ATTACHMENT 12

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SG Indications Restricted from Burst (IRB) Leak Test Report

TR-107625

Final Report, September 1998

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REPORT SUMMARY

A test program was performed to develop a database for leakage from IRBs (indications restricted from burst) for a wide range of crack sizes in steam generator tubes at tube support plates. This report summarizes the results and conclusions of that testing.

Background

To determine total leakage from tubes (with indications remaining in service), voltage-based alternate repair criteria for outside diameter stress corrosion cracking (ODSCC) of steam generator tubes at tube support plates (TSP) rely on a database for freespan leak rates from cracks. NRC permits bobbin indications of 1 volt for 0.75-inch diameter tubes. To justify leaving higher voltage indications in service, Westinghouse proposed a method of minimizing the transient TSP displacement. This method expands a number of tubes above and below the TSPs, turning the expanded tubes into pseudo-stay-rods. NRC, however, observed that there was no database to bound the leak rates from IRB. With EPRI sponsorship, Westinghouse performed a series of tests to develop a database for leakage from IRBs for a wide range of crack sizes.

Objectives

- To define a bounding value of leak rate for the limiting IRB.
- To assure that leakage from cracks left in service under a high-voltage ARC will not result in unacceptable leakage during Steam Line Break conditions.

Approach

Researchers normalized leak rate results to standard conditions so that test-to-test comparisons could be made. Normalization also permitted them to identify bounding leak rates at prototypic conditions. Though the practical limit of cracks to be tested was approximately 0.75 inches, the investigation also included cracks of varying lengths. Researchers tested cracks in two ways: (1) completely contained within the span of the TSP with one end of the crack aligned with the edge of the TSP and (2) with the crack tip positioned outside the TSP by a set distance. A total of fifteen specimens were prepared from prototypic steam generator tubing material.

Results

This report discusses in detail bounding leak rate at prototypic conditions and leak rate trends in relation to crack structural behavior at tube support plates. Also included are descriptions of the test facility and testing methods.

EPRI Perspective

The results of this test program have technically justified the licensing basis for leaving 3V indications in service for operating steam generators with 0.75-inch diameter tubing.

TR-107625

Interest Categories

Steam generators

Keywords

Steam generators
Tubes
NRC
Tube leakage

NOMENCLATURE

IRB	indication restricted from burst
SLB	steam line break
TSP	tube support plate
TW	throughwall
ARC(APC)	alternate repair (plugging) criteria
RT	room temperature
HT	hot (high) temperature
Tp	primary side temperature
ps	secondary side pressure
ΔP	primary to secondary pressure differential
ODSCC	outside diameter stress corrosion cracking

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INTRODUCTION

Voltage-based alternate repair criteria for outside diameter stress corrosion cracking (ODSCC) of steam generator tubes at tube support plates (TSP) rely on the database for freespan leak rates from cracks to compute the total leakage from tubes with indications remaining in service. The NRC generic letter for ODSCC at TSPs, GL 95-05, permits bobbin indications of 1 volt for 3/4 inch diameter tubes, and 2 volts for 7/8 inch diameter tubes, to remain in service, provided the total predicted end of cycle (EOC) leak rate under postulated steam line break (SLB) conditions is less than the licensed, plant-specific, allowable SLB leak rate, and provided that the predicted EOC conditional probability of burst is less than $1x10^{-2}$. The data base for freespan leakage is utilized because the TSPs are expected to displace under the transient SLB loading.

To justify leaving higher voltage indications in service, Westinghouse proposed a method of minimizing the transient TSP displacement by expanding a number of tubes above and below the TSPs, essentially turning the expanded tubes into pseudo-stay-rods. With the TSPs fixed by this method, the risk of exposure of the indications within the span of the TSPs was greatly reduced, but not eliminated. However, the actual TSP displacement could be bounded by a small value, so that only a small portion of even the limiting permissible length indication would be exposed outside the span of the TSP under the postulated SLB conditions. The NRC noted a concern that there was no data base to bound the leak rates from indications restricted from burst (IRB) but potentially partially outside the span of the TSP.

Under EPRI sponsorship, in support of Commonwealth Edison efforts to implement higher voltage ARC at Plants AA and AB, Westinghouse performed a test program to develop a database for leakage from IRBs for a wide range of crack sizes. The principal objective of this test program was to define a bounding value of leak rate for the limiting IRB.

This report summarizes the test program performed and the results and conclusions reached from the test (Section 2). The tests were performed principally in a high energy tests facility available at Westinghouse. The test facility is described in Section 3, and the test methods are discussed in Section 4. The leak rate results were normalized to standard conditions applicable to a postulated SLB (615°F primary water temperature, secondary side at atmospheric conditions) so that test to test comparison could be made, and so that the bounding leak rate at prototypic conditions was identified (Section 5). The trends relating the measured leak rates to crack structural behavior in regard to interaction with the TSP are discussed in Section 6.

The results of this test program were used to technically justify the licensing basis for leaving 3V indication in service in operating steam generators with 3/4-inch diameter tubing.

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SUMMARY AND CONCLUSIONS

2.1 Test Program Overview

To support implementation of high voltage ARC, which utilize tube expansions to minimize TSP displacement during a postulated SLB event, a test program was completed to determine the bounding leak rate and its sensitivity to TSP displacement under Steam Line Break (SLB) conditions for throughwall indications restricted from burst (IRB). An IRB is defined as a tube crack at the intersection of the tube with the support plate that could burst if it were located in the freespan of the tube. The crack is restricted from burst by the TSP, and it is further demonstrated that the leakage flow from an IRB is limited by the presence of the TSP to less than the freespan leakage for a like crack. During a postulated SLB event, the depressurization of the SG causes the TSPs to deflect from their nominal position, thus potentially exposing the cracks at TSP intersections. For the high voltage ARC, TSP motion during a SLB is limited by expanding a number of tubes above and below the TSP, effectively turning the expanded tubes into pseudo-stay rods. The limited deflection capability of the TSP permits an increase in the acceptable bobbin voltage for indications remaining in service.

It was the objective of this test program to establish a data base for leakage from cracks in prototypic steam generator tubing under prototypic pressure and temperature conditions to assure that the leakage from cracks left in service under a high voltage ARC will not result in unacceptable leakage during SLB accident conditions. SLB conditions are defined as 615°F primary coolant temperature and a pressure differential of 2560 psid. The bulk of the tests were performed in a high-energy steam test facility that is capable of flow rates up to about 8 gpm at these conditions. A complete description of the high-energy leak test facility and test operations is contained in Section 3. The high temperature leak tests were augmented by tests performed in a room temperature, high-pressure leak test facility. Room temperature tests are much easier to perform; thus it was the objective of the room temperature tests to demonstrate the adequacy of EPRI method for adjusting RT data to high temperature conditions. This method is discussed in detail in Section 5.

A specific objective of the test program was to determine a bounding leak rate for an IRB that is at, or exceeds, the limit of an indication that could remain in service. GL 95-

05 specifies that no indication that extends beyond the span of the TSP may remain in service. The TSP thickness is 0.750 inch, thus the maximum indication is limited effectively to less than 0.750 inch for the packed crevice condition causing initiation and growth of an ODSCC indication. The critical throughwall crack length in ¾" diameter tubing at lower tolerance limit (LTL) material properties is 0.750 inch (Reference 1). Cracks at, or less than, this throughwall length will not burst under SLB pressure differential. Thus, the practical limit of cracks to be tested was set at approximately 0.750 inch, although shorter cracks and one longer crack were also included in the test program to observe the structural and leakage trends of the cracks. The bounding leak rate is discussed in section 5. Leak rate trends and structural trends are included in Sections 6.

Fifteen specimens were tested as summarized on Table 2.1. The specimens were prepared from prototypic steam generator tubing material, Alloy 600, mill annealed, supported by material certifications (Appendix H). Specimens were prepared by three processes: 1) accelerated corrosion, 2) accelerated corrosion followed by fatigue to increase the length of the crack, and 3) laser cutting. Eight of the specimens were 7/8" diameter specimens, and the remainder was 3/4" specimens. Cracks with different throughwall lengths in a range from 0.24" to 0.809" were tested. The tests simulated a cracked tube at a TSP, but, conservatively, with the maximum diametral clearance of 0.025" between the tube and the TSP. The final 5 tests were fixtured to provide the full 0.025" gap at the side of the tube with the crack to minimize the restriction provided by the TSP. Details of the specimen preparation and fixturing are contained in Section 3.

The longest throughwall crack tested, 0.809 inch, was greater than any crack that could be formed at a TSP intersection, which is 0.750 inch thick. Throughwall cracks of significant length would have bobbin voltages well in excess of the 3Volt limit proposed for the high voltage ARC.

Testing was performed with (a) the cracks completely contained within the span of the TSP with one end of the crack aligned with the edge of the TSP, and (b) with the crack tip intentionally positioned (offset) outside the TSP by a distance. The nominal offset of the crack tip from the tube was 0.1" for the 3/4" diameter specimens and 0.15" for the 7/8" specimens. During the initial series of tests, the offset was determined based on the total length of the crack, and during the final test series, the offset was based on the length of the throughwall portion of the crack outside the TSP. The actual range of offsets was up to 0.210" for the total crack and 0.173 inch for the throughwall cracks based on in-process examination of the test specimens.

Following tests by pressurizing the ID of the tube and measuring the leak rate through the crack (Flow Pressurization), the crack in the tube was opened by installing a bladder at the location of the crack, and pressurizing the bladder to the predicted freespan burst pressure (based on the length of the crack). Bladder pressurization was performed with the tube constrained within the TSP. Following this, the bladder was removed, and additional leak tests were performed in both the non-offset and offset conditions. These tests are referred to as Bladder Pressurized flow tests.

Freespan leak tests were performed on some of the specimens to provide a comparison of IRB and freespan leak rates. Some of the specimens were tested at approximately room temperature conditions as well as prototypic elevated temperature conditions to provide a basis of evaluating analytical techniques for adjusting low temperature data to high temperature conditions. The adjustment method is discussed in Section 5.

The burst pressure vs. bobbin voltage correlation, which is the basis of the ARC for ODSCC at TSPs, results in very conservative burst pressures and burst probabilities when uncertainties are considered. A wide range of burst pressures occurs at a given voltage since different crack morphologies can result in comparable voltages. When a direct structural parameter such as throughwall crack length is correlated with burst pressure, correlation uncertainties are much smaller than for a voltage correlation. As noted, the EPRI burst correlation (Reference 2) for throughwall axial cracks leads to a throughwall crack length of 0.75 inch at a ΔP_{SLB} of 2560 psi for lower tolerance limit (LTL) material properties. Thus the probability of burst at SLB conditions is negligibly small due to the requirement for a throughwall crack length equal to the thickness of the TSP. As noted later in Section 6 , pulled tubes with throughwall cracks near 0.5 inch length have had voltages between 13 and 20 volts; thus, a 0.75 inch throughwall crack could be expected to exceed 20 volts. This demonstrates the conservatism in the burst /voltage correlation for which a 9 volts corresponds to a 10^{-2} burst probability.

The intent of the IRB test program was to develop a leak rate for an indication inside the TSP that could burst at 2560 psi if it occurred in the freespan. Since the ODSCC cracks formed in a TSP crevice do not exceed the 0.75 inch TSP thickness at any significant depth (none have been detected in approximately 20 ARC inspections), specimens could not be prepared that would burst at SLB conditions, since LTL materials were unavailable. Consequently, it was necessary to pressurize the cracked specimens with a bladder to the freespan burst pressure to force a simulation of a "burst" (IRB) inside the TSP. None of the indications, including a 0.81-inch throughwall indication, "burst" when tested at flow conditions near or above 2560 psid. The shorter throughwall indications (<0.6-inch) had to be pressurized to well above the SLB pressures; thus, the length and applied pressures are not as representative as the longer cracks of a SLB IRB. The following tests of Table 2-1 are most representative of IRB conditions: 1-1, 1-2, 1-6, 1-7, 11-1 and 11-2.

Since only cracks near 0.75-inch throughwall could burst at SLB conditions, a shorter crack length in a tube with a 0.75-inch crack would not significantly open, and its leak rate would not approach that of the "burst" crack. The potential for two cracks approaching 0.75-inch throughwall length to exist at a TSP is negligible since the associated bobbin voltage would be well above 20 volts. Thus, multiple cracks in a tube would not increase the bounding leak rate obtained from the tests at crack lengths exceeding 0.6 inch. When multiple shorter cracks are tested and the tube must be pressurized to more than 4000 psi to simulate an IRB, both cracks can open up and contribute to the leakage. However, this is a consequence of the artificially high pressurization and is not prototypic of an indication at a TSP intersection that could burst at SLB conditions. This applies to Test 12-1, which should not be applied to define the bounding IRB leak rate.

One of the specimens tested included a crack simulated by laser cutting a slot through the tube wall. This slot was nominally 0.55" long and 0.001" wide. The purpose of this test was to evaluate if machined flaws could be used to simulate corrosion and/or fatigue cracks for leak testing, since corrosion/fatigue cracked specimens with specific length cracks are costly and time-intensive to prepare in the laboratory. The laser slotted specimen was rejected as an inadequate simulant of corrosion cracks based on a) the observed leak rate was approximately twice that of similar length corrosion cracks, and b) the geometry of machined specimens dictates different structural behavior of the slit, compared to a corrosion/fatigue crack, upon pressurization leading to non-prototypic leak rates. The machined flaw ends include a radius instead of the sharp crack tip of corrosion cracks, leading to absence of crack tearing and excessive crack opening in the machined flaw. Based on the testing of this single specimen, machined specimens were rejected as suitable for the test program and no further machined specimens were tested. The results from the single test sequence performed are included in the discussion of results from the other specimens.

2.2 Bobbin Voltage for Crack Lengths Tested

The limiting leak rate and crack/TSP offset data from these test were derived from tests of very long cracks with throughwall lengths approximately equal to the span of the TSP (0.750"). The leakage behavior of shorter cracks is essentially like that of freespan cracks regardless of offset, since the tests indicated negligible interaction of short cracks with the TSP. If longer cracks would be repaired on the basis of their bobbin voltages, (i.e., such as the proposed 3V ARC limit), the voltages for the test specimens should be consistent with projected EOC conditions which have operationally been bounded by about 11 volts.

Although EC data were not routinely acquired for the test specimens utilized in these tests, a few of the initial specimens were tested with a bobbin probe to determine the voltage range for the relatively large cracks being tested in this program. The laboratory specimens in this test program were generally cracked in doped steam and were not oxidized prior to bobbin voltage measurements. Prior work has shown that this results in bobbin voltages lower than found in pulled tubes due to the increased conductivity across the crack faces. In addition, other specimens that were not utilized for the leak and burst tests of this program were also examined with a bobbin probe and then were characterized for the size of the crack for other purposes. Finally, a number of tubes have been pulled from operating SGs for which bobbin voltage data are available. Consequently, a small database exists for characterizing the bobbin voltage vs. the crack size (length of throughwall crack).

Among the specimens tested for which bobbin voltages are available (Table 2.2), the shortest throughwall length crack exhibited a bobbin voltage of 17.1 volts; however, the specimen included two separate cracks. A tested specimen with a 0.515 throughwall crack exhibited a bobbin voltage of 8 volts. The lowest voltage for any laboratory specimen for which there are bobbin data is 7.9 volts for a 0.15" throughwall crack. The longest throughwall crack actually tested, for which there is a bobbin voltage, was 0.29 inch (0.600 in. total length), with a bobbin voltage of 11.4 volts.

Among the pulled tubes, summarized in Table 2.2, for which there are bobbin voltage and destructive examination data, the lowest bobbin voltage for a 3/4" diameter tube is 6.08 volts for a throughwall crack of 0.26" based on destructive examination. Similarly, for 7/8" diameter pulled tubes, the lowest voltage is 6.73 volts for a throughwall crack of 0.282". The longest throughwall crack, 0.47 inch (0.67-inch total length) exhibits a bobbin voltage of 15.7 volts. The longest total crack, 0.81 inch (0.42 inch throughwall length) had a bobbin voltage of 13.55 inch. All of these throughwall lengths are much shorter than the 0.74 inch throughwall length of the specimen in Test 1-6 which strongly influences the IRB leak rate. Although the no bobbin test was performed on the specimen for Test 1-6, it could be expected to have a bobbin voltage exceeding 20 volts.

Therefore, it is concluded that these tests are very conservative with respect to establishing the limiting leak rate of a crack offset from the TSP, since the lowest voltage of any of the available data is more than a factor of 2 greater than the proposed 3V ARC criterion, and the associated throughwall crack length is a factor of 1.5 - 3 less than the throughwall crack length on which the limiting leak rate is based from these tests. It is judged that the IRB leak rate in this report corresponds to indications exceeding about 20 volts.

2.3 Bounding Leak Rate

The bounding leak rate, based on both flow pressurization and leak testing after bladder pressurization, for the limiting indication for which a high voltage ARC could be considered to apply was determined in these tests to be 5.5 gpm at a SLB pressure differential of 2560 psid, based principally on Test 1-6 . Table 2.3 summarizes the leak rates at the SLB conditions of 2560 psid, and an alternate pressure differential of 2405, for the PORV setpoint plus uncertainties for Plant AC, for the specimens . The pre-tests crack lengths are also include don the table. The SLB (2560 psid) leak rate after bladder pressurization from test 1-6 was 5.0 gpm. With the exception of three specimens with special circumstances noted below, all other tests had SLB leak rates less than the bounding leak rate of 5.5 gpm for both flow pressurization tests and post-bladder pressurization leak tests.

For the alternate accident pressure differential (2405 psid) for the PORV setpoint for plant AC-2, the bounding leak rate is 5.0 gpm, based principally on Test 11-2 and Test 1-6.

The bounding leak rate was determined based on the evaluation of the measured leak rate data for the average pressure during the tests. Therefore, the leak rate is conservative since the plastic crack opening is determined by the peak pressure differential at the start of the test, and this was up to 100 psi greater than the average pressure differential for which the bounding leak rate is evaluated. If the measured leak rates are evaluated against the peak pressure differentials, the 2560 psid leak rate is 5.0 gpm.

The bounding leak rate 5.5 gpm, includes the effects of TSP offset, thus no additional consideration of offset is required. For this test, the offset was established at 0.10" from the crack tip, which included a throughwall length of 0.070". Little crack tearing occurred for this specimen because the crack flanks of a crack of this length rapidly interact with the TSP, which prevents wide crack opening and tearing.

Test 1-6 utilized a specimen with a total crack length of 0.760 inch, and a throughwall crack length of 0.740 inch. This test conservatively establishes the bounding leak rate because the throughwall portion of the crack (0.740", at beginning of test) is essentially the full span of the TSP (0.750"). This throughwall length exceeds any found in operating SGs, including European plants that operated with no repair limitss.

A crack of this length would also not be considered acceptable to remain in service based on voltage criteria. The high voltage ARC implemented at plant AA and AB, and proposed for plant AC, permit 3V indications to remain in service. As noted in section 2.1, all of the specimens tested in these tests would provide bobbin voltages at least a factor of 2 greater than the proposed voltage limit.

The bounding leak rate from Tests 1-6 is supported by the following additional tests:

- Test 11-2, a test of a 0.729 inch total length (0.630 inch throughwall) crack yielded a SLB leak rate of 5.13 gpm for offset flow pressurization a 5.3 gpm SLB leak rate after bladder pressurization of the specimen. This specimen was a 7/8" diameter specimen.

- Test 11-1, a test of a 0.710 inch total length (0.600 inch throughwall) crack yielded a SLB leak rate of 5.0 gpm for offset flow pressurization and after bladder pressurization. This specimen was a 7/8" diameter specimen.

- Test 12-1, a test of specimen with two cracks, 90° separated, of total length 0.607 inch and 0.465 inch. The throughwall lengths of these cracks were 0.518 inch and 0.360 inch respectively. The SLB leak rate of this specimen was 3.2 gpm for offset flow pressurization and 5.7 gpm after bladder pressurization. Multiple cracks with 90° separation lead to maximum leak rates inside a TSP since the crack openings to interact with the TSP hole ID are essentially independent of each other. This specimen was a 7/8" diameter specimen.

Three tests are excluded from consideration for defining the bounding leak rate for an IRB that would be conservatively considered for implementation of a high voltage ARC.

- Test 11-7 was a tests of a crack that was significantly longer than the span of the TSP, and would therefore not be considered in the population of IRBs that would be considered for implementation of the ARC. This specimen included a crack of 0.813 inch total length and 0.809 inch throughwall length. This length exceeds the TSP thickness of 0.75inch which provides the crevice environment for crack initiation and growth. However, this test validates the bounding leak rate discussed above by demonstrating that cracks that extend beyond the TSP lead to only a small increase in the SLB leak rate. This conclusion is true even if the crack is pressurized to its freespan burst pressure.

- Test 2-8 was a test of a specimen with a laser cut flaw, to evaluate if these easily prepared specimens are good simulations of corrosion cracks for leak testing. Laser cut flaws, and machined flaws in general, are characterized by smooth-walled, uniform opening slits, that do not simulate the tortuosity of corrosion/ fatigue cracks. This leads to much higher leak rates for the machined flaws compared to similarly sized corrosion/fatigue cracks. Further, the ends of the machined slits are radiused, instead of the sharp crack tips of corrosion or fatigue cracks, which causes the slit ends to behave like plastic hinges instead of tearing like corrosion/fatigue cracks. The resulting crack opening under pressurization is much greater than for the corrosion cracks. Consequently, machined flaws were rejected as suitable simulants of corrosion cracks for these leak tests, and the measured leak rate for this tests is non-representative of the IRBs addressed by the proposed ARC.

- Test 12-1 resulted in a leak rate of 5.7 gpm after bladder pressurization to the predicted freespan burst pressure for both the zero-offset and the offset tests. This specimen included two cracks, 90° separated, 0.607 inch (0.515 inch TW) and 0.465 (0.360 inch TW) long, respectively. For flow pressurization to 2680 psid, the offset SLB leak rate from this specimen was 3.2 gpm. After bladder pressurization to 3310 psi, the offset SLB leak rate was 4.2 gpm. Up to this point, post-tests inspection showed that the secondary crack had not opened, and the primary crack had opened to about 0.005-inch width. After bladder pressurization to the predicted freespan burst pressure (4850 psi), the primary crack opened to 0.022-inch width and the secondary crack also opened to about 0.005 inch. Thus, for the flow pressurization tests exceeding the SLB pressure differential, this specimen with two moderately long cracks had a leak rate less than 60% of the bounding leak rate. After bladder pressurization about 90% greater than SLB pressure differential, this specimen had a leak rate less than 4% greater than the bounding leak rate. As discussed in Section 2.1, the influence of a realistically sized second crack is an artifact of the high bladder pressurization applied to simulate an IRB. At SLB pressure differentials, shorter cracks would not open sufficiently to significantly increase the leak rate above that of the larger crack that could burst at SLB conditions.

2.4 Applicable Range of Offset

The data from these tests conservatively bound a minimum TSP offset of 0.15 inch. Consistent with the requirements that no crack extending outside the span of the TSP, offset is defined here as the length of the total crack outside of the span of the TSP. The maximum offsets tested were 0.210 inch (Test 1-2), 0.208 inch (Test 11-2) and 0.185 inch (Test 11-1) for flow pressurization, and 0.185 inch (Test 11-1) and 0.180 inch (Test 11-2) for leak tests after bladder pressurization. Two of these tests, Tests 11-1 and 11-2, are principal supporting tests for the bounding leak rate; thus the maximum offsets are represented in the bounding leak rate.

The offset tests were initially set up based on total crack length outside the TSP, nominally 0.10 inch for ¾″ diameter tubes and 0.15 inch for 7/8″ diameter tubes. Later offset tests were conservatively set up based on the throughwall length outside the TSP, thus much longer total crack lengths outside the TSP were actually tested. The offset setup based on total crack length outside the TSP simulates the actual condition of TSP deflection during a postulated SLB.

During pressurization, both the total crack length and the throughwall crack length increased; thus the actual offset lengths tested were frequently greater than the setup offsets. The maximum offsets noted above are the post-test measurements, based on in-process measurement techniques; thus the measured leak rate, and the bounding leak rate, include the effects of the offsets.

Fractographic examination of a number of the specimens was performed after all leak testing had been completed. The results of this examination showed that the in-process measurement techniques were conservative. The crack tips are often tight and cannot be observed even with the aid of a toolmaker's microscope. Similarly, the method of determining throughwall length using a back-lighting technique is limited to a crack opening of 1 mil that is reasonably normal to the plane of vision, to identify throughwall crack length. Therefore, it is concluded that the crack length measurements that define the applicable crack offset, either total crack or throughwall crack, are conservative.

For the limiting acceptable crack length of 0.750 inch, a limiting offset can be defined based on the results of the test. The maximum contact length between the crack flanks and the TSP was estimated at 0.3 inch. The crack opening behavior was observed to be symmetric about the axial and longitudinal crack centerline. Therefore, the length of the crack not in contact with the TSP half the difference between the total length and the length in contact with the TSP, or 0.225 inch, which defines the maximum offset for the limiting crack. An offset less than this distance will not increase the available flow area of the crack, and therefore, the leak rate would not increase up to this offset.

2.5 Bounding Leak Rate Sensitivity to TSP Offset

The bounding leak rate conservatively includes the effects of offset, and is insensitive to offset at the limiting crack length.

The offset leak rates are essentially the same as the zero-offset leak rates for the range of crack lengths tested. Figure 2-1 provides a comparison of the leak rates correlated to crack length for the offset tests and for the zero offset tests. (More detailed evaluations are contained in Section 6.) Figure 2-2 shows that the slope of the correlation for offset tests is slightly greater than for the zero-offset tests, suggesting that there may be a small effect for increasing leak rate with offset. However, the leak rate at the limiting crack length, 0.750 inch, is the same for both offset and zero offset tests. Further, the bounding leak rate is based on the offset test results. Therefore, offset is a negligible factor on the bounding leak rate in the range of offsets tested.

2.6 Leak Rate Sensitivity to Tube Size

The leak data from the tests of 3/4" diameter specimens and 7/8" diameter specimens are equally applicable for both tube sizes.

The leak rates were correlated to the crack properties, length and limiting throughwall area, and were found to have strong correlations in both crack length and area. Figure 2-2 shows a correlation of the leak rates for all of the tests, including ¾" and 7/8" diameter tubing and both offset and zero-offset tests for flow and bladder pressurization. No difference in the data scatter was observed, based on the tube diameter, for the leak rate as a function of crack length, the principal correlation parameter. Additional correlations were performed based on crack area (Section 6), and these, also, did not indicate a bias in the leak rate results based on tubing diameter.

2.7 Leak Rate Correlation With Crack Properties

The measured leak rates correlate well with total crack length and limiting crack area. The leak rates do not correlate well with offset length or offset area.

Analyses were performed (Section 6) to test the correlation of the measured leak rates with various crack properties: Crack length, crack-limiting area, offset length and offset area. Since the crack opening is dictated by the highest Δp applied to it, the leak rate at the peak pressurization condition, correlated to the maximum Δp of the test, normalized to standard SLB conditions was utilized for the trending studies. The limiting crack areas were calculated based on the in-process measurements made on the specimens for crack length, throughwall length, offset length, crack opening width, tube diameter, etc. Calculations were performed to determine the most limiting flow area form among the crack opening area, geometric area, and effective flow area.

Excellent correlation of the leak rate with crack throughwall length was achieved. An adequate correlation was achieved with apparent crack area; however, when the apparent crack area was replaced with limiting crack area, an excellent correlation was achieved. The correlation with limiting crack area demonstrated that the interpretation of crack/TSP interaction regimes is appropriate and that the conclusions relating the bounding leak rate to the liming crack lengths are appropriate.

Correlation of the measured leak rates with offset length and offset area resulted in very weak correlations. Although the data scatter is very large, the data trends suggest that increasing offset very slightly increases the leak rate. This could be explained by a turning loss factor which could also explain the non-linearity of the leak rate correlation with the limiting flow area. Nevertheless, the correlation with offset length or offset area is very tenuous, and the bounding leak rate already includes the effect of the offset. Therefore, it is concluded that the IRB leak rate depends principally on the crack throughwall length and/or limiting flow area, and that the offset length and area are secondary factors.

2.8 Effect of A Second Crack on the Bounding Leak Rate

The bounding leak rate does not need to be adjusted for potential multiple throughwall indications.

Leakage from a tube with two cracks is dominated by the principal crack. Similarly, the structural behavior of a specimen with two cracks is dominated by the principal crack.

The leak rate from a crack is an exponential function of the throughwall length of the crack, neglecting any TSP interaction. Thus, if a tube has a longer crack together with a shorter crack, the leak rate is dominated by the longer crack, and the shorter crack contributes only slightly to the leak rate. The combined leak rate from the principal and secondary cracks is much less than the leak rate from a single crack whose length is the sum of the lengths of the principal and secondary cracks. This observation is supported by pulled tubes from plants AA and AB with indications in the 10-11 volt range, and model boiler tests data both of which show that the secondary crack is much shorter than the principal crack. An exception to this rule is manifested in a tube pulled from Plant S with a 22.9 volt indication that had a principal crack of 0.50 inch and a secondary crack of 0.41 inch. No leak tests were performed on this tube; however, calculations for this tube showed that the principal crack would have a leak rate three times that of the secondary crack.

Test 12-1 of these tests included two cracks comparable in length to the tube pulled from Plant S, in planes about 90° apart. In-process measurements showed that the secondary crack did not open until the specimen was pressurized with a bladder to greater than 70% of the predicted freespan burst pressure for this specimen. Thus, this specimen confirms that the leak rate is dominated by the principal crack in a specimen with two cracks.

The probability of multiple throughwall cracks occurring at the location of the maximum TSP offset is extremely low. The top TSP is the highest loaded (largest displacement) TSP during a postulated SLB accident, while the incidence of ODSCC is dominantly at the lower TSP. The largest TSP offset occurs only at a localized area on the highest loaded TSP. Therefore, it is extremely unlikely that the incidence of multiple cracks will coincide with the location of maximum TSP offset.

Pulled tube data confirm that the location of throughwall cracks is not near the edge of the TSP. Among sixteen available pulled tubes from Plant AA and AB with bobbin voltages 1-16 volts, 1 tube included an indication located ~0.1 inch from the edge of the TSP, 12 tubes included an indication located ~ 0.2 inch from the edge of the TSP, and the remainder included an indication near the center of the TSP. Therefore, it is concluded that indications, where they occur, do not occur at the edge of the TSP, further reducing the likelihood of multiple indications increasing the SLB leak rate due to TSP offset.

2.9 Crack/TSP Interaction

Interaction of cracks with the TSP inherently limits the leak rate of IRBs to small values. TSP interaction occurs at lower pressures for smaller tube/TSP gaps and higher pressures for larger gaps. Similarly, interaction with the TSP occurs for at higher pressures for shorter cracks and lower pressures for longer cracks. The tube/TSP gap utilized for the IRB tests was a 95% confidence upper limit gap.

Short throughwall cracks, < 0.4 inch long, have high burst strength, so that the predicted freespan burst pressure is large compared to the SLB pressure differential. Crack openings for short cracks are small, and interaction with the TSP is not expected to occur. Leak rates for short cracks are low, and because crack opening is small at SLB Δp, remain small at SLB pressure.

Throughwall cracks > 0.4 inch long, up to the limiting crack length of 0.750 inch, have freespan burst capability greater than the SLB Δp. The limiting crack length, defined by the span of the TSP, is also coincidentally the length of the throughwall crack in ¾ inch diameter tubing that has SLB Δp capability when lower tolerance limit material properties are assumed. Cracks of 0.55-inch throughwall length interact with the TSP with a tube/TSP gap of 0.025 inch prior to reaching the SLB Δp. Increasing Δp after this point causes no further increases in leak rate, even after bladder pressurization to the freespan burst pressure in the offset condition.

The sequence of limiting flow area follows from initially the crack opening area to the geometric area. The geometric area is defined prior to actual crack flank/TSP contact as that area between the TSP ID and the tube OD. Further increases in pressure and crack expansion cause physical interaction between the crack flanks and the TSP, further reducing the available flow area progressively with increasing pressure. Finally, greater applied Δp causes the crack flank to buckle toward the centerline of the tube, resulting in the tube being tight in the TSP due to radially outward elastic recovery of the crack flanks.

It is concluded that the bounding leak rate determined in these tests is limited by the interaction between the crack and the TSP, and that the maximum permitted length of cracks will not have a leak rate greater than the bounding leak rate. Additional margin is included in the bounding leak rate due to the conservatively large tube/TSP gap utilized in these tests.

2.10 Crack Tearing for Constrained Cracks

Crack elongation for IRBs is not significant for pressures up to the predicted freespan pressure of the original crack.

Normally, the expected tearing of a crack for a freespan burst is about 250 mils. In comparison, the observed tearing of the IRB specimens was generally less than 50 mils. Tests 1-2 and 2-1 tore 90 and 64 mils , respectively, relative to the original crack length measurements due to previously unobserved, non-throughwall crack segments. Test 12-7 tore 181 mils during inadvertent bladder pressurization to 6200 psi instead of the predicted freespan burst pressure of 3950 psi. The negligible tearing of the IRB specimens reflects the reinforcement provided to the cracked tubes due to interaction with the TSP. Longer cracks, which would burst at lower pressures, also contact the

TSP at lower pressures, and are thus restrained from significant tearing. Shorter cracks required significantly higher pressure for burst, and at these pressure, they also interact with the TSP. Consequently, IRBs of all lengths are inherently restrained from significant tearing and resulting increase in flow area.

It is concluded from these tests that crack tearing is minimal due to the restraint provided by the TSP, and that, therefore, crack elongation and a resulting increase in the bounding leak rate is not a concern.

2.11 Adjustment of Room Temperature Measurements to SLB Conditions

The EPRI method for adjusting leak rate data to a reference set of conditions was utilized. Test results form room temperature and high temperature tests were normalized to SLB conditions defined as 615°F primary temperature, and 15 psig secondary side pressure. Good correlation of room temperature and high temperature data was achieved.

Correlation of the measured leak rates with the test pressures was performed after normalizing the data using the EPRI procedure. The measured leak rates correlated better with the peak Δp of the individual tests than with the average Δp, since the crack opening is determined by the peak Δp applied to it. At the reference SLB conditions, the leak rate correlated to maximum test Δp was generally lower than that correlated to average test Δp. For reporting the bounding leak rate, the more conservative correlation was used. For performing trending studies, the correlation with maximum Δp was used. The conservatism of the leak rates correlated to average Δp is reflected in the uncertainty analysis.

2.12 Leak Rate Uncertainties

The bounding SLB (2560 psid) leak rate, 5.5 gpm, is a conservatively high value.

Evaluation of the uncertainties of these tests (Section 5) identified four sources of potential uncertainty: These and their range of uncertainties are:

1. Fluctuation of leak rate during the tests (±3.1%)
2. Use of the test maximum Δp vs. the use of the test average Δp for the reported leak rates (-10%)
3. Leak rate adjustment procedure for SLB conditions (negligible)
4. Test loop calibrations (+0.1%)

The combined uncertainty for these four sources of uncertainty varies from -7% to -10%, based on the upper and lower limits of the individual uncertainties. The negative values indicate that the test-based bounding leak rate is conservatively high; that is, the uncertainties would reduce the stated leak rate

2.13 Summary

- The bounding SLB (2560 psid) leak rate for the limiting crack lengths is conservatively demonstrated by these tests to be 5.5 gpm.
- The IRB tests demonstrate that the bounding leak rate applies for TSP offsets up to 0.21 inch, which conservatively bounds the recommended offset of 0.15 inch for the high voltage ARC.
- The bounding leak rate includes the effects of offset, which are very small. Thus, the bounding leak rate does not need to be adjusted for offset.
- The bobbin voltages of the limiting crack lengths, which define the bounding leak rate, are expected to be at least 8 volts and, potentially, up to 25 volts. The recommended voltage for current tube expansion (high voltage) ARC is 3 volts.
- The limiting offset for the limiting length crack is estimated at 0.225 inch. This is the offset at which the bounding leak rate would be expected to increase with greater offset.
- Cracks longer than the limiting crack length continue the leak rate trends demonstrated for cracks up to the limiting crack length and do not result in a step increase in leakage.
- The measured leak rates do not depend on tube size; thus the combined data for both ¾" diameter and 7/8" diameter tubes can be applied equally for both tube sizes.
- The bounding leak rate does not need to be adjusted for the potential of multiple indications.
- Throughwall cracks ≥ 0.55 inch length interact with the TSP to effectively limit the leak rate. No significant increases in leak rate are observed with greater applied Δp after interaction occurs.
- Cracks less than 0.55 inch have inherently lower leak rates that are enveloped by the bounding leak rate.

- Crack extension is an insignificant factor for the bounding leak rate for the IRBs. Except for a specimen inadvertently pressurized to almost double its freespan burst pressure, and specimens where the entire beginning of test crack length was not determined, the crack extension was less than 0.05 inch. Interaction of the crack with the TSP inherently limits crack tearing for IRBs.

- The bounding leak rate is conservative due to the conservatively large tube/TSP gap used in these tests. The gap used was 0.025 inch, which is the 95% confidence bound on the expected steam generator tube/TSP gap.

- The bounding leak rate is conservatively high by 7% to 10%, based on evaluation of the tests and analysis uncertainties.

- The EPRI adjustment method for normalizing test data was utilized for these tests and is considered adequate with minor revisions to the method.

2.14 References

1. W-NSD, SG-65-03-010, "Burst Pressure Correlation for Steam Generator Tubes With Throughwall Axial Cracks", March 1995.

3

TEST OBJECTIVES AND FACILITY DESCRIPTION

3.1 Test Objectives

As part of the licensing amendments sought by Commonwealth Edison in 1995 to implement higher voltage TSP alternate repair criteria for steam generator tubes by utilizing tube expansions to limit the TSP displacement in Plants AA and AB Byron, the Nuclear Regulatory Commission identified the need for an experimental data base to validate the proposed analytical leakage model described in Reference 1. In response, The Electric Power Research Institute (EPRI) and ComEd sponsored a test program, performed by Westinghouse Electric Corporation, to measure leakage under postulated Steam Line Break (SLB) accident conditions from axially oriented indications restricted from burst (IRB) by the tube support plates. Westinghouse, in concert with EPRI and ComEd, developed a test program to evaluate the primary to secondary leak characteristics of the indications under temperature and pressure conditions typical of the postulated SLB.

To support the implementation of the higher voltage alternate plugging criteria, a test program with four key objectives was devised:

1. Develop a bounding value for leak rate under steam line break (SLB) conditions for large (>0.6 inch long) indications which are restricted from burst (IRB) by the presence of the tube support plate (TSP), for both conditions of the defect centered in the span of the TSP or offset a reference distance outside the TSP.
2. Determine the influence of crack length on SLB leak rates to support leak rate models and assess the differences in the leak rates between reasonably expected throughwall crack lengths and the postulated bounding conditions of > 0.6" throughwall crack lengths.
3. Evaluate the IRB leak rates relative to the freespan leak rates assumed by NRC GL 95-05
4. Provide test data on the differences between room temperature and operating temperature leak rates to permit comparisons with analytical predictions. These test results could be used to support the utilization of room temperature tests in lieu of

the more costly and time consuming operational temperature tests in future programs.

3.2 Test Overview

Implementation of the test objectives required the following key actions:

1. Fabricate a statistically significant number of tube samples containing a range of lengths of through wall axially oriented defects. The requirements for the test specimens were to be prototypic of, or reasonably simulate, the corrosion cracks in operating steam generator tubes, which are the object of the ODSCC ARC addressed in GL 95-05. (See section 3.2)

2. Construct a test facility capable of high temperature and pressure conditions to simulate the conditions of a postulated SLB event, with sufficient capacity to obtain high leak rates up to 20 gpm and sustain this leak rate for sufficient time to permit measurements under reasonably steady state conditions. (see section 3.4.1)

3. Fixture the test specimens to simulate the tube and TSP for the condition where the crack is centered in the span of the TSP, and for the condition where the crack extends a reference distance outside the span of the TSP. (See section 3.2)

4. Measure the leak rates through the defect for both conditions of 3 above, for an increasing range of pressures up to the limit of the tests facility capability, but at least to the SLB pressure differential of 2560 psid.(See Section 4)

5. Dimensionally characterize the test specimens during the testing sequence to provide data on crack opening behavior for the different constraint and pressurization conditions, and perform post test metallography as a check on the in-process dimensional measurements.

3.3 Test Specimens Preparation and Fixturing

To assure wide applicability of the test results, both 7/8 inch and 3/4 inch outside diameter tubing was selected for use in the program. The actual tubing used was prototypic of operating steam generator tubing. The tubes were processed in the laboratory to provide varying crack lengths from 0.25 to 0.75 inches. The matrix of test specimens actually tested is given in Table 3-1; the crack lengths tested vary from 0.29 inches to 0.809 inches. The 0.809 in. crack specimen tested is longer than could be considered to leave in service, based on the requirements of GL 95-05 which requires that no crack that extends beyond the span of the TSP may remain in service. However, this specimen was included as a bounding case to evaluate if significant crack length growth during an operating cycle would lead to an unacceptable leak rate. The results of this test are summarized in Section 5 and 6.

The majority of the samples were produced through accelerated corrosion techniques utilizing doped steam and masking of the specimens to initiate the corrosion crack. For many of the specimens, the corrosion exposure was augmented by fatigue cycling of the specimen utilizing internal pressurization of the specimens for more controlled growth of the through-wall crack length to achieve the desired crack lengths.

The corrosion, or corrosion plus fatigue, process produced cracks that conservatively simulate the morphology of the corrosion cracks found in operating steam generator tubes. Fatigue cracks have been shown to provide smoother fracture faces with less tortuosity than corrosion cracks. Thus, the leak rates from corrosion plus fatigue cracks would be greater than from a corrosion-only crack of the same throughwall length.

To assure the complete characterization of the condition of the tubes prior to testing, each of the samples selected for testing was subjected to dye penetrant flaw size verification using silastic molding compounds and subsequent bobbin and UT examination to categorize the size, shape and orientation of the initial defect. These techniques are discussed more fully in Section 4.

As a backup to the corrosion/fatigue process, in an attempt to achieve close control of the defect total length and throughwall length, a laser cutting technique was utilized to prepare tests specimens. This technique utilized a visible light copper laser to cut a flaw of the desired length in the sample tube. This technique, developed by the Oxford Laser Co. of Oxford England, was successfully utilized by EPRI to prepare tests specimens for an NDE test program. The laser cutting technique produces a very smooth-wall defect, approximately 0.001 inch wide, with rather rounded crack tips. Although several specimens were produced, testing of the first specimens showed that the leak rate of the laser cut specimens was significantly greater than for a similarly sized corrosion crack due to the uniform, smooth crack opening. In addition, the crack opening behavior of the laser cut specimens is significantly different, since the rounded crack tip acts essentially like plastic hinge, rather than permitting crack tip tearing as the corrosion cracks experience. Consequently, after the first test of a laser cut specimen, no other laser cut specimens were included in this program because of the non-prototypicality of these specimens relative to corrosion cracks.

To facilitate sample testing, the test support fixture shown in Figure 3-1 was utilized to anchor the sample within the leak test fixture and maintain the position of the tube defect relative to a simulated support plate. A locking plate secured the upper portion of the tube. The locking plate located the axial position of the tube within the leak test fixture. With the use of the appropriate shim stock, it also centered the tube within the fixture and the support plate assembly. The support plate assembly was mounted on the locking plate, which provided for axial adjustment of the simulated support plate with respect to the tube defect to achieve the desired amount of the crack tip exposure.

Axial centering of the crack in the span of the TSP was achieved by locating the TSP relative to a reference mark placed on the tube at a fixed location along the tube. Similarly, for the offset tests, the simulated TSP was located relative to the end of the crack (or the end of the throughwall portion of the crack for later tests) based on a mark placed on the tube. For 3/4-inch diameter tubes, the reference offset was established at 0.1 inch, while for 7/8-inch diameter specimens, the reference offset was established at 0.15 inch. These offset values were based on preliminary analysis of TSP deflection during a postulated SLB event, and are considered reference values only. The maximum offset actually tested during these tests was 0.210 inch from the crack tip to the edge of the TSP.

The tube support plate to tube hole clearance was specified as 0.025 inch as a conservative value relative to the expected steam generator conditions. Based on drawing dimensions, the TSP tube-hole clearance for both 3/4 inch and 7/8 inch diameter tubing varies from 16 to 31 mils, assuming nominal diameter tubing. Normal manufacturing processes would be expected to bias the hole diameters toward the smaller clearances; thus the 25 mil test clearance would be expected to be at, or near, the maximum clearance for the large majority of the tubes. A study, performed in support of high voltage Alternate Repair Criteria for steam generators with 3/4" diameter tubing, Reference 1, concluded that the 95% confidence value for tube/TSP clearance would be less than 23 mils.

For the initial series of tests, the test specimens were installed into the test fixture, Figure 3-1, with the tube visually aligned with the TSP bore. A normal tests sequence required removing the specimen from the fixture for in-process dimensional measurements, and then re-assembling the fixture for subsequent tests. Dimensional measurements show that the tube diameter and crack opening increased with each increase of pressure differential; thus the visual alignment of the specimens with the TSP tended to move the non-cracked side of the tube closer to the bore of the TSP. For bladder pressurization steps, that is, pressurization of the specimen, with a tygon bladder installed, to pressures up to the predicted burst pressure for each of the specimens, the flexibility of the alignment plate is believed to have permitted the crack flanks to push the specimen into contact with the TSP opposite the cracked side of the tube and result in opening of essentially the full tube/TSP gap to the crack. Although examination of the final expansion profiles of the specimens tends to confirm this for the majority of the specimens (see Section 6), a second series of five tests was performed for with the test fixture assembles to assure that the tube/TSP gap was located at the crack side of the test specimen.

For the second series of tests (test series 11-x and 12-x), the specimens were installed in the test fixture utilizing shims to assure that the tube/TSP total clearance was located at the cracked side of the tube. The fixture assembly process also utilized a one-half mil shim between the non-cracked side of the test specimen and the simulated TSP as a mechanism to verify that the total clearance was located at the crack side of the tube. The fixture was assembled so that the TSP contacted the tube with the shim between the tube and the TSP. Contact was verified by observation of resistance to pulling the shim from between the tube and the simulated TSP. Figure 3-2 illustrates the test fixture assembly process to insure contact between the tube and the TSP opposite the crack in the test specimen.

3.4 Leak Test Facilities

Two test loops, located at the Westinghouse Science and Technology Center (WSTC) were utilized for the leak tests. The principal test facility utilized was a high capacity, high energy facility which was used for both high temperature and ambient temperature leak testing. However, initial testing was also performed in a small, low temperature facility. These facilities are described in the following sections.

3.4.1 High Energy Leak Test Facility Description

Westinghouse constructed a high temperature, high capacity leak test facility for these tests. The test facility was designed for high temperature (>650°F) and high pressure (up to 3000 psi) operation with sufficient capacity to enable measurement of leak rates up to 20 gpm. Generally, the loop operates in a blowdown mode, with the Δp principally controlled by the setup of the secondary side conditions. To initiate a test, the system is brought to the desired primary side equilibrium conditions, then the blowdown valve is actuated to vent the primary side to the secondary through the test section. After an initial decay of the pressure differential across the test section (characterized by a rise in secondary pressure and a drop in primary pressure), a reasonable steady state Δp is achieved for which the leak data are acquired. Appendix B contains the leak test records for all of the tests and examples of the test primary and secondary side pressure traces.

An overall schematic of the WSTC High leak Rate Test Facility is shown in Figure 3-3. The main accumulator consists of one 100 gallon pressure vessel connected in series to the rest of the system with 0.5" diameter high pressure tubing. The accumulator, which represents the primary side of a steam generator, is heated with external strip heaters on the vessel. A two-liter autoclave contains the leak test sample. The interior of the autoclave simulates the secondary side of a steam generator. The autoclave is heated with external band heaters. During initial pressurization (at ambient or elevated temperature) the accumulator and autoclave can be isolated from each other by an air operated valve (AOV-1) and a hand operated valve (V1). Two discharge ports on the autoclave are available to channel leakage from the tube sample flaws to the collectors. These ports are activated by AOV-2 and AOV-3. The tubing from the discharge AOVs are connected to chilled condensers to de-pressurize the leakage when elevated temperature tests are conducted. The down stream ends of the condensers are open to the atmosphere and dump into containers to quantify the leak rate. The leak rate may be quantified in terms of the weight or volume of water collected. The specific output data for these tests was water level in the condenser accumulator container.

An intermediate, re-heat autoclave is located between the 100 gallon pressure vessel and the autoclave containing the sample being tested. This intermediate autoclave was added to the test facility to help damp the variations in temperature experienced during the leak testing of the samples.

The test sample installation in the test autoclave is shown schematically in Figure 3-4. One end of the test specimen is connected to the primary source tank, and the opposite end of the test specimen is sealed utilizing a Swagelok fitting. Thus the ID of the test specimen simulates the primary side of the system. The test autoclave represents the secondary side of the system.

The loop operating procedure was to control the desired Δp by controlling the primary side conditions; thus the target Δp of a test represented a range rather than a specific setpoint. During setup, the test procedure was to pressurize the primary and secondary sides at the same time so there was essentially zero pressure difference across the tube sample flaw. AOV-1 was generally open during setup, but was closed for those tests with very small, anticipated leak rates to permit manual equilibration of the primary and secondary side. After primary and secondary temperature and pressure conditions were stable, AOV-1 from the 100 gallon pressure vessel was opened (unless it was already open). To initiate a test, one or both of the discharge AOVs (depending on the temperature and the anticipated leak rate) was opened permitting the accumulator to "blow down" through the tube flaw and condenser into the leak collection container. During the leak test, temperatures and pressures time histories from the indicated sensors were automatically recorded along with the leakage weight or volume.

3.4.1.1 Ambient Temperature Test Operations

During ambient tests, the entire system was filled and purged with deionized water to assure that gas pockets were removed. The autoclave was also completely filled with deionized water. At this time AOV-1 and V1 were both gradually opened and the nitrogen pressure gradually increased into vessel head space while observing P1 and P2 to insure that both pressures were increasing together. When pressures were stabilized at the desired level the data acquisition system was energized and valve AOV-2 opened. For ambient temperature tests the condenser could be bypassed. Typically, only one of the leak collection containers was utilized. The test data collection was initiated when the collected liquid volume was equal to the initial system stored volume of about 8 liters. When the leak test was considered complete, and adequate leak rate data had been collected, AOV2 was secured. Typically, the test time ranged from ten seconds to one minute, depending on the leak rate.

3.4.1.2 Elevated Temperature Test Operations

The procedure for elevated temperature testing was similar to the ambient tests, but with increased safety concerns because of the stored energy in the large volume of hot fluid and the requirement to condense the expanding fluid during the leak test. For this reason the normally closed system control valves (AOVs) were all operated remotely.

The 100 gallon tank upstream of AOV- 1 was completely filled with deionized water and allowed to overflow to partially fill a second accumulator. At this time the autoclave was also filled with deionized water. The water inlets to the accumulators and the autoclave along with the vent valves were then closed. Valve V1 was opened and the temperature controls for the accumulator and autoclave heaters were activated. The accumulators and autoclave were heated to the required test temperature, while bleeding the system manually through the vents, as required, to keep the pressures at or below the desired level. After the temperature had stabilized at the desired level, pressure was increased, as necessary, using nitrogen pressure and/or water pressure from an air-powered intensifier.

The data acquisition system was activated, valve AOV- 1 was verified open, followed by the opening of valve AOV-2 or valves AOV-2 and AOV-3 if both condenser systems were to be used. After acquisition of the test data, valves AOV-2 and AOV-3 were closed. Data collection for leak rates commenced when the collected liquid was equal to the initial stored volume (approximately 8 liters. Typically, the test time ranged from one to ten minutes, depending on the leak rate.

For added clarity, photographs of the actual large leak test facility are included in this report. Figure 3-5 shows the relative size and location of the pressurized accumulator tank in the overall arrangement of the test loop. Figure 3-6 shows the relative location of the two condenser tanks, one of the collection tanks where the leakage volume is contained and measured, and the test autoclave containing the test sample. Figure 3-7 shows the condensing tank, the test autoclave where the test sample is contained and one of the air operated valves (AOV) typical of those used throughout the system. Figure 3-8 is a general overview of the remote data acquisition system used to acquire the pressure, temperature and leak rate data during the later phases of the test program.

3.4.2 Small Leak Test Facility Description

A small, low temperature loop, located in a radiologically controlled hot cell facility, is typically used for leak and burst testing of contaminated tubes which have been pulled from operating steam generators. As a consequence, clean samples tested in this loop become contaminated during the testing and must be decontaminated before they may be safely released to test in other non-contaminated test facilities. In the interest of expediting the test schedule, two samples, 4C218(test 2-4) and 2051B(test 2-10), were initially processed through this (radiologically) Hot Facility, subsequently decontaminated, and then completed their test cycle in the non-contaminated high flow test facility.

Figure 3-9 is a schematic of the Small Leak Test Facility in the hot cell test facility. Since the specific conditions for leak rate testing may vary depending on the requirements for a specific specimen, the system was designed to permit modifications to the configuration as necessary. All instruments, gauges, and other measuring equipment are calibrated, and equipment serial numbers and calibration information are recorded in a permanent record book and maintained as part of the program test file.

The test facility consists of a primary autoclave (AC1), a secondary autoclave (AC2). and a supply tank; connected by insulated tubing. The specimen is physically located within AC2, but connected to AC1. AC1 runs with two-phase water and is pressure controlled by a nitrogen pressure bottle connected to AC1. AC2 is connected to a water-cooled condenser that will convert any steam escaping from the specimen into ice temperature water. The pressure in the secondary side (in main body of AC2) is maintained by a back pressure regulator (BPR). The condensate or leakage from the sample is collected in a graduated cylinder, and the amount of water recorded as a function of time.

House deionized (DI) water is used in the primary side of the system. Before the initiation of testing, the primary system is purged with DI water for about five minutes and the conductivity of the (DI) water checked. By a series of fills and purges of the primary side, the conductivity of the fluid is established between 5 μmho to 5 mho. When this condition is achieved, a vacuum line is connected to outlet of V14 and AC1 is backfilled through V5 with approximately eight gallons of DI water (conductivity less than 5 μmho). At this time the primary autoclave and connecting piping is leak tested by applying a nitrogen overpressure from gas bottle 1 (GB1). The pressure regulator valves on the supply tank and AC1 are also adjusted at this time.

A leak test specimen containing the necessary test fittings to connect the sample to the primary system is connected to the AC2 head assembly. AC2 is filled with approximately 200 ml of DI water. The sample and autoclave head assembly are then connected to the autoclave body and checked for leakage under pressure. Following the system pressure check, the system is carefully refilled to makeup for any water lost during the system leak test.

At this point the back pressure is applied using back pressure regulator pressure gage (BPRPG) and GPR2. Container Cl is filled with ice water and the city water is turned on to the cooling coils of C2 and C3.

Autoclaves AC1 and AC2 are raised to the test temperatures specified in the test procedure.

After both AC1 end AC2 reach equilibrium (temperature and pressure), the BPRPG is adjusted to establish the desired test pressure as specified in the test procedure. By adjusting the intermediate valves, Primary flow is initiated. When secondary pressure reaches operating pressure, the collection of the water in the graduated cylinder is initiated.

3.5 References

1. WCAP-14273; Technical Support for Alternate Plugging Criteria With Tube Expansion at Tube Support Plate Intersections for Braidwood-1 and Byron-1 Model D4 Steam Generators; February 1995. (Westinghouse Proprietary Class 2)

4

TEST METHODS

This section describes the test specification and control processes utilized, such as specification of data requirements, specification of the individual tests sequences, data acquisition and reduction methods, etc. The actual test operations, i.e., specimen preparation, fixturing and how the tests were executed, are discussed in Section 3.

4.1 Test Plans

A sample-specific test plan was developed for each specimen tested, to account for the differences in testing sequence required due to the differing crack characteristics. For example, the pressurization sequence and goal pressure is dependent on the specific size of the crack and whether the specimen included more than one crack. In addition to assigning the specimen serial number for tracking through the test program, it provided a physical description of the sample in terms of tube OD, and crack size as well as the test facility to be used in completion of the test. (Note that initially two leak test facilities were used to test the samples).

The test plan for each sample also defined the test parameters of the sample in terms of temperature and pressure as well as flaw offset with respect to the simulated TSP. Additionally, and most importantly, the test plan defined the sequence of test steps to be followed. The key elements of the test plans were the target pressures for leak testing, offset and zero-offset setup sequence, and bladder pressurization levels for each specimen. The leak test pressurization sequence was critical to assure that hysteresis of the crack opening due to prior over-pressurization was avoided. The crack opening is determined by the highest Dp applied to the crack; thus leak testing at a subsequent lower Dp would result in an artificially high measured leak rate. Figure 4-1 is a sample test plan. Copies of the test plans for each of the samples tested are contained in Appendix A.

The leak test program was augmented by other test such as a loop calibration test utilizing calibrated orifices, and a test to estimate the elastic crack opening of the specimens. The test plans for these tests are also included in Appendix A.

4.2 Data Requirements

Since the objective of the test program was to determine leak rates at elevated temperatures and pressures for cracks of varying sizes (lengths) for different conditions of axial alignment with a simulated tube support plate, the required data from these tests were as follows:

- Crack properties (pre-test, in-process and post test)
  - Crack length
  - Crack throughwall length
  - Crack opening width
  - Crack opening profile (tube diameter vs. length)
- Tube Properties
  - Diameter
  - Location of crack relative to the TSP
- TSP Diameter
- Leak Rate Test Data
  - Primary side pressure
  - Primary side temperature
  - Secondary side pressure
  - Secondary side temperature
  - Accumulator volume

These data were recorded for each of the specimens tested. In addition, photographic records were made of many of the specimens, and these are included in the Appendices together with the other measurements made and data taken. Appendix B includes the leak rate data after initial data reduction of the raw data. Appendix C includes the pre-test crack measurement data and the tube diameter profile data. Appendix D includes the in-process crack crack growth (length and crack opening width) data. Appendix E includes the tube diameter profile data. Appendix F includes the photographic records of the cracks at various steps in the tests.

4.3 Crack Dimensional Measurement Methods

To accurately characterize the condition of the flaw both prior to and during the course of the testing, and to assure that the initial size of the flaw being tested was consistent with the test requirements, dimensional measurements were performed on the virgin sample and at various stages as the testing progressed.

The critical measurement for these tests was the length of the total crack and the length of the throughwall portion of the crack. Crack specimens were required that were in the range of 0.25 in. to 0.75 inch throughwall length. The upper length limit is the limiting crack length that is defined by the thickness of the TSP. With the exception of a single specimen that was machined, all crack were corrosion cracks or corrosion cracks propagated in length through cyclic fatigue. Hence, the specimens utilized generally had initially tight cracks. Most of the corrosion cracks were OD originating cracks, thus the throughwall length was defined by the crack length at the ID of the tube.

Pre-test crack length measurements were made utilizing a combination of dye penetrant testing and silastic mold sample replication. Both the inside diameter and outside diameter of the tube were measured. Because the indications of the tubes were very tight in most cases, liquid penetrant testing was consider the most effective measuring tool. For the outside diameter surface of the tube which was readily accessible, standard liquid penetrant test techniques were used. The sample was cleaned, sprayed with the LP solution, wiped down and then sprayed with the developer. The surface bleed out was considered an accurate representation of the crack opening. This dimension was measured and recorded.

In the case of the inside diameter where access was restricted, the same LP technique was used. However in place of the developer, a silastic molding compound was poured into the tube ID after the application of the penetrant and initial wipe. In this technique, as the silastic compound solidifies, it absorbs the residual LP fluid retained in the crack. The result is an imprint or reproduction of the crack on the mold surface from which crack dimensions and orientation can be obtained. Figure 4-2 shows a typical silastic mold print for determining pre-test crack length. All of the available results of the silastic and LP flaw measurements are contained for reference in Appendix C.

A second measurement of pre-test crack length was made visually using a toolmaker's microscope once the sample was committed to test. This method was a convenient and consistent measurement method that was repeated at each step of a test sequence. However, for tight cracks, this technique may not reliably identify the tips of the crack; thus, the actual crack tested may be longer than the indicated measurement. The crack length measurements were recorded on a data sheet for each specimen for each step of the tests sequence. Figure 4-3 shows a typical crack length data sheet. All of the data sheets are included in Appendix C.

Based on the visual measurements using the toolmaker's microscope, initial markings were placed on the tube OD to indicate the location of the crack tip which was used to locate the sample in the support plate during the test runs. Dimensioned sketches were prepared from these microscopic examinations to show key features of the crack topography as well as the dimensional conditions of the flaw as testing progressed. Figure 4-4 shows a typical example of the pre-test marking of the specimen for positioning purposes. Copies of these sketches for all of the specimens are contained in Appendix D.

The length of throughwall cracks was measured by the visual technique utilizing the toolmaker's microscope, in conjunction with a light source inserted into the ID of the specimens to provide back-lighting. Visible light indicated a through-wall condition; however, testing showed that a 1 mil opening was required to see the light because of the tortuosity of the crack. In addition, if the crack is oblique through the wall thickness of the tube, the light source may not be visible even if the specimen is rotated during measurement to enable visualization of the light source. Throughwall lengths less than 1 mil wide, such as might occur near the crack tips, or throughwall potions at an angle less than would allow light to pass from the tube centerline to a radial line of sight may not be visible with this technique. Consequently, this measurement technique, also, is conservative, since the actual crack, and its throughwall portion, may be longer than the indicated measurement. Figure 4-5 shows an in-process photograph of a crack viewed in both a front lighted and a back lighted condition. The scribe mark for specimen positioning purposes is visible on the front lighted photograph.

All available in-process photographs of the specimens are included in Appendix F. Some of the pictures include a reference scale. The graduations on this scale are 1.5 mm per graduation. In some instances, for clarity of description of the sample as the testing progressed, low power magnification photographs of the samples were prepared. These can provide a more graphic representation of the condition of the sample as it progresses through the different test sequences.

To measure the length of the total crack and the width of the visible throughwall length of the crack, a diagram was made based on the microscopic inspection after each step of a test sequence relating the length and width of the crack to the original scribe marks placed on the specimens. The total length was measured and width measurements were made at axial increments of 0.01 inch. These measurements were the basis of crack growth and crack area calculation made to characterize the leak rate trends in Section 6. Figure 4-6 shows a typical crack dimension sketch. All of the in-process crack length and width data are included in Appendix D.

Tube diameter measurements were made at each step of the test sequence to define the limiting flow area (crack area, geometric area, effective crack area) for the test specimens. These measurements were made using standard micrometers and calipers. Figure 4-7 shows a typical data sheet for the tube diameter measurements. Because many of the specimens were prepared by stressing the tube in a clamp which ovalized the tube, it was common that more than one crack occurred around the circumference of the tube. For that reason, and to define the tube diametral growth both in the plane of the crack and out of the plane of the crack, four measurements separated by 45° were made at each axial position of the tube. The spacing of the measurements was included on the data record. The results of these measurements for all the specimens are included in Appendix E.

Several specimens included a second crack that was welded to provide single crack specimens. Because crack interaction with the TSP is closely tied to the available gap between the tube and the TSP, careful tube diameter measurements were made to assure that the test specimen was within the dimensional envelope of the unwelded tube. Generally, welding tends to locally reduce the diameter , and this would be conservative relative to the measured leak rates. The welded specimens are identified in Section 3, 5 and 6, and the dimensional characterizations are include in the appropriate data appendices.

4.4 Destructive Examination

At the conclusion of sample testing, selected specimens were destructively examined. The primary objective of the destructive examination was to find the true crack length and the location of the reference scribe mark relative to the true crack tip following the last series of tests. It was also the objective to determine the amount of crack tearing during test. This was made possible by method of preparing the crack specimens. Tee initial crack was a corrosion crack. The corrosion crack was extended by fatigue loading of the specimen, which can be differentiated form corrosion on the basis of the grain structure. The specimens were exposed to an oxidizing environment prior to leak testing; thus the fatigue surface could be differentiated from crack tearing based on the oxidation state of the crack surface.

Table 4.1 summarizes the specimens that were destructively examined, and summarizes the results from this examination. The complete data from the destructive examination of the specimens noted on Table 4.1 are included as Appendix G. Table 4.1 provides beginning and end of test total crack lengths for both ID and OD cracks. Form this, the total crack growth during the tests can be determined. Also, the crack extension for the two ends of the crack, identified as "bottom" and "top", are provided. These data, in conjunction with the in-process crack measurement data records can be used to determine the offset crack growth from beginning to end of the test.

Comparison of the post test destructive examination data for crack lengths with the in-process visual/microscopic examination data shows that the in-process measurements are slightly conservative. Generally, the destructive examination data show that the end-of test total cracks and throughwall cracks are slightly longer than the in-process measurements indicate.

4.5 Leak Rate Measurements

The objective of this tests was to determine the leak rate of the crack specimens under conditions prototypic of a postulated steam line break (SLB) in an operating steam generator. These conditions are defined as primary temperature, T_p =615°F and secondary pressure, P_a = 15 psia. The normal SLB pressure differential is 2560 psid; therefore, increasing pressure differentials up to, and greater than, this pressure differential were to be tested to provide the leak rate trend in Δp. The true pressure differential in a specific test is determined by the primary water temperature, since, if the secondary side pressure (or local pressure) is less than the saturation pressure at the primary fluid temperature, the leaking water "flashes" to steam, and the vapor flow becomes choked. Since the tests facility was controlled by the changing the primary side conditions, and the secondary side pressure was a function of the condenser flow resistance and the total leak rate, it was anticipated that an adjustment would be required to normalize the test measurements to the standard SLB conditions. Consequently, the necessary data were the primary temperature and pressure, the secondary side pressure (temperature desirable) and the accumulated leakage over the duration of each test. The primary pressure and temperature were measured within the test specimen; the secondary pressure was measured adjacent to the specimen within the test autoclave, and the secondary temperature was measured at the support plate near the crack. A bulk fluid temperature measurement was also provided by a second thermocouple located within the autoclave fluid free stream.

The leak rate was determined during the test by recording the accumulated water level in one, or both, of the condensers. Since the condenser loop has a finite volume, and was initially filled with cold water, leak rate (accumulator volume) measurements were not made until the condenser volume (approximately 8 liters) had been displaced. This delay in leak rate measurement was, of course, unnecessary for cold testing. The actual leak rate was determined by taking the time derivative of the condenser volume over a significant period of time to average out local wave action on the level sensor in the condenser. The initiation of steady state measurements required about ten to forty seconds after the start of the test

4.6 Leak Rate Data Reduction Methods

The recorded test data were digitized on line and exported to and EXCEL spreadsheet for initial data reduction. On the order of 100 to 200 data points were collected for each steady state run for pressure and temperature ,and about ten time this number of points was recorded for the accumulated leakage rate to smooth out the collection tank level oscillations experienced during the initial run. A 9 point incremental slope calculation was used for the instantaneous leak rate calculations rather than point to point averages to damp out the noise that would result from the differentiation of the accumulator volume..

A typical data sheet for a test is shown in Figure 4-8. Each step of each test sequence was recorded on a data sheet like this; all of the data sheets are included in Appendix B. THe data sheet provides a tabular time history of the following: Accumulator volume, primary and secondary pressure, Δp, leak rate, and primary and secondary temperature. The data record also provides a graphical presentation of the data, and key information about the test sequence. These data were they basis for the leak rate analysis of Section 5.

4.7 Calibrated Orifice Loop Calibration Tests

In order to verify the high energy loop leak rate measurements, leak tests were performed according to the normal procedures using several independently calibrated orifices. Although only low temperature calibrations were available, since no other high energy testing facility could be found, both low temperature and high temperature calibration tests were performed. The test plans for the calibration tests are included in Appendix A.

The orifice sizes chosen were based on the range of leak rates measured for the crack specimens. Independent calibrations were performed for a range of pressure differentials from 1400 psid to 2560 psid. The calibration records are included in Appendix H.

Very good agreement was achieved between the high energy loop measurements and the independent calibrations. Analysis of the results for both the low temperature and high temperature calibration tests is included in Section 5.6.

4.8 Crack Flank Elastic Springback Tests

Analysis of the crack growth in conjunction with the measured leak rates indicated that the measured plastic deformation did not fully explain apparent TSP interaction indicated by the flow data. As a result, a benchtop test to determine the elastic crack flank deflection under pressure was performed. The test plan for this test is included in Appendix A.

Two specimens were fitted with an internal bladder and were instrumented with clip gages at two locations as shown in Figure 4-9. The bladder was incrementally pressurized to a pressure less than the highest prior pressurization, and the clip gage deflection was recorded. The data from the elastic springback tests are included in Appendix E.

5

EVALUATION OF TEST RESULTS

5.1 Introduction

In this section, leak rate data for all tests conducted in this program are presented and their results are discussed in detail. Since the main objective of these tests is to obtain leak rate data at the steam line break conditions, each test should provide leak rates at conditions corresponding to a primary temperature of 615°F and 15 psia secondary pressure. Because of the difficulties in precisely controlling the pressure and temperature of the water supply system, the primary temperature varied between tests. Therefore, the test data had to be adjusted to the conditions appropriate for a steam line break event. A detailed discussion of the data adjustment procedure is also presented in this section.

5.2 Data Analysis Methods

Since the secondary pressure drops significantly during a postulated steam line break event, the primary coolant leaking through a crack would "flash", resulting in a two-phase mixture. In such a two-phase mixture, the pressure gradient beyond the flashing location tends to accelerate the vapor phase more than the liquid phase, and the vapor flow becomes choked. Thus, the effective pressure difference driving the leak flow in a steam line break event is the pressure drop from the primary side to the flashing location. Liquid flashing occurs near a location where the local pressure falls below the saturation pressure at the initial liquid temperature. Therefore, the primary system temperature determines the pressure at which flashing occurs and, consequently, also the leak rate.

At temperatures typical of the primary system, the saturation pressure varies rapidly with temperature. Therefore, leak rate under SLB conditions can be expected to be sensitive to the primary system temperature. The primary system temperature also affects leak rate through changes in the fluid density. Due to the difficulties in tightly controlling the pressure and temperature of the leak test water supply system, water temperature varied among the different tests. Also, the secondary pressure in the tests was different from the desired 15 psia due to the backpressure characteristics of the condenser system. Therefore, the measured leak rates had to be adjusted to standard conditions, appropriate for a steam line break event. Adjustment for flashing is typically the largest adjustment required to the test data.

The EPRI leak rate adjustment procedure, given in EPRI report NP-6480-L, Volume 1, Revision 1, Appendix B was applied to adjust the as-measured data to SLB conditions. This procedure is briefly described in Section 5.3. In addition to this adjustment to SLB conditions, other adjustments were also performed to make the data more consistent, and they are discussed below.

5.2.1 Hysteresis Effect

The leak tests sequence was to tests at increasing Δp's, with replication of points in a narrow target Δp range to obtain a number of points over a wide range of Δp's for each individual test. In some tests, the actual pressure differential achieved was less than that of the preceding test, which introduces a hysteresis effect. The hysteresis effect is that the plastic opening of the crack at a higher pressure differential in the previous test sets the crack geometry, and thereby increases the leak rate for the subsequent, lower pressure tests. For this evaluation, data points more than about 40 psid below a prior test for the flow pressurization tests are excluded from the data plots and tables on the basis of hysteresis. The selection of 40 psid as an acceptable difference for subsequent test is a judgment that this change in Δp, and the resulting small increase in leak rate, would not significantly influence the interpretation of the data and the resulting conclusions, and would not reduce the available data base excessively. All test data points deleted for hysteresis effects are identified in the data tables provided for each test.

Data points following bladder pressurization are not deleted for hysteresis effects since this step is specifically applied to maximize the crack opening. The cracks are plastically expanded, utilizing an internal bladder, at pressures which substantially exceed the applied leak rate test pressure differentials, so variation in flow pressure among tests would not further affect the plastic crack opening.

5.2.2 Averaging of Data Points

Data points in the same test condition (zero-offset, offset, etc.) that are within about 40 psi of each other are generally averaged prior to plotting and evaluation. This process reduces non-physical fluctuations in the test data and tends to simplify interpretation of plotted data. All test data averaged are identified in the data tables provided for each test.

5.2.3 Leak Rates at Average and Maximum Δp

Due to the testing procedure utilized (see Section 3), the primary to secondary differential (Δp) immediately after the start of the test was often significantly higher than the average Δp for the test. (See Appendix B for the test time histories.) The data reported for leak rate evaluation are time differentials of an condenser/accumulator fluid level (See Section 4) over a time period during which Δp was relatively constant. Both average and peak Δp are reported for most tests. Since the average Δp is lower than the maximum Δp, the average leak rate data reported for the flow pressurized tests are conservative since the plastic crack opening is determined by the maximum pressure differential existing at test initiation. Therefore, a leak rate corresponding to the maximum Δp condition was also calculated for all tests where the maximum Δp data were also recorded. This hysteresis effect would not be present in the tests conducted following bladder pressurization. Nevertheless, flow rates corresponding to the maximum Δp condition were also calculated for the bladder pressurized tests for uniformity.

A more consistent interpretation of the test results was obtained using the leak rate data based on the maximum Δp since it more accurately reflected the start and end points of test sequences such as zero-offset and offset test sequences. This is particularly significant for evaluation of Test 12-7 since the differences between the maximum and the average pressures were larger than typically found.

5.3 EPRI Leak Rate Adjustment Procedure

5.3.1 Description

This section briefly describes the procedure used to adjust as-measured data to SLB conditions. The methodology used here is described in detail in the EPRI report NP-6480-L, Volume I.

Leak rate through a crack can be calculated with the following equation:

$$L(\Delta p,T) = K\,A(\Delta p,T)\sqrt{\frac{2\,\Delta p}{\rho(T)}} \tag{1}$$

For a leak rate measured at the room temperature we have,

$$L(\Delta p,T)_{T_a} = K\,A(\Delta p,T)\sqrt{\frac{2\,\Delta p}{\rho(T)}}\left(\frac{\rho}{\rho_a}\right)$$

$$= K'\,A(\Delta p,T)\sqrt{2\,\Delta p\,\rho(T)} \qquad (2)$$

where,

L = volumetric leak rate at local temperature,

L_{Ta} = volumetric leak rate measured at room temperature,

K = discharge coefficient,

A = leakage flow area, a function of Δp and T,

Δp = primary to secondary pressure differential,

T = primary water temperature,

ρ = primary water density, a function of T,

ρ_a = water density at room temperature,

and K' = K / ρ_a.

The pressure differential Δp is defined as follows.

$\Delta p = (p_1 - p_2)$, if there is no flashing;

and $\Delta p = (p_1 - p_{1f}) = (p_1 - c_p\,p_s)$, with flashing occurring at p_{1f}. (3)

Here p_1 represents the primary pressure, p_2 the secondary pressure, p_{1f} the pressure at which flashing occurs within the crack and c_p is a parameter which relates flashing pressure to saturation pressure p_s. The c_p parameter is discussed further below.

The volumetric leak rate measured at room temperature during the tests, $L(\Delta p,T)_{m},T_{a}$, can be related to leak rate under the SLB conditions (615° F primary temperature, 15 psia secondary pressure), $L(\Delta p,T)_{p},T_{a}$, as follows.

$$L(\Delta p,T)_{p,T_a} = \alpha\ \beta\ \gamma\ L(\Delta p,T)_{m,T_a} \qquad (4)$$

The above equation includes three factors - the mechanical factor (α) which adjusts for crack opening between two different Δp's, the temperature factor (β) which adjusts for variation of water density and tube material properties with temperature, and the hydraulic factor (γ) for the effective pressure differential which is a flashing adjustment. Development of these adjustment factors is described in detail in the EPRI report cited above, so they are only briefly described below.

The mechanical factor α is not applied in this assessment and is not further discussed herein.

The temperature factor β is given by

$$\beta = \frac{E_m \sigma_{fm}}{E \sigma_f}\sqrt{\frac{\rho}{\rho_m}} \qquad (5)$$

where E is Young's Modulus and σ_f is flow stress, and subscript 'm' applies to test measurement and no subscript refers to prototypic SLB conditions.

Equation 5 is developed for tests without pre-pressurization, i.e., for flow pressurized tests. For bladder pressurized tests conducted near prototypic SLB temperatures, temperature effects on crack opening are expected to be limited as the crack has already undergone large plastic yielding and further deformation during the leak tests is limited. However, this correction could be significant for bladder pressurized tests conducted at room temperature as the correction is applied over a large temperature range. Therefore, one-half of the contribution from the ($E\ \sigma_f$) term to the correction, predicted by Equation 5 was used for the bladder pressurized tests. This correction was applied to both hot and cold tests for uniformity, although the magnitude of correction is very small for the hot tests.

The hydraulic factor γ is given by:

$$\gamma = \sqrt{\frac{(p_l - C_p p_s)/\Delta p}{(p_{ml} - C_{pm} p_{sm})/\Delta p_m)}} \tag{6}$$

where p is the primary pressure, p_s is the saturation pressure at the primary temperature, Δp is the total primary to secondary pressure differential, and c_p is a pressure coefficient to adjust for a non-equilibrium flow process. The subscript 'm' represents the leak test condition and variables in the numerator represent the prototypic SLB conditions.

The use of c_p is important for tests in which the primary pressure is close to the saturation pressure at the primary temperature. In this case, the adjustment without c_p (i.e. assuming a value of 1 for c_p) can become unrealistically large. The need for this term occurs primarily for pressures less than about 2200 psi and temperatures above about 620°F, i.e., when the degree of subcooling becomes small. Physically, this term accounts for the fact that during rapid expansion of a high temperature liquid, the evaporation process is delayed beyond the location of saturation pressure since a finite time is needed for the heat transfer process.

Sensitivity analyses were performed for a range of c_p from 0.75 to 0.85 resulting in no significant differences in the adjusted leak rates. Therefore, a value of 0.80 was selected for the analyses of all tests presented in this report. This value for c_p is consistent with a sensitivity analysis presented in the EPRI report NP-7480-L which indicated a range of 0.72 to 0.88 for c_p to improve agreement on ratios of leak rates obtained with the present adjustment procedure and the CRACKFLO code results.

5.3.2 Evaluation of the EPRI Leak Rate Adjustment Procedure for Cold to Hot Adjustments

Since leak flow in the room temperature tests is not limited by the "flashing" phenomenon, measured leak rates are much higher than those observed at comparable Δp's in the hot tests. Therefore, the magnitude of the leak rate adjustment factor for the cold tests is expected to be higher than those for the hot tests. The adjustment factor used for the cold tests is based on the same principles as the factor applied for the hot tests, which is described in Section 5.3, but there is a small difference in the method of calculation. The difference in the adjustment procedure for the hot and cold tests is described in this section.

The difference in the two procedures lies in the adjustment for possible variation in the crack opening due to material properties (Young's Modulus and flow stress) variation with temperature, through the β factor. Initially, this correction was not applied to leak tests following bladder pressurization based on the rationale that flow pressurization during leak testing does not further increase the crack opening area that is already plastically expanded at a higher pressure during bladder pressurization. (For such cases β is just the square root of the density ratio.) Without adjustment for material property variation, cold test data adjusted to SLB conditions were consistently below those of comparable hot tests. However, there is good agreement between flow pressurized hot and cold tests which include correction for material properties. This suggests that correction for material properties may be necessary for the bladder pressurized tests also. Supplemental tests conducted in the later part of the program specifically to examine elastic deformation during leak testing following bladder pressurization showed that the tube diameter in the crack plane could increase by as much as 5 mils. This confirms the need for accounting for material property variation with temperature in adjusting the bladder pressurized test data.

The method of calculating the β factor for the bladder pressurized tests was revised to include one-half of the correction predicted by Equation 5 in Section 5.3.1 for variation in the material properties (Young's Modulus and flow stress) with temperature. Both hot and cold bladder pressurized test data were adjusted using this revised definition for the b factor. While this revision to calculating the β factor had only a minimal effect on the adjusted results for the hot tests, the impact on the cold test results was relatively more significant because of the large difference in temperature between the test and the SLB conditions. The revised β factor provides a more consistent agreement between the adjusted data from the hot and cold tests.

5.4 Influence of TSP on Leak Rate

The presence of the TSP is expected to reduce the leak rate from a crack. The magnitude of the change in the leak rate, compared to the freespan leak rate for the same crack, is expected to vary depending on the crack dimensions, in particular the crack length and tube-to-TSP gap size. For a relatively small length crack, the increase in the crack opening width and tube diameter due to crack opening is small. The tube-to-TSP gap thickness relative to crack width in such cases could be sufficiently large so that the TSP presence has little effect on the leak rate compared to the freespan leak rate. On the other hand, beyond a certain crack length and/or pressure differential, the crack edge may expand and press against the ID of the TSP, thus reducing the effective flow area available for leakage. This type of tube-TSP interaction could substantially reduce the leak rate. A more detailed discussion of the influence of TSP on leak rate is presented below to facilitate understanding of the test data presented in this section and in Section 6.

Leak flow through an indication under SLB conditions, and in the present tests, can be classified into three regimes:

Regime 1: For relatively short cracks, the tube diameter increase due to crack opening from flow pressurization is small in comparison to the tube-to-TSP gap. (The target gap size for these tests was 0.025 inch; see section 3 for discussion of the gap size). At the SLB conditions, the leak flow is expected to be choked. The choking plane would be located at the minimum leakage area, which in this case, occurs within the crack flanks. In this situation, hydraulic losses due to leak flow interaction with the TSP, which lies further downstream, has no impact on the leak rate. Thus, in such cases leak rate would not be dependent on the TSP displacement, and leak rate vs Δp curves for the zero-offset and offset conditions would be expected to show a continuous trend (without any discontinuity).

Regime 2: As the crack initial length and/or pressure differential increases, the extent of tube diameter increase due to crack opening increases and, consequently, the tube-to-TSP gap decreases. Beyond a certain crack size and/or pressure differential, the area of the gap between the crack edge and the TSP hole surface (geometric area, see Figure 6-1) can become smaller than the crack throughwall flow area. The location of choke plane would then move to the crack edge. In such cases, the geometric area controls the leak rate. The geometric area varies less rapidly with Δp in comparison to the crack opening area, which implies that the leak rate vs Δp curve would flatten under these conditions. The leak flow interacts with the TSP before reaching the choking plane, so additional losses from such an interaction reduces critical mass flux at the choking plane. This condition yields the second leak flow regime. It may occur in both flow pressurized as well as bladder pressurized tests. In offset tests under this condition, flow through the crack area located outside the TSP edge would not be subjected to the geometric area limitation or encounter hydraulic losses due to interaction with the TSP. Therefore, significant TSP displacement could increase leak rate in this leak flow regime if the location of the crack interaction with the TSP were also exposed outside the TSP.

Regime 3: In specimens with a relatively long crack, there is potential for the crack edge to expand and press against the TSP hole surface, especially in tests following bladder pressurization. In such cases, a part of the crack opening may be sealed-off and the effective crack opening area reduced below the geometric area. The minimum flow area once again may occur within the crack opening. In this regime, interaction between the leak flow and the TSP occurs downstream of the choking plane, as in regime 1 and, therefore, hydraulic losses occurring there are not expected to impact the leak rate. Again, as in regime 1, TSP displacement is not expected to impact the leak rate, unless the displacement is very large. Section 6 discusses the limiting TSP offsets.

In summary, short cracks (< 0.4 inch) are expected to be in Regime 1 because their crack opening behavior is small compared to the tube/TSP gap. Leak rates are expected to approximate the freespan leak rate, and are expected to be small. Longer cracks (> 0.4 inch) are expected to be in regime 2, because their crack opening behavior is expected to cause reduction in the available flow area due to interaction with the TSP. Leak rates in regime 2 are expected to be limited to less than the expected freespan leakage at higher pressure differentials due to the interaction with the TSP. Very long cracks (>0.6 inch), or moderately long cracks subjected to high pressure differentials, are expected to be in regime 3, due to the expected extensive interaction of the crack flanks with the TSP. Leak rates I n regime 3 are expected to be significantly less than the freespan leakage due to reduction in available flow area resulting from the interaction with the TSP.

Based on the crack dimensions measured during the tests, crack opening area, geometric area and effective crack area have been calculated. Details of the calculations and the results are presented in Section 6. Using this area data, the regime to which the various tests fall is identified and discussed in the following sections.

5.5 Evaluation of Individual Tests

In the following sections, initial conditions and leak rate data for the individual tests are discussed in detail. The tests are arranged in the order of increasing throughwall (TW) length of the crack in the specimen tested. Since the crack opening, and therefore the leak rate, varies directly with the crack TW length, the tests also appear in the order of increasing leak rates. Two tests which do not contribute directly to the bounding leak rate for the high voltage ARC are presented last.

5.5.1 Test 2-4 Evaluation

5.5.1.1 Test Sequence and Data Analysis

This test sequence utilized a 7/8" dia specimen with two cracks 180° apart. The initial length of the dominant crack was about 0.29" (TW), 0.60" (OD). Some tests in this sequence were carried out in the Small Leak Test Facility and the rest in the Large Leak Test facility. Although this indication would not burst at the SLB conditions, bladder pressurization tests were performed at pressures of 4125 psi and 5550 psi to bound the leak rate, the higher pressure being the estimated free span burst pressure for this specimen. The tests were conducted in the following order: Small Leak Test Facility - zero-offset, free span, offset, offset cold; and in Large Leak Test Facility - bladder pressurization to 4125 psi, cold offset, cold zero-offset, bladder pressurization to free span burst pressure of 5550 psi, cold offset, cold zero-offset, hot offset. The crack diameter increased by 0.021" after bladder pressurization to 5550 psi, which is reasonably close to the 0.025" target gap size. Thus the test results are considered acceptable.

Data for this test sequence are plotted in Figures 5-1 and 5-2. They are also summarized in Table 5-1. Maximum Δp data is available for only one test in this sequence, so data adjustment to SLB conditions was carried out only on the basis of average Δp. Figure 5-1 shows the data adjusted to steam line break conditions, and Figure 5-2 shows the as-measured data. No data points were deleted because of hysteresis effects. The leak rates show consistent trends with modest fluctuations in the data and the test data are acceptable. Even though testing was divided between two leak test facilities, consistency of the data shows that both facilities measure comparable leak rates for the same initial conditions. Crack dimensions measured during the course of various tests are summarized in Appendices D and E.

5.5.1.2 Summary of Test Results

It is evident from Figures 5-1 and 5-2 that all flow pressurized tests in this sequence show a leak rate dependency on Δp that is typical of a free span test. This implies that there was no noticeable interaction between the crack and the TSP. The maximum tube diameter measured during flow pressurized tests (0.878") also indicates a low likelihood of tube-to-TSP contact. Thus, the leak rates measured for the flow pressurized test results are typical of leakage flow regime 1 discussed in Section 5.4.

Flow pressurized tests extended the crack length to 0.33" (TW) and opened a second crack with 0.12" TW length. The high slope of the leak rate versus Δp curve up to about 2200 psid indicates ligament tearing and consequential increase in flow area. A smaller slope for the room temperature tests up to 2716 psid may be due to a hysteresis effect on the 2534 psid measurement since this test Δp is 37 psi lower than that for the prior test.

Bladder pressurization to 4125 psi Δp did not result in crack faces contacting the TSP hole as the maximum tube diameter increased by only 0.003". Leak rates for the offset tests following bladder pressurization show only a modest increase (for e.g., 0.76 gpm at 2535 psi Δp vs. 0.53 gpm for the comparable room temperature test prior to bladder pressurization). The data also show only a weak dependence on Δp which is to be expected since the crack opening area in the leak tests following bladder pressurization does not change significantly as the crack has already been plastically expanded at a much higher pressure. Thus, the leak rate variation in these tests is primarily due to increase in the critical mass flux with Δp, which varies only as square root of Δp.

It appears that the leak rate is only weakly dependent on the extent of bladder pressurization until a pressure close to the tube free span burst pressure. Leak rates after bladder pressurization to 5550 psi, which is approximately the estimated specimen freespan burst pressure, are significantly higher (about factor of 2) than obtained with 4125 psi bladder pressurization. However, further increases in bladder pressurization above the specimen burst pressure do not result in increased leakage. This is evident from the Test 4-1 results presented in Section 5.5.14.

Bladder pressurization to 5550 psi opened the longest throughwall crack to 0.382" (segment with greater than 1 mil width) with an average TW width of 0.010", and the second throughwall crack to 0.284" with an average TW width of 0.004". For the 0.15" offset tests, a TW length of 0.076" with an average width of 0.010" was exposed outside the TSP. The leak rate at SLB conditions for this offset test is about 2 gpm, which is about 45% higher than that for the zero-offset test with crack tip at the edge of TSP (1.4 gpm). Based on the discussion presented in Section 5.4, higher leak rates for the offset test may imply that the leakage is limited by the geometric area (leak flow regime 2), or that additional loss factors are present. The larger than expected increase in offset vs. zero-offset leak rate is likely influenced by the presence of a second TW crack in this specimen 180° apart from the main crack which share closure of the crack-to-TSP gap.

5.5.1.3 Overall Conclusions

1. Initial crack lengths of about 0.29" (TW), 0.60" (OD, average length = 0.445") do not result in interaction with the TSP hole at SLB conditions.

2. Bladder pressurization to 4125 psi resulted in leak rates approximately the same as the free span leak rates when the indication was inside the TSP, and a slightly higher leak rate (about 0.76 gpm vs 0.53 gpm for zero-offset test) with the crack 0.15" offset outside the TSP.

3. Bladder pressurization to the free span burst pressure of 5550 psi resulted in leak rate for SLB conditions of about 1.4 gpm with the crack inside the TSP, and about 2 gpm with the crack offset 0.15" outside the TSP.

5.5.2 Test 2-10 Evaluation

5.5.2.1 Test Sequence and Data Analysis

As in Test 2-4, some tests in this sequence were carried out in the Small Leak Test Facility and the rest in Large Leak Test facility. The specimen used (3/4" dia) had a single crack with length dimensions 0.425" (TW), 0.551" (OD). In addition to flow pressurized tests, bladder pressurized tests were performed to bound the leak rate at pressures of 3850 psi and 4960 psi, the latter being approximately the estimated free span burst pressure for this specimen. The tests were conducted in the following order: Small Leak Test Facility - zero-offset, free span, offset, offset cold; Large Leak Test Facility - bladder pressurization to 3850 psi, cold offset, cold zero-offset, bladder pressurization of about 4960 psi, cold offset, cold zero-offset, hot offset.

After bladder pressurization to the free span burst pressure of 4960 psi, the crack diameter increased by 0.010" which implies that the tube-to-TSP gap size was less than the 0.025" target. Nevertheless, the test results are considered acceptable since tests prior to bladder pressurization are more relevant to the objective for this test, and this test does not establish the bounding leak rate.

The leak rate results for this test sequence are plotted in Figures 5-3 and 5-4. They are also summarized on Table 5-2. Maximum Δp data are not available for the first four tests in this sequence, and therefore data adjustment to SLB conditions was carried out on the basis of average Δp only. Figure 5-3 shows the data adjusted to steam line break conditions and Figure 5-4 shows the as-measured data. As noted in Table 5-3, the lowest pressure data point in the cold, flow pressurized offset test (Test 2-10d) was excluded due to apparent hysteresis effects since the average Δp is about 300 psi lower than the prior hot offset test. Leak rates show consistent trends with modest fluctuations in the data, and the test data are acceptable. The consistency of the data, even though testing was divided between two leak test facilities, shows that both test facilities measured comparable leak rates under similar initial conditions.

5.5.2.2 Summary of Test Results

As evident from Figures 5-3 and 5-4, the slope of the leak rate versus Δp curves for the zero-offset, free span and offset tests with flow pressurization are high and show a continuous trend. A similar trend was noted in Test 2-4 also. The leak rate trend among these tests demonstrates that there was no significant interaction between the leak flow and the TSP for pressures up to the maximum Δp of 2300 psi. Thus, the leakage for the flow pressurized tests fall into flow regime 1 discussed in Section 5.4. The high slope of the leak rate vs Δp curves indicate that the crack opening area and, hence, the leak rate increased significantly with Δp. The maximum leak rate measured in the flow-pressurized tests was at the limit of the Small Leak Test Facility.

The highest leak rate measured for the hot flow pressurized tests was about 0.65 gpm at 2240 psi which extrapolates to about 1.3 gpm at 2560 psi. The plastic crack width following the flow pressurization tests was not measurable by light penetration, which indicates that the crack width was less than 1 mil.

Bladder pressurization to 3850 psi at 0.10" offset resulted in leak rates at SLB conditions of about 1.1 gpm in the offset condition which is below the corresponding leak rate (2 gpm) predicted by the zero-offset data. The leak rate shows weak dependence on Δp, which is to be expected since the crack opening area in the leak tests following bladder pressurization does not change significantly. The leak rate variation seen in these tests is primarily due to increase in the critical mass flux with Δp, which varies only as square root of Δp. The crack opening width following this bladder pressurization step was also not measurable by light penetration.

Following bladder pressurization at 0.10" offset to the free span burst pressure of 4960 psi, the SLB leak rate at the zero-offset condition was about 1.4 gpm with no significant difference from the 0.10" offset condition. The plastic crack width following bladder pressurization was 0.011". A 0.081" TW crack of maximum width 0.006" was exposed outside the TSP for the offset test.

The leak rates after bladder pressurization are significantly higher than in the flow pressurized tests at comparable Δp 's. This increase in leak rate is caused by a significant increase in crack area during bladder pressurization, which is typical for indications that do not show interaction with the TSP under flow pressurized conditions.

5.5.2.3 Overall Conclusions

1. The initial TW crack length of 0.425" (0.551" OD) does not result in interaction with the TSP hole at SLB conditions. The leak rates for the indication inside the TSP (zero-offset) behave as free span indications with an SLB leak rate of about 1.7 gpm.
2. The SLB leak rate for the 0.10" offset condition following bladder pressurization to the free span burst pressure (4960 psi) is about 1.3 gpm, and essentially the same as that obtained for the zero-offset condition.
3. Bladder pressurization to the free span burst pressure resulted in SLB leak rates significantly higher than obtained by flow pressurization at pressures below SLB conditions, which is typical for shorter indications for which the crack faces do not interact with the TSP under flow pressurized conditions.

5.5.3 Test 2-1 Evaluation

5.5.3.1 Test Sequence and Data Analysis

This test sequence utilized a 7/8" diameter specimen with a single crack having initial length measurements of 0.515" (TW), 0.64" (OD). Both flow pressurization and bladder pressurization tests were performed to bound the leak rate. Bladder pressurization was carried out at 4500 psi, which is the estimated free span burst pressure for the specimen. All tests were performed in the Large-Scale Test facility. The tests were conducted in the following order: zero-offset, free span, offset, offset cold, bladder pressurization at 4500 psi with 0.15" offset, offset, zero-offset, offset cold.

Data for this test sequence are plotted in Figures 5-5 to 5-8. They are also summarized in Tables 5-3 and 5-4. The leak data were evaluated on the basis of maximum Δp as well as on the average Δp basis. Figures 5-5 and 5-6 respectively show the data adjusted to the steam line break conditions on the basis of maximum Δp and average Δp. Figures 5-7 and 5-8 show the corresponding data for the test conditions. As noted in Table 5-4, data evaluation based on the average Δp suggested deletion of two data points in the flow pressurization tests (one in Test 2-1A and the other in Test 2-1C) due to apparent hysteresis effects, since the average Δp is more than 40 psi below that of the prior test. However, examination of the data on the basis of maximum Δp does not show any hysteresis effects and, hence, no data is deleted in Table 5-3.

Leak test results show consistent trends with modest fluctuations in the data. The effective crack-to-TSP hole surface clearance for this test was 0.010" based on the crack diameter at the end of the flow pressurization offset test rather than the target 0.025" clearance. Still, data from this test sequence is useful in showing the leak rate trends with crack length.

5.5.3.2 Summary of Test Results

The shallow slope of the leak rate vs Δp curve above 2300 psi for the offset test with flow pressurization, Test 2-1C, suggests crack interaction with the TSP and consequential reduction in leak rate. Furthermore, the leak rate at 2300 psi for this test is about equal to the freespan leak rate at 2150 psi, which also demonstrates that the presence TSP reduced the leak rate significantly. Evaluation of the crack dimensional data obtained after the offset test is described in Section 6. The leak rate for this test was controlled by effective crack area, as in leak flow regime 3 discussed in Section 5.4. The crack- TSP interaction occurs soon after the beginning of the offset test (>1900 psid), since the measured tube diameter after the freespan test was only about 3 mils greater than the base tube diameter (Figure 6-2e). The offset test following the freespan test also resulted in a significant increase in the length of the crack. The apparently small crack-to-TSP gap of 0.010" for this test resulted in crack interaction with the TSP at a lower pressure than would have been obtained with the bounding 0.025" gap. Leak rate at the SLB pressure (2560 psi) for this offset condition is about 1.5 gpm.

Following bladder pressurization to the free span burst pressure of about 4500 psi, the SLB leak rate increased from about 1.5 gpm at the offset condition prior to bladder pressurization to about 3.3 gpm at zero-offset condition, and about 3.6 gpm at the offset condition. Even though the offset test exposed a 0.132" TW crack, there was no significant difference in leakage between the leak rates for the offset and zero-offset tests following bladder pressurization. The flow area data presented in Table 6.7 show that the effective crack area is slightly smaller than the geometric flow area following bladder pressurization and, as in regime 3 discussed in Section 5.4, no significant differences between leak rates in the offset and zero-offset condition would be expected. Bladder pressurization increased the effective crack opening area by only about 6% (see Table 6.8) compared to the flow offset test which is less than expected for the more significant increase in leak rate.

5.5.3.3 Overall Conclusions

1. The SLB leak rate for this 0.52" TW crack at the start of the test is limited to about 1.5 gpm prior to bladder pressurization and 3.3 gpm after bladder pressurization. This is the only test showing interaction with the TSP under flow pressurization conditions that resulted in an increased leak rate after bladder pressurization.
2. Interaction with the TSP is indicated between 2300 and 2500 psi. However, the crack to TSP gap was only 10 mils and interaction with the TSP for the bounding 0.025" gap would be expected to occur at a higher pressure differential.

5.5.4 Test 2-7 Evaluation

5.5.4.1 Test Sequence and Data Analysis

The initial length of the single crack in this 3/4" dia specimen was 0.577" TW. As in the other test sequences, both flow pressurization and bladder pressurization tests were performed to bound the leak rate. Bladder pressurization was carried out at 3700 psi, which is the estimated free span burst pressure. All tests were performed in the Large-Scale Test facility. The tests were conducted in the following order: cold zero-offset, cold free span, offset; after bladder pressurization to 3700 psi, zero-offset, offset, cold offset.

The leak rate results for this test sequence are plotted in Figures 5-9 to 5-12. They are also summarized in Tables 5.5 and 5.6. The data were evaluated on the basis of maximum Δp as well as on the average Δp basis are shown. Figures 5-9 and 5-10 show the data adjusted to the steam line break conditions on the basis of maximum Δp and average Δp, respectively. Figures 5-11 and 5-12 show the corresponding data for the test conditions. Crack dimensional data recorded during the course of the tests are provided in Appendices D and E.

As noted in Tables 5.5 and 5.6, one data point in flow offset Test 2-7C was deleted due to hysteresis, as the average Δp was 400 psi lower than the prior free span test at 2228 psi. An examination of the initial part of the curve for offset Test 2-7C in Figure 5-10 (data based on average Δp) also seems to suggest hysteresis effects from prior higher pressurization as the adjusted leak rate is above the prior free span test between about 2100 and 2200 psi Δp. However, examination of the same data on the basis of maximum Δp (see Figure 5-8) does not suggest any hysteresis effects. This is expected since the evaluation based on maximum Δp includes the effects of the earlier higher pressurization, and is the basis for considering the evaluation based on maximum Δp as the more realistic approach.

Leak test results generally show consistent trends with modest fluctuations in the data. The zero-offset flow measurement at 1970 psi has a significantly lower leak rate than the prior data point at 1878 psi with no interaction with the TSP at this pressure indicated by either the leak rate data or the tube diameter data in Appendices D and E. Therefore, this data point is assumed to be a bad data point.

The initial crack-to-TSP gap is estimated to be 0.022" based on the crack diameter increase at the end of the flow pressurized test, which is only slightly below the target clearance of 0.025". The test results can be expected to differ only slightly from that expected for the target clearance, such as a slight reduction in the pressure for interaction of the crack with the TSP.

5.5.4.2 Summary of Test Results

Leak rates below 2300 psi for the flow pressurization tests are typical of the free span leak rates. The shallow slope of the leak rate vs Δp curve above about 2300 psi for the offset flow pressurized as well as bladder pressurized tests suggests crack interaction with the TSP hole. Since leak rates measured in the flow offset test are approximately equal to leak rate for the free span test conducted just prior to that test, offsetting 0.088" (TW) of the crack outside the TSP had no significant increase in leak rate. This also suggests that the crack opening interacted with the TSP in this test, and leak rate was limited by the effective crack area, as in leak flow regime 3 described in Section 5.4. This is confirmed the analysis of crack dimensional data taken after the offset test, presented in Section 6, which shows that the effective crack opening area was the same as the geometric flow area for this test. Thus no increase in leakage with crack offset should be expected for this test.

Pressurization to 2900 psi in the flow-offset test resulted in a maximum crack width of 0.020" compared to 0.002" after the free span test. At the same time, the TW crack length measured by light penetration increased from 0.515" to 0.636" during the flow-offset test. This offset condition resulted in a maximum SLB leak rate of about 4.05 gpm among all tests both before and after bladder pressurization.

Bladder pressurization to the free span burst pressure of about 3700 psi did not significantly affect the leak rate from that obtained by prior flow pressurization. The leak rate for the zero-offset condition is essentially the same as for the offset test before and after bladder pressurization. The negligible difference (within measurement uncertainty) between the bladder pressurized zero-offset and offset leak rates is consistent with the leak rate limited by the effective flow area as shown by the leakage area data presented in Section 6.

5.5.4.3 Overall Conclusions

1. Results for this test sequence indicate that throughwall cracks of about 0.58" in 3/4" diameter tubing can be expected to interact with the TSP prior to reaching SLB pressure differentials. Since the crack-to-TSP gap for this test is only 3 mils less than the target 0.025" gap, no significant difference in the contact pressure would be expected for the target gap.
2. This test sequence produced an upper bound leak rate of about 4.1 gpm both before and after bladder pressurization.
3. Flow pressurization to about 2300 psi Δp resulted in interaction of the crack face with the TSP hole. The leak rate does not increase further after crack face interaction with the TSP, even in subsequent leak rate tests after bladder pressurization to the free span burst pressure of about 3700 psi.

5.5.5 Test 12-1 Evaluation

5.5.5.1 Test Sequence and Data Analysis

The 7/8" diameter specimen used for this test had two cracks 90° apart at the start of test, which is typical of observed cases of more than one crack, i.e., a dominant crack with a second less significant crack (see Section 6.9). Dye penetrant test showed that the largest crack had an initial length of 0.607" - OD (0.515" TW), and the second crack was 0.465" - OD (0.360" TW). Neither of the TW cracks was visible with back light over the full length of the OD crack, which implies that TW crack opening width was less than one mil. The initial crack to TSP gap was established at 0.026" by forcing the tube to contact the TSP hole surface at 180° from the crack. Bladder pressurization was carried out at two pressures, 3310 and 4850 psi, the latter being the estimated free span burst pressure. All tests were performed in the Large-Scale Test facility. The tests were conducted in the following order: zero-offset, offset 0.15", bladder pressurization to 3310 psi, offset 0.15", bladder pressurization to 4850 psi, offset 0.15" and zero-offset. All the tests were hot tests.

The leak rate results for this test sequence are plotted in Figures 5-13 to 5-16. They are also summarized in Tables 5-7 and 5-8. The data were evaluated on the basis of maximum Δp as well as on the average Δp basis. Figures 5-13 and 5-14 show the data adjusted to the steam line break conditions on the basis of maximum Δp and average

Δp, respectively. Figures 5-15 and 5-16 show the corresponding data for the test conditions. Crack and tube dimensions recorded during the course of the tests are shown in Appendices D and E.

As noted in Tables 5.10 and 5.11, one data point in flow offset Test 12-1C was deleted due to hysteresis effects, as the average Δp is 400 psi lower than the prior free span test at 2228 psi. Leak test results show consistent trends with modest fluctuations in the data.

5.5.5.2 Summary of Test Results

There is no indication of crack interaction with the TSP in either the flow pressurized zero-offset or offset tests. The leak rates increase at essentially a constant rate from the start of the zero-offset test to the end of the offset test. The relatively high slope of the curves suggests that the crack area increased relatively rapidly with Δp and, consequently, the leak rate. Following the zero-offset test, the total OD length for the main crack was 0.633", with TW width visible only intermittently (about 0.001" width) by light penetration through the crack. The crack diameter increase was about 0.001". The second crack showed no visible TW width.

Leak rate at the SLB pressure differential in the flow pressurized offset condition is bounded by 3.3 gpm. Flow pressurization to about 2680 psi in the offset test increased the main crack TW length to about 0.585" (total length of 0.646"), the maximum TW crack opening was 0.005" and the plastic crack diameter increase was about 0.002". There was still no visible TW width for the second crack. The small increase in the crack diameter for this test is consistent with the leak rate results showing no crack to TSP interaction. The TW length outside the TSP was 0.105" with a maximum crack opening width of about 0.003". The offset TW length was less than the target 0.15" since there was no visible TW length following the zero-offset test and the tip of the OD crack was set 0.15" outside the TSP. Following the offset test, 0.105" of the offset length was found to be TW.

Bladder pressurization to about 70% of the predicted free span burst pressure (3310 psi) resulted in an increase in the offset leak rate to 4.2 gpm (at the SLB Δp of 2560 psi). The subsequent zero-offset test shows essentially the same SLB leak rate (4.1 gpm). During the offset leak test, the main crack TW length increased to 0.604" (total length of 0.652"), the maximum TW crack opening to 0.005" and the plastic crack diameter increase was about 0.003". There was still no visible TW width for the second crack, which had an OD length of 0.482".

The shallow slope of the leak rate versus Δp curve following bladder pressurization to 3310 psi does not necessarily imply crack-to-TSP interaction. Here it is attributed to a much smaller increase in the leakage area with Δp during the test since the crack has been previously plastically opened at a much higher Δp during bladder pressurization. The slope of the leak rate curve is determined by some additional elastic opening of the crack and increase in the critical mass flux with pressure differential (mass flux is proportional to $\sqrt{\Delta p}$). The slope of the bladder pressurized leak rate curve exceeding $\sqrt{\Delta p}$ dependence suggests that there is additional elastic opening of the crack. At the intermediate bladder pressurization step (3310 psi) there is no indication (crack diameter increase, difference between zero-offset and offset leak rates, abnormally small slope) that crack-to-TSP interaction occurred.

The SLB leak rates for the offset condition following bladder pressurization to the free span burst pressure of about 4850 psi increased to 5.9 gpm, and there is essentially no difference for the subsequent zero-offset leak rate (5.8 gpm). The bladder pressurization and offset flow test slightly increased the main crack TW length to about 0.630" (total length of 0.656"), the maximum TW crack opening was 0.022", and the plastic crack diameter increase was about 0.020". The second TW crack was now visible with a TW length of 0.391" (total length of 0.481"), the maximum TW crack opening was 0.005" and the plastic diameter increase was approximately zero.

The 5.9 gpm leak rate for this test represents the combined leakage from both 0.630" and 0.391" TW cracks. It appears that both cracks contributed to the leak rate since the leakage is larger than anticipated for the main crack alone. It cannot be accurately determined whether or not the main crack resulted in interaction with the TSP since the plastic diameter increase is less than the crack-to-TSP gap. The slope of the leak rate curve is slightly flatter than obtained for the intermediate bladder pressurization step. The elastic crack opening could have increased the tube diameter to near contact with the TSP, especially since the presence of a second crack tends to cause a greater out-of-plane diameter increase, thus consuming the available flow area between the tube and the TSP. The crack area and geometric area shown in Table 6.8 for this case are essentially equal. Even if there was crack interaction with the TSP, the extent is expected to be small otherwise it would have significantly changed the limiting leakage area and, therefore, the leak rate.

5.5.5.3 Overall Conclusions

1. This test of a 7/8" diameter tube with two intermediate length TW cracks, initial 0.515" TW main crack (0.585" TW after flow pressurized offset test) resulted in a SLB leak rate for flow pressurization of 3.3 gpm at 2560 psid with the crack 0.105" TW outside of the TSP.

2. During flow pressurized tests, there was no crack to TSP interaction (crack behaved as a free span indication) for pressurization up to 2680 psi. The limited crack to TSP interaction may have occurred following bladder pressurization to the free span burst pressure.

3. Bladder pressurization to 3310 psi increased the leak rate to 4.2 gpm and pressurization to the free span burst pressure of about 4850 psi further increased the leak rate to 5.9 gpm. There was no significant difference in zero-offset and offset leak rates following bladder pressurization. Both cracks, spaced 90° apart, contributed to the leak rate.

5.5.6 Test 12-7 Evaluation

5.5.6.1 Test Sequence and Data Analysis

The 3/4" diameter specimen used in this sequence had two nearly coplanar cracks with a total length of 0.590" (OD), 0.580" (TW). The two cracks were separated circumferentially near the crack tips by a ligament 0.012" wide and 0.365" long (in the crack direction). The individual crack lengths were 0.365" (OD), 0.360" (TW) and 0.244"(OD), 0.239" (TW). Silastic mold and dye penetrant examination (see Appendix C) conducted prior to leak tests did not reveal the presence of the ligament. The ligament became apparent after the initial flow pressurization test.

Bladder pressurization was carried out at two pressures 2800 and 6200 psi. The target pressure during bladder pressurization to 6200 psi was free span burst pressure of about 3950, but a higher Δp was reached inadvertently. However, the target burst pressure was estimated on the combined length of the two cracks, and consideration of the ligament would have increased the burst pressure above the estimated 3950 psi value. The ligament did not tear at 2800 psi but did tear during the 6200 psi bladder pressurization step.

All tests were performed in the Large-Scale Test facility. The tests were conducted in the following order: zero-offset, offset 0.1", bladder pressurization to 2800 psi, offset 0.1", bladder pressurization to 6200 psi, offset 0.1" and zero-offset. All tests were hot tests. The initial crack to TSP gap was established at 0.026" by forcing the tube to contact the TSP hole surface at 180° from the crack.

Data for this test sequence are plotted in Figures 5-17 to 5-20. They are also summarized in Tables 5-9 and 5-10. The data was evaluated on the basis of maximum Δp as well as on the average Δp basis. Figures 5-17 and 5-18 show the data adjusted to the steam line break conditions on the basis of maximum Δp and average Δp, respectively. Figures 5-19 and 5-20 show the corresponding data for the test conditions. Crack and tube dimensions recorded during the course of the tests are shown in Appendices D and E.

No data points were deleted due to hysteresis effects. However, as noted in Tables 5-9 and 5-10, leak rate measured for the first zero-offset flow pressurization test (Test 12-7A) could not be adjusted to SLB conditions because of low primary side pressure in that test. Leak test results show consistent trends with modest fluctuations in the data. The higher than planned bladder pressurization may have resulted in a slightly lower leak rate than would have been obtained at the target 3950 psi due to the length of the crack flank interaction with the TSP (see Figure 6-2 (o)). This difference does not significantly impact the test results and conclusions.

5.5.6.2 Summary of Test Results

In this test, the 206 psi difference between the maximum Δp and the average Δp recorded for the zero offset flow pressurization tests was larger than the typical difference of about 125 psi. The leak rate data based on the maximum Δp are used for interpretation of the test results.

The leak rate vs. Δp curve for the zero-offset flow pressurized test is typical of the free span behavior where there is no influence of the TSP, and the increase in leak rate is primarily caused by an increase in the leak area. On the other hand, the leak rate curve for the flow pressurized offset leak rate is relatively flat. It is not clear from the leak rate data alone whether or not crack-to-TSP interaction occurred during this test sequence up to the maximum Δp of 2659 psi tested. However, the crack diameter increase during this offset test was only 5 mils compared to the 25 mil crack to TSP gap, which implies no crack-to-TSP interaction. This is confirmed by the evaluation for the limiting flow area, presented in Section 6, which shows the crack opening area to be the limiting flow area for this test. Furthermore, extrapolation of the zero-offset leak rate data to 2659 psi results in only a slightly larger leak rate than obtained from the offset leak test. Thus, it is concluded that crack-to-TSP interaction did not occur in the flow pressurization tests.

Bladder pressurization to 2800 psi (approximately 70% of the predicted burst pressure for the total crack length) resulted in a slight increase in the offset flow rate, from approximately 3.9 gpm to approximately 4.3 gpm, at the 2560 psi SLB condition. This bladder pressurization step resulted in a flat leak rate as a function of pressure, which may suggest crack-to-TSP interaction, but not in this test. The crack diameter following this pressurization step did not increase significantly over that of the flow pressurization offset test (Figure 6-2 (o)) and, therefore, crack to TSP interaction would not have occurred. The relative flatness of the leak rate curve in this test is attributed to a limited increase of the crack opening area during leak testing since the crack had already been plastically expanded at a higher pressure during bladder pressurization. Thus it would be expected that the leak rate at the lower Δp's for the bladder pressurization would be greater than for the flow pressurization tests, but approximately the same as the flow pressurization tests at the higher Δp's. The leak rate increase over the flow pressurized offset test is consistent with approximately 15% increase in the crack opening area between the tests.

Bladder pressurization to 6200 psi resulted in leak rates lower than the prior tests with no significant difference between the zero-offset and offset test results. This step plastically increased the crack diameter to entirely close the initial crack-to-TSP clearance of 0.025" over a significant length within the span of the TSP. During bladder pressurization, the ductile ligament in the crack tore. The TW length following this bladder pressurization step was 0.726", with a maximum TW crack opening of 0.056" for the offset test. The evaluation for the limiting the flow area, presented in Section 6 shows that the geometric area limited the leak rate for this test. Results in Table 6.8 show that the limiting flow area for this case is about 20% larger than that of the flow offset test (Test 12-7C), yet the measured leak rate is lower. This shows that hydraulic losses due to crack flank interaction with the TSP reduced the critical mass flux and, therefore, measured leak rate.

5.5.6.3 Overall Conclusions

1. The leak rate test of this 3/4" diameter specimen with two TW cracks of 0.375" and 0.256" separated by a 0.012" ligament resulted in leak rates of about 3.9 gpm for the flow pressurization offset condition and 4.3 gpm following bladder pressurization to 2800 psi.
2. There is no indication of crack to TSP interaction after bladder pressurization to 2800 psi.
3. This test demonstrates that the two TW cracks totaling 0.631" over an overall length of 0.629" (TW crack tips separated by a ligament) do not behave, in terms of crack opening and leakage, like a single long TW crack with the same total length. The leak rate from a segmented crack is much less than the leak rate from a single crack of length equal to the total length of a segmented crack.
4. This tests shows that when ligaments between short crack segments fracture to form a single long crack, interaction between the long crack and the TSP limits the leak rate to about the combined leakage from the shorter crack segments (i.e., much less than expected from a single long crack). All other tests in this program indicate that single TW crack lengths of greater than 0.5" result in crack to TSP interaction at a pressure below 2400 psi.

5.5.7 Test 1-1 Evaluation

5.5.7.1 Test Sequence and Data Analysis

This sequence utilized a 3/4" diameter specimen with a single crack having 0.620" initial TW length. Both flow pressurized and bladder pressurized tests were performed to bound the leak rate. Bladder pressurization was carried out at 4250 psi which is the predicted free span burst pressure. All tests were performed in the Large-Scale Test facility. The tests were conducted in the following order: zero-offset, offset, free span, bladder pressurization at 4250 psi with 0.15" offset, zero-offset, offset and offset cold test.

The leak rate results for this test sequence are plotted in Figures 5-21 to 5-24. They are also summarized in Tables 5-11 and 5-12. Both data evaluated on the basis of maximum Δp and on average Δp are shown. Figures 5-21 and 5-22 show the data adjusted to steam line break conditions on the basis of maximum Δp and average Δp, respectively. Figures 5-23 and 5-24 show the corresponding data for the test conditions. Crack and tube dimensional data recorded during the course of the tests are shown in Appendices D and E.

Data evaluation based on the maximum Δp suggests deletion of two data points at the beginning of the free span test (Test 1-1E) due to hysteresis effects, whereas the evaluation based on the average Δp implies hysteresis effects both at the end of the offset test and beginning of the free span test, as noted in Tables 5-17 and 5-18, respectively. The prediction based on the maximum Δp is considered to be more reliable.

Test results show consistent trends with modest fluctuations in data. The effective crack-to- TSP gap for this test, implied from measurements of the crack diameter following the flow pressurization offset test, was 0.009" compared to the target 0.025" (Figure 6-2 (a)).

5.5.7.2 Summary of Test Results

The leak rate measured for the free span test is typical of unimpeded, choked flow. A significantly lower leak rate for the zero-offset and offset tests suggests that there is significant crack-TSP interaction in those tests. The shallow slope of leak rate curves above approximately 2000 psi also suggests crack interaction with the TSP had occurred. The evaluation of the crack and tube dimensional data obtained after the offset test, presented in Section 6, indicates that crack-TSP interaction had occurred in that test. The leak rate for the offset test was controlled by the effective crack area (see Table 6.8). With the larger target gap of 0.025", interaction with the TSP would be at a somewhat higher pressure than obtained for the 0.012"- 0.016" gap in this test.

Leak data for the flow pressurized offset condition show a small (about 15%) initial increase in leakage after TSP offset. This implies that geometric area rather than effective crack area controlled leakage at the end of zero-offset test and beginning of offset test, as in the leak flow regime 2 described in Section 5.4. The leak rate in the offset condition continued to increase at a slope higher than that found for the zero-offset.

Maximum crack width measured after the zero-offset test is 0.004". During the offset test, the measurable throughwall crack length increased from 0.494" to 0.595" and the width increased from 0.004" to 0.011". Maximum leak rate measured for the offset conditions is 4.2 gpm at 2760 psi, which is equivalent to 3.2 gpm at the SLB conditions (2560 psi).

Following bladder pressurization to the free span burst pressure of about 4250 psi, the leak rates for the offset condition are about the same as those obtained with flow pressurization. The offset leak rate is lower than that obtained for the subsequent zero-offset test, which is an unexpected result. As mentioned above, the analysis of the crack and tube dimensional data obtained following this offset test indicate that leak rate was controlled by the geometric area. In such a case, there should not be a significant difference between zero-offset and offset leak rates. Test data were reviewed for a possible reporting error, but the record clearly documented the test condition. However, the difference in zero-offset and offset leak rates is small and the leak rates are within their standard deviation. The bladder pressurization resulted in a modest increase in the maximum TW crack width from 0.011" to 0.012" but no change in the throughwall length.

5.5.7.3 Overall Conclusions

1. The SLB leak rate for this 7/8" specimen with a 0.6" TW crack is limited to about 3.6 gpm prior to and following bladder pressurization to the free span burst pressure. The leak rate is similar to that found for 0.6" TW cracks in 3/4" tubing (4.1 gpm of Test 1-7).

2. Bladder pressurization to the free span burst pressure did not increase the leak rate over that obtained in the prior offset tests.

3. Interaction of the crack edge with the TSP at about 2000 psi is consistent with other tests for greater than 0.5" TW length cracks.

4. The offset constrained test leak rate is much less that the freespan leak rate, although the differences are somewhat masked by hysteresis and the tests loop limitations. The freespan leakage is a minimum leak rate of about 5.5 gpm at about 2550 psid through a crack previously pressurized to about 2760 psid. If the loop capacity would have permitted freespan flow pressurization at 2760 psid, a leak rate greater than 5.5 gpm would have been expected. In contrast, the measured offset constrained leak rate at 2760 psid was approximately 4.2 gpm.

5.5.8 Test 1-2 Evaluation

5.5.8.1 Test Sequence and Data Analysis

The initial length of crack in this 7/8" specimen was 0.620" TW. As with the other specimens, both flow pressurization and bladder pressurization tests were performed to bound the leak rate. Bladder pressurization was carried out at 4080 psi, which is the estimated free span burst pressure. All tests were performed in the Large-Scale Test facility. The tests were conducted in the following order: zero-offset, offset, free span, bladder pressurization to 4080 psi, zero-offset, offset and cold offset.

The leak rate results for this test sequence are plotted in Figures 5-25 to 5-28. They are also summarized in Tables 5-13 and 5-14. Data evaluated on the basis of maximum Δp as well as on the average Δp are shown. Figures 5-25 and 5-26 show the data adjusted to steam line break conditions on the basis of maximum Δp and average Δp, respectively. Figures 5-27 and 5-28 show the corresponding data for the test conditions. Crack and tube dimensions recorded during the course of the tests are provided in Appendices D and E.

As noted in Tables 5-13 and 5-14, one data point at the beginning of the zero-offset test suggests hysteresis effects and it was deleted. Test results show consistent trends with modest fluctuations in the data. The effective tube-to-TSP gap for this test was estimated at 0.015"-0.016" compared to the target 0.025" based on the measured crack OD following the flow pressurized offset test.

5.5.8.2 Summary of Test Results

As in Test 1-1, the leak rates measured for the free span test are typical of unimpeded, choked flow. The freespan leak rate is about 8 gpm at 2387 psi (Δp_{max}), although this value includes hysteresis effects from prior tests at a higher pressure. The freespan leak rate is almost a factor of three higher than the leak rate for the offset test, which clearly demonstrates the benefits of TSP restraint (i.e, reduced leak rates for IRBs). The shallow slope of the leak rate curve beyond about 2500 psi shows that interaction with the TSP reduces leak rate. The pressure differential at which interaction with the TSP becomes would be expected to increase slightly if the crack-to-TSP gap was increased to the target gap of 0.025" from the estimated test condition of 0.015" - 0.016".

The zero-offset test shows no clear interaction with the TSP for Δp_{max} up to 2350 psi and the leak rate curve is similar to that for a free span test where the leakage area, and consequently leak rate, increases with increasing Δp. There is essentially no increase in leakage rate for the offset test as a result of the TSP offset condition. However, as shown in the crack measurement data, Appendices D and E, the maximum crack width increased almost tripled during the offset test. This implies that the crack opening resulted in increased interaction with the TSP along the length of the crack such that the effective crack area was nearly a constant during the test. The measurements of the crack diameter along the crack length (Figure 6-2 (b)) indicates that the crack diameter was nearly constant for about 0.2" following this test, which is consistent with the effective crack area for leakage being less than the total crack area. The evaluation for limiting flow area presented in Table 6.8 provides confirmation of leakage being limited by the effective crack area since the estimated effective crack area is less than the geometrical area.

The maximum leak rate for the offset condition is about 3.4 gpm at the SLB condition of 2560 psi, and it bounds tests prior to and after bladder pressurization. The plastic diametral increase at the center of the crack was 13 mils at the end of this test indicating that the tube- to-TSP gap at the crack was about 15 - 16 mils to account for elastic springback. About 0.145" of TW crack with a maximum width of 0.009", (i.e., almost the entire offset was TW), was exposed outside the TSP at the end of this test. The measurable TW length increased from 0.574" to 0.666" and the maximum crack width increased from 0.005" to 0.014"

The bladder pressurized tests exhibited leak rates slightly lower than the flow pressurized tests, and they show negligible difference between zero-offset and offset test conditions. These results are consistent with expectations when crack opening area is less than the geometrical flow area for the crack within the TSP, as in leak flow regime 3 described in Section 5.4.

The crack dimensions were also measured by fractography following destructive examination of the specimen. The results show that the crack at start of leak testing was a uniform 0.645" throughwall (0.383" by corrosion, the remaining by fatigue) compared to dye penetrant measurements of 0.640" (OD), 0.620" (TW). The final crack length after bladder pressurization and leak testing was 0.675" uniform throughwall compared to 0.688" measured by toolmaker's microscope based on light penetration through the crack. Thus, actual crack growth from all testing was 0.030" compared to 0.028" measured from in-process test measurements. These results demonstrate that the measurement techniques applied during the test phase are conservative

5.5.8.3 Overall Conclusions

1. The SLB leak rate for a 0.645" throughwall crack at the start of the test (0.675" TW at end of test by destructive exam) is limited to about 3.4 gpm in the offset or zero-offset conditions prior to and after bladder pressurization. The effective crack-to-TSP clearance for this test was limited to about 15-16 mils as indicated by the increase in crack diameter at the end of the test.

2. This test also demonstrates that the leakage from an IRB is much less than the freespan leakage from the same crack. Although this reflects some hysteresis, the freespan leakage is a minimum leak rate of about 8 gpm at about 2385 psid through a crack previously pressurized to about 2760 psid. If the loop capacity would have permitted freespan flow pressurization at 2760 psid, a leak rate greater than 8 gpm would have been expected. In contrast, the measured offset constrained (IRB) leak rate at 2760 psid was approximately 3.2 gpm.

5.5.9 Test 1-7 Evaluation

5.5.9.1 Test Sequence and Data Analysis

The 3/4" specimen used in this sequence had a single crack with an initial length 0.60" TW. As in the other test sequences, both flow pressurization and bladder pressurization tests were performed to bound the leak rate. Bladder pressurization was performed only at 2970 psi, which is less than the free span burst pressure of about 3900 psi. Nevertheless, data from this test sequence are considered acceptable as they are used for analysis of trends in the leak rate and they do not establish the leakage upper bound. All tests were performed in the Large-Scale Test facility. The tests were conducted in the following order: zero-offset, offset, bladder pressurization at 2970 psi with 0.10" offset, offset and zero-offset. Neither free span tests nor room temperature tests were conducted in this series.

The leak tests results for this test sequence are plotted in Figures 5-29 to 5-32. They are also summarized in Tables 5.15 and 5.16. Data evaluated on the basis of maximum Δp as well as on the average Δp basis are shown. Figures 5-29 and 5-30 show the data adjusted to steam line break conditions on the basis of maximum Δp and average Δp, respectively. Figures 5-31 and 5-32 show the corresponding data for the test conditions. Crack and tube dimensions recorded during the course of the tests are shown in Appendices D and E.

As noted in Tables 5-15 and 5-16, one data point at the beginning of flow pressurization offset test suggests hysteresis effects and it was deleted. Test results show consistent trends with modest fluctuations in the data. The effective tube-to-TSP gap for this test was 0.020", essentially the full target gap of 0.025" when allowances are made for elastic springback, based on the measured crack OD following the flow pressurization offset test.

5.5.9.2 Summary of Test Results

Except for the initial part of the flow pressurized zero-offset test, the measured leak rates are approximately independent of the pressure differential. This implies that some degree of crack interaction with TSP occurred in almost all tests conducted. The initial increase (20% to 30% at overlapping pressures) in leak rate after 0.10" offset may indicate reduced TSP restriction on flow after offset. The higher temperatures (650 to 690°F) during the offset test resulted in larger data adjustments (leak rate increases) to the reference conditions, which may introduce some uncertainty in the data adjustment.

The evaluation for limiting flow area presented in Section 6 indicate that, in the flow pressurized zero-offset tests, the leak rate is limited by the effective crack area which is less than the geometric area. The effective crack area is likely to have remained nearly constant in this test resulting in a flat leak rate vs Δp curve. The maximum crack width data shown in Appendices D support a limited increase in effective crack area during the offset tests. The data show that the maximum plastic crack opening increased from 0.011" at the end of zero-offset test to only 0.020" at the end of the offset test (Figure 6-2(d)). Leak rate at the SLB condition of 2560 psi for the flow pressurized offset condition is 4.1 gpm, and it is also the peak SLB leak rate for this test sequence.

Following bladder pressurization to 2970 psi (approximately 76% free span burst pressure of about 3900 psi), the leak rates are approximately independent of the crack offset condition. They are about the same as obtained with zero-offset prior to bladder pressurization and less than the maximum 4.2 gpm leak rate measured. The leak rates decreased following bladder pressurization even though the crack width increased from 0.014" to 0.022". This effect indicates that the effective crack area is less than the total area, likely due to interaction of the crack with the TSP over some length of the crack. Tube diameter measurements indicate that crack-TSP interaction occurred over about 0.2" length. The lack of leak rate dependence on the crack offset position following bladder pressurization indicates that leakage is more dependent on effective crack area than on geometrical flow restrictions. This is confirmed by the leak area estimates presented in Tables 6.7 and 6.8, which show that the effective crack area is less than the geometrical flow area.

5.5.9.3 Overall Conclusions

1. The SLB leak rate for this 0.6" TW crack at start of test (0.613" at end of test) is limited to about 4.1 gpm prior to and after bladder pressurization. The effective crack-to-TSP clearance for this test was 0.025" based on the crack diameter at the end of the offset flow test with an allowance for elastic springback.

2. Large (greater than about 0.5") throughwall cracks interact with the TSP to limit leak rates including conditions with a 0.10" TW crack outside the TSP. For this 0.6" TW crack, interaction with the TSP is indicated at about 2100 psi and higher.

3. SLB leak rates following bladder pressurization are less than that obtained for the 0.10" offset condition with prior flow pressurization and are essentially independent of the TSP offset position

5.5.10 Test 11-1 Evaluation

5.5.10.1 Test Sequence and Data Analysis

The 7/8" diameter specimen used in this sequence had two axially aligned cracks with a total TW length of 0.710" separated by an uncorroded ligament. The ligament was located at 0.60" from the end of the crack tip that was used to establish the offset condition; thus a short crack segment <0.11" long existed within the span of the TSP. One or two other ligaments were present in the area separating the longer and shorter crack segments. The specimen initially had three other part-TW cracks that were TIG welded prior to fatiguing the main crack to the desired length. There was no evidence that the welding affected the flow testing of the principal crack. The tube diameter in the plane of the remaining crack remained within the tolerances of the tube after welding. In the plane of the welded cracks, a reduction of the tube diameter of up to 4 mils was observed, and this would conservatively increase the overall gap between the tube and the TSP. The welded cracks did not open during the pressurization of the specimen. Prior to leak testing, the TW crack was intermittently visible with back light over the full length of the OD but was too tight to quantify width (less than 0.001" wide).

All tests were performed in the Large-Scale Test facility. Bladder pressurization was performed at 3670 psi, the estimated burst pressure for the specimen. No intermediate bladder pressurization step was included since the SLB Δp is approximately 70% of the predicted specimen burst pressure. The tests were conducted in the following order: zero-offset, offset 0.15", bladder pressurization to 3670 psi, offset 0.15" and zero-offset. All tests were hot tests. The initial crack-to-TSP gap was established at 0.026" by forcing the tube to contact the TSP hole surface at 180° from the crack.

The leak rate results for this test sequence are plotted in Figures 5-33 to 5-36. They are also summarized in Tables 5-17 and 5-18. The data was evaluated on the basis of maximum Δp as well as on the average Δp basis. Figures 5-33 and 5-34 show the data adjusted to the steam line break conditions on the basis of maximum Δp and average Δp, respectively. Figures 5-35 and 5-36 show the corresponding data for the test conditions. Crack and tube dimensions recorded during the course of the tests are shown in Appendices D and E.

For the flow pressurized offset tests, hysteresis effects are indicated for two data points on the basis of maximum pressure, and for a single data point based on the average pressure, as noted in Tables 5.26 and 5.27. Leak test results show consistent trends with modest fluctuations in the data.

5.5.10.2 Summary of Test Results

The shallow slope of the leak rate curve for the flow pressurized zero-offset test suggests crack interaction with the TSP at approximately 2000 psi. Although the crack measurements do not confirm TSP interaction after the zero-offset test, the large change in the tube diameter suggests that TSP interaction may have occurred if elastic springback of the crack flanks is also considered (see Figure 6-2(k)). The TW length measured following this zero-offset test was about 0.749" (total OD length of 0.752"), the maximum TW crack width was 0.018" and the crack diameter increase was about 0.018". All of the ligaments remained intact during the zero-offset test.

The leak rate for the subsequent offset test was about 1 gpm higher than the zero-offset test. The evaluation for the limiting leak area presented in Table 6.8 shows that crack interaction with the TSP occurred in this test because the effective crack area is the limiting flow area. The shallow slope of the leak rate curve indicates crack/TSP interaction. The leak rate at the SLB pressure differential (2560 psi) for this offset test is about 5.0 gpm. Flow pressurization to about 2560 psi increased the TW length to about 0.749" (total length of 0.755") with the large ligament remaining intact and the two small ligaments broken. The maximum TW crack opening increased to 0.024" and the plastic crack diameter increase was about 0.021". The TW length outside the TSP was 0.15" for this offset test with a maximum crack opening width of about 0.018".

During bladder pressurization to the free span burst pressure of about 3670 psi, the ligament at 0.60" from the end of the crack broke to become a loose piece (0.046" long in axial crack direction by 0.023" wide and approximately the wall thickness deep) which was removed from the crack. The tube was not tight in the TSP after bladder pressurization.

Leak rates for the zero-offset and offset condition following bladder pressurization were approximately equal to that found for the flow pressurized offset tests at the SLB conditions. Leak rate vs Δp curves for these tests have a shallow slope, which is typical of bladder pressurized tests where the crack opening area does not significantly increase during leak testing. In the offset tests, geometric area controlled the leak rate as shown in Table 6.8. Therefore, a change in leak rate can be expected between zero-offset and offset tests, and the data in Figures 5-35 and 5-36 do show such an increase although it is small. The bladder pressurization and the subsequent offset flow test slightly increased the TW length to about 0.754" (total length of 0.757"), the maximum TW crack opening was 0.027" and the plastic crack diameter increase was about 0.023".

5.5.10.3 Overall Conclusions

1. This test of a 7/8" diameter tube, initial 0.70" TW crack (0.749" TW after flow pressurized offset test) resulted in a SLB leak rate at 2560 psid of 5.0 gpm for both flow and bladder pressurization with the crack 0.15" TW outside of the TSP.
2. The leak rate results of this test and the Test 11-2 results in 7/8" tubing are very similar to the bounding leak rate of 5.0 gpm found in 3/4" tubing for Test 1-6 which had a 0.724" TW crack following the flow pressurized offset test. This result indicates comparable leak rates for similar throughwall cracks in both 3/4" and 7/8" diameter tubing and supports use of the5.5 gpm bounding IRB leak rate for both tubing sizes.
3. For this long indication, the leakage results for flow pressurization offset test indicate the TSP interaction occurred at about 2000 psi.
4. Under flow pressurization conditions, there was about a 1 gpm difference in leak rate between the zero-offset and offset test conditions. Following bladder pressurization, the difference in those leak rates is much smaller.
5. Coalescence of crack segments due to fracturing of ductile ligaments between the segments in the span of the TSP does not result in a significant increase in the leak rate, due to resulting crack opening behavior of the resulting longer crack and its interaction with the TSP.

5.5.11 Test 11-2 Evaluation

5.5.11.1 Test Sequence and Data Analysis

As in Test 11-1, the 7/8" specimen used in this test initially also had two axially aligned crack segments separated by an uncorroded ligament. However, the total length of crack in this specimen was 0.729" (versus 0.71" (TW) for the Test 11-1 specimen). The ligament was located at 0.450" from the end of the crack that was used to establish the offset condition; thus, the ligament was located within the span of the TSP. The TW crack was initially tight and not visible with the back light technique. Its length was determined by dye penetrant to be 0.508" TW with a thin wall ligament 0.122" long. Based on prior test experience, the thin wall ligament was expected to tear at low Δp and therefore, the initial TW length was taken to be 0.63". The specimen initially also had two additional cracks that were TIG welded prior to fatiguing to achieve the desired crack length. There is no evidence that the welding affected the flow testing of the principal crack. The welded crack did not open up during specimen pressurization.

All tests were performed in the Large-Scale Test facility. Bladder pressurization was carried at 2940 and 4075 psi, the latter being the estimated burst pressure for the specimen. The tests were conducted in the following order: zero-offset, offset 0.15", bladder pressurization to 2940 psi, offset 0.15", bladder pressurization to 4075 psi, offset 0.15" and zero-offset. All tests are hot tests. The initial crack-to-TSP gap was established at 0.026" by forcing the tube to contact the TSP hole surface at 180° from the crack.

The leak test results for this test sequence are plotted in Figures 5-37 to 5-40. They are also summarized in Tables 5-19 and 5-20. The data were evaluated on the basis of maximum Δp as well as on the average Δp basis. Figures 5-37 and 5-38 show the data adjusted to the steam line break conditions on the basis of maximum Δp and average Δp, respectively. Figures 5-39 and 5-40 show the corresponding data for the test conditions. Crack and tube dimensions recorded during the course of the tests are shown in Appendices D and E.

For the flow pressurized offset test, hysteresis effects are indicated for two data points on the basis of maximum pressure but for a single data point based on the average pressure, as noted in Tables 5.26 and 5.27. Leak test results show consistent trends with modest fluctuations in the data.

5.5.11.2 Summary of Test Results

Results for the flow pressurized zero-offset test are typical of a test with no tube interaction with TSP. The leakage area, and, therefore, leak rate, in this test increases relatively rapidly with pressure differential. This is also evident from the crack dimensions measured following the zero-offset test which show that the TW length was about 0.657", the maximum TW crack width was 0.007" and the crack diameter increase was only about 0.004" (Figure 6-2(c)).

The shallow slope of the leak rate curve for the flow pressurized offset test suggests crack interaction with the TSP at approximately 2350 psi. The evaluation for limiting leak area presented in Section 6 does not indicate crack-TSP interaction as it shows crack opening area to be the limiting area (see Table 6.8). However, the large plastic increase in the tube diameter suggests that interaction may have occurred if the elastic expansion component is also considered. The flatness of the leak rate vs. Δp curve indicates that the limiting leak area did not change significantly for this test. Flow pressurization to about 2550 psi during this offset test increased the TW length to about 0.702", the maximum TW crack opening was 0.014" and the plastic crack diameter increase was about 0.016".

Crack and tube dimensions measured following a leak test do not include the elastic component of the crack deformation during flow testing. To measure the magnitude of the elastic deformation, a supplemental step involving free span bladder pressurization to 3200 psi was performed following all tests, including the tests with prior bladder pressurization to 4075 psi. The results show an average crack diameter increase of 0.005" which indicates that pressurization during leak testing adds significant elastic deformation to the prior plastic deformation. In flow pressurized offset tests, this elastic crack opening could have increased the measured plastic opening of 0.016" to greater than 0.020" at 2560 psid Δp and reduced the 0.026" crack to TSP gap to less than 0.006". (See Section 6.3)

The leak rate at the SLB pressure differential in the offset condition was 5.2 gpm both prior to and after bladder pressurization. The TW length outside the TSP was 0.173" at the end of flow pressurized offset test. This was larger than the 0.15" target TW offset as the visible TW length increased by about 0.023" during this offset test. At about 2360 psi, where the zero-offset and offset tests overlap, there was no difference between the leak rates. This would be expected, as crack to TSP interaction was not observed at this pressure differential.

Bladder pressurization to 2940 psid resulted in no change or a slight decline (about 0.4 gpm) in the offset flow rate compared to the flow pressurized leak rate. The crack diameter did not increase plastically due to this bladder pressurization (Figure 6-2(l)); thus the leak rates were expected to be similar to those of the prior flow offset tests. However, the ligament at 0.45" from the end of the crack was broken during the bladder pressurization and became a loose piece (0.056" long in axial crack direction by 0.011" wide and approximately the wall thickness deep). It was removed from the crack following the bladder pressurization. TSP interaction was indicated by the leak data, but was not confirmed by the tube dimensional measurements, which do not take into account the elastic component of crack opening.

After the final bladder pressurization to the free span burst pressure of 4075 psi, the tube was not tight in the TSP. Leak rates for the offset condition following this bladder pressurization were essentially the same as found for the flow pressurized offset test. However, the zero-offset leak rate was about 10% lower than the offset leak rate. The bladder pressurization increased the TW length to about 0.707", the maximum TW crack opening was 0.022" and the plastic crack diameter increase was about 0.020". Since TSP interaction was indicated after the 2940 psi bladder expansion, higher pressure bladder expansion would be expected to cause a reduction in the leak rate due to elastic/plastic crack expansion and the resulting decrease in the available flow area.

5.5.11.3 Overall Conclusions

1. This test of a 7/8" diameter tube, initial 0.63" TW crack (0.702" TW after flow pressurized offset test) resulted in a maximum SLB leak rate of 5.2 gpm at 2560 psid with 0.173" of TW crack outside the TSP after the test. This leak rate is very similar

to the bounding leak rate found in 3/4" tubing for Test 1-6, which had a 0.724" TW crack following the offset flow pressurization test.

2. The above result indicates comparable leak rates for similar throughwall cracks in both 3/4" and 7/8" diameter tubing and supports use of the 5.5 gpm bounding IRB leak rate for both tubing sizes.

3. For this indication, the leak rate results indicate that crack-TSP interaction occurred at about 2350 psi in both flow pressurized and bladder pressurized offset tests. The crack expansion and tube diameter measurements confirm this for only the bladder pressurized tests; however, the measurements do not take into account the elastic expansion component of the crack.

4. Under flow pressurization conditions, there was no significant change in leak rate between the zero-offset and offset test conditions. However, following bladder pressurization, the zero-offset leak rate was about 10% lower than the offset leak rate.

5.5.12 Test 1-6 Evaluation

5.5.12.1 Test Sequence and Data Analysis

The 3/4" diameter specimen utilized in this test had a single crack with an initial TW length of 0.74". Since cracks with a throughwall length of this magnitude would not be expected even with the full APC repair limit of 10 to 15 volts, with the TSP's locked by tube expansion, this test is expected to yield an upper bound for the leak rate. A 0.74" TW length is larger than would ever be expected to remain in service even for a high voltage repair limit. (Section 6.8 discusses the bobbin voltages expected for long throughwall cracks.)

As in the other test sequences, both flow pressurized and bladder-pressurized tests were performed to bound the leak rate. Bladder pressurization was carried out at 3035 psi, which is the estimated free span burst pressure for the specimen. All tests were performed in the Large-Scale Test facility. The tests were conducted in the following order: zero-offset, offset, free span, bladder pressurization at 3035 psi with zero-offset, offset and offset cold test.

The leak rate results for this test sequence are plotted in Figures 5-41 to 5-44. They are also summarized in Tables 5-21 and 5-22. Data evaluated on the basis of maximum Δp as well as on the average Δp basis are shown. Figures 5-41 and 5-42 show the data adjusted to the steam line break conditions on the basis of maximum Δp and average Δp, respectively. Figures 5-43 and 5-44 show the corresponding data for the test conditions. Crack and tube dimensions recorded during the course of the tests are shown in Appendices D and E.

As noted in Tables 5-21 and 5-22, three data points at the end of the zero-offset tests and three data points at the beginning the offset tests were deleted because of hysteresis effects. Leak test results show consistent trends with modest fluctuations in data. The crack-to-TSP clearance for this test was 0.026", compared to the target 0.025", as supported by the crack diameter measurement showing an increase in the crack diameter of 0.027" following the flow pressurized offset test. The specimen was held tightly in the TSP at the end of flow pressurized offset test. For highly pressurized specimens with relatively long crack, the crack flanks buckle inward due to interaction with the TSP; thus, the elastic springback holds the specimen tightly within the TSP, and results in maximum tube measurement greater than the available nominal tube-to-TSP gap (see Section 6.2).

The freespan test, performed at lower a Δp than prior tests, includes hysteresis effects. This test was performed only to demonstrate the magnitude of the difference in leak rate between freespan condition and the same crack restricted within the TSP; therefore, hysteresis effects are relatively unimportant.

5.5.12.2 Summary of Test Results

The Δp during the free span test was limited to maintain the leak rate within the facility flow capacity. Therefore, leak rate measured for this test, 13.1 gpm at a Δp of 1495 psi, does not correspond to a choked flow condition. However, the free span test followed a flow pressurized offset test with a maximum Δp of 2710 psi, so there is significant hysteresis effect. The fact that leak rate for this test is substantially higher than 5.5 gpm obtained for the crack constrained by the TSP illustrates the benefits of TSP presence in limiting leakage for an IRB.

Significantly lower leak rates for the zero-offset and offset tests relative to the free span test show the impact of the TSP on the leakage flow in those tests. For large size cracks such as this one, the crack-to-TSP gap decreases rapidly and, consequently, the effects of the TSP presence would be apparent at lower Δp's. This specimen produced the widest crack opening among all flow pressurization tests. However, at the lower end of Δp's in the zero-offset test, interaction between the crack and TSP was not expected, yet the TSP presence had substantially reduced the leakage rate. The flattening of the leak rate curve towards the end of zero-offset tests suggests that the leakage area was limited by the geometric area of the gap between the crack flanks and the TSP. This is confirmed by analysis of the crack dimensional data taken after the test, as shown on Figure 6-2(c). There is significant crack plastic deformation after the flow pressurization zero-offset tests.

The leak rate increased from about 3.1 gpm for the zero-offset test to 5.5 gpm at the completion of the offset test with crack tip 0.10" outside the TSP. This is consistent with the post-test crack measurements for the two tests which show that the detectable TW crack length (visible light through crack) increased from 0.619" to 0.724", maximum crack width from 0.024" to 0.044", and crack opening area by factor of 2. Thus, the increase in leak rates is primarily due to increased crack opening at higher Δp's. At comparable Δp's, the offset leak rate is about 30% higher than that for zero-offset. Based on the evaluation for limiting leak area presented in Table6.7, the geometric flow area is less than the effective crack area for the offset test, and an increase in leakage for the offset condition would be expected (as in leak flow regime 2 discussed in Section 5.4). Leak rates at SLB pressure differential (2560 psi) with 0.10" offset are bounded by the 5.5 gpm limit both prior to and after bladder pressurization when evaluated against the average Δp of the tests. Note that this bounding leak rate includes the effects of offset.

The offset test, performed with 0.026" tube-to-TSP gap, resulted in the widest crack opening of all tests performed, except those following bladder pressurization in this sequence, with maximum crack opening widths of 0.044" inside the TSP and 0.024" outside the TSP. This specimen was tight in the TSP collar following flow pressurization to about 2500 psi. The crack opening visible through the crack by the back-light technique was 0.724" of the total 0.750" crack length and was more than 0.019" wide for more than 0.6" length. Plastic deformation increased the crack opening diameter to the TSP hole diameter over about 0.25" at the center of the crack.

Following bladder pressurization to the free span burst pressure of about 3035 psi at 0.10" offset, leak rates for zero-offset and offset tests are approximately equal to that obtained for the offset test prior to bladder pressurization. Thus, bladder pressurization had no significant influence on the leak rate even though the maximum plastic width increased from 0.044" to 0.050". However, the increased bladder pressurization did not significantly open the crack width at the ends of the crack. Leak rate being nearly independent of the TSP offset position implies that effective crack area was less than geometric area following bladder pressurization. The evaluation for limiting leak area presented in Section 6 confirms the effective crack area as being limiting for the offset tests.

5.5.12.3 Overall Conclusions

1. This test of a 0.74" throughwall crack represents an upper bound leak test since throughwall lengths of this magnitude would not be expected even with the full high voltage ARC limit with tube expansion, of up to 10 to 15.

2. The SLB leak rate prior to and after bladder pressurization is bounded by about 5.5 gpm at 2560 psi including the maximum potential 0.10" TSP offset condition, based on the evaluation of the leak rates with average Δp. The bounding leak rate is 5.0

gpm when evaluated with the maximum Δp to account for crack elastic/plastic opening at the peak Δp attained during the test.

3. TSP constraint reduces the maximum SLB leak rate by more than a factor of three compared to free span conditions.
4. For this crack with 0.74" initial TW length, the leakage results indicate that interaction with the TSP occurred at about 2000 psi Δp.

5.5.13 Test 11-7 Evaluation

5.5.13.1 Test Sequence and Data Analysis

The 3/4" diameter test specimen used in this test initially had a single crack with initial dimensions 0.813" (OD) and 0.809" (TW) length. This TW length is larger than the limiting crack length of 0.750" for ODSCC and for freespan burst. The requirements for the ODSCC ARC specify that no crack extending beyond the span of the TSP (0.750") may be left in service. Cracks of this magnitude would not be expected to remain in service for any repair limit. This test was conducted to further examine the leak rate dependence on crack length, and to establish that the observed leak rate trends from other tests are not near a point where leak rates would increase dramatically with crack length despite being constrained by the TSP. However, leak rate data from this test are not considered in establishing the upper bound leak rate.

The bladder pressurization in this sequence was carried out at 2900 psi, which is the predicted burst pressure. No intermediate pressurization step was included since the burst pressure is only slightly greater than the SLB pressure (2560 psid). Since the crack TW length exceeded the TSP thickness, zero-offset tests were performed with the TSP centered on the crack to produce equal projection of the crack above and below the TSP. The crack-to-TSP gap was established at 0.025" by forcing the tube to contact the TSP hole at 180° from the crack. The tests were conducted in the following order: zero-offset, offset 0.1", bladder pressurization to 2900 psi, offset 0.1" and zero-offset. All tests were hot tests and they were conducted in the Large Scale Test Facility.

The leak rate results for this test sequence are plotted in Figures 5-45 to 5-48. They are also summarized in Tables 5-23 and 5-24. The data was evaluated on the basis of maximum Δp as well as on the average Δp basis. Figures 5-45 and 5-46 show the data adjusted to the steam line break conditions on the basis of maximum Δp and average Δp, respectively. Figures 5-47 and 5-48 show the corresponding data for the test conditions. Crack and tube dimensions recorded during the course of the tests are shown in Appendices D and E.

For the flow pressurized offset test, hysteresis effects are indicated for the first data point on the basis of maximum Δp but the data based on average Δp do not indicate any hysteresis effects. As data evaluation on the basis of maximum Δp is believed to be more reliable, this data point is not included in further evaluation. Leak test results show consistent trends, without large data scatter.

5.5.13.2 Summary of Test Results

The leak rate data for the flow pressurized zero-offset test show strong influence of the TSP presence. The evaluation for the area controlling the leakage flow presented in Section 6 indicates that the geometric area between the crack edge and the TSP hole face was controlling the leak rate towards the end of this test. The shallow slope of the latter part of leak rate versus Δp curve for this test indicates that the geometric area did not vary significantly beyond about 2000 psi. A crack of this length would be expected to expand rapidly, and very little further plastic expansion would be expected after flow pressurization, even during bladder pressurization.

The leak rate for the offset test was essentially equal to that of the zero-offset test. Because of the unusually long crack in this specimen, approximately 0.059" of the crack length was projecting outside the TSP even in the zero-offset test compared to 0.102" crack projection in the offset test. Since both tests had significant crack lengths outside the TSP, this test cannot be used to assess zero-offset versus offset leak rates. Offset leak rate data extrapolated to SLB conditions show a leak rate of about 6.2 gpm This SLB leak rate also applies to zero-offset test. Flow pressurization to about 2450 psid (Δp_{max}) opened the plastic crack TW width to about 0.032". The TW crack length, as indicated by visible light through the crack, was 0.811" of the total crack length of 0.838". The crack was more than 0.017" wide for about 0.6" length.

As in Test 11-2, an auxiliary step involving free span bladder pressurization to 2300 psi was performed after each test, including those following bladder pressurization to 2900 psi, to assess the magnitude of elastic deformation of the crack during leaking testing. Data from these auxiliary tests show an average of 0.003" increase in crack diameter. Inclusion of this elastic deformation with the plastic deformation measured at the end of offset test (0.020") indicates that the crack could have opened sufficiently to close the 0.025" crack-to-TSP gap. So, interaction between the crack edge and TSP hole could have occurred during the flow pressurized offset test. The crack area estimates presented in Table 6.8 show that such an interaction occurred for the flow pressurized offset test, which resulted in reduction of the area available for leakage.

The leak rate for the offset condition following bladder pressurization to the free span burst pressure of about 2900 psid is essentially the same as before bladder pressurization indicating that full expansion of the crack flanks had occurred during flow pressurization. Crack width measurements shown in Appendix D provide confirmation of no further increase in crack opening during bladder pressurization. The crack TW length increased only by about 0.002" from the beginning to end of all testing. The tube diameter in the plane of the crack increased by about 0.020" during the flow pressurized tests without further increase during and after bladder pressurization. Because of the flexible crack flanks of this very long crack, large elastic deformation would be expected to cause contact of the crack flanks with the TSP, but with insufficient force to cause inward buckling of the crack flanks.

The zero-offset leak rate after bladder pressurization is slightly less than the prior flow and bladder pressurization leak rate in the offset condition (about 5.8 vs. 6.2 gpm at the SLB condition of 2560 psid). In contrast, there is no difference between zero-offset and offset leak rates for the flow-pressurized tests. There is no clear cause for this small leak rate reduction since both test conditions include TW lengths outside the TSP and crack opening areas and crack diameters were not significantly changed by bladder pressurization.

5.5.13.3 Overall Conclusions

1. The crack tested in this sequence, 0.809" initial throughwall length, is larger than would ever be expected in field service for any repair limit since cracks of significant depth would be less than the 0.75" TSP thickness. Therefore, leak data from this test is not used in establishing the upper bound leak rate for APC.

2. The SLB leak rate prior to and after bladder pressurization is bounded by about 6.2 gpm at 2560 psi including the maximum potential 0.10" TSP offset condition.

3. Leakage results for this indication with 0.809" initial TW length indicate the effective leakage area becomes more or less constant above about 2000 psi Δp.

4. These leak rate results together with supplemental tests to estimate the elastic contribution to crack opening indicate that post-test measured plastic diameter increases of about 20 mils are sufficient to effectively close the crack-to-TSP gap and result in crack-TSP interaction with reduced leak rates.

5. Cracks well outside the acceptable ranges of other constraints (voltage, crack length limits) do not cause a large increase in the IRB leak rate. Although somewhat higher leak rates result for this 0.813" long crack, the observed trend of the TSP to limit leakage through interaction between the crack and the TSP is observed.

5.5.14 Test 4-1 Evaluation

5.5.14.1 Test Sequence and Data Analysis

This test sequence is unique in that it examined leakage from two TW cracks located 180° apart. The test specimen used (7/8" dia) included four cracks at the start of the tests, but only one had progressed throughwall. A bladder pressurization step conducted prior to any leak testing caused two additional cracks to be throughwall, including the one 180° apart from the already throughwall crack. In addition to the initial bladder pressurization, 5 more bladder pressurization steps were conducted with pressure increasing progressively to almost twice the estimated free span burst pressure. The tests were performed in the following order: bladder pressurization at about the predicted free span burst pressure of 5800 psi inside the TSP with zero-offset leak test, at 6000 psi with 0.15" offset and offset leak test, at 6800 psi with 0.15" offset and offset leak test, 8900 psi with 0.15" offset and both zero-offset and offset leak tests, 10120 psi with 0.15" offset and offset leak test , and 11350 psi with 0.15" offset at which time the specimen ruptured like a free span indication outside the TSP. Only the initial and 8900 psi steps had both zero-offset and offset leak tests. All leak tests were conducted at room temperature.

The data for this test sequence are plotted in Figures 5-49 and 5-50. They are also summarized in Table 5-25. Maximum Δp data are available for only one test in this sequence, so the data was evaluated on the basis of average Δp only. Figure 5-49 shows the data adjusted to the steam line break conditions, and Figure 5-50 shows the corresponding data for the test conditions. No leak rate data was excluded from the database because of hysteresis effects. The leak data show consistent trends with modest fluctuations. Crack and tube dimensions recorded during the course of the tests are shown in Appendices D and E.

Since the specimen had four cracks, it was intentionally centered within the TSP for the initial bladder pressurization test as there was no obvious preferred orientation to maximize the leak rates. The initial bladder pressurization expanded two crack openings located 180° apart sufficiently to close the initial 0.023" tube to TSP diametral gap. The test results are considered fully representative of limiting leak rates expected for multiple TW cracks following pressurization to the tube burst pressure, with the offset leak rate differences increased by exposing two TW cracks 180° apart.

5.5.14.2 Summary of Test Results

Only one out of the four cracks present in the specimen had progressed throughwall at the beginning of testing. After the first bladder pressurization step, three cracks were throughwall including two, 180° apart. Offsetting the crack from the TSP exposed both of these throughwall cracks. These two cracks influenced the differences in leak rates between zero-offset and offset conditions due to competition between the two cracks to occupy the clearance between the tube and the tube hole. This item is further discussed below.

The shallow slope of the leak rate vs Δp curves for all tests in this sequence indicate that the flow area controlling the leak rate did not vary much during the individual tests. However, significant differences found between leak rates for some tests indicate that the leakage area varied among the tests. The zero-offset condition was used only in two tests (Tests 4-1B and 4-1J). The results for these tests show that leak rates decrease significantly with increasing bladder pressure beyond the free span burst pressure (6000 psi for this specimen). For the SLB condition of 2560 psid Δp, the projected leak rate drops from about 2.4 gpm at 5800 psi bladder pressure to about 1 gpm at 8900 psi bladder pressure. This leak rate reduction is attributed to decreasing leakage area as the increasing pressures progressively close the crack-to-TSP gap due to plastic deformation of the tube, while crack opening areas only modestly increase. Evaluation of the tube and crack dimensional measurements obtained after the zero-offset test following pressurization to 8900 psi indicates that the crack faces contacted the TSP hole over close to 0.5" of the 0.626" TW length. The two cracks 180° from each other were the larger ones, and they both bulged such that the gap flow area within the TSP reduced for both cracks.

Leak rates with the crack offset 0.15" outside the TSP do not significantly change with increasing bladder pressure. The bounding leak rate for the offset conditions is about 4.3 gpm at SLB conditions or about 70% higher than for the crack within the TSP. This difference in leak rates for the offset and zero-offset conditions is higher than in the other sequences, and it is attributed to the existence of two throughwall cracks exposed outside the TSP.

Based on dye penetrant tests, the throughwall crack at the beginning of test had lengths of 0.24" (TW), 0.67" (OD). After pressurization to approximately the free span burst pressure of about 6000 psi two more cracks extended throughwall. The specimen then had three TW cracks of lengths 0.606, 0.567 and 0.388 inch with maximum crack openings of about 0.020, 0.015 and 0.007 inch. After pressurization to 8900 psi, the three TW lengths became 0.626, 0.603 and 0.408 inch with maximum crack openings of 0.022, 0.018 and 0.009 inch, respectively. The maximum tube diameter inside the TSP is likely to have nearly closed the entire tube-to-TSP gap. After pressurization to 10120 psi, the tube expanded to close the tube-to-TSP gap over almost the entire span of the TSP (Figure 6-2(j)).

At 11350 psid, the crack located at the 90° position burst like a free span crack outside the TSP. The crack was offset 0.15" outside the TSP (0.142" TW) in that test. The burst resulted in about a 1" fishmouth opening extended away from the edge of the TSP. This burst pressure for a TW crack 0.14" outside the TSP is approximately equal to the free span burst pressure of an undegraded tube, and is more than 3000 psi higher than the burst pressure predicted by the current correlation of burst pressure vs. throughwall crack length extending outside the TSP for 7/8" diameter tubing using average material properties. Reference 1 provides this correlation for ¾" diameter tubing.

5.5.14.3 Overall Conclusions

1. The SLB leak rates for this indication with multiple throughwall cracks, up to 0.61" TW length, after bladder pressurization to about the free span burst pressure are bounded by about 4.3 gpm with 0.15" offset, and by about 2.5 gpm for the crack within the TSP.

2. The crack opening areas are limited by the tube-to-TSP gap following contact of the crack face with the TSP hole, and the associated flow areas are less than the minimum geometric flow area formed by the gap.

3. Bladder pressurization beyond the free span burst pressure does not result in increasing leak rates. Based on this early test, it was concluded that it was not necessary to include bladder pressurization beyond the free span burst pressure in subsequent tests. The principal effect of further increases in bladder pressure is to close the tube-to-TSP gap along the crack opening due to plastic deformation and to expand the overall tube diameter to close the gap.

4. The crack located at the 90°-position burst like a free span crack outside the TSP at 11350 psi with the crack 0.15" outside the TSP (0.14" TW). This burst pressure exceeds the value from the applicable burst correlation for cracks extending outside the TSP by more than 3000 psi.

5.5.15 Test 2-8 Evaluation

5.5.15.1 Test Sequence and Data Analysis

The specimen used for this test sequence had an artificial "crack" created by cutting a narrow slit in a 3/4" dia tube using a laser. The main objective of this test was to determine if a substitute can be found for corrosion crack specimens used in these leak tests. The "crack" tested was a 0.55" long slit with a maximum initial width of about one mil. No bladder pressurization tests were performed for this test sequence. The tests were conducted in the following order: zero-offset, free span, offset, cold offset.

Data for this test sequence are plotted in Figures 5-51 and 5-52. They are also summarized in Table 5-26. Figure 5-51 shows the data adjusted to the steam line break conditions and Figure 5-52 shows the corresponding data for the test conditions. The data shown in these figures are presented on the basis of average pressure drop. Crack and tube dimensions recorded during the course of the tests are shown in Appendices D and E. The crack-to-TSP gap of 0.027" for this test, as demonstrated by the increase in crack diameter, is consistent with the target gap of 0.025".

Ten data points were deleted in this test sequence because of hysteresis effects from test pressure differential being lower than in the prior tests. Leak rate measurements show consistent trends with modest fluctuations and the data is considered acceptable.

5.5.15.2 Summary of Test Results

Results presented in Figures 5-51 and 5-52 show that leak rate trends for this laser produced "crack" are similar to those for the corrosion cracks, but the leak rate magnitude is higher especially for the offset conditions. The higher leak rates observed for the laser slit is due to the smooth walls of the slit and the larger crack opening areas especially at the crack tips. This point is further elaborated below.

Figure 5-53 compares the data adjusted to the maximum Δp at the start of the leak test against those based on average pressure drop. It is evident that both sets of data show similar trends regarding the effects of the TSP presence, and the SLB leak rates have not significantly changed, although the test pressures are increased by about 200 psi. However, data based on maximum Δp is more consistent.

The shallow slope of the leak rate curve above 1900 psi and the large increase in leak rate for free span conditions clearly demonstrate that the TSP presence significantly reduces leak rates. The evaluation for the limiting leak area presented in Section 6 shows that the geometric area between the crack edge and the TSP hole controlled the leak rate in the offset tests. Possible contact of the crack tip with the TSP also indicated. The effects of crack-TSP interaction for this laser produced specimen are similar to that for corrosion cracks, although the leak rates are too high to be representative of the corrosion cracks.

The maximum crack width for this specimen increased from about 1 mil width initially to 0.007" after the zero-offset test, 0.021" after the free span test and 0.035" after the offset test. This crack width exceeds the corrosion crack widths for specimens tested with up to 0.62" throughwall indication, and is exceeded in this test program only by the 0.044" width found for the 0.74" TW crack of Test 1-6, the principal basis of the bounding leak rate.

The maximum SLB leak rate for this laser produced specimen is about 6.1 gpm in the offset condition. This leak rate is non-prototypic since the large opening width of the laser slit results in large TW areas exposed by offsetting the TSP, which results in unrealistically large leak rates. Post-test photographs (Appendix F) of the this specimen show well rounded and wide openings at the tips of the slit that are not typical of corrosion cracks (compare photographs, Appendix F, for this specimen after offset test with those for Tests 1-7 and 2-7 which have comparable crack lengths). The crack opening TW area outside the TSP for this offset test of 0.0021 in2 is 60% higher than that for the largest corrosion specimen tested, which was used in Test 1-6 (0.74" TW vs. 0.55" TW for laser slit)

In Figure 5-54, leak rates for the 0.55" TW laser slit are compared with those for the 0.577" TW corrosion crack of Test 2-7. It is evident that the leak rates for the laser slit are significantly higher (factors of 3 to 4 in free span condition). The laser slit specimen also shows interaction with the TSP at lower pressures than the Test 2-7 corrosion specimen even though the crack-to-TSP gap was 0.027" for the laser slit versus 0.022" for Test 2-7.

5.5.15.3 Overall Conclusions

1. Laser-slit specimens are not an acceptable substitute for corrosion cracks for leak testing. Leak rate measured laser cut specimens are higher by a factor of 3 in free span leak rates as indicated by comparing Tests 2-8 and 2-7 results. The large widths at the tips of the laser slit result in non-representative leak rates for offset test conditions.

2. The trends and effects of crack-to-TSP interaction can be demonstrated by laser slits although the leak rates are too high to be representative of corrosion cracks

5.6 Loop Calibration Orifice Tests

5.6.1 Cold Orifice Test Evaluation

A supplemental test program was also performed using calibrated orifices as an overcheck of the leak rates measured in the IRB test program. As a part of this test program, flow rate through three circular orifices of different sizes were measured in the Westinghouse test loop. The same three orifice specimens were re-tested at an independent laboratory and certificates of calibration obtained (Appendix H). Based on the leak rates measured at the orifice calibration facility, uncertainty estimates were made for the leak rates measured in the Westinghouse test loop.

The orifices tested had diameters of 0.020", 0.040" and 0.080", respectively, which correspond to theoretical leak rates of about 0.4, 1.6 and 6.7 gpm at the reference SLB condition of 2560 psi. These leak rates span the range of leak rate measurements in the test program. Tests conducted in both the Westinghouse Test Loop and the independent calibration facility were performed at room temperature but at pressure differentials typical of the SLB conditions (1400 to 2560 psi). The results from both facilities are shown in Figure 5-55. The calibrated leak rates for the two smaller orifices are 1.1% and 0.7% higher than the values measured in the Westinghouse test loop. For the largest orifice, the calibrated leak rate was 1.7% lower than measured in the Westinghouse loop. Thus, there is excellent agreement between the leak rates measured at the two facilities.

5.6.2 Hot Orifice Test Evaluation

The three orifices used in the cold calibration tests were also tested at high temperatures (and pressures) representative of the steam line break conditions. A total of 27 tests were performed and data analyzed. Since no independent test facility, capable of performing high energy calibration tests could be found, the measured leakage rates were compared with analytical predictions based on generally used methodology for estimating two phase flow through orifices and pipes.

Empirical correlations based on two prior tests[2,3] and an analytical model developed by Henry and Fauske[4] to predict critical flow rate through orifices and pipes were used to calculate leak rates at the hot orifice test conditions. The results are shown in Table 5-11 and they are also plotted in Figure5-56. There are some significant differences between the present tests and the earlier work used for comparison which should be considered in comparing the results. Tests conducted by Fauske[2] measured critical flow rates for saturated conditions only, and application of those results to subcooled conditions would result in under prediction of the critical flow rate. Tests performed by Zaloudek[3] utilized subcooled water only and the pressure differential was limited to about 300 psid. While Fauske's test data was applied as is to the present conditions, a previously developed empirical correlation based on Zaloudek's data with modifications to improve predictions for saturated condition was used. Calculations based on the Henry-Fauske model assumed the same contraction loss coefficient (0.95) for all three orifices.

Both independent predictions and measured data show good agreement regarding the dependency of leak rate on pressure difference and primary side temperature. However, the predicted leak rates differ from the measurement by +16% to - 40%. The majority of the differences noted with other tests are attributable to differences in the test conditions. There is also some uncertainty in the applicability of the analytical model at the small L/D values of the orifices (1.2 to 4.1). Considering the complexity of two-phase critical flow phenomenon the agreement between the present data and those based on the earlier work is considered to be good.

The differences between the tests and independent predictions vary inversely with the orifice diameter, and thus, are smallest for the largest orifice diameter. The predictions for the large orifice (0.080" dia) show excellent agreement with the measured data. This provides confidence in the bounding leak rate established for the high voltage

ARC since the leak rate for this orifice size is representative of the bounding leak rate for the steam line break conditions.

Overall, based on the calibration tests at room temperature and the above comparison between measurement and independent predictions for the hot tests, it is concluded that leak rates have been measured accurately in the present program.

5.7 Leak Rate Measurement Uncertainty Evaluation

To assess the magnitude of the uncertainty associated with leak rate data reported herein, a systematic evaluation was carried out to identify the potential contributors for uncertainty and assess the extent of their impact. Design and construction of the test facility, instrumentation and data recording system selection, and test execution were all carried out so as to minimize potential uncertainties. Nevertheless, some uncertainties are to be expected in the data and they are evaluated in this section.

The possible sources of uncertainty are classified into the following categories.

- Fluctuations of leak rate during the test period
- Maximum Δp in test versus average for reported leak rates
- EPRI leak rate adjustment procedure per EPRI Report NP-7480-L
- Test loop calibrations

The total uncertainty is a combination of the contribution from each of the above sources. The individual contribution of these sources is discussed in detail below.

Since the primary objective of this test program is to establish a bound for the IRB leak rate, attention is focused on uncertainties at the high end of the measured leak rate spectrum. Uncertainty associated with average values is considered where appropriate.

5.7.1 Leak Rate Fluctuations During Test Period

The data reduction procedures for the leak rate tests average the measured leak rates, pressures and temperatures over a period of time. There is some fluctuation in the leak rate over this time period and the standard deviation of the fluctuation about the average is determined for each test data point. This value defines the leak rate measurement uncertainty for the test. However, note that the leak rate is determined based on an accumulator tank level measurement; therefore, the instantaneous measurement fluctuations are important only to the extent that they influence the beginning and ending measurements in the period of time where Δp measurements are also made.

The data point at 2543 psi Δp in Test 1-6C principally influences the bounding IRB leak rate of 5.5 gpm at 2560 psi. Thus, the test uncertainty for this data is of primary interest for the uncertainty assessment. This data value is an average of two data points differing in integrated leak rate by only 0.1 gpm and having test uncertainties, i.e., standard deviations of 9.2% and 12.4%. Since these are from independent samples, they each represent an estimate of the standard error of the underlying population for which the pooled estimate of the standard deviation is obtained as the root-mean-square average of these uncertainties, i.e., 10.9%. This uncertainty is typical of other tests with leak rates comparable to Test 1-6.

The estimated standard error of the integrated leak rate is then obtained from the standard error of the individual measurements by dividing by the square root of the sample size. The sample size used for averaging leak rates in the present experiments varied from 12 to 48. Since a smaller sample size yields a larger standard error, the standard error for the bounding leak rate was obtained assuming a sample size of 12 which is at the lower end of the sample size range used. The resulting standard error of the average leak rate is 3.1%. Thus, the leak rate measurement uncertainty on the leak rate measurement of 5.5 gpm is ±3.1%.

The overall uncertainty for the leak rate data collected during this test program can be obtained by developing the mean and standard deviation of the individual leak test uncertainties. Data for the hot and cold tests are considered separately for uncertainty calculation since cold tests have a smaller uncertainty. Figures 5-57 to 5-59 show the percentage standard deviation as a function of the leak rate magnitude. Figure 5-57 shows only hot test data with a leak rate between 1.5 and 6.5 gpm, while Figure 5-58 includes data from all hot tests and Figure 5-59 includes all cold test data. The results show a leak rate measurement uncertainty of 8.2% with a standard deviation of 5.6% for the hot tests and 2.4% with a standard deviation of 0.8% for the cold tests. If the hot test uncertainty is limited to the leak rate measurement range of primary interest (1.5 to 6.5 gpm) for this test program, the measurement uncertainty for hot tests becomes 7.2% with a standard deviation of 3.8%. These results show that the uncertainty on the Test 1-6 leak rate measurement is about 3% higher than the average for all data.

5.7.2 Maximum Δp in Test Versus Average for Reported Values

The maximum Δp applied in the test occurs prior to the time period over which data is averaged. The test Δp reported is the average value and it is lower than the maximum Δp applied to the test specimen. Because of occurrence of maximum Δp, the actual plastic crack opening is expected to be greater than that corresponding to the average Δp for the test. Thus, the reported leak rates are expected to be slightly high for the test conditions cited. This potential source of uncertainty was evaluated for the limiting Test 1-6.

The test leak rates were adjusted to the maximum Δp conditions by applying the hydraulic factor of the EPRI leak rate adjustment procedure, assuming that the primary pressure drop, as typical of most tests, was the predominant source of the observed difference between the maximum Δp and the average Δp. There would only be small differences in the adjusted leak rates if it were also assumed that the secondary pressure was lower at the time of maximum Δp.

The differences between maximum Δp and average Δp tend to be the highest for the largest leak rates and, thus, evaluation of Test 1-6 which defines the bounding leak rate is the appropriate test for evaluation. The differences between maximum and average Δp's are 189 psi for the two test data points in Test 1-6 used to establish the bounding leak rate.

The bounding SLB leak rate of 5.5 gpm (at 2560 psi Δp) is obtained by analyzing Test 1-6 data on the basis of average Δp. Examination of the same data on the basis of maximum Δp yields a bounding leak rate of 5.0 gpm. This implies that the bounding test leak rate of 5.5 gpm should be reduced to 5.0 gpm or a 10% reduction to account for the maximum Δp crack opening. Thus, the uncertainty on the bounding leak rate of 5.5 gpm due to Δp measurement uncertainty is -10%.

This uncertainty is dependent upon the specific test conditions. For other corrosion crack specimens with leak rates of 5 gpm or larger, the differences in SLB condition leak rates based on the average and maximum Δp's are smaller than that for Test 1-6. For these specimens, the SLB leak rates reported in the individual test evaluations presented earlier in this section (Sections 5.5) are the larger of the two predictions, which generally is the one based on maximum Δp. Since other contributions to the leak rate measurement uncertainty are also small, the assessment for Test 1-6 is applied to estimate the overall measurement uncertainty.

5.7.3 EPRI Leak Rate Adjustment Procedure

Potential uncertainty in the leak rate adjustment procedure is assessed by examining the correction applied for the limiting leak rate test, which is the test with 2543 psi Δp in Test 1-6 sequence. The leak rate reported for this test is an average of two data points whose measured leak rates differ by only 0.1 gpm. As the test conditions are close to the reference SLB conditions, the measured leak rates are adjusted only by a maximum of 6% for the two data points. The adjustment is due primarily to the higher difference in primary pressure over saturation pressure in the test, compared to the reference SLB conditions due to the test secondary pressure of 347 psi versus the desired 15 psi. The test temperature being 630°F compared to the desired 615°F also contributed to the correction factor. The hydraulic adjustment factor for this data point is essentially independent of the value used for c_p in the analysis (above a value of about 0.9) .

Based on the leak rate adjustment being only 6%, which is due to the test conditions being close to the reference SLB conditions, it is concluded that the uncertainty in the adjustment factors determined using the EPRI leak rate adjustment procedure for the Test 1-6 leak rate of 5.5 gpm is negligible.

For other specimens with SLB leak rates greater than 5 gpm, the maximum extent of adjustment factors for the measured leak rates are between 9% to 15%. The uncertainty on these adjustment factors would be only a few percent of the total leak rate and it is also justifiable for these tests to ignore the uncertainty in the leak rate adjustment procedure.

5.7.4 Test Loop Calibration

A supplemental test program was also carried out to assure that the leak rates measured in the main test program are sufficiently accurate. It entailed measuring flow rates through circular-hole orifices with a flow area in the same size range as the cracks in the specimens that were tested in the main program, and comparing the results with the leak rates measured at an independent calibration facility and/or with the leak rates predicted using generally accepted methods for two-phase flow through orifices and pipes. The test loop utilized calibrated instruments such that the uncertainty for instrument error can be considered to be negligible.

Two series of tests were performed to calibrate the test loop. In one of them, leak rates were measured at room temperature for three orifice sizes, first in the Westinghouse test loop and then at an independent orifice calibration facility and both sets of measured leak rates were compared. Details of this test and its results are presented in Section 5.6.1. The average adjustment factor to be applied to the Westinghouse loop data to obtain a match to the calibration laboratory data was calculated to be 1.001. This implies that the average uncertainty in the Westinghouse test loop leak rate data is 0.1%. An upper one-sided 95% confidence bound on the adjustment factor to be applied to the Westinghouse loop results was calculated to be 1.022, essentially independent of the size of the orifice. Thus, a 95% confidence bound on the uncertainty of the test data is 2.2%.

In the second calibration test series, the same three orifices were tested at primary system temperatures typical of steam line break conditions. The results of these tests were compared with predictions based on generally used methods for calculating two phase flow through orifices and pipes. Details of this test series and its results are presented in Section 5.6.2. Both independent predictions and measured data show good agreement regarding the dependency of the leak rate on the pressure difference and the primary side temperature. However, the predicted leak rates differ from the measurement by +16% to - 40%. The majority of the differences noted are attributable to the differences in the conditions of the present tests relative to those for the empirical data used for comparison, and uncertainty in the applicability of theoretical model considered. The differences between the tests and the independent predictions vary inversely with the orifice diameter, and they are smallest for the largest orifice diameter. As the leak rates measured in crack tests are comparable to those for the large size orifice, data for the large size orifice are more relevant. Good agreement between the tests and independent predictions for the large size orifice provides confidence in the present leak rate measurements.

Based on the calibration tests at room temperature and comparison between measured and theoretical leak rate for hot tests, there is no reason to question the adequacy of the leak test data for the crack specimens. Average uncertainty of 0.1% indicated by calibration tests at room temperature is used in assessing the overall uncertainty for the bounding leak rate predicted for the SLB conditions.

5.7.5 Summary of Uncertainty Assessment

To summarize, the contributors to the leak rate uncertainty for the bounding measured leak rate of 5.5 gpm are:

• Leak rate measurement uncertainty:	±3.1%
• Δp measurement uncertainty on leak rate:	-10%
• Leak rate adjustment uncertainty:	Negligible
• Test loop orifice test measurement on leak rate:	+0.1%

The overall uncertainty in the bounding leak is obtained by combining the above individual uncertainties. The maximum uncertainty is obtained by considering the upper limit for the individual uncertainties which is [(0.9)´(1.001)´(1.031) - 1] ´100 or -7%, with a 95% confidence bound of -5%. Similarly, the minimum uncertainty is given by [(0.9)´(1.001)´(0.969) - 1] ´100 or -13%. The combined effect of the Δp measurement uncertainty and the loop calibration uncertainty is a factor of [(0.9) ´ (1.001)] or 0.90 for a net uncertainty of -10%.

It can be concluded that the net uncertainty on the bounding leak rate of 5.5 gpm is in between -7% to -13%. The net uncertainty adjustment is negative in all cases, i.e., the bounding leak rate would be reduced; thus, it is conservative to not apply an uncertainty adjustment.

5.8 Conclusions

- Tests were conducted sufficiently close to the prototypic conditions such that the magnitude of the correction necessary to adjust data from hot tests to the SLB conditions is typically about 6%.
- Test conditions included a wide range of crack sizes including cracks larger than those that may occur even with an APC repair limit, with tube expansion, of 10 to 15 volts.
- Leak rates were measured over a wide range of primary system pressure and temperatures.
- The bounding leakage rate for an IRB at SLB conditions of 2560 psi Δp is 5.5 gpm. The uncertainty estimates associated with this bounding leak rate are -7% to -13%. Since both the upper and lower end of the uncertainty range have a negative value, it is conservative to ignore the uncertainties.
- The above bounding leak rate applies to indications offset from the TSP edge by up to 0.017" in both 3/4" as well as 7/8" tubes.
- Same size cracks in both 3/4" and 7/8" diameter tubing produce comparable leak rates. So data obtained for one tube size can be applied to the other tube size.
- The combined leak rate for two co-linear cracks separated by a short ligament is significantly less than that from a single lack with the same total TW length.
- Leak rate data from hot and cold tests with comparable Δp's show good agreement with each other when adjusted to SLB conditions. It is concluded that future leak rate tests for pulled tube specimen can be conducted at room temperature and the data reliably adjusted to the SLB conditions.
- Even after pre-pressurization to the free span burst pressure, the crack diameter may increase by as much as 0.004" due to elastic deformation from pressurization to the SLB Δp of 2560 psi.
- Laser produced specimen is not suitable for bounding the leak rates since it results in a much higher leak rate due a larger crack opening area, especially at the crack tips.

5.9 References

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6

TREND ANALYSIS

6.1 Introduction

It was expected that the IRB leak rates would be limited by three principal geometric factors: Crack area, Geometric Area and Effective Crack Area. These are illustrated in Figure 6.1-1 and are defined as follows:

- The crack area is the simple integral of the crack opening width over the length of the crack.
- The geometric area is the area between the crack flank and the TSP ID for both crack flanks. For simplicity, the crack opening is assumed to be symmetrical around the crack plane; thus the geometric area is twice the integral of the gap between the tube and TSP over the length of the crack. If physical contact occurs between the crack flanks and the TSP, the gap is zero; thus there is no contribution to the geometric area within the span of contact.
- The effective crack area is defined only for instances of contact between the crack flanks and the TSP. The effective crack area is the integral of the crack width over its length outside the crack/TSP contact length.

Initially, the limiting flow area is the crack area which would be expected to increase with increasing Δp up to the point where the geometric area becomes limiting. This occurs when the residual gap between the tube and the TSP becomes small, but not necessarily zero. Further increases in Δp eventually lead to contact between the crack flanks and the TSP. Increasing contact length between the crack flanks and the TSP ID would reduce the geometric area and, more rapidly, the effective crack area, until the effective crack area becomes limiting. This was based on the expectation that was verified during the tests that only limited crack tearing occurs at the predicted freespan burst pressure for cracks within the TSP (see Section 6.5).

Because of this expected crack opening behavior, it was further expected that the slope of the leak rate versus Δp curve would initially be similar to the slope of the freespan leak-rate versus Δp curve. The slope of the curve was expected to flatten as the geometric area became limiting, and finally go to zero slope (or potentially negative slope) in the transition from limiting geometric area to effective crack area since the available flow area continually decreases.

For cracks partially exposed (offset) outside the span of the TSP, it was expected that the leak rates would be essentially the same as the zero-offset leak rates for the crack area limited cases (both basic crack area and effective crack area). For the effective crack area limiting case, an extremely large offset, sufficient to expose a length of crack previously in contact with the TSP, could potentially result in an increased flow rate. For zero offset, geometric area limited tests, it was expected that the crack offset would result in a higher leak rate since additional flow area would be exposed.

6.2 Crack Opening Behavior

The structural behavior of a constrained tube crack depends on the length of the crack , the applied Δp and the interaction between the tube and the TSP. Longer cracks are expected to open to a fixed width and tube diameter at lower applied Δp than are shorter cracks, but the progression of crack opening for IRBs is generically the same for any length of crack within the span of the TSP.

Initially, the crack opening width and the tube diameter increase with increasing applied Δp. It would be expected that both Δd (change in diameter) and Δw (crack width profile) would vary approximately linearly in Δp so that a linear relationship would also exist between Δd and Δw. The total Δd and/or Δw are combined elastic and plastic deformations; thus, upon release of the applied Δp, elastic springback would be expected. (It was noted from the test data that both the longitudinal Δd and Δw profiles along the length of the crack are reasonably approximated by a half sine shape, a fact that permits theoretical studies of crack opening area.)

When the diametral growth is sufficient that the crack flanks contact the TSP ID, the crack flanks and tube section become much stiffer due to the approximately center support of the crack flanks by the TSP, and significantly higher applied Δp's are required for further plastic growth of the tube. Application of higher Δp results in outward plastic Δd growth of the bulk tube section if additional gap is available between the tube and the TSP, but inward plastic deformation (buckling) of the crack flanks. Consequently, at the point of initial contact, elastic springback of the crack flanks is expected to be toward the tube centerline (relaxation of the load), while after application of much higher Δp, the elastic springback of the crack flanks is expected to be outward toward the TSP ID (relaxation of the TSP restraint).

The expectations above are supported by observations from the testing. All of the specimens were pressurized with a bladder to the predicted freespan burst pressure for the final crack length. Figures 6-2(a) through 6-2(o) show the post pressurization Δd's for each step of test series. Test series 11 and 12 were set up to assure that the tube OD opposite the crack was in contact with the TSP ID. The absence of a gap greater than 0.0005" was verified by the use of a 0.0005" indicator shim between the tube and the TSP. For series 11 and 12, although the available TSP gap was 25 -26 mils in all cases, the maximum Δd is consistently between 20- 23 mils, except test 12-7 which was inadvertently pressurized to approximately twice the predicted freespan burst pressure. For test 12-7, the Δd is 26 mils for a significant span along the length of the crack. In test 12-7, the tube was reported to be tight in the TSP following bladder pressurization to the high Δp, while for all other tests, the tube was reported to be loose in the TSP. Therefore, the elastic springback for all except Test 12-7 of the series 11 and 12 tests was in the direction to relieve the interaction load between the tube and the TSP. For the highly pressurized tests, Test 12-7, the elastic springback was in the direction to relieve constraint of the crack flanks, that is, toward the TSP.

Test 1-6 was reported tight after offset flow pressurization. The tube expansion profile, Figure 6-1(c) , confirms the observation. The maximum measured tube expansion is 27 mils, suggesting a slight outward elastic springback to hold the tube tight in the TSP sized to provide a 26 mil gap with the tube. The flat profile at the center of the crack, similar to that observed in test 12-7, suggests progressive sealing of the crack flanks against the TSP ID.

Test 4-1 was also reported tight in the TSP after bladder pressurization. This test included only bladder pressurizations, starting at a Δp in excess of the predicted freespan burst pressure, 5800 psid , and progressing to 8200 psid as the next step. (Subsequent pressurizations were up to tube burst at 11350 psid, at which point the principal crack burst at the offset.) After the 8200 psid pressurization, the tube was reported to be tight in the TSP. Figure 6-1(i) shows the Δd in the principal crack plane (0-180°) and in the secondary crack plane (0-270°). The progression from point contact between the tube and the TSP to surface contact can be seen in the principal crack plane, and the overall tube section growth can be seen in the secondary crack plane. Thus, this test confirms the observations above for tests 12-7 and 1-6 regarding the crack opening and elastic springback behavior of an IRB.

6.3 Elastic Springback Tests

The elastic springback of the crack flanks was determined for two specimens by instrumenting the specimen with deflection gauges at the center of the crack and near the end of the crack, and pressurizing the tube with a bladder to a pressure slightly less than the highest Δp applied during the leak tests. The specimens tested were from tests 11-2 and 11-7, with cracks of 0.729" and 0.811" respectively. (The latter was the longest crack tested in these tests.) These tests confirmed that elastic springback occurs at the center of the crack flanks at a rate of approximately 1.25 mils per 1000 psid applied. A proportionately lower deflection rate would be expected to apply for shorter cracks.

6.4 Beginning of Test Tube to TSP Gap

For test series 1 to 4, the tube specimen was visually aligned within the TSP by balancing the gaps at the crack side of the tube and at the opposite side of the tube. For tests 11 and 12, contact between the TSP and the side of the tube opposite the crack was assured by the assembly sequence and an overcheck to gauge the friction force required to remove a 0.0005" shim from between the tube and the TSP.

The crack expansion, expressed as tube diametral growth, and the test sequence provide a basis for estimating the pre-test gap for test series 1 through 4. It would be expected that pressurization to the predicted freespan burst pressure would expand the crack to the TSP constraint, including an elastic component of expansion. Further, if flow pressurization prior to bladder pressurization results in crack expansion equal to, or exceeding, the bladder expansion, the gap prior to bladder pressurization must be at least equal to the gap that existed for the prior crack expansion. If the crack expansion profiles are similar for the majority of the test steps, including bladder pressurizations, then the tube/TSP gap is established clearly.

Based on this, the pre-test gaps for test series 1 through 4 were estimated as noted below. The gaps are summarized on Table 6.6. The numbers in parentheses are the throughwall crack lengths for reference.

- Test 1-1: (0.620") The maximum tube expansion after offset flow pressurization to 2769 psid was 9 mils. Subsequent freespan flow pressurization to 2603 psid and bladder pressurization to 4250 psid resulted in maximum tube expansion of 13 mils. Therefore the setup tests gap was in the range of 12 to 16 mils, i.e., the measured plastic deformation plus an elastic component of about 3-4 mils. It is likely that the lower end of the range applied for the flow pressurization tests.

- Test 1-2: (0.620") The maximum tube expansion after offset flow pressurization to 2780 psid was 13 mils. Subsequent bladder pressurization to 4080 psid changed this by only 1 mil. Therefore, the test setup gap was in the range of 15-16 mils.

- Test 1-6: (0.740") The test setup gap was 26 mils based on the maximum tube expansion.

- Test 1-7: (0.600") The maximum tube expansion after offset bladder pressurization to 2710 psid was 20 mils. Subsequent bladder pressurization to 2970 psid increased the maximum tube expansion to 22 mils. Therefore the test setup gap was essentially the full gap of 26 mils, with the possibility that prior to bladder pressurization, the gap was 2-3 mils less.

- Test 2-1: (0.515″) The maximum tube expansion after offset flow pressurization and bladder pressurization is between 9 and 11 mils. Therefore the test setup gap was in the range of 12 to 14 mils.
- Test 2-4: (0.290″) This specimen with a short TW crack (0.230") did not expand significantly until bladder pressurization at 5500 psid. At that pressure, the maximum tube expansion was 21 mils. Therefore, the test setup gap was the full 26 mil gap, although the crack properties prevented interaction with the TSP until after pressurization to the predicted freespan burst pressure.
- Test 2-7: (0.577″) The maximum tube expansion after offset flow pressurization of 2900 psid was 22 mils. Subsequent bladder pressurization to 3700 psid did not increase the tube expansion. Therefore, the test setup gap was the full TSP gap of 25 mils.
- Test 2-10: (0.425″) The maximum tube expansion after bladder pressurization to 3850 psid was 3 mils. Following bladder expansion at 4960 psid, the maximum tube expansion was between 9 and 11 mils. Therefore the test setup gap is estimated at 12 - 14 mils.
- Test 4-1: (0.670″) Only leak tests after bladder expansions were performed in this test. Following the initial bladder expansion at 5800 psid, the maximum tube expansion was 25 mils. Increased pressure bladder expansions did not increase the tube expansion. Therefore, the test setup gap was 25 mils.

6.5 IRB Test Crack /TSP Interaction Comparisons with Belgian Crack Opening Diameter Correlation

The interaction between the test specimens and the TSP indicated by the flow measurements can be evaluated by comparing the indicated interaction pressures with prior work (Ref. 1) that related the crack opening diameter for different tube materials and sizes as a function of applied Δp. The prior work included tests of tubes with EDM and laser cut slots, reinforced by a thin shim between the tube and an internal bladder used to pressurize the tubes. The data for crack opening diameter as a function of the ratio of the applied Δp to the freespan burst pressure for Alloy 600 tubes, 0.750" and 0.875" diameter, are shown in Figure 6-3. The linear regression fits for both sets of data, excluding the points at the freespan burst pressure, are also shown. The regression lines can be used to estimate the Δp at which the test specimens crack flank would be expected to contact the ID of the TSP. Based on these data, for 3/4" tubes, a factor of approximately 0.69 on the freespan pressure applies for a 25 mil increase in tube diameter, while for 7/8" tubes, a factor of approximately 0.52 on the freespan burst pressure applies.

Table 6.1 summarizes the test specimen initial crack lengths and flow stress. Based on these, the predicted freespan burst pressures were calculated using the correlation of Ref. 2, and these are also included on Table 6.1. Finally, applying the factors noted above for 3/4" and 7/8" tubes, the expected Δp at which a diameter increase of 0.025" would be expected, and the indicated Δp at which flow interaction was observed in the tests are also included on Table 6.1.

Generally, there is good agreement between the estimated tube/TSP contact Δp for a 0.025" gap and the Δp at which flow interaction was believed to occur in the tests. Since the Belgian data are interpreted as purely plastic deformation, the predicted contact Δp may be somewhat lower than shown on Table 6.1 since the elastic component of the diameter increase would cause tube/TSP contact at a lower Δp.

6.6 Crack Lengths Outside TSP for Offset Test

The crack throughwall length measurements were made using an internal light source and measuring the length of the light visible through the crack. Although the specimen was rotated to view the crack from different angles to assure that the visible light represented the true crack, the crack angle through the tube wall may be such as to prevent seeing the total throughwall crack length. Further, the throughwall length will be underestimated slightly because the resolution of the visual measurement process is a crack opening about 1 mil wide, and the crack tapers to zero at both ends. Therefore, the throughwall crack length measurements to establish the crack offsets for these tests were conservative; that is, the actual throughwall offsets tested are expected to be greater than the measured values.

Leak tests were performed with the crack tip offset from (outside) the edge of the TSP under both flow pressurization and bladder pressurization conditions. The crack offset for 3/4" diameter specimens was nominally 0.10", and for 7/8" diameter specimens, 0.15". For test sequences 1 through 4, the offset of the crack to the TSP edge was determined by the end of the crack defined by the prior test (i.e., not necessarily the end of the confirmed throughwall crack). The offset tests for sequences 11 and 12 were set up based on the tip of the confirmed through-wall crack. For the first offset test in sequence 12-1, the throughwall length could not be identified by the light process noted above, and the test was set up based on the end of the total crack. After flow, pressurization, it was identified that 0.105" of the crack projected outside the TSP.

Table 6.2 summarizes the resulting crack tip offsets at the end of each respective test sequence. In some instances, e.g., Test 11-7, 11-2 and 12-7, the throughwall crack extended further beyond the TSP at the end of the test than prior to the test. This is clearly observed in these tests since the pre-test setup was based on the tip of the throughwall crack, and the post-test throughwall crack offset is greater than the pre-test offset. This also happened in other tests but is less evident due to the test setup procedure. Table 6.2 summarizes the total crack lengths exposed after the completion of the flow-pressurized and bladder pressurized leak test series.

A ¾′ diameter tube pulled from Plant AA-1 (Reference 3) was tested like the specimens in this tests program. The offset of the crack from TSP for the pulled tube test was shown to be 0.20″ based on post-test SEM fractography. The results from the offset test of the pulled tube were the same as the results from the leak tests of the specimen centered n the TSP.

It is seen that the tests include total crack length offsets up to 0.11" (Tests 11-7) for 3/4" diameter tubing and 0.21" (Tests 1-2 and 11-2) for 7/8" diameter tubing, with corresponding throughwall lengths up to 0.1" and 0.17", respectively. A ¾″ pulled tube was tested with 0.2″ offset, without any change on the leak rate data between the offset and zero-offset conditions. Thus the IRB database supports crack offsets up to 0.21 inch.

6.7 Changes in Crack Length from Beginning to End of Test

Prior to any leak testing, the total length of each crack was determined by applying dye penetrant and pouring internal and external silastic molds that absorbed the dye from the crack. The length measurement was then made directly from the dye pattern absorbed by the silastic mould. Because the crack openings became too wide for dye penetrant tests after the pressurization steps in the test sequence, subsequent length measurements were made visually using a toolmaker's microscope. The visual method of length measurement typically resulted in slightly shorter measured cracks than the dye penetrant method for unpressurized tubes as shown by pre-test overcheck length measurements using the visual method. Following pressurization, the cracks opened somewhat and could be much more readily seen with the toolmaker's microscope.

The total crack extensions are summarized on Tables 6.2 and 6.3. Total crack extension is the increase in the length of the total crack (not only the throughwall crack) after pressurization to the Δp shown on the table. The SLB Δp was achieved entirely by flow pressurization, while the freespan burst Δp was achieved by bladder pressurization. The crack length measurements reflect the length of the crack after completion of leak testing for flow pressurization and for bladder pressurization, respectively.

Post test fractography was performed for selected test specimens to determine the pre-test crack (corrosion and fatigue) and the post-test length (crack tearing increment). The pre-test condition was differentiated from the post-test by the oxidation film that had developed in a short pre-test exposure to a high temperature oxidizing environment. Crack tearing that occurred during the leak tests appeared as bright metal in contrast to the oxidized surfaces of the original corrosion/fatigue cracks.

Table 6.3 summarizes the fractography results together with the measurements made during the tests. The "bottom end" noted in the table is the end that was offset from the TSP for the offset leak tests. The fractographic crack lengths are generally slightly longer than the in-process test measurements. This was expected particularly for the post-test measurements due to the lesser resolution of the visual/light-based measurement method which required a 1 mil crack opening to identify a throughwall crack. The fractographic throughwall measurements show that the throughwall length at the end of testing was approximately equal to the OD length. This, together with the overall longer cracks than apparent from the in-process measurements, indicates that the exposed crack lengths and exposed throughwall crack lengths are greater than shown on Table 6.2.

Except for tests 1-2, 2-1 and 12-7, the measured crack extensions, including bladder pressurization to the predicted freespan burst pressure, are less than 50 mils. Expected freespan burst crack tearing is >250 mils; thus the observed crack extensions are considered negligible.

Crack tearing for tests 1-2 and 2-1 was 90 mils and 64 mils, respectively, after flow pressurization to 2387 psid and 3086 psid respectively. Both of these crack extensions were related to opening of additional, previously unobserved, crack segments which were non-throughwall, tight OD cracks that were not visible to the measurement techniques. In specimen 1-2, a branch crack opened up at the side of the main crack. This branch crack was not throughwall until pressurization to the freespan burst pressure. The crack extension of specimen 2-1 was associated with the opening of two microcracks collinear with, but not connected to, the main crack at the start of the test. Test 12-7 was inadvertently pressurized to 6200 psid during the bladder pressurization step. Even at this high pressure, compared to the predicted throughwall burst pressure of 3950 psid, the crack extension of 0.183" was significantly less than the freespan crack tearing associated with tube burst.

Based on this, it is concluded that for cracks within the TSP, crack extension is negligible for pressurization up to the freespan burst pressure of the indication.

6.8 Bobbin Voltage Characteristics of Long Cracks

These tests were performed in support of proposed high voltage Alternate Repair Criteria which utilizes tube expansions to prevent significant TSP displacement during a postulated SLB event. The test specimens were selected to simulate the extreme conditions of crack lengths which could be physically acceptable under the guidelines of NRC GL 95-05 and the longest acceptable throughwall crack based on predicted freespan SLB burst capability.

Based on the burst correlations included in the data base supporting the ARC for ODSCC at TSPs, the limiting freespan crack length for SLB Dp, utilizing lower tolerance limit (LTL) material properties for the tube is 0.75 inches for ¾" diameter tubes and 0.84 inches for 7/8" diameter tubes. In these tests, the longest throughwall ¾ inch diameter specimen tested was 0.806 inches (Test 11-7) and for 7/8" diameter specimens, 0.746 inches (Test 11-1).

GL 95-05 states that no crack that is found to extend beyond the constraint of the TSP may be kept in service, regardless of its bobbin voltage characteristics. Consequently, crack specimens up to, and slightly exceeding, 0.750" in length were selected. Shorter crack specimens were also tested; however, these specimens are difficult to produce in a laboratory environment.

Clearly, throughwall cracks approximating the length of the TSP constraint would be expected to exhibit bobbin voltage characteristics that would require their removal from service on the basis of the bobbin voltage. The proposed high voltage ARC had as an objective an acceptable voltage level of 3V if tube expansions are utilized to fix the TSPs, compared to the allowable GL 95-05 voltage level of 1 to 2 volts, depending on tube diameter, for ARC without tube expansions.

Eddy current testing was not generally performed on all of the test specimens due to the limited time available for the tests. However, early specimen selection process did include bobbin testing of a few specimens. Subsequently, other longer crack specimens were tested under other programs.

Table 6.4 summarizes the available bobbin voltage data for crack specimens tested and other laboratory specimens similar to the test specimens. In addition, Table 6.4 excerpts data for the pulled tubes that support the data base (Ref. EPRI NP-7480-L, Vols 1 & 2, Rev. 1) that supports the ARC for axial ODSCC at the TSPs. The shortest throughwall indication among these data, 0.24" (total crack length of 0.67"), had a bobbin voltage of 8.55 volts . The longest throughwall indication, 0.47" (total crack length of 0.67"), had a bobbin voltage of 15.7 volts. The longest overall crack length, 0.81" (throughwall crack length of 0.42") had a bobbin voltage of 13.55 volts. These data show that a longer throughwall length of a crack results in a much higher bobbin voltage, and that even short throughwall cracks, about one third the length of the cracks tested, have bobbin voltages greater than the proposed ARC voltage limit by a factor of about two to three.

Recent pulled tube data are also included in Table 6.4. Two pulled tubes from Plant AA-1 included bobbin DI calls that were destructively examined. These two indications had field bobbin voltages of 8.93 and 6.08 volts, respectively, for total crack lengths of 0.698" and 0.688", based on destructive examinations. The throughwall portion of these cracks were 0.268" and 0.260", respectively. Even these very short throughwall cracks exhibited bobbin voltages 2-3 times the proposed acceptance criteria under the high voltage ARC, and would therefore not be candidates to remain in service.

The conclusions drawn from the available data are that the voltages for even the shortest length throughwall cracks tested are significantly higher than the proposed allowable limit for the high voltage ARC. Consequently, the cracks tested in this program represent an extremely conservative upper limit relative to any crack that would be considered for retention in service.

6.9 Consideration of Multiple Throughwall Cracks on Leak Rates

The leak tests principally utilized specimens with single cracks to provide a uniform basis for interpretation of the tests. However, the initial tests, test sequences 2-4 and 4-1, utilized available crack specimens that had been prepared for another program, which included more than one throughwall crack. Similarly, crack specimen 12-1, that was prepared using a similar procedure, also included two throughwall cracks. All other specimens included only a single throughwall crack at the start of the pressurizations.

Two of the final specimens tested, tests 11-1 and 11-2, included secondary cracks that were TIG welded to prevent opening of these crack and leakage. These specimens were dimensionally characterized before leak testing and were determined to be acceptable, i.e., dimensionally typical of non-welded specimens. On test 11-1, after bladder pressurization to 3670 psid, the secondary crack became visible on the OD, but no throughwall length was detected. Following the offset leak test, TW pinholes were detected, and the width of the holes was estimated at 4 mils. Post-test destructive examination confirmed a throughwall length of approximately 30 mils.

Pulled tubes and model boiler specimens in the EPRI ARC database (Ref. EPRI NP-7480-L) with significant voltages have generally shown (see exception below) a single dominant crack. When secondary throughwall indications are found, the throughwall length of the secondary crack is much shorter than the dominant crack. A specimen with multiple cracks may have the cracks in separate planes or as separate segments of an apparently longer crack in the same plane. The total leakage of such a specimen is the cumulative leakage of each of the discreet cracks or segments of a crack. Therefore, since leakage increases exponentially with throughwall crack length (for both free span and within TSP), the leak rate for an indication with multiple cracks is almost entirely due to the longest crack. The leakage does <u>not</u> depend on the apparent total length of the crack. Thus based on morphology considerations for prototypically prepared indications, leakage from secondary cracks does not contribute significantly to the total leakage.

In Plant S, pulled tube R42C43 had throughwall cracks 0.50 and 0.41 inch long in a 22.9 volt indication. The similarity of the lengths of these cracks is an exception to the general conclusion that a single crack dominates a multiple crack condition. However, the calculated leak rate for the longer crack is about three times the leakage of the smaller crack. Thus, even for this exception to the general finding that a single crack dominates a multiple crack condition, the leak rate is principally due to the longest crack.

The tube pulled from Plant AB, R20C7, TSP3 also included two comparable TW lengths of 0.602 inches and 0.562 inches at the same TSP location. During burst test, only one of the indications burst, indicating that ligaments existed in the second crack which would have limited the secondary crack leakage to a small value relative to the principal crack that burst.

Burst tests of parallel EDM slots have also shown that the dominant crack is the crack that bursts. In these tests, the burst pressure correlates with the dominant crack and is not significantly influenced by the other indications. Similarly, for an indication restricted from burst by the TSP, the dominant crack would have the dominant crack opening contributing to leakage.

Based on the above leakage and burst dependence on the dominant crack, expected multiple throughwall IRBs would have leakage dominated by the primary crack when the crack is within the TSP. The additional case of offset throughwall cracks is discussed below.

Pulled tube examinations show that the throughwall part of a crack is located away from the edge of the TSP. Of 16 throughwall indications on pulled tubes with 1 to 16 volt indications having sufficient data to locate the end of the throughwall crack relative to the edge of the TSP, only 1 throughwall crack was within 0.1" of the edge of the TSP and 12 were > 0.2" from the edge of the TSP. Structural analysis of the steam generators has shown that the maximum TSP displacement during a postulated SLB occurs in a local area of the upper TSP. The incidence of ODSCC at the TSPs is smallest at the upper TSP, occurring principally at the higher temperatures that exist at the lower TSPs. Thus, only an extremely small fraction of the indications is likely to have throughwall lengths exposed by maximum TSP SLB displacement. Therefore, the likelihood of two throughwall cracks exposed by TSP displacement would be very small and can be ignored for defining the bounding leak rate for IRBs.

Specimens 2-4 and 4-1, as noted above, had multiple throughwall cracks exposed by the TSP test offset of 0.15" with an apparent influence on increasing the offset leak rate. However, this is a unique artifact of the doped steam method of specimen preparation. The doped steam crack specimens are prepared by mechanically slightly ovalizing the tube to increase the stresses and enhance crack initiation and growth for the accelerated tests. This process frequently results in cracks 180° apart that are axially aligned, which increases the offset leakage compared to cracks more randomly located around the tube. However, within the TSP, the cracks at 180° apart reduce the effective flow area for each crack due to interaction with the TSP. Thus, these results do not affect the conclusion that the leak rate from the secondary crack in multiple crack situations can be ignored.

Specimen 12-1 is a typical example of a dominant TW crack (0.515" at start of test and 0.63" after bladder pressurization) plus a smaller secondary TW crack (0.360" at start of test and 0.41" after bladder pressurization). The leak rate for this indication of 3.2 gpm for flow pressurization was dominated by the larger crack and the secondary TW crack remained tight (< 1 mil TW width) with pressurization to 2680 psi. Following bladder pressurization to the free span burst pressure of about 4850 psi for the larger crack, the secondary crack was opened but the primary crack had about nine times larger crack opening area . Thus, the post bladder pressurization leak rate of 5.7 gpm was dominated by the primary crack with only about 10% to 15% of the leakage attributable to the smaller crack. This test result is consistent with the discussion given above that leakage will be dominated by the largest TW crack.

Correlation of the leak rate data with the crack properties (Section 6.10) of the test specimen for test 11-1 also tends to confirm that the principal crack dominates the specimen leak rate. The specimen in this test had two co-axial cracks, 0.620 in. and 0.129 in. in length. Correlation based on the total throughwall length of the principal plus secondary cracks in this specimen cause the point to fall off the regression line for all tests. If only the principal crack length is considered in the correlation, the data point falls on the regression line of leak rate versus throughwall crack length.

Overall, it is concluded that the bounding IRB leak rate, as obtained for a single crack, does not have to be adjusted for potential multiple throughwall indications. This conclusion is based on the high likelihood of finding a single dominant throughwall indication that controls the leak rate, the very low likelihood that two throughwall indications would be exposed as a result of TSP displacements and the Test 12-1 leak rate results which showed that the contribution of the secondary crack to the leak rate was very small.

6.10 Leak Rate Dependence on Crack Properties

This section summarizes the trend of the leak rates with the following crack properties:

- Length
- Opening Area
- Offset Length
- Offset area

The method of evaluation is to correlate the leak rate measured at the highest pressurization, corrected to reference primary temperature (615°F) and secondary pressure conditions (15 psia), with the measured crack properties at the end of the highest pressurization. The use of the leak rate corresponding to the peak Δp is critical for the flow pressurization tests where hysteresis due to prior pressurization could significantly influence the trends if a specimen had been exposed to higher Δp prior to the leak test measurement. Since the crack responds structurally to the highest Δp applied, the use of a flow rate other than the measured flow rate at that condition (such as a reference value at SLB conditions) will lead to scatter due to the mismatch of crack area, length, etc. with the flow rate. For the bladder pressurization leak tests, use of a reference flow rate, such as an extrapolated/interpolated flow rate at a reference Δp condition, is acceptable since the bladder pressurization was at higher pressures than all of the subsequent leak tests, and the crack characteristics will not change due to the leak test pressurization. However, the maximum Δp leak rate was utilized even for the bladder pressurized tests for consistency of comparison with the flow pressurized tests. Table 6.5 summarizes the leak rates used for these correlations, and provides references to the leak rate data tables in Section 5.

The crack properties considered for correlation are length, throughwall length, and width, measured after completion of each test sequence. The basis of correlation is regression analysis of the population of flow rates from both the flow pressurization and bladder pressurization tests. The exception to this is specimen 2-8, the laser slotted specimen that was found to be non-representative of the population of corrosion/fatigue cracks and is therefore excluded from the regression analyses. However, the data points for specimen 2-8 are shown for comparison purposes.

In all cases, flow area calculations were based on the post-test crack offsets measured by using the toolmaker's microscope and the back-light method described previously. The crack area was calculated based on the assumption that the crack tapers linearly to zero from the first and last width measurement to the ends of the measured throughwall crack.

Table 6.6 summarizes the crack lengths and areas for the flow pressurization and bladder pressurization tests, together with the measured flow rates corresponding to the maximum pressurization condition and extrapolated/interpolated flow rates at the reference SLB Δp condition, 2560 psid. The maximum pressurization flow rates are taken from the data tables in Section 5 for the peak pressurization Δp, and the SLB Δp leak rates are manually interpolated or extrapolated from the Section 5 figures. The SLB Δp leak rates are therefore approximate leak rates.

6.10.1 Leak Rate vs Crack Length

Figures 6-4 (a), (b),and (c) show the zero offset maximum Δp leak rates plotted against the throughwall crack length. Figure 6-4(a) shows the leak rates from flow pressurization tests, Figure 6-4(b) shows the leak rates from bladder pressurization tests and Figure 6-4(c) is a combined plot of the flow and bladder pressurization tests. Excellent correlation between the flow rates, both for flow pressurization and bladder pressurization, and the throughwall crack lengths is observed with relatively little scatter around the regression curve.

For the flow pressurization case (Figure 6-4(a)), the greatest variance from the regression curve is test 11-1. The specimen in this test had two co-axial cracks, 0.620 in. and 0.129 in. in length. If only the longer of the two crack segments is considered, the data point falls on the regression line as is indicated by the arrow adjacent to this point. Thus, this specimen tends to confirm the evaluation in Section 6.9 that concludes that the shorter of paired cracks does not contribute significantly to the leakage flow rate.

Figures 6-5 (a), (b) and (c) show the maximum Δp offset leak rates as a function of the total throughwall crack length. Although the scatter about the regression line appears to be somewhat greater than for the zero offset tests, the correlation between offset leak rate and crack length is good. The largest deviation from the regression line is specimen 2-8, the laser cut specimen, and this point is not included in the correlation. As noted previously, the structural response of the laser cut specimens does not simulate the response of corrosion cracks and are therefore not useful in leak rate testing of corrosion cracks, and these results confirm that conclusion.

Figure 6-6 shows a combined correlation in throughwall crack length utilizing both the offset and zero-offset data which also shows the individual correlations for the offset and zero-offset data. The individual regression lines for the zero-offset and the offset leak rates as a function of the throughwall crack length are very similar. The difference in slopes of the regression lines suggest that the offset leak rates are lower for shorter throughwall crack lengths, but are the same for the limiting crack length of 0.75 inches. The slight difference in slope is considered the result of the relatively small number of data points, the distribution of these points and measurement uncertainties of the throughwall and offset crack lengths. The combined correlation suggest that the difference in the slopes of the individual correlations is indeed the result of normal data scatter, and no the result of systematic difference between offset and zero-offset leak rates. Therefore, it is concluded that the leak rate for a crack is the same regardless of whether the crack is offset from the TSP or completely within the envelope of the TSP, within the bounds of the offsets tested. A limiting offset can be defined, beyond which this conclusion is no longer valid. The limiting offset is discussed in Section 6.12.

6.10.2 Correlation of Zero Offset Leak Rate with Crack Area

The data for crack areas and limiting crack areas for the flow pressurization tests and for tests after bladder pressurization are summarized in Table 6.7. The definitions of the respective flow areas were provided in Section 6.1. Calculations of the flow areas were based on the in-process measurement data for the crack specimens provided in Appendix D, with an allowance for elastic deflection included.

Figures 6-7 and 6-8, respectively, show the correlation between the leak rates and flow area for the non-offset flow and bladder pressurization conditions. Figures 6-7 (a) and 6-8 (a) show the correlation between the leak rate and the total crack opening area at the completion of the respective tests. Figures 6-7 (b) and 6-8 (b) show the correlation between the leak rate and the more limiting of the total crack area, the geometric area or the effective crack area.

Two of the flow pressurized tests, Tests 1-6 and 11-7, are limited by the geometric area. Specimens 1-6 and 11-7 are the two longest throughwall cracks tested; thus, it would be expected that the Δp reached during flow pressurization could expand these cracks sufficiently to cause the geometric area to be limiting. Short cracks would not be expected to expand sufficiently to cause the geometric area to be limiting.

Four of the 12 bladder pressurized data tests (Tests 1-2, 1-6, 4-1 and 12-7) are limited by the geometric area. Except for Test 2-1, all of the other tests are limited by the effective crack area, the area of the crack outside of the contact zone between the crack flanks and the ID of the TSP.

For the flow pressurization tests, the correlation is good, however, there is considerable data scatter. The regression line is clearly skewed toward a higher flow by tests 11-2, 12-7, and 1-2 which are well above the regression curve. The largest leak rate is from Test 11-7, a test of a crack longer than the limiting crack length, included to demonstrate that even extremely long cracks do no result in a sudden departure from the leak rate trend of all cracks (IRBs). In fact, the leak rate from test 11-7 lies below the regression line, confirming this conclusion. In general, for small crack opening width, the relative error in measurement is larger than for larger crack opening widths, and this is believed to account for much of the data scatter.

The correlation of leak rate with total crack opening area after bladder pressurization, Figure 6-8 (a) is qualitatively similar to the correlation for flow pressurization leak rates. The regression fit is anchored at the upper end by test 12-7 with an apparently low flow rate for the indicated area. The remaining data suggest a steeper slope than the regression fit which is dominated by Test 12-7 shows. Four of the 12 tests plotted were limited by the geometric area and seven other were limited by the effective crack area (see Table 6.6). The greatest changes (from total crack area to limiting area) occurred in the tests that were tight in the TSP (12-7, 1-6) after pressurization (see

Figure 6-2 c & o). Test 12-7 clearly confirms interaction between the crack flanks and the TSP, since the limiting flow area is almost an order of magnitude smaller than the total crack area.

Tests 12-1 and 4-1 are included in the regression analysis: The specimen for test 12-1 had 2 cracks, 90° separated. For this specimen, the limiting area is the sum of the effective area of the primary crack and the total area of the secondary crack. The Test 4-1 data point is from testing after pressurization to 8900 psid. When the corrections for limiting flow area are included, an excellent correlation of flow with area results. Thus, this evaluation strongly supports the expected crack behavior discussed in section 6.2.

Figure 6-9 shows that the regression fit of the flow pressurized leak rates and the bladder pressurized leak rates as a function of the limiting flow area are characteristically similar as would be expected. As noted above, the flow pressurized leak rates exhibit larger data scatter than the bladder pressurized tests, and this is due to difficulty in characterizing the available flow area of the relatively tight cracks prior to significant crack opening due to the higher pressurizations during bladder pressurization.

It is concluded that there is a strong correlation between the measured leak rates and the crack area (total, geometric or effective). The scatter in the correlation significantly decreases when the limiting area is utilized in the correlation. This confirms the expected behavior that cracks will interact with the ID of the TSP to limit the available area for leakage as noted in Section 6.2 .

6.10.3 Offset Leak Rate vs. Crack Area

Table 6.7 summarizes the crack areas including throughwall area, offset area, geometric area and effective area for the offset test conditions. Area calculations assume that the crack tapers linearly to zero width at the crack tip from the measurement made nearest the crack tip. Because the light based measurement technique resolution is limited to approximately 1 mil or greater crack width, some error occurs in calculating the crack area, proportionately greater for the smaller crack openings. The geometric areas are based on the post-offset test tube diameter but assume that the crack was completely inside the span of the TSP. Therefore, the added flow area bounded by the crack flanks and the TSP ID in the plane of the TSP surface (outside of which the tube is offset) is ignored, and the actual flow area for the geometrically limited cases is slightly greater than shown. Thus, if the calculated geometric area and the crack limited area are approximately equal, the crack area (effective area) can be considered limiting.

Figures 6-10 through 6-12 show the offset leak rate as a function of the crack area. Figure (a) of each figure shows the offset leak rate as a function of the total crack area, and Figure (b) shows the offset leak rate as a function of the limiting flow area. The limiting flow area is taken as the smaller of the effective area or geometric area. The tests (see Table 6.7) for which the geometric area is less than the total or effective crack area are Test 1-6 for the flow pressurized tests, and Tests 1-6, 2-7, 2-10 11-1 and 12-7 for the bladder pressurized tests.

The leak rate correlates reasonably with total crack area for both the flow and bladder pressurized tests (Figures 6-10 (a) and 6-11 (a), respectively). The data show significant scatter over the entire range of the correlation, which would be expected due to the compounded measurement uncertainties for both length and width of the cracks, and most significantly, due to use of the uncorrected total crack opening areas. When corrections are made for the limiting flow area, the scatter is significantly reduced for both the flow and bladder pressurization cases, Figures 6-10 (b) and 6-11 (b), respectively.

Figure 6-10 (b) clearly shows that the laser slotted specimen is outside the population of leak rates, and thus, Test 2-8 is excluded from the regression analysis.

On Figure 6-10, tests 12-1 and 12-7 also are significantly removed from the remainder of the data, and in fact, tend to bias the regression toward a higher flow rate. Specimens 12-1 and 12-7 had pre-test total crack lengths of 0.607" and 0.590" respectively, and throughwall crack length of 0.585" and 0.634" (see Table 6.5), respectively, after the offset flow pressurization. The specimen 12-7 total throughwall crack was composed of two slightly overlapping crack segments of 0.375" and 0.256". Specimen 12-1 also had a second crack, 0.465" total length, with indeterminate throughwall length after the offset flow pressurization. Compared to other test specimens with similar length cracks, the area (width) measurements after flow offset tests were a factor of 2 to 3 less. Therefore, it is judged that the presence of two cracks in both of these specimens caused the crack openings to be below the resolution capability of the light/visual method, causing unusually small areas to be calculated.

Similar observations are made for the bladder pressurized tests, Figure 6-11. The scatter around the correlation of leak rate with total crack area is significantly improved when corrections are made for limiting flow area. The points with the largest deviation from the regression line for total crack area are:

- Test 12-7, lying farthest below the regression line, is the specimen with two collinear cracks. The calculated area for this specimen is the sum of both cracks. For the flow pressurized tests, the leak rate for this specimen lay above the correlation. During the bladder pressurization to an inadvertently high pressure well in excess of the predicted burst pressure, the ligament between the two cracks tore, and the two crack segments coalesced into a single crack of 0.726" throughwall length. Taken together, the flow pressurization and bladder pressurization results show that the leak rate through a network of small cracks is principally a function of the largest individual crack in the network, and if several cracks coalesce into single large crack, interaction with the TSP effectively limits the flow from the single larger crack.

- The interaction lengths for specimens 12-1, 11-2 and 11-7 (see Table 6.7) were based on an assumed interaction depth of 1 mil. If it is assumed that the center of the cracks only touched the TSP ID, the limiting flow areas are the total crack areas rather than the effective crack areas, and all three points would fall essentially on the regression line for limiting crack area.

Figure 6-12 shows the combined correlation for both flow pressurization and bladder pressurization tests. It is concluded that, although individual tests may be difficult to interpret due to the test and measurement variables, overall the tests are well behaved. The analysis of the test data support the pre-test hypothesis that the leak rates would be primarily limited by the changing flow area as the crack opens up within the TSP due to pressurization. Ultimately, the flow area reduction due to higher pressurization limits the flow to less than some maximum value determined by the length of the initial crack, the orientation of the tube in the TSP and the applied pressure differential. It is observed on Figure 6-12 that the flow pressurization tests resulted in generally higher leak rates than the bladder pressurization tests, and more so for smaller cracks than for the larger cracks. This suggests that there is essentially no risk of a sudden increase in the leak rate, even during very high pressurization of an IRB up to its burst pressure. This conclusion holds for both cases of offset cracks and non-offset cracks within the limits tested.

6.10.4 Offset Leak Rate vs. Offset Exposed Crack Area

Figures 6-13 and 6-14 show the leak rate from the offset tests plotted against the crack area that was exposed outside the TSP during the offset tests for both flow and bladder pressurization. The data are significantly scattered, reflecting, in part, the uncertainty of the area calculations for the tips of the cracks. For this calculation, a linear profile of crack opening from zero at the tip to the location of the first width measurement was assumed.

The weak correlation observed for the summary data in Figure 6-14 is expected since the exposed area of the crack in the offset condition varies in a narrow band of the limiting flow area for the large majority of the leak tests (see Figure 6-15). Therefore, the weak correlation observed here reflects the previously noted correlation between leak rate and crack area, as shown in Figures 6-7 and 6-8, and the relatively narrow range of offset area to total area ratio for all of the tests. Therefore, it is concluded that the leak rate does not depend on the offset, but rather depends on the entire flow area of the crack as influenced by interaction with the TSP.

6.10.5 Offset Leak Rate vs. Exposed TW Length

Table 6.2 summarizes the exposed crack lengths outside the TSP for the offset tests along with the maximum Δp applied during the tests. Figures 6-16 (a), (b) and (c) show the offset leak rates plotted against the length of the TW portion of the crack exposed outside the TSP during the offset tests for both flow and bladder pressurization. No correlation is observed, indicating that the IRB leak rate is not dependent on the offset within the range of offsets tested. It is observed that the bladder pressurized tests exhibit a trend to lower leak rates compared to the flow pressurized tests, confirming the expected crack flank/TSP interaction behavior for highly pressurized cracks.

6.10.6 Differential Leak Rates vs. Exposed TW Area

Differential leak rate is defined as the difference between the offset leak rate and the zero offset leak rate at the same applied Δp. The test sequences were examined to identify and eliminate those cases where prior pressurization to a higher Δp biased the leak rate of subsequent tests due to hysteresis in the crack structural response. This is of primary importance for the flow pressurized tests where the crack responds structurally to the actual applied Δp for the leak rate test. For the bladder pressurized tests, the applied bladder Δp was higher in all cases than the subsequent leak test Δp; thus, hysteresis was not a factor for these tests. The differential leak rates used for this evaluation are based on approximately the same Δp for both the offset and zero offset tests.

Figures 6-17 a and b show the differential leak rates plotted against the exposed throughwall crack area for flow and bladder pressurized tests. Figures 6-18 a and b show the differential leak rates plotted against the exposed throughwall crack length for flow and bladder pressurized tests. While no correlation is observed for either the flow pressurized tests or for the bladder pressurized tests, most of the differential leak rates are positive, indicating a slight dependence of leak rate on crack offset. The offset test leak tests were performed after completeion of the non-offset test; thus the Δp ranges from about 37 psi to 947 psi greater than the non-offset test (See Table 6.5). The increase pressure differential accounts for much of the differential leak rate.

For the flow pressurized tests, Figure 6-17a and Figure 6-18a, the three points with the largest flow rates are Tests 12-1, 1-1 and 1-6 which defines the bounding leak rate. Test 12-1 included two cracks, 90° separated, that were exposed in the offset tests, which would be expected to results in a larger differential leak rate, particularly for the flow pressurized tests where no interaction with the TSP was observed (see Section 5). The differential leak rate includes a 390 psid greater pressure differential between the offset and non-offset tests.

Test 1-1 was characterized by a significant increase in the crack throughwall length and in the crack opening width during the flow pressurization offset tests. This is characteristic of fracture of ligaments in the cracks as the applied Δp increased. The differential leak rate for this test includes a 460 psid greater pressure differential between the offset and non-offset tests.

Test 1-6 is the basis of the bounding leak rate, and is a essentially a test of the limiting crack length. The pre-test total crack length was 0.760 inch with a throughwall length of 0.740 inch. For this length of crack, interaction with the TSP is expected at a Δp less than the non-offset flow pressurization Δp; thus, the offset condition would be expected to result in a decrease of the flow resistance implied by the non-linear characteristic of the leak- rate/crack-area correlations. The differential leak rate for this test includes a 243 psi greater pressure differential between the offset and non-offset tests. The recommended bounding leak rate, based principally on this test, includes the effect of the offset; thus no additional adjustment is necessary to account for the small increase in leak rates due to the offset.

The three points clustered at about 0.0003 square inch offset area all include significant pressure differentials between the non-offset and the offset tests from 438 psi to 947 psi. These pressurization differences account for the major part of the differential leak rates, with a secondary effect of crack opening behavior at the higher pressurizations.

The test with the greatest throughwall offset, Test 11-2 on Figure 6-18 a had essentially negligible differential leak rate.

The differential leak rates for the bladder pressurized tests, show on Figure 6-17 b and 6-18 b, are very small, except for Test 4-1. This test specimen included three different cracks which opened after pressurization to about the predicted burst pressure, approximately 6000 psid. All of the three cracks had significantly longer throughwall length than the initial crack. Thus the differential leak rate reflects the opening and offset of multiple cracks, as well as a 200 psi increase in the Δp for the offset tests compared to the non-offset tests.

In summary, the following trending conclusions are drawn from these data:

- Flow pressurized differential leak rates are positive, indicating that crack offset may slightly increase the leak rate. These positive differential leak rates are in large part related to higher pressurization during offset leak tests compared to non-offset leak tests.

- The increase leak rate due to crack offset is small, on the order of 10% of the bounding leak rate, except for cases where high pressurization ruptures ligaments to either cause large crack openings or opening of secondary cracks not previously observed.

- The bounding leak rate from the IRB tests includes the effect of crack offset. Therefore no additional adjustment is required for the bounding leak rate.
- Differential leak rates are smaller for higher pressurization tests, i.e., pressurizations to about the predicted freespan rupture pressure for a crack, due to interaction between the crack flanks and the ID of the TSP.

6.11 Application of Leak Rate Data for Different Tube Diameters

The specimens for these tests were made from tubing of 3/4" and 7/8" diameters to be prototypic of SG tubing utilized in the Model 51 and Model D steam generators. Figures 6-19 (a) and (b) compare the leak rate data for the tests specimen tube diameters using the correlations developed previously for total crack length and limiting flow area. Both zero offset and offset tests are considered, including the flow pressurized and bladder pressurized tests for each condition.

Figure 6-19 (a) shows the correlation of the leak test data with throughwall crack length, including 95% confidence bounds for the fit. It is apparent that the regression fit is a good fit to the data. Data points for 7/8″ diameter tubes and for the ¾″ diameter tubes appear to be uniformly scattered about the regression fit for both the flow pressurized tests and the bladder pressurized tests. Although the individual data fits for ¾″ and 7/8″ diameter tubes may exhibit different slopes, that difference is attributed to the relatively small number of data points and the scatter of the data rather than to real, systematic effects.

Figure 6-19 (b) shows the leak rate correlated with limiting flow area for the cracks. A linear relationship between flow and area would be expected, however, linear regression with a constraint that the regression pass through 0,0 shows that additional flow losses appear to be occurring. A better fit to the data is a power relationship that more adequately represents the apparent flow reduction, compared to the expected flow rate, at the larger flow areas. However, as in the prior figure, the data for the 7/8″ and ¾″ diameter tests, for both flow pressurized and bladder pressurized conditions , are essentially uniformly scattered around the regression curve.

It is concluded that the data from these tests can be applied equally for 3/4" and 7/8" applications without differentiating for specimen tube diameter.

6.12 Leak Rate Dependence on Offset Lengths

It was previously shown that the IRB leak rate is principally dependent on the principal crack properties, total length, or total crack area. Leak rates are not strongly dependent on the offset length or area within the range tested, e.g., up to 0.218 inch offset. A slight offset effect is noted in that the differential leak rates for the flow pressurization tests, while small, are all positive.

An IRB leak test was performed on a pulled tube from Plant AA-1 (Reference 3). This test was set up like the test specimens tested under this program. The pulled tube tested , R28C24, had a total crack length of 0.688", with a throughwall portion 0.260" in length. The crack was offset from the simulated TSP by a distance shown by post-test destructive examination to be 0.20". The leak test results from the tests performed in the offset condition were the same as the results from the tests performed with the crack centered in the simulated TSP.

For short crack, for which interaction with the TSP would not be expected until extremely high pressurization is applied, these conclusions would hold regardless of the offset. Without interaction, the limiting flow area would be dictated by the crack area. Thus, the leak rate for short cracks would be expected to be similar to the freespan leak rate, except for additional loss factors that may be present when the crack is within the span of the TSP as evidenced by the non-linearity of the leak rate in flow area in these data.

For longer cracks for which interaction with the TSP would be expected, the limits within which the conclusions above are expected to apply are defined by the length of the contact zone between the crack and the TSP as illustrated in Figure 6-20. The limiting flow area, Figure 6-20 (a) does not change with crack offset when the crack flanks are in contact with the TSP until the contact zone is partially outside the span of the TSP Figure 6-20 (b). At that point, the limiting flow area increases with increasing offset as additional crack area is exposed.

The longest contact length for a corrosion crack was calculated at 0.26" as noted in Table 6.6 for a crack of 0.760" length (the limiting crack length is 0.75"). Assume the tip of a limiting 0.75" crack were initially aligned with the TSP surface, with a flank to TSP contact length of 0.26", and further, that the crack opening is axially symmetric. (The assumption of axial symmetry can be shown to be true, as the axial crack opening profile is well represented by a half-sine shape). Thus, the tips of the crack would be half the difference between the total crack length and the length of the contact zone, 0.245". Therefore, a crack offset of .245" would be possible before the contact zone would begin to be exposed outside the TSP. Since the leak rates have been shown to be essentially independent of offset, an offset of up to approximately 0.245" throughwall length would not be expected to significantly affect the bounding leak rate determined in these tests, since the bounding leak rate was based on a test of a crack 0.760" long with a throughwall length of 0.740" (Test 1-6).

Longer contact zones would not be expected at pressurization near the SLB Δp. Bladder pressurization to the predicted freespan burst pressure resulted in maximum contact zone lengths approximately the same as noted above, i.e., ~0.25" due to the stiffening effect of contact between the crack flanks and the TSP. Only pressurization far in excess of the freespan burst pressure (Test 12-7, 4-1) resulted in a longer contact zone.

(Specimen 2-8, the laser machined slot specimen, also exhibited a longer contact zone, however this specimen is not representative of a corrosion crack. The laser slot has rounded crack tip ends that permit the tip to act like a hinge, leading to greater slot flank deflection and a longer contact zone.)

6.13 Trending Conclusions

The IRB leak rate data from these tests can be applied equally for 3/4" and 7/8" applications without differentiating for specimen tube diameter.

The IRB leak rates are principally dependent on the principal crack properties, total length, or total crack area.

Leak rates are not strongly dependent on the offset length or area within the range tested, e.g., up to 0.218 inch offset. A slight offset effect is noted in that the differential leak rates for the flow pressurization tests, while small, are all positive.

An offset of up to approximately 0.245" throughwall length would not be expected to significantly affect the bounding leak rate determined in these tests.

The bounding leak rate determined in these tests is not influenced significantly by the presence of multiple cracks within the TSP. Total leakage from multiple cracks is dominated by the larger of the cracks. The sum of the leak rates through the individual areas of each crack is much smaller than the leak rate corresponding to the sum of the areas of all the cracks.

6.14 References:

1. EPRI NP-6626-SD, Belgian Approach to Steam Generator Tube Plugging for Primary Water Stress Corrosion Cracking, March 1990.

2. SG-95-03-010, Burst Pressure Correlation for Steam Generator Tubes with Throughwall Axial Cracks, February 1995; W-NSD.

3. SG-98-01-007, Plant AA-1 Steam Generator Steam Tube Examination, April 1998; W-NSD

A

TEST PLANS FOR IRB LEAK TESTS

EPRI Leak Test Program
General Leak Test Guidelines - Rev. 1, 5/31/95

Tube to TSP Gap

- The tube to TSP diametral clearance for all test specimens is to be 0.025 inch. The average diameter of the tube near the corrosion cracks is to be used to establish the required TSP ID.

Sequence of Testing for Each Specimen

- The leak testing and sequence of leak tests for each specimen are to be prepared by NSD in a format similar to this page, which will include revision number and date. The test requirements for each specimen and the specimen number to be used in the test will be specified.

Crack Locations Within TSP and Offset from TSP

- Separate requirements are provided to STC for locating the corrosion crack tip relative to the edge of the TSP for leak testing.

Establishing Pressure Differentials for Leak Testing Prior to Bladder Pressurization

- While establishing the steady state condition for leak testing, the pressure differential across the tube should not exceed the pressure differential used for the leak test measurement

- The specific test requirements will specify a sequence of testing within the TSP, free span and offset outside the TSP. Following completion of one leak test condition (i.e., crack within the TSP), the starting pressure differential for the next sequence (i.e., free span) shall be as close as possible to the last pressure differential tested (i.e., highest ΔP leak tested for crack within the TSP) but not lower than the prior ΔP by more than about 10-15 psid to avoid hysteresis effects influencing the test results. In this manner, the sequence of leak tests is always at the same or higher ΔP than the prior leak test.

  - It is important to recognize this requirement in establishing the test conditions for the leak test. Some pressure decrease may occur between establishing the initial steady state conditions and the time of the leak measurement. The test objective should be to minimize this pressure decrease while also avoiding application of higher ΔPs across the tube than the test condition.

- When the test requirements specify a hot test followed by a room temperature test or vice versa, the first pressure differential for the second test sequence (i.e., room temperature following prior hot testing) shall be as close as possible to the last pressure differential tested.

Final Corrosion Crack Length/Depth Measurements

- Crack length including throughwall lengths and depths are to be measured during leak testing as specified in the specific test requirements. Throughwall lengths and widths shall include total values and values outside the TSP for the specified crack offset.

- Following completion of all leak testing for each specimen, the corrosion crack length versus depth profile is to be measured for each crack that is throughwall at the end of the test sequence. This should be obtained by fractography of the crack face. NSD release of the specimen is required, however, prior to destructive examination of the specimen. This release can be oral from the designated interface person.

EPRI Leak Test Program
Requirements for Crack Locations Within TSP and Offset from TSP
Rev. 0, 5/16/95

General

- The tip of the corrosion crack is to be located at the edge of the TSP for cracks within the TSP
- For tests with the crack offset from the edge of the TSP, the corrosion crack tip is to be offset from the edge of the TSP by 0.10" for 3/4" diameter tubing and 0.15" for 7/8" tubing

Specimen Preparation

- Prior to leak testing, the specimen OD and ID crack lengths are to be determined by dye penetrant testing. At this time, the location of the crack tip shall be marked on the tube in a manner to facility locating the specimen relative to the TSP for leak testing

Crack Location for Leak Tests Without Prior Bladder Pressurization

- For leak tests specified as crack within the TSP, the corrosion crack tip shall be located at the edge of the TSP such that the total crack is within the TSP
- For leak tests specified as the crack offset from the TSP, the corrosion crack tip shall be located at the specified distance (0.10", 0.15") from the edge of the TSP
- If prior pressurizations during leak testing, open up the crack tip beyond that identified by the dye penetrant test, the new crack tip shall be used for locating the crack as long as the new crack tip can be associated with corrosion rather than tearing at the edges of the corrosion crack

Crack Location for Leak Tests Following Bladder Pressurization

- Bladder pressurization steps are to be performed with the corrosion crack tip offset from the edge of the TSP by the specified length for the tubing diameter (0.10", 0.15").
- Following pressurization, a new corrosion crack tip may be identified. The new corrosion crack tip, if a change occurs, should be used for locating the crack offset distance or at the edge of the TSP for tests within the TSP. Only corrosion crack tips are to be used for locating the crack relative to the TSP edge. If tearing of the crack tip occurs from the pressurization steps, the torn tip is not to be used for locating the crack relative to the TSP

Test Plan for Indications with Restrained Burst (IRBs)
Test 2-4 - (Rev. 3- 5/30/95)

General Test Information

- Utilize small leak test facility followed by testing in large leak test facility
- Test 7/8" diameter specimen 4C 218
  - Crack length: Dye Penetrant - 0.60" with 0.29" TW; UT - 0.62" with 0.40" TW
- Leak test at ≥ 615°F except as noted
- Tubes shall be free to move within TSP during pressurization or, as a minimum, the tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Leak test with crack centered at 1500, 1700 and 2000 psi ΔP

B. Free span leak test at 2000, 2335 and 2560 psi ΔP

C. Leak test with crack 0.15" offset outside TSP at 2560 and 2720 psi ΔP (facility limit)

- Move tube by 0.15" relative to the TSP

D. Leak test at R.T. with 0.15" offset starting from the highest ΔP obtained in Step C and increase to the facility limit

E. Measure crack opening length, diameter, area and evaluate crack tearing extension (beyond corrosion crack length).

Decontaminate the specimen

The following tests are to be performed in the large leak test facility with a collar that provides a 25 mil diametral gap relative to the tube diameter prior to any of the above leak testing:

F. With the crack tip 0.15" offset outside the TSP, pressurize to about 4000 psid with a bladder. If following pressurization, the corrosion crack tip is more than 0.15" outside the TSP, adjust the specimen to obtain 0.15" of the corrosion crack outside the TSP prior to the leak testing of Step G. For each crack (2 expected), measure the total crack length, the through wall length/width, the exposed throughwall length/width and the tube diameter across the crack flanks including at least 5 points along the crack plus the locations of the edges of the TSP with the crack tip 0.15" offset and at the edge of the TSP.

- Report whether the tube is tight or loose in TSP following pressurization.

G. R.T. leak test with corrosion crack tip 0.15" offset outside TSP at 2335 and 2560 psi ΔP

H. R.T. leak test with crack inside the TSP and the crack tip located at the edge of the TSP at 2335 and 2560 psi ΔP

I. Repeat Step F with a bladder pressurization of 5500 psid

J. R.T. leak test with corrosion crack tip 0.15" offset outside TSP at 2335 and 2560 psi ΔP

K. R.T. leak test with crack inside the TSP and the crack tip located at the edge of the TSP at 2335 and 2560 psi ΔP

L. Hot (615°F) leak test with corrosion crack tip 0.15" offset outside TSP at 2335 and 2560 psi ΔP

M. Measure corrosion throughwall length and length versus depth profile.

Test Plan for Indications with Restrained Burst (IRBs)
Test 2-10 - (Rev. 3- 6/7/95)

General Test Information

- Utilize small leak test facility followed by large leak test facility testing
- Test 3/4" diameter, corrosion specimen 2051B
  - Crack length: Silastic mold dye penetrant - 0.551" OD with 0.425" TW
- Leak test at ≥ 615° with selected room temperature tests
- Locate specimen relative to the TSP per requirements for crack locations within TSP and offset from TSP
- Tubes shall be free to move within TSP during pressurization or, as a minimum, the tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Hot (615°) leak test with simulated crack inside the TSP and the crack tip at edge of TSP at 1800, 1900 and 2000 psi ΔP

B. Hot (615°) free span leak test at 2000, 2150 and 2335 psi ΔP

C. Hot (615°) leak test with crack tip 0.10" offset outside TSP at 2335, 2560 and 2750 (or facility limit) psi ΔP

Note: If at any time during this test it appears that the facility limit for measuring leak rate is being approached, increase the ΔP to about the facility limit and terminate testing in the small loop. Testing will than be continued in the large loop.

D. Leak test at R.T. with crack tip 0.10" offset outside TSP at the 2750 ΔP psi or highest pressure obtained in Step C and increase the ΔP to the highest ΔP obtainable at room temperature.

E. Measure crack opening length, diameter, area and evaluate crack tearing extension (beyond corrosion crack length).

Decontaminate the specimen for later testing in large loop facility

F. With the crack tip 0.10" offset outside the TSP, pressurize to 3800 psid with a bladder. If following pressurization, the corrosion crack tip is more than 0.10" outside the TSP, adjust the specimen to obtain 0.10" of the corrosion crack outside the TSP prior to the leak testing of Step G. Measure the total crack length, the through wall length/width, the exposed throughwall length/width and the tube diameter across the crack flanks including at least 5 points along the crack plus the locations of the edges of the TSP with the crack tip 0.10" offset and at the edge of the TSP.

- Report whether the tube is tight or loose in TSP following pressurization.

Move specimen to the large leak test facility for the following tests. Either the hot test sequence or the cold test sequence (lined out) are acceptable and selection of hot or cold testing should be based on most efficient completion of the tests.

G. Hot (615°F) test with crack tip located at the edge of the TSP at 2335 and 2560 psi ΔP

H. Hot (615°F) leak test with 0.10" offset outside TSP at 2335 and 2560 psi ΔP

I. Repeat Step F with a bladder pressurization of 4920 psid

J. Hot (615°F) test with crack tip located at the edge of the TSP at 2335 and 2560 psi ΔP

K. Hot (615°F) leak test with 0.10" offset outside TSP at 2335 and 2560 psi ΔP

L. R.T. leak test with 0.10" offset outside TSP at 2335 and 2560 psi ΔP

M. Measure corrosion throughwall length and length versus depth profile.

Test Plan for Indications with Restrained Burst (IRBs)
Test 2-7 - (Rev. 4 - 6/7/95)

General Test Information

- Utilize large leak test facility testing
- Test 3/4" diameter, corrosion plus fatigue specimen 2051E
  - Original corrosion crack length: Silastic mold dye penetrant - 0.66" with 0.577" TW
  - Specimen fatigued to obtain ID TW length
- Leak test at room temperature with selected ≥ 615°F tests.
- Locate specimen relative to the TSP per requirements for crack locations within TSP and offset from TSP
- Tubes shall be free to move within TSP during pressurization or, as a minimum, the tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. R.T. leak test with simulated crack inside TSP and crack tip at edge of TSP at 1800, 1900 and 2000 psi ΔP

B. R.T. free span leak test at 2000, 2150 and 2335 psi ΔP

C. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335, psi ΔP (adjust, if necessary, to the same ΔP as last test of Step C), 2560, 2700 psi ΔP and another higher ΔP at facility limit

D. Measure crack opening length, diameter, area and evaluate crack tearing extension (beyond corrosion crack length).

E. With the crack tip 0.10" offset outside the TSP, pressurize to 3650 psid with a bladder. If following pressurization, the corrosion crack tip is more than 0.10" outside the TSP, adjust the specimen to obtain 0.10" of the corrosion crack outside the TSP prior to the leak testing of Step G. Measure the total crack length, the through wall length/width, the exposed throughwall length/width and the tube diameter across the crack flanks including at least 5 points along the crack plus the locations of the edges of the TSP with the crack tip 0.10" offset and at the edge of the TSP.

- Report whether the tube is tight or loose in TSP following pressurization.

F. Hot (615°F) test with crack tip located at the edge of the TSP at 2335 and 2560 psi ΔP

G. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335 and 2560 psi ΔP

H. R.T. leak test with crack tip 0.10" offset outside TSP at 2335 and 2560 psi ΔP

I. Measure corrosion throughwall length and length versus depth profile.

Test Plan for Indications with Restrained Burst (IRBs)
Test 2-8 - (Rev. 0 - 6/12/95)

General Test Information

- Utilize large leak test facility testing
- Test 3/4" diameter, laser cut specimen IRB-LC-2: 0.55" TW
- Leak test at ≥ 615°F with selected room temperature tests.
- Locate specimen relative to the TSP per requirements for crack locations within TSP and offset from TSP
- Tubes shall be free to move within TSP during pressurization or, as a minimum, the tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Hot (615°F) leak test with simulated crack inside TSP and crack tip at edge of TSP at 1800, 1900 and 2000 psi ΔP

B. Hot (615°F) free span leak test at 2000, 2150 and 2335 psi ΔP

C. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335, psi ΔP (adjust, if necessary, to the same ΔP as last test of Step C), 2560, 2700 psi ΔP and another higher ΔP at facility limit

D. Measure crack opening length, diameter, area and evaluate crack tearing extension (beyond corrosion crack length).

E. Room Temperature leak test with crack tip 0.10" offset outside TSP at the highest ΔP obtained in the Step C testing and another higher ΔP at facility limit

F. Measure crack opening length, diameter, area and evaluate crack tearing extension (beyond corrosion crack length).

G. Measure corrosion throughwall length and length versus depth profile.

Test Plan for Indications with Restrained Burst (IRBs)
Test 4-1 - (Rev. 2 - 6/12/95)

General Test Information

- Utilize large leak test facility
- Test 7/8" diameter specimen 4B 214
    - Crack length: Dye Penetrant - 0.67" with 0.24" TW; UT - 0.74" with 0.50" TW
- Leak test at room temperature except as specifically noted
- Tube to TSP diametral gap of 0.025" except per adjustments noted
- Tubes shall be free to move within TSP during pressurization or, as a minimum, the tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Pressurize to 5800 psid with a bladder

- If tube is loose in TSP following pressurization, replace TSP to obtain about 0.001" diametral clearance between the maximum diameter of the crack opening and the TSP hole. This requirement applies following all bladder pressurizations of this test sequence.

B. Room temperature leak test at 2335, 2560 psi ΔP

C. Measure crack opening length, diameter, area and evaluate crack tearing extension (beyond corrosion crack length). Estimate corrosion throughwall length.

D. Move crack to 0.15" outside TSP and pressurize to the same pressure as step A

- Move tube by 0.15" relative to the TSP

E. Room temperature leak test at 2335, 2560 psi ΔP. If high temperature facility is available, repeat leak test at 615°F.

F. Measure crack opening length, diameter, area and evaluate crack tearing extension (beyond corrosion crack length).

G. With the 0.15" crack position, pressurize with a bladder (and foil if necessary) to about 1000 psi above the prior pressurization step

H. Room temperature leak test at 2335, 2560 psi ΔP

I. Repeat steps G and H with increases in bladder pressure of 1000 psi increments until bladder/foil pressurization of about 9000 psi is achieved

J. At bladder pressurization of about 8900 psi, also perform R.T. leak test with crack centered in the TSP

K. At bladder pressurization of about 8900 psi, perform hot (≥615°F) leak test with crack tip 0.15 inch offset from the edge of the TSP*

L. Continue bladder pressurization increases in about 1000 psi increments (initially about 9900 psi) and perform either room temperature or hot leak tests (option to increase facility efficiency) at 2335 and 2560 psi with 0.15 inch offset following each pressurization step. Terminate testing when the indication bursts outside the TSP.

M. Measure crack opening length, diameter, area and evaluate crack tearing extension (beyond corrosion crack length). Measure throughwall corrosion length and corrosion depth versus length profile.

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* Test performed prior to acceptance of hot leak test facility and data not included in evaluations.

Test Plan for Indications with Restrained Burst (IRBs)
Test 1-7 - (Rev. 3- 6/30/95)

General Test Information

- Utilize large leak test facility testing
- Test 3/4" diameter, specimen 2051A
    - Corrosion plus fatigue crack length: Silastic mold dye penetrant - 0.58" OD with 0.60" TW
- Leak test at 615°F except as noted. Testing at > 615°F is acceptable.
- Locate specimen relative to the TSP per requirements for crack locations within TSP and offset from TSP
- Tubes shall be free to move within TSP during pressurization or, as a minimum, the tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Hot (615°F) leak test with crack inside the TSP and crack tip at edge of TSP at 1900 and 2050 and 2335 psi ΔP

B. Measure crack opening length, diameter, area (total lengths and throughwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

C. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335, 2560, 2700, 2800 psi ΔP up to facility limit

D. Measure crack opening length, diameter, area (total lengths and throughwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

E. With the crack tip 0.10" offset outside the TSP, pressurize to about 3035 psid with a bladder. If following pressurization, the corrosion crack tip is more than 0.10" outside the TSP, adjust the specimen to obtain 0.10" of the corrosion crack outside the TSP prior to the leak testing of Step G. Measure the total crack length, the through wall length/width, the exposed throughwall length/width and the tube diameter across the crack flanks including at least 5 points along the crack plus the locations of the edges of the TSP with the crack tip 0.10" offset and at the edge of the TSP.

- Report whether the tube is tight or loose in TSP following pressurization.

F. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335 and 2560 psi ΔP

G. Hot (615°F) leak test with crack inside the TSP and crack tip at the edge of the TSP at 2335 and 2560 psi ΔP

H. Measure corrosion throughwall length and length versus depth profile.

Test Plan for Indications with Restrained Burst (IRBs)
Test 1-6 - (Rev. 1- 6/9/95)

General Test Information

- Utilize large leak test facility testing
- Test 3/4" diameter, specimen 2008E
    - Corrosion (no fatigue) crack length: Silastic mold dye penetrant - 0.735" OD with 0.76" ID
- Leak test at 615°F except as noted. Testing at > 615°F is acceptable.
- Locate specimen relative to the TSP per requirements for crack locations within TSP and offset from TSP
- Tubes shall be free to move within TSP during pressurization or, as a minimum, the tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Hot (615°F) leak test with crack inside the TSP and crack tip at edge of TSP at 1900 and 2050 and 2335 psi ΔP

B. Measure crack opening length, diameter, area (total lengths and throughwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

C. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335, 2560, 2700, 2800 psi ΔP up to facility limit

D. Measure crack opening length, diameter, area (total lengths and throughwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

E. Perform hot (615°F) free span leak test. Care must be exercised in performing this test such that higher ΔPs are not applied to the specimen due to the potential for significant tearing of the crack. Although the test results would not be valid, start testing at a ΔP lower than the highest ΔP from Step C and terminate testing if the measured leak rate is about a factor of 3 or more higher than the largest leak rate obtained from Step C.

F. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

G. With the crack tip 0.10" offset outside the TSP, pressurize to 3200 psid with a bladder. If following pressurization, the corrosion crack tip is more than 0.10" outside the TSP, adjust the specimen to obtain 0.10" of the corrosion crack outside the TSP prior to the leak testing of Step H. Measure the total crack length, the through wall length/width, the exposed throughwall length/width and the tube diameter across the crack flanks including at least 5 points along the crack plus the locations of the edges of the TSP with the crack tip 0.10" offset and at the edge of the TSP.

- Report whether the tube is tight or loose in TSP following pressurization.

H. Hot (615°F) leak test with crack inside the TSP and crack tip at the edge of the TSP at 2335 and 2560 psi ΔP

I. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335 and 2560 psi ΔP

J. R.T. leak test with crack tip 0.10" offset outside TSP at 2335 and 2560 psi ΔP

K. Measure corrosion throughwall length and length versus depth profile.

Test Plan for Indications with Restrained Burst (IRBs)
Test 2-1 - (Rev. 1 - 6/30/95)

General Test Information

- Utilize large leak test facility testing
- Test 7/8" diameter, corrosion plus fatigue specimen 8161A,
  - Silastic mold dye penetrant - 0.62" OD with 0.515" ID
- Leak test at 615°F except as noted. Testing at > 615°F is acceptable.
- Locate specimen relative to the TSP per requirements for crack locations within TSP and offset from TSP
- Tubes shall be free to move within TSP during pressurization or, as a minimum, the tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Hot (615°F) leak test with simulated crack inside TSP and crack tip at edge of TSP at 1800, 1900 and 2000 psi ΔP

B. Hot (615°F) free span leak test at 2000, 2150 and 2335 psi ΔP

C. Hot (615°F) leak test with crack tip 0.15" offset outside TSP at 2335, psi ΔP (adjust, if necessary, to the same ΔP as last test of Step C), 2560, 2700 psi ΔP and another higher ΔP at facility limit

D. Leak Test at R.T. with 0.15" offset starting from the highest ΔP obtained in Step C and increase to facility limit

E. Measure crack opening length, diameter, area and evaluate crack tearing extension (beyond corrosion crack length).

F. With the crack tip 0.15" offset outside the TSP, pressurize to 4,450 psid with a bladder. If following pressurization, the corrosion crack tip is more than 0.10" outside the TSP, adjust the specimen to obtain 0.10" of the corrosion crack outside the TSP prior to the leak testing of Step G. Measure the total crack length, the through wall length/width, the exposed throughwall length/width and the tube diameter across the crack flanks including at least 5 points along the crack plus the locations of the edges of the TSP with the crack tip 0.15" offset and at the edge of the TSP.

- Report whether the tube is tight or loose in TSP following pressurization.

G. Hot (615°F) leak test with crack tip 0.15" offset outside TSP at 2335 and 2560 psi ΔP

H. Hot (615°F) leak test with crack tip located at the edge of the TSP at 2335 and 2560 psi ΔP

I. R.T. leak test with crack tip 0.10" offset outside TSP at 2335 and 2560 psi ΔP

J. Measure corrosion throughwall length and length versus depth profile.

Test Plan for Indications with Restrained Burst (IRBs)
Test 1-2 - (Rev. 0 - 6/19/95)

General Test Information

- Utilize large leak test facility testing
- Test 7/8" diameter, corrosion plus fatigue specimen 8161E
  - Silastic mold dye penetrant - 0.64" OD with 0.62" ID
- Leak test at 615°F except as noted. Testing at > 615°F is acceptable.
- Locate specimen relative to the TSP per requirements for crack locations within TSP and offset from TSP
- Tubes shall be free to move within TSP during pressurization or, as a minimum, the tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Hot (615°F) leak test with crack inside the TSP and crack tip at edge of TSP at 1900 and 2050 and 2335 psi ΔP

B. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

C. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335, 2560, 2700, 2800 psi ΔP up to facility limit

D. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

E. Perform hot (615°F) free span leak test at the highest ΔP reached in the Step C test. Care must be exercised in performing this test such that higher ΔPs are not applied to the specimen due to the potential for significant tearing of the crack. Although the test results would not be valid, start testing at a ΔP about 100 psi lower than the highest ΔP from Step C and terminate testing if the measured leak rate is about a factor of 3 (factor of 5 for a cold test) or more higher than the largest leak rate obtained from Step C.

F. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

G. With the crack tip 0.10" offset outside the TSP, pressurize to 4080 psid with a bladder. If following pressurization, the corrosion crack tip is more than 0.10" outside the TSP, adjust the specimen to obtain 0.10" of the corrosion crack outside the TSP prior to the leak testing of Step G. Measure the total crack length, the through wall length/width, the exposed throughwall length/width and the tube diameter across the crack flanks including at least 5 points along the crack plus the locations of the edges of the TSP with the crack tip 0.10" offset and at the edge of the TSP.

- Report whether the tube is tight or loose in TSP following pressurization.

H. Hot (615°F) leak test with crack inside the TSP and crack tip at the edge of the TSP at 2335 and 2560 psi ΔP

I. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335 and 2560 psi ΔP

J. R.T. leak test with crack tip 0.10" offset outside TSP at 2335 and 2560 psi ΔP

K. Measure corrosion throughwall length and length versus depth profile.

Test Plan for Indications with Restrained Burst (IRBs)
Test 1-1 - (Rev. 0 - 6/12/95)

General Test Information

- Utilize large leak test facility testing
- Test 7/8" diameter, corrosion plus fatigue specimen 8161G
  - Silastic mold dye penetrant - 0.62" OD with 0.62" ID
- Leak test at 615°F except as noted. Testing at > 615°F is acceptable.
- Locate specimen relative to the TSP per requirements for crack locations within TSP and offset from TSP

Test Sequence

A. Hot (615°F) leak test with crack inside the TSP and crack tip at edge of TSP at 1900 and 2050 and 2335 psi ΔP

B. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

C. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335, 2560, 2700, 2800 psi ΔP up to facility limit

D. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

E. Perform hot (615°F) free span leak test at the highest ΔP reached in the Step C test. Care must be exercised in performing this test such that higher ΔPs are not applied to the specimen due to the potential for significant tearing of the crack. Although the test results would not be valid, start testing at a ΔP about 100 psi lower than the highest ΔP from Step C and terminate testing if the measured leak rate is about a factor of 3 (factor of 5 for a cold test) or more higher than the largest leak rate obtained from Step C.

F. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width) and evaluate crack tearing extension (beyond corrosion crack length).

G. With the crack tip 0.10" offset outside the TSP, pressurize to 4150 psid with a bladder. If following pressurization, the corrosion crack tip is more than 0.10" outside the TSP, adjust the specimen to obtain 0.10" of the corrosion crack outside the TSP prior to the leak testing of Step G. Measure the total crack length, the through wall length/width, the exposed throughwall length/width and the tube diameter across the crack flanks including at least 5 points along the crack plus the locations of the edges of the TSP with the crack tip 0.10" offset and at the edge of the TSP.

- Report whether the tube is tight or loose in TSP following pressurization.

H. Hot (615°F) leak test with crack inside the TSP and crack tip at the edge of the TSP at 2335 and 2560 psi ΔP

I. Hot (615°F) leak test with crack tip 0.10" offset outside TSP at 2335 and 2560 psi ΔP

J. R.T. leak test with crack tip 0.10" offset outside TSP at 2335 and 2560 psi ΔP

K. Measure corrosion throughwall length and length versus depth profile.

Test Plan IRBs
Test 11-7

General Test Information

- Utilize large leak test facility testing
- Test 3/4" diameter, specimen 2008A
  - Crack dimensions after corrosion and fatigue - 0.818" OD with 0.809" ID
- For this 0.745" diameter specimen, the ID of the TSP shall be 0.770" to obtain a 0.025" tube to TSP diametral gap
- Leak test at about 615°F. Primary temperatures should not exceed 640°F.
- Testing should be targeted to obtaining the specified pressure differentials for the evaluated data (test averages)
- Locate specimen relative to the TSP with the crack centered on the TSP (at start of test) , i.e. equal crack tip projection outside of the TSP on both sides of the TSP since the TW crack dimension is greater than the TSP thickness, for crack locations within TSP - zero offset tests
- Locate the tip of the throughwall crack found after testing with zero offset at 0.10" outside the TSP for offset tests
- The tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Hot leak test with crack centered on the TSP (equal projection of TW crack above and below the TSP) to obtain at least 5 data points between and 2000 and 2335 psi ΔP (recommended ΔPs of 2000, 2100, 2200, 2280, 2335)

B. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width). TW crack width measurements at the TW crack tips shall be measured at 20 to 30 mil spacing for 0.1" and at 50 mil spacing over the remaining TW length. Crack diameter measurements shall be reported at about 0.1" intervals spanning the crack length and about two 0.15" intervals beyond the crack. Report whether or not the tube is tight or loose in the TSP after the last test step.

C. Hot leak test with the TW crack tip 0.10" offset outside TSP to obtain a goal of 6 data points between 2300 psi ΔP and the facility limit. Attempt to obtain a data point as close as practical to 2560 psi and to obtain a reduced (average ΔP) data point below and one above 2560 psi.

D. Repeat Step B.

E. If the tube is not tight in the TSP following flow pressurization of step C, with the crack tip 0.10" offset outside the TSP, pressurize to 2850 psid with a bladder. If following pressurization, the corrosion TW crack tip is more than 0.10" outside the TSP, adjust the specimen to obtain 0.10" of the TW corrosion crack outside the TSP prior to the leak testing of Step F. Repeat Step B.

- Report whether the tube is tight or loose in TSP following pressurization.

F. Repeat Step C.

G. Repeat Step A.

H. Perform fractographic measurements to obtain the corrosion (corrosion plus fatigue for fatigued specimens) throughwall length and length versus depth profile with emphasis at the ends of the TW crack to define the length and depth of the specimen at the start of testing. Attempt to define the length and depth at the crack tips following all leak testing (i.e., prior to opening the specimen for fractography).

practical to 2560 psi and to obtain a reduced (average ΔP) data point below and above 2560 psi.

D. Repeat Step B.

E. With the throughwall crack tip 0.15" offset outside the TSP, pressurize to 3670 psid with a bladder. If following pressurization, the corrosion TW crack tip is more than 0.15" outside the TSP, adjust the specimen to obtain 0.15" of the TW corrosion crack outside the TSP prior to the leak testing of Step F. Repeat Step B.

- Report whether the tube is tight or loose in TSP following pressurization.

F. Repeat Step C.

G. Repeat Step A.

H. Perform fractographic measurements to obtain the corrosion (corrosion plus fatigue for fatigued specimens) throughwall length and length versus depth profile with emphasis at the ends of the TW crack to define the length and depth of the specimen at the start of testing. Attempt to define the length and depth at the crack tips following all leak testing (i.e., prior to opening the specimen for fractography).

Test Plan for IRBs
Test 11-1

General Test Information

- Utilize large leak test facility testing
- Test 7/8" diameter, specimen 5B-403
    - Crack dimensions after corrosion and fatigue - 0.706" OD with 0.707" ID [90° location]
    - Additional non-TW cracks at 0°, 180°, and 270° welded
- For this 0.875" diameter specimen, the ID of the TSP shall be 0.900" to obtain a 0.025" tube to TSP diametral gap.
- Leak test at about 615°F. Primary temperatures should not exceed 640°F.
- Testing should be targeted to obtaining the specified pressure differentials for the evaluated data (test averages)
- Locate specimen relative to the TSP with the crack tip (at start of test) at the inside edge of the TSP for crack locations within TSP - zero offset tests
- Locate the tip of the throughwall crack found after testing with zero offset at 0.15" outside the TSP for offset tests. The 0.15" offset shall be based on the measured throughwall crack.
- The tube shall contact the TSP hole at the start of the test at 180° from the crack being leak tested.

Test Sequence

A. Hot leak test with crack inside the TSP and crack tip at edge of TSP to obtain at least 5 data points between and 2000 and 2335 psi ΔP, i.e. 2000, 2100, 2200, 2280, 2335 psid.

B. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width). TW crack width measurements at the TW crack tips shall be measured at 20 to 30 mil spacing for 0.1" and at 50 mil spacing over the remaining TW length. Crack diameter measurements shall be reported at about 0.1" intervals spanning the crack length and about two 0.15" intervals beyond the crack. Report whether or not the tube is tight or loose in the TSP after the last test step.

C. Hot leak test with the TW crack tip 0.15" offset outside TSP with a goal of obtaining 6 data points between 2300 psi ΔP and the facility limit. Attempt to obtain a data point as close as

Test Plan for IRBs
Test 11-2

General Test Information

- Utilize large leak test facility testing
- Test 7/8" diameter, specimen 8161B
  - Crack dimensions after corrosion and fatigue - 0.7" OD with 0.630" ID [90°location]
  - Specimen had 2 other cracks welded to prevent leakage [0° and 270° locations]
- For this 0.874" diameter specimen, the ID of the TSP shall be 0.899" to obtain a 0.025" tube to TSP diametral gap.
- Leak test at about 615°F. Primary temperatures should not exceed 640°F.
- Testing should be targeted to obtaining the specified pressure differentials for the evaluated data (test averages)
- Locate specimen relative to the TSP with the crack tip (at start of test) at the inside edge of the TSP for crack locations within TSP - zero offset tests
- Locate the tip of the throughwall crack found after testing with zero offset at 0.15" outside the TSP for offset tests. The 0.15" offset shall be based on the measured TW crack.
- The tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Hot leak test with crack inside the TSP and crack tip at edge of TSP to obtain at least 4 data points between and 2000 and 2335 psi ΔP, i.e. 2000, 2100, 2230, 2335 psid.

B. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width). TW crack width measurements at the TW crack tips shall be measured at 20 to 30 mil spacing for 0.1" and at 50 mil spacing over the remaining TW length. Crack diameter measurements shall be reported at about 0.1" intervals spanning the crack length and about two 0.15" intervals beyond the crack. Report whether or not the tube is tight or loose in the TSP after the last test step.

C. Hot leak test with the TW crack tip 0.15" offset outside TSP to obtain a goal of 5 data points between 2300 psi ΔP and the facility limit. Attempt to obtain a data point as close as practical to 2560 psi and to obtain a reduced (average ΔP) data point below and one point above 2560 psi.

D. Repeat Step B.

E. With the crack tip 0.15" offset outside the TSP, pressurize to 2900 psid with a bladder. If following pressurization, the corrosion TW crack tip is more than 0.15" outside the TSP, adjust the specimen to obtain 0.15" of the TW corrosion crack outside the TSP prior to the leak testing of Step F. Repeat Step B.

- Report whether the tube is tight or loose in TSP following pressurization.

F. Repeat Step C.

G. With the crack tip 0.15" offset outside the TSP, pressurize to 4075 psid with a bladder. If following pressurization, the corrosion TW crack tip is more than 0.15" outside the TSP, adjust the specimen to obtain 0.15" of the TW corrosion crack outside the TSP prior to the leak testing of Step F. Repeat Step B.

- Report whether the tube is tight or loose in TSP following pressurization.

H. Repeat Step C.

I. Repeat Step A.

J. Perform fractographic measurements to obtain the corrosion (corrosion plus fatigue for fatigued specimens) throughwall length and length versus depth profile with emphasis at the ends of the TW crack to define the length and depth of the specimen at the start of testing. Attempt to define the length and depth at the crack tips following all leak testing (i.e., prior to opening the specimen for fractography).

Test Plan for IRBs
Test 12-7

General Test Information

- Utilize large leak test facility testing
- Test 3/4" diameter, specimen 2008D
  - Crack dimensions after corrosion plus fatigue - 0.589" OD with 0.580" ID
- For this 0.745" diameter specimen, the ID of the TSP shall be 0.770" to obtain a 0.025" tube to TSP diametral gap
- Leak test at about 615°F. Primary temperatures should not exceed 640°F.
- Testing should be targeted to obtaining the specified pressure differentials for the evaluated data (test averages)
- Locate specimen relative to the TSP with the crack tip (at start of test) at the inside edge of the TSP for crack locations within TSP - zero offset tests
- Locate the tip of the throughwall crack found after testing with zero offset at 0.10" outside the TSP for offset tests. The 0.10" offset shall be based on the measured TW crack.
- The tube shall contact the TSP hole at 180° from the crack being leak tested.

Test Sequence

A. Hot leak test with crack inside the TSP and crack tip at edge of TSP to obtain at least 4 data points between and 2000 and 2335 psi ΔP

B. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width). TW crack width measurements at the TW crack tips shall be measured at 20 to 30 mil spacing for 0.1" and at 50 mil spacing over the remaining TW length. Crack diameter measurements shall be reported at about 0.1" intervals spanning the crack length and about two 0.15" intervals beyond the crack. Report whether or not the tube is tight or loose in the TSP after the last test step.

C. Hot leak test with the TW crack tip 0.10" offset outside TSP to obtain at least 5 data points between 2300 psi ΔP and the facility limit. Attempt to obtain a data point as close as practical to 2560 psi and to obtain a reduced (average ΔP) data point below and above 2560 psi.

D. Repeat Step B.

E. If the tube is not tight in the TSP following the pressurization of step C, with the crack tip 0.10" offset outside the TSP, pressurize to 2800 psid (approximately 70% of burst pressure) with a bladder. If following pressurization, the corrosion TW crack tip is more than 0.10" outside the TSP, adjust the specimen to obtain 0.10" of the TW corrosion crack outside the TSP prior to the leak testing of Step F. Repeat Step B.

- Report whether the tube is tight or loose in TSP following pressurization.

F. Repeat Step C.

G. With the crack tip 0.10" offset outside the TSP, pressurize to 3950 psid with a bladder. If following pressurization, the corrosion TW crack tip is more than 0.10" outside the TSP, adjust the specimen to obtain 0.10" of the TW corrosion crack outside the TSP prior to the leak testing of Step F. Repeat Step B.

H. Repeat Step C.

I. Repeat Step A.

J. Perform fractographic measurements to obtain the corrosion (corrosion plus fatigue for fatigued specimens) throughwall length and length versus depth profile with emphasis at the ends of the TW crack to define the length and depth of the specimen at the start of testing. Attempt to define the length and depth at the crack tips following all leak testing (i.e., prior to opening the specimen for fractography).

Test Plan IRBs
Test 12-1

General Test Information

- Utilize large leak test facility testing
- Test 7/8" diameter, specimen 8161C
  - Specimen has 2 cracks located at 0° and 90°; primary crack is the 90° crack
  - Primary crack [90°] dimensions after corrosion and fatigue - 0.607" OD with 0.515" ID
  - Secondary crack [0°] dimensions after corrosion and fatigue - 0.465" OD with 0.360" ID
- For this 0.875" diameter specimen, the ID of the TSP shall be 0.900" to obtain a 0.025" tube to TSP diametral gap.
- Leak test at about 615°F. Primary temperatures should not exceed 640°F.
- Testing should be targeted to obtaining the specified pressure differentials for the evaluated data
- Locate specimen relative to the TSP with the crack tip (at start of test) at the inside edge of the TSP for crack locations within TSP - zero offset tests
- Locate the tip of the throughwall crack found after testing with zero offset at 0.15" outside the TSP for offset tests. The 0.15" offset shall be based on the measured TW crack.
- The tube shall contact the TSP hole at 180° from the primary [90°] crack being leak tested.

Test Sequence

A. Hot leak test with crack inside the TSP and crack tip at edge of TSP to obtain at least 5 data points between and 1800 and 2200 psi ΔP

B. Measure crack opening length, diameter, area (total lengths and thruwall lengths/width). TW crack width measurements at the TW crack tips shall be measured at 20 to 30 mil spacing for 0.1" and at 50 mil spacing over the remaining TW length. Crack diameter measurements shall be reported at about 0.1" intervals spanning the crack length and about two 0.15" intervals beyond the crack. Report whether or not the tube is tight or loose in the TSP after the last test step.

C. Hot leak test with the TW crack tip 0.15" offset outside TSP to obtain at least 6 data points between 2200 psi ΔP and the facility limit. Attempt to obtain a data point as close as practical to the highest ΔP obtained in the Step A test and to 2560 psi. Obtain a reduced (average ΔP) data point below and above 2560 psi.

D. Repeat Step B.

E. With the crack tip 0.15" offset outside the TSP, pressurize to 3300 psid with a bladder. If following pressurization, the corrosion TW crack tip is more than 0.15" outside the TSP, adjust the specimen to obtain 0.15" of the TW corrosion crack outside the TSP prior to the leak testing of Step F. Repeat Step B (crack diameter need not be reported to NSD prior to further testing).

F. Repeat offset leak test of Step C.

G. Repeat zero offset leak test of Step A.

H. With the crack tip 0.15" offset outside the TSP, pressurize to 4850 psid with a bladder. If following pressurization, the corrosion TW crack tip is more than 0.15" outside the TSP, adjust the specimen to obtain 0.15" of the TW corrosion crack outside the TSP prior to the leak testing of Step F. Repeat Step B.

I. Repeat offset leak test of Step C.

J. Repeat zero offset leak test of Step A.

K.Perform fractographic measurements to obtain the corrosion (corrosion plus fatigue for fatigued specimens) throughwall length and length versus depth profile with emphasis at the ends of the TW crack to define the length and depth of the specimen at the start of testing. Attempt to define the length and depth at the crack tips following all leak testing (i.e., prior to opening the specimen for fractography).

Test Plan for Indications Restricted from Burst (IRBs)
Loop Orifice Calibration Test

General Test Information

- Three orifice plates in the form of Swagelock fittings and tube with pressure tap provided by NSD are to be used for the test
- Pressure from pressure tap on tube as well as standard pressure, temperature instrumentation for leak testing are to be recorded for the tests
- Tests at multiple pressure differentials for both hot and cold tests are to be performed
- The test sequence given below can be modified to run either the hot or cold tests first
- Test procedures and data reduction for the orifice tests are to be the same as used for the IRB crack leak tests.

Test Sequence

A. Small orifice, cold test, minimum of six pressure differentials between 1400 and 2700 psid, including as close to 2335 and 2560 psid that can be attained.

B. Middle size orifice, cold test, minimum of six pressure differentials between 1400 and 2700 psid, including as close to 2335 and 2560 psid that can be attained.

C. Large size orifice, cold test, minimum of six pressure differentials between 1400 and 2700 psid, including as close to 2335 and 2560 psid that can be attained.

D. Small orifice, hot test with primary temperature in 610 to 620 °F range, minimum of five pressure differentials between 1400 and 2700 psid, including as close to 2335 and 2560 psid that can be attained.

E. Small orifice, hot test with primary temperature in 630 to 645 °F range, minimum of five pressure differentials between 1400 and 2700 psid, including as close to 2335 and 2560 psid that can be attained.

F. Middle size orifice, hot test with primary temperature in 610 to 620 °F range, minimum of five pressure differentials between 1400 and 2700 psid, including as close to 2335 and 2560 psid that can be attained.

G. Middle size orifice, hot test with primary temperature in 630 to 645 °F range, minimum of five pressure differentials between 1400 and 2700 psid, including as close to 2335 and 2560 psid that can be attained.

H. Large orifice, hot test with primary temperature in 610 to 620 °F range, minimum of five pressure differentials between 1400 and 2700 psid, including as close to 2335 and 2560 psid that can be attained. Test to highest pressure differential within facility limits.

I. Large orifice, hot test with primary temperature in 630 to 645 °F range, minimum of five pressure differentials between 1400 and 2700 psid, including as close to 2335 and 2560 psid that can be attained. Test to highest pressure differential within facility limits.

J. Measure orifice sizes for all three orifices. Measurements to determine hole diameter and shape as accurately as practical. The primary side of the orifice plate has a large, conical shape due to drilling of swagelock fitting. This shape should be dimensionally characterized as well as any radius on the secondary side of the hole. Report dimensions to NSD. The orifices and fittings are not to be damaged by these measurements.

K. Return orifices to NSD for further laboratory calibration of the flow rate as a function of the pressure differential.

Evaluation of Crack Flank Springback After Bladder Pressurization

1. The purpose of this test is to determine the degree of elastic springback of the flanks of a crack in a specimen after pressurization of the specimen using an internal bladder for selected specimens from the IRB Leak Tests.

2. Specimens to be tested are 2008-A (from Test 11-7) and 8161-B (from Test 11-2).

3. Test as follows:

4. Make close-up photographic records of the condition of the crack tips on the specimens.

5. Install the bladder for pressurization the same as the setup for bladder pressurization in the IRB leak tests.

6. Test setup shall be a freespan setup (i.e., no TSP is utilized).

7. Attach clip gauges, one near the end of the crack, but within the length of the crack, and another at the center of the crack, oriented to measure diameter changes in the plane of the crack.

8. While increasing the bladder pressure to the pressure noted below, record the changes in tube diameters (clip gauge output). When the maximum pressure has been achieved, continue the test by reducing bladder pressure to zero.

9. Pressurize as follows:

Specimen 2008-A	2300 psid
Specimen 8161-B	3200 psid

10. Remove the clip gauges and measure the diameter of the tube, recording the tube diameters in the same format as used during the IRB leak tests.

11. Measure the length of the crack and record the dimension. This measurement is an overcheck to maintain integrity of the IRB post-tests crack measurements.

B

LEAK RATE RAW DATA