STEAM GENERATOR TUBE INTEGRITY PROGRAM

**Quarterly Report
January 1 - March 31, 1977**

**Battelle Pacific Northwest Laboratories
for
U. S. Nuclear Regulatory Commission**

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January 1 - March 31, 1977**

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STEAM GENERATOR TUBE INTEGRITY PROGRAM

QUARTERLY REPORT

JANUARY 1, 1977 TO MARCH 31, 1977

SUMMARY

A laboratory research program to investigate the failure characteristics of artificially defected steam generator tubes representative of those found in PWR steam generators is underway at the Pacific Northwest Laboratory. The primary objectives of the program are:

- Carry out a selected number of burst and collapse tests on baseline and artificially defected tubes representative of tubes presently installed in PWR steam generators. These tests are to be conducted in environments similar to those found in service.
- Create controlled defects to be similar to those found in PWR steam generators and fully characterize them by the use of replication and eddy current and/or other nondestructive testing methodology.
- Develop burst and collapse pressure margins-of-safety as functions of flaw geometry, tube type and operating conditions.
- Develop methodology (techniques) for correlating the results of field inspection defect determination with the results of laboratory burst and collapse testing of flawed tubes.
- Develop criteria for estimating margins-of-safety to be applied to the evaluation of tubes in which flaw indications are found during inservice inspection of PWR steam generators.

A draft of the detailed program plan in the form of an Analysis Before Test document has been prepared.

A draft of the literature survey of PWR steam generator problems has been completed.

A Quality Assurance Plan Index has been completed for the Steam Generator Tube Integrity program.

The single frequency eddy current inspection system has been received, checked out and calibrated.

Burst, collapse and leak rate facilities have been designed and construction work has been started.

The corrosion research activities to chemically induce tube defects are in progress.

The tensile tester for measuring tube hoop strength has been designed, built and tested.

Three of the six heats of tubing to be used in the program have been received and are being processed.

A reference metallographic observation of one steam generator tube wall has been completed.

Bulging test criteria have not yet been defined.

CONTENTS

SUMMARY	iii
INTRODUCTION	1
DISCUSSION	2
PROGRAM MANAGEMENT	2
QUALITY ASSURANCE	3
TRIPS	3
Review Meeting with NRC at Silver Springs, MD	3
Trips to CE - Chattanooga	4
NON-DESTRUCTIVE TESTING	5
BURST, COLLAPSE AND LEAK RATE FACILITIES	6
CORROSION RESEARCH	14
RING TENSILE TESTS	17
TUBE PROCUREMENT	22
STEAM GENERATOR TUBE WALL METALLOGRAPHY	22
APPENDIX - ANALYSIS BEFORE TEST	
APPENDIX "A" -	
RING TENSILE TEST APPARATUS AND PROCEDURES	
HARDNESS TESTING APPARATUS AND PROCEDURES	
APPENDIX "B"	
GENERATION OF SLOTS AND WASTAGE: REPLICATIONS	
TUBE DENTING PROCESS	
APPENDIX "C"	
LEAKAGE RATE ESTIMATES	

APPENDIX "D"

PRELIMINARY ASSESSMENT OF TUBE BURST TEST PLAN

APPENDIX "E"

GEOMETRIC COMPUTATIONS AND PLOTS OF A_i/A_o FOR ECT CHECK

APPENDIX "F"

TEST SPECIMEN IDENTIFICATION TABLES

FIGURES

1	Tubing High Pressure System	7
2	Autoclave Pressure System	8
3	Burst and Collapse Test Facility	9
4	Controlled Secondary-Side Leak Rate Setup	10
5	Experimental Setup for Leak Rate Tests into Ambient Pressure	11
6	Fatigue Test Design/Instrumentation - Primary Loop	12
7	Fatigue Test Design/Instrumentation - Secondary Loop	13
8	Tubes with End Fittings Before Burst	15
9	Tubes After Burst	16
10	Selective Attack of Inconel 600 Tubing	18
11	Anodic Dissolution of Inconel 600 Tubing	19
12	Denting Specimen - Inconel 600 Tubing and Simulated Tube Support Plate	20
13	Ring Tensile Tester	21
14	Section of 0.875 x 0.050 Tubing #B-02-2	24
15	Microphotograph Locations	26
16	Microphotographs of Longitudinal Wall Specimen B - Top	27
17	Microphotographs of Longitudinal Wall Specimen B - Bottom	28
18	Microphotographs of Longitudinal Wall Specimen C - Top	29
19	Microphotographs of Longitudinal Wall Specimen C - Bottom	30
20	Microphotographs of Transverse Wall Specimen D	31
21	Steam Generator Tube Wall Local Hardness	34

LIST OF FIGURES

Figure

1	Sketch of Tube-Marking and Cutting Plan (10 ft Length) -----	10
2	Sketch of Section Marking and Cutting for Hardness/Ring-Tensile Specimens -----	11
3a	General Schematic of High Pressure System -----	14
3b	Functional Details of High Pressure System -----	15
4	Collapse Test Set-Up (and Water Chemistry Table) -----	16
5	Controllable Secondary-Side System for Leak Rate Tests -----	33
6	Open Secondary-Side System for Leak Rate Tests -----	34
7	Fatigue Test Design/Instrumentation, Primary Loop -----	37
8	Fatigue Test Design/Instrumentation, Secondary Loop -----	38
9	Pressure Difference Versus Critical Slot Length -----	43

LIST OF TABLES

Burst Tests

A	Slotted Tubes -----	20
B	Elliptical Wastage -----	21
C	Elliptical Wastage Plus Through-Wall Slot -----	23
D	Uniform Circumferential Thinning -----	24
E	Denting -----	25
F	Denting Plus Elliptical Wastage -----	25
G	Denting Plus Uniform Circumferential Thinning -----	27
H	Burst Test Summary -----	27

Bulging Tests

I	Bulging -----	28
---	---------------	----

Collapse Tests

J	Slotted Tubes -----	29
K	Elliptical Wastage -----	30
L	Elliptical Wastage Plus Through-Wall Slot -----	31
M	Uniform Circumferential Thinning -----	31
N	Collapse Test Summary -----	31

Leak Rate Determination

O	Through-Wall Slots -----	32
P	Leak Rate of Fatigue-Cracked Specimens -----	35
Q	Summary of Leak Rate Tests -----	35
R	Examination of Tube Strength on Burst and Collapse Behavior -----	35

BACKGROUND AND INTRODUCTION

Steam generators form the final link between nuclear heat and the electric-producing system. PWR's include the steam generator as part of the primary pressure loop. Under normal operations, or under the possible chance of unscheduled events, integrity of the steam generator tubing is essential.

Tubing in steam generators can suffer degradation in service beyond that expected in the design envelope if the fluids on either side of the tubing exceed process control limits of chemistry. The experiences with nuclear plants of the PWR type demonstrate that unexpected service performance can occur--some of it quite undesirable. These degrading happenings include stress corrosion cracking, corrosion wastage, tubing/tube support interactions and combinations of these situations.

Field Examination with Eddy Current Testing

Nondestructive evaluation of tubing can be carried out with eddy current test (ECT) methods. In PWR's, the usual method at the present time utilizes a close-coupled pair of coils operated at a single frequency and in a differential mode. The differential mode generates a signal which is characterized by the difference in coupling between each coil and the tubing. In operation, the probe containing the coils is inserted down the tubing and then withdrawn at a fixed rate, the signals being recorded during the withdrawal activity.

Differential ECT is designed to be insensitive to gradual changes in tube dimensions. This produces a limitation--under single frequency operation--which influences the sensitivity of the system to slowly changing section shapes. In a given situation, there is some section shape change, which if sufficiently moderate and smoothly contoured, will be undetected by the ECT system.

At the present time, ECT signals are processed and displayed on an appropriate Cathode Ray Tube (CRT) and visually examined for indications of tube degradation. Interpretation of the signals is essentially subjective although calibration standards are used to provide a reference level for signal processing adjustments. The standard for ECT calibration consists of tubing into which are end-milled small holes to various depths. These defects have little physical correlation with the usual forms of tubing degradation.

Field Experiences and NRC's Role

Water quality control has been a recognized requirement for successful operation of boilers and related equipment for a century and one-half or more. Nevertheless, with each new method for power generation from boiling water, there have been in-service leak experiences involving heat exchangers and, more recently, PWR steam generators. Almost all the PWR's throughout the world that have operated for several years have contributed to the list of field problems with steam generator tubing leaks. In the U.S., the licensing and responsibility for safe operation of all components of PWR's now comes under the aegis of the Nuclear Regulatory Commission (NRC).

The Present Program

Following a proposal draft, an NRC team worked with appropriate personnel at Pacific Northwest Laboratories to jointly devise a program outline for providing NRC with some of the needed information to assess integrity of PWR steam generator tubing based on existing, commercial ECT examinations. The program is intended to produce several types of results, incident to the several technical areas encompassed by the NRC team.

Tubing material is to be tested in a series of identified schemes to produce some of the results needed by NRC to perform their regulatory functions. Four tubing sizes, each from Inconel 600 produced to meet ASME BPVC Section II, B, SB-163 (ASTM B163-66), are to be intentionally defected in graded amounts and patterns to reflect findings from field examinations and to provide a considerable range of experimental data from which the integrity of differently degraded tubing might be determined. This original plan was documented in a Schedule 189, titled "Steam Generator Tube Integrity Program" and submitted to NRC September 10, 1976.

Funds to begin work were provided in the first quarter of FY-1977, initiating program performance.

ANALYSIS BEFORE TEST

One of the prime features of the present program is the Analysis Before Test (ABT). This activity focuses on a review of the content of the original program plan with emphasis on uncovering weaknesses which might impair the attainment of technical goals.

The present document constitutes final Analysis Before Test considerations and upon concurrence by NRC becomes the controlling definition of technical work for Phase I.

Procedures Employed in Technical Review of Program

Between the period of program submittal and the present writing, contributing contractor personnel examined, re-evaluated, discussed and explored many of the technical aspects intended to be instituted by adoption of the program plan. Periodic meetings with management permitted opportunities for interactive communications. A draft was submitted to NRC and the contractor attended review sessions at NRC offices in Silver Spring, Maryland, March 8, 1977. This document reflects revisions to the ABT resulting from that meeting.

ECT-Related Actions

Simulated defect generation as well as nondestructive examinations fall within the scope of planned work in the ECT-related areas.

Preliminary contact with vendors and laboratory scoping experiments were completed for initial technical review of program action.

Pressure Test Related Actions

Water quality requirements for testing are provided in a subsequent section. Re-examination of the modified test plan and the scheduling problems associated with acquisition of tubing resulted in some alterations of testing sequence in attempts to avoid any schedule slide because of the delays in tubing delivery. Requirements for fatigue testing are clarified, together with adjustments in the flow rate tests. These details are also provided in subsequent sections.

Analysis Related Actions

In a preliminary trial of candidate analysis procedures, hypothetical data were plotted and processed. Based on this examination, modifications and alterations to the original program plan were developed. These arrangements are detailed below, and were derived after reviews and discussions of program goals with NRC. Subsequently, a more extensive examination of potential analysis methods was undertaken. Results comprise the concluding section of this document.

Quality Control

Quality assurance can be considered a management tool and is treated as such in this program. Its full description can be found in appropriate management documents. With respect to the detailed test plans described below, QA responsibilities and documents were worked into the program at the earliest times to ensure greatest overall practicality of the effort.

Exploratory trials on nearly every phase of work have been launched to test the efficacy of both equipment and tentative QA procedures, suitable adjustments being effected when potential weaknesses are identified by technical or management personnel. These actions are intended to diminish the likelihood of undesirable omissions or oversights during execution of the specified program tasks.

Overview Program Goals

The overall program is designed to accomplish several goals. One is to provide a broad baseline of data and performance trends from burst and

collapse tests on representative PWR steam generator tubing which has been intentionally defected to simulate observed tube degradation. This goal is encompassed by the first two scope items in the Schedule 189.

Another goal is to develop an understanding and attempt quantification of field ECT results in light of laboratory ECT examinations on a range of artificially flawed tubes. We expect the effort will clarify the degree of confidence and reliability which can be placed in field examinations.

An additional goal of this program is the development of practical, viable and credible techniques for describing the safety margins in PWR steam generators based on field examinations, while retaining full cognizance of the philosophy behind the program goals.

The remainder of this document describes such changes or alterations of the original program outline and thereby provides definition of tasks, tests and procedures to be implemented upon NRC concurrence of these plans.

ALTERATIONS OF THE PRESSURE TEST PROGRAM PLAN - SUMMARY

- A few deletions of defect sizes have been made.
- Elliptical wastage configurations were clarified, which subsequently resulted in an increase of specimens in that category.
- Number of specimens per test condition was adjusted to accommodate the above mentioned increase.

REVISED PROGRAM PLAN

Overview

Steps to be followed for pre-test tube characterization are shown on the following page, with a description of the identification plan and associated sketches.

NDE techniques are described in the next section, then the pressure test apparatus functions are outlined and sketched in line diagrams.

Specific details of the test matrices are provided for both burst and collapse evaluations. These occupy several pages and are followed by descriptions of leak rate tests and strength-effect tests.

Fatigue testing is outlined next; ovality and "real defects" plans are then sketched.

The text is concluded with discussions of the test plan, anticipated problems, and descriptions of the likely analytical procedures which will be carried out with the test data.

Appendices are:

- A - Ring Tensile Test Apparatus and Procedures;
Hardness Testing Apparatus and Procedures
- B - Generation of Slots and Wastage; Replications;
Denting Methods
- C - Leakage Rate Estimates
- D - Preliminary Assessment of Tube Burst Test Plan
(Example Plots Only - Hypothetical Data)
- E - Geometric Computations & Plots of A_i/A_o for ECT Check
- F - Test Specimen Identification Tables

Pretest Tube Characterization

The greatest number of tests will be conducted on specimens taken from four runs of tubing, one run being of each size; no more than one heat per run.

0.875" x 0.050"

0.750" x 0.048" (actual wall thickness expected to be 0.050")

0.750" x 0.043"

0.625" x 0.034"

These tubes will initially be identified in 10 foot lengths (approx.), then they will be processed and characterized through the following steps:

1. Helical ultrasonic scan on 100% of as-received tubing, to determine tube wall thickness at selected locations, plus characterize I.D., O.D. and ovality.
2. Baseline eddy current examination, per standard field practice, on as-received tubing. (Single frequency I.D. probes; permanent chart recordings.)
3. Identification of each minor portion of tube; cut to sections.
Identification of hardness/ring-tensile specimens; cut to sections.
4. Hardness tests on section adjacent to each tube specimen to confirm strength properties.
5. Ring tensile tests on each 10 foot length as received; samples to be from a similar location on each tube length.
6. ASTM tubular tensile tests; five per heat or per run.
7. Flaw fabrication or preparation per plan.
8. Flaw characterization by replicating techniques, as required.
9. Eddy current examination, per standard field practice, on all tube specimens in their condition prior to testing.
10. Advanced multifrequency, multiparameter eddy current examination on 10-20% of flawed tubes prior to testing.

Identification Plan (Tube Lengths and Sections)

Tube length 10 feet

X Letter designating vendor and tube size

X-00 Accession numerals indicating specific tube

X-00-0 Tube specimen number

Identify* tube length, one end. This becomes "head end" (10 ft lengths).

Record - ship to scan vendor.

Helical ultrasonic scan (on identified tube lengths only).

- Locate and mark with noncorrosive crayon the minimum gage at each of five locations spaced 2 ft apart along tube, beginning 6 in. from the head end
- Provide definition of section at marked locations - ID, OD, ovality, minimum gage (indicate course of minimum gage trace).
- Transmit identified scan records and tubes to BNW.

Conduct baseline eddy current examination; record.

Mark cut locations along tube length; crayon or scribe.

Identify* tube sections on head end of each section per assigned plan; record.

Verify identification and cut locations.

Cut tube length into specified sections (abrasive cut-off saw).

Identify 1 in. lengths parallel to axis at foot of each section, pierce 1/4 in. reference hold,** cut through hole with $\sim 1/16$ in. precision abrasive blade. After hardness test, trim off end with hole remnant to produce length of $15t \pm 0.005$; measure and record (t = wall thickness).

Hardness test adjacent to the identification marks and at 180° ; record, bundle in section groups, tag and store.

Bundle, tag and store each group of sections (per tube length).

See accompanying sketch for example of marking method to be used before cutting tube length into sections.

*Identification marks with electro-pencil approximately $3/16$ in. high, running circumferentially around tube, approximately $1/2$ in. from head end of tube or tube section.

**Reference hole placed in axial alignment with mid-tube minimum gage, $+3^\circ$, unless track of minimum gage crossing ring specimens is clearly more than $\pm 10^\circ$ off axial alignment with minimum gage at mid-tube. In latter event, reference hole will be at minimum gage of ring specimen $+5^\circ$, and angular deviation/direction from reference hole to position of mid-tube minimum gage will be evaluated and recorded on control sheet for each affected tube section.

Cut tubes with abrasive cut-off saw.

After cutting, tube sections are to be $11 \frac{7}{8} \pm \frac{1}{8}$ except for special lengths as required.

FIGURE 1. Sketch of Tube Marking and Cutting Plan (10 ft lengths).

FIGURE 2. Sketch of Section Marking and Cutting for Hardness/Ring-Tensile Specimens.

Nondestructive Examination (Including Flaw Preparation)

Preliminary analysis of the flaw characterization procedures and techniques to be used during the NRC Steam Generator Tube Integrity program has revealed certain additional requirements. The effects of these additional items upon the program performance, costs and time schedule have been evaluated. All of these items will be incorporated into the current program with no change in schedule or costs although minor adjustments in specific test procedures or tubing specimen allocations have been required.

Ultrasonic and eddy current baseline examinations of the tubing will be performed on raw tubing sections prior to placement of flaws. It is cost-effective to perform these examinations on full tubing lengths (tubing to be procured in 10 ft lengths) prior to sectioning as individual specimens. Testing a 10 ft length will reduce handling and setup costs and will provide more complete data on the tubes, especially in regions to be mechanically severed. In the case of ultrasonic examination, inspection of 10 ft specimens will reduce difficulty and expense of transporting tubes past the inspection transducer array.

Eddy current inspection of 10 ft sections will reduce loss of data caused by tube end effects. Test schedules have been rearranged to permit ultrasonic and baseline eddy current examination prior to tube sectioning.

An existing eddy current probe drive and tube support system has been modified to accommodate the longer tube sections. It will also be used to examine pressure-test specimens after placement of flaws in the tubes. The probe drive system has been demonstrated by using existing laboratory tube specimens and should be adequate for future baseline and flawed specimen eddy current tests. Other existing portions of the eddy current test system have been assembled and checked out using calibration guidelines established in Section XI, Appendix IV of the ASME B & PV Code.

Description of flaw preparation and replication is in Appendix C.

Description of Pressure Test Apparatus and Testing Procedures

Burst testing will be conducted in an autoclave assembly as outlined in Figures 3a and 3b. Similarly, Figure 4 shows the set-up for collapse tests. Pressurization of both the tube (or primary side) and the autoclave (or secondary side) will be with water chemically simulating PWR steam generator feed water.* Initial water supply will be treated by condensing on-plant steam, running through an anion-cation exchange bed, then through a sulfite deoxygenator. (Testing water can be stored in separate, stainless steel tanks where individual chemistries can be created for the experiment at hand, e.g., pH control, hydrazine additions, etc.)

During burst testing the autoclave and its load of tubes will be simultaneously pressurized to 2250 psi, then heated to 600°F. The autoclave will then be slowly depressurized to 1000 psi. (Some tubes may burst during this period.) This will establish starting conditions for the experiment. At this point, all valves will be closed but one and that tube will be rapidly pressurized to bursting (1000-2000 psi/min).** Then the burst tube will be valved off and the next tube tested in the same manner until all tubes loaded in the assembly have been burst. (Simulated in-service leakage rates on most burst specimens will be measured in a separate facility.)

Collapse tests (Figure 4) start by pressurizing the tube and surrounding pipe section to 2250 psi. The autoclave will be pressurized to 2250 psi and heated to 600°F, thus heating the test assembly. Upon commencing the test, the tube-side pressure will be vented to ~1600 psig (some tubes may collapse during this period). The pipe (secondary) pressure will then be increased at the rate of 1000 to 2000 psi/min until tube collapse. Testing of companion tube/pipe systems will continue until all tubes in that autoclave load have collapsed.

For both burst and collapse tests, the information obtained will be primary side and secondary side pressures and temperatures, pressurization rate, and failure or peak pressure. Tube characterization before testing will be conducted as described earlier. Post-testing metallographic documentation will be provided on all specimens.

*Chemistry is defined on chart accompanying Figure 4.

**The autoclave pressure is not expected to exceed 3000 psi, although some tubing test pressures will go beyond that.

FIGURE 3a. General Schematic of High Pressure System

FIGURE 3b. Functional Details of High Pressure System

Several fully instrumented assemblies can be handled per autoclave run.

FIGURE 4. Collapse Test Set-Up.

Water Chemistry

Total Base H ₂ O Conductivity	10 mho/cm ^(a)
Hydrazine (for O ₂ Control)	100 ppm ^(a)
O ₂	20 ppb ^(b)
pH (Controlled With Ammonia)	8.5-9.5 ^(a)
Cl ⁻	10 ppb ^(a)

(a) Feed water and tank chemistry.

(b) Measured at bleed end of test.

TEST MATRIX DESCRIPTION

Burst Tests

Analysis of the burst test program as originally planned was initiated by plotting the proposed tests as (hypothetical) data, shown in Appendix E. This promoted interaction with PNL NDE personnel to forecast whether the data were likely to permit achievement of program goals; some adjustments appeared in order from both NDE and analytical viewpoints.

Wastage defects were plotted to scale to help define the geometry* of so-called elliptical wastage. It was expected that these shapes could be simulated by chemical processes or by machining to minimum size, followed by chemical treatment to remove worked material and, in either case, thereby simulate field surface conditions.** From mechanics analyses considerations, a flawed tube is compromised in one mode when the wastage is all from one side, but from another mode when the wastage "wraps around" the tube. (Uniformly thinned wastage can be viewed as an extreme of the "wrap around" elliptical wastage.) Mechanistically, then, it is very desirable to have data at various levels of "wrap around" wastage in order to validate the changing analytical conditions and likely failure modes. The test plan was adjusted to provide this data.

All four sizes were initially scheduled for denting plus uniform wastage, but only one tube size was planned with uniform wastage alone. Since reference tests with wastage alone were needed in all tube sizes to provide a sound analytical reference frame, the test plan was adjusted to accommodate this need. However, the smallest tube size was finally eliminated from all denting tests, as discussed below, and the test matrices reflect this deletion. Other changes appeared desirable, too, and these are discussed in the following paragraphs.

*Flaw geometries are described by calculations and sketches as shown in Appendix F.

**Chemical metal removal will be accomplished with either 30% H_2O_2 , Reagent Grade (RG) HCl and H_2O in 1-2-2 volumetric proportions or RG HCl, RG HNO_3 and RG $C_2H_4O_2$ in equal volumetric proportions, according to the choice of the flaw fabricator.

Slotted tube burst tests were scheduled for five different lengths, variously distributed among the four tube sizes; however, simplifications were in order, particularly because of flaw fabrication considerations. Furthermore, discrimination of results between two sizes of defect that are both small is often masked by data scatter.

Based on the above reasoning, slot lengths were reduced to three sizes: 1/4 in., 1/2 in., and 1 1/2 in. In our opinion, these dimensions cover the ranges of interest at this time. Base reference tests--no slot and through wall slot--were retained at three each, but other portions of the matrix were reduced from three to two replications. The changed matrix format is judged adequate to complete reference level analyses commensurate with program goals.

In addition, bulging plans were changed so the total tests were reduced from 12 to eight specimens, which together with the other adjustments, permitted doubling the number of elliptically-wasted specimens so that the "wrap around" wastage geometry could be brought into the program. From a practical fabrication viewpoint, the many different elliptical flaw geometries are most unattractive. It was reasoned that if the number of shapes could be sharply reduced, it would, on one hand, permit the attractive option of grinding a special cutter for each machining operation. Since this action is cost-effective and, with proper cutter selection* has no deleterious effect on the required data generation, the matrix reflects consolidation to just three radii contours.

* The study indicated that flexibility in choice of radii was possible, and some of these calculations are included in Appendix E.

The adjusted plan, as shown in Table B, now calls for 64 elliptically-wasted specimens, as against 36 originally.

The total number of elliptical wastage plus through-wall slot specimens was maintained at 48 specimens, but a more complete test matrix was established.

Axial lengths of the wastage were finally based on doubled dimensions, rather than by progression in one-half inch increments. Replicate testing was reduced from three to two, as shown in Table D.

Denting tests were modified to eliminate the smaller tube size, Table E, since denting problems are not expected with generators employing this tube size. The demonstrated denting procedure is outlined in Appendix B.

Denting plus elliptical wastage are covered in Table F. The same number of total tests is planned, but under the revision, testing is scheduled for various types of "wrap around" wastage, in agreement with baseline tests as to dimensions. Again, the smallest tube size tests were eliminated. Denting plus uniform circumferential wastage has been modified in a similar manner.

Text matrices are shown in the following pages.

A. Slotted Tubes - Burst

Slot Depth % Wall	Slot Length	Number of Tests Per Tube Condition				Totals
		.875 x .050	.750 x .048	.750 x .043	.625 x .034	
None	-0-	3	3	3	3	12
25-30%	1/4	2	2	2	2	8
	1/2	2	2	2	2	8
	1 1/2	2	2	2	2	8
55-60%	1/4	2	2	2	2	8
	1/2	2	2	2	2	8
	1 1/2	2	2	2	2	8
85-90%	1/4	2	2	2	2	8
	1/2	2	2	2	2	8
	1 1/2	2	2	2	2	8
Thru- Wall	1/4	3	-	-	-	3
	1/2	3	-	-	-	3
Totals		27	21	21	21	
					Total	90

Comments: End radius of slot 0.01 to 0.02 in.
Slot width 0.003 to 0.004 in.

B. Elliptical Wastage - Burst

Table shows defect length and
number of tests per condition.

Max. Depth % Wall	Wastage Wrap Angle	.875 x .050 Cutter Radius			.750 x .048 Cutter Radius			.750 x .043 Cutter Radius			.625 x .034 Cutter Radius			Totals
		6	12	24	6	12	24	6	12	24	6	12	24	
25-30%				1.549*			1.518*			1.437*			1.277*	
	Flat			2			2			2			2	8
	45°			2			2			2			2	8
	135°			2			2							4
55-60%		1.148*	1.624*		1.125*	1.591*		1.064*	1.506*		0.947*	1.339*		
	Flat		2		2	2			2		2	2		12
	45°	2	2			2		2	2			2		12
	135°	2	2		2	2								8
85-90%		1.426*			1.397*	1.977*		1.323*			1.176*	1.665*		
	Flat	2			2	2		2			2	2		12
Subtotals		6	6	6	6	8	6	4	4	4	4	6	4	
Tube Totals			18			20			12			14		
													Total	64

*Axial length of flaw.

B. continued

Example method for making
elliptical wastage cut;
finished to dimension
by chem-milling, locally.

*Thermal methods for mandrel insertion or removal will not heat tubing beyond 500°F in neutral atmosphere, nor produce interior scratches or marks deeper than 0.0005 in.

C. Elliptical Wastage Plus Through-Wall Slot - Burst

Wastage % Wall	Slot Length	.875 x .050 Cutter Radius			.750 x .048 Cutter Radius			.750 x .043 Cutter Radius			.625 x .034 Cutter Radius			Totals
		6	12	24	6	12	24	6	12	24	6	12	24	
25-30%	1/4			(1.549)*			(1.518)*			(1.437)*			(1.277)*	8
	1/2			2			2			2			2	8
50-60%	1/4			(1.624)*			(1.591)*			(1.506)*			(1.339)*	8
	1/2			2			2			2			2	8
85-90%	1/4			(1.426)*			(1.397)*			(1.323)*			(1.665)*	8
	1/2			2			2			2			2	8
Subtotals		4	4	4	4	4	4	4	4	4	4	4	4	
Tube Totals		12			12			12			12			
Total														48

-23-

*Axial length of wastage.

D. Uniform Circumferential Thinning - Burst

Table shows number of tests
per tube size.

Thinning % Wall	Thinned Length	.875 x .050	.750 x .048	.750 x .043	.625 x .034	Totals
25-30%	3/8	2		2		4
	3/4	2	2			4
	1 1/2	2	2			4
55-60%	3/16	2		2		4
	3/8	2		2		4
	3/4	2	2			4
	1 1/2	2				2
75-80%	3/16	2				2
	3/8	2				2
	3/4	2				2
	1 1/2	2				2
Totals		22	6	6	-0-	34

FIGURE 8. Tubes with End Fittings Before Burst

FIGURE 9. Tubes After Burst

Pitting attack of Inconel 600 was evaluated in both FeCl_2 and CuCl_2 solutions. The procedure was to wrap 1-in. wide asbestos strip around the tubing after saturating in FeCl_3 or CuCl_2 solution. The asbestos was resaturated on a daily basis. Deeper pits with less metal wastage were obtained with CuCl_2 solution. A photograph of a pitted tubing section is shown in Figure 10A. The pits shown were produced in a 3-day exposure at 25°C and are about 20 mils deep. A smaller number of 20-mil deep pits were produced in 24-hr exposures. Pitting attack under controlled potentials is planned.

Intergranular attack has been produced only on sensitized specimens to date. A photograph of a sensitized (4 hr at 700°C) specimen after a 24-hr exposure to boiling $\text{H}_2\text{SO}_4 \cdot \text{Fe}_2(\text{SO}_4)_3$ solution is shown in Figure 10B.

Metal wastage to produce locally attacked areas can be accomplished in several ways. A smooth surface can be produced by electropolishing (see Figure 11A) and a surface evidencing intergranular attack can be produced by anodic dissolution. A photograph of a tubing section anodically dissolved in 6M HCl at 30°C is shown in Figure 11B. Rapid dissolution of Inconel 600 can also be attained in the absence of an applied potential, e.g., exposure to $\text{HCl} \cdot \text{H}_2\text{O}_2$ solution.

Denting is believed to be a result of "runaway" magnetite formation. Hydrolysis of (Fe-Cr-Ni) phosphate in crevices, especially in unbuffered systems, produces an acid system which, in the presence of a chloride ion and high temperature, represents conditions thought to be conducive to "runaway" corrosion of the carbon steel support plate. A specimen designed to evaluate the above hypothesis is shown in Figure 12. (Fe-Cr-Ni) phosphate precipitate will be clamped in the crevice area and the specimen exposed to water at 350°C containing 1 ppm chloride.

RING TENSILE TESTS

During the first quarter of 1977 the ring tensile test device shown in Figure 13 was designed, built and evaluated. The apparatus consists of jaws and half-rounds. Adaptors permit use of the device in any convenient loading

A. Pitting Attack, CuCl_2

B. Intergranular Attack, $\text{H}_2\text{SO}_4 \cdot \text{Fe}_2(\text{SO}_4)_3$

FIGURE 10. Selective Attack of Inconel 600 Tubing

A. Electropolish in $\text{H}_3\text{PO}_4\text{-H}_2\text{SO}_4$ Solution

B. Anodic Dissolution in HCl Solution

FIGURE 11. Anodic Dissolution of Inconel 600 Tubing

FIGURE 12. Denting Specimen - Inconel 600 Tubing
and Simulated Tube Support Plate

FIGURE 13. Ring Tensile Tester

fixture. The design of the apparatus facilitates rapid placement and removal of the test specimen. There are four sets of half-rounds; each set fits the same jaws. One set of half-rounds was prepared for each tube size. Ring tensile specimens are to be 15 wall thicknesses in length.

Practice tests to develop test procedures indicated very uniform properties for specimens from the same heat. Ultimate strength was very close to that expected from the literature and variation in several tests was less than 5%. A clip gage is being built so that more precise displacement readings can be made. Output from the ring tensile tests will be recorded on an x-y plotter.

TUBE PROCUREMENT

Programmatic arrangements were made to obtain steam generator tubing produced in a Westinghouse facility and fabricated to Westinghouse specifications. Four sizes of tubing are to be examined: 0.875 in. x 0.050 in., 0.750 in. x 0.048 in., 0.750 in. x 0.043 in. and 0.625 in. x 0.034 in. All tubing of one size will be from the same heat except for the 0.875 x 0.050. There will be three different strength levels for this size. The majority will be of normal strength tubing. In addition there will be tubing from two heats annealed to give yield strengths different from normal. During this reporting period the normal strength level 0.875 x 0.050 tubing and the 0.75 x 0.048 and the 0.75 x 0.043 tubing were received. The 0.625 x 0.034 size and the two heats of different strength 0.875 x 0.050 have yet to arrive.

STEAM GENERATOR TUBE WALL METALLOGRAPHY

During routine inspection of the first shipment of steam generator tubing received from Westinghouse, helical patterns were noticed on both outside and inside tube surfaces. The outside surface had very shallow but definite circumferential scratches typical of centerless grinding operations.

The helical pattern visible on the outside surface of the tubes had a rate of twist of approximately three turns per inch. It was postulated that this pattern could have resulted from the centerless grinding operation used

to bring the outside diameter to its final dimensions; the appearance was caused by variations in the surface finish and therefore might signify variations in the amount of cold work that different segments of the tube received.

The helical pattern visible on the inside of the tube was harder to examine due to its location. It had a twist rate of approximately one to two turns per inch and the pattern appeared to be due to variations of the inside dimensions and not surface finish. It was postulated that the inside helix was a carryover from some portion of the manufacturing process that took place after the tube was extruded.

Because the helical patterns possibly signified variations in both the tube dimensions and the material properties of the Inconel, metallographic samples were made from a representative sample of tubing so that both the wall dimensions of the tube and the metallographic structure of the Inconel could be more fully characterized.

If the inner helix signified variation in the wall thickness, the distance between two consecutive minimum wall thicknesses could be 1/2 to 1 in. (1.2 to 2.5 cm), and since some of the flaws to be machined into the tube walls were 1-1/2 in. (3.8 cm) long, it would make little sense to locate and mark the minimum wall thickness at the midsection of each tube section since the flaw could contain more than one local minimum wall thickness. By having metallographic specimens made, it would be possible to characterize tube dimensional variation both along the tube axis and around its circumference. Also, if the helical patterns signify changes in the metallographic structure of the tube wall, the eddy current and ultrasonic testing examinations could show these changes, and, unless they were identified as due to property variation, they might be interpreted as dimensional variations.

A section of the 0.875 x 0.050 tubing was selected for preparation of metallographic specimens. Specimen number B-02-2, which was to be used for a tube tensile test, had a 6-in. long piece removed from the end. From this sample, five rings were cut as shown in Figure 14. Samples B-02-2a and B-02-2e were set aside to be used for hardness and ring tensile tests. Samples B-02-2b and B-02-2c were to be used for longitudinal specimens showing

FIGURE 14. Section of 0.875 x 0.050 Tubing #B-02-2
(for Metallographic Examination)

the tube wall along the axis. Sample B-02-2d was to be used for a transverse specimen to show a cross section of the tube. The samples were mounted, polished and etched to bring out the grain structure; they were photographed at 60X to show the entire wall cross section. Photographs were taken of the wall at the locations shown in Figure 15. Figures 16 through 19 show the longitudinal specimen and Figure 20 shows the transverse specimen.

The photographs showed that the wall thickness varied slowly along the tube axis. Along an axial length of 1-1/2 in. (3.8 cm) of specimens b and e, the wall thickness varied only 0.4% for one wall and 0.8% for the other wall. This rate of change was very much slower than expected. The difference in wall thicknesses seen in specimen d was only 2% between maximum and minimum, or about 0.001 in. (0.0025 cm). The maximum was almost exactly opposite the minimum. It appears that a trace of the minimum wall thickness will mark a spiral with a pitch of several feet around the tube and that locating the flaws at the minimum wall thickness is not a bad choice. Therefore, it appears that, if the sample specimen chosen is characteristic of the remaining tubes, the tube characterization procedures as outlined in the Analysis Before Test document are appropriate to obtaining the needed data.

The next point of interest visible in the pictures (from specimens b and c) was the very uniform nature of the grain structure along the tube axis. Whereas visible differences in the grain structure due to variation in amount of cold work were expected, instead the grain structure was very uniform. Running throughout the wall are streaks parallel to the axis of the tube. These developed during manufacturing and are intermetallics of some kind. The grain structure is not markedly elongated along the axis as might be expected, but appears to be approximately equiaxed, signifying at least partial recrystallization has taken place. The pictures of specimen d show grain structures similar to specimens b and c, except that the carbide streaks are not present. The carbide streak would appear in end view in these pictures and are probably the dark spots seen throughout the wall.

FIGURE 15. Microphotograph Locations

FIGURE 16. Microphotographs of Longitudinal Wall Specimen B - Top (60X)

FIGURE 17. Microphotographs of Longitudinal Wall Specimen B - Bottom (60X)

FIGURE 18. Microphotographs of Longitudinal Wall Specimen C - Top (60X)

FIGURE 19. Microphotographs of Longitudinal Wall Specimen C - Bottom (60X)

0°

90°

180°

270°

FIGURE 20. Microphotographs of Transverse Wall Specimen D (60X)

Because the grain structure appears very uniform across the wall thickness, it was felt that the material properties are probably fairly uniform. As a check to see if directional dependence of the properties exists in the tubing, microhardness readings were made at several locations on the specimens. Hardness was measured using the Diamond Pyramid Hardness (DPH) scale and a 500-g load. The results of these hardness tests are given in Table 1, but their variations were very unexpected. They showed that the wall was harder at the surface and softer in the middle. This suggested that the Inconel had not been fully annealed but was only partially recrystallized.

The correlation of surface hardness to tube strength becomes questionable in light of these findings. Since strength tends to increase with increasing hardness, it would appear that the strength of the Inconel will vary across the tube wall. However, in the tensile test it will be average strength over the entire cross section that would be measured. Depending on the amount of cold working experienced by the tube and the degree of recrystallization that took place, variations in strength across the wall could be significant. This may make surface hardness a poor indicator of average strength.

To get a clearer picture of how the hardness varied across the wall, a more detailed series of hardness tests was run on specimen d. The specimen was repolished to remove any effects of the etch. A series of 23 hardness tests was made across the wall at both the maximum and minimum wall thicknesses using a 100-g load. The results of these tests are plotted in Figure 21. The possibility of hardness variation between maximum and minimum wall thickness was examined because the differences in hardness would probably be largest for these two locations.

As can be seen from Figure 21, the hardness probably varies only slightly around the outer circumference. However, the surface very close to the outside is significantly harder than that of the immediate underlying metal, due to cold working of the surface metal during the finish grinding. Consequently, surface hardness may not be a good indication of strength because the surface hardness is measured at a location where variable levels of cold working may have taken place.

TABLE 1. Diamond Pyramid Hardness Data - 500 Gram Load

<u>Longitudinal Specimen #b</u>		<u>Transverse Specimen #d</u>	
<u>Indent Location</u>	<u>DPH</u>	<u>Indent Location</u>	<u>DPH</u>
<u>Area 1</u>		<u>0°</u>	
OD Edge	184	OD Edge	201
OD Midpoint	167	OD Midpoint	184
Center	157	Center	158
ID Midpoint	171	ID Midpoint	175
ID Edge	186	ID Edge	187
<u>Area 2</u>		<u>90°</u>	
OD Edge	181	OD Edge	181
OD Midpoint	168	OD Midpoint	171
Center	157	Center	159
ID Midpoint	168	ID Midpoint	170
ID Edge	181	ID Edge	171
<u>Area 3</u>		<u>180°</u>	
OD Edge	184	OD Edge	181
OD Midpoint	170	OD Midpoint	169
Center	158	Center	162
ID Midpoint	172	ID Midpoint	169
ID Edge	184	ID Edge	177
<u>Area 4</u>		<u>270°</u>	
OD Edge	180	OD Edge	184
OD Midpoint	170	OD Midpoint	162
Center	155	Center	151
ID Midpoint	172	ID Midpoint	172
ID Edge	182	ID Edge	185
<u>Average of Areas 1 through 4</u>		<u>Average of 0° through 270°</u>	
OD Edge	182 ±2	OD Edge	187 +14 -6
OD Midpoint	169 ±2	OD Midpoint	172 +12 -10
Center	157 ±1	Center	158 +4 -7
ID Midpoint	171 ±2	ID Midpoint	172 ±3
ID Edge	183 ±2	ID Edge	180 +7 -9

FIGURE 21. Steam Generator Tube Wall Local Hardness

The tube wall metallographic specimens provided considerable information. The helical patterns visible on the inner and outer surfaces of the tubes do not cause significant variations in tube geometry. The outer helix is probably due to centerless grinding and the inner helix is probably an indication of the differences in the maximum and minimum of inside diameter and is similar to the pattern seen in a rifle barrel. The variations appear to be so large possibly because of the shallow angle at which they are viewed. A trace of the minimum wall thickness is expected to make a slow spiral down the tube, with maximum to minimum wall variation of about 0.001 in. (0.0025 cm).

The metallographic structure of the Inconel is typical of partially recrystallized wrought tubing; streaks of intermetallics are visible, but the grains are fairly equiaxed. The tube had not been fully annealed as was obvious from hardness profiles; the center of the tube wall was softer than either surface. Metallographic examination of other tubes is expected to provide further insight into possibilities of correlating surface hardness testing of tube specimens with the ring tensile and burst strength of adjacent tubular material.

ANALYSIS BEFORE TEST

Phase I

by

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Steam Generator Tube Integrity Program

for

The Nuclear Regulatory Commission

Approved by:

Milton Vagins,
Program Manager

July 1977

BATTELLE PACIFIC NORTHWEST LABORATORIES
RICHLAND, WASHINGTON

CONTENTS

	<u>Page</u>
LIST OF FIGURES -----	iii
LIST OF TABLES -----	iv
BACKGROUND AND INTRODUCTION -----	1
Field Examination With Eddy Current Testing -----	1
Field Experiences and NRC's Role -----	2
The Present Program -----	2
ANALYSIS BEFORE TEST -----	3
Procedures Employed in Technical Review of Program -----	3
ECT-Related Actions -----	3
Pressure Test Related Actions -----	4
Analysis Related Actions -----	4
Quality Control -----	4
Overview Program Goals -----	4
ALTERATIONS OF THE PRESSURE TEST PROGRAM PLAN - SUMMARY -----	6
REVISED PROGRAM PLAN -----	7
Overview -----	7
Pretest Tube Characterization -----	8
Identification Plan (Tube Lengths and Sections) -----	9
Nondestructive Examination (Including Flaw Preparation) -----	12
Description of Pressure Test Apparatus and Testing Procedures -----	13
TEST MATRIX DESCRIPTION -----	17
Burst Tests -----	17
Collapse Tests -----	28
Leak Rate Determination -----	32
Cyclic Fatigue -----	36
Ovality -----	36
Real Defects -----	36

DISCUSSION OF TEST PLAN -----	39
Eddy Current Testing Problems -----	39
Tube Pressure Test Problems -----	39
Cyclic Fatigue -----	40
Test Data Presentation -----	40
Test Specimen and Data Identification -----	41
ANALYSIS PROBLEMS -----	42

APPENDICES

- A Ring Tensile Test Apparatus and Procedures
Hardness Testing Apparatus and Procedures
- B Generation of Slots and Wastage; Replications
Tube Denting Process
- C Leakage Rate Estimates
- D Preliminary Assessment of Tube Burst Test Plan
(Example plots only - hypothetical data)
- E Geometric Computation and Plots of A_i/A_o
for ECT Check
- F Test Specimen Identification Tables

STEAM GENERATOR TUBE INTEGRITY PROGRAM

QUARTERLY REPORT

JANUARY 1, 1977 TO MARCH 31, 1977

INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has authorized the Pacific Northwest Laboratory (PNL) to perform a laboratory research program to investigate the behavioral characteristics of defected tubing similar to those found in PWR steam generators. Called the Steam Generator Tube Integrity Program (SGTI), the primary objectives of this effort are:

- Carry out a selected number of burst and collapse tests on baseline and artificially defected tubes representative of tubes presently installed in PWR steam generators. These tests are to be conducted in environments similar to those found in service.
- Carefully control defect creation to be similar to those expected in PWR steam generator defects and fully characterize them by the use of replication, eddy current and/or other nondestructive testing methodology.
- Develop burst and collapse pressure margins-of-safety as functions of flaw geometry, tube type and operating conditions.
- Develop methodology (techniques) for correlating the results of field inspection defect determination with the results of laboratory burst and collapse testing of flawed tubes.
- Develop criteria for estimating margins-of-safety to be applied to the evaluation of tubes in which flaw indications are found during inservice inspection of PWR steam generators.

This report is the first published progress review of the program. The period covered is November 1, 1976 to March 31, 1977.

DISCUSSION

During this reporting period, PNL conducted a number of activities related to the SGTI Program objectives. These efforts are described in detail in this section.

PROGRAM MANAGEMENT

The detailed program plan in the form of the Analysis Before Test (ABT) document has been prepared and upon concurrence by NRC will become the controlling definition of technical work to be performed. The ABT document is one of the prime features of the present program. It reviews the content of the original program plan with emphasis on uncovering weaknesses which might impair the attainment of technical goals. The ABT document becomes the controlling definition of technical work for Phase I of the Steam Generator Tube Integrity Program upon concurrence by NRC.

Included in the ABT is a description of the test program. Areas covered include pre-test tube characterization and identification, NDT techniques, and descriptions of pressure test apparatus and test programs. The pressure tests are to include burst, collapse and leak rate tests as well as tests to investigate tube material yield strength-effects, fatigue and ovality. In addition to undefected tubes, tests will be run on tubes having Electro Discharge Machined (EDM) slots, elliptical wastage, elliptical wastage plus through wall slots, uniform thinning, denting, denting plus elliptical wastage and denting plus uniform thinning. Since these defects are representative of those reported to occur in PWR steam generators, they were selected to provide a broad base-line of data and performance trends from the burst and collapse tests. Defect geometries are described in the ABT and the test matrices are provided for the various tests. To understand and attempt quantification of field eddy current testing (ECT) results, laboratory ECT examination of the artificially flawed tubes will be conducted. It is expected that the effort will clarify the degree of confidence and reliability which can be placed in field examinations.

The text concludes with a discussion of the test plan, anticipated problems, and description of the likely analytical procedures that will be carried out with the test data.

QUALITY ASSURANCE

During the first quarter of 1977 the Quality Assurance Plan Index was completed for the SGTI Program. Implementation of the QA Plan Index will help ensure that the work performed will meet high standards of quality and reliability. Systematic and formal quality assurance procedures were developed to monitor technical progress and to ensure the orderly, efficient attainment of project objectives. Areas examined in the QA Plan Index include: project approach and methods; procurement control; inspection, test and work procedures; document control; identification and control of materials, parts and components; control of special processes; calibration of equipment; handling, packaging and shipping; nonconformance reporting; and quality assurance records and audits.

TRIPS

Two trips were made during this reporting period. Trip purpose, participants, and topics discussed are documented in this section.

Review Meeting with NRC at Silver Springs, MD

A review meeting with NRC staff was held at Silver Springs, MD, on March 8, with M. Vagins and W. E. Anderson representing BNW. Progress in hardware development was discussed.

The problem of testing burst tubes for flow rates which simulated actual PWR conditions was outlined. Discussions led to general acceptance of a compromise situation, which permitted bursting in one test facility, then removing specimens to another facility and leak testing.

Other questions regarding availability of different eddy current probes, the need for NRC to define what was intended for the bulging tests, and NRC dissatisfaction with possible use of low-melting alloys as stiffening mandrels during machining were discussed and resolved.

Trips to Combustion Engineering - Chattanooga

M. Vagins, R. A. Clark and J. C. Crowe, with J. Muscara (NRC), visited the Combustion Engineering (CE) Plant in Chattanooga, TN, on March 28 and 29, 1977. Preceding the meeting, the morning of March 28 was spent touring CE's nuclear reactor fabrication facilities and their adjacent high pressure hydraulic laboratory. On the afternoon of March 29, the visit concluded with a tour of the research facilities at Chattanooga. The participating CE people were:

P. R. Habicht, Materials & Chemistry Development, Windsor.
J. K. Hayes, Nuclear Component Engineering, Chattanooga.
W. J. Heilker, Nuclear Component Engineering, Chattanooga.
F. P. Hill, Nuclear Component Engineering, Chattanooga.
W. T. McMinn, Nuclear Component Engineering, Chattanooga.
R. R. Mills, Licensing, Windsor.
J. E. Simmons, Nuclear Component Engineering, Chattanooga.

During the meeting, initial discussions reviewed PNL's 189 to NRC on the Steam Generator Tube Integrity Program. Joe Muscara explained the objectives, need and timing for the program. The CE tube burst test program was then reviewed by Peter Habicht, Bill Heilker, and Jim Hayes who explained their test and analysis procedures. Discussions developed around why certain experiments were run and what dictated the choice of defects placed in the tubes. CE's burst test program was related to a request for a check of tubing viability after several tubes were pulled from the Palisades steam generators. The defects CE placed in their 27 specimens mechanically simulated the worst cases found in the inservice tubing.

The maximum inservice defects found in Palisades tubing were 5/16-inch length wastage; 300° circumferential wastage, and 70% wall wastage. Collapse tests run in 1969 indicated that no loss of tube integrity occurred when defects were less than 80% of wall thickness.

Peter Habicht spoke on CE's artificial defect preparation. He brought representative examples and gave Bob Clark copies of documented experimental techniques used in preparing the samples. He mentioned that both stress

corrosion cracking and intergranular attack have been observed. Intergranular attack appears to have occurred in low crud areas during steam generator lay-up, mainly around upper support plates, while sulfur contamination was blamed for intergranular attack.

PNL personnel discussed their approach in the SGTI program. CE personnel were supportive of tests underway at reactor operating temperatures. They had no adverse comments on the PNL burst/collapse or leak rate tests. They did, however, question the selected PNL fatigue loading conditions. CE considered the thermal-pressure conditions occurring during scrams to be much more important than plant startup and shutdown conditions. Although the magnitude of the scram temperature/pressure variations is less, scrams occur much more frequently. CE believes that the main fatigue-induced cause of failure originates from high frequency tube vibration in the generator.

Finally, Jim Crowe (PNL) presented some of PNL's NDT technique results and ideas. Bob Stone (CE) then commented on CE's field practice and experiences. Discussion ensued on PNL's multifrequency multiparameter eddy current device. In closing, Peter Habicht and Bill Heilker agreed to examine the possibility of providing PNL with some free CE tubing which PNL will test as part of the NRC-SGTI program. This will help accomplish the programmatic goal of comparing tubing at different strength levels.

NONDESTRUCTIVE TESTING

During this reporting period the single-frequency eddy current inspection system (EM 3300, magnetic tape recorder, strip-chart recorder, and probe drive system) was received, checked out and calibrated using existing tube specimens. The EM 3300 eddy current tester required return to the vendor for repair of component failure. It is now functioning and proper operation of the system has been confirmed and documented.

The holding tray of the eddy current inspection system was modified to eliminate interfering signals from portions of the metal tray. Nonconductive phenolic supports were incorporated to hold the tube sections above the metal

tray. This minor modification proved satisfactory. The probe drive system has also been adapted to accept the 10-ft (3-m) tube specimen.

Calibration standards machined to ASME Section XI, Appendix IV specifications will be fabricated for each tube size to be inspected. Formal PNL QA drawings were completed and included in a purchase requisition for fabrication of the eddy current standards. Two 5-ft (1.52-m) specimens of available tubing (0.875 x 0.050 and 0.750 x 0.043) were sent to the offsite vendor for fabrication of the initial two calibration standards. Eddy current examination will begin as soon as the initial tube standards become available.

Procedures were established for the ultrasonic examination of the tubes. This examination will be performed by Exxon Nuclear.

BURST, COLLAPSE AND LEAK RATE FACILITIES

Facilities to conduct all phases of pressure tests were designed, with the exception of a bulge test facility. These facilities include a system to conduct tube burst and collapse tests in a heated autoclave (Figures 1, 2, and 3). Two leak rate test setups have been developed. One allows measurement of leakage from a burst tube into a controlled heated and pressurized environment (Figure 4); the other permits leakage to air (Figure 5). A facility to fatigue steam generator tubes in a manner simulating reactor startup/shutdown was devised (Figure 6). All components for these systems have been purchased or otherwise obtained. Physical assembly of the burst/collapse, leak rate into air, and fatigue assemblies has been initiated. A few needed components having long delivery lead times have not yet arrived, although virtually everything should be on plant by May 15th. The critical items not yet on plant are the data logger recording system and the high temperature flow meter. New controllers for the autoclave have not yet arrived, though some temporary substitution is possible here.

Experimental test development included designing the fatigue test facility shown in Figures 6 and 7. This system will provide independent programmable cycling of tube and shell-side temperatures between 75°F (24°C) and

FIGURE 1. Tubing High Pressure System

FIGURE 2. Autoclave Pressure System

FIGURE 3. Burst and Collapse Test Facility

FIGURE 4. Controlled Secondary-Side Leak Rate Setup

FIGURE 5. Experimental Setup for Leak Rate Tests into Ambient Pressure

FIGURE 6. Fatigue Test Design/Instrumentation - Primary Loop

FIGURE 7. Fatigue Test Design/Instrumentation - Secondary Loop

650°F (340°C) and programmable tube-side pressure control between 0 psig (0 Mpa) and 2500 psig (17.2 Mpa). Thus temperature/pressure cycles simulating reactor startup or scrams can be programmed into the experiment. The system is designed to mimic an actual steam generator to the extent that a thermal gradient across the test specimen is maintained. All heat enters through the tube side and is removed from the shell side. In addition, the leak rate into air experiment was developed this quarter. This system was designed in response to NRC's request to run leakage rate evaluation on all burst tubes. The system will allow a fairly rapid and economical method of determining burst tube leakage rates as a function of ΔP tube to shell side, and will allow flow rates up to 20 gpm ($4.5 \text{ m}^3/\text{sec}$) to be achieved.

Weldable end fittings for tube specimens were obtained; sample tubes were then fabricated and burst in air to judge the effectiveness of the joining technique. Figures 8 and 9 show the tubes before and after bursting. Notice that there was no failure at the end fitting weld and also that failure of the tube was not initiated at the weld. The end fittings are standard high pressure 2000-psia (138 Mpa) line couplings which have been machined for adaptation to each size tube specimen; a weld bead is run around the tube/coupling joint. The free end of the coupling then provides a rugged high pressure fitting which can be tightened into its mating part without damaging the tube specimen.

CORROSION RESEARCH

An early start on the chemical defecting study was achieved this past quarter. The objective of this part of the program is to produce tubing defects via chemical means which simulate actual PWR steam generator tubing flaws. Defects to be produced include pits, locally attacked areas, stress corrosion cracks, intergranularly attacked areas and denting flaws. In most cases the defects will be limited to a small area ($\sim 19 \text{ cm}^2$) of the tubing by masking the major area with tape or heat shrinkable tubing.

E. Denting - Burst

	.875 x .050	.750 x .048	.750 x .043	.625 x .034	Totals
50 mil dent (on diameter)	3	3	3		9
				Total	9

F. Denting Plus Elliptical Wastage - Burst

Table shows number of tests per tube condition.

50 mil dent

Wastage Depth % Wall	Wastage Wrap Angle	.875 x .050 Cutter Radius	.750 x .048 Cutter Radius	.750 x .043 Cutter Radius	.625 x .034 Cutter Radius	Totals
		12	24	12	24	Totals
25-30%	Flat	(1.549)* 2	(1.518)* 2	(1.437)* 2		4
	45°	2	2			4
	135°	2	2			4
55-60%	Flat	(1.624)* 2	(1.591)* 2	(1.506)* 2		4
	45°	2	2			4
	135°	2	2			4
Subtotals		6	4	2	2	
Tube Totals		12	8	4		
					Total	24

*Axial length of wastage.

Twice-Size Sketches - Items F and G

Elliptical wastage and uniform circumferential wastage in proximity to dent nominally 50 mils on the diameter.

Wastage to be simulated first, then denting at a temperature range 575-625°F.

Denting to be targeted for 0.042 on diameter as maximum, to permit passage of eddy-current probe.

G. Denting Plus Uniform Circumferential Thinning - Burst

Table shows number of tests per tube size.

Thinning % Wall	Thinned Length	.875 x .050	.750 x .048	.750 x .043	.625 x .034	Total
25-30%	3/8	2		2		4
	3/4	2	2			4
	1 1/2	2	2			4
55-60%	3/16	2		2		4
	3/8	2		2		4
	3/4	2	2			4
	Totals	12	6	6		24

H. Burst Test Summary

Test Group	.875 x .050	.750 x .048	.750 x .043	.625 x .034	Total
A	27	21	21	21	90
B	18	20	12	14	64
C	12	12	12	12	48
D	22	6	6	0	34
E	3	3	3	0	9
F	12	8	4	0	24
G	12	6	6	0	24
Totals	106	76	64	47	

Total 293

Bulging Tests

The number of bulging specimens has been reduced from 12 to eight. Specimens have 1/2 in. and 1 1/2 in. through-wall slots. Neoprene bladders inside the tubes will be used to allow pressurization of the tubes. A grid will be placed on the specimens using a photo emulsion that does not affect the tube properties. Specimens in ambient air will be pressurized with room temperature water. The pressure will be increased until the bladder either comes through the slot or ruptures. Motion pictures will be taken during tests.

<u>I. Bulging</u>				
	<u>Slot Length</u>	<u>.875 x .050</u>	<u>.750 x .043</u>	<u>Totals</u>
Thru- Wall Slots	1/2	2	2	4
	1 1/2	2	2	4
	Totals	4	4	
Total				8

Collapse Tests -

The slotted tube matrix was modified so that the slot length dimensions agree with those of the burst tests. This is expected to permit improved defect fabrication economics. Reference, no-slot tests were maintained at three replications, but only two at the other conditions. This resulted in a slight reduction in specimen totals, from 63 to 60. This is shown in Table J.

Inclusion of the "wrap around" configurations for elliptical wastage increased the matrix size, but by employing only two replications per condition, the total was kept within reasonable limits--44 as compared to the 27 originally outlined. Ellipse radii dimensions were placed at the same values as for the burst tests to enhance the economic aspects; Table K.

For the elliptical wastage plus through-wall slot, by modifying the slot lengths, a matrix total of 12 specimens was developed, compared with 18 as originally planned, as shown in Table L.

Changing of the 85 to 90% wastage depth in the uniform circumferentially wasted specimens to 75 to 80%, and reduction of the replications produced a plan, as shown in Table M, for collapsing 20 tubes of the one size, compared to 27 per the original scheme.

Summary of the collapse tests is provided in Table N.

J. Slotted Tubes - Collapse

Table shows number of
tests per tube condition.

Slot Depth % Wall	Slot Length	Tube Size				Totals
		.875 x .050	.750 x .048	.750 x .043	.625 x .034	
None	0	3	3	3	3	12
25-30%	1/2	2	2		2	6
	1 1/2	2	2	2	2	8
55-65%	1/4				2	2
	1/2	2	2		2	6
	1 1/2	2	2	2	2	8
85-90%	1/4	2			2	4
	1/2	2	2		2	6
	1 1/2	2	2	2	2	8
	Totals	17	15	9	19	
						Total 60

K. Elliptical Wastage - Collapse

Table shows number of tests
per tube condition.

Max. Depth % Wall	Wastage Wrap Angle	.875 x .050 Cutter Radius			.750 x .048 Cutter Radius			.750 x .043 Cutter Radius			.625 x .034 Cutter Radius			Totals
		6	12	24	6	12	24	6	12	24	6	12	24	
25-30%	Flat			2			2			2			2	8
	45°									2			2	4
	135°			2			2							4
55-60%	Flat		2			2						2		6
	45°					2			2			2		6
	135°		2			2								4
85-90%	Flat	2			2	2		2			2	2		12
Subtotals		2	4	4	2	8	4	2	2	4	2	6	4	
Tube Totals			10			14			8			12		
Total													44	

L. Elliptical Wastage Plus Through Wall Slot - Collapse

<u>Wastage % Wall</u>	<u>Slot Length</u>	<u>.875 x .050 Cutter Radius</u>			
		<u>6</u>	<u>12</u>	<u>24</u>	
25-30%	1/4			(1.549)*	
	1/2			2	
50-60%	1/4			(1.624)*	
	1/2			2	
85-90%	1/4			(1.426)*	
	1/2			2	
Totals		4	4	4	Total 12

*Axial length of major axis of elliptical wastage.

M. Uniform Circumferential Thinning - Collapse

<u>Thinning % Wall</u>	<u>Thinned Length</u>	<u>.875 x .050</u>	
25-30%	3/8	2	
	3/4	2	
	1 1/2	2	
55-60%	3/8	2	
	3/4	2	
	1 1/2	2	
75-80%	3/16	2	
	3/8	2	
	3/4	2	
	1 1/2	2	
			Total 20

N. Collapse Test Summary

<u>Test Group</u>	<u>.875 x .050</u>	<u>.750 x .048</u>	<u>.750 x .043</u>	<u>.625 x .034</u>	<u>Totals</u>
J	17	15	9	19	60
K	10	14	8	12	44
L	12	--	--	--	12
M	20	--	--	--	20
Totals	59	29	17	31	136

Leak Rate Determination

Equilibrium leakage rates on specimens having various combinations of through slots and wastage were calculated to be beyond the capacity of the high pressure pumping system incorporated in the burst/collapse test apparatus. Therefore, two test setups were designed to conduct the leak rate tests. The test setup shown in Figure 5 can be used for leakage into either air or pressurized water or steam. However, since some components of this system are used in the burst and collapse systems, this setup will not be available until the burst and collapse tests have been completed.

Figure 6 illustrates the test apparatus which will produce leak rate data into air only. Under the present phase, this system will be used for the leak rate tests.

In the leak rate experimental setup the tube will be internally pressurized with 600°F water taken from an autoclave which serves as a heated pressurized reservoir and is maintained at 3000 psig through use of He gas overpressure. Pressurization of the tube will be through a pressure reducing and controlling regulator. Leak rates for each tube will be determined at three values of ΔP (internal to external) between 500 and 2500 psig. Leak rates will be defined in terms of flow in the high pressure water system. Maximum capacity is 20 gpm.

Table 0. Through Wall Slots Leak Rate

<u>Wastage % Wall</u>	<u>Slot Length</u>	<u>.875 x .05 Cutter Radius</u>			
		<u>None</u>	<u>12</u>	<u>24</u>	
None	1/4	2			
	1/2	2			
	1	2			
25-30%					(1.549)*
	1/4			2	
	1/2			2	
	1			2	
55-60%			(1.624)*		
	1/4		2		
	1/2		2		
	1		2		
Subtotal		6	6	6	
					Total 18

*Major axis of elliptical wastage.

FIGURE 5. Controllable Secondary-Side System for Leak Rate Tests

FIGURE 6. Open Secondary-Side System for Leak Rate Tests.

P. Leak Rate of Fatigue-Cracked Specimens

(Primary to Secondary)

Tube size 0.875 x 0.050
Specimens One each, tube wasted elliptically about 1 1/2 inches long at 25 to 30 percent and 55 to 60 percent, plus one with no wastage. Superimposed on each tube, an EDM slot 1 inch in length will be cut down to 90 percent of the initial wall thickness. The tubes will then be cyclically fatigued to failure using procedures similar to those outlined for the cyclic fatigue tests.

Starting from 600°F and 2250 psi on both sides, the secondary pressure will be reduced until leakage starts; test continues until tube burst or system flow limit is reached.

Number of tests - Three total.

Q. Summary of Leak Rate Tests

O. Through Wall Slots Leak Rate	18
P. Fatigue Cracked Leak Rate	<u>3</u>
Total	21

In addition to the above, additional leak tests on burst specimens will be done as time and funds permit.

R. Examination of Tube Strength on Burst and Collapse Behavior

Repeat parts shown below for 0.875 x 0.050 tubing from each of two different heats or runs.

Burst Tests	A	12 (Three no slot and nine 1/2 in. slot only).
	B	2 55-60% wastage, flat cut only.
	C	2 55-60% wastage, 1/2 in. slot only.
	D	2 55-60% wastage, 3/8 in. thinned length only.
	E	3 (Dented only).
Collapse	J	17 (Full repetition for tube size).
	K	2 55-60% wastage, flat cut only.
Total		40 Specimens per strength level; two strength levels = 80 specimens.

Cyclic Fatigue

Tubing Size 0.875 x 0.050

Specimens Dented and dented plus elliptical wastage

Experimental Conditions:

ΔT Primary 70-610°F

ΔT Secondary 70-520°F

ΔP Primary 0-2250 psig or 1000-2250 psig

400 cycles/specimen

Heating and pressurization rate for both primary and secondary sides to be mutually determined at a later date by NRC and PNL.

Tests of six samples, three with dents only and three with dents plus elliptical wastage at 55-60% depth with 45° wrap around.

Functional schematics of the fatigue test apparatus are shown in Figures 7 and 8.

Ovality -

A series of collapse tests on tubes with different ovality to examine the significance of this parameter on collapse strength.

12 samples.

Real Defects

During the course of the program, any out of reactor tubing obtained with in-service defects will be tested to provide correlations with the properties of simulated defect tubing. The exact nature of the tests will be governed by the level of radioactivity in the specimens. The level of radioactivity will also determine financial aspects of this part of the program, which have not yet been budgeted.

FIGURE 7. Fatigue Test Design/Instrumentation Primary Loop.

FIGURE 8. Fatigue Test Design/Instrumentation Secondary Loop.

DISCUSSION OF TEST PLAN

Eddy Current Testing Problems

One of the objectives of the program is to obtain typical eddy current inspection data for the various machined defects in the tube specimens and to correlate this data with tube integrity. Conventional eddy current probes and inspection techniques are to be used in these tests (advanced multi-parameter eddy current techniques will be used on a small sampling of the specimens). The eddy current probe design has a significant effect upon the eddy current system response to the different flaw types. In fact, certain machined defects may be difficult to detect using conventional probe designs. Our evaluation of the defect types specified for this program indicates that certain simulated wastage types fall into this category. This limitation must be considered, and defect detection capabilities of the eddy current system must be defined to permit a meaningful interpretation of eddy current test data with likely tube integrity. An example problem follows.

At any given section, through a flaw in the tube, the area which has been removed can be calculated. This is termed A_i . The full cross-section area is termed A_0 . The ratio of A_i/A_0 has been determined for example flaws, and plots are shown in Appendix E. Lack of ECT sensitivity can be visualized as a sloping line on these plots; area changes below the line being undetectable in practice. This limitation may not apply to other probe designs.

It is important to find any other conditions which might be "unseeable" by the field ECT methods and assess the significance of these problems on steam generator safety. The present program is expected to identify some of these conditions.

Tube Pressure Test Problems

The most obvious limitation in pressure testing is that of obtaining satisfactory simulation of flow rates and temperatures. Experimental flow rates near those of service generators will be expensive. Flow rate calculations (Appendix D) are in reasonable agreement with other experience, which emphasizes the problem difficulty. Nonetheless, we believe our test plan is a reasonable and satisfactory compromise of the problem.

The initial program anticipated bursting specimens and then pumping until maximum flow was attained in the high pressure system. After initial analysis, it was determined that equilibrium leak rates in the burst tubes would be substantially greater than available pumping capacity. Thus, the data obtained would have little relevance.

To obtain useful data on equilibrium flow rates through burst tubes, the system diagramed in Figure 6 will be employed; operation of this system has been outlined previously. Though not in the original program cost analysis, this method is preferred to the leak rate test scheme shown in Figure 5. The initial leak rate facility was designed to accommodate a limited number of runs, as originally programmed, and is manpower intensive. The simplified setup shown in Figure 6 provides significant increase of flow rate and will be used for the tests outlined in Table Q.

Cyclic Fatigue

Figures 7 and 8 showed schematics of the experimental setup for this task. The system is designed to have a large degree of correspondence to actual steam generator service. All heat is introduced through the primary side while heat is extracted from the shell side. Primary side (and secondary) temperatures are independently programmable between room temperature and 610°F. Secondary (shell) side pressure is maintained at 1000 psig while primary (tube) side pressure can be programmed to vary between 0 and 2500 psig. The facility will be capable of simulating both scan and startup-shutdown type temperature/pressure variations. The magnitude of the variations programmed in the test will determine the maximum cyclic rate obtainable. A worst-case program will allow approximately four cycles per day.

Test Data Presentation

Thus far, four methods have been identified for displaying and comparing test data. One is a plot of the failure pressure against the defect parameter of primary interest. This may prove best for portraying safety margins in a particular reactor/generator system.

Another method is that presented in Appendix E. Here, the hoop stress at failure is plotted versus the defect parameter. Problems with this method involve decisions whether corrections for ovality, tube stretch with pressure, local thinning of the basic tube, thin or thick-wall formulations, or corrections for diametral increase with thermal expansion should be considered.

The third method of data display is the normalizing scheme which compares the defected tube failure pressure to the undefected tube failure pressure. This ratio effectively removes the problem of deciding which stress calculation to use. The ratio is plotted against the defect parameter, as in the other cases.

A further method will plot the ratio:failure (burst) pressure to design (accident) pressure for varying defect lengths. This presentation has the advantage of providing an immediate assessment of prevailing margin of safety.

Test Specimen and Data Identification

An example manner for assignment and accountability of specimens and resulting data is given in Appendix F.

ANALYSIS PROBLEMS

Analysis of steam generator tubing failures is complicated by several factors: The radius-to-thickness ratio is between thick-wall and thin-wall proportions; consequently, the more elegant theories may not be applicable. The bulk of analysis literature deals with through-wall cracks in pressure structures of the subject proportions; many of the subject tests are with part-through flaws. Very little reference information can be found regarding strength analysis of substantially eroded piping or tubes, as represented by "wastage" in the subject program. No information has been found relating analytical burst strength of defected tubing wherein the entire tube suffers gross plastic deformation before failure. Nor have predicted burst or collapse pressures of dented tubing been located. Yet, the subject program will certainly provide experimental results which fall in each of the above mentioned categories.

It seems unreasonable to expect that any one mode of data presentation will properly display all theoretical or empirical formulations which might be found in the literature or proprietary records. Consequently, we expect that the data should be displayed in at least the four general modes described earlier, and that various versions or interpretations might be attempted. One such method of interpretation is described in Hartzman* although it involves through-wall cracks only; a plot is illustrated in Figure 9.

It must be noted at this point that development of analytical procedures for predicting flawed pressure tube performance is not within the scope of this program, nor is it planned to use computational procedures such as the Finite Element Method (FEM) of mechanics analysis for establishing a prediction rationale. The PNL Structures and Mechanics Section has extensive experience in the application of FEM to structural and mechanics research problems and could use this approach. However, there is neither the time nor budgetary scope for such an analysis procedure in the current program.

* Hartzman, M., "Factors of Safety of Degraded Cylindrical Tubes with Axial Through-Wall Cracks Under Internal Pressure," NRC Mechanical Engineering Branch Memo to J. P. Knight, January 4, 1977.

FIGURE 9. Pressure Difference Versus Critical Slot Length (from Hartzman).

APPENDIX "A"

Ring Tensile Test Apparatus and Procedures

Hardness Testing Apparatus and Procedures

J. M. Alzheimer

G. H. Beeman

RING TENSILE PROCEDURES

Ring tensile tests will be performed using a set of grips designed especially for this purpose. Figure B-1 shows the grips and the loading sequence.

The ring specimens will have specimen identification numbers marked on them. On one end of each ring will be the remnant of the reference drill hole. Diamond pyramid hardness marks may also be present. Before testing, specimen length and wall thickness measurements will be made and recorded along with the specimen identification number. To load the ring specimen into the grips, the half-rounds are inserted into the ring and this assembly inserted into the jaws as shown in the sketch. The ring is centered in the jaws with the remnant of the drill hole up. Tests have shown that the stress concentration due to the drill hole does not cause the ring to fail at the hole if the hole is at the center of the half-round where friction between the ring and half-round reduces the stress in the ring. Tests have also shown that due to the ductile nature of the Inconel, the hardness dents have very little effect on the ultimate strength of the ring, even if the dents are in the unsupported region between the half-rounds. A displacement transducer will be used to measure the elongation of the ring and a 10,000 lb load cell will be used to measure the force. The displacement transducer and load cell will be connected to an X-Y recorder to record load versus displacement curves for each specimen.

FIGURE A-1. Ring Tensile Test Grips.

HARDNESS TEST PROCEDURE

Hardware testing will be done on the Tukon microhardness tester available in the metallurgical labs. Hardness will be measured using the Diamond Pyramid Hardness (DPH) scale and indenter. Hardness values will be measured at two locations on the outer surface of the tube. One axis of the DPH indenter will be parallel to the longitudinal axis of the tube and the other normal to the axis. One hardness measurement will be made at the mid-length on the thinnest section as marked by the remnant of the reference drill hole and the other measurement will be on the same axis but with the tube rotated 180° with respect to the first test. The diagonals of the indentation will be measured with a Filar eyepiece. While the hardness tests are being made, the ring specimen will be supported by steel mandrels as shown in Figure B-2.

Appropriate records will be maintained to permit tracing by specimen number and tube.

FIGURE A-2. Stage for Supporting Ring Specimen
During Hardness Tests

APPENDIX "B"

- Generation of Slots and Wastage; Replications
- Tube Denting Process

J. C. Crowe

E. I. Husa

W. E. Anderson

DESCRIPTION OF SLOT AND WASTAGE GENERATION - REPLICATION

Machined defects are to be placed in most of the steam generator tube specimens to simulate real tube defects such as cracks and wastage or a combination of these. Conventional electro-discharge machining (EDM) techniques will be used to produce narrow (3 to 4 mil) notches of various lengths and depths to simulate cracks within the tube specimens. EDM notches are commonly used to simulate cracks or other defects in tubing for testing and equipment calibration purposes. Vendors have indicated that the EDM machining requirements anticipated for this program can be accomplished using existing equipment and facilities.

Wastage areas will be simulated by two configurations. Uniform circumferential thinning will simulate general wastage around the entire circumference of the tube. Localized wastage will be simulated by producing an elliptically thinned area over a portion of the tube circumference. Several potential methods exist for producing machined defects of this type; however, the technique to be used will be a combination of conventional milling to remove the major portion of material and a final chemical milling to etch away any disturbed surface material, using either:

- 30% H_2O_2 , Reagent Grade (RG) HCl and H_2O in 1-2-2 volumetric proportions; or
- RG HCl, RG HNO_3 and RG $C_2H_4O_2$ in equal volumetric proportions

according to the choice of the flaw fabricator.

All defects will be replicated by a conventional replication technique to confirm proper size, shape and position within the tube. This technique normally entails pouring a replicating fluid over the flaw, allowing the fluid to harden, and removing the hardened layer containing a replica of the flawed region. The dimensions of the replica are then measured and recorded.

One additional tube flaw standard will be required for each tube size. A series of flat bottomed holes and an internal groove will be placed in a

section of each size tubing to permit calibration of the eddy current inspection system as specified in ASME Section XI, Appendix IV. These specimens can be fabricated by conventional machining techniques, preferably by the same vendor that produces the other flaw specimens.

TUBE DENTING PROCESS

- Clean ring and label permanently on one face.
 - Measure and record dimensions of the ring (ID, OD, thickness, shoulder radius)
 - Slip the identified ring on proper tube, locate and secure as required. Plug one end of tube with appropriate stopper (if flawed tube, the end with the flaw) to suppress air circulation, and place assembly in preheat furnace of $550^{\circ}\text{F} \pm 25^{\circ}$.
 - One at a time, the ring/tube assembly is brought to the calibrated tube furnace by carrying with a preheated thrust tube slipped on from unplugged tube end, the recording thermocouple inserted, and all placed inside the furnace. Temperature range for removal to swage operation is (stabilized) 625°F , $+ 25^{\circ}$, -0° , as established from thermocouple chart record.
 - When ready, the complete assembly is taken from tube furnace, located properly. and pushed (by the thrust pipe against the ring) into the rotating swage dies to finish denting process.
 - Upon removal from swage, the assembly is placed on cooling table and covered with aluminum foil; thermocouple and thrust pipe are taken away and the chart record identified.
 - Last three steps are repeated for each tube/ring assembly.
 - Cooled ring/tube assemblies stored and transported in suitable container; stopper removed.
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APPENDIX "C"

Leakage Rate Estimates

J. M. Alzheimer

W. E. Anderson

Assumed slot width = .005"

If the flow is isentropic, solid line curves give a good estimate of the upper limit on flow rate. This assumes that the water is liquid as it flows out of the slot.

If the water in the tube is close to saturation, then some vapor will be produced as the water flows through the slot. From Moody*, predictions of critical flow for liquid-vapor mixtures can be made for various enthalpies. If the water in the pipe is assumed to be saturated liquid, the critical flow would be that marked by dashed lines in the above figure.

It can be seen that the isentropic solution is generally higher than that for critical flow and actual results will depend on how close the water is to saturation in the tube.

*"Maximum Discharge Rate of Liquid-Vapor Mixtures From Vessels," page 3, Figure 1.

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APPENDIX "D"

Preliminary Assessment of Tube Burst Test Plan

(Example Plots Only - Hypothetical Data)

W. E. Anderson

WFO
25 Nov 76
E. Blum

Item II A

Greatest Magnitude of Readily Identified Signal Level Deviation During Lab Eddy Current Test

WFO
25 Nov 76
E. Blum

Hypothetical Results, Elliptically Wasted Tubes, Burst Test Data

Item II C

all 76
5000

Item III

Figure IVC-2

Deep Flow

Figure IVC-3

all 76
5000

Item III

Hypothetical Results, Burst Test Data, Circumferentially Welded Tubes

Figure IVD-1

WFO 76
20 Nov 76

NEUF ALL 13 0000

WFO 76
20 Nov 76

NEUF ALL 13 0000

APPENDIX "E"

Geometric Computations and Plots of
 A_i/A_o for ECT Check

J. M. Alzheimer

W. E. Anderson

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33-6735-20013-721

TABLE IV - ONE									
$h = \frac{OD - t_o}{2}$ $r_m = \frac{OD - t_o}{3}$									
OD	t _o	r _m	h/t _o	h	2W	t _o - h	r _m /t _o	r _m e/t _o - h	
0.875	0.050	0.427	.25	.01250	.2076	.0375			10.83
			.30	.015	.22715	.135			11.57
			.55	.0275	.30533	.02550	.025		17.12
			.60	.0300	.31843	.0200			19.875
			.85	.0425	.3762	.0075			52.16
			.90	.0450	.3865	.0050			78.00
			.25	.0120	.1882	.0360			9.583
			.30	.0144	.20584	.0336			10.232
0.750	0.048	0.351	.55	.0264	.27643	.0216	.7325		15.639
			.60	.0288	.28824	.0192			17.531
			.85	.0408	.3402	.0072			45.916
			.90	.0432	.34948	.0048			69.625
			.25	.01075	.1783	.03225			10.795
			.30	.0129	.1950	.0301			11.530
0.750	0.048	0.35335	.55	.02365	.2621	.01935	.8221		17.659
			.60	.0258	.2734	.0172			19.802
			.85	.03455	.3230	.00645			51.973
			.90	.0367	.3318	.0043			77.709
			.25	.0085	.1448	.0255			11.422
			.30	.0102	.15838	.0238			12.202
0.625	0.034	0.29557	.55	.0187	.2130	.0153	.8691		18.703
			.60	.0204	.2221	.0136			20.978
			.85	.0289	.2625	.0051			55.108
			.90	.0306	.2697	.0034			82.412

62-0738-200

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62-0738-200

01 01 01 01 01

RC	h/c	h	4/2	h/c	24/2	A	1/1
24	85	0.0125	1.42765	0.0125	3.7670	0.0107	0.08308
				0.0125	3.6478	0.0099	0.0751
				0.0125	3.5286	0.0091	0.0672
				0.0125	3.4094	0.0083	0.0593
				0.0125	3.2902	0.0075	0.0514
				0.0125	3.1710	0.0067	0.0435
				0.0125	3.0518	0.0059	0.0356
				0.0125	2.9326	0.0051	0.0277
				0.0125	2.8134	0.0043	0.0198
				0.0125	2.6942	0.0035	0.0119
				0.0125	2.5750	0.0027	0.0040
				0.0125	2.4558	0.0019	0.0000
				0.0125	2.3366	0.0011	0.0000
				0.0125	2.2174	0.0003	0.0000
				0.0125	2.0982	0.0000	0.0000
				0.0125	1.9790	0.0000	0.0000
				0.0125	1.8598	0.0000	0.0000
				0.0125	1.7406	0.0000	0.0000
				0.0125	1.6214	0.0000	0.0000
				0.0125	1.5022	0.0000	0.0000
				0.0125	1.3830	0.0000	0.0000
				0.0125	1.2638	0.0000	0.0000
				0.0125	1.1446	0.0000	0.0000
				0.0125	1.0254	0.0000	0.0000
				0.0125	0.9062	0.0000	0.0000
				0.0125	0.7870	0.0000	0.0000
				0.0125	0.6678	0.0000	0.0000
				0.0125	0.5486	0.0000	0.0000
				0.0125	0.4294	0.0000	0.0000
				0.0125	0.3102	0.0000	0.0000
				0.0125	0.1910	0.0000	0.0000
				0.0125	0.0718	0.0000	0.0000
				0.0125	0.0000	0.0000	0.0000

0.0125

0.0125
Z = 0.05
A = 1.12959

0.0125

0.0125
Z = 0.05
A = 1.12959

RC	h/c	h	4/2	h/c	24/2	A	1/1
8	85	0.0408	0.82852	0.0408	3.4020	0.00936	0.05541
				0.0408	3.2828	0.00851	0.04756
				0.0408	3.1636	0.00766	0.03971
				0.0408	3.0444	0.00681	0.03186
				0.0408	2.9252	0.00596	0.02401
				0.0408	2.8060	0.00511	0.01616
				0.0408	2.6868	0.00426	0.00831
				0.0408	2.5676	0.00341	0.00046
				0.0408	2.4484	0.00256	0.00000
				0.0408	2.3292	0.00171	0.00000
				0.0408	2.2100	0.00086	0.00000
				0.0408	2.0908	0.00001	0.00000
				0.0408	1.9716	0.00000	0.00000
				0.0408	1.8524	0.00000	0.00000
				0.0408	1.7332	0.00000	0.00000
				0.0408	1.6140	0.00000	0.00000
				0.0408	1.4948	0.00000	0.00000
				0.0408	1.3756	0.00000	0.00000
				0.0408	1.2564	0.00000	0.00000
				0.0408	1.1372	0.00000	0.00000
				0.0408	1.0180	0.00000	0.00000
				0.0408	0.8988	0.00000	0.00000
				0.0408	0.7796	0.00000	0.00000
				0.0408	0.6604	0.00000	0.00000
				0.0408	0.5412	0.00000	0.00000
				0.0408	0.4220	0.00000	0.00000
				0.0408	0.3028	0.00000	0.00000
				0.0408	0.1836	0.00000	0.00000
				0.0408	0.0644	0.00000	0.00000
				0.0408	0.0000	0.00000	0.00000

Jan. 1902

P_c	h/c	h	L/c	$L/2$	$h/2$	$2h/c$	A	A_1/A
24	85	0408	1.37823	0	0408	34020	00936	08841
				34971	03824	33002	00851	08036
				64942	03063	24686	00411	05774
				104913	01788	82886	00274	02596
	55	0284	1.12537	0	0284	27642	00490	04629
				28135	02475	26498	00445	04206
				56270	01981	24054	00319	03017
				84404	01156	18492	00143	01350
	75	0120	75885	0	0120	18822	00187	01427
				11971	01125	18234	00137	01296
				36943	00940	16334	00078	00728
				56914	00525	12310	00044	00414

RC	h/c	A	h ₂	h _{1/2}	h ₂	2h ₂	A ₂	A _{1/4}
6	RS	03635	16126	0	03455	32296	00795	08324
				16531	03427	31324	00782	07265
				33063	02743	28158	00519	05433
				49569	01602	11686	00233	02435
55	RS	03365	53220	0	02365	36214	00416	04855
				13305	02207	25708	00378	03957
				26620	01795	22798	00271	02538
				37965	01086	17506	00121	01269
25	RS	01025	35480	0	01425	17830	00178	01942
				08475	01048	17222	00116	01218
				17950	00806	15470	00883	00873
				26925	00471	11844	00037	00390
12	RS	02635	95588	0	03655	32496	00795	05324
				23397	03487	31344	00723	07565
				46794	02743	28158	00519	05433
				70141	01602	11686	00233	02435
55	RS	01365	75302	0	02365	26214	00416	04855
				18826	02217	25408	00378	03957
				37651	01795	22798	00271	02538
				56477	01086	17506	00121	01269
25	RS	01075	50782	0	01075	17830	00118	01342
				12186	01008	17272	00116	01218
				25341	00806	15470	00883	00873
				38087	00471	11844	00037	00390

Jan 14, 1973
JMA

$QD = 0.750$
 $F = 0.043$
 $A = 0.09551$

Rc	h/E	h	L/2	L ² /2	A _i	2A _i	A _i	A _i /A
24	.85	.03455	1.32403					
				0	.03655	.32296	.00795	.08324
				.33101	.03427	.31324	.00722	.07565
				.66202	.02743	.28158	.00519	.05433
				.99302	.01602	.11666	.00233	.02435
.55	.0265	1.06520		0	.02365	.76714	.00416	.04355
				.26630	.02217	.25408	.00398	.03457
				.53260	.01775	.22798	.00271	.02838
				.79890	.01036	.17506	.00121	.01269
.25	.01075	.71825		0	.01025	.17930	.00178	.01342
				.17956	.01009	.17272	.00166	.01288
				.35913	.00896	.15476	.00083	.00873
				.53869	.00471	.11844	.00027	.00398

93 6725 200

Jan 14, 1973
JMA

$QD = .625$
 $F = .034$
 $A = .06313$

Rc	h/E	h	L/2	L ² /2	A _i	2A _i	A _i	A _i /A
6	.85	.0289	.58819					
				0	.02890	.26250	.00511	.08089
				.14705	.02710	.25558	.00464	.07551
				.29409	.02169	.22878	.00333	.05277
				.44114	.01266	.17610	.00149	.02364
.55	.0187	.47384		0	.01870	.21296	.00267	.04231
				.11823	.01753	.20640	.00243	.03844
				.23647	.01403	.18518	.00174	.02756
				.35500	.00819	.14214	.00078	.01232
.25	.0085	.31926		0	.00850	.14478	.00082	.01303
				.07982	.00797	.14024	.00075	.01183
				.15963	.00638	.12560	.00054	.00848
				.23945	.00372	.09616	.00024	.00378
12	.85	.0111	.85232					
				0	.02890	.26250	.00511	.08089
				.20808	.02710	.25558	.00464	.07551
				.41616	.02169	.22878	.00333	.05277
				.62424	.01266	.17610	.00149	.02364
.55	.0187	.66166		0	.01870	.21296	.00267	.04231
				.16742	.01753	.20640	.00243	.03844
				.33483	.01403	.18518	.00174	.02756
				.50225	.00819	.14214	.00078	.01232
.25	.0085	.45169		0	.00850	.14478	.00082	.01303
				.11290	.00797	.14024	.00075	.01183
				.22579	.00638	.12560	.00054	.00848
				.33869	.00372	.09616	.00024	.00378

BC	WK	H	L _{1/2}	L _{1/2}	W ₁	2W ₁	A ₁	A _{1/2}
24	85	0.889	1.17244	0	0.2890	2.2250	0.0511	0.8288
				2.9434	0.2710	2.5558	0.0464	0.7351
				5.8872	0.2169	2.2878	0.0333	1.05277
				8.8308	0.1766	1.7610	0.0149	0.23664
	55	0.187	0.4723	0	0.01870	2.1246	0.0267	0.4251
				23.681	0.1753	2.0640	0.0243	0.3944
				47.362	0.1403	1.8518	0.0174	0.2756
				71.042	0.0819	1.4114	0.0078	0.1832
	35	0.085	0.2869	0	0.0085	1.4478	0.0001	0.0101
				15.967	0.0797	1.4024	0.00075	0.1181
				31.935	0.0638	1.2560	0.0054	0.0948
				47.902	0.0372	0.9416	0.0034	0.0578

[illegible]

BENDING EDGE

314 1 E. E

1-1-102 1-1-102 1-1-102

00/217

APPENDIX "F"

Test Specimen Identification Tables

J. M. Alzheimer

W. E. Anderson

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

F-1

A. SLOTTED TUBES - BURST

SLOT DEPTH (% WALL)	SLOT LENGTH (INCHES)	.875x.050	.750x.048	.750x.043	.625x.034
NONE	0	_____	_____	_____	_____
		_____	_____	_____	_____
		_____	_____	_____	_____
25-30%	1/4	_____	_____	_____	_____
		_____	_____	_____	_____
	1/2	_____	_____	_____	_____
		_____	_____	_____	_____
	1 1/2	_____	_____	_____	_____
		_____	_____	_____	_____
55-60%	1/4	_____	_____	_____	_____
		_____	_____	_____	_____
	1/2	_____	_____	_____	_____
		_____	_____	_____	_____
	1 1/2	_____	_____	_____	_____
		_____	_____	_____	_____
85-90%	1/4	_____	_____	_____	_____
		_____	_____	_____	_____
	1/2	_____	_____	_____	_____
		_____	_____	_____	_____
	1 1/2	_____	_____	_____	_____
		_____	_____	_____	_____
THRU WALL	1/4	_____			

	1/2	_____			

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

B. ELLIPTICAL WASTAGE - BURST

MAX DEPTH (% WALL)	WASTAGE WRAP ANGLE	RC (IN)	.875x.050	.750x.048	.750x.043	.0625x.034
25-30%	FLAT	24	_____	_____	_____	_____
			_____	_____	_____	_____
	45°	24	_____	_____	_____	_____
			_____	_____	_____	_____
	135°	24	_____	_____	_____	_____
			_____	_____	_____	_____
55-60%	FLAT	6		_____		_____
				_____		_____
		12	_____	_____	_____	_____
			_____	_____	_____	_____
	45°	6	_____		_____	
			_____		_____	
		12	_____	_____	_____	_____
			_____	_____	_____	_____
	135°	6	_____	_____		
			_____	_____		
		12	_____	_____		
			_____	_____		
85-90%	FLAT	6	_____	_____	_____	_____
			_____	_____	_____	_____
		12		_____		_____
				_____		_____

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

C. ELLIPTICAL WASTAGE PLUS THRU-WALL SLOT - BURST

MAX DEPTH (% WALL)	SLOT LENGTH (INCHES)	RC (IN)	.875x.050	.750x.048	.750x.043	.625x.034
25-30%	1/4	24				
	1/2	24				
55-60%	1/4	12				
	1/2	12				
85-90%	1/4	6				
	1/2	6				

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

D. UNIFORM CIRCUMFERENTIAL THINNING - BURST

DEPTH (% WALL)	THINNED LENGTH (IN)	.875x.050	.750x.048	.750x.043	.625x.034
25-30%	3/8	_____		_____	
		_____		_____	
	3/4	_____	_____		
		_____	_____		
55-60%	1 1/2	_____	_____		
		_____	_____		
	3/16	_____		_____	
		_____		_____	
	3/8	_____		_____	
		_____		_____	
	3/4	_____	_____		
		_____	_____		
75-80%	1 1/2	_____			

	3/16	_____			

	3/8	_____			

	3/4	_____			

	1 1/2	_____			

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

E. DENTING - BURST

50 mil dent

.875x.050 .750x.048 .750x.043 .625x.034

F. DENTING PLUS ELLIPTICAL WASTAGE - BURST

50 mil dent

MAX WASTAGE (% WALL)	WASTAGE WRAP ANGLE	RC (IN)
-------------------------	-----------------------	------------

25-30%

FLAT

24

45°

24

135°

24

55-60%

FLAT

12

45°

12

135°

12

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

G. DENTING PLUS UNIFORM THINNING - BURST

THINNING (% WALL)	THINNED LENGTH (INCHES)	.875x.050	.750x.048	.750x.043	.625x.034
25-30%	3/8	_____		_____	
		_____		_____	
	3/4	_____	_____		
		_____	_____		
	1 1/2	_____	_____		
		_____	_____		
55-60%	3/16	_____		_____	
		_____		_____	
	3/8	_____		_____	
		_____		_____	
	3/4	_____	_____		
		_____	_____		

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

I. THRU WALL SLOTS - BULGING

SLOT LENGTH (INCHES)	.875x.050	.750x.048	.750x.043	.625x.034
-------------------------	-----------	-----------	-----------	-----------

1/2

1 1/2

J. SLOTTED TUBES - COLLAPSE

SLOT DEPTH
(% WALL)SLOT LENGTH
(INCHES)

NONE

0

25-30%

1/2

1 1/2

55-60%

1/4

1/2

1 1/2

85-90%

1/4

1/2

1 1/2

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

K. ELLIPTICAL WASTAGE - COLLAPSE

MAX DEPTH (% WALL)	WASTAGE WRAP ANGLE	RC (IN)	.875x.050	.750x.048	.750x.043	.625x.034
25-30%	FLAT	24	_____	_____	_____	_____
			_____	_____	_____	_____
	45°	24			_____	_____
					_____	_____
	135°	24	_____	_____		
			_____	_____		
55-60%	FLAT	12	_____	_____		_____
			_____	_____		_____
	45°	12		_____	_____	_____
				_____	_____	_____
	135°	12	_____	_____		
			_____	_____		
85-90%	FLAT	6	_____	_____	_____	_____
			_____	_____	_____	_____
		12		_____		_____
				_____		_____

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

L. ELLIPTICAL WASTAGE PLUS THRU WALL SLOT - COLLAPSE

WASTAGE (% WALL)	SLOT LENGTH (INCHES)	RC (IN)	.875x.050	.750x.048	.750x.043	.625x.034
25-30%	1/4	24	_____	_____	_____	_____
	1/2	24	_____	_____	_____	_____
55-60%	1/4	12	_____	_____	_____	_____
	1/2	12	_____	_____	_____	_____
85-90%	1/4	6	_____	_____	_____	_____
	1/2	6	_____	_____	_____	_____

STEAM GENERATOR TUBE INTEGRITY TUBE SPECIMEN ASSIGNMENT SHEET

M. UNIFORM THINNING - COLLAPSE

THINNING (% WALL)	THINNED LENGTH (INCHES)	.875x.050	.750x.048	.750x.043	.625x.034
25-30%	3/8	_____	_____	_____	_____
		_____	_____	_____	_____
	3/4	_____	_____	_____	_____
		_____	_____	_____	_____
	1 1/2	_____	_____	_____	_____
		_____	_____	_____	_____
55-60%	3/8	_____	_____	_____	_____
		_____	_____	_____	_____
	3/4	_____	_____	_____	_____
		_____	_____	_____	_____
	1 1/2	_____	_____	_____	_____
		_____	_____	_____	_____
75-80%	3/16	_____	_____	_____	_____
		_____	_____	_____	_____
	3/8	_____	_____	_____	_____
		_____	_____	_____	_____
	3/4	_____	_____	_____	_____
		_____	_____	_____	_____
	1 1/2	_____	_____	_____	_____
		_____	_____	_____	_____

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

O. THRU WALL SLOT - LEAK RATE

WASTAGE (% WALL)	SLOT LENGHT (INCHES)	RC (IN)	.875x.050	.750x.048	.750x.043	.625x.034
NONE	1/4	-	_____	_____	_____	_____
	1/2	-	_____	_____	_____	_____
	1	-	_____	_____	_____	_____
25-30%	1/4	24	_____	_____	_____	_____
	1/2	24	_____	_____	_____	_____
	1	24	_____	_____	_____	_____
55-60%	1/4	12	_____	_____	_____	_____
	1/2	12	_____	_____	_____	_____
	1	12	_____	_____	_____	_____

P. FATIGUE CRACKED - LEAK RATE

WASTAGE (% WALL)	SLOT LENGHT (INCHES)	
NONE	1	_____
25-30%	1	_____
55-60%	1	_____

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

VARIOUS STRENGTH LEVELS - BURST

	.875x.050 EXTRA STRENGTH	.875x.050 ANNEALED
NO SLOT	_____	_____
	_____	_____
	_____	_____
25-30% 1/2"	_____	_____
	_____	_____
55-60% 1/2"	_____	_____
	_____	_____
85-90% 1/2"	_____	_____
	_____	_____
THRU WALL 1/2"	_____	_____
	_____	_____
ELLIPTICAL WASTAGE	_____	_____
	_____	_____
55-60% FLAT CUT 12" RADIUS	_____	_____
	_____	_____
ELLIPTICAL WASTAGE PLUS THRU WALL SLOT		
55-60% 1/2" SLOT	_____	_____
	_____	_____
UNIFORM THINNING		
55-60% 3/8"	_____	_____
	_____	_____
DENTING	_____	_____
	_____	_____
	_____	_____

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

VARIOUS STRENGTH LEVELS - COLLAPSE

SLOT DEPTH SLOT LENGTH (% WALL) (INCHES)		.875x.050 EXTRA STRENGTH	.875x.050 ANNEALED
NONE	0	_____	_____
		_____	_____
		_____	_____
25-30%	1/2	_____	_____
		_____	_____
	1 1/2	_____	_____
		_____	_____
55-60%	1/2	_____	_____
		_____	_____
	1 1/2	_____	_____
		_____	_____
85-90%	1/4	_____	_____
		_____	_____
	1/2	_____	_____
		_____	_____
	1 1/2	_____	_____
		_____	_____
ELLIPTICAL WASTAGE			
55-60%	FLAT CUT	_____	_____
		_____	_____

STEAM GENERATOR TUBE INTEGRITY SPECIMEN ASSIGNMENT SHEET

CYCLIC FATIGUE

.875x.050

DENTING ONLY

DENTING PLUS ELLIPTICAL
WASTAGE AT 55-60% DEPTH
AND 45° WRAP ANGLE

OVALITY