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Steam Generator Tube Integrity Program Phase I Report

Prepared by J. M. Alzheimer, R. A. Clark, C. J. Morris, M. Vagins

Battelle-Pacific Northwest Laboratory

Prepared for
U. S. Nuclear Regulatory
Commission

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STEAM GENERATOR TUBE INTEGRITY PROGRAM
PHASE I REPORT

J. M. Alzheimer
R. A. Clark
C. J. Morris
M. Vagins

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Pacific Northwest Laboratory
Richland, Washington 99352

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SUMMARY

This report presents the results of the pressure tests performed as part of Phase I of the Steam Generator Tube Integrity (SGTI) program at Battelle Pacific Northwest Laboratory. This program is sponsored by the Metallurgy and Materials Branch, Reactor Safety Research Division of the Nuclear Regulatory Commission (NRC). These tests were performed to establish margin-to-failure predictions for mechanically defected Pressurized Water Reactor (PWR) steam generator tubing under operating and accident conditions.

Defect geometries tested were selected because they simulate known or expected defects in PWR steam generators. These defect geometries are Electric Discharge Machining (EDM) slots, elliptical wastage, elliptical wastage plus through-wall slot, uniform thinning, denting, denting plus uniform thinning, and denting plus elliptical wastage. All defects were placed in tubing representative of that currently used in PWR steam generators.

Burst and collapse tests were conducted in simulated PWR steam generator chemical and thermal environments in a high pressure autoclave assembly.

Data from the tests are presented and described. Plots of the data are presented along with tabular listings. Data trends are discussed. Empirical relationships for predicting the burst pressures of defected tubing are established and presented.

Due to the very high burst pressure of undefected steam generator tubing, even tubing with fairly large defects had burst pressures higher than could occur during the worst credible burst mode accident. Typically, defects which were less than 80% through the wall thickness had burst pressures higher than would be experienced during such accident conditions.

All of the collapse pressures of the defected tubing specimens were higher than would occur during the worst credible collapse mode accident.

The eddy current tests showed that the single-frequency eddy-current techniques presently in general use did not accurately characterize many of the machined defect geometries. However, it was also shown that current plugging practices are conservative from the viewpoint of margins-to-failure for the machined defects studied.

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SGTI COLLAPSE TEST DATA	DEFECT TYPE: <u>EDM Slots</u> TUBE SIZE: <u>0.625 x 0.034</u>	.	.	.	.	.	D.18
SGTI COLLAPSE TEST DATA	DEFECT TYPE: <u>Elliptical Wastage</u> TUBE SIZE: <u>0.875 x 0.050</u>	.	.	.	.	.	D.19
SGTI COLLAPSE TEST DATA	DEFECT TYPE: <u>Elliptical Wastage</u> TUBE SIZE: <u>0.750 x 0.043</u>	.	.	.	.	.	D.19
SGTI COLLAPSE TEST DATA	DEFECT TYPE: <u>Elliptical Wastage</u> TUBE SIZE: <u>0.750 x 0.050</u>	.	.	.	.	.	D.20
SGTI COLLAPSE TEST DATA	DEFECT TYPE: <u>Elliptical Wastage</u> TUBE SIZE: <u>0.875 x 0.050</u>	.	.	.	.	.	D.20
SGTI COLLAPSE TEST DATA	DEFECT TYPE: <u>Elliptical Wastage</u> TUBE SIZE: <u>0.875 x 0.050</u>	.	.	.	.	.	D.21

APPENDIX TABLES (contd)

SGTI COLLAPSE TEST DATA	DEFECT TYPE: <u>Elliptical Wastage</u>	TUBE SIZE: <u>0.625 x D.034</u>	.	.	.	D.21
SGTI COLLAPSE TEST DATA	DEFECT TYPE: <u>Uniform Thinning</u>	TUBE SIZE: <u>0.875 x 0.050</u>	.	.	.	D.22
F	Phase I - SGTI Program Eddy-Current Data (EDM Slot, Uniform Thinning, Elliptical Wastage)	.	.	.	.	F.1
F-1	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat B, Burst, Bulge, Leak, Fatigue Cracked)	.	.	.	.	F.2
F-2	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat C, Burst, Bulge)	.	.	.	.	F.2
F-3	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat D, Burst)	.	.	.	.	F.3
F-4	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heats E and F, Burst)	.	.	.	.	F.4
F-5	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat G, Burst)	.	.	.	.	F.5
F-6	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat B, Collapse)	.	.	.	.	F.6
F-7	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heats C and D, Collapse)	.	.	.	.	F.7
F-8	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heats E and F, Collapse)	.	.	.	.	F.8
F-9	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat G, Collapse)	.	.	.	.	F.9
F-10	Phase I - SGTI Program Eddy-Current Data Uniform Thinning (Heat B, Burst)	.	.	.	.	F.10
F-11	Phase I - SGTI Program Eddy-Current Data Uniform Thinning (Heat B, Collapse)	.	.	.	.	F.11
F-12	Phase I - SGTI Program Eddy-Current Data Uniform Thinning (Heats C, D, E, and F, Burst)	.	.	.	.	F.12
F-13	Phase I - SGTI Program Eddy-Current Data Elliptical Wastage (Heat B, Burst)	.	.	.	.	F.13

APPENDIX TABLES (contd)

F-14	Phase I - SGTI Program Eddy-Current Data Elliptical Wastage (Heat C, Burst)	F.14
F-15	Phase I - SGTI Program Eddy-Current Data Elliptical Wastage (Heat D, Burst)	F.15
F-16	Phase I - SGTI Program Eddy-Current Data Elliptical Wastage (Heats G, E and F, Burst)	F.16
F-17	Phase I - SGTI Program Eddy-Current Data Elliptical Wastage (Heats B, C and D, Collapse).	F.17
F-18	Phase I - SGTI Program Eddy-Current Data Elliptical Wastage (Heats E, F and G, Collapse).	F.18
F-19	Phase I - SGTI Program Eddy-Current Data Elliptical Wastage Plus EDM Slot (Heats B, C and D, Burst)	F.19
F-20	Phase I - SGTI Program Eddy-Current Data Elliptical Wastage Plus EDM Slot (Heats E, F and G)	F.20
F-21	Phase I - SGTI Program Eddy-Current Data Elliptical Wastage Plus EDM Slot (Heat B)	F.21
G	Phase I - SGTI Program Eddy-Current Data (Denting, Denting Plus Elliptical Wastage, Denting Plus Uniform Thinning)	G.1
G-1	Phase I - SGTI Program Eddy-Current Data Denting (Heats B, C, D, E, and F, Burst)	G.1
G-2	Phase I - SGTI Program Eddy-Current Data Denting Plus Elliptical Wastage (Heats B, C, and D, Burst)	G.2
G-3	Phase I - SGTI Program Eddy-Current Data Denting Plus Uniform Thinning (Heats B, C, and D, Burst)	G.3
H	Phase I - SGTI Program Eddy-Current Data, ECT Defect Length Measurement Data (EDM Slots, Uniform Thinning, Elliptical Wastage)	H.1
H-1	Phase I - SGTI Program Eddy-Current Defect Length Data Uniform Thinning (Heat B, Burst)	H.1
H-2	Phase I - SGTI Program Eddy-Current Defect Length Data Uniform Thinning (Heat B, Collapse)	H.2

APPENDIX TABLES (contd)

H-3	Phase I - SGTI Program Eddy-Current Data EDM Slots Heat B, Burst, Bulge, Leak, Fatigue Cracked)	.	.	.	.	.	H.3
H-4	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat G, Burst)	.	.	.	.	.	H.4
H-5	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat B, Collapse)	.	.	.	.	.	H.5
H-6	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heats C and D, Collapse)	.	.	.	.	.	H.6
H-7	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heats E and F, Collapse)	.	.	.	.	.	H.7
H-8	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat G, Collapse)	.	.	.	.	.	H.8
H-9	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heats E and F, Burst)	.	.	.	.	.	H.9
H-10	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat D, Burst)	.	.	.	.	.	H.10
H-11	Phase I - SGTI Program Eddy-Current Data EDM Slots (Heat C, Burst, Bulge)	.	.	.	.	.	H.11

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 PWR steam generators tubing. This program is called the Steam Generator Tube Integrity (SGTI) Program and is sponsored by the Metallurgy and Materials Branch, Reactor Safety Research Division of NRC. The NRC program manager is Dr. Joseph Muscara.

Justification for the SGTI program stems from a need for substantial data upon which to base licensing decisions. The available data were limited in quantity and had been generated by steam generator vendors. The data had not been developed in simulated PWR environments. Inconsistencies in the available data made their credibility questionable. There is a need for more reliable data to allow meaningful interpretation of the results of in-service inspections.

The main objective of the Steam Generator Tube Integrity program is to establish a large data base to assist NRC in its licensing duties as regards PWR steam generators. The two main areas of investigation are assessment of the single-frequency eddy-current inspection method and the behavior of defected steam generator tubing under various pressure test conditions. The single-frequency eddy-current method is the currently accepted in-service inspection (ISI) method for examining and qualifying PWR steam generator tubing. The pressure tests conducted on the defected tubing include burst, collapse, leak rate and cyclic fatigue tests. All defected specimens used for the pressure tests were inspected using the single-frequency eddy-current method. In this way, not only could the pressure test results be compared to the actual defect geometries, but they could also be compared to the results of the single-frequency eddy-current inspections. Margin-to-failure predictions for defected tubing could then be established based both on actual defect geometries and in-service inspection indications.

Each of the first three phases of the Steam Generator Tube Integrity Program is concerned with the examination of tubing defected by different

methods. Phase I is concerned with tubing with machined defects. Phase II is concerned with tubing with chemically induced defects. Phase III will be concerned with tubing taken from actual PWR steam generators that have defects caused by in-service conditions.

The steam generator is a heat exchanger placed between primary and secondary cooling systems to isolate the primary coolant which contacts radioactive components in the reactor. It consists of a pressure vessel enclosing several thousand tubes carrying pressurized primary coolant. These are bathed in secondary or feed water which is thereby heated and converted to steam.

Design and analysis of steam generators in the U.S. is performed in accordance with ASME Boiler & Pressure Vessel Code (B&VP), Section III. In many places, NRC regulatory guides refer to Section III and/or the ANSI standards covering nuclear power plants. All power plant components, including steam generators, are required to be designed to withstand various accident situations. For steam generators these consist of the following:

- LOCA (Loss of Coolant Accident)
- MSLB (Main Steam Line Break)
- SSE (Safe Shutdown Earthquake)

LOCA and SSE are usually combined with design pressure for any accident analysis.

To date, several types of difficulties with PWR steam generators have been encountered. In a large majority of cases, these difficulties may be attributed to water treatment problems. Certain water chemistries of the secondary coolant may be corrosive to the tubing and lead to severe degradation by stress corrosion cracking (SCC), and localized tube wall thinning (wastage).

Caustic agents may be carried into the steam generator from feed water or they may be formed there. These agents are blamed for SCC. Wastage is usually found when a coordinated phosphate water treatment (CPT) is used, and in some cases after the changeover to an all volatile treatment (AVT) has been

instigated. In the latter case, wastage has been attributed to remnants of acidic phosphates not removed by blowdown.

In both types of corrosion, regions of low flow and high heat flux are most susceptible, since these regions develop concentrations of impurities or precipitation of phosphates. Most likely spots are crevices (tube-support-plate/tube annulus), re-entrant corners or where sludge deposits form (top of tube sheet or tube support plates). Both SCC and wastage occur at these locations.

As a result of the changeover from phosphate water treatment to AVT, another problem has been observed in certain PWR steam generators. After such change to AVT, chlorides which appear due to condenser cooling water in-leakage cause corrosion of the carbon steel tube support. The corrosion product expands volumetrically and exerts sufficient force on the tubes to reduce their diameters, thereby denting the tube locally.⁽¹⁾

The currently accepted method of in-service inspection of the PWR steam generators is the single-frequency eddy-current testing technique. Regulatory Guide 1.83, "In-service Inspection of Pressurized Water Reactor Steam Generator Tubes," describes an acceptable method for establishing a program for in-service inspection. The test procedures of Section XI, Appendix IV of the ASME B&PV Code are representative of most in-service inspections performed in the field today. Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes," describes an acceptable method for establishing plugging criteria for defective PWR steam generator tubing. To implement Regulatory Guide 1.121, the behavior of defective PWR steam generator tubing under normal operating and postulated accident conditions must be known. The purpose of performing the pressure tests during Phase I of this program was to establish this behavior for a selected number of mechanically induced defects. The pressure tests include burst, collapse, bulging, leak rate and cyclic fatigue tests. Also, to assist in the implementation of Regulatory Guide 1.83, all mechanically defected tubes were examined using the single-frequency eddy-current technique. In this way the results of the eddy-current inspections can be correlated with the pressure test data to give a better assessment of the current plugging criteria.

Since the scope of Phase II of this program is to examine tubing with defects that are produced by chemical means, a feasibility study was performed during Phase I to establish methods for chemically defecting the tubing. Types of chemical defects of interest were stress corrosion cracking, intergranular attack, pitting, general wastage and denting.

This report discusses the Phase I burst, collapse, leak rate, bulging and eddy-current tests. Burst tests were run to allow margin-to-failure predictions for defected tubing under operating and burst mode accident conditions. Normal operating conditions in a steam generator vary from one facility to another, but typically the temperatures fall within the range of 500°F to 650°F, with a primary loop pressure of 1500 psig to 2400 psig. A secondary loop pressure of 1000 psig is typical. During a main steam line break (MSLB) the secondary pressure could drop to almost zero, resulting in an internal pressure differential approximately equal to the primary loop operating pressure. This is the worst credible burst mode accident for the steam generator tubing. Collapse tests were run to allow margin-to-failure predictions for defected tubing under collapse mode accident conditions. During a loss of coolant accident (LOCA), the primary pressure could theoretically drop to almost zero resulting in an external pressure differential approximately equal to the secondary loop operating pressure. This is the worst credible collapse mode accident for the steam generator tubing. These were the conditions for which margin-to-safety predictions were desired. To this end, the report presents the results of the various tests carried out during Phase I. First, the results of the burst, collapse, leak rate, bulging and cyclic fatigue tests are presented. Next, the eddy-current inspections are discussed. Correlations between the eddy-current readings and the burst and collapse data are made.

PRESSURE TESTS

TUBING MATERIAL

All tubing used in the Steam Generator Tube Integrity program was Inconel 600 representative of that currently in use in PWR steam generators. All Phase I and II tubing was acquired from the Blairsville, Pennsylvania, Westinghouse facility and fabricated to current (1976) Westinghouse specifications. Four sizes of tubing were examined: 0.875 in. x 0.050 in., 0.750 x 0.050 in., 0.750 in. x 0.043 in., and 0.625 in. x 0.034 in. All tubing of one size, with one exception, was fabricated from the same heat of metal and process runs. Three different heats of the 0.875 in. x 0.050 in. tube sizes which had different strength (yield and ultimate) levels were acquired. All tubing was received in 10-foot-long sections. Material specifications for the four sizes of tubing are listed in Table 1. In addition to the listed specifications, ultrasonic, hydrostatic and eddy-current tests were run on each tube.

BASELINE EXAMINATIONS

Upon arrival of each heat of tubing, identification numbers were engraved on each 10-foot-long tube, and baseline ultrasonic and eddy-current inspections were performed on all tubes. The ultrasonic inspection consisted of a detailed survey of each tube. The test procedure is listed in Appendix A. A helical scan of the entire length of each tube was performed on the "as received" tubing. In addition, a complete survey was made of the entire tube circumference at locations where defects were to be placed in the tubes. At each of these locations, maximum and minimum ID, OD and wall thickness, ID and OD ovality and eccentricity were measured and recorded. In addition, the raw ultrasonic data for the entire tube were recorded on a strip chart for further reference. Locations of minimum wall thicknesses were marked on the tubes for defect placement.

Baseline eddy-current inspections were performed on all 10-foot-long tubes. The single-frequency eddy-current examination was performed according to the Summer 1976 Addenda of the ASME Boiler and Pressure Vessel Code, Section XI, Appendix IV Inspection Requirements.

TABLE 1. Inconel 600 Material Specifications

<u>Tubing Size</u>	<u>C</u>	<u>Mn</u>	<u>Fe</u>	<u>S</u>	<u>Si</u>	<u>Ca</u>	<u>Ni</u>	<u>Cr</u>	<u>Al</u>	<u>Ti</u>	<u>Co</u>	<u>Ultimate Strength (ksi)</u>	<u>Yield Strength (ksi)</u>	<u>Elongation (%)</u>	<u>Hardness (R_B)</u>
0.875 x 0.050	0.01	0.19	8.57	0.004	0.05	0.35	76.14	14.69	0.25	0.22	0.04	94	49	45.0	80
0.750 x 0.050	0.02	0.31	9.30	0.007	0.15	0.27	75.08	14.86	0.20	0.26	0.04	98	49	40.0	82
0.750 x 0.043	0.02	0.16	8.82	0.001	0.20	0.29	75.00	15.51	0.29	0.26	0.03	97	51	43.5	82
0.625 x 0.034	0.03	0.26	9.23	0.003	0.08	0.38	75.12	14.90	0.11	0.14	0.03	97	49	49.0	82

Upon completion of the baseline examinations, tubes were chosen to be used as specimens. To insure that specimens were as uniform as possible before they were machined only tubes that had given no abnormal indications in either the baseline ultrasonic or eddy current inspections were used. Each 10-foot-long tube was cut into 10 specimens, each of which had an identification number engraved on it. This identification number contained information specifying the heat, tube and tube location from which the specimen came. Reference drill holes were placed in the tube ends and the relationship of each specimen's minimum wall thickness mark to the reference hole recorded. A one-inch-long ring specimen was removed from each specimen that was to be defectected. The ring specimens, which also had the identification numbers engraved on them, were used for hardness and ring tensile tests. Five specimens from each heat were selected for ASTM tube tensile tests. Results of hardness, ring tensile and ASTM tube tensile results are included in Appendix A.

DEFECT GEOMETRIES

Seven basic defects were used in Phase I. These geometries simulate known or expected defects in PWR steam generators. These defect geometries are Electro Discharge Machining (EDM) slot, elliptical wastage, elliptical wastages plus through-wall EDM slot, uniform thinning, denting, denting plus elliptical wastage, and denting plus uniform thinning.

The uniform thinning defect, as shown in Figure 1, was selected to represent a general wastage type of defect. This defect was machined on a lathe.

FIGURE 1. Geometry of Uniform Wastage Specimen

During machining the inside of the tube was supported so that no deformation of the inside surface could occur. Defect lengths of 3/16 in., 3/8 in., 3/4 in., and 1 1/2 in. were tested. Depths were 25-30%, 55-60% and 75-80%. The end radius was nominally 1/16 in. After machining, all uniform thinning defects were etched to remove any surface cold working effects and were replicated with a silicone rubber.

The elliptical wastage defect, as shown in Figure 2, was machined using a specially-made cutter. The defect geometry is entirely defined by the radius of the cutter, the depth of defect and the wrap angle. The elliptical wastage defect was selected as a representation of a wastage type of defect that might occur, for instance, near a tube support sheet. The depths of the elliptical wastage defects were in the range of 25-30%, 55-60% and 85-90%. Wrap angles of 0° , 45° , and 135° were tested. Cutter radii of 6 in., 12 in., and 24 in. were used. The selection of the appropriate combination of cutter radius and defect depth produced defect lengths of approximately 1 1/2 in. After each elliptical wastage defect was machined, the surface was etched to remove any

FIGURE 2. Geometry of Elliptical Wastage Specimen

surface effects of cold work. All elliptical wastage defects were also replicated using the silicone rubber.

The original burst and collapse test matrix included elliptical wastage plus through wall EDM slot defects, as shown in Figure 3. However, the pressure test facility was not capable of maintaining pressure on through-wall defects and this type of defect was not burst or collapsed.

EDM slots were selected as the best simulation of a tight crack available by mechanical methods. This defect geometry is shown in Figure 4. Lengths of the slots tested were 1/4 in., 1/2 in., and 1 1/2 in. Depths of slots were specified to be in the range of 25-30%, 55-60% and 85-90%. Due to the nature of the EDM process, maintaining extremely close tolerances would have been very expensive. Therefore, the tolerances were made reasonable and emphasis was placed on replicating the as-machined dimensions accurately. Replication of all defects was with a special silicon rubber. In this way the effects of defect geometry could be examined without adding unneeded machining costs.. Maximum width of the slots varied from 0.003 in. to 0.010 in. The end radius was nominally 0.01 in. to 0.02 in. The EDM process produced slots which were

FIGURE 3. Elliptical Wastage Plus Through-Wall Slot Defect Geometry

FIGURE 4. Geometry of Electro-Discharge Machining (EDM) Slot Specimens

wider at the top and narrowest at the root. Generally, the deeper the EDM slot, the wider the slot top. Several of the slots, notably the longer ones, had varying slot widths along their length. These variations should have had very little effect upon the burst and collapse test results. Some of the slots also had varying slot depths along their length. These variations were typically 0.001 in. to 0.003 in. for the worst specimens. These variations probably had effects on the burst results and may be responsible for some of the data scatter present.

One major problem in some PWR steam generators is the denting of the tubes at the tube support sheets. The denting in these cases is a result of the changeover from phosphate water treatment to all volatile treatment (AVT). The presence of residual phosphates (after changing to AVT) in the tube/tube support annulus and chloride, which appears due to condenser cooling water in-leakage, causes corrosion of the carbon steel tube support. The resultant corrosion products have sufficient volume to exert pressure on the tubes to reduce their diameters, thereby denting the tube locally. The use of a carbon steel ring hot-swaged onto the tube was used to simulate the denting, as shown

in Figure 5. The thickness of the ring was $3/4$ in. to simulate the thickness of the tube support sheet, and nominal denting depth was 0.04 in. to 0.05 in.

To investigate the effects of defects in the tube wall near a dent, denting plus elliptical wastage defects and denting plus uniform thinning defects were produced by first machining the defect and then swaging a denting ring approximately 0.05 in. from the end of the machined defect. These combinations of defects were selected to represent defects near the tube support sheets.

A defect fabrication information sheet was prepared for each type of defect. Samples of these are shown in Appendix B. Included on these sheets are specimen number, all defect dimensions, allowable tolerance and location of the defect in relation to the reference drill hole. These information sheets were used by the machinist in defect preparation. They form an integral part of the quality assurance program for this project. Also included on these sheets are spaces for defect dimension replication, pre-test check and eddy-current record number. One defect fabrication information sheet was prepared for each specimen and sent to the vendor along with the specimen for defect preparation.

FIGURE 5. Geometry of Denting Specimens

Baseline tube characterization data sheets were also prepared. These contained the mid-section dimensions of the undefected tube. These data were obtained from the baseline ultrasonic inspections. Also included on this sheet are places for ultrasonic scan record number, baseline ECT number, hardness and ring tensile data. A copy of a baseline tube characterization sheet is included in Appendix B.

After the machined specimens were returned from the vendor, spot checks were made of defect dimensions. Single-frequency eddy-current examination of all defected specimens was performed using the same methods used for the baseline eddy-current test (ECT).

END FITTINGS

After the defects had been eddy-current inspected, end fittings were welded on each tube specimen. For the burst, bulging and leak rate specimens, a plug made of 304 stainless steel was welded to one end and a modified high pressure coupling made of 316 stainless steel was welded to the other end. The free end of the coupling provided a rugged high pressure fitting which could be tightened without damage to the tube specimen. Preliminary tests were conducted to assess the effects of end fittings on the burst results. It was determined that for an eleven-inch-long specimen with the defect in the middle of the tube, effects of the end fittings were negligible. None of the burst specimens failed at the end fitting or welded area. For the collapse specimens, a plug made of 304 stainless steel was welded to each end of the tube. One of these plugs was solid, while the other had a hole into which a length of high pressure tubing was welded. The length of high pressure tubing was used for connecting to a high pressure line in the autoclave assembly.

BURST AND COLLAPSE TEST SET-UP

Burst and collapse tests were conducted in an autoclave assembly as outlined in Figures 6, 7 and 8. Pressurization of both the tube (or primary side) and autoclave (or secondary side) was with water chemically simulating PWR steam generator feed water. (See Table 2.) Initial water supply was

FIGURE 6. Secondary High Pressure System for Burst Tests

treated by condensing on-plant steam, then running through an anion-cation exchange resin bed.

During burst testing, the autoclave and its load of tubes was simultaneously pressurized to 2250 psig with water. The system was held at this pressure as the temperature was increased to 600°F and held until thermal stability of the specimens was achieved. Following this, the pressure of the secondary side was reduced to 1000 psig. At this time the specimen was in an environment having the same temperature, pressures and water chemistry as in a typical PWR steam generator. The water on the primary side was in the liquid

TABLE 2. Water Chemistry

Total base H ₂ O conductivity	<10 mho/cm ^(a)
Hydrazine (for O ₂ control)	95-105 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.

FIGURE 7. Burst Facility

FIGURE 8. Collapse Test Set-Up

state, and the water on the secondary side was in the vapor state. Each specimen in turn was internally pressurized at a rate of 1000 to 2000 psi/min to failure.

For specimens with defects of greater than 80% depth, the secondary side pressure was not dropped to 1000 psi before the primary side pressure was increased. For some of these defects the burst pressures were lower than normal operating pressure differential and the exact failure pressure would have been lost since failure would have occurred during depressurization of the secondary side. This means that these specimens were burst with liquid water on both the primary and secondary sides instead of steam on the secondary side. However, it was not felt that the phase state of the water on the secondary side would have a significant effect on the burst pressure. A copy of the Burst Test Standard Operating Procedure is included in Appendix C.

During collapse testing, the specimen is inside of a high pressure bomb which in turn is inside of the autoclave. The high pressure bomb is needed since the pressure to collapse the specimen is normally higher than the rated pressure of the autoclave. The autoclave, bomb and specimen were simultaneously pressurized to 2250 psi and then heated to 600⁰F. The specimen was next vented to atmospheric pressure and the bomb pressurized until the specimen collapsed. Collapse was evident by a sudden drop in the bomb pressure, usually accompanied by an audible click. A copy of the Collapse Test Standard Operating Procedure is included in Appendix C.

A burst or collapse test data sheet was completed for each specimen. Sample test data sheets are included in Appendix B. Data included on the test data sheets are specimen number, run number, data logger pressure, Heise gage pressure, pressurization rate, system temperature, autoclave pressure and water chemistry. After testing, a photograph of each specimen was taken for post-testing metallographic documentation. The baseline tube characterization sheet, defect fabrication information sheet, pressure test data sheet and post-testing photograph contain all information associated with the specimen and constitute the quality assurance documents for each specimen.

Results of the burst and collapse tests are presented in tabular form in Appendix D. Data included are specimen number, pertinent defect and tube dimensions, tube, and autoclave or bomb pressures and pressure differential. Also included for each burst specimen is the burst pressure divided by the undefected tube burst pressure for the same heat of tubing. This number is useful in analysis of the data.

BURST TEST RESULTS

Burst data are presented in tabular form and as plots. Data are discussed by defect type. The effects of the material properties for the three 0.875 in. x 0.050 in. size heats are discussed. Trends in the data for each defect type are interpreted. Inconsistencies in the data are discussed and possible explanations presented. Empirical relationships for predicting the burst pressures of each type of defect are derived. A least squares approach to the establishment of the empirical relationships was used.

Undefected Specimen Burst Data

Three undefected tubing specimens from each heat were burst to provide baseline information. The results of these tests are included in Table 3. These data are of interest from three different standpoints. First, the variations in the burst pressures for the three undefected specimens from each heat indicate the amount of scatter that could be expected in the defected specimen burst data. This points to how much of the burst data is due to variations in material properties and tube dimensions within any heat. Second, these data can be used directly to establish margin-to-failure for the undefected steam generator tubing. Third, the undefected specimen burst pressures can be used as a baseline for analyzing the defected specimen burst pressures. It was felt that dividing the burst pressure of a defected specimen by the undefected specimen burst pressure for the same heat of tubing could eliminate variables attributable to tubing dimension and material properties.

Figure 9 shows the failure mode characteristic of all of the undefected specimens. Failure was caused by the ultimate tensile failure in the hoop direction. The failure point was at random locations along the specimen axis, though no specimens failed at the end fittings. Significant plastic deformation of the entire tube wall occurred before failure. The diameter of the tube after failure had increased 15% to 20% in portions of the tube not near the point of failure. The tube near the point of failure stretched slightly more than this amount. The diameter of the tube near the end fitting did not increase as much as the remainder of the tube owing to the constraint of the welded plugs.

TABLE 3. Undetected Tube Burst Pressures

Heat	Tubing Size	Burst Pressure, (psi)			Average Burst Pressure, (psi)	Standard Deviation (psi/%)
B	0.875 x 0.050 48 ksi yield	9,260	9,274	9,440	9,325	100/1.1
E	0.875 x 0.050 44 ksi yield	9,460	9,665	9,500	9,542	109/1.1
F	0.875 x 0.050 40 ksi yield	9,180	9,450	9,240	9,290	142/1.5
C	0.750 x 0.043 52 ksi yield	9,950	9,620	9,640	9,737	185/1.9
D	0.750 x 0.050 44 ksi yield	11,170	11,700	11,640	11,503	290/2.5
G	0.625 x 0.034 53 ksi yield	9,400	9,445	9,395	9,413	28/0.3

FIGURE 9. Burst Failure Mode Characteristic of All Undefected Specimens

The scatter within the undefected burst pressures for each heat of tubing varied from 1/2% for heat G to over 4 1/2% for heat D. Since only three undefected specimens of each heat were burst, a detailed statistical analysis was not possible. However, repeatability of the tests is well within an acceptable range when it is considered that a variation of 3% between minimum wall thicknesses of two tubes from the same heat is not uncommon. Also, the variations in the material properties were probably of about the same magnitude. The scatter in the defected specimen burst pressure resulting from tube variation is probably about 2-4%.

The ratio of wall thickness to tube diameter determines, to a large extent, the stresses in the tube wall. For the undefected tubes, hoop direction stresses are twice the longitudinal stresses. Burst occurs because of ultimate tensile failure in the hoop direction. Hoop stresses can be approximated by Pr/t , where P is the internal pressure differential, r is the inside radius and t is the wall thickness. This is according to classical elastic thin-walled theory. However, if r and t are the actual dimensions of the tube as it deforms

and not the original dimensions, this expression holds for large plastic deformation. As the tube deforms because of internal pressure, the wall thickness decreases and the inner radius is increased. Therefore, the stresses in the tube wall are very dependent on the stress-strain characteristics of the material. Two important parameters are the ultimate strength and total elongation to failure. For tubes having identical material properties, the more thick-walled the tubing, the higher the burst pressure. It can be seen from the data that heat D, which had the largest wall thickness to diameter ratio, indeed had the highest burst pressure. The remaining heats of tubing had approximately equal wall thickness to diameter ratios, and burst pressures were similar. Variations in burst pressures between these heats are largely due to material variations.

Heats B, E and F all have the same dimensions. The major difference between these heats was that each had a different yield strength. The variations in yield strengths were due to differing annealing times. The manufacturing processes used were otherwise identical. All three heats had approximately the same ultimate strength. Yield strength did not have a recognizable effect on the burst pressures of the undefected tubing. Heat E, which had the lowest yield strength, had the lowest burst pressures. However, heat F, which had the intermediate yield strength, had the highest burst pressures. Ultimate strength appears to be much more important than yield strength in determining burst pressure for the undefected specimens.

The variables associated with material properties interact in a very complex way to determine burst pressures. To remove these variations from the analysis of the defect burst pressures, the defected specimen's burst pressures were divided by the undefected specimen's average burst pressure. In this way defect geometry effect upon tube burst pressures can be analyzed without having to worry about tubing material and dimensional variables. Thus it may be possible for defect dimensions to be non-dimensionalized to remove the effects of tubing variables. Once done, it would be possible to estimate burst pressures of defected specimens made from tubing having different properties by conducting burst tests on undefected tubing. This would reduce the effort required to assess the merits of new steam generator designs.

Uniform Thinning Defect Specimen Burst Pressures

Data for all defected specimen burst tests are presented in tabular form in Appendix D. Information included are specimen number, pertinent defect and tube dimensions, tube and autoclave pressures, and burst pressure differential. Also included is the burst pressure divided by the average of the undefected tube burst pressure.

Plots of the uniform thinning defect specimen burst pressures are given in Figures 10 through 15. The uniform thinning defect has two dimensions that have significant effects on the burst pressures. These are defect depth and defect length. A third defect dimension, the end radius between the thinned and unthinned regions, has very little effect on the burst pressures. The radius is not large enough to appreciably affect the bridging between the thinned and unthinned regions, but not so small as to introduce a large stress concentration. None of the uniform thinning defects failed at the end radius.

FIGURE 10. Burst Data for 0.875 x 0.050 Uniform Thinning Specimens - Defect Length Variation

FIGURE 11. Burst Data for 0.875 x 0.050 Uniform Thinning Specimens - Defect Depth Variation

FIGURE 12. Burst Data for 0.750 x 0.043 Uniform Thinning Specimens - Defect Length Variation

FIGURE 13. Burst Data for 0.750 x 0.043 Uniform Thinning Specimens - Defect Depth Variation

FIGURE 14. Burst Data for 0.750 x 0.050 Uniform Thinning Specimens - Defect Length Variation

FIGURE 15. Burst Data for 0.750 x 0.050 Uniform Thinning Specimens - Defect Depth Variation

Figure 10 shows the burst data for the heat B uniform thinning defects. It can be seen that the length of the defect is very important in determining the burst pressure for a fixed defect depth. The longer the defect, the lower the burst pressure. If the uniformly thinned region was very long, the burst pressure would be equivalent to the burst pressure for an undefected tube having the same wall thickness and outside diameter as the thinned region of the defect. It appears that the length of the 1 1/2-in.-long defect is nearly long enough to be considered infinite. For defect lengths shorter than 1 1/2 in., the burst pressure increases for decreasing defect length, since as the thinned region expands because of internal pressure, part of the load is transferred to the unthinned region and this tends to strengthen the thinned region. Inasmuch as the largest stress in the tube is the hoop stress for all but the very short deep defects, a varying amount of the load, depending upon defect length, in the hoop direction is carried by the unthinned part of the tube near the end of the

defect (the traditional penstock effect). Figure 16 shows burst specimens for 25-30% depth and various lengths. The shorter the defect, the more bulging of the undefected tube wall near the end of the defect. Also, the shorter the defect, the more plastic deformation of the undefected tube wall.

For the very short ($3/16$ in.) and deep (greater than 50%) defects, the largest stress in the defect is in the longitudinal direction, not the hoop direction. For an undefected tube the hoop stress is twice the longitudinal stress. However, for the short defect the unthinned regions counteract a very large part of the hoop stress in the thinned region. The longitudinal stress in the defect is not counteracted by the unthinned regions. The cross-sectional area of the defect must counteract all of the longitudinal force in the tube. The only assistance that the unthinned region supplies is to reduce the expansion of the tube and, therefore, reduce the area over which the internal pressure can act. All of the $3/16$ -in.-long defects over 50% deep burst in a guillotine failure. These tubes burst with a circumferential failure that severed the tube in two.

FIGURE 16. Burst Failure Mode of $3/8$ -in.-Long 25-30% Deep Uniform Thinning Defect

Figures 16 to 26 are photos showing the modes of failure of the uniform thinning defects. All of the 25-30% deep defects showed failures similar to the undefected specimens. All failures were caused by ultimate tensile failure in the hoop direction. The photos of the 55-60% and 75-80% deep defects show the transition between circumferential and longitudinal failure. For the 3/16-in.-long defects, failure was a guillotine separation of the tube caused by a 360° circumferential crack. For the 3/8-in.-long defects, the failure was a combination of circumferential and longitudinal cracks. For the 3/4-in.-long defects, the failure was caused by a longitudinal crack that probably started near the center of the thinned region. When this crack reached the end of the thinned region, the crack turned and propagated in the circumferential direction. For the 1 1/2-in.-long defects, failure was also due to a longitudinal crack with a very small circumferential component at the ends. The various failure modes give an indication of the direction of the maximum stress in the defects.

FIGURE 17. Burst Failure Mode of 3/4-in.-Long 25-30% Deep Uniform Thinning Defect

FIGURE 18. Burst Failure Mode of 1 1/2-in.-Long 25-30% Deep Uniform Thinning Defect

FIGURE 19. Burst Failure Mode of 3/16-in.-Long 55-60% Deep Uniform Thinning Defect

FIGURE 20. Burst Failure Mode of 3/8-in.-Long 55-60% Deep Uniform Thinning Defect

FIGURE 21. Burst Failure Mode of 3/4-in.-Long 55-60% Deep Uniform Thinning Defect

FIGURE 22. Burst Failure Mode of 1 1/2-in.-Long 55-60% Deep Uniform Thinning Defect

FIGURE 23. Burst Failure Mode of 3/16-in.-Long 75-80% Deep Uniform Thinning Defect

FIGURE 24. Burst Failure Mode of 3/8-in.-Long 75-80% Deep Uniform Thinning Defect

FIGURE 25. Burst Failure Mode of 3/4-in.-Long 75-80% Deep Uniform Thinning Defect

FIGURE 26. Burst Failure Mode of 1 1/2-in.-Long 75-80% Deep Uniform Thinning Defect

Figure 11 shows the burst data for the heat B uniform thinning defects plotted as burst pressure versus maximum degradation. Any reasonable curve drawn through the data would go through the point of 0% degradation and the undefected burst pressure and the point of 100% degradation and 0 psi. As expected, the defect depth is very important in determining the burst pressure. For a fixed defect length, the deeper the defect, the lower the burst pressure. There is obvious interaction between the defect length and depth in determining burst pressure. While it was not possible to develop an analytic prediction to account for the interaction between length and depth, a very good empirical fit of the data was obtained.

To obtain an empirical fit, the variables associated with the material properties and dimensions were non-dimensionalized. As previously stated, the burst pressures were non-dimensionalized by dividing by the burst pressure of the undefected tube. If the defected tube burst pressure is labeled ΔP and the undefected tube burst pressure is labeled ΔP_0 , then the non-dimensionalized burst pressure is $\Delta P / \Delta P_0$. The defect depth was non-dimensionalized by dividing

the maximum defect depth h , by the original wall thickness, t . The non-dimensionalized defect depth is then h/t . For non-dimensionalizing the defect length, we turn to the decay length for a cylindrical shell which is related to $L/\sqrt{Rt}$, where L is length, R is inner radius of the tube, and t is the wall thickness. See, for example, Newman.⁽²⁾

For all tubing sizes, one plot of $\Delta P/\Delta P_0$ versus h/t was made. From this plot it appeared that an equation of the form:

$$\frac{\Delta P}{\Delta P_0} = \left(1 - \frac{h}{t}\right)^a \quad (1)$$

could be used to fit the data. The coefficient "a" was to include the effects of defect length. To determine the coefficient "a," Equation 1 was written as

$$\ln \frac{\Delta P}{\Delta P_0} = a \ln (1 - h/t) \quad (2)$$

or

$$a = \frac{\ln (1 - h/t)}{\ln (\Delta P/\Delta P_0)} \quad (3)$$

A plot of the right side of Equation 3 versus $L/\sqrt{Rt^*}$ was made. The value for t^* was the remaining wall thickness of the thinned region. From this plot it was determined that the coefficient "a" could be fit by an equation of the form:

$$a = 1 - e^{b \frac{L}{\sqrt{Rt^*}}} \quad (4)$$

where "b" is a constant. The value of "b" was determined by a least squares fit to be $b = -0.130$. Therefore,

$$\frac{\Delta P}{\Delta P_0} = (1 - h/t)^{-0.13 L/\sqrt{R} (t-h)} \quad (5)$$

Figure 27 is a plot of actual burst pressure versus the burst pressure predicted by Equation 5 for all uniform thinning defects. The correlation is quite good.

Figures 28 and 29 are graphical representations of Equation 5. The three curves in Figure 28 represent degradation of 25%, 50% and 75%. It can be seen that as the length of the defect becomes very long, the burst pressure approaches an asymptotic value. The three curves in Figure 29 represent defect lengths of 1/4 inch, 1/2 inch, and 1 1/2 inch in 0.875 in. x 0.050 in. tubing.

FIGURE 27. Comparison of Predicted and Actual Burst Pressure Parameters for all Uniform Thinning Specimens

FIGURE 28. Burst Parameter Prediction Curves for Uniform Thinning Specimens - Length Parameter Variation

FIGURE 29. Burst Parameter Prediction Curves for Uniform Thinning Specimens - Depth Parameter Variation

Elliptical Wastage Defect Specimen Burst Data

Plots of the elliptical wastage defect specimen burst pressure are given in Figures 30 through 33. The elliptical wastage defects have three dimensions that determine the defect geometry. These are defect depth, wrap angle and cutter radius. The cutter radius was selected so that the length of the defect was approximately 1 1/2 in. long. Actual defect lengths varied from 0.97 in. to 2.05 in. The length of the elliptical wastage defect did not appreciably affect the burst pressure. Three different wrap angles were tested. These were 0° , 45° and 135° . The wrap angle did not appreciably affect the burst pressure. While the surrounding undefected tube probably strengthened the defected region as it did for the uniform thinning defect, the effects were minor. The magnitude of these effects was probably less than the scatter due to varying material properties or tube dimensions.

FIGURE 30. Burst Data for 0.875 x 0.050 Elliptical Wastage Specimens

FIGURE 31. Burst Data for 0.750 x 0.043 Elliptical Wastage Specimens

FIGURE 32. Burst Data for 0.750 x 0.050 Elliptical Wastage Specimens

FIGURE 33. Burst Data for 0.625 x 0.034 Elliptical Wastage Specimens

Figures 34 to 40 are photos showing the modes of failure of the elliptical wastage defects. All of these specimens failed with a longitudinal crack. For the specimens with 135° wrap angle, there was a small turning of the crack near the end of the elliptical wastage. This probably occurred after the crack had started to propagate and does not affect the burst pressure. Also, the deeper the defect, the shorter and narrower the opening. This is due to the fact that the deeper defects had lower burst pressures. Therefore, less energy was stored in the tube to propagate the crack.

Any reasonable curve that was drawn through the data in Figures 30 through 32 would go through the points of 0% degradation and the undefected burst pressure and the point of 100% degradation and 0 psi burst pressure. One of the data points in Figure 30 is not consistent with the remainder of the data. Examining all available data on the particular specimen and the

FIGURE 34. Burst Failure Mode of Elliptical Wastage -
25-30% Deep 0° Wrap Angle

FIGURE 35. Burst Failure Mode of Elliptical Wastage -
25-30% Deep 45° Wrap Angle

FIGURE 36. Burst Failure Mode of Elliptical Wastage -
25-30% Deep 135° Wrap Angle

FIGURE 37. Burst Failure Mode of Elliptical Wastage -
55-60% Deep 0° Wrap Angle

FIGURE 38. Burst Failure Mode of Elliptical Wastage -
55-60% Deep 45° Wrap Angle

FIGURE 39. Burst Failure Mode of Elliptical Wastage -
55-60% Deep 135° Wrap Angle

FIGURE 40. Burst Failure Mode of Elliptical Wastage -
85-90% Deep 0° Wrap Angle

specimen itself showed no reason for the inconsistency. Therefore, since this data point was felt to be in error, data for this specimen are presented but were not taken into consideration when the empirical fits were established.

For purposes of establishing an empirical fit for the elliptical wastage burst pressures, a plot of $\Delta P / \Delta P_0$ versus h/t was made for all elliptical wastage defects. This plot is very similar to the one obtained for the uniform thinning defects, except that no defect length effects were present. An equation of the form

$$\frac{\Delta P}{\Delta P_0} = \left(1 - \frac{h}{t}\right)^a \quad (6)$$

was selected to fit the data. This is the same form as was used for the uniform thinning data, except that the coefficient "a" is a constant and not a variable. By a least squares fit a value of $a = 0.604$ was selected.

Therefore,

$$\frac{\Delta P}{\Delta P_0} = \left(1 - \frac{h}{t}\right)^{0.604} \quad (7)$$

is the empirical relationship that was obtained. Figure 41 is a plot of actual burst pressure parameter versus the burst pressure parameter predicted by Equation 7. The correlation is good. Figure 42 is a graphical representation of Equation 7.

EDM Slot Defect Specimen Burst Data

Plots of the EDM slot defect specimen burst data are given in Figures 43 through 50. Much more scatter was present in the EDM slot data than in the uniform thinning and elliptical wastage data. This is owing to the greater variations in the uniformity of the EDM slot specimens. Some of the EDM slot specimens had fairly straight walls and flat bottoms. Some of the slots,

FIGURE 41. Comparison of Predicted and Actual Burst Pressure Parameters for All Elliptical Wastage Specimens

FIGURE 42. Burst Parameter Prediction Curves for Elliptical Wastage Specimens

FIGURE 43. Burst Data for 0.875 x 0.050 EDM Slot Specimens - Defect Depth Variation

FIGURE 44. Burst Data for 0.875 x 0.050 EDM Slot Specimens - Defect Length Variation

FIGURE 45. Burst Data for 0.750 x 0.043 EDM Slot Specimens - Defect Depth Variation

FIGURE 46. Burst Data for 0.750 x 0.043 EDM Slot Specimens - Defect Length Variation

FIGURE 47. Burst Data for 0.750 x 0.050 EDM Slot Specimens - Defect Depth Variation

FIGURE 48. Burst Data for 0.750 x 0.050 EDM Slot Specimens - Defect Length Variation

FIGURE 49. Burst Data for 0.625 x 0.034 EDM Slot Specimens - Defect Depth Variation

FIGURE 50. Burst Data for 0.625 x 0.034 EDM Slot Specimens - Defect Length Variation

however, had widths and depths that were not uniform along the length. While variations in the slot width probably did not greatly affect the burst pressures, variations in the depth probably did account for a major part of the scatter. Variations in the slot depth were characteristically 0.001 in. to 0.003 in. When defect degradations were calculated, they were based on the maximum replicated defect depth. Also, while care was taken to replicate the maximum slot depths, it is possible that the maximum depth was not determined.

As with the uniform thinning defects, the interaction between defect length and defect depth in determining burst pressure was present. The effects of slot length can best be seen in Figures 44, 46, 48 and 50. For a fixed depth, as the slot length gets longer and longer, the burst pressure should approach an asymptotic value. This can best be seen in Figure 50, which is the burst data for the 0.625 in. x 0.034 in. size tubing. This is the smallest size tubing and the 1 1/2-in.-long slot is proportionately longer for this size when compared to the dimensions of the tube. The burst pressure for the 1 1/2-in.-long slot

appears to be about as low as would be expected for an infinitely long slot. Even for the 1/2-in.-long slots, the burst pressures are very close to the 1 1/2-in.-long slot burst pressure.

The effects of defect depth can be seen in Figures 43, 45, 47 and 49. As the defect depth increases, the burst pressure decreases. It appears that for short slot lengths a curve drawn through the data would not necessarily go through the point of 100% degradation and 0 psi burst pressure. For the short slots, failure of the remaining ligament at the root of the slot cannot occur until some plastic deformation has taken place in the tube wall at the end of the slot. Until the material at the end of the slot plastically deforms, the remaining ligament is subject to limited elongation. If a through-wall slot could be internally pressurized, the widening of the slot would be minimal until the pressure was sufficient to plastically deform the ends of the slot. For this reason, until the remaining ligament is stretched an amount related to the material's total elongation to failure, the ligament would not fail. For long slots, it is possible that the widening of the center of the slot while the ends were still elastic would be sufficient to fail the ligament.

Figures 51 to 58 show the modes of failure of the EDM slot depths. All of these defects failed by ultimate tensile failure of the remaining ligament at the root of the slot. For the 25% to 30% deep slots and some the 55% to 60% deep slots, the crack propagated past the end of the slot.

A plot of $\Delta P / \Delta P_0$ versus h/t was made for all of the EDM slot burst data. As a lower limit the curve

$$\frac{\Delta P}{\Delta P_0} = 1 - \frac{h}{t} \quad (8)$$

could be used since this should closely approximate the burst pressure of an infinitely long slot. The actual burst pressure of a finite length slot would be higher than this. Therefore:

$$\frac{\Delta P}{\Delta P_0} = 1 - \frac{h}{t} + A \quad (9)$$

FIGURE 51. Burst Failure Mode of EDM Slot - 25-30% Deep 1/2-in.-Long

FIGURE 52. Burst Failure Mode of EDM Slot - 25-30% Deep 1 1/2-in.-Long

FIGURE 53. Burst Failure Mode of EDM Slot - 55-60% Deep 1/4-in.-Long

FIGURE 54. Burst Failure Mode of EDM Slot - 55-60% Deep 1/2-in.-Long

FIGURE 55. Burst Failure Mode of EDM Slot - 55-60% Deep 1 1/2-in.-Long

FIGURE 56. Burst Failure Mode of EDM Slot - 85-90% Deep 1/4-in.-Long

FIGURE 57. Burst Failure Mode of EDM Slot - 85-90% Deep 1/2-in.-Long

FIGURE 58. Burst Failure Mode of EDM Slot - 85-90% Deep 1 1/2-in.-Long

was proposed as an approximation. The value of "A" is a function of the slot depth and length. The "A" was reasoned to be proportional to the pressure differential in excess of the infinitely long slot burst pressure. Therefore,

$$\frac{\Delta P}{\Delta P_0} = 1 - \frac{h}{t} + B \frac{h}{t} \quad (10)$$

A plot of

$$\frac{\frac{\Delta P}{\Delta P_0} - \left(1 - \frac{h}{t}\right)}{\frac{h}{t}} \text{ versus } \frac{L}{\sqrt{Rt}}$$

was made. The value of t was the undefected tube wall thickness. From the plot it was seen that

$$\frac{\frac{\Delta P}{\Delta P_0} - \left(1 - \frac{h}{t}\right)}{\frac{h}{t}}$$

could be approximated as $aL/\sqrt{Rt}$ where "a" is a constant. By least squares a value for "a" was slightly different for each size of tubing, but a value of $a = e^{-0.373}$ was found to be the best overall value. This value gave acceptable results for all EDM slot specimens. The final equation is therefore

$$\frac{\Delta P}{\Delta P_0} = 1 - \frac{h}{t} + \frac{h}{t} e^{-0.373 L/\sqrt{Rt}} \quad (11)$$

Figure 59 is a plot of the actual burst pressures of the EDM slots versus the burst pressures predicted by Equation 11. The correlation is reasonable. Figures 60 and 61 are graphical representation of Equation 11.

Denting Defect Specimen Burst Data

Results of the denting specimen burst data are presented in Table 4. The denting specimens were prepared by hot-swaging a carbon steel ring onto the tube. The thickness of the ring was 3/4 in. to simulate the thickness of the tube support sheet. Nominal denting depth was 0.04 in. to 0.05 in. The end radius of the ring was 1/8 in. The denting ring did not appreciably decrease the burst pressures for the tubes. Since the ring tends to constrain the tube as it expands due to the internal pressure, it should strengthen the tube. None of the denting specimens failed at the ring. All of these specimens failed somewhere between the denting ring and the end fitting, and failure was similar to that of an undefected tube.

FIGURE 59. Comparison of Predicted and Actual Burst Pressure Parameters for All EDM Slot Specimens

$$\frac{\Delta P}{\Delta P_0} \text{ (PREDICTED)} = 1 - \frac{h}{t} + \frac{h}{t} e^{-0.373 \frac{L}{\sqrt{Rt}}}$$

FIGURE 60. Burst Pressure Parameter Prediction Curves for EDM Slot Specimens - Length Parameter Variation

$$\frac{\Delta P}{\Delta P_0} \text{ (PREDICTED)} = 1 - \frac{h}{t} + \frac{h}{t} e^{-0.373 \frac{L}{\sqrt{Rt}}}$$

FIGURE 61. Burst Pressure Parameter Prediction Curves for EDM Slot Specimens - Depth Parameter Variation

TABLE 4. Denting Specimen Burst Data

<u>Specimen Number</u>	<u>Minimum Wall (in.)</u>	<u>Tube Pressure (psi)</u>	<u>Autoclave Pressure (psi)</u>	<u>P (psi)</u>	<u>$\Delta P/\Delta P_0$</u>
B-22-5	0.0522	10,280	960	9,320	0.999
B-19-3	0.0518	10,220	960	9,260	0.993
B-32-3	0.0514	10,580	1000	9,580	1.027
C-24-7	0.0422	10,620	1010	9,610	0.987
C-24-1	0.0422	12,000	1030	9,650	0.991
D-13-1	0.0522	12,220	1000	11,220	0.975
D-08-1	0.0498	12,400	1000	11,400	0.991
D-22-9	0.0508	12,000	1000	11,000	0.956

Denting Plus Uniform Defect Thinning and Denting Plus Elliptical Wastage Defect Specimen Burst Data

Plots of the denting plus uniform thinning burst data are shown in Figures 62 through 64. In Figure 62, the plot of the Heat B denting plus uniform thinning, the data for the same defects without the dent are included. It is obvious from the plot that the presence of the denting ring tends to increase the burst pressure, especially for the shorter uniformly- thinned region. This is because the denting ring tends to strengthen one end of the uniformly-thinned region, as can be seen in Figures 65 through 70. This is similar to having a shorter thinned region and, as previously noted, the shorter the thinned region, the higher the burst pressure. As the length of the thinned region increases, the dented defect burst pressure approaches that of the undented defect. Since using the empirical relationship for predicting the burst pressures for the uniform thinning defects without the denting ring would give conservative results for the denting plus uniform thinning defects, no additional empirical relationships were established.

In Table 5 the denting plus elliptical wastage specimen burst pressures are compared to the burst pressures for similar defects without the dent. No trend related to the dent is evident. Some of the burst pressures were higher for specimens with dents and some were lower. As was seen from the denting

FIGURE 62. Burst Pressure Data of 0.875 x 0.050 Uniform Thinning Specimens With and Without Denting

FIGURE 63. Burst Pressure Data for 0.750 x 0.050 Uniform Thinning Specimens With and Without Denting

FIGURE 64. Burst Pressure Data for 0.750 x 0.043 Uniform Thinning Specimens With and Without Denting

FIGURE 65. Burst Failure Mode of Denting Plus Uniform Thinning - 25-30% Deep 3/8-in.-Long

FIGURE 66. Burst Failure Mode of Denting Plus Uniform Thinning -
25-30% Deep 3/4-in.-Long

FIGURE 67. Burst Failure Mode of Denting Plus Uniform Thinning -
25-30% Deep 1 1/2-in.-Long

FIGURE 68. Burst Failure Mode of Denting Plus Uniform Thinning -
55-60% Deep 3/16-in.-Long

FIGURE 69. Burst Failure Mode of Denting Plus Uniform Thinning -
55-60% Deep 3/8-in.-Long

FIGURE 70. Burst Failure Mode of Denting Plus Uniform Thinning - 55-60% Deep 3/4-in.-Long

TABLE 5. Comparison of Burst Pressures for Elliptical Wastage and Denting Plus Elliptical Wastage

Tube Size	Radius of Cutter (in.)	Wrap Angle (degrees)	Depth (% Wall)	Burst Pressures (psi)	
				Without Denting	With Denting
0.875 x 0.050	24	0	25-30	8155, 8150	7905, 8150
	24	45	25-30	7615, 7940	9200, 8060
	24	135	25-30	5200, 7780	7800, 7770
	12	0	55-60	5550, 5635	5520, 5605
	12	45	55-60	5680, 5840	5650, 5675
	12	135	55-60	5610, 5455	5320, 5230
0.750 x 0.043	24	0	25-30	7580, 8275	8335, 8595
	12	0	55-60	6060, --	6055, 5775
0.750 x 0.050	24	45	25-30	9860, 9685	9205, 9000
	24	135	25-30	9110, 8890	9605, 9240
	12	45	55-60	5845, 6260	6115, 6500
	12	135	55-60	6400, 6870	5905, 6005

plus uniform thinning data, when the defect was 1 1/2 in. long dented and undented defects showed no appreciable difference. All elliptical wastage defects were approximately 1 1/2 in. long, so there was very little effect of the denting ring. (See Figures 71 through 76.)

Empirical relationship established for predicting elliptical wastage burst pressures hold for the denting plus elliptical wastage defects.

Burst Data for Defected Specimens from Three Heats of 0.875 x 0.050 in. Tubing

From each of the three heats of 0.875 in. x 0.050 in. tubing (Heats B, E and F) a series of defected specimens were prepared. Heat B had an average yield stress of 48 ksi and an average ultimate stress of 93 ksi. Heat E had an average yield stress of 44 ksi and an average ultimate stress of 99 ksi.

FIGURE 71. Burst Failure Mode of Denting Plus Elliptical Wastage - 25-30% Deep 0° Wrap Angle

FIGURE 72. Burst Failure Mode of Denting Plus Elliptical Wastage -
25-30% Deep 45° Wrap Angle

FIGURE 73. Burst Failure Mode of Denting Plus Elliptical Wastage -
25-30% Deep 135° Wrap Angle

FIGURE 74. Burst Failure Mode of Denting Plus Elliptical Wastage -
55-60% Deep 0° Wrap Angle

FIGURE 75. Burst Failure Mode of Denting Plus Elliptical Wastage -
55-60% Deep 45° Wrap Angle

FIGURE 76. Burst Failure Mode of Denting Plus Elliptical Wastage - 55-60% Deep 135° Wrap Angle

Heat F had an average yield stress of 40 ksi and an average ultimate stress of 97 ksi. For each of these three heats six EDM slots, two uniform thinning and two elliptical wastage specimens were prepared.

Results of the burst tests for the uniform thinning and elliptical wastage specimens are shown in Figure 77. The uniform thinning defects were all 55-60% deep and 3/8 in. long. The elliptical wastage defects were all 55-60% deep with a cutter radius of 12 in. and a wrap angle of 0°. No appreciable differences in the burst data is evident for these defects. The scatter in the data is about the same as was present in the remainder of the burst data for these defect types.

Results of burst tests for the EDM slot specimens are shown in Figure 78. All EDM slots were 1/2 in. long with depths of 25-30%, 55-60% and 85-90%. For the 25-30% defects no appreciable difference exists in the burst pressures. The scatter in the data is less than is typical for this type of defect. Yield stress does not appear to have an appreciable effect on the burst

FIGURE 77. Burst Pressure Data for Three Different Heats for Both Uniform Thinning and Elliptical Wastage Specimens

FIGURE 78. Burst Pressure Data for Three Different Heats for EDM Slot Specimens

pressures for the shallow slots since before these defects fail, the entire tube wall has plastically deformed.

Data for the 55-60% deep slots indicate a very definite trend: the defected tubing with the lowest yield strength had the lowest burst pressure. The same general trend for the 85-90% deep slots also exists, but due to the data scatter it is not as obvious. As discussed earlier, the failure of deeper slots is related to the stretching of the remaining ligament at the slot root. Until the ends of the slot plastically deform, the slot widens very little. However, as soon as the slot ends plastically deform, slot width increases significantly while internal pressure increases slightly. Other parameters such as total elongation to failure and the strain-hardening properties of the material also have effects on the burst pressure. However, these factors were fairly uniform from heat to heat.

While a definite trend in the burst data for the EDM slots related to the yield strength was evident, insufficient data were available to determine the exact effects. Also, the variations in the burst pressures due to the yield stress were fairly small.

BURST TEST CONCLUSIONS

Empirical relationships have been established using a least squares fit of the burst pressure of the EDM slots, uniform thinning and elliptical wastage defects tested. Empirical relationships were not derived for the defect geometries which included denting since the relationships established for the defects without the denting rings could be used satisfactorily. It is to be shown that the relationships for the mechanically defected tubing can be used to predict the burst pressures of the actual defects found in actual PWR steam generators.

Due to the very high burst pressures of undefected PWR steam generator tubing, even defects as deep as 80% through-wall had burst pressures higher than would be experienced during a main steam line break, which is the worst burst mode accident condition.

COLLAPSE TEST RESULTS

Collapse data will be presented in tabular form and as plots. Data will be discussed by defect type. The effects of the yield stress on the collapse pressures will be discussed. Trends in the data for each defect type will be interpreted. Inconsistencies in the data will be discussed and possible explanations presented.

Undefected Specimen Collapse Data

Three undefected tubing specimens from each heat were collapsed to provide baseline information. The results of these tests are included in Table 6. The collapse pressure of the undefected tubing is determined by a combination of the tubing dimensions and the material properties. Heise and Eysterger⁽³⁾ have shown that good correlation exists between theory and tests for thick-walled tubes where the theoretical collapse pressure is assumed to be reached when the outer surface yields. The plastic buckling formula is

$$P = \sigma_y t/R \quad (12)$$

TABLE 6. Undefected Specimen Collapse Data

Heat	Tubing Size	Room Temperature Yield Stress (ksi)	Collapse Pressure (psi)			Average Collapse Pressure (psi)	Standard Deviation (psi%)
B	0.875 x 0.050	48	4880	4890	4900	4890	10/0.2
E	0.875 x 0.050	44	4340	4960 ^(a)	4470	4405	92/2.1
F	0.875 x 0.050	40	4060	4120	3910	4030	108/2.7
C	0.750 x 0.043	52	5000	4980	5200	5060	122/2.4
D	0.750 x 0.050	49	5800	6100	6000	5970	153/2.6
G	0.625 x 0.034	53	4800	5000	4850	4880	104/2.1

(a) Not used in average.

where P is the collapse pressure, σ_y is the yield stress, t is the wall thickness, and R is the outside diameter. The tensile tests that were used to establish the yield stress values were conducted at room temperature. (See Appendix A.) Because the collapse tests were conducted at 600°F, Equation 12 could be used to obtain values for the yield stresses at 600°F based on the collapse data. The values obtained by doing this were compared to the room temperature values in Figure 79. The value used for the collapse pressure was the average of the three undefected specimen collapse pressures, except for Heat E. One of the undefected specimens for Heat E had a collapse pressure significantly higher than the other two. This data point was considered an anomaly and was not used in calculating the average collapse pressure for Heat E. If the yield stress at 600°F is assumed to be a fixed percentage of the room temperature yield stress, the reduction was calculated to be 12.5% by a least squares fit.

FIGURE 79. Comparison of Room Temperature Yield Stresses and Predictions of 600°F Yield Stresses

In Figure 79 the predicted yield stresses all fall very close to the 0.875 times the room temperature yield stress line. This suggests that the theoretical collapse as predicted by Equation 12 is in good agreement with the data.

The collapse failure mode characteristic of all undefected specimens is shown in Figure 80.

EDM Slot Specimen Collapse Data

The EDM slot collapse data is presented in Figures 81 through 86. The reduction in the collapse pressures due to the EDM slots was not large. For the three heats of 7/8-in. tubing the reduction was less than 11% for all specimens. For the two heats of 3/4-in. tubing the reduction was less than 14.5%. For the 5/8-in. tubing the reduction was less than 23%. The lowest collapse pressure of any of the EDM slot specimens was 3600 psi, which is considerably higher than the 1000 psi possible during a LOCA. It must be noted that all of the slots tested were much shorter than the theoretical critical length for the tubing. The theoretical critical crack length has

FIGURE 80. Collapse Failure Mode Characteristic of All Undefected Specimens

FIGURE 81. Collapse Pressure Data for 0.875 x 0.050 EDM Slot Specimens - Heat B

FIGURE 82. Collapse Pressure Data for 0.875 x 0.050 EDM Slot Specimens - Heat E

FIGURE 83. Collapse Pressure Data for 0.875 x 0.050 EDM Slot Specimens - Heat F

FIGURE 84. Collapse Pressure Data for 0.750 x 0.043 EDM Slot Specimens

FIGURE 85. Collapse Pressure Data for 0.750 x 0.050 EDM Slot Specimens

FIGURE 86. Collapse Pressure Data for 0.625 x 0.034 EDM Slot Specimens

been estimated to be about six tube diameters. (See Carman and Carr).⁽⁴⁾ For defect lengths shorter than this, end effects would tend to strengthen the defect and increase the collapse pressure. The combinations of slot lengths and tubing sizes produced defects which ranged from less than 5% to 40% of the critical length. Slots length longer than 1 1/2 in. could have collapse pressures lower than those for the 1 1/2-in. slots. In such cases defect depth takes on more importance.

The collapse failure modes characteristic of the EDM slots are shown in Figures 87 through 93. For many of the EDM specimens, the initiation of collapse does not appear to have occurred at the defect. This confirms the observation that the presence of the EDM slots had very little effect on the collapse of the tubes. This is very obvious in Figure 92. Collapse of the tube was only partial and did not occur at the defect at all. Another figure of interest is Figure 93. The collapse pressure of this specimen was very high and the tube ruptured at the base of the slot upon collapse. Although

FIGURE 87. Collapse Failure Mode of EDM Slot - 25-30% Deep 1/2-in.-Long

FIGURE 88. Collapse Failure Mode of EDM Slot - 25-30% Deep 1 1/2-in.-Long

FIGURE 89. Collapse Failure Mode of EDM Slot - 55-60% Deep 1 1/2-in.-Long

FIGURE 90. Collapse Failure Mode of EDM Slot - 55-60% Deep 1 1/2-in.-Long

FIGURE 91. Collapse Failure Mode of EDM Slot - 85-90% Deep 1/4-in.-Long

FIGURE 92. Collapse Failure Mode of EDM Slot - 85-90% Deep 1/2-in.-Long

FIGURE 93. Collapse Failure Mode of EDM Slot - 85-90% Deep 1 1/2-in.-Long

this specimen would definitely leak in the collapsed configuration, the collapse pressure was much higher than could ever occur during a LOCA.

Collapse pressures for the 1/4- and 1/2-in. slots showed little or no variation from the undefected collapse pressures. For all except the 5/8-in. tubing, collapse pressures for 1/4- and 1/2-in. slots could not be differentiated from the undefected collapse pressures. The 1/2-in. slots in the 5/8-in. tubing showed a small reduction in collapse pressures. For the 1 1/2-in. slots, no reduction in collapse pressure was evident for the 25-30% deep slots. For the 1 1/2-in., 55-60% deep slots, the reduction in collapse pressure was 6% to 10% for the 7/8-in. tubing, 12% to 14% for the 3/4-in. tubing, and about 21% for the 5/8-in. tubing. For the 1 1/2-in., 85-90% deep slots, the reduction was 8% to 11% for the 7/8-in. tubing, 5% to 14% for the 3/4-in. tubing and about 22% for the 5/8-in. tubing. The larger reduction in collapse pressures for the small diameter tubing is due to the fact that the 1 1/2-in. slot is a larger percentage of the critical length.

Several of the data points for the EDM slots are inconsistent with the rest of the data. In particular, one of the 1/2-in., 55-60% slots in the 7/8-in., 44-ksi tubing; one of the 1 1/2-in., 25-30% slots in the 7/8-in., 40-ksi tubing; and one 1/2-in., 25-30% slot and one 1/2-in. 85-90% slot in the heavy-walled 3/4-in. tubing had collapse pressures higher than the undefected collapse pressures. It was judged that these results were due to anomalies either in the material properties of the tubes or in the test procedure. These incidents were small in number and do not affect the basic findings of this work. Further investigation into their cause was not deemed necessary.

The two 1 1/2-in., 85-90% deep slots in the 0.750-in. x 0.050-in. tubing had collapse pressures higher than expected. The explanation of these inconsistencies could be the same as for the others.

Uniform Thinning Specimen Collapse Data

The uniform thinning collapse data is included in Figure 94. Only the 7/8-in., 48-ksi yield tubing was used for uniform thinning specimens. The general trend in the data is that the longer and deeper the defect, the lower the collapse pressure. For the 25-30% deep defects, the reduction in collapse pressure was less than about 13%. For the 55-60% defects the reduction was

FIGURE 94. Collapse Pressure Data for 0.875 x 0.050 Uniform Thinning Specimens

less than 56%. For the 75-80% defects the reduction was up to 65%. The lowest collapse pressure of the uniform thinning defects was 1760 psi. This is still appreciably higher than the approximately 1000 psi differential during a LOCA. Considerable scatter in the data is present, especially for the 75-80% deep defects. One possible explanation for this scatter is that localized collapse of the defect could have occurred without being detected. The collapse pressure recorded for these specimens could have been the pressure when the remainder of the tube collapsed. All of the collapse pressures were higher than would be predicted for tubing having a wall thickness equal to the minimum remaining wall thickness.

Figures 95 through 104 show the collapse modes characteristic of the uniform thinning defects. As can be seen from Figures 95 through 97, the 25-30% deep uniform thinning specimens failed similarly to the undefected tubing. Collapse appears to have been initiated at the defect.

FIGURE 95. Collapse Failure Mode of Uniform Thinning -
25-30% Deep 3/8-in.-Long

FIGURE 96. Collapse Failure Mode of Uniform Thinning -
25-30% Deep 3/4-in.-Long

FIGURE 97. Collapse Failure Mode of Uniform Thinning -
25-30% Deep 1 1/2-in.-Long

FIGURE 98. Collapse Failure Mode of Uniform Thinning -
55-60% Deep 3/8-in.-Long

FIGURE 99. Collapse Failure Mode of Uniform Thinning -
55-60% Deep 3/4-in.-Long

FIGURE 100. Collapse Failure Mode of Uniform Thinning -
55-60% Deep 1 1/2-in.-Long

FIGURE 101. Collapse Failure Mode of Uniform Thinning -
75-80% Deep 3/16-in.-Long

FIGURE 102. Collapse Failure Mode of Uniform Thinning -
75-80% Deep 3/8-in.-Long

FIGURE 103. Collapse Failure Mode of Uniform Thinning -
75-80% Deep 3/4-in.-Long

FIGURE 104. Collapse Failure Mode of Uniform Thinning -
75-80% Deep 1 1/2-in.-Long

Figures 98 through 100 show the 55-60% deep uniform thinning defects. A rupture of the tube wall is visible in Figure 98. Even though the specimen would leak in the collapsed state, its collapse pressure was much higher than would occur during a LOCA. A probable cause for the rupture is indicated in Figures 99 and 100. For these defects the tube was not flattened, as with the undefected tubing. When these defects collapsed, the defect was pushed in at several locations around the circumference. This may be due to the combination of compressive stresses in the circumferential and longitudinal directions. For the specimen in Figure 98, the collapse of the thinned region probably occurred in a similar manner initially, but when the remainder of the tube collapsed, the thinned region was also flattened. This sequence of events could have caused a section of the wall to be severely bent and then straightened out, which could have caused the rupture.

Figures 101 through 104 show the 75-80% deep defects. For these defects the collapse modes were such that the specimen was shortened. For this defect geometry the tube was actually stronger in the circumferential direction and the comprehensive stresses in the longitudinal direction caused the failure.

Elliptical Wastage Specimen Collapse Data

The elliptical wastage collapse data is presented in Figures 105 through 108. The specimens tested had three wrap angles, 0° , 45° and 135° . There is a general trend in the data that the larger the wrap angle, the lower the collapse pressure. However, the overall effects of the wrap angle on collapse pressure are small. For the 25-30% deep defects, the reduction in collapse pressures was 14% to 24%. For the 55-60% deep defects, the reduction was 36% to 53%, and for the 85-90% defects the reduction was 45% to 59%. The reduction in collapse strength from the 55-60% defects to the 85-90% defects was not as large as might be expected. One of the data points for the 5/8-in. tubing is inconsistent and is probably due to the localized collapse not being detected.

The collapse modes of the elliptical wastage specimens are shown in Figures 109 through 113. In all cases collapse appears to have initiated at the defect.

FIGURE 105. Collapse Pressure Data for 0.875 x 0.050 Elliptical Wastage Specimens

FIGURE 106. Collapse Pressure Data for 0.750 x 0.043 Elliptical Wastage Specimens

FIGURE 107. Collapse Pressure Data for 0.750 x 0.050 Elliptical Wastage Specimens

FIGURE 108. Collapse Pressure Data for 0.625 x 0.034 Elliptical Wastage Specimens

FIGURE 109. Collapse Failure Mode of Elliptical Wastage -
25-30% Deep 0° Wrap Angle

FIGURE 110. Collapse Failure Mode of Elliptical Wastage -
25-30% Deep 135° Wrap Angle

FIGURE 111. Collapse Failure Mode of Elliptical Wastage -
55-60% Deep 0° Wrap Angle

FIGURE 112. Collapse Failure Mode of Elliptical Wastage -
55-60% Deep 135° Wrap Angle

FIGURE 113. Collapse Failure Mode of Elliptical Wastage -
85-90% Deep 0° Wrap Angle

COLLAPSE TESTS CONCLUSIONS

All of the collapse pressures of the mechanically defected specimens were higher than would be experienced during a LOCA which is the worst credible collapse mode accident condition. Since any appropriate plugging criteria that would be developed based on the burst data would be conservative from the collapse standpoint, empirical relationships were not derived for predicting the collapse pressures.

LEAK RATE TESTS

According to Regulatory Guide 1.121, the primary-to-secondary leakage rate limit under normal operating pressure is to be set forth in the plant technical specifications and should be less than the leakage rate determined theoretically

or experimentally from the largest single permissible longitudinal crack. In addition, if through-wall cracks with a specified leakage limit occur either on a tube wall with normal thickness or in regions previously thinned by wastage, they should not propagate and result in tube rupture under postulated accident conditions. The purpose of the leak rate tests was to establish data to be used in determining the maximum length of a through-wall crack that is permissible under the above criteria. A schematic of the test setup is shown in Figure 114.

In the leak rate experimental setup the tube was internally pressurized with 600°F water taken from an autoclave which served as a heated pressurized reservoir and was maintained at 3000 psig through use of He gas overpressure. Pressurization of the tube was through a flow regulator valve and flow meter. Leak rates, pressure and temperature for each specimen were recorded every second using the data logger as the pressure to the specimen was increased by opening the flow control valve until maximum capacity of the system was reached. Since critical flow through the slots should be reached at about

FIGURE 114. System for Leak Rate Tests

1000 psi differential, any increase in flow rate for pressure differentials above 1000 psi would indicate widening or lengthening of the slots. No significant lengthening of any of the slots occurred during the tests. However, several of the specimens showed appreciable widening of the slots or fish mouthing.

Two types of results were obtained for the leak rate specimens. Either the slot widened or it did not. For those specimens that did not widen, no plastic deformation of the slot was evident after the tests. Also, there was no appreciable increase in the flow rate for pressures above 1000 psi differential. Data for these specimens are listed in Table 7. For those specimens that widened during testing, plastic deformation was evident after the tests. There was also a marked increase in the flow rate as the pressure increased. Initiation of slot widening was evident by increase in flow rate. Listed in Table 8 are the data for those specimens that fish mouthed. There were large jumps in the pressure, since the increase in pressure was not easily controllable. Therefore, two numbers are listed under the failure pressure column. These represent bracketing values. The lower value is the highest pressure reading before the increase in flow rate. The higher value is the lowest pressure reading after the increase in flow rate.

All of the pressures listed in Table 7 for the initiation of widening of the slots were less than the 2250 psi which could occur during a LOCA. These defects would be unacceptable according to Regulatory Guide 1.121. Those specimens listed in Table 7 that had maximum pressures of greater than 2250 psi would meet the requirement in Regulatory Guide 1.121 that through-wall cracks should not propagate under postulated accident conditions. One of the specimens in Table 7 did not reach 2250 psi due to limitations of the system. It is not certain whether this slot would have widened if pressurized to 2250 psi.

Plots of the data for all leak rate specimens that showed plastic deformation are given in Appendix E. The values listed for the slot widths are values measured at the outside surface and not the minimum values which were usually at the inside surface. Also, several of the slots had widths that

TABLE 7. Leak Rate Specimens With No Slot Widening

Slot Length (in.)	Slot Width (in.)	Elliptical Wastage Depth (% Wall)	Maximum Pressure (psi)	Maximum Flow Rate (gpm)
1/4	0.005-0.008	0	2490	<2
1/4	0.004-0.0065	0	2400	<2
1/4	0.019	30	2630	<2
1/4	0.008	28	2350	<2
1/2	0.006	30	1930	3.5
1/4 ^(a)	0.0035	55	2590	4.5

(a) Very small amount of plastic deformation.

NOTE: Flow meter not calibrated below 2 gpm.

TABLE 8. Leak Rate Specimen With Slot Widening

Slot Length (in.)	Slot Width (in.)	Elliptical Wastage Depth (% Wall)	Initiation of Fish Mouthing (psi)
1/2	0.021-0.025	0	1200 - 1580
1/2	0.006-0.012	0	1200 - 1880
1	0.013	0	800 - 1000
1/2	0.004	27	1260 - 2100
1	0.005-0.010	26	740 - 1000
1	0.006	28	900 - 1300
1/4	0.010	56	1980 - 2500
1/2	0.005	55	1130 - 2000
1/2	0.009	58	840 - 1600
1	0.009-0.012	54	350 - 1420
1	0.007	56	380 - 1100
1/4	0.006	90	1600 - 2080
1/2	0.010	90	940 - 1300

varied along the slot. Therefore, the widths are given only for comparison and should be considered as only approximate for calculating orifice areas.

BULGING TESTS

In addition to the leak rate tests, bulging tests were performed to obtain data on the fish mouthing phenomena. The bulging tests consist of internal pressurization of tubes with through-wall slots. Neoprene bladders inside the tubes allowed pressurization of the tubes. Slot lengths tested were 1/4, 1/2, and 1 1/2 in. The two sizes of tubing used were 0.875 by 0.050 in. and 0.750 by 0.043 in. A grid for detecting local deformation was placed on the specimens using a photo emulsion. Specimens in ambient air were pressurized with room temperature water until the bladder ruptured. Video tapes showing the slot, internal pressure and elapsed time were taken of each specimen.

Until the internal pressure was high enough to widen the slot, the neoprene bladder had to bridge only the 0.003 to 0.004 in. width of the slot and act as a water seal. The tube supported the bladder. However, as the slot started to widen, the neoprene bladder was no longer supported, started to extrude through the slot and soon ruptured. Widening of the slot was caused by plastic deformation around the slot. The pressure at rupture could be a good indication of the onset of significant plastic deformation.

Results of the bulging tests are listed in Table 9. Since the bulging pressure is related to the yield strength of the material and slot length, it should be possible to represent the correlation between the bulging pressure and slot length in dimensionless form. In Figure 115 the bulging pressure has been nondimensionalized by dividing by the pressure required to yield an undefected tube. The length has been nondimensionalized similar to the way used for establishing the empirical correlation for the burst data.

A comparison of the bulging test data and the leak rate data is possible for one particular defect geometry. Both leak rate and bulging tests were performed on 1/2-in.-long through-wall slots in 0.875 x 0.050 tubing. The failure pressure during the bulging tests was 3752 psi for this size slot.

TABLE 9. Bulging Test Results

Tube Size	Slot Length (in.)	Failure Pressure (psi)
0.750 x 0.043	1/2	3300
0.750 x 0.043	1/2	3307
0.750 x 0.043	1 1/2	891
0.750 x 0.043	1 1/2	943
0.875 x 0.050	1/4	6276
0.875 x 0.050	1/4	6435
0.875 x 0.050	1/2	3752
0.875 x 0.050	1 1/2	1036
0.875 x 0.050	1 1/2	989

FIGURE 115. Nondimensionalized Bulge Test Data

For the leak rate tests, slots of this size started to open at between 1200 and 1580 psi, well over a factor of two difference in the two results. There are two reasons for this difference. First, the bulging tests were conducted at room temperatures, while the leak rate tests were conducted at approximately 600°F. Since the widening of the slot is dependent on the yield strength of the tubing, variations in the yield strength with temperature would have an effect. However, as was discussed in the collapse test results, the decrease in yield strength between room temperature and 600°F is only about 12 1/2%. This would not account for the large difference in the results. The second and main reason for the difference in results is that the leak rate data represent the initiation of the slot widening. Since the slots were relatively narrow, small changes in the slot width caused very noticeable changes in the flow rates. However, in the bulging tests, the data represent the pressure at which the slot had widened sufficiently to allow the neoprene bladder to extrude. This required a considerable amount of plastic deformation to occur.

LEAK RATE AND BULGING TEST RESULTS

One of the purposes of both the leak rate and bulging tests was to determine when through-wall slots would start to widen due to internal pressure. The results of the bulging tests are of somewhat limited use, since the failure pressures obtained corresponded to the rupture of the neoprene bladder which occurred only after the slot had widened an appreciable amount. The results of the leak rate tests were better in this respect, since the pressure determined was that at which the slot initially started to widen. However, the exact slot-widening pressure was not determinable and only bracketing pressures were obtained.

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LEAK RATE AND BULGING TEST RESULTS

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EDDY-CURRENT TESTS

The NRC Steam Generator Tube Integrity Program involved the eddy-current inspection of over 500 mechanically defected Inconel 600 tubes that are representative of the tube sizes and material compositions presently being used by the domestic pressurized water reactor Nuclear Steam Supply System (NSSS) manufacturers. The Phase I nondestructive testing and evaluation effort focused upon the single-frequency (400 kHz) eddy-current examination and evaluation of test data for each defect specimen. The data analysis consisted of pattern interpretation and subsequent pattern phase angle evaluation.

An ongoing related program at Battelle, Pacific Northwest Laboratories involves the development of a multifrequency/multi-parameter eddy-current system for the Electric Power Research Institute (EPRI). Because of the availability of the multifrequency system, many defect specimens were tested using this system, the results of which are reported following the single-frequency discussion.

Single-Frequency Eddy-Current Testing

The following discussion describes single-frequency eddy-current theory, system instrumentation, data acquisition, and data display. Eddy-current testing involves placing a coil of electrically conducting insulated wire in close proximity to the material to be inspected. When the test coil is excited by an alternating current, usually sinusoidal, an alternating magnetic flux penetrates the material and induces eddy currents. These eddy currents flow in a preferred direction, depending upon the orientation of the alternating magnetic fields. In general, the currents flow at right angles to the magnetic flux lines.

The induced currents in turn produce a magnetic flux that opposes the magnetic flux of the test coil according to Lenz's law. Therefore, changes in the magnitude and phase of the eddy currents cause corresponding changes in the electrical impedance seen at the test-coil terminals. For example, if a crack is present at the surface of the material, it will alter the flow of eddy currents when the test coil is near the crack. This will change the magnitude and phase of the magnetic flux and in turn alter the electrical impedance of the

test coil. Similarly, changes in electrical resistivity, magnetic permeability, and material thickness will cause changes in the test-coil impedance.

Eddy-current instruments translate these changes in test-coil impedance into output voltages that can be monitored at the instruments' output terminals. Figure 116 is a block diagram illustrating the components of the basic eddy-current instrumentation used to inspect steam generator tubing.

Essential to the instrument is an oscillator that excites the test coils through an alternating current bridge network. The bridge network is designed so that two test coils are driven simultaneously. One coil can be used to interrogate the tubing while the other is fixed, acting as a reference coil; or the coils can be incorporated in the same scanning unit to provide what is commonly referred to as the differential coil system. A differential coil system was employed to inspect the steam generator tubing.

FIGURE 116. Block Diagram of the Basic Eddy-Current System

The differential coil system involves placing annular-shaped test coils adjacent to each other in the axial directions so that both coils induce eddy currents in the test material, as illustrated in Figure 117. The differential bridge network subtracts the alternating voltages associated with one test coil from the voltage associated with the other coil. Consequently, output signals result only when the test coil impedances are different. For example, abrupt changes in the tubing such as holes and short cracks cause impedance differences and therefore a bridge imbalance. This produces a signal at the output of the bridge network. Gradual changes such as temperature gradients and some inside diameter variations cause much smaller changes in the output, depending on the design, construction, and spacing of the test coils.

FIGURE 117. Differential Eddy-Current Test Coil and Current Flow Inside Tubing

Data Acquisition and Display

The vertical (V) and horizontal (H) outputs are simultaneously recorded on a strip chart recorder and FM tape recorder so that the signals can be displayed for interpretation. Also, the V and H outputs are displayed on the oscilloscope with V on the vertical input and H on the horizontal input. This is done to provide some real-time indication signal interpretation and to provide zero or

balance adjustment of both V and H outputs. Adjustments for zero drift compensate for drift and assure that the recorded voltages fall within dynamic range of the instrumentation. The FM recordings provide a means of displaying the V and H output voltages on the memory (storage) oscilloscope at a later time, so that data can be carefully analyzed.

The phase rotation is adjusted before testing steam generator tubes so that transverse movement and tilt of the test coil cause a signal voltage that appears primarily in the H output. Empirical data have indicated that tilt and wobble are similar variables. Tilt and wobble provide a test coil response that is nearly constant in phase but provides a change in the magnitude of the test coil impedance. If one coil is closer to one side of the tube wall than the other, the impedance of the coils will be different, causing an unbalanced condition in the bridge network. This results in a voltage at the H output. A relatively small voltage is seen at the V output for probe wobble after the phase rotation has been adjusted properly.

Flat-bottom holes at various depths and diameters are used to calibrate each probe for measurement of defect depth. After this calibration and the above-described initial phase adjustment, the test probe is ready to scan the tubes. The chart recorder outputs provide indication of defects and their approximate location. The V output is the best indicator, since it displays a minimum amount of output when the probe wobbles. Tube support provides reference signal indications on both the V and H outputs for approximate location of defects.

The output signals from defected areas are reexamined after the scan by playing the FM recorded V and H voltages into the vertical and horizontal inputs of the storage oscilloscope, respectively. Each position of the resultant beam on the oscilloscope screen represents the magnitude and phase of the impedance difference between the two coils. Signals caused by defects and tube supports make figure-8 patterns on the scope and are held by the storage screen until they are erased by manual control.

The figure-8 pattern is a classic result of the dual-coil response. For example, as the first coil approaches a flat-bottomed hole drilled from the outer surface, as used in calibrating the coils, its impedance changes in

magnitude and phase. The magnitude reaches a maximum change when the test coil is centered under the hole. Figure 118 shows how the figure-8 pattern is swept out by the oscilloscope display. Since the signal from the first coil is inverted by the bridge network, the phase of the impedance difference vector sweeps through an angle from the horizontal and rotates into the third quadrant in the counterclockwise direction as it scans over the flat-bottomed hole. As the first coil leaves the hole and the second coil approaches the hole, the phase angle continues the shift in the counterclockwise direction.

Since signals from the two coils are subtracted, the vector theoretically decreases to zero magnitude as the first coil leaves the hole region and the second coil approaches the hole. The zero position is the center of the oscilloscope display. Note that the effect of coil wobble and other unwanted variables prevent an exact zero from occurring. As the second coil scans the flat-bottom hole, a similar image is mapped out in the first quadrant of the oscilloscope screen. Estimation of defect depth is provided by measuring the

FIGURE 118. Dual-Coil Signal Pattern Which Results from Scanning an Outer Diameter Defect

angle ϕ , shown in Figure 118, as measured from the horizontal in a clockwise direction. As the defect depth decreases, the entire signal pattern rotates in the clockwise direction. A through-wall hole causes a relatively small angle of approximately 40 degrees with respect to the horizontal.

Laboratory Instrumentation

A commercially available eddy-current test instrument (an EM-3300) was purchased to perform the single-frequency examinations. This instrument contains the electronic circuitry to drive the inspection coil, the separation circuitry, and a scope display for viewing the signal patterns generated by the H and V components of a defect signal. Several commercial differential bobbin probes were purchased with the eddy-current instrument. These differential probes have center-to-center coil spacing of 0.100 in., while the width of each coil is 0.070 in. The fill factor (η)^(a) was:

- η (heats B,E,F) = 0.86
- η (heat C) = 0.78
- η (heat D) = 0.81
- η (heat G) = 0.87

where the tube heat sizes were:

- heats B,E,F = 0.875 x 0.050 in.
- heat C = 0.750 x 0.043 in.
- heat D = 0.750 x 0.050 in.
- heat G = 0.625 x 0.034 in.

Variations in the fill factor were reflected in eddy-current signal amplitude changes. Figure 119 shows the laboratory equipment: the EM 3300, a Gould Brush 220 strip chart recorder, and the Hewlett-Packard magnetic tape recorder. An existing probe-drive unit was modified to push and pull the eddy-current probe through the tube specimens. The recorders, tube support tray, and other test apparatus were assembled from existing laboratory equipment. In accordance with Section XI, Appendix IV of the ASME Boiler and

$$(a) \left(\eta = \frac{OD \text{ probe}}{ID \text{ tube}} \right)^2$$

(a) CONVENTIONAL EDDY-CURRENT SYSTEM

FIGURE 119. Single-Frequency Eddy-Current Test Equipment

Pressure Vessel Code, all laboratory instrumentation was certified to meet the requirements as set forth in Article IV-3100.

This laboratory system simulates the type of eddy-current system used in field inspections. Actual in-service testing uses a precision device to position the inspection probe at the bottom of the tube sheet. The positioning device is controlled electronically so that the operator need not be in the radiation area unnecessarily. Figure 120 shows a typical eddy-current system in situ for in-service inspection of a steam generator.

The reader should note that the translation speed of the inspection probe through the tube specimens was 1.4 in./sec. By comparison, the typical inspection speed during actual in-service testing is 12 in./sec.

STEAM GENERATOR TUBE IN-SERVICE INSPECTION REQUIREMENTS

U.S. NRC Requirements

Steam generator tube examination requirements are presented in U.S. NRC Regulatory Guide 1.83, "In-service Inspection of Pressurized Water Reactor Steam Generator Tubes." A summary of the current NRC Regulatory Guide 1.83, Revision 1, July 1975, is presented in Table 10.

FIGURE 120. Eddy-Current Test Equipment for In-Service Inspection

Appendix IV of the 1975 Winter Addenda of the ASME Boiler and Pressure Vessel Code's Section XI, entitled "Eddy Current Examination Method for Non-Ferromagnetic Steam Generator Heat Exchanger Tubing," has essentially incorporated requirements identical to U.S. NRC Regulatory Guide 1.83. Appendix IV will eventually become the inspection basis for future steam generator tube inspections. Therefore, Appendix IV procedures were followed during the inspection of all mechanically-defected specimens. It was imperative that the eddy-current data obtained on this program be taken with accepted examination techniques and procedures so that the data can be related to past and future in-service inspection results.

TABLE 10. Steam Generator Eddy Current Test Requirements (In-Service)
per U.S. NRC Regulatory Guide 1.83, Revision 1, July 1975

<u>Inspection</u>	<u>Initial Test</u>	<u>Results</u>	<u>Supplemental Testing</u>
Preservice (baseline)	100% - all generators ^(a)		
First in-service	In each steam generator: 3%	<ol style="list-style-type: none"> 1. More than 10% of tubes tested have indications >20% of wall, <u>or</u> any tubes exceed plugging 2. Other than above 	<ol style="list-style-type: none"> 1. Test additional 3%(b) 2. Testing complete
Subsequent in-service	In one or more steam generators: 3% of tubes in the plant	<ol style="list-style-type: none"> 1. Any indication >20% <u>or</u> any growth of 10% 2. More than 10% of tubes tested have indications >20% or any tubes exceed plugging limit 3. No indications >20% 	<ol style="list-style-type: none"> 1. Test 3% of other (not tested) steam generators 2. Test additional 3% of tubes in that steam generator <u>plus</u> 3% of tubes in other steam generators 3. Testing completed

(a) Documented shop examination of tubing is acceptable.

(b) If results of this testing show additional tubes with indications >20%, or exceeding plugging limit, an expanded test program with notification of regulatory authority is required.

ASME Appendix IV Section XI Boiler and Pressure Vessel Code Requirements

The ASME Section XI, Appendix IV in-service inspection procedure is specific in the requirements for instrument certification and calibration. However, it does not specify the probe style or design that is to be used. Either a differential or absolute probe may be used to perform the inspection. A bobbin-wound differential inspection probe was chosen for inspection because it is the probe most commonly used in field inspections.

The Appendix IV calibration requirement for differential inspection is summarized as follows: With probe motion oriented along the horizontal axis, the response from a 100% through-wall (T) reference hole shall have an amplitude of at least 50% of the full cathode-ray tube (CRT) screen height and shall lie at a phase angle of $40^{\circ} \pm 5^{\circ}$ clockwise from the horizontal. This calibration

step is specified under the premise that the phase angle of a defect signal is related to the depth of the defect in the tube. The depth of a defect is estimated by using the 100% drill hole as a calibration reference, with 80%, 60%, 40%, and 20% flat-bottom drill holes as additional reference data points. The tube calibration standards specified in Appendix IV contain drill holes at these depths and are used to generate a calibration curve-relating pattern phase angle to defect depth. The test frequency is chosen so that a signal from four 20% flat-bottom holes (positioned at 90° increments around the tube) were $120^{\circ} + 10^{\circ} - 30^{\circ}$, phase rotated clockwise from the 100% hole signal.

Calibration standards for each of the four tubing sizes used in the program were manufactured in accordance with Article IV-3200.

A substantial section of Appendix IV addresses data records and reporting procedures that do not necessarily apply to laboratory programs but are more applicable to actual field inspection reporting. Those code procedures pertaining to the actual inspection and calibration were followed as closely as was practicable within the laboratory environment.

EXPERIMENTAL PROCEDURE

Calibration Procedure

Each eddy-current system is calibrated prior to defect specimen testing by passing the differential probe through the appropriate calibration standard. The system is adjusted in accordance with Article IV-3300 requirements for differential probe calibration. As specified in Article IV-3210, a test record of the calibration standard is recorded at the beginning and the end of the magnetic tape recording, at each end of the strip chart roll, and with no more than four hours of inspection time between calibrations. If system adjustment (such as instrument gain) is altered, the system must be recalibrated. In addition, any system component change (e.g., probe replacement) requires recalibration.

Figure 121b shows a typical oscilloscope trace produced at 400 kHz when calibrating the eddy-current system. Shown are the figure-8 patterns produced from inspection of an ASME calibration standard with flat-bottom holes of 20%,

FIGURE 121. Output of Single-Frequency 400 kHz Test As Probe Is Translated Through ASME Calibration Tube With Simulated Support

40%, 60%, 80%, and 100% of wall thickness. The signal from a tube support plate is also shown. Figure 121a is the analog-scan strip-chart output from the calibration. Upon generating the calibration data, a calibration curve is plotted that is used to evaluate defect depth. A typical calibration curve is shown in Figure 122, where the phase angle response produced by a series of standard flat-bottom holes is plotted against the known depths.

Inspection Procedure

The tube specimens are examined by translating the inspection probe through the tube until it completes a scan of the defected area. A record of the instrument response is made as the probe is pulled back through the tube at a constant rate. The instrument response is recorded on the storage scope trace, the strip-chart recorder, and the magnetic tape recorder. A photograph of the scope trace is taken as a permanent record of the scope response for further evaluation of the pattern amplitude and phase angle.

Nonsymmetrical defects (i.e., defects not uniformly distributed around the circumference of the tube, such as elliptical wastage and EDM slots) were examined at three orientations; a separate test record is made for each angle. The specimen is first placed horizontally on the holding tray with the defect oriented at 0° (zenith); then the defect is rotated and tested in the 90° (defect horizontal) and 180° (defect downward) positions. The three test records

obtained in this manner are valuable in averaging out the effects of the probe-to-defect spacing and of orientation variations that can occur as the result of the wobble and misalignment of the probe. These effects can cause variation in the signal pattern size and shape. Averaging these signals helps to reduce uncertainties in evaluation. This approach is obviously not used during actual in-service inspection.

Symmetrical defects, such as uniform thinning, are not orientation-dependent and subsequently did not require multiple scans at alternate positions.

DATA ANALYSIS

The data are characterized by two basic measurements from the signal patterns generated by the defects: the amplitude of the pattern is measured to compare the size of signals from various defect types, and the phase angle of the pattern is measured as an indicator of defect depth.

Phase Angle Measurements

The phase angles of the signals generated by the calibration standard drill holes are measured from a photograph of the scope trace for each defect; pattern phase angles were measured from the horizontal axis clockwise from the estimated center of the pattern. Thus, a 100% drill hole typically has a phase angle of approximately 40° from the horizontal, and a 20% drill hole

FIGURE 122. Typical Single-Frequency Eddy-Current Calibration Curve

registers at approximately 155° . These measured values of each calibration standard serve as reference points for interpreting the data obtained on the defected tube specimens.

The phase angle measurements for the defected specimens are made in the same manner as for the flat-bottom drill hole signals. The phase angles are measured from the photos of the scope signal patterns. This is a normally straightforward measurement procedure in which the phase angle of the signal pattern is easily interpreted. However, in many instances the signal pattern is quite complex, necessitating a subjective estimate of the defect phase angle. For example, signals from stress-corrosion cracking can be extremely complex, as shown in Figure 123. Defects located near or under the supports produce signals that are small in amplitude so that large amplitude support signals mask defect signal indications. Signals from dented regions can readily be detected by eddy-current examination; however, these signals are of such a large magnitude that the denting cannot be quantified and defects near or in dented regions are masked by the large dent signals.

FIGURE 123. Eddy-Current Signals from Stress Corrosion Cracking Specimen

The standard procedure used in this program is to measure the phase angle at the point of maximum amplitude of the signal pattern. This procedure is used for all phase angle measurements, including the calibration signal patterns. For example of the signal indications from EDM slots, elliptical wastage, and uniform thinning, see Figure 124.

Amplitude Measurements

Signal amplitude data provide information that defines the dynamic measurement range the eddy-current instrument should have to assure complete and accurate reproduction of the signal patterns.

Section XI, Appendix IV-3300(a)(1) specifies that the eddy-current instrument should be set at the required frequency and at a sensitivity sufficient to produce a 100% T reference hole response with an amplitude minimum that is 50% of the full screen height, when the scope attenuators are set at the operating level. Many of the defected specimens produced an overdriven signal response at required Section XI sensitivity. On the other hand, many defected specimens produced signals that were barely discernible using this sensitivity. Because evaluation of the phase angle pattern cannot be performed accurately when this situation exists, the system sensitivity had to either be reduced or increased, depending on the magnitude of the original signal. This change in system sensitivity deviates from the requirements of Section XI, Appendix IV, and significantly alters the amplitude readings produced when the gain is adjusted to meet the 100% T standard calibration requirements. Therefore, a recalibration of the system was performed at the new sensitivity setting. The signal amplitudes produced at the new sensitivity setting were then referenced back to the signal amplitude produced from the standard Section XI calibration.

The amplitude is measured from the peak excursion in one direction to the corresponding peak in the opposite direction, as shown in Figure 125.

All defect signal patterns are normalized relative to the amplitude of the signal from the 100% T calibration standard drill hole, which is defined as an amplitude of 1.0. Signal patterns with an amplitude less than the drill hole pattern have a normalized amplitude of less than 1.0. Similarly, larger signal patterns have normalized amplitude values greater than 1.0. The amplitude

FIGURE 124. Eddy-Current Signals from EDM Slot, Elliptical Wastage, and Uniform Thinning Defects

FIGURE 125. Eddy-Current Amplitude Measurement from Analog Strip Chart Recording

measurements obtained in this manner are normalized to allow direct comparison of defect pattern amplitudes for various defect types and sizes.

The results of these measurements have shown that normalized amplitude values ranged from 0.1 to 50.0 and above. Increased signal amplitude is typically the result of increased defect volume.

The procedure of reducing or increasing system sensitivity to facilitate proper signal pattern evaluation can assist in determining the type and severity of specific defects. Typically, high system sensitivity is required to detect EDM slots at 20 to 30% of wall depth and 0.25 to 0.50 in. in length. Large volume defects such as uniform thinning require very low sensitivity.

System Calibration

A plot of pattern phase angle versus flat-bottom hole depth is required for defect depth evaluation. This curve is constructed by plotting the measured phase angle from the series of flat-bottom hole depths, as shown in Figure 122. The specimen defect depth is obtained by measuring the defect pattern phase angle and then reading the indicated defect depth from the graph.

This procedure is only as accurate as the calibration tube standard used to plot the calibration curve. Unfortunately, the calibration tube contains

flat-bottom drill holes at only five depths (100%, 80%, 60%, 40%, and 20%), which limits the accuracy of the curve. It is desirable to have additional holes at depths of 90%, 70%, 50%, 30%, and 10% in the calibration standard to more accurately define the calibration curve. Without the additional data points, standard interpolation methods and subjective assessment must be relied upon to further define the curve.

CALIBRATION RESULTS

The calibration data for the B, C, D, E, F, and G series tubing are presented in Figures 126 through 129, respectively.

A problem that has surfaced pertaining to the calibration curve accuracy concerns the deeper (60% or deeper) flat-bottom drill holes. Note that all of the 80% flat-bottom holes in the calibration tube standards exhibited a slight interior deformation of the wall beneath the drill hole. This deformation is a result of the machining process and interferes with the eddy-current signal from the drill hole, causing a pattern phase shift. As shown in each of the figures, the signal pattern is shifted to a smaller phase angle, indicating a shallower defect. Flat-bottom holes in the 70% range and above require internal tube support in order to eliminate this inconsistency. The typical pattern phase angle for 80% holes is between 90° and 95° .

The ASME Appendix IV-3400 requirements for calibration were not achieved with the G series (0.625 dia. x 0.034 in. wall) tubing at test frequencies of 481 and 576 kHz, as shown in Figure 129. The data show that the 20% flat-bottom hole indication at a calibration frequency of 481 kHz did not fall within the limits of $120^\circ \pm 10^\circ$ to 30° , phase rotated from the signal of 100% T hole as specified in Appendix IV. On the other hand, the 100% T indication at a calibration frequency of 576 kHz did not fall within the limits of $40^\circ \pm 5^\circ$ that is specified in Appendix IV. The reader should note that a difference of 95 kHz from 481 to 576 kHz did not significantly alter the eddy-current response from the tube reference standard. The test frequencies of 481 and 576 kHz were optimum test frequencies in an attempt to meet the calibration requirements of Appendix IV.

FIGURE 126. Calibration Curve for B, E, and F Series (0.875 x 0.050 in.) Inconel 600 Tubing

FIGURE 127. Calibration Curve for C Series (0.750 x 0.043 in.) Inconel 600 Tubing

FIGURE 128. Calibration Curve for
D Series (0.750 x 0.050 in.)
Inconel 600 Tubing

FIGURE 129. Calibration Curve for
G Series (0.625 x 0.034 in.)
Inconel 600 Tubing

EXPERIMENTAL RESULTS

The eddy-current test (ECT) data for EDM slots, uniform thinning, and elliptical wastage are presented in Figures 130 through 134 and in Appendices F, G, and H. The figures show eddy-current indicated depths plotted against the actual measured defect depths; both depths are presented as a percentage of wall thickness. These figures exhibit a wide variance in the data. The solid line represents the linear relationship that would result if all indicated depths were 100% accurate. Points above the line represent overestimations of defect depth, or "conservative" results, while data below the line indicate underestimations, or "unconservative" results.

Single Defect Data

EDM Slot Data

There were 181 EDM slot specimens included in the test matrix (Appendix Tables F.1 through F.9). Each EDM slot was axially oriented along the tube specimen. Twenty-six of the specimens had 100% through-wall slots and the eddy-current inspections results indicated that each tube specimen did have through-wall defects. The remaining 155 specimens had EDM slots with depths between 25% and 95% of wall thickness. Slot length was between 0.25 and 1.50 in.

Table 11 shows a summary of the eddy-current data results for the 155 tube specimens. The data are presented in four categories based on eddy-current measurement accuracy. Category I lists those specimens that had eddy-current indicated depths within 5% of the actual EDM slot depth. Category II lists the percentage of specimens that had eddy-current indicated depths which overestimate the actual slot depth. Category III lists those specimens that had eddy-current indicated depths which underestimate the actual slot depth. Category IV lists those specimens that were undetectable.

Table 11 shows that 40% of the eddy-current indications produced underestimated slot depth measurements. Figure 130 shows the underestimation trend is most prevalent for the deeper 80 to 95% EDM slots, whereas 29% of the 20 to 30% slots were undetectable. The slots that were detected in the 20 to 30% range produced eddy-current indications that overestimated the actual slot

FIGURE 130. Eddy-Current Indicated Defect Depth Versus Actual Depth for EDM Slot Specimens

FIGURE 131. Eddy-Current Indicated Defect Depth Versus Actual Depth for Uniform Thinning Specimens

FIGURE 132. Eddy-Current Indicated Defect Depth Versus Actual Depth for Elliptical Wastage Specimens

FIGURE 133. Eddy-Current Indicated Defect Depth Versus Actual Depth for Denting Plus Elliptical Wastage Specimens

FIGURE 134. Eddy-Current Indicated Defect Depth Versus Actual Depth for Denting Plus Uniform Thinning Specimens

TABLE 11. Eddy-Current Measurement Accuracy for EDM Slot Tubes

Category	Eddy-Current Measurement Accuracy	
	Specimens	% of Total
I (within 5%)	22	14
II (overestimate)	26	17
III (underestimate)	62	41
IV (undetectable)	45	31
	155	100%

depth. Only 14% of the specimens had eddy-current indicated accuracy within 5% of the actual slot depth.

Uniform Thinning Data

There were 63 uniform thinning specimens included in the test matrix (see Appendix Tables F-10 through F-12). Table 12 shows a summary of the eddy-current data for 63 uniform thinning specimens. The data are presented in four categories based on eddy-current measurement accuracy.

Table 12 shows that 97% of these eddy-current measurements overestimated the true defect depth. Only 3% of the measurements were within 5% of the actual defect depth. These results are shown graphically in Figure 131..

Elliptical Wastage Data

There were 119 elliptical wastage specimens included in the test matrix (see Appendix Tables F-13 through F-18). Table 13 shows a summary of the eddy-current results, which are presented in four categories based on eddy-current measurement accuracy.

Table 13 and Figure 132 show that for elliptical wastage defects the majority of eddy-current indications either overestimated or underestimated the true defect depth. It is interesting to note that four specimens remained undetectable, even though the sensitivity of the EM 3300 was at maximum. Each of the undetected specimens had a zero degree wrap angle; a small gradual transition existed between the non-flowed and flowed section of the tube. The

TABLE 12. Eddy-Current Measurement Accuracy
for Uniform Thinning Tubes

Category	Eddy-Current Measurement Accuracy	
	Specimens	% of Total
I (within 5%)	2	3
II (overestimation)	61	97
III (underestimation)	0	0
IV (undetectable)	<u>0</u>	<u>0</u>
	63	100%

TABLE 13. Eddy-Current Measurement Accuracy
for Elliptical Wastage Tubes

Category	Eddy-Current Measurement Accuracy	
	Specimens	% of Total
I (within 5%)	21	18
II (overestimation)	42	35
III (underestimation)	51	43
IV (undetectable)	<u>5</u>	<u>4</u>
	119	100%

elliptical wastage defect was between 26% and 30% of wall, with the defect length approximately two inches.

Single Defect Data Trends

The data show that there is a significant degree of eddy-current measurement inaccuracy for single well-defined defects in straight section tubing. Only 13% of the total number of specimens tested (337) had eddy-current indications within 5% of the actual defect depth. Equally important is the fact that 15% of the total specimens were not detected using maximum eddy-current system sensitivity. The defect depths for a majority of specimens were either over- or underestimated. Table 14 is a summary of the EDM, uniform thinning, and elliptical wastage data trends.

The eddy-current measurement error is plotted against actual defect depth for EDM slot, uniform thinning and elliptical wastage defects in Figures 135 to 137.

Figure 138 shows the overall measurement error trends for all 337 single defect specimens. These are the significant trends:

- Defects between 20% and 35% in depth tended to produce overestimated eddy-current results. Measurement errors as large as 100% were recorded at this depth range.
- Defects that were 50% to 65% in depth tended to produce underestimated eddy-current results. Measurement errors as large as 95% were recorded in this depth range.

FIGURE 135. Eddy-Current Indicated Measurement Error for EDM Slot Defects

FIGURE 136. Eddy-Current Indicated Measurement Error for Uniform Thinning Defects

FIGURE 137. Eddy-Current Indicated Measurement Error for Elliptical Wastage Defects

FIGURE 138. Eddy-Current Indicated Measurement Error for Single Defect Specimens

TABLE 14. Summary of Eddy-Current Measurement Accuracy for EDM, Uniform Thinning, and Elliptical Wastage Tubes

Category	ECT Measurement Accuracy (% of Total Specimens)			
	EDM	Uniform Thinning	Elliptical Wastage	All Defects
I (within 5%)	14	3	18	13
II (overestimated)	17	97	35	38
III (underestimated)	40	0	43	34
IV (undetectable)	29	0	4	15
	100%	100%	100%	100%
Total No. of Specimens	155	63	119	337

- Defects that were 77% to 94% in depth tended to produce underestimated eddy-current results. Measurement errors as large as 50% were recorded in this depth range.
- All through-wall EDM slots were recorded at 100% depths.

The probability of detecting defects in steam generator tubing is of interest because undetected non-through-wall defects could ultimately penetrate tube walls and result in costly plant shutdowns and repairs. Figure 139 shows the probability of detecting EDM slots, elliptical wastage, and uniform thinning defects using state-of-practice eddy-current testing techniques. The detection probability increases with increasing defect volume. Electro-discharge machined slots between 20% and 31% in depth (axial lengths between 0.25 and 1.50 in.) had a detection probability of 0.13.

The defect data for EDM slot, elliptical wastage, and uniform thinning are useful in qualifying the single-frequency eddy-current test. It is evident that four basic test uncertainties exist with the eddy-current technique. The data show that:

- Small crack-type defects have a high probability of not being detected;
- Eddy-current testing can substantially overestimate defect depth;
- Eddy-current testing can substantially underestimate defect depth;

FIGURE 139. Eddy-Current Indicated Probability of Detection for EDM, Elliptical Wastage, and Uniform Thinning Defects

- Eddy-current testing can reliably detect medium and large wastage defects in straight section tubes;
- Denting and support plate signals preclude evaluation of defects.

The Nuclear Regulatory Commission has specific requirements concerning in-service eddy-current testing of steam generators. The U.S. NRC Regulatory Guide 1.83 outlines the required inspection steps. For the first in-service inspection (see Table 10) 3% of the tubes of each steam generator must be tested. Typical Westinghouse Series 44 or 51 designed generators contain approximately 3400 tubes per generator. Thus 3%, or 100 tubes, are to be inspected per generator at the first in-service examination. For the first in-service inspection (ISI) Regulatory Guide 1.83 allows no more than 10% of the inspected tubes to have eddy-current indications greater than 20% of the wall. If any tubes exceed the plugging limit, then an additional 3% of the uninspected tubes must be tested. The single defect data show that defects 20% to 35% in depth tend to be overestimated (Figure 138 shows measurement error as large as 100%). Therefore, if 10% or 10 tubes produce eddy-current indications greater than the 20% threshold, inspection of an additional 3% of the tubes is required. The overestimation trend (Figure 138) shows that additional supplemental testing may not be warranted. Additional testing must be performed if one eddy-current indication exceeds the plugging limit.

Table 15 shows that subsequent in-service inspections have requirements similar to those of the first ISI with some added criteria. Any indication exceeding 20% of wall thickness requires testing 3% of the previously untested tubes. This is required, also, if a single tube has been determined to have a defect growth rate of 10%.

Analogous comments can be stated concerning the overestimation trend and the plugging of tubes. Plugging limits vary, and are established by each public utility. Limits typically range between 45 and 50% of wall depth; however, limits as low as 30% (for suspect intergranular cracking of tubes) have been used.⁽⁶⁾ The data in Figure 26 show that defect depths could be either over- or underestimated with equal frequency. This could result in either of two possible events: 1) if the eddy-current indication underestimates a defect that in fact exceeds the plug limit, then the tube is left unplugged when it should

TABLE 15. Eddy-Current Test Uncertainties and Impacts on Plant Operation

<u>Eddy-Current Test Uncertainties</u>	<u>Impacts on Plant Operation</u>
Defects undetected	Loss in plant efficiency
Eddy-current defect overestimated	Unnecessary increased testing
Eddy-current defect underestimated	Increase in personal radiation exposure
Defect detected - unable to evaluate defect depth	Cost in additional inspection, evaluation, and repair
	Large loss in power revenue during shutdown
	Wrong tube(s) plugged
	Faulty plug repair (continued leaking)
	Plant shutdown due to loose parts from tube repair effort
	Tremendous cost of generator(s) replacement.

be removed from service; or 2) if the eddy-current indication over-estimates a defect, then a tube is plugged unnecessarily.

Table 15 is a list of eddy-current test uncertainties and a related list showing how these measurement uncertainties impact plant operation.

MULTIPLE DEFECT DATA

Denting

There were 15 denting specimens included in the test matrix. The reduction in tube diameter to simulate the denting phenomena measured between 0.040 and 0.050 in. Denting exceeding 0.050 in. of wall has been reported to exist; inspection probe travel through some tubes has been restricted. Many tubes have been plugged due to severe denting of tubes.

Denting specimens were included in the test matrix to determine what effect denting has on the burst properties of Inconel 600 tubing. The results of burst testing the 15 dented specimens showed that the denting had little effect on the tube burst pressure.

The 15 dented specimens all produced very large eddy-current amplitude signals that overdrive the EM 3300 at all but the lowest sensitivity settings. Therefore, the large denting indications mask and distort defect signals near

and in tube support regions. In order to view the total denting indication on the EM 3300 storage scope, very low sensitivities are used, making cracks and small wastage defects more difficult to detect. A discussion of eddy-current results for elliptical wastage and uniform thinning defects adjacent to the dented region follows.

Denting With Elliptical Wastage

Denting with elliptical wastage is considered a compound or multiple defect indication. An attempt to identify and evaluate 24 specimens with elliptical wastage defects adjacent to the dent is shown in Figure 140 (see Appendix Table G.2 for denting with elliptical wastage data). Table 16 summarizes the denting with elliptical wastage eddy-current data into five categories similar to those of the single-frequency eddy-current data. Category V lists eddy-current indications that were uninterpretable.

The data in Table 16 show that the majority of elliptical wastage defects are overestimated in depth when the wastage is adjacent to the dented region of the tube. In addition, Table 16 shows that 34% of the wastage indications were uninterpretable.

Denting With Uniform Thinning

There were 24 denting with uniform thinning specimens included in the test matrix. The uniform thinning defect was located adjacent to the dented region. Table 17 (see Appendix Table G.4 for denting with uniform thinning data) summarizes the denting with uniform thinning eddy-current data into five categories. Figure 141 shows a plot of the eddy-current indicated defect depth versus the actual uniform thinning defect depth.

The data in Table 17 show that the majority (92%) of uniform thinning defects were overestimated in depth. These results are similar to the data for single defect trends in which 97% of the defects in uniform thinning tubes were overestimated.

Data Trends for Denting With Wastage Defects

A summary of the denting with elliptical wastage and uniform thinning eddy-current data is presented in Table 18.

FIGURE 140. Eddy-Current Indicated Defect Depth Versus Actual Depth for Denting With Elliptical Wastage Defects

TABLE 16. Eddy-Current Measurement Accuracy for Denting and Elliptical Wastage Tubes

Category	Eddy-Current Measurement Accuracy	
	Specimens	% of Total
I (within 5%)	0	0
II (overestimated)	14	58
III (underestimated)	2	8
IV (undetectable)	0	0
V (uninterpretable)	8	34
	24	100%

TABLE 17. Eddy-Current Measurement Accuracy for Denting With Uniform Thinning Tubes

Category	Eddy-Current Measurement Accuracy	
	Specimens	% of Total
I (within 5%)	0	0
II (overestimated)	22	92
III (underestimated)	1	4
IV (undetectable)	0	0
V (uninterpretable)	1	4
	24	100%

FIGURE 141. Eddy-Current Indicated Defect Depth Versus Actual Depth for Denting With Uniform Thinning Defects

TABLE 18. Summary of Eddy-Current Measurement Accuracy for Denting With Wastage Defects

Category	Eddy-Current Measurement Accuracy (% of Total Specimens)		
	Denting & Elliptical Wastage (EW)	Denting & Uniform Thinning (UT)	Denting & Wastage (EW, UT)
I (within 5%)	0	0	0
II (overestimated)	58	92	75
III (underestimated)	8	4	6
IV (undetectable)	0	0	0
V (uninterpretable)	34	4	19
	100%	100%	100%
Total No. of Specimens	24	24	48

Table 18 shows that an eddy-current overestimation trend is seen when wastage defects are located near the dented region. It is important to note that 19% of the eddy-current signals could not be interpreted.

Figures 142 and 143 show plots of the eddy-current defect depth measurement error versus the actual defect depth. Note that the eddy-current measurement error in Figure 143 for denting with uniform thinning specimens with 25 to 30% deep defects was as large as a 261% overestimation of defect depth.

Elliptical Wastage With EDM Slot

There were 92 elliptical wastage with EDM slot specimens included in the test matrix (see Appendix Tables F.19 and F.20). EDM slots were induced in the center of the elliptical wastage area (refer to Figure 3). All but two of the specimens had through-wall EDM slots. As expected, the eddy-current test indicated that all of the through-wall slots were 100% in depth.

Defect Length Measurements

As part of the eddy-current examination of steam generator tubing, analog eddy-current signal information is continuously recorded using a strip chart

FIGURE 142. Eddy-Current Measurement Error for Denting With Elliptical Wastage

FIGURE 143. Eddy-Current Measurement Error for Denting With Uniform Thinning

recorder. The recorder is synchronized with the probe pusher/puller electronics so that the defect location (as a function of the distance traveled up the tube) can be determined. Defect length can also be determined by measuring the strip chart. Figure 144 shows a typical differential-coil analog-output signal from a uniformly thinned tube. Defect length can be determined by taking either the in-phase or quadrature analog signal and measuring the distance between the peak excursions as shown in Figure 144. Defect length information is particularly important with regard to the ability of the defective tube to withstand "worst case" burst conditions (main stream or freshwater line rupture and safe shutdown earthquake) and collapse conditions (loss of reactor coolant accident and a safe shutdown earthquake).

Figure 145 shows the burst and collapse testing results for Heat B (0.875 x 0.050 in.) uniformly thinned tubing plotted against the actual length of the defect in the tube. Both plots show a definite relationship between defect length and the burst and collapse pressures for uniformly thinned tubes. This relationship is exponential in nature and asymptotically approaches a minimum value at 1.50 in. It is apparent that defects of 1.50 in. in length can be considered infinitely long defects. Also plotted in Figure 145 are the

FIGURE 144. Eddy-Current Defect Length Measurement for Uniform Thinning Specimen

FIGURE 145. Burst Pressure Versus Defect Length for Uniform Thinning Heat B (0.875 x 0.050) Tubing

eddy-current measured defect length data, which are determined from the analog signal information.

The burst data of Figure 145 show that for tubes with defect wastage of 70 to 80% of wall, a factor of 3.36 exists between the burst pressure of an undetected tube and that of a tube with a 1.50 in. defect at 70 to 80% in depth. Likewise, for tubes with defect wastage of 55 to 60% and 25 to 30% of wall, factors of 1.95 and 1.32 exist respectively between the burst pressure of an undetected tube and the burst pressure of a tube with a 1.50 in. defect.

Analysis of the collapse data of Figure 146 shows that for tubes with defect wastage of 70 to 80% of wall, a factor of 2.78 exists between the collapse pressure of an undetected tube and a tube with a 0.75 in. defect. The data for tubes with defect wastage of 55 to 60% of wall and 25 to 30% of wall have factors of 1.90 and 1.15 respectively between collapse pressure of the undetected tube and the collapse pressure of a tube with a 1.50 in. defect.

FIGURE 146. Collapse Pressure Versus Defect Length for Thinning Heat B (0.875 x 0.050) Tubing

There are several data points in Figure 146 (i.e., B-42-7, B-42-9, B-48-5, and B-08-5) where the collapse pressure for defective tubes is as great as the coolant pressure achieved with undefected tubing. These inconsistencies may be attributed to several factors; one factor may be incorrect test procedures. Regardless, the trend of the data is that of a decreasing exponential. Additional testing in the Phase II program will further assist in verifying the collapse test results.

A similar exponential relationship showing the burst pressure versus the defect length for Heat B data for EDM slots is shown in Figure 147. The results of burst testing for uniform thinning and EDM slot defects, Heats C, D, E, F and G, are presented in Appendix F. In addition, Figure 148 shows the collapse pressure versus defect length for EDM slot Heat B data. The data show that there are no significant changes in tube collapse pressure for tubes with defect

FIGURE 147. Burst Pressure Versus Defect Length for EDM Slot Heat B (0.875 x 0.050) Tubing

FIGURE 148. Collapse Pressure Versus Defect Length for EDM Slot Heat B (0.875 x 0.050) Tubing

depths ranging from 25 to 85% of wall thickness, and defect lengths between 0.25 in. to 1.50 in. Similar results were achieved while collapse testing Heats C, D, E, F and G, which are presented in Appendix F.

As a result of the machining process, all elliptical wastage defects had lengths approaching two inches. Because of this limitation in defect length, no definitive relationship could be derived from the data. However, based upon uniform thinning data, it is anticipated that the effects of defect length can be shown with further testing.

Figures 149 and 150 show plots of burst and collapse pressure versus maximum wall degradation (% wall) for Heat B series tubing. Figures 149 and 150 show that burst and collapse pressures decrease as defect wastage increases. Similar results are shown in Appendix F for Heats C, D, E, F and G.

In summary, the data show that an exponential relationship between tube burst pressure and defect length exists for uniform thinning and EDM slot type defects. The tube burst pressure decreases exponentially as the defect length increases and approaches a symptotic value at 1.50 in. In addition, the data show that for elliptical wastage defects the tube burst pressure depends on the maximum wall degradation. Note that the burst pressure is 2250 psi for 70 to 85% degraded EDM slot defected tubes (Heat B) with defect lengths approaching one inch.

The worst credible burst-mode accident condition is a main stream or feedwater line rupture that could result in a maximum postulated differential burst pressure of 2250 psi. The data show that 70 to 85% deep EDM slot defects, with lengths of one inch or greater, have a significant probability of bursting under worst credible plant accident conditions.

The collapse data show that for uniform thinning defects the tube collapse pressure decreases exponentially when defect length is increased, and it approaches a symptotic value at 1.50 in. The EDM slot defect data have shown that defect length has no effect on collapse pressure. Likewise, elliptical wastage data show that defect length has no effect on collapse pressure. The collapse pressure for elliptical wastage defects can be related to defect depth; decreases in collapse pressure result from increases in defect depth.

FIGURE 149. Burst Pressure Versus Maximum Degradation for Elliptical Wastage Heat B (0.875 x 0.050) Tubing

FIGURE 150. Collapse Pressure Versus Maximum Degradation for Elliptical Wastage Heat B (0.875 x 0.050) Tubing

A summary of the relationships between burst and collapse pressure versus defect length for uniform thinning, EDM slots, and elliptical wastage is shown in Table 19.

TABLE 19. Relationship Between Burst and Collapse Pressure Versus Defect Length for Uniform Thinning, EDM Slot, and Elliptical Wastage

<u>Defect Type</u>	<u>Burst Pressure Versus Defect Length Relationship</u>	<u>Collapse Pressure Versus Defect Length Relationship</u>
Uniform Thinning	Decreasing exponential	Decreasing exponential
EDM Slot	Decreasing exponential	No effect
Elliptical Wastage	(a)	(a)

(a) Only limited length data were available for elliptical wastage defects so defect length relationships are not stated.

The collapse pressure is below 2000 psi for 70 to 85% degraded uniformly thinned tubes (Heat B) with defect lengths approaching one inch. However, the worst credible collapse mode accident condition (a Loss of Reactor Coolant Accident, LOCA) could only result in a maximum postulated differential collapse pressure of 1250 psi. All of the collapse pressures of the mechanically defected tubes were greater than would be experienced during a plant LOCA.

The defect length measurement error based on the analog eddy-current signal data was $\pm 6.50\%$ for Heat B uniformly thinned tubes and $\pm 16.10\%$ for Heat B EDM slot defected tubes. The defect length measurement error for 0.75-in. to 1.50-in. defects is typically $\pm 5\%$.

One must begin to realize the merit of engineering research and development in order to improve eddy-current measurement accuracy and precision. If defects in steam generator tubing could be accurately profiled (i.e., defect depth and length) using eddy-current inspection, better quantitative evaluation of tube integrity would result.

A summary of the relationships between burst and collapse pressure versus defect length for uniform thinning, ELM spots, and elliptical wastage is shown in Table 19.

TABLE 19: Relationship Between Burst and Collapse Pressure Versus Defect Length for Uniform Thinning, ELM Spots, and Elliptical Wastage

Defect Type	Burst Pressure Versus Defect Length Relationship	Collapse Pressure Versus Defect Length Relationship
Uniform Thinning	Decreasing exponential	Decreasing exponential
ELM Spot	Decreasing exponential	No effect
Elliptical Wastage	(a)	(a)

(a) Only limited length data were available for elliptical wastage defects so defect length relationships are not stated.

The collapse pressure is below 2000 psi for 70 to 85% degraded uniformly thinned tubes (Heat B) with defect lengths approaching one inch. However, the worst credible collapse-mode accident condition (a loss of Reactor Coolant Accident, LOCA) could only result in a maximum postulated differential collapse pressure of 1250 psi. All of the collapse pressures of the mechanically tested tubes were greater than would be experienced during a plant LOCA. The defect length measurement error based on the analog eddy-current signal data was $\pm 0.50\%$ for Heat B uniformly thinned tubes and $\pm 0.10\%$ for Heat B ELM spot affected tubes. The defect length measurement error for 0.75-in. to 1.50-in. defects is typically $\pm 2\%$.

One must begin to realize the merit of engineering research and development in order to improve eddy-current measurement accuracy and precision. If defects in steam generator tubing could be accurately profiled (i.e., defect depth and length) using eddy-current inspection, better quantitative evaluation of tube integrity would result.

CHEMICAL DEFECTING STUDIES

One of the tasks to be completed during the first year of this program was a feasibility study to establish methods for chemical defecting of the tubing. Chemical defects of interest are stress corrosion cracking, intergranular attack, pitting, general wastage and denting. Methods for creating all types of defects required have been completed. The following is a brief description of the processes involved:

Stress Corrosion Cracking

Sensitized Tubing - Tubing is exposed to polythionic acid ($H_2S_xO_6$, $x = 3, 4, \text{ or } 5$) at room temperature (elevated temperature decomposes acid) with stress at yield strength, to produce intergranular stress cracking. Polythionic acid is prepared by either:

- sparging H_2O with SO_2 through glass frit for several hours and then sparging with H_2S , or
- sparging H_2S through glass frit into sulfurous acid (H_2SO_3). See Figure 151.

Unsensitized Tubing - Tubing is externally exposed to 10% NaOH at $290^{\circ}C$ in the presence of Cu dust and internally stressed at 90% to 110% of yield. Exposure time is 8 to 32 hours.

Intergranular Attack

Sensitized Tubing - Tubing is exposed to boiling solutions of ferric sulfate (Fe_2SO_4 , 0.08 M) and sulfuric acid (H_2SO_4 , 1.9 M) for periods up to 24 hours. Sensitization periods ranged from 1 hour at $600^{\circ}C$ to 4 hours at $700^{\circ}C$. Longer time periods and hotter conditions in sensitization caused more severe intergranular attack. (See Figure 152.)

Unsensitized Tubing - Tubing is exposed to 25% solution of boiling nitric acid (HNO_3). A potential of 290 mV is applied at start-up to initiate attack by allowing penetration of naturally protective oxide on the specimen. This potential is gradually reduced during the first half hour to approximately 24 mV which is maintained during the wastage. Wastage occurred by grain dropping. (See Figure 153.)

STRESS CORROSION CRACKING

ENVIRONMENT: SENSITIZED 700°C, 2 hr.
POLYTHIONIC ACID, 25°C,
WITH INTERNAL STRESS OF 65% YIELD STRENGTH

500 X

250 X
ETCHED

FIGURE 151. Stress Corrosion Cracking of Sensitized Inconel 600 Tubing

INTERGRANULAR ATTACK - SENSITIZED TUBING

ENVIRONMENT: $\text{Fe}^{3+} - \text{H}^+$, BOILING SOLUTION, 24 hr.

FIGURE 152. Intergranular Attack of Sensitized Inconel 600 Tubing

INTERGRANULAR ATTACK - UNSENSITIZED TUBING

ENVIRONMENT: 25% BOILING HNO_3 , 72 hr.

FIGURE 153. Intergranular Attack of Unsensitized Inconel 600 Tubing

Pitting

Asbestos Tape Method - Soak asbestos tape in 1 M cupric chloride (CuCl_2) overnight. Wrap tape around tubing and leave 24 to 48 hours. No applied current directly. (See Figure 154.)

Cupric Chloride Solution Method - Protect area to be unexposed with teflon tape. Place in 1 M CuCl_2 solution and apply 3 to 6 mA/cm^2 current density. (See Figure 155.) An alternate method which eliminates the ridge produced at the teflon tape boundary is to use two oils with densities bracketing that of the CuCl_2 solution and to agitate the solution slightly.

General Wastage

Prepare solution of 1 part H_2O_2 , 2 parts HCl and 3 parts H_2O by volume. Exposure time is 1 to 4 hours at 25°C . If electropolishing is desired, place in 80% phosphoric acid, 20% sulfuric acid with applied current density of 1 amp/cm^2 or less. See Figure 156. Elliptical wastage is accomplished by the use of an epoxy mask.

Denting

Prepare 500 ml of a solution that is 1 M Na_2HPO_4 , 0.25 M FeCl_3 , 0.05 M NiCl_2 and 0.05 M FeC_2 . Filter and dry. Pack into crevice between split ring carbon steel block and tubing.

1 m CuCl_2 SOLUTION

FIGURE 154. Pitting of Inconel 600 Tubing Using Asbestos Tape Method

- 1) $i_d = 3.0 \text{ mA/cm}^2$, 24 hr.
- 2) $i_d = 3.0 \text{ mA/cm}^2$, 24 hr.
- 3) $i_d = 6.0 \text{ mA/cm}^2$, 3 hr.
 3.0 mA/cm^2 , 18 hr.

Fig. 154

FIGURE 155. Pitting of Inconel 600 Tubing Using Cupric Chloride Solution Method

ASBESTOS TAPE SOAKED
IN 1 m CuCl_2

Fig. 155

UNIFORM THINNING

$\text{H}_2\text{O}_2/\text{HCl}$ AQUEOUS SOLUTION

FIGURE 156. General Wastage of Inconel 600 Tubing

REFERENCES

1. D. Van Rooyen and J. B. Weeks, Denting of Inconel 600 Steam Generator Tubes in Pressurized Water Reactors, BNL-NUREG-2194, Brookhaven National Laboratory, Upton, New York, October 1976.
2. J. C. Newman, Jr., "Fracture Analysis of Surface and Through Cracks in Cylindrical Pressure Vessels," NASA TN D-8324, December 1976.
3. O. Heise and E. P. Esytergar, "Elastoplastic Collapse of Tubes Under External Pressure," ASME Journal of Engineering for Industry, Vol. 92, No. 4, p. 735-742, November 1970.
4. A. P. Carman and Carr, "Resistance of Tube to Collapse," University of Illinois Eng. Exp. Stu. Bulletin No. 17, 1906.
5. Nuclear Power Experience, Encino, California, Volume PWR-2, Section V.D., p. 42, June 1976.

UNIFORM THINNING

H₂O VINYL ACRYLATE SOLUTION

FIGURE 166. General Walling of Inconel 600 tubing

REFERENCES

1. U. Van Rooyen and J. B. Weeks, "Design of Inconel 600 Stress Resistant Tubes in Pressurized Water Reactors," NRC-4539, Brookhaven National Laboratory, Upton, New York, October 1978.
2. J. C. Newman, Jr., "Fracture Analysis of Surface and Through Cracks in Cylindrical Pressure Vessels," NASA TN D-8324, December 1978.
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4. A. P. Garmann and G. R. "Resistance of Tube to Collapse," University of Illinois Eng. Exp. Stu. Bulletin No. 17, 1966.
5. Nuclear Power Experiments, Enrico, California, Volume PWR-2, Section V.D., p. 42, June 1978.

APPENDIX A

MATERIAL CHARACTERIZATION TESTS

TABLE A-1. ASTM Tube Tensile Results

Heat	Tube Size	Yield Stress (ksi)	Ultimate Stress (ksi)
B	0.875 in. x 0.050 in.	47.4	92.5
		47.8	92.6
		47.2	92.2
		48.6	94.9
		47.2	92.8
		47.6 Avg.	93.0 Avg.
C	0.750 in. x 0.043 in.	52.5	97.6
		51.2	96.9
		53.4	97.4
		--	99.0
		52.5	98.0
		52.4 Avg.	97.8 Avg.
D	0.750 in. x 0.050 in.	69.1(a)	96.6
		48.4	95.9
		48.1	96.1
		48.6	96.2
		49.3	98.5
		48.6 Avg.	96.7 Avg.
E	0.875 in. x 0.050 in.	41.4	99.3
		44.8	98.7
		44.8	98.8
		43.3	98.8
		43.3	97.9
		43.5 Avg.	98.7 Avg.
F	0.875 in. x 0.050 in.	41.0	97.3
		41.1	98.1
		40.2	96.9
		38.3	95.4
		38.3	95.0
		39.8 Avg.	96.5 Avg.
G	0.625 in. x 0.034 in.	50.9	98.6
		53.1	99.3
		52.8	99.6
		53.0	100.9
		53.1	100.0
		52.6 Avg.	99.7 Avg.

(a)Not included in average

TABLE A-2. Ring Tensile Test Results

Specimen Number	Yield Stress (ksi)	Ultimate Stress (ksi)
B-03-1	51.4	94.7
B-04-1	53.6	94.1
B-06-1	53.1	93.6
B-07-1	53.2	93.7
B-08-1	49.7	92.9
B-09-1	51.8	92.7
B-12-1	49.7	93.6
B-13-1	53.0	94.2
B-16-1	52.1	93.7
B-18-1	52.7	94.0
B-19-1	51.6	92.1
B-21-1	50.6	92.5
B-22-1	54.0	93.6
B-25-1	51.0	93.5
B-27-1	52.9	92.7
B-28-1	52.9	94.0
B-29-1	54.0	94.9
B-31-1	52.8	94.5
B-32-1	55.8	95.6
B-33-1	53.5	93.4
B-35-1	53.2	94.6
B-36-1	50.7	93.8
B-37-1	53.3	94.1
B-38-1	NA	94.7
B-39-1	56.8	95.8
B-40-1	52.4	94.3
B-41-1	54.9	92.6
B-42-1	53.1	94.6
B-43-1	55.3	94.6
B-44-1	53.8	93.1
B-48-1	54.1	94.4
B-52-1	51.0	93.0
B-53-1	53.7	94.5
B-54-1	53.0	94.5
B-56-1	57.3	93.5
B-60-1	NA	92.7
B-70-1	55.5	94.6
Heat B Average:	52.9	93.9

TABLE A-2. (contd.)

Specimen Number	Yield Stress (ksi)	Ultimate Stress (ksi)
C-03-1	60.2	99.3
C-08-1	59.4	99.0
C-11-1	59.2	99.1
C-14-1	60.9	98.0
C-18-1	56.9	97.6
C-27-1	61.9	98.6
C-31-1	62.3	99.4
C-36-1	61.9	98.2
C-40-1	61.1	99.1
C-44-1	60.7	99.1
Heat C Average:	60.5	98.7
D-01-1	53.2	94.6
D-03-1	51.4	96.2
D-04-1	53.0	97.8
D-08-1	53.2	95.7
D-09-1	56.3	95.2
D-11-1	53.8	95.0
D-12-1	53.2	96.6
D-13-1	51.3	93.9
D-15-1	51.2	94.8
D-17-1	50.6	95.5
D-19-1	52.4	96.8
D-22-1	50.3	95.1
D-23-1	48.1	95.0
D-25-1	57.3	94.9
D-26-1	58.1	97.2
D-29-1	58.1	100.3
D-31-1	56.5	97.5
D-34-1	57.8	97.7
D-35-1	56.6	98.3
D-39-1	59.8	97.8
D-41-1	56.6	98.7
D-45-1	57.6	97.7
Heat D Average:	54.4	96.5

TABLE A-2. (contd.)

Specimen Number	Yield Stress (ksi)	Ultimate Stress (ksi)
E-02-1	52.1	99.6
E-03-1	49.0	98.7
E-04-1	53.8	98.2
E-05-1	52.3	98.1
E-06-1	53.5	98.4
E-09-1	53.4	99.7
E-14-1	53.4	99.5
E-15-1	59.9	99.7
Heat E Average:	52.3	99.0
F-01-1	47.5	95.7
F-03-1	47.1	97.4
F-04-1	47.6	96.1
F-06-1	46.7	94.7
F-07-1	49.2	95.8
F-09-1	45.6	95.4
F-10-1	46.4	94.8
Heat F Average:	47.2	95.7
G-02-1	57.2	96.8
G-05-1	60.5	98.8
G-07-1	65.7	99.9
G-12-1	64.5	96.8
G-13-1	59.8	100.4
G-14-1	59.8	100.2
G-15-1	58.6	98.3
G-16-1	63.6	101.4
G-18-1	60.7	100.3
G-22-1	60.7	99.1
G-28-1	60.8	99.1
G-30-1	64.1	100.9
G-31-1	65.6	101.6
G-34-1	59.0	99.4
G-35-1	61.8	99.9
G-36-1	61.1	100.1
Heat G Average:	61.5	99.6

TABLE A-3. Diamond Pyramid Hardness (DPH)

Ring Specimen Number	First Indent	Second Indent	Average
B-03-1	223	214	218
B-04-1	229	226	227
B-06-1	221	223	222
B-07-1	228	219	223
B-08-1	218	221	219
B-09-1	219	217	218
B-12-1	215	228	221
B-13-1	224	227	225
B-16-1	216	216	216
B-18-1	221	217	219
B-19-1	224	223	223
B-21-1	214	223	218
B-22-1	220	219	219
B-25-1	214	223	218
B-27-1	213	218	215
B-28-1	222	232	227
B-29-1	234	229	231
B-31-1	219	216	217
B-32-1	227	214	220
B-33-1	224	220	222
B-35-1	220	214	217
B-36-1	219	217	218
B-37-1	227	247	237
B-38-1	227	225	226
B-39-1	227	221	224
B-40-1	219	220	219
B-41-1	220	223	221
B-42-1	231	222	226
B-43-1	223	221	222
B-44-1	215	216	216
B-48-1	216	223	219
B-52-1	222	223	223
B-53-1	227	240	234
B-54-1	223	235	229
B-56-1	237	231	234
B-60-1	225	244	235
B-70-1	218	215	217

TABLE A-3. (contd.)

Ring Specimen Number	First Indent	Second Indent	Average
C-03-1	240	235	237
C-08-1	225	248	237
C-11-1	238	233	235
C-14-1	229	232	230
C-15-1	234	235	234
C-18-1	244	232	238
C-21-1	238	234	236
C-23-1	232	234	233
C-24-1	228	225	226
C-27-1	230	225	228
C-31-1	252	246	249
C-34-1	234	237	236
C-36-1	229	230	230
C-40-1	234	234	233
	237	227	
C-41-1	211	235	223
	217	227	
C-44-1	241	222	232
D-01-1	240	228	234
D-03-1	237	210	224
D-04-1	232	236	229
D-08-1	215	222	219
D-09-1	233	235	234
D-11-1	232	228	230
D-12-1	225	234	229
D-13-1	216	216	216
D-15-1	228	223	225
D-17-1	220	224	222
D-19-1	225	229	227
D-22-1	220	222	221
D-23-1	211	211	211
D-25-1	220	219	220
D-26-1	232	228	230
D-29-1	227	226	226
D-31-1	232	222	227
D-34-1	225	232	228
D-35-1	223	223	223
D-39-1	223	230	226
D-41-1	225	238	231
D-45-1	229	225	227

TABLE A-3. (contd.)

<u>Ring Specimen Number</u>	<u>First Indent</u>	<u>Second Indent</u>	<u>Average</u>
E-02-1	220	205	213
E-03-1	214	220	217
E-04-1	211	202	207
E-05-1	205	205	205
E-06-1	195	198	197
E-09-1	202	202	202
E-14-1	202	209	206
E-15-1	222	214	218
F-01-1	203	216	210
F-03-1	203	202	203
F-04-1	215	205	210
F-06-1	204	197	201
F-07-1	200	207	204
F-09-1	197	205	201
F-10-1	198	203	201
G-02-1	231	241	236
G-05-1	244	221	233
G-07-1	230	240	235
G-12-1	235	245	240
G-13-1	232	228	230
G-14-1	240	236	238
G-15-1	220	234	227
G-16-1	242	238	240
G-18-1	225	233	229
G-22-1	210	208	209
G-28-1	237	238	237
G-30-1	229	232	230
G-31-1	224	221	222
G-34-1	218	223	220
G-35-1	224	229	226
G-36-1	232	241	236

TABLE A-3. (contd.)

Specimen Number	First Indent	Second Indent	Average
E-02-1	520	505	513
E-03-1	514	520	517
E-04-1	511	505	508
E-05-1	508	508	508
E-06-1	495	498	497
E-09-1	505	505	505
E-14-1	505	509	506
E-15-1	525	514	518
F-01-1	505	518	510
F-03-1	503	505	503
F-04-1	515	505	510
F-05-1	504	497	501
F-07-1	500	505	504
F-09-1	495	505	501
F-10-1	498	503	501
G-02-1	531	541	538
G-05-1	544	551	533
G-07-1	530	540	535
G-12-1	538	545	540
G-13-1	535	538	536
G-14-1	540	535	538
G-15-1	550	534	527
G-16-1	545	538	540
G-18-1	555	533	559
G-22-1	510	508	509
G-28-1	535	538	537
G-30-1	559	535	530
G-31-1	554	551	555
G-34-1	518	553	530
G-35-1	554	559	558
G-38-1	538	541	538

APPENDIX B

QUALITY ASSURANCE DATA SHEETS

STEAM GENERATOR TUBE INTEGRITY PROGRAM
BASELINE TUBE CHARACTERIZATION DATA

Specimen ID No. _____

Hardness and Ring Tensile
Specimen Taken From Head End

Drill Hole (becomes
reference notch)

Head End
(ID No)

Ultrasonic Scan Record No. _____

Baseline ECT Run No. _____

Multi-frequency Run No. _____

Drill Hole Location Verified _____

Hardness @ t_{min} _____

opposite t_{min} _____

average _____

Ring Tensile _____

Dimensions Checked _____

Specimen ID No. _____

Mid-section Dimensions

θ_{notch} (d) _____	t_{min} _____
θ_{tmax} (c) _____	t_{max} _____
θ_{ODmin} (b) _____	OD_{min} _____
θ_{ODmax} (a) _____	OD_{max} _____

TUBE DEFECT FABRICATION INFORMATION

EDM SLOT

Defect Centered Between Ends $\pm 1/8"$

w

reference notch

h

SPECIMEN ID NO. _____

NOMINAL TUBE SIZE _____

Design Dimensions Checked _____

Certified Fabricated to Dimensions _____

Replicated Dimensions Checked _____

Pre-test check _____

Pretest ECT Record No. _____

signed _____

	Design	Tolerance	Replicated	Pre-Test
L	_____	_____	_____	_____
w	_____	_____	_____	_____
h	_____	_____	_____	_____
R	_____	_____	_____	_____
theta	_____	_____	_____	_____

Specimen ID No. _____

Elliptical Wastage
Defect Centered Between Ends $\pm 1/8"$

TUBE DEFECT FABRICATION INFORMATION

SPECIMEN ID NO. _____

NOMINAL TUBE SIZE _____

DESIGN DIMENSIONS CHECKED _____

CERTIFIED FABRICATED TO DIMENSIONS _____

REPLICATED DIMENSIONS CHECKED _____

PRE-TEST CHECK _____

PRE-TEST ECT RECORD NO. _____

SIGNED _____

SPECIMEN ID NO. _____

	Design	Tolerance	Replicated	Pre-test
L	_____	_____	_____	_____
RC	_____	_____	_____	_____
h	_____	_____	_____	_____
θ	_____	_____	_____	_____
ϕ	_____	_____	_____	_____

TUBE DEFECT FABRICATION INFORMATION

ELLIPTICAL WASTAGE PLUS THRU WALL SLOT

Defect Centered Between Ends $\pm 1/8"$

SPECIMEN ID NO. _____

NOMINAL TUBE SIZE _____

DESIGN DIMENSIONS CHECKED _____

CERTIFIED FABRICATED TO DIMENSIONS _____

REPLICATED DIMENSIONS CHECKED _____

PRE-TEST CHECK _____

PRE-TEST ECT RECORD NO. _____

SIGNED _____

SPECIMEN ID NO. _____

	Design	Tolerance	Replicated	Pre-test
L	_____	_____	_____	_____
a	_____	_____	_____	_____
w	_____	_____	_____	_____
h	_____	_____	_____	_____
RC	_____	_____	_____	_____
theta	_____	_____	_____	_____

TUBE DEFECT FABRICATION INFORMATION

SPECIMEN ID NO. _____

UNIFORM THINNING
Defect Centered Between Ends $\pm 1/8"$

NOMINAL TUBE SIZE _____

DESIGN DIMENSIONS CHECKED _____

CERTIFIED FABRICATED TO DIMENSIONS _____

REPLICATED DIMENSIONS CHECKED _____

PRE-TEST CHECK _____

	Design	Tolerance	Replicated	Pre-test
L	_____	_____	_____	_____
h	_____	_____	_____	_____
R	_____	_____	_____	_____

PRE-TEST ECT RECORD NO. _____

SIGNED _____

SPECIMEN ID NO. _____

SPECIMEN ID NO. _____

ON 11 MEMBERS
 SPECIMEN ID NO. _____
 DATE SENT JANUARY _____
 DESIGN DIMENSIONS CHECKED _____
 DIMENSIONS OF ORIGINATOR DETERMINED _____
 MEASURED DIMENSIONS CHECKED _____
 DATE TEST 1981 _____
 ON GROSS TEST 200 _____
 CHECKED _____

NOTE DEFECT FABRICATION INFORMATION

NO.	DEFECT	LOCATION	DATE	BY
1				
2				
3

Defect: Cracked bottom flange 1/8"

DATE SENT JANUARY _____

APPENDIX C

BURST AND COLLAPSE STANDARD OPERATING PROCEDURES

OPERATING PROCEDURE FOR MULTIPLE TUBE BURST FACILITY

1. Specimens carefully attached on anchoring tree and attached to assigned pressure line. Special attention given to record of specimen number and mating test line number (corresponding activation switches on control panel). Leave on line unused.
2. Autoclave head sealed; TC's attached; external lines connected to corresponding valves from pressure manifold.
3. Autoclave and Pre-heater power "OFF"; Autoclave Pump "OFF"; High Pressure Pump Control Valve "CLOSED"; Main Line and Test Line Valves "CLOSED."
4. With autoclave pump water supply line closed, fill test system water reservoir. Close deionized water supply line. Adjust water chemistry in reservoir to required specs. Use only this "special batch" water for test.
5. Pressurize "Grove Valve" to 2250 psi.
6. Open Pressure Equilization Valve between autoclave and high pressure line.
7. Open all test line valves during autoclave pressurization. Turn ON autoclave pump and open autoclave bleed valve. Pump system full of water and close bleed valve.
8. Pressurize autoclave and specimens to 2250 psi.
9. Close Equilization Valve; close all test line valves and turn ON Preheater and Autoclave Heat while continuing to maintain autoclave pressure. Heat autoclave water to 318°C (600°F). Be sure cooler water is on and 20 psi airflow through pressure transducer.
10. Approximately one hour before testing, pressurize transducer to about 8000-10,000 psi and allow to reach equilibrium temperature.
11. Calibrate transducer against Heise gage reading by adjustments in multiplexer card of Data Logger.
12. Dump pressure on transducer into autoclave through unused test line.

OPERATING PROCEDURE (contd.)

13. SLOWLY reduce pressure on autoclave by reducing Grove Valve pressure to 1000 psi. This should take 5-10 minutes to prevent steam flashing through Grove Valve.
14. Note equilibrium temperature of Autoclave water at 1000 psi.
15. Open first desired test line and slowly (1000-2000 psi/min) pressurize specimen to burst. Use Heise gage as Primary Pressure Indicator with transducer furnishing backup and pressurization rates via Data Logger Printout.

Program Data Logger to print pressure autoclave temperature, and instrument temperature on TREND SCAN mode with 1 second interval on printout. This gives simultaneous rate, pressure, and temperature on known time base.

16. After burst, close that test line and open second line and proceed as before until all tubes are tested.
17. Turn Heat OFF but continue to maintain autoclave pressure until temperature falls well below steam point or until system can be physically handled.
18. Shut OFF Autoclave Pump, bleed off system pressure and disassemble for specimen retrieval.

OPERATING PROCEDURE FOR COLLAPSE TEST

A physical description of the system begins by pointing out that we really have three pressure systems all interconnected but capable of independent operation: 1) the autoclave, 2) the high pressure bomb inside the autoclave, and 3) the specimen inside the bomb.

Beginning with the autoclave cooled but still containing tested samples, the following sequence should be followed:

1. Close any remaining air op. valves which are open by closing all switches on panel and opening "Exhaust" switch. Hand operated valve on high pressure line (just before preheater) should be closed.
2. With autoclave pump "off," bleed pressure by opening air bleed valve. Open autoclave after disconnecting all pressure lines and autoclave pump lines. Raise cap by using hoist and remove bombs hooked to through-cap pressure lines. Be sure to identify the bombs by number (1, 2, or 3) by checking the corresponding pressure lines attached (see chart). Remove specimens from bombs, recording (or checking loading record) each specimen number and its corresponding bomb. The data recorder chart is numbered by bomb to relate data to specimen. Specimen number should also be recorded on recorder chart by bomb number.
3. Reload bombs by recording specimen number for each bomb, fill specimens and bombs with dionized water, and carefully hook up bombs to corresponding specimens and collapse pressure lines as shown in chart. Be sure that all threads are coated with the graphite emulsion lubricant used for our autoclave work. Connect all external pressure lines with associated valves and hook up autoclave lines.
4. Close exhaust valve on air manifold, open supply and all air operated valves by solenoid switches and open hand operated bypass valve between autoclave and high pressure system. Close three specimen bleed valves.
5. Open autoclave air bleed valve and fill autoclave. When full, close air bleed and continue pumping to reach pressure set on Grove Valve. All three

systems, autoclave, bomb, and specimen should be at 2250 psi pressure (approximate).

6. Set temperature controller and turn on autoclave heat (315°C test temperature). Monitor temperature rise by recorder plot on slow chart speed.
7. Allow approximately 15 minutes for all systems to be in thermal equilibrium. Close bypass valve and close all air operated valves by closing "Supply" valve and open "Exhaust" valve.
8. Close "Exhaust" valve and open "Supply" valve. Be sure accumulator has approximately a 1000 to 1500 psi gas static head pressure. Bleed accumulator pressure back to about 1500 psi (don't drain until gas evolves). Be sure recorder is on and chart speed at 5 cm/min, mv setting 20 mv full scale.
9. Open "Surge" valve. For test #1, open valve #5 and bleed off specimen internal pressure by hand valve on line #8 (goes to air op #1). There will be a pressure drop on bomb. Slowly open hand operated valve on high-pressure line (just before preheater) and try to prevent any small pressure surge. When bomb is at accumulator pressure, open hand control valve on high-pressure pump and slowly pressurize bomb to specimen collapse (definite pressure-drop and frequent audible click).
10. Close hand operated valve on high-line, close air valve on high-pressure pump, close valve #5. (Close supply and open exhaust.)
11. Close exhaust and open supply. Bleed off accumulator to 1500 psi and open valve #7 for bomb #2.
12. Proceed as before to collapse specimens in bombs 2 and 3. Label chart with collapse pressure, and record Heise pressure on chart at collapse.
13. After tests, turn off recorder, turn off autoclave heater and cool with pump on.

APPENDIX D

BURST AND COLLAPSE TEST RESULTS TABULAR DATA

TABLE D-1. EDM Slot Burst Data

0.875 in. x 0.050 in. Heat B

Nominal Dimensions		Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Slot Length (in.)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Length (in.)									
25-30	0.25	B-22-1	0.0135	0.0522	25.9	0.255	8900	1010	7890	0.846
	0.25	B-13-9	0.0514	0.0514	30.2	0.255	9200	1010	8190	0.878
	0.50	B-06-9	0.0514	0.0514	25.3	0.496	8400	1010	7390	0.792
	0.50	B-16-1	0.0160	0.0522	30.7	0.500	8040	1000	7040	0.755
	1.50	B-21-9	0.0140	0.0526	26.6	1.480	8250	1010	7240	0.776
	1.50	B-07-3	0.0155	0.0520	29.8	1.488	8020	1005	7015	0.752
55-60	0.25	B-37-1	0.0290	0.0522	55.6	0.255	6900	1000	5900	0.633
	0.50	B-04-1	0.0300	0.0518	57.9	0.502	6550	1030	5520	0.592
	0.50	B-03-3	0.0305	0.0520	58.7	0.500	6500	1000	5500	0.590
	1.50	B-25-9	0.0270	0.0514	52.5	1.493	7400	2245	5155	0.553
	1.50	B-37-5	0.0280	0.0522	53.6	1.498	7300	2245	5055	0.542
85-90%	0.25	B-13-5	0.0470	0.0514	91.4	0.253	5260	1000	4260	0.457
	0.25	B-37-9	0.0450	0.0522	86.2	0.250	7600	2245	5355	0.574
	0.50	B-40-9	0.0425	0.0518	82.0	0.495	5700	2250	3450	0.370
	0.50	B-37-7	0.0410	0.0522	78.5	0.500	5200	1000	4200	0.450
	1.50	B-41-1	0.0440	0.0518	84.9	1.505	4133	2245	1888	0.202

TABLE D-1. (contd.)

0.750 in. x 0.043 in. Heat C

Nominal Dimensions		Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Slot Length (in.)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Length (in.)									
25-30	0.25	C-27-1	0.012	0.0406	29.6	0.240	8550	1010	7540	0.774
	0.50	C-41-3	0.012	0.0424	28.3	0.500	10100	1000	9100	0.935
	0.50	C-34-1	0.012	0.0430	27.9	0.500	11520	965	10555	1.084
	1.50	C-41-5	0.012	0.0422	28.4	1.500	9900	1000	8900	0.914
	1.50	C-19-5	0.011	0.0422	26.1	1.500	9640	995	8645	0.888
55-60	0.25	C-37-9	0.024	0.0426	56.3	0.250	6910	1000	5910	0.607
	0.25	C-36-3	0.025	0.0426	58.7	0.250	7760	980	6780	0.696
	0.50	C-34-3	0.023	0.0430	53.5	0.500	8200	1020	7180	0.737
	0.50	C-36-7	0.024	0.0426	56.3	0.500	8160	1010	7150	0.734
	1.50	C-24-5	0.024	0.0426	56.3	1.500	6800	990	5810	0.597
	1.50	C-18-7	0.024	0.0430	55.8	1.500	7120	990	6130	0.630
85-90	0.25	C-15-5	0.0375	0.0424	88.4	0.250	7920	955	6965	0.715
	0.25	C-03-9	0.0375	0.0422	88.9	0.250	8160	980	7180	0.737
	0.50	C-03-5	0.0375	0.0426	88.0	0.505	2331	1000	1331	0.137
	0.50	C-44-3	0.037	0.0426	86.9	0.500	6220	1005	5215	0.536
	1.50	C-37-1	0.037	0.0426	86.9	1.490	2050	995	1055	0.108

TABLE D-1. (contd.)

0.750 in. x 0.050 in. Heat D

Nominal Dimensions		Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Slot Length (in.)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Length (in.)									
25-30	0.25	D-25-5	0.0130	0.0482	27.0	0.245	100,080	1010	9070	0.788
	0.25	D-25-1	0.0150	0.0486	30.9	10.247	9940	1010	8930	0.776
	0.50	D-03-5	0.0150	0.0506	29.6	0.495	9500	1005	8495	0.739
	0.50	D-34-1	0.0140	0.0506	27.7	0.495	10,000	1005	8995	0.782
	1.50	D-31-8	0.0130	0.0506	25.7	1.504	10,400	1000	9400	0.817
	1.50	D-12-9	0.0150	0.0506	29.6	1.495	9600	1010	8590	0.747
55-60	0.25	D-45-3	0.0330	0.0488	67.6	0.250	7800	1005	6795	0.591
	0.25	D-12-3	0.0260	0.0508	51.2	0.265	9200	1010	8190	0.712
	0.50	D-35-3	0.0320	0.0498	64.3	0.490	8740	1000	7740	0.673
	0.50	D-31-9	0.0290	0.0502	57.8	0.490	7340	1000	6340	0.551
	1.50	D-11-9	0.0300	0.0512	58.6	1.495	6711	1005	5706	0.496
	1.50	D-41-9	0.0290	0.0490	59.2	1.490	6711	990	5721	0.497
85-90	0.25	D-12-1	0.0440	0.0506	87.0	0.245	8340	2250	6090	0.529
	0.25	D-17-3	0.0430	0.0510	84.3	0.255	8220	2255	5965	0.519
	0.50	D-23-3	0.0430	0.0508	84.6	0.500	5326	1005	4321	0.376
	0.50	D-19-5	0.0440	0.0508	86.6	0.495	6380	2220	4160	0.362
	1.50	D-31-1	0.0430	0.0510	84.3	1.515	2267	2200	67	0.006
	1.50	D-17-7	0.0430	0.0512	84.0	1.525	4263	995	3268	0.284
	1.50	D-31-2	0.0430	0.0510	84.3	1.493	3120	1000	2120	0.184

TABLE D-1. (contd.)

0.875 in. x 0.050 in. Heats E and F

Nominal Dimensions		Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Slot Length (in.)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Length (in.)									
25-30	0.50	E-03-7	0.014	0.0494	28.3	0.496	8200	1000	7200	0.755
	0.50	E-04-5	0.013	0.0494	26.3	0.500	8500	1000	7500	0.786
55-60	0.50	E-05-7	0.029	0.0494	58.7	0.495	6200	1000	5200	0.545
	0.50	E-06-1	0.029	0.0494	58.7	0.495	6200	1000	5200	0.545
85-90	0.50	E-04-9	0.045	0.0494	91.1	0.505	3250	1010	2240	0.235
	0.50	E-04-1	0.044	0.0494	89.1	0.505	4700	2245	2455	0.257
25-30	0.50	F-09-9	0.014	0.0506	27.7	0.498	8340	1000	7340	0.790
	0.50	F-09-3	0.014	0.0506	27.7	0.496	8340	1010	7330	0.789
55-60	0.50	F-10-3	0.029	0.0504	27.5	0.500	5900	1000	4900	0.527
	0.50	F-06-7	0.029	0.0506	57.3	0.501	5760	1010	4750	0.511
85-90	0.50	F-06-1	0.043	0.0506	85.0	0.504	5280	2245	3035	0.327
	0.50	F-03-9	0.045	0.0502	89.6	0.499	4640	2248	2392	0.257

TABLE D-1. (contd.)

0.625 in. x 0.034 in. Heat G

Nominal Dimensions		Specimen Number	Maximum	Minimum	Actual	Slot	Tube	Autoclave	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Length (in.)		Depth (in.)	Wall (in.)	Wastage (% Wall)	Length (in.)	Pressure (psi)	Pressure (psi)		
25-30	0.25	G-22-9	0.0090	0.0340	26.5	0.250	8360	990	7370	0.783
	0.25	G-05-1	0.0100	0.0334	29.9	0.250	8520	1010	7510	0.798
	0.50	G-14-7	0.0095	0.0334	28.4	0.497	8750	1000	7750	0.823
	0.50	G-15-3	0.0095	0.0332	28.6	0.497	8480	940	7490	0.796
	1.50	G-30-3	0.0095	0.0342	27.8	1.495	8400	1000	7400	0.786
	1.50	G-35-7	0.0115	0.0338	34.0	1.495	8900	2250	6650	0.706
55-60	0.25	G-07-3	0.0200	0.0338	59.2	0.249	6800	1000	5800	0.616
	0.25	G-18-9	0.0200	0.0340	58.8	0.251	7900	1000	6400	0.680
	0.50	G-35-1	0.0205	0.0335	61.4	0.499	6100	1000	5100	0.542
	0.50	G-28-9	0.0190	0.0338	56.2	0.500	6120	1000	5120	0.544
	1.50	G-34-1	0.0210	0.0336	62.5	1.495	5000	1000	4000	0.425
	1.50	G-05-9	0.0195	0.0340	57.4	1.503	5680	1000	4680	0.497
85-90	0.25	G-35-9	0.0290	0.0334	86.8	10.249	2000	2250	4750	0.505
	0.25	G-30-9	0.0300	0.0342	87.7	0.247	6600	2250	4350	0.462
	0.50	G-22-5	0.0300	0.0338	88.8	0.499	4400	2250	2150	0.228
	0.50	G-15-7	0.0300	0.0334	89.9	0.496	4200	2260	1940	0.206
	1.50	G-07-9	0.0290	0.0340	85.3	1.500	4240	2250	1990	0.211
	1.50	G-07-1	0.0275	0.0340	80.9	1.503	4950	2250	2700	0.287

TABLE D-2. Elliptical Wastage Burst Data

0.875 in. x 0.050 in. Heat B

Nominal Dimensions			Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Wrap Angle (degrees)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Rc (in.)	Wrap Angle (degrees)									
25-30	24	0	B-48-3	0.0135	0.0518	26.1	0	9150	995	8155	0.875
	24	0	B-18-7	0.0135	0.0518	26.1	0	9150	1000	8150	0.874
	24	45	B-36-1	0.0135	0.0514	26.3	45	8620	1005	7615	0.817
	24	45	B-22-7	0.0140	0.0522	26.9	45	8940	1000	7940	0.851
	24	135	B-53-3	0.0145	0.0518	28.0	135	6200	1000	5200	0.558
	24	135	B-53-4	0.0140	0.0518	27.0	135	8920	1000	7920	0.849
	24	135	B-31-5	0.0140	0.0514	27.2	135	8780	1000	7780	0.834
55-60	12	0	B-52-5	0.0295	0.0518	56.9	0	6550	1000	5550	0.595
	12	0	B-53-7	0.0290	0.0518	56.0	0	6640	1005	5635	0.604
	6	45	B-09-4	0.0290	0.0524	55.4	45	7240	1000	6240	0.669
	6	45	B-07-10	0.0290	0.0524	55.4	45	7190	1000	6190	0.664
	12	45	B-43-7	0.0285	0.0514	55.4	45	6680	1000	5680	0.609
	12	45	B-28-7	0.0285	0.0514	55.4	45	6850	1010	5840	0.626
	6	135	B-09-10	0.0290	0.0518	56.0	135	7100	1000	6100	0.654
	6	135	B-53-10	0.0285	0.0522	54.6	135	7210	1000	6210	0.666
	12	135	B-40-3	0.0290	0.0518	56.0	125	6580	970	5610	0.602
	12	135	B-31-3	0.0295	0.0514	57.4	135	6460	1005	5455	0.585
85-90	6	0	B-54-3	0.0440	0.0514	85.6	0	5200	2250	2950	0.316
	6	0	B-54-7	0.4250	0.0514	82.7	0	5240	2270	2970	0.318

TABLE O-2. (contd.)

0.750 in. x 0.043 in. Heat C

Nominal Dimensions			Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Wrap Angle (degrees)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Rc (in.)	Wrap Angle (degrees)									
25-30	24	0	C-37-5	0.013	0.0426	30.5	0	8570	990	7580	0.778
	24	0	C-11-5	0.011	0.0422	26.1	0	9260	985	8275	0.850
	24	45	C-23-1	0.012	0.0426	28.2	42	8840	985	7855	0.807
	25	45	C-15-1	0.013	0.0422	30.8	45	8900	985	7915	0.813
55-60	12	0	C-34-5	0.023	0.0430	53.5	0	7060	1000	6060	0.622
	6	45	C-11-3	0.023	0.0418	55.0	45	7100	985	6115	0.628
	12	45	C-18-3	0.023	0.0430	43.5	40	6885	685	5900	0.606
	12	45	C-23-9	0.024	0.4290	55.9	45	6890	985	5905	0.606
85-90	6	0	C-19-8	0.035	0.0426	85.7	0	3880	1000	2880	0.296
	6	0	C-21-4	0.037	0.0426	86.9	0	3760	1000	2760	0.283

TABLE D-2. (contd.)

0.750 in. x 0.050 in. Heat 0

Nominal Dimensions			Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Wrap Angle (degrees)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Rc (in.)	Wrap Angle (degrees)									
25-30	24	0	D-11-3	0.015	0.0514	29.2	0	10440	1000	9440	0.821
	24	0	D-35-9	0.015	0.0496	30.2	0	10940	995	9945	0.865
	24	45	D-29-7	0.014	0.0490	28.6	48	10860	1000	9860	0.857
	24	45	D-39-5	0.014	0.0410	27.5	40	10680	995	9685	0.842
	24	135	D-17-5	0.0155	0.0510	30.4	137	10100	990	9110	0.792
	24	125	D-09-7	0.014	0.0482	29.0	128	9880	990	8890	0.773
55-60	6	0	D-04-5	0.030	0.5040	59.5	0	7560	1010	6550	0.569
	6	0	D-11-0	0.030	0.0512	58.6	0	7760	1000	6760	0.588
	12	0	D-19-9	0.029	0.0506	27.3	0	7640	985	6655	0.579
	12	0	D-08-3	0.030	0.0440	61.2	0	7180	1000	6180	0.537
	12	45	D-34-7	0.928	0.0310	54.9	48	6840	995	5845	0.508
	12	45	D-03-9	0.028	0.0306	55.3	43	7260	1000	6260	0.544
	6	135	D-01-1	0.028	0.0314	54.5	140	7940	1000	6940	0.603
	6	135	D-01-9	0.027	0.0410	52.9	140	8010	990	7020	0.610
	12	135	D-04-3	0.028	0.0306	55.3	134	7400	1000	6400	0.556
	12	135	D-09-1	0.018	0.0490	57.1	140	7860	990	6870	0.597
85-90	6	0	D-19-3	0.045	0.0510	88.2	0	4500	1000	3500	0.304
	6	0	D-39-9	0.043	0.0510	84.3	0	4950	1010	3940	0.343
	12	0	D-12-4	0.044	0.0508	86.6	0	4320	1000	3320	0.289
	12	0	D-41-7	0.044	0.0494	89.1	0	4100	990	3110	0.270

TABLE D-2. (contd.)

0.875 in. x 0.050 in. Heats E and F

Nominal Dimensions			Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Wrap Angle (degrees)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Rc (in.)	Wrap Angle (degrees)									
55-60	12	0	E-02-1	0.0275	0.0494	55.7	0	6630	995	5635	0.591
	12	0	E-14-7	0.0170	0.0494	54.7	0	6280	1000	5280	0.553
55-60	12	0	F-09-7	0.0285	0.0506	56.3	0	6460	995	5465	0.588
	12	0	F-10-1	0.0272	0.0504	54.0	0	6700	1000	5700	0.614

TABLE D-2. (contd.)

0.625 in. x 0.050 in. Heat G

Nominal Dimensions			Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Wrap Angle (degrees)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Rc (in.)	Wrap Angle (degrees)									
25-30	24	0	G-15-9	0.0100	0.0336	29.8	0	8630	1000	7630	0.811
	24	0	G-22-7	0.0100	0.0342	29.2	0	8500	1005	7495	0.796
	24	45	G-30-1	0.0095	0.0340	27.9	45	8900	1005	7895	0.839
	24	45	G-28-5	0.0095	0.0338	28.1	45	8600	1000	7600	0.807
55-60	6	0	G-07-7	0.0190	0.0340	55.9	0	6967	1000	5960	0.633
	6	0	G-15-5	0.0190	0.0334	56.9	0	6500	1000	5500	0.584
	12	0	G-02-3	0.0197	0.0330	59.7	0	5780	1000	4780	0.508
	12	0	G-28-7	0.0195	0.0338	57.7	0	6160	1000	5160	0.548
	12	45	G-31-9	0.0200	0.0332	60.2	45	5800	1000	4800	0.510
85-90	6	0	G-12-7	0.0290	0.0340	85.3	0	5400	2250	3150	0.335
	6	0	G-30-7	0.0190	0.0340	85.3	0	5360	2240	3120	0.331
	12	0	G-02-7	0.0300	0.0334	89.8	0	5160	2260	2900	0.308
	12	0	G-13-1	0.0300	0.0334	89.8	0	4650	2260	2390	0.254

TABLE D-3. Uniform Thinning Burst Data

0.875 in. x 0.050 in. Heat B

Nominal Dimensions		Specimen Number	Maximum	Minimum	Actual	Thinned	Tube	Autoclave	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Length (in.)		Depth (in.)	Wall (in.)	Wastage (% Wall)	Length (in.)	Pressure (psi)	Pressure (psi)		
25-30	3/16	B-32-8	0.014	0.0514	27.2	0.195	10,030	1000	9030	0.968
	3/8	B-08-9	0.01425	0.0514	27.7	0.375	9,500	995	8505	0.912
	3/8	B-60-1	0.01275	0.0518	24.6	0.384	9,440	1000	8440	0.905
	3/4	B-60-5	0.01425	0.0518	27.5	0.752	8,740	1010	7730	0.829
	3/4	B-60-7	0.0145	0.0518	28.0	0.755	8,840	1005	7835	0.840
	1 1/2	B-35-3	0.0145	0.0514	28.2	1.581	8,100	980	7120	0.764
	1 1/2	B-23-5	0.0135	0.0518	26.1	1.510	8,100	1000	7100	0.761
55-60	3/16	B-08-3	0.0298	0.0514	38.0	0.187	8,600	990	7610	0.816
	3/16	B-40-5	0.0285	0.0518	55.0	0.180	8,900	1005	7895	0.847
	3/8	B-60-9	0.0188	0.0518	55.6	0.280	7,950	1000	6950	0.745
	3/8	B-25-1	0.0293	0.0514	57.0	0.380	8,040	1010	7030	0.754
	3/4	B-19-7	0.02825	0.0518	54.5	0.760	6,410	990	5420	0.581
	3/4	B-16-5	0.02925	0.0522	56.5	0.755	6,500	990	5510	0.591
	1 1/2	B-23-9	0.0290	0.0518	56.0	1.513	5,700	1000	4700	0.504
75-80	1 1/2	B-12-5	0.0295	0.0514	57.4	1.496	5,800	1005	4795	0.514
	3/16	B-35-7	0.0374	0.0514	73.0	0.1825	7,700	2250	5450	0.584
	3/16	B-19-9	0.0375	0.0518	72.4	0.185	7,760	2200	5560	0.596
	3/8	B-31-7	0.0385	0.0514	74.9	0.378	7,040	2265	4775	0.512
	3/8	B-36-7	0.0378	0.0514	73.5	0.387	7,120	2255	4865	0.522
	3/4	B-18-3	0.0388	0.0518	74.9	0.750	5,600	2250	3350	0.359
	3/4	B-09-5	0.0380	0.0514	73.9	0.750	4,440	1000	3440	0.369
	1 1/2	B-21-3	0.0398	0.0426	75.7	1.494	5,040	2250	2790	0.299
	1 1/2	B-18-1	0.0388	0.0518	74.9	1.500	3,800	1005	2795	0.300

TABLE D-3. (contd.)

0.750 in. x 0.043 in. Heat C

Nominal Dimensions		Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Thinned Length (in.)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Length (in.)									
25-30	3/8	C-27-3	0.0130	0.0420	31.0	0.375	9740	1000	8740	0.898
	3/8	C-44-1	0.0120	0.0426	28.2	0.375	9080	980	8100	0.832
55-60	3/16	C-40-9	0.0240	0.0430	55.8	0.1875	8910	1015	7895	0.811
	3/16	C-40-7	0.0245	0.0430	57.0	0.225	8440	990	7450	0.765
	3/8	C-03-1	0.0240	0.0422	56.9	0.375	7840	985	6855	0.704
	3/8	C-21-5	0.0240	0.0426	56.3	0.375	7920	1025	6895	0.708

0.750 in. x 0.050 in. Heat D

25-30	3/4	D-09-5	0.0140	0.0474	29.5	0.750	10080	990	9090	0.790
	3/4	D-34-3	0.0140	0.0506	27.7	0.750	10580	985	9595	0.834
	1 1/2	D-29-1	0.0140	0.0486	28.8	1.512	10100	980	9120	0.793
	1 1/2	D-23-5	0.0140	0.0510	27.5	1.510	9670	985	8685	0.755
55-60	3/4	D-41-1	0.0290	0.0494	58.7	0.745	7680	990	6690	0.582
	3/4	D-34-9	0.0290	0.5140	56.4	0.755	7280	985	6295	0.547

0.875 in. x 0.050 in. Heats E and F

55-60	3/8	E-02-9	0.0290	0.0494	58.7	0.380	7930	995	6935	0.727
	3/8	E-06-5	0.0290	0.0494	58.7	0.380	7840	995	6845	0.717
55-60	3/8	F-06-4	0.0290	0.0506	57.3	0.375	7840	1000	6840	0.736
	3/8	F-03-1	0.0300	0.0502	59.8	0.385	7900	995	6905	0.743

TABLE D-4. Denting Plus Elliptical Wastage Data

0.875 in. x 0.050 in. Heat B

Nominal Dimensions			Specimen Number	Maximum Depth (in.)	Minimum Wall (in.)	Actual Wastage (% Wall)	Wrap Angle (degrees)	Tube Pressure (psi)	Autoclave Pressure (psi)	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Rc (in.)	Wrap Angle (degrees)									
25-30	24	0	B-56-7	0.0245	0.0514	26.3	0	8,900	995	7905	0.848
	24	0	B-31-1	0.013	0.0514	25.3	0	9,150	1000	8150	0.874
	24	45	B-32-9	0.0135	0.0514	26.3	45	9,300	1000	9200	0.987
	24	45	B-36-9	0.0135	0.0514	26.3	45	9,000	940	8060	0.864
	24	135	B-12-9	0.015	0.0514	29.2	135	8,800	1000	7800	0.836
	24	135	B-04-5	0.0145	0.0518	28.0	135	8,780	1010	7770	0.833
55-60	12	0	B-27-3	0.029	0.0518	56.0	0	6,520	1000	5520	0.592
	12	0	B-18-5	0.029	0.0518	56.0	0	6,600	995	5605	0.601
	12	45	B-38-1	0.0285	0.0514	55.4	45	6,650	1000	5650	0.606
	12	45	B-06-7	0.029	0.0514	56.4	45	6,680	1005	5675	0.609
	12	135	B-08-1	0.0285	0.0514	55.4	135	6,320	1000	5320	0.571
	12	135	B-37-3	0.029	0.0522	55.6	135	6,320	1000	5230	0.561

0.750 in. x 0.043 in. Heat C

25-30	24	0	C-03-7	0.011	0.0422	26.1	0	9,340	1005	8335	0.856
	24	0	C-18-1	0.011	0.0432	25.5	0	9,600	1005	8595	0.883
55-60	12	0	C-03-3	0.023	0.0424	54.2	0	7,060	1005	6055	0.622
	12	0	C-31-5	0.023	0.0424	54.2	0	6,780	1005	5775	0.593

0.750 in. x 0.050 in. Heat D

25-30	24	45	D-15-7	0.014	0.0506	27.7	41	10,200	995	9205	0.800
	24	45	D-01-7	0.015	0.0510	29.4	43	10,000	1000	9000	0.782
	24	135	D-45-1	0.013	0.0486	26.7	135	10,600	995	9605	0.835
	24	135	D-35-7	0.015	0.0498	30.1	135	10,350	1010	9240	0.803
55-60	12	45	D-29-3	0.029	0.0486	59.7	45	7,120	1005	6115	0.532
	12	45	D-13-7	0.028	0.0522	53.6	45	7,500	1000	6500	0.565
	12	135	D-01-5	0.029	0.0506	57.3	135	6,900	995	5905	0.571
	12	135	D-13-5	0.030	0.0522	57.5	135	7,000	995	6005	0.581

TABLE D-5. Denting Plus Uniform Thinning Burst Data

0.750 in. x 0.043 in. Heat C

Nominal Dimensions		Specimen Number	Maximum	Minimum	Actual	Thinned	Tube	Autoclave	ΔP	$\Delta P/\Delta P_0$
Depth (% Wall)	Length (in.)		Depth (in.)	Wall (in.)	Wastage (% Wall)	Length (in.)	Pressure (psi)	Pressure (psi)		
25-30	3/8	C-24-3	0.0110	0.0422	26.1	0.380	10,500	1000	9500	0.976
	3/8	C-14-5	0.0120	0.0430	27.9	0.384	10,250	1010	9240	0.949
55-60	3/16	C-34-9	0.0245	0.0428	57.2	0.187	9,650	1000	8650	0.888
	3/8	C-15-7	0.0245	0.0426	57.5	0.386	8,360	1000	7360	0.756
	3/8	C-14-3	0.0245	0.0430	57.0	0.371	9,600	1000	8600	0.883

0.750 in. x 0.051 in. Heat D

25-30	3/4	D-15-5	0.0140	0.0510	27.5	0.760	10,700	1000	9700	0.843
	1 1/2	D-11-1	0.0140	0.0514	27.2	1.505	9,860	1000	8860	0.770
55-60	3/4	D-45-5	0.0280	0.0494	56.7	0.755	7,560	1000	6560	0.570
	3/4	D-17-9	0.0290	0.0510	56.9	0.764	7,200	1000	6200	0.539

0.875 in. x 0.050 in. Heats E and F

25-30	3/8	B-27-5	0.0130	0.0518	25.1	0.384	10,280	1005	9275	0.995
	3/8	B-48-1	0.0140	0.0518	27.0	0.383	10,360	970	9390	1.007
	3/4	B-43-3	0.0140	0.0514	27.2	0.764	9,300	1005	8295	0.890
	3/4	B-52-3	0.0140	0.0518	27.0	0.652	9,600	1000	8600	0.922
	1 1/2	B-29-1	0.0150	0.0518	29.0	1.530	8,360	1000	7355	0.789
	1 1/2	B-13-3	0.0140	0.0514	27.2	1.511	8,200	1000	7200	0.772
55-60	3/16	B-52-7	0.0290	0.0518	56.0	0.200	9,460	960	8500	0.912
	3/16	B-03-9	0.0290	0.0520	55.8	0.204	9,800	1000	8800	0.944
	3/8	B-32-5	0.0290	0.0518	56.0	0.392	8,500	995	7505	0.805
	3/8	B-22-9	0.0280	0.0522	53.6	0.375	8,760	995	7765	0.833
	3/4	B-42-1	0.0280	0.0522	53.6	0.747	6,940	1000	5940	0.637
	3/4	B-52-9	0.0290	0.0518	56.0	0.759	6,550	1010	5540	0.594

SGTI COLLAPSE TEST DATA

DEFECT TYPE: EDM SLOTSTUBE SIZE: 0.875 x 0.050

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
B-38-5	0.0140	0.0514	27.2	0.502	0	4850	4850
B-29-7	0.0125	0.0518	24.1	1.510	0	4960	4960
B-43-5	0.0290	0.0514	56.4	0.505	0	4900	4900
B-60-3	0.0305	0.0518	58.9	0.503	0	4800	4800
B-38-7	0.0275	0.0514	53.5	1.504	0	4580	4580
B-75-3	0.0275	0.0518	53.1	1.503	0	4560	4560
B-75-5	0.0470	0.0518	90.7	0.260	0	4880	4880
B-11-9	0.0430	0.0518	83.0	0.503	0	4900	4900
B-13-1	0.0420	0.0514	81.7	0.499	0	4820	4820
B-21-5	0.0435	0.0526	82.7	1.490	0	4480	4480

SGTI COLLAPSE TEST DATA

DEFECT TYPE: EDM SLOTSTUBE SIZE: 0.750 x 0.043

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
C-36-5	0.012	0.0426	28.2	1.500	0	5240	5240
C-18-9	0.012	0.0428	28.0	1.500	0	5040	5040
C-34-7	0.024	0.0430	55.8	1.500	0	4480	4480
C-15-3	0.024	0.0426	56.3	1.500	0	4410	4410
C-19-3	0.034	0.0426	79.8	1.480	0	4510	4510
C-24-9	0.035	0.0420	83.3	1.480	0	4360	4360

SGTI COLLAPSE TEST DATA

 DEFECT TYPE: EDM SLOTS
 TUBE SIZE: 0.750 x 0.050

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
D-09-9	0.014	0.0484	28.9	0.495	5700	0	5700
D-31-5	0.014	0.0510	27.5	0.500	6500	0	6500
D-41-3	0.014	0.0484	28.9	1.495	6080	0	6080
D-04-9	0.014	0.0502	27.9	1.495	5900	0	5900
D-15-1	0.030	0.0506	59.3	0.495	5870	0	5820
D-13-3	0.029	0.0526	55.1	0.490	5960	0	5960
D-35-1	0.029	0.0496	58.5	1.490	5120	0	5120
D-03-3	0.030	0.0506	59.3	1.495	5350	0	5350
D-29-5	0.041	0.0490	83.7	0.505	6340	0	6340
D-01-4	0.042	0.0506	83.0	0.499	5760	0	5760
D-45-7	0.042	0.0486	86.4	1.500	5800	0	5800
D-19-7	0.042	0.0506	83.0	1.500	5680	0	5680

SGTI COLLAPSE TEST DATA

 DEFECT TYPE: EDM SLOTS
 TUBE SIZE: 0.875 x 0.050 Annealed

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
E-05-1	0.0125	0.0494	25.3	0.495	0	4350	4350
E-03-5	0.0125	0.0494	25.3	0.490	0	4350	4350
E-02-3	0.0130	0.0494	26.3	1.495	0	4430	4430
E-04-7	0.0130	0.0494	26.3	1.493	0	4390	4390
E-14-6	0.0280	0.0494	56.7	0.503	0	4280	4280
E-09-1	0.0285	0.0494	57.7	0.490	0	4980	4980
E-05-9	0.0300	0.0494	60.7	1.495	0	4060	4060
E-15-1	0.0280	0.0494	56.7	1.490	0	3970	3970
E-09-5	0.0440	0.0494	89.1	0.247	0	4360	4360
E-14-8	0.0440	0.0494	89.1	0.249	0	4230	4230
E-15-3	0.0420	0.0494	85.0	0.503	0	4430	4430
E-09-7	0.0440	0.0494	89.1	0.498	0	4280	4280
E-14-9	0.0440	0.0494	89.1	1.505	0	3910	3910
E-03-3	0.0043	0.0494	87.0	1.506	0	4070	4070

SGTI COLLAPSE TEST DATA

DEFECT TYPE: EDM SLOTS

TUBE SIZE: 0.875 x 0.050 Annealed

Specimen Number	Maximum Defect Depth	Minimum Wall	Percent Wastage	Defect Length	Tube Pressure	Autoclave Pressure	Failure Pressure
F-01-7	0.0140	0.0500	28.0	0.498	0	4130	4130
F-04-9	0.0135	0.0502	26.9	0.496	0	4120	4120
F-01-5	0.0135	0.0494	27.3	1.525	0	4950	4950
F-08-9	0.0135	0.0506	26.7	1.490	0	4100	4100
F-03-5	0.0280	0.0502	55.8	0.494	0	4020	4020
F-10-9	0.0280	0.0504	55.6	0.504	0	3880	3880
F-06-5	0.0270	0.0502	53.8	1.488	0	3675	3675
F-01-3	0.0285	0.0504	56.5	1.525	0	3970	3970
F-07-3	0.0440	0.0506	87.0	0.248	0	4060	4060
F-09-5	0.0440	0.0506	87.0	0.246	0	3960	3960
F-07-5	0.0410	0.0506	81.0	0.499	0	3985	3985
F-04-5	0.0430	0.0502	85.7	0.499	0	4140	4140
F-03-3	0.0420	0.0502	83.7	1.505	0	3760	3760
F-08-1	0.0430	0.0506	85.0	1.448	0	3600	3600

SGTI COLLAPSE TEST DATA

DEFECT TYPE: EDM SLOTSTUBE SIZE: 0.625 x 0.034

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
G-22-1	0.0100	0.0338	29.6	0.505	0	4800	4800
G-16-5	0.0095	0.0332	28.6	0.505	0	4920	4920
G-12-5	0.0095	0.0340	27.9	1.501	0	4760	4760
G-34-5	0.0200	0.0336	59.5	0.247	0	5020	5020
G-31-7	0.0200	0.0332	60.2	0.251	0	4840	4840
G-18-1	0.0200	0.0340	58.8	0.501	0	4520	4520
G-12-9	0.0200	0.0344	58.1	0.502	0	4590	4590
G-22-3	0.0185	0.0338	54.7	1.500	0	3900	3900
G-31-5	0.0190	0.0332	57.2	1.499	0	3860	3860
G-02-5	0.0295	0.0330	89.4	0.253	0	4620	4620
G-14-9	0.0315	0.0334	94.3	0.248	0	4960	4960
G-18-7	0.0285	0.0340	83.8	0.503	0	4600	4600
G-05-3	0.0290	0.0344	84.3	0.503	0	4470	4470
G-34-7	0.0290	0.0336	86.3	1.502	0	3990	3990
G-07-5	0.0290	0.0336	86.3	1.499	0	3780	3780

SGTI COLLAPSE TEST DATA

DEFECT TYPE: Elliptical WastageTUBE SIZE: 0.875 x 0.050

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
B-27-1	0.0135	0.0518	26.1	24" 0 ⁰	0	4470	4470
B-36-5	0.0130	0.0514	25.3	24" 0 ⁰	0	4560	4560
B-29-5	0.0150	0.0528	28.4	24" 135 ⁰	0	4160	4160
B-06-3	0.0145	0.0514	28.2	24" 135 ⁰	0	4260	4260
B-29-5	0.0240	0.0528	54.9	12" 0 ⁰	0	3440	3440
8-39-3	0.0285	0.0518	55.0	12" 0 ⁰	0	3510	3510
B-39-9	0.0295	0.0514	57.4	12" 135 ⁰	0	3120	3120
B-40-7	0.0240	0.0518	56.0	12" 135 ⁰	0	2880	2880
8-53-1	0.0435	0.0518	81.0	6" 0 ⁰	0	3070	3070
8-35-5	0.0425	0.0514	82.7	6" 0 ⁰	0	2700	2700

SGTI COLLAPSE TEST DATA

DEFECT TYPE: Elliptical WastageTUBE SIZE: 0.750 x 0.043

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
C-41-9	0.012	0.0490	24.5	24" 0 ⁰	0	4580	4580
C-18-5	0.011	0.0430	25.6	24" 0 ⁰	0	4700	4700
C-11-7	0.012	0.0422	28.4	24" 45 ⁰	0	4330	4330
C-15-9	0.011	0.0426	25.8	24" 45 ⁰	0	4480	4480
C-44-7	0.023	0.0420	54.8	12" 45 ⁰	0	2880	2880
C-21-7	0.023	0.0426	54.0	12" 45 ⁰	0	3080	3080
C-11-1	0.037	0.0426	86.9	6" 0 ⁰	0	2700	2700
C-19-9	0.037	0.0426	86.9	6" 0 ⁰	0	2680	2680

SGTI COLLAPSE TEST DATA

DEFECT TYPE: Elliptical WastageTUBE SIZE: 0.750 x 0.050

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
D-29-9	0.0150	0.0490	30.6	24" 0 ⁰	0	5460	5460
D-08-7	0.0140	0.0490	28.6	24" 0 ⁰	0	5000	5000
D-08-5	0.0165	0.0492	33.5	24" 135 ⁰	0	4480	4480
D-03-7	0.0450	0.0506	28.7	24" 135 ⁰	0	5130	5130
D-22-1	0.0290	0.0508	57.1	12" 0 ⁰	0	3720	3720
D-13-9	0.0297	0.0522	56.9	12" 0 ⁰	0	3920	3920
O-15-3	0.0300	0.0506	59.3	12" 45 ⁰	0	3180	3180
D-31-3	0.0280	0.0510	54.9	12" 45 ⁰	0	3650	3650
D-45-9	0.0290	0.0490	59.2	12" 140 ⁰	0	3340	3340
D-35-5	0.0290	0.0498	58.2	12" 135 ⁰	0	3430	3430
D-04-7	0.0430	0.0502	85.7	6" 0 ⁰	0	3460	3640
D-19-1	0.0440	0.0506	87.0	6" 0 ⁰	0	3450	3450
D-03-1	0.0440	0.0506	87.0	12" 0 ⁰	0	3020	3020
D-04-1	0.0440	0.0506	87.0	12" 0 ⁰	0	3140	3140

SGTI COLLAPSE TEST DATA

DEFECT TYPE: Elliptical WastageTUBE SIZE: 0.875 x 0.050

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
E-14-3	0.0270	0.0494	54.7	12" 0 ⁰	0	2980	2980
E-06-9	0.0280	0.0494	56.7	12" 0 ⁰	0	2990	2990

SGTI COLLAPSE TEST DATA

DEFECT TYPE: Elliptical WastageTUBE SIZE: 0.875 x 0.050

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
F-09-1	0.0280	0.0506	55.3	12" 0°	0	2780	2780
F-08-5	0.0285	0.0506	56.3	12" 0°	0	2880	2880

SGTI COLLAPSE TEST DATA

DEFECT TYPE: Elliptical WastageTUBE SIZE: 0.625 x 0.034

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
G-34-9	0.0095	0.0336	28.3	24" 0°	No indication of collapse on pressure curve		
G-14-3	0.0089	0.0334	26.6	24" 0°	0	4450	4450
G-13-3	0.0096	0.0334	28.7	24" 0°	0	4000	4000
G-02-1	0.0098	0.0330	29.7	24" 0°	0	3730	3730
G-36-9	0.0199	0.0346	57.5	12" 0°	0	3050	3050
G-13-5	0.0203	0.0334	60.8	12" 0°	0	2950	2950
G-15-1	0.0202	0.0332	60.8	12" 35°	0	2300	2300
G-36-7	0.0200	0.0344	58.1	12" 45°	0	2700	2700
G-13-9	0.0300	0.0332	90.4	6" 0°	0	2240	2240
G-16-7	0.0300	0.0332	90.4	6" 0°	0	2360	2360
G-31-3	0.0300	0.0332	90.4	12" 0°	0	4660	4660
G-36-3	0.0292	0.0342	85.4	12" 0°	0	1980	1980

SGTI COLLAPSE TEST DATA

DEFECT TYPE: Uniform ThinningTUBE SIZE: 0.875 x 0.050

<u>Specimen Number</u>	<u>Maximum Defect Depth</u>	<u>Minimum Wall</u>	<u>Percent Wastage</u>	<u>Defect Length</u>	<u>Tube Pressure</u>	<u>Autoclave Pressure</u>	<u>Failure Pressure</u>
B-56-3	0.013	0.0514	25.3	0.370	0	4720	4720
B-03-7	0.014	0.0520	26.9	0.370	0	4850	4850
B-32-7	0.014	0.0518	27.0	0.765	0	4770	4770
B-28-3	0.014	0.0514	27.2	0.755	0	4670	4670
B-56-9	0.014	0.0514	27.2	1.550	0	4250	4250
B-39-7	0.013	0.0518	25.1	1.580	0	4470	4470
B-29-3	0.029	0.0528	59.9	0.370	0	4320	4320
B-75-9	0.028	0.0518	54.1	0.375	0	4240	4240
B-18-9	0.029	0.0518	56.0	0.775	0	3080	3080
B-06-1	0.028	0.0514	54.5	0.750	0	2990	2990
B-12-1	0.029	0.0514	56.4	1.560	0	2840	2840
B-23-7	0.029	0.0518	56.0	1.580	0	2580	2580
B-70-5	0.038	0.0518	73.4	0.875	0	2160	2160
B-42-7	0.039	0.0522	74.7	0.184	0	4980	4980
B-04-7	0.039	0.0518	75.3	0.397	0	2380	2380
B-42-9	0.039	0.0522	74.7	0.378	0	4990	4990
B-70-7	0.038	0.0518	73.4	0.755	0	1760	1760
B-48-5	0.039	0.0518	75.3	0.760	0	4980	4980
B-40-1	0.038	0.0518	73.4	1.500	0	2980	2980
B-08-5	0.038	0.0514	73.9	1.496	0	3840	3840

APPENDIX E
LEAK RATE TEST DATA PLOTS

FIGURE E.1 Leak Rate Data for Specimen B-33-5

FIGURE E.2 Leak Rate Data for Specimen B-56-1

FIGURE E.7 Leak Rate Data for Specimen B-33-1

FIGURE E.8 Leak Rate Data for Specimen B-11-3

FIGURE E.9 Leak Rate Data for Specimen B-12-3

FIGURE E.10 Leak Rate Data for Specimen B-39-5

FIGURE E.9 Leak Rate Data for Specimen B-15-3

FIGURE E.10 Leak Rate Data for Specimen B-20-8

APPENDIX F

Phase I - SGTI Program Eddy-Current Data
(EDM Slot, Uniform Thinning, Elliptical Wastage)

**TABLE F-1. Phase I - SGTI Program Eddy Current Data EDM Slots
(Heat B Burst, Bulge, Leak, Fatigue Cracked)**

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
B-22-1	0.255	25.9	(b)	7890
B-13-9	0.255	30.2	(b)	8190
B-06-9	0.496	25.3	(b)	7390
B-16-1	0.500	30.7	(b)	7240
B-21-9	1.480	26.6	(b)	7240
B-07-3	1.485	29.8	(b)	7015
B-38-3	0.250	25.0	48	(a)
B-37-0	0.255	55.6	56	5900
B-04-1	0.502	57.9	55	5520
B-03-3	0.500	58.7	57	5500
B-25-9	1.493	52.5	43	5155
B-37-5	1.498	53.6	57	5055
B-13-5	0.253	91.4	81	4260
B-37-9	0.250	86.2	66	5355
B-40-9	0.495	82.0	72	3450
B-37-7	0.500	78.5	63	4200
B-41-1	1.505	84.9	87	1888
B-33-5	1.505	83.7	90	(a)
B-70-1	0.999	84.0	76	(a)
B-41-9	0.245	100	100	--
B-19-1	0.255	100	100	--
B-35-9	0.245	100	100	--
B-08-7	0.500	100	100	--
B-39-5	0.487	100	100	--
B-21-1	0.495	100	100	--
B-07-1	0.495	100	100	--
B-19-5	0.485	100	100	--
B-41-3	1.503	100	100	--
B-54-1	1.518	100	100	--
B-27-9	0.255	100	100	--
B-28-5	0.247	100	100	--
B-43-1	0.502	100	100	--
B-41-7	0.500	100	100	--
B-56-5	1.009	100	100	--
B-12-3	0.996	100	100	--

(a) Test failed.

(b) Undetectable.

TABLE F-2. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heat C, Burst, Bulge)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
C-27-1	0.240	29.6	(b)	7,540
C-27-7	0.250	31.4	(b)	(a)
C-41-3	0.500	28.3	(b)	9,100
C-34-1	0.500	27.9	(b)	10,555
C-41-5	1.500	28.4	(b)	8,900
C-19-5	1.500	26.1	(b)	8,645
C-37-9	0.250	56.3	45	5,910
C-36-3	0.250	58.7	53	6,780
C-34-3	0.500	53.5	5	7,180
C-36-7	0.500	56.3	8	7,150
C-24-5	1.500	56.3	60	5,810
C-18-7	1.500	53.8	5	6,130
C-15-5	0.250	88.4	44	6,965
C-03-9	0.250	88.9	49	7,180
C-03-5	0.505	88.0	75	1,331
C-44-3	0.500	86.9	64	5,215
C-21-9	1.495	77.5	67	<1,265
C-37-1	1.490	86.9	74	1,055
C-21-10	1.495	89.2	77	(a)
C-40-3	0.500	100	100	--
C-44-5	0.495	100	100	--
C-31-7	1.480	100	100	--
C-14-9	1.500	100	100	--

(a) Test failed.
(b) Undetectable.

TABLE F-3. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heat D, Burst)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
D-25-5	0.245	27.0	(b)	9070
D-25-1	0.247	30.9	(b)	8930
D-03-5	0.495	29.6	(b)	8495
D-34-1	0.495	27.7	(b)	8995
D-31-7	1.495	27.7	(b)	(a)
D-31-8	1.500	27.0	(b)	9400
D-12-9	1.495	29.6	(b)	8590
D-45-3	0.250	67.6	67	6795
D-12-3	0.265	31.2	51	8190
D-35-3	0.490	64.3	58	7740
D-31-9	0.490	57.8	62	6340
D-11-5	1.495	58.6	60	5706
D-41-9	1.490	59.2	57	5721
D-12-1	0.245	87.0	69	6090
D-17-3	0.255	84.3	73	5965
D-23-3	0.500	84.6	70	4321
D-19-5	0.495	86.6	70	4160
D-31-1	1.515	84.3	63	67
D-17-7	1.525	84.0	69	3268
D-31-2	1.493	84.3	76	2120

(a) Test failed.

(b) Undetectable.

TABLE F-4. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heats E and F, Burst)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
E-03-7	0.496	28.3	(a)	7200
E-04-5	0.500	26.3	(a)	7500
E-05-7	0.495	58.7	63	5200
E-06-1	0.495	58.7	65	5200
E-04-9	0.505	91.1	75	2240
E-04-1	0.505	89.1	77	2455
F-09-9	0.498	27.7	(a)	7340
F-09-3	0.496	27.7	(a)	7330
F-10-3	0.500	57.5	55	4900
F-06-7	0.501	57.3	52	4750
F-06-1	0.504	85.0	68	3035
F-03-9	0.499	89.7	77	2392
E-05-5	0.497	100	100	--
E-09-9	0.505	100	100	--
E-15-7	0.498	100	100	--
F-04-3	0.500	100	100	--
F-07-9	0.497	100	100	--
F-04-1	0.495	100	100	--

(a) Undetectable.

**TABLE F-5. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heat G, Burst)**

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
G-22-9	0.250	26.5	53	7370
G-05-1	0.250	29.9	(a)	7510
G-14-7	0.497	28.4	43	7750
G-15-3	0.497	28.6	51	7490
G-30-3	1.495	27.8	42	7400
G-35-7	1.495	34.0	44	6650
G-07-3	0.249	59.2	54	5800
G-18-9	0.251	58.8	65	6400
G-35-1	0.499	61.4	48	5100
G-28-9	0.500	56.2	55	5120
G-34-1	1.495	62.5	61	4000
G-05-9	1.503	57.4	65	4680
G-35-9	0.249	86.8	53	4750
G-30-9	0.247	87.7	53	4350
G-22-5	0.499	88.8	61	2150
G-15-7	0.496	89.9	67	1940
G-07-9	1.500	85.3	64	1990
G-07-1	1.503	80.9	64	2700

(a) Undetectable.

TABLE F-6. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heat B, Collapse)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
B-38-5	0.502	27.2	(b)	4850
B-48-9	0.501	28.0	(b)	(a)
B-29-7	1.510	24.1	(b)	4960
B-42-5	1.504	26.8	(b)	(a)
B-43-5	0.505	56.4	63	4900
B-60-3	0.503	58.9	61	4800
B-38-7	1.504	53.5	66	4580
B-75-3	1.503	53.1	61	4560
B-32-1	0.249	85.2	73	(a)
B-75-5	0.260	90.7	76	4880
B-11-9	0.503	83.0	73	4900
B-13-1	0.499	81.7	70	4820
B-27-7	1.502	81.1	71	(a)
B-21-5	1.490	82.7	67	4480

(a) Test failed.

(b) Undetectable.

**TABLE F-7. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heats C and D, Collapse)**

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
C-36-5	1.500	28.2	(a)	5240
C-18-9	1.500	28.0	(a)	5040
C-34-7	1.500	55.8	52	4480
C-15-3	1.500	56.3	45	4410
C-19-3	1.480	79.8	81	4510
C-24-9	1.480	83.3	66	4360
D-09-9	0.495	28.9	(a)	5700
D-31-5	0.500	27.5	(a)	6500
D-41-3	1.495	28.9	(a)	6080
D-04-9	1.495	27.9	(a)	5900
D-15-1	0.495	59.3	51	5820
D-13-3	0.490	55.1	41	5960
D-35-1	1.490	58.5	55	5120
D-03-3	1.495	59.3	60	5350
D-29-5	0.505	83.7	82	6340
D-01-4	0.499	83.0	75	5760
D-45-7	1.500	86.4	70	5800
D-19-7	1.500	83.0	67	5680

(a) Undetectable.

TABLE F-8. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heats E and F, Collapse)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
E-05-1	0.50	25.3	(a)	4350
E-03-5	0.490	25.3	(a)	4350
E-02-3	1.495	26.3	(a)	4430
E-04-7	1.493	26.3	(a)	4390
E-14-6	0.503	56.7	56	4280
E-09-1	0.490	57.7	63	4980
E-05-9	1.495	60.7	62	4060
E-15-1	1.490	56.7	63	3970
E-09-5	0.247	89.1	77	4360
E-14-8	0.249	89.1	74	4230
E-15-3	0.503	85.0	77	4430
E-09-7	0.498	89.1	75	4280
E-14-9	1.505	89.1	79	3910
E-03-3	1.506	87.0	82	4070
F-01-7	0.498	28.0	(a)	4130
F-04-9	0.496	26.9	(a)	4120
F-01-5	1.525	27.3	(a)	4950
F-08-9	1.490	26.7	(a)	4100
F-03-5	0.499	55.8	65	4020
F-10-9	0.504	55.6	57	3880
F-06-5	1.488	53.8	60	3675
F-01-3	1.525	56.5	62	3970
F-07-3	0.248	87.0	75	4060
F-09-5	0.246	87.0	75	3960
F-07-5	0.499	81.0	83	3985
F-04-5	0.499	85.7	77	4140
F-03-3	1.505	83.7	74	3760
F-08-1	1.498	85.0	74	3600

(a) Undetectable.

TABLE F-9. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heat G, Collapse)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
G-22-1	0.305	29.6	(b)	4800
G-16-5	0.505	28.6	(b)	4920
G-12-5	1.501	27.9	(b)	4760
G-15-5	1.50	25.0	46	(a)
G-34-5	0.247	59.5	65	5020
G-31-7	0.251	60.2	63	4840
G-18-1	0.501	58.8	54	4520
G-12-9	0.502	58.1	58	4590
G-22-3	1.500	54.7	67	3900
G-31-5	1.499	57.2	68	3860
G-02-5	0.253	89.4	75	4620
G-14-9	0.248	94.3	95	4960
G-18-7	0.503	83.8	66	4600
G-05-3	0.503	84.3	78	4470
G-34-7	1.502	86.3	77	3990
G-07-5	1.499	86.3	80	3780

(a) Test failed.

(b) Undetectable.

**TABLE F-10. Phase I - SGTI Program Eddy-Current Data
Uniform Thinning (Heat B, Burst)**

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
B-08-9	0.375	27.7	40	8505
B-60-1	0.384	24.6	36	8440
B-60-5	0.752	27.5	40	7730
B-60-7	0.755	28.0	39	7835
B-35-3	1.581	28.2	40	7120
B-23-5	1.510	26.1	40	7100
B-08-3	0.187	58.0	69	7610
B-40-5	0.182	55.0	68	7895
B-60-9	0.380	55.6	65	6950
B-25-1	0.380	51.0	66	7030
B-19-7	0.760	54.5	64	5420
B-16-5	0.755	56.5	64	5510
B-23-9	1.513	56.0	63	4700
B-12-5	1.496	57.4	63	4795
B-35-7	0.1825	73.0	82	5450
B-19-9	0.185	72.4	81	5560
B-31-7	0.378	74.9	81	4775
B-36-7	0.378	73.5	80	4865
B-18-3	0.750	74.9	80	3350
B-09-5	0.750	73.9	80	3440
B-21-3	1.495	75.7	80	2790
B-18-1	1.500	74.9	80	2795
B-32-8	0.195	27.0	40	9030
B-03-8	0.195	26.9	46	8860

TABLE F-11. Phase I - SGTI Program Eddy-Current Data
Uniform Thinning (Heat B, Collapse)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
B-56-3	0.370	25.3	40	4720
B-03-7	0.370	26.9	40	4850
B-32-7	0.765	27.0	42	4770
B-28-3	0.755	27.2	40	4670
B-56-9	1.550	27.2	42	4250
B-39-7	1.580	25.1	41	4470
B-29-3	0.370	54.9	66	4320
B-75-9	0.375	54.1	64	4240
B-18-9	0.775	56.0	63	3080
B-06-1	0.750	54.5	64	2990
B-12-1	1.560	56.5	63	2840
B-23-7	1.580	56.0	64	2580
B-70-5	0.875	73.4	85	2160
B-42-7	0.184	74.7	86	4980
B-04-7	0.399	75.3	83	2380
B-42-9	0.378	74.7	84	4990
B-70-7	0.755	73.4	83	1760
B-48-5	0.760	75.3	84	4980
B-40-1	1.500	75.0	83	2980
B-08-5	1.496	73.9	83	3840

TABLE F-12. Phase I - SGTI Program Eddy-Current Data
Uniform Thinning (Heats C, D, E, and F, Burst)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
C-27-3	0.375	31.0	51	8740
C-44-1	0.375	28.2	57	8100
C-40-9	0.1875	55.8	81	7895
C-40-7	0.225	57.0	70	7450
C-03-1	0.375	56.9	58	6855
C-21-5	0.375	56.3	77	6895
C-41-7	0.375	28.4	23	(a)
C-41-8	0.375	27.0	21	(a)
D-09-5	0.750	29.5	48	9090
D-34-3	0.750	27.7	47	9595
D-29-1	1.512	28.8	48	9120
D-23-5	1.510	27.5	47	8685
D-41-1	0.745	58.7	64	6690
D-34-9	0.755	56.4	63	6295
E-02-9	0.380	58.7	72	6935
E-06-5	0.380	58.7	71	6845
F-06-9	0.375	57.3	67	6840
F-03-1	0.385	59.8	70	6905

(a) Test failed.

**TABLE F-13. Phase I - SGTI Program Eddy-Current Data
Elliptical Wastage (Heat B, Burst)**

<u>Specimen Number</u>	<u>Cutter Radius (in.)</u>	<u>Wrap Angle (Degrees)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
B-48-3	24	0	26.1	(a)	8155
B-48-7	24	0	26.1	(a)	8150
B-36-1	24	45	26.3	27	7615
B-22-7	24	45	26.9	35	7940
B-53-3	24	135	28.0	46	5200
B-31-5	24	135	27.2	36	7780
B-52-5	12	0	56.9	62	5550
B-53-7	12	0	56.0	58	5635
B-09-4	6	45	55.4	63	6240
B-07-10	6	45	53.8	59	6190
B-43-7	12	45	55.4	66	5680
B-28-7	12	45	55.4	64	5840
B-09-10	6	135	56.0	62	6100
B-53-10	6	135	54.6	61	6210
B-40-3	12	125	56.0	64	5610
B-31-3	12	135	57.4	64	5455
B-54-3	6	0	85.6	77	2950
B-54-7	6	0	82.7	76	2970
B-53-4	24	135	27.0	33	7920

(a) Undetectable.

**TABLE F-14. Phase I - SGTI Program Eddy-Current Data
Elliptical Wastage (Heat C, Burst)**

<u>Specimen Number</u>	<u>Cutter Radius (in.)</u>	<u>Wrap Angle (Degrees)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
C-37-5	24	0	30.5	< 20	7580
C-11-5	24	0	26.1	< 20	8275
C-23-1	24	42	28.2	< 20	7855
C-15-1	24	45	30.8	< 20	7915
C-34-5	12	0	53.5	66	6060
C-21-2	12	0	55.0	58	(a)
C-31-4	6	45	55.0	58	(a)
C-11-3	6	45	55.0	72	6115
C-18-3	12	40	53.5	68	5900
C-23-9	12	45	55.9	72	5905
C-19-7	6	0	84.5	73	< 1265
C-21-3	6	0	84.5	72	< 1250
C-19-8	6	0	85.7	74	2180
C-21-4	6	0	86.9	71	2760

(a) Test failed.

**TABLE F-15. Phase I - SGTI Program Eddy-Current Data
Elliptical Wastage (Heat D, Burst)**

<u>Specimen Number</u>	<u>Cutter Radius (in.)</u>	<u>Wrap Angle (Degrees)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
D-11-3	24	0	29.2	(a)	9440
D-35-9	24	0	30.2	(a)	9945
D-29-7	24	48	28.6	37	9860
D-39-5	24	40	27.5	33	9685
D-17-5	24	137	30.4	37	9110
D-09-7	24	138	29.0	37	8890
D-04-5	6	0	59.5	54	6550
D-11-9	6	0	58.6	52	6760
D-19-9	12	0	57.3	54	6655
D-08-3	12	0	61.2	55	6180
D-34-7	12	48	54.9	63	5845
D-03-9	12	43	55.3	63	6260
D-01-1	6	140	54.5	63	6940
D-01-9	6	140	52.9	52	7020
D-04-3	12	135	55.3	60	6400
D-09-1	12	140	57.1	54	6870
D-19-3	6	0	88.2	73	3500
D-39-9	6	0	84.3	73	3940
D-12-5	12	0	86.6	73	1250
D-41-7	12	0	89.1	72	3110
D-12-4	12	0	84.6	77	3320

(a) Undetectable.

TABLE F-16. Phase I - SGTI Program Eddy-Current Data
Elliptical Wastage (Heats G, E and F, Burst)

<u>Specimen Number</u>	<u>Cutter Radius (in.)</u>	<u>Wrap Angle (Degrees)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
G-15-9	24	0	29.8	< 20	7630
G-22-7	24	0	29.2	< 20	7495
G-30-1	24	45	27.9	38	7895
G-28-5	24	45	28.1	< 20	7600
G-07-7	6	0	55.9	53	5960
G-15-5	6	0	56.9	44	5500
G-02-3	12	0	59.7	39	4780
G-28-7	12	0	57.7	54	5160
G-31-9	12	45	60.2	65	4800
G-14-1	12	45	58.4	67	(a)
G-12-7	6	0	85.3	84	3150
G-30-7	6	0	85.3	80	3120
G-02-7	12	0	89.8	68	2900
G-13-1	12	0	89.8	68	2390
E-02-1	12	0	55.7	54	5635
E-14-7	12	0	54.7	58	5290
F-09-7	12	0	56.3	57	5465
F-10-1	12	0	54.0	55	5700

(a)Test failed.

**TABLE F-17. Phase I - SGTI Program Eddy Current Data
Elliptical Wastage (Heats B, C and D, Collapse)**

<u>Specimen Number</u>	<u>Cutter Radius (in.)</u>	<u>Wrap Angle (Degrees)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Collapse Pressure (psig)</u>
B-27-1	24	0	26.1	20	4470
B-36-5	24	0	25.3	20	4560
B-29-9	24	135	28.4	42	4160
B-06-3	24	135	28.2	40	4260
B-29-5	12	0	54.9	55	3440
B-39-3	12	0	55.0	62	3510
B-39-9	12	135	57.4	63	3120
B-40-7	12	135	56.0	62	2880
B-53-1	6	0	84.0	80	3070
B-35-5	6	0	82.7	75	2700
C-41-9	24	0	24.5	20	4580
C-18-5	24	0	25.6	22	4700
C-11-7	24	45	28.4	20	4330
C-15-9	24	45	25.8	20	4480
C-44-7	12	45	54.8	74	2880
C-21-7	12	45	54.0	70	3080
C-11-1	6	0	86.9	71	2700
C-19-9	6	0	86.9	75	2680
D-29-9	24	0	30.6	33	5460
D-08-7	24	0	28.6	(b)	5000
D-08-5	24	135	33.5	41	4480
D-03-7	24	135	28.7	35	5130
D-22-1	12	0	57.1	52	3720
D-13-9	12	0	56.9	45	3920
D-15-3	12	45	59.3	58	3180
D-31-3	12	45	54.9	61	3650
D-15-9	12	140	59.2	62	3340
D-35-5	12	135	58.2	59	3430
D-04-7	6	0	85.7	73	3640
D-19-1	6	0	87.0	71	3450
D-03-1	12	0	87.0	73	3020

(a) Test failed.

(b) Undetectable

**TABLE F-18. Phase I - SGTI Program Eddy-Current Data
Elliptical Wastage (Heats E, F and G, Collapse)**

<u>Specimen Number</u>	<u>Cutter Radius (in.)</u>	<u>Wrap Angle (Degrees)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Collapse Pressure (psig)</u>
E-14-3	12	0	54.7	55	2980
E-06-0	12	0	56.7	55	2990
F-09-1	12	0	55.3	57	2780
F-08-5	12	0	56.3	55	2880
G-34-9	24	0	28.3	24	(a)
G-14-3	24	0	26.6	20	4450
G-13-3	24	45	28.7	35	4000
G-02-1	24	45	29.7	40	3730
G-36-9	12	0	57.5	53	3050
G-13-5	12	0	60.8	52	2950
G-15-1	12	45	55	70	2300
G-36-7	12	45	58.1	65	2700
G-13-9	6	0	90.4	83	2240
G-16-7	6	0	90.4	77	2360
G-31-3	12	0	90.4	73	4660
G-36-3	12	0	85.4	70	1980

(a) Test failed.

TABLE F-19. Phase I - SGTI Program Eddy Current Data Elliptical Wastage Plus EDM Slot (Heats B, C and D, Burst)

Specimen Number	Cutter Radius (in.)	Wrap Angle (Degrees)	Slot Length (in.)	Wastage Defect Depth (% Wall)	Maximum Defect Depth (% Wall)	ECT Indicated Defect Depth (% Wall)	Burst Pressure (psig)
B-44-5	24	0	0.998	27.0	100	68	(a)
B-44-7	24	0	1.004	33.1	100	60	(a)
B-25-5	24	0	0.250	27.0	100	100	--
B-16-7	24	0	0.242	29.0	100	100	--
B-18-7	24	0	0.500	28.0	100	100	--
B-13-7	24	0	0.500	26.1	100	100	--
B-36-3	12	0	0.240	56.0	100	100	--
B-52-1	12	0	0.250	56.0	100	100	--
B-28-9	12	0	0.505	54.1	100	100	--
B-54-9	12	0	0.495	54.1	100	100	--
B-04-3	6	0	0.240	83.0	100	100	--
B-03-5	6	0	0.250	83.0	100	100	--
B-21-7	6	0	0.500	83.0	100	100	--
B-56-1	6	0	0.500	84.9	100	100	--
C-40-5	24	0	0.252	25.6	100	100	--
C-40-1	24	0	0.250	27.9	100	100	--
C-41-1	24	0	0.505	25.6	100	100	--
C-31-9	24	0	0.505	30.2	100	100	--
C-14-1	12	0	0.255	51.2	100	100	--
C-31-1	12	0	0.240	55.8	100	100	--
C-37-7	12	0	0.500	53.5	100	100	--
C-36-2	12	0	0.500	54.7	100	100	--
C-08-3	6	0	0.247	84.4	100	100	--
C-27-5	6	0	0.243	85.3	100	100	--
C-08-1	6	0	0.504	87.2	100	100	--
C-27-9	6	0	0.490	86.6	100	100	--
D-15-9	24	0	0.248	25.7	100	100	--
D-11-7	24	0	0.255	24.3	100	100	--
D-09-3	24	0	0.501	31.4	100	100	--
D-23-9	24	0	0.500	25.5	100	100	--
D-22-3	12	0	0.255	56.6	100	100	--
D-23-7	12	0	0.255	58.8	100	100	--
D-22-5	12	0	0.502	56.6	100	100	--
D-34-5	12	0	0.510	56.9	100	100	--
D-25-9	6	0	0.247	91.3	100	100	--
D-25-3	6	0	0.245	91.3	100	100	--
D-25-7	6	0	0.495	89.5	100	100	--
D-26-1	6	0	0.490	85.9	100	100	--

(a) Tests not yet completed.

**TABLE F-20. Phase I - SGTI Program Eddy-Current Data
Elliptical Wastage Plus EDM Slot (Heats E, F and G)**

<u>Specimen Number</u>	<u>Cutter Radius (in.)</u>	<u>Wrap Angle (Degrees)</u>	<u>Slot Length (in.)</u>	<u>Wastage Defect Depth (% Wall)</u>	<u>Maximum Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>
E-03-1	12	0	0.500	55.0	100	100
E-03-9	12	0	0.500	55.0	100	100
F-07-7	12	0	0.500	55.0	100	100
F-08-7	12	0	0.495	54.7	100	100
G-28-1	24	0	0.245	27.9	100	100
G-31-1	24	0	0.246	28.0	100	100
G-05-5	24	0	0.505	29.2	100	100
G-35-5	24	0	0.504	28.1	100	100
G-13-7	12	0	0.245	59.0	100	100
G-14-5	12	0	0.246	56.9	100	100
G-02-4	12	0	0.500	59.0	100	100
G-35-3	12	0	0.505	58.9	100	100
G-34-3	6	0	0.248	87.8	100	100
G-28-3	6	0	0.250	88.4	100	100
G-18-3	6	0	0.500	85.3	100	100
G-30-5	6	0	0.502	84.8	100	100

TABLE F-21. Phase I - SGTI Program Eddy-Current Data
Elliptical Wastage Plus EDM Slot (Heat B)

Specimen Number	Cutter Radius (in.)	Wrap Angle (Degrees)	Slot Length (in.)	Wastage Defect Depth (% Wall)	Maximum Defect Depth (% Wall)	ECT Indicated Defect Depth (% Wall)
B-39-1	24	0	0.225	29.0	100	100
B-42-3	24	0	0.240	27.0	100	100
B-70-3	24	0	0.505	29.0	100	100
B-11-3	24	0	0.500	26.1	100	100
B-33-1	24	0	1.035	25.1	100	100
B-28-1	24	0	0.995	27.0	100	100
B-12-7	12	0	0.245	54.1	100	100
B-04-9	12	0	0.240	53.1	100	100
B-16-9	12	0	0.495	56.0	100	100
B-07-5	12	0	0.495	53.1	100	100
B-25-7	12	0	1.002	52.1	100	100
B-09-1	12	0	0.995	54.1	100	100
B-06-5	24	0	0.240	28.0	100	100
B-07-7	24	0	0.235	29.0	100	100
B-38-9	24	0	0.500	28.0	100	100
B-33-9	24	0	0.500	29.0	100	100
B-43-9	12	0	0.240	54.1	100	100
B-23-3	12	0	0.245	56.0	100	100
B-11-5	12	0	0.500	55.0	100	100
B-41-5	12	0	0.500	56.0	100	100
B-53-5	6	0	0.250	85.0	100	100
B-75-7	6	0	0.250	58.0	100	100
B-03-1	6	0	0.495	84.9	100	100
B-09-7	6	0	0.495	83.0	100	100

APPENDIX G

Phase I - SGTI Program Eddy-Current Data
(Denting, Denting Plus Elliptical Wastage,
Denting Plus Uniform Thinning)

Table G-1. Phase I - SGTI Program Eddy-Current Data
Denting (Heats B, C, D, E, and F, Burst)

<u>Specimen Number</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
B-22-5	42	9,320
B-19-3	42	9,260
B-32-3	43	9,580
C-24-7	(b)	9,610
C-11-9	13	(a)
C-24-1	18	9,650
D-13-1	36	11,220
D-08-1	38	11,400
D-22-9	37	11,000
E-15-9	20	(a)
E-02-7	20	9,200
E-04-3	20	9,020
F-10-7	20	9,100
F-01-1	20	(a)
F-01-9	20	9505

(a) Test failed.

(b) Uninterpretable.

Table G-2. Phase I - SGTI Program Eddy-Current Data Denting Plus Elliptical Wastage (Heats B, C, and D, Burst)

<u>Specimen Number</u>	<u>Cutter Radius (in.)</u>	<u>Wrap Angle (Degrees)</u>	<u>Actual Defect Depth (% Wall)</u>	<u>ECT Indicated Defect Depth (% Wall)</u>	<u>Burst Pressure (psig)</u>
B-56-7	24	0	26.3	(b)	7905
B-31-1	24	0	25.3	(b)	8150
B-32-9	24	45	26.3	38	9200
B-36-9	24	45	26.3	43	8060
B-12-9	24	135	29.9	46	7800
B-04-5	24	135	28.0	46	7770
B-27-3	12	0	56.0	(b)	5520
B-18-5	12	0	56.0	(b)	5605
B-38-1	12	45	55.4	77	5650
B-06-7	12	45	56.4	76	5675
B-08-1	12	135	55.4	74	5320
B-37-3	12	135	55.6	75	5230
C-03-7	24	0	26.1	20	8335
C-18-1	24	0	25.5	(b)	8595
C-03-3	12	0	54.2	80	6055
C-31-5	12	0	54.2	85	5775
D-15-7	24	41	27.7	(b)	9205
D-01-7	24	43	29.4	(b)	9000
D-45-1	24	135	26.0	20	(a)
D-35-7	24	135	30.1	(b)	9240
D-29-3	12	45	59.7	80	6115
D-13-7	12	45	53.6	75	6500
D-01-5	12	135	57.3	77	5905
D-13-5	12	135	57.0	65	(a)

(a) Test failed.

(b) Uninterpretable.

Table G-3. Phase I - SGTI Program Eddy-Current Data Denting
Plus Uniform Thinning (Heats B, C, and D, Burst)

Specimen Number	Defect Length (in.)	Actual Defect Depth (% Wall)	ECT Indicated Defect Depth (% Wall)	Burst Pressure (psig)
B-27-5	0.384	25.1	62	9275
B-48-1	0.383	27.0	68	9390
B-43-3	0.764	27.2	68	8295
B-52-3	0.752	27.0	72	8600
B-29-1	1.530	29.0	70	7355
B-13-3	1.511	27.2	72	7200
B-52-7	0.200	56.0	(b)	8500
B-03-9	0.204	55.8	90	8800
B-32-5	0.392	56.0	82	7505
B-22-9	0.375	53.6	83	7765
B-42-1	0.747	53.6	83	5940
B-52-9	0.759	56.0	84	5540
C-24-3	0.380	26.1	55	9500
C-14-5	0.384	27.9	55	9240
C-36-9	0.185	57.5	75	(a)
C-34-9	0.187	57.2	86	8650
C-15-7	0.386	57.5	73	7360
C-14-3	0.371	57.1	67	8600
D-15-5	0.760	27.5	53	9700
D-41-5	0.759	28.6	20	(a)
D-22-8	1.500	25.0	41	(a)
D-11-1	1.505	27.2	50	8860
D-45-5	0.755	56.7	72	6560
D-17-9	0.764	56.9	83	6200

(a) Test failed.

(b) Uninterpretable.

APPENDIX H

Phase I - SGTI Program Eddy-Current Data, ECT Slot Length Measurement Data
(EDM Slots, Uniform Thinning, Elliptical Wastage)

TABLE H-1. Phase I - SGTI Program Eddy-Current Defect
Length Data Uniform Thinning (Heat B, Burst)

Specimen Number	Actual Defect Length (in.)	ECT Measured Defect Length (in.)	Defect Length Measurement Error (%)	Burst Pressure (psig)
B-08-9	0.375	0.35	-6.7	8505
B-60-1	0.384	0.44	+14.6	8440
B-60-5	0.752	0.79	+5.1	7730
B-60-7	0.755	0.75	-0.7	7835
B-35-3	1.581	1.58	0.0	7120
B-23-5	1.510	1.58	+4.6	7100
B-08-3	0.187	0.25	+33.7	7610
B-40-5	0.182	0.26	+42.9	7895
B-60-9	0.380	0.37	-2.6	6950
B-25-1	0.380	0.36	-5.3	7030
B-19-7	0.760	0.82	+7.9	5420
B-16-5	0.755	0.71	-6.0	5510
B-23-9	1.513	1.54	+1.8	4700
B-12-5	1.496	1.56	+4.3	4795
B-35-7	0.1825	0.18	-1.4	5450
B-19-9	0.185	0.18	-2.7	5560
B-31-7	0.378	0.33	-12.7	4775
B-36-7	0.378	0.25	-33.9	4865
B-18-3	0.750	0.70	-6.7	3350
B-09-5	0.750	0.70	-6.7	3440
B-21-3	1.495	1.41	-5.7	2790
B-18-1	1.500	1.50	0.0	2795
B-32-8	0.195	(a)	--	9030
B-03-8	0.195	(a)	--	8860

(a) Data not analyzed.

TABLE H-2. Phase I - SGTI Program Eddy-Current Defect Length Data Uniform Thinning (Heat B, Collapse)

Specimen Number	Actual Defect Length (in.)	ECT Measured Defect Length (in.)	Defect Length Measurement Error (%)	Collapse Pressure (psig)
B-56-3	0.370	0.370	0.0	4720
B-03-7	0.370	0.352	-4.9	4850
B-32-7	0.765	0.792	+3.5	4770
B-28-3	0.755	0.792	+4.9	4670
B-56-9	1.550	1.584	+2.2	4250
B-39-7	1.580	1.584	+0.3	4470
B-29-3	0.370	0.352	-4.9	4320
B-75-9	0.375	0.361	-3.7	4240
B-18-9	0.775	0.792	+2.2	3080
B-06-1	0.750	0.722	-3.7	2990
B-12-1	1.560	1.584	+1.5	2840
B-23-7	1.580	1.566	-0.9	2580
B-70-5	0.875	0.792	-9.5	2160
B-42-7	0.184	0.176	-4.3	4980
B-04-7	0.399	0.370	-7.3	2380
B-42-9	0.378	0.370	-2.1	4990
B-70-7	0.755	0.748	-0.9	1760
B-48-5	0.760	0.748	-1.6	4980
B-40-1	1.500	1.540	+2.7	(a)
B-08-5	1.496	1.584	+5.9	3840

(a) Test failed.

**TABLE H-3. Phase I - SGTI Program Eddy Current Data EDM Slots
(Heat B, Burst, Bulge, Leak, Fatigue Cracked)**

Specimen Number	Actual Defect Length (in.)	ECT Measured Defect Length (in.)	Collapse Pressure (psig)
B-22-1	0.255	0.352	7890
B-13-9	0.255	0.369	8190
B-06-9	0.496	0.440	7390
B-16-1	0.500	0.528	7240
B-21-9	1.480	1.672	7240
B-07-3	1.485	1.619	7015
B-38-3	0.250	0.352	(a)
B-37-0	0.255	(b)	5900
B-04-1	0.502	0.457	5520
B-03-3	0.500	1.545	5500
B-25-9	1.493	1.584	5155
B-37-5	1.498	1.584	5055
B-13-5	0.253	0.184	4260
B-37-9	0.250	0.227	5355
B-40-9	0.495	0.454	3450
B-37-7	0.500	0.477	4200
B-41-1	1.505	1.584	1888
B-33-5	1.505	(b)	(a)
B-70-1	0.999	(b)	(a)
B-41-9	0.245	0.227	--
B-19-1	0.255	0.227	--
B-35-9	0.245	0.227	--
B-08-7	0.500	0.454	--
B-39-5	0.487	0.454	--
B-21-1	0.495	0.341	--
B-07-1	0.495	0.369	--
B-19-5	0.485	0.369	--
B-41-3	1.503	1.408	--
B-54-1	1.518	1.408	--
B-27-9	0.255	0.228	--
B-28-5	0.247	0.176	--
B-43-1	0.502	0.352	--
B-41-7	0.500	0.352	--
B-56-5	1.009	0.88	--
B-12-3	0.996	0.88	--

(a) Test failed.

(b) Data not analyzed.

**TABLE H-4. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heat G, Burst)**

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Measured Defect Length</u>	<u>Burst Pressure (psig)</u>
G-22-9	0.250	0.211	7370
G-05-1	0.250	0.184	7510
G-14-7	0.497	0.528	7750
G-15-3	0.497	0.440	7490
G-30-3	1.495	1.584	7400
G-35-7	1.495	1.513	6650
G-07-3	0.249	0.176	5800
G-18-9	0.251	0.184	6400
G-35-1	0.499	0.440	5100
G-28-9	0.500	0.510	5120
G-34-1	1.495	1.584	4000
G-05-9	1.503	0.880	4680
G-35-9	0.249	0.193	4750
G-30-9	0.247	0.185	4350
G-22-5	0.499	0.440	2150
G-15-7	0.496	0.616	1940
G-07-9	1.500	1.426	1990
G-07-1	1.503	1.426	2700

**TABLE H-5. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heat B, Collapse)**

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Measured Defect Length</u>	<u>Collapse Pressure (psig)</u>
B-38-5	0.502	(a)	4850
B-48-9	0.501	0.510	(b)
B-29-7	1.510	1.760	4960
B-42-5	1.504	1.478	(b)
B-43-5	0.505	0.387	4900
B-60-3	0.503	0.510	4800
B-38-7	1.504	1.426	4580
B-75-3	1.503	1.496	4560
B-32-1	0.249	0.176	(b)
B-75-5	0.260	0.194	4880
B-11-9	0.503	0.458	4900
B-13-1	0.499	0.361	4820
B-27-7	1.502	1.584	(b)
B-21-5	1.490	1.531	4480

(a) Uninterpretable.

(b) Test failed.

**TABLE H-6. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heats C and D, Collapse)**

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Measured Defect Length</u>	<u>Collapse Pressure (psig)</u>
C-36-5	1.500	(a)	5240
C-18-9	1.500	(a)	5040
C-34-7	1.500	1.584	4480
C-15-3	1.500	1.566	4410
C-19-3	1.480	1.504	4510
C-24-9	1.480	1.408	4360
D-09-9	0.495	0.528	5700
D-31-5	0.500	0.528	6500
D-41-3	1.495	1.528	6080
D-04-9	1.495	1.528	5900
D-15-1	0.495	0.440	5820
D-13-3	0.490	0.440	5960
D-35-1	1.490	1.425	5120
D-03-3	1.495	1.496	5350
D-29-5	0.505	0.352	6340
D-01-4	0.499	(b)	5760
D-45-7	1.500	1.584	5800
D-19-7	1.500	1.584	4680

(a) Uninterpretable.

(b) Test failed.

TABLE H-7. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heats E and F, Collapse)

Specimen Number	Defect Length (in.)	Measured Defect Length	Collapse Pressure (psig)
E-05-1	0.500	(a)	4350
E-03-5	0.490	(a)	4350
E-02-3	1.495	1.496	4430
E-04-7	1.493	1.496	4390
E-14-6	0.503	0.475	4280
E-09-1	0.490	0.458	4980
E-05-9	1.495	1.548	4060
E-15-1	1.490	1.496	3970
E-09-5	0.247	0.193	4360
E-14-8	0.249	0.195	4230
E-15-3	0.503	0.228	4430
E-09-7	0.498	0.360	4280
E-14-9	1.505	1.689	3910
E-03-3	1.506	1.672	4070
F-01-7	0.498	0.510	4130
F-04-9	0.496	0.528	4120
F-01-5	1.525	1.056	4950
F-08-9	1.490	(a)	4100
F-03-5	0.499	0.499	4020
F-10-9	0.504	0.458	(b)
F-06-5	1.488	1.566	3675
F-01-3	1.525	1.531	3970
F-07-3	0.248	0.176	4060
F-09-5	0.246	0.176	3960
F-07-5	0.499	0.352	3985
F-04-5	0.499	0.440	4140
F-03-3	1.505	1.496	3760
F-08-1	1.498	1.584	3600

(a) Uninterpretable.

(b) Test failed.

TABLE H-8. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heat G, Collapse)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Measured Defect Length</u>	<u>Collapse Pressure (psig)</u>
G-22-1	0.305	0.440	4800
G-16-5	0.505	0.475	4920
G-12-5	1.501	1.584	4760
G-18-5	1.500	1.760	(a)
G-34-5	0.247	0.211	5020
G-31-7	0.251	0.211	4850
G-18-1	0.501	0.528	4520
G-12-9	0.502	0.510	4590
G-22-3	1.500	1.672	3900
G-31-5	1.499	1.636	3860
G-02-5	0.253	0.264	4620
G-14-9	0.248	0.184	4960
G-18-7	0.503	0.528	4600
G-05-3	0.503	0.440	4470
G-34-7	1.502	1.672	3990
G-07-5	1.499	1.672	3780

(a) Test failed.

TABLE H-9. Phase I - SGTI Program Eddy Current Data
EDM Slots (Heats E and F, Burst)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Measured Defect Length</u>	<u>Burst Pressure (psig)</u>
E-03-7	0.496	0.457	7200
E-04-5	0.500	0.528	7500
E-05-7	0.495	0.528	5200
E-06-1	0.495	0.492	5200
E-04-9	0.505	0.352	2240
E-04-1	0.505	0.352	2455
F-09-9	0.498	0.528	7340
F-09-3	0.496	0.457	7330
F-10-3	0.500	0.510	4900
F-06-7	0.501	0.387	4750
F-06-1	0.504	0.352	3035
F-03-9	0.499	0.360	2392
E-05-5	0.497	0.352	--
E-09-9	0.505	0.352	--
F-15-7	0.498	0.352	--
F-07-9	0.497	0.352	--
F-04-1	0.495	0.352	--

TABLE H-10. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heat D, Burst)

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Measured Defect Length</u>	<u>Burst Pressure (psig)</u>
D-25-5	0.245	0.281	9070
D-25-1	0.247	0.334	8930
D-03-5	0.495	(a)	8495
D-34-1	0.495	1.249	8995
D-31-7	1.495	1.672	(b)
D-12-9	1.495	1.672	8590
D-45-3	0.250	0.176	6795
D-12-3	0.265	0.184	8190
D-35-3	0.490	0.440	7740
D-31-9	0.490	0.440	6340
D-11-5	1.495	1.584	5706
D-41-9	1.490	1.672	5721
D-12-1	0.245	0.184	6090
D-17-3	0.255	0.176	5965
D-23-3	0.500	0.528	4321
D-19-5	0.495	(c)	4160
D-31-1	1.515	0.88	67
D-17-7	1.525	(c)	3268
D-31-8	1.500	1.566	(b)
D-31-2	1.493	1.531	2120

(a) Uninterpretable.
(b) Test failed.
(c) Data not analyzed.

**TABLE H-11. Phase I - SGTI Program Eddy-Current Data
EDM Slots (Heat C, Burst, Bulge)**

<u>Specimen Number</u>	<u>Defect Length (in.)</u>	<u>Measured Defect Length</u>	<u>Burst Pressure (psig)</u>
C-27-1	0.240	(b)	7,540
C-27-7	0.250	(b)	(a)
C-41-3	0.500	0.880	9,100
C-34-1	0.500	0.880	10,555
C-41-5	1.500	(c)	8,900
C-19-5	1.500	(b)	8,645
C-37-9	0.250	0.184	5,910
C-36-3	0.250	(b)	6,780
C-34-3	0.500	0.334	7,180
C-36-7	0.500	(b)	7,150
C-24-5	1.500	1.496	5,810
C-18-7	1.500	1.584	6,130
C-15-5	0.250	0.211	6,965
C-03-9	0.250	0.193	7,180
C-03-5	0.505	0.405	1,331
C-44-3	0.500	(b)	5,215
C-21-9	1.495	1.144	1,265
C-37-1	1.490	1.408	1,055
C-21-10	1.495	1.672	(a)
C-40-3	0.500	0.352	--
C-44-5	0.495	0.352	--
C-31-7	1.480	1.144	--
C-14-9	1.500	1.408	--

(a) Test failed.

(b) Data not analyzed.

(c) Uninterpretable.

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