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Revision 0

Burst Pressure Data for Steam Generator Tubes with Combined Axial & Circumferential Cracks

Westinghouse Electric Company LLC

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1.0 Introduction

This report summarizes burst pressure test data on combined axial and circumferential cracks in steam generator (SG) tubing. Most test results are for cracks simulated by electrical discharge machined (EDM) slits (also referred to as slots and notches) since this is the only practical method of systematically varying combinations of cracks' sizes and orientations. Limited data is presented for combined axial and circumferential cracks produced in laboratory stress corrosion tests.

The bulk of the test data presented is from tests at the Westinghouse Research Laboratories conducted circa. 1990. For completeness, similar tests results from Laborelec and Tecnatom are included. These Laborelec and Tecnatom results, along with a subset of Westinghouse test data, are presented in an EPRI Report, NP-6865-L, Reference 1. This present document includes additional Westinghouse test data.

Burst test results for laboratory stress corrosion cracking (SCC) specimens are presented first, followed by sections dealing with Laborelec, Tecnatom and Westinghouse test data. This is followed by a section on the analysis and implications of the pressure test data.

2.0 Burst Tests on Laboratory SCC Specimens

As part of an EPRI program dealing with the burst and leak characteristics of primary water stress corrosion cracking (PWSCC) of hard roll expansion transitions, Reference 2, burst tests were conducted by Westinghouse on laboratory cracked mockups of roll transitions. Some of these roll transitions exhibited circumferential cracking combined with normally expected axial cracks. The axial cracks in these specimens were 100% throughwall since internal pressure SCC tests continued until inside diameter (ID) to outside diameter (OD) leakage was detected. Destructive examination after burst testing revealed that the maximum depths of circumferential cracks was on the order of 85% throughwall (TW).

Burst testing was conducted in a conventional fashion. A plastic bladder sealed the axial throughwall cracks to prevent leakage of the pressurizing fluid, i.e., to permit pressurization. There was no reinforcement of the plastic bladder (current practice is to reinforce the bladder with a thin metal foil to prevent premature loss of the bladder). To prevent premature seal release bursting was accomplished within ten seconds of first pressurization. The test material tube diameter was 0.750 inches with a wall thickness of 0.043 inches. The tube material room temperature 0.2% offset yield strength is 56.4 ksi and the ultimate tensile strength is 106.9 ksi.

Sketches of crack geometries are shown in Figure 2.1 along with measured burst pressures. Combined axial and circumferential cracks can be represented as combinations of "L", "T" and "U" shapes. Burst data is also listed in Table 2.1. Figures 2.2 and 2.3 illustrate the burst appearance of specimens HOUTM 2 and HOUTM 10. Note that the presence of the mockup tubesheet has not influenced the burst pressure. The circumferential cracks are located about 0.30 inches above the top of the simulated tubesheet. Hence the test data is applicable to essentially freespan conditions.

The measured burst pressures ranged from 7500 psi to 9075 psi. This is fully consistent with the expected burst pressures of throughwall axial cracks with lengths from 0.20 to 0.30 inches. In this range of axial crack sizes, very deep circumferential cracks with arc lengths up to 109° had no significant effect on the burst pressure.

Table 2.1
Combined Axial and Circumferential SCC Burst Test Data

b,c

b,

Figure 2.1: Sketches of Axial and Circumferential Cracks

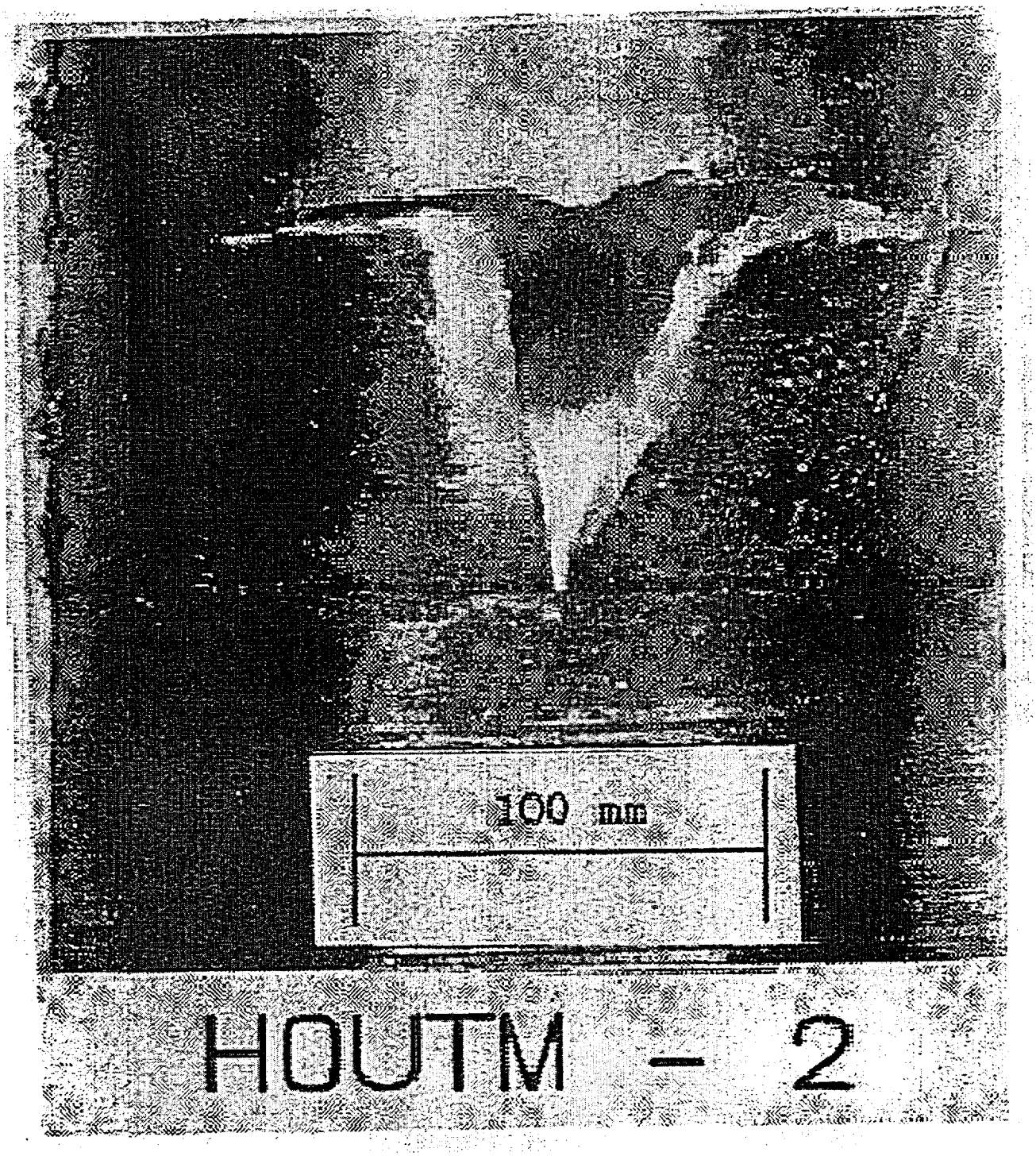


Figure 2.2: Combined Axial and Circumferential Cracks in a Roll Transition Mockup Leading to a "T" Shaped Burst.

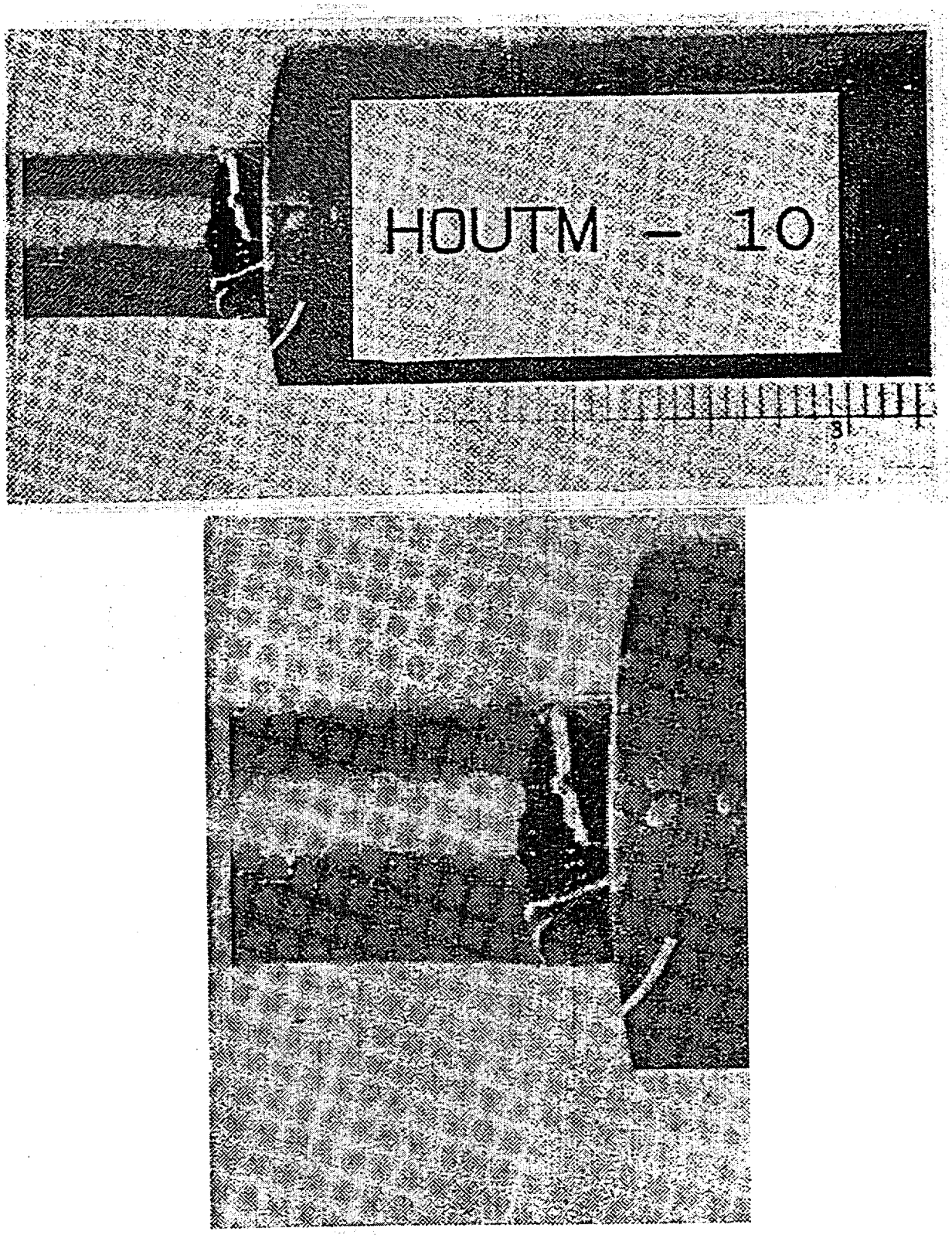


Figure 2.3: Combined Axial and Circumferential Cracks in a Roll Transition Mockup Leading to a "Flap" Tube Burst.

3.0 Laborelec Combined Axial and Circumferential EDM Slot Pressure Test Data

For completeness, Laborelec pressure test results for combined axial and circumferential EDM slots are presented below. This data can be found in Reference 1. The test material was Alloy 600 steam generator tubing with an outer diameter of 0.875 inches and a wall thickness of 0.050 inches. The burst pressure results were normalized (actually, the term non-dimensionalized is more accurate, but the term normalized is in common usage) by the tubing tensile properties and dimensions. The normalizing equation is,

$$P_{BAR} = \frac{P_B R_m}{(S_y + S_u)t}$$

where S_y and S_u are the yield and ultimate strength of the material, P_B is the measured burst pressure, R_m is the mean radius of the tube, and t is the thickness of the tube.

For ease of reference and comparison to data in other sections, burst pressures are listed assuming an 0.2 % offset yield strength of 50 ksi and an ultimate strength of 100 ksi. These values are typical room temperature properties.

Table 3.1 lists burst tests results for both straight EDM slots located at different angles to the tube axis and combined axial and circumferential EDM slots. The separation distance between axial and circumferential slots varies form 0.0 to 0.04 inches. Figure 3.1 illustrates the combined axial and circumferential test geometries. All axial and circumferential EDM slots are 100% throughwall. A plastic sealing bladder with a metal foil reinforcement was use to permit pressurization. Common Laborelec test practice limits the pressurization rate to less than 200 psi/second.

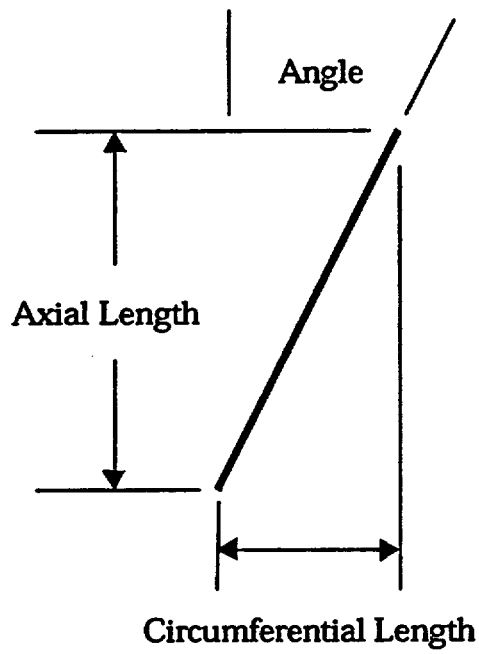
The expectation for straight cracks at any angle to the tube axis is that the burst pressure should not be less than the minimum of either the projected axial length for an axial slot or the projected circumferential length for a circumferential slot. Table 3.1 shows this expectation is met. The test data demonstrates that this expectation is valid for projected axial slot lengths up to 0.63 inches and an angle to the tube axis of 45° or less. In this range, the measured burst pressure is less than or equal to an axial slot having the same length as the projected axial length of the slanted slot. These calculated values are shown for comparison using the EPRI Flaw Handbook solution, Reference 3.

For "L" shaped slots, the circumferential slot length is 0.24 inches and the axial length is 0.63 inches. The circumferential arc length is about 33°. Table 3.1 shows that for a limited circumferential slot length the burst pressure relative to a single axial crack is reduced by about 10 to 15%. A line from the tip of the circumferential slot to the tip of the

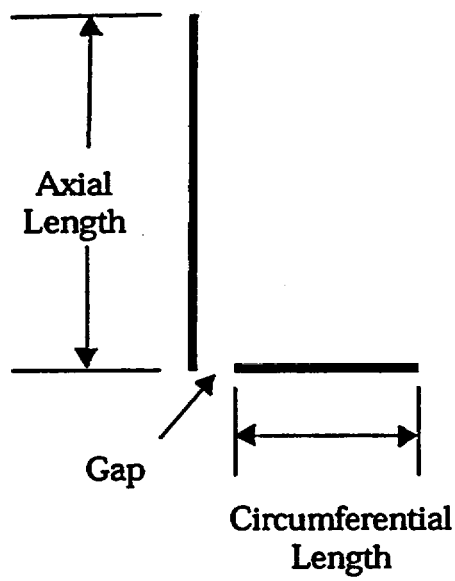
axial slot makes about a 20° angle with the tube axis. Other axial/circumferential cracks sizes with this same angle or less are expected to experience a similar percentage strength reduction.

Table 3.1
Laborelec Combined Axial and Circumferential Slot Pressure Test Data

b,c



Inclined Axial Slots



"L" Shaped Slots

Figure 3.1: Laborelec Combination Slot Geometries

4.0 Tecnatom Combined Axial and Circumferential EDM Slot Pressure Test Data

Part of the information gathered in an EPRI study of tube repair limits for PWSCC at roll transition tube expansions consisted of pressure test data of combined axial and circumferential EDM slots produced by Tecnatom, Reference 1. The axial slots were 100% throughwall and the circumferential slots varied from 30% to 94% TW. The arc lengths of the circumferential EDM slots were 270° to 360°. Hence, the circumferential length effect was maximized. As shown on Figure 4.1 the placement of axial throughwall slots intersecting the circumferential slots created mostly "U" shaped geometries. As will be shown below, the sealing system led these slot combinations to act as "L" shapes.

The test material was Alloy 600 tubing with a outer diameter of 0.750 inches and a nominal wall thickness of 0.043 inches. The sum of yield plus ultimate strength of the test material was 165.6 ksi. Pressure test results are listed in Table 4.1. The first entry is for a single throughwall axial crack. The measured burst pressure is 30% higher than that calculated by the industry standard approach in Reference 3. This is consistent with the time frame of the tests and the then conventional European practice of using a relatively thick foil (brass or stainless steel) to reinforce the plastic sealing bladder. This was later shown to elevate the burst pressure by 10% to 30% depending on the circumstances. Therefore, the effect of axial and circumferential interactions is best interpreted in terms of a ratio to the single isolated axial flaw burst pressure. This is possible for axial slot lengths near 0.51 inches.

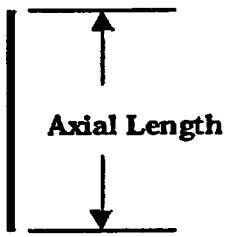
Figure 4.2 shows a plot of burst pressure versus circumferential slot depth for 0.51 inch long axial slots. These axial slots are separated in the circumferential direction by either 18° or 90°. The slots separated by 90° are far enough apart to prevent any interaction. Development of a "U" shaped flap opening, under the action of radial pressure against the surface of the "U", is hindered by both the extent of curvature between the axial slots and the ligament of the partial depth circumferential slot. Burst occurs when the axial slots begin to bulge and tearing develops at the intersection of the axial slot tip with the partial depth circumferential slot.

The axial slots separated by 18° in the circumferential direction cannot form a "U" shaped flap via the action of a radial outward pressure because the sealing bladder reinforcement in this case is heavy enough to bridge the narrow gap between the axial slots and essentially preclude radial motion of a narrow slice of material. However radial displacements over a large scale such as sidewall bulging of an axial crack occur, albeit at a higher pressure. Hence the narrow pairs of axial slots act the same as a isolated single axial slot intersecting the partial depth circumferential crack. Figure 4.2 shows the decrease in burst pressure for narrow gap axial slot pairs and 90° gap pairs is about the

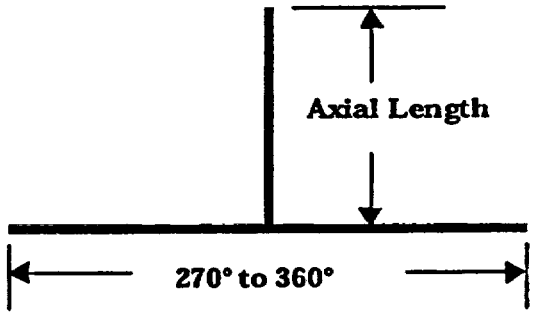
same. The true behavior of relatively narrow gap "U" shaped slots is described in the next section.

For a maximized circumferential length effect and axial slot lengths near 0.50 inches, the axial/circumferential interaction reduces the burst pressure linearly as a function of circumferential slot depth. Figure 4.2 illustrates this linear relationship and suggests a maximum strength reduction for very long 100% TW circumferential slots of about a factor of 2 relative to burst pressure of a single axial slot with no circumferential component.

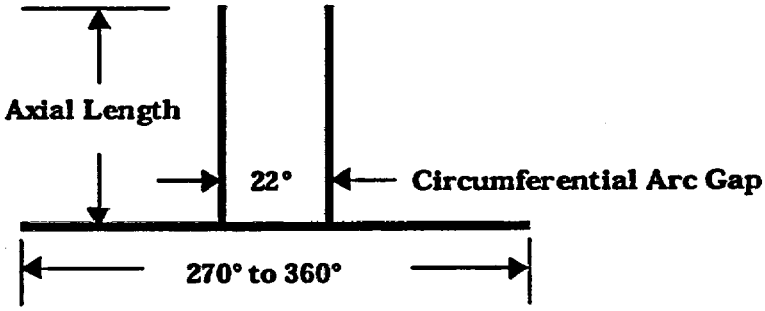
Axial Slots Are 100% TW, Circumferential Slots Are 30% TW to 94% TW



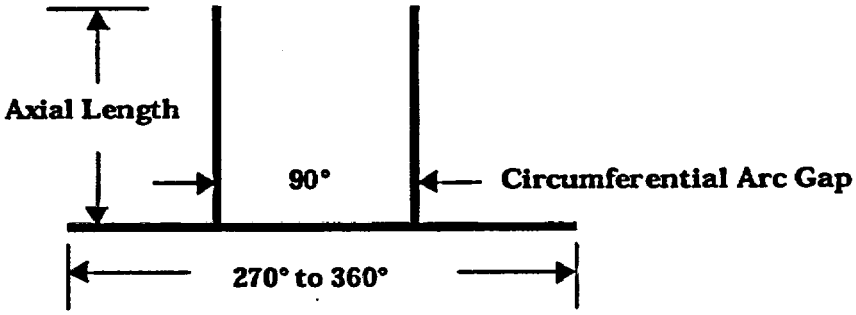
Single Axial Slot



"T" Shaped Slot



Narrow Gap "U" Shaped Slot



Wide Gap "U" Shaped Slot

Figure 4.1: Tecnatom Combined Axial and Circumferential Slots.

b,c

Ratio of Burst Pressure,
Combined Slot to Single Axial Slot

Circumferential Slot Fractional Depth, d/t

Figure 4.2: Ratio of Burst Pressure of Combination EDM Slot to a Single Axial Slot versus Circumferential Slot Fraction Throughwall

Table 4.1
Tecnatom Combined Axial and Circumferential Slot Pressure Test Data

b,c

5.0 Westinghouse Combined Axial and Circumferential DM Slot Pressure Test Data

An extensive series of burst tests were performed at Westinghouse on combined axial and circumferential EDM slots in steam generator tubing. These tests were performed in the 1990 timeframe and were motivated by the appearance of circumferential in addition to axial PWSCC in roll transition expansions at the top of the tubesheet in some SGs. A review of pulled tube destructive examination results, together with eddy current inspection data, indicated that the wide variety of axial and circumferential crack combinations could be characterized by various combinations and orientations of "L", "T" and "U" shaped cracks. The vertical legs of these letters symbolize axial cracks and the horizontal components symbolize circumferential cracks.

The next three subsections present pressure test results for "L", "T" and "U" shaped EDM slots in steam generator tubing. The original context of these tests was the development of an alternate repair criteria for axial PWSCC at roll transition expansions. A length based approach had proven to be successful in Europe. Here, operation with axial throughwall cracks was not unusual. Normal operation and projected accident leak rates were maintained at an acceptably low levels. In this context, axial components of "L", "T" and "U" shaped slots in test programs were selected to be 100% throughwall. Typically, test program circumferential components were partially throughwall and 100% TW circumferential slots were included as a limiting case. These choices modeled field experience where axial cracking developed first followed by circumferential cracking. The degree of correspondence between EDM combined axial and circumferential slots and actual service induced SCC is discussed in Section 6. If 100% TW cracking is considered, EDM axial/circumferential interactions are substantially more conservative than actual SCC interaction effects.

Westinghouse Test Material — All tests results presented in Section 5 were obtained using mill annealed Alloy 600 SG tubing. This tubing had an OD of 0.875 inches and a nominal wall thickness of 0.050 inches. Three heats of Alloy 600 tubing were used. Room temperature tensile properties are listed in Table 5.1.

All axial components of all test configurations were 100% throughwall. Therefore, some type of sealing had to be used to permit pressurization. Plastic tubing was used to seal throughwall EDM penetrations. In some cases a 0.006 inch thick brass foil was used to reinforce the soft plastic bladder and prevent premature seal release before tearing commenced and indicated an actual tube burst condition. In a very limited number of cases a 0.010 inch thick stainless steel foil was used as a reinforcement. As discussed below and in Section 6, possible seal reinforcement effects on measured burst pressures need to be considered.

5.1 Pressure Test Results on "L" Shaped EDM Slots

Burst test data for "L" shaped EDM slots are listed in Table 5.2, 5.3 and 5.4. The axial components were 100% TW with lengths of either 0.24 inches or 0.48 inches. The shorter length is typical of field observations of axial PWSCC and the longer length leads to burst pressures slightly above 3ΔP for single throughwall axial cracks. Table 5.2 lists burst pressures when both axial and circumferential slots are 100% TW. A similar series of tests were performed for circumferential slot depths of 50% TW and 85% TW. These test results are listed in Table 5.3.

Figure 5.1 shows plots of burst pressure versus circumferential slot length. There are two groups of plots. One for axial lengths of 0.24 inches and one for axial lengths of 0.48 inches. At a circumferential length of zero, that is, single axial slots, the burst strengths are about 7200 psi and 5000 psi respectively. Adding a circumferential component decreases the burst strength. From the upper series of plots, use of a reinforced bladder is seen to raise the burst strength. This strengthening is about equivalent to that of a 50% TW partial depth circumferential slot. In contrast to stress corrosion cracks, TW EDM slots offer no shear stress resistance as slot faces move past another to form an "L" shaped flap via displacement normal to the cylindrical tube surface. Actual service cracks, even if 100% TW, have crack face irregularities which resist this type of motion. Both the foil reinforcement and partial depth circumferential slots model the end result behavior expected in actual SCC axial/circumferential combinations. This expected behavior of SCC combinations is demonstrated by the test results presented Section 2. The minimum burst pressure in Figure 2.1 for axial cracks with lengths from 0.20 to 0.30 inches and 85% TW circumferential components is 7500 psi. All other burst pressure values in Figure 2.1 would lie completely above the plots in Figure 5.1. Tests of EDM slots are conservative with respect to SCC axial/circumferential crack combinations

If the circumferential component of "L" slots are covered by a support structure, such as a tube support plate or a tube sheet, radially outward motion will be resisted and development of an "L" shaped flap will be hindered. The degree of hindrance is a function of the support overlap, as shown in Figure 5.3. Burst pressure increases for 0.48 by 0.48 inch "L" shaped slots as support overlap increases. Approximately 0.030 to 0.080 inches of overlap is sufficient to increase the burst pressure near the vicinity of a single axial flaw. Because the support overlap does not provide resistance to tensile forces parallel to the tube axis, bulging of the axial portion of the "L" eventually pulls the circumferential slot from beneath the support and a flap type opening develops. Because of this lack of resistance to a tensile force parallel to the tube axis, a small support overlap which prevents radial displacement does not return the "L" completely to the strength of a single axial slot.

5.2 Pressure Test Results on "T" Shaped EDM Slots

Pressure test results on "T" shaped slots are summarized in Tables 5.5 and 5.6. All axial component lengths are 0.48 inches. A plot of data in Table 5.5 shows a modest decrease in burst pressure of an axial slot as it is intersected at its midpoint by a circumferential slot. Figure 5.3 shows a drop from about 5000 psi to about 4200 psi as the circumferential length increases form zero to 0.48 inches. At this point the circumferential length effect has achieved its maximum effect. Tables 5.5 and 5.6 show that increasing the circumferential slot length to 270° (1.94 inches) does not cause a further drop in burst pressure. It should be noted that tearing at the slot tips did not develop in these tests, just a bulging open of the "T" shaped slot.

The effect of an axial slot intersecting a circumferential slot at its midpoint is illustrated by data in Table 5.5 and the plot of Figure 5.4. Since a circumferential slot is stronger than an axial slot, the burst pressure is essentially determined by the length of the axial slot. Figure 5.4 shows that the "T" slot where the axial slot intersects the midpoint of the circumferential slot produces only a small decrease in burst pressure compared to a single axial slot. This is shown to be true in Figure 5.4 for 0.48 inches long circumferential slots. Data in Tables 5.6 and 4.1 show there is no dramatic drop in burst pressure if the circumferential slot length is much longer.

Burst test data for very long circumferential slots are shown in Table 5.6. The 270° arc length is near the 3ΔP structural limit for replacement steam generator (RSG) plants. The burst pressure for a single 270° circumferential slot is 5417 psi per Reference 3. Various axial crack interactions are shown to have a mild effect when the circumferential throughwall slot size is near the 3ΔP structural limit.

5.3 Pressure Test Results on "U" Shaped EDM Slots

Flaw configurations shaped like a "U" require multiple axial cracking. "U" flaws created by multiple circumferential flaws are not an issue based on service experience with SCC in steam generator tubing. The significance of "U" shaped flaws is not tube burst, but rather the development of a flap opening with a substantial leakage area. Shearing resistance around the periphery of the "U" caused by surface irregularities and partial depth cracking are not present in throughwall EDM "U" slots. Tests results of EDM slots are therefore substantially conservative relative to service induced SCC. European experience with axial and circumferential PWSCC at roll transitions, where a length based alternate repair criterion has been applied, supports this view.

Pressure test data on "U" shaped EDM slots is listed in Tables 5.7, 5.8 and 5.9. "U" shaped flaws have a very low frequency of occurrence in service, but they present a potential for flap formation at lower pressures than "T" or "L" type flaws. Table 5.7 lists data for 100% TW "U" slots. The effect of partial depth circumferential components is illustrated by the data in Table 5.8. As with "L" shaped slots, tube support overlap of the circumferential components provides substantial resistance to flap formation. This is evident from the data in Table 5.9.

Figure 5.5 shows that throughwall "U" slots with axial legs 0.24 inches long can form a flap opening at a pressure on the order of 3500 psi. This is about one half of the burst pressure of a single axial throughwall slot. A foil reinforcement to the sealing bladder elevates the flap formation pressure to about the same level as closing the gap between the sides of the circumferential slot by a wedged insert. The "U" flap forms by rotation about a plastic hinge formed on a line between the tips of the axial slot legs. With an SCC "U" shaped flaw, the circumferential crack would have almost no gap between the circumferential crack face even without crack face surface irregularities. Rotation about the plastic hinge would then require overcoming some degree of interference of the circumferential crack faces. A wedge insert in the circumferential component of an EDM "U" slot simulates this condition. The wedged circumferential slot with no reinforcement to the sealing bladder provides about the same flap formation pressure as use of foil reinforcement to the pressure seal. For small flap opening areas, the plastic bladder seal alone offers some resistance to the radial displacements required for flap formation. A estimated correction for this effect leads to corrected flap formation pressures about at the level expected for the operation of a simple plastic hinge across the axial legs at the top of the "U". As discussed in the next section, application of this approximation to a postulated "U" shaped SCC flaw is grossly over conservative.

Figure 5.6 shows a plot of flap formation pressure versus circumferential component length for an axial slot length of 0.48 inches. The relatively long axial length lowers the flap formation pressure. Plots for reinforced and non-reinforced seals are similar. Narrow "U" slots show that both types of seals impart some degree of strengthening. Wider "U" slots should be stronger than narrow "U" slots since the plastic hinge is strengthened by curvature. As above, a no seal effect flap formation pressure range is estimated. More realistic flap formation pressures for SCC "U" flaws are better illustrated by Figure 5.7.

Figure 5.7 shows flap formation pressure versus axial slot length for "U" shaped slots where the circumferential slot length is either 0.24 or 0.48 inches and the depth of circumferential slots is either 50% TW or 84%TW. Sealing effects are not an issue since no foil reinforcement was used. In terms of leakage integrity, "U" slots with 100%TW axial components are not an issue if peripheral shear stress resistance is equivalent to a 50%

TW circumferential EDM slots. This covers the gamut of throughwall axial slot lengths out to values challenging 3ΔP structural integrity requirements. For circumferential slots with a depth of 84% TW , flap formation at steam line break pressure differentials is a consideration for throughwall axial lengths beyond about 0.35 inches, assuming no other resistance along the crack face periphery.

Figure 5.8 shows that flap formation pressure for 100% TW "U" shaped EDM slots is substantially hindered by the presence of a tube support structure which overlaps the circumferential component by a distance of about 0.04 inches or more. The plotted data is for an axial leg length of 0.48 inches. Just as with "L" shaped EDM slots, the lack of a tensile force resistance parallel to the tube axis does not allow return of the burst pressure to the full single axial slot value. However, in terms of leakage integrity, a support overlap in the vicinity 0.04 inches is sufficient to eliminate leakage integrity concerns.

Table 5.1
Tubing Material Tensile Properties

b,c

Table 5.2
Burst Strength of "L" Shaped 100% Throughwall EDM Slots

b,c

Table 5.3
Burst Strength of "L" Shaped Partial Throughwall EDM Slots
Axial Component 100% TW, Circumferential Component 50% TW or 84% TW

b,c

Table 5.4
Burst Strength of "L" Shaped 100% Throughwall EDM Slots
Circumferential Component Overlapped by Tube Support Clamp

b,c

Table 5.5
Burst Strength of "T" Shaped 100% Throughwall EDM Slots

b,c

Table 5.6
Burst Strength of 100% Throughwall EDM Slots

b,c

Table 5.7
Strength of "U" Shaped 100%
Throughwall EDM Slots

b,c

Table 5.8
Strength of "U" Shaped Partial Throughwall EDM Slots
Axial Component 100% TW, Circumferential Component 50% TW or 84% TW

b,c

Table 5.9
Strength of "U" Shaped 100% Throughwall EDM Slots Circumferential Component Overlapped by Simulated Tube Support

b,c

b,c

Figure 5.1: Burst Pressure of "L" Shaped Throughwall EDM Slots versus Circumferential Component Length

b.c

Figure 5.2: Burst Pressure of a 0.48" by 0.48" "L" Shaped Slot versus Circumferential Support Overlap

b,c

Figure 5.3: Burst Pressure of "T" Shaped Throughwall EDM Slot versus Circumferential Component Length

b,c

[ ]

Figure 5.4: Burst Pressure of "T" Shaped Throughwall EDM Slot versus Axial Component Length

b,c

Figure 5.5 Flap Pressure of Throughwall "U" Shaped EDM Slot versus Circumferential Component Length

b,c

Figure 5.6 Flap Pressure of Throughwall "U" Shaped EDM Slot versus Circumferential Component Length

b,c

Figure 5.7: Flap Pressure of "U" Shaped EDM Slots with Partial Depth Circumferential Components

b,c

Figure 5.8: Flap Pressure of 0.48" by 0.48" "U" Shaped Slot versus Circumferential Support Overlap

6.0 Analysis and Implications of Combined Axial and Circumferential EDM Slot Pressure Test Data

Almost all test results in this report are on EDM slots. The limited test data on combined axial and circumferential cracks shows that, with comparable dimensions, combined EDM slots are not as strong actual stress corrosion cracks. This stems from the fact that there is about a 0.006 to 0.008 inch spacing between the faces of EDM slots. Service induced cracking leads to irregularities on the crack faces, meandering crack paths and essentially no spacing between opposing crack faces. Loading modes which shear crack faces past one another in combined axial and circumferential combinations encounter a resistance with SCC flaws which is not present for EDM slots. However, testing of EDM combined slot configurations provides lower bound information and is the only practical method of systematically evaluating the effect of combined axial and circumferential flaw on burst pressure.

Evaluation of pulled tube and field eddy current information shows that the observed range of axial and circumferential crack geometries can be represented by "L", "T" and "U" shapes. The vertical legs of these letters symbolize axial cracks and the horizontal portions symbolize circumferential cracks. Since axial cracks or slots have a much stronger effect on burst pressure than circumferential cracks, axial length is the dominant consideration even for combined axial and circumferential geometries. The burst pressure is never larger than that of the corresponding single axial or single circumferential flaw in a combination flaw.

Throughwall axial flaws burst by first bulging open and then tearing at the crack Tips. Hoop stresses cause the crack to tear in the axial direction. Bulging heightens axial stresses at the crack tip as the crack length is forced to increase. In effect, the axial crack attempts to pull back from the crack tip.

When a partial depth circumferential crack intersects the tip of an axial throughwall crack, the circumferential crack tends to tear as the axial crack bulges and generates additional axial stresses. Once tearing of the circumferential crack develops, radially outward displacements created by the internal pressure acts as though one is tearing a piece of paper. If the axial crack is not 100% TW, the onset of bulging requires tearing of the remaining depth ligament of the axial crack. Hence, in combination cracks, the flaw configuration is considerably strengthened if the axial legs are not completely throughwall.

The minimum strength interaction for an axial/circumferential geometry is a tip to tip intersection. A circumferential crack joining an axial crack at its midpoint makes bulging of one side of the axial crack easier by reducing the moment required for bending. A tip to tip intersection makes tensile tearing of the circumferential crack more likely.

For 100% TW cracks or slots, internal pressure loading can cause flaps to develop as rotation about a plastic hinge occurs. For "L" and "T" shapes this rotation typically produces significant tearing at the axial and/or circumferential crack tips and the mode of failure can be considered a tube burst. For "U" shaped flaws, flap formation does not lead to a true tube burst. Rather the issue is leakage integrity as "U" flaps may form substantial openings at pressures lower than those require for "L" or "T" flaws with the same axial and circumferential dimensions.

The bulk of the test data in previous sections is for throughwall axial EDM slot lengths of 0.24 inches and 0.48 inches. The smaller length is characteristic of field observations of axial PWSCC and the longer length challenges typical $3\Delta P$ structural limits. The interaction of circumferential slots with these axial slots produced burst strength reductions for "L" and "T" shapes in the range of 10% to 25% compared to single axial slots. For the shorter lengths, axial/circumferential interactions do not challenge structural integrity margins. For axial flaws lengths approaching the throughwall structural limit, axial/-circumferential interactions need to be considered. Here, axial and circumferential components need to 100% TW with very limited crack face irregularities for a structural issue to be present.

A minimum separation distance, beyond which interaction effects need not be considered, can be developed as follows. The internal pressure range under consideration is first limited to the vicinity of three times the normal operating pressure differential, $3\Delta P_{NO}$. Hence, the minimum separation distance ensures that structural integrity evaluations are correct, not that very high burst pressure geometries will show no influence of neighboring cracks. For a given crack length, axial cracks are the limiting consideration. This is a good starting point. The field of influence ahead of an axial crack, in terms of very high plastic stresses and strains, extends several times the blunted crack opening displacement at the crack or EDM slot tip. Since the critical value of the critical crack tip opening displacement for the onset of tearing, $CTOD_c$, is about 0.040 inches for Alloy 600 steam generator tubing, the field of crack tip influence is on the order of 0.10 to 0.20 inches. Narrow EDM slots effectively behave as cracks because they plastically blunt to about 5 times the starting opening before cracking develops. This is sufficient to create a stationary crack tip plastic singular field that lies at the heart of elastic plastic and fully plastic fracture mechanics.

The field of influence ahead of an axial crack can be approximated by applying the Cochet approach, Reference 1, for partial throughwall cracks to 100% TW cracks. The 100% TW crack section is unable to carry the pressure load that would normally be carried over this length in an unflawed tube. Instead this load is shed to the material in front of the crack tips. The correct distance over which this load shedding is distributed can be

found by adjustment to make the calculated burst pressure equal that of actual test results. The average stress in front of the crack tip for a distance of k times the thickness is set equal to the average hoop stress leading to bursting of an unflawed tube.

$$F_{closure} = 0.6(S_y + S_u)2kt^2$$

This closure force is set equal to the opening force, which is just the average unflawed hoop stress times the cross sectional area occupied by the crack plus the load shed region.

$$F_{opening} = P_B \frac{R_m}{t}(L + 2kt)t$$

Thus the burst pressure is given by:

$$P_B = \frac{0.6(S_y + S_u)2kt^2}{R_m(L + 2kt)}$$

Via trail and error, a value of k of 4 was found to provide a good match of calculated burst strength for 100% TW cracks with the industry standard EPRI throughwall burst equation of Reference 4. This is illustrated in Figures 6.0-1 and 6.0-2. Figure 6.0-1 shows calculations from the load shedding approach compared to results from the EPRI throughwall equation. The match is very good, particularly in the vicinity of the 3ΔP range of pressures. Figure 6.0-2 shows the same plot with normalized burst pressure and normalized crack length. The four curves in addition to the EPRI throughwall curve show that the load shedding formulation works equally well for all sizes of domestic Alloy 600 steam generator tubing.

In the load shedding Cochet type formulation, the material beyond the crack tip in excess of a distance of 4 times the tube wall thickness does not contribute to the strength of the axial crack. A circumferential crack or a free surface beyond this distance would not influence the burst strength. Taking this distance and adding an extra wall thickness for conservatism provides the minimum separation distance, 5 times the wall thickness, needed between axial and circumferential cracks, beyond which interaction effects need not be considered in tube integrity evaluations. For Westinghouse plants, such as Sequoyah and Diablo Canyon, with 0.875 inch diameter by 0.050 inch wall steam generator tubes this "5t"criterion becomes 0.25 inches.

The 100% TW axial crack case evaluated via the load shedding approach is the bounding case. For partial throughwall cracks less load is shed ahead of the crack tip in the axial

direction because ligaments in the depth direction are load bearing. For circumferential cracks with sizes that do not independently challenge $3\Delta P_{NO}$ requirements, load shedding ahead of a circumferential crack is less severe than an axial crack since there is less pressure load to shed. For circumferential cracks large enough to challenge $3\Delta P_{NO}$, the 0.25 minimum separation distance essentially ensures the minimum remaining tube cross section needed to meet total axial force requirements at $3\Delta P_{NO}$. Circumferential cracks larger than the individual $3\Delta P_{NO}$ limit would be needed to violate the minimum separation distance. Finally, the minimum separation distance was evaluated against lower bound plastic collapse flap formation calculations for limiting case axial and circumferential 100% TW cracks. The lower bound plastic collapse calculation substantially underpredicted test results and thus is conservative by a good margin. These conservative lower bound plastic collapse calculations showed that the minimum separation distance of 0.25 inches always ensured flap formation burst strengths well in excess of $3\Delta P_{NO}$ levels.

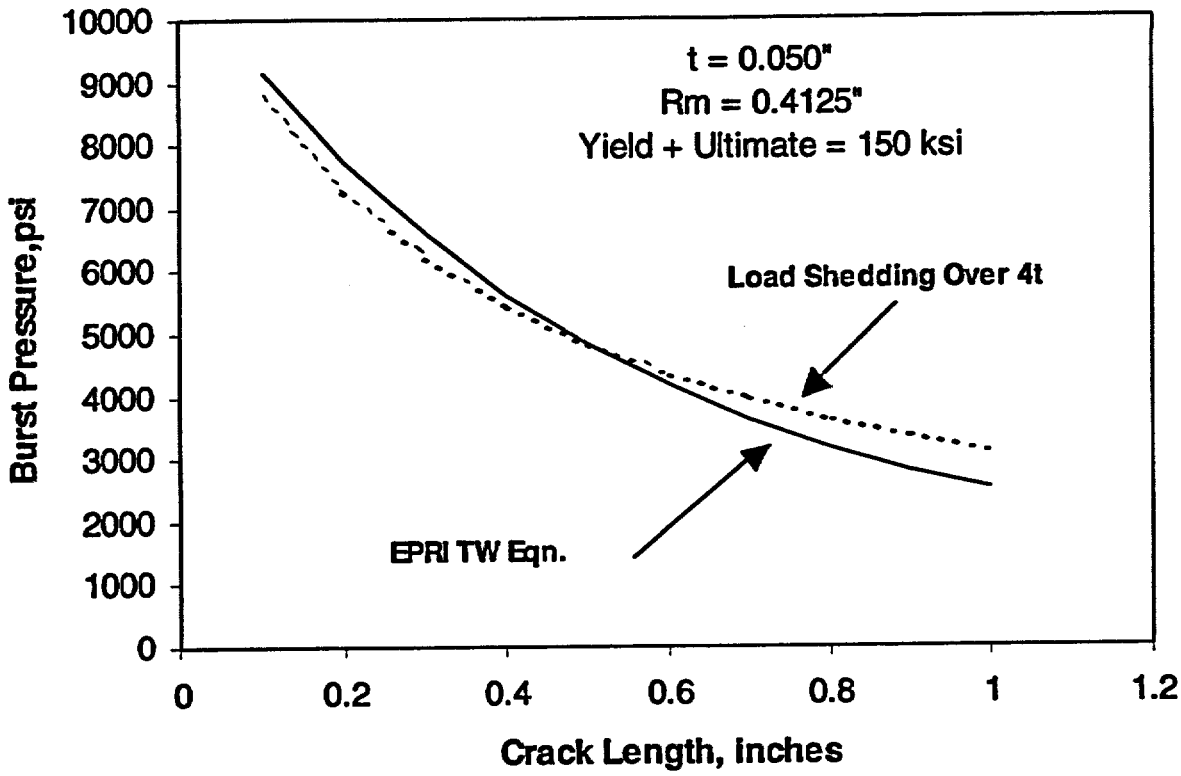


Figure 6.1: Burst Pressure versus Crack Length for 100% TW Cracks, EPRI Equation versus Load Shedding over 4t Ahead of Crack Tips

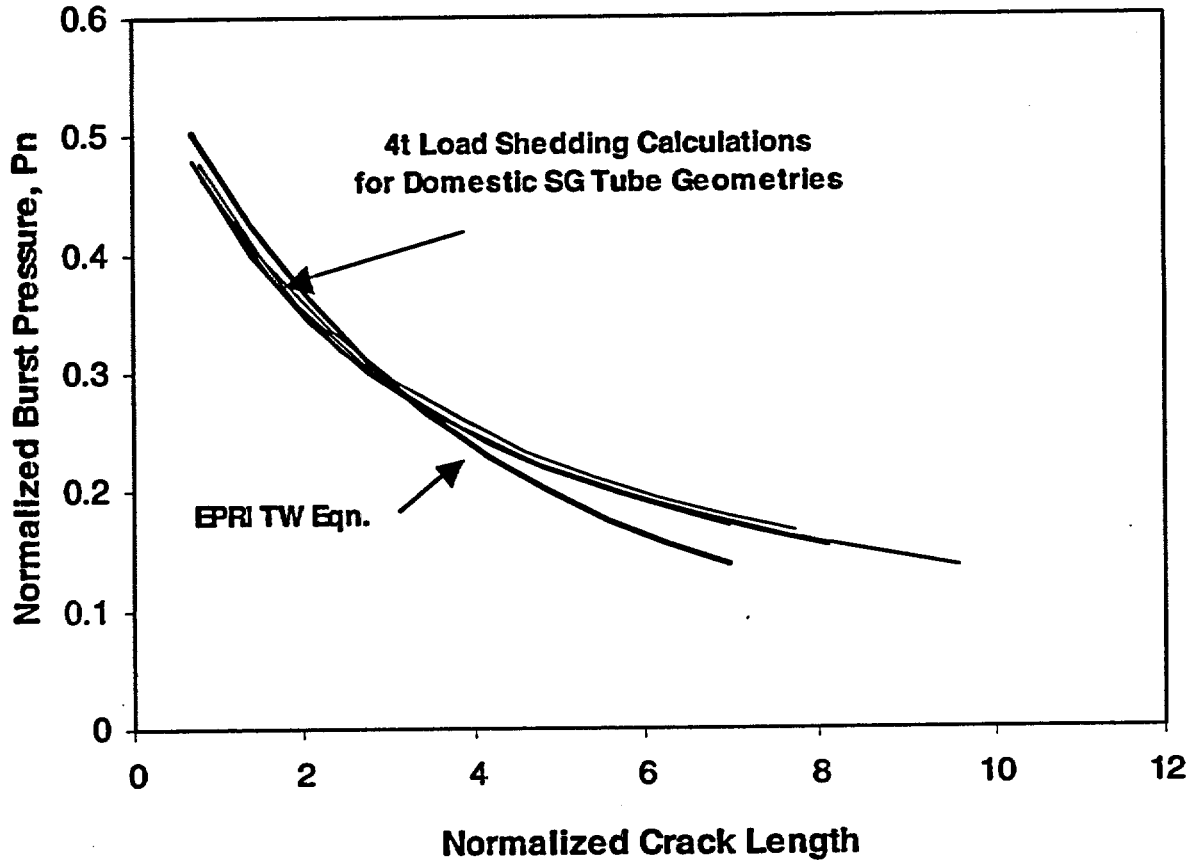


Figure 6.2 Normalized Burst Pressure versus Normalized Crack Length for 100% TW Cracks, EPRI Equation versus Load Shedding over 4t Ahead of Crack Tips, Domestic SG Tube Geometries

7.0 Summary

This report summarizes pressure test data on combined axial and circumferential cracks in steam generator tubing. Most test results are for cracks simulated by EDM slots since this is the only practical method of systematically varying combinations of cracks sizes and orientations. The limited test data on combined axial and circumferential cracks shows that, with comparable dimensions, combined EDM slots are not as strong actual stress corrosion cracks.

The bulk of the test data presented is from tests at the Westinghouse Research Laboratories conducted in a time period around 1990. For completeness, similar tests results form Laborelec and Tecnatom are included. These Laborelec and Tecnatom results, along with a subset of Westinghouse test data, are presented in an EPRI Report, NP-6865-L, Reference 1. This present document includes additional Westinghouse test data.

The interaction of circumferential slots with these axial slots produced burst strength reductions for "L" and "T" shapes in the range of 10% to 25% compared to single axial slots. For the shorter lengths, axial/circumferential interactions do not challenge structural integrity margins. For axial flaws lengths approaching the throughwall structural limit, axial/circumferential interactions need to be considered. Here, it is judged that axial and circumferential components need to 100% TW with very limited crack face irregularities for a structural issue to be present.

A minimum separation distance, beyond which axial and circumferential cracks may be evaluated as single, isolated cracks in tube integrity evaluations, was developed. The minimum separation distance is based on test data, a load shedding type of analysis, lower bound plastic collapse flap calculations and elastic plastic/fully plastic fracture mechanics toughness considerations. For Westinghouse steam generators with 0.875 inch diameter by 0.050 inch wall thickness tubing, this distance is 0.25 inches, that is, 5 times the wall thickness.

8.0 References

1. NP-6864-L, "PWR Steam Generator Tube Repair Limits: Technical Support Document for Expansion Zone PWSSS in Roll Transitions, Rev. 2," EPRI, Palo Alto, CA (Draft Report, August 1993).
2. NP-7474, "Evaluation of Leak and Burst Characteristics of Roll Transitions Containing Primary Water Stress Corrosion Cracks," EPRI, Palo Alto, CA (May 1993).
3. TR-1XXXXX (Final Draft), "Steam Generator Tubing Flaw Handbook," EPRI, Palo Alto, CA (August 2000).
4. TR-105505, "Burst Pressure Correlation for Steam Generator Tubes with Through-wall Axial Cracks," EPRI, Palo Alto, CA (October 1997).