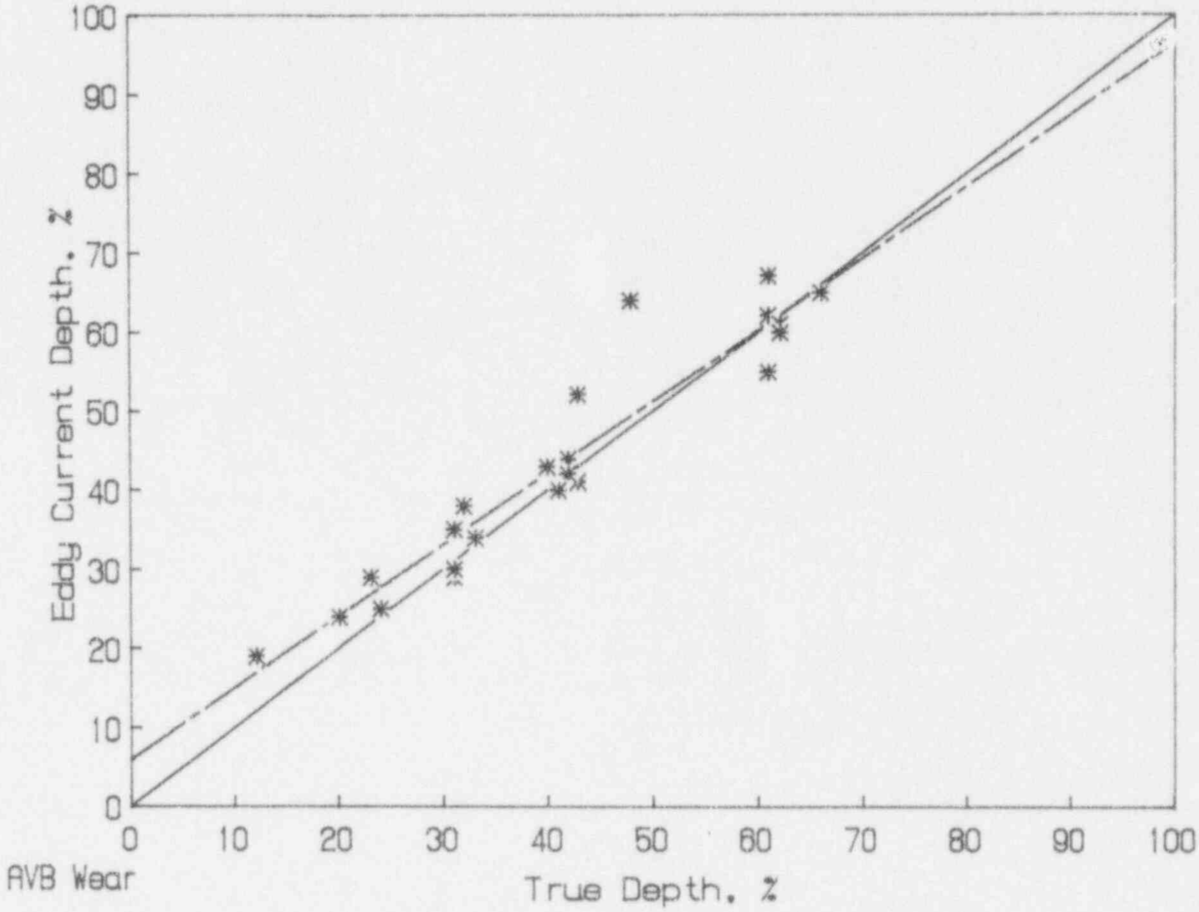


Figure C-33. Measurement Accuracy - AVB Wear (Lab Data) sided wear scar standard; signal amplitude derived from a (630 x 160) KHz differential mix (11/16" diameter tubing, 0.043" wall) was used as the estimator of depth. A least-squares fit to the data in Figure C-33 is given by $y = 0.90x + 6.14$, with a correlation coefficient of 0.95. As can be seen from the figure, the predicted depths are statistically conservative over the normal range of plugging limits. Estimated lower bound detection capability derived from laboratory experiments is on the order of 20-30% through wall.

The pulled tube data base for wear at vertical and diagonal support straps in Combustion Engineering units is also somewhat sparse. Only one tube has been removed (Calvert Cliffs) with a wear scar (9). This tube (R99-L143) is shown in Figure C-34. The measured maximum depth was 32% through wall whereas the field eddy current analysis was <20% through wall. Batwing wear was present on both sides of the tube.

Laboratory data has been generated which can be used to provide estimates for detection and sizing of wear at support straps in Combustion Engineering units. This information was developed in support of San Onofre 2 (10) which has experienced wear at the diagonal support straps near the central stay cylinder region of the steam generator (See Appendix B Figure B-20). The diagonal support strap intersects the tube at a 60 degree angle as shown in Figure C-35. The dynamics of the wear process can result in wear scars of different lengths l, and wear penetration angles as shown in Figure C-36. Figure C-37 shows a scatter plot of predicted eddy current depth versus true depth for wear scars varying in length from 1/2" to 2". A single-sided wear scar standard was used to establish the initial calibration curve; signal amplitude was used for sizing using a (100 x 300) KHz absolute mix. The least squares fit to the experimental data is given by $y = (0.86)x + 5.45$ with a correlation coefficient of 0.99. The results are statistically conservative over the range of normal plugging limits. A lower limit on detection is estimated at 20% through wall.

C.4.1.4 Intergranular Attack - Stress Corrosion Cracking

Intergranular attack is defined as the three dimensional corrosion of grain boundaries. The attack can be volumetric with no preferred growth direction or can grow with stress assistance in preferred directions referred to as intergranular penetrations. Stress corrosion cracking is defined as a two dimensional corrosion degradation of grain boundaries. Stress corrosion cracking is typically axially oriented because of normally dominant tube hoop stresses. However, circumferential

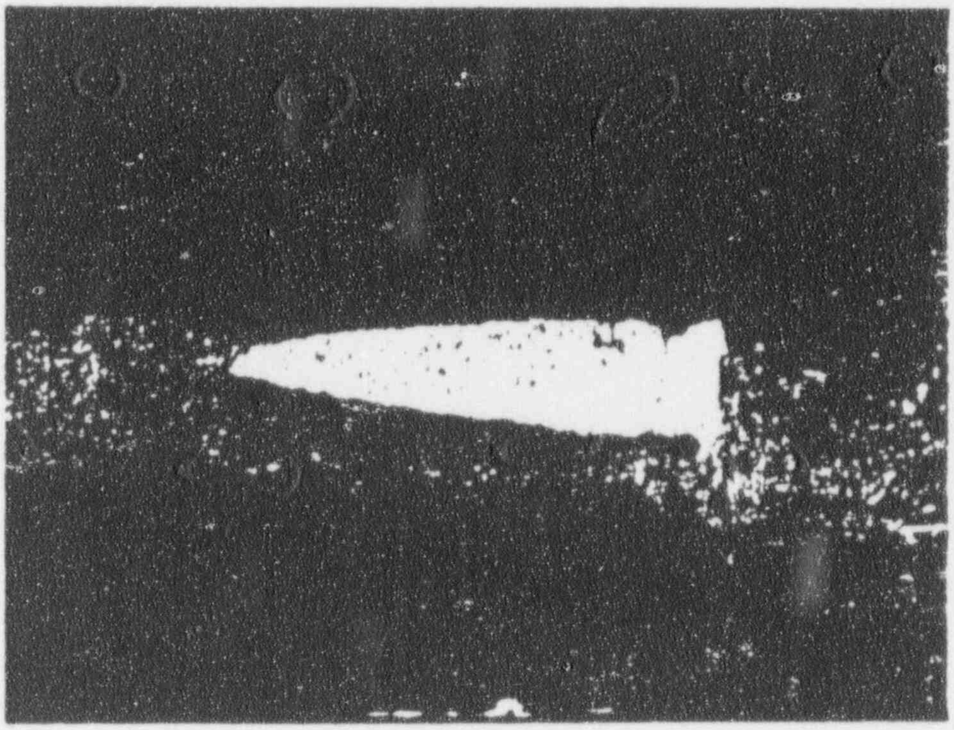


Figure C-34. Batwing Wear - Calvert Cliffs 1

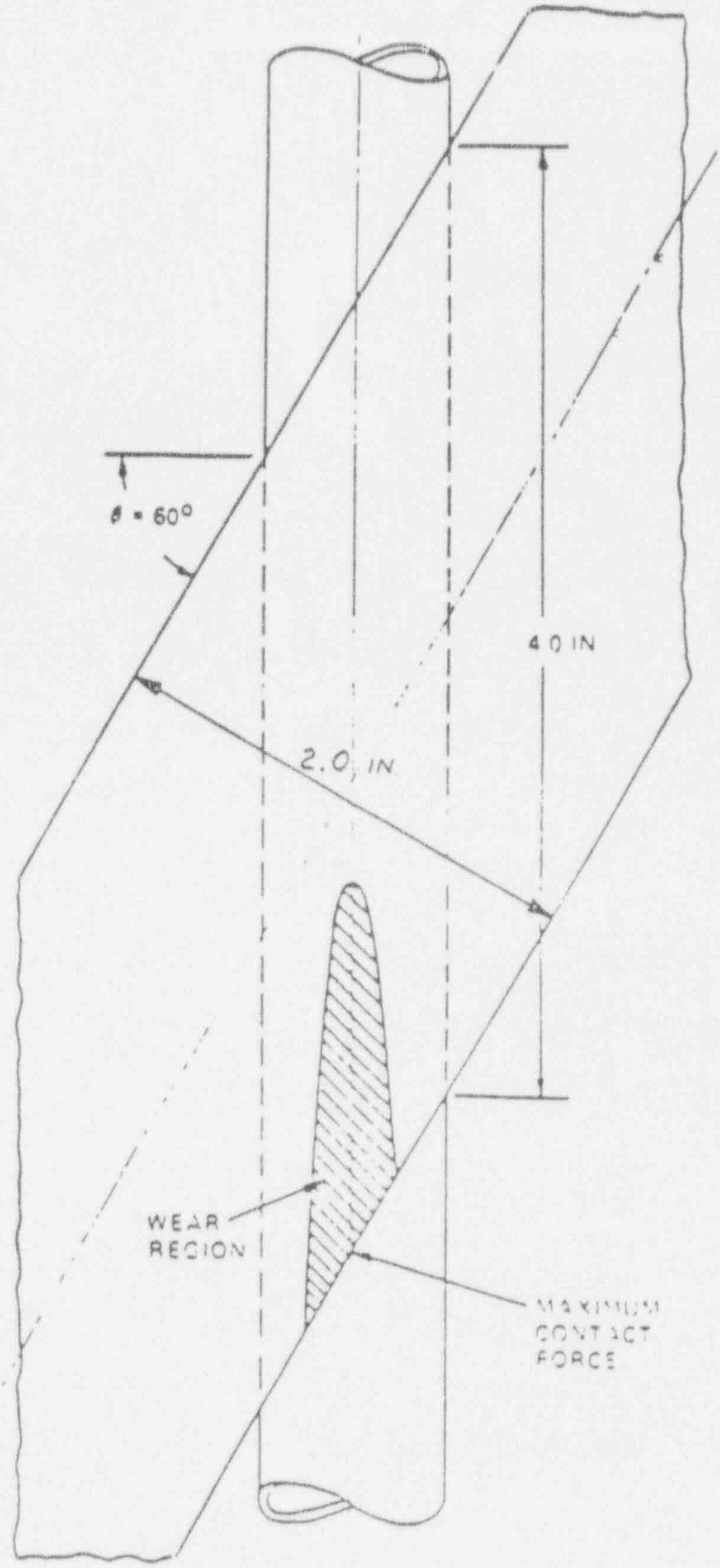


Figure C-35. Batwing Strip Wear Geometry (San Onofre 2)

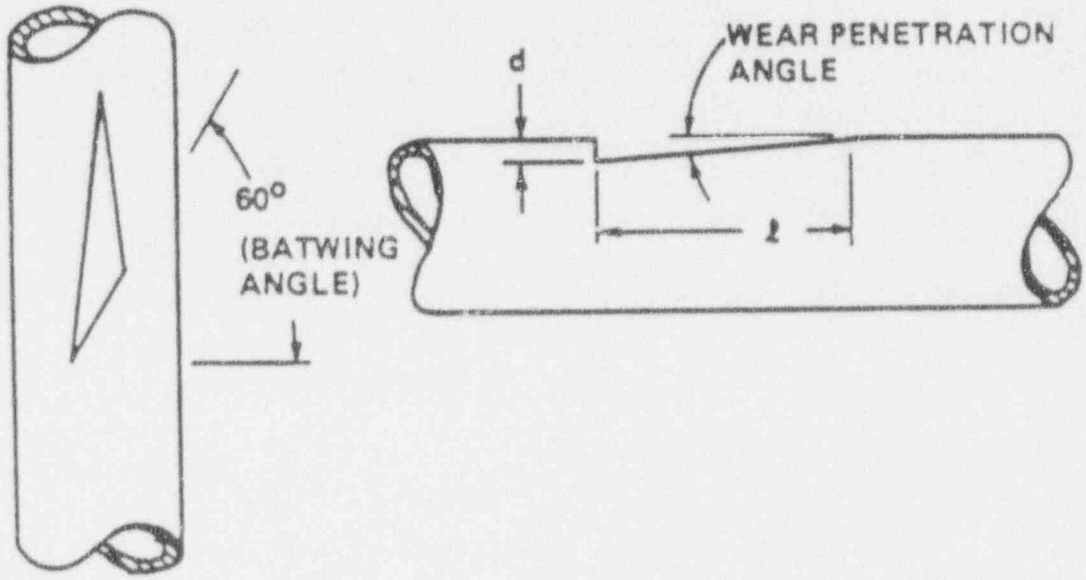


Figure C-36. Batwing Wear Scar Standards

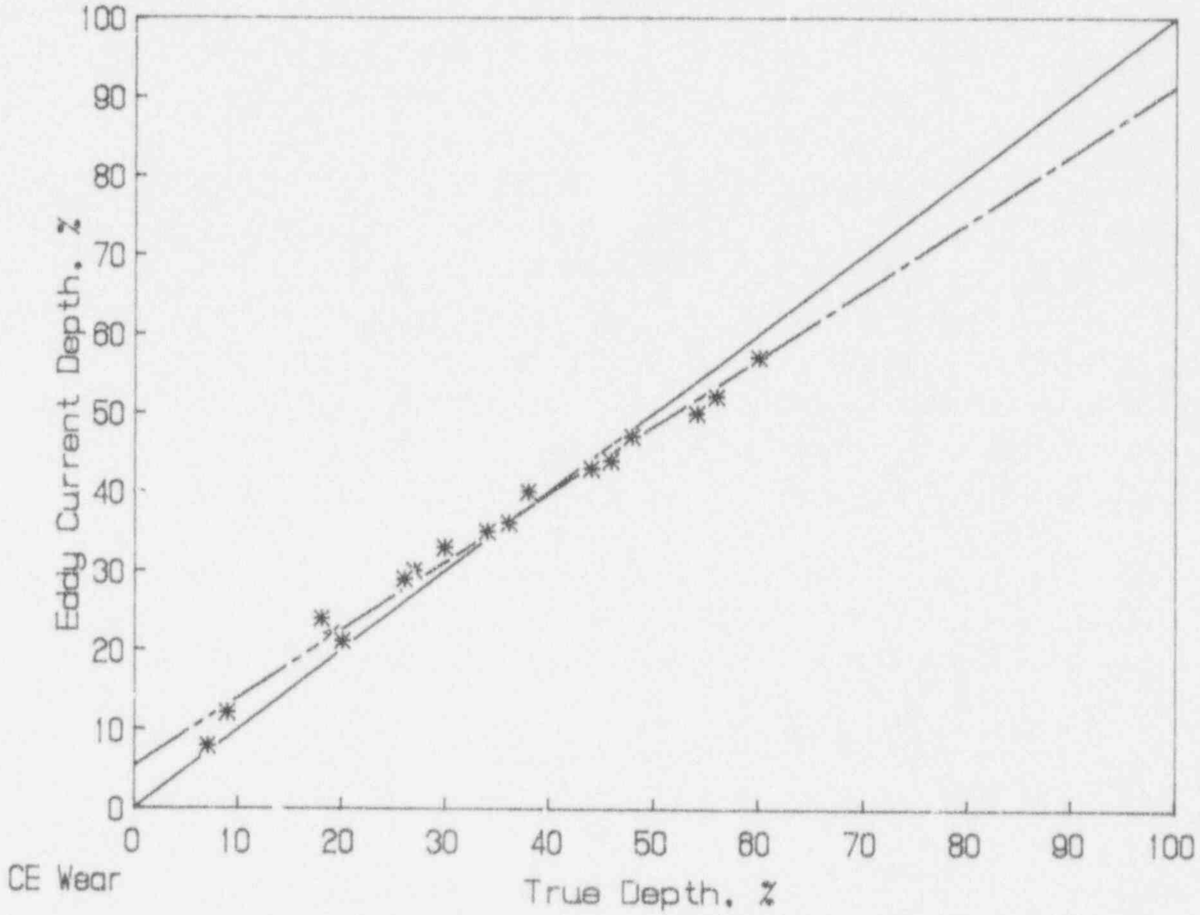


Figure C-37. Measurement Accuracy - Batwing Wear (Lab Data) cracking or hybrid combinations of the two can occur if unusual stresses happen to locally dominate over the normal hoop stresses (4). Figure C-38 illustrates typical morphologies of stress corrosion cracking and intergranular attack.

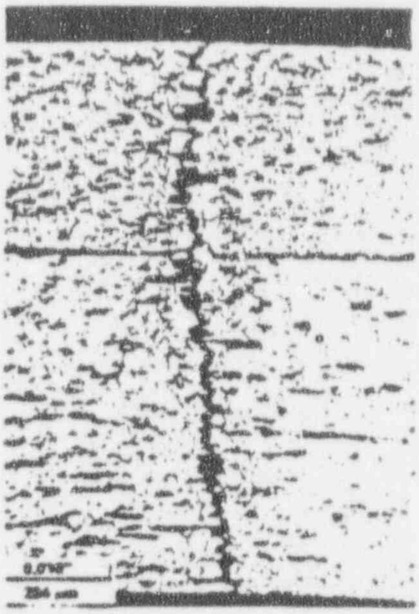
Most of the intergranular attack and stress corrosion cracking has been confined to the tube sheet crevice in units with open crevices. Some units have also experienced attack within the sludge pile at and above the top of the tube sheet and at support plates. See Figure C-39. Intergranular attack within the tube sheet crevice region in Westinghouse units has for the most part been attributed to high temperature caustic attack (11). Stress corrosion cracking at the support plates has been attributed to residual from welding flux rods during steam generator manufacturing (12). In Combustion Engineering units, intergranular attack has occurred within the sludge pile (Calvert Cliffs 1) at eggcrates (St. Lucie 1) and in the free span of the tube within the upper tube bundle (Palisades). This attack has been attributed to low-temperature sulfur compounds.

As will be discussed in subsequent paragraphs, detection of intergranular attack has in some cases proven difficult, with caustic induced intergranular attack more difficult to detect than attack resulting from sulfur compounds. Intergranular attack occurs as the result grain boundary degradation. Physically, there is no decrease in tube wall thickness; rather, a region of the tube has its material property values i.e., resistivity, permeability, or both, altered as the result of corrosion. The effects of resistivity variations have been modeled in (13) using finite element computer codes. Results from this study show that the signal amplitude is a function of the ratio of the resistivity of the intergranular attacked region to that of the nominal resistivity of Inconel. This is shown in Figure C-40 for various ratios. Resistivity ratios for intergranular attack on pulled tubes have not been measured directly but have been inferred using plant eddy current data and finite element codes (13). The estimated range for this ratio was 2-4. Measured resistivity values for intergranular attacked tubes prepared in the laboratory using different methods are given in Table C-1 (14):

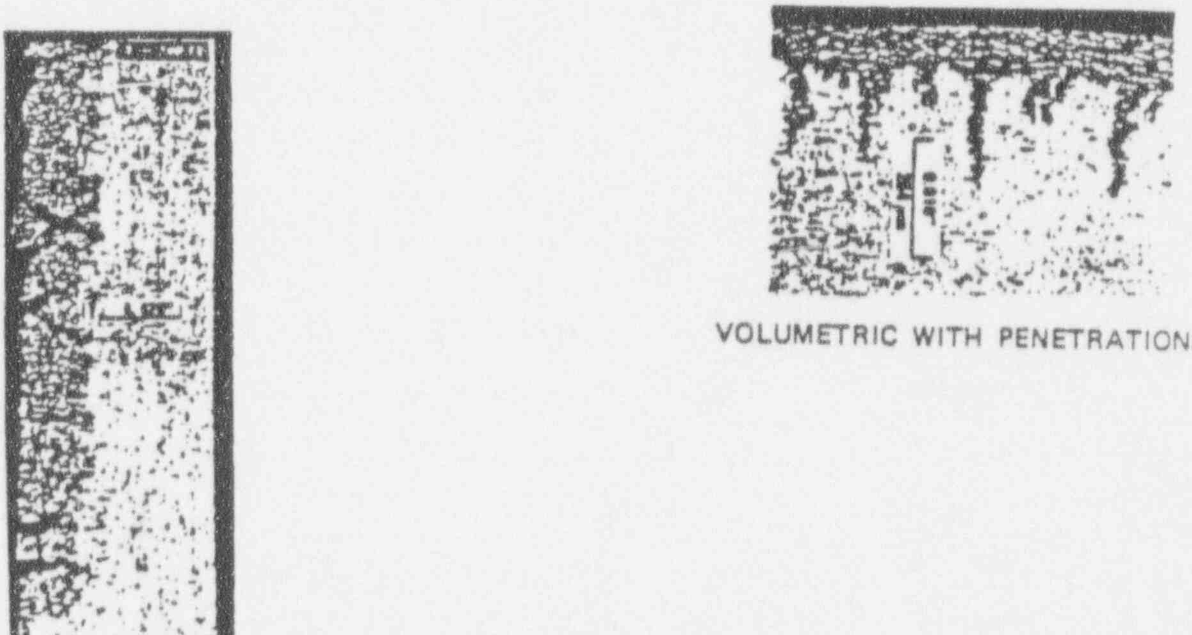
Table C-1

INTERGRANULAR ATTACK RESISTIVITY RATIOS

Method of Preparation	Resistivity Ratio
• Low-Temperature Sulphur	1.5
• High-Temperature Caustic	2.4
• Nitric Acid	10.0



(A) STRESS CORROSION CRACKING

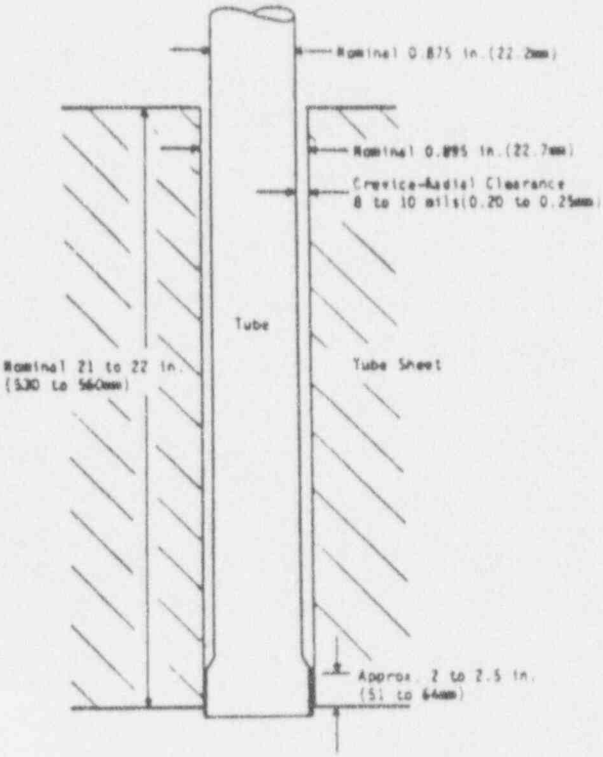


VOLUMETRIC

VOLUMETRIC WITH PENETRATIONS

(B) INTERGRANULAR ATTACK

Figure C-38. Stress Corrosion - Intergranular Attack Morphology



Typical Tube Sheet Crevice (2)

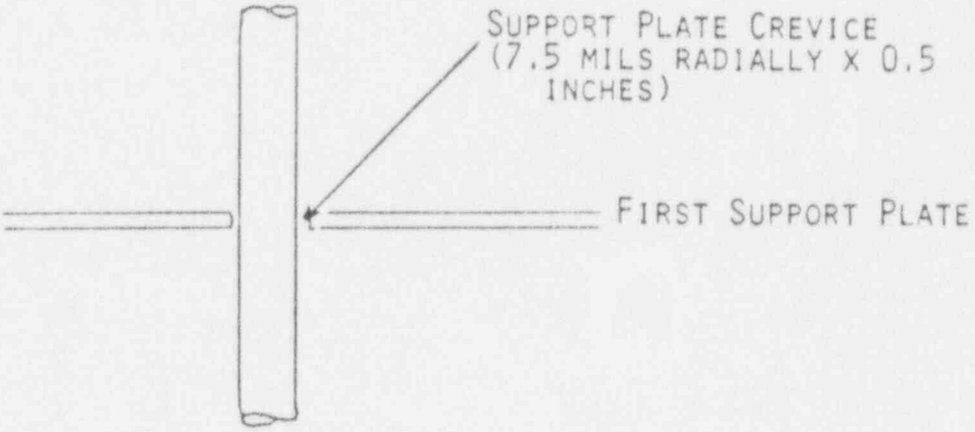
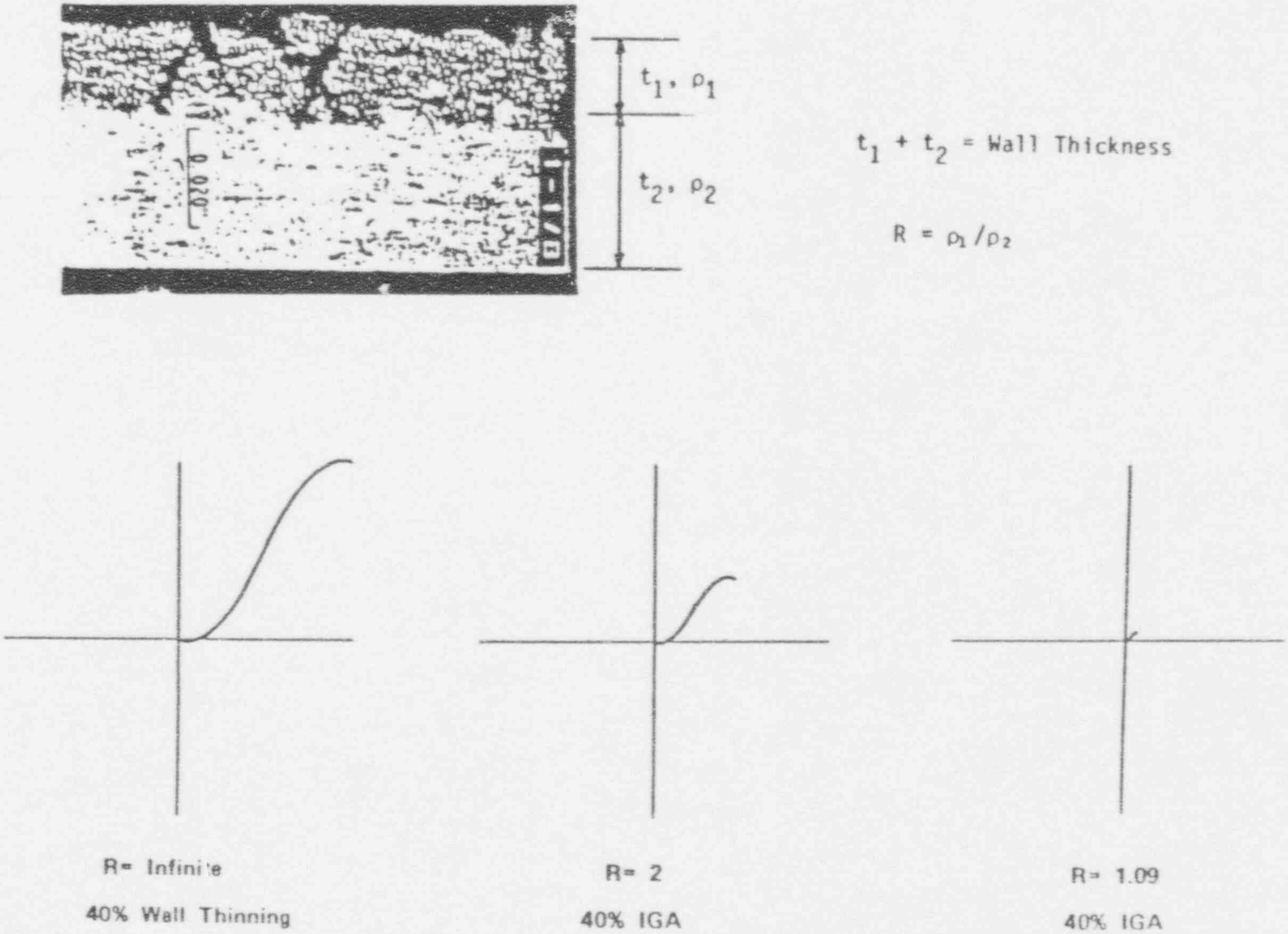


Figure C-39. IGA/SCC - Support Plate and Tube Sheet Crevice



$t_1 + t_2$ = Wall Thickness

$R = \rho_1/\rho_2$

R= Infinite
40% Wall Thinning

R= 2
40% IGA

R= 1.09
40% IGA

Figure C-40. Finite Element Eddy Current Code Predictions - Effect of Resistivity Ratio on Signal Amplitude

Direct measurement of the resistivity of laboratory caustic intergranular attacked specimens gives a value consistent with that estimated for a plant tube. The laboratory data also shows that the high-temperature caustic produced intergranular should be easier to detect than the low-temperature sulphur attack because of a higher resistivity ratio. This simply has not been reflected in plant experience; the reason for this difference has yet to be explained.

C.4.1.4.1 Tube Sheet Crevice Region

Crevice region secondary side intergranular attack and stress corrosion cracking have caused numerous forced outages in Westinghouse steam generators. Analysis practices for intergranular attack and stress corrosion cracking vary widely from plant-to-plant generally because experience with the damage mechanism - in terms of consequences - has varied. In some cases, the mere detection of a signal believed attributable to IGA/SCC is sufficient cause for initiating tube repair. In other cases, amplitude threshold criteria are utilized before repair action is initiated. Specific analysis channels have typically included the use of low and intermediate frequencies in a differential mode, e.g., 100 KHz and 400 KHz, a mixed differential channel, (100 x 400) KHz, and absolute coil mode.

A review of plant forced outages, in-plant eddy current data, and pulled tube metallographic results has identified several factors which have contributed to unscheduled plant outages. Key factors include:

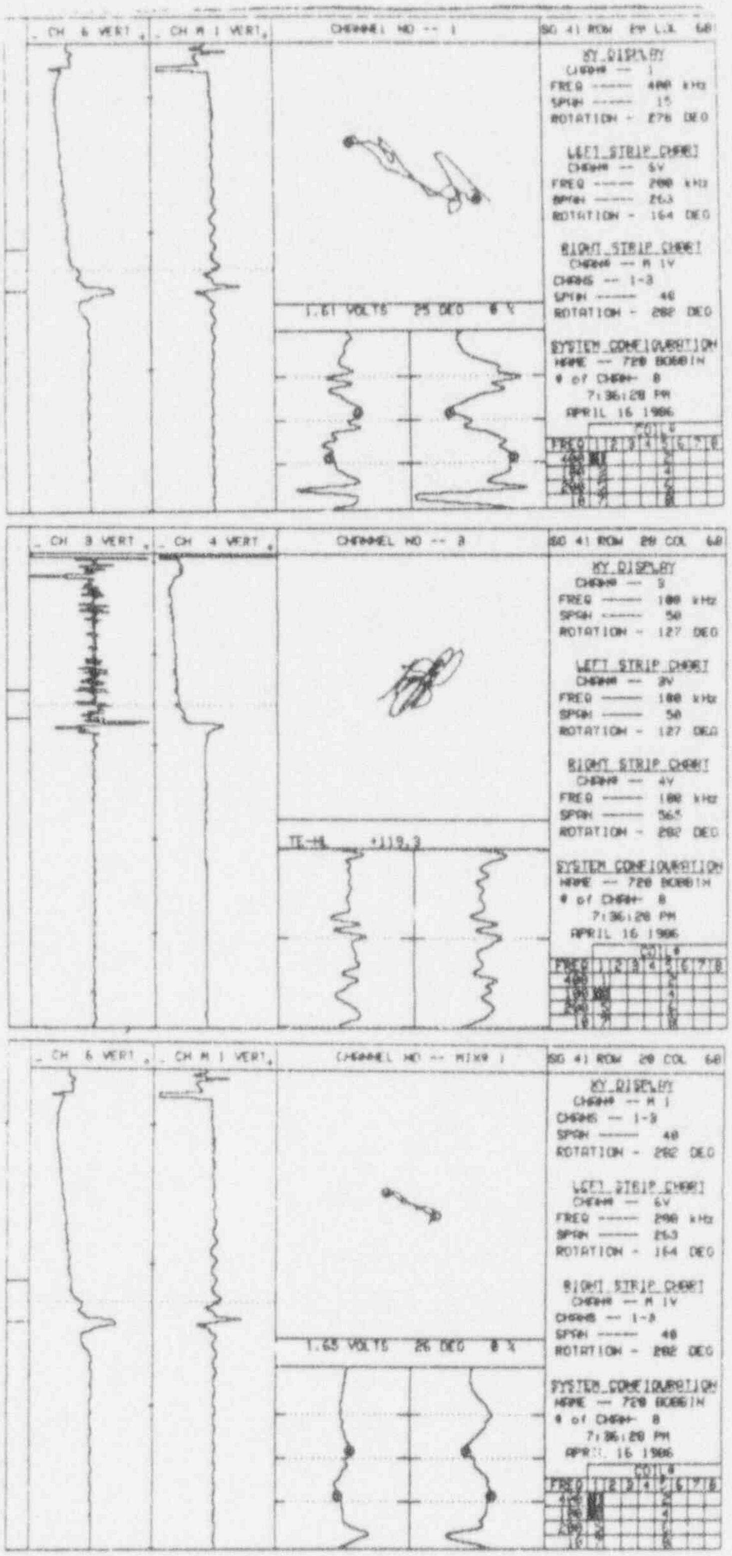
- Inadequate sampling of the steam generator
- Rapid growth rates
- Limitations of conventional eddy current bobbin coil technology
- Eddy current data analysis practices

Various plant case studies are now presented which focus on these reliability issues. As discussed in an earlier section, some units with intergranular attack have attempted to implement standard technical specifications sampling procedures, i.e., 3% basic plus expansion programs. This has proven to be inadequate in that leakage on start-up has occurred. As a general rule, 100% of the affected region of the steam generator must be examined to assure the removal of all defective tubes.

Some tubes which developed leaks have shown no evidence of tube wall degradation during the previous examination. This suggests rapid growth rates or technology limitations in detection. Rapid growth rates and technology limitations can be accommodated by more sensitive inspection methods or shorter operating intervals. Evidence for bobbin coil technology limitations is given in Figure C-41. Bobbin coil data acquired from the crevice region of a tube is shown at 400 KHz, 100 KHz and (400 x 100) KHz mix top-to-bottom. The tube was judged not to be degraded based on analysis of the bobbin coil data; a large copper residual was identified just below the top of the tubesheet. Rotating pancake coil data from this region of the tube shown in Figure C-42 clearly shows the presence of a linear indication suggestive of stress corrosion cracking estimated to be 80% through wall. Improved detection with the rotating pancake coil is consistent with the concept that a small pancake coil has a better signal-to-noise ratio in the presence of secondary side extraneous variables distributed around the tube circumference.

Evidence for rapid growth rate is given by the example shown in Figure C-43. Shown is rotating pancake coil data from a tube that developed a leak approximately two months after the outage. The presence of linear indications characteristic of stress corrosion cracking is apparent. By chance, this particular tube was examined during the previous scheduled outage using both bobbin and rotating pancake coil (the latter is shown in the lower part of the figure) throughout the tube sheet crevice region. No indications were present in either of the two data sets. This particular plant does not have copper in its balance-of-plant so that copper signals were not a contributing factor in decreasing the signal-to-noise. A lower bound detection estimate of rotating pancake coil technology for secondary-side stress corrosion cracking is estimated at 40% through wall. This suggests that the tube possibly had a crack present on the order of 40% through wall that subsequently propagated to a through wall condition. Start up transient stresses which occurred during the return to power following the scheduled outage may have contributed to the rapid growth rate.

Another important factor affecting reliability is the analysis of all applicable 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 with data redundancy increasing detection probability and characterization capability. However, all relevant data must be reviewed which has not always been the case. Figure C-44 shows an example of a tube which was judged to be acceptable based on an analysis of standard eddy current data (400 KHz - 0.050" wall tubing). The tube was found to contain intergranular 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



SG 41 ROW 20 COL 68

XY DISPLAY
CHAN# -- 1
FREQ ------ 400 kHz
SPAN ------ 15
ROTATION - 276 DEG

LEFT STRIP CHART
CHAN# -- 6V
FREQ ------ 200 kHz
SPAN ------ 263
ROTATION - 164 DEG

RIGHT STRIP CHART
CHAN# -- M 1V
CHANS -- 1-3
SPAN ------ 46
ROTATION - 282 DEG

SYSTEM CONFIGURATION
NAME -- 720 BOBBIN
# of CHAN- 8
7:36:20 PM
APRIL 16 1986

SG 41 ROW 20 COL 68

XY DISPLAY
CHAN# -- 3
FREQ ------ 100 kHz
SPAN ------ 50
ROTATION - 127 DEG

LEFT STRIP CHART
CHAN# -- 3V
FREQ ------ 100 kHz
SPAN ------ 50
ROTATION - 127 DEG

RIGHT STRIP CHART
CHAN# -- 4V
FREQ ------ 100 kHz
SPAN ------ 565
ROTATION - 282 DEG

SYSTEM CONFIGURATION
NAME -- 720 BOBBIN
# of CHAN- 8
7:36:20 PM
APRIL 16 1986

SG 41 ROW 20 COL 68

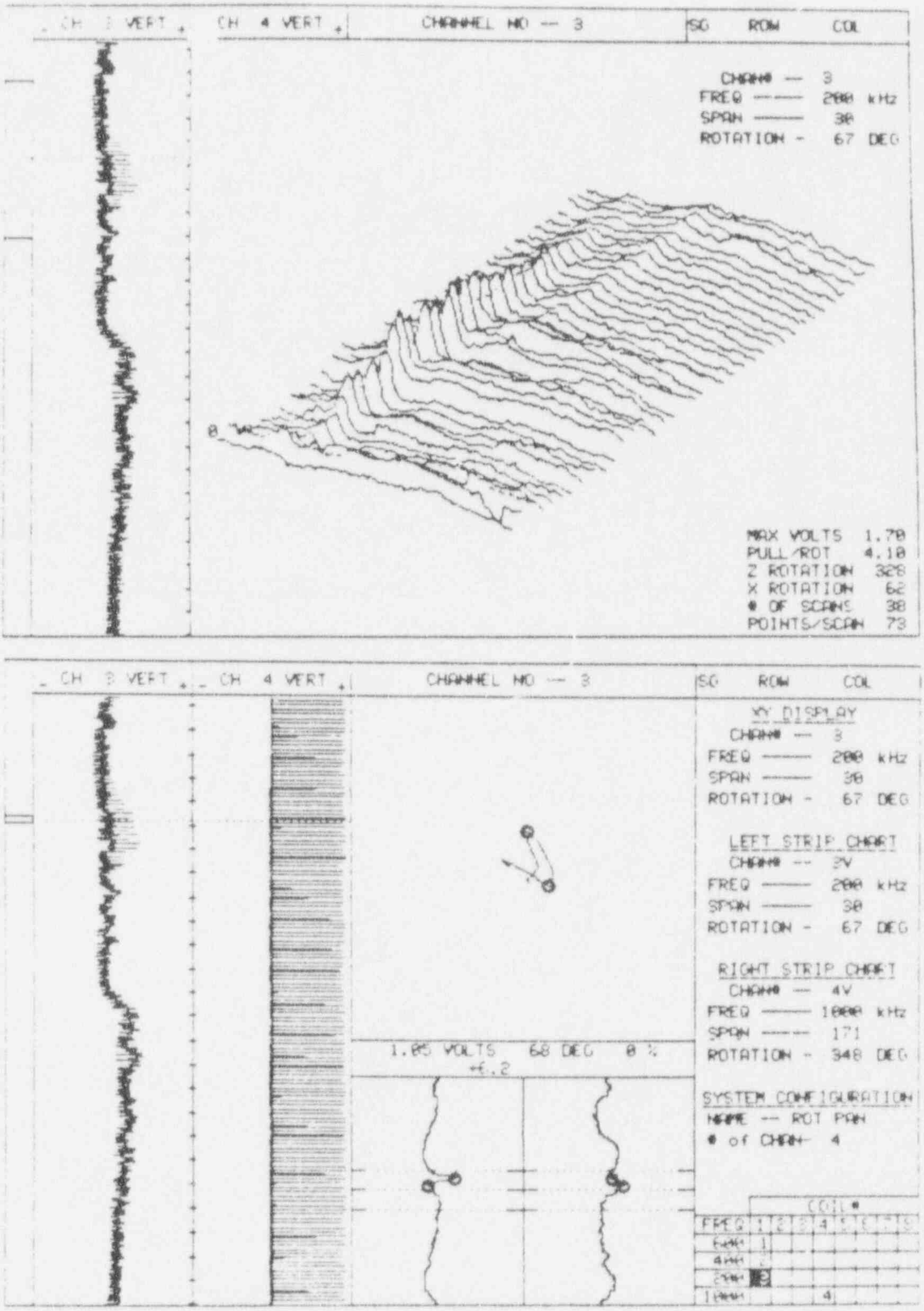
XY DISPLAY
CHAN# -- M 1
CHANS -- 1-3
SPAN ------ 40
ROTATION - 282 DEG

LEFT STRIP CHART
CHAN# -- 6V
FREQ ------ 200 kHz
SPAN ------ 263
ROTATION - 164 DEG

RIGHT STRIP CHART
CHAN# -- M 1V
CHANS -- 1-3
SPAN ------ 40
ROTATION - 282 DEG

SYSTEM CONFIGURATION
NAME -- 720 BOBBIN
# of CHAN- 8
7:36:20 PM
APRIL 16 1986

Figure C-41. R20 C68 Bobbin Coil Data - Copper Residual



CHAN# — 3
FREQ ——— 200 kHz
SPAN ——— 30
ROTATION - 67 DEG

MAX VOLTS 1.70
PULL/ROT 4.10
Z ROTATION 328
X ROTATION 62
OF SCANS 38
POINTS/SCAN 73

XY DISPLAY
CHAN# — 3
FREQ ——— 200 kHz
SPAN ——— 30
ROTATION - 67 DEG

LEFT STRIP CHART
CHAN# — 3V
FREQ ——— 200 kHz
SPAN ——— 30
ROTATION - 67 DEG

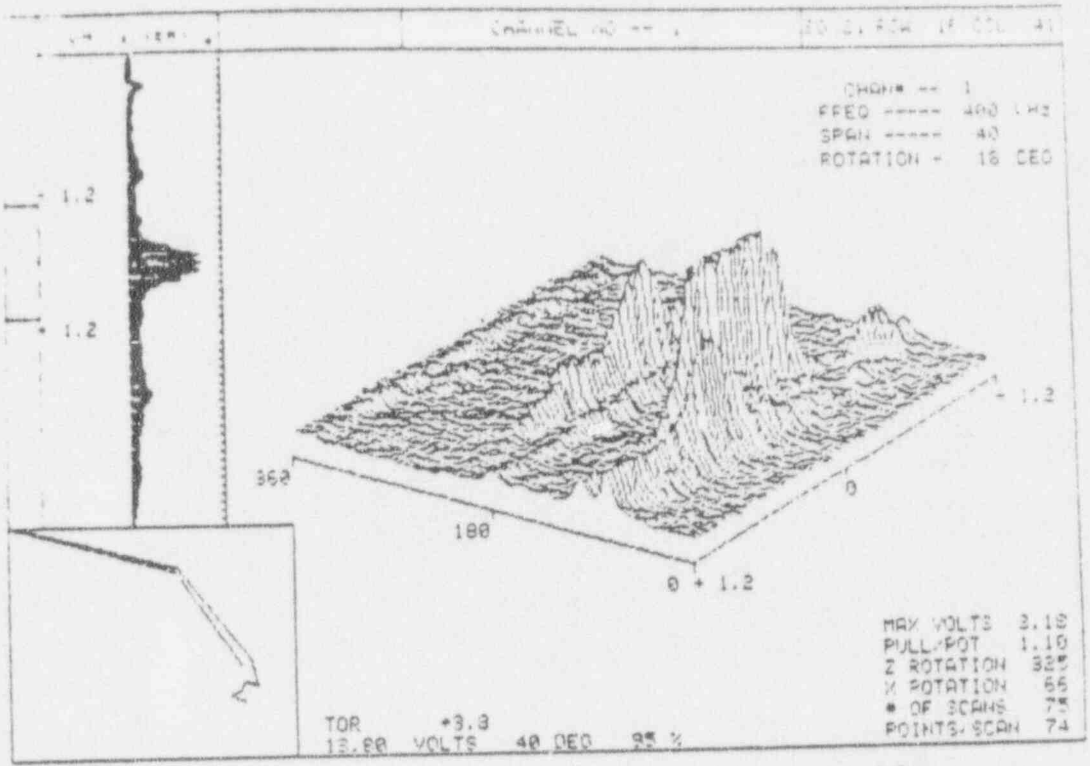
RIGHT STRIP CHART
CHAN# — 4V
FREQ ——— 1000 kHz
SPAN ——— 171
ROTATION - 348 DEG

1.05 VOLTS 68 DEG 0 %
+6.2

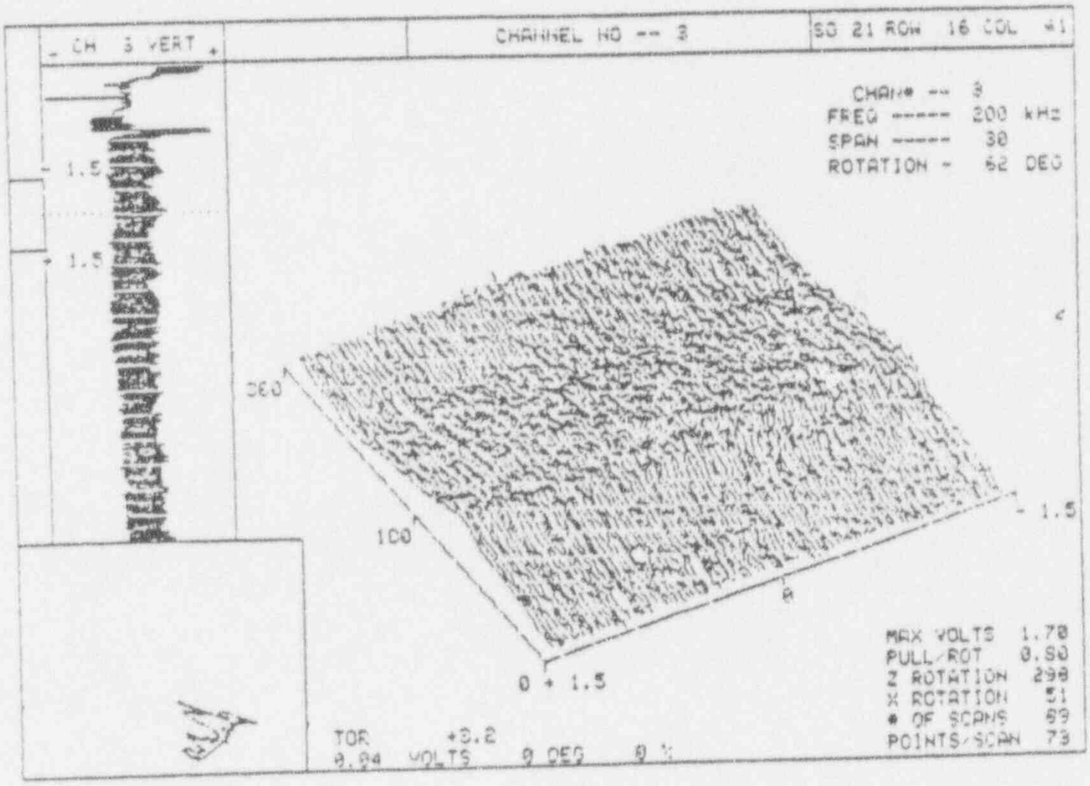
SYSTEM CONFIGURATION
NAME — ROT PAN
# of CHAN— 4

	COIL #							
FREQ	1	2	3	4	5	6	7	8
600	1							
400	2							
200	3							
1000				4				

Figure C-42. R20 C68 Rotating Pancake Coil Data - Stress Corrosion Cracking

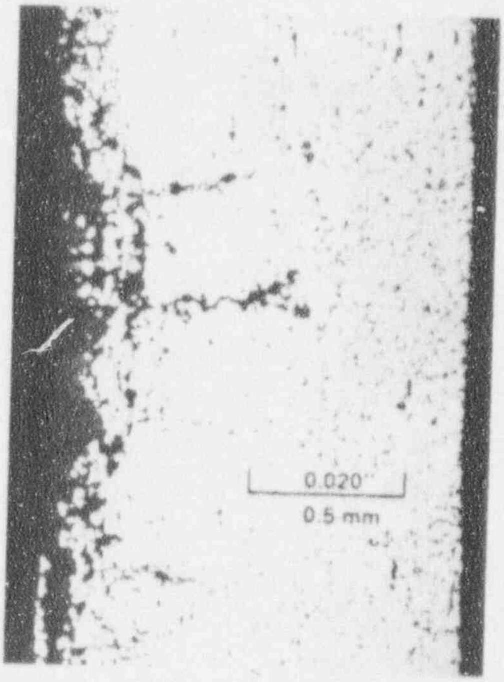


After

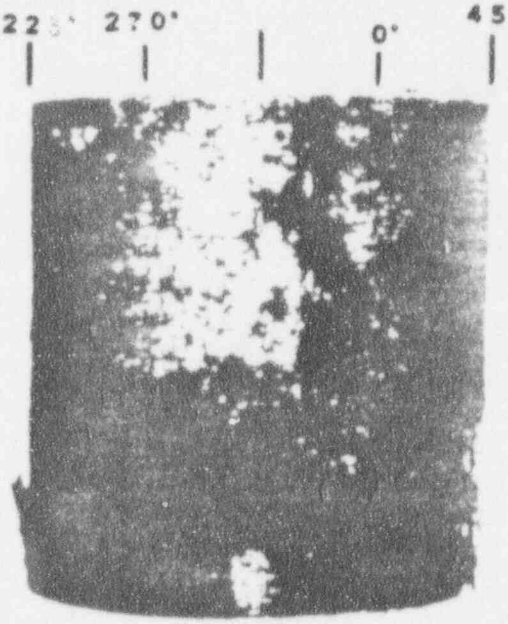


Before

Figure C-43. R16 C41 Rotating Pancake Coil Data - Before and After Forced Outage



Axial Section Just Above
Roll Transition Showing
General IGA Attack < 10%
Through Wall With
Circumferential Penetrations
60% Through Wall



Tube Section Containing
Roll Transition - Sectioned
Axially Through Dashed
Line (See Above)

Roll Transition

Figure C-44. Eddy Current Indications Above Roll Transition

KHz eddy current data clearly shows indications which were not analyzed which correspond to the location of the intergranular attack identified during the metallographic examination.

Eddy current test coil mode has also been shown to be an important factor in detecting intergranular attack. Figure C-45 shows an axial cross section of a tube with volumetric intergranular attack on the order of 40% through wall located just above the top of the tube sheet. Also shown is the in-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 an indication above the tube sheet. On the other hand, the absolute coil data set shows an indication which corresponds to the location of the intergranular attack.

Another example of the importance of the absolute coil is shown in Figure C-46. Shown is a transverse cross section of a tube containing intergranular 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 channel shows a general drift which is a characteristic feature of signals attributable to intergranular attack within the tube sheet crevice region.

Additional data supporting the validity of the absolute drift concept as a basis for identifying a pluggable tube condition has recently been derived from studies conducted on tubes removed from the replaced Point Beach 1 steam generators (15). A summary of eddy current and metallography results for five tubes is given in Table C-2. Examples of strip chart records for the tubes listed in the table are shown in Figures C-47.

Table C-2

EDDY CURRENT AND METALLOGRAPHY RESULTS FOR
TUBES REMOVED FROM RETIRED POINT BEACH UNIT

Row	Column	Differential	Absolute	Metallography
8	72	NDD	Drift	60% - 75%
8	73	93%	Drift	90%
8	74	92%	Drift	70% - 85%
10	74	NDD	NDD	25% - 40%
9	75	NDD	Drift	40% - 55%
10	76	NDD	NDD	25%

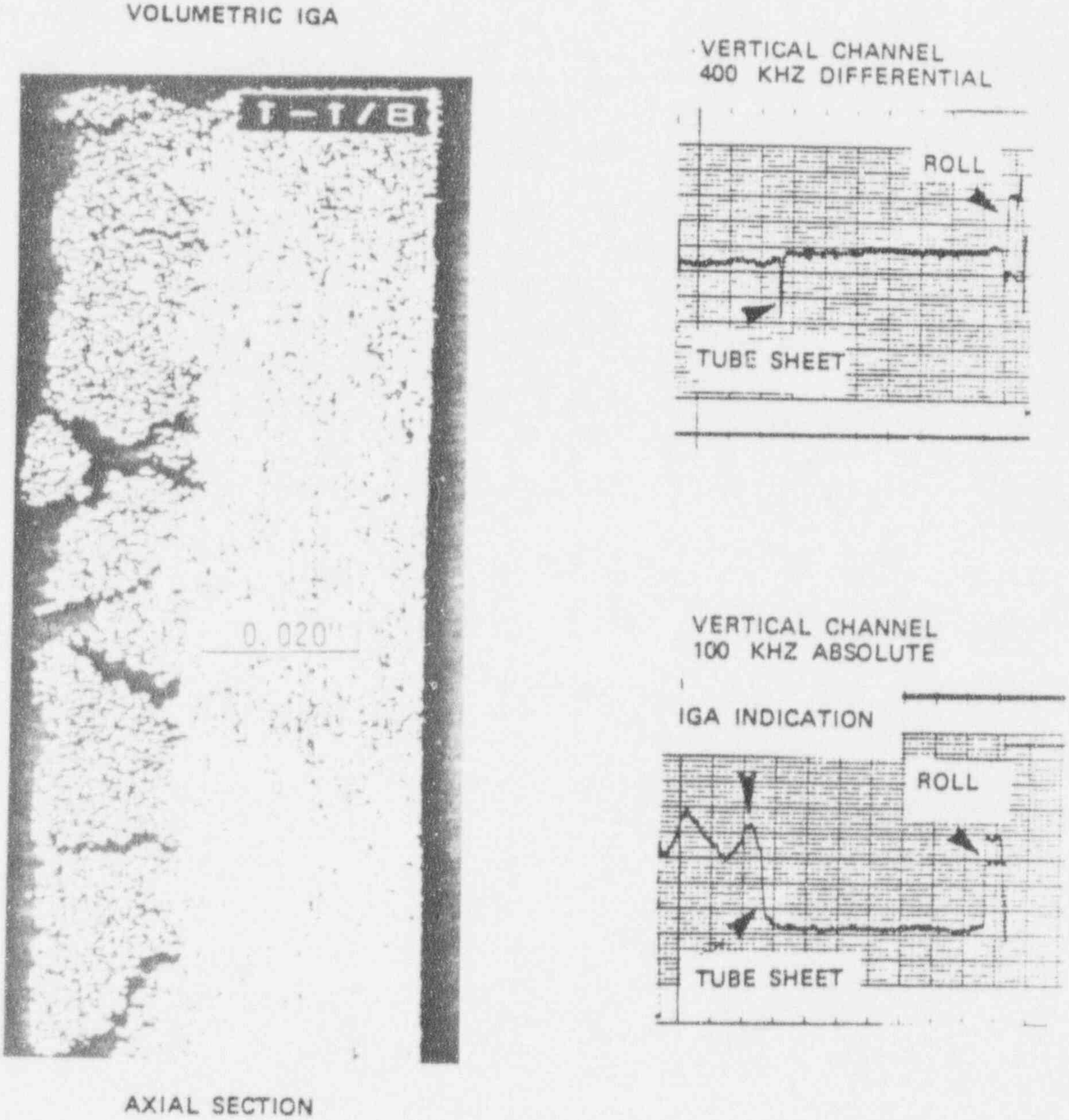
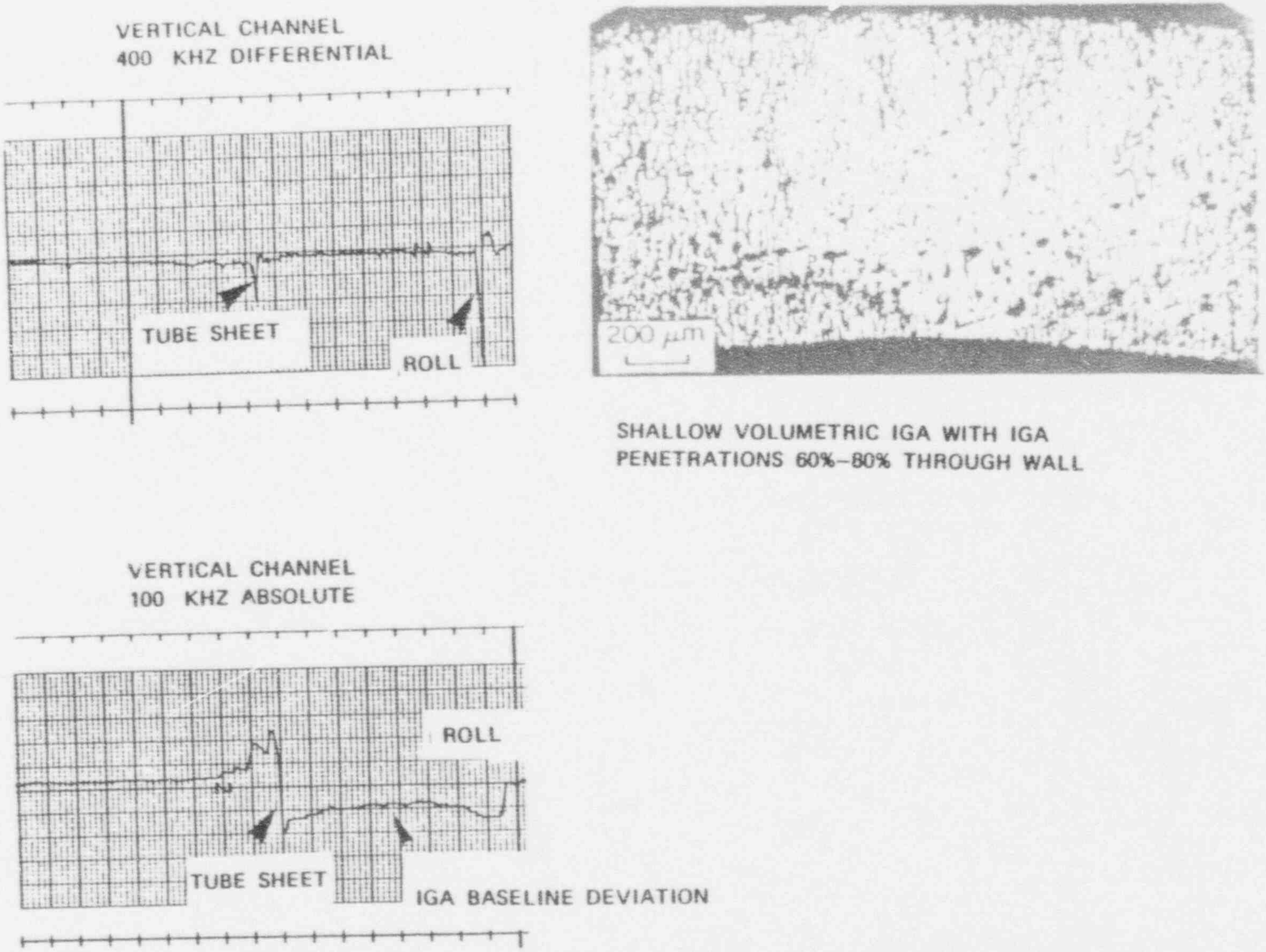


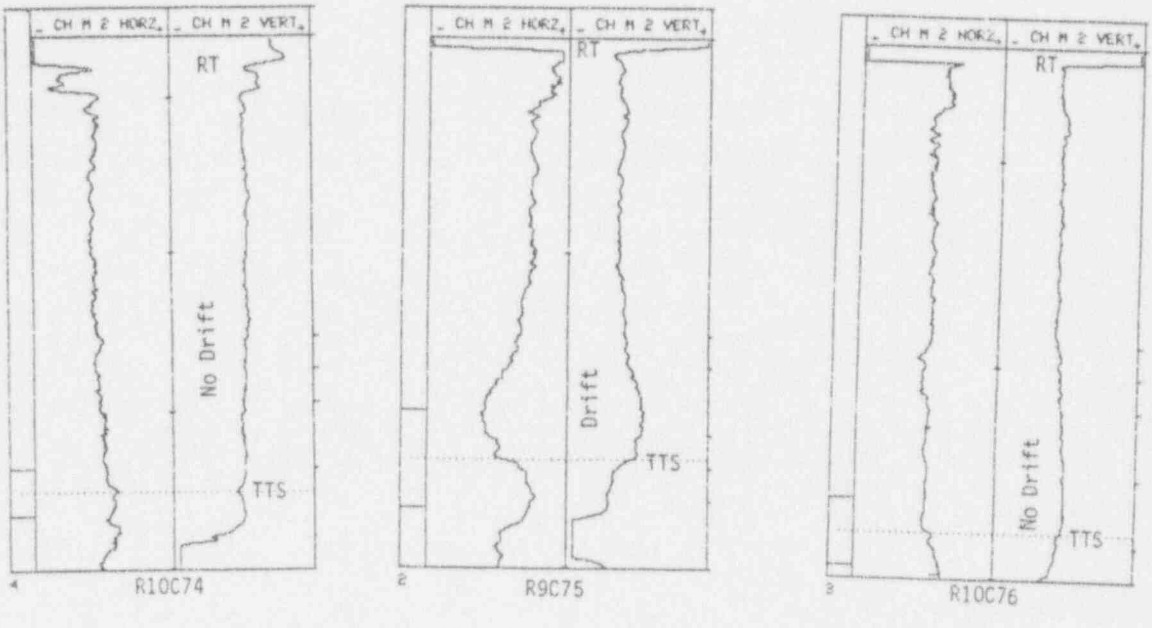
Figure C-45. Importance of Absolute Coil


VERTICAL CHANNEL
400 KHZ DIFFERENTIAL

SHALLOW VOLUMETRIC IGA WITH IGA PENETRATIONS 60%-80% THROUGH WALL

VERTICAL CHANNEL
100 KHZ ABSOLUTE

Figure C-46. Tube Sheet Crevice - "IGA Drift"



R10C74 R9C75 R10C76

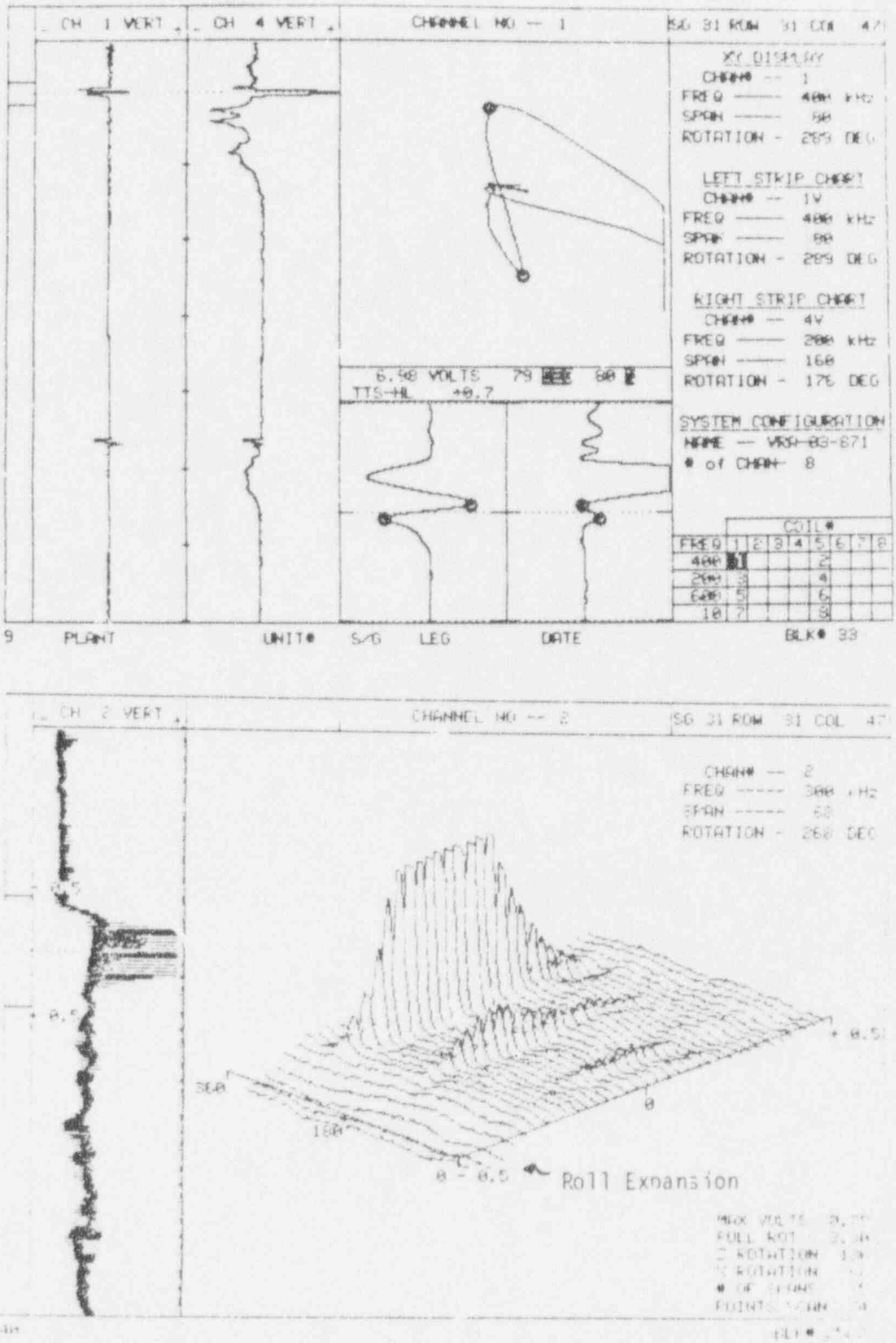
R8C72 R8C74 R8C73

Figure C-47. Absolute Drift - Tube Sheet Crevice

C.4.1.4.2 Sludge Pile

Several units have recently experienced intergranular attack and stress corrosion cracking within the sludge pile above the top of the tube sheet (Calvert Cliffs 1, Krsko, and North Anna 1). This has been confirmed via tube pulls in the case of the first two units and rotating pancake coil eddy current data in the case of North Anna 1. The mechanism at Krsko is caustic stress corrosion cracking whereas at Calvert Cliffs 1, sulphur and lead are the probable culprits. The cause of the North Anna 1 cracking has not been established since no tubes with the secondary side cracking have been removed. In all cases, eddy current indications appear to be bounded by the extent of the sludge pile.

Secondary side stress corrosion cracking at North Anna 1 is of particular interest since it occurs in proximity to the Wextex expansion at the top of the tube sheet. This can present challenges in its detection because of the geometrical influence of the expansion. An example of a more obvious bobbin coil indication is shown in the upper part of Figure C-48. The indication forms three-quarters of its impedance plane trajectory before being influenced by the expansion signal. Rotating pancake coil data for this indication is shown in the lower part of the figure. Multiple linear indications characteristic of stress corrosion cracking are present. Rotating pancake coil data for another example is shown in Figure C-49. Oblique and end-on views looking up towards the secondary side of the tube sheet are illustrated. As before, multiple (five) linear indications are present with one of the indications blending into the Wextex expansion. Differential and absolute bobbin coil data for this tube are shown in Figure C-50. The absolute coil data shows a small amplitude indication forming before being overwhelmed by the expansion signal; no obvious indication is present in the bobbin coil data other than a distorted expansion signal. Numerous tubes were examined with this condition and it was observed that the absolute coil mode provided the most reliable definition of the condition of the top of the tube sheet near the expansion. (8x1) array coil data was also taken on numerous tubes with the objective of investigating more reliable production examination methods for this condition. An example of this type of data for the tube previously illustrated in Figure C-50 is shown in Figure C-51. Three indications (Channels 1, 3 & 8) are apparent in the strip chart data. Cases where other tubes had only single indications as determined using a rotating pancake coil were not always detected using the array coil. This is not surprising since (8x1) array coil coverage about the tube circumference is in general not complete. Gaps in the coverage can occur resulting in the nondetection of single linear discontinuities.

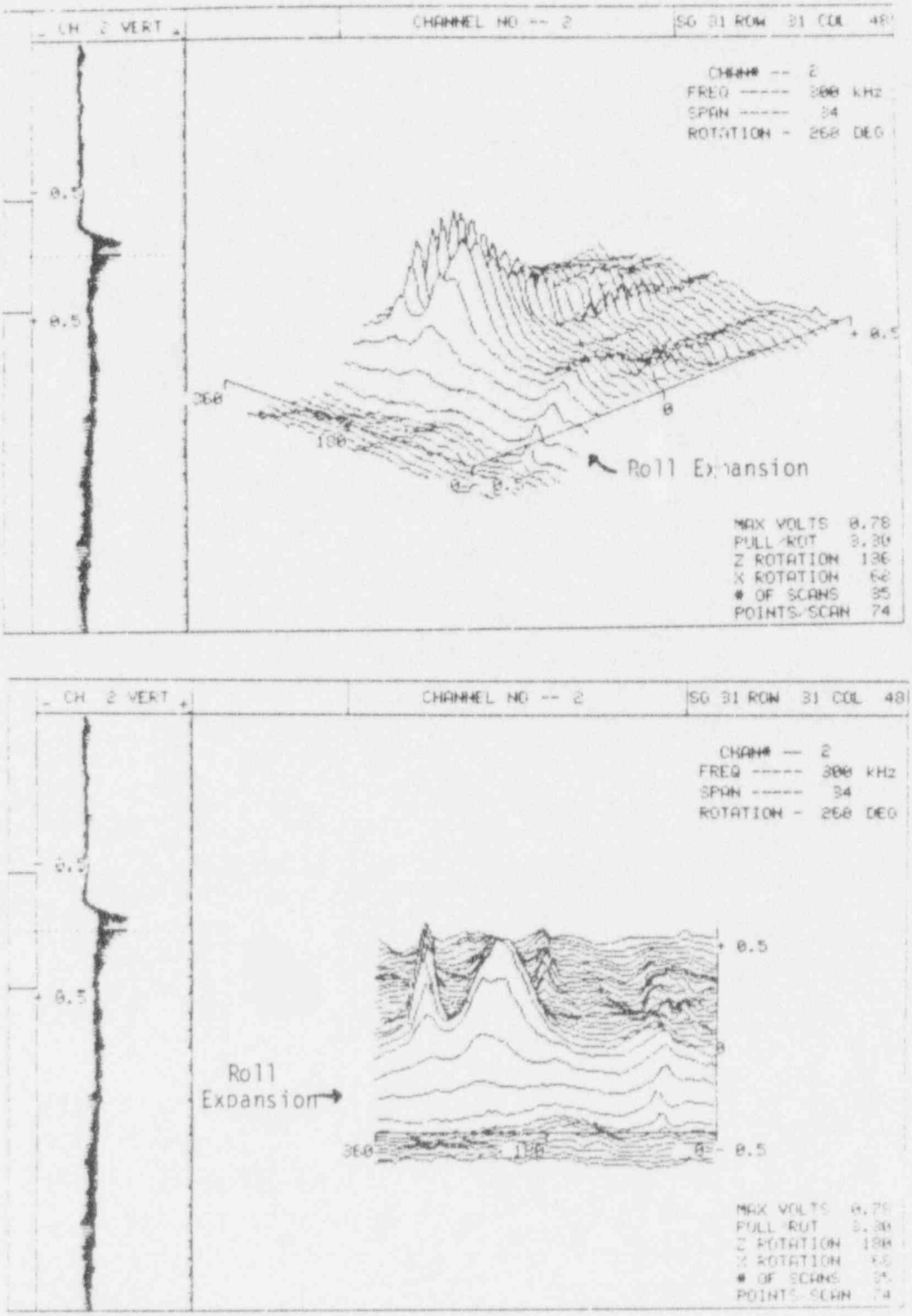


```
SG 31 ROW  31 COL  47

   XY DISPLAY
  CHAN# --  1
FREQ ------  400 kHz
SPAN ------   80
ROTATION -  289 DEG

  LEFT STRIP CHART
  CHAN# --  1V
FREQ ------  400 kHz
SPAN ------   80
ROTATION -  289 DEG

  RIGHT STRIP CHART
  CHAN# --  4V
FREQ ------  200 kHz
SPAN ------  160
ROTATION -  176 DEG

SYSTEM CONFIGURATION
NAME -- VRA-83-871
# of CHAN  8
```

	COIL#							
FREQ	1	2	3	4	5	6	7	8
400	1				2			
200	3				4			
600	5				6			
10	7				8			

```
BLK# 33

SG 31 ROW  31 COL  47

  CHAN# --  2
FREQ -----  300 kHz
SPAN -----   68
ROTATION -  268 DEG

MAX VOLTS
FULL ROT
ROTATION
ROTATION
# OF SCANS
POINTS/SCAN
```

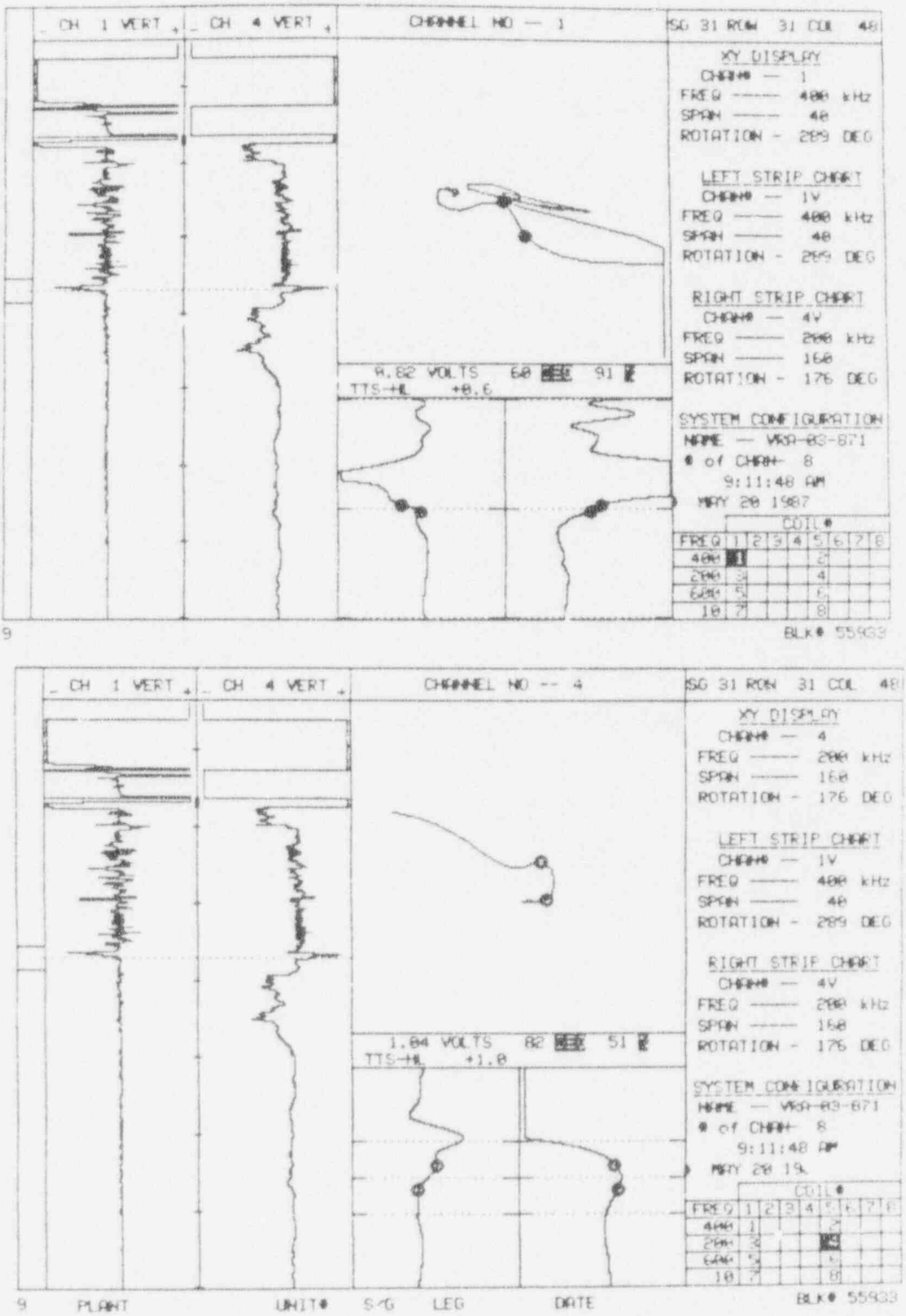
Figure C-48. Secondary Side Stress Corrosion Cracking - Bobbin Coil and Rotating Pancake Coil Data



```
CHANNEL NO -- 2                SG 31 ROW 31 COL 48

CHAN# -- 2
FREQ ----- 300 kHz
SPAN -----  34
ROTATION - 268 DEG

MAX VOLTS  0.78
PULL/ROT   3.30
Z ROTATION  136
X ROTATION   62
# OF SCANS   35
POINTS/SCAN  74
```

```
CHANNEL NO -- 2                SG 31 ROW 31 COL 48

CHAN# -- 2
FREQ ----- 300 kHz
SPAN -----  34
ROTATION - 268 DEG

MAX VOLTS  0.78
PULL/ROT   3.30
Z ROTATION  180
X ROTATION   68
# OF SCANS   35
POINTS/SCAN  74
```

Figure C-49. R31 C48 Rotating Pancake Coil Data



SG 31 ROW 31 COL 48

XY DISPLAY
CHAN# — 1
FREQ —— 400 kHz
SPAN —— 40
ROTATION - 289 DEG

LEFT STRIP CHART
CHAN# — 1V
FREQ —— 400 kHz
SPAN —— 40
ROTATION - 289 DEG

RIGHT STRIP CHART
CHAN# — 4V
FREQ —— 200 kHz
SPAN —— 160
ROTATION - 176 DEG

SYSTEM CONFIGURATION
NAME — VRA-03-871
# of CHAN 8
9:11:48 AM
MAY 20 1987

	COIL#							
FREQ	1	2	3	4	5	6	7	8
400	1				2			
200	3				4			
600	5				6			
10	7				8			

BLK# 55933

SG 31 ROW 31 COL 48

XY DISPLAY
CHAN# — 4
FREQ —— 200 kHz
SPAN —— 160
ROTATION - 176 DEG

LEFT STRIP CHART
CHAN# — 1V
FREQ —— 400 kHz
SPAN —— 40
ROTATION - 289 DEG

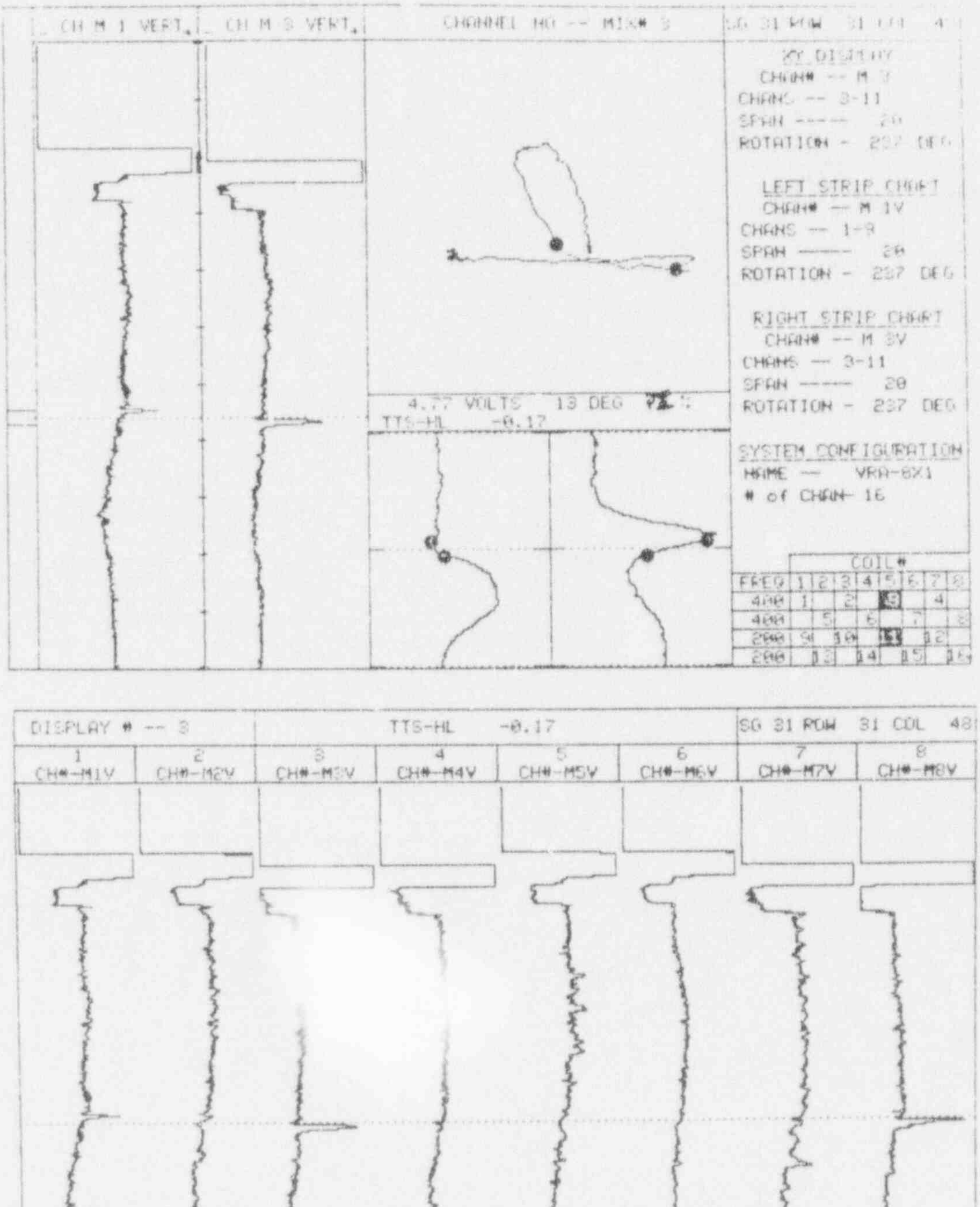
RIGHT STRIP CHART
CHAN# — 4V
FREQ —— 200 kHz
SPAN —— 160
ROTATION - 176 DEG

SYSTEM CONFIGURATION
NAME — VRA-03-871
# of CHAN 8
9:11:48 AM
MAY 20 19

	COIL#							
FREQ	1	2	3	4	5	6	7	8
400	1				2			
200	3				4			
600	5				6			
10	7				8			

BLK# 55933

Figure C-50. R31 C48 Bobbin Coil Data



XY DISPLAY
CHAN# -- M 3
CHANS -- 3-11
SPAN ----- 20
ROTATION - 237 DEG

LEFT STRIP CHART
CHAN# -- M 1V
CHANS -- 1-9
SPAN ----- 20
ROTATION - 237 DEG

RIGHT STRIP CHART
CHAN# -- M 3V
CHANS -- 3-11
SPAN ----- 20
ROTATION - 237 DEG

SYSTEM CONFIGURATION
NAME -- VRA-8X1
# of CHAN- 16

	COIL#							
FREQ	1	2	3	4	5	6	7	8
400	1		2		3		4	
400		5		6		7		8
200	9		10		11		12	
200		13		14		15		16

Figure C-51. R31 C48 - (8 x 1) Array Coil Data

C.4.1.4.3 Support Plates

Numerous units have also experienced stress corrosion cracking at support plates on both the hot-leg and cold-leg sides of the steam generator. When viewed on a tubesheet map, the degradation is distributed randomly throughout the steam generator and tends to be concentrated at the lower support plates (as shown by the data presented in Figure C-52) on the hot-leg side, while on the cold-leg side, the upper support elevations are affected.

Many tubes have been removed in order to identify the cause of the cracking and to confirm eddy current examination results. Metallography results show the cracking to be confined to within the support plate. Numerous cracks are generally distributed around the tube circumference which contributes to the ready detection using bobbin coil technology. Estimated lower bound detection is 30% through wall based on tube pulls. A problem in oversizing small amplitude signals has been observed; this results from a poor signal-to-noise ratio in the mixed channel output due to large mixed residuals. The mixed residual tends to add vectorially with the indication in a counter-clockwise direction resulting in a significant depth overestimation. Figure C-53 shows the bobbin coil single frequency and mixed channel output from a large amplitude indication along with rotating pancake coil data from the same support plate. The existence of multiple linear indications in the rotating pancake coil data confirms the presence of multiple axial stress corrosion cracking. In this case, the relatively large amplitude bobbin coil signal present in the mixed channel signal is readily deteced and sized. See Supplement I for further details.

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C.4.1.4.4 IGA/SCC Detection & Sizing Experience

Industry experience in sizing and detecting intergranular attack and stress

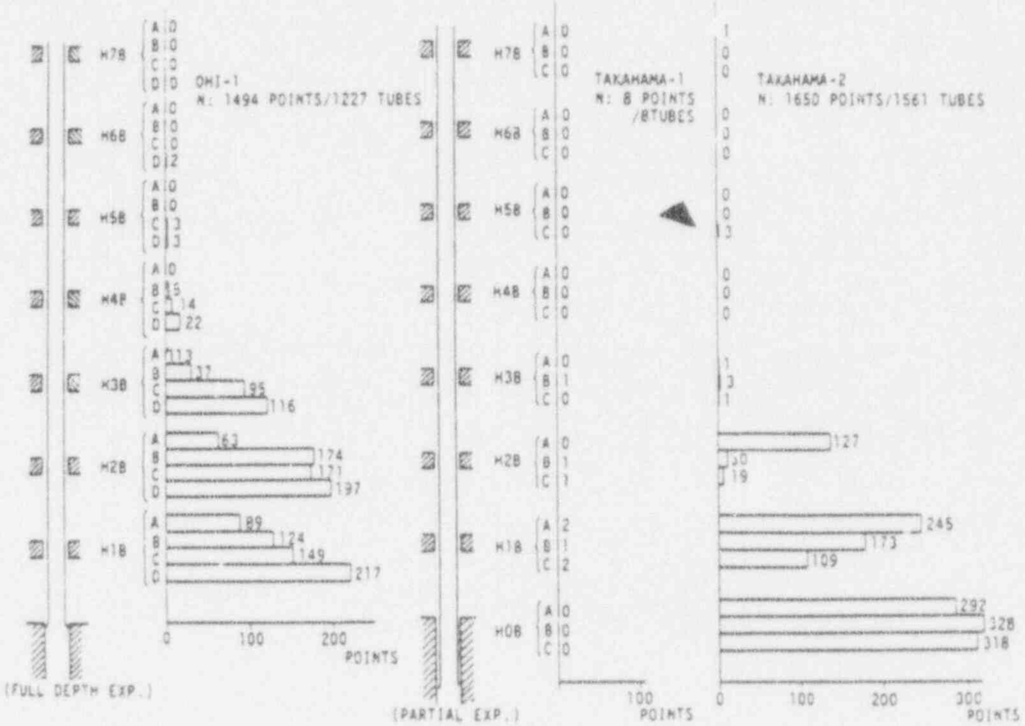

Figure C-52. Stress Corrosion Cracking at Support Plate Showing Concentration at Lower Supports

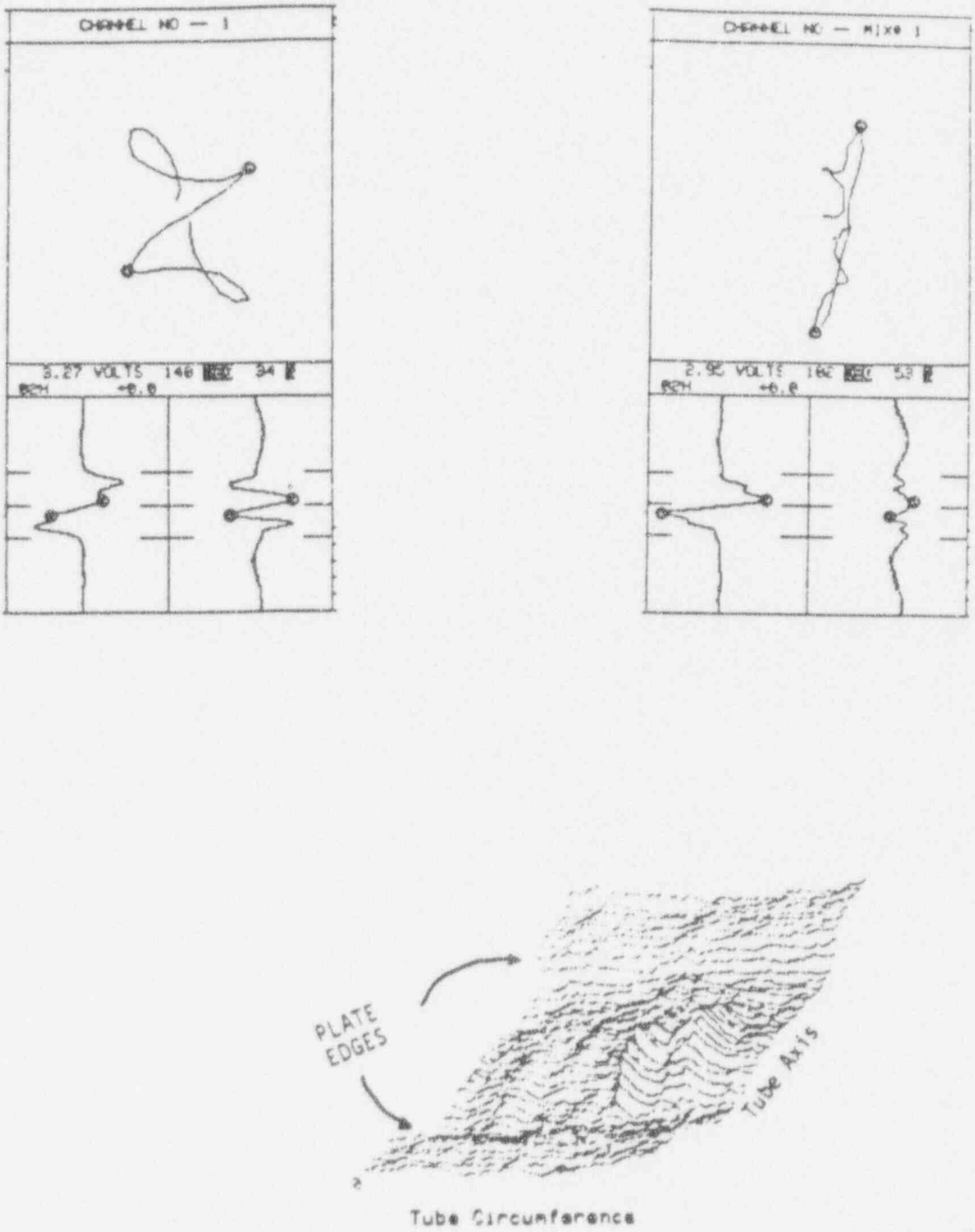

Figure C-53. Stress Corrosion Cracking at Support Plate - Pluggable Condition (Bobbin Coil and Rotating Pancake Coil Data)

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Figure C-54. Figure Deleted in Revision 3

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Figure C-55. Figure Deleted in Revision 3 corrosion cracking is shown in Figures C-56 and C-57. A scatter plot of eddy current predicted versus depth measured metallographically is shown in Figure C-56. A least squares fit to the data is given by the equation $y = (0.76)x + 15.6$ with a correlation coefficient of 0.86. Detection probability estimates are shown in Figure C-57. Reliable detection is not achieved until depths on the order of 80% through wall are achieved.

In conclusion, 100% examination of the affected region of the steam generator, along with the acquisition and analysis of multifrequency, multiple coil mode (differential and absolute) eddy current data coupled with two-party analysis cannot be overemphasized for the effective monitoring of intergranular attack and stress corrosion cracking.

C.4.1.5 Primary Side Stress Corrosion Cracking

Primary side stress corrosion cracking has been experienced in the inner row U-bends (Row 1 & 2) of numerous Westinghouse Model 51 steam generators and recently some Model D's; at the Wextex tube sheet expansions in two Model 51 (Fessenheim 1 and North Anna 1); at dented support plate intersections in several Model 44's and 51's; and recently at the "kiss-roll" expansions of numerous European steam generators of Westinghouse design. The cracking is associated with some geometrical distortion of the tube as the result of tube manufacturing processes e.g., roll expansion, U-bend tangent point, or caused by secondary side corrosion processes in the case of denting. Because of the ever present tube distortion, the condition is difficult to inspect for using conventional bobbin coil technology and is usually not detected until significant cracking has occurred.

C.4.1.5.1 Inner row U-bend cracking

Some twenty-six Row 1 and three Row 2 U-bends have been removed from Trojan for investigation of non-denting assisted primary side cracking at the U-bend tangent point (16). Two of these tubes (R1-C6, R1-C26) had field reported indications with one of the tubes identified as a leaker (R1-C6). Upon removal, an additional tube (R1-C7) was identified as having an eddy current indication. Eddy current indications in all three tubes were subsequently confirmed using radiography. Only tube R1-C6 was destructively examined; the remaining two tubes with indications were retained for future use as eddy current standards. An external view of tube R1-C6 is shown in Figure C-58. The through wall crack is visible in the extrados view just above the transition region. Field and laboratory bobbin coil eddy current

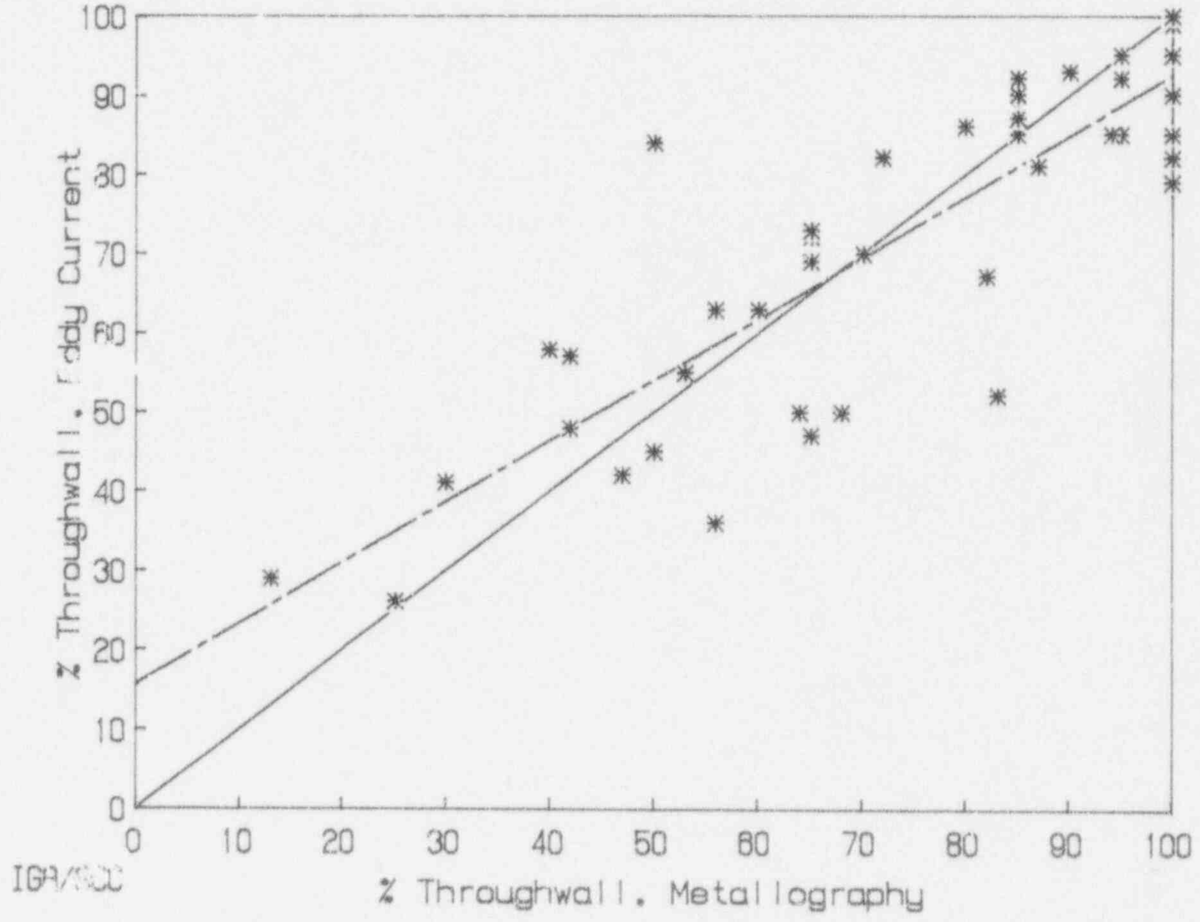


Figure C-56. Measurement Accuracy - IGA/SCC

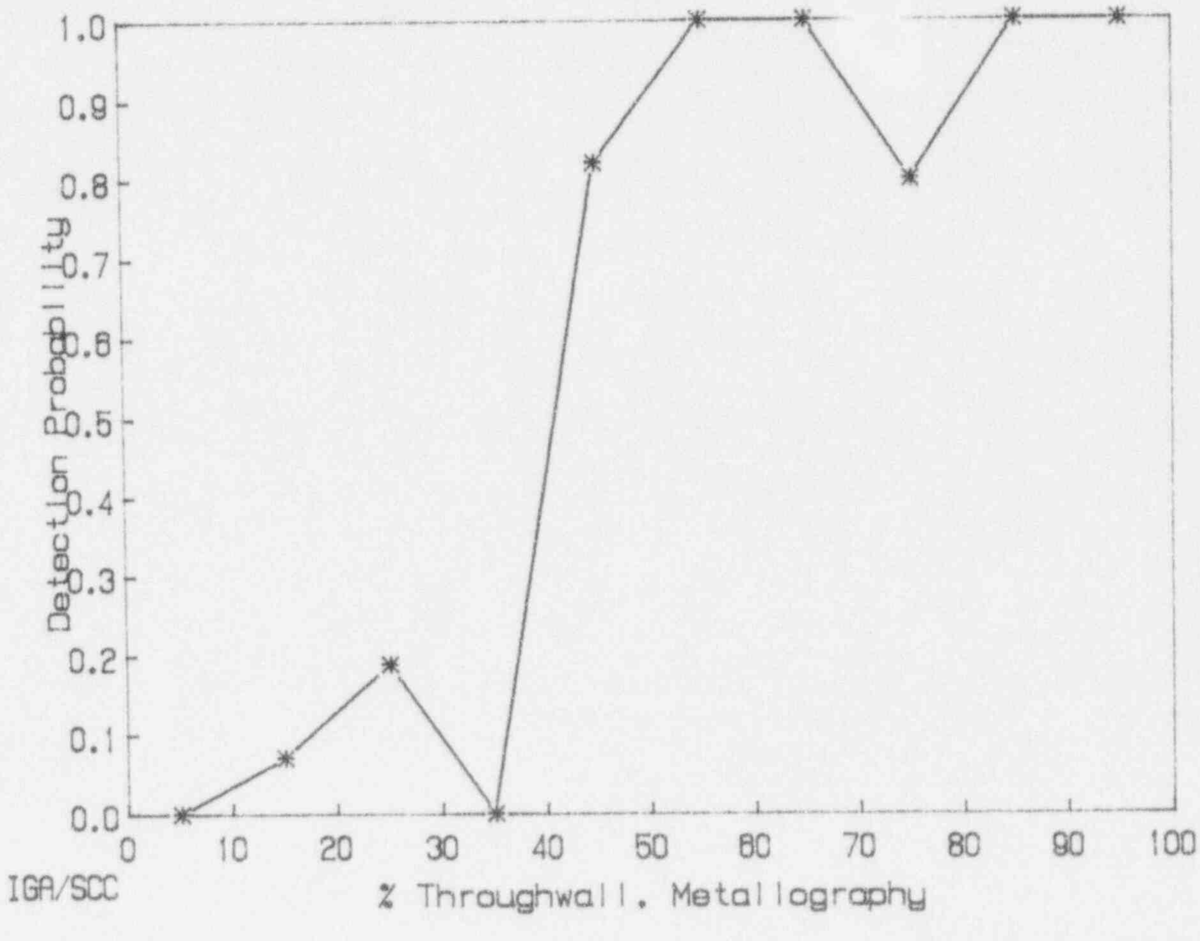


Figure C-57. Detection Probability - IGA/SCC

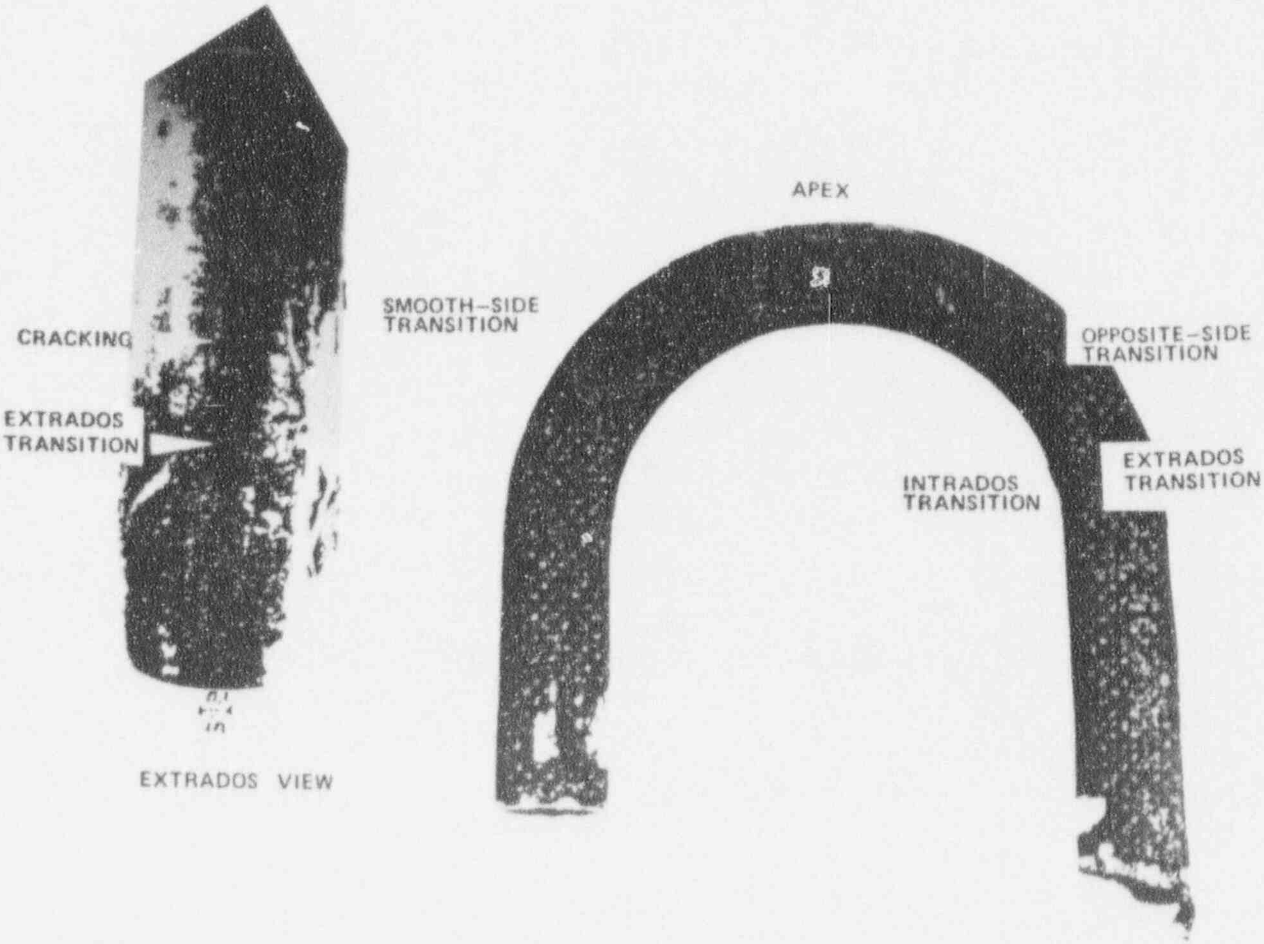
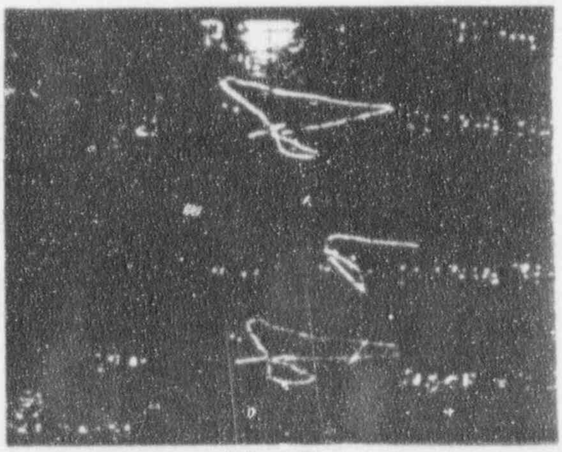


Figure C-58. Row 1 U-Bend Primary-Side Cracking data for tube R1-C6 is shown in Figure C-59. Signals from the through wall crack and the transition are clearly visible. Eddy current examination of inner row U-bends has historically been conducted using 100 KHz absolute and differential bobbin coil techniques. Of importance is the magnitude of the crack signal in comparison with the transition 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.

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 sufficient 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 examination reliability at the U-bend tangent point. Segmented bobbin coils mounted on a strap which can flex in one direction (tongue-depressor probe) providing coil surface stabilization (17) and rotating pancake coil designs configured for U-bend insertion (18) are two approaches that have been pursued for improving examination reliability. Laboratory data for a segmented bobbin coil taken from U-bend samples with EDM notches showed a significant improvement in examination capability. Standard bobbin probes were only able to detect EDM notches 70% through wall; EDM notches ranging from 35% to 60% through wall were not detectable. The segmented bobbin coil was able to detect all EDM notches in the U-bend test samples. A typical result is shown in Figure C-60. The upper part of the figure shows conventional bobbin coil data from a tube containing a 55% through wall EDM notch at the tangent point; there is no clear indication evidenced in the eddy current data. Segmented bobbin coil data from the same tube is shown in the lower part of the figure; the indication is quite obvious. Field tests of the segmented bobbin probe have also been conducted in a generator with known U-bend cracking with mixed results (Sequoyah 1). Although the segmented bobbin coil has identified defective tube conditions not apparent with a bobbin coil, there have been instances where defective tubes - identified using a rotating pancake probe and confirmed with helium leak testing - have not been classified as such using a segmented probe.

R1-C6 CL 4 V/DIV



100 kHz (DIFFERENTIAL)

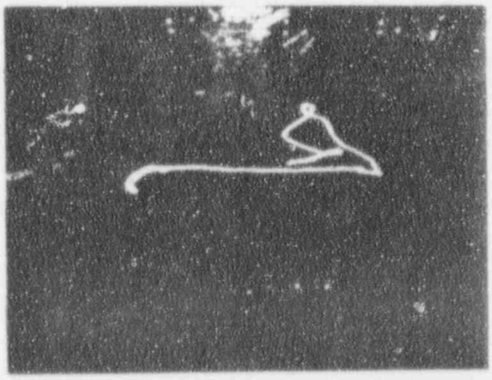
100 kHz (ABSOLUTE)

400 kHz (DIFFERENTIAL)

HL→CL

Field
Data

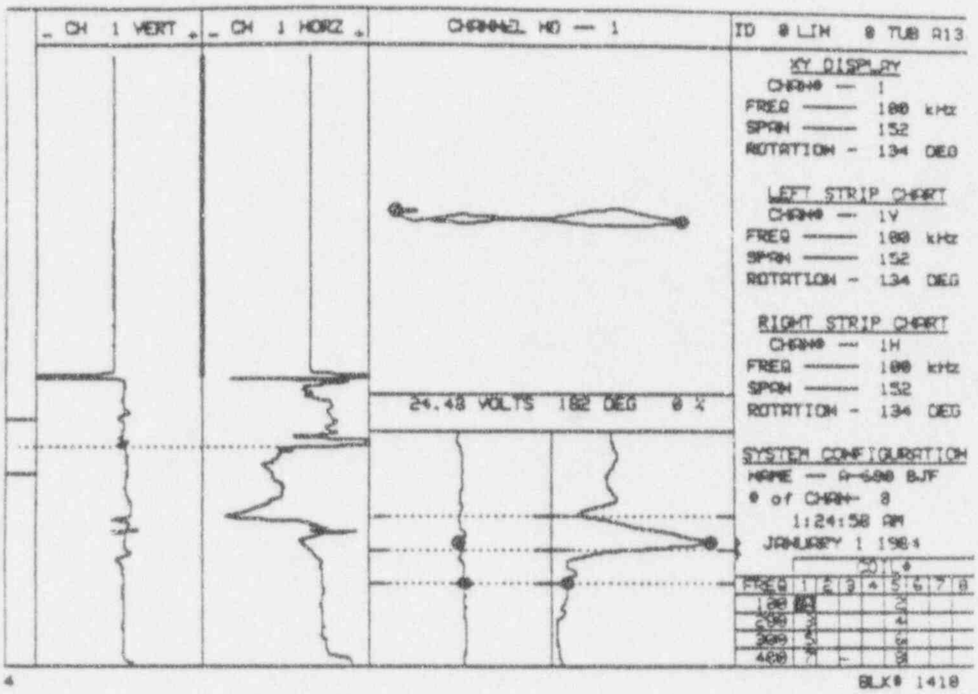
R1-C6 CL 2 V/DIV



CL→HL

Labor
Data

Figure C-59. R1 C6 Bobbin Coil Eddy Current Data -
Throughwall Crack at Tangent Point



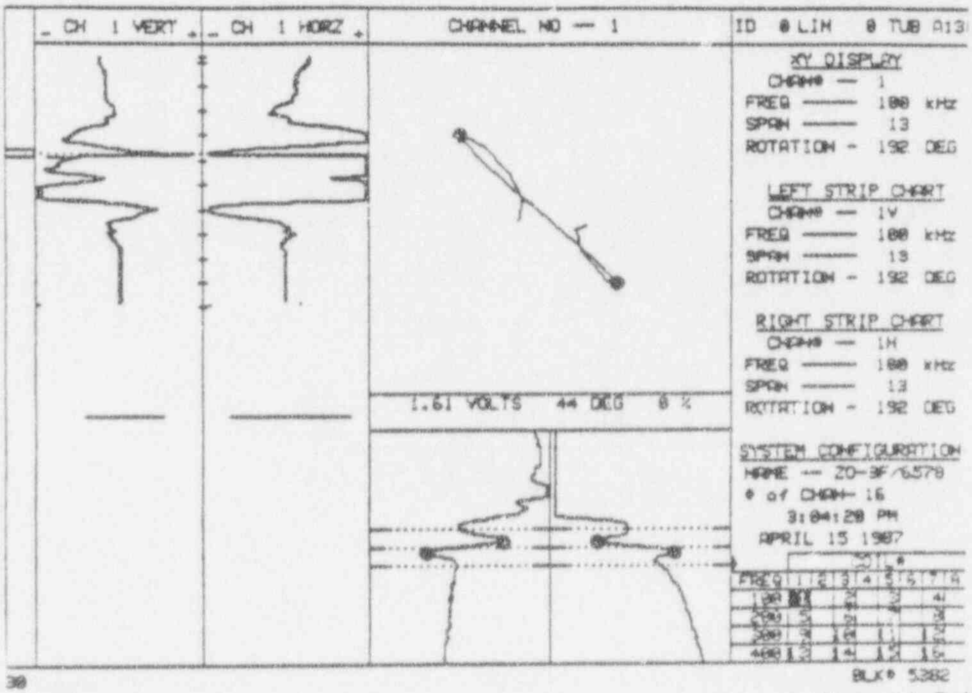
```
ID  0 LIN    0 TUB A13
      XY DISPLAY
  CHAN# — 1
FREQ ——— 100 kHz
SPAN ——— 152
ROTATION - 134 DEG

   LEFT STRIP CHART
  CHAN# — 1V
FREQ ——— 100 kHz
SPAN ——— 152
ROTATION - 134 DEG

   RIGHT STRIP CHART
  CHAN# — 1H
FREQ ——— 100 kHz
SPAN ——— 152
ROTATION - 134 DEG

SYSTEM CONFIGURATION
NAME — A-600 BJF
# of CHAN- 8
    1:24:58 AM
  JANUARY 1 1984
                BLX# 1410
```

Conventional Bobbin



```
ID  0 LIN    0 TUB A13
      XY DISPLAY
  CHAN# — 1
FREQ ——— 100 kHz
SPAN ——— 13
ROTATION - 192 DEG

   LEFT STRIP CHART
  CHAN# — 1V
FREQ ——— 100 kHz
SPAN ——— 13
ROTATION - 192 DEG

   RIGHT STRIP CHART
  CHAN# — 1H
FREQ ——— 100 kHz
SPAN ——— 13
ROTATION - 192 DEG

SYSTEM CONFIGURATION
NAME — ZO-3F/6578
# of CHAN- 16
    3:04:20 PM
  APRIL 15 1987
                BLX# 5302
```

Segment Bobbin

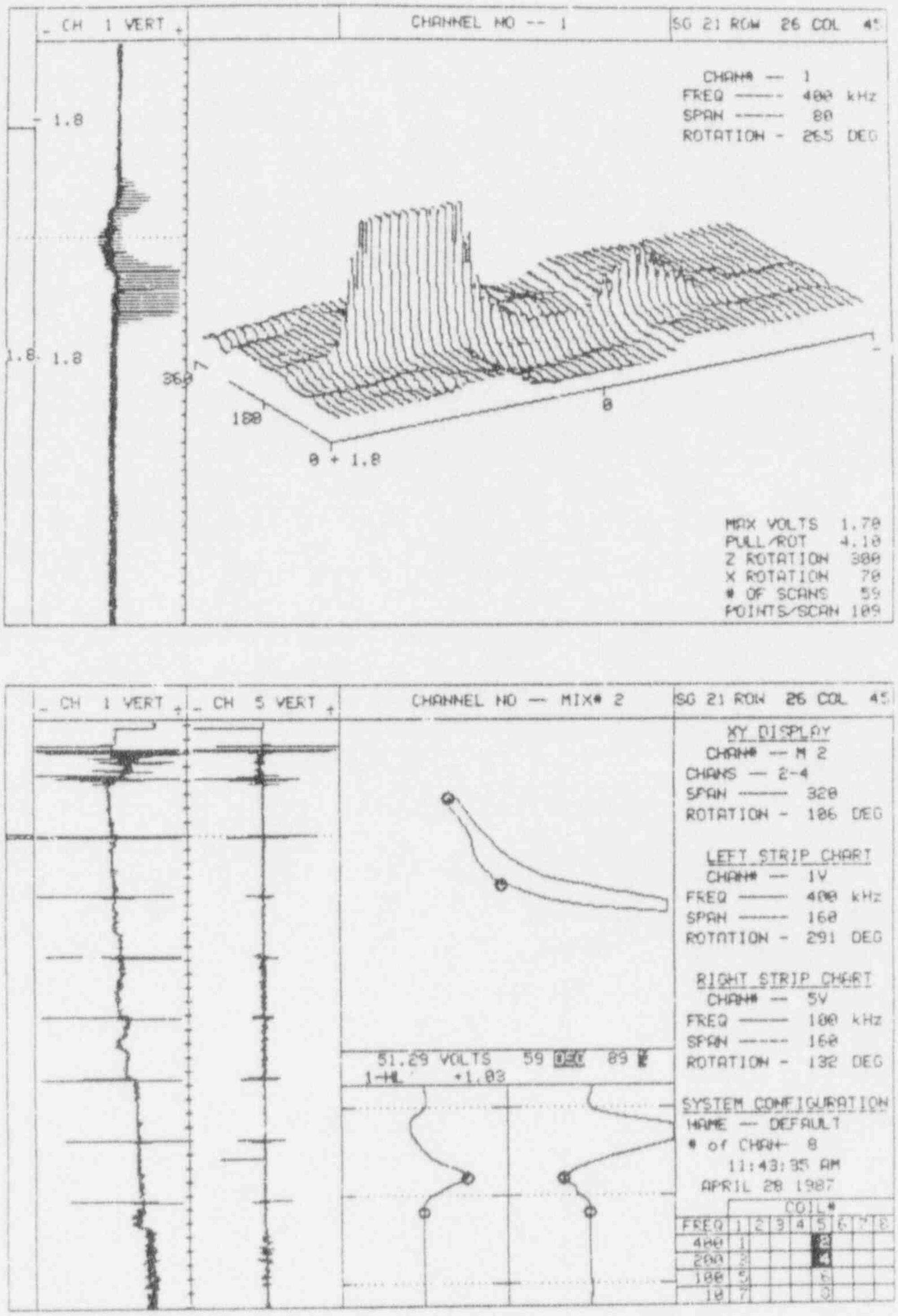
Figure C-60. Comparison of Conventional and Segmented Bobbin Coil - 55% EDM Notch at U-bend Tangent Point

Field testing of a U-bend rotating pancake coil has also been conducted at Ringhals 4 (19). Helium leak testing was first used to identify numerous leaking Row 1 tubes. The tubes were then examined using conventional a bobbin coil, a segmented bobbin coil, and a rotating pancake coil. Some fifteen tubes identified as having no detectable degradation with the bobbin coil had clear indications with the rotating pancake coil and were plugged. Numerous tubes identified as having no detectable degradation when examined with the segmented bobbin coil clearly were defective when examined with a rotating probe.

C.4.1.5.2 Denting assisted cracking

Denting assisted primary side stress corrosion cracking has for the most part become a non-issue with the replacement of steam generators at four extensively dented plants (Surry 1 & 2, and Turkey Point 3 & 4). However, one unit (North Anna 1) has recently experienced predominantly primary side cracking at dented support plate intersections. Minor denting was observed early in its operating cycle; the denting was stopped by appropriate changes in water chemistry. At some later time, eddy current indications were identified at the dented support plates which were subsequently shown to be due to primary side stress corrosion cracking (20). Indications have been observed on both the hot and cold leg sides of the generator and are distributed randomly through the steam generator.

An extensive in-plant investigation using rotating pancake coil technology showed that the cracking tends to initiate at one of the two edges of the support plate - generally the upper edge - and then propagate away from the plate edge. Conventional bobbin coil technology used in an absolute coil mode was shown to be very effective in detecting cracking at the plate edges. Indications evidenced in the absolute coil mode were not always visible using the differential mode. Rotating pancake coil and bobbin coil data for a particular support plate intersection are shown in Figure C-61. Primary side stress corrosion cracking is evidenced by the linear indication shown in the rotating pancake coil data (upper figure). In this example, two cracks have initiated at the upper and lower edge of the support plate and joined together. Extension of the cracks beyond the plate edges is also apparent. Absolute channel (200 x 400) KHz mix bobbin coil data for the upper edge of this same support plate intersection is shown in the lower part of the figure. Since the crack is above the plate edge, the crack indication forms first followed by a dent signal (horizontal component shown in the figure) which occurs within the support plate. For this examination, sizing was not attempted. All tubes with indications were removed from service.



CHAN# — 1
FREQ ------ 400 kHz
SPAN ------ 80
ROTATION - 265 DEG

MAX VOLTS 1.70
PULL/ROT 4.10
Z ROTATION 300
X ROTATION 70
OF SCANS 59
POINTS/SCAN 109

XY DISPLAY
CHAN# — M 2
CHANS — 2-4
SPAN ——— 320
ROTATION - 106 DEG

LEFT STRIP CHART
CHAN# — 1V
FREQ ——— 400 kHz
SPAN ——— 160
ROTATION - 291 DEG

RIGHT STRIP CHART
CHAN# — 5V
FREQ ——— 100 kHz
SPAN ----- 160
ROTATION - 132 DEG

SYSTEM CONFIGURATION
NAME — DEFAULT
# of CHAN- 8
11:43:35 AM
APRIL 28 1987

	COIL#							
FREQ	1	2	3	4	5	6	7	8
400	1				2			
200	3				4			
100	5				6			
10	7				8			

Figure C-61. Primary Cracking at Dented Support Plate - Rotating Pancake Coil and Bobbin Coil Data

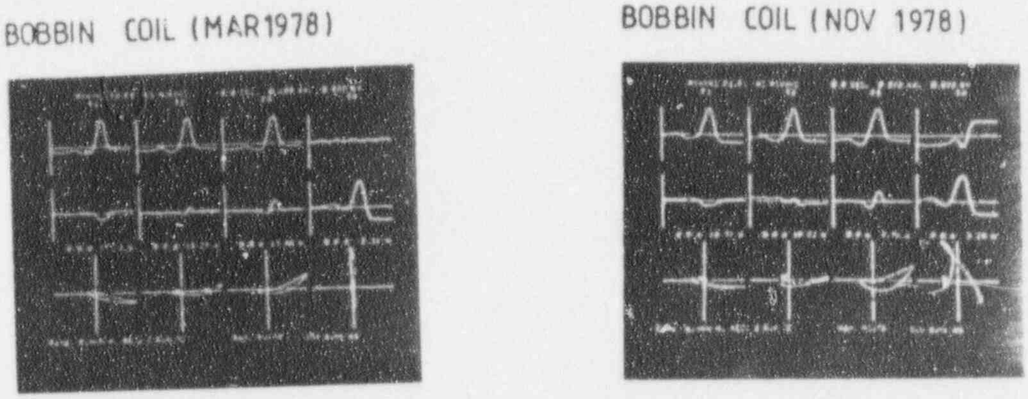
At some units with extensive denting, preventative plugging of tubes is conducted based on strain criteria. Profilometry techniques are used to estimate tube strain at dented support plate intersections. Plant specific strain criteria - based on plant history - are used to remove a tube from service prior to the likely formation of cracking.

C.4.1.5.3 Roll Transition Cracking in Partially Rolled Tubes

Early Westinghouse designed steam generators have tubes rolled for only part of the tube sheet depth e.g., generally 2 1/2 - 3 inches. Roll transition cracking has caused operational problems in some units (Doel 2 and Ringhals 2) in the form of undesirable leakage.

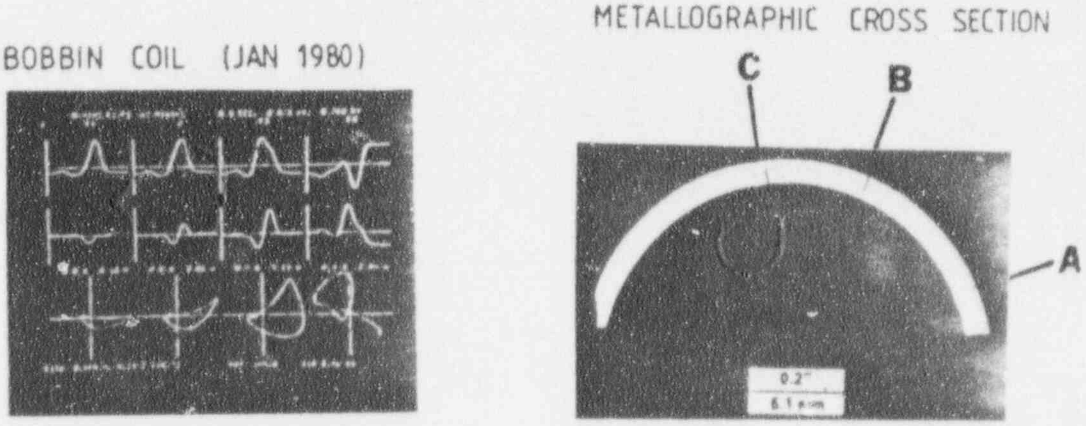
Detection of primary side cracking at the roll transition using bobbin coil technology requires paying careful attention to the shape and rotation of the roll transition signal. It is especially important to review bobbin coil eddy current data at an intermediate frequency e.g., 100-200 KHz. Evidence of roll transition cracking is provided indirectly by loop opening or rotation of the normal roll transition signal, or is provided directly by distorted or distinct indications. This open loop structure has been confirmed directly from pulled tubes (21) and rotating pancake coil data. Figure C-62 shows metallography results from a tube removed from Doel 2 and a chronology of bobbin coil data up to the time of the tube removal. Of interest are the eddy current impedance plane trajectories shown in the bobbin coil data for each of the examinations. One can note the flat loop structure for the March 1978 data, and the distinct loop openings present in the November 1978 and January 1980 data.

Laborelec (22) has conducted extensive in-plant studies in which the detection capabilities of conventional bobbin coil and rotating pancake coil technology were compared for roll transition inspection. In general, only those transitions which had multiple extensive cracking (four to five cracks minimum - near through wall) could be detected with the bobbin coil. This is illustrated with data shown in Figure C-63 which shows a comparison of rotating pancake coil and bobbin coil results at a roll transition. The bobbin coil signal is distorted as evidenced by the loop opening. No clear indication is obvious precluding an estimate of depth. Rotating pancake coil results for the same transition are shown in the lower part of the figure. The presence of multiple (seven) axially-oriented indications characteristic of stress corrosion cracking is apparent.



BOBBIN COIL (MAR1978)

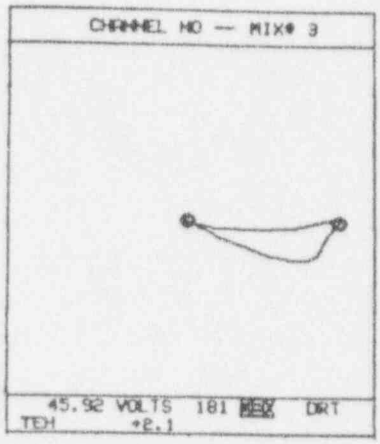
BOBBIN COIL (NOV 1978)



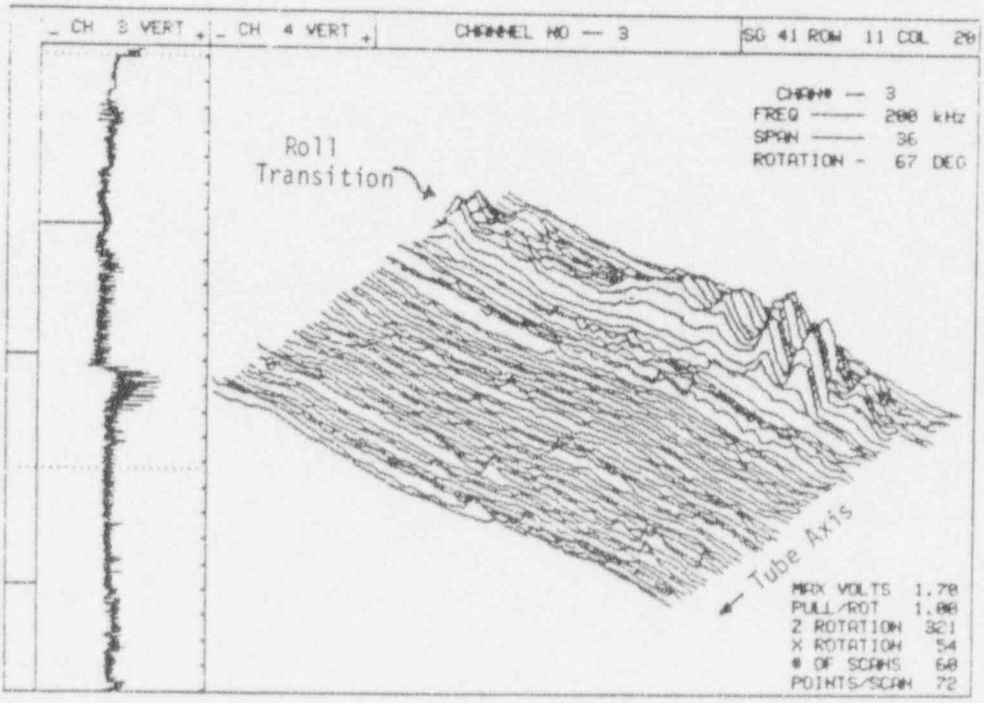
BOBBIN COIL (JAN 1980)

METALLOGRAPHIC CROSS SECTION

Figure C-62. R14 C72 Evolution of Bobbin Coil Data - Doel 2



Bobbin Coil - Distorted Roll Transition Signal



Rotating Pancake Coil Data

Figure C-63. Roll Transition Cracking - Partially Rolled Crevice

In conclusion, the presence or the extent of roll transition cracking can be grossly underestimated based on conventional bobbin coil examination results.

C.4.1.5.4 Fully Expanded Crevices

Later model Westinghouse designed steam generators had tubes expanded for the full depth of the tube sheet in order to eliminate the crevice as a potential sink for the accumulation of secondary side corrodents. Mechanical, hydraulic, and explosive tube expansion methods were used. Numerous European plants with full depth expanded (mechanically rolled) crevices have experienced cracking at the upper roll expansion; in addition, some of these plants have also experienced cracking and leaks in expanded areas at mid tube sheet locations. The incidence of cracking in US plants is not as extensive; the reason for this difference is generally attributed to the presence of a "kiss-roll" introduced by EdF to reduce secondary-side tube stresses at the expense of increasing primary-side tube stresses.

A tabulation of tube sheet expansion method versus Westinghouse design steam generators is given in Table C-3. Units with susceptible tubing expanded using mechanical rollers (second row of Table C-3) are considered high-risk units in terms of likely experiencing primary-side stress corrosion cracking. Various remedial measures in the form of shot peening or rotopeening have been implemented in these units. However, it is not clear whether this action will be completely effective in prohibiting or retarding cracking. Cracking within the tube sheet crevice has been an operational problem in some units causing minor leakage. It can also be a licensing issue since cracking deep within the tube sheet is not a safety issue. Tubes with indications - of no safety or operational significance - may have to be removed from service because of present technical specification requirements which require the plugging of tube without consideration of the location of the indication. Proactive efforts on the part of the utility and the NSSS vendor e.g. implementation of F* or P* criteria, are recommended to avoid these licensing issues.

Table C-3

WESTINGHOUSE DESIGN STEAM GENERATORS - TUBE SHEET EXPANSION -

Expansion Method /	Steam Generator Model										
	24	27	33	44	51	D2	D3	D4	D5	E	F
Part-Depth Roll	MA	MA	MA	MA	MA						
Full Depth Roll (Mechanical)					MA	MA	MA	MA		MA	
WEXTEX (Explosive)					MA						
Full Depth Roll (Hydraulic)									TT	MA	TT

MA = Mill Annealed Alloy 600

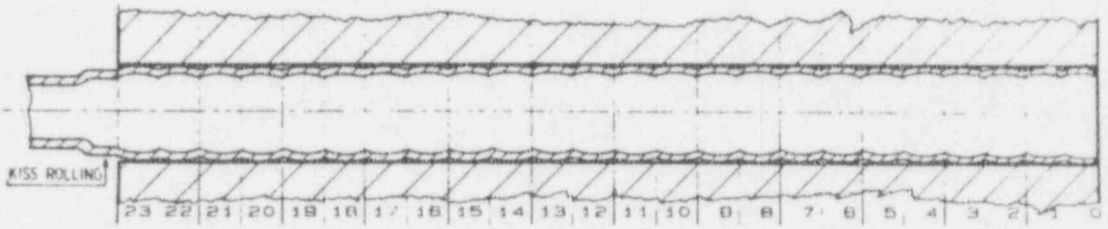
TT = Thermally Treated Alloy 600

Mechanical Roll

The basic mechanical rolled tube expansion geometry is shown in Figure C-64. Mechanical rolling was typically performed using a roller stepped through the tubesheet with a 5mm roll overlap. Eddy current profilometry acquired from tubes mechanically expanded has shown many interesting rolling variations including:

- Unexpanded tubes
- Skip rolls
- Irregular shapes
- Overexpansions
- Non-overlap
- Waves
- Oversized hole diameters
- Missed kiss roll
- Weak rolls
- Bulging

From a safety standpoint, the condition of the of tube near the top of the tube sheet is of primary concern since the tube is no longer restrained as with the case of a partial rolled tube. Two basic final roll variations have been utilized; kiss or DAM roll, and no kiss roll; examples of these two geometries along with observed crack locations are shown in Figure C-65. A kiss roll is a two step final roll intended to reduce secondary-side tube stress at the expense of increasing primary-side stress; it is prevalent in Framatome manufactured and modified steam generators. The none kiss roll geometry has a single final roll and is the only roll configuration in US steam generators with full depth mechanical expansions.



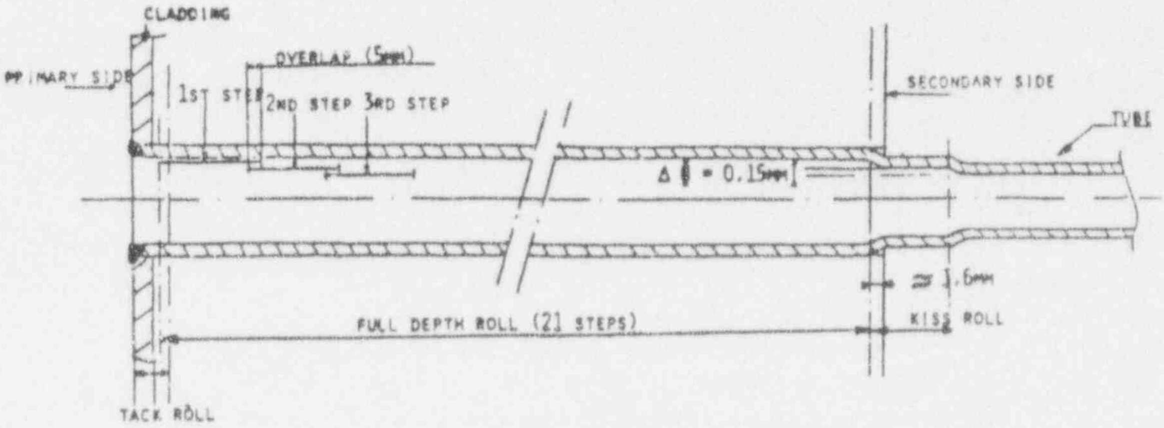
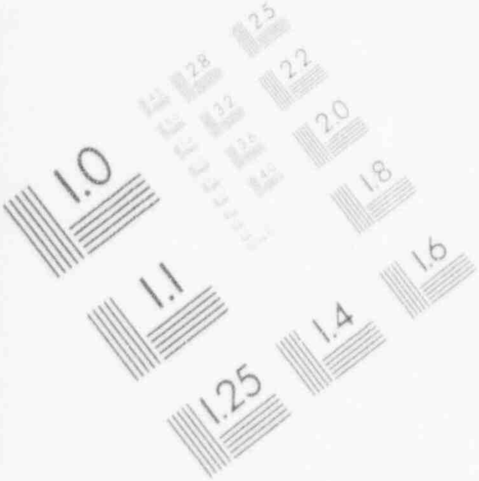
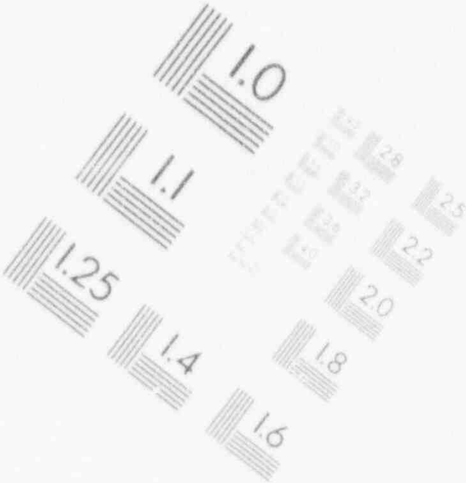


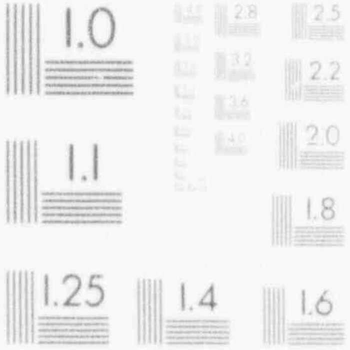
Figure C-64. Full Depth Rolled Tube - Mechanically Rolled

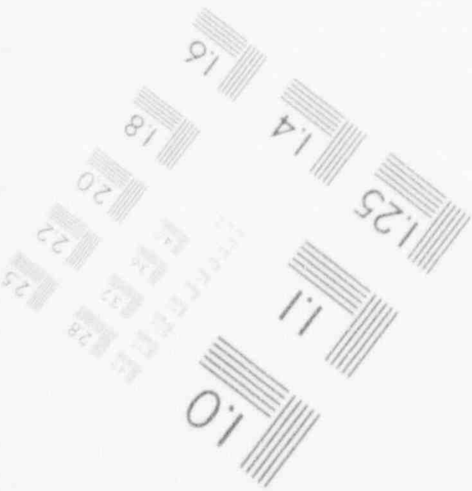
2

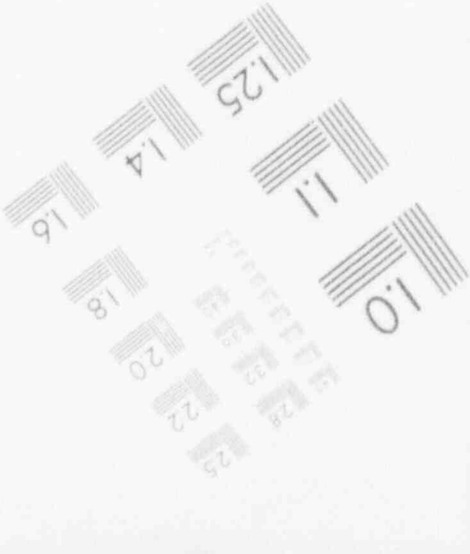
IMAGE EVALUATION TEST TARGET (MT-3)











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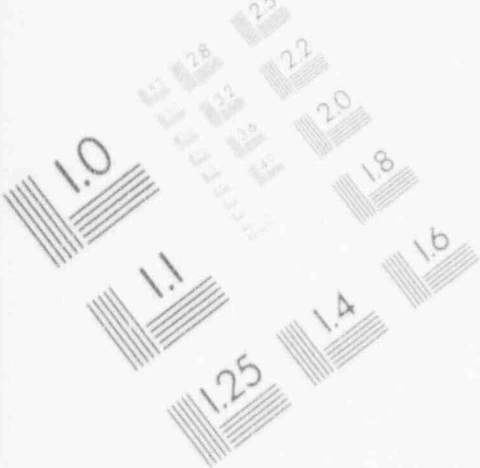

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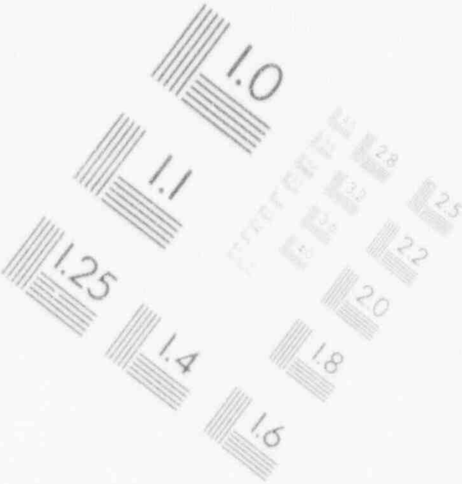
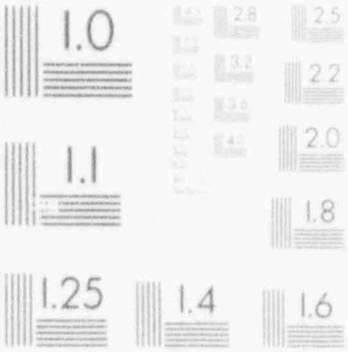
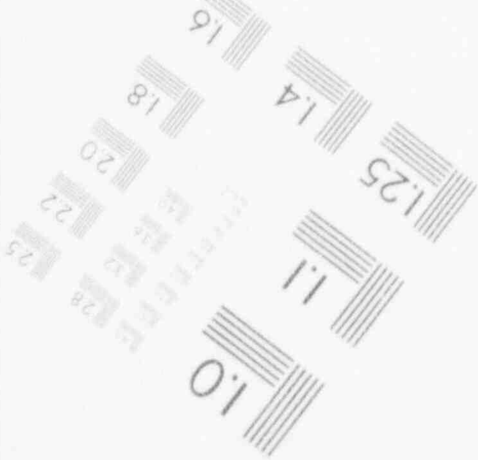
IMAGE EVALUATION
TEST TARGET (MT-3)







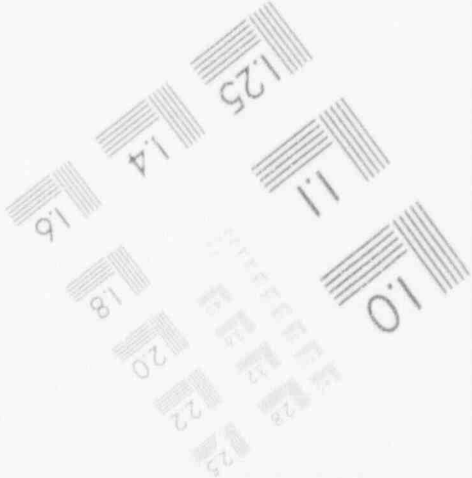


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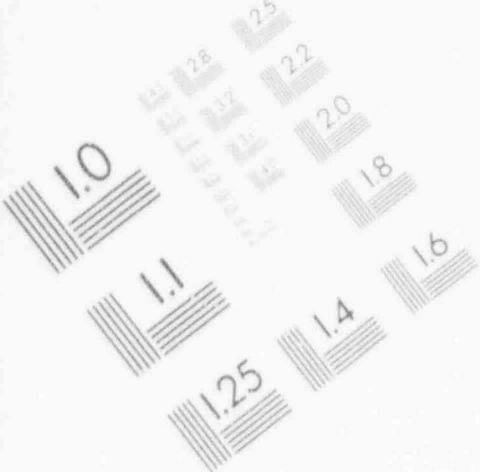
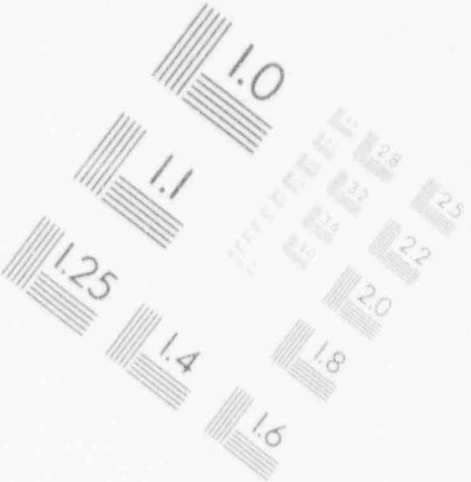
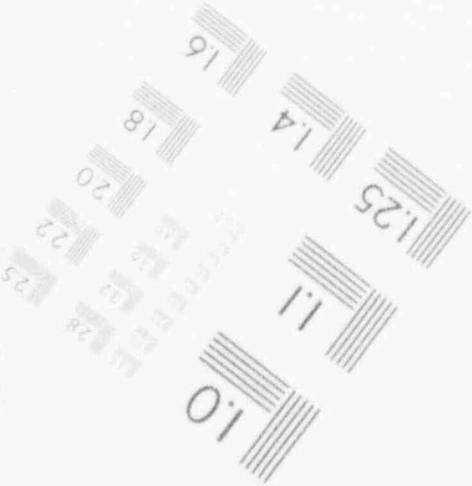
IMAGE EVALUATION
TEST TARGET (MT-3)







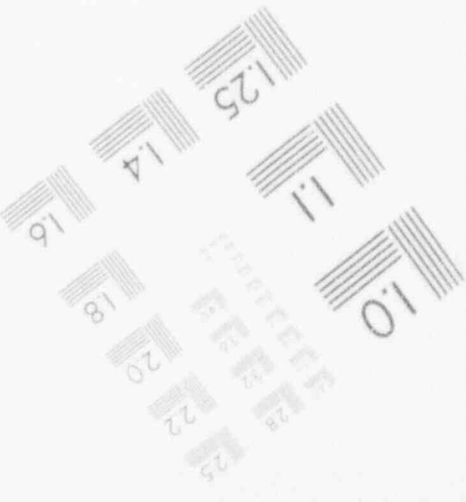


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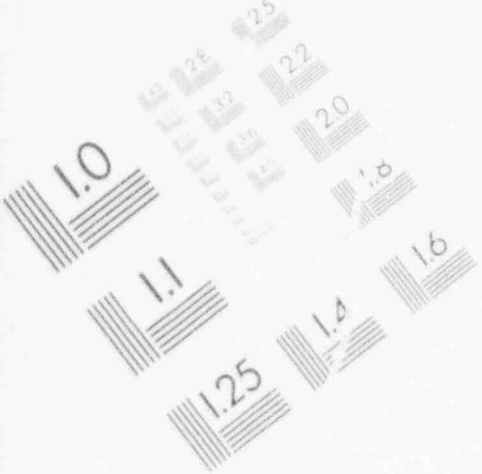
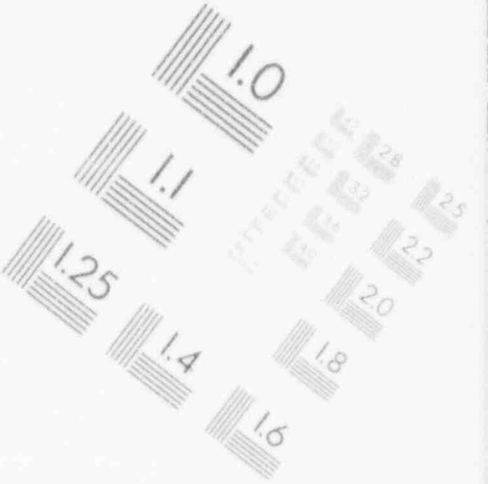
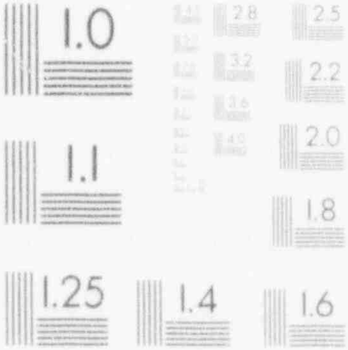
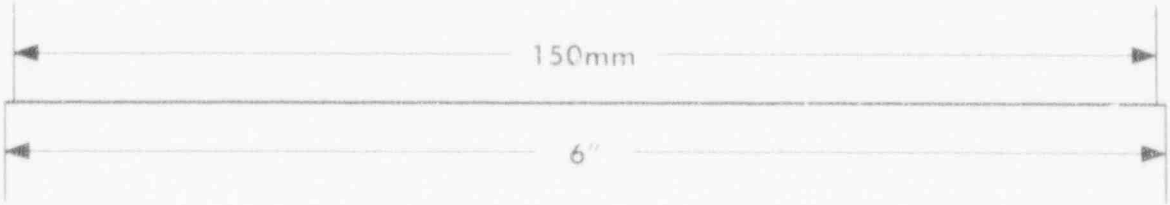
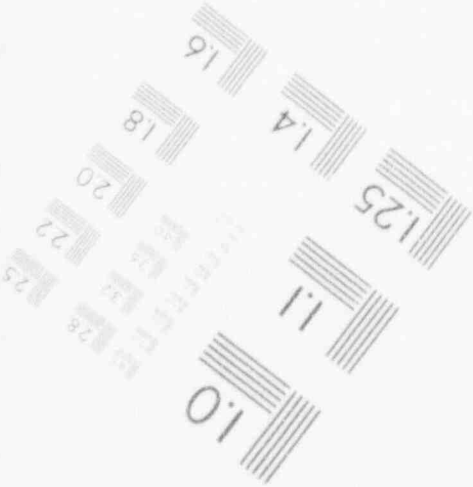
IMAGE EVALUATION TEST TARGET (MT-3)

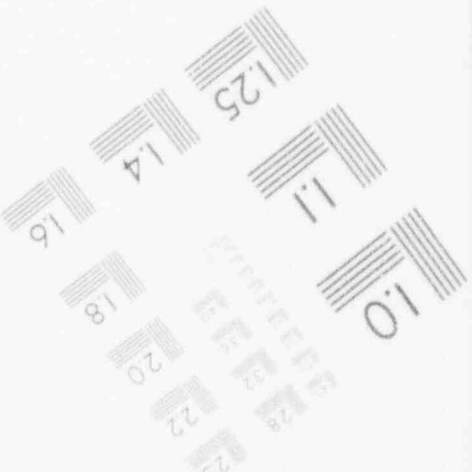












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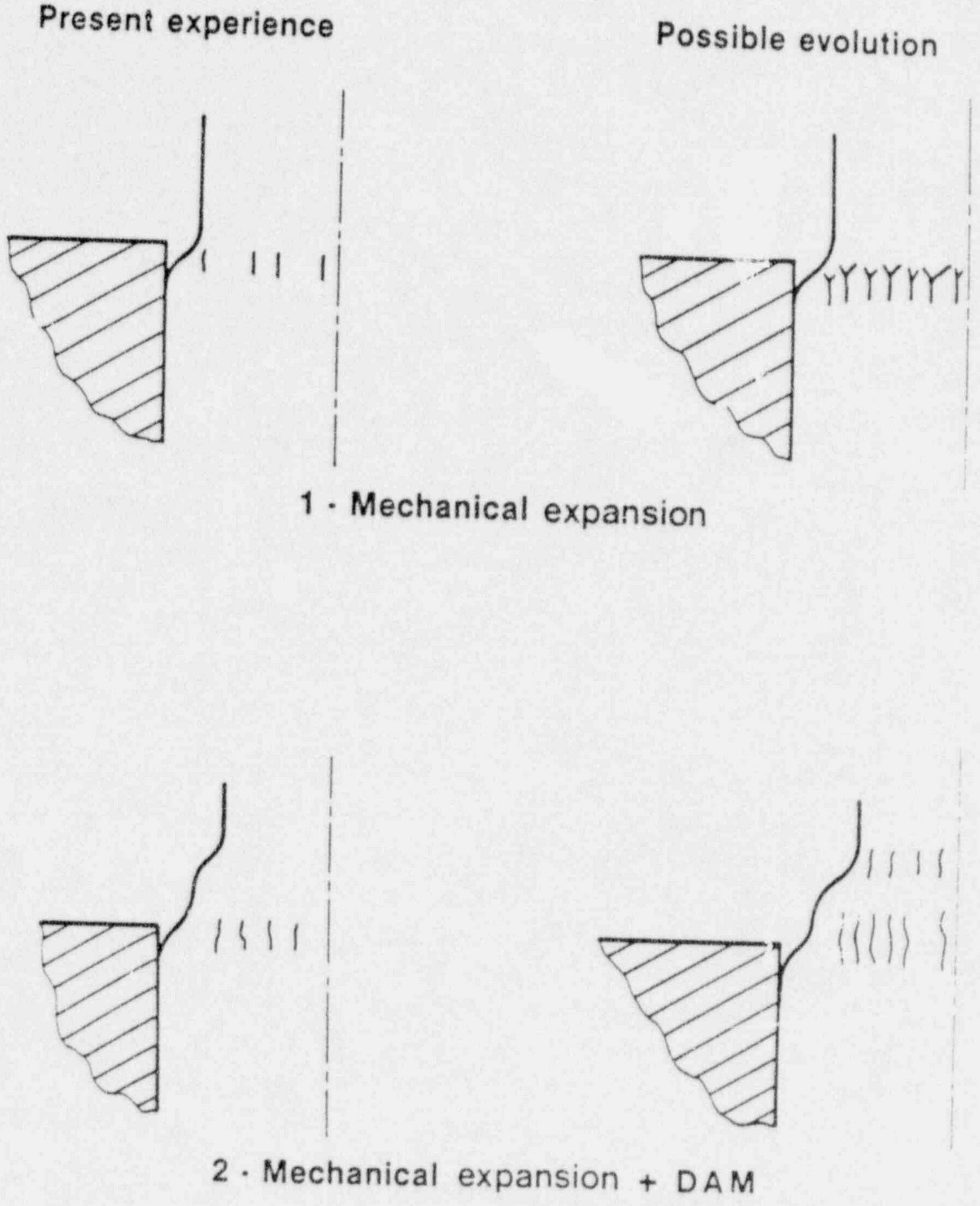


Figure C-65. Primary-Side Stress Corrosion Cracking - Mechanically Expanded Tubes

Steam generator examination and plugging strategies are derived from French, Belgian and Swedish experience since they have the lead units in terms of operating history. Numerous tubes (in excess of 120 tubes) have been removed from operating units with the objective of developing a basic understanding of expected crack morphologies and determining the reliability of various eddy current examination methods. In addition, extensive analytical and experimental programs have been conducted by EdF and Laborelec justifying a leak-before-risk-of-break approach in order to implement plugging criteria based on crack length rather than depth (23,24). This has been deemed necessary because a significant number of tubes are believed to be cracked in excess of existing plugging limits. Rigid implementation of plugging criteria based on depth alone would require an excessive number of tubes to be repaired or plugged. Basic steam generator examination strategy differs from country to country. French strategy relies on a helium leak test to identify tubes for rotating pancake coil examination. Belgian strategy consists of a 100% rotating pancake coil examination to determine crack length in the upper part of the tube sheet (+30mm to -125 mm from the top of the tube sheet). In Belgium, the full length of the tube sheet was examined during the first in-service inspections. However, the comparison with the baseline profilometry data showed that the majority of the roll transition cracks in the tube sheet were related to oversized tube sheet holes with insufficient tube expansion. Preventative plugging of overexpanded and bulged tubes based on profilometry data is recommended. In addition, special consideration should be given to abnormal expansion geometries.

Although rotating pancake coil inspection is recommended, bobbin coil data provides interesting information when a close comparison between preservice and inservice signals at the roll expansion is performed. An example of bobbin coil signal evolution between preservice and the first inservice examination is shown in Figure C-66. Illustrated are multiple roll transition signals throughout the length of the crevice. Of interest is the change in signal structure for transition 15-14. The baseline data shows an open loop signal whereas data obtained during the first inservice examination shows a larger amplitude signal with a clear transition. This tube had developed a leak within the tubesheet. Profilometry data for the same tube showed the tubesheet hole to be oversized in the vicinity of the leak allowing for a leak path to develop. Rotating pancake coil data for the same tube showed clear indications of cracking at the 15-14 transition in addition to transitions 8-7, 11-10, and DAM-21. As can be seen, the inservice examination bobbin coil data does not show strong evidence of cracking at these other locations. Based on tube pull information, it was found that multiple cracks (4-5 minimum) approximately 10 mm in length, near through wall must be present before bobbin coil detection.

▨ CRACKED AREA FOR ROTATING PROBE

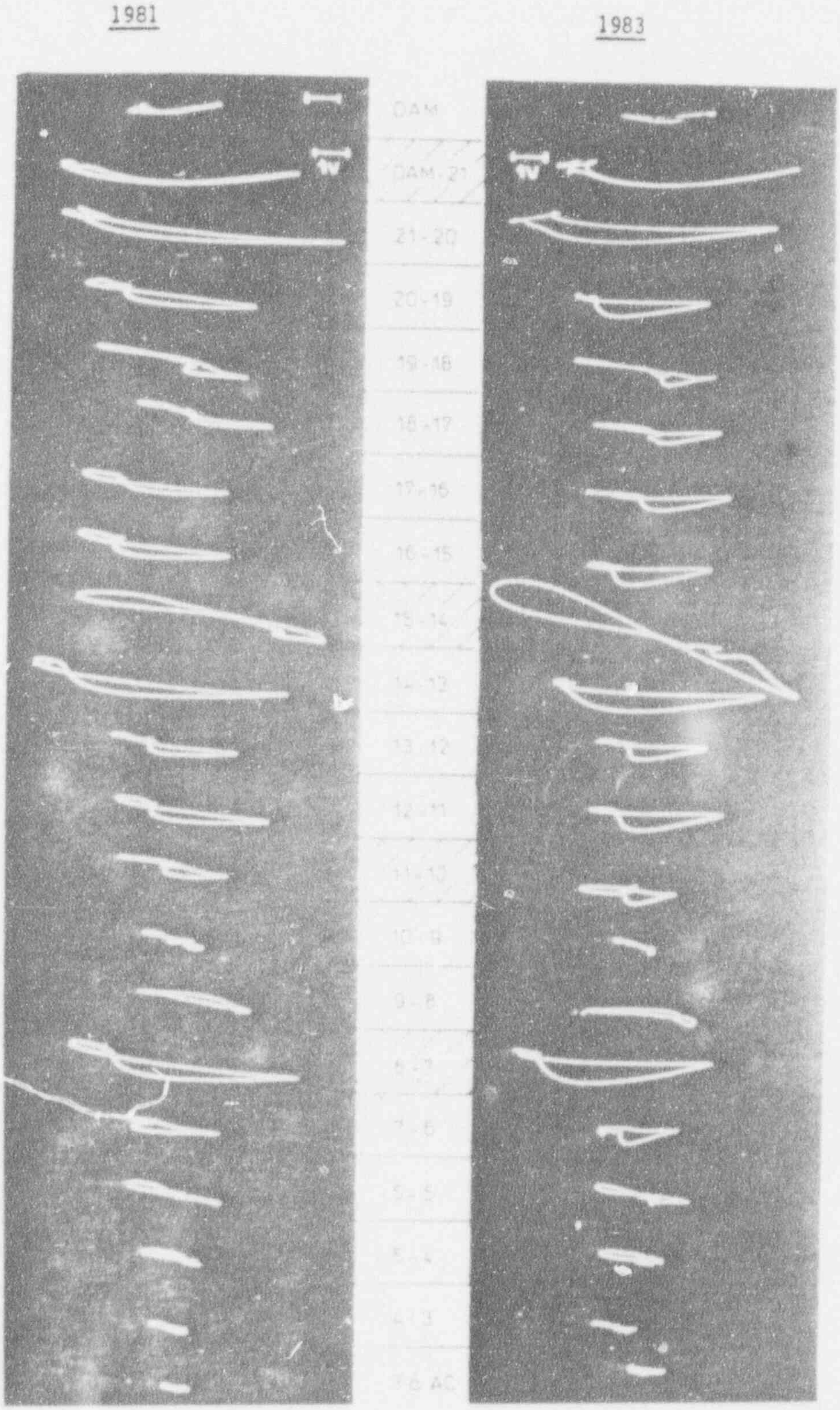


Figure C-66. R15 C29 (Doel 3) - Bobbin Coil Examination of Expansion

Swedish State Power Board has pulled six tubes from Ringhals 3 (Model D3) with mechanically rolled tubes and reached similar conclusions with regards to bobbin coil detectability (25). No cracking was observed at the kiss roll. All of the cracking was found within the tube sheet crevice at or near roll overlaps. Short banded axial primary side cracking with a maximum length of 10 mm was identified. In one case, at least one crack was through wall. Cracking was only observed in areas that were identified to have bobbin coil indications. Figure C-67 shows examples of primary side cracking found on tubes removed from Ringhals 3. Laborelec and EdF have also pulled numerous tubes in order to establish the reliability of rotating pancake coil technology in detecting the extent of cracking and in estimating crack length at the kiss roll. Depth is of no concern; in fact cracks are assumed to be through wall. Based on tubes removed from Doel 3 in 1986 the following conclusions were identified:

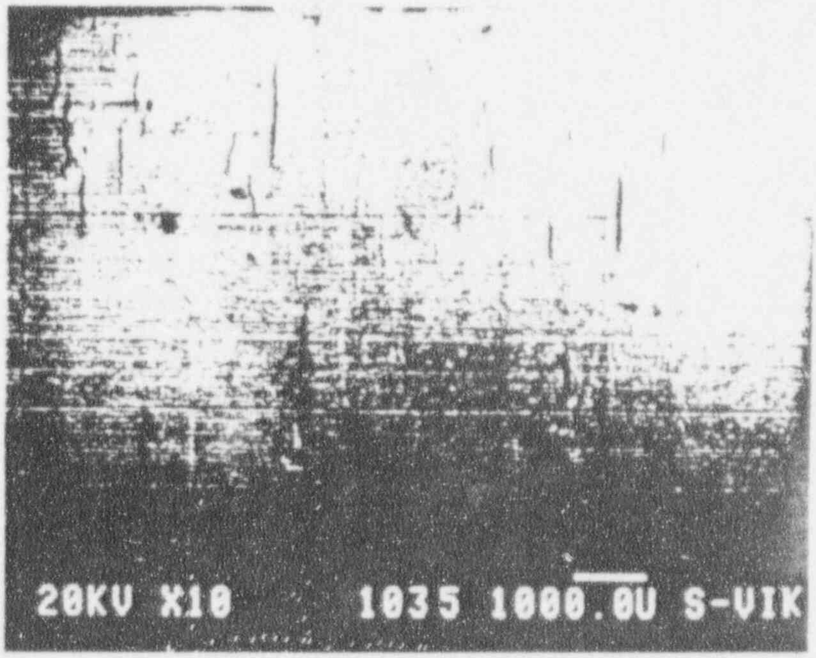
- Excellent agreement between eddy current predicted and actual angular distributions of detected cracks
- No "false calls"
- Some small additional cracks were not detected by eddy current; most with a length less than 1 mm.
- Crack depths measured for 21 cracks; all very deep (80% to 100%).

A scatter plot of eddy current predicted lengths versus measured lengths on tubes removed from Doel 3 (July 1986) is shown in Figure C-68. A least squares fit to the data is given by $y = 0.96x - .98$, with a correlation coefficient of 0.69. The least squares fit was taken on 15 points with lengths greater than 4.5 mm. Indeed, below this value the detectability cannot be assumed as 100% as it appeared from the undetected cracks in the pulled tubes. Belgium has implemented a Regulatory Guide 1.121 approach which allows for through wall cracks less than the critical length. Plugging criteria are derived from a maximum allowable length by subtracting a margin for length sizing accuracy and crack propagation up to the next examination. For Model D steam generators (Ø 7/8") and based on average tube properties, the critical crack length has been calculated to be 49 mm. A safety factor of three on length reduces the allowable length to 16.3 mm. The combined additional margin allowed for eddy current length underestimation and annual crack propagation is 4.5 mm. For cracks located in the roll transition, the vicinity of the tubesheet yields a reinforcing effect which has been experimentally evaluated to an equivalent 3 mm increase in length. The plugging criterion is thus

$$PL = 16.3 \text{ mm} - 6 \text{ mm} + 3 \text{ mm} = 13.3 \text{ mm}.$$

rounded off to an actual limit of 15 mm.

Studsvik



Ringhals 3 SG3
Tube R2-C30
Axial cracks

Figure C-67. Primary-Side Cracking at Roll Overlap (Ringhals 3)

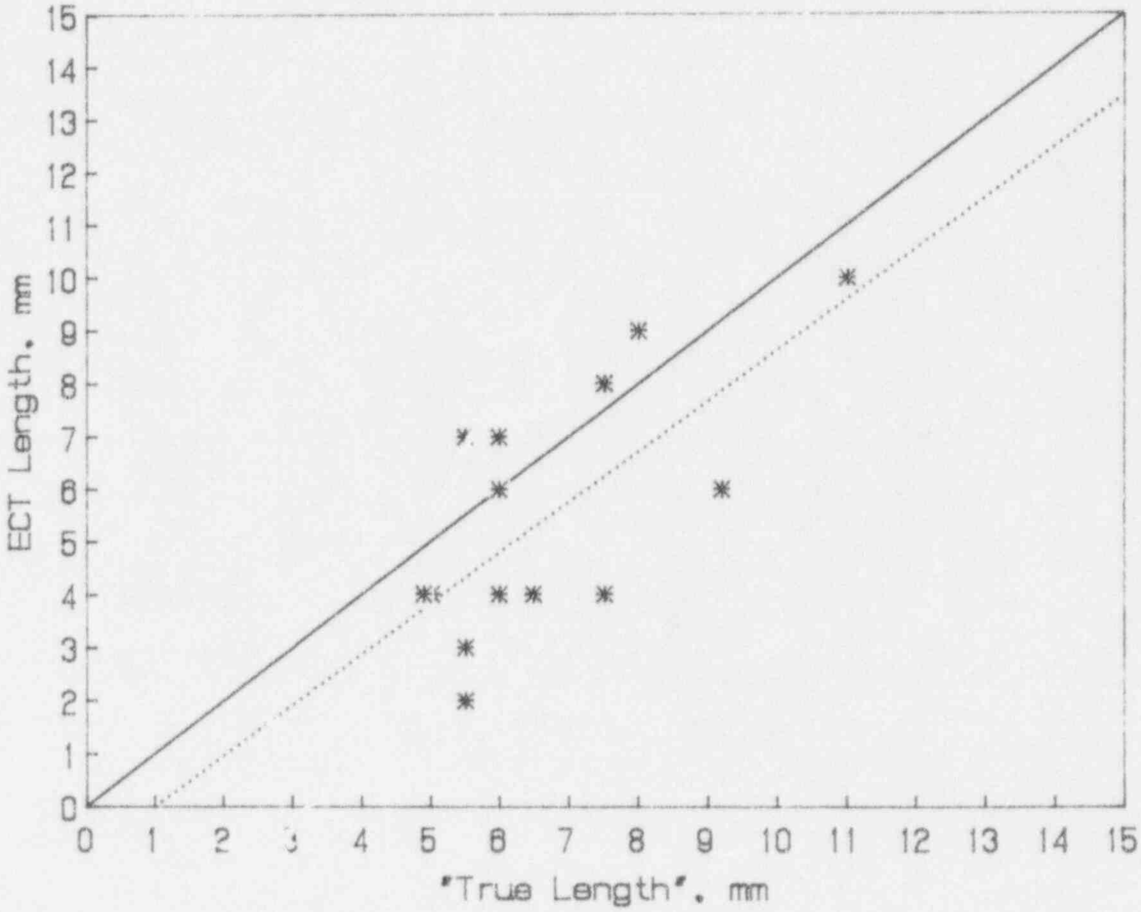


Figure C-68. Eddy Current Predicted Crack Lengths
Compared with Metallographic Results

EdF has conducted similar analyses and utilize a plugging limit of 16 mm. They are in the process of installing sensitive N-16 leak monitoring equipment and have a very conscientious leak monitoring program. Any significant ramping in leak rate is sufficient to bring a unit off line for examination. Typical examination programs for their units depend to what extent the steam generators are effected by cracking which is determined by sampling a percentage of tubes with a rotating pancake coil. See Table C-4.

Table C-4

STEAM GENERATOR EXAMINATION - ROLL TRANSITION REGION
EXAMINATION PROGRAM AND PLUGGING CRITERIA

Plant Condition	Eddy Current Program	Leak Test	
Ratio of Affected Tubes		Leakage During Cycle	No Leakage During Cycle
< 5%	12% each year 1 steam generator	Hydro test	---
> 5% but < 10%	12% each year 1 steam generator	Hydro test plus helium test if small leak	---
> 10%	25% each year 2 steam generators	Hydro test plus helium test	Helium test

All tubes examined using bobbin probe. Eddy current indications are classified into categories:

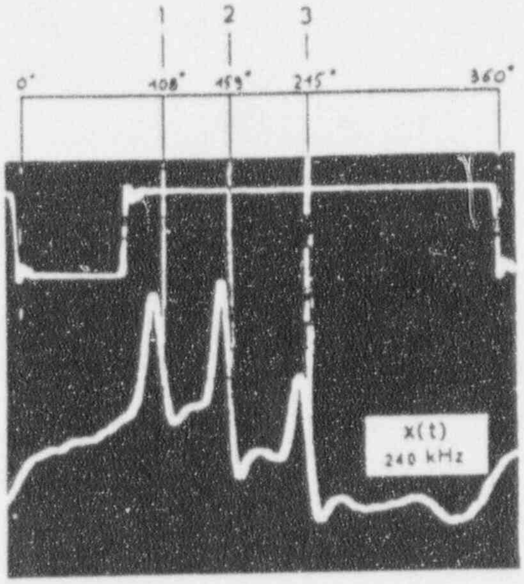
- A and B: short cracks

- C and D: more important cracks; these tubes are examined by rotating probe for estimates of crack length.

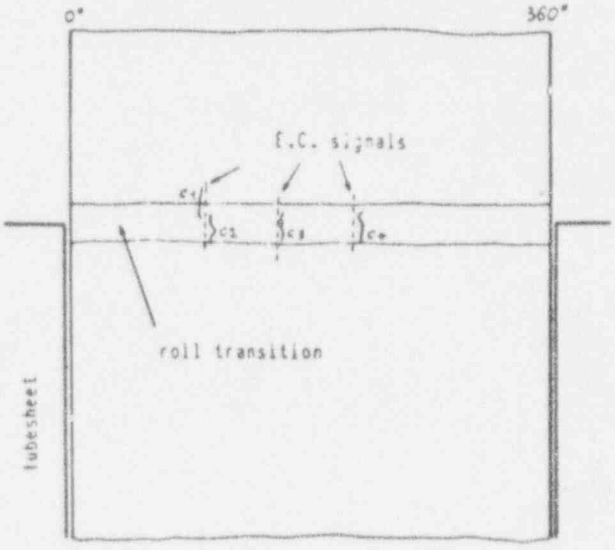
Plugging Criteria (Roll transition region)

- Hydro test - leak — Preventative plugging of tubes with roll anomalies (bulge, over roll)
- Helium test - significant leak
- Rotating probe - length > 16 mm

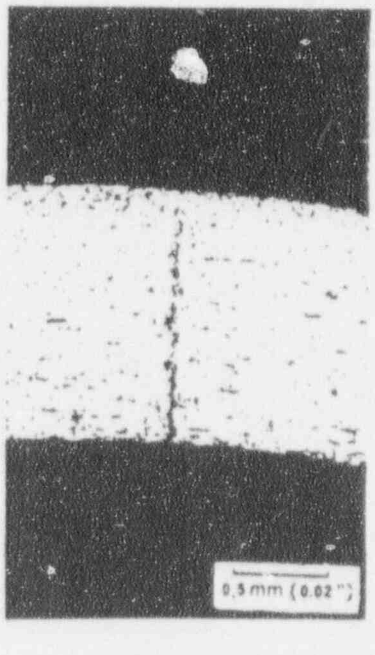
EdF has also done extensive work comparing the eddy current predicted condition of the tube at the roll expansion with that determined metallographically (26). An example is shown in Figure C-69 which shows the in-plant rotating pancake coil eddy



E.C. signals in a section of the tube



radiographic examination
(cracks c1, c2, c3, c4)



Micrography of the C4

Figure C-69. Correlation Between Rotating Probe Eddy Current
Data and Radiography - Metallography Results

current data (three major crack networks predicted), radiography results and their correlation with the eddy current data, and metallography for one of the cracks showing its origin from the primary side. In general, very good correlation has been established between the eddy current predicted condition of the tube and its true state.

As of January 1, 1987, the number of tubes listed in Table C-5 have been plugged because of primary side stress corrosion cracking (27).

Table C-5

TUBES PLUGGED - MECHANICAL EXPANSION

Cause	Tube Leaks (a)	ECT Signal	Preventative	Total
Roll Transition PWSCC	206	190	145	541
Roll Steps	5	8		13
				554

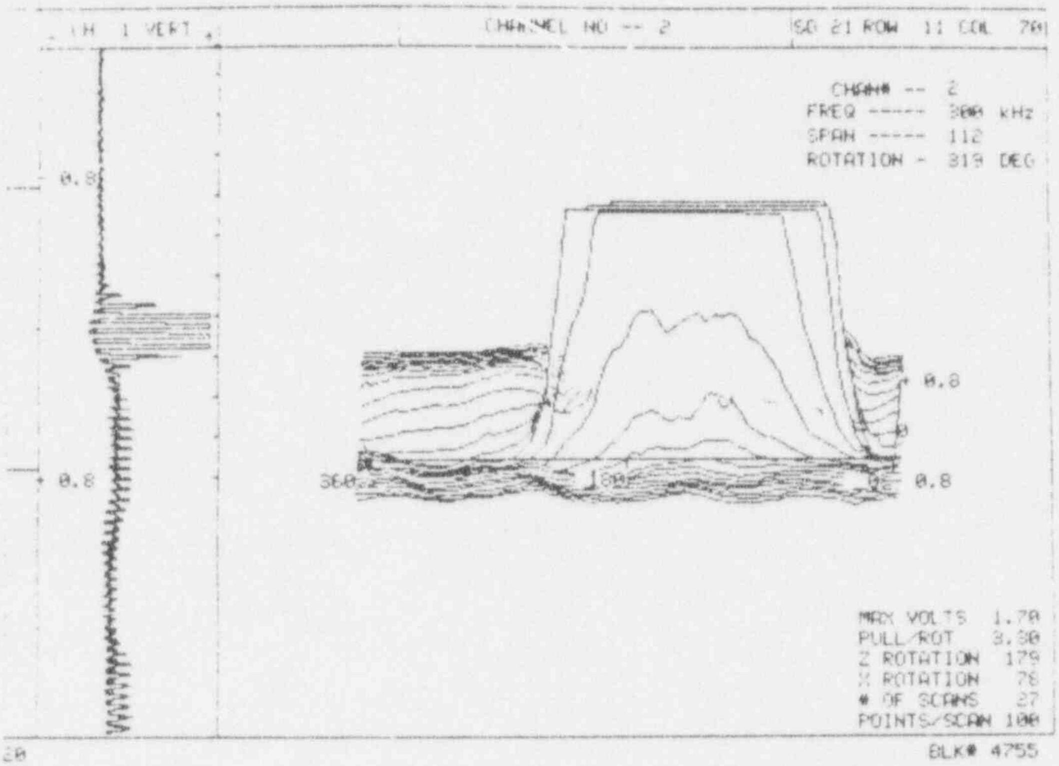
Note: Total plant population is 33 units.

(a) Hydrotest or helium leak testing

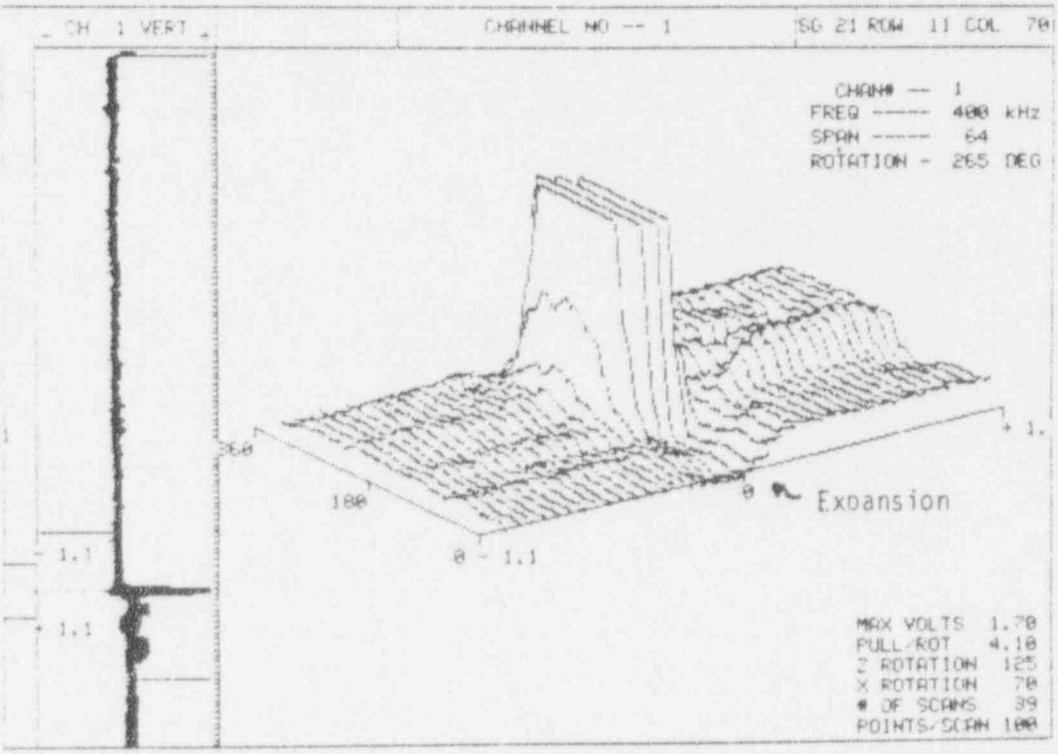
Explosive Expansion (Wextex Process)

Two units with Wextex expanded crevices have experienced primary side circumferential stress corrosion cracking (Fessenheim 1 and North Anna 1). At Fessenheim 1, the occurrence of circumferential cracking was attributed to abnormal residual stresses; tubes with this condition were isolated to a particular region of the steam generator.

Circumferential cracking at North Anna 1 was discovered during the course of a scheduled outage in June, 1987. Bobbin coil examination of a leaking tube was not able to identify the location of a leak within the tube. Subsequent examination of the tube with a rotating pancake coil at the support plates and at the top of the tube sheet readily identified the latter region as the source of the leak. Review of the isometric plot of the rotating probe eddy current data showed the indication to be circumferentially oriented as shown in Figure C-70 which illustrates an end-on and oblique view looking up towards the top of the tube sheet. Two tubes were



End-on View



Oblique View

Figure C-70. R11 C70 Rotating Pancake Coil Data - Circumferential Crack removed during the course of the outage; destructive examination of one tube confirmed the circumferential orientation and showed the mechanism to be primary side stress corrosion cracking. Sampling with a rotating pancake probe was conducted in all three steam generators and additional tubes with indications were identified. Ultimately, a 100% examination of all steam generators was conducted using (8x1) array coil technology for production inspection. Numerous tubes were identified with indications. Confirmation of all (8x1) indications was achieved using rotating pancake coil. An example of (8x1) data for the leaking tube shown in the previous figure is given in Figure C-71. The impedance plane trajectory is shown in the upper part of the figure whereas the eight-channel strip chart data is shown below. Five of the eight channels show clear indications which suggests a circumferential extent of approximately 225 degrees. This agrees fairly well with the extent determined by examining the end-on view from the rotating pancake coil data shown in Figure C-70.

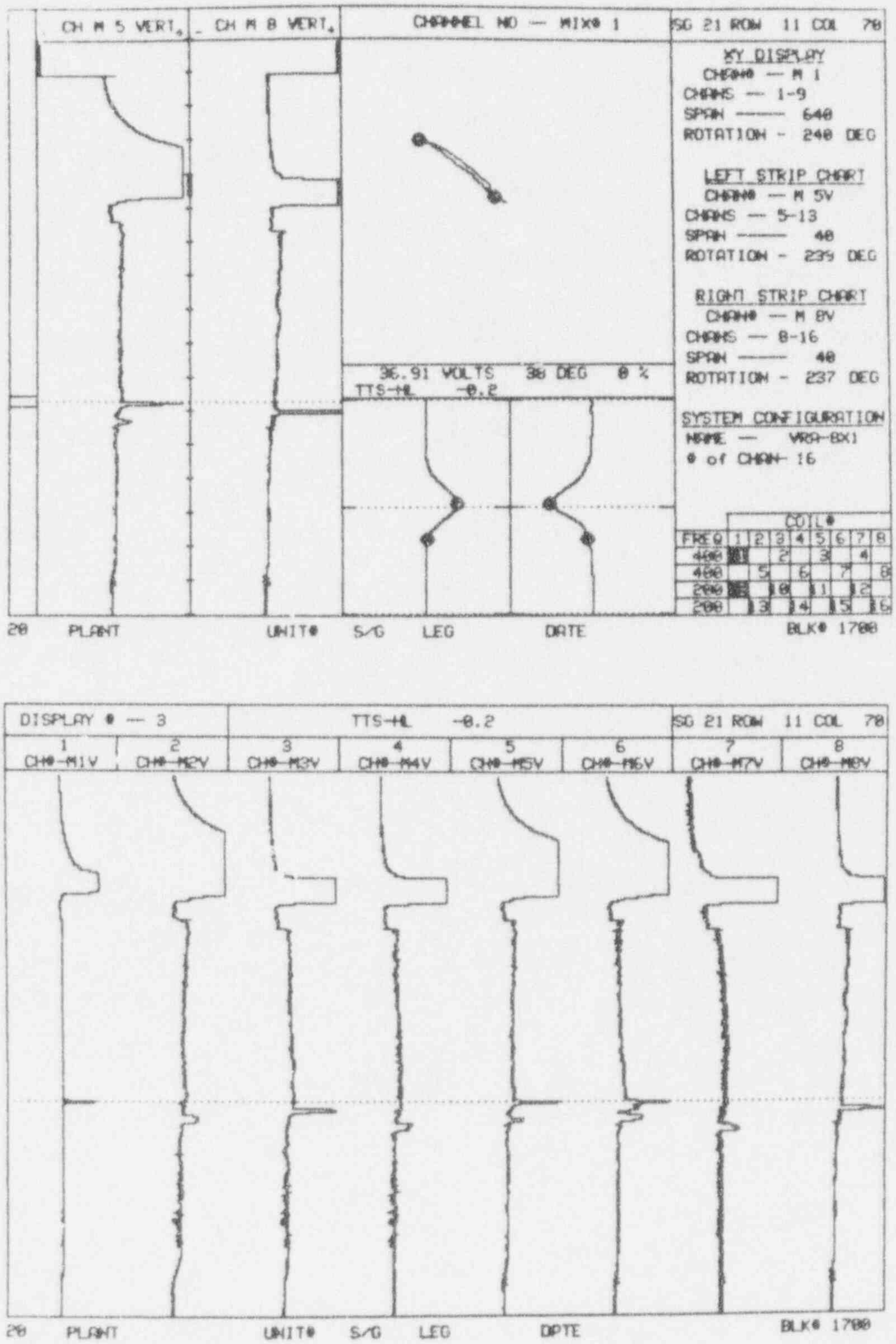
C.4.2 Once-Through Units

Once-through steam generators have experienced four principal damage mechanisms including corrosion fatigue, impingement damage, wear, and intergranular attack-stress corrosion cracking. The first three mechanisms are attributable to flow related phenomenon and account for a majority of the plugged tubes in once-through steam generators. Relatively few number of tubes have been pulled from once-through steam generators in order to establish performance estimates of NDE capability.

C.4.2.1 Corrosion Fatigue

Fatigue failures in steam generator tubing have typically been due to simple, transgranular cracking, usually circumferential in orientation (4). Corrosion-assisted high-cycle fatigue cracking is the primary cause of leaker outages in once-through steam generators and occurs along the lane region. The cracking is circumferential with a typical failed tube and through wall crack shown in cross section in Figure C-72.

Until recently, no partial through wall crack had been identified, i.e., the crack was either non-existent or completely through wall. This is not surprising since failure times have been estimated at less than 24 hours. Oconee 3 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



XY DISPLAY
CHAN# — M 1
CHANS — 1-9
SPAN —— 640
ROTATION - 240 DEG

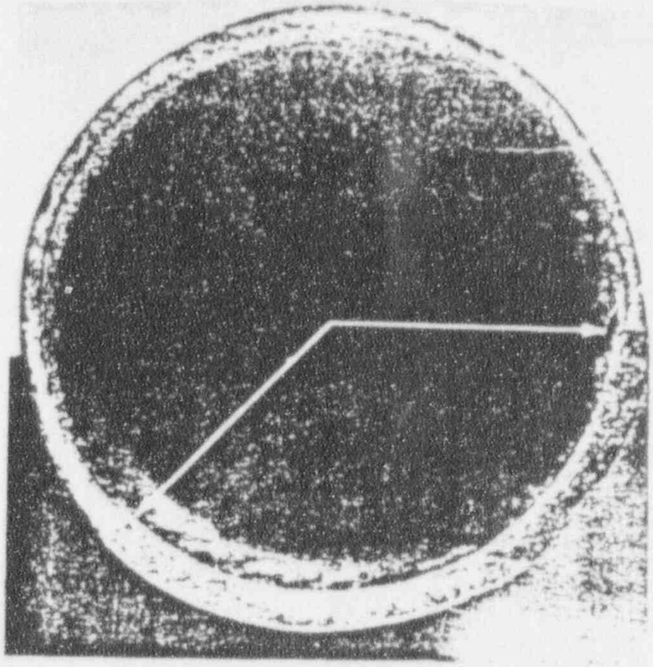
LEFT STRIP CHART
CHAN# — M 5V
CHANS — 5-13
SPAN —— 40
ROTATION - 239 DEG

RIGHT STRIP CHART
CHAN# — M 8V
CHANS — 8-16
SPAN —— 40
ROTATION - 237 DEG

SYSTEM CONFIGURATION
NAME — VRA-8X1
# of CHAN- 16

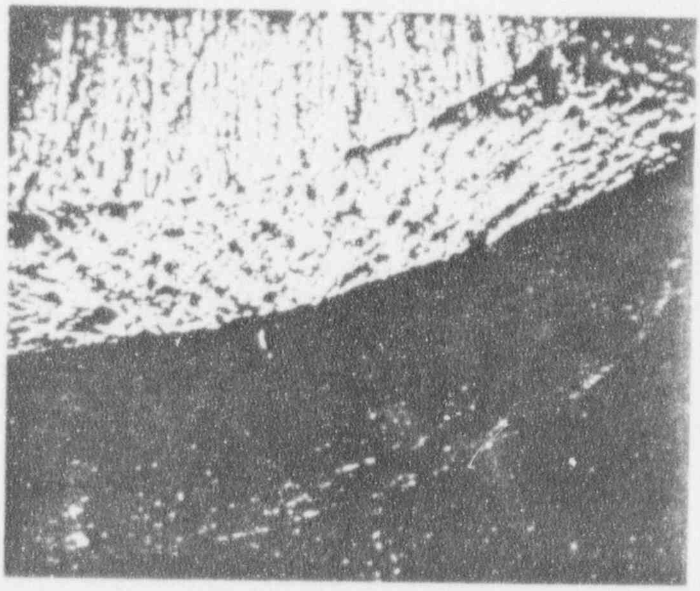
	COIL#							
FREQ	1	2	3	4	5	6	7	8
400	1		2		3		4	
400		5		6		7		8
200	9		10		11		12	
200		13		14		15		16

Figure C-71. R11 C70 (8 x 1) Array Coil Data



120° Service Fracture (5.6X)

End View of Failed Tube



Crack Initiator

Figure C-72. Corrosion-Assisted High-Cycle Fatigue

* Please note that the illustration(s) on this page has been reduced 10% in printing.

tube (79-5) was identified as having an eddy current indication 40% through wall using the (8x1) but had no bobbin coil indication. The tube was removed and sectioned; a photograph is shown in Figure C-73. The presence of a circumferential discontinuity is apparent just above the light rectangular patch; this 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 crack 63% through wall. This is the only example of a partial through wall crack.

Since 1977, numerous other tubes have been removed from the Oconee units with through wall corrosion-fatigue cracks. A scatter plot of eddy current predicted versus measured depth doesn't offer useful sizing statistics since all the bobbin coil data is for a through wall condition. A similar situation exists for detection probability estimates.

The use of a bobbin coil for the detection of circumferential fatigue cracking does not represent good examination practice. (8x1) array coil technology is recommended although as pointed out in Appendix B Section B.5.1.1, examination of a tube for this condition may be meaningless because of rapid failure times.

C.4.2.2 Impingement Damage

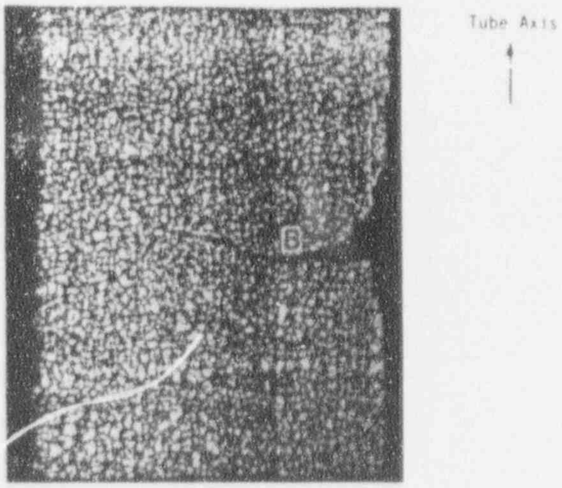
Impingement damage is a form of erosion (material loss) caused by suspended solids and/or liquid droplets hitting a surface (28). In once-through steam generators, it is believed to be caused by the flow-induced impingement of micron sized particles against the tube wall. The source of the particles is debris distributed throughout the secondary side of the steam generator. Most of the eddy current indications attributable to this damage mechanism occur at the 14th support plate within the outer periphery of the steam generator. Hence the mechanism is sometimes referred to as "14th support plate" defects. However, indications have been reported as low as the 2nd support plate and occur at other support plate elevations as well.

Figure C-74 shows examples of impingement damage on a tube removed from one of the Oconee steam generators. The damage typically occurs near the support plate requiring the use of a mix channel in order to reduce the influence of the support plate signal. The morphology typically assumes the shape of a tear drop or candle flame and is quite irregular in depth.

Three tubes have been removed with this damage mechanism. A scatter plot of

(8X)*

Crack at Upper End of Land Contact Wear Region



(75X)*

Longitudinal Section

Figure C-73. Partial Throughwall Fatigue Crack

* Please note that the illustration(s) on this page has been reduced 10% in printing.

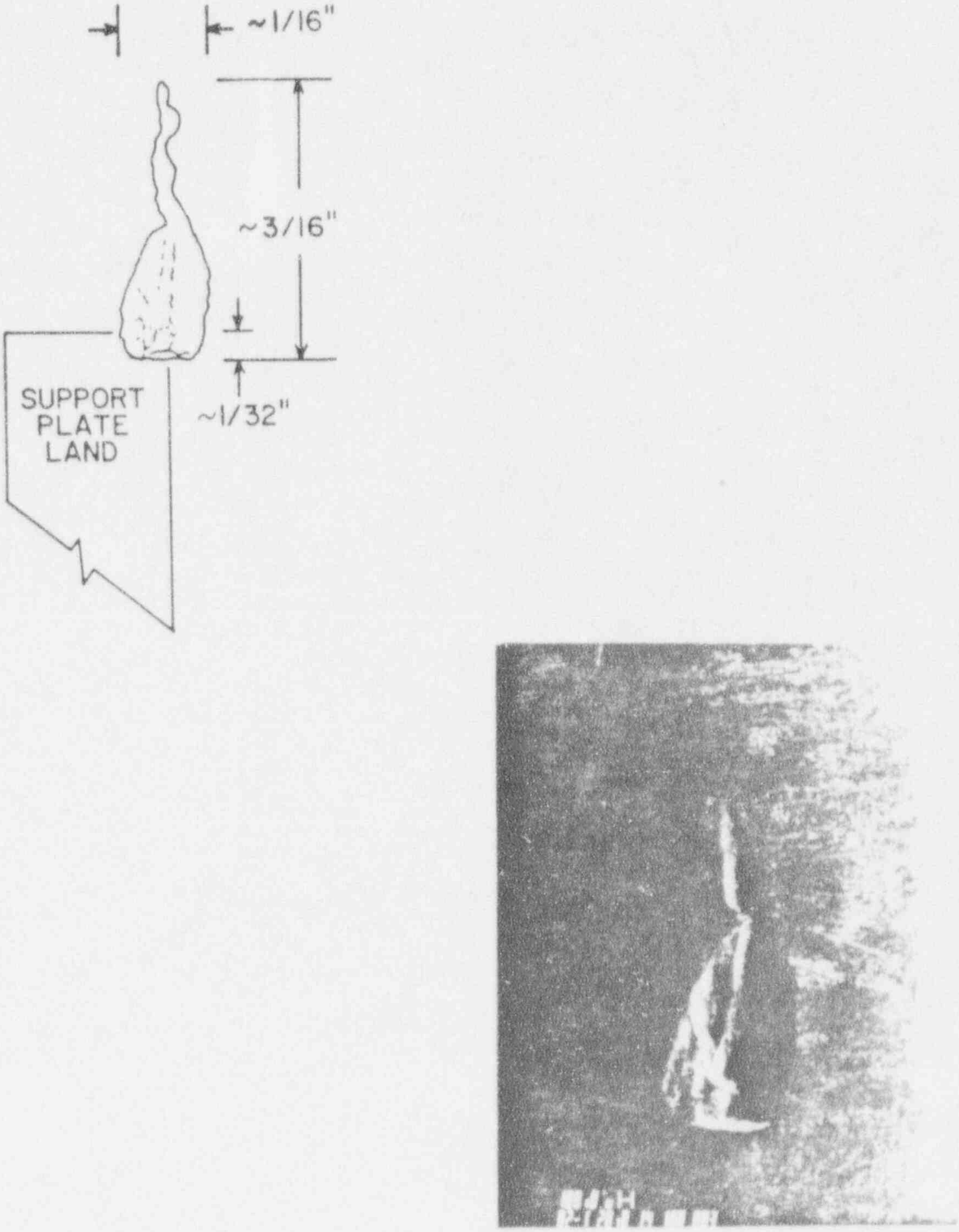


Figure C-74. Flow Impingement Damage

predicted versus measured depth for three data points is shown in Figure C-75. Insufficient data exists at shallower depths precluding a least-squares fits to the data points. However, as can be seen, both conservative and nonconservative errors are present with a worst case error on the order of 25% through wall.

A signal-to-noise ratio criterion has been established for "14th support plate" indications in order to avoid excessive tube plugging. A threshold value of 5 is presently used; signals with a ratio in excess of this value are dispositioned using normal phase angle analysis methods; those with a ratio less than this value are reported and monitored during future examinations.

C.4.2.3 Wear

Wear in once-through steam generators is the result of cross-flow induced tube vibration within the upper region of the steam generator. Degradation is limited to lane region tubes at elevations between the 14th support plate and upper tube sheet. In wearing, the tube makes contact with the broached support plate land contact areas of which there are three. The wear pattern tends to assume the rectangular geometry of the support plate land (See Figure C-76); the wear is generally tapered which suggests that an eddy current absolute coil mode is the preferred choice for examination.

Very few tubes have been removed from once-through units for wear. This precludes a reliable estimate of sizing accuracy. Laboratory sizing studies have been conducted and are reported in (29). A scatter plot of eddy current predicted versus actual wear depth is shown in Figure C-77. The data is described by the equation $y = .97x - 0.14$.

C.4.2.4 Intergranular attack-stress corrosion cracking

Significant intergranular attack and stress corrosion cracking has been confirmed in only one once-through unit (Arkansas 1) although it may be in the early stages of formation at two other units (Oconee 1 and Rancho Seco) based on comparing the distribution of eddy current indications. At Arkansas 1, the intergranular attack is concentrated within the wedge region (See Appendix B Figure B-12) at the upper support plate and tube sheet crevice. Figure C-78 shows the intergranular attack morphology for a tube removed from Arkansas 1. Several forced outages have occurred at Arkansas 1 as a result of intergranular attack. Estimates of sizing accuracy are shown in Figure C-79. Relatively little data exists for a reliable performance

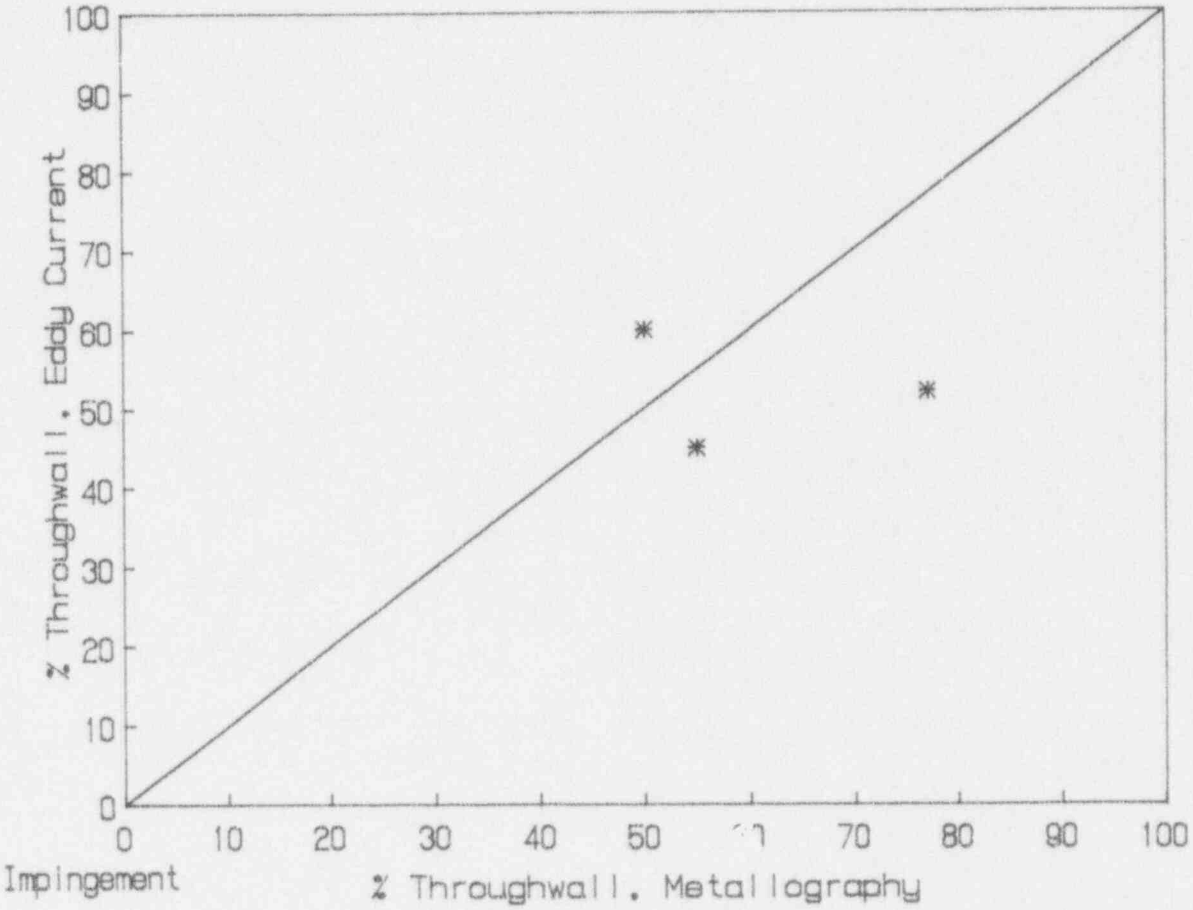


Figure C-75. Measurement Accuracy - Impingement Damage

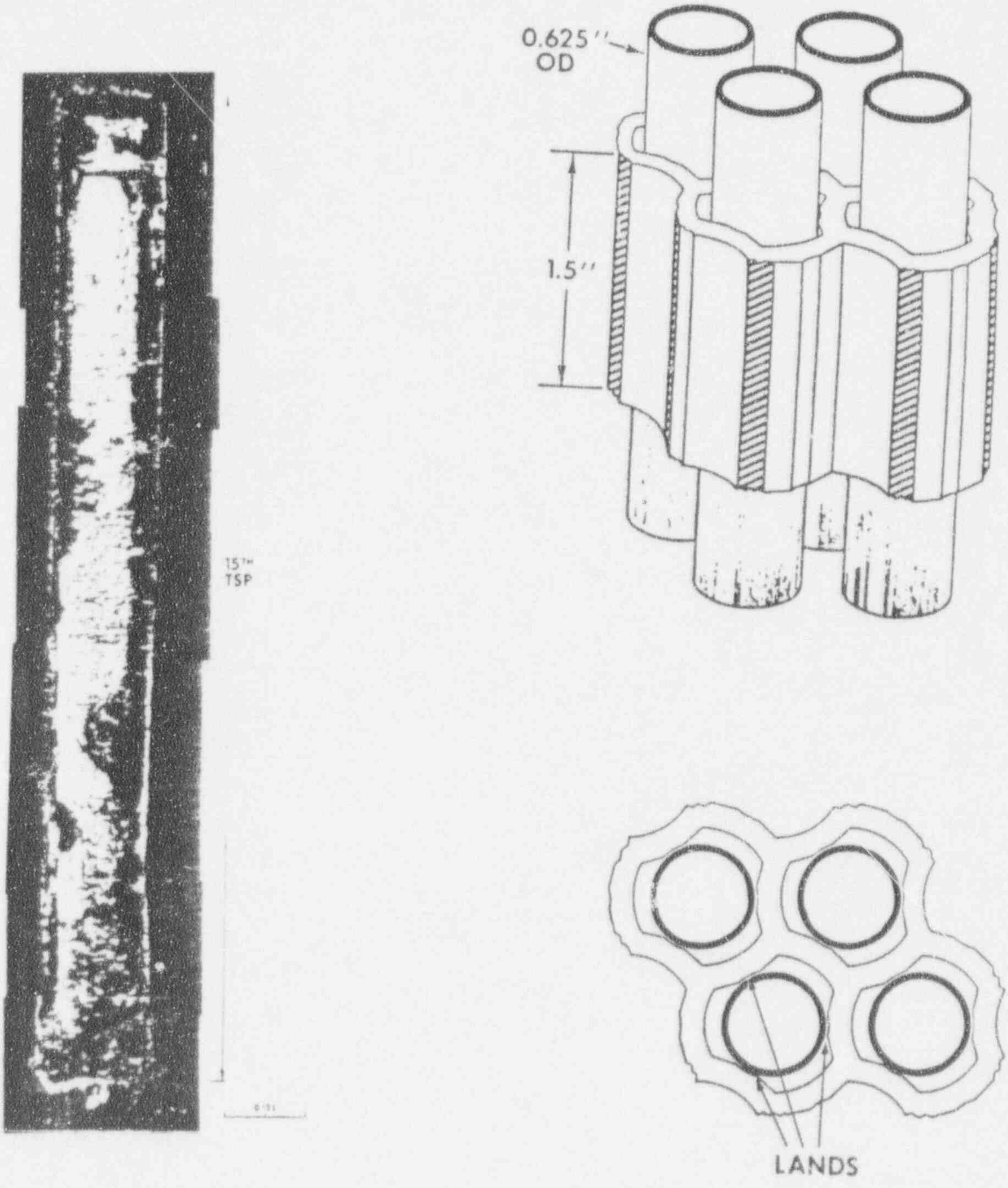


Figure C-76. Wear at Broached Support Plate Lands

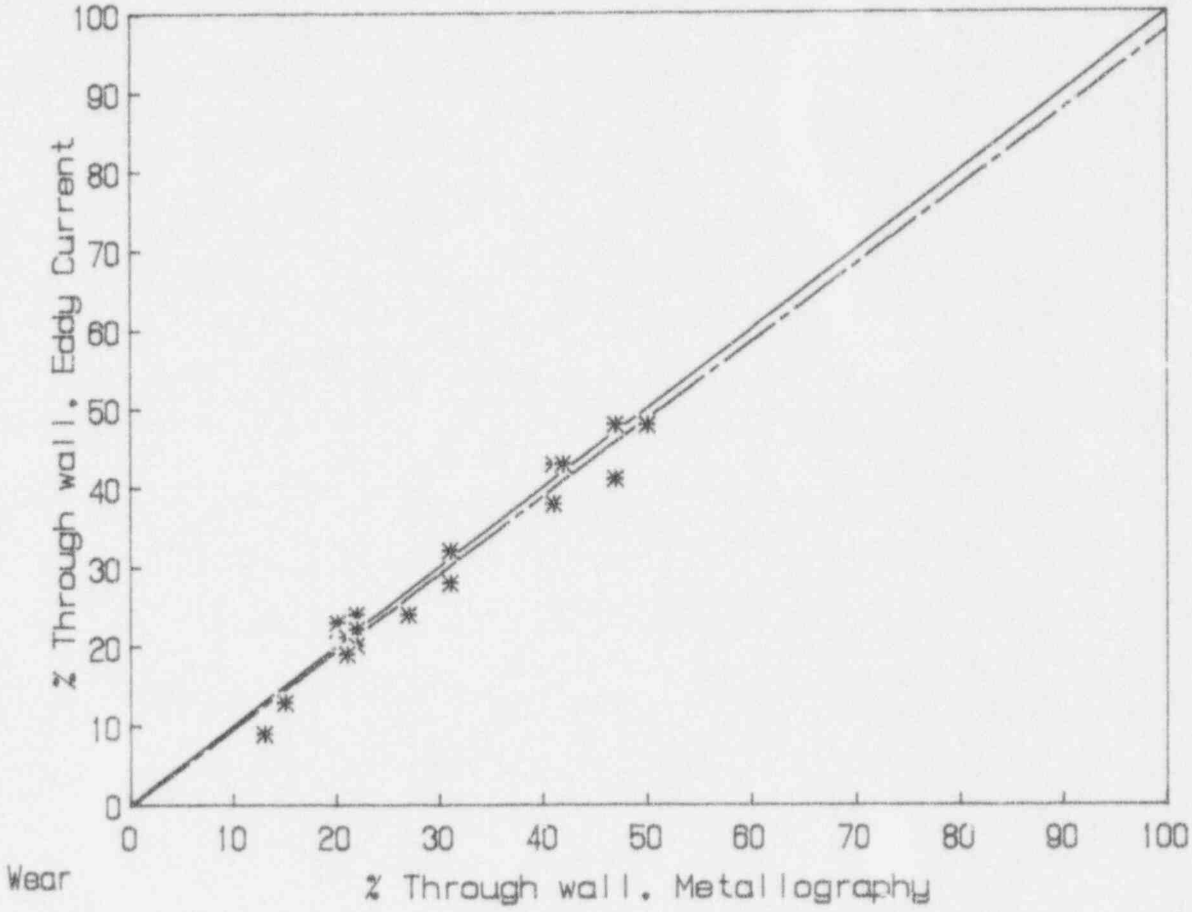


Figure C-77. Measurement Accuracy - Wear (Lab Data)

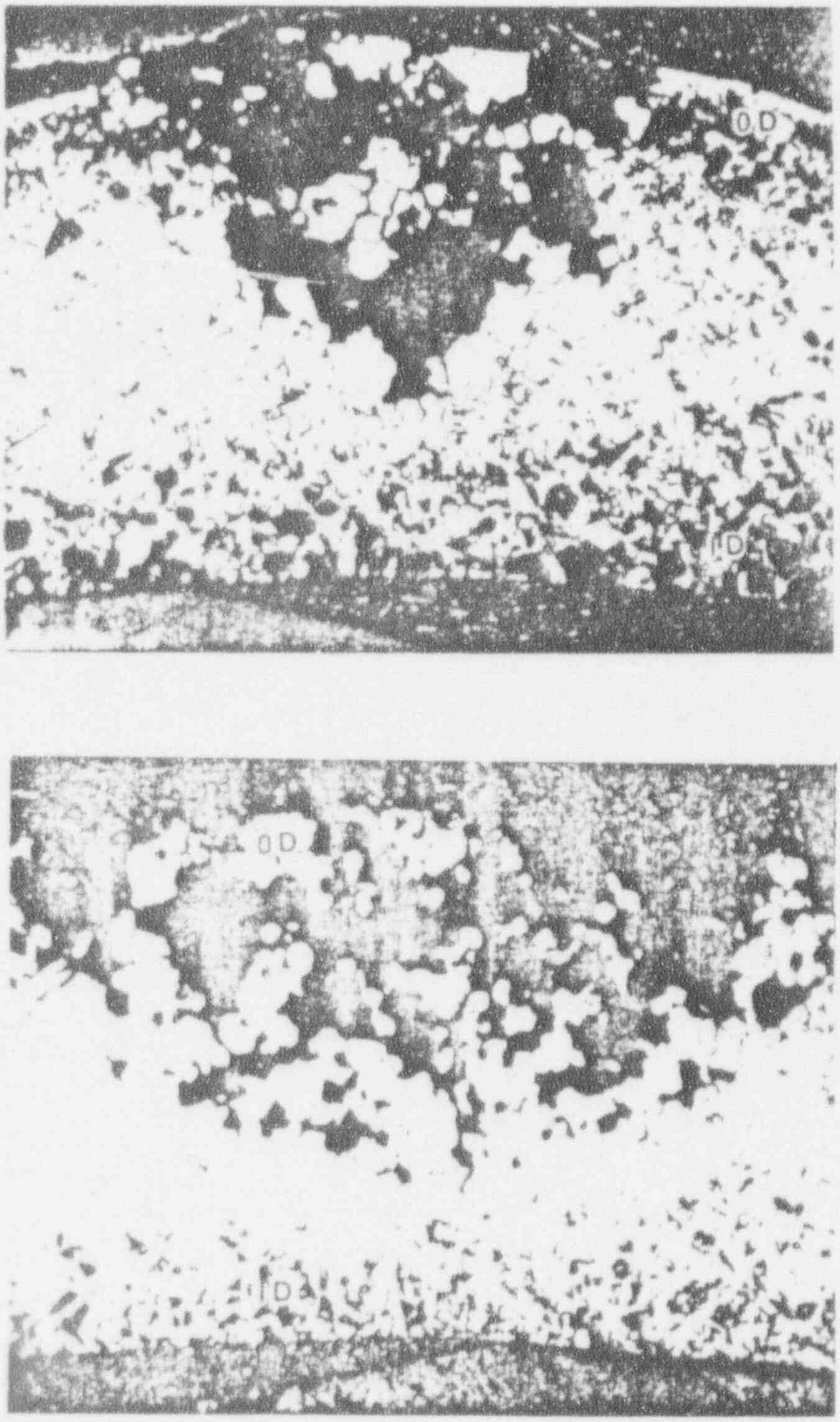


Figure C-78. Intergranular Attack Morphology

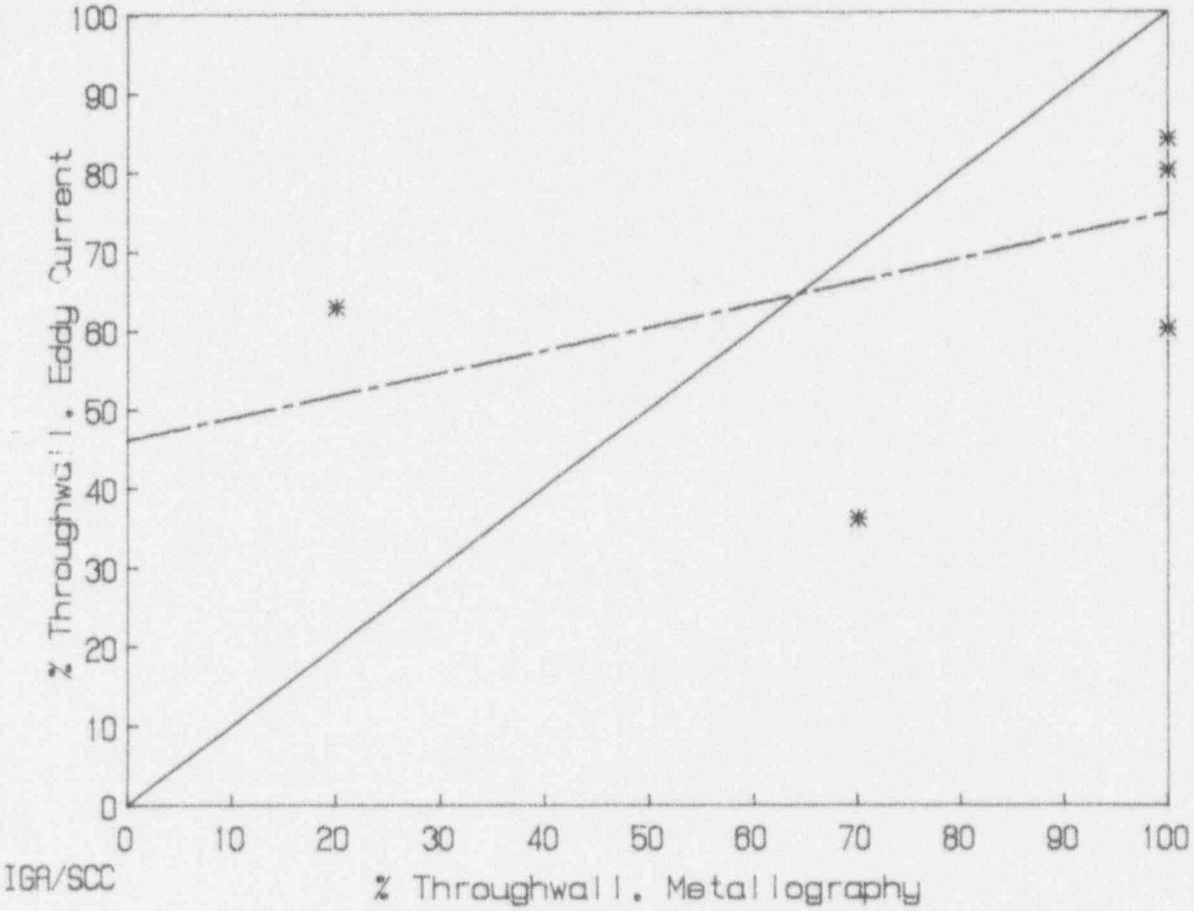


Figure C-79. Measurement Accuracy - IGA/SCC estimate. The least-squares fit to the data is given by $y = (0.29)x + 46$, with a correlation coefficient of 0.48.

References

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26. "Application of Eddy Currents for Identification of Dimensional Variations in PWR Steam Generator Tubes and Detection of Stress Corrosion Cracks." R. Comby and A. Gourmelon, EdF.

27. "French PWR Plant Experience." P. Berge and F. Nordmann, EdF.

28. EPRI NP-1794 "Evaluation of Steam Generator Tubes 85-127 from Oconee 1B, EPRI - Steam Generator Owners Group Research Project S136-1, Final Report." April 1981.

Appendix D

TYPICAL DATA ANALYSIS GUIDELINES

One of the general recommendations in Section 3 is to prepare written plant specific data analysis guidelines and provide these to the analysts prior to the start of the examination. The reason for this is to help ensure a uniform and consistent examination and interpretation of results. The various analysts performing the examination will all be working to the same groundrules and the reporting and documentation will be consistent from one examination to the next. Although the content and format of analysis guidelines may vary from one utility to the next, a general outline is provided below to show the typical items which are usually included:

Outline for Plant Specific Steam Generator ECT Analysis Guideline

Part I Introduction

- A. Statement of Purpose
- B. Guideline Objectives
- C. Course Schedule - If Applicable
- D. Requirements for Successful Completion - If Applicable
- E. Mandatory Requirements as Opposed to Suggestions

Part II Description of Steam Generators

- A. Manufacturer and Model Number
- B. Number of Steam Generators
- C. Number of Tubes per S/G
- D. Tubing Material and Dimensions
- E. Tube Support Layout
- F. Tubesheet Expansion Type

Part III Steam Generator Operating History

A. Current Fuel Cycle

B. Most Recent ECT Baseline

C. Distribution of Identified Flaws

D. Postulated or Confirmed Defect Mechanisms

E. Tube Pull Destructive Examinations

F. ECT Depth Correlation - Measured vs. Actual

G. Denting Magnitude and Distribution

H. Number of Tubes Plugged

I. Number of Tubes Sleeved

J. Any Unique Detection or Sizing Deficiencies

K. Potential Problem Areas - Based on the operating experience of other utilities with the same steam generators and similar water chemistry.

Part IV Description of Bobbin Coil Test

A. Hardware and Software Required

B. Examination Frequencies - including the specific purpose of each.

C. Frequency Mixes - including the specific purpose of each.

D. Probe Types - including coil dimension, fill factors, probe chassis, centering device, magnetic saturation, etc.

E. Required Test Extent

F. Location Abbreviations

G. Designated Probe Speed - with tolerance

H. Calibration Standard Drawings

I. Qualification Standard Drawings - If Applicable

Part V Calibration Sequence (Should be illustrated with Lissajous)

A. Mixing

1. Standardized Mix Identification Numbers

2. Null Point

    3. Signal to Mix On
    4. Typical Residual
- B. Phase Setpoints for All Frequencies and Mixes (with tolerances)
- C. Sensitivity or Span Values for all Frequencies and Mixes
- D. Phase vs. Depth Curves
    - 1. Which Frequencies and Mixes
    - 2. Artificial or Fit Curves
    - 3. Curve Setpoints
- E. Voltage Setpoints with Tolerance (if using digital equipment)
- F. Storing Calibration/Qualification Signals on Disk
- G. Final Report Format
- H. Required Summary Information
- I. Screening Channels
    - 1. Left Strip Chart
    - 2. Right Strip Chart
    - 3. Lissajous

Part IV Flaw Analysis (Should be illustrated with Lissajous and augmented with actual field inspection tapes whenever possible.)

- A. Typical Flaw Signals with Percent Through Wall Estimates
- B. Examples of Laboratory Tests - if appropriate
- C. Typical Nonrelevant Signals
- D. Examples of Rejectable Data
- E. Setting and Checking the Axial Position Scale
- F. Measuring Probe
- G. Reporting Requirements
    - 1. E. C. Data File
    - 2. Lissajous Printouts
    - 3. Final Report
    - 4. Undefined Signals

    5. Permeability Variations

    6. Tubesheet Expansion Abnormalities

  H. Documentation Requirements

  I. Record Keeping

  J. Flaw Signals of Removed Tubes with Destructive Examination Results, if Available

Part VII Other Analysis

  A. Dent Measurements

  B. Sludge/Copper Height Measurements

  C. Etc.

Part VIII Independent Review

  A. Delineation of Responsibilities

  B. Definition of "Discrepancy"

  C. Resolution Process for Discrepancies

Part IX Specialty Tests - As Required

Appendices

- Tubesheet Maps with Plugged/Sleeved Tubes
- Tubesheet Maps of Degraded Tubes
- Tubesheet Maps of Sludge Profiles
- Tubesheet Maps of Dents
- Plant Technical Specifications
- Referencing Section of ASME Code
- Vendor Test Procedure

Appendix E

TYPICAL STEAM GENERATOR NDE BID SPECIFICATION

The purpose of this appendix is to provide guidance to steam generator examination engineers in preparation of specifications for steam generator examination activities. A typical specification for steam generator examination activities is included.

Technical material is included in this specification while commercial and quality assurance material, which is appropriately utility-specific, has been excluded.

The specification is formatted to serve both as a Bid Specification for use in soliciting bids, and subsequently as the actual Working Specification for the successful bidder(s). The format provides a method for specifying the following information and requirements:

Information

a. Unit-specific configuration;

b. Anticipated plant conditions and environment;

c. Utility-provided support.

Requirements

a. Bid submittal requirements (Technical/Commercial);

b. Actual work requirements (Technical/Project Management/Quality/Commercial).

A typical specification for steam generator examination is provided below.

SPECIFICATION FOR STEAM GENERATOR EXAMINATION

____
(Utility Name)

QUALITY CLASS I - __________ UNIT(S) ________
(Station)

____
(Specification Number)

STEAM GENERATOR EXAMINATION SERVICES

THIS SPECIFICATION PROVIDES TECHNICAL REQUIREMENTS AND COMMERCIAL SUBMITTAL REQUIREMENTS FOR STEAM GENERATOR EXAMINATION SERVICES INCLUDING:

- Eddy Current Testing/Independent Third Party Data Analysis/Tube End Marking
- Ultrasonic Tubing Testing
- Tube Sample Examination/Analysis
- Secondary Side Examination

Approved for Issue:

Steam Generator Examination Engineer(s)	Manager, (of the organization which includes Steam Generator Examination Engineering)
Supervisor, Steam Generator Examination Engineering	Quality Assurance Station Manager

TABLE OF CONTENTS

Section 1

GENERAL TERMS AND CONDITIONS

An example of this section is not included in this specification because this is inherently a commercial issue and is utility specific.

Section 2

PROJECT MANAGEMENT REQUIREMENTS

2.1 WORK SCHEDULE

The Contractor home office pre-planning Work shall commence upon award of Purchase Order. The Work to be performed at the Jobsite is anticipated to begin in ______________________, and shall be performed on a ___ hour per day schedule, ___ days per week. The schedule shall allot a minimum of ____ days for training, security processing and drug screen urinalysis processing. All Jobsite Work (will/will not) be performed on a critical path basis. The work shall be performed at the time determined by Unit's integrated outage schedules.

2.2 CONTRACTUAL/COMMERCIAL CORRESPONDENCE

All correspondence of a contractual and commercial nature shall be directed to:

____
Procurement Agent, Address

2.3 UTILITY REPRESENTATIVE

After award of Purchase Order, all correspondence of a work-administrative and technical nature shall be directed to:

____
(Steam Generator Examination
Engineering Supervisor or Manager
Address)

2.4 SHIPPING

A. For information relative to shipping Material to the Jobsite, inquiries shall be addressed as follows:

____
(Responsible Utility
Material Coordinator
Address)

B. All Material to be shipped to the Jobsite shall be marked with the following shipping address and the applicable Purchase Order number.

Steam Gen. Examination Services
Attn: ________________________
Purchase Order #_______________

2.5 WORK SCHEDULE

Within 30 calendar days after notification of award of Purchase Order, Contractor shall submit to the Utility Representative, for approval, two copies of its proposed Work schedule or provide confirmation that no changes have occurred in the schedule provided in Contractor Proposal. (See Table 2-1)

2.6 PROGRESS MEETINGS

Unless waived by the Utility Representative, Contractor shall attend daily progress meetings at the end of each shift. The participants shall include the Contractor's principal representatives, Subcontractors' representatives, as appropriate, and the Utility Steam Generator Examination Engineer. The purpose shall be to review progress and to schedule Work and deliveries of Material. The result to be desired from the progress meetings shall be to inform all concerned on the matters discussed and to obtain coordinated action that will best assure performance pursuant to the basic schedule.

2.7 QUALITY ASSURANCE AND QUALITY CONTROL

A. The following submittals shall be provided to the Utility Representative within 30 calendar days after notification of award of Purchase Order for review and acceptance.

1. Contractor's Quality Assurance Program (only if not currently qualified by the Utility)
2. Contractor's Quality Plan, and implementing procedures which describe the planned QA/QC activities, the onsite Contractor QA/QC manpower requirements, and the Utility QA/QC interface requirements for this Purchase Order.
3. Contractor's Qualification, Certification and Testing Program for Level I, II, IIA and III Nondestructive Examination personnel.

B. Access to Contractor's facilities (or work location) and documentation shall be provided to the Utility to perform audits or reviews to establish the degree of implementation of Contractor's quality assurance program.

C. Contractor shall prepare a Quality Assurance Examination and Audit report documenting contractor QA/QC Work performed. Submittal shall be sent to the Utility Representative.

ITEM	TYPE OF DOCUMENTATION REQUIRED	REFERENCE SECTION	NUMBER AND TYPE OF SUBMITTALS AFTER AWARD OF CONTRACT FOR APPROVAL QTY.	AFTER APPROVAL QTY.	APPROVAL DOCUMENTS REQUIRED NO. OF DAYS AFTER AWARD	REMARKS
1.	Work Schedule	2.5	2	1	30	------
2.	Contractor's Quality Assurance Program (if not qualified by Utility	2.7.A	1	1	30	------
3.	Contractor's Quality Plan and Implementing Procedures	2.7.A	1	1	30	------
4.	Contractor's Qualification, Certification and Testing Program	2.7.A	1	1	30	------
5.	Work Procedures	3B.1.C 3C.1.B 3E.1.B	2	2	-	90 calendar days prior to start of work.
6.	Nondestructive Testing Personnel Certification Documentation	3B.7.B 3B.7.B	2	-	-	30 calendar days prior to start of work
7.	Final Technical Reports	3B.9 3C.9 3D.5 3E.9	1	2	-	Within 45 days of completion of each work segment.
8.	Quality Assurance Inspection/ Audit Report	2.7.E	1	1	-	Within 45 days of completion of all work segments.

TABLE 2-1 DOCUMENTATION SUBMITTAL SCHEDULE

Subsection 2A

SITE ACCESS, HEALTH PHYSICS AND SECURITY REQUIREMENTS

A full example of this section is not included in this sample specification because this is inherently a site-specific rather than a technical section. However, one significant note is provided below for consideration.

NOTE

All Security and Health Physics Training/Testing are provided in English only by the utility. The supplier is responsible for any expenses or delays incurred in attempts to process employees without requisite fluency.

Section 3

STEAM GENERATOR DESCRIPTIVE INFORMATION AND GENERAL TECHNICAL REQUIREMENTS

3.1 STEAM GENERATOR DESCRIPTIVE INFORMATION

A. Steam Generator Description

______________ ______________ has _________ steam generators of
(Station) (Unit) (quantity)

the __________________ design manufactured by ________________.
(Model/Series)

There are _________ _____________ tubes in each steam generator
(number) (material)

that have a _____ inch diameter with _________ inch average wall thickness.

The tubes form a _______________________ pitch array.
(square/triangular)

For square pitch tube arrays:

The nominal dimension between tube centerline in the row axis is _______ inches. The nominal dimension between tube centerlines in the column axis is _________ inches.

For triangular pitch tube arrays:

A drawing of physical dimensions of the array is included as Figure 1 of this appendix.

B. Sleeve Description (if applicable)

_________ _____________ manufactured by _____________________
(number) (material(s))

are installed at the __________________________ and are
(inlet or outlet tube ends)

_______ inches in length. The sleeves have an outside diameter of _______ inches and _______ inch average wall thickness.

The ___________ joint was formed by _________________. The
(lower, etc.) (process(es))

____________ was formed by _________________.
(upper, etc.)   (process(es)

C. Handhole/Inspection Access Description

A _________ inch diameter handhole provides access into the secondary side of the steam generator at one end of the _________ inch wide ______________.

SAMPLE SPECIFICATION NOTES

(Provide further descriptive information on other handholes of interest for the work in similar format)

(Provide drawings or sketches of other critical dimensions of interest to the work, such as shell - wrapper, wrapper - tube bundle, wrapper bottom - top of the tubesheet, etc.)

3.2 CODES, STANDARDS AND REGULATIONS

A. The work and any materials used shall comply with the codes, standards, and regulations listed in Section 3A and in the Specific Technical Requirement Appendices. By this reference they are incorporated herein and made apart of this Specification. All exceptions or deviations require prior approval by the utility. Where this Specification appears in conflict with requirements of a referenced document, such conflict shall be brought to the attention of the utility for resolution.

B. The work shall be of a quality that will ensure that the steam generators are maintained in compliance with the codes, standards, and regulations referenced in this Specification.

C. It is not the intent of the utility to specify in the Specific Technical Condition Appendices of this Specification, all details necessary for conducting the work. Contractor shall be solely responsible for the adequacy of design review, the preparation of complete plans and procedures, and the performance of the program to comply with the intent and requirements of codes, standards, and regulations referenced in this Specification.

D. The Work shall be in compliance with any local, state, and Federal codes, standards, and regulations having jurisdiction in the area in which the service is rendered.

3.3 PERFORMANCE OF WORK BY CONTRACTOR

A. Performance of Contractor's Work shall be subject to surveillance and audit by the Utility Quality Assurance Organization to ensure conformance to applicable acceptance standards. Quality Assurance includes Quality Control which comprises those Quality Assurance actions related to the physical characteristics of a material, structure, component or system to predetermined requirements.

B. Contractor shall provide all necessary transportation for all offsite Work, if required. Contractor shall be either a licensed carrier of radioactive contaminated material or use the services of a licensed carrier. Contractor's facility shall be licensed to receive radioactive contaminated equipment and apparatus.

C. All parts, tools, and instruments used for performing the Work shall comply and conform with the Utility QA and QC programs (NRC 10 CFR 50, Appendix B).

D. The Utility shall not supply any special tools for the Work required by this Specification. Contractor shall develop and provide all special tools or inspection devices that may be needed for the Work.

E. The (Utility/Contractor) shall be responsible for foreign material exclusion (FME) in zones defined by ______________________________.
(applicable procedures)

Contractor shall comply with procedure(s).

F. All data collection work shall be performed using approved, written procedures.

G. The Work shall be performed with remotely operated equipment to the maximum extent possible to maintain radiation exposure As Low As Reasonably Achievable (ALARA).

H. All instruments, measuring equipment, and test equipment shall be properly calibrated with traceability to the National Bureau of Standards, when such standards exist.

I. Contractor's personnel shall have the ability to respond to the Jobsite within a short time period in the event of emergencies.

Appendix 3A

GENERAL QUALITY ASSURANCE REQUIREMENTS FOR

____
(UTILITY)

____
(SITE)

A full example of this section is not provided because of its non-technical and utility-specific nature.

Succeeding appendices contain Specific Technical Requirements for each type of steam generator inspection. Abbreviating the reference sections of these appendices (by minimizing repetition of general requirement references) is useful for clarity. This may be best accomplished by listing these general requirements referenced in this Section, and providing reference to this listing in succeeding sections.

The following listing of general requirement references serves solely as a reference for succeeding Specific Technical Requirement Appendices. It must be emphasized that this is an example listing. It is not a generic listing. A completed utility-specific listing, with appropriate editions, revisions, and addenda, can be assembled with the guidance of Utility Quality Assurance personnel.

EXAMPLE GENERAL REQUIREMENT REFERENCE SECTION

10 CFR 50, Appendix B

10 CFR, Part 21 - Reporting of Defects and Noncompliance

Regulatory Guide 1.8 - Personnel Selection and Training

Regulatory Guide 1.16 - Reporting of Operating Information - Appendix A Technical Specifications

Regulatory Guide 1.17 - "Industrial Security for Nuclear Power Plants"

Regulatory Guide 1.26 - Quality Group Classification and Standards for Water Steam and Radio-Waste-Containing Components of Nuclear Power Plants

Regulatory Guide 1.33 - Quality Assurance Program Requirements (Operations)

Regulatory Guide 1.37 - Quality Assurance Requirements for Cleaning of Fluid Systems and Associated Components of Water-Cooled Nuclear Power Plants

Regulatory Guide 1.38 - Quality Assurance Requirements for Packaging, Shipping, Receiving, Storage and Handling of Items for Water-Cooled Nuclear Power Plants.

Regulatory Guide 1.39 - Housekeeping Requirements for Water-Cooled Nuclear Power Plants.

Regulatory Guide 1.58 - Qualification of Nuclear Power Plant Inspection Examination, and Testing Personnel

Regulatory Guide 1.88 - Collection, Storage and Maintenance of Nuclear Power Plants Records

Regulatory Guide 1.120 - Fire Protection Guidelines for Nuclear Power Plants

Regulatory Guide 1.123 - Quality Assurance Requirements for Control of Procurement of Items and Services for Nuclear Power Plants

Regulatory Guide 1.144 - Requirements for Auditing of Quality Assurance Programs for Nuclear Power Plants

Regulatory Guide 1.146 - Qualification of Quality Assurance Program Audit Personnel for Nuclear Power Plants

Regulatory Guide 8.10 - Operating Philosophy for Maintaining Occupational Exposures as Low as is Reasonably Achievable (Nuclear Power Reactors)

IEEE 498 - Standard Requirement for the Calibration and Control of Measuring and Test Equipment used in the Maintenance of Nuclear Power Generating Station.

SNT-TC-1A - American Society of Nondestructive Testing - Recommended Practice

ASME B&PV Code, Section III - Specific Code Edition and Addenda are based on the Purchase Order date for the component or the original construction Code used. Reference individual Code Data Reports for specific Code applicability.

ASME B&PV Code, Section XI

Appendix 3B

SPECIFIC TECHNICAL CONDITIONS FOR EDDY CURRENT TESTING OF STEAM GENERATOR TUBES QUALITY CLASS I

3B.1 SCOPE OF WORK

A. This Appendix 3B covers the requirements and conditions necessary to perform and document the inservice eddy current examination of steam generator tubes. Contractor shall provide all eddy current data collection and analysis equipment, tube marking equipment associated personnel, and supervision/management/documentation of the Work.

B. The basis of the inspection process shall be the Technical Specifications and the rules and requirements stipulated in ASME B&PV, Section XI, Appendix IV. Those requirements of the code that Contractor is unable to meet, or recommends an alternate approach, shall be specifically addressed in Part A of the Proposal Requirements.

C. At least 90 calendar days prior to starting this Work, Contractor shall submit to the Utility, for review and approval, two copies of the complete procedures Contractor proposes to use to perform this Work. Procedures shall contain adequate technical detail to allow a 10 CFR 50.59 evaluation of the procedure by the Utility

3B.2 CODES, STANDARDS AND REGULATIONS

The Work shall be performed in accordance with the codes, standards, and regulations listed in Section 3A, and below:

1. ____________ ____________ Technical Specifications and Facility
   Site Unit

   Operating License No. ___________ Section ___________.

2. Final Safety Analysis Report Inservice Inspection

   ____________ ____________
   Site Unit

   Section ___________

3. U.S. Nuclear Regulatory Commission (NRC)

NRC Guide 1.83 July 1975, Rev. 1	Inservice Inspection of Pressurized Water Reactor Steam Generator Tubes

4. American Society of Mechanical Engineers (ASME)

Section V	Nondestructive Examination
Section XI	Rules for Inservice Inspection of Nuclear Power Plant Components
Boiler and Pressure Vessel Code Case N-401	Digitized Collection and Storage of Eddy Current Test Data

5. American Society for Nondestructive Testing (ASNT)

ASNT Recommended Practice No. SNT-TC-1A	Nondestructive Testing Personnel Qualifications and Certification

6. Code of Federal Regulations

10 CFR 50.55a	Codes and Standards
10 CFR 50.59	Changes, Tests, and Experiments

7. Utility Station Procedure	Steam Generator Tube Inspection

3B.3 DESCRIPTION OF WORK BY CONTRACTOR

Contractor shall perform eddy current examination on a selected sample of tubes in the steam generator(s).

3B.3.1 Examination Guidelines

A. Contractor shall utilize multifrequency/multiparameter eddy current equipment and the most appropriate and qualified analysis equipment and techniques for complete tubing inspection, including the tubesheet area. Probe selection shall account for U-bend area (and 90 degree bend area) inspection.

B. Contractor shall notify the Utility of any tube noted to be restricted. The Utility will authorize testing from the other tube end and profilometry testing as appropriate.

C. In the event that an indication equal to or greater than 20% through wall, or an increase of 10% through wall, or a restriction is noted in a tube, the necessary extension pattern shall be determined and directed by the utility. The examination normally shall be extended to cover adjacent tubes until tubes free of indications are noted within 3 pitches of the tube containing the indication. However, if a particular degradation mechanism is postulated, a specifically tailored extension program shall be directed. Further expansion of the inspection program shall be as directed by the Utility in accordance with Technical Specifications.

D. Monitoring for denting at support locations shall be conducted on eddy current bobbin coil signal amplitude. Contractor shall provide the utility with a listing of tubes with unexpected signals including their location and amplitude. The utility will consider these tubes for incorporation into a supplementary dent profilometry examination program.

E. Eddy current data from all channels, both differential and absolute, shall be interpreted by Contractor and the results submitted to the Utility. Additional interpretation of data may be performed by an independent contractor at the discretion of the Utility.

F. Contractor shall be responsible for the evaluation and submittal of the results of each tube examination. The signal response recorded on the magnetic tape shall be evaluated by Contractor for each tube tested. An evaluation shall be made of any indication 20% or greater, detected during any examination. The Utility shall be informed of unusual or ambiguous indications detected during the course of the data analysis.

G. Contractor shall advise the Utility of differential bobbin coil probe indications and ambiguities that could be more fully characterized using other equipment/techniques. The Utility will authorize further testing as Additional Work if deemed appropriate.

3B.3.2 Specific Work Description

Sample Specification Note

This may be a convenient location to indicate a predictable scope of the eddy current techniques requested. The scope of each technique generally includes:

1. Probe type;
2. Area of specific interest (if test is other than general surveillance);
3. Axial extent (length) of examination;
4. Total number of tubes to be examined with this technique.

The scope of the eddy current inspection may be highly indeterminate and/or separate pricing for different techniques may be desired for scope decision-making. In this situation, Part C (Commercial Submittal Requirements) of the Proposal Submittal Requirements may be the optimum location to address the inspection scope.

A. Contractor shall provide positive identification of those tubes specified by the Utility to require plugging. The tube plugging preparation services Scope includes the following for __________ tube ends (_____ tubes) (for each outage):

1. Marking of inlet and outlet side of the tubes to be plugged.

2. A list of row and column of each tube to be plugged.

3. Eddy current Retesting of each tube to be plugged to include the indication of interest. The purpose of this is to provide maximum confidence in identification of tubes to be plugged.

B. Time available to conduct this testing is _______ week(s).

C. Contractor shall make the eddy current fixture equipment and supporting operation/maintenance personnel available on an Additional Work basis as requested by the Utility. This includes any pre-outage modifications that may reasonably be requested. It is anticipated that this existing platform may be needed, in the interest of ALARA. for ultrasonic testing or helium leak testing of steam generator tubes by another contractor.

3B.4 UTILITY-FURNISHED EQUIPMENT AND SERVICES

A. A tube examination program detailed on tube listings and tubesheet maps;

b. A unit-specific eddy current data analysis guideline;

C. Overall coordination of steam generator outage services;

D. Removal and replacement of steam generator manways;

E. Access to primary channelheads;

F. Air ejectors or other means to maintain a dry condition in the channelhead;

G. Health physics coverage and support;

H. Temporary nozzle covers or nozzle dams installed;

I. Electrical, water and service air supply, as required.

J. Anti-contamination clothing, air supplied bubble hoods, lockers and change areas, dosimetry and badging as required;

K. Suitable space to park eddy current trailer within 500 feet from steam generator.

L. Access to containment for data station control wiring;

M. Telephone service for Contractor's onsite coordinator;

N. ASME tubing (and sleeving) eddy current calibration standards. (Include in Specifications if such material is possessed by the Utility.)

3B.5 CONTRACTOR RESPONSIBILITIES

A. All eddy current data collection/analysis equipment, associated personnel, and documentation of certifications and inspection results;

B. All consumables, eddy current probes, spare parts and components for all Contractor-furnished equipment;

C. Program coordination and supervision;

D. Provide all personnel required to perform Quality Assurance audits, reviews, tests, etc., as described in Appendix 3A, General Quality Assurance Requirements.

3B.6 PLANT CONDITION

A. Primary Plant shall be in Mode 5 (Cold Shutdown) or Mode 6 (Refueling) and channelhead nozzle dams installed or the primary system drained to a level below the steam generator channelhead with nozzle covers installed.

B. Primary manways shall be open to provide access to the channelhead.

C. A ventilation system shall be attached to the manway opposite the channel head in which Work is to be performed for drying the tubes, tubesheet and for personnel protection.

D. Health physics shall have the steam generator platforms available for platform work and channelhead entry.

E. Electrical power and air supply shall be available at the steam generator platforms.

3B.7 PERSONNEL QUALIFICATION

A. In addition to the requirements specified in Section 3.A, all personnel involved with acquisition and interpretation of data during this inspection shall be qualified per ASME Section XI to the appropriate level of ASNT Recommended Practice No. SNT-TC-1A, Nondestructive Testing Personnel Qualifications and Certification.

B. Qualification summaries/certification documentation shall be submitted to the Utility 30 calendar days prior to commencement of work for approval of those personnel involved in this inspection per Item A above, to include, as a minimum:

1. Educational background;
2. Eddy current training record;
3. Work experience;
4. Description of any examination or evaluation restrictions.

C. All eddy current data analysts shall review the utility-provided data analysis guideline and familiarization data tape(s). Each analyst shall subsequently conduct a performance demonstration to the satisfaction of the Utility.

D. The Utility reserves the right to refuse individuals considered unfit or unqualified.

3B.8 ADMINISTRATION

A. The Utility shall review and approve the qualifications of Contractor's onsite manager of the Steam Generator Inservice Examination prior to Contractor starting this Work.

B. Contractor shall conduct, and document, training of its data collection personnel on the use of equipment, material, and procedures required to perform the steam generator examination using a steam generator mockup.

3B.9 REPORTS AND DOCUMENTATION

A. Contractor shall compare the results of any multiple tests for each flaw. This is necessary when a tube, or a segment of a tube, is tested multiple times. Contractor shall provide the final compared report of such results to the Utility, indicating the final analysis result for the most representative test data (by tape number) for each indication in multiple tested tubes or segments of tubing. This report shall also include a listing of duplicative, or non-representative indication evaluations that may exist in data analysis diskettes or other documentation that may be provided to the Utility within one week of the completion of the inspection.

B. Steam generator tube data submitted by Contractor to the Utility shall be compatible with the Utility data management system for data entry by electronic media devices.

Sample Specification Note

Provide format/media details if system requirements dictate.

C. Within 45 days of examination completion, a final Quality Assurance reviewed report shall be prepared and submitted to the Utility. The report shall include the appropriate information necessary to complete the history of the examinations performed. This information shall include, but not be limited to, the following:

1. Description of examination program - describe in detail the techniques used, including probe size, construction, and signal frequency. Denote on tubesheet map(s) the locations of areas examined with different techniques. Include all equipment parameters of significance, and any modifications;
2. Description of the equipment used in sufficient detail to permit duplication of the examination at a later date;
3. Copies of all procedures;
4. Copies of all nonconformance reports;
5. Copies of personnel qualification certificates;

6. Copies of instrumentation calibration documentation;

7. Copies of tube end marking material chemical analysis (if Contractor - provided);

8. Copies of quality assurance inspection/audit reports;

9. Copies of Calibration Standard Drawings (if standards provided by Contractor);

10. Detailed description of all defects, indications and other anomalous signals including, as a minimum:

    a. Tube location in bundle;

    b. Axial location on tube;

    c. Percent through wall;

    d. Other defect characteristics.

11. The original copy of all data diskettes and magnetic tape cartridges shall be left with the Utility before Contractor leaves Jobsite. The original copies of all other data records that are used or could be used for defect evaluation shall become the property of the Utility and shall be included in the preliminary report and by reference in the final report.

Appendix 3C

SPECIFIC TECHNICAL CONDITIONS FOR ULTRASONIC TESTING OF STEAM GENERATOR TUBES

QUALITY CLASS .

3C.1 SCOPE OF WORK

A. This Appendix 3C covers the conditions necessary to perform and document the ultrasonic testing of steam generator tubes. Contractor shall provide all ultrasonic data collection and analysis equipment, associated personnel, and supervision/management/documentation of the work.

B. At least 90 calendar days prior to starting this Work, Contractor shall submit to the Utility, for review and approval, two copies of the complete procedures Contractor proposes to use to perform this Work. Procedures shall contain adequate technical detail to allow a 10 CFR 50.59 evaluation of the procedure by the Utility.

3C.2 CODES, STANDARDS AND REGULATIONS

A. The Work shall be performed in accordance with the codes, standards, and regulations listed in Section 3A and below:

1. Code of Federal Regulations

10 CFR Part 50.59	Changes, Tests, and Experience

2. American Society for Nondestructive Testing (ASNT)

ASNT Recommended Practice No. SNT-TC-1A	Nondestructive Testing Personnel Qualification and Certification

3C.3 DESCRIPTION OF WORK BY CONTRACTOR

Contractor shall perform ultrasonic testing on a selected sample of tubes in the steam generator(s).

3C.3.1 Examination Guidelines

A. Contractor shall utilize state-of-the-art equipment and the most appropriate and qualified analysis equipment and techniques.

B. Contractor's equipment shall be compatible with eddy current remotely installed fixtures that are presently in common industry use. (It should be anticipated that in the interest of ALARA the eddy current testing contractor's remotely installed fixture and personnel support will be provided by the Utility for ultrasonic testing.)

C. Contractor's equipment shall minimize the amount of water couplant discarded to the primary channelhead.

3C.3.2 Specific Work Description

Sample Specification Note

This may be a convenient location to indicate a predictable scope of the ultrasonic techniques requested. The scope of each technique generally include:

1. Anticipated nature of degradation (based on eddy current testing - i.e., wall thinning or cracking);
2. Specific axial location of tubing of interest, if applicable;
3. Axial extent (length) of inspection;
4. Total number of tubes to be inspected with this technique.

The scope of the ultrasonic examination may be highly indeterminate and/or separate pricing for different techniques may be desired for scope decision-making. In this situation, Part C (Commercial Submittal Requirement) of the Proposal Submittal Requirements may be the optimum location to address the inspection scope.

A. Time available to conduct this testing is ________ days.

3C.4 UTILITY-FURNISHED EQUIPMENT AND SERVICES

A. A tube inspection program;

B. Overall coordination of steam generator outage services;

C. Removal and replacement of steam generator manways;

D. Access to primary channelheads;

E. Air eductors or other means to maintain a dry condition in the channelhead;

F. Health physics coverage and support;

G. Temporary nozzle covers or nozzle dams;

H. Electrical, water and service air supply, as required;

I. Anti-contamination clothing, air supplied bubble hoods, lockers and change areas, dosimetry and badging as required;

J. Suitable space in eddy current trailer within 500 feet of containment access;

K. Access to containment for data collection wiring;

L. Telephone service for Contractor's onsite coordinator;

3C.5 CONTRACTOR RESPONSIBILITIES

A. All ultrasonic data collection/analysis equipment, associated personnel and documentation of certifications and inspection results and results and recording instruments.

B. All consumables, ultrasonic probes, calibration standards, spare parts and components for all Contractor-furnished equipment;

C. Program coordination and supervision;

D. Provide all personnel required to perform Quality Assurance audits, reviews, tests, etc., as described in Appendix 3A, General Quality Assurance Requirements.

3C.6 PLANT CONDITION

A. Primary Plant shall be in Mode 5 (Cold Shutdown) or Mode 6 (Refueling) and channelhead nozzle dams installed, or the primary system drained to a level below the steam generator channelhead with nozzle covers installed.

B. Primary manways shall be open to provide access to the channelhead.

C. A ventilation system shall be attached to the manway opposite the channelhead in which Work is to be performed for drying the tubes, tubesheet and for personnel protection.

D. Health physics shall have the steam generator platforms available for platform work and channelhead entry.

E. Electrical power and air supply shall be available at the steam generator platforms.

3C.7 PERSONNEL QUALIFICATION

A. In addition to the requirements specified in Section 3.A, all personnel involved with acquisition and interpretation of data during this inspection shall be qualified to the appropriate level of ASNT Recommended Practice No. SNT-TC-1A, Non-destructive Testing Personnel Qualifications and Certifications.

B. Qualification summaries/certification documentation shall be submitted to the Utility 30 calendar days prior to commencement of work for approval of those personnel involved in this inspection per Item A above, to include, as a minimum:
   1. Educational background;

   2. Eddy Current training record;

   3. Work experience;

   4. Description of any inspection or evaluation restrictions.

C. The Utility reserves the right to refuse individuals considered unfit or unqualified.

3C.8 ADMINISTRATION

A. The Utility shall review and approve the qualifications of Contractor's onsite manager of the Steam Generator Ultrasonic Testing prior to Contractor starting this Work.

B. Contractor shall conduct, and document, training of data collection personnel on the use of equipment, material, and procedures required to perform the ultrasonic testing, using a steam generator mockup.

3C.9 REPORTS AND DOCUMENTATION

A. Preliminary analysis results shall be provided to the Utility within one week of the completion of the inspection. The original copies of all other data records that are used or could be used for defect evaluation shall become the property of the Utility and shall be included in the preliminary report and by reference in the final report.

B. Within 45 days of examination completion, a final Quality Assurance reviewed report shall be prepared and submitted to the Utility. The report shall include the appropriate information necessary to complete the history of the examinations performed. This information shall include, but not be limited to, the following:

   1. Description of examination program - describe in detail the techniques used, including probe size, construction, and signal frequency. Denote on tubesheet map(s) the locations of areas examined with different techniques. Include all equipment settings, adjustments, and modifications;

   2. Description of the equipment used in sufficient detail to permit duplication of the examination at a later date;

   3. Copies of all procedures;

   4. Copies of all nonconformance reports;

   5. Copies of all personnel qualification certificates;

6. Copies of instrumentation calibration documentation.

7. Detailed description of all defects and other anomalous signals including, as minimum:

    a. Tube location in bundle;

    b. Axial location on tube;

    c. Percent through wall;

    d. Other defect characteristics.

8. Copies of calibration standard drawings.

Appendix 3D

SPECIFIC TECHNICAL CONDITIONS FOR EXAMINATION/ ANALYSIS OF REMOVED STEAM GENERATOR TUBE SAMPLES

3D.1 SCOPE OF WORK

A. This Appendix 3D covers the requirements and conditions necessary to perform and document the examination/analysis of steam generator tube samples removed from ________________ (site) ________________ (unit).

Contractor shall provide hardware, software, records, and documentation, for the Work.

3D.2 DESCRIPTION OF WORK BY CONTRACTOR

A. Contractor shall perform an analysis of the steam generator tube sample(s) to provide information regarding the following items:

1. Nature of defect, e.g., pit, stress corrosion cracking, etc.;
2. Elemental content of any deposits in defect;
3. Cause of defects or other anomalous conditions found in tubing samples;

3D.3 UTILITY-FURNISHED EQUIPMENT AND SERVICES

A. Health physics and radwaste coverage to support Contractor shipping of sample(s);

B. Packaging services and materials to ship tube sample(s).

3D.4 CONTRACTOR RESPONSIBILITIES

A. Shipment of tube sample(s) to Contractor facility;

B. Program conduct, coordination, and supervision;

C. Provide all personnel required to perform Quality Assurance audits, review, tests, etc., as described in Appendix 3A, General Quality Assurance Requirements.

3D.5 REPORTS AND DOCUMENTATION

A. Upon completion of the tube sample analysis, a preliminary report shall be submitted to the Utility.

B. Within 14 days of completion of the steam generator tube sample analysis, a final report shall be provided to the Utility.

C. Final report shall contain, as a minimum, the following information:

1. Description of analysis program - describe the techniques and equipment used.
2. Description of methods used to characterize defect;
3. Original photographs;
4. Results of each analysis.

Appendix 3E

SPECIFIC TECHNICAL CONDITIONS FOR STEAM GENERATOR SECONDARY SIDE INSPECTION

3E.1 SCOPE OF WORK

A. This Appendix 3E covers the requirements and conditions necessary to perform and document the steam generator secondary side examination. Contractor shall provide all data collection equipment, associated personnel, and supervision, management, and documentation of the Work.

B. At least 90 calendar days prior to starting this Work, Contractor shall submit to the Utility, for review and approval, two copies of the complete procedures Contractor proposes to use to perform this Work. All procedures for performance of this Work and evaluation of data shall contain adequate technical detail to allow a 10 CFR 50.59 evaluation of the procedure by the Utility.

3E.2 CODES, STANDARDS AND REGULATIONS

This Work shall be performed in accordance with all applicable codes, standards and regulations listed in Section 3A.

3E.3 DESCRIPTION OF WORK BY CONTRACTOR

The basis of measurements and dimensional checks shall be the Steam Generator Technical Manual, and any other Utility approved Steam Generator drawings.

3E.3.1 Examination Guidelines

A. Photograph any deficiencies or anomalies in the "as found" condition.

B. Take samples of any significant deposits and deliver to the Utility Representative for analysis.

Tubesheet Annulus/Blowdown Lane Area

C. Examine the periphery of the steam generator tubesheet and blowdown lane area, present the data to the utility, and recommend prudent retrieval efforts.

D. Perform retrieval efforts, as directed by the utility, on an Additional Work, best effort basis.

Feedwater Sparger Area

E. Inspect physical condition of feedwater sparger, discharge nozzles and supports.

F. Dimensionally check for circumferential gap between feedwater thermal sleeve and nozzle.

Moisture Separator Area

G. Check condition of steam dryer chevrons, and associated threaded fittings.

(For Combustion Engineering Steam Generator)

H. Perform a visual examination of steam separator cans. If any perforations are plugged, document with photographs and samples.

I. Physically check separator threaded fittings (Marman Couplings).

Upper Tube Bundle Area

Notes

- Minimize time in this area for ALARA Considerations.
- Strictly minimize examination materials (even though attached to examiners) in this area.
- Minimize the number of examination personnel.

J. Visually examine condition of selected tubes in the bend region. Note any bundle shift, support deformation and tube degradation.

K. Measure and record thickness of tube supports in the bend region and sample any significant deposits.

3E.4 UTILITY-FURNISHED EQUIPMENT AND SERVICES

A. Overall coordination of steam generator outage services;

B. Removal and replacement of steam generator secondary manways and handholes.

C. Access to the steam generator secondary manways and handholes;

D. Health physics coverage and support;

E. Anti-contamination clothing, change area dosimetry and badging, as required;

F. Electrical, water, and service air supply at the platforms, as required;

G. Analysis of significant deposits.

3E.5 CONTRACTOR RESPONSIBILITIES

A. Provide all personnel and equipment necessary to complete the inspection;

B. All spare parts and components for all Contractor-furnished equipment;

C. Program Coordination and Supervision.

D. Provide all personnel required to perform Quality Assurance audits, review, tests, etc., as described in Appendix 3A, General Quality Assurance Requirement.

3E.6 PLANT CONDITION

A. Primary Plant shall be in Mode 5 (Cold Shutdown) or Mode 6 (Refueling) and the secondary side of the steam generators drained.

B. Secondary handholes and manways shall be removed to provide access to the secondary side.

C. Platforms shall be ready with appropriate lighting, electric, service air and health physics requirement complete.

3E.7 ADMINISTRATION

A. The Utility shall review and approve the qualifications of Contractor's onsite manager of the examination services prior to Contractor starting this Work.

B. Contractor shall conduct and document, training of its personnel involved in the inspection on the use of equipment, material, and procedures required to perform the inspection.

3E.8 REPORTS AND DOCUMENTATION

Contractor shall submit to the Utility, within 45 days of completion of this work, a final report summarizing all aspects of the inspection. This report shall contain, as a minimum, the following:

A. Summary of results and significant observations with recommended corrective action if needed;

B. All video and photographic products annotated in a meaningful manner.

PROPOSAL SUBMITTED REQUIREMENTS

Part A
General

A.1 SCOPE

Bidder shall comply with all requirements of these Proposal Requirements. These Proposal Requirements shall be submitted with all instructions fulfilled to present a complete proposal for the Work described in the Specification.

All proposals submitted by Bidder, including drawings and other data, shall become the property of the Utility and shall not be used for any purpose other than in connection with procurement of the Work.

A.2 INSPECTION OF JOBSITE

Each Bidder, before submitting its proposal, may visit the Jobsite to satisfy itself as to the nature and location of the Work, the general and local Jobsite conditions, the transportation and handling of Material, the environmental and physical conditions at the Jobsite, the character of the equipment, facilities, Utility-furnished equipment and services; labor conditions, safety and security precautions, and all matters which may affect the performance of the Work and its cost. Notification of the initial Jobsite visit shall be made through the Procurement Agent.

PROPOSAL SUBMITTAL REQUIREMENTS

Part B
Technical Submitted Requirements

B.1 EXCEPTIONS TO THE SPECIFICATION

A. In order for Bidder's proposal to be considered, Bidder shall indicate its compliance with the Specification by having its representative who signs its proposal sign adjacent to the following appropriate statements:

1. No Exceptions

   Our proposal is in strict accordance with the complete Specification. We take no exceptions. ______________________ (Signature)

2. Exceptions to Specification Section 1, 2 or 3

   Our proposal is in strict accordance with the Specification, except as specifically listed. We take no other exceptions. ______________________ (Signature)

   All exceptions shall be fully explained on a separate attachment with the proposal and shall refer to the Section No. of the Specification where the exception applies.

3. Exceptions to Table 2-1

   Our proposal is in strict accordance with the Documentation submittal dates ______________________ (Signature)

B.2 SUBCONTRACTORS

Bidder shall list the Subcontractors and the work to be performed by each.

Subcontractor	Female (F) Minority (M)	Work by Subcontractor

B.3 EXPERIENCE RECORD OF SUPERINTENDENT

Bidder shall provide an attachment listing the name(s) and experience record of the superintendent(s) whom it expects to employ for this Work. The record shall cover in detail the superintendent's experience in the subject Work, and indicate his reliability for satisfactorily meeting scheduled completion dates.

B.4 WORK PLAN

Bidder shall provide a narrative description of how the Work is planned to be performed, including:

A. The Work area and laydown area required.

B. Bidder shall provide a schedule of the number of shifts and work hours per shift.

C. A listing of the major types and quantities of equipment to be used (both Bidder-owned and leased).

D. A summary milestone schedule showing the time phasing of the main activities to be performed.

E. A man-loaded schedule of work (commencing upon award of Purchase Order) by activities and employee classification (technician, engineer, etc.) including:

1. Travel to and from
2. Training/Security Processing/Drug Screening Urinalysis (up to four days depending on term of employment with present employer and previous badging history at the Utility.
3. Equipment set-up
4. Work
5. Pack-up

B.5 TECHNICAL DATA

Bidder shall include the following technical data with the proposal:

NOTE

The following assumptions should be used for ALARA Evaluations:

1. Steam Generator channelhead general area radiation field is ________ REM/hour.
2. Steam Generator platform general area radiation field is ________ MILLIREM/hour.

3. Steam Generator moisture separator general area radiation field is _______ REM/hour.

4. The radiation field in the vicinity of the wrapper, inside the handhole, is _______ REM/hour.

B.5.1 Appendix 3B, Eddy Current Testing

A. An ALARA evaluation explaining the benefits of the method, equipment and special tools used to reduce radiation exposure.

B. A detailed listing of all Jobsite services required from the Utility.

C. An expected production rate, tubes inspected, per shift.

D. A list of previous experience in eddy current testing including jobsite, NSSS vendor and number of tubes tested.

E. A description of the data analyst training program. The following areas of interest should be specifically addressed:

   1. The company and/or Division Administering Level IIA Certification Testing.

   2. Training on recent industry experience/new techniques.

   3. The level of effort allotted, prior to inspection start, for unit specific data analysis training such as:

      a. Correlations of previous pulled tube metallography and eddy current indications.

      b. Review of actual previous data.

      c. Training on previous data analysis techniques/conventions.

B.5.2 Appendix 3C, Ultrasonic Testing

A. An ALARA evaluation explaining the benefits of the method, equipment and special tools used to reduce radiation exposure.

B. A detailed listing of all Jobsite services required from the Utility.

C. A detailed description of the proposed testing system and a detailed description of work previously completed either at a mockup or on actual steam generators.

B.5.3 Appendix 3D, Examination/Analysis of Removed Steam Generator Tube Samples

A. A description of the techniques and analysis equipment available for examination of contaminated tube samples.

B. A list of previous experience including nuclear unit from which sample was removed, and degradation mechanism of interest.

B.5.4 Appendix 3E, Steam Generator Secondary Side Examination

A. A description of examination equipment, recording or photographic equipment, and method of manipulating equipment when inside the steam generator.

B. An ALARA evaluation explaining the benefits of the method, equipment and special tools used to reduce radiation exposure.

C. A detailed listing of all Jobsite services required from the Utility.

D. A description of remotely operated equipment features for retrieval from the steam generator in case of failure of remote operation.

E. A list of previous experience in steam generator secondary side inspection with proposed equipment, including jobsite and NSSS vendor.

PROPOSAL SUBMITTAL REQUIREMENTS

Part C
Commercial Submittal Requirements

An example of this section is not included in this sample specification.

Appendix F

DEFINITIONS

The following definitions are provided 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. Current flow in the test object parallels the coil's windings.

Absolute Drift

Positive drifting on the vertical component of an absolute channel which can be associated with intergranular attack.

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.

ASME Calibration Standard

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

Bulge

An expansion of a tube from the inside outwards.

Chatter

This condition can appear in a tube in any area and appears as uniform horizontal noise signals. It is due to variations in the tube inner diameter.

Copper

Presence of copper is due to the corrosion of copper-based materials within the balance-of-plant heat exchangers. Copper with the appropriate faulted secondary side chemistry promotes denting, SCC and pitting.

Cracked Support Plates

This is a known problem in drilled carbon steel support plates, primarily in the areas of extensive tube denting. This is due to the magnetite growth in the annuli region.

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 so that their respective fields overlap a common region. 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.

Distorted Roll Transition Signal

This is a roll transition signal which forms abnormally due to known or unknown causes. May be caused by improper machining or tooling used during inspection work.

Distorted Tube Support Plate Signal

A support signal which is distorted due to known or unknown cause. No recordable defect signal on any test frequency.

Distorted Tube Sheet Signal

This is a tube sheet signal which forms abnormally due to no detectable flaw. May be caused by deposits or small dents which are not yet of any measurable size.

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 or against another tube.

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 is a variation in fill-factor.

Incomplete Test

This is when a tube or tubes are not inspected to the pre-determined extent as stated in the approved inspection program for given outage.

Intergranular Attack

This is a general term denoting the corrosive attack of grain boundaries in Inconel-600 with no preferential (stress-related) orientation.

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.

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.

Magnetite

Carbon steel support plate corrosion products in the tube-to-tube support annuli.

Multiparameter Eddy Current

A signal processing method that vectorially combines 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.

No Detectable Defects

The tube has no signal responses meeting the minimum recording criteria for defects in the established data analysis procedure.

Obstructed

This is any tube or tubes that will not allow a probe any larger than a minimum diameter, to pass a given location. Smaller probes will be used to examine the area obstructed and evaluate for corrective action.

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. 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.

Permeability

Permeability describes the intrinsic willingness of a material to conduct magnetic flux lines. Eddy current indications from permeability variations may start up or down first and typically do not exhibit normal phase rotation at different frequencies characteristic of tube wall degradation.

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. For an absolute coil, the angle is measured at the signal peak.

Pitting

Localized attack on tubing resulting from non-uniform corrosion rates caused by the formation of local corrosion cells.

Preheater Wear

See Fretting.

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. 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 give 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.

Single Frequency Eddy Current

The application of one frequency to a test coil.

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

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.

Three Letter Code

A code consisting of three letters has evolved over the years to describe eddy current indications. Unfortunately, not all utilities and vendors use the same code to describe a similar indication. These codes are only used when a signal is not quantifiable as a flaw. The codes are grouped into categories as follows:

CATEGORY I

No further action required.

CATEGORY II

Possible flaw - further action required.

CATEGORY III

Possible loose part.

CATEGORY IV

Further action required - Retest condition

CATEGORY V

No further action required - Non-Relevant Signals

Table F-1 provides a listing of three letter codes and their definitions. Use of these codes on an industry-wide basis is recommended.

To Be Retested

This is when there is a signal to noise ratio lower than acceptable limits, a signal needing further quantification or other questionable areas causing the Data Analyst to request a re-test.

U-Bend Cracking

Identified as intergranular Stress Corrosion Cracking (SCC) and are normally I.D. initiated, axially oriented cracks. Crack initiated on the extrados side of the irregular transitions and propagate intergranularly.

Undefined Signal

This is a signal response that is masked by noise or other interference or is of a nature different from those signal responses commonly seen in normal tube inspections. Further examination with other test frequencies or coil designs or both may be used to define the signal in question.

Table F-1

THREE LETTER CODES
(For when through-wall depths cannot be defined.)

CATEGORY I - No Further Action Required	
No Detectable Degradation	NDD
Plugged	PLG
Sleeved	SLV
CATEGORY II - Possible Flaw, Further Action Required	
Non-quantifiable Indication	NQI
Absolute Drift Indication	ADI
Distorted Support Indication	DSI
Distorted Tube Sheet Indication	DTI
Distorted Roll Indication	DRI
Loose Part Indication	LPI
CATEGORY III - Possible Loose Part	
Possible Loose Part	PLP
CATEGORY IV - Further Action Required, Retest Condition	
Bad Data	RBD
Incomplete Test	INC
Obstructed	OBS
Template Plug	TMP
Tube No Test	TNT
To Be Re-Tested	TBR
Fixture	FIX
Tube Number Check	TNC
Positive Indication	PID

THREE LETTER CODES (CONT.)

CATEGORY V - Non-Relevant Signal

Bulge	BLG
Dent	DNT
Ding	DNG
Copper Deposit	CUD
Expansion	EXP
Absolute Drift	ADR
Distorted Support Signal	DSS
Distorted Tube Sheet Signal	DTS
Distorted Roll Transition	DRT
Chatter (Pilgering, etc./I.D. Variations, etc.)	IDC
Indication Not Found	INF
No Support Expansion	NSE
Over Expansion	OXP
No Tubesheet Expansion	NTE
Partial Tubesheet Expansion	PTE
Skip Rolled	SKR
Permeability Variation	PVN
Sludge	SLG
Noisy Tube	NSY
Top Main Roll	TMR
Deposit	DEP

Appendix G

QUALIFICATION OF NONDESTRUCTIVE EXAMINATION PERSONNEL FOR ANALYSIS OF EDDY CURRENT DATA

Appendix G

QUALIFICATION OF NONDESTRUCTIVE EXAMINATION PERSONNEL FOR ANALYSIS OF EDDY CURRENT DATA

1.0 SCOPE

This Appendix specifies personnel training and qualification requirements for nondestructive examination (NDE) personnel who analyze eddy current data for pressurized water reactor steam generator tubing. Its purpose is to insure a continuing uniform knowledge base and skill level for data analysts. The appropriate knowledge base is imparted using a comprehensive classroom and laboratory training program. Analysts are qualified by successful completion of written and practical examinations defined in this appendix.

2.0 QUALIFICATION LEVEL

2.1 General Requirements

a. Individual who successfully completes the requirements described herein is recognized as a Qualified Data Analyst. The individual's certification record, as compiled and maintained by the employer, shall clearly indicate compliance with this document.

b. Candidate seeking qualification as a data analyst shall be certified Level II or III in accordance with the employer's written practice in Eddy Current Examination.

c. Formal certification of personnel and compliance with the requirements of this document is the exclusive responsibility of the employer.

3.0 WRITTEN PRACTICE

3.1 General Requirements

Organizations performing data analyst qualification activities shall prepare a written program for their control and administration.

3.1.1 Training

The written practice shall specify the following:

a. Classroom and laboratory training requirements. These shall be in accordance with Section 4.1

b. Course outline including the number of instruction hours.

3.1.2 Annual Training

The written practice shall specify the requirements for annual training. Annual training shall be in accordance with Section 4.1.3.

3.1.3 Examinations

The written practice shall specify the examination requirements; these shall be in accordance with Section 4.2.

3.2 Responsibilities

The written practice shall specify the responsibilities, duties, and qualifications required for personnel who implement the personnel qualification program and provide classroom or laboratory training.

3.3 Use of an outside agency

An outside agency is an organization or an individual that provides instructor or qualification services and whose qualifications have been accepted by the organization that engages the outside agency. The written practice of the organization that engages the outside agency shall specify requirements for insuring that the outside agency meets the applicable requirements of this Appendix.

3.4 Confidentiality

Provisions to insure the confidentiality of the qualification materials (e.g., test questions, answer sheets, and test data) shall be included in the written practice. Access to such materials shall be limited and the examination material shall be maintained in secure files.

3.5 Availability of Training Course Materials

Training course materials shall be available for review or audit by user organizations and cognizant authorities. Training course materials shall not be subject to any confidentiality requirements other than the normally applicable copyright laws.

4.0 QUALIFICATION REQUIREMENTS

4.1 Training

4.1.1 Program, Facilities, and Materials

a. The training program shall include formal classroom and structured practical laboratory exercises.

b. Training course material shall be prepared and made available to the candidate.

4.1.2 Training Course Content and Duration

a. Training course content shall be in accordance with Attachment 1.

b. The training shall consist of a minimum of 40 hours to include classroom and laboratory exercises.

4.1.3 Annual Training

Supplemental training is required on an annual basis to impart knowledge of new developments, material failure modes, and pertinent technical topics as determined by the employer. The extent of this training shall be a minimum of 8 hours per year. A record of attendance and topics covered during the training shall be maintained.

4.2 Examinations

To be considered for examination, candidates shall have completed the training required in Section 4.1.

4.2.1 Qualification Examinations and Data Sets

4.2.1.1 Written Examinations

a. For each written examination administered as part of the qualification examination, a "question bank" containing at least twice the minimum number of questions shall be available. Each qualification examination shall be assembled from the question bank using a random selection process.

b. The written examination shall contain a minimum of forty (40) questions covering the lecture material outlined in Attachment 1.

4.2.1.2 Practical Examination

a. The practical examination data sets shall contain eddy current indications indicative of all damage mechanisms covering steam generator operating experience. Damage mechanism categories are identified in Table G-1.

Table G-1

Flaw Matrix

1	Thinning
2	Pitting
3	Wear
4	IGA/SCC
5	Primary-side SCC
6	Impingement Damage

b. Grading units for each practical examination data set shall be established using data acquired with techniques qualified in accordance with Appendix H.

c. Adequate numbers of flawed and unflawed grading units shall be used to meet the probability of detection (POD), statistical confidence level (CL), and false-call requirements of Table G-2.

d. The minimum number of flawed grading units for each damage mechanism category (Table G-1) is identified in Table G-2. The number of unflawed grading units selected for the practical examination shall be equal to at least twice the number of flawed grading units.

e. Extraneous test variables (e.g, denting, deposits, tube geometry changes) shall be included for each damage mechanism category, where applicable, based on steam generator operating experience.

Table G-2

Performance Demonstration Detection Test Acceptance Criteria *

Detection Acceptance Criteria					False Call Acceptance Criteria	
Total # of Flawed Grading Units	# of Flawed Grading Units		Minimum Detection Criteria		Minimum # of Unflawed Units	Maximum # of False Calls Grading
	20-39%	≥ 40%	20-39%	≥ 40%		
16	5	11	4	11	32	3
20	8	12	6	12	40	4
20	7	13	6	13	40	4
21	7	14	6	14	42	4
23	8	15	6	15	46	5
26	9	17	7	16	52	5
27	9	18	7	17	54	5
29	10	19	8	18	58	6
30	10	20	8	19	60	6
33	11	22	9	20	66	7
35	12	23	10	21	70	7
36	12	24	10	22	72	7
38	13	25	10	23	76	8
39	13	26	10	24	78	8
42	14	28	11	26	84	8

* (80% POD, 90% Confidence Level applicable to ≥ 40% through-wall)

f. Grading units shall have an associated steam generator type, row-column, steam generator leg, and other pertinent identification which will typically be available to a data analyst.

g. For each practical examination data set, the examinee will be provided with examination and analysis techniques. The grading criteria to be applied shall also be provided.

4.2.2 Analyst Qualification Criteria

4.2.2.1 A passing grade of 80% is required for the written examination.

4.2.2.2 Practical examinations for each data set shall be graded for both detection and sizing. Qualification may be based on detection, sizing, or both.

(1) Personnel shall be considered qualified for detection if the requirements of Table G-2, are demonstrated.

(2) Personnel shall be considered qualified for sizing if a relative root-mean-square error (RMSE) of less than or equal to 10% is demonstrated. The sample set, relative RMSE, is calculated using the following equation:

$$RMSE = \{1/n \sum_{i=1}^{n} (M_i - T_i)^2\}^{1/2}$$

where M_i is the eddy current measured flaw depth assigned by the candidate analyst for the ith indication, T_i is the eddy current measured flaw depth for the ith indication determined by expert opinion, and n is the number of measured grading units in the data set.

4.2.3 Re-examination

4.2.3.1 Prior to re-examination, those individual failing a qualification examination must receive additional training on topics or subjects in which the individual failed to attain a passing grade.

4.2.3.2 The written re-examination containing the same number of questions shall be assembled by a random selection process augmented by the inclusion of questions specific to the areas of deficiency.

4.2.3.3 A practical re-examination shall be given for each of the practical examination data set in which the examinee received less than a passing grade.

4.2.4 Interrupted Service

A Qualified Data Analyst who has not analyzed data during any consecutive 15-month period shall be considered to have interrupted service and shall be required to successfully complete the practical examination as required by Section 4.2.1.2 to insure continued proficiency prior to further assignment. The results of this examination shall be documented and maintained as part of the individuals qualification records.

5.0 QUALIFICATION RECORDS

The required documentation listed is intended to supplement, not replace, any requirements identified by the employer's written practice. Records of Certification to Level II or III, as required in paragraph 2.1, can be separately maintained at the discretion of the employer.

5.1 Required Documentation

5.1.1 A written testimony of qualification shall include:

a. Name of individual;

b. Statement indicating record of completion of training (annual and initial), including training hours, dates attended, and training institution;

c. Dates and pass/fail results assigned to the Written Examination and to each practical examination data set.

5.1.2 The employer shall maintain examinations with grades assigned and records of material covered in the annual training.

ATTACHMENT 1

TRAINING & LABORATORY PROGRAM CONTENT
- Steam Generator Eddy Current Data Analysis -

LECTURE

1.0 INTRODUCTION
- Purpose of Course
- Inspection Requirements Overview
  - ASME
  - ISI Guidelines
  - Plant Technical Specifications

2.0 STEAM GENERATORS
- Design and Operation
- Operating Experience

3.0 INDUSTRY PULLED TUBE EXPERIENCE
- Thinning
- Pitting
- IGA/SCC
- PWSCC
- Wear
- Fatigue
- Impingement Damage
- Denting
- Manufacturing Anomalies

4.0 INSTRUMENTATION OVERVIEW
- Data Acquisition
- Data Analysis

5.0 PROBES
- Volumetric/Axial Applications
- Circumferential Applications
- Other Specialized Probes
- Diagnostic Applications

6.0 CALIBRATION STANDARDS
- ASME
- Wear Scar
- Other

7.0 DATA ANALYSIS PRINCIPLES
- Signal Rotation Versus Frequency
- Factors Affecting Frequency Selection
  - S/N
  - Detection
  - Measurement
- Multiparameter Signal Suppression
- Flaw Specific Detection/Analysis Techniques

LABORATORY

- Calibration Procedures
- Analysis Techniques
- Practical Examination Data Sets
  - Application of Analysis Techniques
  - Grading Criteria
- Self Study

Appendix H

PERFORMANCE DEMONSTRATION FOR EDDY CURRENT EXAMINATION

APPENDIX H

PERFORMANCE DEMONSTRATION FOR EDDY CURRENT EXAMINATION

1.0 SCOPE

1.1 General

(a) This Appendix provides performance demonstration requirements for eddy current examination techniques and equipment.

(b) Each organization (e.g., Owner or Vendor) shall have a written program that ensures compliance with this Appendix. Each organization that performs eddy current examinations shall use techniques and equipment qualified in accordance with this Appendix. The organization may contract implementation of the program.

(c) The performance demonstration requirements specified in this Appendix apply to the acquisition process but do not apply to personnel involved in the data acquisition process. Data acquisition personnel shall be trained and qualified by their employer in a manner commensurate with the tasks they perform. The requirements for training and qualification of such personnel shall be described in the employer's written practice.

(d) Techniques which have been qualified in accordance with this Appendix may be used in procedures without regard to the organization that qualified the technique.

2.0 GENERAL EXAMINATION SYSTEM REQUIREMENTS

2.1 Technique Requirements

The technique specification shall contain a statement of scope that specifically defines the limits of the technique's applicability in the context of damage mechanism/extraneous test variables combinations, material, and geometry.

(a) The Acquisition Technique Specification (ACTS - see Attachment 1) shall define the following essential variables as a single value, range of values or formula:

Equipment Variables

(1) instrument or system including manufacturers name and model

(2) probe size and type including manufacturer's name and part number

(3) analog cable type and length including;

(a) probe cable type and length

(b) extension cable type and length

Technique Variables

(1) examination frequencies;

(2) coil excitation modes (e.g., absolute and differential);

(3) calibration method to insure proper data acquisition;

(4) minimum data to be recorded (e.g., number of channels);

(5) method of data recording (e.g., analog or digital);

(6) digitizing rate (samples per inch);

(7) scan pattern where applicable (e.g., pitch and direction).

(b) The Analysis Technique Specification (ANTS - See Attachment 2) shall define the following:

(1) method of calibration (e.g., calibration curves and mixes) used for signal characterization;

(2) data review requirements;

(3) reporting requirements;

(4) instrument or computerized system algorithms including manufacturer's name and part number.

3.0 PERFORMANCE DEMONSTRATION

3.1 General

(a) Data sets specified in Supplement 2 shall be used.

(b) Successful completion of Supplement 2 constitutes qualification of an acquisition technique and an analysis method. An industry peer review must be performed prior to inclusion in Appendix G.

3.2 Essential Variable Ranges

(a) Any two techniques with the same essential variables are considered equivalent. Equipment with essential variables that vary within the tolerances specified in Section 4 are considered equivalent. When variations in the technique allow more than one value or range for an essential variable, technique qualification shall be repeated at the minimum and maximum value for each essential variable with all other variables remaining at their nominal values.

(b) When the method does not specify a range for essential variables and establishes criteria for selecting values, the criteria must be demonstrated for frequency calculations, digitizing rates, etc..

3.3 Requalification

When a change in an acquisition technique or analysis technique causes an essential variable to exceed a qualified range, the acquisition or analysis technique shall be requalified for the revised range.

4.0 ESSENTIAL VARIABLE TOLERANCES

4.1 Instruments and Probes

The qualified acquisition technique may be modified to substitute or replace instruments or probes without requalification when the range of essential variables defined in the Acquisition Technique Specification (when applicable) are met providing both the original and replacement instruments or probes are characterized utilizing Supplement 1.

4.2 Computerized System Algorithms

Algorithms may be altered when the modified algorithms are demonstrated to be equivalent or better than those initially qualified.

4.3 Calibration Methods

Alternative calibration methods may be used without requalification if it can be demonstrated that the calibration method is equivalent to those described in the qualified acquisition technique or qualified analysis method.

5.0 RECORD OF QUALIFICATION

5.1 General

(a) The organization's written program shall specify the documentation that shall be maintained as technique qualification records. Documentation shall include identification of acquisition techniques and analysis methods, equipment and data sets used during qualification, and the results of the qualification.

(b) Acquisition Technique and Analysis Technique Specification forms i.e., Attachments 1 & 2, and associated qualification records shall not be subject to any confidentiality limitations or restrictions.

SUPPLEMENT 1

EQUIPMENT CHARACTERIZATION

1.0 SCOPE

(a) This Supplement specifies essential variables associated with eddy current data acquisition instrumentation and establishes a protocol for essential variable measurement.

(b) Essential variables are divided into two categories;

(1) Those associated with an individual instrument, probe or cable
(2) Those associated with particular on-site equipment configurations.

(c) Essential variables described in this Supplement have been selected to insure that eddy current instrumentation, including the probe type and cable length, as used on-site, which satisfy the essential variable requirements specified in the examination procedure may be used without any supplemental performance demonstration.

2.0 EDDY CURRENT INSTRUMENT

The essential variables for the eddy current instrument are related to the three basic modules of the instrument;

- The transmitter (signal generation and injection)
- The receiver (probe signal detection, amplification, demodulation and filtering)
- Analog to digital conversion

2.1 Transmitter

2.1.1 Total Harmonic Distortion

Harmonic distortion is due to non-linearities in the amplitude transfer characteristics of the instrument. The output contains not only the fundamental frequency but also integral multiples of the fundamental frequency. For eddy current instruments, harmonic distortion is a measure of the quality of the sinusoidal signal injected into the coil(s). The total harmonic distortion is expressed in either percent (%) distortion compared to the fundamental sinusoidal frequency or the ratio in Db of the amplitude of the fundamental frequency to the amplitude of the largest sidelobe as displayed on a frequency spectrum plot. It should be measured for each frequency specified.

When used as an essential variable, the maximum harmonic distortion should be specified.

2.1.2 Output Impedance

The output impedance is measured for each test frequency at the output connector of the instrument. Both, the magnitude and phase should be measured for each specified frequency. When used as an essential variable, the tolerance of the ratio of the output (transmitter) to input (receiver) impedance should be specified.

2.2 Receiver

2.2.1 Input Impedance

The input impedance is to be measured independently of the output impedance if the transmitter and receiver are not wired to the same coil(s) as is the case for reflection (driver/pickup) arrangements. Both, the magnitude and phase should be measured at each specified frequency.

When used as an essential variable, the tolerance of the ratio of the output (transmitter) to input (receiver) impedance should be specified.

2.2.2 Amplifier Linearity and Stability

Amplifier linearity and stability of each channel used for inspection is measured as the ratio of the signal injected at the instrument input to the magnitude of the signal measured at the data analysis screen. It is a measurement of the similarity between the eddy current signal sensed at the coil side and the signal observed on the analysis screen after signal amplification and filtering. The measurement is performed:

- For five different gain settings equally spaced between the smallest and largest gain values available on the instrument and,
- For five different signals injected at the instrument input at each gain setting, equally spaced between the smallest detectable signal and the largest signal that can be obtained without saturation.

linearity is expressed in terms of percentage deviation from a best-fit linear relationship between corresponding input and output values when plotted on a graph. The percentage is determined by dividing the maximum deviation from the line by the full scale value.

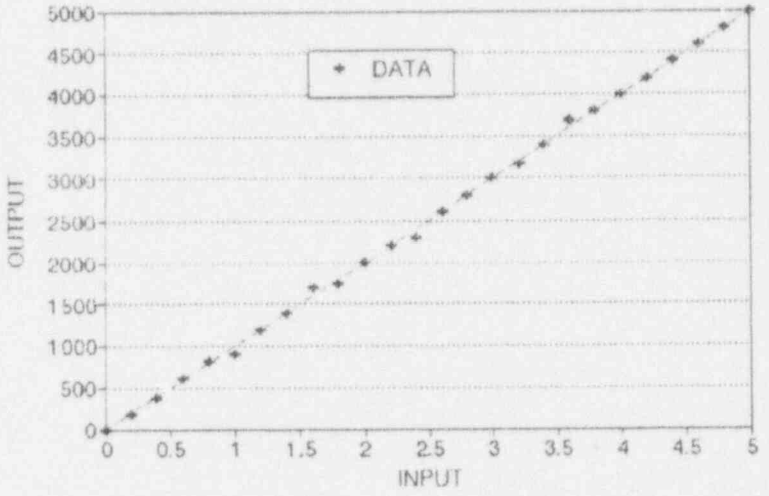


FIGURE S1-1

Instrument Linearity

When used as essential variables, linearity and/or stability shall be expressed as minimum requirements. The output/input graph shown in Figure S1-1 illustrates the curve fitting method used to determine amplifier linearity.

2.3 A/D Converter

2.3.1 A/D Resolution

The resolution of the analog to digital converter is the value of the input voltage that corresponds to a change of one bit. It is a measurement of the smallest change in the eddy current signal that can be observed after digitization. If applicable, it is measured for five equally spaced gain settings between the smallest and the largest gain values available on the instrument.

When used as an essential variable, the resolution of the analog to digital converter shall be expressed as a minimum value.

2.3.2 Dynamic Range

The number of bits for full scale input determines the dynamic range of the A/D converter. It is a measure of the maximum eddy current signal that can be recorded without distortion after digitization.

When used as an essential variable, the number of bits for full scale input shall be expressed as a minimum value.

2.3.3 Sample Rate

The sample rate is the frequency in Hz at which the analog to digital conversions are made. The sample rate in combination with the probe traverse speed determines the digitization rate.

$$\text{DIGITIZATION RATE}_{(\text{SAMPLES/INCH})} = \frac{\text{SAMPLE RATE}_{(\text{SAMPLES/SEC})}}{\text{PROBE SPEED}_{(\text{INCHES/SECOND})}}$$

When used as an essential variable, the minimum digitization rate shall be specified. The minimum sample rate of the A/D converter must be then capable of providing the specified digitization rate at the probe speeds to be used.

$$\text{SAMPLE RATE}_{\text{MIN}} = \text{DIGITIZATION RATE}_{(\text{MIN})} \times \text{PROBE SPEED}$$

Conversely, the maximum probe speed is determined by the maximum sample rate of the instrument divided by the minimum digitization rate specified.

$$\text{Probe Speed}_{\text{Max}} = \frac{\text{Sample Rate}_{\text{Max}}}{\text{Digitization Rate}_{\text{Min}}}$$

Note: See Section 4.3.1 Eddy Current Instrumentation of the PWR Steam Generator Examination Guidelines (EPRI NP-6201 Rev.3)

3.0 PROBE CHARACTERIZATION

3.1 Impedance

The impedance (magnitude and phase) shall be measured for each test coil at the test frequencies selected for the examination. This is considered to be the INPUT IMPEDANCE of the instrument as defined in Section 2.2.1.

3.2 Resonant Frequency

The resonant frequency is measured with the full cable length between the coil and the instrument input connector.

When used as an essential variable, the allowable range of the resonant frequency shall be specified.

3.3 Magnetic Field

Measurements are performed with the eddy current instrument wired according to the on-site conditions (including the cable length) between the eddy current instrument and the coils. Essential variables are defined for both bobbin and pancake coils.

3.3.1 Bobbin Coil

3.3.1.1. Effective Scan Field Width

The Effective Scan Field Width (ESFW) is a measure of the extent of the effective magnetic field in the preferred direction. It is also a measure of the spatial resolution. This resolution determines the minimum spacing between three successive notches which is compared to a single flaw of equal depth.

The measurement is performed for each eddy current examination frequency and mode of coil operation e.g., absolute or differential. A 100% through-wall notch of 0.2 mm (0.008") width, and a minimum length equal to the coil width + 25 mm (1.0") is scanned perpendicular to the coil preferred direction.

A curve is plotted for signal amplitude as a function of the probe displacement. The effective scan field width in mm (inches) is determined by subtracting the crack length from the measured distance between corresponding signal amplitude points for a given attenuation below the maximum amplitude. The effective scan field width can be a negative value for one or all of the four points measured on the curve.

When used as an essential variable, the effective scan field width shall be specified for absolute and differential modes, as a maximum distance and a point on the curve used to determine the VALUE minimum of four points, equally spaced, are to be selected so as to define the curve on either side of the minimum and maximum signal amplitudes.

Example: $ESFW_{-12dB}$ = -0.08"

3.3.1.2 Fill Factor Coefficient

The Fill Factor Coefficient (FFC) is a measure of the drop in the effective magnetic field perpendicular to the tube. The measurement is performed for each eddy current examination frequency and absolute/differential coil configurations. A 100% through-wall notch of 0.2 mm (0.008") width, and of a minimum length equal to the coil width +25 mm (1.0") is scanned perpendicular to the coil preferred direction.

The gain setting is adjusted for an 80% full scale peak signal for the signal having the largest amplitude. The measurements are performed for three or more fill factors (ratio of square of OD probe diameter to ID tube diameter) between the largest and smallest to be encountered in the steam generator tubes.

When used as an essential variable, the fill factor shall be specified, for absolute and differential modes, as the amplitude attenuation from the largest fill-factor to the smallest fill factor.

Example: FFC 0.85 to 0.70 = -5 Db

3.3.1.3 Depth Coefficient

The Depth Coefficient (DC) is a measure of the drop of the magnetic field within the wall thickness of the tube. The measurement is performed for each eddy current examination frequency and absolute/differential coil configurations at the nominal fill-factor to be encountered in the steam generator tube.

The following notches of 0.2 mm (0.008") width, and a minimum length equal to the coil width plus +25 mm (1.0") will be fabricated from the OD surface and the ID surface of the tube.

- one notch of 100% depth
- one notch of 80% depth
- two notches of 60% depth in the same cross-section 180 degrees apart
- four notches of 40% depth in the same cross-section 90 degrees apart
- six notches of 20% in the same cross-section 60 degrees apart

The notches are scanned perpendicular to the coil preferred direction. The gain setting is adjusted for an 80% full scale peak signal for the signal having the largest amplitude (100% depth). The amplitude of each eddy current signal will be divided by the number of notches in the same cross-section.

When used as an essential variable, the defect depth coefficient shall be specified, for absolute and differential modes, as a maximum amplitude attenuation for each depth relative to 100%.

Example: $DC_{80\%} = -2dB$
$DC_{60\%} = -5dB$

3.3.1.4 Axial Length Coefficient

The Axial Length Coefficient (ALC) is a measure of the influence of the axial crack length on the amplitude of the eddy current signal. The measurement is performed for each of the examination frequencies, absolute/differential coil modes, at the nominal fill-factor expected in the steam generator tube. A 100% through-wall notch of

0.2 mm (0.008") width, and of varying length from a minimum length equal to the coil width and up to the coil width +13 mm (0.5"), at increments of 2.5 mm (0.1"), is scanned perpendicular to the coil preferred direction. The gain setting is adjusted for an 80% scale peak signal for the signal having the largest amplitude.

When used as an essential variable, the axial length coefficient shall be specified, for absolute and differential modes, as a maximum amplitude attenuation for each length relative to longest one.

Example: $\mathrm{ALC}_{2.5\mathrm{mm}}$ = 0 Db
$\mathrm{ALC}_{5.0\mathrm{mm}}$ = -2 Db

3.3.1.5 Transverse Width Coefficient

The Transverse Width Coefficient (TWC) is a measure of the dependency of transverse crack width on the amplitude of the eddy current signal. The measurement is performed for each eddy current examination frequency for absolute /differential coil mode and nominal fill-factor. A 100% through-wall notch of the same length as the total coil(s) width, and the width of 0.2mm (0.008") to 0.6mm (0.02"), at increments of 0.1 mm (0.004"), is scanned parallel to the coil preferred direction. The gain setting is adjusted for an 80% full scale peak signal for the signal having the largest amplitude.

When used as an essential variable, the transverse width coefficient shall be specified, for absolute and differential modes, as a maximum amplitude attenuation for each defect width relative to largest one.

Example: $\mathrm{TWC}_{0.1\mathrm{mm}}$ = -0.5 Db
$\mathrm{TWC}_{0.2\mathrm{mm}}$ = -1.0 Db

3.3.1.6 Phase to Depth Curve

The Phase to Depth Curve (PDC) is a measure of the dependency of defect depth on the phase of the eddy current signal. The measurement is performed for each eddy current examination frequency for absolute and differential coil mode and nominal fill-factor. Notches from 20% ID to 100% and 20% OD to 100%, of the same length as the total coil(s) width +13mm (0.5"), and 0.2mm (0.008") width, are scanned perpendicular to the coil preferred direction for detection. The gain setting is adjusted for an 80% full scale peak signal for the signal having the largest amplitude.

When used as an essential variable, the phase to depth curves shall be given, for absolute and differential modes, as a minimum phase spread between each consecutive defect depth.

Example: $PDC_{(20\% \text{ to } 40\% \text{ OD})}$ = 30 degree

$PDC_{(40\% \text{ to } 60\% \text{ OD})}$ = 20 degree

Phase to depth curves may be given for complementary defect types such as holes, laboratory induced defects or site specific defects. Except otherwise specified, the phase spread between consecutive defect depth shall be considered as a minimum requirement.

3.3.1.7 D.C. Saturation Strength

The Direct Current Saturation Strength (DCSS) concerns only with probes delivered with a supplemental coil or a magnet designed to suppress the influence of possible magnetic variations. The direct current saturation strength is measured in air with a gaussmeter located at the center of the coil at a nominal distance from the tube's inner surface. It is expressed in milliTesla.

When used as an essential variable, the direct current saturation strength coefficient and direction shall be specified as a minimum requirement.

3.3.2 Pancake Coil

3.3.2.1 Effective Scan Field Width

See Section 3.3.1.1

3.3.2.2 Effective Track Field Width

The Effective Track Field Width

The Effective Track Field Width (ETFW) takes into account the combined influence of the coil magnetic field and the coil scanning pitch. It measures the drop in signal amplitude when the coil scans the defect at increasing scanning distances. A 100% through wall notch of 0.2 mm (0.008") width, and of a minimum length equal to the coil width +25mm (1.0") is scanned perpendicular to the coil preferred direction for defect detection.

The gain setting is adjusted for an 80% full scale peak signal for the signal having the largest amplitude.

A curve is plotted for the signal amplitude as a function of the distance between the center of the coil and the center of the notch.

When used as an essential variable, the effective track field width coefficient shall be specified, for absolute and differential modes, as the maximum distance from the notch where a given signal attenuation is measured minimum of four points which are equally spaced and are to be selected so as to define the curve on either side of the minimum and maximum signal amplitudes.

Example: $\mathrm{ETFW}_{3dB} = 3$ mm

3.3.2.3 Lift-Off Value (LOV)

The Lift-Off Value (LOV) is a measure of the drop in the effective magnetic field in a direction perpendicular to the tube. The measurement is performed for each eddy current examination frequency and absolute/differential coil configurations. A 100% through-wall notch of 0.2mm (0.008") width and of a minimum length equal to the coil width +25mm (1.0") is scanned perpendicular to the coil preferred direction.

The gain setting is adjusted for an 80% full scale peak signal for the signal having the largest amplitude. The measurements are performed for three or more lift-off values between the largest and smallest to be encountered in the steam generator tubes.

When used as an essential variable, the lift-off value shall be specified, for absolute and differential modes, as the amplitude attenuation from the smallest lift-off to the largest lift-off value.

Example: LOF 0.85 to 0.70 = -5 dB

3.3.2.4 Depth Coefficient

See Section 3.3.1.3

3.3.2.5 Axial Width Coefficient

See Section 3.3.1.4

3.3.2.6 Transverse Width Coefficient

See Section 3.3.1.5

3.3.2.7 Phase to Depth Curve

See Section 3.3.1.6

4.0 DEFINITIONS

The decibel, abbreviated as dB, is an adaption of a logarithmic unit defined to represent a power transmission unit known as the bel.

$$dB = 10 \log10 \frac{P(Out)}{P(In)} = 10 \log10 \frac{V^2(Out)}{V^2(In)} = 20 \log10 \frac{V(Out)}{V(In)}$$

dB	V(Out)/V(In)
96	63,095 (16 bits = 65,536)
84	15,849 (14 bits = 16,384)
80	10,000
....	....
6	2
3	1.41
0	1
-3	0.71

SUPPLEMENT 2

QUALIFICATION REQUIREMENTS FOR STEAM GENERATOR TUBING

1.0 GENERAL

Steam generator tubing examination techniques and equipment used to detect and size flaws shall be qualified by performance demonstration.

2.0 QUALIFICATION DATA SET REQUIREMENTS

2.1 General

(a) Qualification data sets shall consist of flawed and unflawed grading units and shall be established for each of the categories in Table S2-1. Flawed grading units shall consist of damage mechanisms/extraneous test variable combinations applicable to the scope of the examination procedure.

Table S2-1
Flaw Matrix

(1)	Thinning
(2)	Pitting
(3)	Wear
(4)	IGA/SCC
(5)	Primary-Side SCC
(6)	Impingement Damage

(b) Limited qualification to a subset of the categories listed in Table S2-1 is permissible.

(c) Test sample damage mechanism morphology and dimensions used to construct qualification data set grading units shall be based on steam generator operating experience as inferred from tube pulls where practical.

(d) Where applicable, the influence of extraneous test variables associated with each of the damage mechanisms (e.g, denting, deposits, tube geometry changes) shall be assessed.

(e) Test samples fabricated using mechanical or chemical methods may be used to generate qualification data set grading units provided that it has been established that responses comparable with in-generator samples are obtained.

(f) Flaw dimensions for samples, used to construct grading units included in the qualification data set, shall be verified.

2.2 Detection Data Set

(a) The detection data set shall be selected according to the requirements of Table S2-2 for each damage mechanism/ extraneous test variable combination. The minimum detection set is 16 flawed grading units. For a missed detection, testing may either be continued using larger data sets or another test initiated using an independent data set.

(b) Flawed grading units data set elements shall meet the following criteria for flaw depth.

(1) At least 2/3 (rounded to the nearest whole number) shall have a maximum true depth equal to or greater than 60% of the nominal tube wall thickness. The data set shall be uniformly distributed over the depth range of 60% to 100% through-wall.

(2) The remainder shall have true maximum depths less than 60% of the nominal tube wall thickness. The data set shall be uniformly distributed over the depth range of 20% to 59% through-wall.

(3) All grading units shall have true maximum depths >60% of the nominal tube wall thickness when flaw sizing is not reliable and only an accept/reject criteria is applied.

2.3 Depth Sizing Data Sets

The detection qualification data set shall be used to demonstrate depth sizing.

3.0 ACCEPTANCE CRITERIA

Qualification may be based on detection, sizing, or both.

3.1 Detection Acceptance Criteria

Techniques shall be considered qualified for detection if the results of the performance demonstration meet the requirements of Table S2-2.

3.2 Depth Sizing Acceptance Criteria

Techniques shall be considered qualified for sizing if a root-mean-square error (RMSE) of less than or equal to 25% through-wall is demonstrated. The sample set RMSE is calculated by the following equation

$$RMSE = \{ 1/n \sum_{i=1}^{n} (Mi-Ti)^2 \}^{1/2}$$

where M_i is the eddy current measured flaw depth for ith flaw, T_i is the true maximum flaw depth determined for the ith flaw and n is the number of measured flawed samples in the data set.

Table S2-2
Performance Demonstration Detection Test Acceptance Criteria

Detection Acceptance Criteria			
Total # of Flawed Grading Units	# of Flawed Grading Units		Minimum Detection Criteria ≥ 60%
	20-59%	≥ 60%	
16	5	11	11
20	8	12	12
20	7	13	13
21	7	14	14
23	8	15	15
26	9	17	16
27	9	18	17
29	10	19	18
30	10	20	19
33	11	22	20
35	12	23	21
36	12	24	22
38	13	25	23
39	13	26	24
42	14	28	26

* (80% POD, 90% Confidence Level applicable to ≥ 60% through-wall)

ATTACHMENT 1

Acquisition Technique Specification Sheet	
ACTS#	Page:
Examination Scope	
Material:	
Outer Diameter:	Wall Thickness:
Applicability:	
Instrument	Probe
Manufacturer:	Type:
Model:	Manufacturer:
Software/Mfg./Rev.:	Size:
	Part #:
Cables	
Probe Cable:	Extension Cable:
Type:	Type:
Length:	Length:
Frequencies	
Mode:	Mode:
Channels/Frequencies:	Channels/Frequencies:
1 - 5 -	1 - 5 -
2 - 6 -	2 - 6 -
3 - 7 -	3 - 7 -
4 - 8 -	4 - 8 -
Calibration Method	Sampling Rate
Standard:	Samples/Sec:
Data Recording	
Equipment Manufacturer:	Model:
Media:	Format:
Scan Pattern	Probe Speed
Direction:	Maximum:
Pitch:	

ACQUISITION TECHNIQUE SPECIFICATION SHEET (ACTS)

ATTACHMENT 2

Analysis Technique Specification

ANTS #

Page:

Instrument

Manufacturer:

Model:

Software/Mfg./Rev.:

Reference ACTS #

Differential Channels

	Channel __	Channel __	Channel __	Mix __
Span				
Phase				
Cal. Std				
Curve				
Volts				

Absolute Channels

	Channel __	Channel __	Channel __	Mix ___
Span				
Phase				
Cal. Std				
Curve				
Volts				

Screen Setup (Minimum):

Analysis Protocol:

ANALYSIS TECHNIQUE SPECIFICATION SHEET (ANTS)

Supplement I

GUIDELINES FOR DISPOSITION OF BOBBIN COIL INDICATIONS ATTRIBUTED TO ODSCC AT NON-DENTED AND DRILLED TUBE SUPPORT PLATES

Some units have experienced secondary-side or outer diameter stress-corrosion cracking (ODSCC) at non-dented tube support plates. The degradation is distributed across the tube bundle, tending to be most prevalent at the lowest (highest temperature) support plates on the hot-leg side. The incidence of ODSCC usually diminishes with increasing support plate elevation on the hot-leg side, though some outlet side indications have been reported.

Many tube sections have been removed to identify the causes of cracking and to validate eddy current examination results. Metallographic examinations show that virtually all the cracking is confined to within the support plate. The morphology of the cracking ranges from shallow, single cracks to broadly distributed, short cracks sometimes linking into networks extending axially through the thickness of the support plate. When the affected volume, i.e., length, width and depth, is sufficient, detection with bobbin probes can be effective, as shown from tube pulls. However, the coincidence of signals from the support plates themselves, mix channel residual, probable tube alloy changes, deposits, and denting, can sometimes render signals attributed to cracking ambiguous. In these cases, testing with rotating pancake coil (RPC) technology usually permits improved signal characterization. Other qualified techniques may be applied to clarify ambiguous bobbin coil results as appropriate.

The variety of depths and numbers of cracks which may occur leads to the possibility of signal amplitude variability for a given observed phase angle or depth estimate. It has been established from various tube pulls that bobbin signals with small amplitudes, i.e., < 0.6 volts in the mix channel, have been associated with axial crack depths greater than 40% through-wall determined metallographically. (For reference, this voltage level assumes that the signal amplitude from a carbon steel drilled support plate has been normalized to six volts at 400 Khz for 7/8" diameter tubing).

While small amplitude signals may be associated with ODSCC depths greater than plant Technical Specification limits for repair, the potential exists for false calls (both false positives and false negatives) resulting from a variety of interference's possible at support structures. To limit false calls e.g., overly conservative tube repair based on false positives, and nonconservative tube repair associated with false negatives, RPC or other qualified methods should be performed in order to adequately characterize tube support plate intersections.

Specific written instructions for reviewing tube support plate signals for evidence of tube wall degradation should be incorporated within the overall plant data analysis guidelines. These rules should recognize the possibility of ambiguous data caused by various interfering conditions. For ***non-dented*** support plate intersections, the analysis rules will typically specify the review of midrange and upper-range primary frequencies e.g., 200 Khz and 400 Khz respectively, and the support plate mix analysis channel (typically 400 Khz/100 Khz) for evidence of an indication. These frequencies are for 0.050" wall tubing; appropriate frequencies based on phase spread equivalence can be defined for other tube wall thicknesses. No preference is recognized for the order in which the various data channels are to be reviewed. If an indication is believed to be masked or influenced by a dent signal, an alternative NDE method or technique should be considered for this intersection, along with an augmented inspection program to examine dented support plate intersections.

A recommended logical framework for evaluating bobbin coil data at non-dented tube support plates for plants ***without*** a licensed Alternate Repair Criteria (ARC) program is shown in flow-chart format in Figure 1. It is emphasized that ***there is no minimum voltage threshold for reporting purposes!*** Because of possible test ambiguities associated with varying bobbin coil signal-to-noise ratio, the flow-chart logic recognizes three possible analysis outcomes for a given support plate intersection; 1) conclusive evidence for an indication (right-most path of Figure 1), 2) inconclusive evidence for an indication, (center path of Figure 1), and 3) no detectable degradation (left-most path of Figure 1).

Units ***with*** licensed ARC should utilize plant-specific analysis guidelines and reporting criteria, dispositioning bobbin coil indications according to the applicable alternate repair criteria.

- Conclusive Results

This guideline defines conclusive analysis results as a situation in which there is confirmatory evidence of an indication in the bobbin coil ***mix channel*** and ***either or both*** of the mid-range and upper-range primary frequencies. This evidence typically consists of an indication (possibly distorted) that rotates counterclockwise with decreasing frequency while subtending a phase angle that generally remains in the OD plane as defined by the ASME calibration curve. There may not be ***any*** agreement in depth estimates among the various data channels. If the bobbin coil analysis results are deemed ***conclusive*** in the context defined previously then the tube may be dispositioned using the right most path of Figure 1. The ***mix channel*** is used for depth estimation using conventional phase angle analysis, the ASME calibration standard, and a depth based repair criterion.

- Inconclusive Results

Inconclusive analysis results are defined as the case in which the bobbin coil inter-channel rotational behavior described above does not hold. Mix channel indications may not be supported or confirmed by ***any or all*** of the primary analysis channels. For this situation, the bobbin coil result for a particular support plate intersection is deemed ***inconclusive***; the intersection in question ***must*** be examined using RPC - in order for the tube to remain in service - or repaired. If subsequent RPC examination confirms linear indications diagnosed as cracking, then the tube is dispositioned in accordance with applicable plant tube repair practices; if not, the intersection in question may be flagged for monitoring during subsequent outages. See the center path of Figure 1.

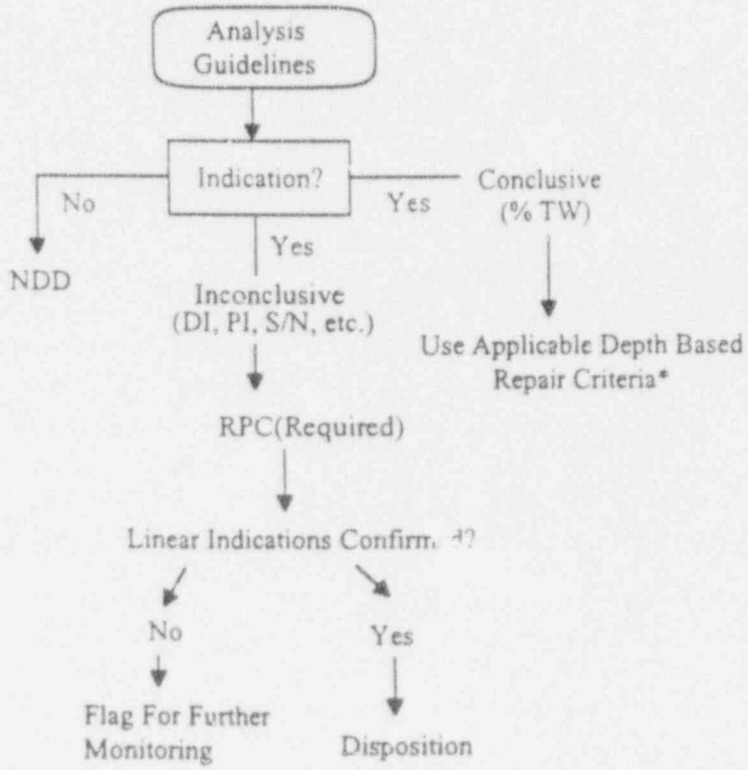
- No Detectable Degradation

The condition of no detectable degradation (NDD) is defined as a situation in which no reportable indications are observed at a support plate intersection.

Figure 1

Flow Chart for Disposition of Bobbin Coil Indications Attributed to ODSCC at Non-Dented Tube Support Plates

- Applicable to Plants Without Licensed Alternate Repair Criteria -



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* RPC may be used to prevent false calls