Commonwealth Edison Company
1400 Opus Place
Downers Grove, IL 60515

ComEd

August 25, 1995

Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
Attn: Document Control Desk

Subject: Additional Information Pertaining to the to Application for Amendment to Facility Operating Licenses.

Byron Nuclear Power Station, Units 1 and 2
NPF-37/66; NRC Docket Nos. 50-454/455

Braidwood Nuclear Power Station, Units 1 and 2
NPF-72/77; NRC Docket Nos. 50-456/457

Reference:

1) D. Saccomando letter to the Nuclear Regulatory Commission dated February 13, 1995, transmitting Proposed Technical Specification Amendment Regarding Increase in the IPC Criteria

2) D. Saccomando letter to the Nuclear Regulatory Commission dated April 3, 1995, transmitting the Proposed Leak Rate Test Program

3) Denise M. Saccomando letter to Nuclear Regulatory Commission dated June 20,1995, transmitting Preliminary Leak Rate Test Results for Indications Restricted from Burst

4) Harold D. Pontious, Jr. letter to the Nuclear Regulatory Commission dated July 7, 1995, transmitting a revised proposed Technical Specification Amendment Regarding Increase in the Alternate Plugging Criteria

5) D. Saccomando letter to the Nuclear Regulatory Commission dated July 21, 1995, transmitting the Leak Rate Test Report

Reference 1 transmitted Commonwealth Edison Company's (ComEd's) proposal to amend Appendix A, Technical Specifications of Facility Operating Licenses NPF-37, NPF-66, NPF-72 and NPF-77. The proposed amendment request addresses Technical Specification changes necessary to increase the Interim Plugging Criteria (IPC) value for Braidwood and Byron Station Unit 1 Steam Generators from 1.0 volt to 3.0 volts. This was subsequently superceded via Reference 4.

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Subsequent to that submittal, ComEd and the Nuclear Regulatory Commission (NRC) met on February 23, 1995, to discuss the submittal. During that meeting ComEd presented a model which addressed leakage from indications restricted from burst (IRBs). After discussions, ComEd pursued the development of an alternate leak rate model along with a test program to support the alternate leak rate model.

Testing was conducted on the original 9 specimen test matrix proposed by ComEd in the April 3, 1995 submittal (Reference 2). A report of the testing completed by mid June was submitted to the NRC on June 20, 1995. As the final test results (as reported on July 21, 1995, Reference 5) were undergoing review, inconsistencies in the data were observed. Investigation indicated that some specimens were mispositioned in the test rig in a manner that the cracks were not exposed to the maximum tube to tube support plate gap. ComEd then proceeded to consider supplemental testing, to compensate for this mispositioning.

During the original test program, specimens 1-1, 1-2, and 2-1 (all 7/8" diameter tubing) had significantly undersized gaps. Specimens 1-7 and 2-7 (3/4" diameter tubing) had close to the target 25 mil gap allowance. In order to assure testing was conducted in a conservative manner, similar specimens test 11-1, 11-2, 11-7 12-1 and 12-7 were added to the test program. Testing was then conducted at the target 25 mil gap for these specimens.

The following identifies misposition specimens and their correlated supplemental specimens.

Original specimens	Supplemental specimens
1-1	11-1
1-2	11-2
1-7	11-7
2-1	12-1
2-7	12-7

Because of the limited number of cracks available for this supplemental test program, ComEd chose to test specimens which conservatively replicated original test condition specifically :

- 1 specimen with a single 0.809" (specimen 11-7) long crack, which exceeds the original throughwall length crack criteria, and
- 1 specimen with 2, approximately 0.5" throughwall cracks 90^0 apart (specimen 12-1).

As indicated by the testing results, ComEd chose to use the multiple cracked specimen to redefine the bounding leak rate for indications restricted from burst (IRBs) as 6.0 gpm.

ComEd believes that their specimen selection is indeed conservative. It is important to note that the largest indications seen at Byron and Braidwood (approximately 10 volts) were found to contain short cracks of 0.20" to 0.27" in length, centered within the tube support plates. Cracks tested in the IRB leak rate program had lengths of 1 to 3 times the length of the actual service induced cracks. Additionally, the Byron and Braidwood pulled tubes had eddy current bobbin voltages of at least 3 times the ComEd proposed voltage repair criteria. Based on this information, ComEd concludes that the proposed bounding IRB leak rate of 6.0 gpm is conservative and provides defense in depth.

Additional actions to be implemented as part of the 3 volt IPC including locked TSPs and steam generator internal inspections minimizes the risk of outside diameter stress corrosion cracking (ODSCC) leading to tube rupture during main steam line break, and thereby enhances safety.

Attached are the final results of the leak rate test program along with the results of the test loop orifice calibrations.

The historical perspective and the program development of the IRB Leak Rate Test Program was previously submitted via Reference 5, Attachment 1. Included in the attached report is the final leak rate test report which consists of:

Section 1.0	Overall Test Conclusions
Section 2.0	Test Data and Reduction Methods
Section 3.0	Data Evaluation Methods
Section 4.0	Test Evaluations
Section 5.0	Trend Analyses
Section 6.0	Leak Rate Uncertainty Assessment

To the best of my knowledge and belief, the statements contained in this document are true and correct. In some respects these statements are not based on my personal knowledge, but on information furnished by other ComEd employees, contractor employees, and/or consultants. Such information has been reviewed in accordance with company practice, and I believe it to be reliable.

Sincerely,

Denise M. Saccomando

Denise M. Saccomando
Nuclear Licensing Administrator

cc: D. Lynch, Senior Project Manager-NRR
R. Assa, Braidwood Project Manager-NRR
G. Dick, Byron Project Manager-NRR
S. Ray, Senior Resident Inspector-Braidwood
H. Peterson, Senior Resident Inspector-Byron
Office of Nuclear Safety-IDNS

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Patricia J. Cirrincione
8-25-95

Indications Restricted from Burst (IRBs)
Summary Leak Test Report

Revision 1

August, 1995

IRB Summary Leak Test Report
Table of Contents

Test Matrix for Indications Restricted from Burst (IRBs) - As Tested

Test No.	Tube Dia.	Specimen Type, No.	Throughwall Crack Length			Free Span Leak Test (1)	Crack to TSP Offset[1]						Bladder Press. ΔP[2] Offset (inch)
							Flow Press.			Bladder Press.			
			.25-.45	.45-.60	.60-.75		0.0"	0.10"	0.15"	0.0"	0.10"	0.15"	
1-1	7/8	Corr./Fatg. 8161G			0.62"	H	H		H	H		H, C	0.15
1-2	7/8	Corr./Fatg. 816¹E			0.62"	H	H		H	H		H, C	0.15
1-6	3/4	Corrosion 2008E			0.74"	H	H	H		H	H, C		0.10
1-7	3/4	Corr./Fatg. 2051A			0.60"		H	H		H	H		0.10
2-1	7/8	Corr./Fatg. 8161A		0.515"		H	H		H	H		H, C	0.15
2-4[3]	7/8	Corrosion 4C218	0.29"			H	H		H, C	C		C, H	0.15
2-7	3/4	Corr./Fatg. 2051E		0.577"		C	C	H		H	H, C		0.10
2-8	3/4	Laser Cut IRB-LC-2		0.55"		H	H	H, C					None
2-10[3]	3/4	Corrosion 2051B	0.425"			H	H	H, C		H	H, C		0.10
4-1	7/8	Corrosion 4B214	0.24"							C		C	0.15

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Test No.	Tube Dia.	Specimen Type, No.	Throughwall Crack Length			Free Span Leak Test (1)	Crack to TSP Offset[1]						Bladder Press. ΔP[2] Offset (inch)
							Flow Press.			Bladder Press.			
			.25-.45	.45-.60	.60-.75		0.0"	0.10"	0.15"	0.0"	0.10"	0.15"	
11-1	7/8	Corr./Fatg. 5B403			0.71		H		H	H		H	0.15
11-2	7/8	Corr./Fatg. 8161B			0.63		H		H	H		H	0.15
11-7	3/4	Corr./Fatg. 2008A			0.809		H	H		H	H		0.10
12-1	7/8	Corr./Fatg. 8161C		0.515[4] 0.360			H		H	H		H	0.15
12-7	3/4	Corr./Fatg. 2008D		0.580[5]			H	H		H	H		0.10

Notes:
1. H is hot test at operating temperatures, C is a room temperature test
2. Test sequences include pressurizing with a bladder typically to the free span burst pressure. Test 4-1 includes incremental increases in bladder pressure beyond that equivalent to a free span burst. Tests 2-4,2-10, 11-1, 11-2, 12-1 and 12-7 include bladder pressurizations below and at the free span burst pressure. Bladder press. is performed to open the crack beyond that obtained within the pressure capability of the facility.
3. Leak tests in small leak test facility prior to bladder pressurization and large facility after pressurization. All other tests in large leak test facility.
4. Specimen has two throughwall cracks 90° apart.
5. Two essentially co-planar cracks (0.012" circumferential offset) separated by a ligament at 0.365" from the end of the longer segment.

Nomenclature

SLB	-	steam line break
TSP	-	tube support plate
TW	-	throughwall
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

1.0 Overall Test Conclusions

IRB Leak Test Results

Overall Conclusions

SLB leak rates including maximum TSP displacement at any tube location in a SLB event are bounded by < 6.0 gpm.

- The bounding <6.0 gpm is based on enveloping the following test results:
  - Test 1-6, 3/4" tubing, initial 0.74" TW crack with a flow pressurization offset leak rate of 5.5 gpm and lower bladder pressurized leak rate of 5.0 gpm..
  - Test 11-1, 7/8" tubing, initial 0.71" TW crack with an offset leak rate of 5.0 gpm with both flow and bladder pressurization.
  - Test 11-2, 7/8" tubing, initial 0.63" TW crack with an offset leak rate of 5.3 gpm with both flow and bladder pressurization.
  - Test 12-1, 7/8" tubing, two initial TW cracks of 0.515" and 0.360" with a bladder pressurized offset leak rate of 5.7 gpm and lower flow pressurized leak rate of 3.2 gpm.
- This bounding value envelopes all leak rates for flow and bladder pressurizations for TW cracks contained within the TSP and crack lengths well in excess of that conservatively expected for implementation of the tube expansion based APC.
- The test results show negligible differences in leak rates between 3/4" and 7/8" diameter tubing for large cracks with crack openings limited by the TSP.

Leak rate tests of a 3/4" tubing, 0.809" TW crack in Test 11-7 with a resulting offset leak rate of 6.2 gpm for both flow and bladder pressurization demonstrate additional margins in the very unlikely event of a throughwall indication exceeding the TSP thickness of 0.75".

- A 0.809" TW length is larger than would be expected in field service for any repair limit.
- Since this TW crack length exceeds realistic expectations, the resulting leak rate need not be considered for the bounding IRB leak rate.
- Application of the APC excludes cracks that extend beyond the TSP.

Summary of Bounding Leak Rate Measurement Uncertainty Assessment.

- The contributors to the leak rate uncertainty for the measured leak rate of 5.5 gpm for a single throughwall crack are:
  - Leak rate measurement uncertainty on test average leak rate: ±3.1%
  - ΔP measurement uncertainty on leak rate: -10%
  - Leak rate adjustment uncertainty: negligible
  - Test loop orifice test measurement on leak rate: 0.1% (RT calibration)
- 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 6.0 gpm is -7%/-13%. The actual uncertainties are found as follows:
  - The maximum uncertainty is obtained as [(0.9)·(1.001)·(1.031)-1]·100 or -7%, with a 95%

confidence bound of -5%.
  - The minimum uncertainty is obtained as [(0.9)·(1.001)·(0.969)-1]·100 or -13%.

- It can be concluded that the net uncertainty on the bounding leak rate of 6.0 gpm is acceptably small and an uncertainty adjustment to the bounding value is not necessary. Furthermore, if an uncertainty adjustment was to be applied, the bounding leak rate would be reduced.

Indications > about 0.55" throughwall interact with the TSP for crack to TSP gaps of about 25 mils prior to reaching ΔP_{SLB} and show no significant increases in leakage above the TSP offset leak rate at ΔP_{SLB} even after bladder pressurization to the free span burst pressure at the offset condition.

- Indications > about 0.5" throughwall interact with the TSP for smaller crack to TSP gaps typical of radial clearances of about 12 mils or typical of packed crevices.
- Decreasing the crack to TSP gap below the upper tolerance value of 25 mils reduces the crack length that interacts with the TSP prior to SLB conditions or reduces the ΔP for TSP interaction for a constant crack size.

For throughwall indications < about 0.55", which can be expected to bound indications at Braidwood-1 and Byron-1 following implementation of a 3.0 volt repair limit, the crack openings do not interact with the TSP and the resulting leak rates are typical of free span leak rates.

Leak Rate Dependence on TSP Displacement.

- SLB leak rates following bladder pressurization to the free span burst pressure are independent (within about 10%) of TSP displacement within the limits of the maximum displacements with tube expansion.
  - Test exceptions occur only for specimens with two TW cracks 180° apart
- SLB leak rates for flow pressurization increased with TSP displacement (offset test condition) by 10% to 30% for only 4 of the 10 tests for which this difference could be evaluated. The test increases (4 tests) in leak rates between zero offset and offset conditions are attributable to the leakage being limited by the geometric flow area (confirmed for 3 of the 4 tests by estimates of the effective crack area and geometric flow area based on the test dimensional measurements) in the zero offset tests, such that an increase in leakage is expected for the offset condition.
- Bases for conclusion: Leak rates for IRBs are primarily dependent on the effective throughwall crack area (area not in approximate contact with the TSP hole ID) in comparison with the geometric flow area (area between opened crack edge and TSP hole ID). Crack opening areas that are less than the geometrical flow area would be expected to result in leak rates that are approximately independent of limited TSP displacements. A reduction in turning losses with TSP displacement, although expected to be small for small displacements, could also contribute to the leak rate increase in the offset condition.

Based on crack length measurements currently available, there has been no significant (within about 0.05" for most specimens, maximum 0.097") crack length extension as a result of flow or bladder pressurization to the free span burst pressure.

An appropriate SLB leak rate methodology with tube expansion is free span analysis with an upper limit of 6.0 gpm applied to any Monte Carlo sample leak rate that exceeds 6.0 gpm. Thus, the analyses performed for Byron-1 and Braidwood-1, which explicitly consider IRB leak rates and do not employ a bound on the leak rate obtained from the leak rate to volts correlation, are conservative.

The bounding IRB leak rate, as obtained for single crack and multiple cracks, does not have to be adjusted for potential multiple throughwall indications. This conclusion is based on test results for two throughwall cracks, the high likelihood of finding a single dominant throughwall indication and the very low likelihood that two throughwall indications would be within 0.10" of the TSP edge.

Leak Rate Dependence on Crack Length, Crack Opening Area, Offset Area, etc.

- SLB leak rates for IRBs are primarily a function of the throughwall crack length and effective crack opening area.
- SLB leak rates do not increase linearly with the crack opening area, as would be expected for free span cracks, since the larger openings interact with the TSP hole ID to retard leakage flow from the largest crack widths near the center of the crack.
- SLB leak rates for offset tests do not correlate with the throughwall crack length outside the TSP.
- The increase in leakage from cracks offset outside the TSP relative to the total crack within the TSP is a function of the crack opening area outside the TSP prior to but not after reaching the free span burst pressure of the indication.

Flow Area and Crack Offset Considerations for Influence on IRB Leak Rates.

- The principal factors influencing IRB leak rates are:
  - The TSP limits the crack opening area for throughwall indications greater than about 0.55".
  - The effective crack opening area is further reduced for long cracks (clearly from test results at > 0.6", which might conceptually burst in free span) by tube to TSP gap closure for some length (expect < 0.25" based on test results) along the length of the crack.
  - IRB leak rates are primarily dependent on the effective crack opening area with a modest (<30%) effect of limited TSP displacements on leakage.
  - Upon contact of the crack opening with the TSP, leak rates have a modest or no increase in leakage with increased pressurization and tend toward smaller increases in leakage with throughwall cracks outside the TSP compared to the crack within the TSP.
  - Bases for conclusions
    - o Leak rates for offset and zero offset tests following bladder pressurization (constant effective crack area) are very similar and, in some cases, lower for offset than zero offset conditions. For bladder pressurization tests, there is an increased likelihood for the leakage to be limited by the effective crack area rather than the geometric flow area and there is no correlation between the change in leak rate (offset minus zero offset) and the exposed throughwall crack area. The exception for Test 4-1 is attributable to multiple TW cracks 180° apart exposed by the TSP displacement and by diametral increases in the tube diameter.
    - o Leak rates correlate reasonably well with throughwall crack length and with crack opening

area.

o For flow pressurized tests with the offset test run after (and at higher pressures) the zero offset test, the increase in leakage for the offset condition is less than that expected for the increase in the total crack area. The less than expected increase is attributable to blockage of the flow area near the center of the crack by the TSP which reduces the total crack area to an effective crack area for leakage considerations.

An IPC of 3.0 volts with tube expansion is more conservative than a 1.0 volt IPC without tube expansion.

- Tube burst is essentially eliminated with an insignificant tube burst probability ($<10^{-10}$) for tube expansion with "locked" TSPs
- The maximum SLB leak rate, irrespective of the likelihood of occurrence of the large bounding indications, is limited to < 6.0 gpm

IRB Leak Test Results

Key Conclusions

Test 1-6

- This test of a 0.74" throughwall crack in 3/4" diameter tubing represents the highest leak measurement for a single corrosion crack within bounds of the TSP. Throughwall lengths of this magnitude would not be expected even for the full APC repair limit with tube expansion of 10 to 15 volts
  - A repair limit of only 3.0 volts has been requested by ComEd for implementation of tube expansion at Braidwood-1 and Byron-1
- The SLB leak rate for a single throughwall corrosion crack prior to or after bladder pressurization is bounded by 5.5 gpm including the maximum potential 0.10" TSP offset
- TSP constraint reduces the maximum SLB leak rate by more than a factor of three compared to free span conditions
- For this indication, the leakage results indicate that TSP interaction occurred at about 2000 psi ΔP

Test 12-1

- This test of a 7/8" diameter tube with two intermediate length TW cracks, initial 0.515" TW main crack (0.585" TW after offset flow pressurization test) resulted in a SLB leak rate for flow pressurization of 3.2 gpm at 2560 psid with the crack 0.105" TW outside of the TSP.
  - The two TW cracks for this specimen are typical of what might be expected following implementation of tube expansion based, full APC repair limits - a dominant TW crack with a second, less significant TW indication.
- For this indication, there was no crack to TSP interaction (crack behaved as a free span indication) for flow pressurization up to 2680 psi. Crack to TSP interaction is indicated following bladder pressurization to the free span burst pressure.
- 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 5.7 gpm. The IRB bounding leak rate is based on this result, rounded up to 6.0 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.

Throughwall Corrosion Crack Lengths > About 0.55" - Tests 1-6, 1-7, 2-7, 11-7 (3/4"): 1-1, 1-2, 11-1, 11-2, (7/8")

- Indications with throughwall crack lengths greater than about 0.55" result in crack faces opening to interact with the TSP prior to reaching SLB conditions of 2560 psi ΔP and result in leak rates less than free span indications
- SLB leak rates resulting from flow pressurization to ΔP_{SLB} are about 4.1, 4.1, 5.5 and 6.2 gpm for initial start of test throughwall crack lengths of 0.577", 0.60", 0.74" and 0.81", respectively, in 3/4" tubing.
- SLB leak rates resulting from flow pressurization to ΔP_{SLB} are about 3.2, 3.7, 5.3 and 5.0 gpm for initial start of test throughwall crack lengths of 0.620", 0.620", 0.63" and 0.71" respectively,

in 7/8" tubing.

Throughwall Crack Lengths < About 0.55" - Tests 2-10, 12-7 (3/4"), 2-1, 2-4, 12-1 (7/8")

- Indications with throughwall crack lengths less than about 0.55" have leak rates typical of free span indications and show no significant interaction with the TSP at flow pressurization SLB conditions and large (0.025") crack to TSP clearance. Indications between 0.50" and 0.55" length can interact with the TSP at smaller crack to TSP clearances.
- SLB leak rates resulting from flow pressurization to ΔP_{SLB} are about 0.37, 1.7, 1.7, 3.9 and 3.2 gpm for initial throughwall crack lengths of 0.29", 0.425", 0.515", 0.375" (longer of 2 cracks separated by a ligament) and 0.515" (longer of 2 cracks separated by 90°), respectively.

Contribution From Elastic Crack Opening

- Free span bladder pressurization of specimens previously plastically opened at higher ΔPs increased the crack diameter indicating that elastic deformation adds about 0.003" to 0.005" to the crack diameter and contributes to crack interaction with the TSP. Based on plastic plus elastic crack diameter increases, it can be concluded that the following tests had crack to TSP interaction typical of the target 0.025" crack to TSP gap: 1-6, 1-7, 2-7, 2-8, 11-1, 11-2 and 11-7. Tests 1-1, 1-2 and 2-1 had crack to TSP interaction typical of smaller gaps in the range of about 0.012" to 0.016". Tests 2-4, 2-10, 12-1 and 12-7 did not indicate crack to TSP interaction under flow pressurization conditions and the flow pressurization leak rates are independent of the gap although tests 2-4, 12-1 and 12-7 had gaps typical of the target gap.

Effects of Bladder Pressurization on Leak Rates

- SLB leak rates following bladder pressurization at the TSP offset condition are not significantly different from leak rates obtained by flow pressurization to 2560 psi for throughwall crack lengths > about 0.55 inch which result in interaction with the TSP prior to reaching SLB conditions
- For crack lengths < about 0.55", which do not interact with the TSP prior to reaching SLB conditions, bladder pressurization to the free span burst pressure increases the leak rates above that obtained by flow pressurization but the leak rates for single cracks remain less than those obtained with > 0.55" crack lengths
- Leak rates following bladder pressurization to the free span burst pressure are independent (within 10%) of TSP displacements within the limits tested.
  - Estimated changes in effective crack area and geometric flow area after bladder pressurization help to explain why there is less of a trend for increased leakage after pressurization than before pressurization. After bladder pressurization, the effective crack area tends to be reduced by the flattening of the crack opening near the center of the crack in contact with the TSP while the geometric flow area is less affected and there is an increased likelihood that effective crack areas rather than geometric flow areas limit the leakage.
- Bladder pressurizations above the free span burst pressure do not result in significant increases in the leak rate compared to that obtained following the free span burst pressurization.

Laser Cut Specimens

- Laser cut specimens are not an acceptable substitute for corrosion cracks for leak testing
  - Laser cut specimens result in a factor of 3 increase 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 slot result in non-representative leak rates for offset test conditions.
- The trends and effects of crack to TSP interaction can be demonstrated by laser slots although the leak rates are too high to be representative of corrosion cracks.

Accuracy of In-Process Dimensional Measurements

- Destructive examination of the one specimen examined to date (Test 1-2) shows initial and final throughwall crack length measurements in good agreement with the values obtained by the measurement techniques used in the test program.

Summary of SLB Leak Rates[1] (2560 psid) and Crack Length Data								
Test	Specimen	Initial Lengths		Offset Test			Zero Offset Tests	
		Total	TW	TW Length	Offset TW Length	2560 psi Leak Rate (gpm)	TW Length	2560 psi Leak Rate (gpm)
Flow Pressurization Tests								
2-4	7/8,4C218	0.600	0.290	0.330	0.000	0.37	N.M.	0.37
2-10	3/4,2051B	0.551	0.425	0.425	0.000	1.70	N.M.	1.70
2-1	7/8,8161A	0.640	0.515	0.504	0.134	1.65	0.230	0.93
2-7	3/4,2051E	0.660	0.577	0.636	0.088	4.10	0.515	N.R.[2]
2-8	3/4,IRB-LC2	0.553	0.550	0.558	0.104	6.10	0.525	2.30
1-1	7/8,8161G	0.626	0.620	0.595	0.147	3.70	0.494	2.30
1-2	7/8,8161E	0.645	0.620	0.666	0.145	3.20	0.574	N.R.
1-7	3/4,2051A	0.600	0.600	0.602	0.091	4.10	0.530	3.20
1-6	3/4,2008E	0.760	0.740	0.724	0.070	5.50	0.619	3.40
4-1	7/8,4B214	0.670	0.240	-	-	N.M.[3]	-	N.M.[3]
11-1[6]	7/8,5B403	0.710	0.600 0.110	0.620 0.129	0.150	5.00	0.620 0.129	4.00
11-2	7/8,8161B	0.729	0.630	0.720	0.173	5.30	0.657	N.R.
11-7	3/4,2008A	0.813	0.809	0.811	0.102	6.20	0.809	6.20
12-1[4]	7/8,8161C	0.607 0.465	0.518 0.360	0.585 N.M.	0.105	3.20	N.M. N.M.	3.20
12-7[5]	3/4,2008D	0.590	0.375 0.256	0.375 0.259	0.100	3.90	0.375 0.259	3.90
Bladder Pressurization Tests								
2-4	7/8,4C218	0.600	0.290	0.382	0.076	1.9	0.382	1.3
2-10	3/4,2051B	0.551	0.425	0.492	0.081	1.6	0.492	1.6
2-1	7/8,8161A	0.640	0.515	0.504	0.132	3.1	0.509	3.2
2-7	3/4,2051E	0.660	0.577	0.637	0.087	3.7	0.637	4.2
2-8	3/4,IRB-L62	0.553	0.550	-	-	N.M.[3]	-	N.M.[3]
1-1	7/8,8161G	0.626	0.620	0.595	0.147	2.4	0.595	3.5
1-2	7/8,8161E	0.645	0.620	0.668	0.085	2.8	0.666	2.7
1-7	3/4,2051A	0.600	0.600	0.613	0.100	3.3	0.613	3.2

Summary of SLB Leak Rates[1] (2560 psid) and Crack Length Data

Test	Specimen	Initial Lengths		Offset Test			Zero Offset Tests	
		Total	TW	TW Length	Offset TW Length	2560 psi Leak Rate (gpm)	TW Length	2560 psi Leak Rate (gpm)
1-6	3/4,2008E	0.760	0.740	0.726	0.070	5.0	0.726	4.8
4-1	7/8,4B214	0.670	0.240	0.606	0.099	4.2	0.606	2.5
11-1[6]	7/8,5B403	0.710	0.600 0.110	0.754	0.154	5.0	0.754	5.0
11-2	7/8,8161B	0.729	0.729	0.707	0.150	5.3	0.707	4.9
11-7	3/4,2008A	0.813	0.809	0.811	0.100	6.2	0.811	5.7
12-1[4]	7/8,8161C	0.607 0.465	0.518 0.360	0.630 0.411	0.151	5.7	0.629 0.411	5.7
12-7[5]	3/4,2008D	0.590	0.375 0.256	0.726	0.100	3.3	0.726	3.2

Notes:
(1) Approximate leak rates at 2560 psid based on linear extrapolation of log leak rate vs ΔP plots.
(2) N.R. - Estimate not reliable due to low pressure tested in zero offset condition or absence of crack to TSP interaction at lower pessures
(3) N.M. - not measured. Test not performed.
(4) Specimen has two throughwall cracks 90° apart
(5) Specimen has two parallel throughwall cracks separated by a circumferential ligament 0.012" at the crack tips
(6) Specimen has two aligned axial cracks separated by a ligament

2.0 Test Data and Reduction Methods

Test and Data Reduction Methods

Test Methods

- Primary pressure and temperature measured at specimen
- Secondary temperature and pressure measured in autoclave
- Leak rate measured as condensed volume versus time
- General test operation
  - Primary and secondary pressures set up at approximately equal values at above the target pressure, water supply tank set up at desired hot or cold conditions
  - Secondary pressure "instantaneously" vented to atmospheric pressure
  - Approximate steady state conditions obtained in order of about 10 to 40 seconds dependent on the leak rate
    - o The water volume in the secondary system must also be flushed by leakage volume prior to recording data
  - Adequate leak rate sample volume obtained and test terminated
- Variations over test period
  - Primary pressure tends to decrease as water volume in supply tank decreases
  - Secondary pressure tends to increase, higher with larger leak rates, as a result of steam pressure on the secondary side - function of condensation rate
  - The crack pressure drop (ΔP) is highest early in the test and tends to drop toward a more steady state value
    - o Thus, some hysteresis exists in each test wherein the plastic opening at the higher ΔP tends to result in higher leak rates at the lower ΔP at which the leak rate is measured. This adds conservatism to the measured leak rates
  - Primary temperature also tends to change over the test period. The water in the storage tank has some axial gradient and makeup water for large leak rates also tends to affect the temperature. An intermediate autoclave is used to reduce the temperature variations but some remain in the tests
    - o Due to these variations, the primary temperature cannot be tightly controlled for a given test. Between tests, temperatures may vary from about 605° to about 645°, which is consistent with test plan goals.

Test Data Reduction

- Test data is averaged over a time period after approximate steady state conditions are reached. The time period selected is as necessary to obtain an adequate leak rate volume and varies between tests.
- Averages for leak rate, primary pressure and temperature, secondary pressure and temperature and ΔP are reported
- The maximum ΔP for the test is also reported
- The standard deviation on the average leak rate over the analysis period is reported as the leak rate uncertainty

Crack Length and Crack Opening Area Measurements

- Crack ID and OD dimensions following sample preparation are measured using dye penetrant with a silastic mold for the ID length
- Crack lengths following testing are measured with a toolmaker's microscope. Throughwall lengths and widths are measured using light penetration through the crack opening. Throughwall lengths < 1 mil wide may not be detected by this technique.

Tube to TSP Gap Considerations in Leak Test Program

Test Objective for Leak Test
- Establish diametral gap at 25 mils based on specimen diameter prior to leak testing
- Locate tube within TSP so that free to move or in contact with TSP at 180° from crack

Tube to TSP Fixture (Figure 1) Implemented for Test Sequences Numbered 1 to 4
- Tube end held in a clamshell about 1" above TSP
- Far tube end plugged and unconstrained about 4" below clamshell (~2.5" in clamshell)
- TSP attached to clamshell with two flat bars with slots/attachment screws that permit TSP to be moved axially to locate TSP relative to the crack
- TSP hole centerline nominally aligned with centerline of clamshell

Review of TSP Fixture for Tests Sequences Numbered 1 to 4
- Generally expect tube to TSP gap at radial rather than diametral gap
- For tube diameters less than nominal a shim was included in clamshell to tightly hold the tube.
  - Assembly could result in misalignment of tube in TSP relative to nominally centered as indicated by resulting increases in crack diameters after pressurizing the specimen
  - 3/4" tubes tested were generally less than nominal diameter and crack to TSP gap above nominal
- Tube is very stiff at TSP elevation due to short distance below the clamshell such that lateral movement of tube relative to the TSP ID by hydraulic forces (impingement of leakage on TSP) is very unlikely and movement of tube by crack opening is also expected to be minimal
  - Stiffness of tube is demonstrated by bladder expansion results. The increase in tube diameter across the crack centerline was 1 mil or less except for 1 specimen with a 4 mil increase.

Application of TSP Fixture for Test Sequences Numbered 11 and 12
- For test sequences numbered 11 and 12, the crack to TSP gap was forced to the maximum 0.025" gap adjacent to the crack by alignment of the test fixture (Figure 1). This was verified by requiring that a thin (0.0005") plastic strip inserted between the tube and the TSP at a location 180° from the crack be tight after test fixture assembly (the plastic shim was removed prior to the test). Thus, these tests have the desired 25 mil crack to TSP gap.

Evaluation of Elastic Component of Gap Closure
- To assess the magnitude of elastic deformation of the crack, a free span bladder pressurization to approximately 80% of predicted freespan burst pressure was performed for two specimens. The results of this evaluation showed that there is an elastic diameter increase of 0.003"- 0.005". This elastic deformation is in addition to the prior plastic deformation and indicates that the elastic crack opening increases the measured plastic opening.

Conclusions
- For specimens shown to interact with the TSP during flow testing, the measured plastic crack diameter increase, increased by about 3 mils for the elastic contribution to crack opening, is a good measure of the crack to TSP gap
  - If crack opening could laterally displace the tube significantly, the diameters after bladder expansion should have increased but they did not show increases above a mil
- Estimated crack to TSP gaps based on the crack diameter increase are shown in the attached

table

- Tests 1-6, 2-4, 2-8, 2-10 and 4-1 have been clearly performed to satisfactory gap requirements
- Tests 1-7 and 2-7 had close to desired gap and are within the target 25 mil gap when allowance for the expected elastic expansion of about 3 mils is added to the measured plastic diameter increase. These test results are considered representative of that expected for the target gap.
- Tests 1-1, 1-2 and 2-1 (all 7/8" diameter tests) had significantly undersized gaps
- Tests 11-1, 11-2, 11-7, 12-1 and 12-7 have achieved acceptable gaps by aligning the tube opposite to the primary crack against the ID of the TSP hole.

Summary of Crack Diameter Increases/Implied Gap			
Test	**Initial Diameter (in.)**	**Crack ΔD after Offset Flow Test (in.)**	**Comment**
Leak Tests With Variable Crack to TSP Gap			
1-6, 3/4"	0.745	0.027	Gap requirement satisfied
1-7, 3/4"	0.747	0.020	Gap requirement satisfactory - supplemental tests show that elastic deformation could have effectively closed the crack to TSP gap.
1-1, 7/8"	0.875	0.009	Test results typical of small gap.
1-2, 7/8"	0.874	0.013	Test results typical of small gap.
2-1, 7/8"	0.874	0.010	Test results typical of small gap.
2-4, 7/8"	0.875	0.003 No TSP Interaction	Gap large enough to prevent tube to TSP interaction
2-7, 3/4"	0.747	0.022	Gap requirement satisfactory as noted for Test 1-7.
2-8, 3/4"	0.744	0.030	Gap requirement satisfied Larger ΔD on opening clamshell indicates elastic springback
2-10, 3/4"	0.748	0.001 No TSP Interaction	Gap large enough to prevent tube to TSP interaction
4-1, 7/8"	0.876	0.025	Gap requirement satisfied
Leak Tests With Fixed 0.025" Crack to TSP Gap			
11-1, 7/8"	0.874	0.021	Tests show crack to TSP int.
11-2, 7/8"	0.874	0.016	TSP interaction demonstrated with plastic plus elastic ΔD about 0.023" based on supplemental tests to estimate elastic ΔD.
11-7, 3/4"	0.745	0.020	TSP interaction demonstrated with plastic plus elastic ΔD about 0.023" based on supplemental tests to estimate elastic ΔD.
12-1, 7/8"	0.875	0.002	No TSP interaction.
12-7, 3/4"	0.745	0.005	No TSP interaction.

Figure 1 Test Fixture Assembly

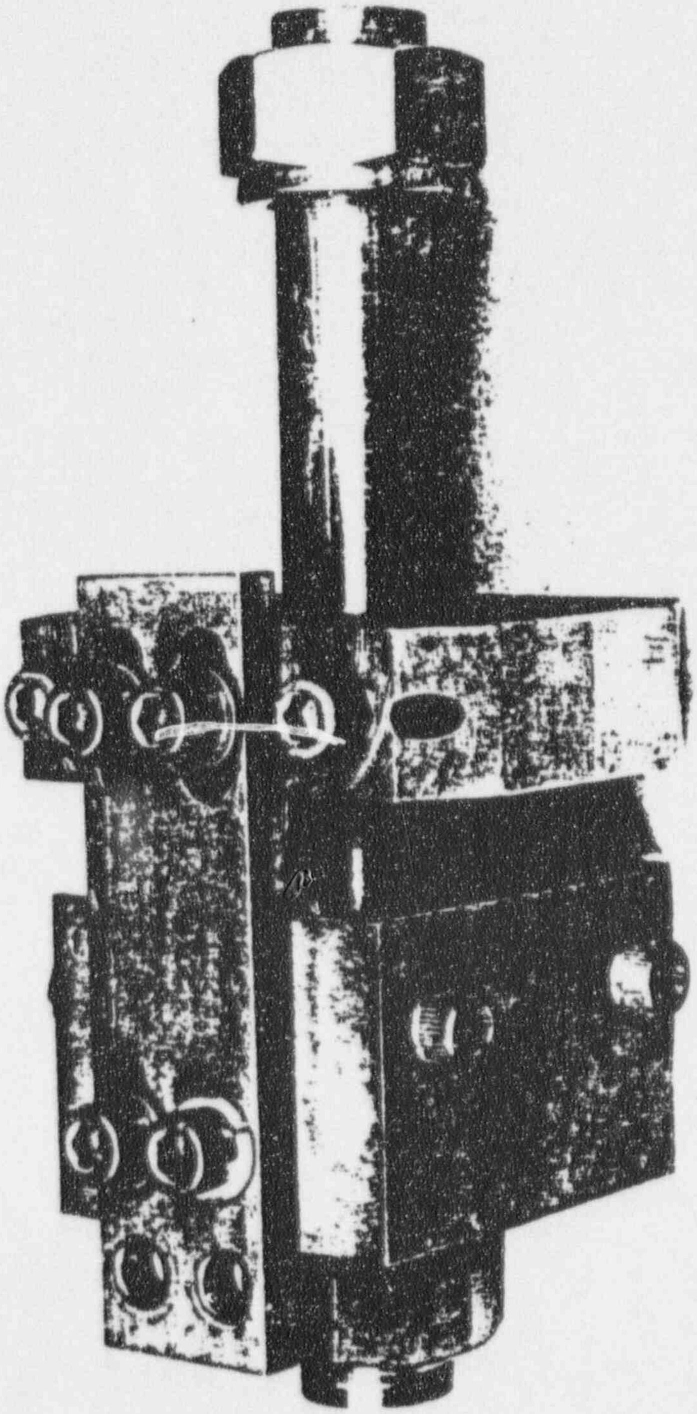
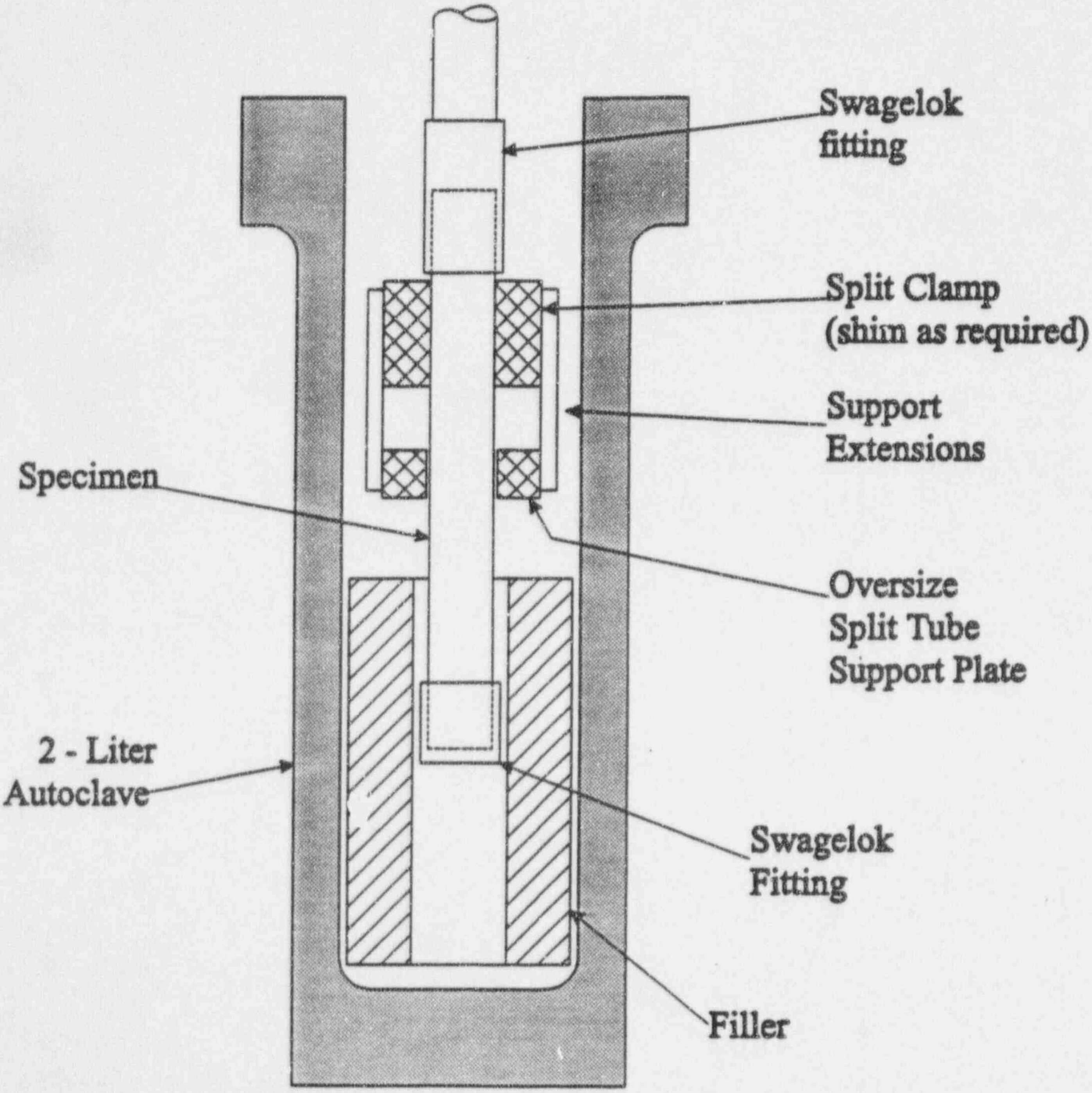


Figure 2 Typical Installation of Test Sample in Autoclave



3.0 Data Evaluation Methods

Need for Data Normalization

- Leak rates are desired at SLB conditions of 615°F and 15 psi secondary pressure which cannot be tightly controlled in the tests
- Primary temperature influences the saturation pressure which is the effective secondary pressure when flashing to steam occurs (all cases near SLB conditions)for the primary water , the water density and the material properties
  - Adjustments for flashing are typically the largest adjustments required to the test data. Saturation pressure increases significantly with temperature and many test results have temperatures and pressures higher than the reference conditions of 615°F and 15 psi
- The EPRI leak rate adjustment procedure given in EPRI report NP-6480-L, Volume 1, Revision 1, Appendix B is applied for the data normalization/adjustments

EPRI Leak Rate Adjustment Procedure

- The adjustment procedure includes three terms - the hydraulic factor (γ) for the effective pressure differential which is a flashing adjustment, the temperature factor (β) which adjusts for density and material properties and the mechanical factor (α) which adjusts for crack opening between two different ΔPs. The mechanical factor is not applied in this assessment and is not further discussed herein.
- Hydraulic factor

$$\gamma = \sqrt{\frac{(p - C_p p_s)/\Delta p}{(p_o - C_{po} p_{so})/\Delta p_o}}$$

where p is the primary pressure, p_s is the saturation pressure at the primary temperature, Δp is the primary to secondary pressure differential, C_p is a pressure coefficient to adjust for a non-isentropic process, subscript o represents the leak test condition and no subscript represents the target (reference) conditions.

  - CRACKFLO analyses in NP-7480-L indicate a range of .72 to .88 for C_p to improve agreement on ratios of leak rates between the adjustment procedure and the CRACKFLO results. Sensitivity analyses were run on Test 1-6 for a range from .75 to .85 with no significant differences in the adjusted leak rates for the higher pressure tests and a value of .80 was selected for the analyses of this report. Higher values tend to decrease the adjusted leak rates for the test conditions. A higher value than 0.80 may be appropriate for the larger crack sizes in the Sequence 1 tests and the higher test pressure differentials.
  - The use of C_p is most significant for tests in which the primary pressure is close to the saturation pressure at the primary temperature. In this case, the adjustment can become unrealistically large without including C_p. The need for this term occurs primarily for pressures less than about 2200 psi and temperatures above about 620°F.

EPRI Leak Rate Adjustment Procedure

- Temperature Factor

$$\beta = \frac{E_o \sigma_{fo}}{E \sigma_f} \sqrt{\frac{\rho_o}{\rho}}$$

where E is Young's modulus and σ_f is the flow stress.

- The hydraulic and temperature factors are applied to the test data to obtain leak rates at standard or reference conditions prior to further evaluation of the data.
- Evaluation of cold to hot adjustment factor
  - F oom temperature to operating temperature adjustments are applied to all room temperature test results in this report. The adjusted data vary in a narrow range above and below the hot temperature test results. The cold to hot adjustment factor is not further evaluated in this report. A more detailed study including sensitivity results will be included in the EPRI test report.

Evaluation of Test Data

- Hysteresis effects
  - Some test points are obtained at a lower ΔP than a prior data point which introduces a hysteresis effect. This results in plastic opening of the crack such that the leak rate for the subsequent, lower pressure test is typically overestimated. For this analysis, data points more than about 40 psi lower than a prior test are excluded on the basis of hysteresis from the data plots and evaluation. The selection of 40 psi is a judgement 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.
  - Data points following bladder pressurization are not deleted for hysteresis effects since this step is specifically applied to maximize the crack opening and the bladder pressures substantially exceed the leak rate test pressures.
- Averaging of Data Points
  - Data points in the same test condition (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 or deleted for hysteresis effects are identified in the data sheets provided herein for each test.
- Use of average or maximum ΔP in evaluating leak rate data
  - The test data reduction methods develop the average leak rate over time and the average ΔP over the same time period. The average ΔP is lower than the maximum value (also reported) and use of the average value introduces hysterisis effects since the plastic crack opening is determined by the maximum ΔP.
  - Test sequences numbered 1 to 4 were evaluated using the average ΔP while test sequences 11 and 12 were evaluated using the maximum ΔP. Based on the evaluation of the early tests (sequence numbers 1 to 4), it was found that a more consistent interpretation of the test results could be obtained using the maximum pressure value since it more accurately reflected the start and end points of test sequences such as zero offset and offset test sequences. This was particularly significant for evaluation of Test 12-7 since the differences between maximum and

average pressures were larger than typically found.
  - Since the limiting Test 1-6 of test sequence numbers 1 to 4 was evaluated by both average and maximum ΔP methods, the change of data evaluation methods between the test series does not influence the conclusions of this report.
- Terminology used in data analyses.
  - Crack opening area or crack area: the area of the TW crack as measured by light penetration through the crack after important test sequences such as offset tests, bladder pressurization, etc.
  - Effective crack area: the measured crack area reduced by the crack area associated with the crack length in contact with the ID of the hole as estimated from diameter measurements. It is assumed, based on diameter measurements, that the crack length within a radial distance of about 1 mil of the TSP hole ID does not contribute to leakage and the leakage flow must pass through the effective crack area. The 1 mil distance accounts for minor elastic springback of the crack flanks at low pressure.
  - Geometric flow area: for cracks within the TSP, the area between the opened or bulged crack and the TSP hole ID define a geometrical limit on the area that leakage must pass through. This area is determined as the integrated area between the bulged crack (using crack diameter measurements along the crack) and the hole ID and includes the area on both sides of the crack opening.
  - Limiting flow area: the smaller of the effective crack area and the geometric flow area. If the effective crack area is smaller than the geometric flow area, the leakage is limited by the crack area and moving the crack outside the TSP (offset tests) would not be expected to significantly increase the leak rate. If the geometric area is limiting, moving the crack outside the TSP in the offset tests increases the flow area to closer to the effective area and the offset test would be expected to result in an increase in leak rate. These relations apply as long as the maximum crack diameter does not move outside the TSP which is the case in all tests and can be expected in all cases of limited TSP displacements (maximum tested is 0.15")

Trend Analyses

- The trends for the leak rates as a function of measured parameters such as throughwall crack length, crack opening area, offset length, etc. are also evaluated and documented in this report.

Leak Rate Uncertainty Considerations

Potential Sources of Uncertainty in the Leak Rates

- Leak rate fluctuations during the test period
  - This uncertainty is developed for each leak rate measurement as the standard deviation of the leak rate about the average value reported for the test.
- Maximum ΔP in test occurs prior to averaging data for reporting leak rates
  - This effect is evaluated for the bounding leak rate (Test 1-6) by adjusting the leak rates to the maximum ΔP in the test and comparing the resulting value at the SLB pressure differential of 2560 psi with the value obtained for the reference analysis based on averaging the test data over a time interval.
- EPRI leak rate adjustment procedure
  - This uncertainty has been reduced by applying the C_p factor in the hydraulic factor of the adjustment procedure to maximize the leak rates. This is evaluated by comparing leak rates for different values of C_p for the bounding leak rates test (Test 1-6)
- Test loop calibrations
  - All instruments used in the tests have updated calibrations and the important primary pressure and temperature are measured at the test specimen. Thus the uncertainty for loop calibrations is negligible.
  - To further evaluate the test loop accuracy, room temperature leak tests were performed for three orifices of different diameters and the leak rates compared with measurements made at an orifice calibration laboratory. This comparison is used to define the test loop measurement uncertainty. For additional information, hot test loop measurements were performed for the three orifices and these results are compared with analytical calculations.

An Uncertainty Assessment for the Above Considerations is Included in This Report, Section 6.

4.0 Test Evaluations

Test 11-1: Summary of Test Results and Evaluation

Test Sequence

- Order of tests: zero offset, offset 0.15", bladder pressurization to 3670 psi, offset 0.15" and zero offset. All tests are hot tests.
  - No intermediate pressurization step was included since the SLB ΔP is approximately 70% of the predicted specimen burst pressure
  - The crack to TSP gap was established at 0.026" by forcing the tube to contact the TSP hole ID at 180° from the crack.
- There is no basis to question the adequacy of the data - leak test results show consistent trends, without large data scatter.

Summary of Test Results

- The start of test crack is a total of 0.710" long, composed principally (two additional short ligaments near top of crack opened during initial testing) of two axially aligned segments separated by an uncorroded ligament. The ligament is located at 0.60" from the end of the crack used to establish the offset condition. The crack length is throughwall except for the ligament.
  - TW crack was intermittently visible with back light over the full length of the OD but too tight to quantify width (<0.001").
  - The ligament at 0.60" from the end of the crack was broken after bladder pressurization to 3670 psid. The ligament broke to become a loose piece (0.046" long in axial crack direction by 0.023" wide and approximately the wall thickness deep) that was removed from the crack following the bladder pressurization offset flow test.
  - This specimen initially had three other part-TW cracks that were TIG welded prior to fatiguing the main crack to the desired length. There is no evidence that the welding affected the flow testing of the principal crack. Leakage behavior was consistent with that expected based on throughwall crack length. The welded cracks did not open during testing.
  - The tube was not tight in the TSP after the final bladder pressurization.
- Crack interaction with the TSP occurs at approximately 2150 psid based on the shallow slope of the leak rate curve of the flow pressurized zero offset test.
  - Following the zero offset test, the TW length was about 0.749" (total OD length of 0.752") with the three ligaments remaining intact, the maximum TW crack width was 0.018" and the crack diameter increase was about 0.018".
- The leak rate at the SLB pressure differential in the flow pressurized offset condition is bounded by 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 was 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".

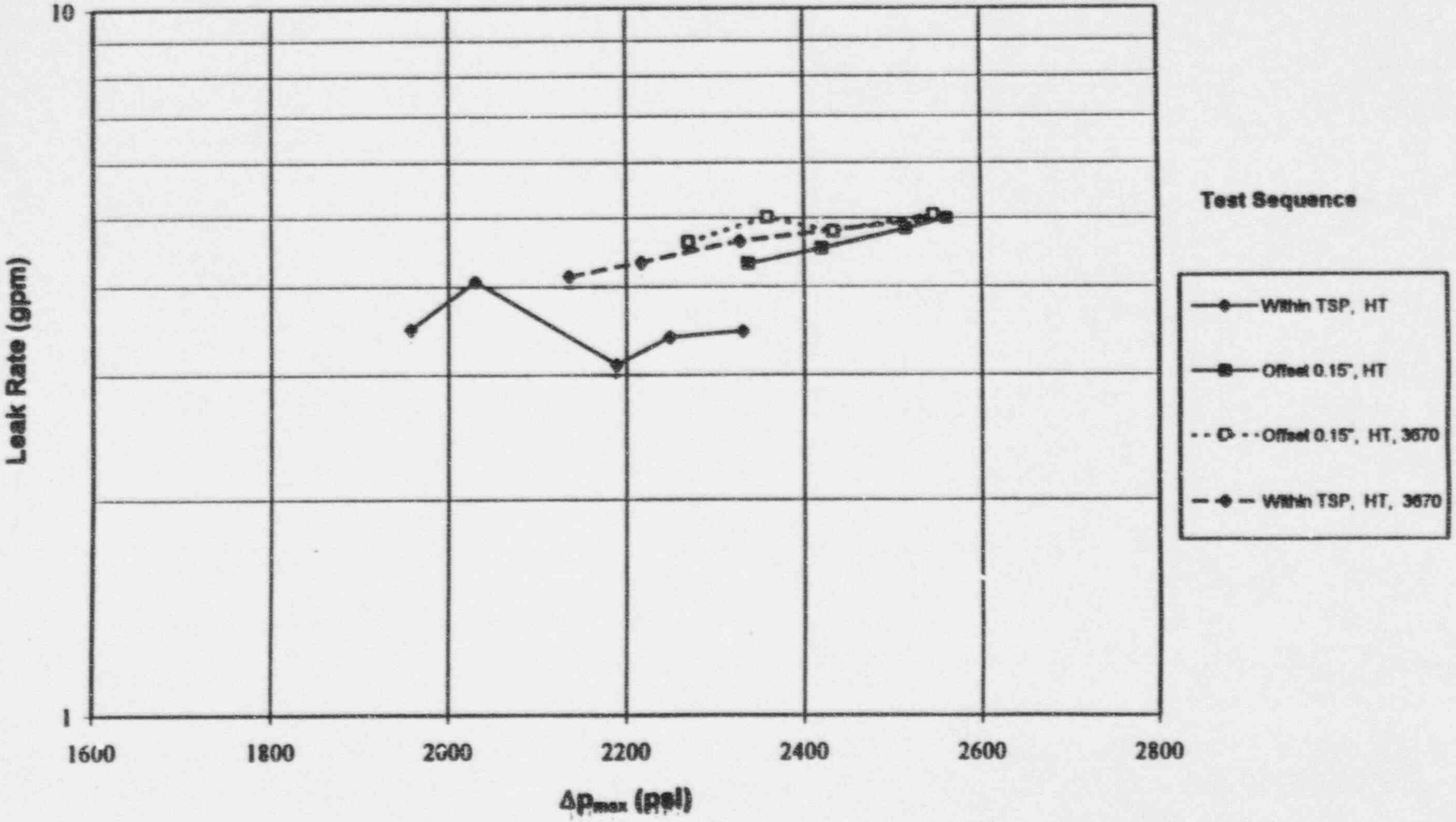
- The leak rate for the offset test was about 1 gpm higher than the zero offset test.

- Leak rates for the zero offset and offset condition following bladder pressurization to the free span burst pressure of about 3670 psi were approximately equal to that found for the offset flow pressurization test at SLB conditions.
  - The bladder pressurization and 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".

Overall Conclusions

- This test of a 7/8" diameter tube, initial 0.70" TW crack (0.749" TW after offset flow pressurization test) resulted in a SLB leak rate at 2560 psid of 5.0 gpm for flow and bladder pressurization with the crack 0.15" TW outside of the TSP.
  - This leak rate and the Test 11-2 results in 7/8" tubing are very similar to the bounding leak rate of 5.5 gpm found in 3/4" tubing for Test 1-6 which had a 0.724" TW crack following the offset flow pressurization test.
  - This 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.
- For this indication, the leakage results indicate the TSP interaction occurred at about 2150 psi.
- 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 zero offset leak rate was the same as the offset leak rate.

Test 11 - 1
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp= 615°F and ps = 15 psia Conditions - based on test leak rate at Δp_{max})



31

ChNorm_11-1Dpmax

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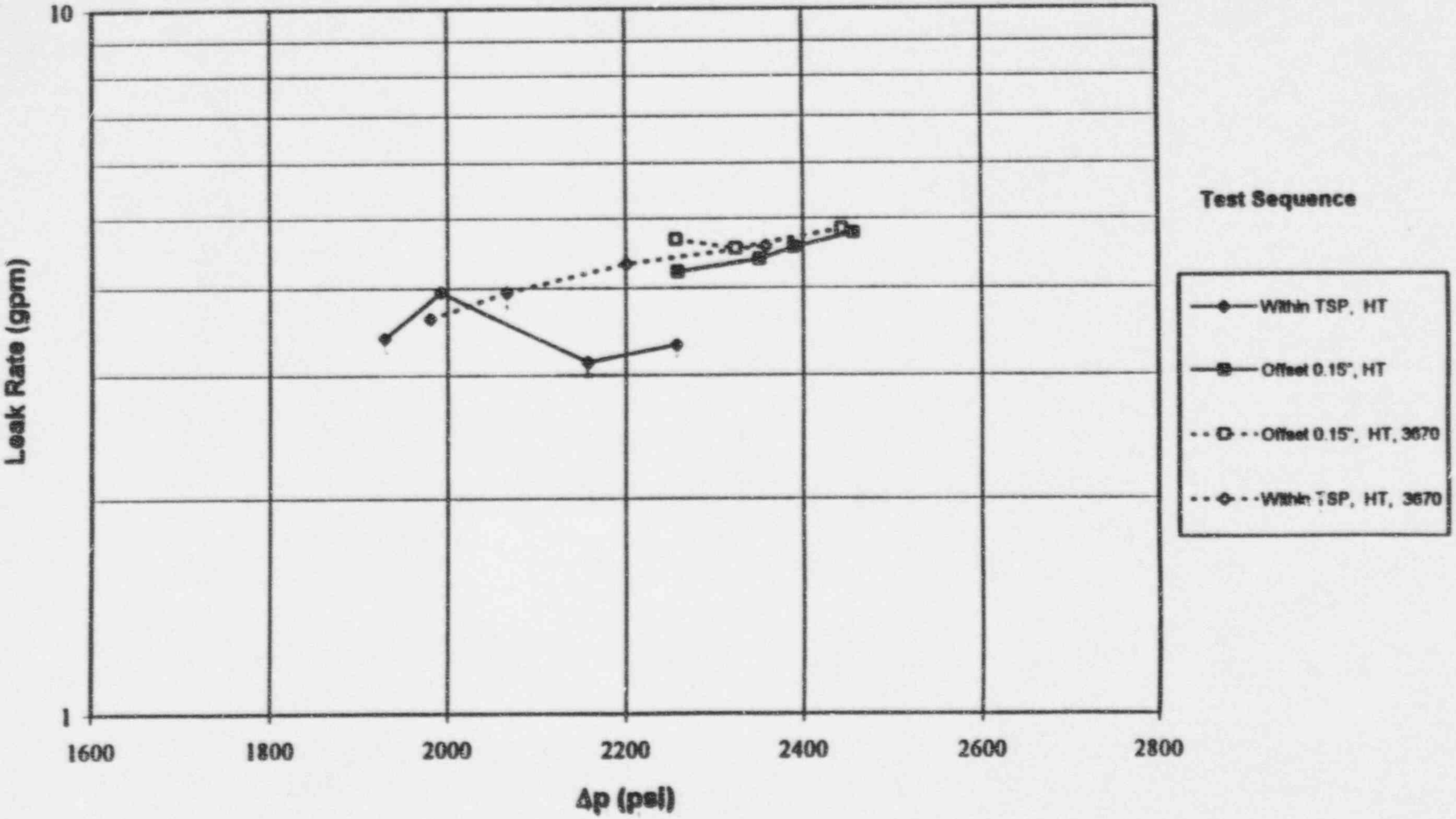
Test 11 - 1
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp= 615°F and ps = 15 psia Conditions - based on test leak rate at Δp_{avg})



35

ChNorm 11-1

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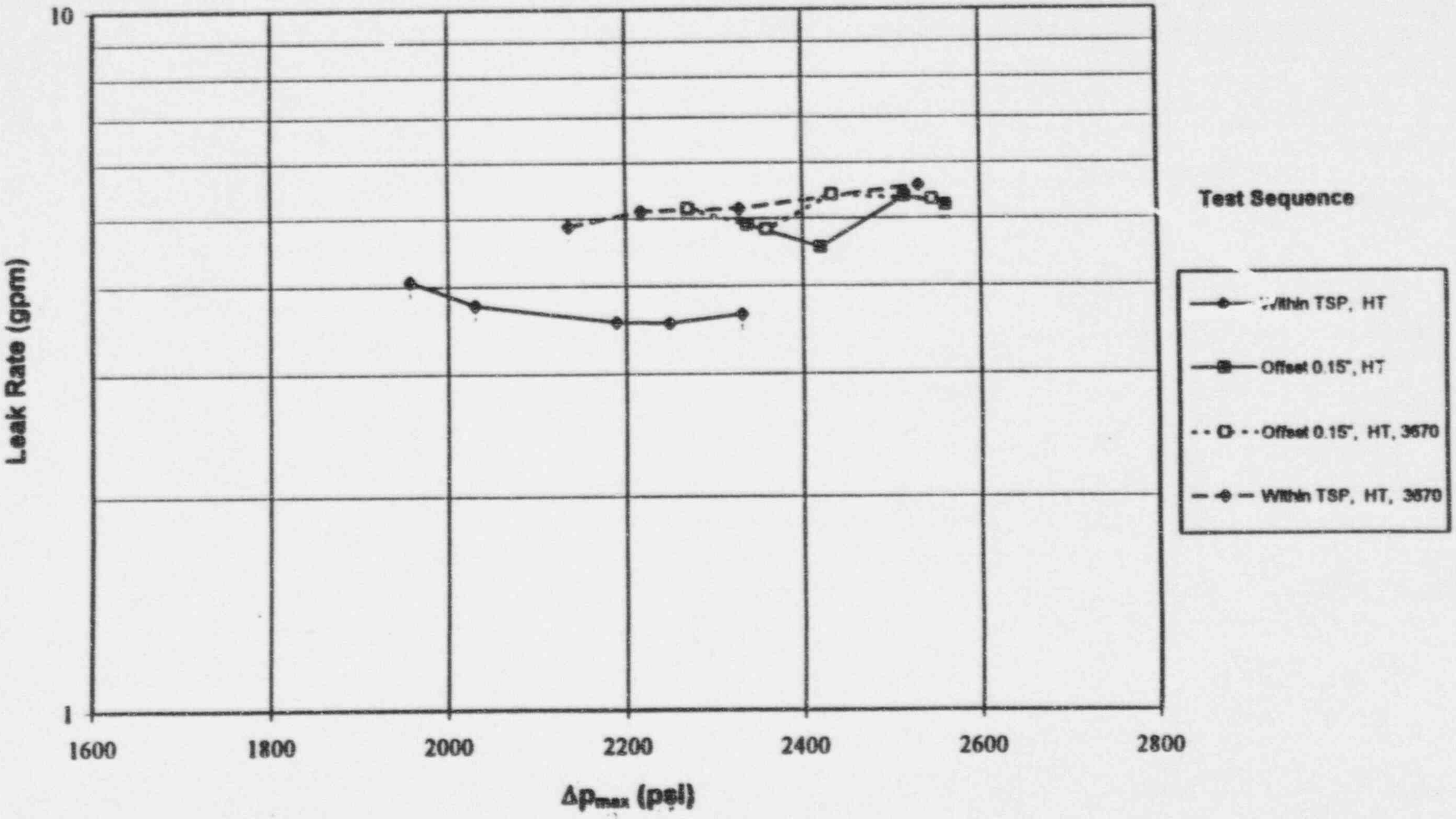
Test 11 - 1

Indications Restricted From Burst Leak Rate Tests

(Test leak rate at Δp_{max}, without adjustment to reference SLB conditions)



ChRaw 11-1Dpmax

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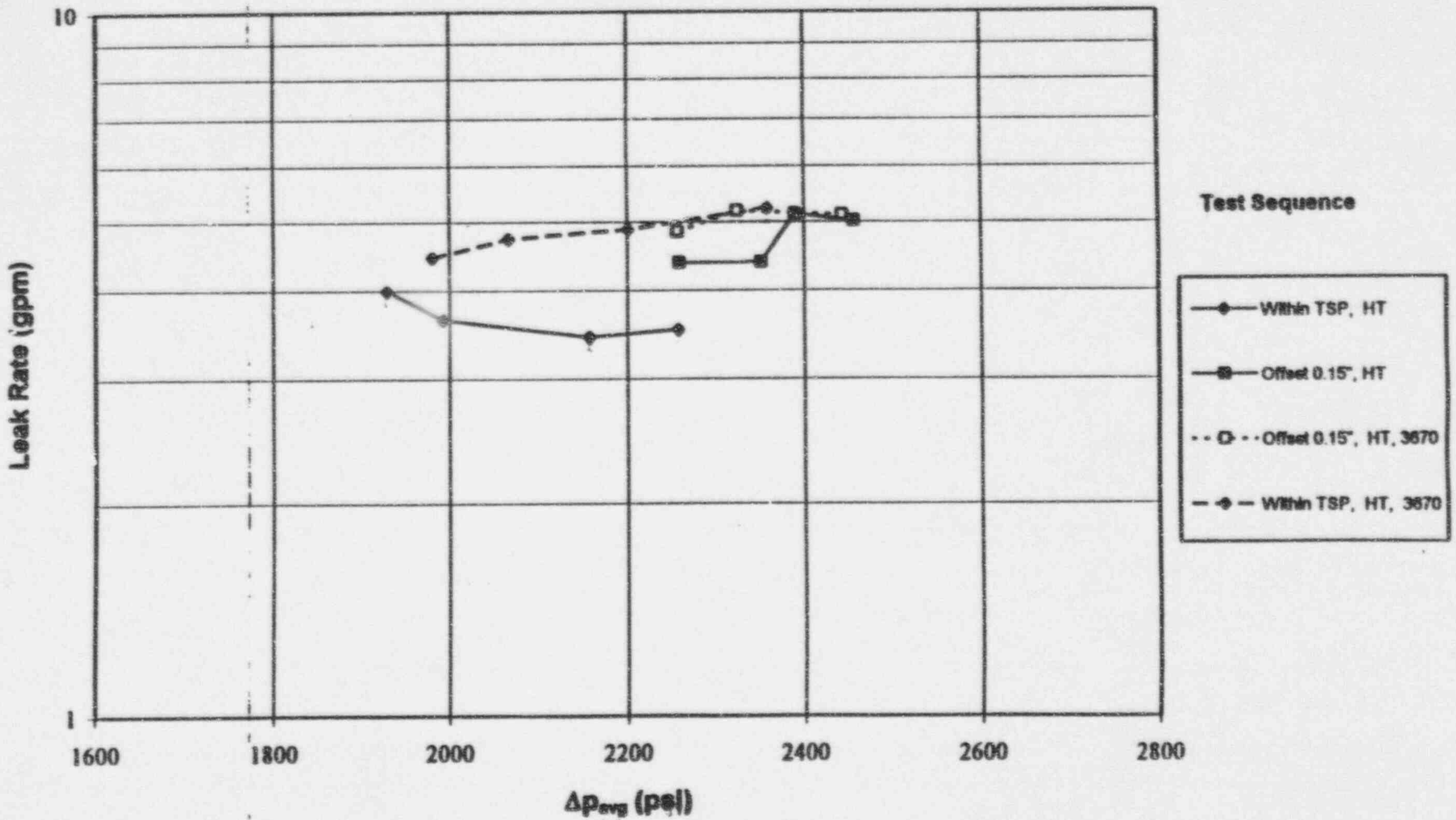
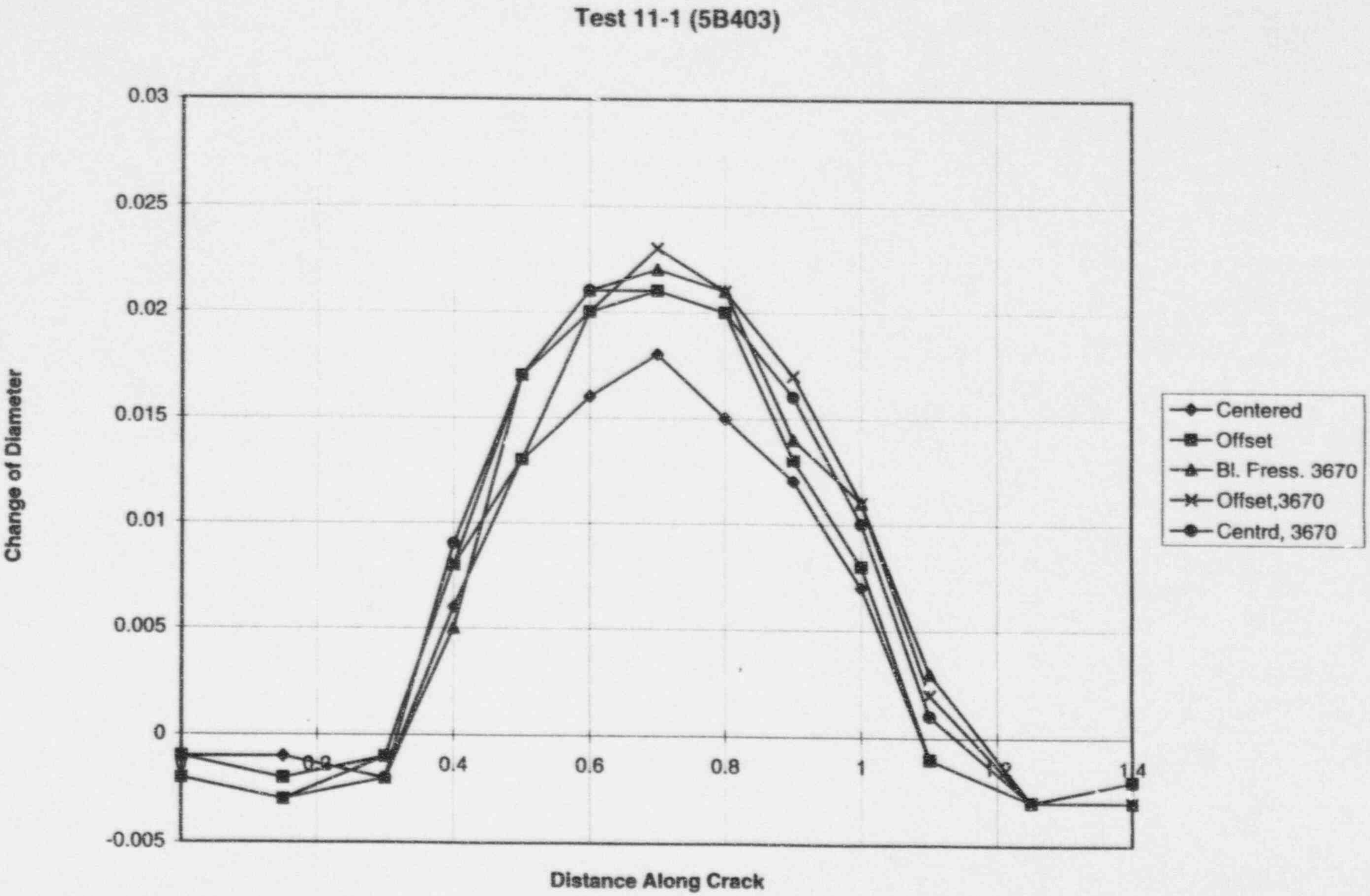
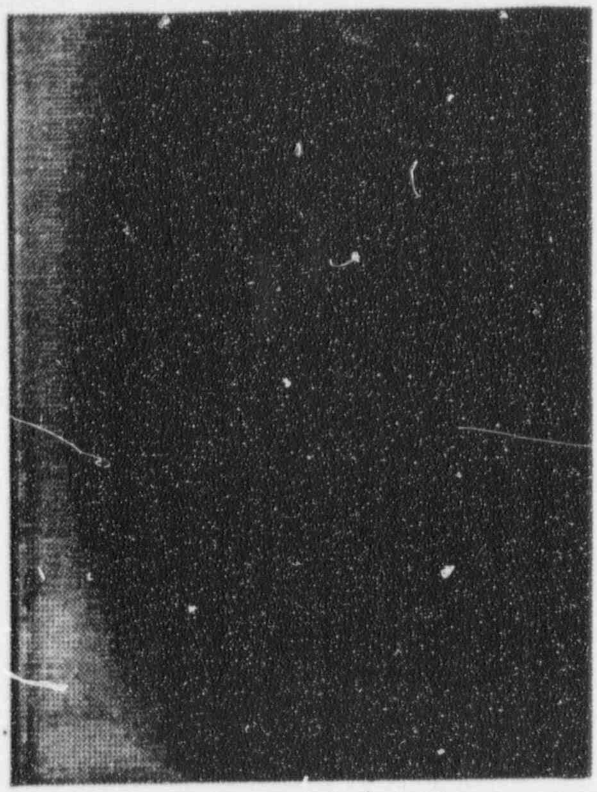
Test 11 - 1
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)



34


Test 11-1 (5B403)
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
Change of Diameter
0.2
0.4
0.6
0.8
1
1.2
1.4
Distance Along Crack
Centered
Offset
Bl. Fress. 3670
Offset,3670
Centrd, 3670



After Flow Pressurization; Within TSP

After Bladder Pressurization to 3670 psid and Subsequent Leak Tests

Test 11-1 (Sample 5B403)

Test 11 - 1

Summary of Leak Test and Analysis Results (Based on Maximum Test Δp)

Specimen 5B483, Tube Diameter = 0.875", Gap = 0.026"

			Evaluated Test Averages						Adjusted Leak Rate at Δp_{max}				Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{max} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	Test Leak Rate (RT) at Δp_{max} (gpm)	β	γ	Leak (@ Δp_{max}) Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (@Δp_{max}) (gpm)	Comments
1-1 A Within TSP	1	1957	2186	257	1929	619	3.99	0.26	4.06	1.00	0.85	3.48	3.48	
	2	2030	2241	249	1992	644	3.64	0.13	3.76	0.99	1.05	4.07	4.07	
	3	2189	2351	212	2139	611	3.47	0.19	3.55	0.96	0.88	3.10	3.10	
	4	2249	2386	210	2176	626	3.41	0.24	3.54	0.97	0.95	3.40	3.40	
	5	2304	2448	227	2221	621	3.68	0.16	3.83	0.97	0.92	3.54	3.46	Average of 5 &6
	6	2357	2511	218	2293	628	3.37	0.15	3.48	0.97	0.96	3.37		
11-1 C Offset 0.15"	1	2260	2500	271	2229	635	4.25	0.47	4.32	1.02	0.97	4.25	-	Delete - Hysteresis
	2	2317	2531	267	2264	645	4.03	0.25	4.16	0.99	1.03	4.41	-	Delete - Hysteresis
	3	2337	2542	290	2252	616	4.72	0.31	4.89	0.96	0.88	4.31	4.31	
	4	2420	2637	286	2351	638	4.38	0.49	4.52	0.98	0.98	4.52	4.52	
	5	2515	2705	315	2390	618	5.13	0.39	5.37	0.96	0.89	4.81	4.81	
	6	2561	2773	317	2456	631	5.01	0.53	5.22	0.97	0.94	4.98	4.98	
11-1F Expanded 3670 psi Offset 0.15"	1	2270	2555	316	2239	622	5.09	0.34	5.16	1.01	0.89	4.61	4.61	
	2	2359	2572	298	2274	643	4.6	0.38	4.81	1.04	1.00	5.00	5.00	
	3	2433	2644	320	2324	617	5.18	0.25	5.40	1.00	0.88	4.78	4.78	
	4	2546	2764	321	2443	629	5.11	0.31	5.32	1.02	0.93	5.05	5.05	
11-1G Expanded 3670 psi Within TSP	1	2012	2257	277	1980	612	4.45	0.16	4.53	1.00	0.82	3.72	3.72	
	2	2122	2337	280	2057	629	4.67	0.27	4.83	1.01	0.88	4.25	4.14	Average of 2 & 3
	3	2150	2358	297	2061	609	4.7	0.06	4.89	0.99	0.83	4.03		
	4	2217	2369	288	2081	611	4.81	0.6	5.11	1.00	0.85	4.33	4.33	
	5	2328	2495	294	2201	620	4.88	0.31	5.16	1.01	0.89	4.63	4.63	
	6	2531	2679	321	2358	616	5.23	0.38	5.57	1.00	0.89	4.95	4.95	

TEST11-1.XLS 11-1 Table/Report 0/0/95 4:29 PM

Test 11 - 1
Summary of Leak Test and Analysis Results (Based on Average Test Δp)
Specimen 5B403, Tube Diameter = 0.875", Gap = 0.026"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{test} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
1-1 A Within TSP	1	1957	2186	257	1929	619	3.99	0.26	1.00	0.85	3.40	3.40	
	2	2030	2241	249	1992	644	3.64	0.13	1.03	1.06	3.95	3.95	
	3	2189	2351	212	2139	611	3.47	0.19	1.00	0.87	3.01	3.13	Average of 3 & 4
	4	2249	2386	210	2176	626	3.41	0.24	1.01	0.95	3.25		
	5	2304	2448	227	2221	621	3.68	0.16	1.00	0.91	3.38	3.32	Average of 5 &6
	6	2357	2511	218	2293	628	3.37	0.15	1.01	0.96	3.26		
11-1 C Offset 0.15"	1	2260	2500	271	2229	635	4.25	0.47	1.02	0.97	4.18	-	Delete - Hysteresis
	2	2317	2531	267	2264	645	4.03	0.25	1.03	1.04	4.29	4.20	Average of 2 & 3
	3	2337	2542	290	2252	616	4.72	0.31	1.00	0.87	4.12		
	4	2420	2637	286	2351	638	4.38	0.49	1.02	0.98	4.37	4.37	
	5	2515	2703	315	2390	618	5.13	0.39	1.00	0.88	4.55	4.55	
	6	2561	2773	317	2456	631	5.01	0.53	1.01	0.94	4.76	4.76	
11-1F Expanded 3670 psi Offset 0.15"	1	2270	2555	316	2239	622	5.09	0.34	1.01	0.88	4.53	4.66	Average of 1 & 2
	2	2359	2572	298	2274	643	4.6	0.38	1.04	1.00	4.79		
	3	2433	2644	320	2324	617	5.18	0.25	1.00	0.87	4.53	4.53	
	4	2546	2764	321	2443	629	5.11	0.31	1.02	0.93	4.82	4.82	
11-1G Expanded 3670 psi Within TSP	1	2012	2257	277	1980	612	4.45	0.16	1.00	0.82	3.62	3.62	
	2	2122	2337	280	2057	620	4.67	0.27	1.01	0.87	4.07		
	3	2150	2358	297	2061	609	4.7	0.06	0.99	0.81	3.80	3.94	Average of 2 ,3 & 4
	4	2217	2369	288	2081	611	4.81	0.6	1.00	0.83	3.97		
	5	2328	2495	294	2201	620	4.88	0.31	1.01	0.88	4.32	4.32	
	6	2531	2679	321	2358	616	5.23	0.38	1.00	0.87	4.57	4.57	

TEST11-1.XLS 11-1 Table 8/10/95 4:21 PM

Test 11-1 Summary of Test Dimensional Measurement Results
Specimen 5B403, Tube Dia. = 0.875", Gap =0.026"

Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in.²)	Max Dia. (in.)	Min. Dia. (in.) [1]
None	NA	Pre-test	90° [5]	0.710	0.71[2]	NA [3]	NA	NA	0.876	0.873 0.872
None	0.0 Step A	Hot		0.752	0.749[4] (.018)	.00811	NA	NA	0.893	0.874 0.873
None	0.15 Step C	Hot		0.755	0.749[4] (.024)	0.01178	0.15 (0.017)	0.00134	0.896	0.874
3670	0.15 Step E	NA		0.755	0.749[4] (0.026)	0.01395	NA	NA	0.897	0.878 0.873
3670	0.15 Step F	Hot		0.757	0.754[4] (0.027)	0.01439	0.254 (0.019)	0.00168	0.898	0.877 0.874
3670	0.0 Step G	Hot		0.757	0.754[4] (0.027)	0.01459	NA	NA	0.896	0.876 0.873

Test 11-1 Summary of Test Dimensional Measurement Results Specimen 5B403, Tube Dia. = 0.875", Gap =0.026"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in.^{2})	Max Dia. (in.)	Min. Dia. (in.) [1]

Notes: [1] Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.875" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
[2] Based on silastic mold and dye penetrant test.
[3] Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
[4] Crack length from toolmaker's microscope. Minimum measurable TW crack opening ~0.001".
[5] Non-TW cracks at 0°,180° and 270° TIG welded

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 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 11-2: Summary of Test Results and Evaluation

Test Sequence

- Order of tests: 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.
  - Intermediate bladder pressurization step is approximately 70% of the predicted specimen burst pressure.
  - The crack to TSP gap was established at 0.026" by forcing the tube to contact the TSP hole ID at 180° from the crack.
- There is no basis to question the adequacy of the data - leak test results show consistent trends, without large data scatter.

Summary of Test Results

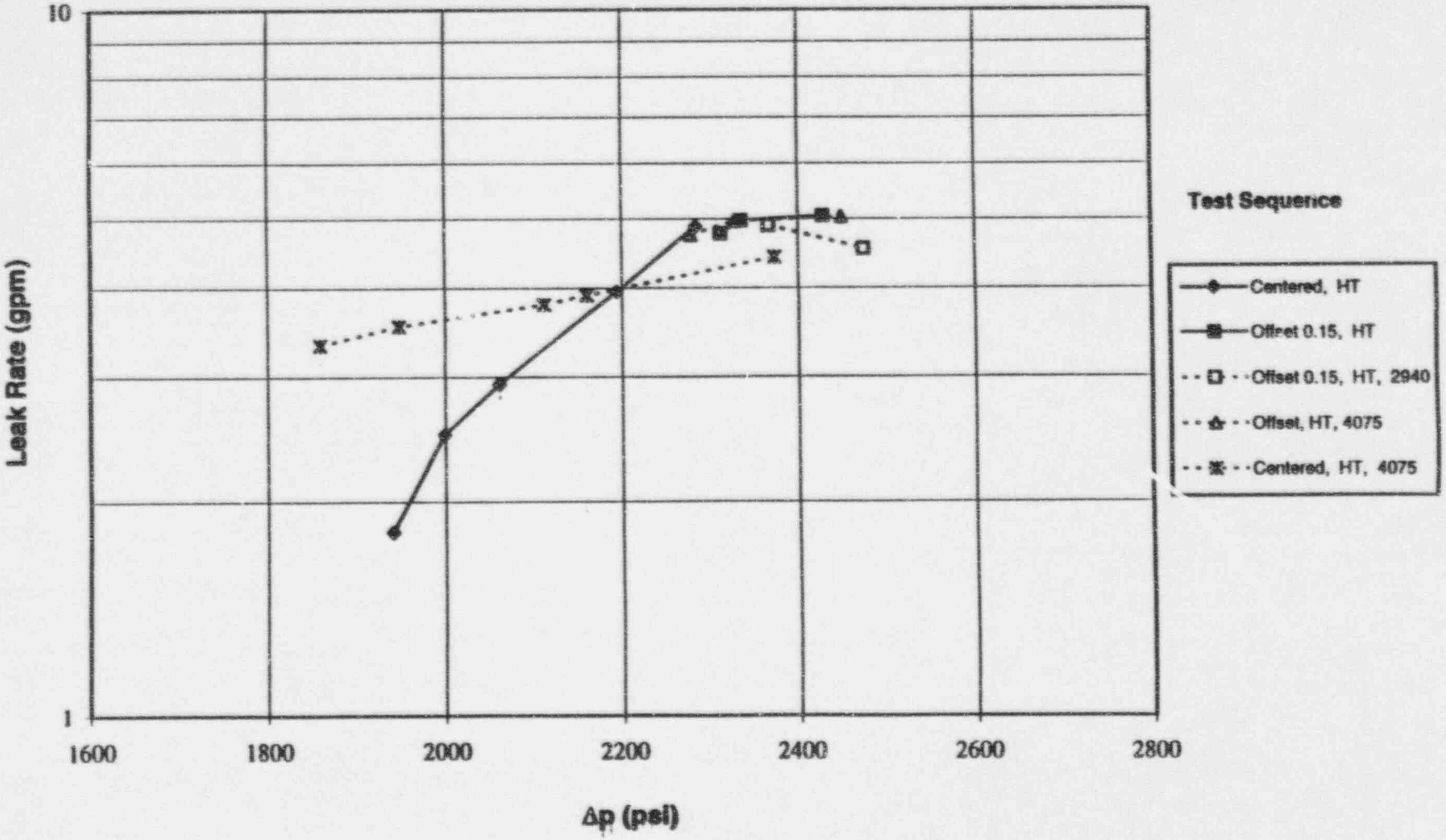
- The start of leak test specimen crack is a total of 0.729" long, composed of two axially aligned segments separated by an uncorroded ligament. The ligament is located at 0.450" from the end of the crack used to establish the offset condition.
  - TW crack was tight - not visible with back light, but 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 can be expected to tear at low ΔPs and the initial TW length can be assumed to be 0.63".
  - The ligament at 0.45" from the end of the crack was broken after the offset flow test following bladder pressurization to 2900 psid. The ligament broke to become a loose piece (0.056" long in axial crack direction by 0.011" wide and approximately the wall thickness deep) that was removed from the crack following the bladder pressurization.
  - This specimen initially 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. Leakage behavior was consistent with that expected based on throughwall crack length. The welded cracks did not open during testing.
  - The tube was not tight in the TSP after the final bladder pressurization.
- Crack interaction with the TSP occurs at approximately 2400 psid based on the shallow slope of the leak rate curve of the flow pressurized offset test.
  - There is no indication of crack to TSP interaction in the zero offset test up to about 2280 psi.
    - Following the zero offset test, the TW length was about 0.657", the maximum TW crack width was 0.007" and the crack diameter increase was about 0.004".
- The leak rate at the SLB pressure differential in the offset condition is 5.3 gpm prior to and after bladder pressurization.
  - Flow pressurization to about 2550 psi 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 to TSP interaction occurred with a plastic crack diameter increase of 16 mils in a 26 mil crack to TSP gap. Free span bladder pressurization to 3200 psi following all

tests (including prior bladder pressurization to 4075 psi) resulted in a crack diameter increase of 0.005". This pressurization adds elastic deformation to the prior plastic deformation and indicates that the elastic crack opening could increase the measured plastic opening of 0.016"to greater than 0.020" at flow pressurization of 2560 psid and reduce the 0.026" crack to TSP gap to less than 0.006".
  - The TW length outside the TSP was 0.173" at the end of this offset test. This is 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 is no difference between the leak rates. This would be expected as crack to TSP interaction was not present at this pressure differential.
- Bladder pressurization to approximately 70% of the predicted rupture pressure 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 plastic crack diameter increased by 0.004" to 0.020" by this bladder pressurization which likely increased crack interaction with the TSP due to the additional elastic deflection of the crack faces at this pressure. The diameter increase as a result of bladder pressurization offset the small increase in crack area to result in no change in leakage.
- Leak rates for the offset condition following bladder pressurization to the free span burst pressure of about 4075 psi were essentially the same as found for the offset flow pressurization 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".

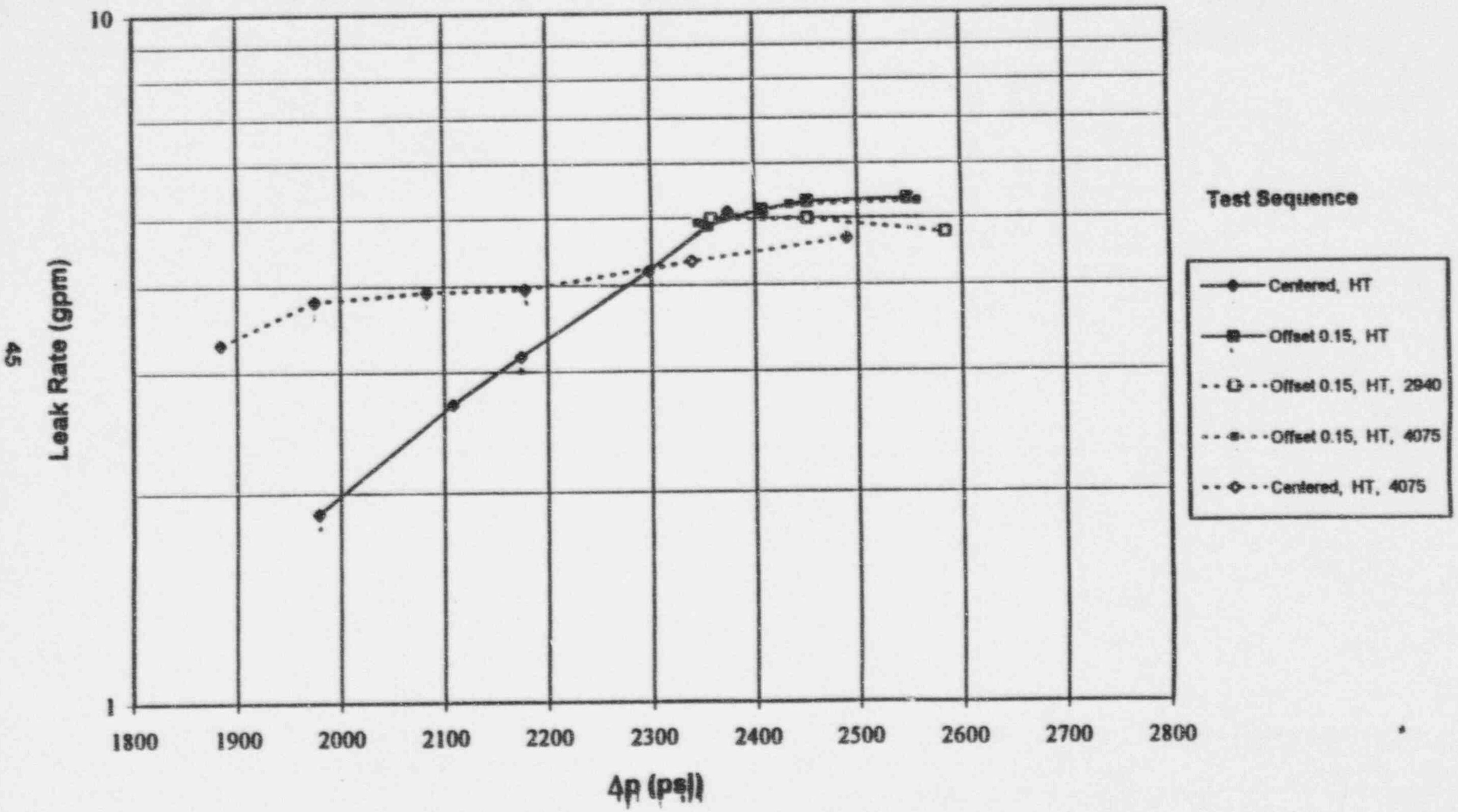
Overall Conclusions

- This test of a 7/8" diameter tube, initial 0.63" TW crack (0.702" TW after offset flow pressurization test) resulted in a SLB leak rate of 5.3 gpm at 2560 psid with the crack 0.173" TW outside of the TSP after the test.
  - This leak rate in 7/8" tubing 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.
  - This 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.
- For this indication, the leakage results indicate the TSP interaction occurred at about 2400 psi.
- Under flow pressurization conditions, there was no difference in leak rate between the zero offset and offset test conditions. Following bladder pressurization, the zero offset leak rate was about 10% lower than the offset leak rate.
- Supplemental test results indicate that the elastic increase in the crack diameter is about 0.004" compared to the plastic increase of 0.016" (following offset flow pressurization test). Together, the elastic plus plastic crack diameter increase is 0.020" compared to the 0.026" crack to TSP gap. The offset flow pressurization test demonstrates crack to TSP interaction even though the indicated gap between the tube and the TSP is about 0.006".

Test 11 - 2
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp= 615°F and ps = 15 psia Conditions - based on average test Δp)



Test 11 - 2
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp=615°F and ps=15 psia Conditions - based on test leak rate at Δp_{max})

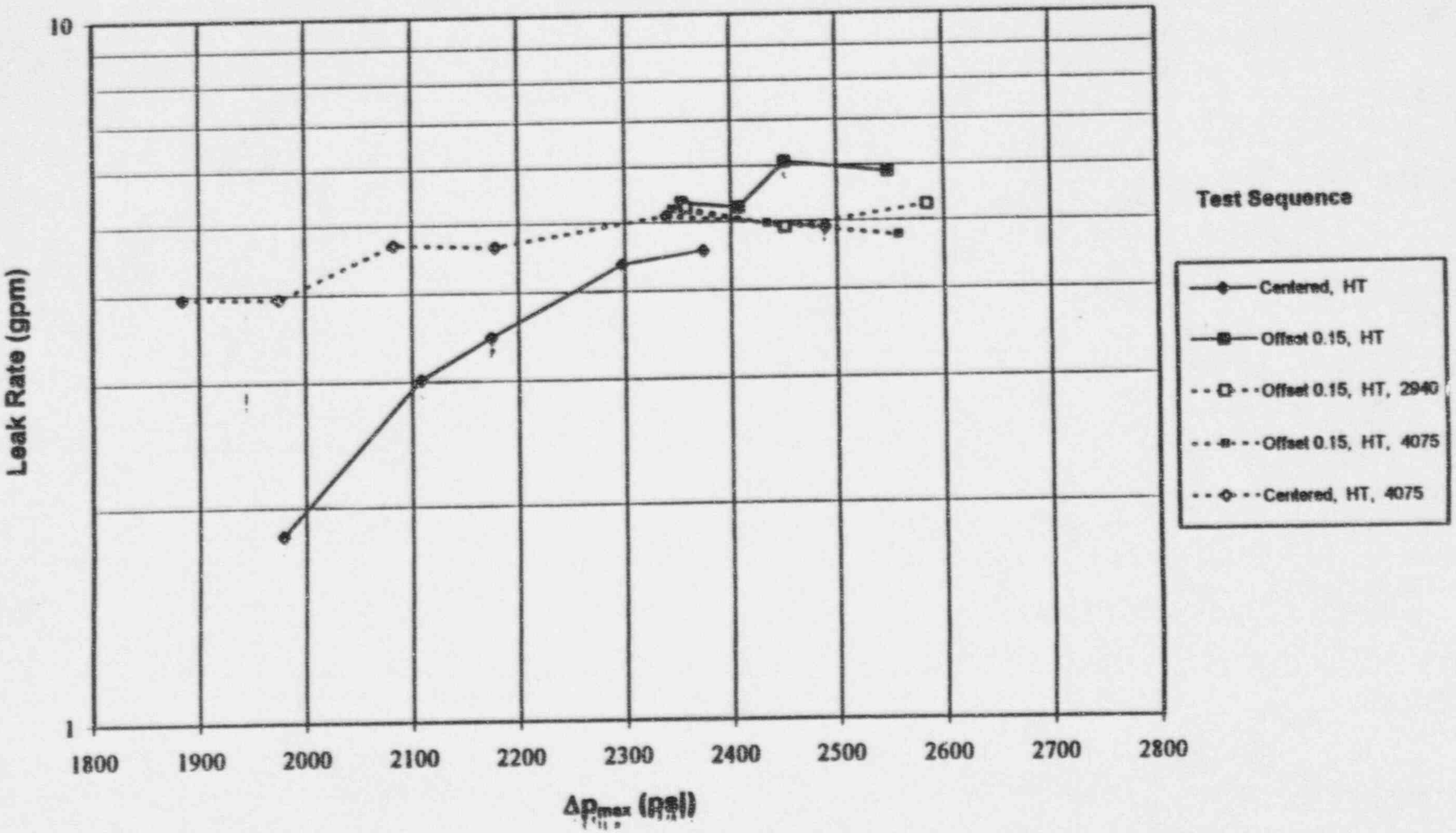


45

ChNorm_11-2Dpmax

TEST11-2.XLS 8/8/95

Test 11 - 2
Indications Restricted From Burst Leak Rate Tests
(Test leak rate at Δp_{max}, without adjustment to reference SLB conditions)

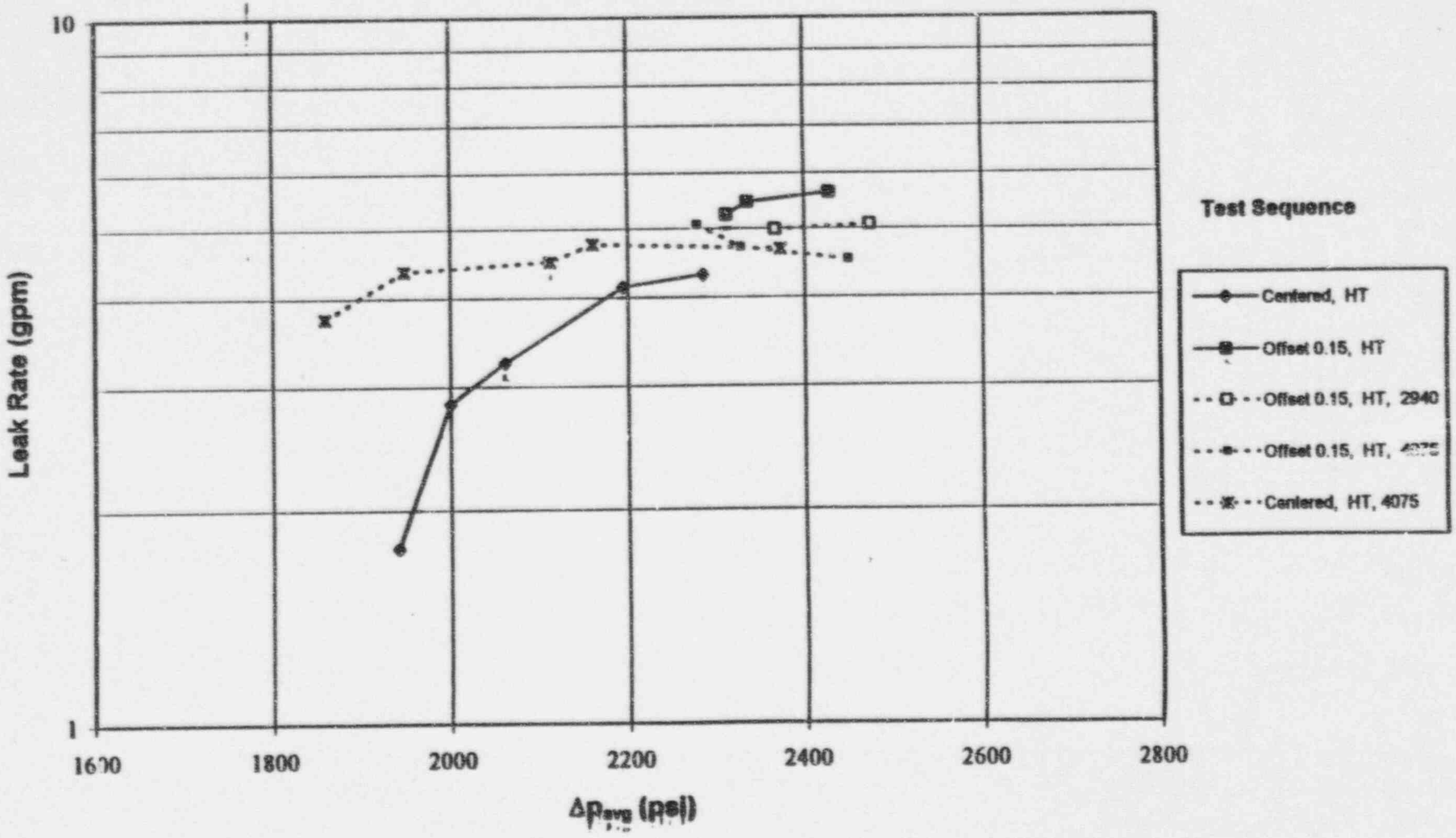


46

ChRaw_11-2Dpmax

TEST11-2.XLS 8/8/95

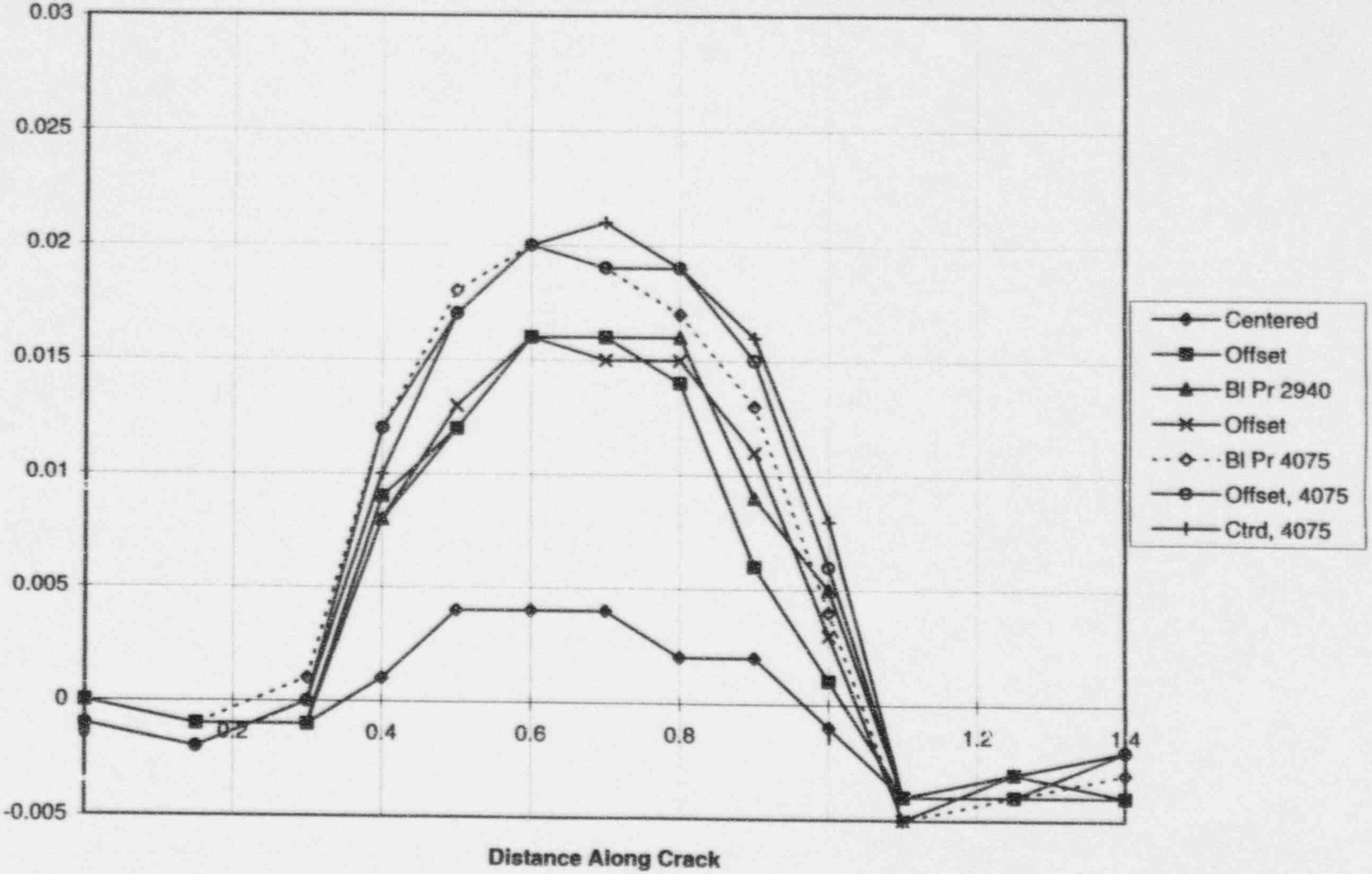
Test 11 - 2
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)



ChRaw_11-2

TEST11-2.XLS 8/8/95

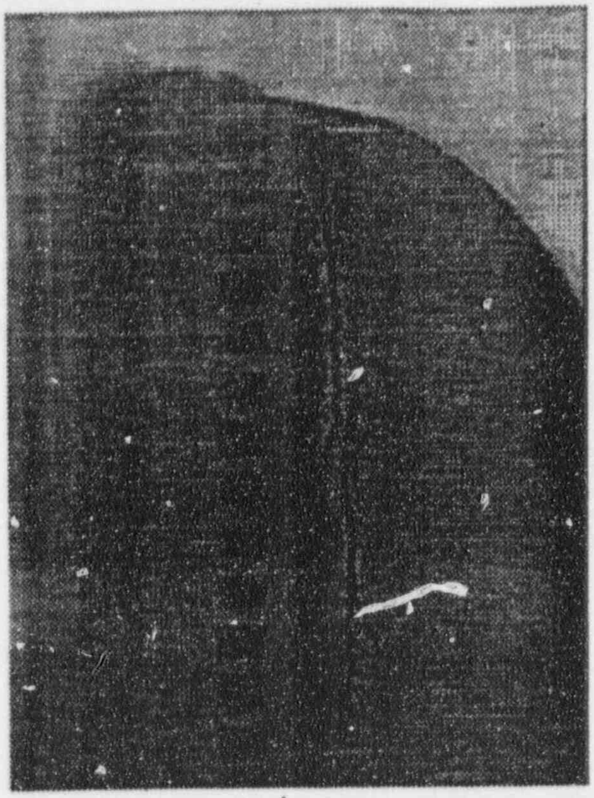
11-2 (8161B)



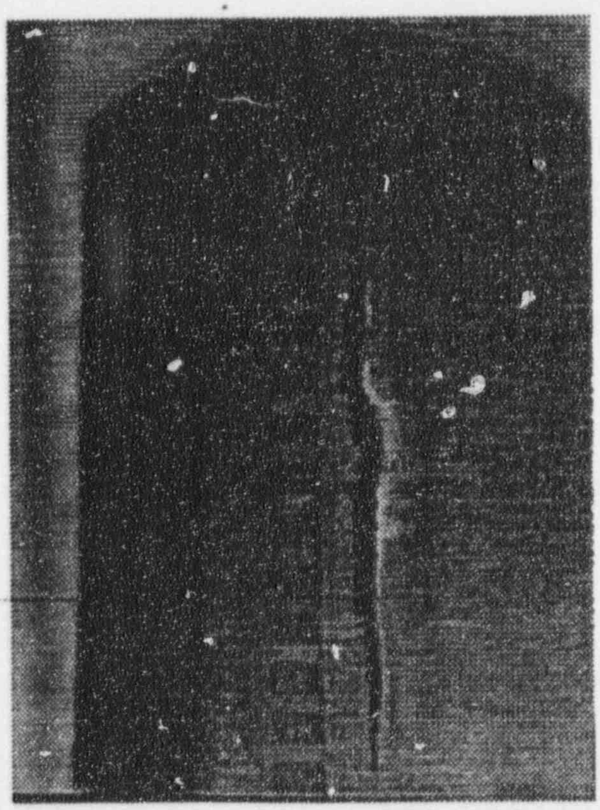
48

Ch11-2,8161B

IRBRTDIA.XLS8/15/95



After Flow Pressurization Within TSP



After Bladder Pressurization to 4075 psid and Subsequent Leak Tests

Test 11-2 (Sample 8161B)

Test 11 - 2

Summary of Leak Test and Analysis Results (Based on Maximum Δp)

Specimen 8161B, Tube Diameter = 0.874", Gap = 0.026"

			Evaluated Test Averages						Adjusted Leak Rate at Δp_{max}				Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{tot} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{tot} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	Test Leak Rate (RT) at Max. Δp_{max} (gpm)	β	γ	Leak (@ Δp_{max}) Adjusted for temp & Pressure(βγ) (gpm)	Average Leak Rate (@Δp_{max}) (gpm)	Comments
11-2A Within TSP	1	1964	2050	127	1923	634	1.56	0.18	1.61	1.01	0.97	1.58	1.87	Average of 1 & 2
	2	1993	2098	140	1958	633	1.98	0.18	2.04	1.01	1.04	2.16		
	3	2108	2165	166	1999	613	2.83	0.14	3.01	1.00	0.89	2.69	2.69	
	4	2154	2233	185	2048	630	2.94	0.12	3.15	1.01	0.98	3.14	3.16	Average of 4 & 5
	5	2194	2285	211	2074	605	3.55	0.21	3.75	0.99	0.85	3.18		
	6	2297	2454	260	2194	630	4.14	0.25	4.36	1.01	0.95	4.19	4.19	
	7	2374	2573	289	2284	654	4.3	0.36	4.54	1.04	1.08	5.10	5.10	
11-2C Offset 0.15"	1	2354	2641	329	2312	625	5.23	0.43	5.32	1.01	0.91	4.87	4.87	
	2	2407	2663	324	2339	638	5.07	0.27	5.23	1.02	0.96	5.14	5.14	
	3	2451	2685	353	2332	615	5.82	0.21	6.08	1.00	0.87	5.28	5.28	
	4	2548	2780	352	2428	623	5.62	0.17	5.87	1.01	0.90	5.32	5.32	
11-2F 2940 psi Expanded Offset 0.15"	1	2358	2660	330	2330	632	5.17	0.32	5.23	1.02	0.93	4.98	4.98	
	2	2451	2717	314	2403	641	4.79	0.42	4.90	1.03	0.98	4.98	4.98	
	3	2584	2785	311	2474	618	5.06	0.41	5.26	1.00	0.90	4.75	4.75	
11-2H 4075 psi Expanded Offset 0.15"	1	2345	2596	318	2278	630	5.06	0.67	5.22	1.02	0.93	4.91	4.91	
	2	2434	2634	306	2328	645	4.7	0.24	4.96	1.04	1.01	5.23	5.23	
	3	2557	2750	302	2448	653	4.49	0.26	4.76	1.05	1.05	5.28	5.28	
11-2I 4075 psi Expanded Within TSP	1	1884	2079	244	1835	617	3.82	0.23	3.95	1.00	0.83	3.30	3.30	
	2	1975	2129	246	1883	631	3.67	0.19	3.95	1.02	0.95	3.81	3.81	
	3	2083	2206	258	1948	611	4.36	0.17	4.68	1.00	0.84	3.92	3.92	
	4	2178	2379	267	2112	612	4.49	0.01	4.63	1.00	0.86	3.95	3.95	
	5	2339	2448	288	2160	608	4.75	0.5	5.10	0.99	0.85	4.33	4.33	
	6	2489	2665	292	2373	628	4.67	0.38	4.90	1.02	0.94	4.66	4.67	

TEST11-2.XLS 11-2 Table(Max Dp) 9/8/93 6:19 PM

Test 11 - 2

Summary of Leak Test and Analysis Results (Based on Average Test Δp)

Specimen 8151B, Tube Diameter = 0.874", Gap = 0.026"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{tsn} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{tsn} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
11-2A Within TSP	1	1964	2050	127	1923	624	1.56	0.18	1.01	0.97	1.52	1.81	Average of 1 & 2
	2	1993	2098	140	1958	633	1.98	0.18	1.01	1.05	2.10		
	3	2108	2165	166	1999	6:3	2.83	0.14	1.00	0.88	2.49	2.49	
	4	2154	2233	185	2048	630	2.94	0.12	1.01	0.98	2.92	2.93	Average of 4 & 5
	5	2194	2285	211	2074	605	3.55	0.21	0.99	0.83	2.94		
	6	2297	2454	260	2194	630	4.14	0.25	1.01	0.94	3.95	3.95	
	7	2374	2573	289	2284	654	4.3	0.36	1.04	1.09	4.87	4.87	
11-2C Offset 0.15"	1	2354	2641	329	2312	626	5.23	0.43	1.01	0.90	4.76	4.76	
	2	2407	2663	324	2339	638	5.07	0.27	1.02	0.96	4.97	4.97	Average of 2 & 3
	3	2451	2685	353	2332	615	5.82	0.21	1.00	0.86	4.98		
	4	2548	2780	352	2428	623	5.62	0.17	1.01	0.89	5.05	5.05	
11-2F 2940 psi Expanded Offset 0.15"	1	2358	2660	330	2330	632	5.17	0.32	1.02	0.93	4.91	4.89	Average of 1 & 2
	2	2451	2717	314	2403	641	4.79	0.42	1.03	0.98	4.87		
	3	2584	2785	311	2474	618	5.06	0.41	1.00	0.89	4.53	4.53	
11-2H 4075 psi Expanded Offset 0.15"	1	2345	2596	318	2278	630	5.06	0.67	1.02	0.92	4.74	4.74	
	2	2434	2634	306	2328	645	4.7	0.24	1.04	1.01	4.96	4.96	
	3	2557	2750	302	2448	653	4.49	0.26	1.05	1.06	5.03	5.03	
11-2I 4075 psi Expanded Within TSP	1	1884	2079	244	1835	617	3.82	0.23	1.00	0.82	3.14	3.32	Average of 1 & 2
	2	1975	2129	246	1883	631	3.67	0.19	1.02	0.94	3.51		
	3	2083	2206	258	1948	611	4.36	0.17	1.00	0.81	3.53	3.53	
	4	2178	2379	267	2112	612	4.49	0.01	1.00	0.85	3.79	3.79	
	5	2339	2448	288	2160	608	4.75	0.5	0.99	0.83	3.91	3.91	
	6	2491	2660	291	2309	628	4.66	0.37	1.02	0.93	4.42	4.42	

TEST11-2.XLS 11-2 Table(Avg Dp) 8/10/95 4:42 PM

Test 11-2 Summary of Test Dimensional Measurement Results Specimen 8161-B, Tube Dia. = 0.874", Gap =0.026"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in.^{2})	Max Dia. (in.)	Min. Dia. (in.) [1]
None	NA	Pre-test	0	0.729 [6]	0.508[2] 0.630 [5]	NA [3]	NA	NA	0.874	0.873 0.870
None	0.0 Step A	Hot		0.745	.657[4] (0.006)	0.00284	NA	NA	0.878	0.873 0.870
None	0.15 Step C	Hot		0.748	.702[4] (0.014)	0.00681	0.173 [7] (0.010)	0.00102 [7]	0.890	0.873 0.870
2940	NA Step E	NA		0.748	0.702[4] (0.16)	0.00740	NA	NA	0.890	0.873 0.870
2940	0.15 Step F	Hot		0.749	0.703[4] (0.016)	0.00740	0.151[7] (0.010)	0.000868 [7]	0.890	0.873 0.869
4075	NA Step G	NA		0.749	0.707[4] (0.022)	0.01137	NA	NA	0.894	0.875 0.869
4075	0.15 Step H	Hot		0.749	0.707[4] (0.022)	0.01161	0.15[7] (0.017)	0.00151 [7]	0.894	0.874 0.870

Test 11-2 Summary of Test Dimensional Measurement Results Specimen 8161-B, Tube Dia. = 0.874", Gap =0.026"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area ($in.^2$)	Max Dia. (in.)	Min. Dia. (in.) [1]
4075	0.0 Step I	Hot		0.749	0.707[6] (0.023)	0.011191	NA	NA	0.895	0.874 0.870

Notes:
[1] Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.875" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
[2] Based on silastic mold and dye penetrant test.
[3] Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
[4] Crack length from toolmaker's microscope. Minimum measurable TW crack opening ~0.001".
[5] Confirmed TW length plus 0.122" thin ligament at ID.
[6] Two essentially co-planar cracks separated by a ligament at 0.45" from the end of the longer segment.
[7] Post test dimension; initial test setup was 0.15" offset.

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 11-7: Summary of Test Results and Evaluation

Test Sequence

- Order of tests: zero offset, offset 0.1", bladder pressurization to 2900 psi, offset 0.1" and zero offset. All tests are hot tests.
  - No intermediate pressurization step was included since the predicted burst pressure for the specimen was only slightly greater than 2560 psid.
  - Zero offset tests were performed with he TSP centered on the crack to produce equal projection of the crack above and be' the TSP since the TW length exceeded the TSP thickness.
  - The crack to TSP gap was established at 0.025" by forcing the tube to contact the TSP hole ID at 180° from the crack.
- There is no basis to question the adequacy of the data - leak test results show consistent trends, without large data scatter.

Summary of Test Results

- The start of leak test specimen had a 0.813" OD length with a TW length of 0.809".
- Shallow slope of leak rate versus ΔP curve above about 2000 psi indicates interaction with the TSP and reduced leak rates.
- The offset leak rate of about 6.2 gpm at SLB conditions (extrapolated from 2450 psi data) before bladder pressurization is essentially the same as the centered leak rate, although both tests include TW cracks outside the TSP.
  - The centered crack length projecting outside the TSP was approximately 0.059" compared to the 0.102" 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.
- The offset leak rate was essentially the same before and after bladder pressurization indicating that full expansion of the crack flanks had occurred during flow pressurization.
  - Flow pressurization to about 2450 psid opened the plastic crack TW width to about 0.032". No further increase in the crack opening occurred during bladder pressurization to the free span burst pressure of about 2900 psid. The crack TW length only increased by about 0.002" from beginning to end of all testing.
  - The tube diameter in the plane of the crack increased by about 0.020" during offset flow pressurization without further increase during bladder pressurization.
    - o The crack to TSP gap was 0.025". To assess the magnitude of elastic deformation of the crack, a free span bladder pressurization to 2300 psi following all tests (including prior bladder pressurization to 2900 psi) was performed, which resulted in a crack diameter increase of 0.003". This pressurization adds elastic deformation to the prior plastic deformation and indicates that the elastic crack opening could increase the measured plastic opening of 0.020" to approximately close the 0.025" crack to TSP gap.
    - o These results 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 to TSP interaction with reduced leak rates.
  - The TW crack length, as indicated by visible light through the crack was 0.811" of the total crack length of 0.838" and the crack was more than 0.017" wide for about 0.6" length.
- The centered leak rate after bladder pressurization was slightly less (about 5.7 vs 6.2 gpm)

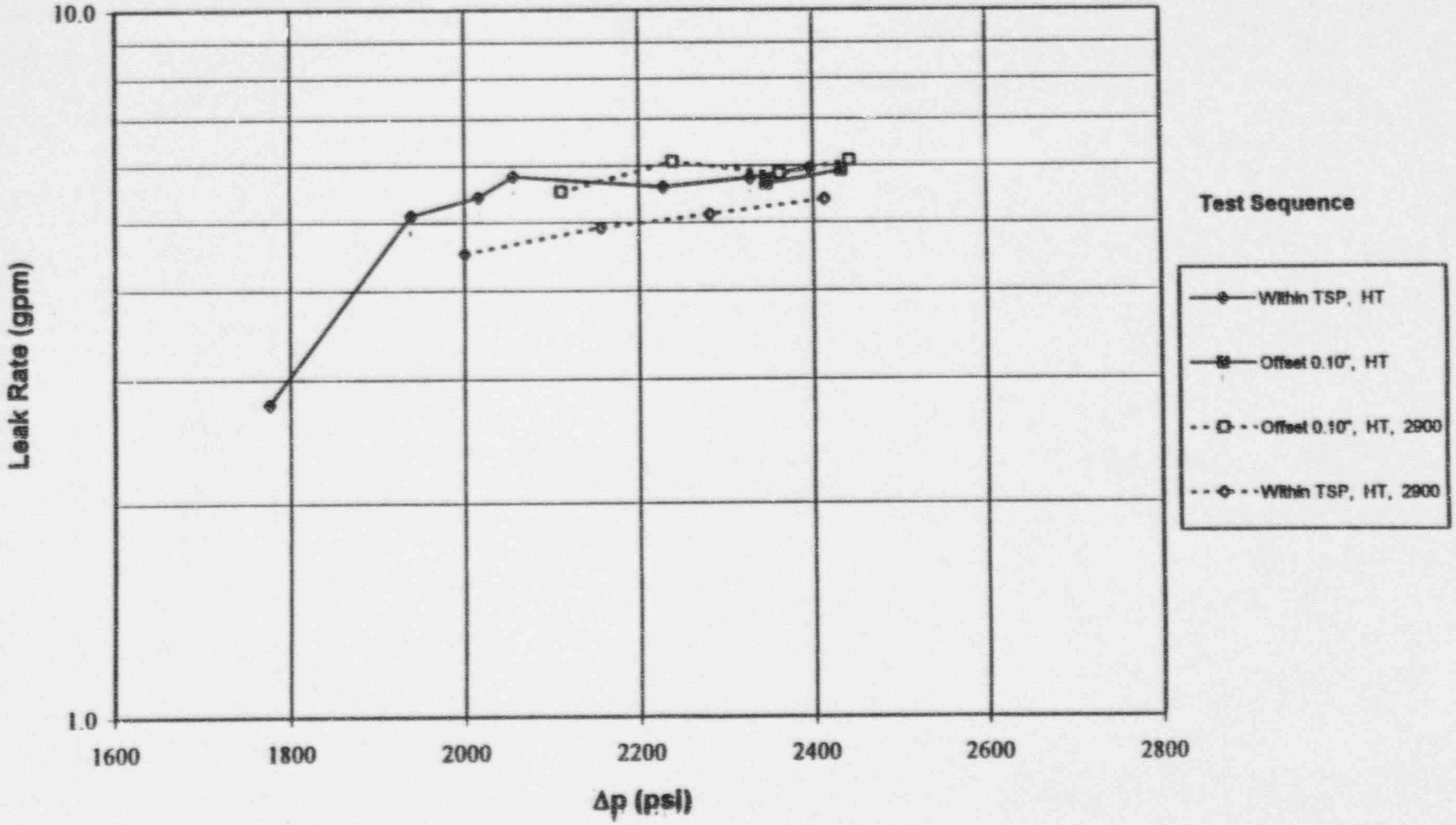
than the prior flow and bladder pressurization leak rate in the offset condition. In contrast, there was no difference between the centered and offset leak rates for the flow pressurization tests.

- 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.

Overall Conclusions

- This test of a 0.809" throughwall crack in 3/4" diameter tubing represents a very conservative upper bound leak test since cracks of significant depth would be less than the 0.75" TSP thickness.
  - A 0.809" TW length is larger than would ever be expected in field service for any repair limit.
- 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.
- For this 0.809" TW indication prior to leak testing, the leakage results indicate the TSP interaction occurred at about 2000 psi ΔP.
- 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 to TSP interaction with reduced leak rates.
  - It can be concluded that Tests 1-7 and 2-7, which were performed without forcing the tube to contact the TSP at 180° from the crack and resulted in plastic diameter increases of 0.020" and 0.022", may have had about a 0.025" crack to TSP gap. Elastic deformation would have effectively closed the gap and the test results are acceptable tests for assessing large tube to TSP clearances.

Test 11 - 7
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp= 615°F and ps = 15 psia Conditions - based on test leak rate at Δp max)



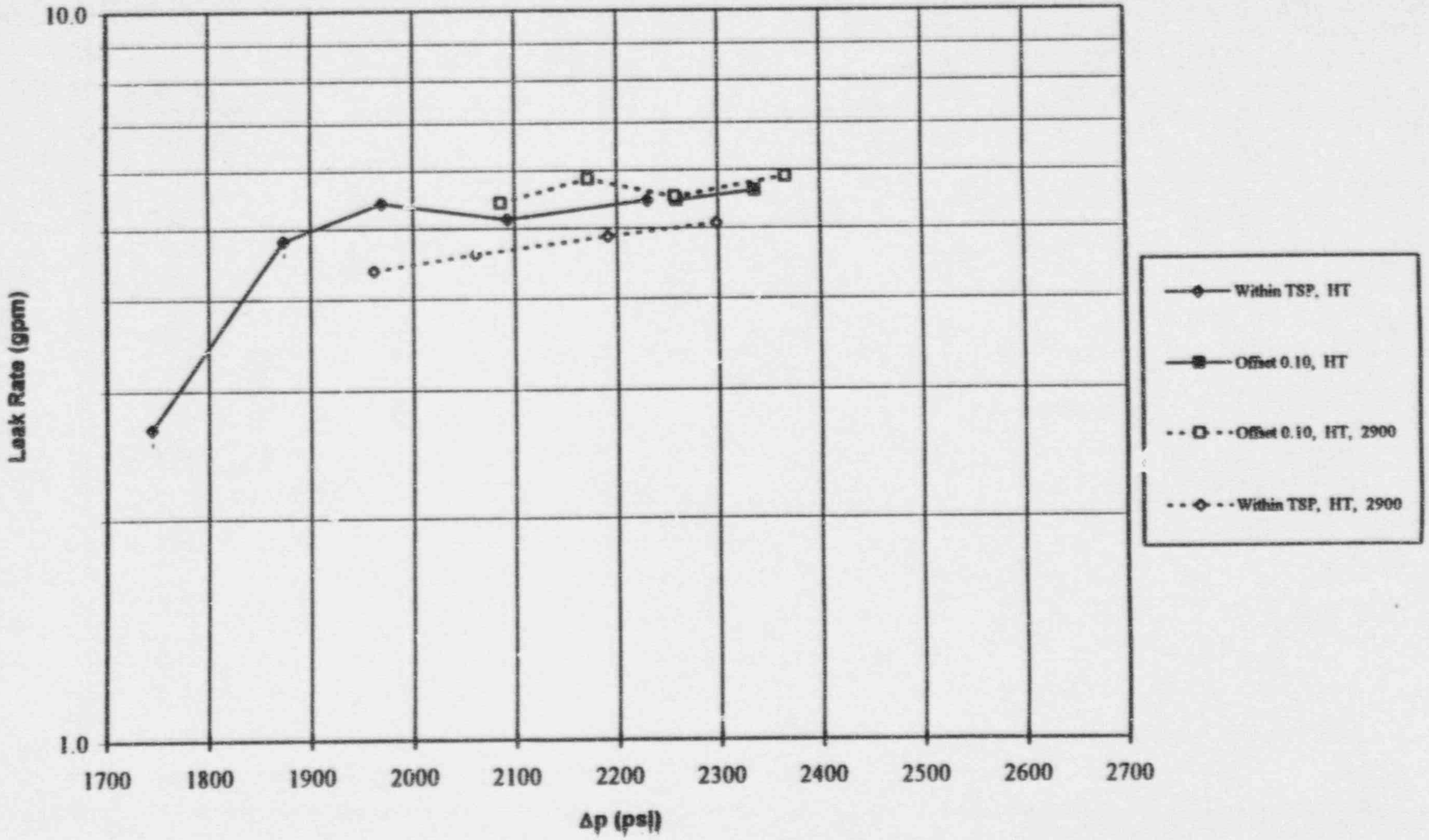
ChNorm-11-7Dpmax

TEST11-7.XLS 8/8/95

Test 11- 7

Indications Restricted From Burst Leak Rate Tests

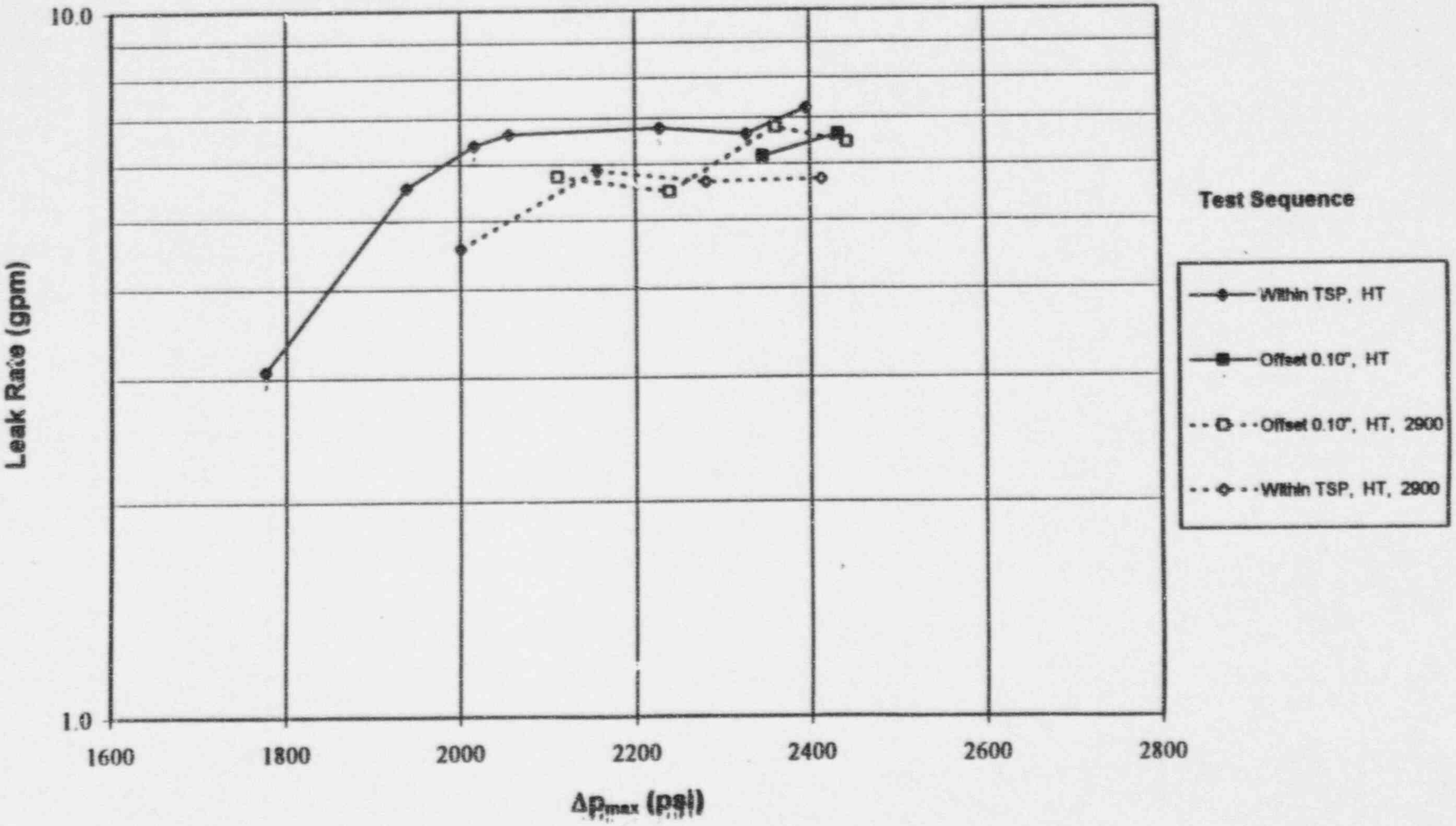
(Normalized to Tp= 615°F and ps = 15 psia conditions - based on test leak rate at Δp_{avg})



Ch_Norm 11-7

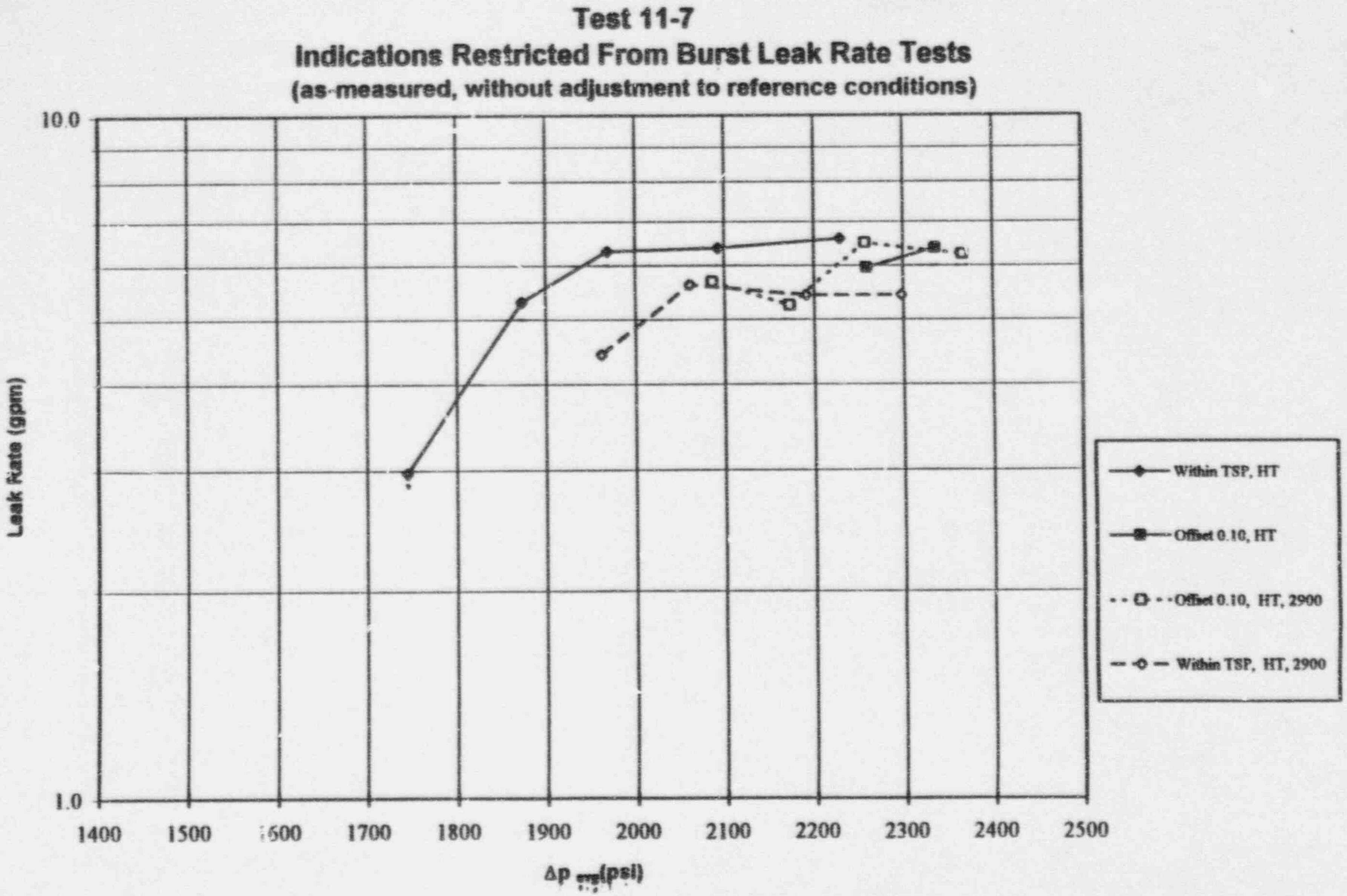
TEST11-7.XLS 8/8/95

Test 11 - 7
Indications Restricted From Burst Leak Rate Tests
(Test leak rate at Δp_{max}, without adjustment to reference SLB conditions)



ChRaw-11-7Dpmax

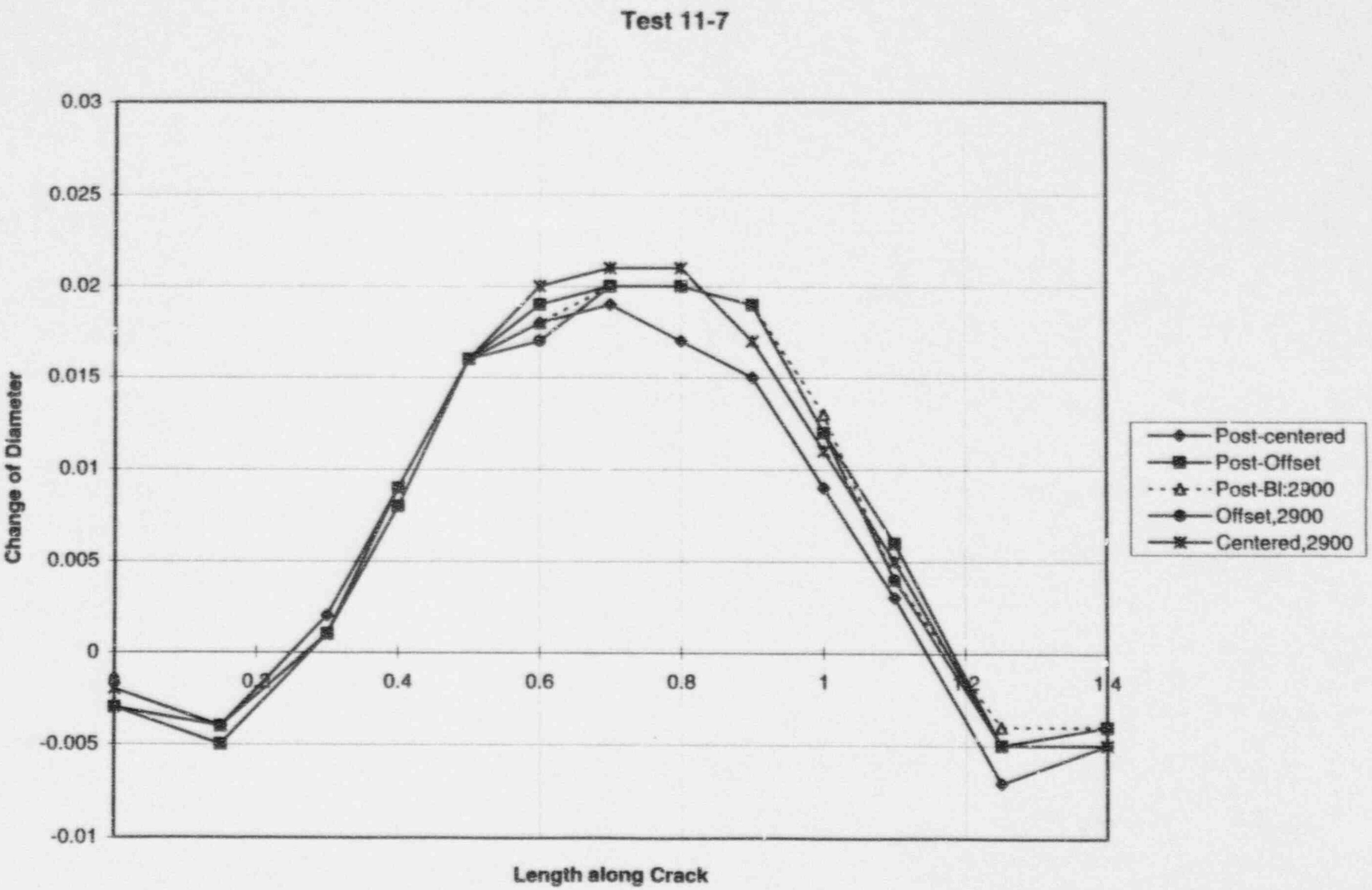
TEST11-7.XLS 8/8/95



60

Ch_Raw 11-7

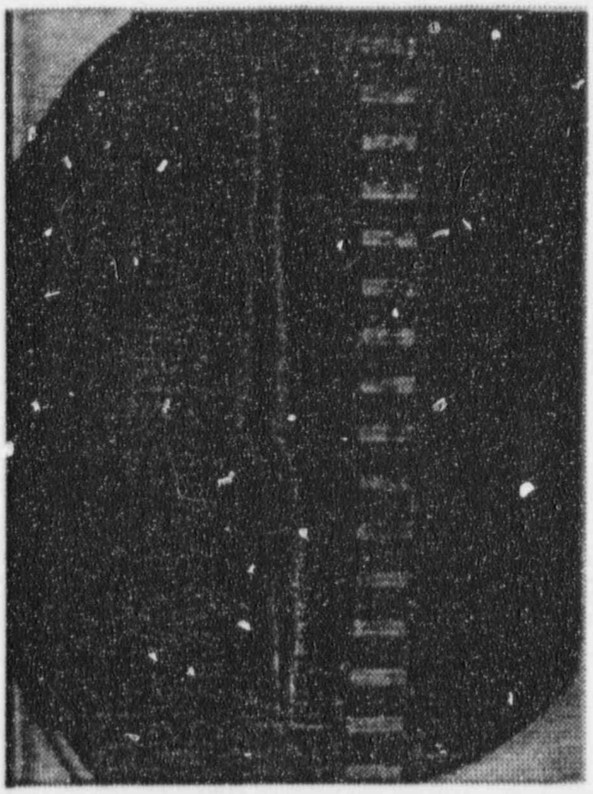
TEST11-7.XLS 8/8/95



61

Ch11-7,2008A

IRBRTDIA.XLS 8/15/95



After Flow Pressurization Within TSP

After Bladder Pressurization to 2900 psid and Subsequent Flow Tests

Test 11-7 (Sample 2008A)

Test 11 - 7
Summary of Leak Test and Analysis Results (Based on Maximum Δp)
Specimen 2008A, Tube Diameter = 0.745", Gap = 0.025"

			Evaluated Test Averages						Adjusted Leak Rate at Δp_{max}				Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{test} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	Test Leak Rate (RT) at Δp_{max} (gpm)	β	γ	Leak (@ Δp_{max}) Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (@Δp_{max}) (gpm)	Comments
11-7A Within TSP	1	1776	1985	242	1744	628	2.97	0.27	3.07	1.01	0.89	2.76	2.76	
	2	1902	2168	304	1864	644	4.8	0.22	4.98	1.03	1.01	5.17	5.17	
	3	1975	2226	344	1882	620	5.81	0.26	6.13	1.00	0.82	5.05	5.05	
	4	2056	2350	381	1969	629	6.31	0.13	6.63	1.01	0.86	5.79	5.79	
	5	2228	2474	381	2093	614	6.38	0.45	6.75	1.00	0.83	5.60	5.60	
	6	2327	2607	389	2218	622	6.33	0.4	6.62	1.01	0.87	5.77	5.77	
	7	2396	2640	399	2241	607	6.85	0.32	7.23	0.99	0.83	5.95	5.95	
11-7C Offset 0.10"	1	2268	2625	375	2250	633	6	0.28	6.05	1.01	0.91	5.58	-	Delete - Hysteresis
	2	2345	2648	356	2292	645	5.39	0.29	5.54	1.03	0.99	5.61	5.66	Average of 2 & 3
	3	2347	2627	393	2234	615	6.48	0.57	6.76	1.00	0.85	5.72		
	4	2416	2719	385	2334	630	6.04	0.6	6.24	1.01	0.91	5.73	5.89	Average of 4 & 5
	5	2449	2741	404	2337	619	6.71	0.47	6.99	1.00	0.86	6.06		
11-7F Expanded 2900psi Offset 0.10"	1	2111	2446	360	2086	638	5.67	0.33	5.75	1.03	0.93	5.51	5.51	
	2	2239	2515	343	2172	653	5.24	0.29	5.48	1.05	1.05	6.07	6.07	
	3	2361	2652	395	2257	619	6.5	0.43	6.77	1.00	0.86	5.83	5.83	
	4	2442	2763	397	2366	635	6.24	0.46	6.44	1.03	0.92	6.10	6.10	
11-7G 2900 psi Expanded Within TSP	1	2001	2274	309	1965	627	4.79	0.29	4.90	1.01	0.88	4.38	4.51	Average of 1 & 2
	2	1999	2259	301	1958	648	4.06	0.43	4.21	1.05	1.05	4.65		
	3	2156	2401	340	2061	615	5.62	0.42	5.87	1.00	0.84	4.91	4.91	
	4	2279	2533	331	2202	637	5.16	0.43	5.37	1.03	0.95	5.25	5.13	Average of 4 & 5
	5	2283	2528	348	2180	613	5.7	0.29	5.94	1.00	0.84	5.01		
	6	2413	2643	345	2298	631	5.43	0.39	5.70	1.02	0.93	5.38	5.38	

Test 11 - 7
Summary of Leak Test and Analysis Results (Based on Average Δp)
Specimen 2008A, Tube Diameter = 0.745", Gap = 0.025"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{test} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
11-7A Within TSP	1	1776	1986	242	1744	628	2.97	0.27	1.01	0.88	2.65	2.65	
	2	1902	2168	304	1864	644	4.8	0.22	1.03	1.01	4.98	4.82	Average of 2 & 3
	3	1975	2226	344	1882	620	5.81	0.26	1.00	0.80	4.65		
	4	2056	2350	381	1969	629	6.31	0.13	1.01	0.85	5.42	5.42	
	5	2228	2474	381	2093	614	6.38	0.45	1.00	0.81	5.14	5.14	
	6	2327	2607	389	2218	622	6.33	0.4	1.01	0.85	5.43	5.45	Average of 6 & 7
	7	2396	2640	399	2241	607	6.85	0.32	0.99	0.80	5.48		
11-7C Offset 0.10"	1	2268	2625	375	2250	633	6	0.28	1.01	0.91	5.54		
	2	2345	2648	356	2292	645	5.39	0.29	1.03	0.99	5.45	5.50	Average of 1, 2 & 3
	3	2347	2627	393	2234	615	6.48	0.57	1.00	0.83	5.38		
	4	2416	2719	385	2334	630	6.04	0.6	1.01	0.90	5.50	5.62	Average of 4 & 5
	5	2449	2741	404	2337	619	6.71	0.47	1.00	0.85	5.74		
11-7F Expanded 2900psi Offset 0.10"	1	2111	2446	360	2086	638	5.67	0.33	1.03	0.93	5.42	5.42	
	2	2239	2515	343	2172	653	5.24	0.29	1.05	1.06	5.84	5.84	
	3	2361	2652	395	2257	619	6.5	0.43	1.00	0.85	5.52	5.52	
	4	2442	2763	397	2366	635	6.24	0.46	1.03	0.92	5.88	5.88	
11-7G 2900 psi Expanded Within TSP	1	2001	2274	309	1965	627	4.79	0.29	1.01	0.87	4.25	4.37	Average of 1 & 2
	2	1999	2259	301	1958	648	4.06	0.43	1.05	1.06	4.50		
	3	2156	2401	340	2061	615	5.62	0.42	1.00	0.82	4.61	4.61	
	4	2279	2533	331	2202	637	5.16	0.43	1.03	0.95	5.02	4.87	Average of 4 & 5
	5	2283	2528	348	2180	613	5.7	0.29	1.00	0.83	4.72		
	6	2413	2643	345	2298	631	5.43	0.39	1.02	0.92	5.08	5.08	

Test 11-7 Summary of Test Dimensional Measurement Results Specimen 2008-A, Tube Dia. = 0.745", Gap =0.025"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in.^{2})	Max Dia. (in.)	Min. Dia. (in.) [1]
None	NA	Pre-test	0	0.820	0.809 [2]	NA[3]	NA	NA	0.745	0.744
None	0.0 Step A	Hot		0.823	0.809 [4] (0.030)	0.01662	0.059 [5] (0.009)	0.000268 [6]	0.764	0.747 0.748
None	0.10 Step C	Hot		0.838	0.811 [4] (0.032)	0.01855	0.102 (0.018)	0.00120	0.765	0.746 0.751
2900	NA Step E	NA		Same as after offset test prior to bladder pressurization, Step C					0.765	0.746 0.749
2900	0.10 Step F	Hot		0.838	0.811 [4] (0.032)	0.01857	0.100 (0.018)	0.00118	0.765	0.746 0.749
2900	0.0 Step G	Hot		0.838	0.811[4] (0.033)	0.01910	0.061 [5] (0.011)	0.00042 [6]	0.766	0.746 0.750

Test 11-7 Summary of Test Dimensional Measurement Results
Specimen 2008-A, Tube Dia. = 0.745", Gap =0.025"

Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in.^{2})	Max Dia. (in.)	Min. Dia. (in.) [1]

Notes:
[1] Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.750" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
[2] Based on silastic mold and dye penetrant test.
[3] Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
[4] Crack length from toolmaker's microscope. Minimum measurable TW crack opening ~0.001".
[5] Exposed length equally distributed above and below TSP since crack length > TSP thickness.
[6] Sum of exposed TW crack lengths above and below TSP

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).

Test 12-1: Summary of Test Results and Evaluation

Test Sequence

- Order of tests: 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 tests are hot tests.
  - Intermediate bladder pressurization step is approximately 70% of the predicted specimen burst pressure.
  - The crack to TSP gap was established at 0.026" by forcing the tube to contact the TSP hole ID at 180° from the crack.
- There is no basis to question the adequacy of the data - leak test results show consistent trends, without large data scatter.

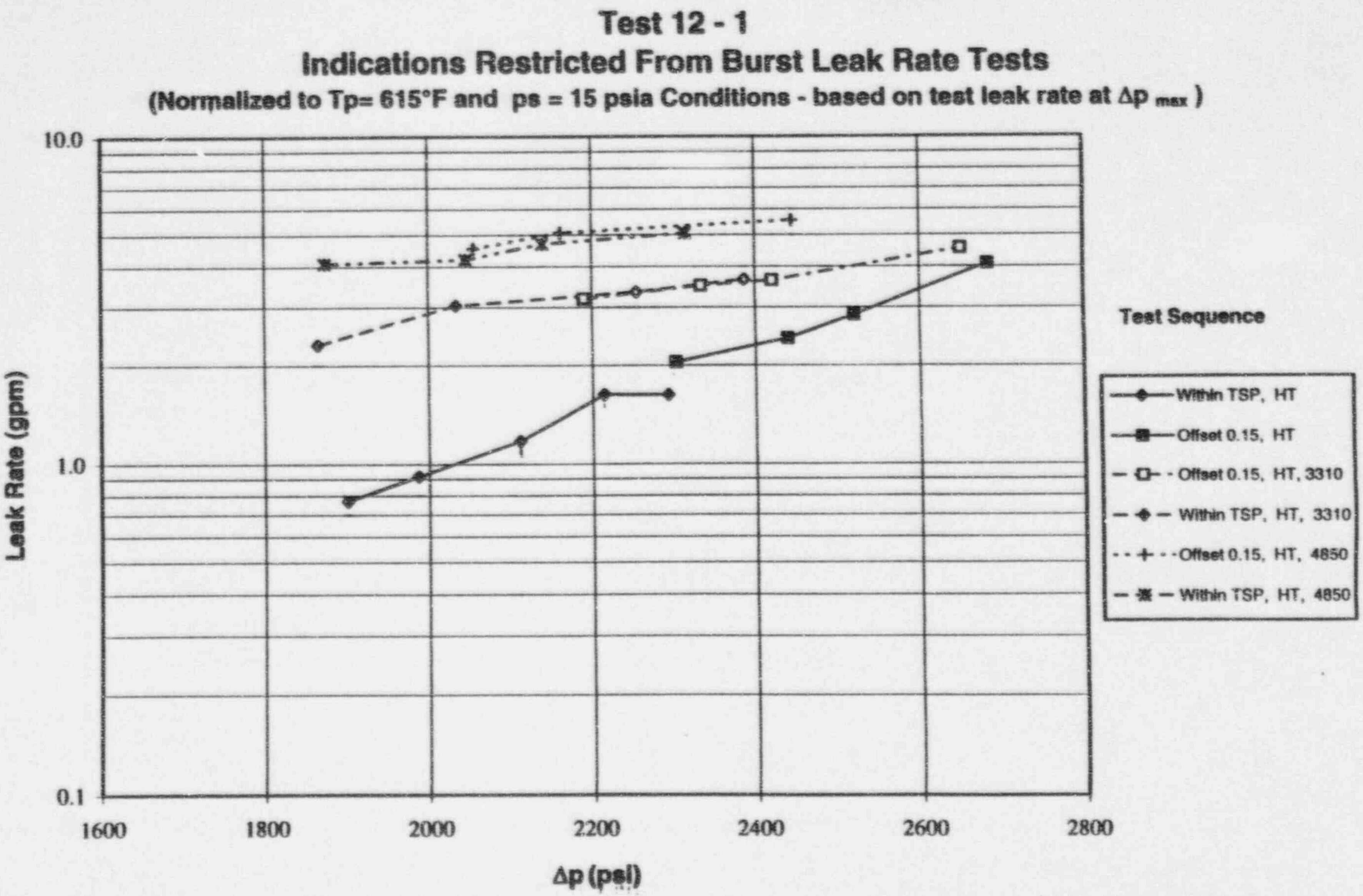
Summary of Test Results

- The 7/8" diameter specimen for this test had two cracks at the start of test. By dye penetrant test, the largest crack was 0.607" OD and 0.515" TW and the second crack, 90° from the main crack, was 0.465" OD with 0.360" TW.
  - Neither of the TW cracks were visible with back light over the full length of the OD (i.e., <0.001" TW crack opening width).
- There is no indication of crack interaction with the TSP in either the flow pressurized zero offset or offset test. The leak rates increase at essentially a constant slope from the start of the zero offset test to the end of the offset test.
  - 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 and the crack diameter increase was about 0.001". Similarly, there was no visible TW width for the second crack.
- The leak rate at the SLB pressure differential in the flow pressurized offset condition is bounded by 3.2 gpm.
  - Flow pressurization to about 2680 psi 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 no visible TW width for the second crack.
    - o The small increase in the crack diameter is consistent with the leak rate results showing no crack to TSP interaction.
  - The TW length outside the TSP was 0.105" for this offset test 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, only 0.105" of the offset length was found to be TW.
- Bladder pressurization to about 70% (3310 psi) of the predicted free span burst pressure resulted in an increase in the offset leak rate to 4.2 gpm.
  - Following the bladder pressurization and offset leak test, the main crack TW length increased to 0.604" (total length of 0.652"), the maximum TW crack opening was 0.005" and the plastic crack diameter increase was about 0.003". There was no visible TW width for the second crack with an OD length of 0.482".
  - Following bladder pressurization, the shallow slope of the leak rate versus ΔP curve does not clearly imply crack to TSP interaction. The crack has been previously plastically opened such that hysterisis affects the leak rate slope. The slope would be expected to be caused by some additional elastic opening of the crack and the increasing

pressure differential (leak rate proportional to $\sqrt{\Delta P}$). The slope of the bladder pressurized leak rate curve exceeds a $\sqrt{\Delta P}$ dependence as would be expected.
  - There is no indication (crack diameter increase, difference between zero offset and offset leak rates, abnormally small slope) that crack to TSP interaction occurred at this bladder pressurization step.
- Leak rates for the offset condition following bladder pressurization to the free span burst pressure of about 4850 psi increased to 5.7 gpm and there is essentially no difference for the zero offset leak rate.
  - 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 5.7 gpm leak rate for this test represents leakage from both the 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 single main crack.
  - 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. Since the elastic crack opening could have increased the tube diameter to near contact with the TSP, it is expected that the leak rates were limited by interaction with the TSP.

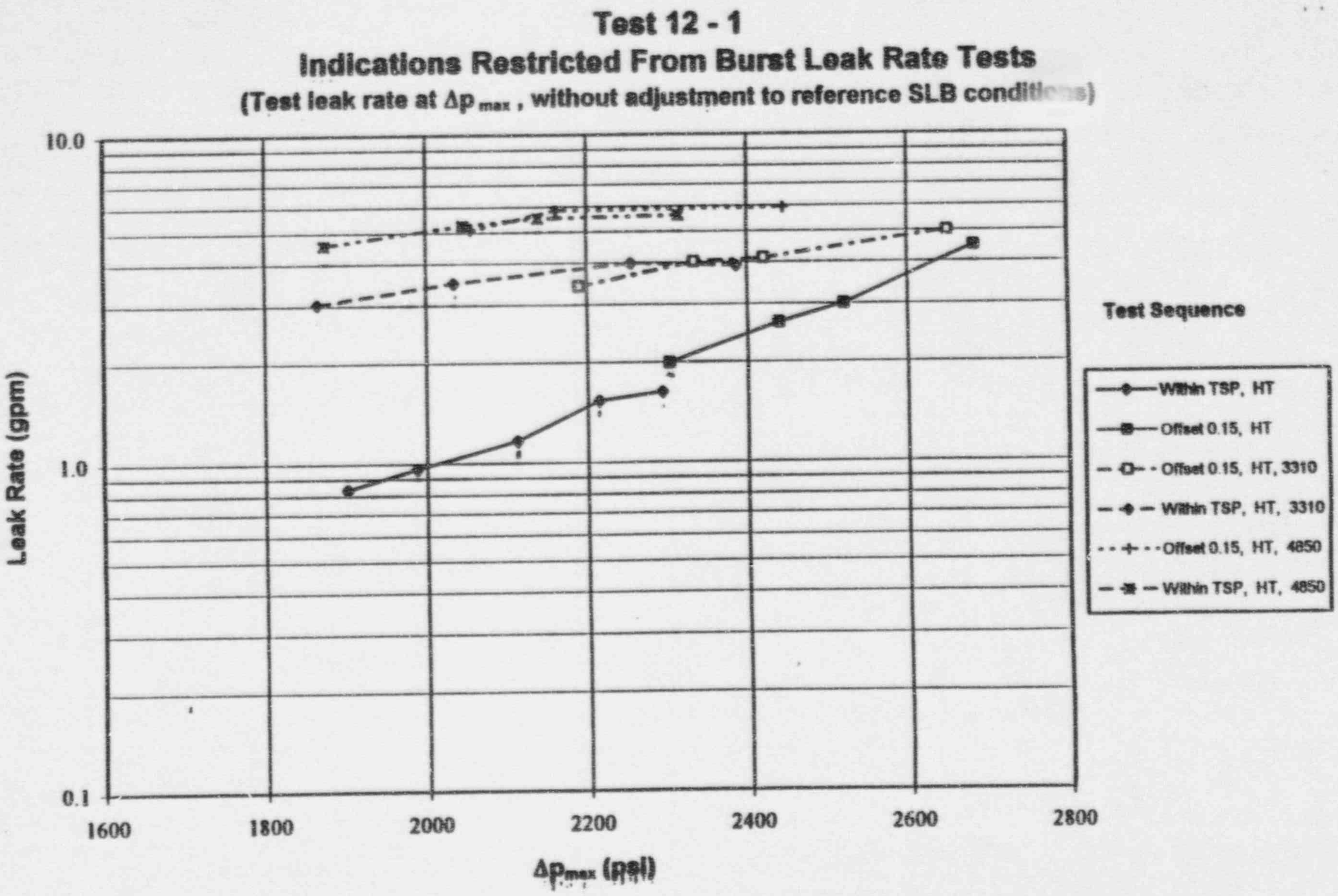
Overall Conclusions

- This test of a 7/8" diameter tube with two intermediate length TW cracks, initial 0.515" TW main crack (0.585" TW after offset flow pressurization test) resulted in a SLB leak rate for flow pressurization of 3.2 gpm at 2560 psid with the crack 0.105" TW outside of the TSP.
  - The two TW cracks for this specimen are typical of what might be expected following implementation of tube expansion based, full APC repair limits - a dominant TW crack with a second, less significant TW indication.
- For this indication, there was no crack to TSP interaction (crack behaved as a free span indication) for flow pressurization up to 2680 psi. Crack to TSP interaction is indicated following bladder pressurization to the free span burst pressure.
- 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 5.7 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.



ChNorm 12-1Dpmax

TEST12-1.XLS 8/10/95



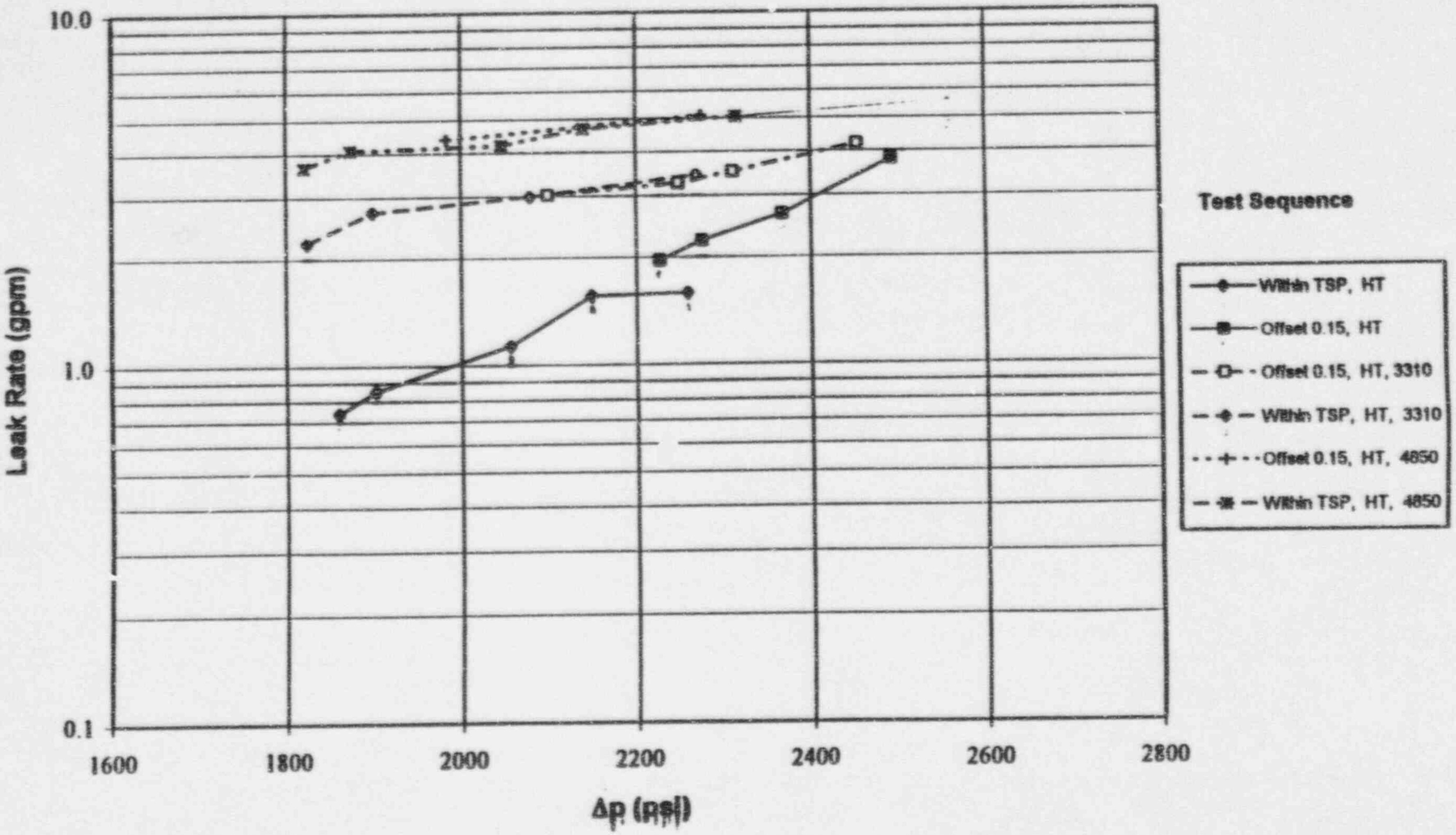
ChRaw12-1Dpmax

TEST12-1.XLS 8/7/95

Test 12 - 1

Indications Restricted From Burst Leak Rate Tests

(Normalized to Tp= 615°F and ps = 15 psia Conditions - based on test leak rate at Δp_{avg})



72

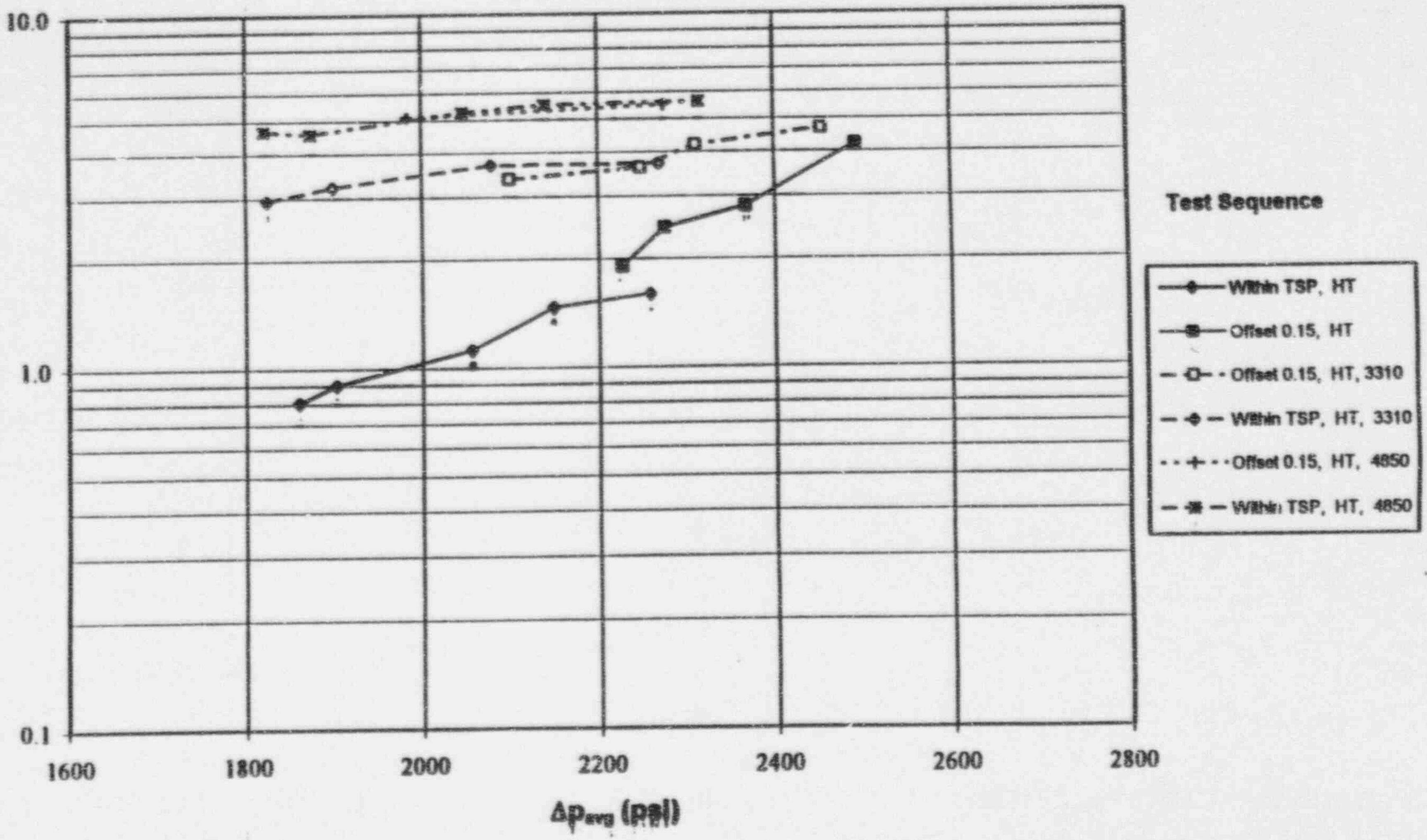
ChNorm12-1

TEST12-1.XLS 8/7/95

Test 12 - 1

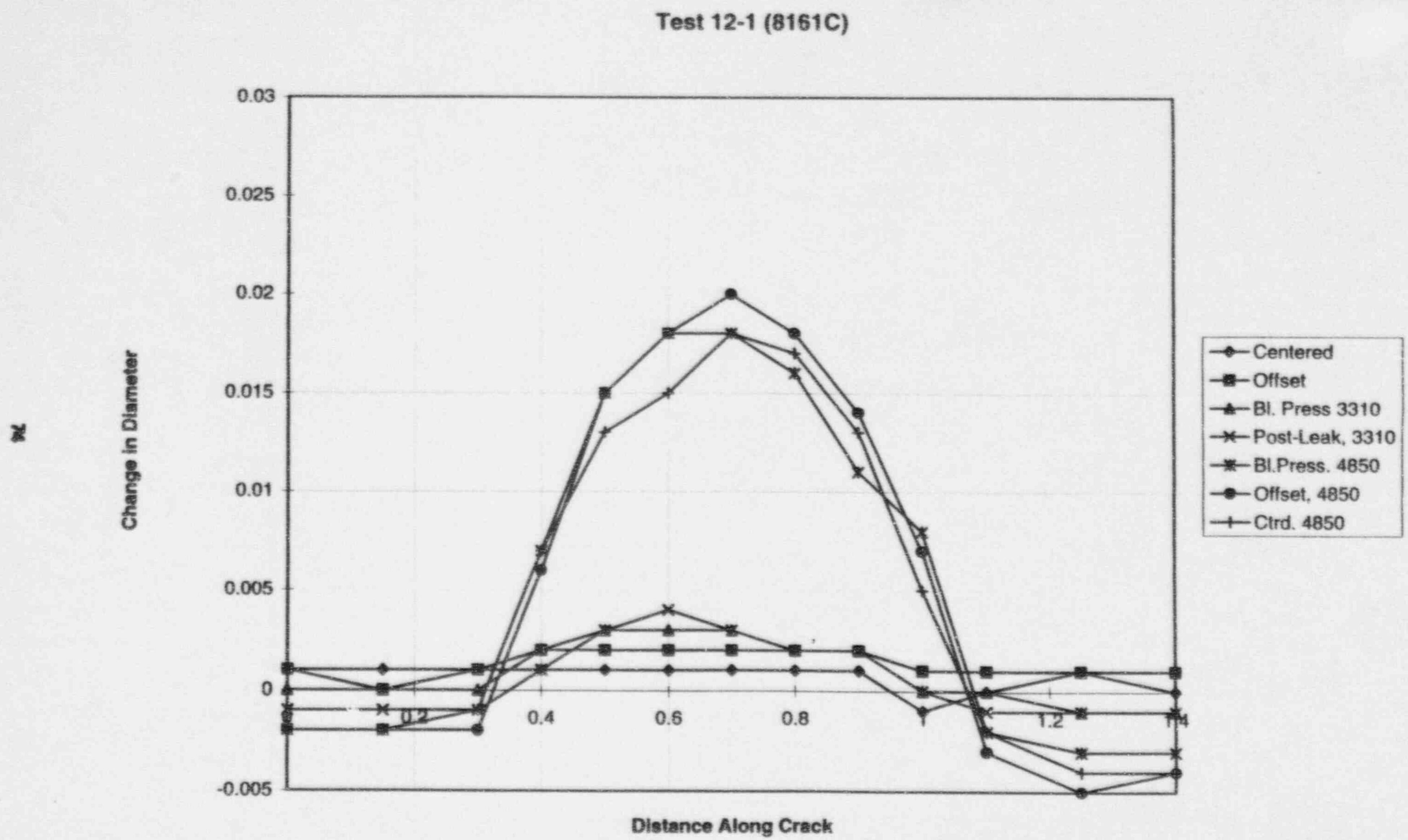
Indications Restricted From Burst Leak Rate Tests

(as-measured, without adjustment to reference conditions)



ChRaw12-1

TEST12-1.XLS 8/7/95



Ch12-1(8161C)

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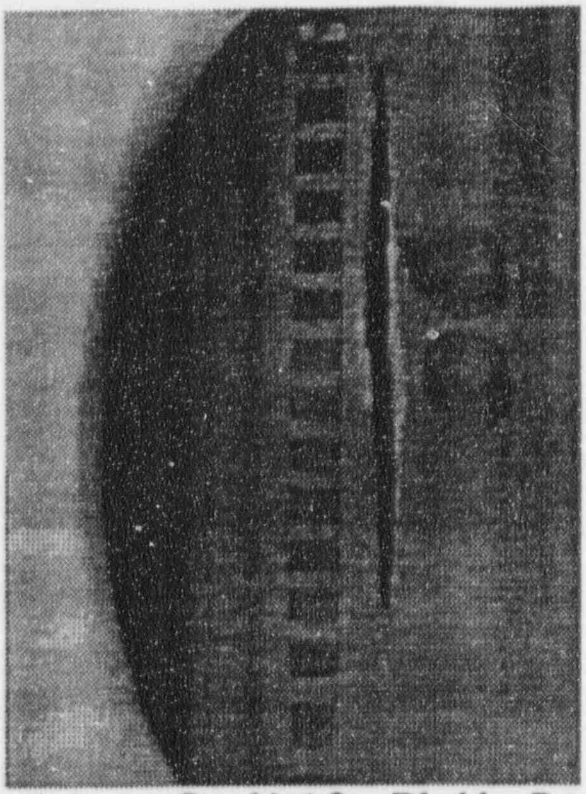
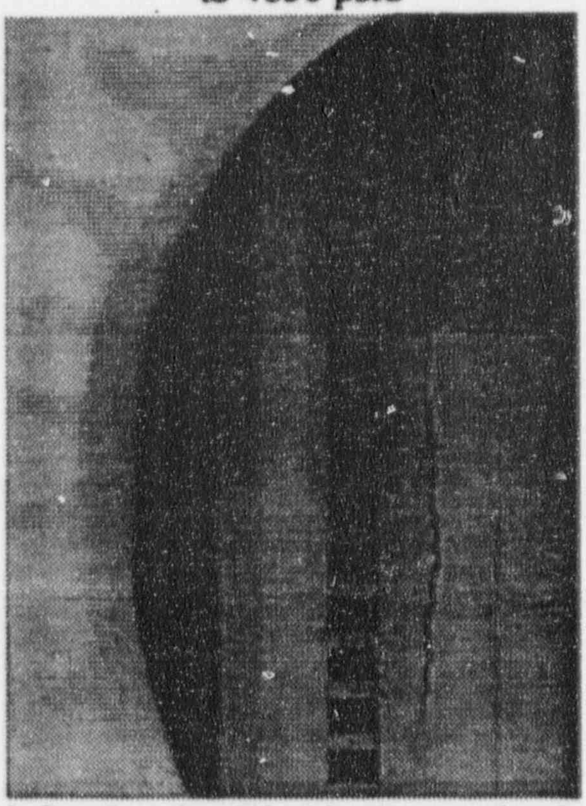


90° Crack (Primary Crack) After Bladder Pressurization
to 4850 psid



0° Crack After Bladder Pressurization
to 4850 psid

Test 12-1 (Sample 8161C)

Test 12 - 1

Summary of Leak Test and Analysis Results (Based on Maximum Test Δp)

Specimen 8161A, Tube Diameter = 0.875", Gap = 0.026"

			Evaluated Test Averages						Adjusted Leak Rate at Δp_{max}				Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{set} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{set} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	Test Leak Rate (RT) at Δp_{max} (gpm)	β	γ	Leak (@ Δp_{max}) Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (@Δp_{max}) (gpm)	Comments
12-1A Within TSP, HT	1	1883	1881	36	1845	608	0.83	0.1	0.86	1.00	0.91	0.78	0.77	Average of 1 & 2
	2	1918	1913	42	1875	612	0.78	0.08	0.81	1.00	0.94	0.76		
	3	1987	1946	44	1902	613	0.90	0.06	0.96	1.00	0.95	0.91	0.91	
	4	2104	2124	61	2063	627	1.09	0.07	1.12	1.01	1.05	1.19	1.18	Average of 4 & 5
	5	2119	2110	63	2047	615	1.16	0.05	1.21	1.00	0.96	1.17		
	6	2214	2229	81	2148	630	1.47	0.12	1.54	1.01	1.05	1.63	1.63	
	7	2293	2367	109	2258	624	1.60	0.08	1.63	1.01	0.99	1.63	1.63	
12-1C Offset 0.15", HT	1	2313	2350	115	2235	630	1.90	0.12	1.95	1.01	1.02	2.06	2.05	Average of 1 & 2
	2	2290	2346	129	2217	625	1.92	0.07	2.00	1.01	1.01	2.03		
	3	2439	2420	145	2275	611	2.45	0.15	2.63	1.00	0.92	2.42	2.42	
	4	2530	2539	172	2367	619	2.81	0.21	2.99	1.00	0.95	2.85	2.85	
	5	2683	2766	263	2503	615	4.21	0.4	4.47	1.00	0.91	4.08	4.69	
	6	2604	2757	275	2482	617	4.21	0.21	4.59	1.00	0.91	2.53	-	Delete - Hysteresis
12-1F Expanded 3310 psi Offset 0.15", HT	1	2165	2297	205	2092	618	3.24	0.34	3.37	1.00	0.91	3.06	3.18	Average of 1 & 2
	2	2215	2281	203	2078	626	3.17	0.21	3.45	1.01	0.95	3.31		
	3	2234	2343	216	2127	607	3.68	0.31	4.03	0.99	0.88	3.50	3.50	
	4	2412	2477	229	2248	618	3.61	0.29	3.87	1.00	0.91	3.55	3.63	Average of 4 & 5
	5	2430	2555	244	2311	603	4.19	0.07	4.38	0.99	0.86	3.71		
	6	3650	2733	279	2454	616	4.67	0.36	3.80	1.00	0.91	4.55	4.55	
12-1G Expanded 3310 psi Within TSP, HT	1	1865	2008	184	1824	600	2.95	0.13	3.03	0.98	0.78	2.31	2.31	
	2	2034	2091	192	1899	613	3.21	0.13	3.46	1.00	0.87	3.04	3.04	
	3	2235	2293	215	2078	602	3.69	0.21	3.99	0.99	0.85	3.34	3.34	
	4	2387	2498	229	2269	621	3.71	0.18	3.91	1.01	0.95	3.65	3.65	
12-1I Expanded 4850 psi Offset 0.15", HT	1	2056	2309	311	1998	626	4.91	0.43	5.05	1.01	0.88	4.54	4.54	
	2	2162	2292	323	1969	630	5.29	0.28	5.84	1.01	0.98	5.07	5.07	
	3	2445	2621	346	2275	629	3.31	0.3	3.92	1.02	0.92	3.33	3.33	
12-1J Expanded 4850 psi Within TSP, HT	1	1853	2107	286	1821	615	4.67	0.35	4.77	1.00	0.79	3.77	3.77	
	2	1953	2159	285	1874	628	4.57	0.22	4.84	1.02	0.89	4.39	4.39	
	3	2175	2362	316	2046	609	3.27	0.35	3.58	0.99	0.83	4.39	4.39	
	4	2306	2467	327	2140	617	3.52	0.48	3.93	1.00	0.87	3.16	3.16	
	5	2489	2655	340	2315	624	3.61	0.35	4.00	1.01	0.91	3.49	3.49	

TEST12-1.XLS 12-1 Table_Dpmax 8/7/95 7:47 PM

Test 12 - 1
Summary of Leak Test and Analysis Results (Based on Average Δp)
Specimen 8161A, Tube Diameter = 0.875", Gap = 0.026"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{set} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
12-1A Within TSP, HT	1	1883	1881	[illegible]	1845	608	0.83	0.1	1.00	0.91	0.75	0.74	Average of 1 & 2
	2	1918	1913	42	1875	612	0.78	0.08	1.00	0.94	0.73		
	3	1967	1946	44	1902	613	0.90	0.06	1.00	0.93	0.83	0.85	
	4	2104	2124	61	2063	627	1.09	0.07	1.01	1.05	1.15	1.13	Average of 4 & 5
	5	2119	2110	63	2047	613	1.16	0.05	1.00	0.96	1.11		
	6	2214	2229	81	2148	630	1.47	0.12	1.01	1.05	1.57	1.57	
	7	2293	2347	109	2238	624	1.60	0.08	1.01	0.99	1.60	1.60	
12-1C Offset 0.15", HT	1	2313	2330	115	2235	630	1.90	0.12	1.01	1.03	1.97	1.96	Average of 1 & 2
	2	2290	2346	129	2217	629	1.92	0.07	1.01	1.01	1.95		
	3	2439	2429	145	2275	611	2.43	0.13	1.00	0.91	2.22	2.22	
	4	2320	2359	172	2367	619	2.81	0.21	1.00	0.94	2.65	2.65	
	5	2683	2766	263	2503	615	4.21	0.4	1.00	0.90	3.79	3.79	Average of 5 & 6
	6	2604	2757	275	2482	617	4.21	0.21	1.00	0.90	3.79		
12-1F Expanded 3310 psi Offset 0.15", HT	1	2165	2297	203	2092	618	3.24	0.34	1.00	0.90	2.92	3.02	Average of 1,2 & 3
	2	2215	2281	203	2078	626	3.17	0.21	1.01	0.94	3.03		
	3	2334	2343	216	2127	607	3.68	0.31	0.99	0.85	3.10		
	4	2412	2477	229	2248	618	3.61	0.29	1.00	0.90	3.26	3.26	
	5	2430	2555	244	2311	603	4.19	0.07	0.99	0.83	3.50	3.50	
	6	2630	2733	279	2454	616	4.67	0.36	1.00	0.90	4.18	4.18	
12-1G Expanded 3310 psi Within TSP, HT	1	1863	2008	184	1824	600	2.95	0.13	0.96	0.76	2.21	2.21	
	2	2034	2091	192	1899	613	3.21	0.12	1.00	0.85	2.71	2.71	
	3	2253	2293	213	2078	602	3.69	0.21	0.99	0.82	2.99	2.99	
	4	2387	2498	[illegible]	2269	621	3.71	0.18	1.01	0.92	3.43	3.43	
12-1I Expanded 4850 psi Offset 0.15", HT	1	2056	2309	311	1998	626	4.91	0.43	1.01	0.87	4.35	4.38	Average of 1 & 2
	2	2162	2292	323	1969	620	5.29	0.28	1.01	0.83	4.41		
	3	2443	2621	346	2275	629	3.31	0.3	1.02	0.91	3.08	5.08	
12-1J Expanded 4850 psi Within TSP, HT	1	1853	2107	286	1821	615	4.67	0.35	1.00	0.78	3.65	3.65	
	2	1953	2139	285	1874	628	4.57	0.22	1.02	0.88	4.08	4.08	
	3	2175	2362	316	2046	609	5.37	0.33	0.99	0.80	4.20	4.20	
	4	2306	2467	327	2140	617	5.52	0.48	1.00	0.85	4.68	4.68	
	5	2489	2833	340	2313	624	5.61	0.35	1.01	0.89	5.05	5.05	

Test 12-1 Summary of Test Dimensional Measurement Results Specimen 8161-C, Tube Dia. = 0.875", Gap =0.026"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in.²)	Max Dia. (in.)	Min. Dia. (in.) [1]
None	NA	Pre-test	90° 0°	0.607 0.465	.515 [2] .360	NA [3]	NA	NA	.876 .875	.876 .875 .872 .873
None	0.0 Step A	Hot	90° 0°	0.633 NA	[5] (<0.001) [6]	<0.00058	NA	NA	.876 .875	.876 .875 .872 .873
None	0.15 Step C	Hot	90° 0°	0.646 NA	0.585[4] (0.005) [6]	0.00176	0.105 (0.002)	0.00010	.877 .880	.876 .873 .870
3310	NA Step E	NA	90° 0°	0.649 NA	0.603[4] (0.005) [6]	0.00182	NA	NA	.878 .879	.875 .875 .874 .873
3310	0.15 Step F	Hot	90° 0°	0.652 NA	0.604[4] (0.005) [6]	0.00190	0.151 (0.004)	0.00026	.878 .879	.874 .874

Test 12-1 Summary of Test Dimensional Measurement Results Specimen 8161-C, Tube Dia. = 0.875", Gap =0.026"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in.²)	Max Dia. (in.)	Min. Dia. (in.) [1]
3310	0.0 Step G	Hot			Same as 0.15 offset test after bladder pressurization to 3300 psid					
4850	NA Step H	NA	90° 0°	0.654 0.481	0.629[4] (0.022) 0.411[4] (0.005)	0.00946 0.00107 Sum= 0.01053	NA	NA	.893 .883	.874 .873 .877
4850	0.15 Step I	Hot	90° 0°	0.656 0.481	0.630 (0.022) 0.411 (0.005)	0.01063 0.00112 Sum= 0.01174	0.151 (0.018)	0.00181	.895 .884	.872 .873 .877
4850	0.0 Step J	Hot	90° 0°	0.658 0.483	0.630[4] (0.022) 0.411[4] (0.005)	0.01074 0.00117 Sum = 0.01191	NA	NA	.893 .884	.874 .873 .877

Test 12-1 Summary of Test Dimensional Measurement Results Specimen 8161-C, Tube Dia. = 0.875", Gap =0.026"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in.²)	Max Dia. (in.)	Min. Dia. (in.) [1]

Notes: [1] Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.875" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.

[2] Based on silastic mold and dye penetrant test.

[3] Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.

[4] Crack length from toolmaker's microscope. Minimum measurable TW crack opening ~0.001".

[5] TW length could not be accurately determined due to negligible crack opening.

[6] No light was visible through the crack; therefore TW length could not be determined.

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 12-7: Summary of Test Results and Evaluation

Test Sequence

- Order of tests: 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 are hot tests.
  - The bladder pressurization to 6200 psi was an inadvertently high ΔP and should have been the target free span burst pressure of about 3950 psi. However, this target burst pressure assumed the ligament between the two circumferentially separated (by a 0.012" ligament) would tear to result in a long 0.58" TW crack. The ligament did not tear at 2800 psi but did tear at the 6200 psi bladder pressurization. The ligament would likely have increased the burst pressure above the estimated 3950 psi value.
  - Intermediate bladder pressurization step is approximately 70% of the predicted specimen burst pressure.
  - The crack to TSP gap was established at 0.025" by forcing the tube to contact the TSP hole ID at 180° from the crack.
- There is no basis to question the adequacy of the data other than the higher than planned bladder pressurization noted above - leak test results show consistent trends, without large data scatter.
  - The higher than planned bladder pressurization may have resulted in a slightly lower leak rate than would have been obtained at the target 2800 psi. This difference does not significantly impact the test results and conclusions.
  - However, the zero offset flow pressurization tests show a larger (up to 260 psi) than normal (typically about 125 psi or less) difference between the maximum ΔP in the leak test and the average ΔP used for general interpretation of the test results. As a result, it is necessary to use leak rate trends based on the maximum ΔP to assess crack to TSP interaction and the difference in leak rates between zero offset and offset conditions.

Summary of Test Results

- The specimen tested had overall lengths of 0.590" OD, 0.580" TW with the total length comprised of two TW cracks separated circumferentially near the crack tips by a 0.012" ligament between the cracks at about 0.365" from the end of the longer crack. The individual crack lengths were 0.365" OD, 0.360" TW and 0.244" OD, 0.239" TW.
  - Pre-test silastic mold and dye penetrant examination did not reveal the presence of the ligament. The ligament became apparent after the initial flow pressurization test.
  - The test results indicate that the ligament between the two cracks did not tear until the 6200 psi bladder pressurization test.
- As noted above, the leak rate versus maximum ΔP plot is used for the following interpretation of the test results.
- Although the flow pressurization offset leak rate slope 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.
  - The zero offset test up to 2509 psi shows no indication of crack to TSP interaction. Extrapolation of the zero offset leak rates with no interaction to 2659 psi results in only a slightly larger leak rate than obtained from the offset leak test.
  - The crack diameter increase following the flow pressurization offset test was only 5 mils compared to the 25 mil crack to TSP gap and no interaction would be expected.

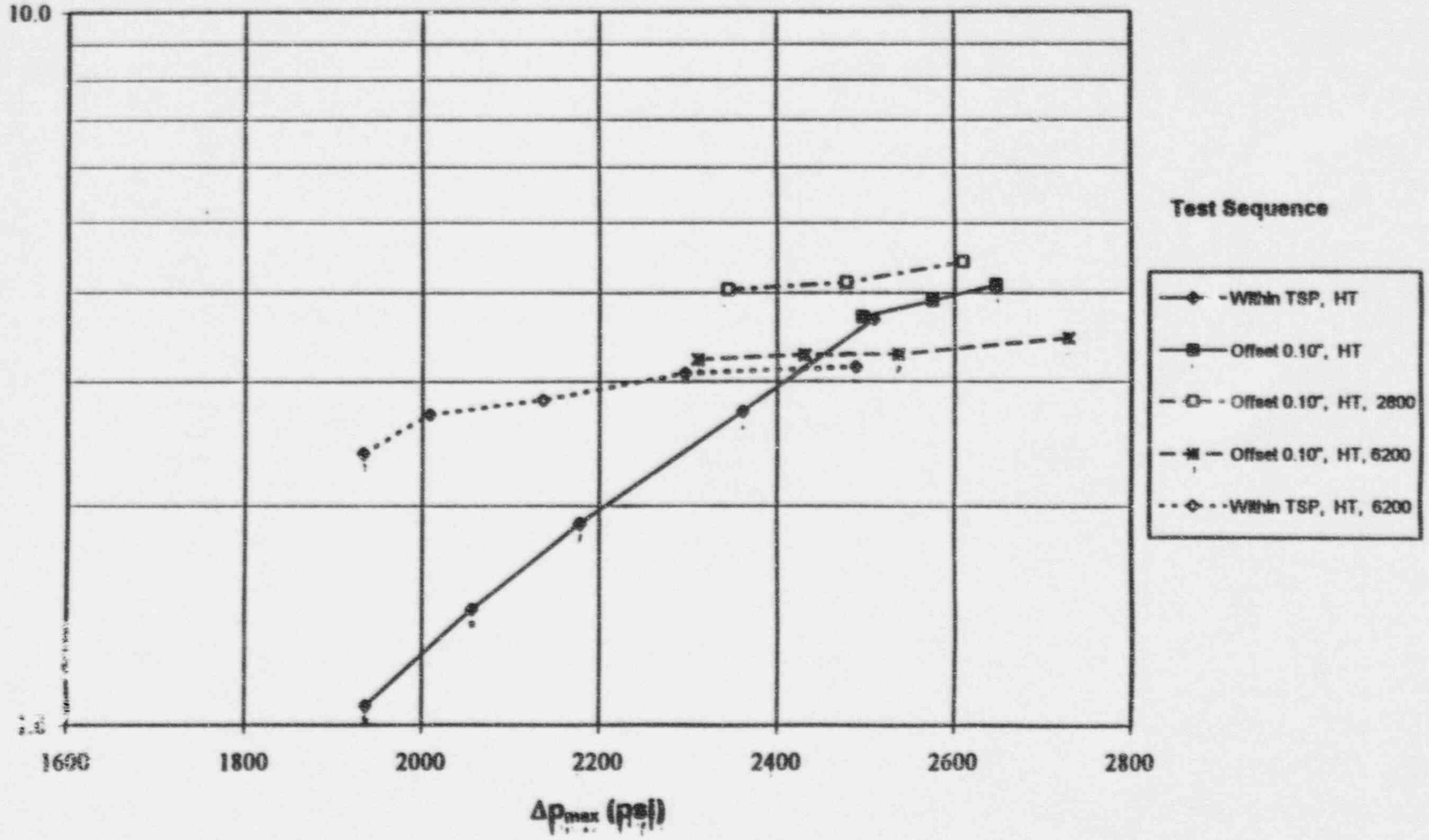
- The results indicate only a very small increase in the leak rate between the zero offset and offset test conditions.
- It is concluded that crack to TSP interaction did not occur in the flow pressurization tests.

- Bladder pressurization to 2800 psi (approximately 70% of predicted rupture pressure) 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 would indicate crack to TSP interaction.
    - o The crack diameter following this pressurization step did not significantly increase over that of the flow pressurization offset test and crack to TSP interaction would not have been expected.
  - The leak rate increase is consistent with the 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 increased the plastic crack diameter to entirely close the initial crack to TSP clearance of 0.025".
  - The TW length following this bladder pressurization step was 0.726" with a maximum TW crack opening of 0.056" for the offset test.

Overall Conclusions

- 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.
- There is no indication of crack to TSP interaction prior to the bladder pressurization of 2800 psi.
  - This demonstrates that the two TW cracks totalling 0.631" over an overall length of 0.629" (ligament separates TW crack tips) do not behave in terms of crack opening and leakage as a single long TW crack near 0.63". All other tests in this program indicate that single TW crack lengths of > 0.5" result in crack to TSP interaction at < 2400 psi.

Test 12 - 7
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp= 615°F and ps = 15 psia Conditions - based on test leak rate at Δp_{max})

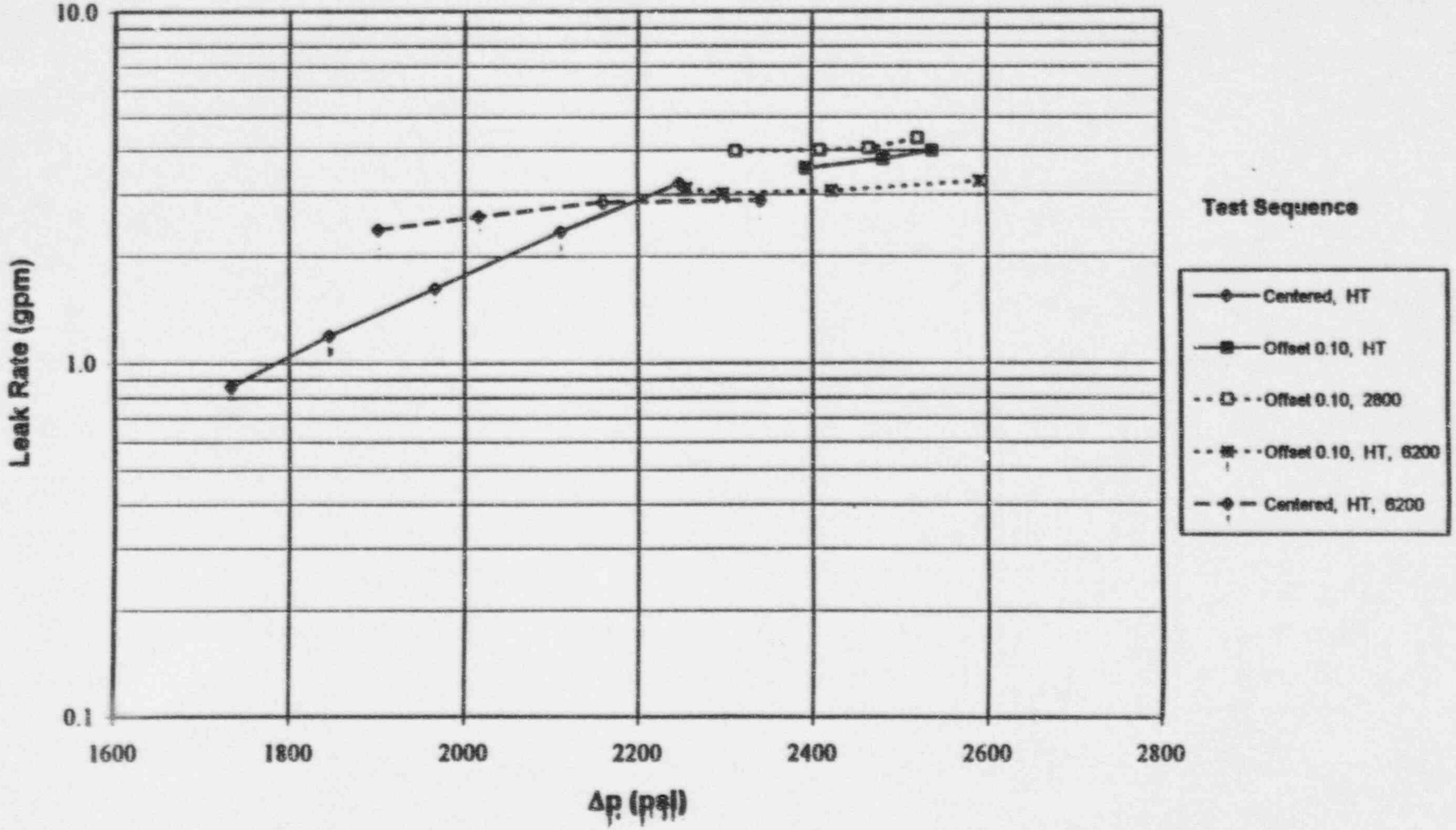


84

ChNorm_12-7Dpmax

TEST12-7.XLS 8/7/95

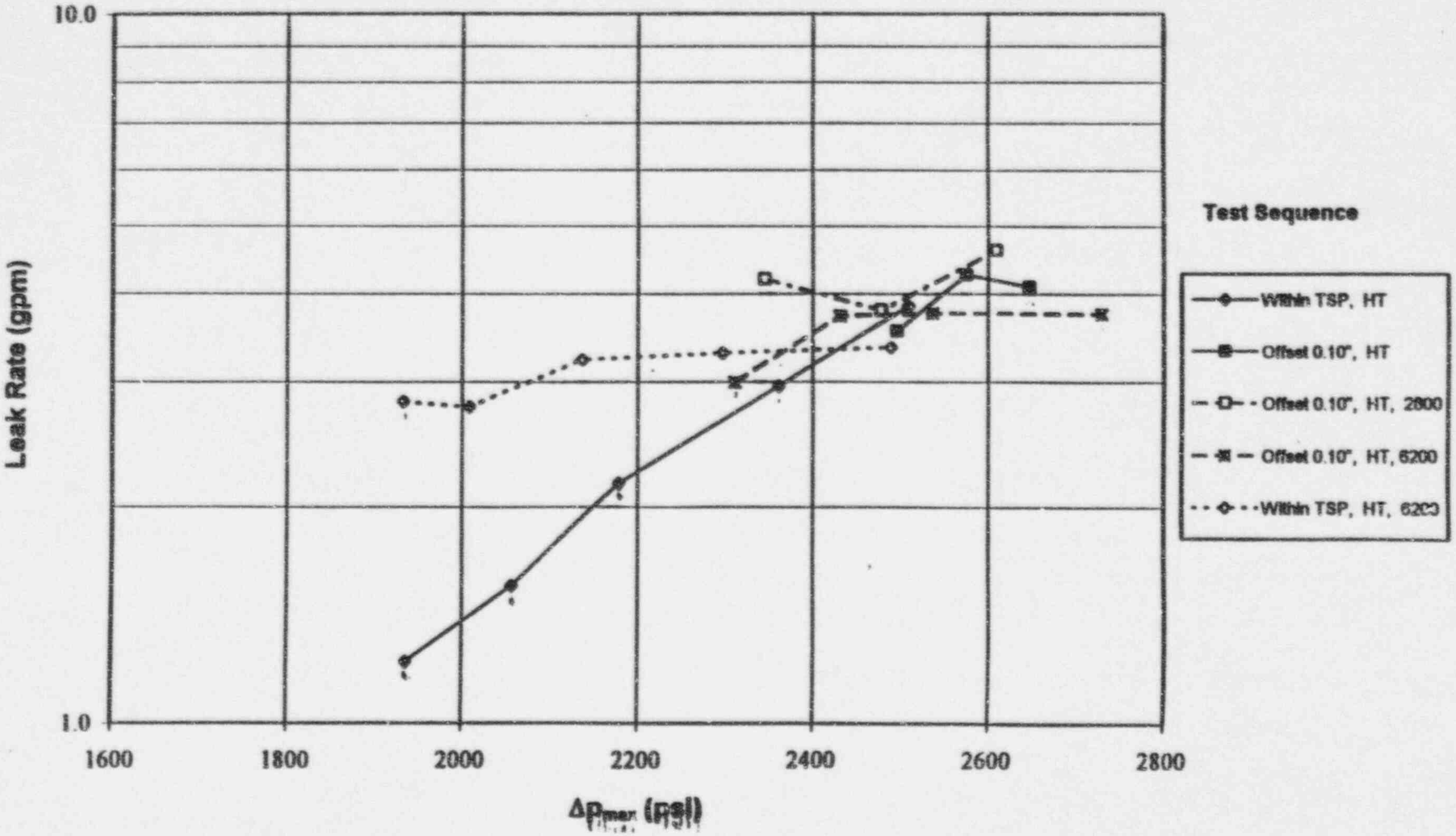
Test 12 - 7
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp= 615°F and ps = 15 psia Conditions - based on test leak rate at Δp_{avg})



ChNorm_12-7

TEST12-7.XLS 8/7/95

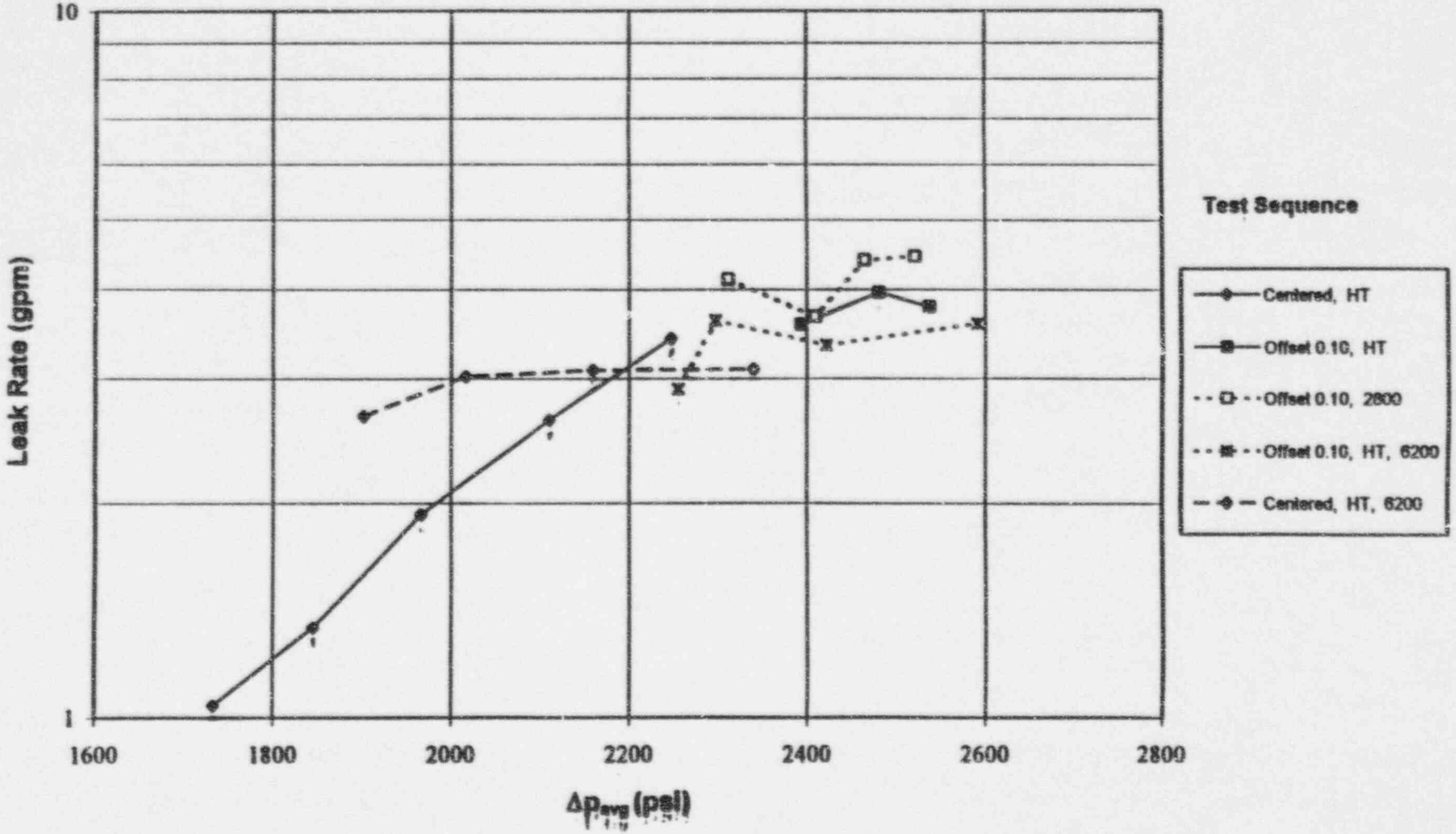
Test 12 - 7
Indications Restricted From Burst Leak Rate Tests
(Test leak rate at Δp_{max}, without adjustment to reference SLB conditions)

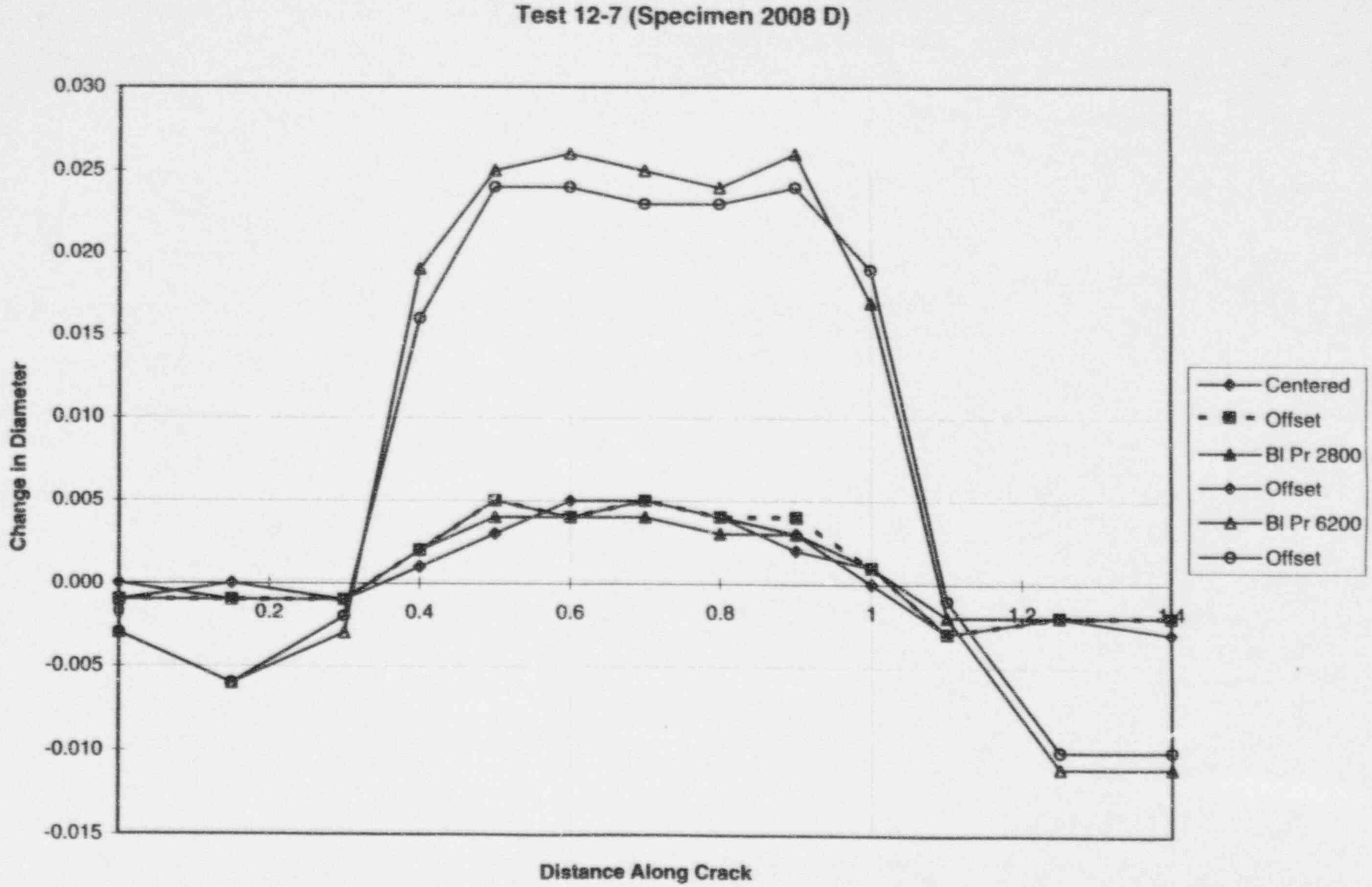


ChRaw_12-7Dpmax

TEST12-7.XLS 8/7/95

Test 12 - 7
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)

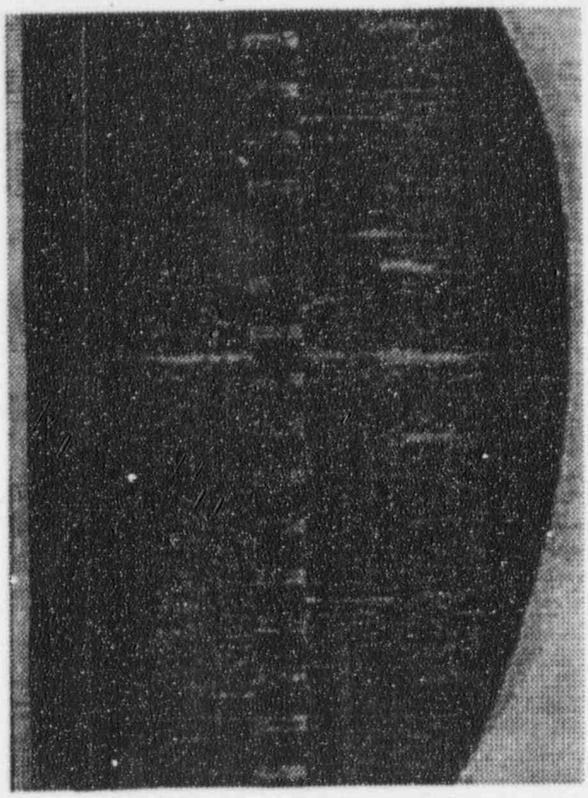




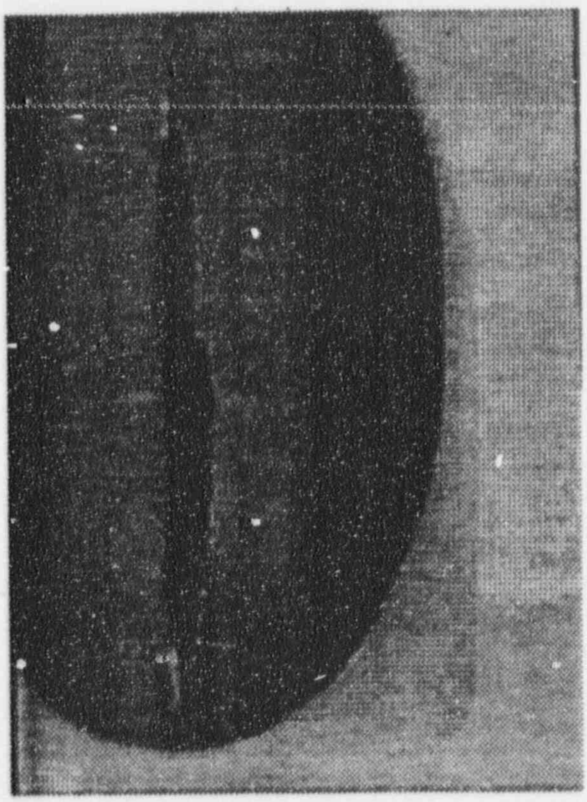
88

Ch12-7,2008D

IRBRTDIA.XLS 8/15/95



After Flow Pressurization Within TSP



After Bladder Pressurization to 6200 psid and Subsequent Flow Tests

Test 12-7 (Sample 2008D)

Test 12 - 7

Summary of Leak Test and Analysis Results (based on Maximum Test Δp)

Specimen 2008D, Tube Diameter = 0.745", Gap = 0.025"

			Evaluated Test Averages						Adjusted Leak Rate at Δp_{max}				Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{test} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	Test Leak Rate (RT) at Δp_{max} (gpm)	β	γ	Leak (@ Δp_{max}) Adjusted for temp & Pressure(βγ) (gpm)	Average Leak Rate (@Δp_{max}) (gpm)	Comments
12-7A Within TSP HT	1	1846	1610	23	1585	593	0.84	0.05	1.05	0.98	-	-	-	Δp too low for SLB Projection
	2	1936	1775	40	1733	602	1.04	0.09	1.22	0.99	0.88	1.06	1.06	
	3	2056	1908	63	1845	610	1.34	0.14	1.56	1.00	0.93	1.44	1.44	
	4	2178	2070	104	1966	602	1.93	0.11	2.16	0.99	0.88	1.89	1.89	
	5	2361	2269	159	2110	613	2.62	0.17	2.95	1.00	0.92	2.72	2.72	
	6	2509	2461	214	2247	624	3.42	0.24	3.84	1.01	0.95	3.68	3.68	
12-7C Offset 0.10" HT	1	2484	2645	226	2419	632	3.53	0.33	3.63	1.01	0.98	3.61	3.70	Average of 1 & 2
	2	2509	2574	207	2367	647	3.19	0.18	3.44	1.03	1.07	3.80		
	3	2575	2638	244	2394	618	3.98	0.33	4.28	1.00	0.92	3.98	3.90	
	4	2634	2731	250	2481	626	3.96	0.34	4.20	1.01	0.95	4.02	4.11	Average of 3 & 4
	5	2659	2789	252	2537	644	3.78	0.19	3.98	1.03	1.03	4.19		
12-7F Expanded, 2800 Offset 0.10" HT	1	2343	2571	259	2312	629	4.15	0.48	4.19	1.02	0.95	4.04	4.04	
	2	2478	2655	246	2409	646	3.66	0.22	3.79	1.04	1.05	4.13	4.13	
	3	2592	2746	281	2465	622	4.39	0.27	4.60	1.01	0.92	4.28	4.41	Average of 3 & 4
	4	2626	2806	285	2521	632	4.46	0.27	4.62	1.02	0.96	4.53		
12-7H Expanded, 6200 Offset 0.10" HT	1	2295	2430	189	2241	636	2.89	0.19	2.98	1.03	1.02	3.11	3.22	Average of 1 & 2
	2	2326	2467	194	2273	642	2.95	0.22	3.00	1.04	1.07	3.34		
	3	2431	2515	214	2301	606	3.59	0.19	3.72	0.99	0.89	3.28	3.28	
	4	2531	2652	214	2438	614	3.43	0.26	3.51	1.00	0.93	3.25	3.28	Average of 3 & 4
	5	2522	2736	375	2361	602	3.77	0.39	4.00	0.99	0.84	3.31		
	6	2729	2850	228	2622	611	3.69	0.27	3.75	1.00	0.92	3.46	3.46	
12-7I Expanded, 6200 Within TSP HT	1	1933	2065	173	1892	610	2.74	0.17	2.81	0.99	0.85	2.37	2.37	
	2	2008	2097	174	1923	623	2.61	0.11	2.76	1.01	0.96	2.69	2.69	
	3	2136	2197	181	2016	610	3.02	0.23	3.22	0.99	0.88	2.82	2.82	
	4	2297	2357	190	2167	618	3.10	0.18	3.30	1.00	0.93	3.08	3.08	
	5	2504	2555	201	2354	619	3.12	0.24	3.31	1.01	0.94	3.12	3.14	Average of 5 & 6
	6	2474	2533	196	2339	618	3.22	0.03	3.41	1.00	0.93	3.17		

Test 12 - 7
Summary of Leak Test and Analysis Results (Based on Average Δp)
Specimen 2008D, Tube Diameter = 0.745", Gap = 0.025"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{test} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
12-7A Within TSP HT	1	1846	1610	25	1585	592	0.84	0.05	-	-	-	-	Δp too low for SLB Projection
	2	1936	1773	40	1733	602	1.04	0.09	0.99	0.83	0.85	0.83	
	3	2056	1908	63	1845	616	1.34	0.14	1.00	0.90	1.20	1.20	
	4	2178	2070	104	1966	602	1.93	0.11	0.99	0.85	1.63	1.63	
	5	2361	2269	159	2110	613	2.62	0.17	1.00	0.90	2.35	2.35	
	6	2509	2461	214	2247	624	3.42	0.24	1.01	0.94	3.23	3.23	
12-7C Offset 0.10" HT	1	2484	2645	226	2419	632	3.33	0.33	1.01	0.98	3.30	3.55	Average of 1, 2 & 3
	2	2509	2574	207	2367	647	3.19	0.18	1.03	1.08	3.55		
	3	2575	2638	244	2394	616	3.98	0.33	1.00	0.90	3.59		
	4	2634	2731	250	2481	626	3.96	0.34	1.01	0.94	3.77	3.77	
	5	2639	2789	252	2537	644	3.78	0.19	1.03	1.03	3.99	3.99	
12-7F Expanded, 2800 Offset 0.10" HT	1	2345	2571	259	2312	629	4.13	0.48	1.02	0.95	3.97	3.97	
	2	2478	2655	246	2409	646	3.66	0.22	1.04	1.05	4.00	4.00	
	3	2592	2746	281	2465	622	4.39	0.27	1.01	0.92	4.06	4.06	
	4	2626	2806	285	2521	632	4.44	0.27	1.02	0.96	4.34	4.34	
12-7H Expanded, 6200 Offset 0.10" HT	1	2295	2430	189	2241	636	2.89	0.19	1.03	1.02	3.02	3.12	Average of 1 & 2
	2	2326	2467	194	2273	642	2.95	0.22	1.03	1.06	3.22		
	3	2431	2515	214	2301	606	3.39	0.19	0.99	0.87	3.10	3.06	Average of 3 & 5
	4	2551	2652	214	2438	614	3.43	0.26	1.00	0.91	3.12	3.12	
	5	2522	2736	375	2361	602	3.77	0.39	0.99	0.82	3.03	-	
	6	2729	2850	228	2622	611	3.69	0.27	1.00	0.91	3.33	3.33	
12-7I Expanded, 6200 Within TSP HT	1	1933	2065	173	1892	610	2.74	0.17	0.99	0.84	2.29	2.36	Average of 1 & 2
	2	2008	2097	174	1923	623	2.61	0.11	1.01	0.92	2.43		
	3	2136	2197	185	2016	610	3.02	0.23	0.99	0.86	2.59	2.59	
	4	2297	2337	190	2167	618	3.10	0.18	1.00	0.91	2.84	2.84	
	5	2304	2335	201	2354	619	3.12	0.24	1.00	0.93	2.90	2.90	

Test 12-7 Summary of Test Dimensional Measurement Results Specimen 2008-D, Tube Dia. = 0.745", Gap =0.025"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area ($in.^2$)	Max Dia. (in.)	Min. Dia. (in.) [1]
None	NA	Pre-test	0	0.590	0.580[3] [5] Cr1- 0.375 Cr2-0.256	NA [3]	NA	NA	0.745	0.743
None	0.0 Step A	Hot		0.634	0.375[4] (0.005) 0.256[4] (0.003) [5]	0.00168	NA	NA	0.750	0.744 0.742
None	0.10 Step C	Hot		0.635	0.375[4] (0.006) 0.259[4] (0.004) [5]	0.00213	0.10 [6] (0.0024)	0.00010	0.750	0.744 0.742
2800	NA Step E	NA		0.635	0.375[4] (0.006) 0.259[4] (0.004) [5]	0.00247	NA	NA	0.749	0.744 0.743

Test 12-7 Summary of Test Dimensional Measurement Results Specimen 2008-D, Tube Dia. = 0.745", Gap =0.025"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in.)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in.^{2})	Max Dia. (in.)	Min. Dia. (in.) [1]
2800	0.10 Step F	Hot			Same as after bladder pressurization to 2800 psid, Step E		0.10 [6] (0.0034)	0.00012	0.750	0.744 0.742
6200	NA Step G	NA		.764	0.726[4] (0.060)	0.03284	NA	NA	0.771	0.743 0.742
6200	0.10 Step H	Hot		0.773	0.726[4] (0.056)	0.03159	0.10 [6] (0.039)	0.00215	0.769	0.744 0.743
6200	0.0 Step I	Hot		0.773	0.726[4] (0.057)	0.03175	NA	NA	0.769	0.745 0.744

Notes:
[1] Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.750" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
[2] Based on silastic mold and dye penetrant test.
[3] Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
[4] Crack length from toolmaker's microscope. Minimum measurable TW crack opening ~0.001".
[5] Two essentially co-planar cracks (0.012" circumferential offset) separated by a ligament at 0.365" from the end of the longer segment.
[6] Post test dimension. Test setup with 0.10 TW offset.

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 1-1: Summary of Test Results

Test Sequence

- Order of tests: zero offset, offset, freespan, bladder pressurization at 4250 psi with 0.15" offset, zero offset, offset and offset cold test.
    - Data points deleted at end of offset test and beginning of free span test due to hysteresis effects.
- Test results show consistent trends with modest fluctuations in data - data appear reliable although the offset leak rate after pressurization lower than the zero offset leak rate is an unexpected result. The effective crack to TSP hole ID clearance for this test was 0.009" compared to the target 0.025" based on measurements of the crack diameter following the flow pressurization offset test.

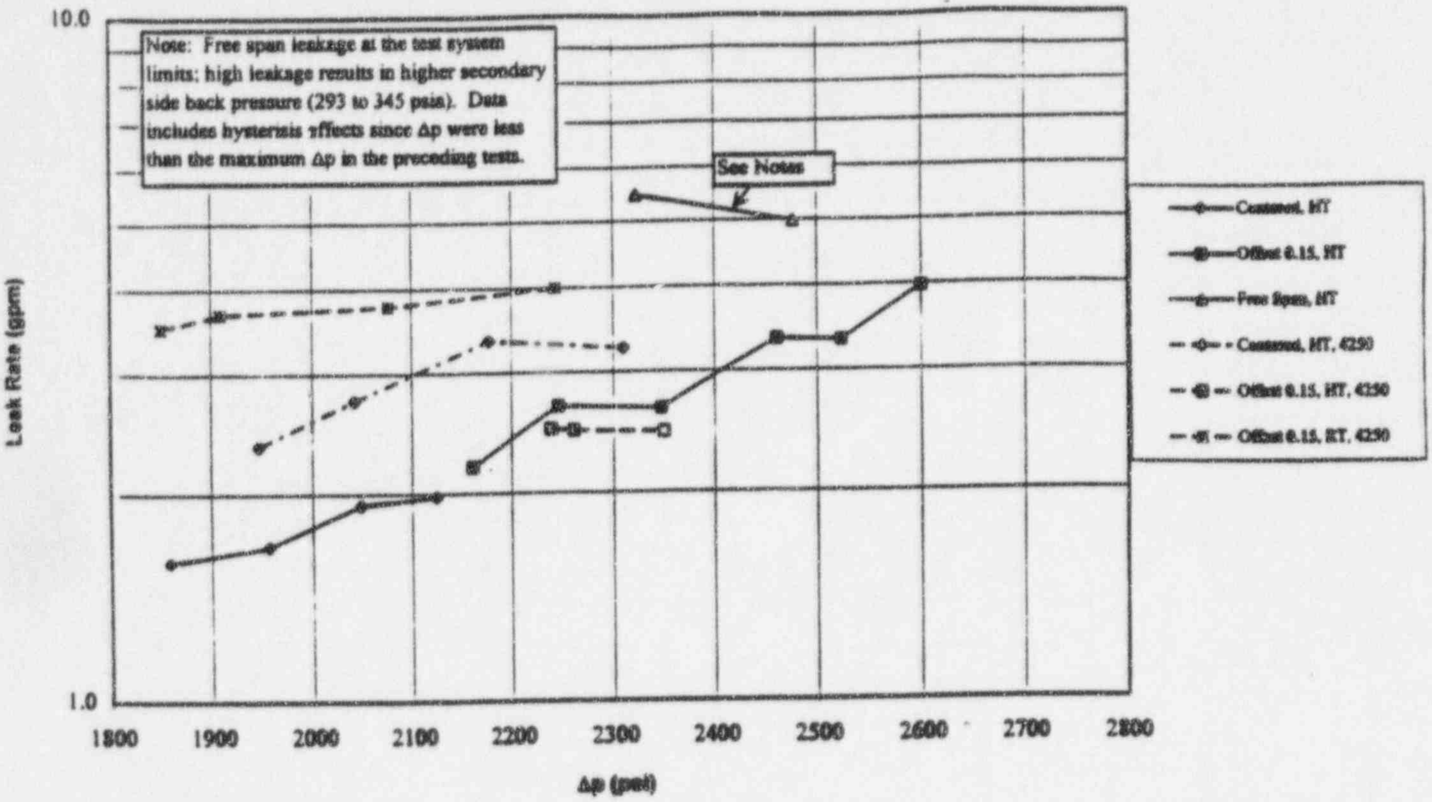
Summary of Test Results

- Shallow slope of leak rate curve above about 2000 psi indicates interaction with the TSP. None of the test points show slopes typical of free span indications.
    - Pressurization up to about 2130 psi with zero offset opened the crack width to a maximum of 0.004".
    - With the larger target gap of 0.025", interaction with the TSP would be at a somewhat higher pressure than obtained for the 0.009" gap in this test.
        - o Based on estimates in Section 5, the geometric flow area is slightly smaller than the effective crack area and some increase in leakage for the offset condition would be expected.
- Maximum leak rate is 4.3 gpm (3.7 gpm at 2560 psi) at 2600 psi for offset conditions
    - The initial increase in leakage after TSP offset is small (about 15%)
    - For this test, the leak rate continued to increase at a modest slope in the offset condition with a larger step at 2600 psi. The measurable throughwall crack length increased from 0.494" to 0.595" and the width increased from 0.004" to 0.011". It is expected that the increasing leak rate is attributable to increases in the crack area and breaking of ligaments as the pressure increased.
- The free span leak rate at 2480 Psi is about 60% higher than the offset leak rate. This is a relatively small reduction in the free span leak rate compared to other tests of long crack lengths. This would indicate that the crack has not interacted with the TSP over a significant length of the crack (estimate of about 0.1" in Section 5).
- Following bladder pressurization to the free span burst pressure of about 4250 psi, the leak rates are about the same as the offset leak rates obtained with flow pressurization. The offset leak rate following pressurization was lower than obtained with zero offset.
    - The bladder pressurization resulted in a modest increase in the maximum TW crack width from 0.011" to 0.012" and no change in the throughwall length. It is expected that the bladder pressurization resulted in increased crack length interacting with the TSP so as to reduce the effective crack area.
    - The lower leak rate with crack offset is not expected although the flow area assessments of Section 5 would indicate that the leak rate following bladder pressurization should not increase for the offset condition. Test records were reviewed for a possible reporting error but the records clearly documented the appropriate test condition.

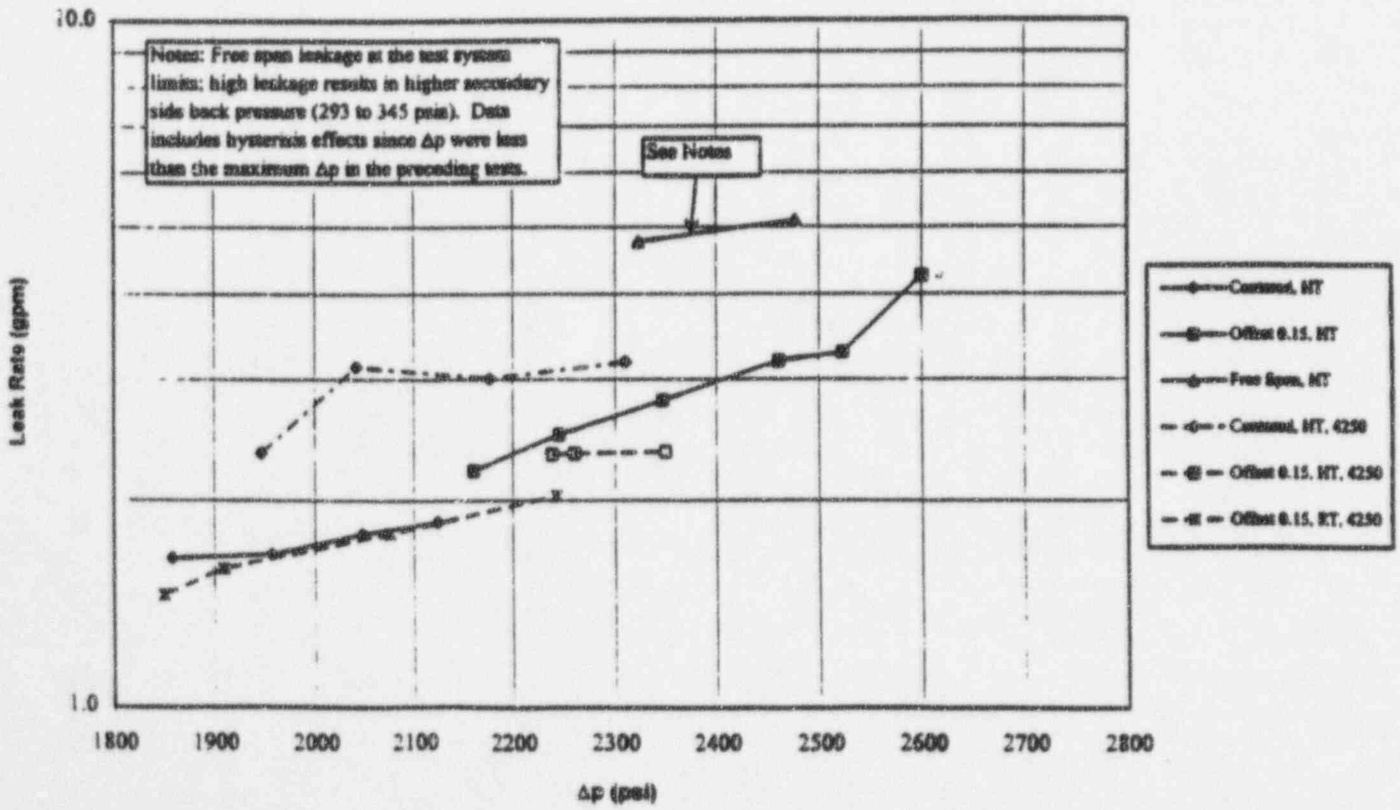
Overall Conclusions

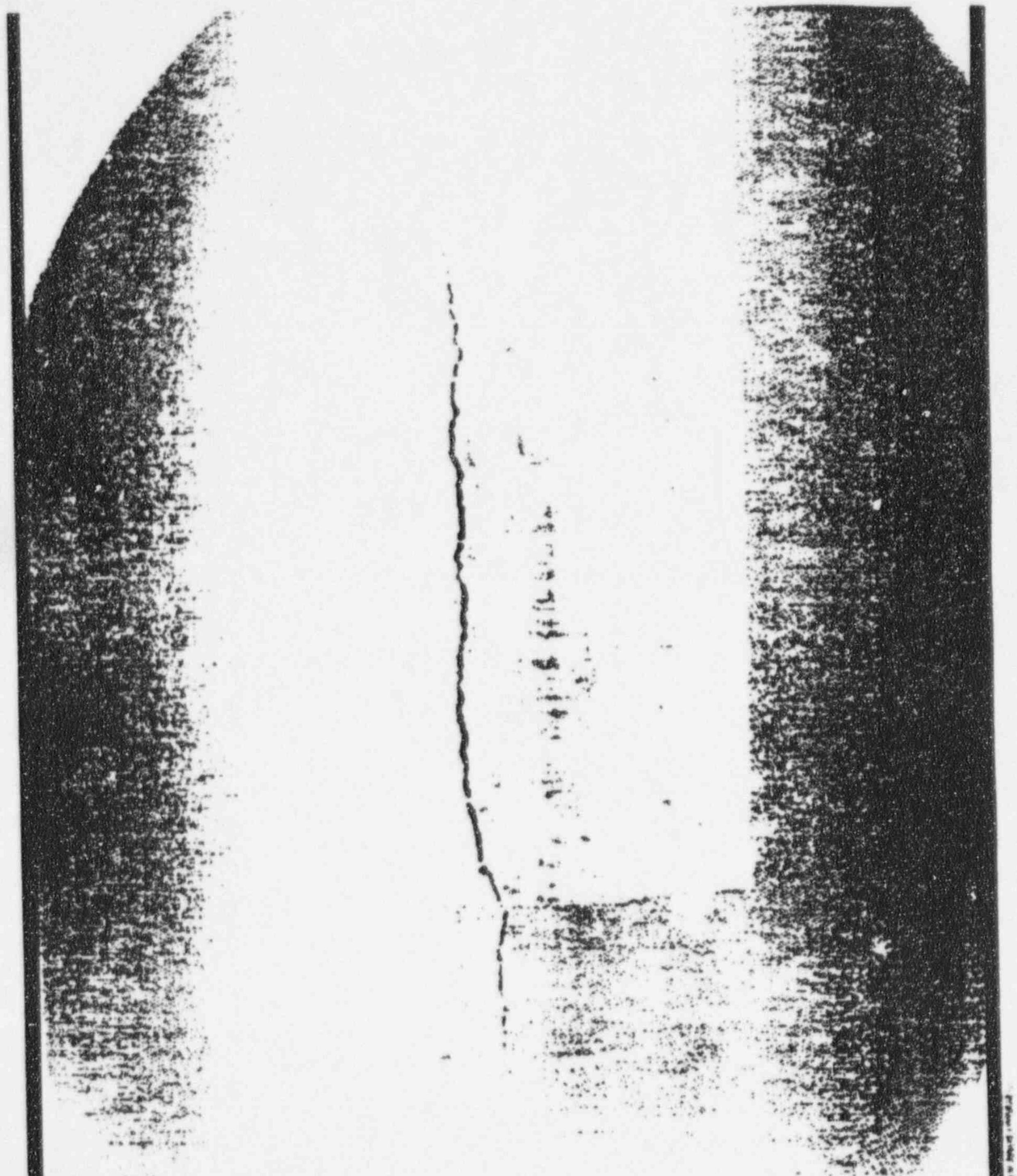
- The SLB leak rate for this 0.6" TW crack is limited to about 3.7 gpm prior to and following bladder pressurization to the free span burst pressure.
  - The effective crack to TSP clearance for this test was 0.009" based on measurements of the crack OD following the flow pressurization offset test.
  - The leak rate for this 7/8" specimen is similar to that found for 0.6" TW cracks in 3/4" tubing (4.1 gpm of Test 1-7).
- Interaction of the crack face with the TSP at about 2000 psi is consistent with other tests of > 0.5" TW cracks
- Bladder pressurization to the free span burst pressure did not increase the leak rate over that obtained in the prior offset tests

Test 1-1
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)

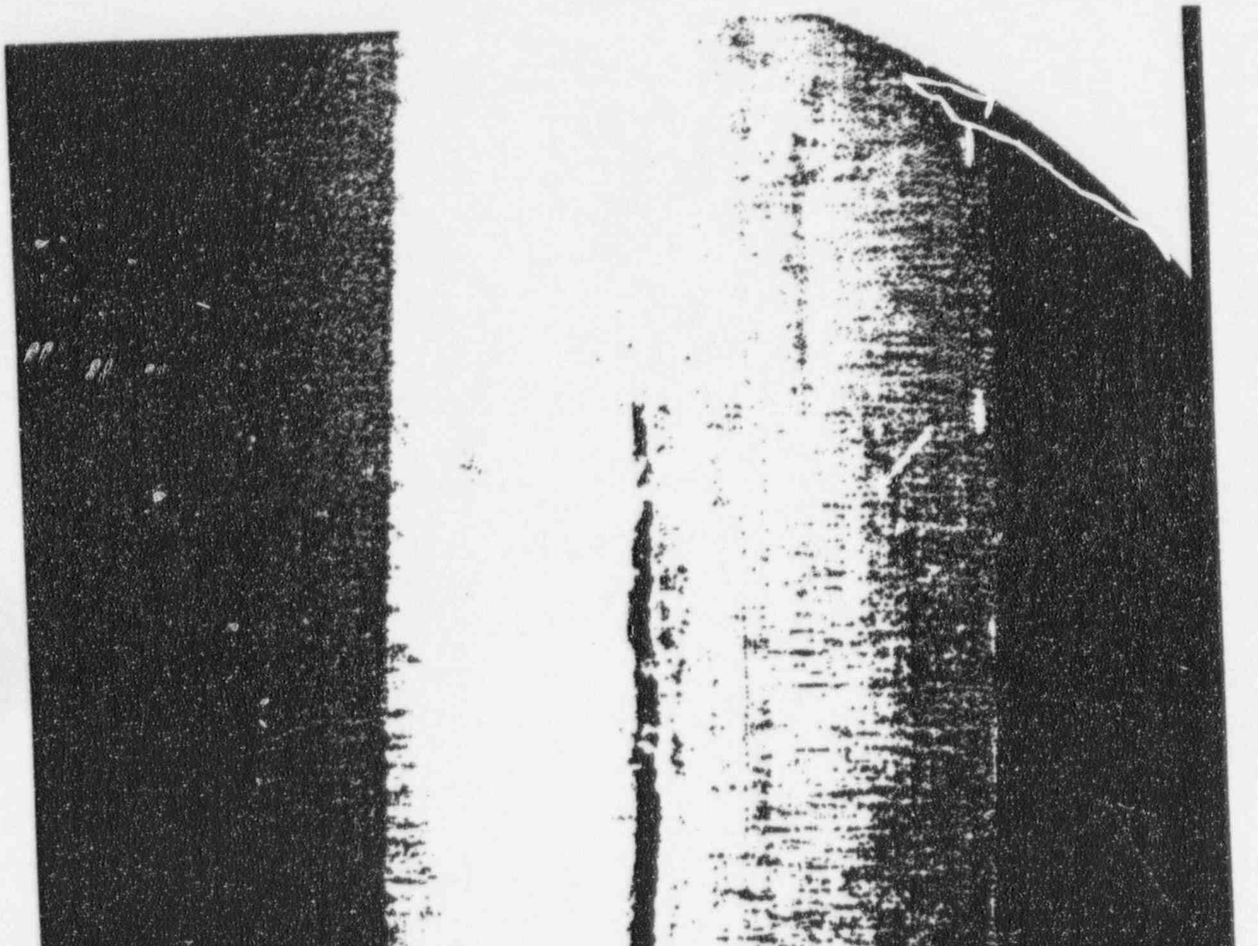


Test 1-1
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp=615°F and ps=15 psia Conditions)

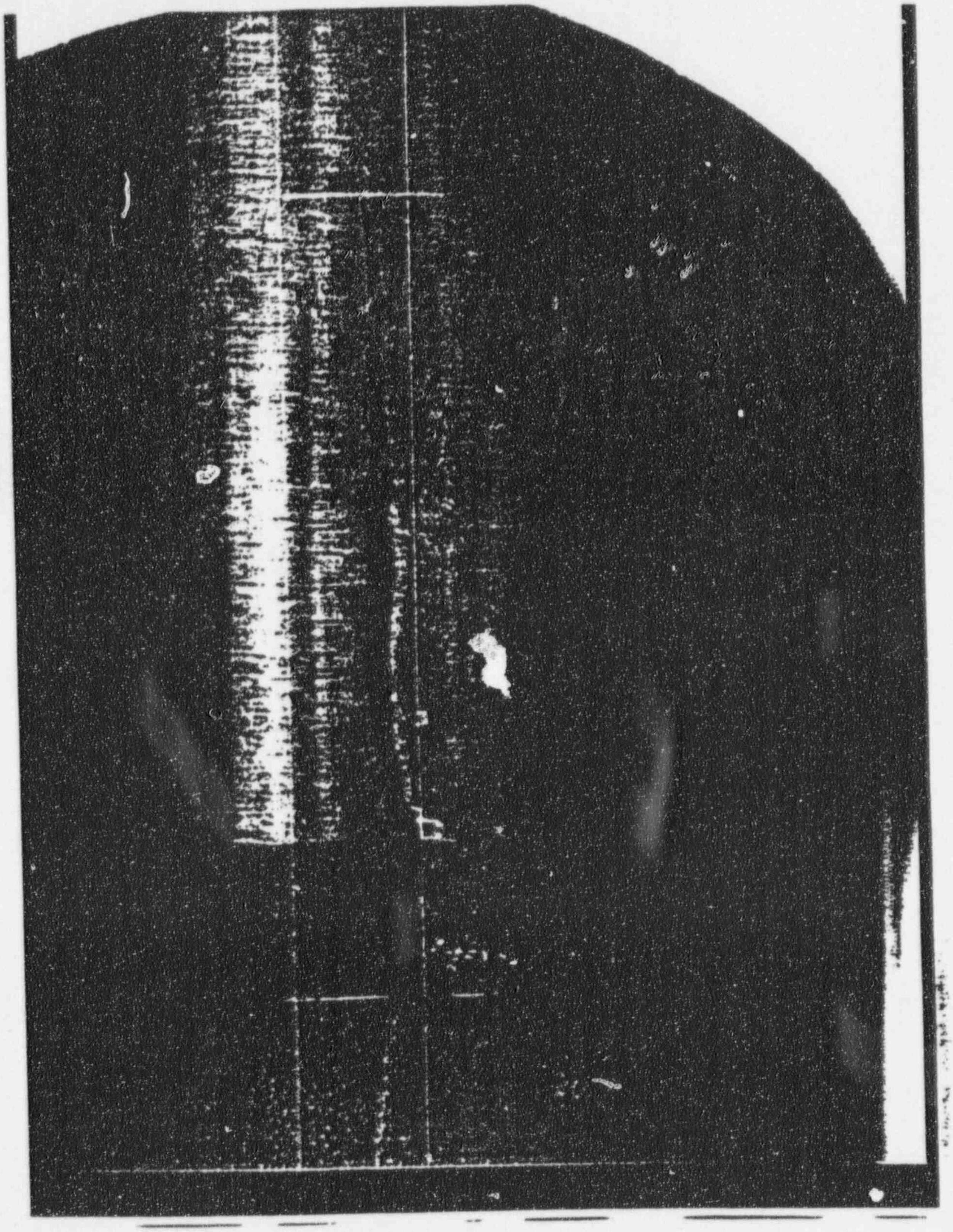




Test 1-1a. After Zero Offset Leak Test



Test1-1b. After Offset Leak Test



Test 1-1c. After Bladder Pressurization to 4250 psi and Leak Testing

Test 1 - 1
Summary of Leak Test and Analysis Results
Specimen 8161G, Tube Diameter = 0.875", Gap = 0.026"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{sec} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{sec} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
1-1 A Within TSP	1	1900	1967	89	1878	631	1.28	0.27	1.01	1.09	1.41	1.65	Average of 1, 2 & 3
	2	1892	1957	88	1869	630	1.43	0.27	1.01	1.08	1.56		
	3	2025	1908	80	1828	618	2.07	0.17	1.00	0.95	1.97		
	4	2074	2052	99	1953	631	1.66	0.16	1.01	1.07	1.79	1.67	Average of 4 & 5
	5	2069	2061	101	1960	613	1.7	0.08	1.00	0.91	1.55		
	6	2258	2171	110	2061	625	1.87	0.22	1.01	1.00	1.88	1.79	Average of 6 & 7
	7	2297	2151	116	2035	603	1.99	0.15	0.99	0.86	1.70		
	8	2302	2245	121	2124	617	1.98	0.16	1.00	0.94	1.86	1.86	
1-1 C Offset 0.15"	1	2328	2263	129	2134	622	2.12	0.25	1.01	0.96	2.05	2.21	Average of 1 & 2
	2	2346	2321	134	2187	633	2.25	0.37	1.01	1.04	2.37		
	3	2487	2406	160	2246	617	2.68	0.21	1.00	[illegible]	2.49	2.49	
	4	2526	2503	169	2334	631	2.71	0.17	1.01	1.00	2.74	2.80	Average of 4 & 5
	5	2540	2529	170	2359	643	2.59	0.2	1.02	1.08	2.85		
	6	2656	2671	210	2461	624	3.34	0.17	1.01	0.95	3.20	3.20	
	7	2678	2742	219	2523	638	3.32	0.16	0.98	1.01	3.29	3.29	
	8	2769	2829	229	2600	651	3.97	0.26	0.99	1.08	4.26	4.26	
	9	2751	2662	246	2418	605	4.1	0.19	0.95	0.87	3.40	-	Delete - Hysteresis
1-1 B Free Span	1	-	-	-	-	-	-	-	-	-	-	-	Bad Data
	2	2312	2342	293	2049	633	4.6	0.21	0.98	0.93	4.18	-	Delete - Hysteresis
	3	2303	2351	304	2047	612	5.11	0.34	0.96	0.82	4.02		
	4	2526	2655	322	2333	637	5.04	0.27	0.98	0.96	4.72	4.77	Average of 4, 6 & 7
	5	2568	2808	331	2477	651	4.98	0.15	0.99	1.03	5.12	5.12	
	6	2603	2651	347	2304	614	5.87	0.32	0.96	0.85	4.80	-	
	7	2585	2676	345	2331	626	5.48	0.15	0.97	0.90	4.77		
1-1 H Expanded 4250 psi Within TSP	1	2171	2130	183	1947	630	2.35	0.25	1.02	0.98	2.34	2.34	
	2	2255	2227	185	2042	643	2.74	0.17	1.04	1.10	3.13	3.13	
	3	2368	2361	[illegible]	2157	613	3.41	0.22	1.00	0.88	3.00	3.01	Average of 3 & 4
	4	2381	2396	199	2197	619	3.28	0.16	1.00	0.92	3.02		
	5	2529	2508	208	2300	612	3.4	0.12	1.00	0.89	3.03	3.18	Average of 5, 6 & 7
	6	2553	2497	201	2296	630	3.16	0.22	1.02	0.98	3.15		
	7	2577	2537	204	2333	639	3.19	0.16	1.03	1.03	3.38		
1-1 I Expanded 4250 psi Offset 0.15"	1	2447	2392	153	2239	618	2.48	0.15	1.00	0.94	2.33	2.33	
	2	2473	2394	151	2243	628	2.39	0.13	1.02	0.99	2.41	2.34	Average of 2 & 3
	3	2590	2434	154	2280	609	2.54	0.15	0.99	0.90	2.27		
	4	2599	2506	157	2349	621	2.45	0.13	1.01	0.95	2.35	2.35	
1-1 J Expanded 4250 psi Offset 0.15" RT	1	2348	1867	17	1850	70	1.51	0.1	0.81	0.51	1.46	1.46	
	2	2382	1926	17	1909	70	3.68	0.08	0.81	0.53	1.59	1.59	
	3	2479	2086	17	2069	70	3.74	0.1	0.81	0.58	1.77	1.79	Average of 3 & 4
	4	2493	2101	17	2084	70	3.8	0.08	0.81	0.59	1.81		
	5	2581	2254	18	2236	70	3.96	0.11	0.81	0.62	2.00	2.03	Average of 5 & 6
	6	2601	2269	18	2251	70	4.04	0.13	0.81	0.63	2.05		

TEST1-1.XLS 1-1 Table 7/25/95 4:03 PM

Test 1-1. Summary of Test Dimensional Measurement Results Specimen 8161G, Tube Dia. = 0.875", Gap = 0.026"											
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in²)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in²)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
None	0.0 Steps A, B	Initial Dim.	0°	0.620 OD(3) 0.626(4)	0.620 ID(3)	N.A.(2)	0.0	N.A.(2)	0.879	0.876 0.875
		Hot	0°	0.626(4)	0.494(4) (0.004W)	0.002[illegible]	0.0	N.A.	0.880	0.875 0.876
None	0.15 Steps C, D	Hot	0°	0.633(4)	0.595(4) (0.011W)	0.0045	0.147 (0.007W)	0.00074	0.884	0.880 0.875
None	Free Span Steps E, F	Hot	No change							
4250	0.0 Steps G, H	Hot	0°	0.633	0.595 (0.012W)	0.0052	0.0	0.0	0.888	0.881 0.875
4250	0.15 Step I	Hot	0°	0.633	0.595 (0.012W)	0.0052	0.147 (0.007W)	0.00074	0.888	0.881 0.875
4250	0.15 Step J	Cold	0°	0.633	0.595 (0.012W)	0.0054	0.147 (0.008W)	0.00088	0.888	0.876 0.874

Notes:
1. Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.745" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
2. Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
3. Crack lengths from dye penetrant tests.
4. Crack lengths from toolmaker's microscope. Minimum measurable TW crack opening ~0.001"

Test Plan IRBs
Test 1-1

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 thru wall 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 1-2: Summary of Test Results

Test Sequence

- Order of tests: zero offset, offset, freespan, bladder pressurization to 4080 psi, zero offset, offset and cold offset
  - One data point in the initial zero offset test was deleted as the ΔP was about 90 psi lower than a prior test result.
- Test results show consistent trends with modest fluctuations in the data - no basis to question data adequacy. The effective tube to TSP hole ID for this test was 0.013" compared to the target 0.025" based on the measured crack OD following the flow pressurization offset test.
- The specimen used for this test has been destructively examined (only specimen to date) to provide comparisons of crack lengths and depths made using the test methods with destructive exam results.

Summary of Test Results

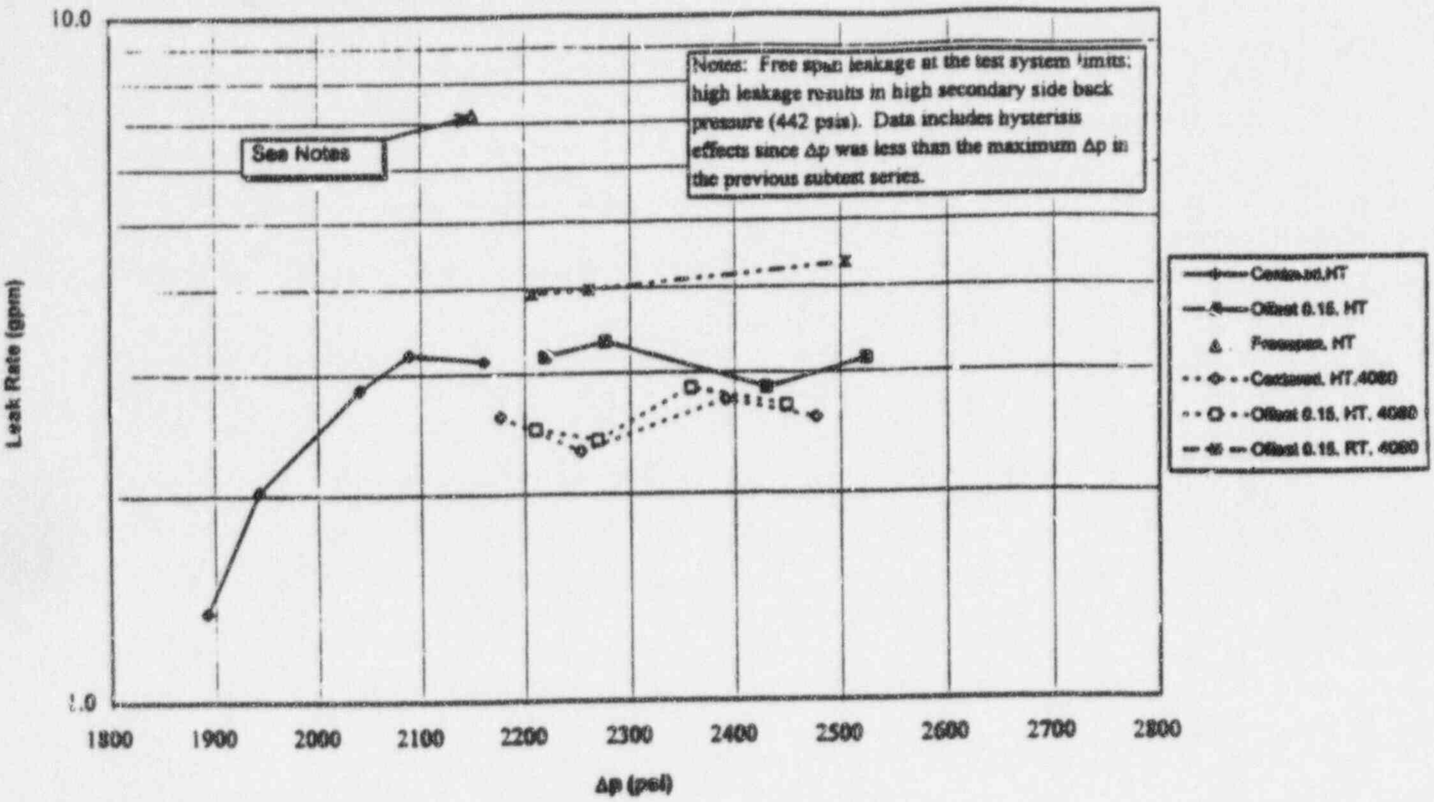
- The shallow slope of the leak rate curve above about 2250 psi shows interaction with the TSP reduces the leak rates.
  - The pressure causing interaction with the TSP would likely increase slightly if the crack to TSP gap was increased from the 0.013" test value to the target 0.025".
- The zero offset test up to 2160 psi shows no clear interaction with the TSP and is typical of free span behavior. A slight change in slope at 2160 psi could be indicative of near interaction but the changes are too small to draw conclusions.
- Maximum leak rate is about 3.2 gpm for the 0.15"offset test at SLB conditions prior to and after bladder pressurization
  - The plastic diametral increase at the center of the crack was 13 mils at the end of the test indicating that the tube to TSP at the crack was about 13 mils
  - There is essentially no increase in leakage as a result of the TSP offset condition
    - o Based on estimates given in Section 5, the effective crack area is about equal to the geometrical flow area available for leakage within the TSP and leakage would be expected to be limited by the effective crack area.
  - The offset test exposed 0.145" of TW crack with a maximum width of 0.009", i.e., almost the entire offset was TW
  - The measurable TW length increased from 0.574" to 0.666" during this test phase and the maximum crack width increased from 0.005" to 0.014"
    - o The crack opening area increased by almost a factor of four over this test phase while leakage was essentially constant. 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 over the test phase. The measurements of the crack diameter along the crack length 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.
- Free span leak rate of about 8 gpm at 2150 psi, although includes hysteresis effects at this lower pressure, is almost a factor of three higher than for offset test, which clearly demonstrates the benefits of TSP restraint.
- Bladder pressurization tests have leak rates slightly lower than obtained with flow pressurization and also show negligible difference between zero offset and offset test results.
  - Results consistent with expectations when crack opening area is less than the geometrical flow area for the crack within the TSP

- Crack dimensions by fractography following destructive examination of the specimen
  - Crack at start of leak testing was a uniform 0.645" throughwall (0.383" by corrosion, remaining by fatigue) compared to dye penetrant measurements of 0.640" OD, 0.620" ID
  - Final crack 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
  - Crack growth from all testing was 0.030" compared to 0.028" measured from in-process test measurements
  - Results for this specimen demonstrate that measurement techniques applied during the test phase are adequate

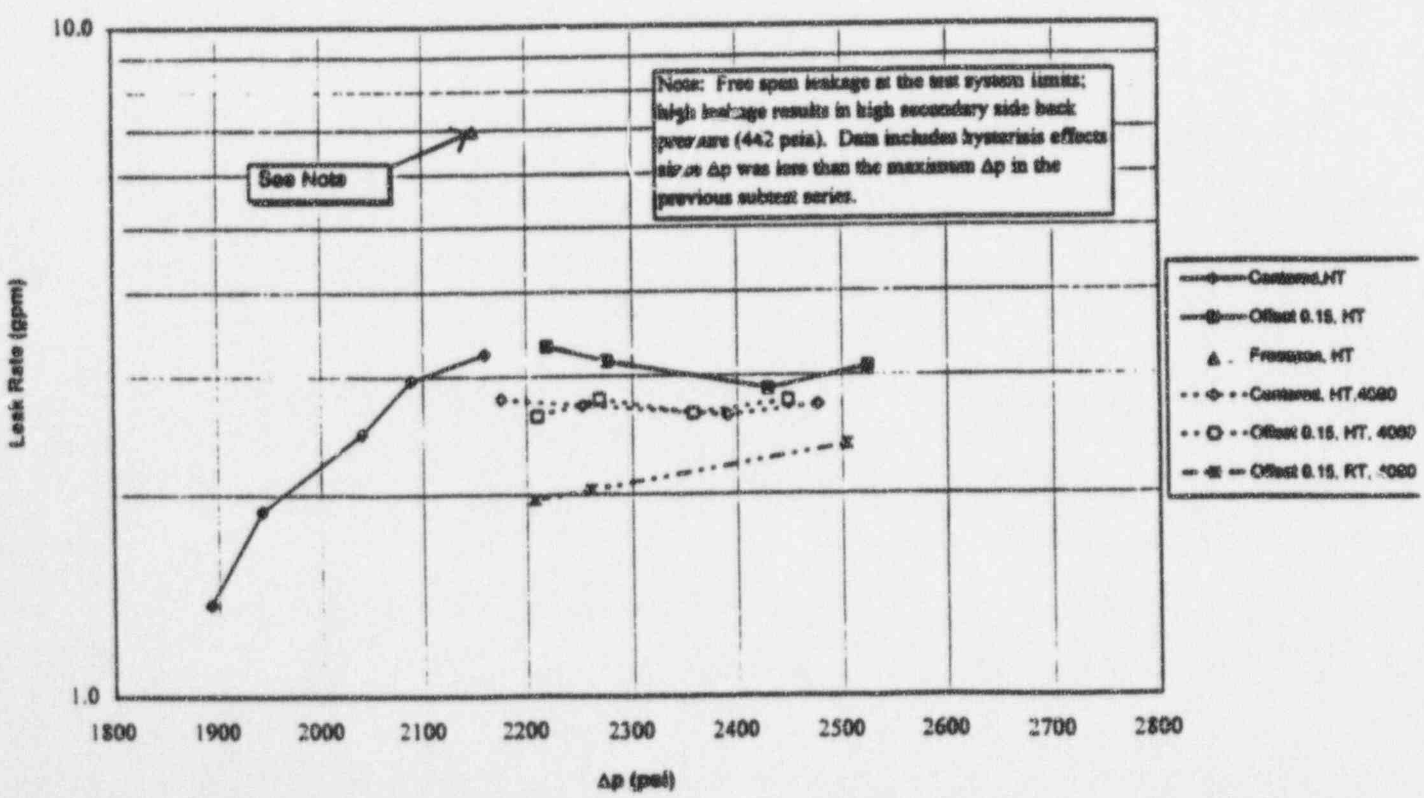
Overall Conclusions

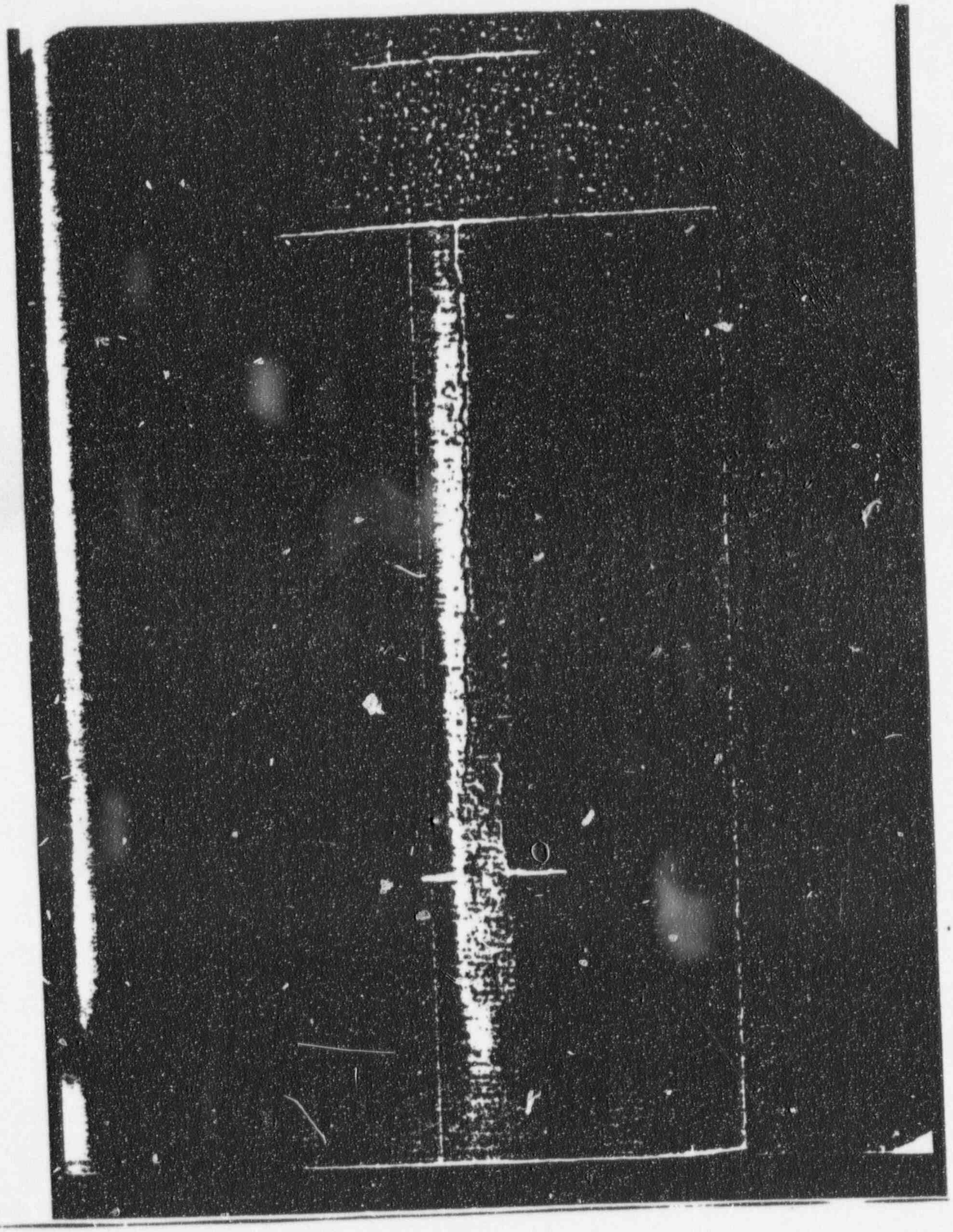
- The SLB leak rate for a 0.645" throughwall crack at the start of the test (0.675" TW at end of test by destructive exam) is limited to about 3.2 gpm in the offset or zero offset conditions prior to and after bladder pressurization.
  - The effective crack to TSP clearance for this test was limited to about 13 mils as indicated by the increase in crack diameter at the end of the test
- Destructive examination of the specimen following all testing demonstrates that the measurement techniques applied for crack dimensions before and during the test are adequate

Test 1-2
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)

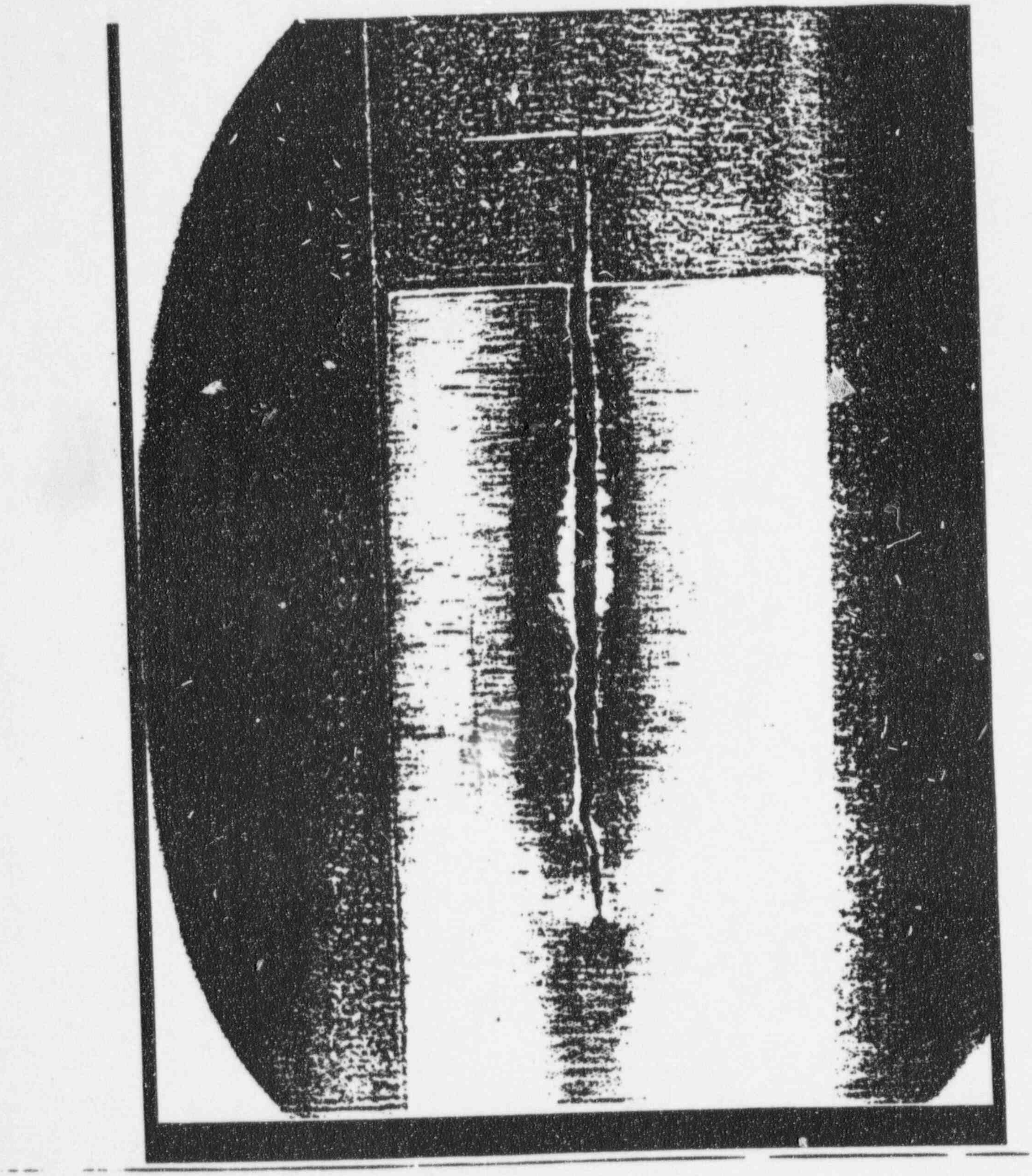


Test 1-2
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp=615°F and ps=15 psia Conditions)

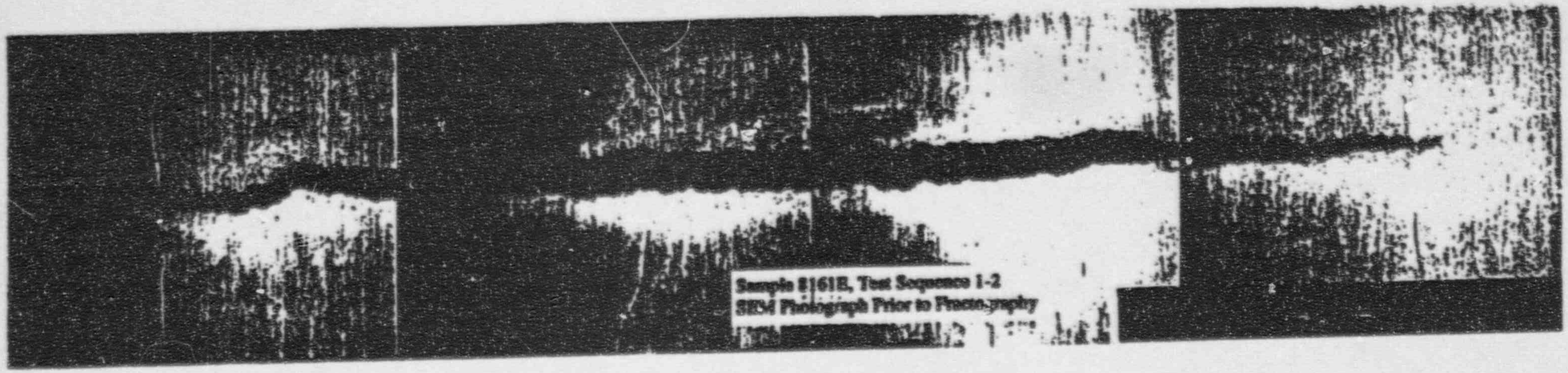




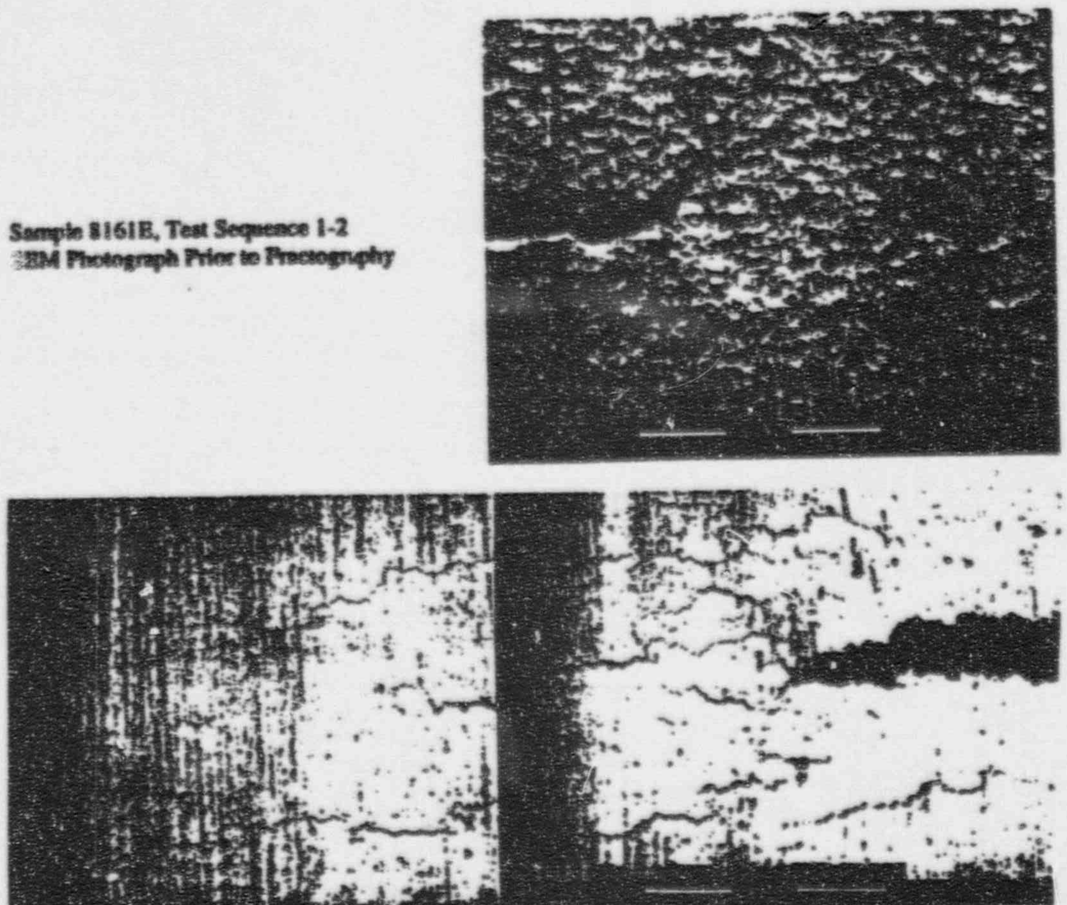
Test 1-2a. Prior to Leak Testing



Test 1-2b. After Offset Leak Test



Sample 8161E, Test Sequence 1-2
SEM Photograph Prior to Fractography



Sample 8161E, Test Sequence 1-2
SEM Photograph Prior to Fractography

Test 1 - 2
Summary of Leak Test and Analysis Results
Specimen 8161E, Tube Diameter = 0.874", Gap = 0.027"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{test} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
1-2A Within TSP	1	1892	1961	89	1872	622	1.24	0.13	1.01	0.98	1.22	1.37	Average of 1 & 2
	2	1931	2005	93	1912	627	1.46	0.13	1.01	1.03	1.52		
	3	1869	1909	89	1820	612	1.55	0.11	1.00	0.89	1.38	1.38	Delete - Hysteresis
	4	2022	2071	116	1955	627	1.93	0.17	1.01	1.01	1.96	1.89	Average of 4, 5 & 6
	5	2068	2048	122	1926	607	2.1	0.12	0.99	0.86	1.79		
	6	2072	2073	125	1948	619	2.05	0.1	1.00	0.93	1.92		
	7	2288	2213	173	2040	610	2.85	0.08	1.00	0.87	2.46	2.46	
	8	2324	2283	194	2089	621	3.21	0.12	1.00	0.92	2.96	2.96	
	9	2337	2356	196	2160	636	3.13	0.04	1.02	1.02	3.24	3.24	
1-2C Offset 0.15"	1	2312	2412	193	2219	637	3.18	0.11	1.02	1.03	3.32	3.32	
	2	2346	2464	206	2258	628	2.96	0.1	1.01	0.96	2.88	3.15	Average of 2 & 3
	3	2517	2528	235	2293	621	3.72	0.15	1.00	0.92	3.43		
	4	2665	2614	184	2430	631	2.85	0.08	1.01	0.99	2.87	2.87	
	5	2720	2728	198	2530	625	3.11	0.22	1.01	0.96	3.01	3.09	Average of 5, 6 & 7
	6	2780	2740	197	2543	639	2.99	0.18	1.02	1.03	3.13		
	7	2773	2715	212	2503	621	3.31	0.22	1.00	0.94	3.12		
1-2E Free Span	1	2387	2591	442	2149	646	7.21	0.44	1.03	0.94	6.98	6.98	
1-2H 4080 psi Expanded Within TSP	1	2374	2326	150	2176	635	2.6	0.24	1.03	1.04	2.77	2.77	
	2	2374	2404	152	2252	646	2.31	0.25	1.04	1.13	2.71	2.71	
	3	2643	2565	174	2391	621	2.74	0.22	1.01	0.95	2.62	2.62	
	4	2659	2649	173	2477	636	2.58	0.17	1.03	1.02	2.71	2.71	
1-2I Expanded 4080 psi Offset 0.15"	1	2379	2368	158	2210	634	2.49	0.11	1.02	1.03	2.62	2.62	
	2	2397	2426	158	2268	645	2.4	0.22	1.04	1.11	2.77	2.77	
	3	2672	2537	179	2358	616	2.85	0.15	1.00	0.92	2.64	2.64	
	4	2677	2624	175	2449	632	2.69	0.15	1.02	1.00	2.75	2.75	
1-2J RT Expanded 4080 psi Offset 0.15"	1	2358	2228	21	2207	70	3.93	0.04	0.81	0.62	1.97	1.97	
	2	2377	2281	21	2260	70	3.98	0.06	0.81	0.63	2.03	2.03	
	3	2673	2509	22	2487	70	4.34	0.07	0.81	0.67	2.36	2.37	Average of 3 & 4
	4	2678	2544	22	2522	70	4.31	0.05	0.81	0.68	2.37		

Test 1-2. Summary of Test Dimensional Measurement Results Specimen 8161E, Tube Dia. = 0.874", Gap = 0.027"										
Bladder Pressure (psi)	**Tube Offset (in.)**	**Test Temp. Condition**	**Angle**	**Total Crack Length (in.)**	**Total TW Length (Max. Width) (in.)**	**Total TW Area (in²)**	**Exposed TW Length (Max. Width) (in.)**	**Exposed TW Area (in²)**	**Max. Dia. (in.)**	**Min. Dia. (in.) Note 1**
None	0.0 Steps A, B	Initial Dim.	0°	0.640 OD(3) 0.645(4)	0.620 ID(3)	N.A.(2)	0.0	N.A.(2)	0.876	0.873 0.874
		Hot	0°	0.673(4)	0.574(4) (0.005W)	0.0017	0.0	N.A.	0.879	0.873 0.874
None	0.15 Steps C, D	Hot	0°	0.735(4)	0.666(4) (0.014W)	0.0065	0.145 (0.009W)	0.00087	0.887	0.882 0.875
None	Free Span Steps E, F	Hot	No change							
4080	0.0 Steps G, H	Hot	0°	0.735	0.666 (0.015W)	0.0073	0.0	0.0	0.887	0.873 0.874
4080	0.15 Step I	Hot	0°	0.735	0.668 (0.015W)	0.0078	0.085 (0.007W)	0.00051	0.888	0.882 0.874
4080	0.15 Step J	Cold	0°	0.735	0.668 (0.015W)	0.0079	0.085 (0.008W)	0.00055	0.888	0.880 0.874

Notes:
1. Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.874" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
2. Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
3. Crack lengths from dye penetrant tests.
4. Crack lengths from toolmaker's microscope. Minimum measurable TW crack opening ~0.001"

Test Plan for IRBs
Test 1-2

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 1-6: Summary of Test Results and Evaluation

Test Sequence

- Order of tests: zero offset, offset 0.1", freespan, bladder pressurization to 3220 psi, zero offset and offset 0.1". All tests are hot tests.
  - Freespan test, performed at lower ΔP than prior tests, includes hysteresis effects - test performed only to demonstrate magnitude of difference in leak rate between free span and crack within TSP
  - Data points below maximum ΔP of 2439 psi were deleted in zero offset test at end of test sequence and offset test at beginning of sequence
- Leak test results show consistent trends with modest fluctuations in data - no basis to question data adequacy. 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 pressurization offset test.

Summary of Test Results

- Shallow slope of leak rate versus ΔP curve above about 2000 psi indicates interaction with TSP and reduced leak rates
  - All slopes of leak rate curve are less than typical of free span slope
  - Pressurization to 2439 psi with the crack within the TSP opened the plastic crack width to a maximum of 0.024"
- Leak rates at SLB pressure differential with 0.10" offset are bounded by about 5.5 gpm prior to and after bladder pressurization
  - This test, performed with a 0.026" tube to TSP gap, resulted in the widest crack openings of all tests performed (except subsequent bladder pressurization for this specimen) with maximum crack opening widths of 0.044" inside the TSP and 0.024" outside the TSP
    - o This specimen was the only crack that was tight in the TSP collar following flow pressurization to about 2500 psi
  - The crack opening visible by light through the crack was 0.724" of the total 0.750" crack length and was more than 0.019" wide for > 0.6" length
  - Plastic deformation increased the crack opening diameter to the ID of the tube over about 0.25" at the center of the crack
  - Leak rate increased from about 3.1 gpm for zero offset to 5.5 gpm at completion of the offset test with the crack tip 0.10" outside the TSP. This range of leak rates includes increased crack opening due to higher ΔPs. At comparable ΔPs, the offset leak rate was about 30% higher than found for zero offset.
    - o Consistent with detectable (visible light through crack) increases in TW crack length (0.619" to 0.724"), maximum crack width (0.024" to 0.044") and crack opening area (factor of 2).
    - o Based on estimates in Section 5, the geometric flow area is less than the effective crack area for this test and an increase in leakage for the offset condition would be expected.
- Leak rates for the crack within the TSP and offset 0.1" following bladder pressurization to the free span burst pressure of about 3220 psi at 0.10" offset are approximately equal to that

obtained for 0.10" offset prior to bladder pressurization. The leak rate following bladder pressurization is approximately independent of the TSP offset position.

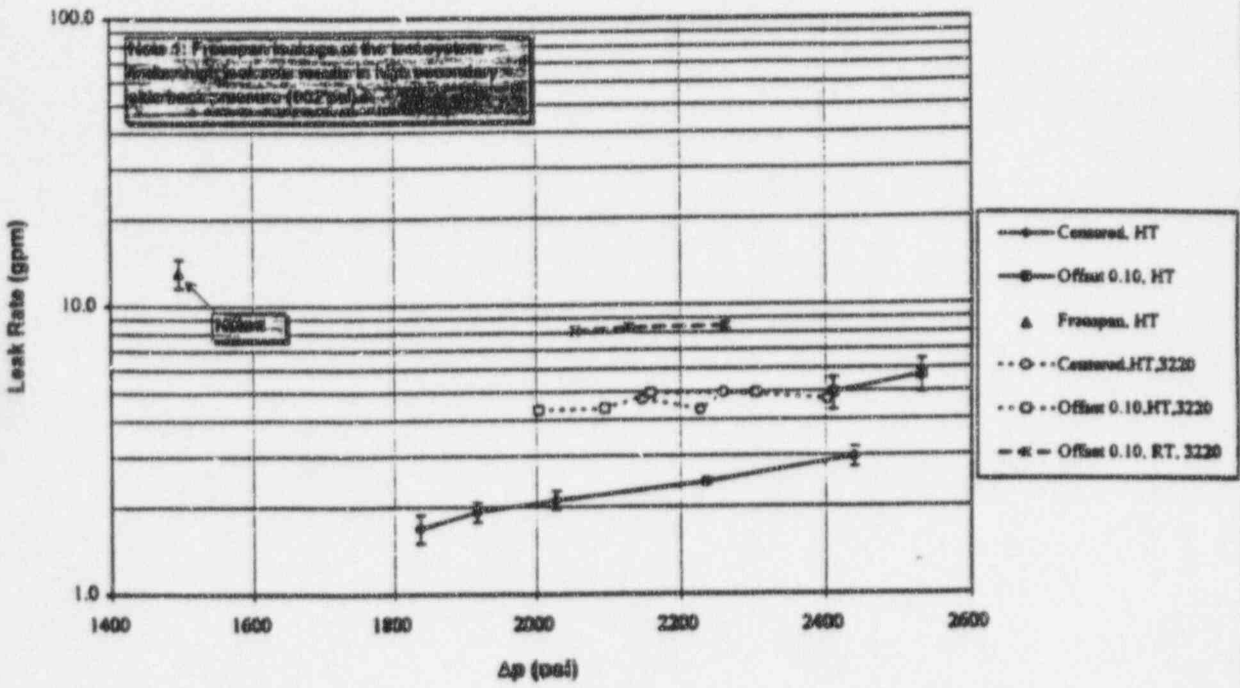
- The bladder pressurization had no significant influence on the leak rate even though the maximum plastic width increased from 0.044" to 0.050". However, the increased bladder pressurization did not significantly open the crack width at the ends of the crack

- The measured freespan leak rate of 13.1 gpm (facility limit) at a ΔP of 1495 psi following prior testing at 2530 psi is substantially higher than the 5.5 gpm obtained for the crack constrained by the TSP even though the pressure differential is much lower
  - The measured leak rate at 1495 psi is high due to hysteresis effects.

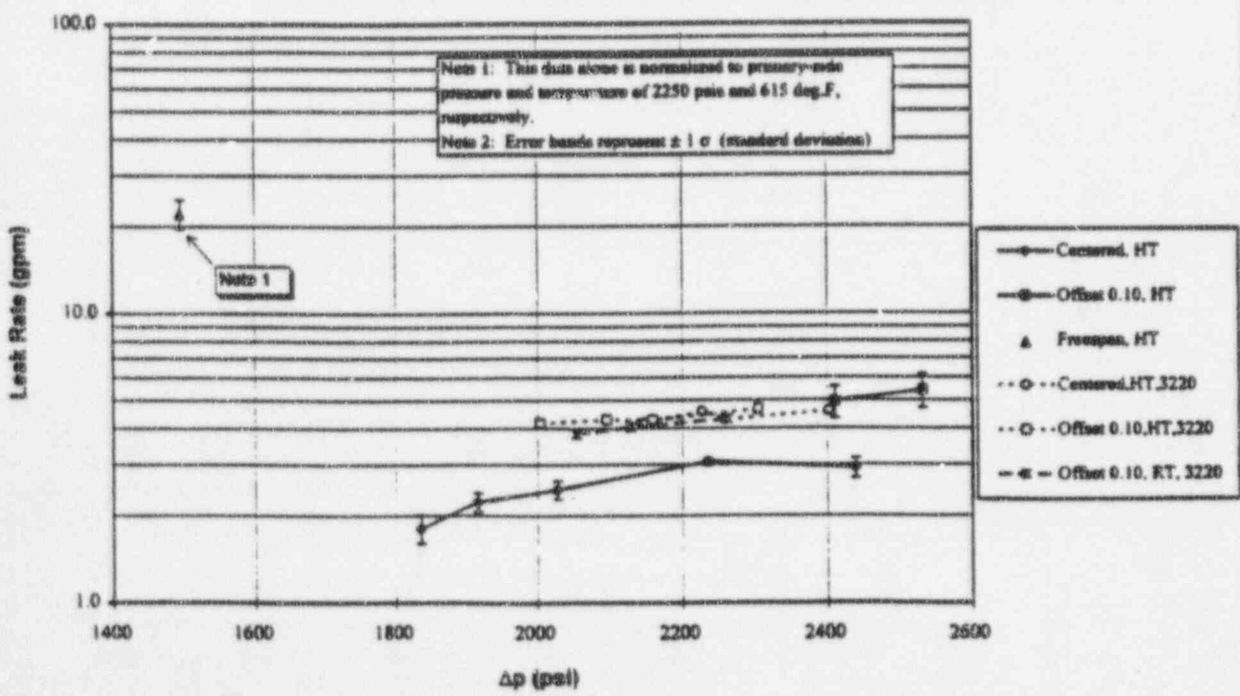
Overall Conclusions

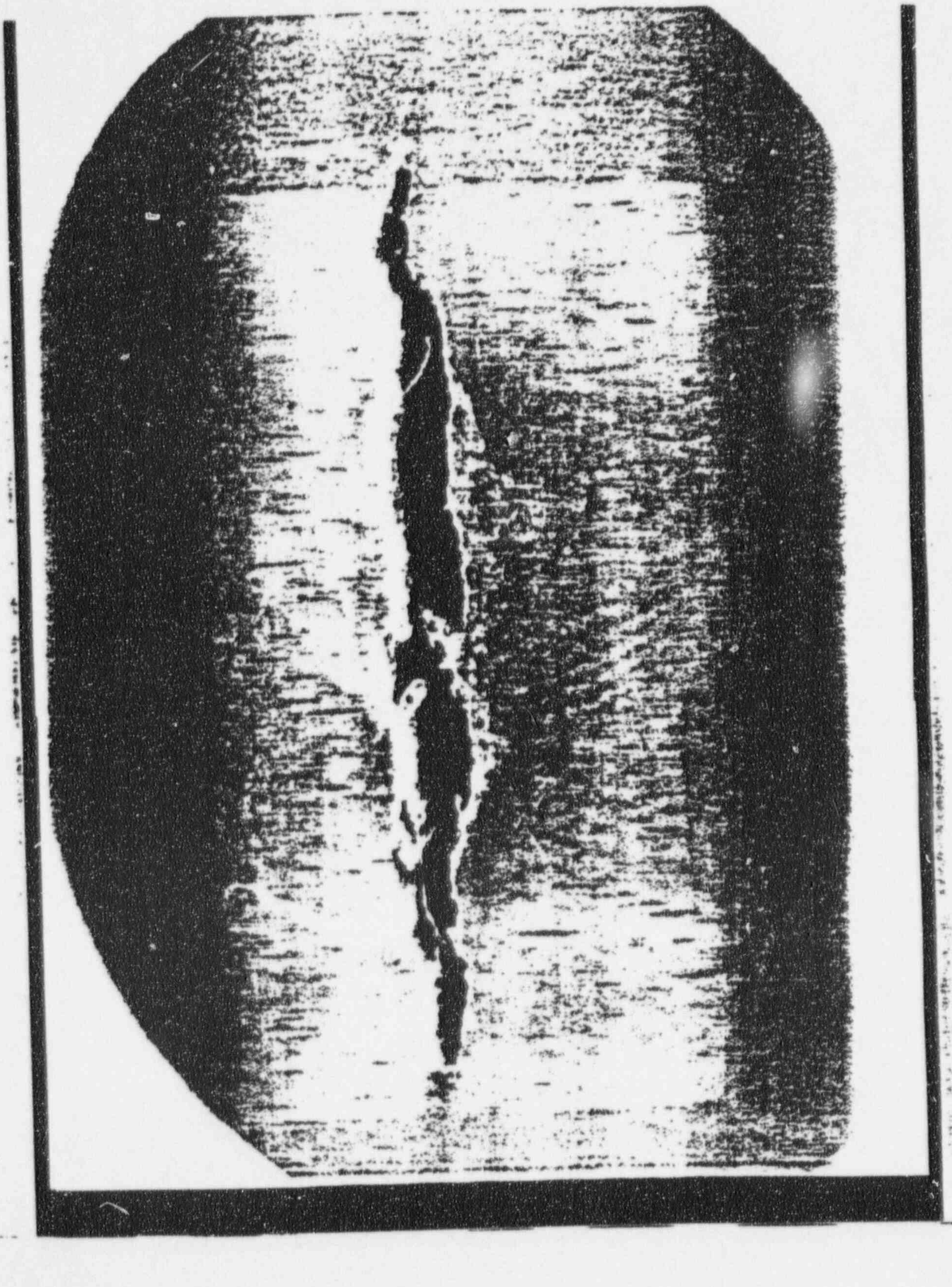
- This test of a 0.74" throughwall crack represents an upper bound leak test since throughwall lengths of this magnitude would not be expected even with the full APC repair limit with tube expansion of 10 to 15 volts
  - A repair limit of only 3.0 volts has been requested by ComEd for implementation of tube expansion at Braidwood-1 and Byron-1
  - A 0.74" TW length is larger than would ever be expected in field service even for a repair limit of about 15 volts as shown by European experience
- 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
- TSP constraint reduces the maximum SLB leak rate by more than a factor of three compared to free span conditions
- For this 0.74" TW indication prior to leak testing, the leakage results indicate the TSP interaction occurred at about 2000 psi ΔP

Test 1-6
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)



Test 1-6
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp=615 oF and Ps =15 psia conditions- except as noted)





Test 1-6. After Bladder Pressurization to 3320 psi and Leak Testing

Test 1 - 6
Summary of Leak Test and Analysis Results
Specimen 2008E, Tube Diameter = 0.745", Gap = 0.026"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{net} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{net} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure($\beta\gamma$) (gpm)	Average Leak Rate (gpm)	Comments
1-6A Within TSP	1	1848	1946	109	1837	630	1.69	0.19	1.01	1.06	1.81	1.81	
	2	1928	2045	125	1920	638	1.89	0.17	1.02	1.13	2.18	2.23	Average of 2 & 3
	3	1930	2041	126	1915	639	1.96	0.12	1.02	1.14	2.29		
	4	2044	2167	138	2029	639	2.06	0.18	1.02	1.10	2.32	2.46	Average of 4 &5
	5	2050	2172	146	2026	645	2.16	0.12	1.03	1.18	2.61		
	6	2258	2409	173	2236	655	2.44	0.06	1.04	1.21	3.07	3.07	
	7	2478	2650	211	2439	630	2.96	0.23	1.01	0.98	2.92	2.92	
	8	2364	2461	204	2257	632	3.20	0.12	1.01	0.99	3.20	-	Delete - Hysteresis
	9	2388	2447	212	2235	611	3.53	0.21	1.00	0.88	3.10	-	Delete - Hysteresis
	10	2370	2493	220	2273	623	3.45	0.12	1.01	0.93	3.23	-	Delete - Hysteresis
1-6B Offset 0.10"	1	2272	2511	252	2259	648	3.85	0.36	1.03	1.07	4.25	-	Delete - Hysteresis
	2	2294	2524	254	2270	663	3.45	0.49	1.05	1.25	4.54	-	Delete - Hysteresis
	3	2326	2493	287	2206	631	4.78	0.71	1.01	0.94	4.53	-	Delete - Hysteresis
	4	2554	2692	290	2402	648	4.66	0.53	1.03	1.04	4.99	4.95	Average of 4 & 5
	5	2568	2736	316	2420	629	5.23	0.93	1.01	0.93	4.91		
	6	2732	2877	334	2543	635	5.64	0.52	1.02	0.93	5.46	5.42	Average of 6 & 7
	7	2710	2868	347	2521	630	5.74	0.71	1.01	0.93	5.39		
1-6C Freespan	1	1520	2397	902	1495	646	13.05	1.51	1.03	1.65	22.16	22.16	
1-6F Expanded 3220 psi Within TSP	1	2272	2490	253	2237	650	4.37	0.77	1.05	1.09	4.99	4.57	Average of 1,2 & 4
	2	2292	2518	284	2234	646	4.10	0.44	1.04	1.03	4.42		
	3	2386	2446	298	2148	622	4.72	0.80	1.01	0.88	4.19	4.19	
	4	2396	2509	296	2213	631	4.53	0.56	1.02	0.93	4.31	-	
	5	2524	2563	306	2257	616	4.89	0.43	1.00	0.87	4.24	4.28	Average of 5 & 7
	6	2582	2702	299	2403	634	4.70	0.80	1.02	0.96	4.60	4.60	
	7	2536	2579	315	2264	613	5.07	0.06	1.00	0.85	4.32	-	
1-6G Expanded 3220 psi Offset 0.10"	1	2106	2245	265	1980	639	4.19	0.21	1.03	0.99	4.29	4.17	Average of 1 & 2
	2	2226	2305	277	2028	626	4.46	0.12	1.01	0.90	4.05		
	3	2362	2387	292	2095	636	4.37	0.14	1.03	0.96	4.28	4.28	
	4	2370	2464	305	2159	618	4.95	0.16	1.00	0.86	4.27	4.27	
	5	2580	2610	310	2300	633	4.94	0.07	1.02	0.94	4.76	4.66	Average of 5 & 6
	6	2560	2636	327	2309	611	5.41	0.11	1.00	0.85	4.57		
1-6H Expanded 3220 psi Offset 0.10", RT	1	2285	2109	55	2054	75	8.14	0.23	0.81	0.58	3.82	3.82	
	2	2416	2187	58	2129	75	8.34	0.18	0.81	0.60	4.05	4.05	
	3	2571	2323	62	2261	75	8.46	0.26	0.81	0.63	4.32	4.31	Average of 3 & 4
	4	2576	2323	61	2264	75	8.42	0.32	0.81	0.63	4.30		

TEST1-6.XLS 1-6 Table 7/23/95 4:11 PM

Test 1-6. Summary of Test Dimensional Measurement Results
Specimen 2008E, Tube Dia. = 0.745", Gap = 0.026"

Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in²)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in²)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
None	0.0 Steps A, B	Initial Dim.	- 0°	0.735 OD(3) 0.738(4)	0.760 ID(3)	N.A.(2)	0.0	N.A.(2)	0.746	N.A.(2)
		Hot	0°	0.738(4)	0.619(4) (0.024W)	0.0118	0.0	N.A.	0.760	0.743 0.747
None	0.10 Steps C, D	Hot	0°	0.751(4)	0.724(4) (0.044W)	0.0249	0.070 (0.024W)	0.0013	0.772 Tight in collar	0.765 0.741
None	Free Span Steps E, F	Hot		Not measured						
3220	0.0 Steps G,H	Hot	0°	0.750	0.726 (0.050W)	0.0257	0.004 (0.003W)	0.000012	0.773 Tight	0.752 0.755
3220	0.10 Step I	Hot	0°	0.756	0.726 (0.052W)	0.0262	0.070 (0.025W)	0.0016	0.772 Tight	0.765 0.742
3220	0.10 Step J	R.T.		Not measured						

Notes:
1. Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.745" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
2. Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
3. Crack lengths from dye penetrant tests.
4. Crack lengths from toolmaker's microscope. Minimum measurable TW crack opening ~0.001"

Test Plan for IRBs
Test 1-6

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 1-7: Summary of Test Results

Test Sequence

- Order of tests: zero offset, offset, bladder pressurization at 2970 psi with 0.10" offset, offset and zero offset. All tests are hot tests.
  - Initial data point in offset test deleted due to ΔP below prior test at 2382 psi.
- Leak test results show consistent trends with modest fluctuations in data - no basis to question data adequacy. However, the effective crack to TSP hole ID clearance for this test was 0.020" based on the crack diameter at the end of the flow pressurization offset test rather than the target 0.025".

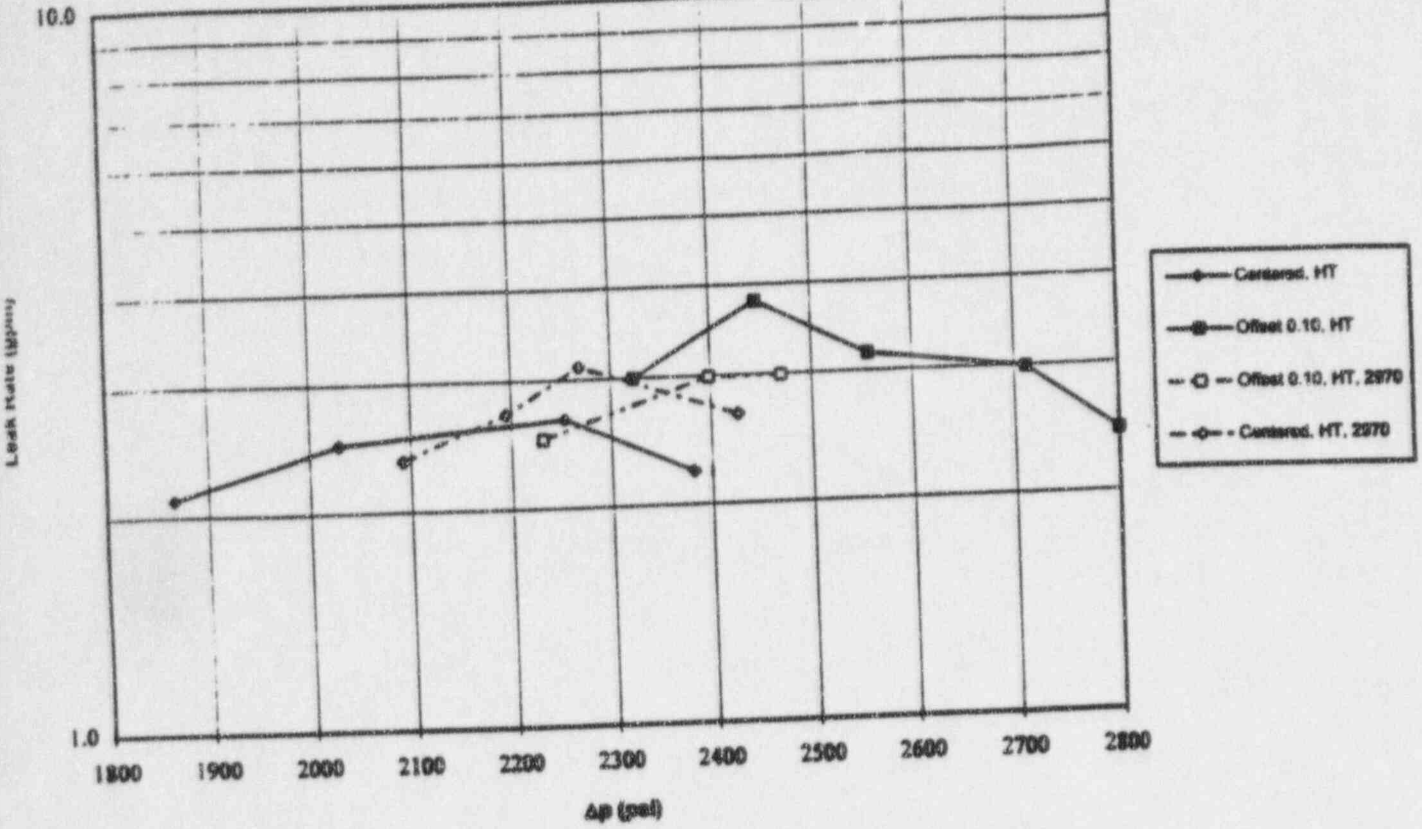
Summary of Test Results

- Shallow slope of leak rate versus ΔP curve above 2200 psi shows interaction with TSP reduces leak rates
  - Initial slope of leak rate curve up to 2030 psi test point is more typical of free span slope
  - Pressurization to 2380 psi with zero offset opened the plastic crack width to a maximum of 0.011"
- Maximum leak rate is 4.1 gpm for offset condition at SLB conditions prior to and after bladder pressurization
  - 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.
    - o Based on estimates in Section 5, the effective crack area should be smaller than the geometric flow area for the offset test and the offset test leakage would not be expected to be significantly higher than the zero offset leakage. For tests that can be compared, Test 1-7 is the only test for which the more limiting of the effective crack area or geometrical flow area may not be consistent with the difference in zero offset and offset leak rates.
  - The maximum ΔP of 2800 psi resulted in a maximum crack width of 0.014"
- Following bladder pressurization to 2970 psi (under the free span burst pressure of about 3900 psi), the leak rates are approximately independent of the crack offset condition and about the same as obtained with zero offset prior to bladder pressurization and less than the maximum 4.2 gpm leak rate
  - 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 (diameter measurements indicate about 0.2")
  - The lack of leak rate dependence on the crack offset position indicates that leakage is more dependent on effective crack area than on geometrical flow restrictions. This is expected since the crack area is less than the geometrical flow area.

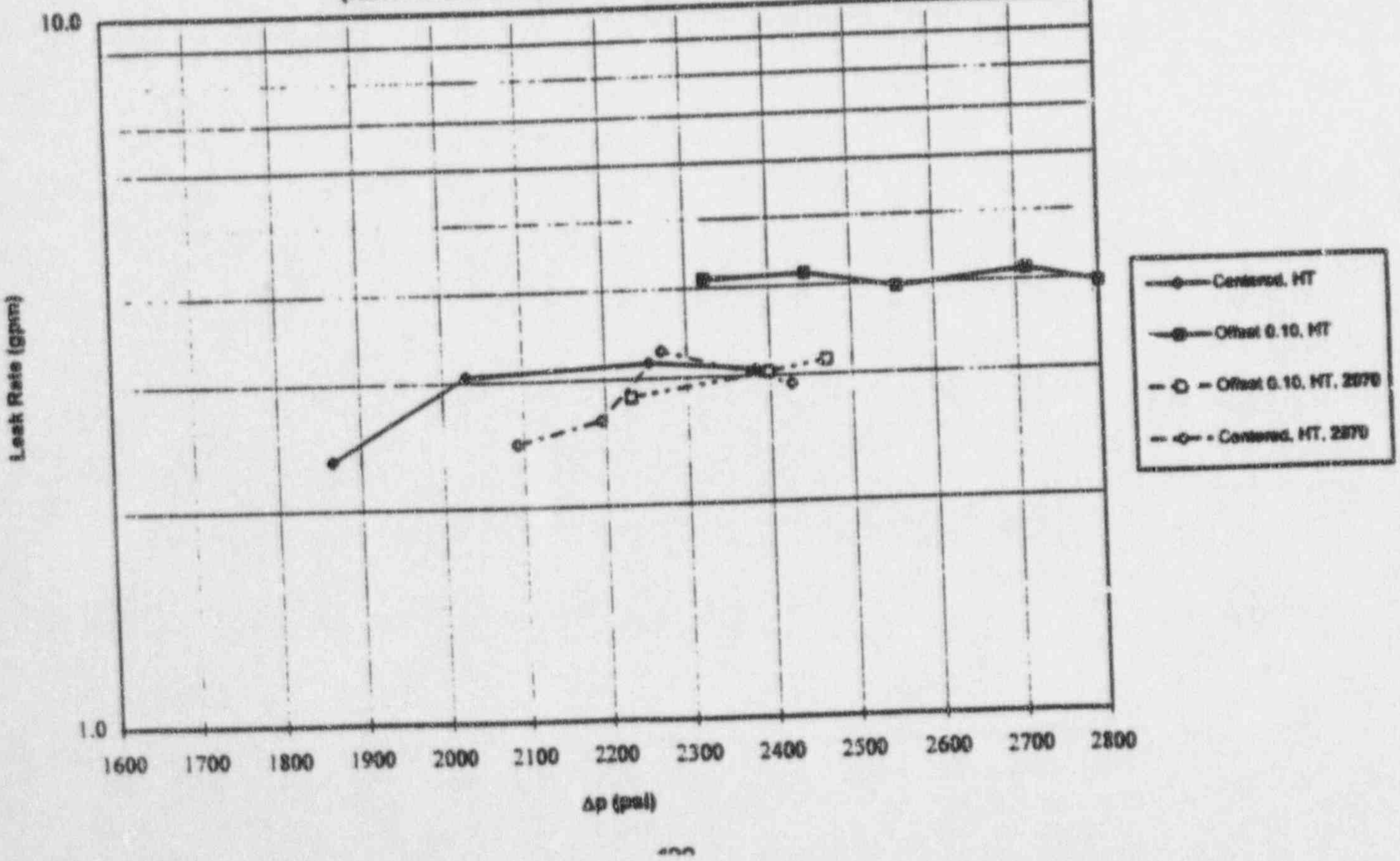
Overall Conclusions

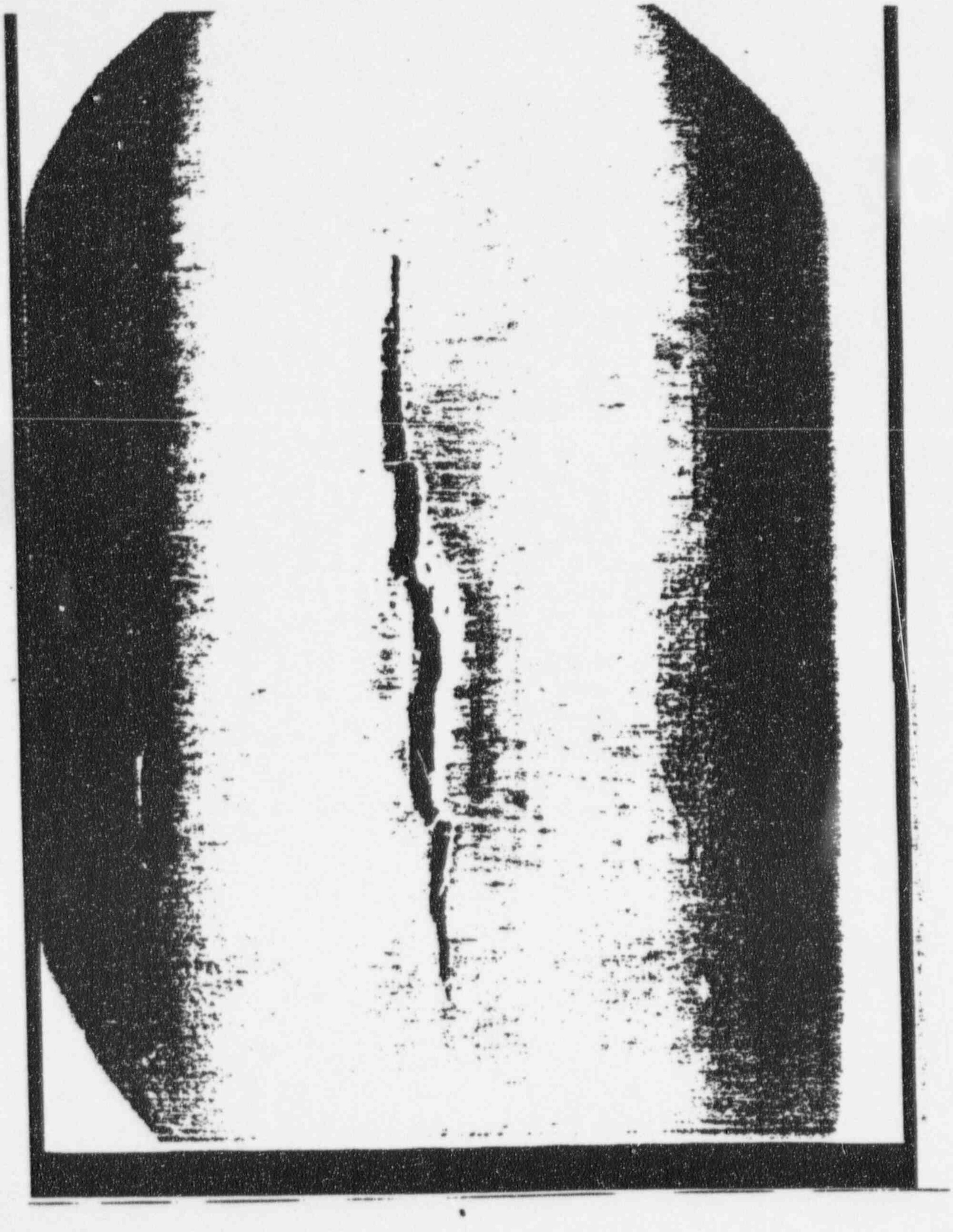
- The SLB leak rate for 0.6" TW crack at start of test (0.613" at end of test) is limited to about 4.2 gpm prior to and after bladder pressurization
  - The effective crack to TSP clearance for this test was 0.020" based on the crack diameter at the end of the offset flow test.
- Large (> about 0.5") 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 2200 psi and higher
- 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

Test 1-7
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)



Test 1-7
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp=615°F and ps=15 psia Conditions)





Test 1-7. After Bladder Expansion to 2970 psi and Leak Testing

Test 1 - 7
Summary of Leak Test and Analysis Results
Specimen 2051A, Tube Diameter = 0.747", Gap = 0.026"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{est} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{est} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure($\beta\gamma$) (gpm)	Average Leak Rate (gpm)	Comments
1-7A Within TSP	1	1948	1976	134	1842	635	1.99	0.18	1.02	1.09	2.21	2.35	Average of 1 & 2
	2	1898	2027	139	1888	636	2.23	0.21	1.02	1.09	2.48		
	3	2024	2170	151	2019	647	2.48	0.19	1.03	1.20	3.07	3.06	Average of 3 & 4
	4	2048	2192	152	2040	647	2.48	0.23	1.03	1.19	3.05		
	5	2284	2424	169	2255	650	2.65	0.17	1.03	1.15	3.16	3.16	
	6	2392	2521	139	2382	664	2.22	0.09	1.05	1.31	3.07	3.07	
1-7B Offset 0.10"	1	2162	2343	210	2133	641	3.6	0.37	1.02	1.05	3.86	-	Delete - Hysteresis
	2	2309	2536	239	2297	666	2.7	0.44	1.06	1.27	3.62	4.11	Average of 2 & 3
	3	2370	2584	236	2348	670	3.29	0.19	1.06	1.31	4.60		
	4	2482	2684	239	2445	648	3.79	0.51	1.03	1.06	4.16	4.16	
	5	2614	2769	215	2554	658	3.18	3.18	1.04	1.14	3.77	3.96	Average of 5 & 6
	6	2602	2782	223	2559	669	3.16	0.22	1.06	1.24	4.15		
	7	2824	2924	212	2712	677	2.99	0.3	1.08	1.29	4.14	4.14	
	8	2836	3001	201	2800	690	2.43	0.21	1.13	1.44	3.96	3.96	
1-7F Expanded 2970psi Offset 0.10"	1	2348	2471	217	2254	652	2.31	0.27	1.05	1.13	2.76	2.83	Average of 1 & 2
	2	2322	2409	198	2211	641	2.67	0.33	1.03	1.05	2.90		
	3	2632	2613	212	2401	636	2.86	0.45	1.03	1.01	2.95	3.04	Average of 3 & 4
	4	2622	2602	206	2396	631	3.12	0.1	1.02	0.98	3.13		
	5	2598	2666	197	2469	638	2.99	0.5	1.03	1.02	3.15	3.15	
1-7G 2970 psi Expanded Within TSP	1	2130	2328	236	2092	639	2.35	0.13	1.03	1.01	2.46	2.46	
	2	2338	2384	126	2258	649	2.595	0.19	1.05	1.18	3.21	3.28	Average of 2 & 5
	3	2304	2334	139	2195	623	2.7	0.09	1.01	0.97	2.64	2.64	
	4	2544	2565	139	2426	640	2.65	0.12	1.03	1.07	2.92	2.92	
	5	2542	2531	249	2282	622	3.65	0.14	1.01	0.91	3.35	-	

TEST1-7.XLS 1-7 Table 7/23/95 4:44 PM

Test 1-7. Summary of Test Dimensional Measurement Results
Specimen 2051A, Tube Dia. = 0.747", Gap = 0.026"

Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in^2)	Exposed TW Length Max. Width) (in.)	Exposed TW Area (in^2)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
None	0.0 Steps A, B	Initial Dim.	0°	0.60 ID (3)	0.58 OD(3)	N.A.(2)	0.0	N.A.(2)	0.748	0.747 0.748
		Hot	0°	0.609(4)	0.530(4) (0.011W)	0.0043	0.011 (.005W)	0.000055	0.759	0.749 0.748
None	0.10 Steps C, D	Hot	0°	0.621	0.602 (0.014W)	0.0071	0.091 (~.007W)	0.00064	0.767	0.755 0.745
2970	0.10 Steps E, F	Hot	0°	0.625	0.613 (0.022W)	0.0087	0.100 (~.011W)	0.00087	0.766	0.756 0.747
2970	0.00 Step G	Hot	0°	0.625	0.613 (0.022W)	0.0090	0.0	0.0	0.764	0.748 0.746

Notes:
1. Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.747" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
2. Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
3. Crack lengths from dye penetrant tests.
4. Crack lengths from toolmaker's microscope. Minimum measurable TW crack opening ~0.001"

Test Plan for IRBs
Test 1-7

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 2-1: Summary of Test Results

Test Sequence

- Order of tests: zero offset, free span, offset, offset cold, bladder pressurization at 4500 psi with 0.15" offset, offset, zero offset, offset cold.
- One data point in the offset flow test was deleted due to ΔP below prior test at 2266 psi.
- Leak test results show consistent trends with modest fluctuations in the data - no basis to question data adequacy. However, the effective crack to TSP hole ID 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.

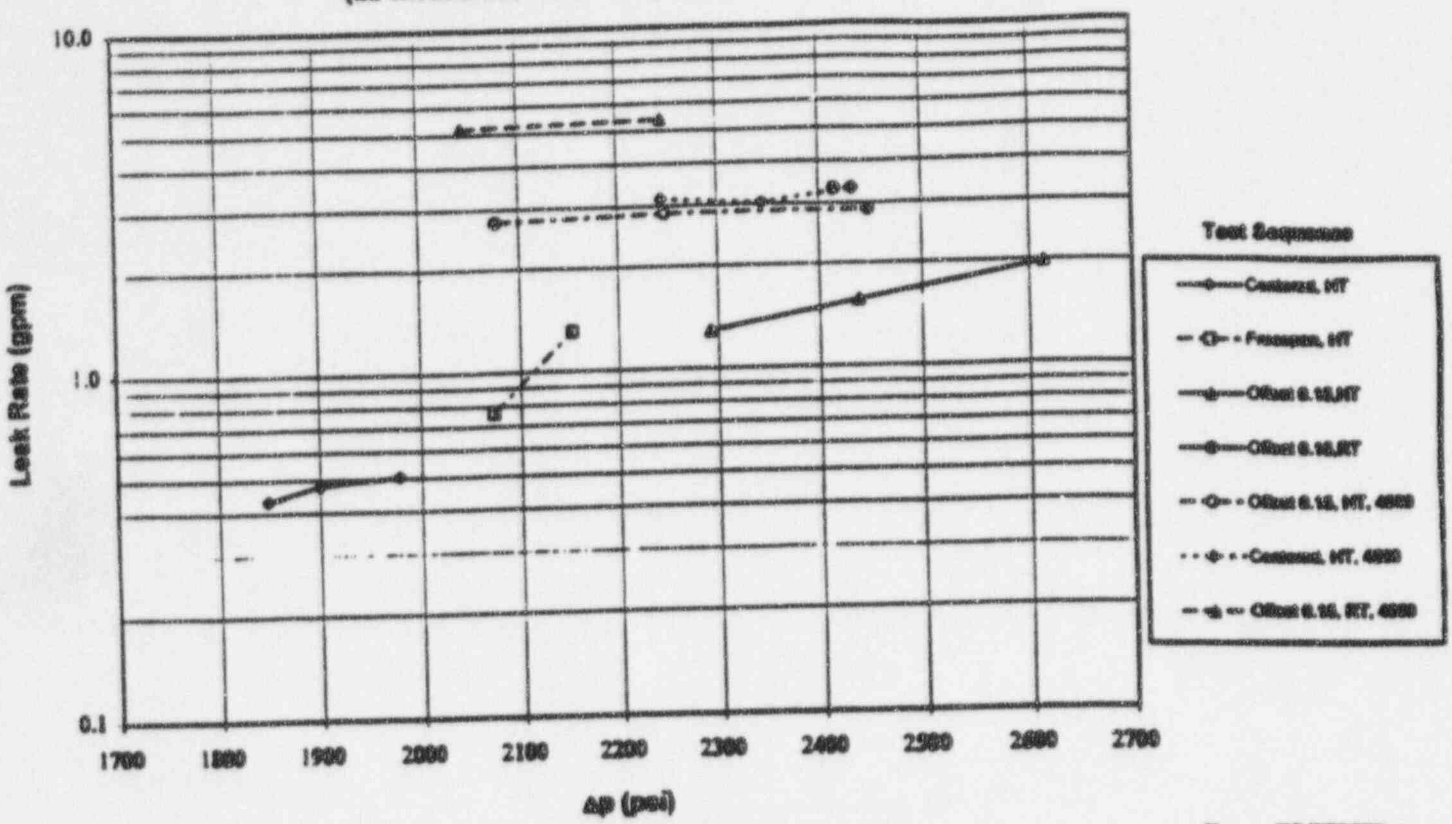
Summary of Test Results

- Shallow slope of leak test results above 2300 psi shows interaction with the TSP reduces leak rates.
  - Interaction with the TSP occurred between 1900 and 2300 psi but cannot be further refined as free span leak rates were performed between these two pressures.
  - The small crack to TSP gap of 0.010" for this test likely resulted in crack interaction with the TSP at a lower pressure than would have been obtained with the bounding 0.025" gap.
- The offset condition resulted in a SLB leak rate of about 1.7 gpm at 2560 psi for this 0.52" throughwall crack at the start of the test.
  - Pressurization to 2624 psi in the flow offset test opened the plastic crack width to a maximum of 0.010"
  - The offset leak rate at 2300 psi is about equal to the free span leak rate at 2150 psi, which demonstrates that the TSP reduced the leak rate significantly compared to that expected for a free span indication.
- Following bladder pressurization to the free span burst pressure of about 4500 psi, the SLB leak rate increased from about 1.7 gpm prior to bladder pressurization to about 3.1 gpm and the leak rates are approximately independent of the crack offset condition.
  - Even though the offset test exposed a 0.132" TW crack, there is no significant difference in leakage between the leak rates for the offset and zero offset tests following bladder pressurization. From the trend analyses of Section 5, the effective crack area is slightly smaller than the geometric flow area following bladder pressurization and 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 15% compared to the flow offset test which is less than expected for the more significant increase in leak rate.

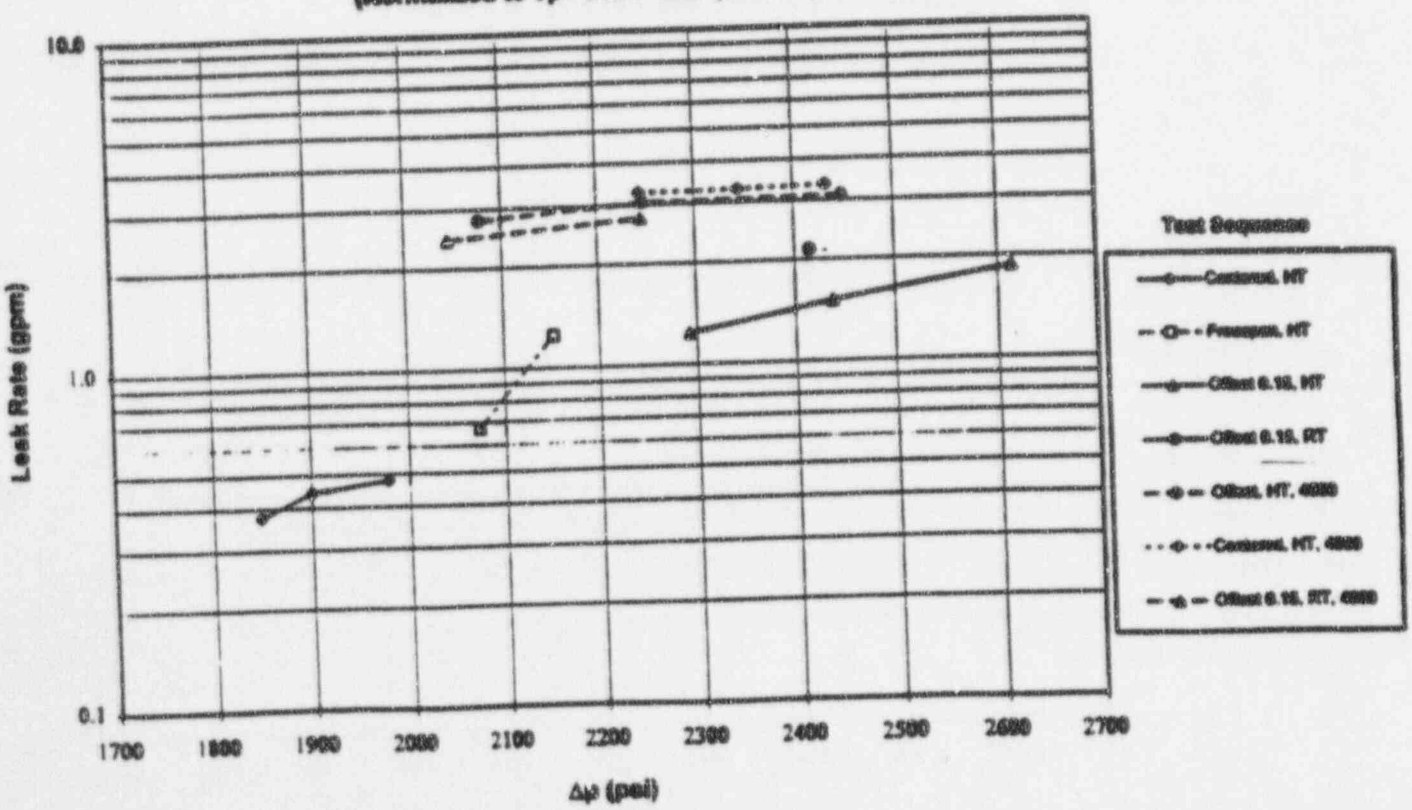
Overall Conclusions

- The SLB leak rate for this 0.52" TW crack at the start of the test is limited to about 1.7 gpm prior to bladder pressurization and 3.1 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.
- This 0.52" TW crack demonstrated interaction with the TSP between 1900 and 2300 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 higher pressure differentials.

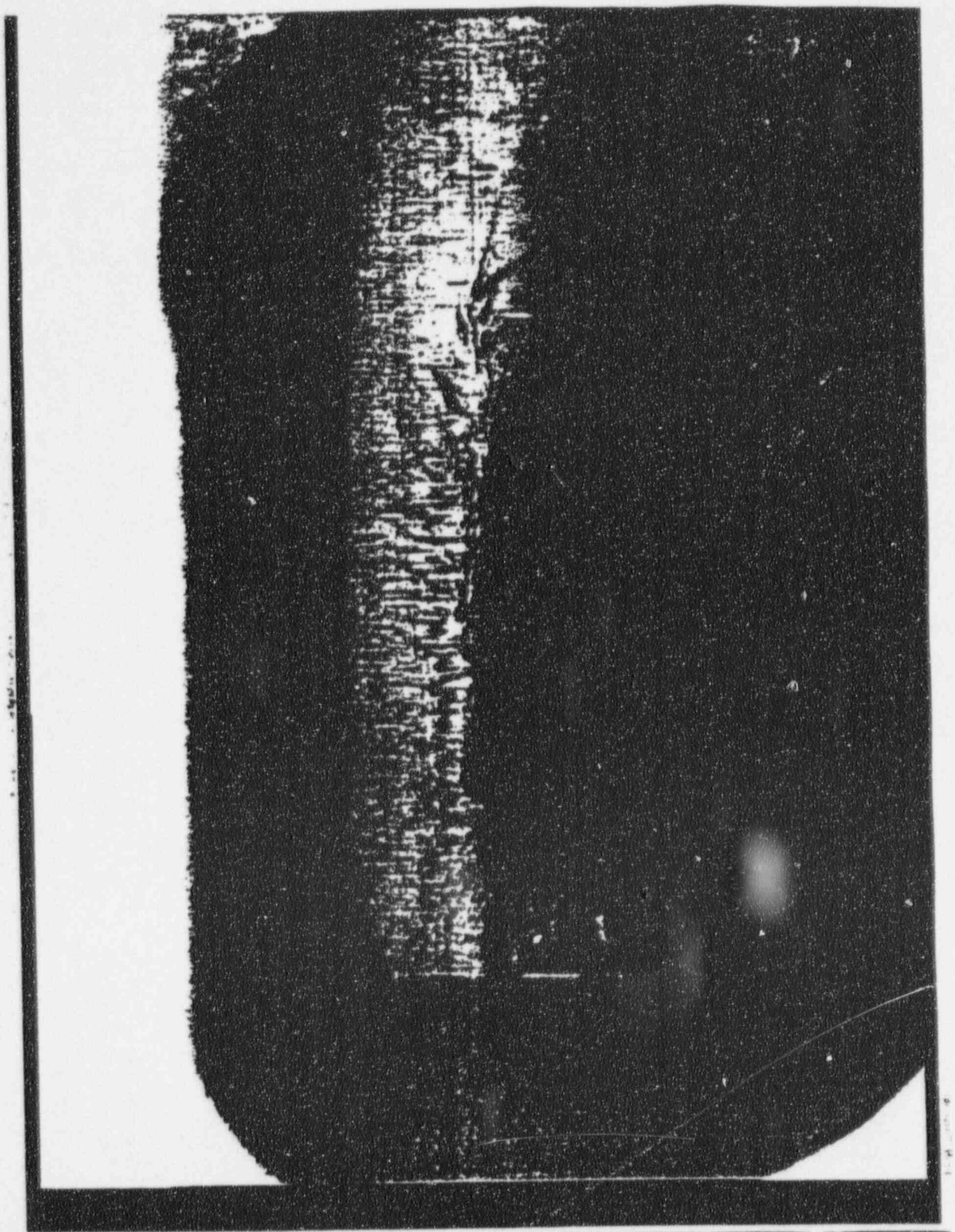
Test 2-1
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)



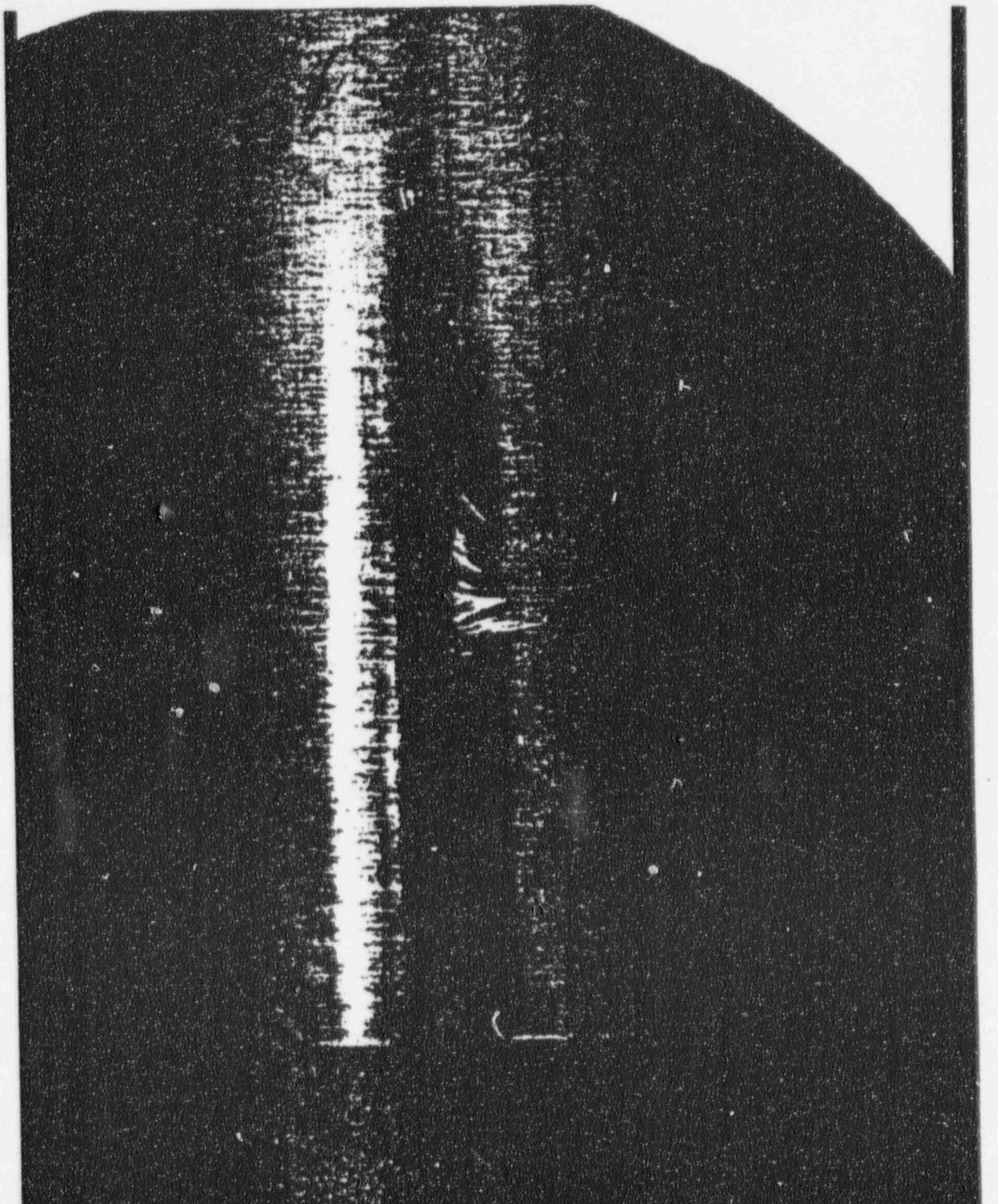
Test 2-1
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp= 615°F and ps = 15 psia Conditions)



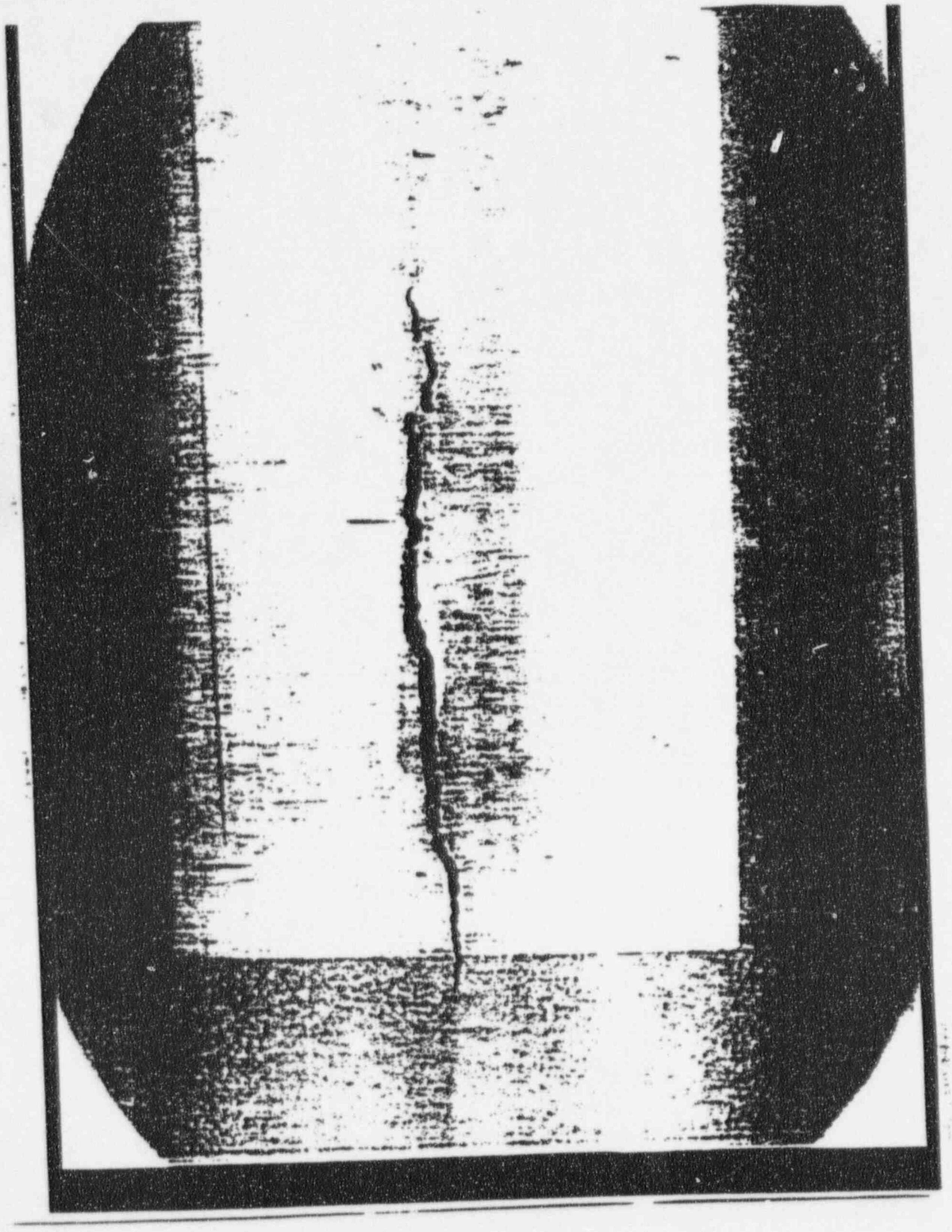
T C1



Test 2-1a. After Zero Offset Leak Test



Test 2-1b. After Free Span Leak Test



Test 2-1c. After Offset Flow Test

Test 2 - 1
Summary of Leak Test and Analysis Results
Specimen 8161A, Tube Diameter = 0.874", Gap = 0.027"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{max} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
2-1A Within TSP, HT	1	1872	1877	22	1855	605	0.38	0.06	0.99	0.90	0.34	0.38	Average of 1, 2 & 5
	2	1872	1863	17	1846	606	0.44	0.03	0.99	0.91	0.40	-	
	3	1839	1710	13	1697	600	0.43	0.02	0.99	-	-	-	Delete - Hysteresis
	4	1916	1917	17	1900	608	0.48	0.19	1.00	0.93	0.44	0.44	
	5	1903	1859	17	1842	594	0.48	0.06	0.99	0.83	0.39	-	
	6	2006	1981	23	1958	608	0.50	0.05	1.00	0.93	0.46	0.48	Average of 6 & 7
	7	2018	2022	25	1997	614	0.51	0.12	1.00	0.97	0.50		
2-1B Free Span, HT	1	2152	2122	39	2083	590	0.80	0.38	0.98	0.85	0.67	0.67	Average of 1 & 2
	2	2167	2098	36	2062	607	0.73	0.16	0.99	0.93	0.67		
	3	2331	2216	63	2153	608	1.16	0.07	1.00	0.93	1.07	1.25	Average of 3 & 4
	4	2322	2216	63	2153	619	1.45	0.17	1.00	0.99	1.43		
2-1C Offset 0.15", HT	1	2335	2333	67	2266	618	1.14	0.14	1.00	0.98	1.12	1.24	Average of 1 & 3
	2	2326	2222	60	2162	630	1.05	0.13	1.01	1.07	1.13	-	Delete - Hysteresis
	3	2534	2402	84	2318	612	1.44	0.15	1.00	0.95	1.36	-	
	4	2578	2490	94	2396	623	1.53	0.08	1.01	0.99	1.53	1.51	Average of 4, 5 & 6
	5	2725	2528	99	2429	609	1.62	0.07	1.00	0.93	1.51		
	6	2763	2582	93	2489	619	1.54	0.07	1.00	0.98	1.51		
	7	2972	2724	120	2604	607	1.98	0.1	0.99	0.93	1.83	1.87	Average of 7 & 8
	8	2946	2749	125	2624	619	1.98	0.11	1.00	0.97	1.92		
2-1D Offset 0.15", RT	1	2946	2433	12	2421	75	3.28	0.08	0.98	0.66	2.12	2.13	Average of 1, 2, 3 & 4
	2	2994	2440	12	2428	75	3.30	0.1	0.98	0.66	2.13		
	3	3145	2420	13	2407	75	3.33	0.11	0.98	0.66	2.14		
	4	3086	2419	14	2405	75	3.34	0.11	0.98	0.66	2.15		
2-1G Expanded, 4500 Offset 0.15", HT	1	2189	2260	183	2077	631	2.75	0.21	1.02	0.99	2.78	2.78	
	2	2321	2439	183	2256	652	2.68	0.21	1.05	1.16	3.28	3.04	Average of 2 & 3
	3	2334	2430	192	2238	619	3.03	0.14	1.00	0.92	2.81		
	4	2544	2628	198	2430	632	3.09	0.17	1.02	0.99	3.04	3.10	Average of 3 & 4
	5	2562	2655	188	2467	649	2.75	0.16	1.05	1.10	3.17		
2-1H Expanded, 4500 Centered, HT	1	2348	2524	195	2329	662	2.42	0.38	1.07	1.25	3.24	3.28	Average of 1 & 4
	2	2324	2422	204	2218	631	3.22	0.21	1.02	0.98	3.22	3.26	Average of 2 & 3
	3	2372	2472	203	2269	641	3.06	0.17	1.03	1.05	3.31		
	4	2544	2588	228	2360	618	3.64	0.25	1.00	0.91	3.33	-	
	5	2573	2652	219	2433	632	3.33	0.16	1.02	0.98	3.34	3.34	
2-1I Expanded, 4500 Offset 0.15", RT	1	2352	2063	31	2032	75	5.25	0.09	0.81	0.57	2.44	2.43	Average of 1 & 2
	2	2343	2089	31	2058	75	5.16	0.07	0.81	0.58	2.43		
	3	2595	2256	33	2223	75	5.38	0.04	0.81	0.62	2.71	2.74	Average of 3 & 4
	4	2610	2299	33	2266	75	5.41	0.06	0.81	0.63	2.77		

TEST2-1.XLS 2-1 Table 7/23/95 4:33 PM

Test 2-1. Summary of Test Dimensional Measurement Results
Specimen 8161A, Tube Dia. = 0.874", Gap = 0.027"

Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in²)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in²)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
None	0.0 Step A	Initial Dim.	0°	0.640 OD(3) 0.522(4)	0.515 ID(3)	N.A.(2)	0.0	N.A.(2)	0.877	0.875 0.874
		Hot	0°	0.522(4)	< 0.001W	-	0.0	N.A.	0.877	0.875 0.874
None	Free Span Step B	Hot	0°	0.575(4)	0.230(4) (0.003W)	0.00058	-	-	0.879	0.871 0.876
None	0.15 Step C	Hot	0°	0.586	0.504 (0.010W)	0.0033	0.134 (0.006W)	0.00060	0.884	0.879 0.876
None	0.15 Steps D, E	Cold	0°	0.588	0.504 (0.010W)	0.0033	0.134 (0.006W)	0.00060	0.885	0.881 0.876
4500	0.15 Steps F, G	Hot	0°	0.588	0.504 (0.011W)	0.0038	0.132 (0.007W)	0.00073	0.885	0.880 0.875
4500	0.00 Step H	Hot	0°	0.588	0.509 (0.011W)	0.0041	0.0	0.0	0.886	0.874 0.875
4500	0.15 Step I	Cold	0°	0.619	0.509 (0.011W)	0.0041	0.137 (0.007W)	0.00082	0.886	0.881 0.876

Notes:
1. Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.874" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
2. Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
3. Crack lengths from dye penetrant tests.
4. Crack lengths from toolmaker's microscope. Minimum measurable TW crack opening ~0.001"

Test Plan for IRBs
Test 2-1

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 2-4: Summary of Test Results

Test Sequence

- Order of tests: Small leak test facility - zero offset, free span, offset, offset cold; 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.
  - No data points were deleted from the data base.
- 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, tends to support comparable leak rates between facilities.
- Since this test shows no tube to TSP interaction (behaves as a free span test), the flow pressurization test results are independent of the actual crack to TSP gap. After bladder pressurization to the free span burst pressure of 5550 psi, the crack diameter increased by 0.022" which is reasonably close to the 0.025" target and these test results are considered acceptable since they do not influence the bounding leak rate assessment.

Summary of Test Results

- Leak rates for the crack at edge of TSP, free span and offset 0.15" result in leak rates typical of free span behavior
  - The flow pressure increases extended the length of the initial TW crack to 0.33" and opened a second TW crack of 0.12". High slopes of leak rate versus ΔP indicate ligament tearing up to about 2200 psid
  - Maximum tube diameter of 0.878" after test also indicates a low likelihood of tube to TSP contact at test conditions
  - Small slope of room temperature tests up to 2716 psid may be due to hysteresis effect on 2534 psid measurement since this test ΔP is 37 psi lower than the prior pressurization
- Bladder pressurization to a ΔP of 4125 psi did not result in crack faces contacting the TSP ID and leak rates are significantly lower (about factor of 2) than obtained with bladder pressurization at the estimated free span burst pressure of 5550 psi
  - Test 4-1 results show that further increases in bladder pressurization above the free span burst pressure do not result in increased leakage
- For this indication, the leak rates following bladder pressurization to 4125 psi with the crack inside the TSP are only slightly higher (0.76 vs 0.53 gpm for comparable room temperature tests) than obtained prior to bladder pressurization
- For 0.15" offset and bladder pressurization to the free span burst pressure of 5550 psi, the leak rates at SLB conditions are about 1.8 gpm and about 50% higher than with the crack inside the TSP and the crack tip at the edge of the TSP
  - Pressurization opened the longest throughwall crack to 0.382" (> 1.0 mil wide) with an average TW width of 0.010" and the second TW to 0.284" with an average TW width of 0.004". A TW length of 0.076" with an average width of 0.010" was exposed outside the TSP.
  - The larger than expected increase in offset vs zero offset leak is likely influenced by the two TW cracks in this specimen 180° apart which share closure of the crack to TSP gap.

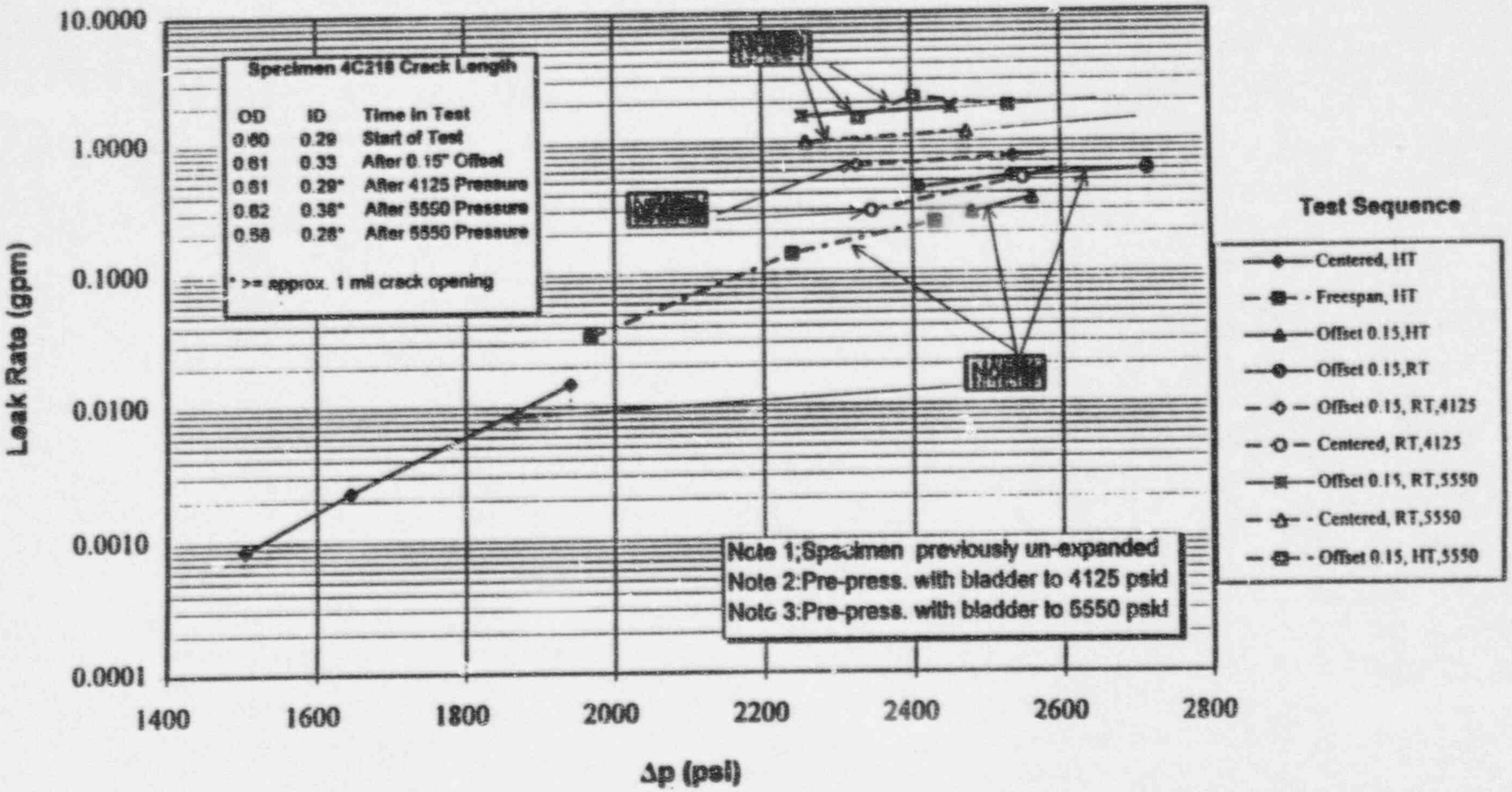
Overall Conclusions

- Initial TW crack lengths of about 0.29", OD = 0.60" (Average length = 0.445") do not result in interaction with the TSP ID at SLB conditions and the leak rates for the indication inside the TSP behave as free span indications with an SLB leak rate < 0.4 gpm
- Although this indication would not burst at SLB conditions, bladder pressurization tests were performed to bound the leak rate at pressures of 4125 psi and 5550 psi (estimated free span burst pressure for this indication)
- Bladder pressurization to 4125 psi resulted in a leak rate approximately the same as the free span leak rate for the indication inside the TSP and about 0.76 gpm with the crack 0.15" offset outside the TSP
- Bladder pressurization to the free span burst pressure of 5550 psi resulted in SLB leak rates of about 1.2 gpm with the crack inside the TSP and about 1.8 gpm with the crack offset 0.15" outside the TSP

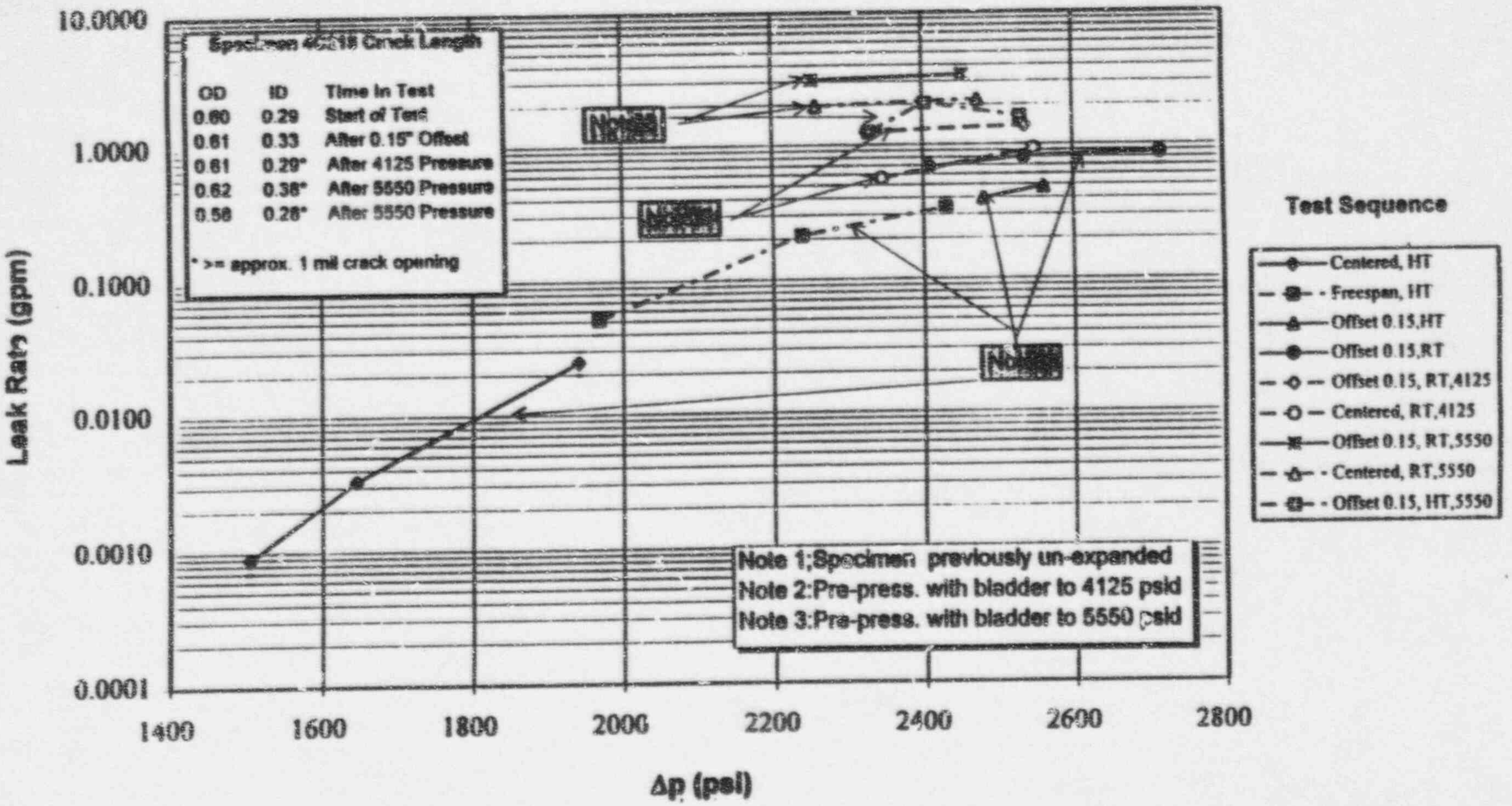
Test 2-4

Indications Restricted From Burst Leak Rate Tests

(Normalized to 615 F and 15 psi Secondary Pressure)



Test 2-4
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)



TEST2-4.XLS 7/12/95

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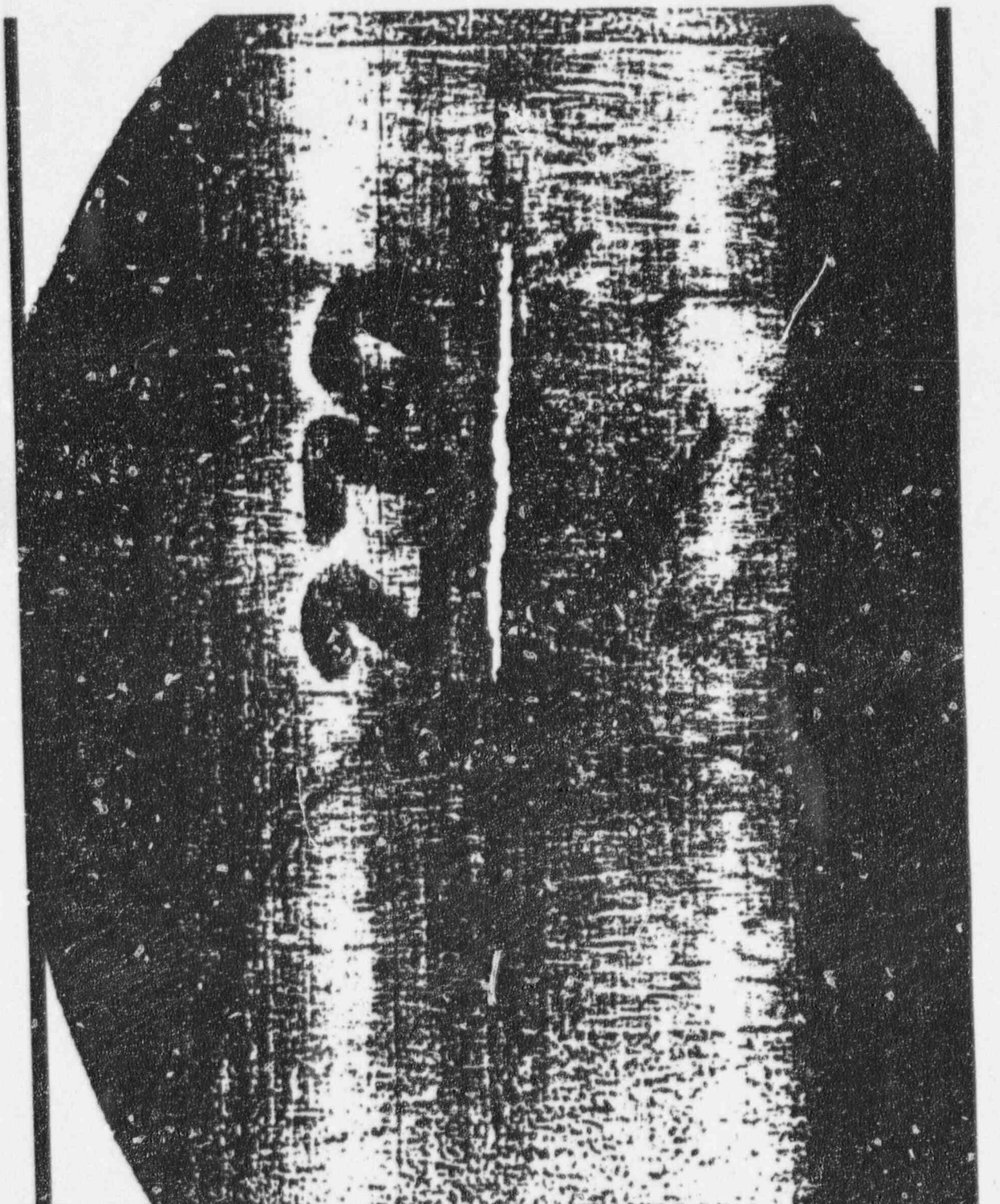
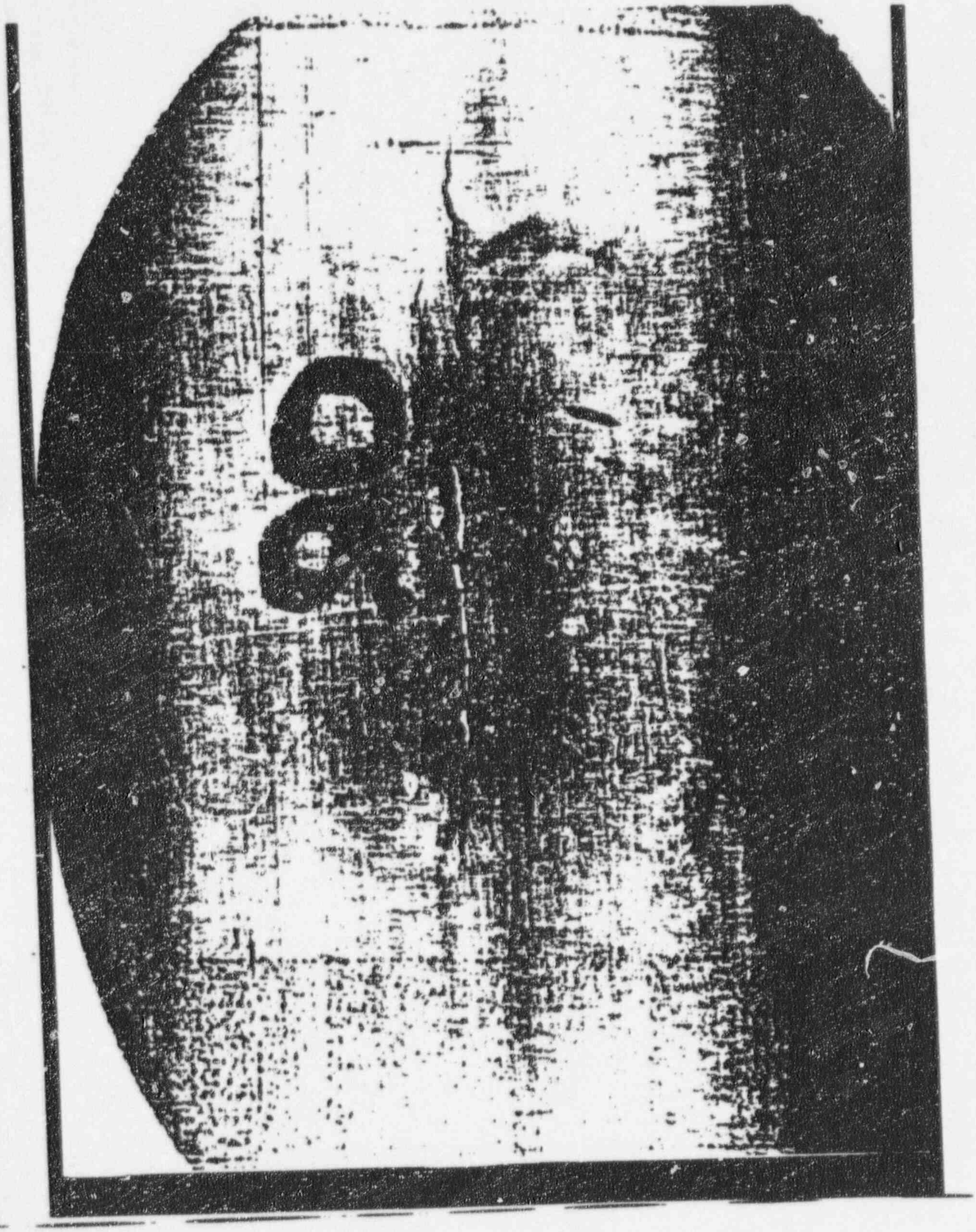


Test 2-4a. 270° After Crack After Bladder Pressurization to 5500 psi and Leak Testing



Test 2-4b. 90°Crack After Bladder Pressurization to 5500 psi and Leak Testing

Test 2 - 4
Summary of Leak Test and Analysis Results
Specimen 4C 218, Tube Diameter = 0.875", Gap = 0.26"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{net} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{net} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
2-4A Within TSP	1	n/a	2270	766	1504	613	0.0009	n/a	1.02	0.98	0.0009	0.0009	
	2	n/a	2220	575	1645	311	0.0033	n/a	0.94	0.74	0.0023	0.0023	Average value from 2 runs
	3	n/a	2475	534.5	1940.5	569.5	0.0245	n/a	0.97	0.62	0.0147	0.0147	Average value from 2 runs
2-4B Free Span	1	n/a	2490	522	1968	590	0.052	n/a	0.98	0.67	0.034	0.034	Average value from 2 runs
	2	n/a	2730	492	2238	359	0.212	n/a	0.97	0.69	0.141	0.141	
	3	n/a	2910	480.5	2429.5	567.5	0.337	n/a	0.97	0.74	0.241	0.241	Average value from 2 runs
2-4C Offset 0.15" HT	1	n/a	2870	389	2481	547	0.39	n/a	0.96	0.73	0.28	0.28	Average of 1 & 2
	2	n/a	2840	363	2477	555	0.40	n/a	0.96	0.75	0.29		
	3	n/a	2870	321	2549	561	0.47	n/a	0.97	0.77	0.35	0.36	Average of 3 & 4
	4	n/a	2880	309	2571	564	0.49	n/a	0.97	0.78	0.38		
2-4D Offset 0.15" RT	1	n/a	2460	52	2408	88	0.68	n/a	0.98	0.66	0.44	0.44	
	2	n/a	2605	71	2534	89	0.81	n/a	0.98	0.68	0.53	0.53	
	3	n/a	2790	74	2716	91	0.87	n/a	0.98	0.71	0.60	0.60	
2-4G Expanded, 4125 Offset 0.15", RT	1	n/a	2325	0	2325	70	1.25	n/a	0.81	0.64	0.65	0.65	
	2	n/a	2535	0	2535	70	1.38	n/a	0.81	0.68	0.76	0.76	
2-4 H Expanded, 4125 Centered, RT	1	n/a	2345	0	2345	70	0.56	n/a	0.81	0.65	0.29	0.29	
	2	n/a	2548	0	2548	70	0.93	n/a	0.81	0.68	0.51	0.51	
2-4 J,L Expanded, 5550 Offset 0.15", RT	1	n/a	2253	0	2253	70	3.11	n/a	0.81	0.63	1.58	1.58	
	2	n/a	2453	0	2453	70	3.37	n/a	0.81	0.67	1.82	1.82	
2-4 J,L Expanded, 5550 Offset 0.15", HT	1	2348	2408	77	2331	633	1.24	0.15	1.02	1.06	1.35	1.53	Average of 1 & 2
	2	2346	2405	79	2326	655	1.26	0.12	1.06	1.28	1.70		
	3	2520	2487	84	2403	632	2.05	0.29	1.02	1.05	2.20	2.20	
	4	2590	2607	81	2526	636	1.72	0.16	1.03	1.07	1.89	1.88	Average of 4 & 5
	5	2596	2610	77	2533	650	1.53	0.11	1.05	1.17	1.88		
2-4K Expanded, 5550 Centered, RT	1	n/a	2258	0	2258	70	1.96	n/a	0.81	0.63	1.00	1.00	
	2	n/a	2473	0	2473	70	2.18	n/a	0.81	0.67	1.18	1.18	

TEST2-4.XLS 2-4 Table 7/23/95 4:28 PM

Test 2-4 Summary of Test Dimensional Measurement Results Specimen 4C-218, Tube Dia. = 0.875", Gap = 0.026"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in²)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in²)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
None	0.0 Step A	Initial Dim. Hot Test	270°	0.60[3]	0.29[3]	N.A.[2]	0.0	N.A.[2]	0.875	N.A.[3]
			0°	0.60[3]	0.0					
None	Free span Step B	Hot	-	Not measured					-	-
None	0.15 Step C	Hot	-	Not measured					-	-
None	0.15 Steps D,E	Cold	270°	0.611[3]	0.33[3]	Tight	0.0	0.0	0.878	0.877 0.875
			90°	0.570[3]	0.12[3]	Tight	0.0	0.0		
4125	0.15 Steps F,G	Cold	270°	0.609[4]	0.286[4] (0.003W)	0.00086	0.032 (0.003W)	0.00009	0.881	0.879 0.875
			90°	0.570[4]	Tight	Tight	0.0	-		
4125	0.00 Step H	Cold	270°	Same as above for 4125 psi bladder pressure with 0.15" offset					0.881	0.875 0.875
			90°							

Test 2-4 Summary of Test Dimensional Measurement Results
Specimen 4C-218, Tube Dia. = 0.875", Gap = 0.026"

Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in²)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in²)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
5550	0.15 Steps I, J & L	After bladder press.	270°	0.617	0.382 (0.010W)	0.00382	0.076 (0.010W)	0.00076	0.897	0.885 0.876
			90°	0.588	0.284 (0.004W)	0.00114	0.0	0.0		
		After Step L Hot & Cold Tests	270°	0.617	0.351(5) (0.010W)	0.0035	0.067 (0.010W)	0.00067	0.897	0.885 0.876
			90°	0.588	0.247(5) (0.004W)	0.00099	0.0	0.0		
5550	0.0 Step K	Cold	270°	Same as above for 5500 psi bladder pressure with 0.15" offset					0.897	0.875 0.876
			90°							

Notes:
1. Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.875" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
2. Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
3. Crack lengths from dye penetrant tests.
4. Crack lengths from toolmaker's microscope. Minimum measurable TW crack opening ~0.001".
5. Smaller final measurements likely more accurate based on using light inside tube to improve measurements.

Test Plan for IRBs
Test 2-4

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 tnat 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 2-7: Summary of Test Results

Test Sequence

- Order of tests: cold zero offset, cold freespan, offset, bladder pressurization to free span burst pressure of 3700 psi, zero offset, offset, cold offset.
- One data point in the flow offset test was deleted due to hysteresis due to being 400 psi lower than the prior free span test at 2228 psi.
- Leak test results 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 the data set and this test result is assumed to be a bad data point.
- The 0.022" crack to TSP hole ID clearance, based on the crack diameter at the end of the flow pressurization test, 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.

Summary of Test Results

- The flattening of the leak rate slope above about 2300 psi ΔP indicates interaction of the crack face with the TSP ID.
  - Leak rates below 2300 psi are typical of free span leak rates.
  - Due to the large pressure differential of 2210 to 2650 psi between the highest flow offset data points, interaction with the TSP could have occurred anywhere in this pressure range.
- The offset condition resulted in a maximum SLB leak rate of about 4.1 gpm (0.577" TW crack at the start of the test) both before and after bladder pressurization.
  - The normalized test results for the flow offset test show an increase in the leak rate above the prior free span test at comparable pressures. The free span test was run as a cold test and the leak rate adjustment procedure has resulted, in some cases, in the adjusted hot leak rate being below the comparable hot test result. Thus, the higher leak rate for the offset test may be the result of an overestimate in the cold to hot adjustment factor. An evaluation of the cold to hot adjustment factor will be included in the final EPRI report for this test program.
  - Pressurization to 2544 psi in the flow offset test resulted in a maximum crack width of 0.020" compared to 0.003" after the free span test. The TW crack length measured by light penetration increased from 0.515" after the free span test to 0.636" after the flow offset test. Even though the crack opening increased significantly in the offset test, the leak rate shows essentially no increase from start to finish of the offset test due to interaction of the crack with the TSP.
  - There appears to be no significant increase in leakage as a result of the crack offset (0.088" TW outside TSP) for this test since the leak rate is approximately free span prior to the start of the offset test and did not increase after crack opening interaction with the TSP. From the analyses of Section 5, it would be expected that the effective crack opening area was less than the geometric flow area for this test and no increase in leakage with crack offset would have been expected for this test.
- 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
  - Following bladder pressurization to the free span burst pressure, the leak rate with the crack inside the TSP 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 expected based on the Section 5 analyses.

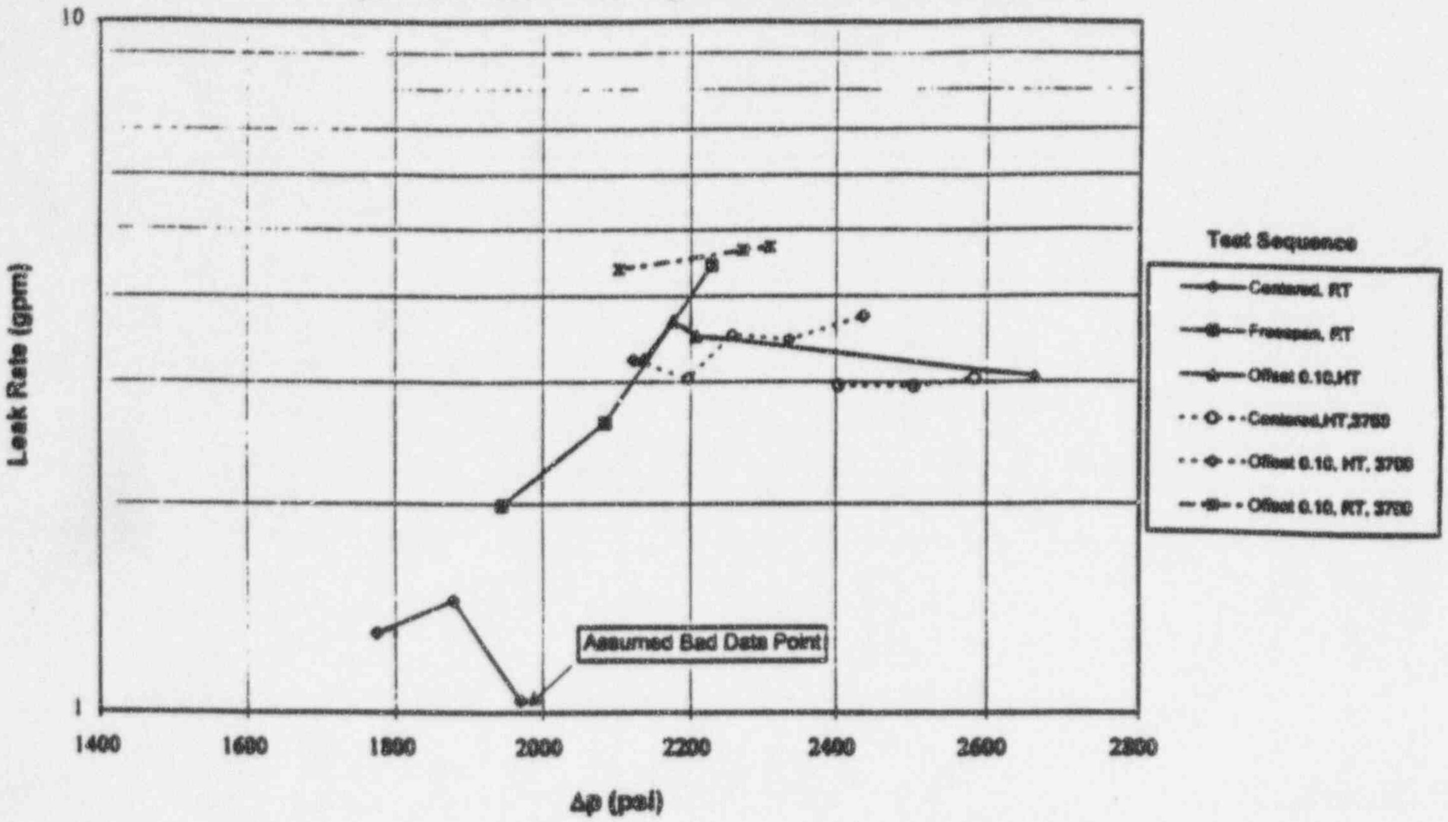
Overall Conclusions

- Flow pressurization to about 2300 psi ΔP resulted in interaction of the crack face with the TSP ID and resulted in an upper bound leak rate of about 4.1 gpm both before and after bladder pressurization.
- After crack face interaction with the TSP at about 2300 psi, the leak rate did not further increase including subsequent leak rate tests after bladder pressurization to the free span burst pressure of about 3700 psi.
- The test results for this test 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.

Test 2-7

Indications Restricted From Burst Leak Rate Tests

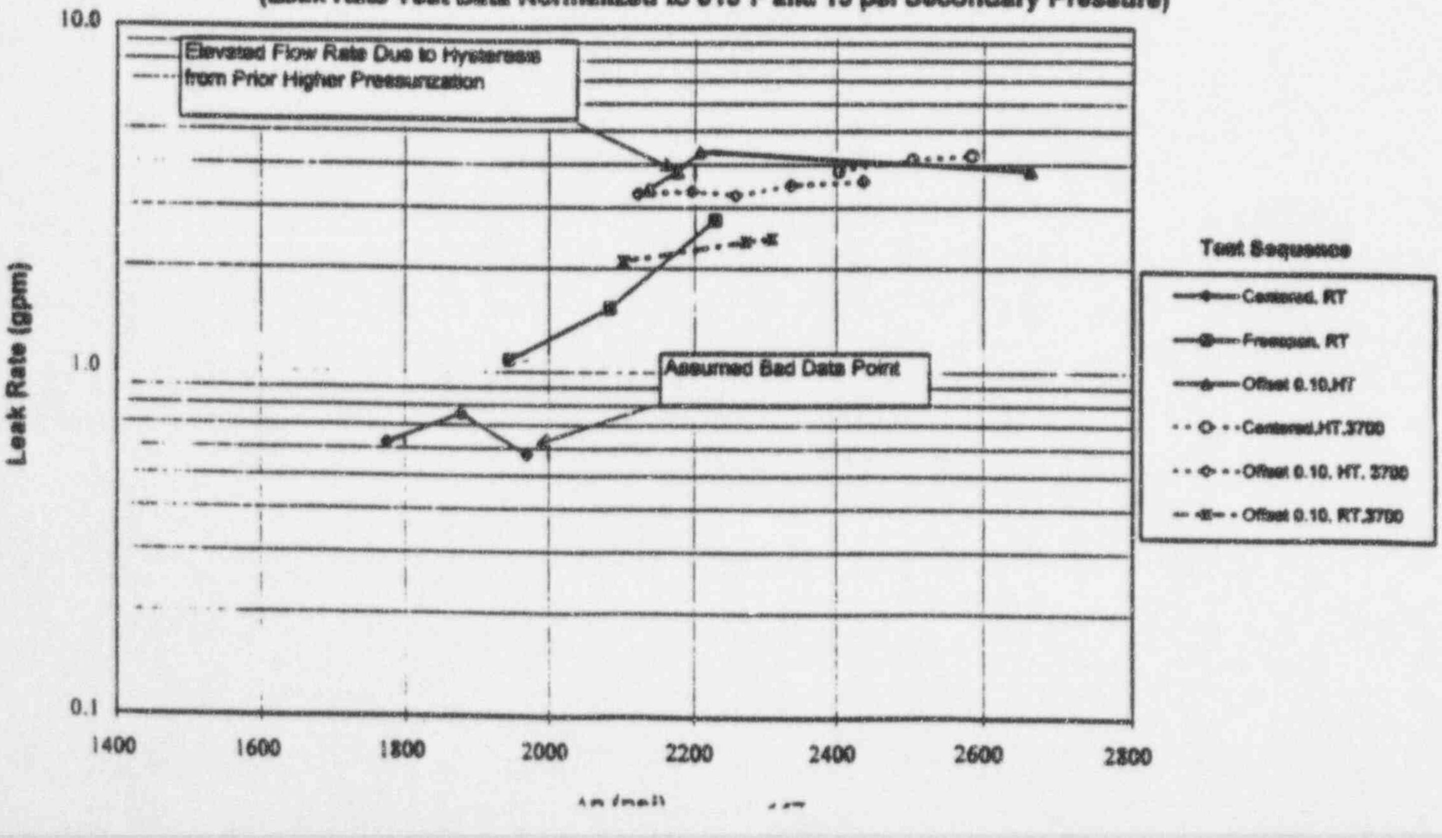
(as-measured, without adjustment to reference conditions)

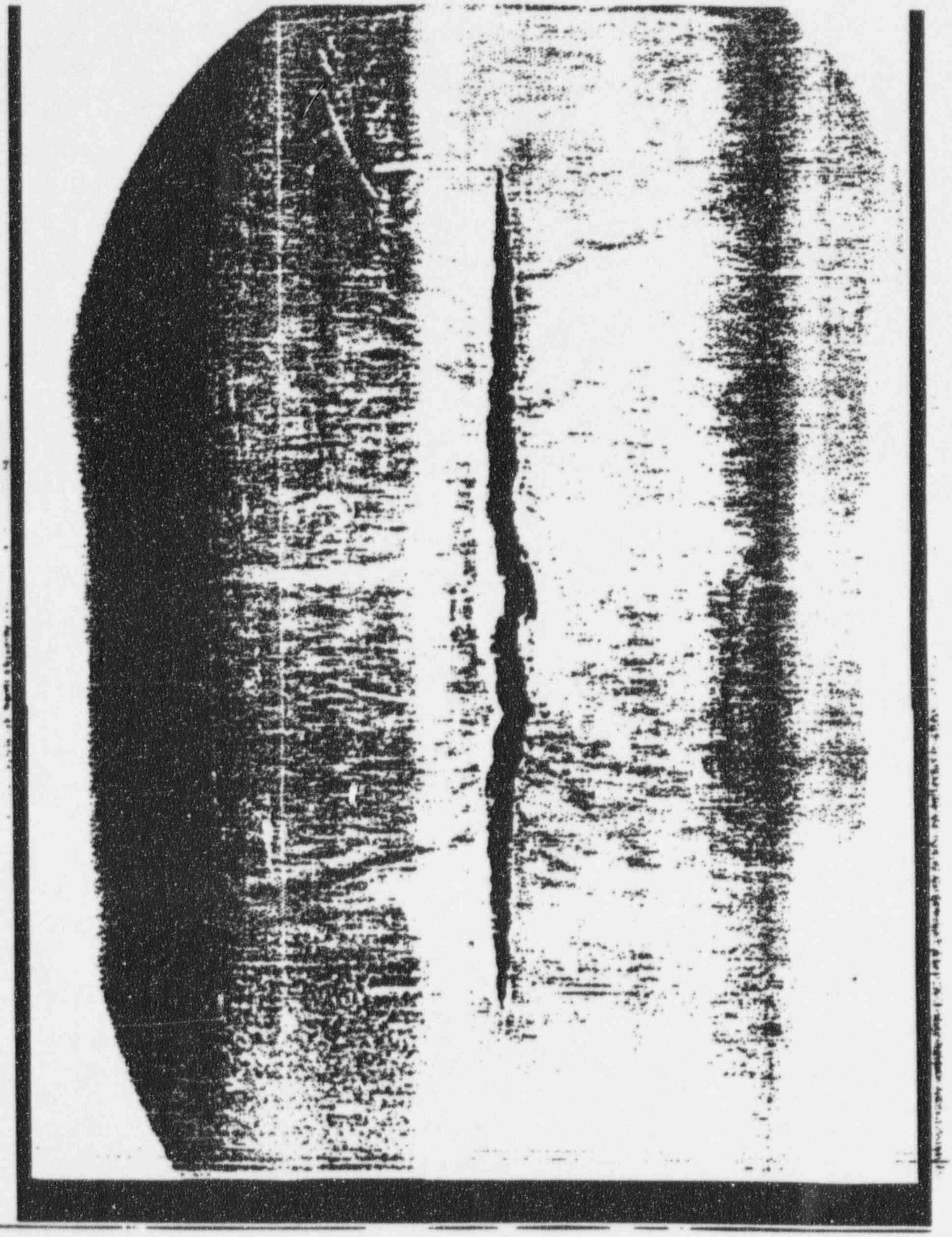


Test 2-7

Indications Restricted From Burst Leak Rate Tests

(Leak Rate Test Data Normalized to 615°F and 15 psi Secondary Pressure)





Test 2-7. After Bladder Pressurization to 3700 psi and Subsequent Leak Testing

Test 2 - 7
Summary of Leak Test and Analysis Results
Specimen 2051E, Tube Diameter = 0.747", Gap = 0.026"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{sm} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{sm} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
2-7A Within TSP, RT	1	n/a	1775	0	1775	70	1.30	n/a	1.00	0.48	0.62	0.62	
	2	n/a	1878	0	1878	70	1.45	n/a	1.00	0.52	0.76	0.76	
	3	n/a	1970	0	1970	70	1.04	n/a	1.00	0.55	0.58	0.58	
2-7B Free Span, RT	1	n/a	1945	0	1945	70	1.99	n/a	1.00	0.55	1.09	1.09	
	2	n/a	2085	0	2085	70	2.62	n/a	1.00	0.59	1.54	1.54	
	3	n/a	2228	0	2228	70	4.44	n/a	1.00	0.62	2.76	2.76	
2-7C Offset 0.10", HT	1	2032	2094	259	1835	640	2.27	0.29	1.02	1.01	2.34	-	Delete - Hysteresis
	2	2324	2489	352	2137	649	3.24	0.59	1.03	1.02	3.40	3.40	
	3	2490	2585	409	2176	652	3.68	0.29	1.03	1.00	3.82	3.82	
	4	2360	2414	207	2207	656	3.50	0.12	1.04	1.20	4.36	4.36	
	5	2900	2855	176	2679	658	3.32	0.41	1.04	1.14	3.95	3.84	Average of 5 & 6
	6	2840	2800	156	2644	568	2.80	0.16	1.06	1.25	3.72		
2-7F Expanded, 3700 Centered HT	1	2412	2583	216	2367	655	2.98	0.23	1.06	1.14	3.60	3.60	
	2	2478	2650	211	2439	668	2.95	0.21	1.09	1.27	4.08	4.08	
	3	2624	2821	222	2599	672	3.11	0.35	1.10	1.26	4.29	4.25	Average of 3 & 4
	4	2622	2797	227	2570	674	2.97	0.33	1.10	1.29	4.21		
2-7g Expanded, 3700 Offset 0.10" HT	1	2228	2395	196	2199	643	2.84	0.08	1.04	1.07	3.16	3.16	Average of 1 & 3
	2	2278	2320	197	2123	633	3.23	0.16	1.02	1.00	3.29	3.35	
	3	2360	2392	199	2193	642	3.23	0.09	1.04	1.06	3.55	-	
	4	2356	2460	204	2256	620	3.51	0.15	1.01	0.92	3.26	3.26	
	5	2452	2545	210	2335	633	3.45	0.21	1.02	0.99	3.49	3.49	
	6	2582	2647	227	2420	621	3.84	0.18	1.01	0.93	3.59	3.58	Average of 6 & 7
	7	2592	2700	246	2454	630	3.64	0.22	1.02	0.96	3.57		
2-7h Expanded, 3700 Offset 0.10" RT	1	2333	2108	19	2089	75	4.38	0.1	0.81	0.59	2.09	2.10	Average of 1 & 2
	2	2367	2136	19	2117	75	4.38	0.12	0.81	0.60	2.12		
	3	2562	2291	21	2270	75	4.67	0.13	0.81	0.63	2.39	2.39	
	4	2591	2332	24	2308	75	4.72	0.1	0.81	0.64	2.45	2.45	

TEST2-7.XLS 2-7 Table 7/23/95 4:22 PM

Test 2-7. Summary of Test Dimensional Measurement Results Specimen 2051E, Tube Dia. = 0.747", Gap = 0.026"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in^2)	Exposed TW Length Max. Width) (in.)	Exposed TW Area (in^2)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
None	0.0 Step A	Initial Dim. Cold Test	0°	0.66(3) 0.648(4)	0.577(3)	N.A.(2)	0.0	N.A.(2)	0.749	0.748 0.748
None	Freespan Step B	Cold	0°	0.667(4)	0.515(4) (0.002W)	0.00090	-	-	0.756	0.748 0.749
None	0.10 Steps C, D	Hot	0°	0.671	.636 (.020W)	0.0085	.088 (0.007W)	.00048	0.769	0.757 0.747
3700	0.0 Steps E, F	Hot	0°	0.672	0.637 (.020W)	0.0092	0.0	0.0	0.766	0.748 0.748
3700	0.10 Step G	Hot	0°	0.674	0.637 (.020W)	.0095	0.087 (0.008W)	.00052	0.766	0.758 0.748
3700	0.10 Step H	Cold	0°	0.674	0.637 (.021W)	.0104	0.087 (0.011W)	.00070	0.765	0.759 0.746

Notes:
1. Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.747" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
2. Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
3. Crack lengths from dye penetrant tests
4. Crack lengths from toolmaker's microscope. Minimum measurable TW crack opening ~0.001"

Test Plan for IRBs
Test 2-7

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 2-10: Summary of Test Results

Test Sequence

- Order of tests: Small leak test facility - zero offset, free span, offset, cold offset: large leak test facility - bladder pressurization to 3850 psi, zero offset, offset, bladder pressurization to the free span burst pressure of about 4960 psi, zero offset, offset, cold offset.
- The lowest pressure data point in the cold, flow offset test was deleted from the data base due to hysteresis effects since the test pressure differential was 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, tends to support comparable leak rates between facilities.
- Since this test shows no tube to TSP interaction (behaves as a free span test), the flow pressurization test results are independent of the actual crack to TSP gap. After bladder pressurization to the free span burst pressure of 4960 psi, the crack diameter increased by 0.010" which is less than the 0.025" target. These test results are considered acceptable since the testing prior to bladder pressurization is the most important objective for this test and the test results do not influence the bounding leak rate assessment.

Summary of Test Results

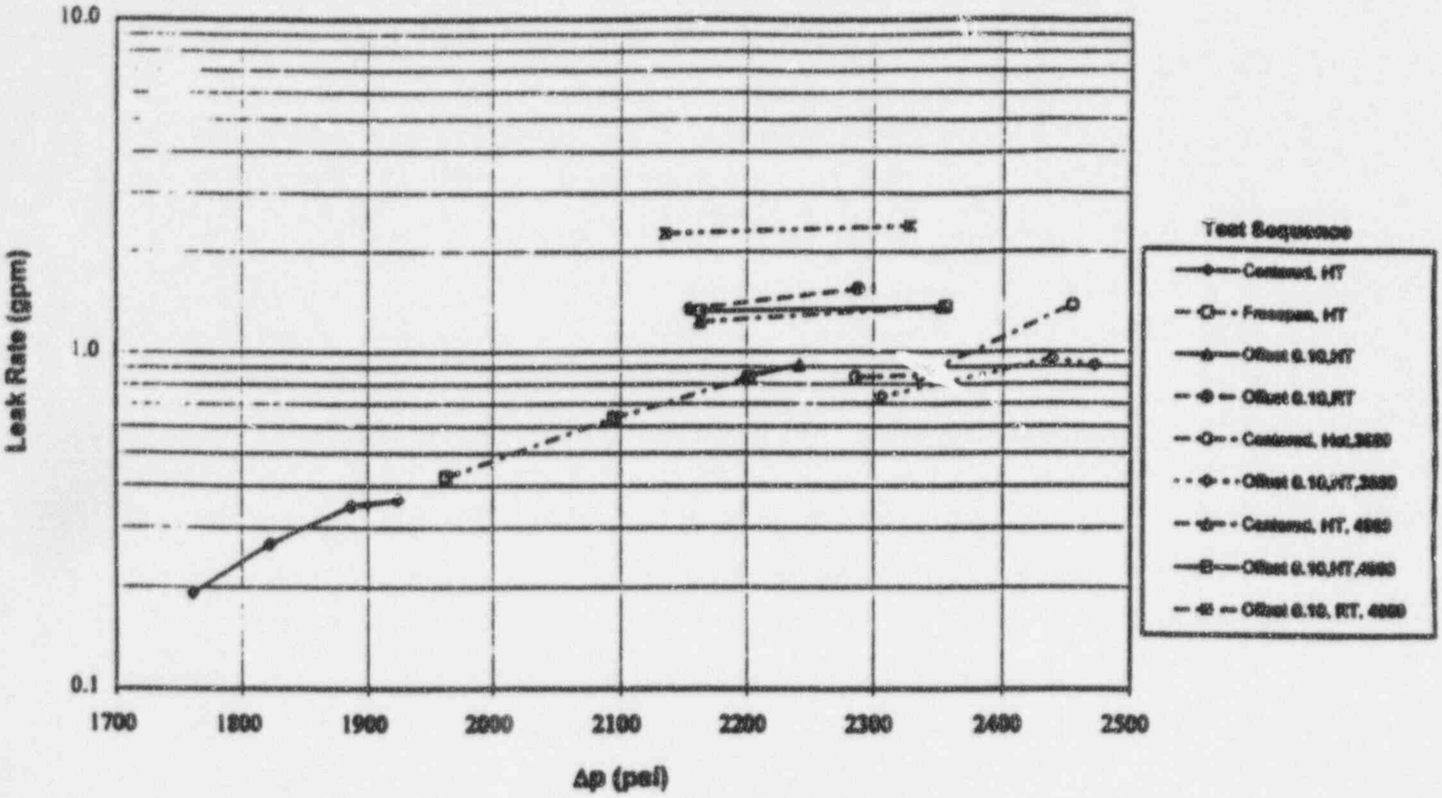
- The slope of the leak rate versus ΔP curve indicates essentially free span leak rates with no TSP interaction up to the maximum ΔP of 2300 psi tested under flow pressurization conditions.
  - The maximum leak rate tested is about the limit of the small leak test facility used for this test.
  - The absence of crack to TSP interaction is demonstrated by the continuous leak rate trend between the offset, free span and offset tests.
- The maximum measured hot flow pressurization leak rate for this 0.425" TW indication was about 0.65 gpm at 2240 psi which would extrapolate to about 1.7 gpm at 2560 psi.
  - The plastic crack width following the flow pressurization tests was not measurable by light penetration which would indicate a width < 1 mil.
- Bladder pressurization to 3850 psi at 0.10" offset resulted in leak rates at SLB conditions of about 1.9 gpm in the offset condition which exceeded the leak rate in the zero offset condition.
  - The plastic crack 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 0.10" offset condition was about 1.5 gpm with no significant difference from the zero offset condition.
  - The increase in leak rates following bladder pressurization is typical for indications which do not show interaction with the TSP under flow pressurization conditions.
  - The plastic crack width following this pressurization to the free span burst pressure was 0.011". A 0.081" TW crack of maximum width 0.006" was exposed outside the TSP for the offset test.

Overall Conclusions

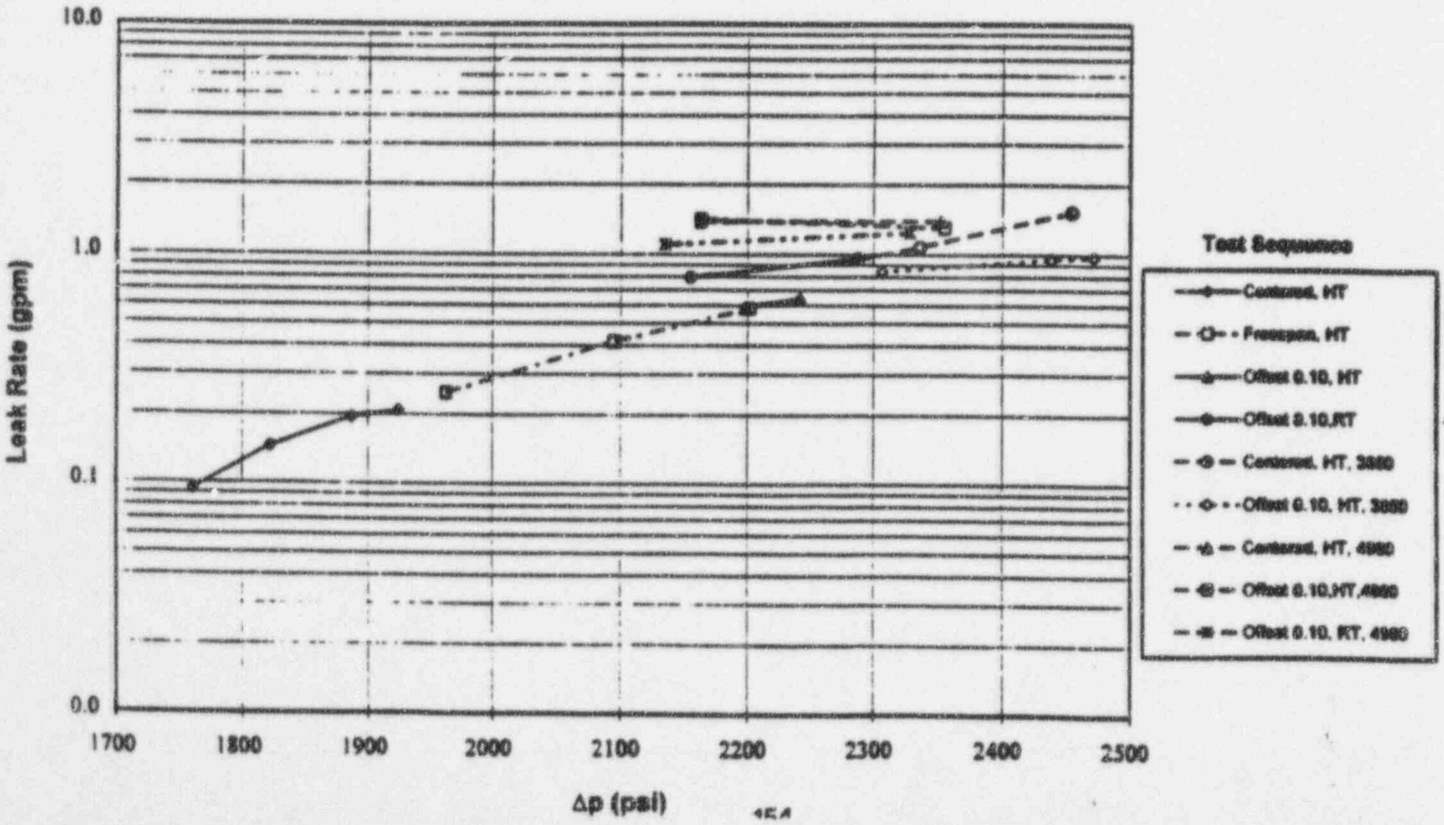
- The initial TW crack length of 0.425", OD = 0.551" (Average length = 0.488") for this test does not result in interaction with the TSP ID at SLB conditions and the leak rates for the indication inside the TSP behave as free span indications with an SLB leak rate of about 1.7 gpm.

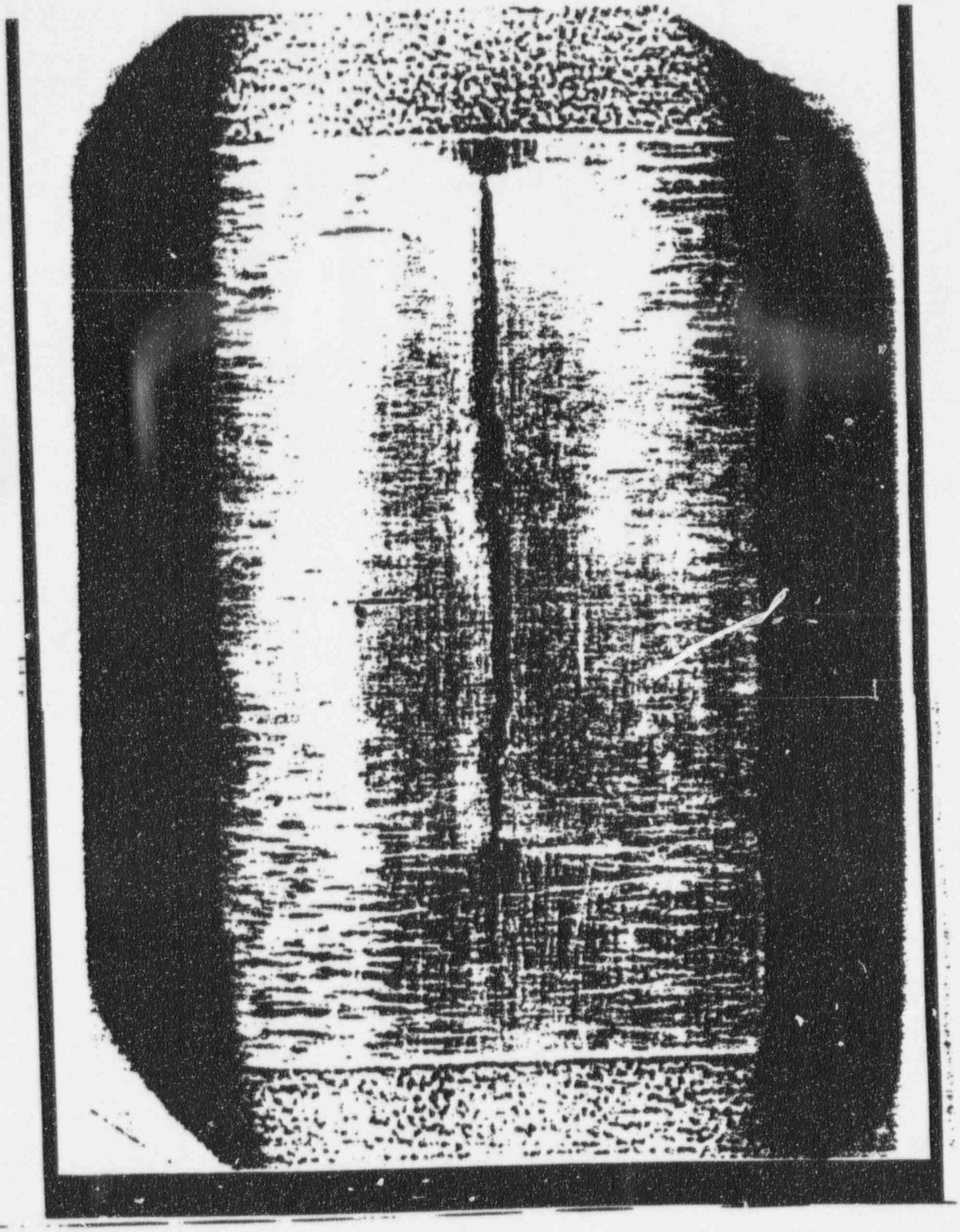
- Although this indication would not burst at SLB conditions, bladder pressurization tests were performed to bound the leak rate at pressures of 3850 psi and 4960 psi (estimated free span burst pressure for this indication).
- The SLB leak rate for the 0.10" offset condition following bladder pressurization to the free span burst pressure was about 1.5 gpm and essentially the same as obtained for the crack within the TSP.
- Bladder pressurization to the free span burst pressure resulted in SLB leak rates higher than obtained by flow pressurization at pressures below SLB conditions, which is typical for the shorter indications for which the crack faces do not interact with the TSP under flow pressurization conditions, but essentially the same at SLB conditions due to the small leak rate dependence on pressure following bladder pressurization.

Test 2-10
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)



Test 2-10
Indications Restricted From Burst Leak Rate Tests
(Normalized to 615°F and 15 psi Secondary Pressure)





Test 2-10. After Bladder Pressurization to 4960 psi and Leak Testing

Test 2 - 10
Summary of Leak Test and Analysis Results
Specimen 2051 B, Tube Diameter = 0.748", Gap = 0.025"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{test} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	ΔP_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
2-10A Within TSP, HT	1	n/a	2270	510	1760	540	0.19	n/a	0.96	0.51	0.09	0.09	
	2	n/a	2350	528	1822	539	0.27	n/a	0.96	0.56	0.14	0.14	
	3	n/a	2440	553	1887	561	0.35	n/a	0.97	0.58	0.20	0.20	
	4	n/a	2470	546	1924	560	0.36	n/a	0.97	0.59	0.21	0.21	
2-10B Free Span, HT	1	n/a	2451	488	1963	553	0.42	n/a	0.96	0.61	0.25	0.25	
	2	n/a	2578	483	2095	571	0.64	n/a	0.97	0.67	0.42	0.42	
	3	n/a	2732	530	2202	584	0.84	n/a	0.98	0.71	0.58	0.58	
2-10C Offset 0.10", HT	1	n/a	2708	510	2198	584	0.84	n/a	0.98	0.72	0.59	0.59	
	2	n/a	2781	539	2242	586	0.91	n/a	0.98	0.72	0.65	0.65	
2-10D Offset 0.10", RT	1	n/a	2058	131	1927	75	1.13	n/a	0.98	0.54	0.60	-	Delete - Hysteresis
	2	n/a	2350	196	2154	75	1.35	n/a	0.98	0.61	0.80	0.80	
	3	n/a	2554	266	2288	76	1.56	n/a	0.98	0.63	0.96	0.96	
2-10G Expanded, 3850 Centered, HT	1	2367	2329	43	2286	634	0.84	0.04	1.02	1.10	0.95	0.95	
	2	2378	2385	48	2337	648	0.85	0.12	1.05	1.22	1.08	1.08	
	3	2540	2533	73	2460	629	1.39	0.15	1.02	1.04	1.46	1.53	Average of 3 & 4
	4	2546	2531	81	2450	642	1.38	0.18	1.04	1.11	1.59		
2-10H Expanded, 3850 Offset 0.10", HT	1	2366	2336	38	2298	634	0.74	0.13	1.02	1.10	0.83	0.84	Average of 1 & 2
	2	2352	2356	41	2315	639	0.73	0.08	1.03	1.14	0.86		
	3	2564	2486	47	2439	620	0.95	0.12	1.01	1.00	0.96	0.96	
	4	2578	2518	46	2472	630	0.91	0.08	1.02	1.05	0.98	0.98	
2-10J Expanded, 4960 Centered, HT	1	2308	2213	67	2146	632	1.29	0.14	1.02	1.08	1.42	1.39	Average of 1 & 2
	2	2348	2243	65	2178	636	1.18	0.11	1.03	1.11	1.35		
	3	2340	2419	79	2340	619	1.37	0.09	1.00	0.98	1.35	1.40	Average of 3 & 4
	4	2367	2444	78	2366	629	1.37	0.1	1.02	1.04	1.44		
2-10K Expanded, 4960 Offset 0.10", HT	1	2270	2223	76	2147	632	1.23	0.08	1.02	1.07	1.35	1.42	Average of 1, 2 & 3
	2	2300	2210	68	2142	639	1.35	0.13	1.03	1.15	1.60		
	3	2380	2273	75	2198	611	1.40	0.11	1.00	0.94	1.31		
	4	2600	2421	75	2346	619	1.50	0.11	1.00	0.98	1.48	1.31	Average of 4 & 5
	5	2600	2445	79	2366	606	1.24	0.1	0.99	0.93	1.14		
2-10L Expanded, 4960 Offset 0.10", RT	1	2396	2131	9	2122	75	2.30	0.09	0.81	0.60	1.11	1.10	Average of 1 & 2
	2	2396	2155	9	2146	75	2.24	0.06	0.81	0.60	1.10		
	3	2585	2337	11	2326	75	2.40	0.07	0.81	0.64	1.25	1.25	Average of 3 & 4
	4	2595	2344	12	2332	75	2.38	0.06	0.81	0.64	1.24		

Test 2-10. Summary of Test Dimensional Measurement Results Specimen 2051B, Tube Dia. = 0.746", Gap = 0.025"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in^2)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in^2)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
None	0.0 Step A	Initial Dim. Hot Test	0°	0.551$^{(3)}$	0.425$^{(3)}$	N.A.$^{(2)}$	0.0	N.A.$^{(2)}$	0.749	0.746 0.746
None	Free span Step B	Hot	-	Not Measured						
None	0.10 Step C	Hot	-	Not measured						
None	0.10 Steps D, E	Cold	0°	0.554$^{(3)}$ 0.546$^{(4)}$	0.425$^{(3)}$	N.A.$^{(2)}$	-0.005	N.A.$^{(2)}$	0.749	0.747 0.747
3850	0.0 Steps F, G	Hot	0°	Not measurable. Crack width not sufficiently wide for uniform light penetration to measure crack.					0.749	0.746 0.746
3850	0.10 Step H	Hot	0°	Not measurable. Crack width not sufficiently wide for uniform light penetration to measure crack.					0.749	0.749 0.746

Test 2-10. Summary of Test Dimensional Measurement Results
Specimen 2651B, Tube Dia. = 0.746", Gap = 0.025"

Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in^2)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in^2)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
4960	0.0 Steps I, J	Hot	0°	.562	.492 (.010W)	.0031	0.0	0.0	.755	.746 .746
4960	0.10 Step K	Hot	0°	.575	.492 (.011W)	.0038	.081 (.006)	.00048	0.756	.752 0.746
4960	0.10 Step L	Cold	Approximately same as after Step K 0.10" offset test							

Notes: 1. Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.746" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
2. Cracks are tight for specimens not pressurized with a bladder and TW area is not applicable.
3. Crack lengths from dye penetrant tests
4. Crack lengths from toolmaker's microscope. Minimum measurable TW crack opening ~0.001"

Test Plan for IRBs
Test 2-10

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 4-1: Summary of Test Results

Test Sequence

- Order of tests: All bladder pressurization tests - at about 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, 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. Room temperature leak tests were performed for all tests. Note that only the initial and 8900 psi steps had both zero offset and offset leak tests.
- No leak test results were excluded from the data base.
- Leak test results show consistent trends with modest fluctuations in the data and there is no basis to question the data adequacy. However, this specimen had four cracks, one throughwall at the start of the test. After the first bladder pressurization step, three cracks were throughwall including two cracks 180° apart. Throughwall cracks 180° apart influence the differences in leak rates between zero offset and offset tests due to competition between the two cracks to occupy the clearance between the tube and the tube hole. Offsetting the crack from the TSP exposes two throughwall cracks in this test.
  - Due to the multiple cracks in this specimen, the tube was intentionally centered in the tube for the initial bladder pressurization tests as there was no obvious preferred orientation to maximize the leak rates. The initial bladder pressurizations expanded the two 180° crack openings to close the 0.023" tube to TSP diametral gap for this test. It is believed the test results are fully representative of limiting leak rates expected for multiple TW cracks following bladder pressurization with the offset leak rate differences increased by exposing two TW cracks 180° apart.

Summary of Test Results

- Leak rates with the crack within the TSP decrease significantly (about 2.4 gpm at 5800 psi bladder pressure to about 1 gpm after 8900 psi after extrapolation to SLB ΔP = 2560 psid) with increasing bladder pressure as the increasing pressures progressively close the tube to TSP gap due to plastic deformation of the tube while crack opening areas only modestly increase.
  - After pressurization to 8900 psi, the crack faces contact the TSP ID over close to 0.5" of the 0.626" TW length. The two largest cracks are 180° from each other and both are bulged such that the gap flow area within the TSP is reduced for both cracks
- Leak rates with the crack offset 0.15" outside the TSP do not significantly change (slight decrease) with increasing bladder pressure
- Leak rates with 0.15" offset are about 4 gpm at SLB conditions or about 60% higher than for the crack within the TSP
  - Two throughwall cracks are exposed outside the TSP and contribute to the higher leak rate with the 0.15" offset
- 7/8" diameter specimen with 0.24" TW, 0.67" OD by dye penetrant at start of test
  - After pressurization to approximately the free span burst pressure of about 6000 psi, the specimen includes 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 are 0.626, 0.603 and 0.408 inch with

maximum crack openings of 0.022, 0.018 and 0.009 inch. The maximum tube diameters inside the TSP have nearly closed the entire tube to TSP gap.

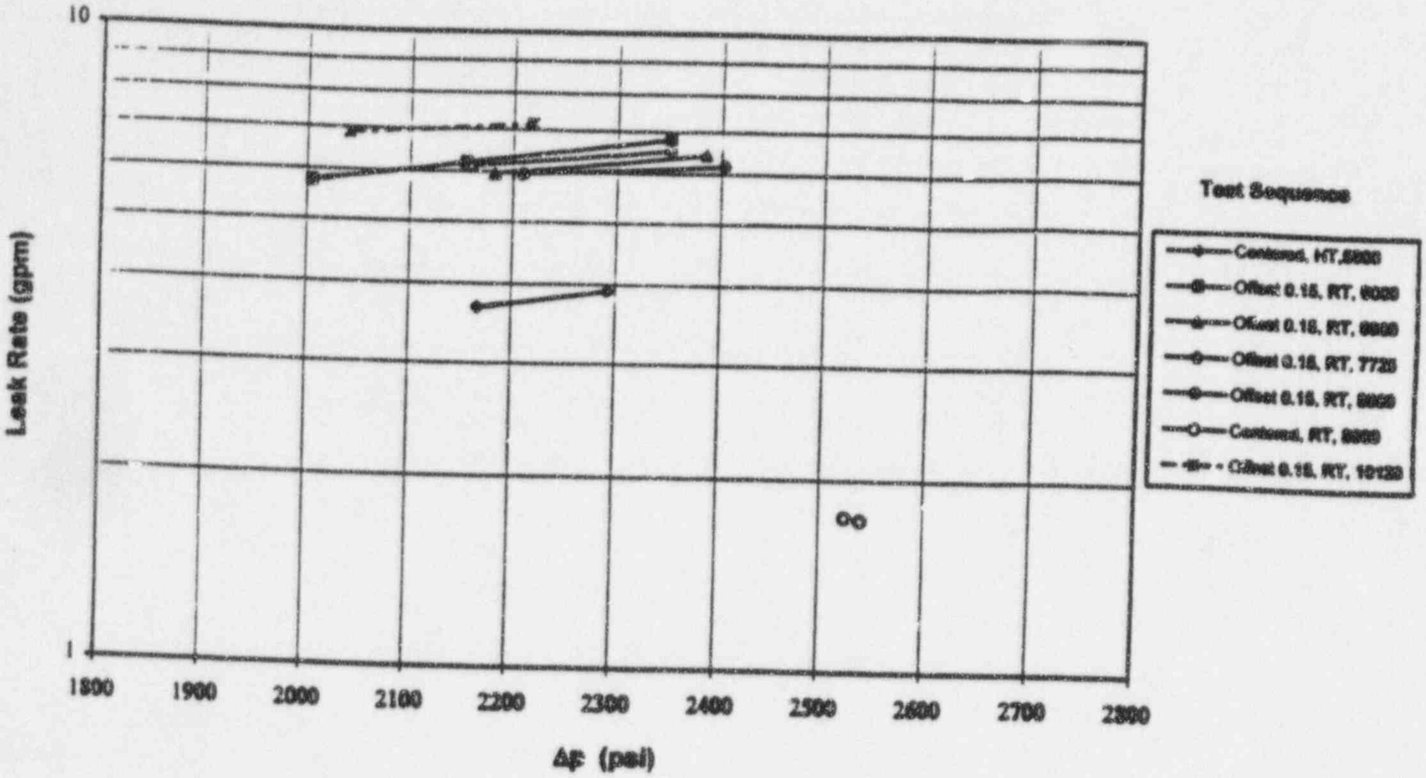
  - After pressurization to 10120 psi, almost the entire tube has expanded to close the tube to TSP gap.

- The 90° crack burst like a free span crack outside the TSP at 11350 psi with the crack 0.15" outside the TSP (0.142" TW). 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 WCAP-14273, Figure 9-2 burst correlation (after adjustment to the 7/8" tube size of this test) for throughwall cracks extending outside the TSP.

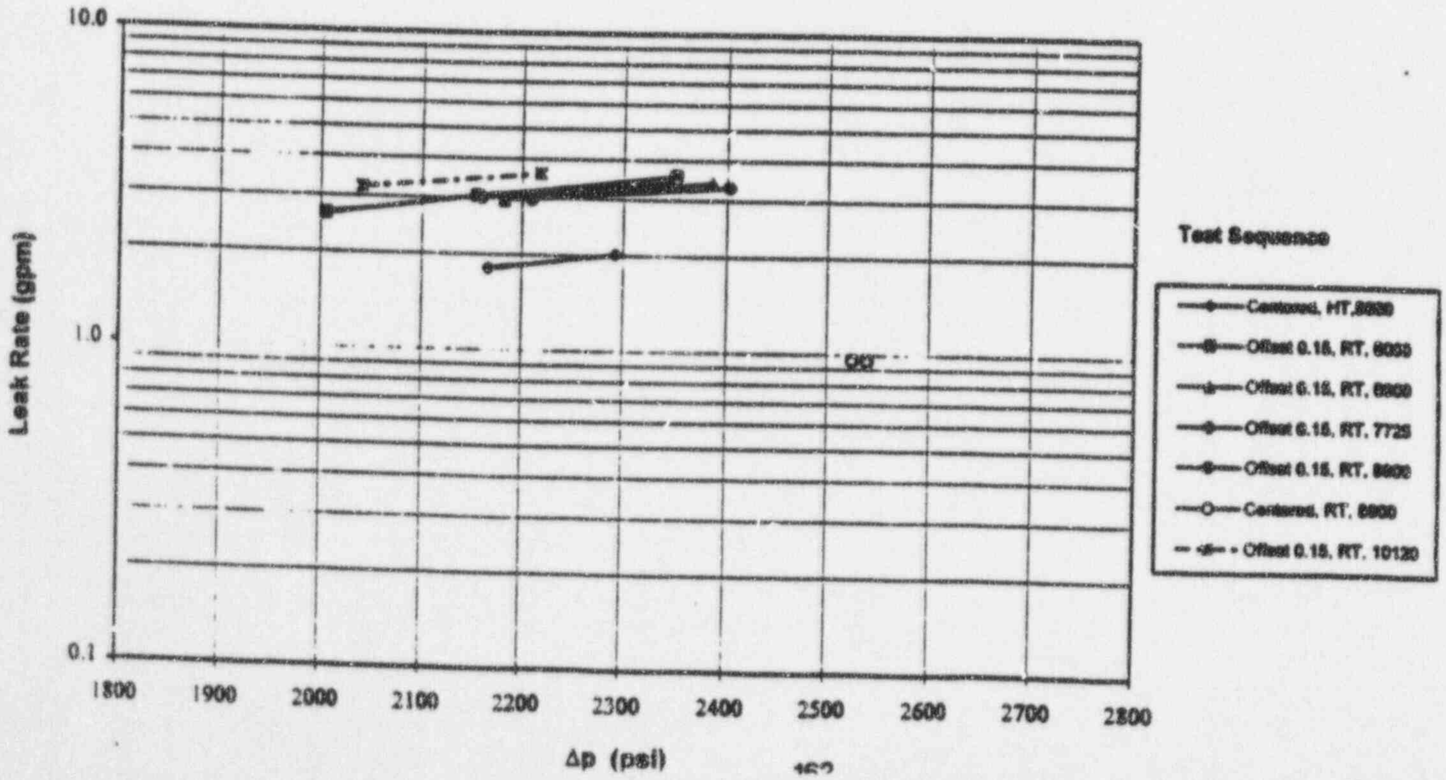
Overall Conclusions

- SLB leak rates for this indication with multiple throughwall cracks up to 0.61" TW after bladder pressurization to about the free span burst pressure are bounded by about 4.2 gpm with 0.15" offset and about 2.5 gpm for the crack within the TSP.
- Crack opening areas are limited by the tube to TSP gap following contact of the crack face with the TSP ID and the associated areas are less than the minimum geometric flow area formed by the gap.
  - WCAP-14273 model overestimates the flow area and leak rate.
- Bladder pressurizations above the free span burst pressure do not result in increasing leak rates
  - Therefore, it is was not necessary to include bladder pressurizations above the free span burst pressure in tests following Test 4-1.
  - The principal effect of further increases in bladder pressure is to close the tube to TSP gap within the TSP along the crack opening due to plastic deformation and to expand the overall tube diameter to close the gap.
- The 90° crack burst like a free span crack outside the TSP at 11350 psi with the crack 0.15" outside the TSP (0.142" TW). This burst pressure is more than 3000 psi higher than the WCAP-14273, Figure 9-2 burst correlation for throughwall cracks extending outside the TSP.

Test 4-1
Indications Restrained From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)



Test 4-1
Indications Restrained From Burst Leak Rate Tests
(Normalized to Tp=615°F and ps=15 psia Conditions)



Test 4 - 1
Summary of Leak Test and Analysis Results
Specimen 4B-214, Tube Diameter = 0.876", Gap = 0.023"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{test} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
4-1B Bladder 5800 Within TSP, RT	1	n/a	2175	0	2175	70	3.86	n/a	0.81	0.61	1.91	1.81	Average of 1 & 2
	2	n/a	2160	0	2160	70	3.49	n/a	0.81	0.61	1.72		
	3	n/a	2270	0	2270	70	3.91	n/a	0.81	0.63	2.00	2.02	Average of 3 & 4
	4	n/a	2315	0	2315	70	3.91	n/a	0.81	0.64	2.03		
4-1E Bladder 6000 Offset 0.15", RT	1	n/a	2005	0	2005	70	5.76	n/a	0.81	0.56	2.64	2.64	
	2	n/a	2155	0	2155	70	6.21	n/a	0.81	0.61	3.05	3.05	
	3	n/a	2350	0	2350	70	6.82	n/a	0.81	0.65	3.58	3.57	Average of 3 & 4
	4	n/a	2350	0	2350	70	6.80	n/a	0.81	0.65	3.57		
4-1H(i) Bladder 6900 Offset 0.15", RT	1	n/a	2175	0	2175	70	5.95	n/a	0.81	0.61	2.94	2.96	Average of 1 & 2
	2	n/a	2190	0	2190	70	5.99	n/a	0.81	0.61	2.98		
	3	n/a	2390	0	2390	70	6.72	n/a	0.81	0.65	3.57	3.41	Average of 3 & 4
	4	n/a	2380	0	2380	70	6.15	n/a	0.81	0.65	3.26		
4-1H(ii) Bladder 7725 Offset 0.15", RT	1	n/a	2160	0	2160	70	6.04	n/a	0.81	0.61	2.97	3.01	Average of 1 & 2
	2	n/a	2160	0	2160	70	6.20	n/a	0.81	0.61	3.05		
	3	n/a	2350	0	2350	70	6.59	n/a	0.81	0.65	3.46	3.43	Average of 3 & 4
	4	n/a	2350	0	2350	70	6.48	n/a	0.81	0.65	3.40		
4-1H(iii) Bladder 8900 Offset 0.15", RT	1	n/a	2210	0	2210	70	5.99	n/a	0.81	0.62	3.00	2.99	Average of 1 & 2
	2	n/a	2210	0	2210	70	5.95	n/a	0.81	0.62	2.98		
	3	n/a	2395	0	2395	70	6.15	n/a	0.81	0.66	3.27	3.29	Average of 3 & 4
	4	n/a	2410		2410	70	6.20	n/a	0.81	0.66	3.31		
4-1J Bladder 8900 Within TSP, RT	1	n/a	2525	0	2525	70	1.75	n/a	0.81	0.68	0.96	0.96	
	2	n/a	2540	0	2540	70	1.73	n/a	0.81	0.68	0.95	0.95	
4-1L Bladder 10120 Offset 0.15", RT	1	2343	2076	42	2034	70	6.82	0.17	0.81	0.57	3.17	3.21	Average of 1 & 2
	2	2294	2092	43	2049	70	6.94	0.17	0.81	0.58	3.25		
	3	2532	2253	46	2207	70	7.13	0.21	0.81	0.62	3.57	3.59	Average of 3 & 4
	4	2532	2275	46	2229	70	7.17	0.15	0.81	0.63	3.62		

4-1 XLS 4-1 Table 7/15/95 4:50 PM

Test 4-1 Summary of Test Dimensional Measurement Results Specimen 4B-214, Tube Dia. = 0.876", Gap = 0.023"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in^2)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in^2)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
5800	0.0 Steps A, B, C	Initial Dim.	90°	0.650(2)	0.0	Tight	0.0	0.0	0.901	0.875 0.878
			270°	0.670(2)	0.24(2)	Tight	0.0	0.0		
			0°	0.610(2)	0.0		0.0	0.0	0.893	0.882 0.883
			180°	0.590(2)	0.0		0.0	0.0		
		Cold Test	Crack lengths following bladder pressurization are approximately the same as those measured after 0.15" offset test				0.0	0.0		
6000	0.15 Steps D, E, F	Cold	90°	0.665	0.606 (0.020W)	0.0099	0.099 (0.013W)	0.0011	0.901	>0.875 0.871
			270°	0.676	0.567 (0.015W)	0.0067	0.112 (0.009W)	0.0008		
			0°	0.606	0.388 (0.007W)	0.0022	0.0	0.0	0.893	>0.882 0.881
			180°	0.583	0.0	0.0	0.0	0.0		
6800	0.15 Steps G1, H1		Not Measured							
7725	0.15 Steps G2, H2		Not Measured							

Test 4-1 Summary of Test Dimensional Measurement Results
Specimen 4B-214, Tube Dia. = 0.876", Gap = 0.023"

Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in^2)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in^2)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
8900	0.15 Steps G3, H3, I	Cold	90°	0.668	0.626 (0.022W)	0.0125	0.133 (0.013W)	0.0017	0.901	0.898 0.877
			270°	0.680	0.603 (0.018W)	0.0090	0.122 (0.010W)	0.0010		
			0°	0.608	0.408 (0.009W)	0.0030	0.0	0.0	0.895	0.895 0.888
			180°	0.583	0.0	0.0	0.0	0.0		
8900	0.0, Step J	Cold	90°	Same as for 8900 psi bladder pressure with 0.015" offset			0.0	0.0	0.901	0.879 0.880
			270°				0.0	0.0		
			0°				0.0	0.0	0.898	0.889 0.888
			180°				0.0	0.0		
10120	0.15 Steps L1, M	Cold	90°	0.673	0.658 (0.026W)	0.0138	0.142 (0.026W)	0.0033	0.904	0.904 0.886
			270°	0.684	~.6 w/lig. (0.025W)	0.0130	0.100 (0.016W)	0.0016		
			0°	0.608	0.408 (0.010W)	0.0030	0.078 (0.006W)	0.00047	0.900	0.901 0.896
			180°	0.582	0.0	0.0	0.0	0.0		

Test 4-1 Summary of Test Dimensional Measurement Results Specimen 4B-214, Tube Dia. = 0.876", Gap = 0.023"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in^2)	Exposed TW Length (Max. Width) (in.)	Exposed TW Area (in^2)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
11350	0.15 Step L2	N/A	Tube burst outside TSP at the 90° crack with about a 1" crack tearing extension							

Notes:
1. Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.876" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
2. Crack lengths from dye penetrant measurements prior to bladder pressurization.
3. Crack lengths from toolmaker's microscope. Minimum measurable TW crack opening ~0.001".

Test Plan for IRBs
Test 4-1

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 3800 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.

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

Test 2-8: Summary of Test Results
Laser Slot Specimen

Test Sequence

- Order of tests: zero offset, freespan, offset, cold offset. No bladder pressurization tests were performed for this test.
- This test required 10 data points to be deleted because of hysteresis effects resulting from tests under flow pressurization that a run at lower pressure differentials than prior tests.
- The leak rate measurements show consistent trends and modest fluctuations such that the data are considered adequate test data for a laser specimen. However, the larger crack opening areas for a laser slot, especially at the crack tips, result in high leak rates that are not prototypic of corrosion cracks as discussed below.
- 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".

Summary of Test Results

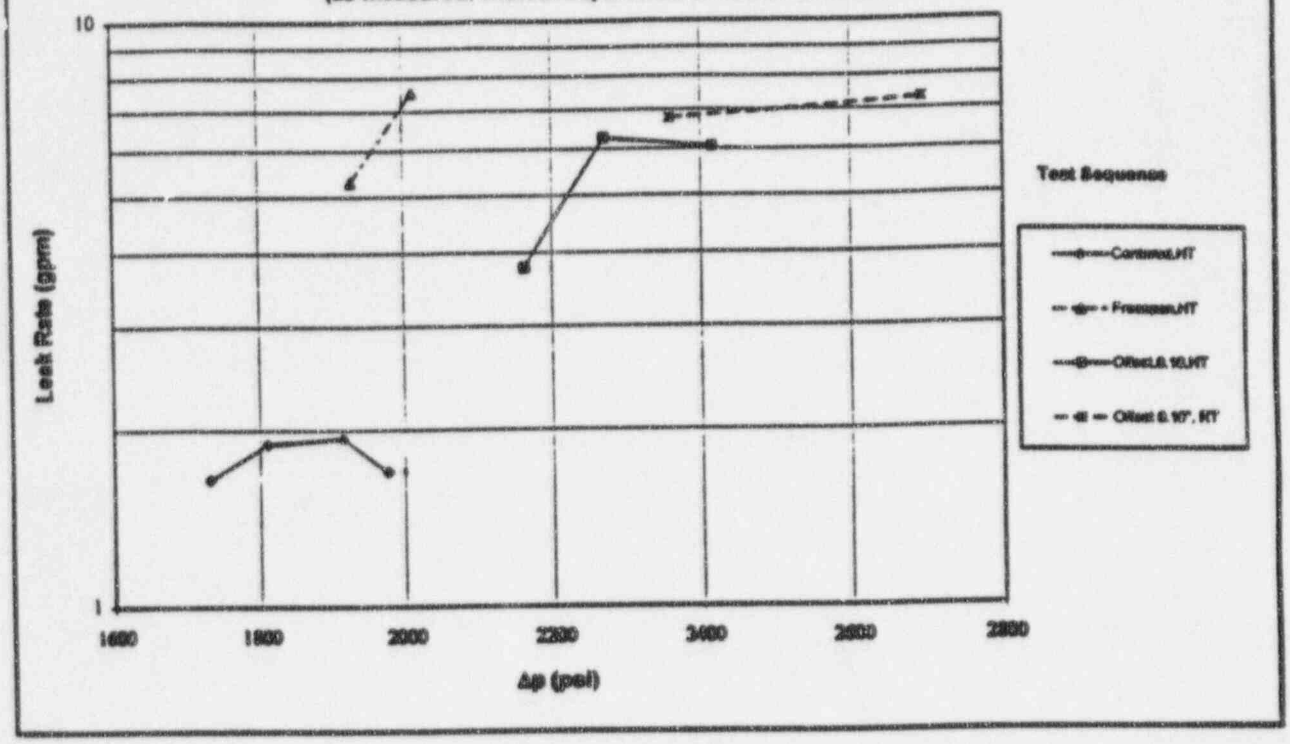
- The shallow slope of the leak rate curve above 1900 psi and the large increase in leak rate for free span conditions clearly demonstrate that interaction with the TSP significantly reduces leak rates.
  - The effects of crack to TSP interaction are similar to that for corrosion cracks although the lake rates are too high to be representative of corrosion cracks.
- The maximum SLB leak rate for this laser cut specimen is about 6.1 gpm in the offset condition.
  - The maximum crack width for this specimen increased from an initial about 1 mil width to 0.007" after the zero offset test, 0.021" after the freespan test and 0.035" after the offset test. This crack width exceeds the corrosion crack widths for specimens tested up to 0.62" throughwall 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 large width of this specimen at the tips of the laser slot result in the laser slot being an unacceptable specimen for testing leak rate effects of TSP offset. The non-prototypic, large TW areas of the laser slot exposed by offsetting the TSP result in unrealistically large leak rates for offset tests.
  - Photographs of the post-test laser cut specimen show well rounded and wide openings at the tips of the laser slot that are not typical of corrosion cracks (compare laser slot after offset test to photographs for Tests 1-7 and 2-7 which have comparable crack lengths).
  - The crack opening TW area outside the TSP for the laser specimen offset test of 0.0021 in^2 is 60% higher than the largest corrosion specimen in Test 1-6 (0.74" TW vs. 0.55" for laser slot)
- The leak rates for the 0.55" TW laser slot are significantly higher (factors of 3 to 4 in free span) than obtained for the 0.577" TW corrosion crack of Test 2-7.
  - The laser slot 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 slot and 0.022" for Test 2-7.
- When the test pressure drops are adjusted to the maximum ΔP at the start of the leak test as compared to the average pressure drop used for reporting test results, the trends related to

interaction with the TSP and the SLB leak rate are not significantly changed although the test pressures are increased by about 200 psi.

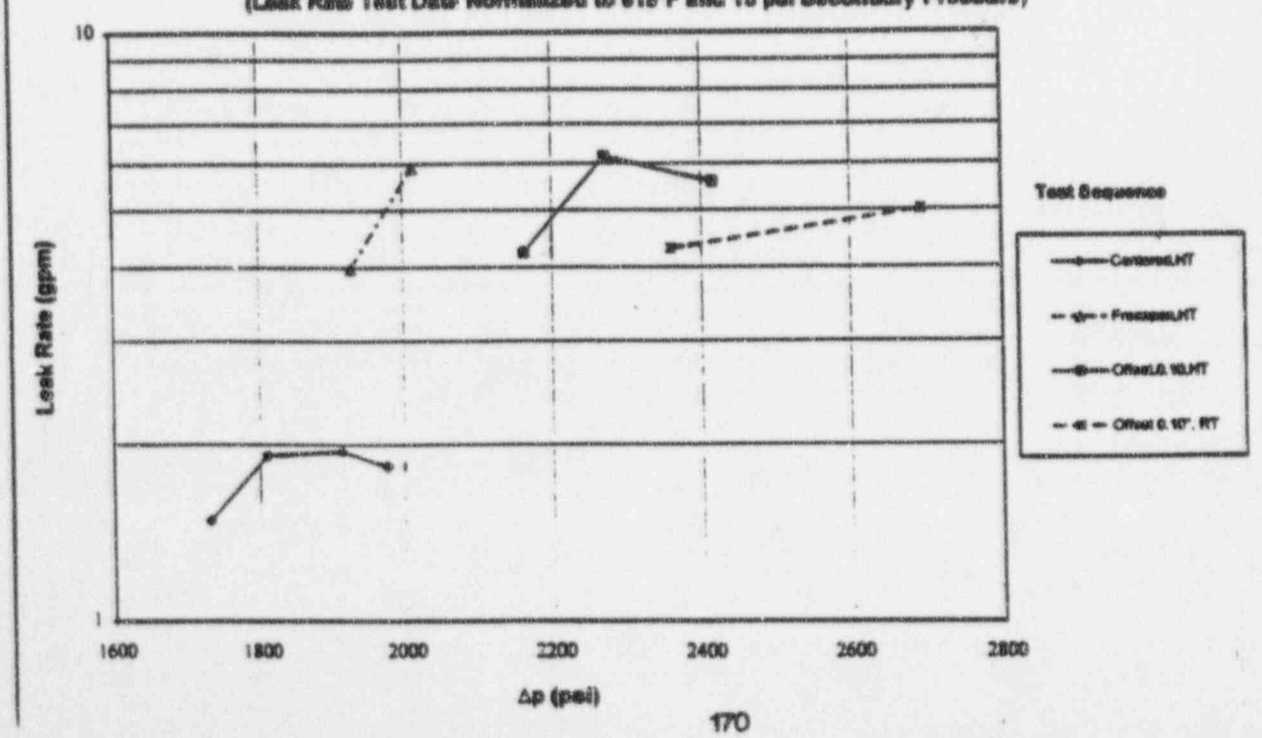
Overall Conclusions

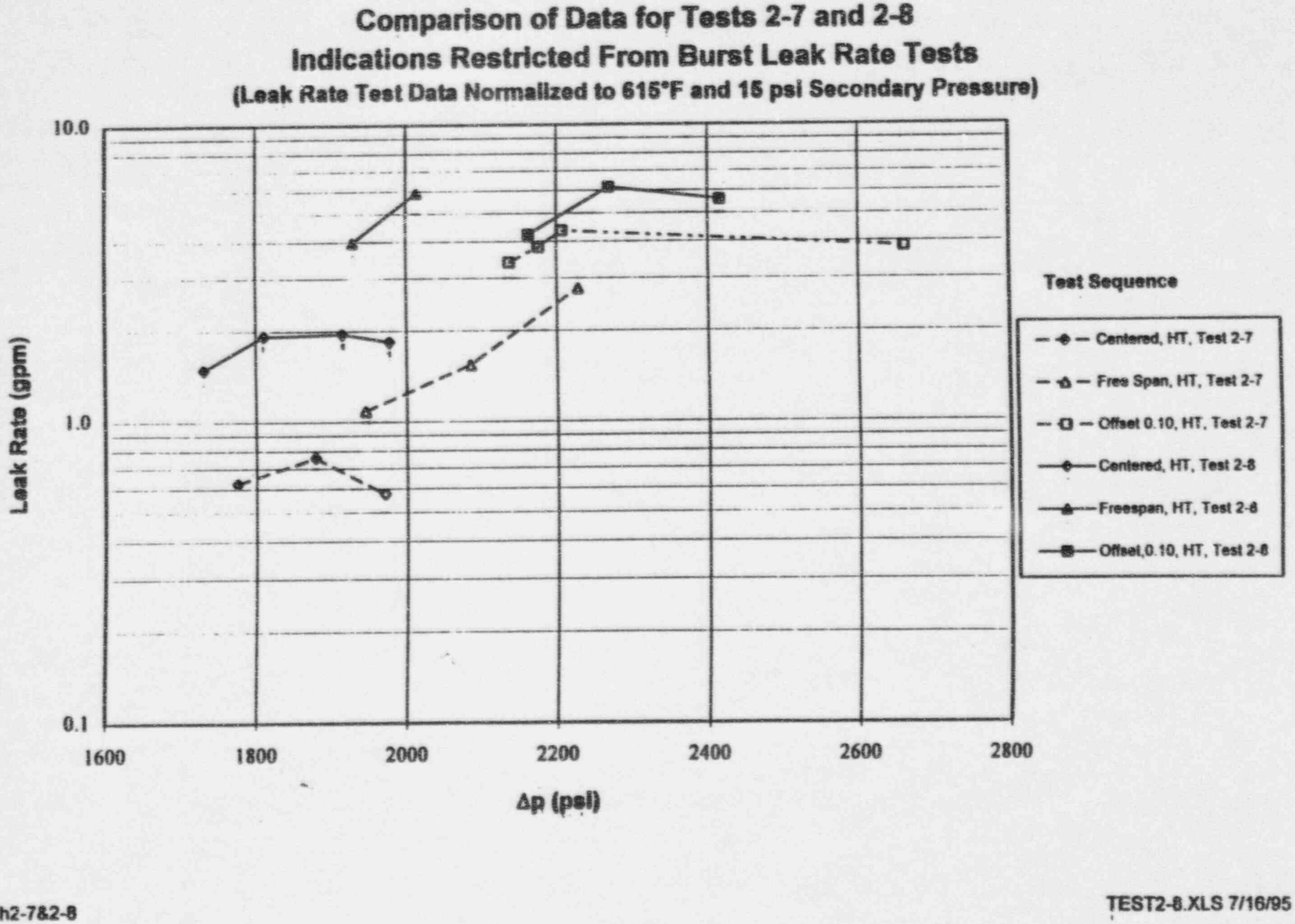
- Laser cut specimens are not an acceptable substitute for corrosion cracks for leak testing
  - Laser cut specimens result in a factor of 3 increase in free span leak rates as indicated by comparing Tests 2-8 and 2-7 results
  - The large widths at the tips of the laser slot result in non-representative leak rates for offset test conditions.
- The trends and effects of crack to TSP interaction can be demonstrated by laser slots although the leak rates are too high to be representative of corrosion cracks

Test 2-8
Indications Restricted From Burst Leak Rate Tests
(as-measured, without adjustment to reference conditions)



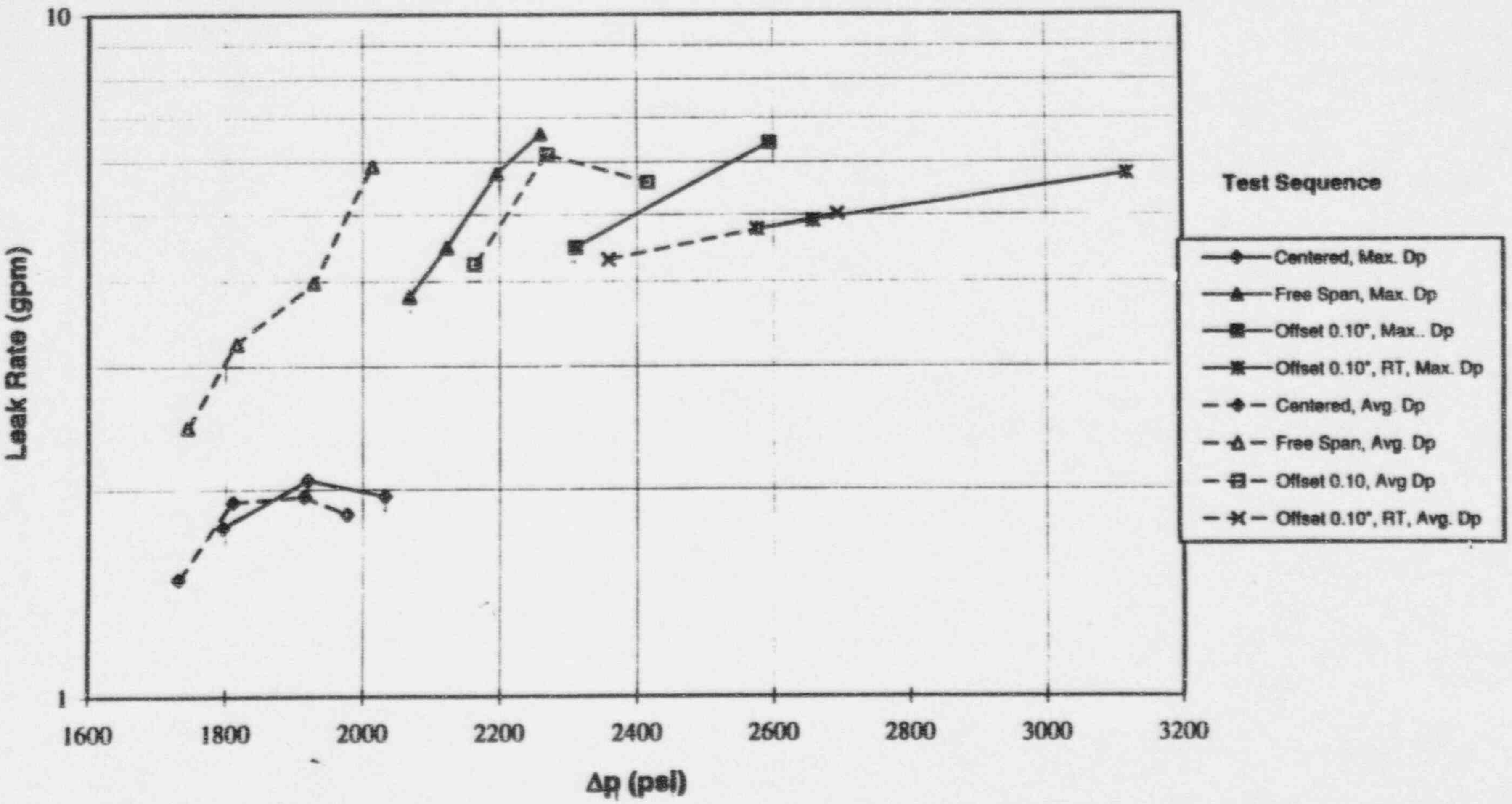
Test 2-8
Indications Restricted From Burst Leak Rate Tests
(Leak Rate Test Data Normalized to 615°F and 15 psi Secondary Pressure)

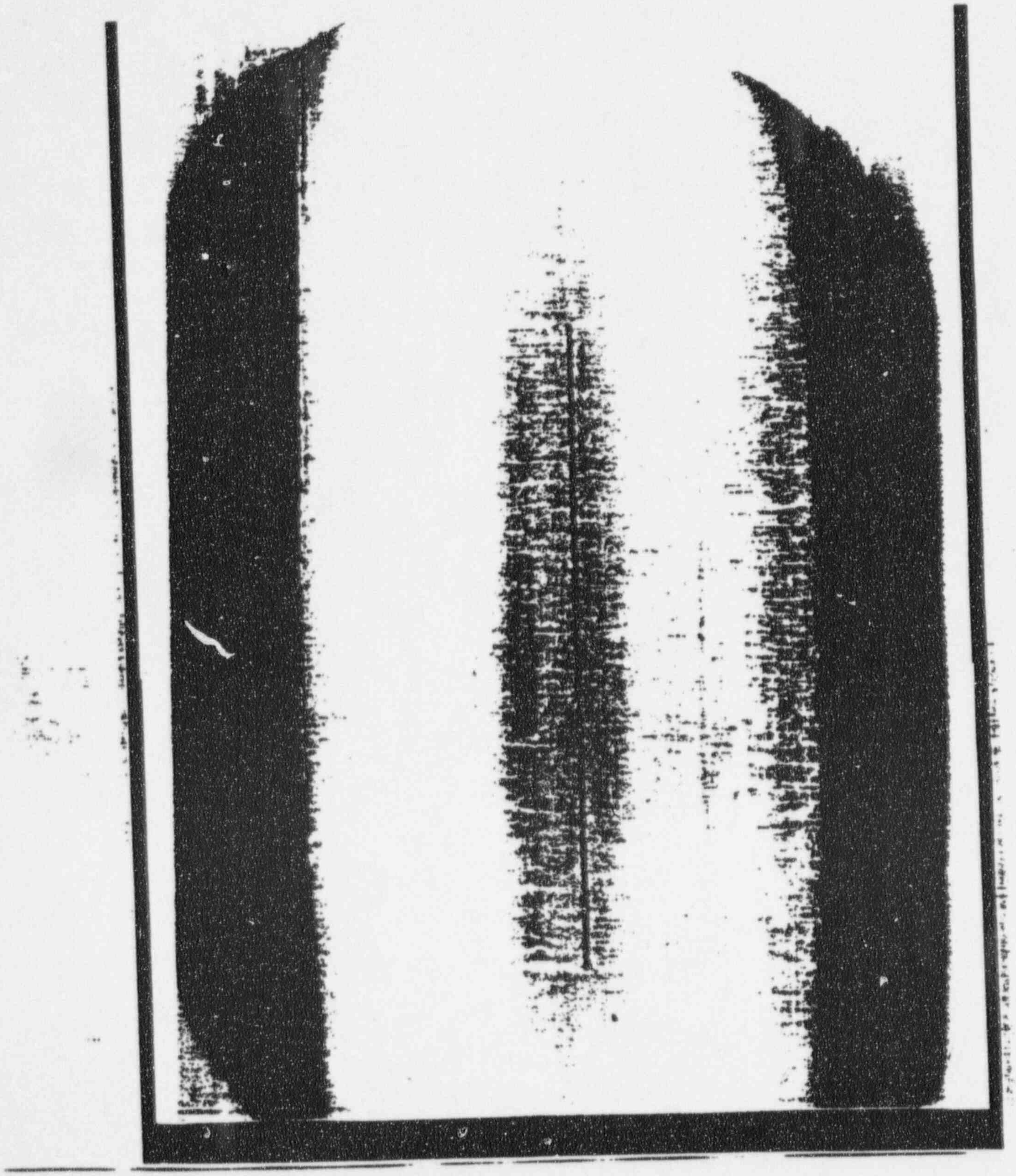



Comparison of Data for Tests 2-7 and 2-8
Indications Restricted From Burst Leak Rate Tests
(Leak Rate Test Data Normalized to 615°F and 15 psi Secondary Pressure)
10.0
1.0
0.1
Leak Rate (gpm)
1600
1800
2000
2200
2400
2600
2800
Δp (psi)
Test Sequence
Centered, HT, Test 2-7
Free Span, HT, Test 2-7
Offset 0.10, HT, Test 2-7
Centered, HT, Test 2-8
Freespan, HT, Test 2-8
Offset,0.10, HT, Test 2-8
Ch2-7&2-8
TEST2-8.XLS 7/16/95

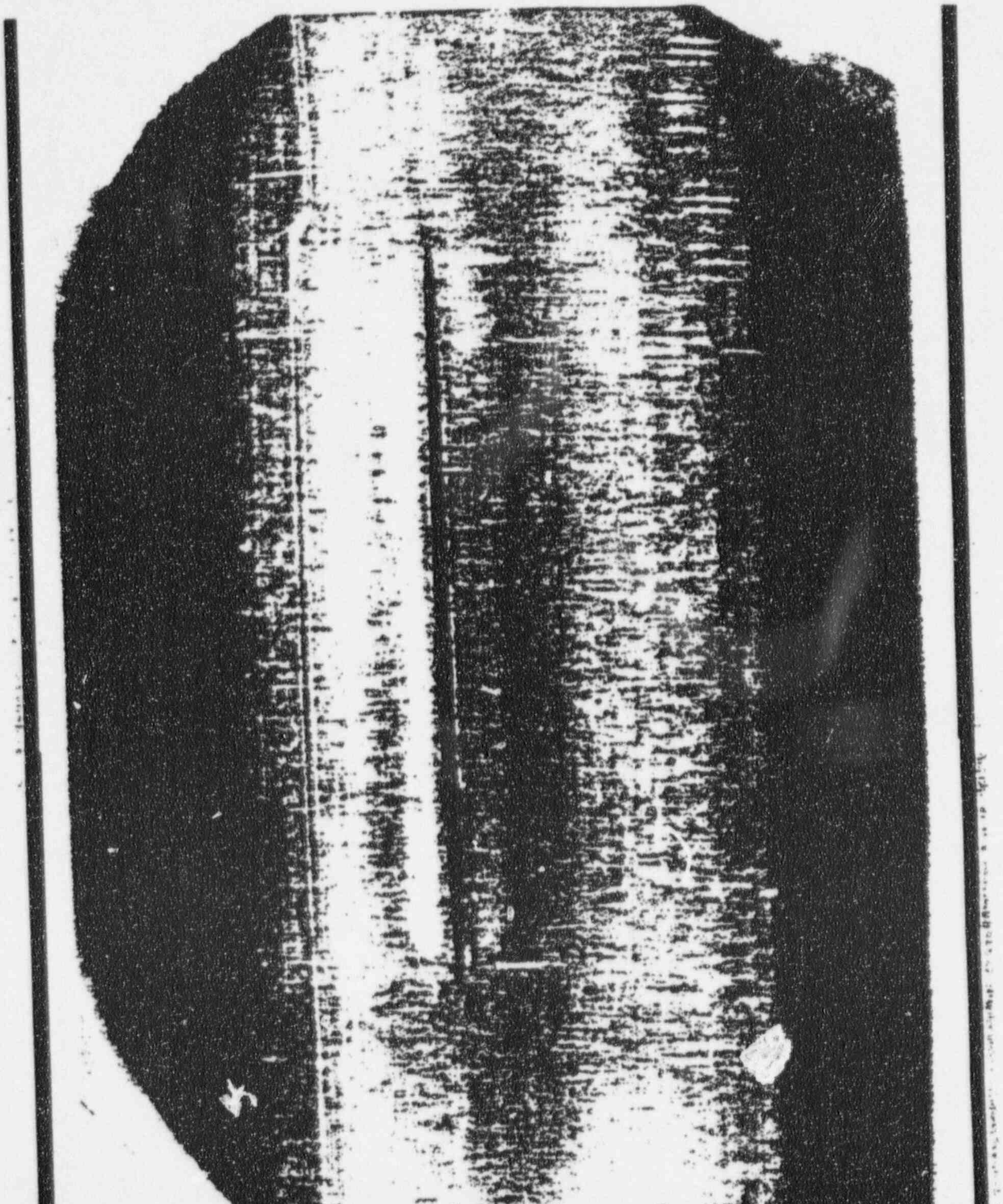
Test 2-8
Comparison of Leak Rates Based on Average and Max. Dp Indications Restricted From Burst Leak Rate Tests

(Leak Rate Test Data Normalized to 615°F and 15 psi Secondary Pressure)

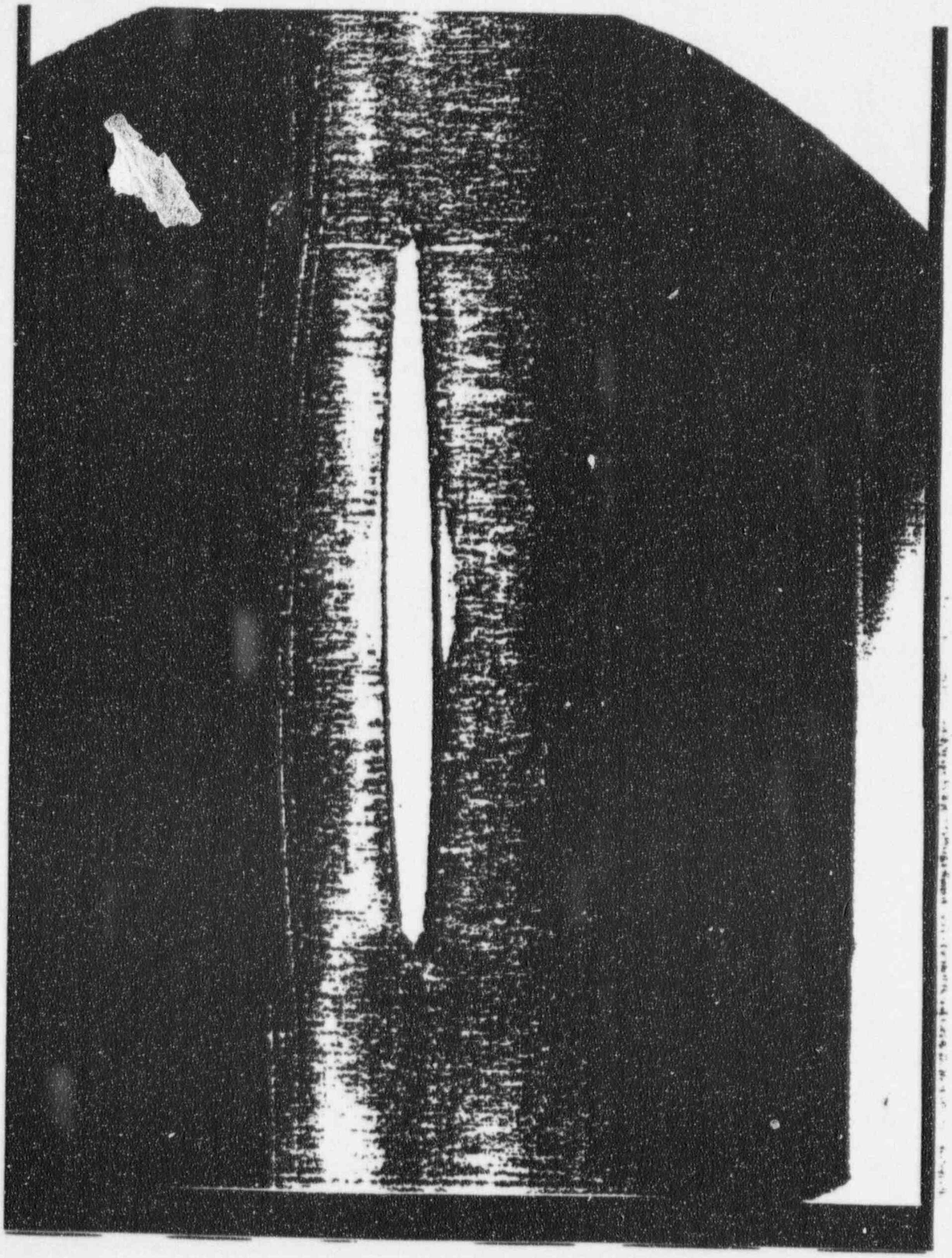




Test 2-8a. Laser Slot Prior to Leak Testing



Test 2-8b. Laser Slot After Test with Zero Offset



Test 2-8c. Laser Slot After Leak Test in Offset Condition

Test 2 - 8
Summary of Leak Test and Analysis Results
Specimen LC-2, Tube Diameter = 0.744", Gap = 0.025"

			Evaluated Test Averages						Adjusted Test Averages			Evaluation for Plots	
Test Sequence	Subtest No.	Max. ΔP_{test} (psi)	$P_{primary}$ (psig)	$P_{secondary}$ (psig)	Δp_{test} (psi)	$T_{primary}$ (F)	Measured Average Leak Rate (RT) (gpm)	Leak Rate Uncertainty (gpm)	β	γ	Leak Adjusted for temp. & Pressure(βγ) (gpm)	Average Leak Rate (gpm)	Comments
2-8A Within TSP HT	1	1766	1828	97	1731	616	1.65	0.15	1.00	0.90	1.48	1.48	
	2	1818	1912	106	1806	630	1.75	0.09	1.01	1.06	1.89	1.92	Average of 2, 4 & 5
	3	1804	1805	102	1703	611	1.97	0.17	1.00	0.84	1.65	-	Delete - Hysteresis
	4	1886	1938	114	1824	628	2.07	0.14	1.01	1.03	2.14	-	
	5	1885	1914	112	1802	618	1.87	0.18	1.00	0.92	1.72		
	6	1988	2045	119	1926	632	1.89	0.18	1.01	1.06	2.03	1.95	Average of 6 & 7
	7	2010	2017	114	1903	519	1.99	0.12	1.00	0.94	1.87		
	8	2055	2084	107	1977	632	1.70	0.1	1.01	1.07	1.84	1.84	
2-8B Free Span HT	1	1832	1939	195	1744	612	3.10	0.1	1.00	0.79	2.45	-	Delete - Hysteresis
	2	1933	2002	206	1796	621	3.28	0.18	1.00	0.86	2.85	-	Delete - Hysteresis
	3	1997	1921	224	1697	604	3.78	0.13	0.99	0.71	2.65	-	Delete - Hysteresis
	4	2012	2037	225	1812	613	3.73	0.16	1.00	0.80	2.99	-	Delete - Hysteresis
	5	2068	1977	255	1722	596	4.47	0.21	0.99	0.67	2.96	-	Delete - Hysteresis
	6	2118	2150	309	1841	607	5.24	0.2	0.99	0.74	3.87	-	Delete - Hysteresis
	7	2127	2244	315	1929	604	5.30	0.23	0.99	0.76	3.98	3.98	
	8	2195	2399	396	2003	622	6.46	0.24	1.01	0.81	5.28	5.90	Average of 8 & 10
	9	2259	2350	455	1895	604	8.04	0.3	0.99	0.70	5.56	-	Delete - Hysteresis
	10	2325	2516	491	2025	615	8.62	0.48	1.00	0.76	6.53	-	
2-8C Offset 0.10" HT	1	2196	2409	243	2166	640	3.70	0.07	1.02	1.02	3.83	4.23	Average of 1 & 2
	2	2317	2405	245	2160	655	3.84	0.19	1.04	1.16	4.63		
	3	2304	2326	273	2053	602	4.67	0.25	0.99	0.80	3.68	-	Delete - Hysteresis
	4	2585	2269	352	2269	620	5.84	0.37	1.00	1.03	6.03	6.16	Average of 4 & 5
	5	2619	2270	382	2270	605	6.67	0.28	0.99	0.95	6.29		
	6	2590	2799	383	2416	631	6.05	0.32	1.01	0.91	5.59	5.59	
2-8E Offset 0.10" RT	1	2576	2305	33	2272	75	6.68	0.16	0.98	0.63	4.12	-	Delete - Hysteresis
	2	2654	2387	36	2351	75	6.78	0.11	0.98	0.65	4.29	4.30	Average of 2 & 3
	3	2662	2404	38	2366	75	6.78	0.18	0.98	0.65	4.31		
	4	3124	2744	51	2693	75	7.42	0.24	0.98	0.70	5.09	5.02	Average of 4 & 5
	5	3115	2748	53	2695	75	7.20	0.2	0.98	0.70	4.94		

Test 2-8. Summary of Test Dimensional Measurement Results Specimen IRB-LC2, Tube Dia. = 0.744", Gap = 0.025"										
Bladder Pressure (psi)	Tube Offset (in.)	Test Temp. Condition	Angle	Total Crack Length (in.)	Total TW Length (Max. Width) (in.)	Total TW Area (in^2)	Exposed TW Length Max. Width) (in.)	Exposed TW Area (in^2)	Max. Dia. (in.)	Min. Dia. (in.) Note 1
None	0.0 Step A	Initial Dim.	0°	0.553(4)	N.M.(2)	~0.00053	0.0	0.0	0.744	0.745 0.744
		Hot Test	0°	0.553(4)	0.525(4) (0.007W)	0.0029	0.0	0.0	0.748	0.744 0.744
None	Freespan Step B	Hot	0°	0.554(4)	0.547(4) (0.021W)	0.0093	-	-	0.764	0.742 0.743
None	0.10 Steps C, D	Hot	0°	0.565	0.558 (.035W)	0.0164	0.104 (0.025W)	0.0021	0.774	0.763 0.745
None	0.10 Steps E, F	Cold	0°	0.569	0.558 (.035W)	0.0164	0.097 (0.025W)	0.0020	0.773	0.760 0.744

Notes:
1. Diameters given are approximately the values at the two edges of the TSP. Diameters greater than the initial 0.749" diameter indicate bulging of the tube at the edges of the TSP as a result of the tube pressurization.
2. Not measurable. Irregular light penetration through slot. Maximum measurable width of laser slow ~ 0.0015".
3. Crack lengths from dye penetrant tests
4. Crack lengths from toolmaker's microscope. Minimum measurable TW crack opening ~0.001"

Test Plan for IRBs
Test 2-8

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.

5.0 Trend Analyses

Leak Rate Dependence on Crack Length, Crack Opening Area, Offset Area, etc.

- Method of analysis - all leak rates adjusted to 2560 psid based on linear extrapolation of log leak rate versus pressure data plots. Crack lengths and open areas obtained from dimensional measurements for each test.
- Leak rates correlate well with throughwall crack length
  - Good agreement between correlations for zero offset and offset leak rates
  - Except for laser slot used in Test 2-8 which has twice the leak rate found for throughwall cracks of comparable length
- Leak rates correlate reasonably well with total crack opening area
  - Slope of correlation decreases (does not follow linear relation typical of free span cracks) with increasing area indicating tube to TSP interaction reduces leak rate and effective crack area for large crack opening areas
  - Good agreement between correlations for offset and zero offset data
  - Leak rates for test sequences 11 and 12 generally lie above the regression curve based on all of the test data. Following bladder pressurization, Test 12-7 had a large crack area and lies below the regression lines since this specimen was pressurized well above the free span burst pressure (pressurized to 6200 psi compared to free span burst pressure of about 3950 psi). Test 12-7 has been deleleted from the correlations with crack opening area.
  - Some spread in the data about the regression curve can be expected due to uncertainties in the throughwall crack area measurements
- Offset test leak rates show no correlation with the offset throughwall length and only a weak correlation with the offset TW area outside the TSP
- The differences in leak rates between offset and zero offset crack locations correlate reasonably with the offset flow area outside the TSP for tests prior to bladder pressurization but not for tests following pressurization to the free span burst pressure
- The leak rate trends for the laser slot of Test 2-8 are distinctly different than that for corrosion cracks. The leak rate is about twice that of corrosion cracks of comparable throughwall lengths and the crack opening area is more than three times that found for corrosion cracks of comparable lengths. Thus laser slots are not an adequate simulant for corrosion cracks in leak rate testing.
- Summary conclusions
  - SLB leak rates for IRBs are primarily a function of the throughwall crack length
  - SLB leak rates do not increase linearly with the crack opening area, as would be expected for free span cracks, since the larger openings interact with the TSP hole ID to retard leakage flow from the largest crack widths near the center of the crack
  - The increase in leakage from cracks offset outside the TSP relative to the total crack within the TSP is a function of the crack opening area outside the TSP prior to reaching the free span burst pressure of the indication.

Summary of SLB Leak Rates[1] (2560 psid) and Crack Length/Area Data

Test	Specimen	Initial Lengths		Offset Test					Zero Offset Tests		
				TW Length	Total TW Area	Offset		2560 psi Leak Rate (gpm)	TW Length	Total TW Area	2560 psi Leak Rate (gpm)
		Total	TW			TW Length	TW Area				
Flow Pressurization Tests											
2-4	7/8,4C218	0.600	0.290	0.330	0.00033	0.000	0.00000	0.37	N.M.	N.M.	0.37
2-10	3/4,2051B	0.551	0.425	0.425	0.00043	0.000	0.00000	1.70	N.M.	N.M.	1.70
2-1	7/8,8161A	0.640	0.515	0.504	0.00330	0.134	0.00060	1.65	0.230	0.00058	0.93
2-7	3/4,2051E	0.660	0.577	0.636	0.00850	0.088	0.00048	4.10	0.515	0.00090	N.R.[2]
2-8	3/4,IRB-LC2	0.553	0.550	0.558	0.01640	0.104	0.00210	6.10	0.525	0.00290	2.30
1-1	7/8,8161G	0.626	0.620	0.595	0.00450	0.147	0.00074	3.70	0.494	0.00200	2.30
1-2	7/8,8161E	0.645	0.620	0.666	0.00650	0.145	0.00087	3.20	0.574	0.00170	N.R.
1-7	3/4,2051A	0.600	0.600	0.602	0.00710	0.091	0.00064	4.10	0.530	0.00430	3.20
1-6	3/4,2008E	0.760	0.740	0.724	0.02490	0.070	0.00130	5.50	0.619	0.01180	3.40
4-1	7/8,4B214	0.670	0.240	-	-	-	-	N.M.[3]	-	-	N.M.[3]
11-1[6]	7/8,5B403	0.710	0.600 0.110	0.620 0.129	0.01178	0.150	0.00134	5.00	0.620 0.129	0.00811	4.00
11-2	7/8,8161B	0.729	0.630	0.720	0.00681	0.173	0.00102	5.30	0.657	0.00284	N.R.
11-7	3/4,2008A	0.813	0.809	0.811	0.01855	0.102	0.00120	6.20	0.809	0.01660	6.20
12-1[4]	7/8,8161C	0.607 0.465	0.518 0.360	0.585 N.M.	0.00176	0.105	0.0001	3.20	N.M. N.M.	N.M.	3.20
12-7[5]	3/4,2008D	0.590	0.375 0.256	0.375 0.259	0.00213	0.100	0.0001	3.90	0.375 0.259	0.00168	3.90

Summary of SLB Leak Rates[1] (2560 psid) and Crack Length/Area Data

Test	Specimen	Initial Lengths		Offset Test					Zero Offset Tests		
		Total	TW	TW Length	Total TW Area	Offset TW Length	Offset TW Area	2560 psi Leak Rate (gpm)	TW Length	Total TW Area	2560 psi Leak Rate (gpm)
Bladder Pressurization Tests											
2-4	7/8,4C218	0.600	0.290	0.382	0.0038	0.076	0.00076	1.9	0.382	0.00380	1.3
2-10	3/4,2051B	0.551	0.425	0.492	0.0038	0.081	0.00048	1.6	0.492	0.00310	1.6
2-1	7/8,8161A	0.640	0.515	0.504	0.0038	0.132	0.00073	3.1	0.509	0.00410	3.2
2-7	3/4,2051E	0.660	0.577	0.637	0.0095	0.087	0.00052	3.7	0.637	0.01040	4.2
2-8	3/4,IRB-L62	0.553	0.550	-	-	-	-	N.M.[3]	-	-	N.M.[3]
1-1	7/8,8161G	0.626	0.620	0.595	0.0052	0.147	0.00074	2.4	0.595	0.00520	3.5
1-2	7/8,8161E	0.645	0.620	0.668	0.0078	0.085	0.00051	2.8	0.666	0.00730	2.7
1-7	3/4,2051A	0.600	0.600	0.613	0.0087	0.100	0.00087	3.3	0.613	0.00900	3.2
1-6	3/4,2008E	0.760	0.740	0.726	0.0262	0.070	0.00160	5.0	0.726	0.02570	4.8
4-1	7/8,4B214	0.670	0.240	0.606	0.0099	0.099	0.00110	4.2	0.606	0.00990	2.5
11-1[6]	7/8,5B403	0.710	0.600 0.110	0.754	0.0144	0.154	0.00168	5.0	0.754	0.01460	5.0
11-2	7/8.8161B	0.729	0.729	0.707	0.0116	0.150	0.00151	5.3	0.707	0.01140	4.9
11-7	3/4,2008A	0.813	0.809	0.811	0.0186	0.100	0.00118	6.2	0.811	0.01910	5.7
12-1[4]	7/8,8161C	0.607 0.465	0.518 0.360	0.630 0.411	0.0117	0.151	0.00181	5.7	0.629 0.411	0.01053	5.7
12-7[5]	3/4,2008D	0.590	0.375 0.256	0.726	0.0316	0.100	0.00215	3.3	0.726	0.03175	3.2

Summary of SLB Leak Rates[1] (2560 psid) and Crack Length/Area Data

Test	Specimen	Initial Lengths		Offset Test					Zero Offset Tests		
				TW Length	Total TW Area	Offset		2560 psi Leak Rate (gpm)	TW Length	Total TW Area	2560 psi Leak Rate (gpm)
		Total	TW			TW Length	TW Area				

Notes:

(1) Approximate leak rates at 2560 psid based on linear extrapolation of log leak rate vs Δp plots.

(2) N.R. - Estimate not reliable due to low pressure tested in zero offset condition or absence of crack to TSP interaction at lower pessures

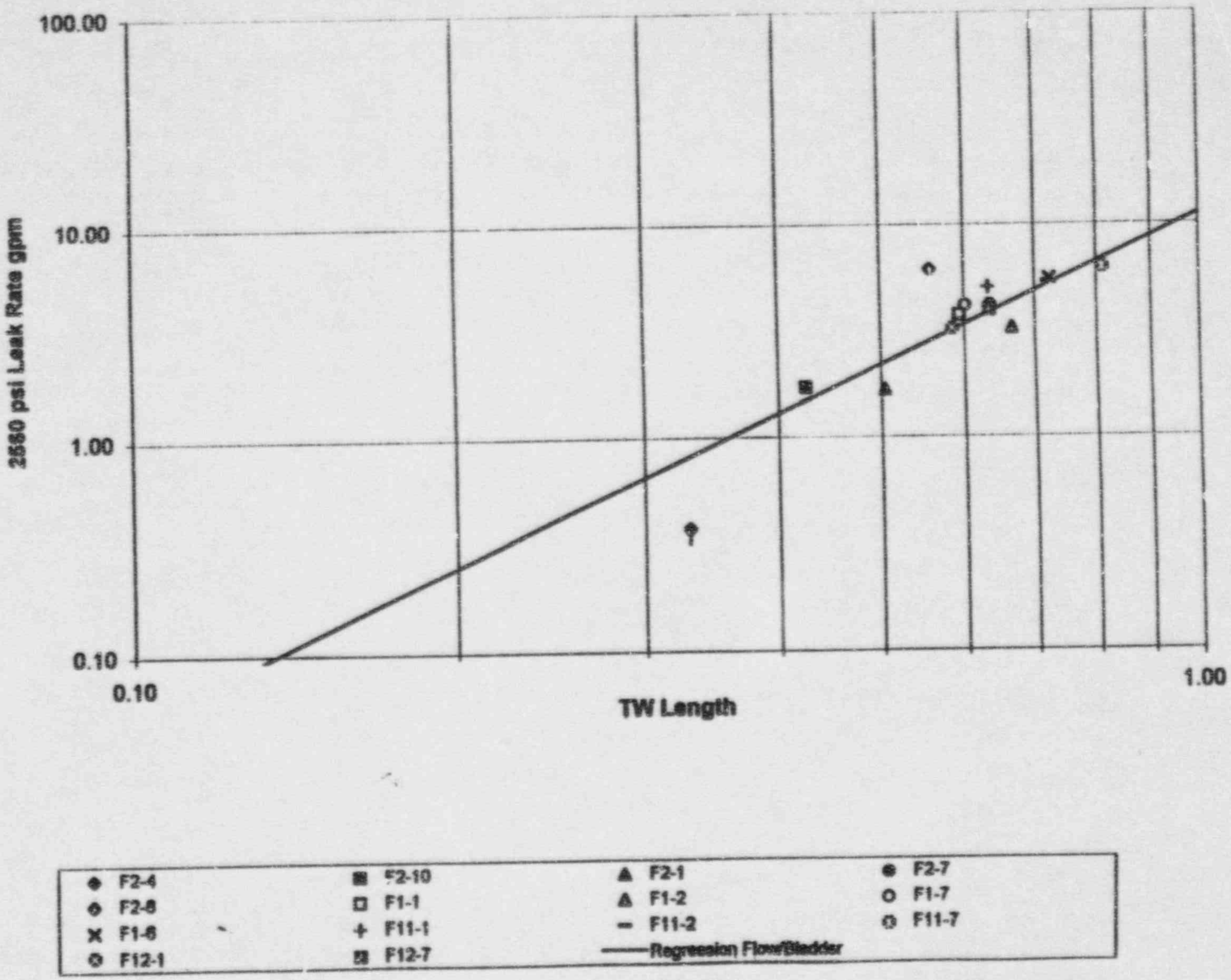
(3) N.M. - not measured. Test not performed.

(4) Specimen has two throughwall cracks 90° apart

(5) Specimen has two parallel throughwall cracks separated by a circumferential ligament 0.012" at the crack tips

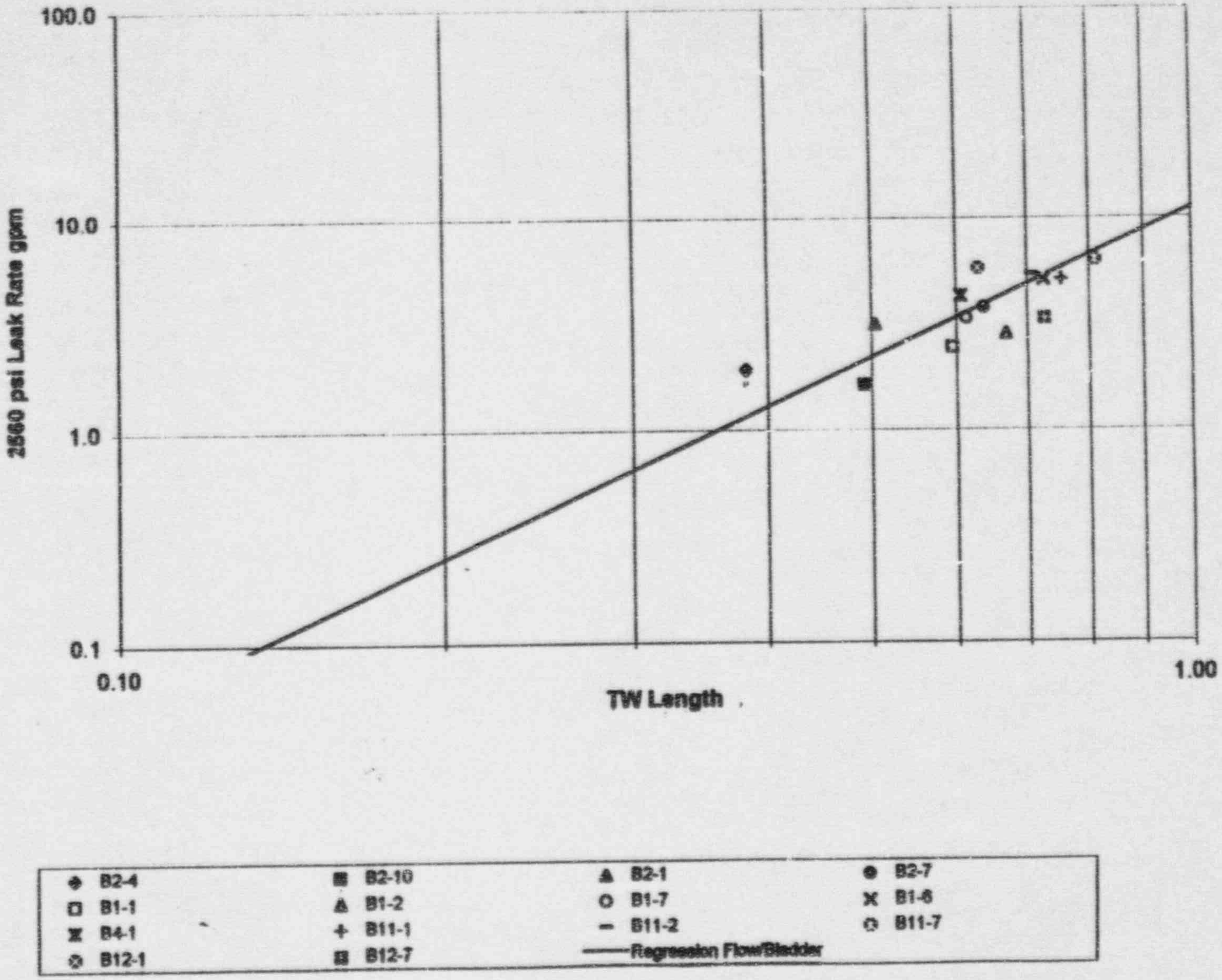
(6) Specimen has two aligned axial cracks separated by a ligament

Offset Leak Rate vs. Throughwall Crack Length for Flow Pressurization



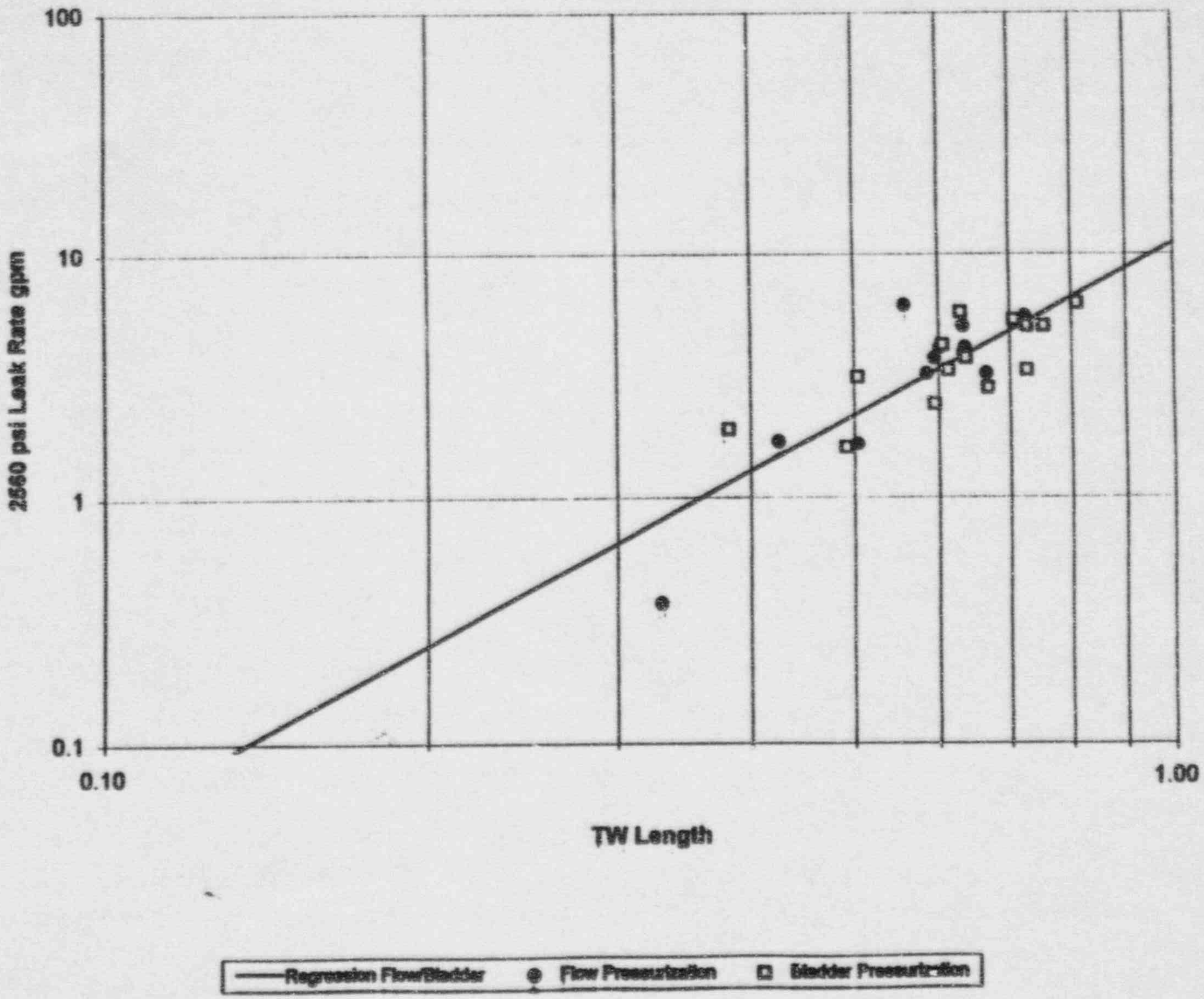
IRBLRCOR.XLS:TW Length - F:8/11/95

Offset Leak Rate vs. Throughwall Crack Length for Bladder Pressurization



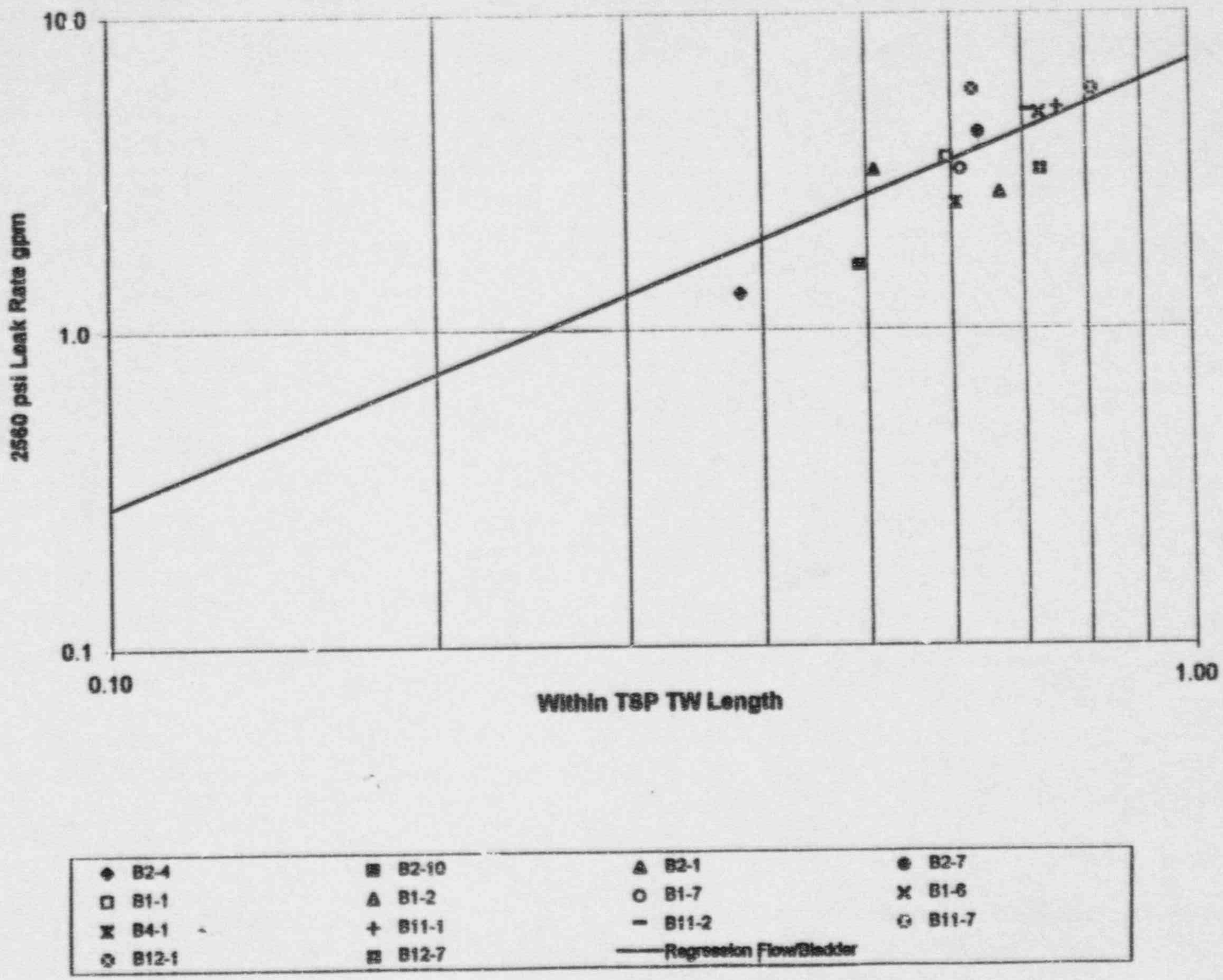
IRBLRCOR.XLS:TW Length - B:8/11/95

Offset Leak Rate vs. Throughwall Crack Length for Flow and Bladder Pressurization



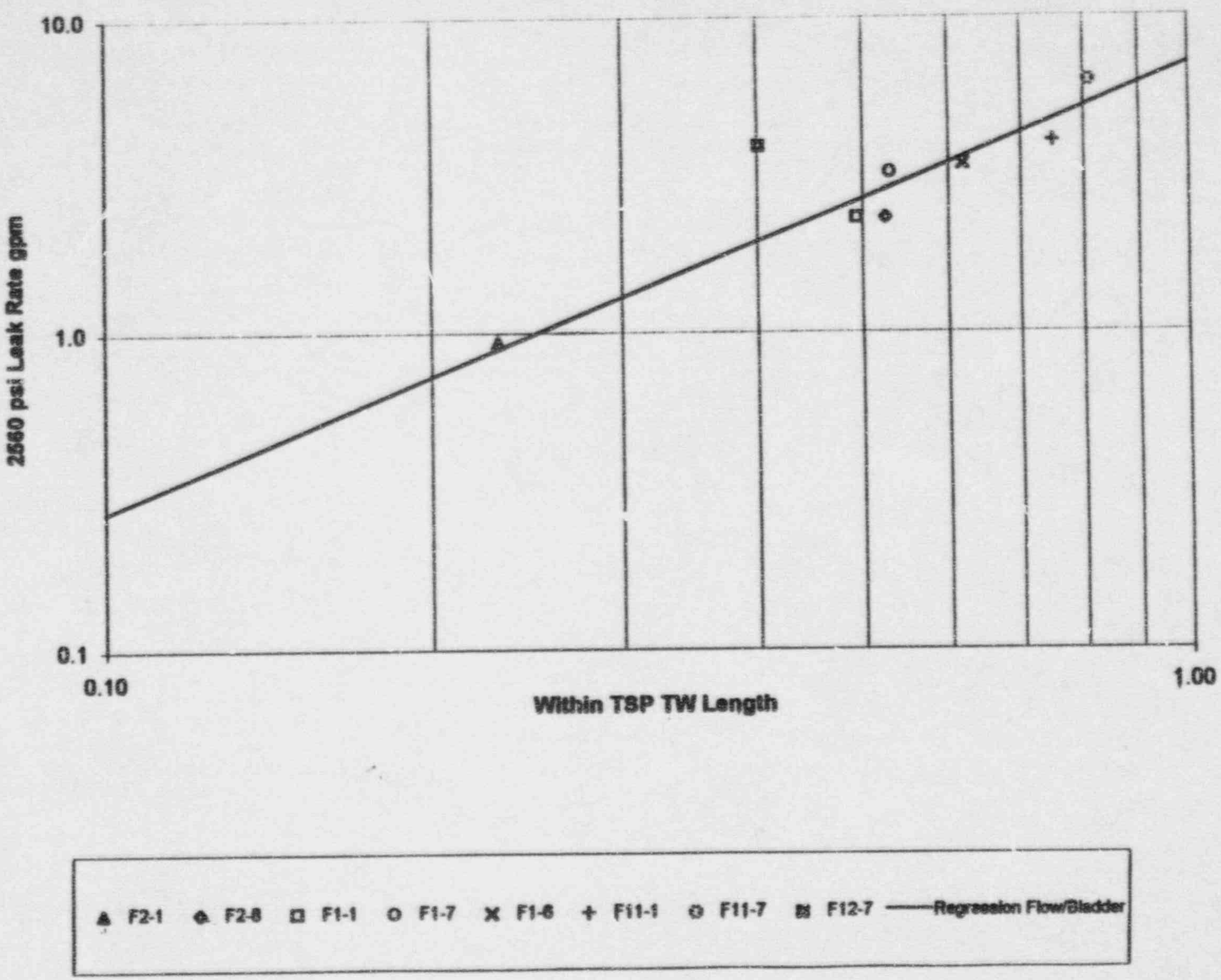
IRBLRCOR.XLS:TW Length - Comb:8/10/95

Zero Offset Leak Rate vs. Throughwall Crack Length for Bladder Pressurization



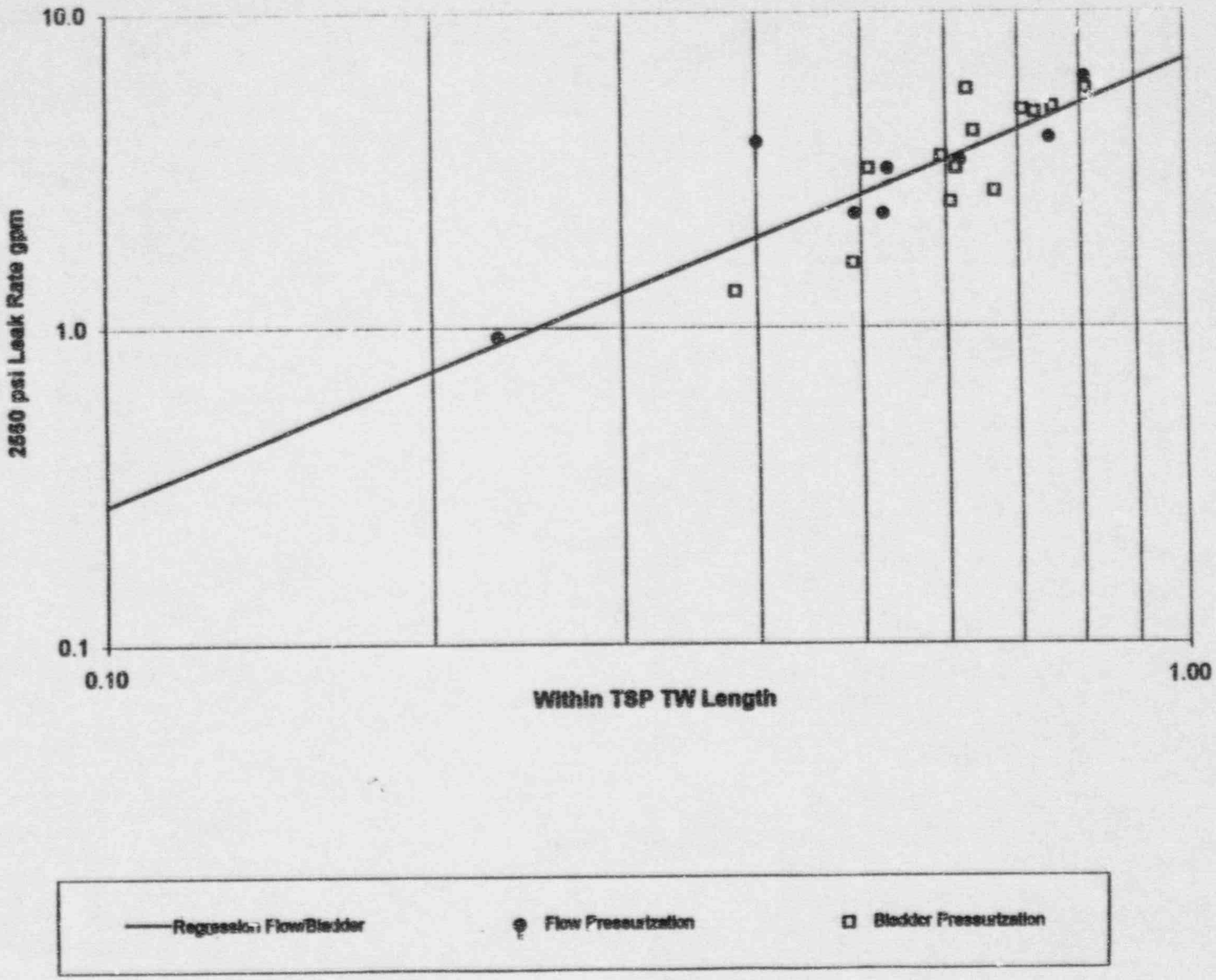
IRBLRCOR.XLS:TSP TW Length - B:8/11/95

Zero Offset Leak Rate vs. Throughwall Crack Length for Flow Pressurization



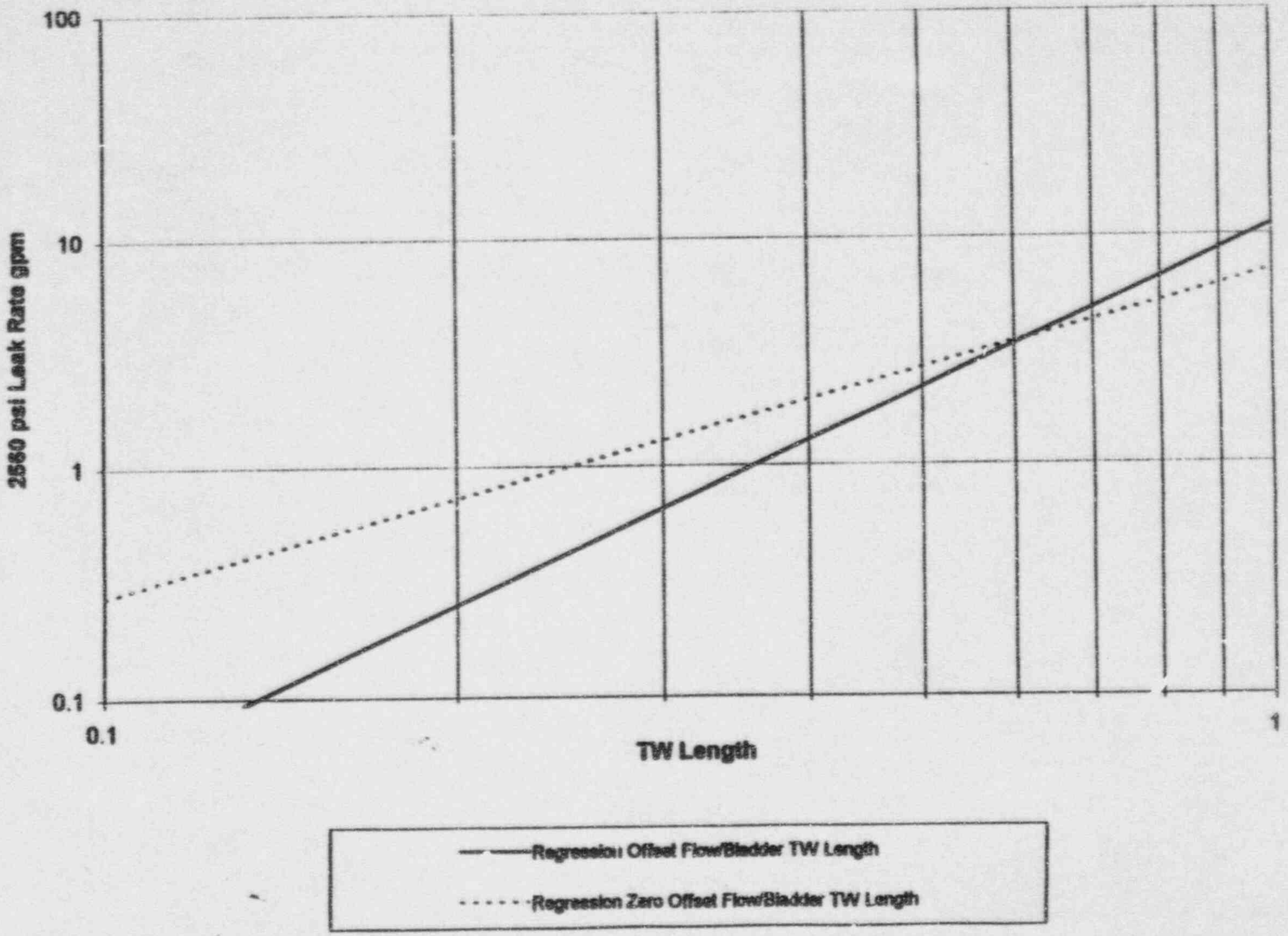
IRBLRCOR.XLS:TSP TW Length -F:8/11/95

Zero Offset Leak Rate vs. Throughwall Crack Length for Flow and Bladder Pressurization

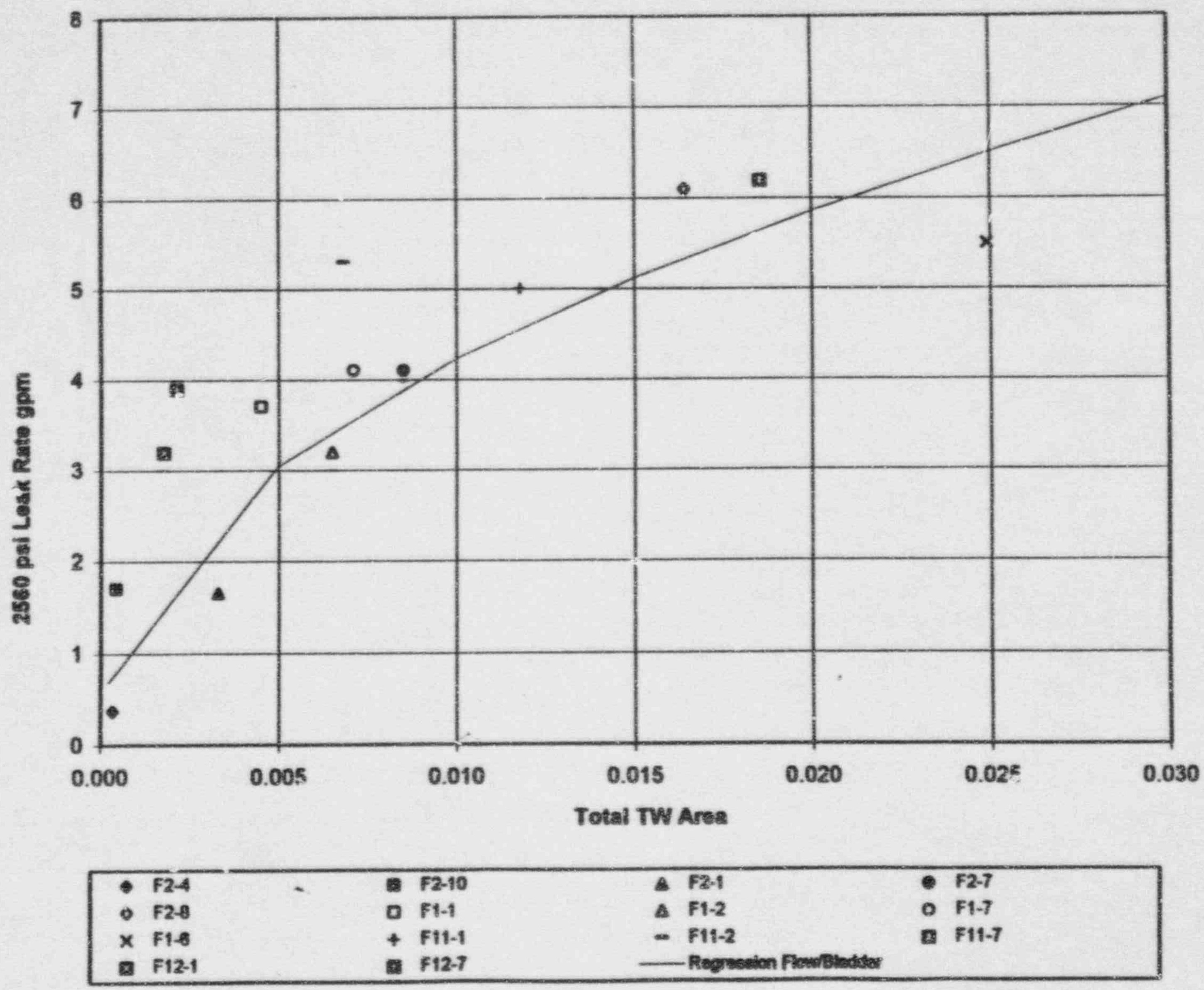


IRBLRCOR.XLS:TSP TW Length - Comb:8/11/95

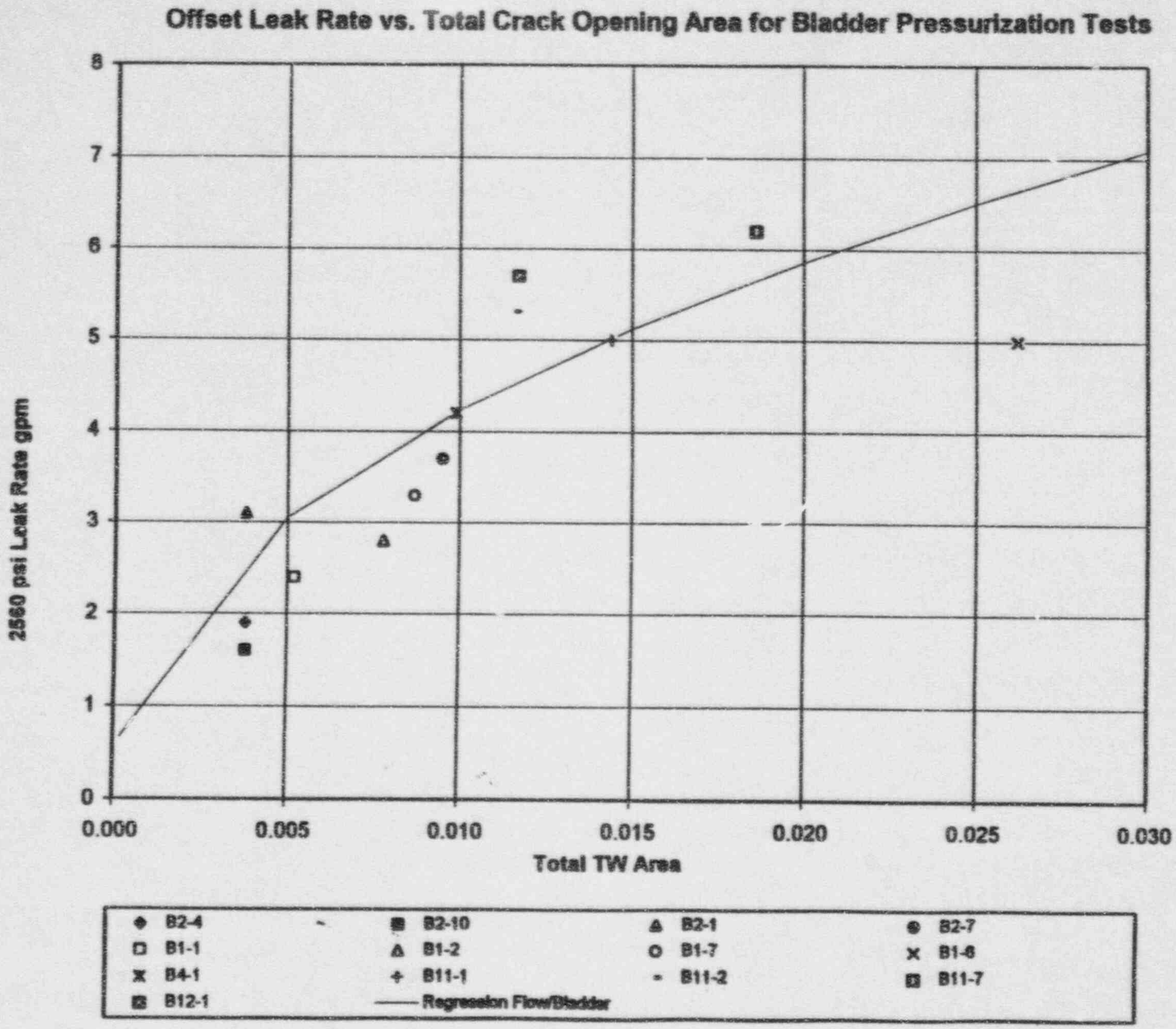
Comparison of Offset and Zero Offset Leak Rates vs. TW Length Regression Results



Offset Leak Rate vs. Total Crack Opening Area for Flow Pressurization Tests



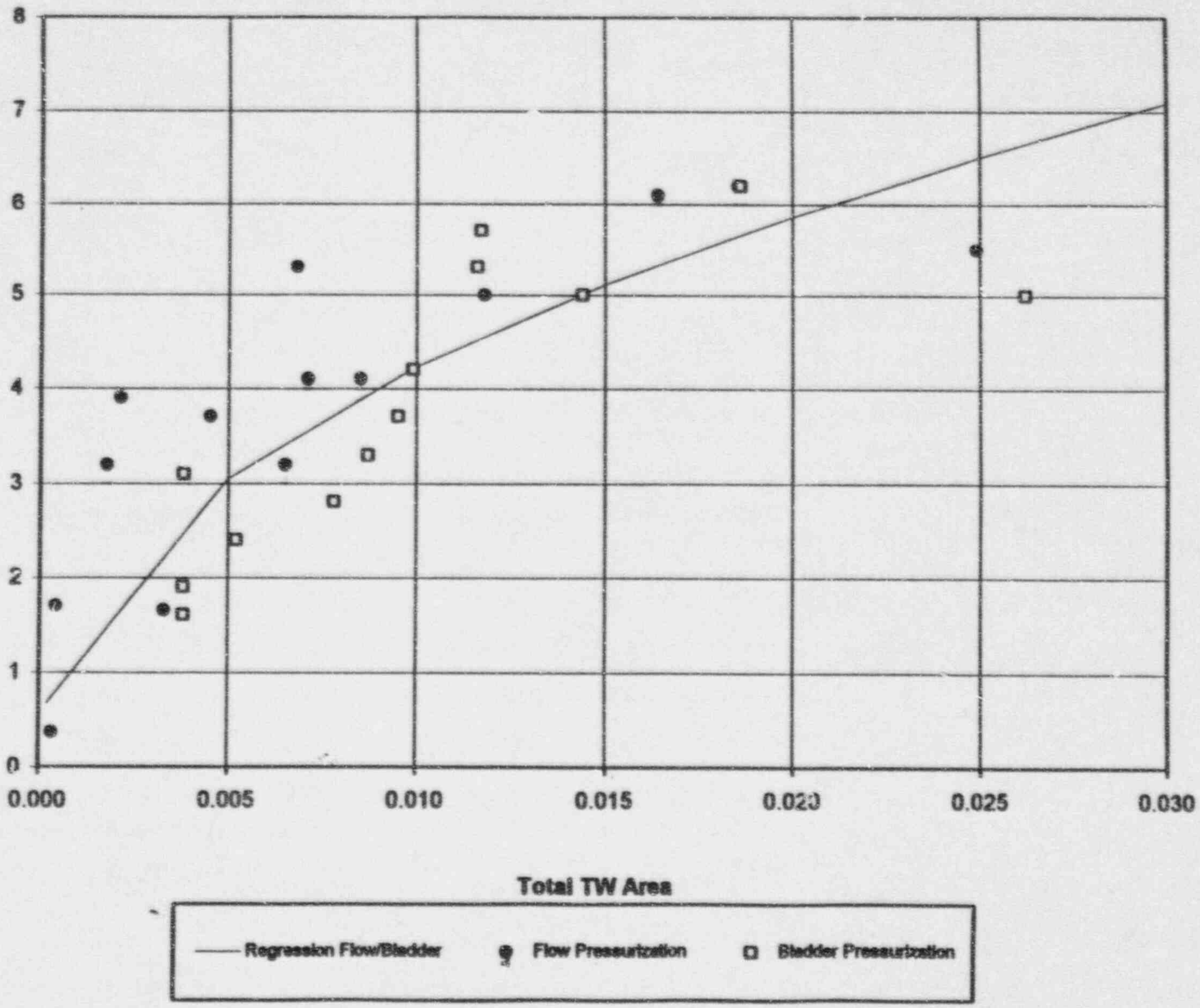
IRBLRCOR.XLS:Total TW Area - F:8/13/95



262

IRBLRCOR.XLS:Total TW Area - B:8/13/95

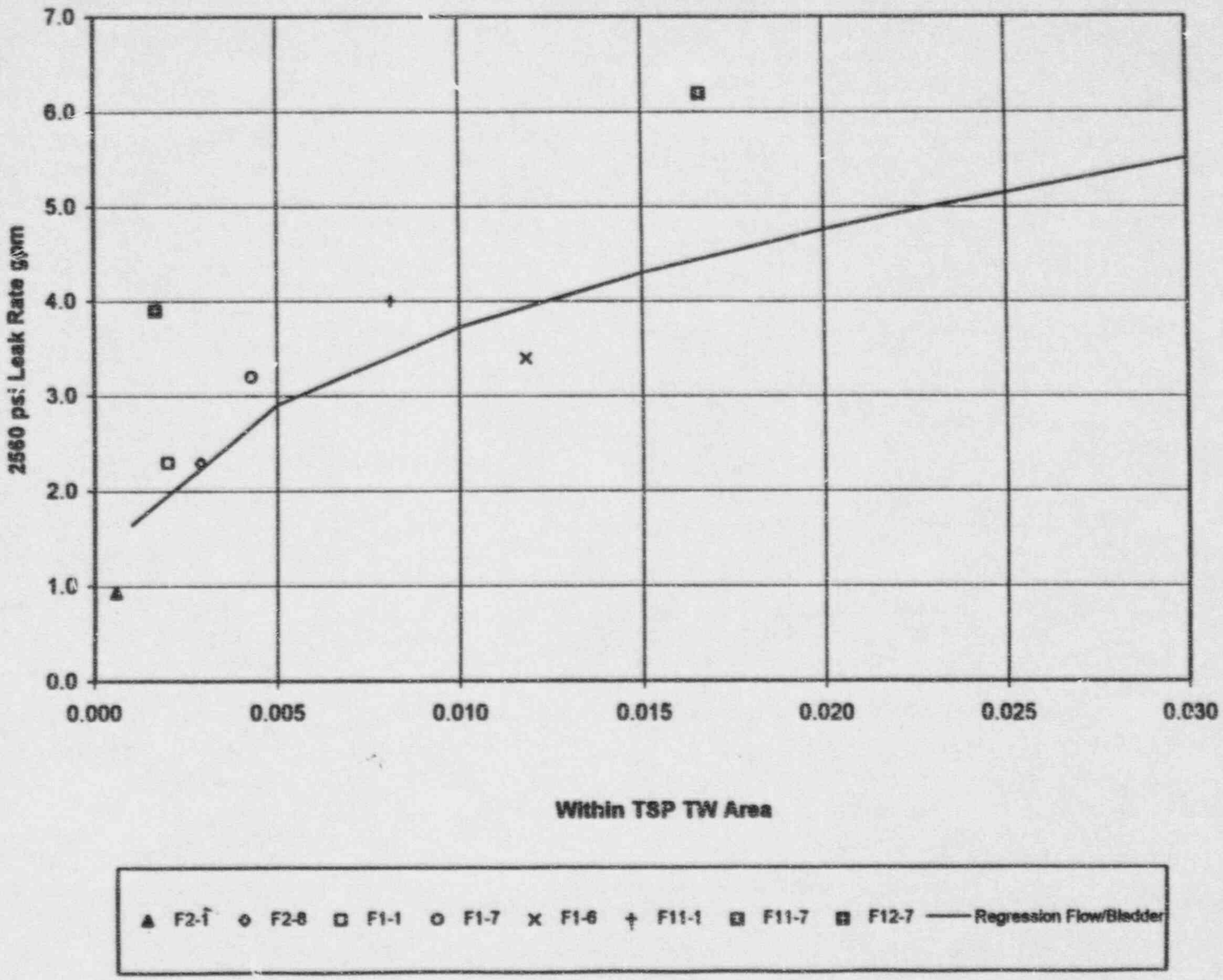
Offset Leak Rate vs. Total Crack Opening Area for Flow and Bladder Pressurization Tests



183

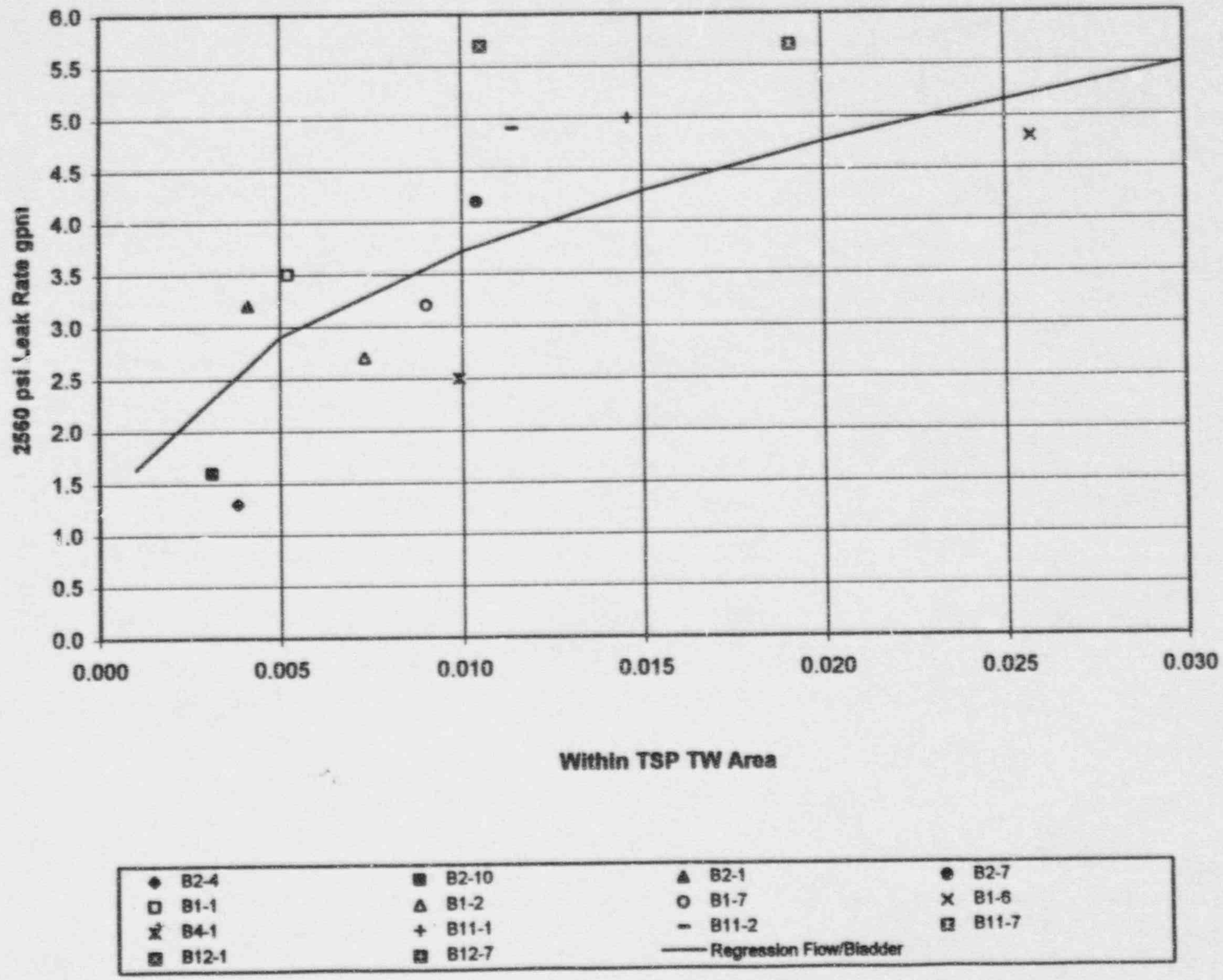
IRBLRCOR.XLS:Total TW Area - Comb:8/13/95

Zero Offset Leak Rate vs. Total Crack Opening Area for Flow Pressurization



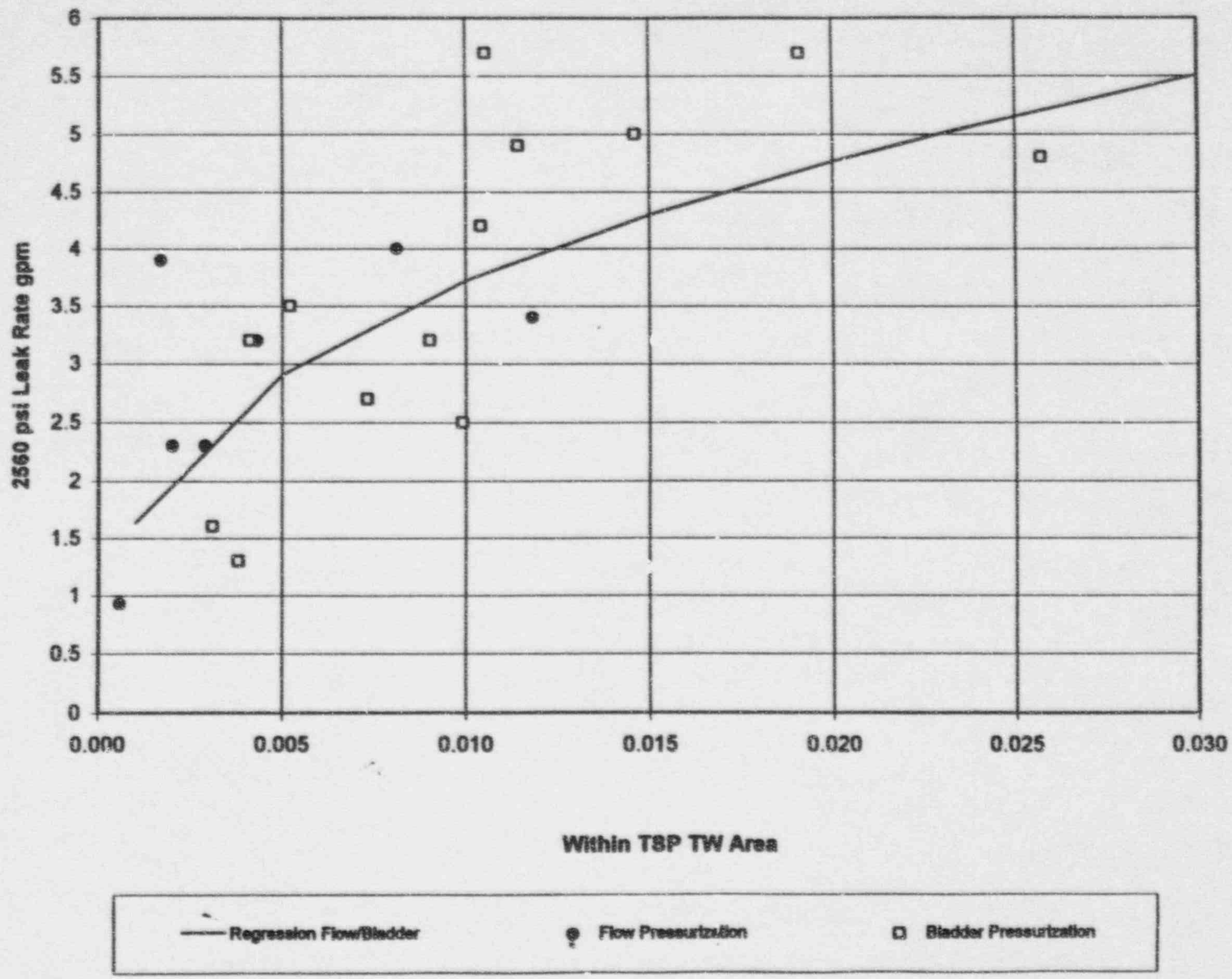
IRBLRCOR.XLS:TSP TW Area - F:8/13/95

Zero Offset Leak Rate vs. Total Crack Opening Area for Bladder Pressurization



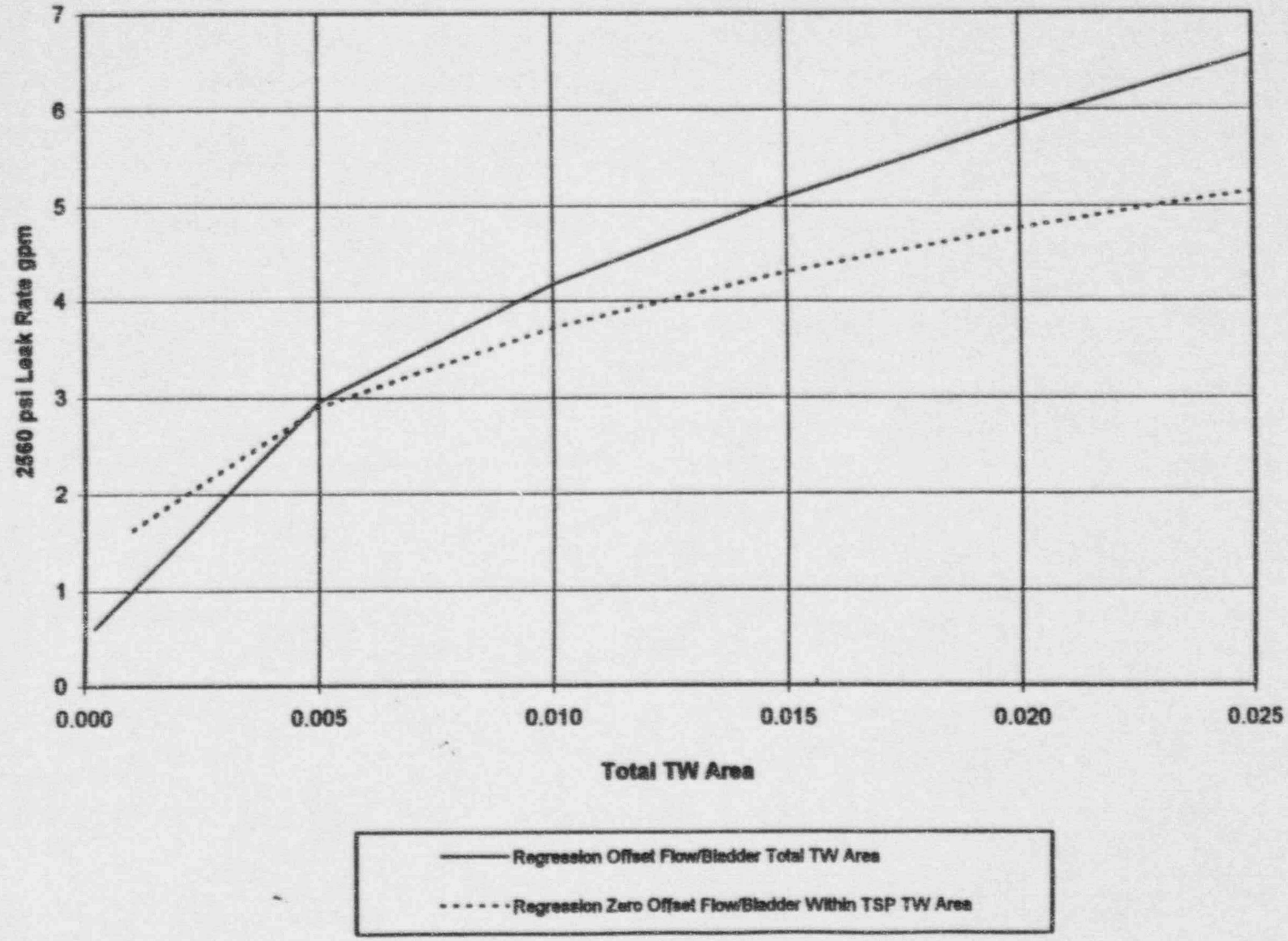
IRBLRCOR.XLS:TSP TW Area - B:8/13/95

Zero Offset Leak Rate vs. Total Crack Opening Area for Flow and Bladder Pressurization



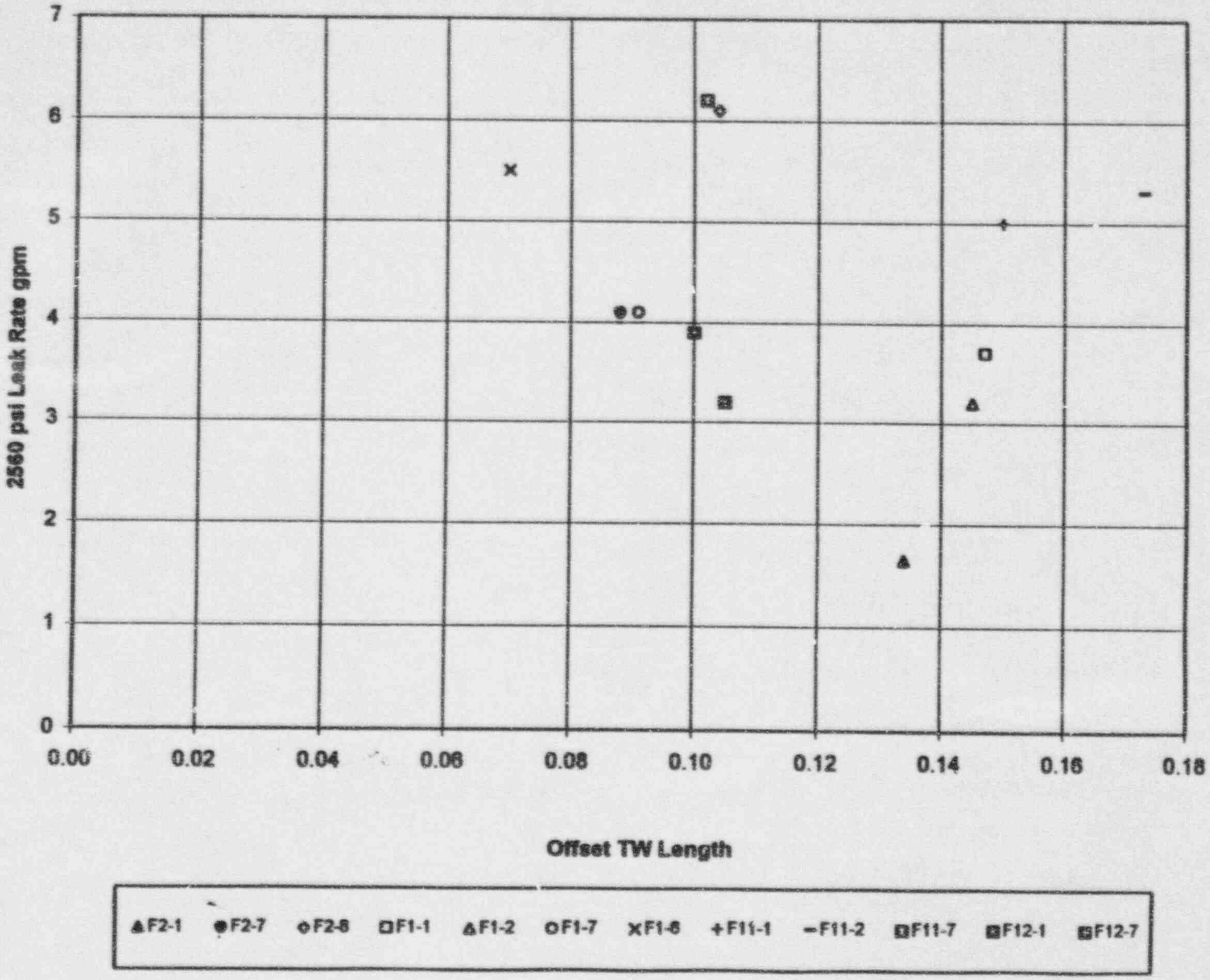
IRBLRCOR.XLS:TSP TW Area - Comb:8/13/95

Comparison of Offset and Zero Offset Leak Rate vs. Total Crack Area Regression Results



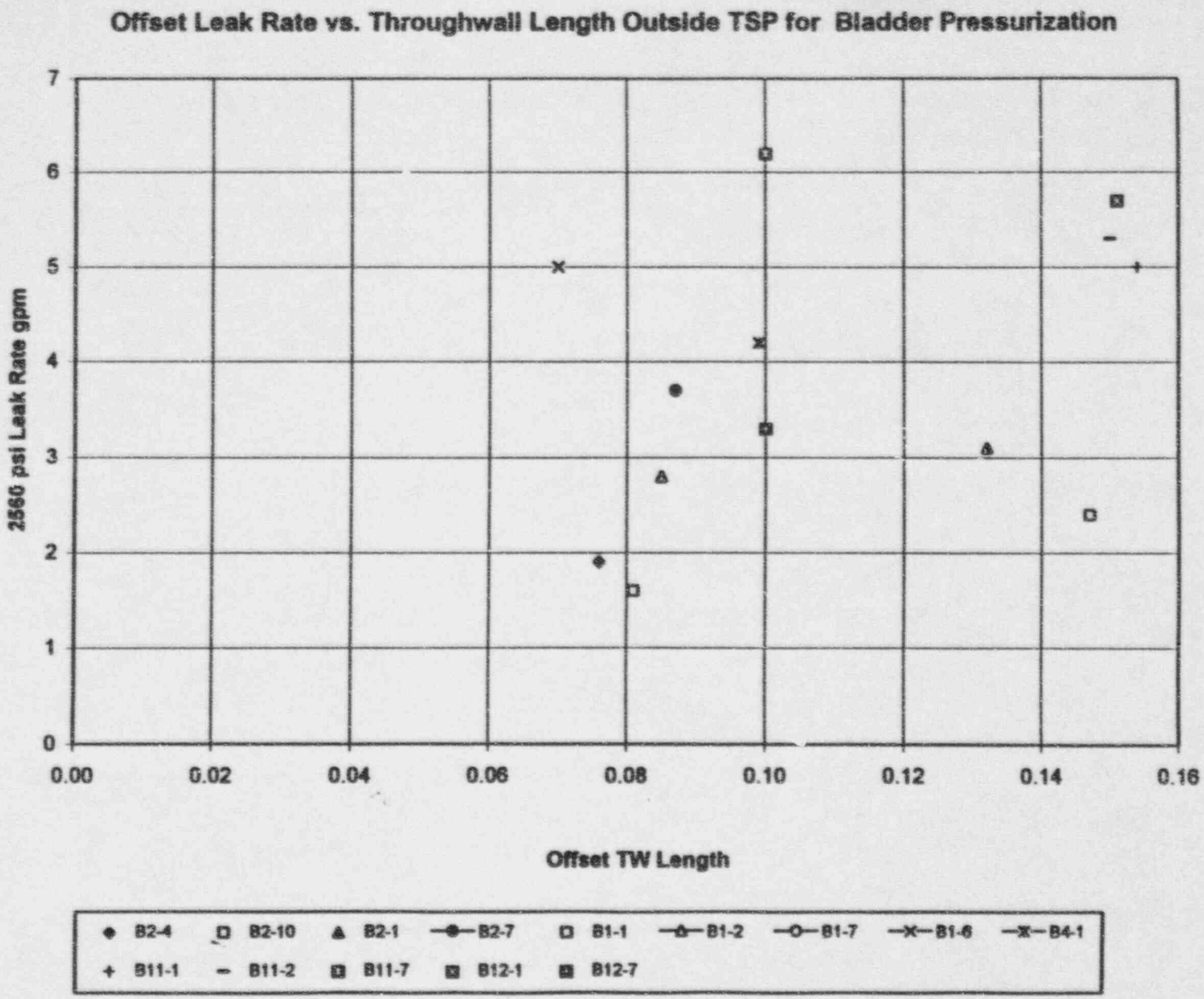
IRBLRCOR.XLS:Comp Total & Within TSP TW Area:8/13/95

Offset Leak Rate vs. Throughwall Length Outside TSP for Flow Pressurization

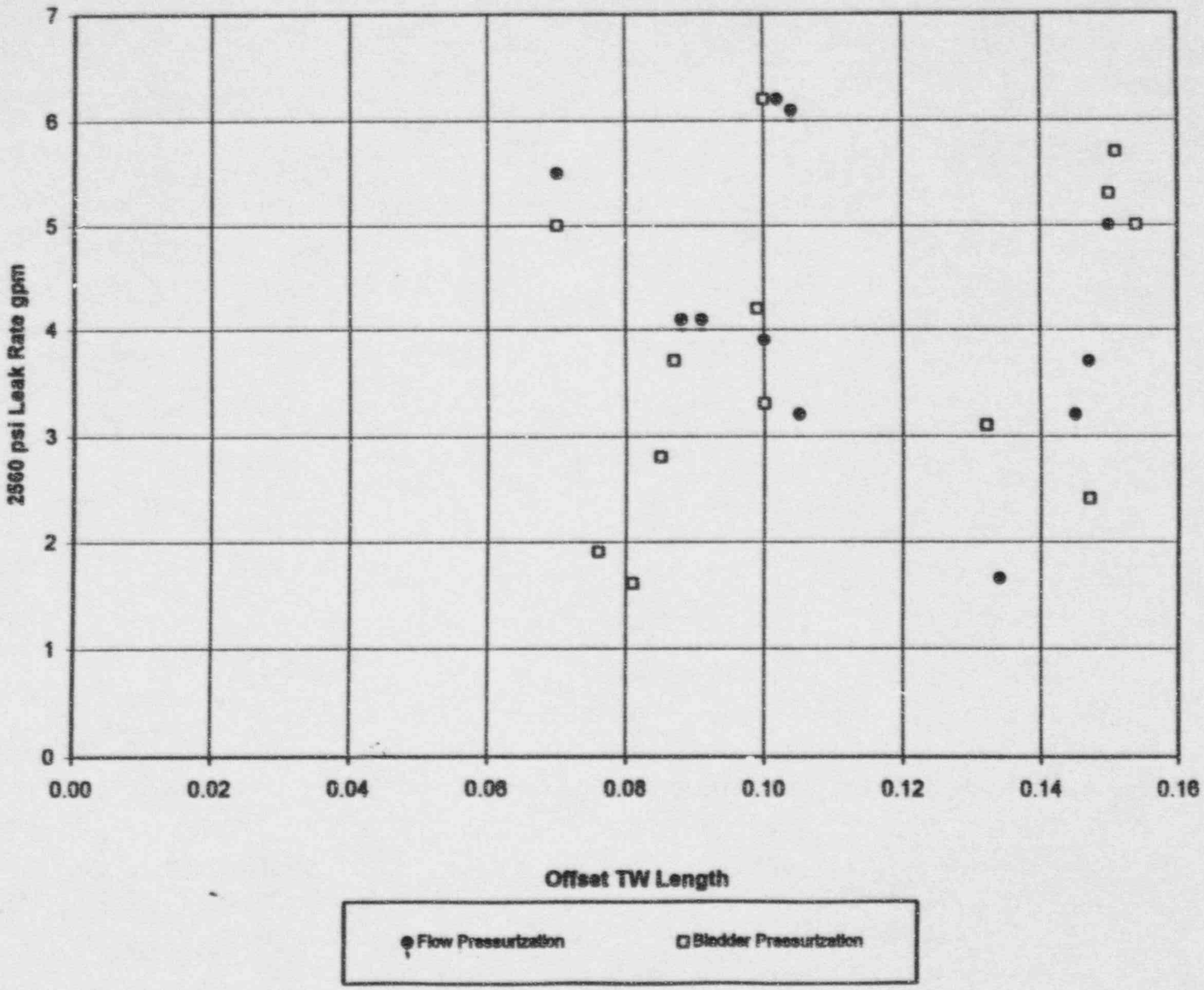


964

IRBLRCOR.XLS:Offset TW Length - F:8/13/95

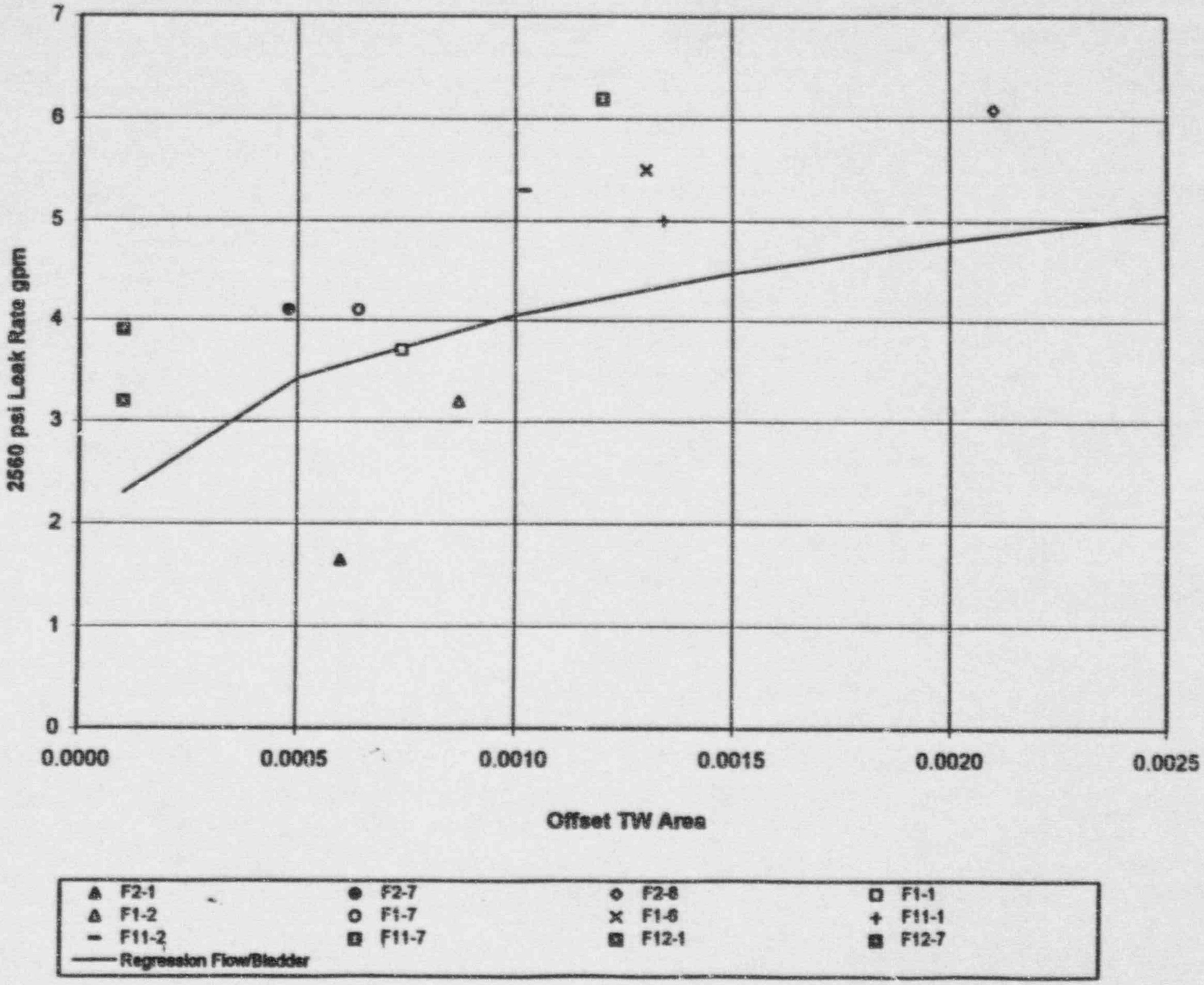

Offset Leak Rate vs. Throughwall Length Outside TSP for Bladder Pressurization
2560 psi Leak Rate gpm
0
1
2
3
4
5
6
7
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
Offset TW Length
B2-4
B2-10
B2-1
B2-7
B1-1
B1-2
B1-7
B1-6
B4-1
B11-1
B11-2
B11-7
B12-1
B12-7

Offset Leak Rate vs. Throughwall Length Outside TSP for Flow and Bladder Pressurization



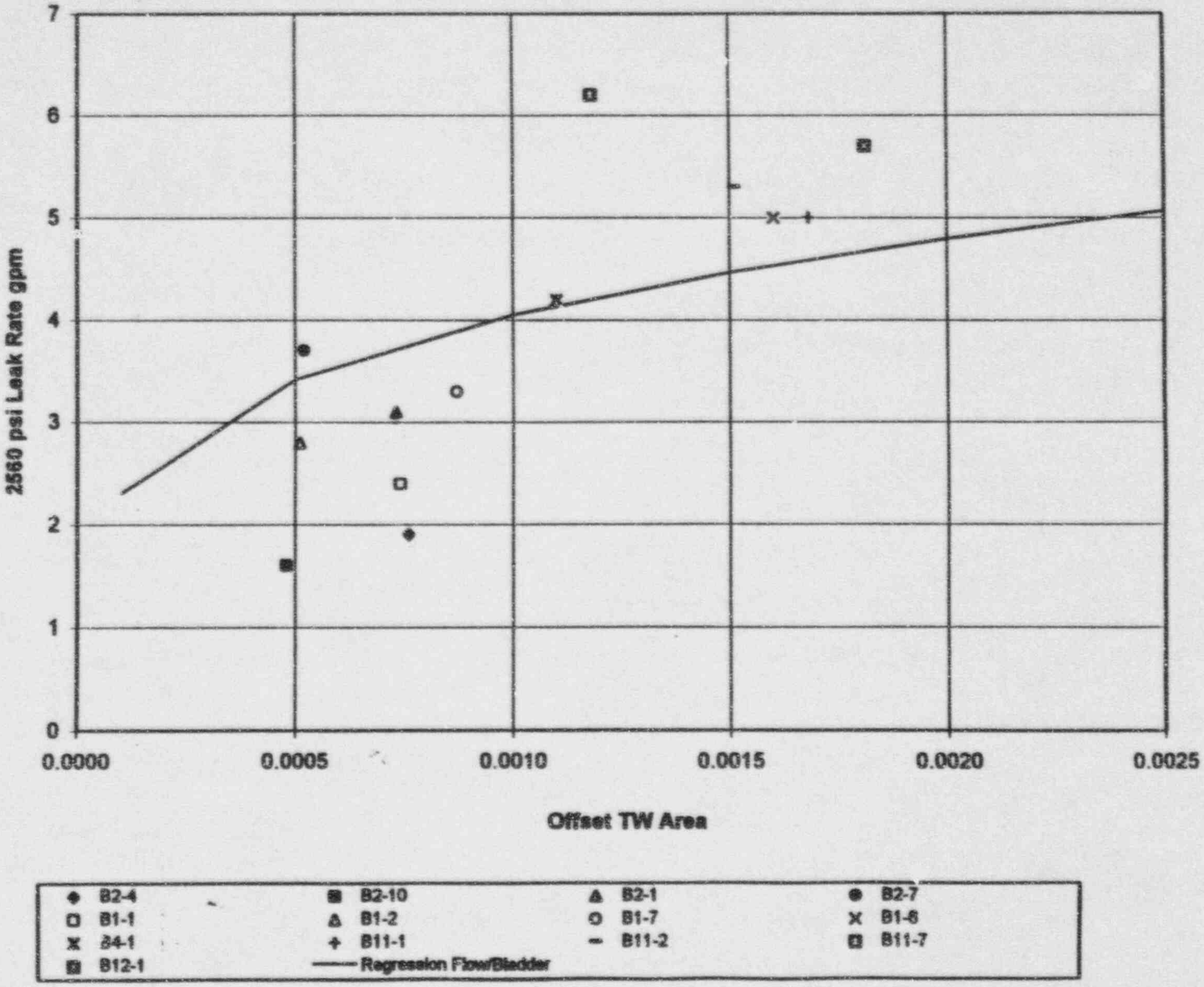
IRBLRCOR.XLS:Offset TW Length - Comb:8/13/96

Offset Leak Rate vs. Crack Opening Area Outside TSP for Flow Pressurization

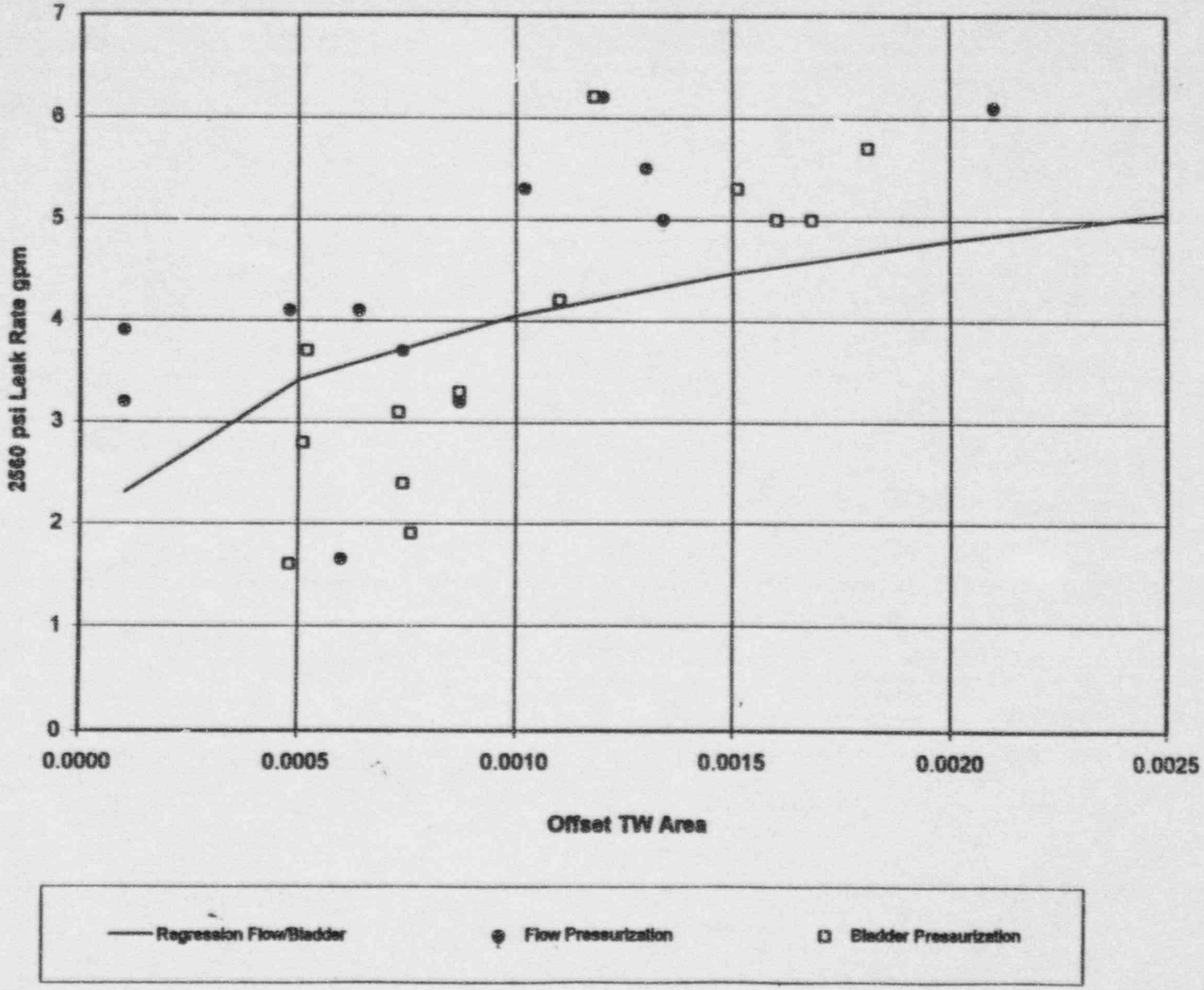


IRBLRCOR.XLS:Offset TW Area - F:8/13/95

Offset Leak Rate vs. Crack Opening Area Outside TSP for Bladder Pressurization

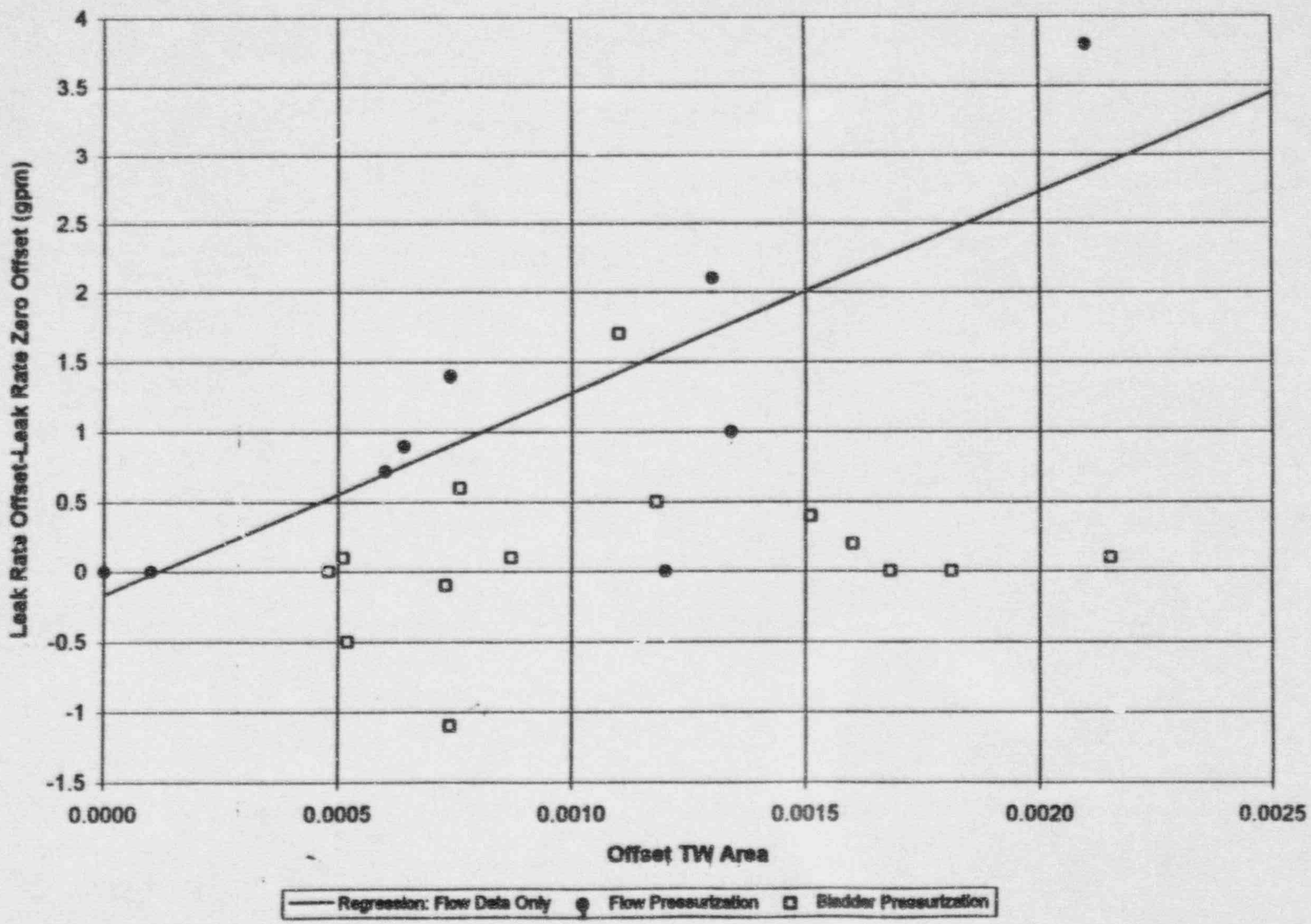


Offset Leak Rate vs. Crack Opening Area Outside TSP for Flow and Bladder Pressurization



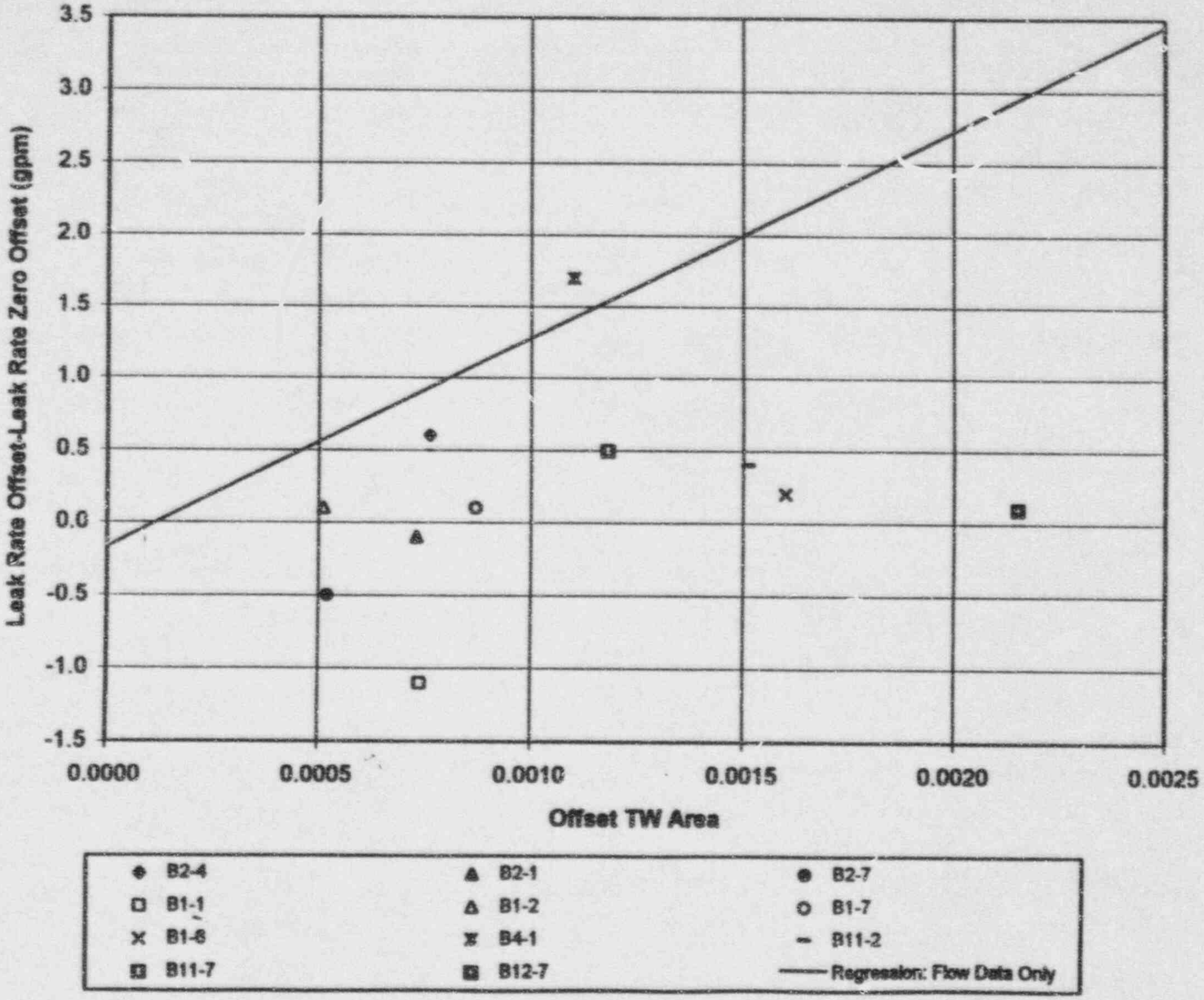
IRSLRCOR.XLS:Offset TW Area - Comb:8/13/95

Leak Differences Between Offset and Zero Offset vs. Offset TW Area Outside TSP



IRBLRCOR.XLS:Leak Rate - Comb:8/13/95:3:16 PM

Leak Differences Between Offset and Zero Offset vs. Offset TW Area Outside TSP



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Comparisons of Tube to TSP Interaction Predicted by Belgian Crack Opening Diameter Versus Pressure Measurements with Interaction Inferred from Leak Tests

- Belgian measurements of crack opening diameter as a function of the ratio of the applied ΔP to the free span burst pressure provide an estimate of the ΔP at which contact of the crack face (at center of crack) would contact the ID of the TSP hole.
- The leak rate tests can be used to infer interaction with the TSP by the leak rates becoming weakly dependent on ΔP, as compared to free span behavior for which leak rates increase significantly with ΔP due to increased crack opening widths.
- Interaction with the TSP as inferred from leak rate trends is consistent with that obtained from the Belgian data. In general, the leak rates imply interaction at somewhat lower ΔPs than the Belgian data.
- Ten of the fourteen specimens tested by flow pressurization (excludes 4-1 which had only bladder pressurization to expand the crack) resulted in leak rates reduced by interaction with the TSP. Only the shortest crack lengths tested (Tests 2-4, 2-10, 12-1 and 12-7) did not result in interaction with the TSP.

Throughwall Crack Lengths Outside the TSP for Offset Tests

- Leak tests were performed for the crack tip offset from the edge of the TSP for both flow and bladder pressurization tests
- The throughwall length measurements are based on measuring the length of light visible through the crack. The width of the crack must be about one mil wide for light to be visible. These measurements may underestimate the throughwall length since the crack width at the tip of the crack may be less than a mil wide. For some tests (Tests 1-1, 1-6, 2-1), the ID crack length at the start of the test, as measured by dye penetrant with silastic molds, is larger than the throughwall length at the end of testing.
- For the 3/4" tubing tests with the crack tips offset by 0.10", the throughwall lengths outside the TSP at the end of the offset test ranged from 0.005" to 0.104" with flow pressurization and from 0.007" to 0.100" with bladder pressurization. Except for the shortest crack length tested (Test 2-10), the throughwall lengths outside the TSP exceeded 0.07" of the 0.10" offset.
  - Six test have TW lengths outside the TSP at the bounding TSP displacement of 0.1".
  - The offset throughwall lengths for the six largest cracks and twelve leak tests are equivalent to or exceed the maximum TSP displacements at the most limiting tube location for the lowest four TSPs which include 98% of the TSP indications at Braidwood-1 and Byron-1.
  - Without the conservative factor of two applied to TRANFLO loads for the TSP displacement analyses, the throughwall lengths outside the TSP exceed the maximum TSP displacement of < 0.05" for all tube locations on all plates
  - It is concluded that the TSP offset distance of 0.10" used for the IRB tests and the resulting TW lengths outside the TSP provide a very conservative assessment of the effect of TSP displacement on the leak rate.

Estimated Pressures for Crack Face to TSP Contact								
Test	Specimen		Crack Length-in.		Flow Stress ksi	Burst Pressure ksi	Predicted[2] Crack Face to TSP Contact ΔP ksi	Leak Test Implied Tube to TSP Interaction ΔP - ksi
	Number	Diameter inch	OD	ID				
3/4" Diameter Specimens								
1-6	2008E	0.745	0.735	0.76	78.2	3.061	2.1	~ 2.0
1-7	2051A	0.748	0.58	0.60	80.5	3.981	2.7	~ 2.2
2-7	2051E	0.747	0.66	0.577	80.5	3.800	2.7	> 2.2, < 2.6
2-8	IRB-LC2	0.750	0.55	0.55	72.5	3.822	2.7	~ 1.9
2-10	2051B	0.746	0.551	0.425	80.5	4.700	3.3	>2.3 max. tested
11-7	2008A	0.745	0.813	0.809	78.2	2.850	2.0	~ 2.0
12-7	2008D	0.744	0.590	0.580[1]	78.2	3.950	2.7	>2.6 max. tested
7/8" Diameter Specimens								
1-1	8161G	0.875	0.62	0.62	76.6	4.141	2.4	~ 2.0
1-2	8161E	0.875	0.64	0.62	76.6	4.084	2.3	> 2.1, < 2.3
2-1	8161A	0.875	0.62	0.515	76.6	4.462	2.5	> 1.9, <2.3
2-4	4C218	0.875	0.60	0.29	78.3	5.470	3.1	>2.6 max. tested
4-1	4B214	0.876	0.67	0.24	81.9	5.635	3.2	Not tested
11-1	5B403	0.874	0.71	0.70	76.6	3.670	2.1	~ 2.2
11-2	8161B	0.874	0.73	0.63	76.6	4.075	2.3	~ 2.4
12-1	8161C	0.875	0.607	0.515	76.6	4.850	2.7	>2.7 max. tested

Note 1. Specimen has two cracks separated circumferentially by 0.012" which affects estimated burst pressure.
Note 2. Based on Belgian test data for crack opening diameter vs ΔP; includes only plastic component of crack opening.

Summary of TW Lengths Outside TSP and Crack Extension				
Test	TW Outside TSP at 0.10" Offset		Crack Extension - inch	
	SLB ΔP	Freespan Burst ΔP	SLB ΔP	Freespan Burst ΔP
3/4" Diameter Specimens				
1-6	0.070	0.070	0.0016	0.021
1-7	0.091	0.100	0.021	0.025
2-7	0.088	0.087	0.011	0.014
2-8	0.104	[2]	0.012	[2]
2-10	0.005	0.081	0.003	0.024
11-7	0.102	0.100	0.009	0.009
12-7	0.100	0.100	0.045	0.183[1]
Test	TW Outside TSP at 0.15" Offset		Crack Extension - inch	
	SLB ΔP	Freespan Burst ΔP	SLB ΔP	Freespan Burst ΔP
7/8" Diameter Specimens				
1-1	0.147	0.147	0.013	0.013
1-2	0.145	0.085	0.090	0.090
2-1	0.134	0.132	0.064	0.097
2-4	0.0	0.076	0.011	0.017
4-1	[3]	0.099, 0.112	[3]	0.015
11-1	0.150	0.154	0.045	0.047
11-2	0.173	0.150	0.019	0.020
12-1	0.105	0.151	0.039	0.051

Note 1. Bladder pressurization of 6200 psi exceeded free span burst estimate of 3950 psi and contributed to the larger increase in crack length.

Note 2. Bladder pressurization condition not tested.

Note 3. Flow pressurization condition not tested. Initial test was bladder pressurization at > SLB ΔP.

- For the 7/8" tests with a 0.15" offset of the crack tip outside the TSP, the TW lengths outside the TSP range from 0.105" to 0.173" for six of the seven tests under flow pressurization conditions and from 0.076" to 0.154" for eight bladder pressurization tests.
  - Eight leak tests had TW lengths ≥0.145" outside the TSP including the maximum TW offset length of 0.173".
  - It is concluded that the TSP offset distances for the 7/8" tests also provide a very conservative assessment of the effect of TSP displacements on the leak rate.

- For test sequences 11 and 12, the crack alignment objective for offset tests was to offset the TW crack length by the offset goal. Throughwall measurements after the zero offset test were used to identify the tip of the TW crack for this objective. When crack extension occurred during the offset test, the end of test TW length exceeded the objective. For Test 12-1, the TW length after the zero offset test could not be seen by light penetration and the end of the crack tip was set at 0.15" outside the plate. At the end of the offset test, it was identified by light penetration that 0.105" throughwall was outside the TSP.

Comparison of Total Crack Length at Beginning and End of Test Including Bladder Pressurization to Freespan Burst Pressure

- Total crack lengths prior to initiating leak testing were measured by dye penetrant tests. Lengths following leak tests were measured by visual observations with a toolmaker's microscope. Although the latter measurement would be expected to be less accurate and typically shorter for comparable conditions, the measurements after leak testing follow pressurization of the tube which tends to open the cracks and facilitate visual observation.
- With the exception of the specimens for Tests 1-2, 2-1 and 12-7, the growth in measured crack lengths including pressurization to the free span burst pressure is less than about 50 mils, which can be considered negligible. Crack tearing for a free span burst exceeds 250 mils.
- The crack length measurements for Tests 1-2 and 2-1 indicate an increase in length of 90 and 64 mils following flow pressurization to 2540 psi. The length increase for 1-2 was associated with the opening of a branch crack at the side of the main crack. It is likely that this branch crack existed prior to testing but was too tight for detection. The branch crack was not throughwall following pressurization to the free span crack length. The length increase for 2-1 was associated with opening of two, non-throughwall microcracks in-line with but not continuous with the main macrocrack identified at the start of the test.
- The crack length measurements for Test 12-7 indicate an increase in length of 0.183" following bladder pressurization to 6200 psi. This larger increase is due to bladder pressure exceeding the target free span pressure of 3950 psi.
- It is concluded that the crack extension for cracks inside the TSP is negligible for pressurizations as high as the free span burst pressure of the indication.

Flow Area and Crack Offset Considerations for Influence on IRB Leak Rates

- The leak tests following bladder pressurization show almost no differences (within 10%) in leak rate between the offset and zero offset conditions. This would be the expected result if the crack opening area is less than the geometrical flow area such that leakage is limited only by crack area. If limited by crack area, only differences in flow turning losses between the crack inside the TSP and offset would result in a difference in leak rate and this effect would generally be small. However, some of the tests performed prior to bladder pressurization show an apparent increase in leak rate with the crack offset from the TSP. These tests are further evaluated below.

- Tests 4-1 and 2-4 were the only initial tests (test sequence numbers 1 to 4) that showed an increase in leak rate for the offset condition following bladder pressurization. In Test 4-1, the indication was pressurized to about 10% above the calculated free span burst pressure (all other tests were expanded at the free span burst pressure or lower) and the leak rate increased from about 2.5 gpm with 0.0" offset to about 4.2 gpm with 0.15" offset. However, this test included three throughwall cracks of 0.606", 0.567" and 0.388" and pressurization increased the diameter of the tube. The significant increases in the tube diameter (not across crack opening) occur only at high burst pressures (5800 psi for 4-1) and would not be present in a burst at SLB conditions. The two largest TW cracks were 180° apart from each other such that, within the TSP, the ID of the hole could restrict leakage from one or both of these cracks. When offset, these two cracks had exposed lengths of 0.099" and 0.112". Therefore, for Test 4-1, it is believed that the combination of multiple long throughwall cracks 180° apart and the diameter changes were the cause of the increase in leakage for the offset condition. Test 2-4 also had two throughwall cracks 180° apart although only one throughwall crack was exposed in the offset condition. It is believed that the combination of multiple TW cracks and diameter changes at the higher bladder pressurization were the cause of the increase in leakage for the offset condition for this case as well as Test 4-1.

- For the later tests (test sequence numbers 11and 12), tests 11-2, 11-7 and 12-7 showed some increase in leak rate for the offset condition compared to the zero offset condition. These increases are less than or equal to a 10% increase in the leak rate which is a significant change. These tests are evaluated below considering effective crack opening areas and the geometric flow areas for these tests.
- In WCAP-14273, a geometrical model is developed to define the maximum flow area for a throughwall crack within the TSP based on the assumptions that the crack widths are very large and that the crack diameter increases linearly from the crack tip to the center of the crack. Both of the assumptions are conservative. The maximum geometrical flow area is the crack length times the tube to TSP gap. For the throughwall crack of 0.726" (Test 1-6) with a 0.026" gap, the maximum geometrical flow area is 0.0189 in^2. However, the actual geometric flow area is the area available between the edge of the open crack and the TSP ID. This can be significantly lower than the maximum area due to closure of the gap along some length about the center of the crack and due to curvature of the edge of the crack. The actual geometric flow area can be approximated from the crack diameter measurements made following the leak tests. The attached figures, and figures given in Section 4 for test sequences numbered 11 and 12, show the measured plastic crack diameter increases (measured after test diameter minus initial tube diameter) following the flow pressurization offset leak test and following bladder pressurization to the free span burst pressure with the subsequent offset leak test. The diametral increases show a range less than the target 0.025" diametral clearance even for leak tests that demonstrated tube to TSP interaction. As discussed elsewhere in this report, for tests that had tube to TSP interaction, the plastic diametral increases represent the crack to TSP clearance present in the test with about a 3-5 mil adjustment for elastic deformation. The attached figures comparing the diameter increases before and after bladder pressurization show the increased width of the maximum diameter at the center of the crack following bladder pressurization. This increased width tends to decrease the effective crack area and helps to explain the reductions in leakage for most tests following bladder pressurization.
- For tests performed prior to bladder pressurization, the offset tests followed the tests for 0.0" offset and the increases in leakage for the offset tests include increases in the crack opening area as well as the effect of moving the crack outside the TSP. In all tests for which throughwall areas were measurable and for which the 0.0" offset leak rates could be reasonable extrapolated to 2650 psi ΔP, the ratios of the crack area after the offset test to the crack area after the zero

offset test were significantly larger than the leak rate ratios (see table). The lower leak rate ratios in the attached table were obtained at comparable ΔPs between the two tests and should include little additional crack opening for the offset tests. These ratios (1.1 to 1.3 for Tests 1-1, 1-6, 1-7, 11-1) represent the increase in leakage with TSP offset that requires further evaluation. The larger ratios result from increases in the crack opening area. The increases in leakage for the offset tests is further evaluated below based on estimating the effective crack opening area and the geometric flow area from the dimensional measurements.

- From the dimensional measurements for crack area, crack diameter profiles and estimates of the crack length in or near contact with the TSP from the diameter measurements, the effective crack area and the geometric flow area can be approximated. While the dimensional measurements do not have enough detail or precision for precise area calculations, the approximate crack and geometric areas can be used to estimate the effective crack and geometric flow areas to assess the likelihood of a leakage increase with offset of the through wall crack from the TSP. If the effective crack area is less than the geometric flow area, no increase in leakage would be expected for the offset test since leakage is limited by crack opening rather than the geometry of the crack opening within the TSP hole. The attached table shows the estimated effective crack area, the geometric flow area and whether or not the test leak rate increased for the offset test compared to the zero offset test. For the offset tests performed prior to bladder pressurization, the geometric flow area is limiting for 4 of the 10 tests evaluated. Of the 10 test results, 4 showed an increase in leakage, 2 cannot be reliably estimated due to the large pressure difference between the zero offset and offset tests (although both would be predicted to show an increase with offset) and 4 showed no increase in leakage. Only for Tests 1-7 and 11-1 are the predictions that the crack area would be limiting inconsistent with the test results. Given the approximate estimates for the areas, these results support the expected trend that leakage for cracks within the TSP is dependent upon the more limiting of the effective crack area and the geometric flow area. For large crack openings (Tests 1-6, 2-8, 11-1 and 11-7), the geometric flow area tends to become limiting and the leak rate can be expected to be bounded by the geometric flow area of the TSP as well as the effect of the TSP on limiting the crack opening area. The geometric flow area is also more more likely to be limiting for crack to TSP gaps that are smaller than the target diametral clearance of 0.025". While cracks having leakage limited by the geometric flow area will show an increase in leakage for offset throughwall cracks, the net effects of the geometric flow area and constrained crack opening limit the increase in leakage with crack offset to the 10% to 30% range indicated by the test results.
- The attached table also shows the estimated effective crack area and geometric flow area after bladder pressurization. After bladder pressurization, the effective flow area is limiting for the shorter cracks and larger crack to TSP gaps while the geometric flow area is limiting for the larger cracks with wider crack openings. The differences in leak rates are within 10% and less than the range found for flow pressurization tests. The bladder tests do not include significant changes in crack opening due to the prior pressurization above the leak test pressure and thus are more representative of the effects of displacing the crack outside of the TSP.
- When leak rates are correlated with effective crack opening area, the correlation is somewhat improved over that obtained correlating leakage with total crack area. Whereas a linear correlation between leak rate and effective crack area is expected, the resulting correlation is nonlinear at large crack areas. This would indicated that the effective crack areas for large crack openings may be overestimated.
- These results, together with the above trending results that show leak rates are primarily correlated with crack length and effective crack area, indicate that crack length/area as limited by the TSP are the principal factors influencing the leak rate and offsetting the crack outside the TSP has a secondary influence on the leak rate.
- Overall conclusions

- The principal factors influencing IRB leak rates are:
  - o The TSP limits the crack opening area for throughwall indications greater than about 0.55".
  - o The effective crack opening area is further reduced for long cracks (clearly from test results at > 0.6", which might conceptually burst in free span) by tube to TSP gap closure for some length (expect < 0.25" based on test results) along the length of the crack.
  - o IRB leak rates are primarily dependent on the effective crack opening area with a modest (<30%) effect of limited TSP displacements on leakage.
  - o For long cracks which result in relatively large crack opening areas, the geometrical flow area formed by the TSP and the crack opening can become limiting and reduce the leakage compared to that expected for the effective crack area.
- Upon contact of the crack opening with the TSP, leak rates have a modest or no increase in leakage with increased pressurization and tend toward smaller increases in leakage with throughwall cracks outside the TSP compared to the crack within the TSP
- Bases for conclusions
  - o Leak rates for offset and zero offset tests following bladder pressurization (constant effective crack area) are very similar and, in some cases, lower for offset than zero offset conditions. For bladder pressurization tests, there is no correlation between the change in leak rate (offset minus zero offset) and the exposed throughwall crack area. The exception for Test 4-1 is attributable to multiple TW cracks 180° apart exposed by the TSP displacement and by diametral increases in the tube diameter.
  - o Leak rates correlate reasonably well with throughwall crack length and with crack opening area.
  - o For flow pressurized tests with the offset test run after (and at higher pressures) the zero offset test, the increase in leakage for the offset condition is less than that expected for the increase in the total crack area. The less than expected increase is attributable to blockage of the flow area near the center of the crack by the TSP which reduces the total crack area to an effective crack area for leakage considerations.

Considerations of Multiple Throughwall Cracks on Leak Rate

- Following Tests 2-4 and 4-1, which used specimens prepared under another program and included multiple throughwall cracks, all specimens except Test 12-1 were prepared with single deep cracks to more closely represent field experience showing a single dominant crack for large indications and to facilitate interpretation of the test data. This section discusses whether or not the bounding leak rate should be adjusted for the potential of multiple throughwall cracks.
- Pulled tubes and model boiler specimens in the EPRI ARC database with significant voltages have generally shown a single dominant crack, such as the Braidwood-1 and Byron-1 pulled tube indications at 10 to 11 volts. When secondary throughwall indications are found, the throughwall length is much shorter than the dominant crack. Even when two comparable TW lengths are present, such as Byron-1, R20C7, TSP3, one indication burst and ligaments remaining in the second crack would have limited the leakage relative to the other crack. Since leakage increases exponentially with throughwall crack length (free span and within TSP), the leak rate for an indication is almost entirely due to the longest crack. Thus based on morphology considerations for prototypically prepared indications, leakage from secondary cracks can be ignored.
  - A partial exception to the above is Plant S, pulled tube R42C43 which had throughwall cracks 0.50 and 0.41 inch long in a 22.9 volt indication. The calculated leak rate for the longer crack is about three times the leakage of the smaller crack. Thus, even for this exception to a single dominant crack, the leak rate is principally due to the longest crack.
- Burst tests of parallel EDM slots have also shown that the dominant crack is the crack that bursts

and the burst pressure correlates with the dominant crack and has little influence from 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 dominant 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 including the Braidwood-1 and Byron-1 indications. Thus, only a small fraction (about 6%) of the indications are likely to have throughwall lengths exposed by maximum TSP displacement of 0.10" (TSP displacement analyses show a maximum of 0.094" displacement in a small region of one TSP with a factor of two conservatism applied to the TRANFLO loads). Therefore, the likelihood of two throughwall cracks exposed by the 0.1" maximum displacement would be very small and can be ignored for defining the bounding leak rate for IRBs.
  - Specimens 2-4 and 1-4, as discussed above, had multiple throughwall cracks exposed by the TSP offset of 0.15" with an apparent influence on increasing the offset leak rate. However, this is unique to the method of specimen preparation. The doped steam specimens are prepared by slightly ovalizing the tube to increase the stresses and enhance crack initiation and growth for the accelerated tests. This process results in cracks 180° apart which increases the offset leakage compared to cracks more randomly located around the tube. 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 likelihood of exposing two throughwall cracks is negligibly small.
  - 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 (about six times larger effective crack area since the primary crack interacted with the TSP). 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.
- 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, the very low likelihood that two throughwall indications would be within 0.10" of the TSP edge and the Test 12-1 leak rate results.

Ratios of Offset to Zero Offset Leakage and Crack Opening Areas Flow Pressurization Tests		
Test	**Leakage Ratio**	**Approximate Total Throughwall Area Ratio**
2-1	1.8[1]	57
2-8	2.6[1]	5.7
1-1	1.1 to 1.6[2]	2.3
1-2	~ 1.0	3.8
1-6	1.3 to 1.6	2.1
1-7	1.2 to 1.3	1.7
11-1	1.25	1.5
11-2	1.0	2.4
11-7	1.01	1.1
12-1	1.0 No TSP Interaction	3
12-7	1.0 No TSP Interaction	1.3

Notes:

1. Tests noted have free span tests between zero offset and offset test sequences such that significant crack opening occurs between these tests. The remaining tests have small or no pressure difference between the highest zero offset test and the lowest offset test.
2. Lower leak rate ratios apply where ΔP values between zero offset and offset tests overlap. Larger ratios are based on leakage at 2560 psi ΔP.

Summary of Effective Crack Areas and Geometric Flow Area for Flow Offset Tests

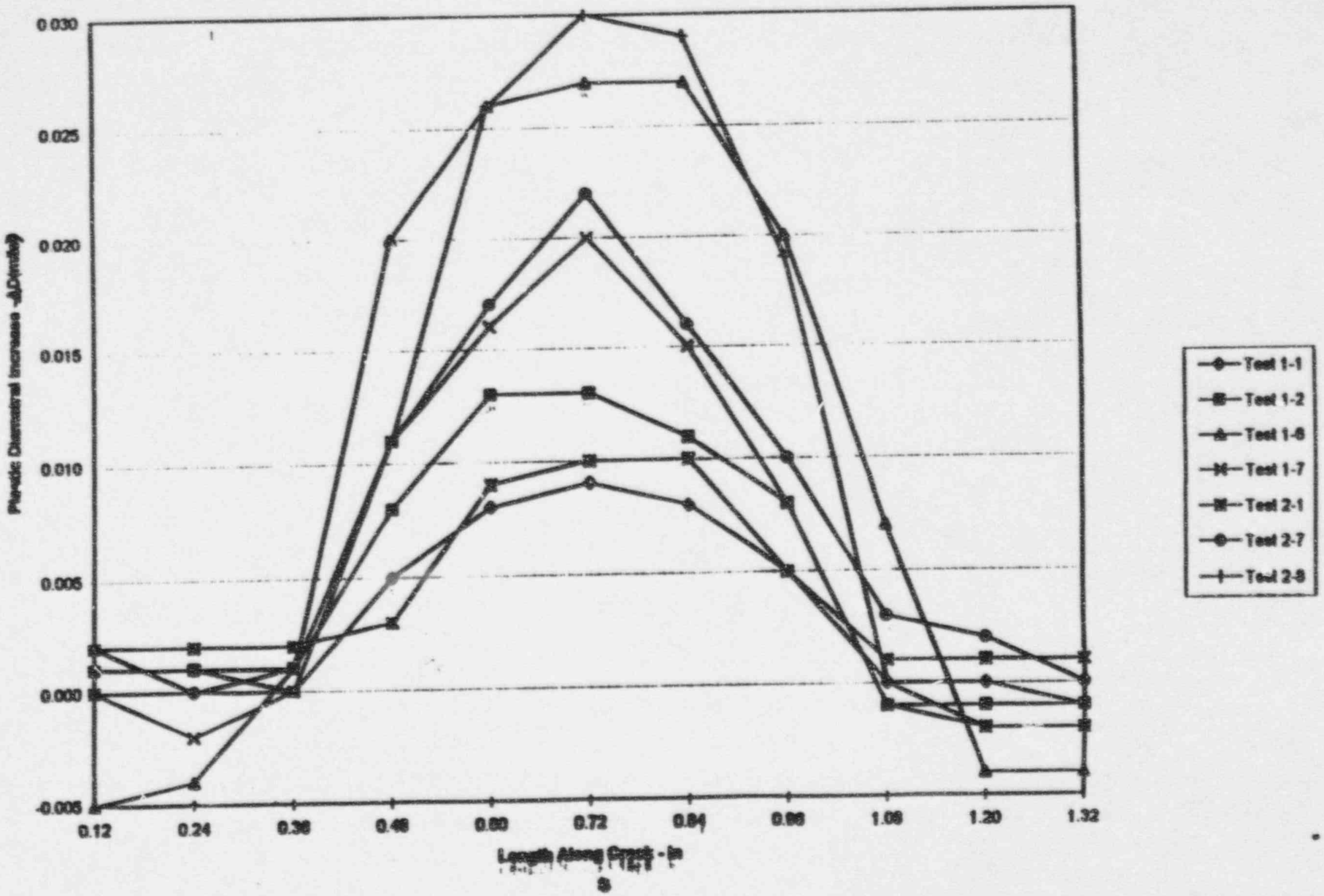
Test	Pre-Test Crack to TSP Gap (inch)	Total Crack Opening Area (in^2)	Crack/TSP Contact Length (in.)	Effective Crack Area (in^2)	Geometric Flow Area (in^2)	Limiting Flow Area	Test Leak Rate Increase In Offset Test
Before Bladder Pressurization Tests With Crack to TSP Interaction							
1-1	0.009(1)	0.0045	0.10	0.0034	0.0030	~ Geometric	Yes, ~10%
1-2	0.013(1)	0.0065	0.12	0.0050	0.0050	No difference	No
1-6	0.026(1)	0.0249	0.25	0.014	0.0098	Geometric	Yes, ~30%
1-7	0.020(1)	0.0071	0.05	0.0065	0.0084	Crack	Yes,~20%(2)
2-1	0.010(1)	0.0033	0.10	0.0024	0.0020	~ Geometric	Not Rel.(3)
2-7	0.022(1)	0.0085	0.05	0.0075	0.0102	Crack	No
2-8	0.027(1)	0.0164	0.25	0.014	0.0062	Geometric	Not Rel.(3)
11-1	0.026	0.0118	0.20	0.0060	0.0099	Crack	Yes, ~25%(2)
11-2	0.026	0.0068	0.10	0.0048	0.0097	Crack	No
11-7	0.025	0.0186	0.30	0.0084	0.0083	No difference	No

Summary of Effective Crack Areas and Geometric Flow Area for Flow Offset Tests							
Test	**Pre-Test Crack to TSP Gap (inch)**	**Total Crack Opening Area (in^2)**	**Crack/TSP Contact Length (in.)**	**Effective Crack Area (in^2)**	**Geometric Flow Area (in^2)**	**Limiting Flow Area**	**Test Leak Rate Increase In Offset Test**
After Bladder Pressurization							
1-1	0.013[(1)]	0.0052	0.20	0.0029	0.0058	Crack	No, decrease
1-2	0.014[(1)]	0.0078	0.20	0.0050	0.0056	~ Crack	No
1-6	0.026[(1)]	0.0262	0.28	0.013	0.0080	Geometric	Yes, small
1-7	0.019[(1)]	0.0087	0.05	0.0079	0.0072	~ Geometric	No
2-1	0.012[(1)]	0.0038	0.10	0.0027	0.0030	~ Crack	No
2-7	0.019[(1)]	0.0095	0.10	0.0075	0.0084	~ Crack	No, decrease
11-1	0.026	0.0140	0.20	0.0077	0.0099	Crack	No
11-2	0.026	0.0114	0.20	0.0061	0.0076	Crack	Yes, ~10%[(2)]
11-7	0.025	0.0186	0.30	0.0084	0.0084	No difference	Yes, ~10%
12-1	0.026	0.0105	0.20	0.0062	0.0084	Crack	No
12-7	0.025	0.0316	0.40	0.0089	0.0058	Geometric	Yes, small

Notes

1. Gap implied from increase in crack diameter (bulge at crack center)
2. It would be expected that the offset test would show no increase in leakage if the effective crack area is less than the geometric flow area. Tests 1-7 BS 11-1 for flow pressurization and 11-2 for bladder pressurization do not follow this expectation.
3. No reliable estimate can be made since the zero offset test was run at much lower pressures than the offset test and the test results can not be directly compared to determine if the leak rate increased for the offset test

Crack Diameter Increase After Flow Pressurization Offset Test



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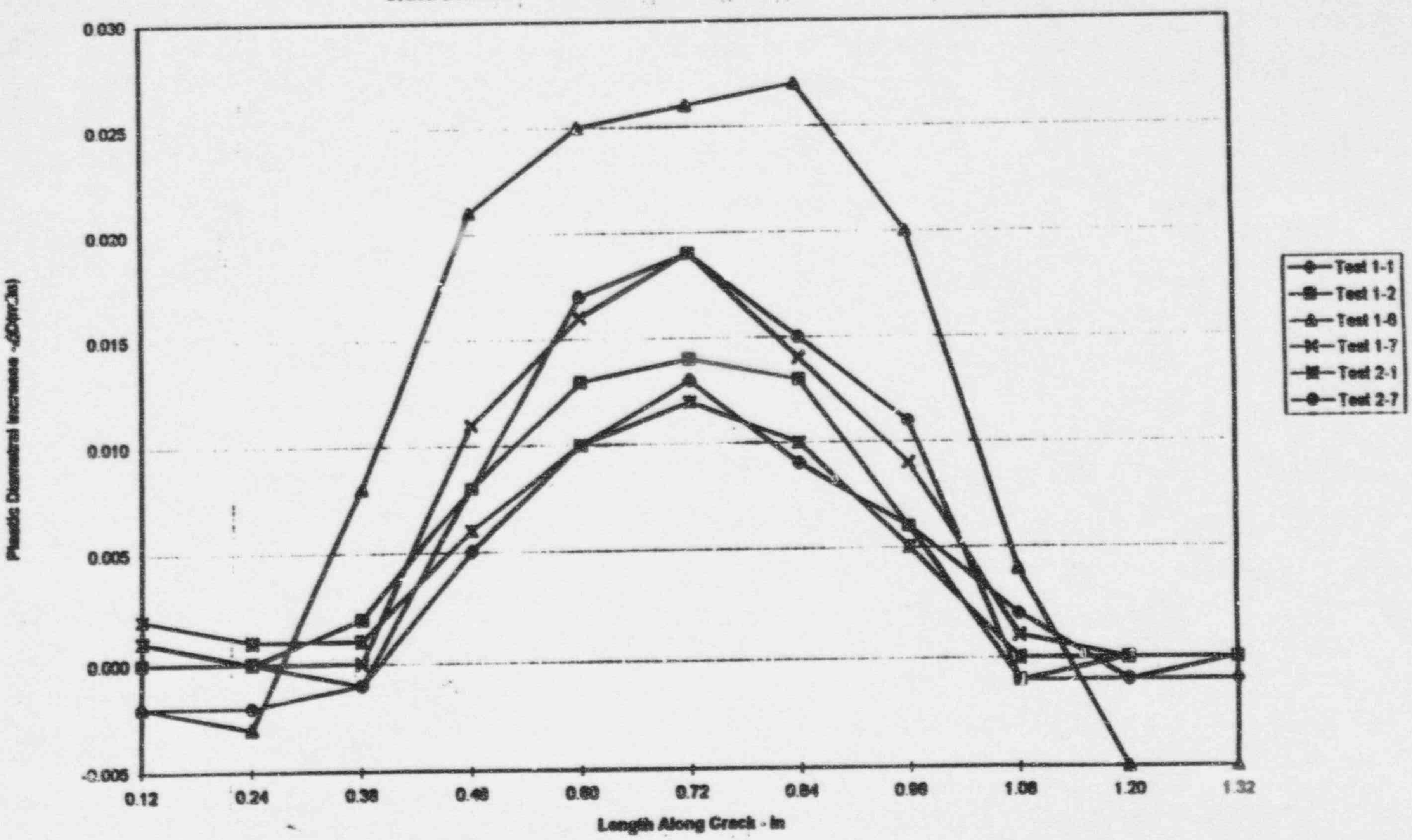
Crack Diameter Increase After Bladder Pressurization and Offset Test



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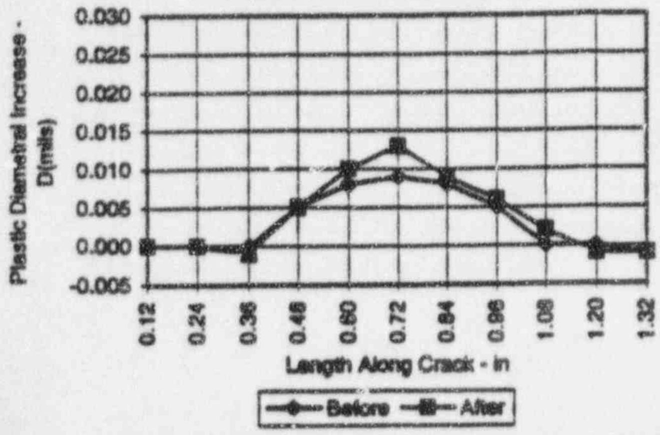
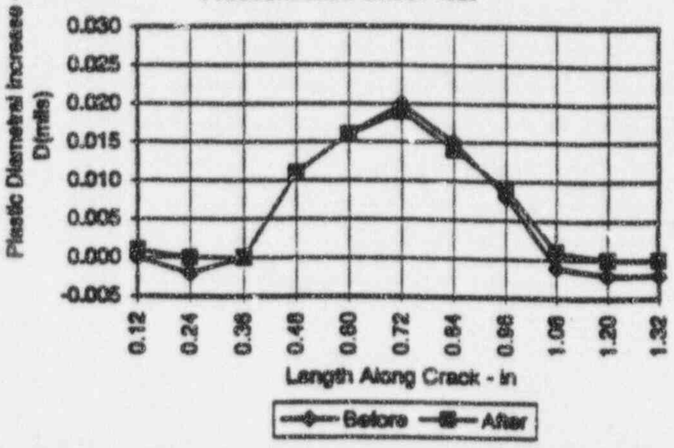
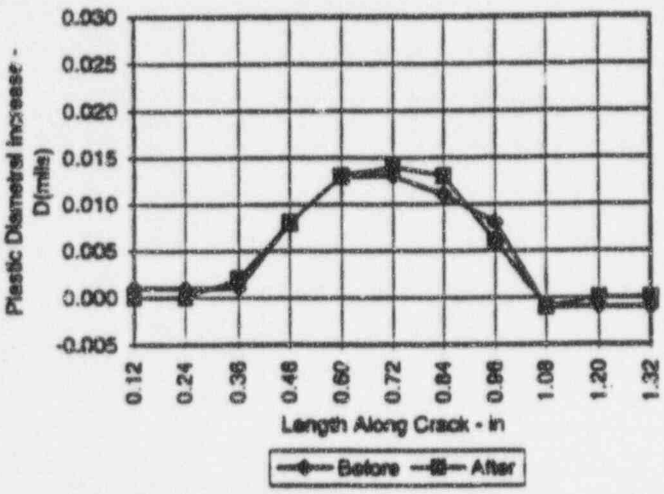
Test 1-1 Crack Diameter Increase After Flow Pressurization Offset Test



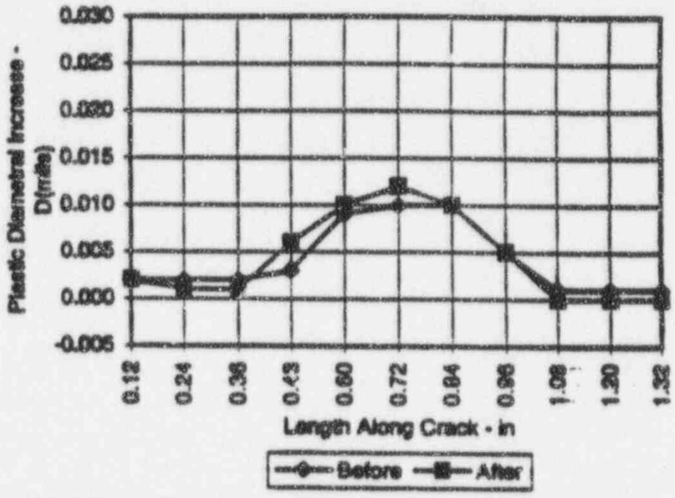
Test 1-7 Crack Diameter Increase After Flow Pressurization Offset Test



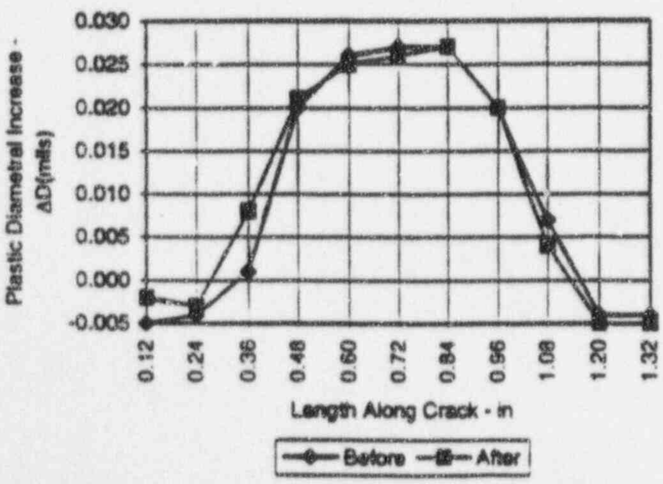
Test 1-2 Crack Diameter Increase After Flow Pressurization Offset Test



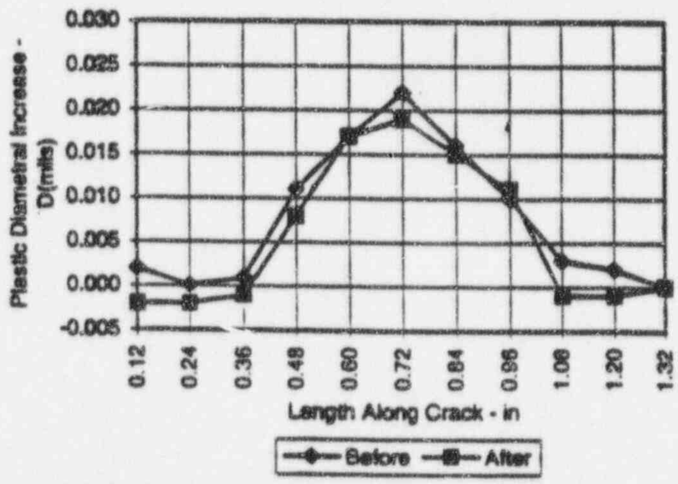
Test 2-1 Crack Diameter Increase After Flow Pressurization Offset Test

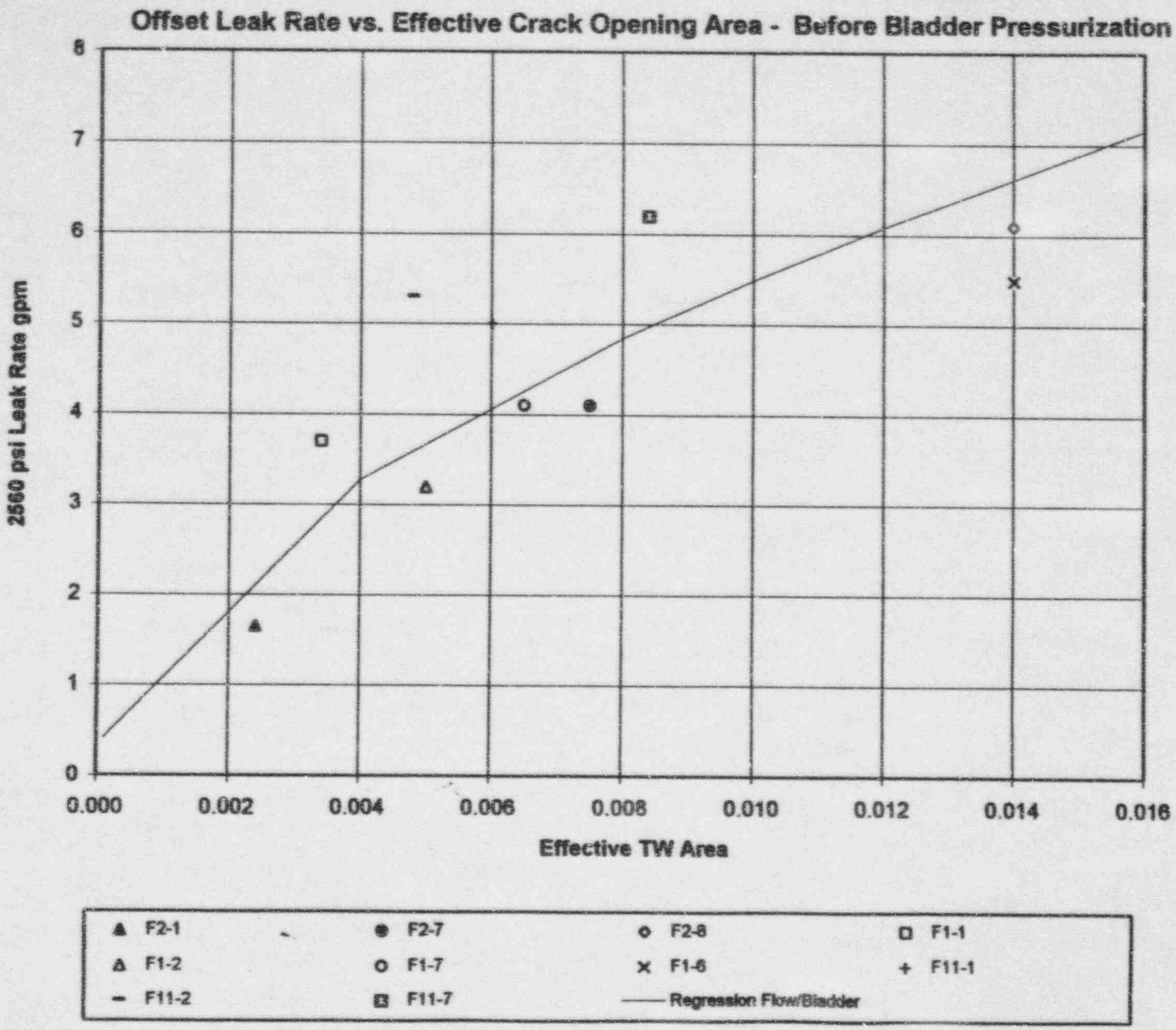


Test 1-6 Crack Diameter Increase After Flow Pressurization Offset Test



Test 2-7 Crack Diameter Increase After Flow Pressurization Offset Test

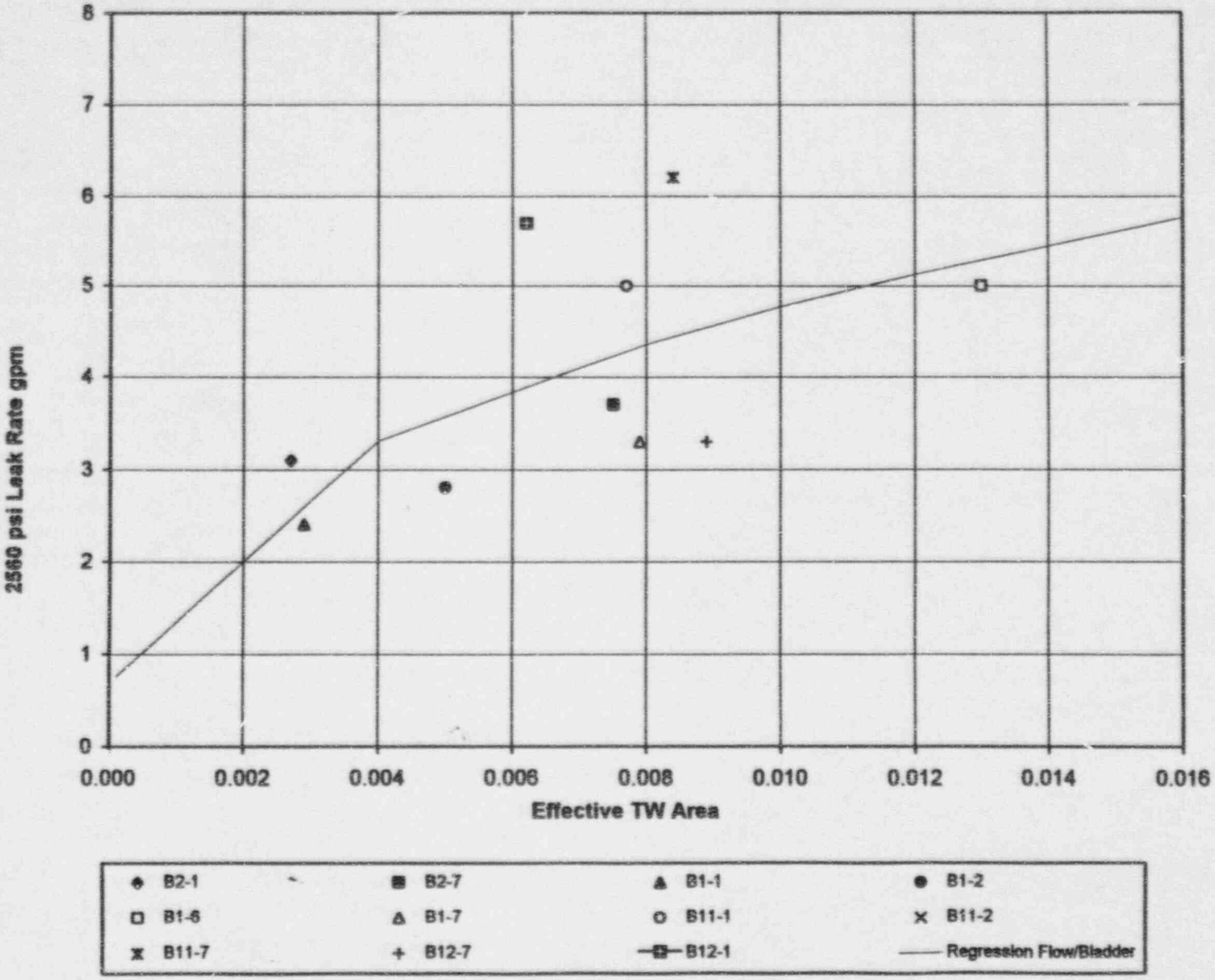




220

IRBLRCOR.XLS:Effective TW Area - F .:8/13/95

Offset Leak Rate vs. Effective Crack Opening Area - After Bladder Pressurization



IRBLRCOR.XLS:Eff.TW Area - B:8/13/95

6.0 Leak Rate Uncertainty Assessment

Leak Rate Uncertainty Assessment

Potential Leak Rate Uncertainty Contributors Evaluated

- Fluctuations of leak rate during the test perio
- Maximum ΔP in test versus average for reported leak rates
- EPRI leak rate adjustment procedure per EPRI Report NP-7480-L
- Test loop calibrations
- Total uncertainty is a combination of these factors

Leak Rate Measurement Uncertainty - Leak Rate Fluctuations During Test Period

- The data reduction procedure for the leak rate tests average the measured leak rates over a period of time. There are some fluctuations in the leak rate over this time period and the standard deviation of the fluctuations about the average is determined for each test data point. This value defines the leak rate measurement uncertainty for the test.
- The Test 1-6 data point at 2543 psi ΔP is one of the principal influences the bounding IRB leak rate of 6.0 gpm at 2560 psi. Thus, the test uncertainty for this data point is of primary interest for the uncertainty assessment. This data point 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 standard deviation of the measurements was obtained from data sample sizes of 12 in each case. 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. Thus, the 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 test program uncertainty on the leak rate measurement can be assessed by developing the mean and standard deviation of the individual leak test uncertainties. This is developed separately for hot and cold tests since the uncertainty is smaller for cold tests. Attached plots show the percentage standard deviation as a function of the leak rate magnitude. 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 hot measurement uncertainty becomes 7.2% with a standard deviation of 8.8%. These results show that the uncertainty on the Test 1-6 leak rate measurement is about 3% higher than the average for all data.

ΔP Measurement Uncertainty - Maximum ΔP in Test Versus Average for Reported Values

- The maximum ΔP applied in the test occurs prior to the collection of the test data. The test ΔP is reported as the average value over the data collection period and is lower than the maximum applied to the test specimen. It would be expected that the maximum ΔP adds plastic crack opening above that expected at the average ΔP for the test data. Thus, it is expected that the leak rates would be slightly high for the test condition. 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 the primary pressure drop, as typical of most tests, was the dominant pressure drop between maximum ΔP and the average ΔP. There would only be small differences in the adjusted leak rates if it was 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, thus, evaluation of Test 1-6, which defines the bounding leak rate, is the appropriate test for evaluation.
- The differences between maximum and average ΔPs are 150 and 186 psi for the two test data points with 0.10" offset for Test 1-6.
- The SLB leak rates at the SLB 2560 psi are 5.0 gpm for the maximum ΔP case and 5.5 gpm for the average ΔP case. The average 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 measured 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 between average and maximum ΔP are smaller than that for Test 1-6. For these specimens, the leak rates reported in the individual test evaluations (Section 4) are the largest obtained at SLB conditions and generally is obtained using maximum ΔP for the data analysis. 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.

Leak Rate Adjustment Uncertainty - EPRI Leak Rate Adjustment Procedure

- Assessment for limiting leak rate test: Test 1-6 at 2543 ΔP psi
  - The evaluated test point is an average of two data points differing in the measured leak rates by only 0.1 gpm. The measured leak rates are adjusted by a maximum factor of 0.94 for the two data points. The adjustment is due primarily to the higher primary pressure difference above saturation in the test compared to the reference conditions due to the test secondary pressure of 347 psi versus the desired 15 psi. The hydraulic adjustment factor for this data point is independent of the value used for C_p in the analysis. The test temperature was 630°F compared to the desired 615°F.
  - Based on the leak rate adjustment being only 6% since the test conditions are close to the reference SLB conditions, it is concluded that the uncertainty on the Test 1-6 leak rate of 5.5 gpm is negligible for the EPRI leak rate adjustment procedure and would be a maximum of a few percent.
- For other specimen SLB leak rates greater than 5 gpm, the maximum measured leak rates are adjusted by factors of 9% to 15%. The uncertainty on these adjustments would also only be 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.

Test Loop Flow Rate Orifice Test Measurement

- The test loop uses calibrated instruments such that the uncertainty for instrument error can be considered to be negligible.
- Room temperature leak tests were performed for three orifice sizes to compare the test loop measured leak rates with leak rates measured at an orifice calibration facility. The orifice sizes correspond to leak rates of about 0.4, 1.6 and 6.7 gpm which span the range of leak rate measurements in the test program.
- The three orifice specimens were retested at an independent laboratory over a range of differential pressures of 1400 to 2560 psi at room temperature and certificates of calibration obtained.
- The calibrated leak rates for the two smaller orifices were 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.
  - 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. Alternatively, the average uncertainty implied by the calibration 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%.
- The three orifices were also tested at high temperatures (and pressures) representative of steam line break conditions. A total of 27 tests were performed and data analyzed.
- Leakage rates for the hot orifice tests were also predicted using accepted methodology for predicting two phase flow through orifices and pipes. Both analytical predictions and measured data show good agreement on the dependency of leak rate on pressure difference and primary side temperature. The average ratio of test to analysis for the three analysis methods ranges from 1.00 to 1.07 for the large orifice to 1.31 to 1.55 for the small orifice (see Hot Orifice Test Analysis Summary) Therefore, assuming the orifice test analytical results are correct, the measured leak rate for large leak rates (5.0 gpm) would be reduced by 1% to 7%. Small leak rates wold be reduced by 30% to 55%. The majority of the differences are attributable to uncertainty in the analytical predictions, especially at the small L/D values of the orifices (1.2 to 4.1) where the analytical methods are known to be less accurate.
- The difference between the tests and the analytical prediction varies inversely with orifice diameter, and thus, is smallest for the largest orifice diameter. The leak rates from the crack tests are relatively large; thus , confidence is derived from the good agreement between the tests and the theoretical predictions at these leak rates.
- Based on the calibration tests at room temperature and the 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.

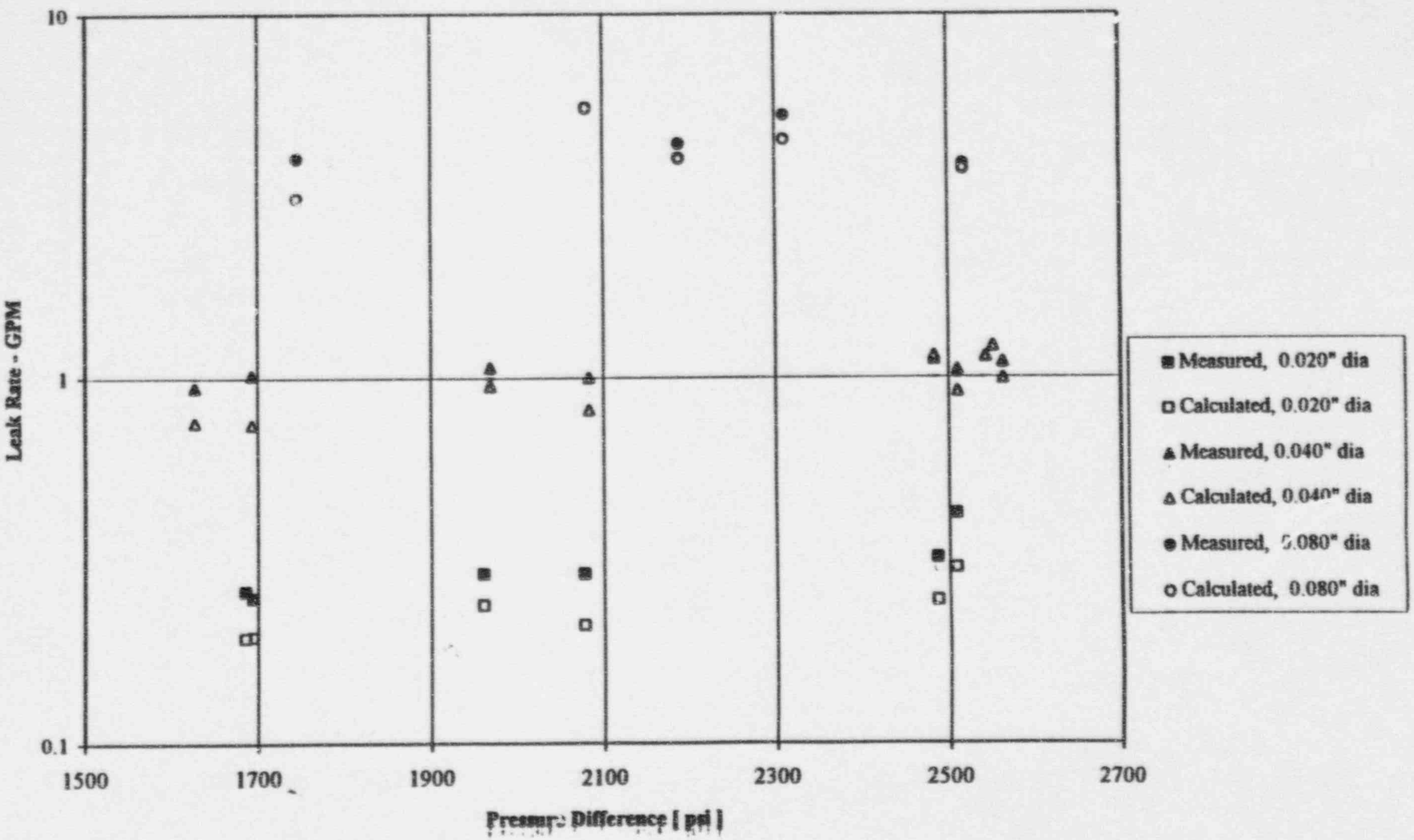
Summary of Uncertainty Assessment

- The contributors to the leak rate uncertainty for the measured leak rate of 5.5 gpm for a single throughwall crack 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 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 6.0 gpm is on the order of -7%/-13%. The actual uncertainties are found as follows:
  - The maximum uncertainty is obtained as [(0.9)·(1.001)·(1.031)-1]·100 or -7%, with a 95% confidence bound of -5%.
  - The minimum uncertainty is obtained as [(0.9)·(1.001)·(0.969)-1]·100 or -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.

IRB Leak Test Loop calibration
Comparison of Measured and Predicted Leak Rates for Hot Tests



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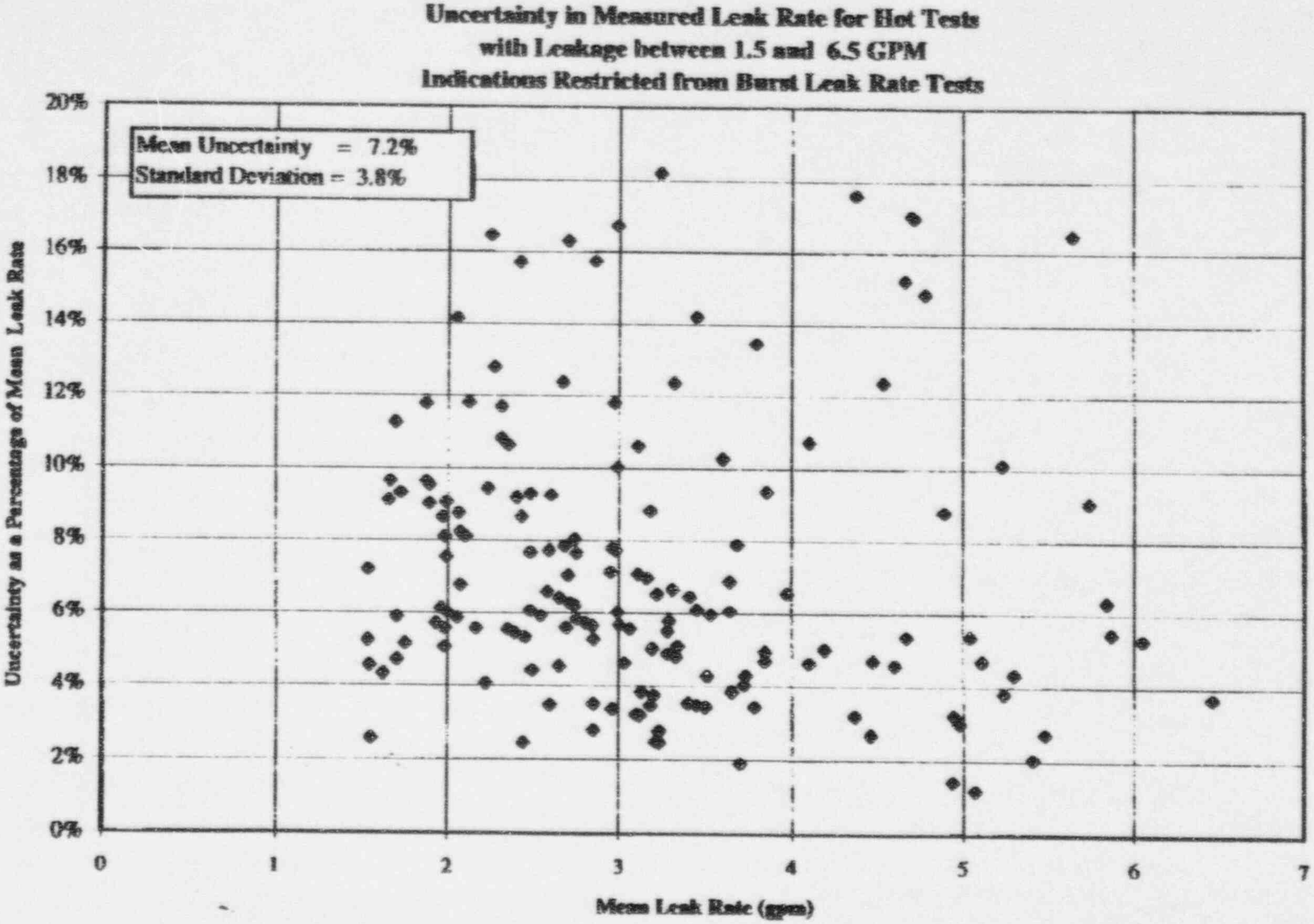

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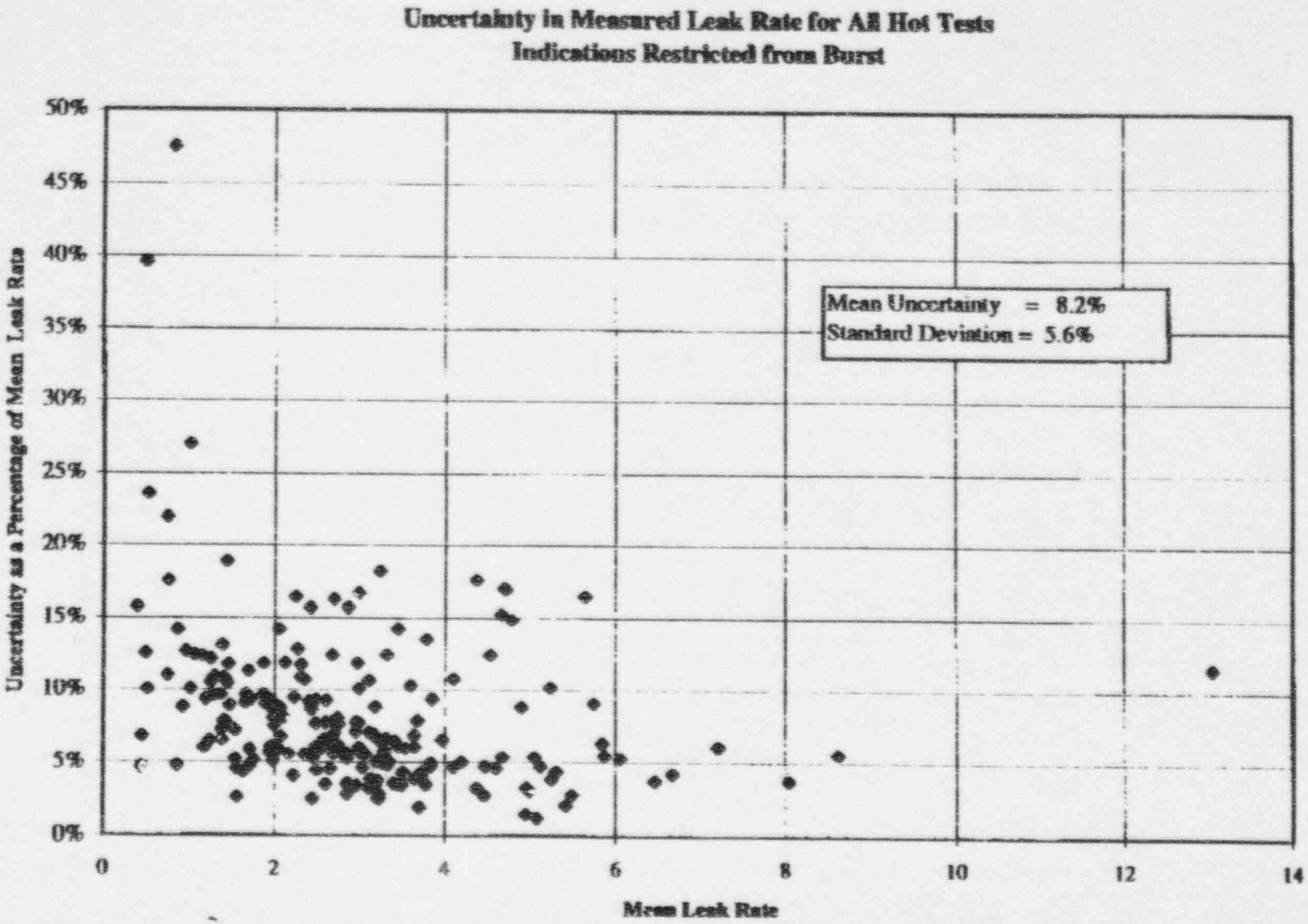
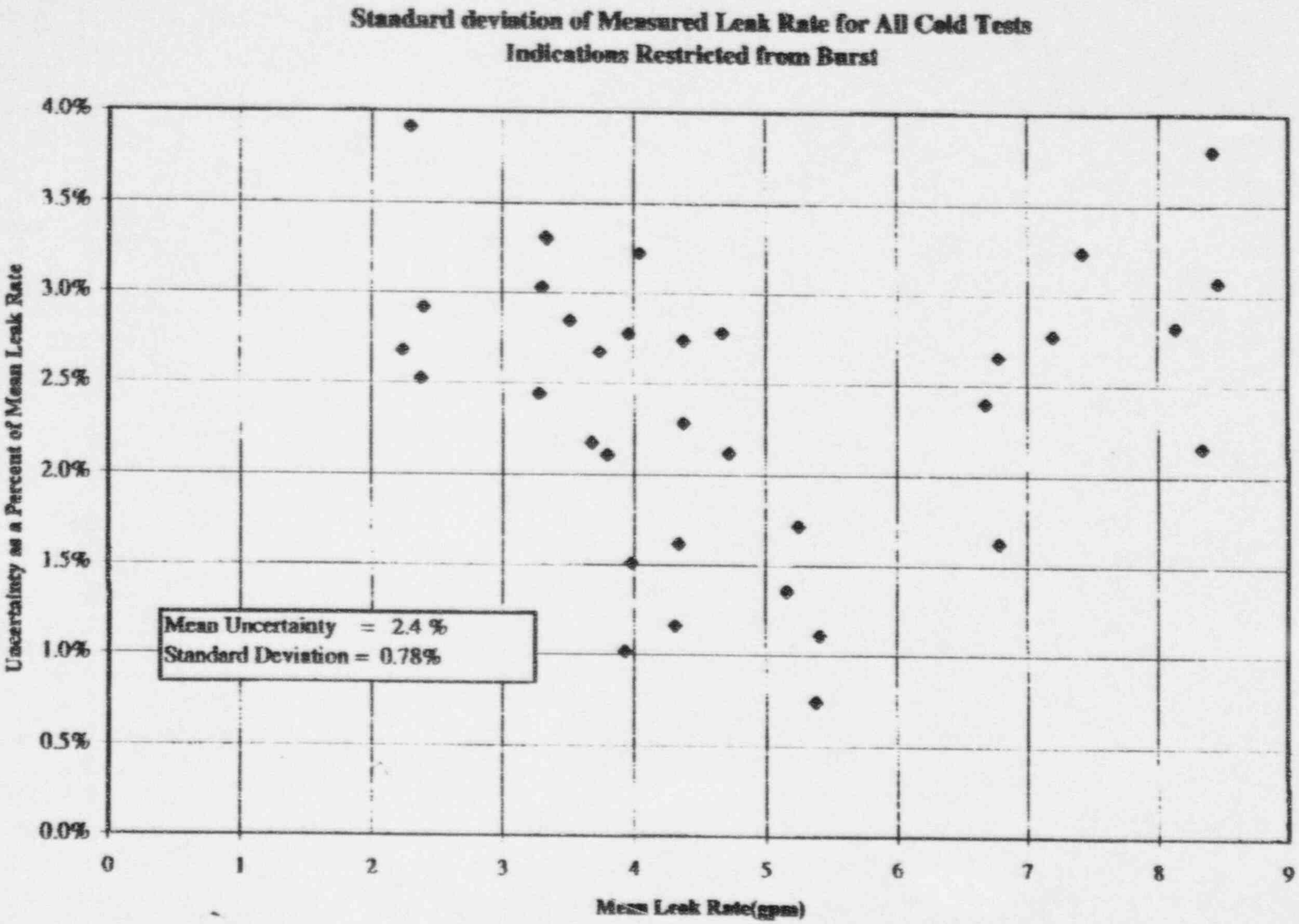
229


Uncertainty in Measured Leak Rate for All Hot Tests
Indications Restricted from Burst
Uncertainty as a Percentage of Mean Leak Rate
Mean Leak Rate
Mean Uncertainty = 8.2%
Standard Deviation = 5.6%
0%
5%
10%
15%
20%
25%
30%
35%
40%
45%
50%
0
2
4
6
8
10
12
14

230


Standard deviation of Measured Leak Rate for All Cold Tests
Indications Restricted from Burst
4.0%
3.5%
3.0%
2.5%
2.0%
1.5%
1.0%
0.5%
0.0%
Uncertainty as a Percent of Mean Leak Rate
Mean Uncertainty = 2.4 %
Standard Deviation = 0.78%
0
1
2
3
4
5
6
7
8
9
Mean Leak Rate(gpm)

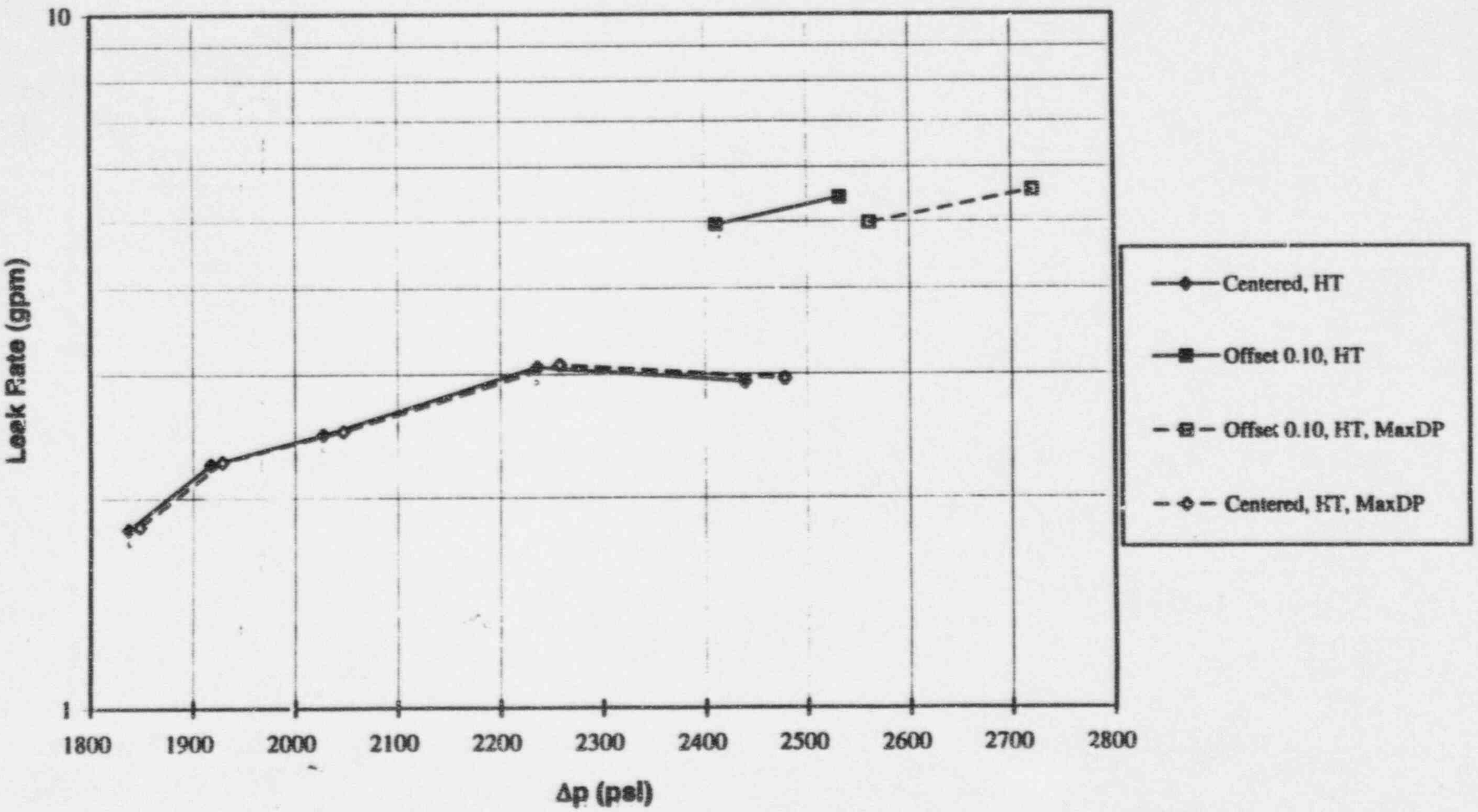
Test 1-6

Comparison of Leak Rates Based on Average ΔP and Maximum ΔP

Indications Restricted from Burst Leak Rate Tests

Test Sequence	Subtest #	Avg. ΔP (psi)	Leak Rate with Avg. Δp (gpm)		Max. ΔP (psi)	Leak Rate with Max. Δp (gpm)	
			Test Conditions	SLB Conditions		Test Conditions	SLB Conditions
1-6A Centered	1	1837	1.69	1.81	1848	1.71	1.82
	2	1920	1.89	2.18	1928	1.90	2.19
	3	1915	1.96	2.29	1930	1.99	2.31
	4	2029	2.06	2.32	2044	2.08	2.33
	5	2026	2.16	2.61	2050	2.20	2.64
	6	2236	2.44	3.07	225[illegible]	2.47	3.09
	7	2[illegible]9	2.96	2.92	247[illegible]	2.99	2.95
	8	2257	3.2	3.20	2364	3.30	3.31
	9	2235	3.53	3.10	2388	3.64	3.25
	10	2273	3.45	3.23	2370	3.53	3.33
1-6B Offset Tests 0.10"	1	2259	3.85	4.25	2272	3.87	4.26
	2	2270	3.45	4.54	2294	3.50	4.58
	3	2206	4.78	4.53	2326	4.57	5.17
	4	2402	4.66	4.99	2554	5.10	4.88
	5	2420	5.23	4.91	2568	5.39	5.07
	6	2543	5.64	5.46	2732	6.01	5.49
	7	2521	5.74	5.39	2710	5.89	5.63
1-6C Freespan	1	1495	13.05	22.16	1520	13.17	22.12
1-6F Expanded 3220 centered	1	2237	4.37	4.99	2272	4.44	5.05
	2	2234	4.1	4.42	2292	4.19	4.51
	3	2148	4.71552	4.19	2386	4.97	4.53
	4	2213	4.53	4.31	2396	4.74	4.57
	5	2257	4.89	4.24	2524	5.12	4.57
	6	2403	4.6971	4.60	2582	4.88	4.80
	7	22[illegible]4	5.07	4.32	2536	5.29	4.66
1-6G Expanded offset	1	1980	4.19055	4.29	2106	4.46	4.56
	2	2028	4.45764	4.05	2226	4.74	4.40
	3	2095	4.36554	4.28	2362	4.75	4.72
	4	2159	4.94577	4.27	2370	5.17	4.59
	5	2300	4.94	4.76	2580	5.25	5.12
	6	2309	5.41	4.57	2560	5.61	4.89
1-6H Expanded offset, RT	1	2054	8.14	3.82	2285	8.59	4.42
	2	2129	8.34	4.05	2416	8.88	4.75
	3	2261	8.46	4.32	2571	9.02	5.01
	4	2264	8.42	4.30	2576	8.98	4.99

Test 1-6
Indications Restricted From Burst Leak Rate Tests
(Normalized to Tp=615 oF and Ps =15 psia conditions



222

Ch Avg-vs-Max Dp

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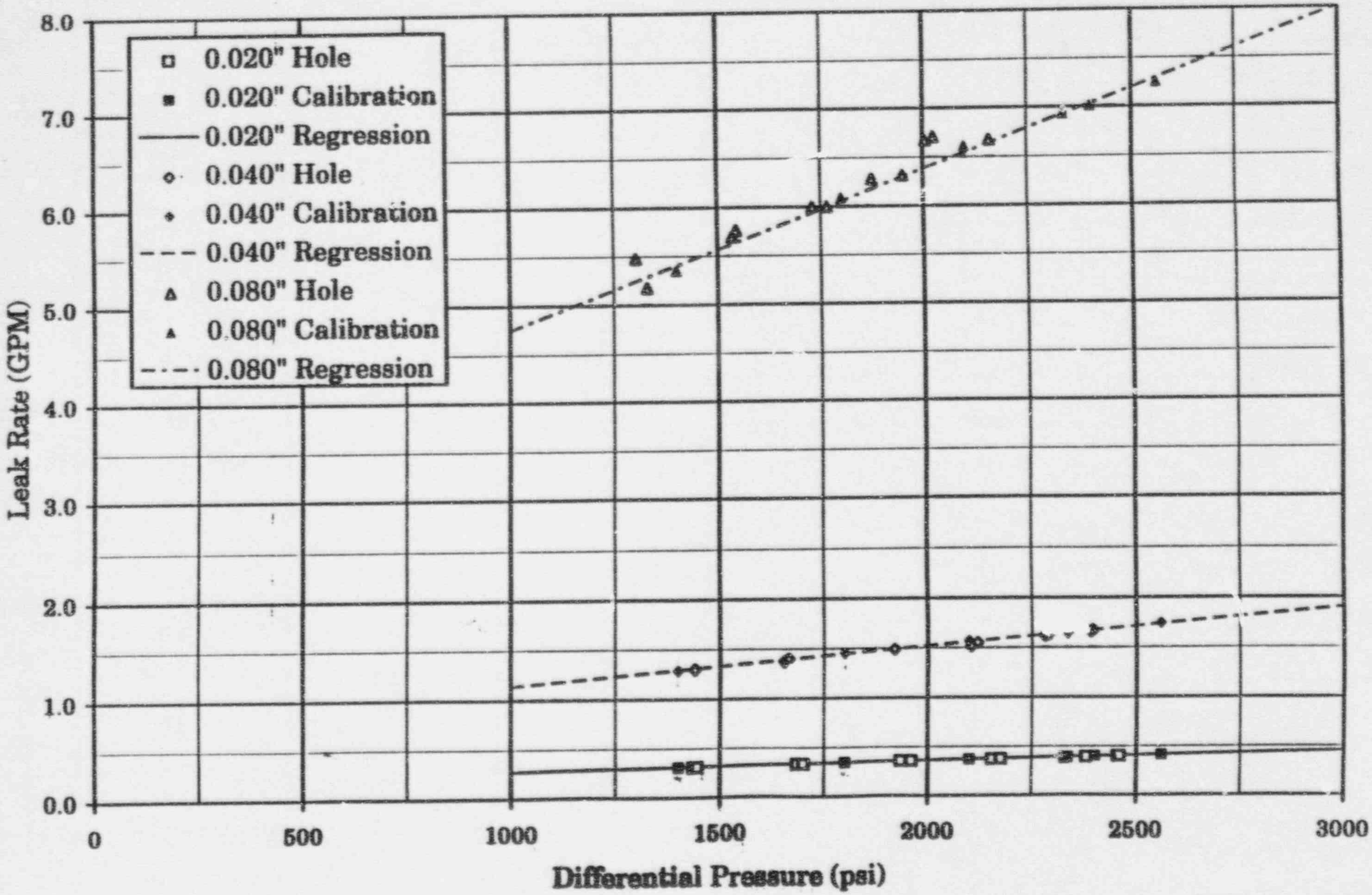
Comparison of W Leak Rates to Calibration Lab



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Summary of Hot Orifice Test Evaluation

Purpose

To compare the leak rates measured in the hot orifice tests against predictions based on two phase flow models/correlations often used in nuclear safety analysis.

Approach

- Empirical correlations from two prior well known tests[1,2] and an analytical model developed by Henry and Fauske[3] to predict critical flow rate through orifices and pipes were used to calculate leak rates at the hot test conditions. The version of Zaloudek empirical correlation used is modified to improve agreement with data for saturated water.

- Leak rates were predicted for all 27 tests carried out for the three orifice sizes (0.020", 0.040" and 0.080" dia.)

- Calculations based on the Henry-Fauske model assumed same contraction loss coefficient (0.95) for all three orifices.

Results

- Both analytical predictions and measured data show good agreement regarding the dependency of leak rate on the primary-to-secondary pressure difference and primary fluid temperature.

- Predictions for the large orifice (0.080" dia) show excellent agreement with the measured data. This provides added confidence in the bounding leak rate established for APC since the leak rate for this orifice size is representative of bounding leak rate for the steamline break conditions.

- Predicted leak rates differ from measured values by 0% to 55% on an average basis, with the present data being higher. The majority of the differences noted are attributable to uncertainty in applying the empirical/analytical correlations to present tests. For example, Fauske correlation is based on data for saturated water alone where as in the present tests the extent of subcooling varied substantially. Also, the assumptions used in Henry and Fauske model are appropriate for orifices and pipes with L/D > 12, where as the L/D ratio for the three orifices tested here varies from 1.2 to 4.1.

- Overall, based on the calibration tests at room temperature and the above comparison between measured and theoretical leak rate, it is concluded that leak rates were measured sufficiently accurately during tests with crack specimen.

1) Fauske, H. K., "The Discharge of Saturated water Through Tubes," Chemical Engineering Progress Symposium Series, Vol. 61, 1965, p. 210.

2) Zaloudek, F. R., "The Critical Flow of Hot Water Through Short Tubes," HW-77594, Hanford Works, 1963.

3) Henry, R. E. and Fauske, H. K., "The Two-Phase Critical Flow of One-Component Mixtures in Nozzles, Orifices, and Short Tubes," Journal of Heat Transfer, May 1971, pp. 179-187.

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.

Calibration of the Westinghouse Test Loop - Room Temperature

Hole Dia	**0.020"**							
Calibration Lab.		Regression		Comparison of W Loop to Calibration				
dP (psi)	Leak Rate	dP (psi)	Leak Rate	Test	Avg. dP (psi)	W Loop (gpm)	Regress Q	Ratio Cal/W
1400	0.305	1000	0.269966	A1	1435	0.3038	0.3096	1.019
1800	0.345	3000	0.452287	A2	1445	0.3065	0.3105	1.013
2100	0.370			A3	1685	0.3303	0.3324	1.007
2335	0.390			A4	1700	0.3303	0.3338	1.011
2400	0.401			A5	1935	0.3567	0.3552	0.996
2560	0.410			A6	1960	0.3567	0.3575	1.002
Regression of Cal Data				A8	2155	0.3699	0.3753	1.015
b.1	9.12E-05	0.178806	b.0	A7	2175	0.3725	0.3771	1.012
SE.b1	2.62E-06	0.005591	SE.b0	A10	2330	0.3831	0.3912	1.021
r^2	99.7%	0.002533	SE.y	S9	2380	0.3884	0.3958	1.019
F	1213.071	4	DoF	A11	2455	0.3989	0.4026	1.009
SS.reg	0.007785	2.57E-05	SS.res	A12	2460	0.3989	0.4031	1.010
F.Prob	4.06E-06	936820.8	SS.X				Count	12
P1.Value	4.06E-06	5.7E-06	P0.Value	**Conf.**	**t**	**Bound**	**Average**	**1.011**
N	6	1.166667	1 + 1/N	**95.0%**	**1.7959**	**1.0242**	**St Dev**	**0.007**
var.X	187364.2	2099.167	mu.X				Max	1.021
Pred. %	0.95	2.131846	t.val				Min	0.996
								Median	1.011

Calibration of the Westinghouse Test Loop - Room Temperature								
Hole Dia	**0.040"**							
Calibration Lab.		Regression		Comparison of W Loop to Calibration				
dP (psi)	Leak Rate	dP (psi)	Leak Rate	Test	Avg. dP (psi)	W Loop (gpm)	Regress Q	Ratio Cal/W
1400	1.287	1000	1.139458	B2	1440	1.2972	1.3076	1.008
1800	1.450	3000	1.90375	B1	1440	1.2972	1.3076	1.008
2100	1.572			B4	1655	1.3712	1.3896	1.014
2335	1.639			B3	1665	1.3976	1.3936	0.997
2400	1.670			B6	1920	1.4875	1.4910	1.002
2560	1.739			B5	1920	1.4875	1.4910	1.002
Regression of Cal Data				B7	2105	1.5165	1.5617	1.030
b.1	0.000382	0.757311	b.0	B8	2120	1.5509	1.5675	1.011
SE.b1	9.58E-06	0.020472	SE.b0	B10	2280	1.6196	1.6286	1.006
r^2	99.7%	0.009276	SE.y	B9	2290	1.6275	1.6324	1.003
F	1589.82	4	DoF	B12	2390	1.6592	1.6706	1.007
SS.reg	0.136809	0.000344	SS.res	B11	2395	1.6724	1.6726	1.000
F.Prob	2.36E-06	936820.8	SS.X				Count	12
P1.Value	2.36E-06	3.19E-06	P0.Value	**Conf.**	**t**	**Bound**	**Average**	**1.007**
N	6	1.166667	1 + 1/N	**95.0%**	**1.7959**	**1.0225**	**St Dev**	**0.008**
var.X	187364.2	2099.167	mu.X				Max	1.030
Pred. %	0.95	2.131846	t.val				Min	0.997
							Median	1.006

Calibration of the Westinghouse Test Loop - Room Temperature

Hole Dia	**0.080"**							
Calibration Lab.		Regression		Comparison of W Loop to Calibration				
dP (psi)	Leak Rate	dP (psi)	Leak Rate	Test	Avg. dP (psi)	W Loop (gpm)	Regress Q	Ratio Cal/W
1400	5.350	1000	4.748086	C1	1303	5.4769	5.2421	0.957
1800	6.090	3000	8.008581	C2	1330	5.1757	5.2861	1.021
2100	6.610			C4	1535	5.6962	5.6203	0.987
2335	6.930			C3	1545	5.7622	5.6366	0.978
2400	7.010			C5	1730	6.0000	5.9382	0.990
2560	7.250			C6	1765	6.0000	5.9952	0.999
Regression of Cal Data				C8	1875	6.2774	6.1746	0.984
b.1	0.00163	3.117838	b.0	C7	1950	6.3091	6.2968	0.998
SE.b1	5.37E-05	0.114695	SE.b0	C9	2005	6.6711	6.3865	0.957
r^2	99.6%	0.051972	SE.y	C10	2025	6.7054	6.4191	0.957
F	921.7869	4	DoF	C11	2160	6.6711	6.6392	0.995
SS.reg	2.489796	0.010804	SS.res					
F.Prob	7.01E-06	936820.8	SS.X				Count	11
P1.Value	7.01E-06	1.09E-05	P0.Value	**Conf.**	**t**	**Bound**	**Average**	**0.984**
N	6	1.166667	1 + 1/N	**95.0%**	**1.8125**	**1.0210**	**St Dev**	**0.020**
var.X	187364.2	2099.167	mu.X				Max	1.021
Pred. %	0.95	2.131846	t.val				Min	0.957
							Median	0.987