Steam Generator Program Status

SGTF / NRC Meeting

July 6, 2000

NEI

Agenda

- Introduction
- Steam Generator Pressure Testing
  - Background
  - Immediate Implications
  - Issue Resolution
- NDE Issues Related to IP2
- Summary

NEI

ATTACHMENT 2

Pressure Testing Results

- ANO pressure test results appear to be dependent upon hold times
- Implications on industry burst models
- E&R IRG is addressing

NEI

SG Pressure Testing

- ANO Pressure Tests - Bob Keating
  - Problem background
  - Immediate implications
  - Resolution

NEI

ANO Pressure Testing - Overall:

- No immediate safety concern
  - Other tests do not show this dependence
  - In situ pressure test results demonstrate structural integrity
- Additional study underway:
  - Understand and validate ANO tests
  - Obtain details on previous lab tests
  - NRC feedback needed by 7/13

NEI

NDE Issues Related to IP2

- IP2 Implications - Dan Mayes
  - Data quality
  - Signal-to-noise issue
  - Small radius U-bends
  - High frequency probes

NEI

NDE Issues Related to the IP2 Event

- Applicability of IP2's signal-to-noise issue
  - Not seen as a wide spread concern
  - Sample data being obtained at several plants to illustrate typical response
  - Discussion topic at NDE Workshop

NEI

Summary

- Pressure testing hold time effect
  - Not an immediate safety concern
  - Additional study is underway to understand the phenomenon
- Signal to noise issue
  - Not typical across the industry
  - Comparative data being obtained for non stress relieved plants
- Will keep the staff informed

NEI

SG Tube Burst Testing

R. F. Keating
Westinghouse NSBU
Madison, PA

Background

- ANO 2, SG B, R72C72 was in situ tested during the 2P99 inspection outage.
  - The maximum pressure attained was on the order of 4150 psi, less than 3ΔP for the plant.
  - Whole tube test, no bladder over the flaw.
- Results were inconclusive.
  - Pressure less than 3ΔP, but
  - Burst pressure not demonstrated from the test record.

ATTACHMENT 3

Background (Cont.)

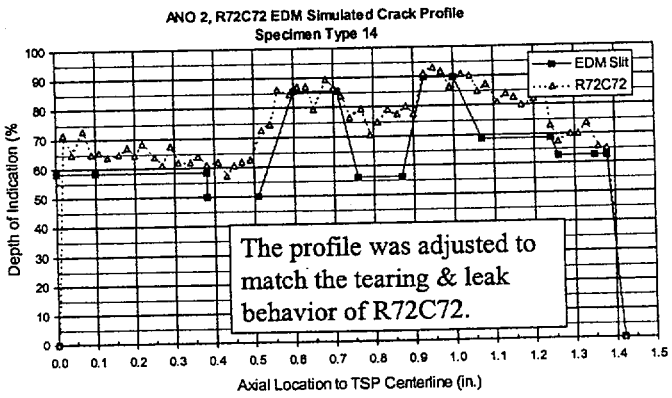
- Prior presentations to the staff based on available test data were not convincing that burst pressure greater than 3ΔP could have been attained.
- A series of leak, ligament tearing, and burst tests was performed on surrogate specimens.
  - EDM machined profile to approximate the RPC profile of R72C72, adjusted to approximately match the in situ pressure test leakage characteristics

Type 14 Specimen Configuration

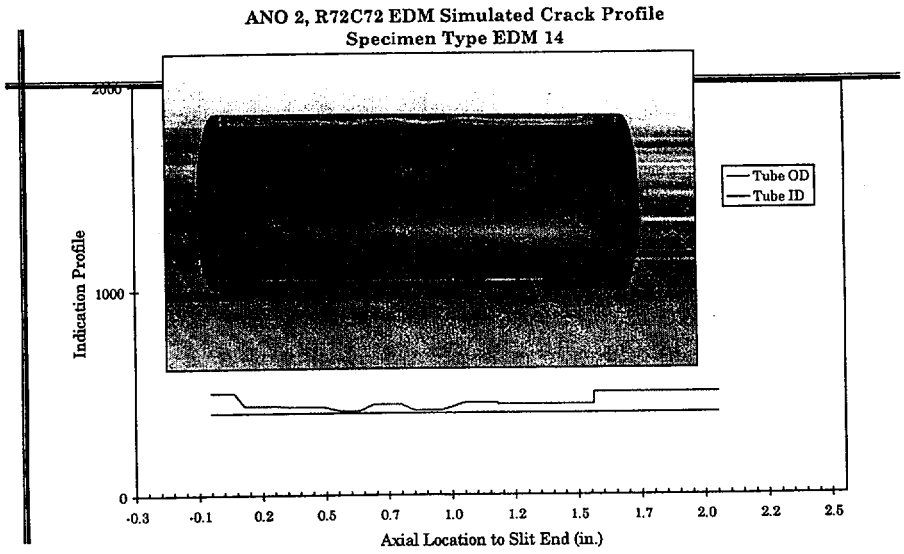
Specimen typified by two deep central penetrations with 60% deep segments on each side.

Total length on the 'order or 1.4".

Pressure changes by about 125 psi per mil of depth of the profile.



Type 14 Specimens – EDM Notch



Test Results

- Ligament tearing pressures involving hold times of 5 to 90 minutes were significantly below the value of 3ΔP for ANO 2.
- Burst pressure tests at 2000 psi/sec performed on specimens that had been leak tested did not result in values that were greater than the tearing pressure.
- Burst pressure tests at 2000 psi/sec on virgin specimens had burst pressures well in excess of 3ΔP for ANO 2.

Test Results Interpretation — NRC

- If the pressure was raised slowly, and if hold times were included, the tubes would have failed at pressures significantly lower than $3\Delta P$.
- Rapid increase in pressure did not allow time for ligament failures to occur.
  - Artificially elevated the burst pressure of the test specimens.

Test Results Extension — NRC

- Raises safety concerns regarding analytical burst models based on similar testing.
- Specifically raised question of ODSCC database.
- If the validity of the data can be questioned, then so can the operability of the steam generators at plants that have implemented ARCs.
- **Industry Response:** There is enough other information regarding test rates to imply that the ANO 2 test results are not generally applicable.

Specific Information Available

- Initial effort at quick survey of available information and determination of the urgency of addressing the concerns.
  - Throughwall cracking
  - Part-Throughwall cracking
  - ODSCC ARC
  - PWSCC ARC
- Steam generator operability

Throughwall Cracking

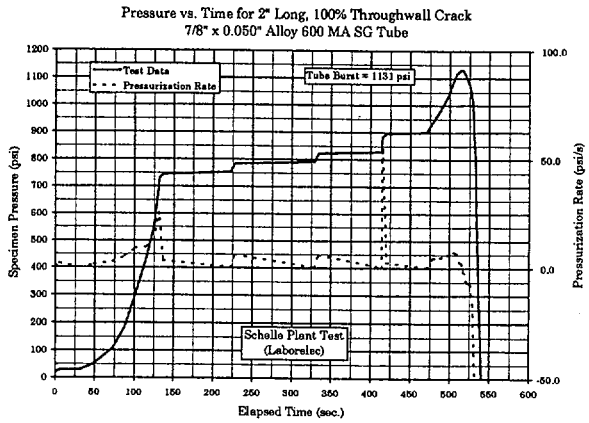
- Laborelec testing — Specific investigation of slow to extremely fast pressurization rates.
  - Schelle tests.
- EdF/Framatome testing — Specific investigation of slow to intermediate rates (17 to 435 psi/s).
- Industry standard tests are performed at 200 to 2000 psi/sec
- Test data demonstrated no dependence of the burst pressure on the pressurization rate.

Schelle Pressurization

Pressurization rates for the Schelle test specimens is quite slow.

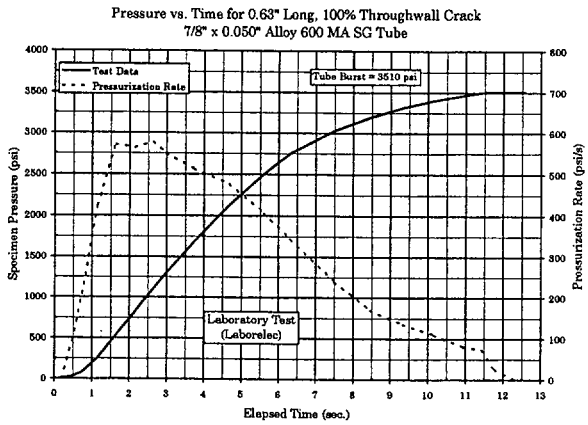
Near burst, the rate is quasi-static, about 5 psi/sec.

No sealing bladder is used for these tests



Laboratory Pressurization

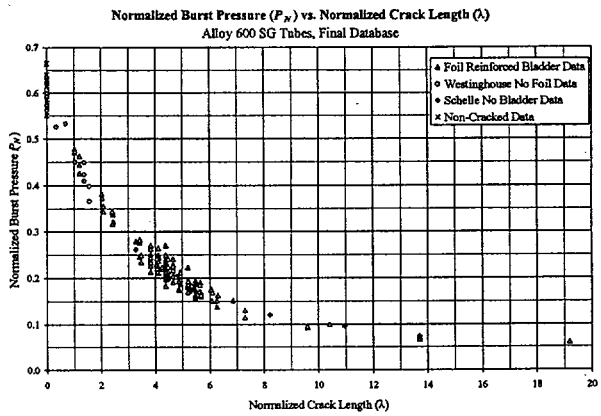
Laborelec laboratory test rates are also quite slow, and are quasi-static near the burst pressure.



Throughwall Cracking Database

There is no difference between the Schelle, Laborelec laboratory, or Westinghouse laboratory test results.

There is no apparent rate effect for throughwall cracks.



Throughwall Cracking (Cont.)

- Battelle data from NUREG/CR-0718 were taken at about 30 psi/s and are not at variance with industry data.
- Need to look at circumferential cracking, but the effects should not be worse.
  - One may expect less dependence because of the lack of bulging associated with bursting of circumferentially cracked tubes.

Part-Throughwall Cracking

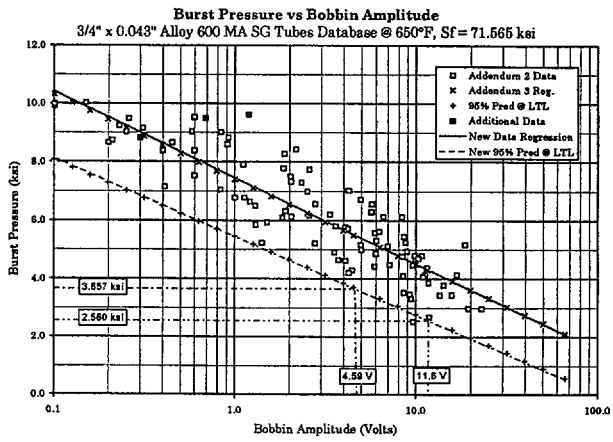
- Results from different laboratories are in general agreement despite different test rates.
  - Laborelec at about 200 psi/s
  - EdF/Framatome at about 500 psi/s
  - Westinghouse at about 1000-2000 psi/s
  - CE at about 15 to 35 psi/s (quasi static)
  - Battelle at about 30 psi/s
- ANL data for 1/4" long, 60 to 90% deep
  - Quasi-Steady to 3200 psi/s – No significant effect (still being studied)

ODSCC ARC

- Tests at several laboratories in three different countries.
  - Rate of about 15(?) to 2000 psi/s with no effect.
  - EdF at 500 psi/s has highest burst pressures.
- Nominal burst at 620°F about 7000 psi for both 3/4" & 7/8" tubes at 1 and 2 V respectively.
  - SLB at 2560 and 1.4·SLB at 3600 respectively.
  - Significant margin to potential load and to the criterion burst resistance.

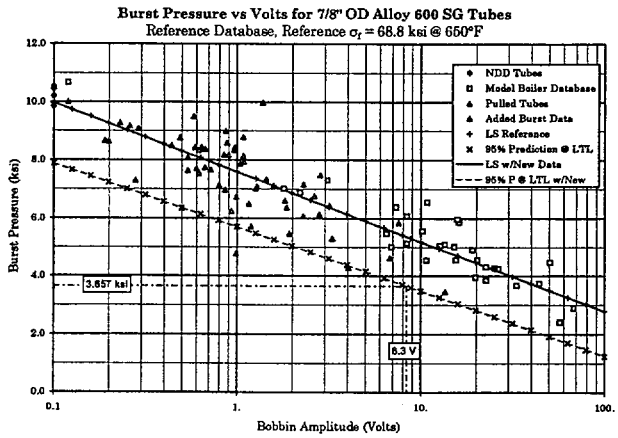
ODSCC ARC Database for 3/4" Tubes

There is significant margin, cracking is less than about 0.7", and free span leak testing has shown no time dependent effects at pressures greater than P_{SLB} at elevated temperature.



ODSCC ARC Database for 7/8" Tubes

As for 3/4" tubes, there is significant margin, cracking is less than about 0.7", and free span leak testing has shown no time dependent effects at pressures greater than P_{SLB} at elevated temperature.



ODSCC ARC Additional Information

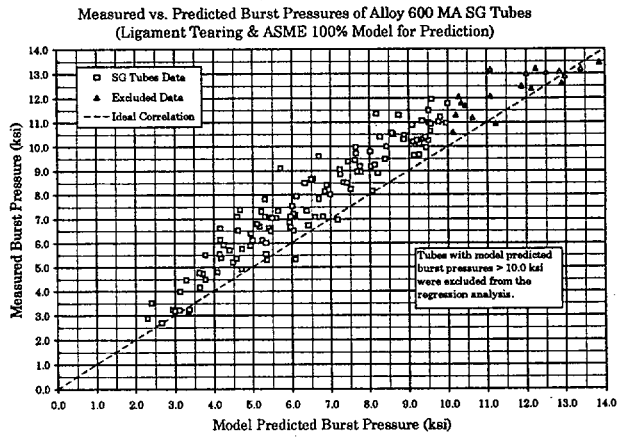
- Leak tests performed at 620°F and 3000 psi showed no propensity toward time-dependent behavior.
- Tests performed at significant voltage levels.
- Morphologies that might be susceptible would likely exhibit high voltage and would probably be plugged.

PWSCC ARC and Other

- Tests somewhat similar to the ODSCC ARC tests have been performed, data is incomplete.
  - Data base consists of pulled tube and laboratory test specimens.
  - No EDM fabricated specimens were used.
- Earlier test data at vendor laboratories tended to slower pressurization rates and no dichotomy has been evident in the data (further look warranted).

PWSCC ARC Model

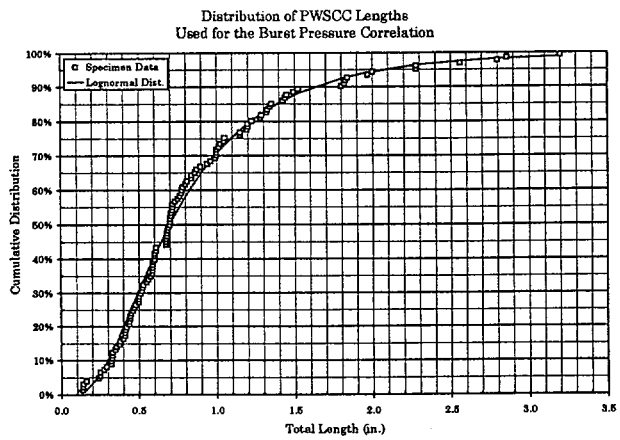
The prediction model is based on the French ligament tearing prediction using a *weak link* approach and the ASME throughwall burst prediction equation.



PWSCC ARC Database

Even though significant lengths are involved, the data were generally above the prediction curve.

Dented tube ARC cracks would not be expected to be greater than 0.7".



Additional Industry Data

- Other vendor laboratory procedures have included hold points at MSLB and 3NODP
  - Also elevated temperature leak testing
  - Pressurization rates above 3NODP at 2000 psi/s
- Number of In Situ Procedures include hold times at 3NODP
- No evidence of results similar to ANO results
- Additional review to be conducted

Pulled Tube Test - example

Flaw Test Program

Pressurized to NOP and held for five minutes

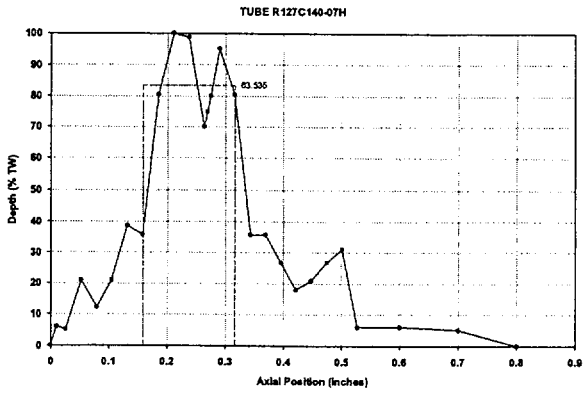
Leak developed at 2900 psi

Elevated temperature leak test at 2300 psi (~75 minutes)

Bladder installed - pressurized to 4450 and held for five minutes

Flaw taken to failure at 5734 psi (4914 psi temperature corrected)

Predicted burst 4500 psi



Open Items

- There are some unknowns with respect to the recent test data for ANO EDM specimens.
  - Post-test examinations have not yet been performed to measure the as-built dimensions of the specimens.
    - One initial examination indicates greater depths than on the drawing. (Ligament tearing pressures will vary with depth.)

Initial Conclusions

- Sufficient information exists to indicate that <u>it is likely that several modes of degradation are not affected</u> by the pressurization rate.
  - Throughwall cracks, Some Part-Throughwall cracks, ODSCC ARC, PWSCC ARC, etc.
- No immediate operability concerns.

Initial Conclusions (Continued)

- The test results indicate that a time dependent deformation and burst phenomenon does exist for at least one specific EDM notch morphology.
- Additional information is needed from the test specimens, e.g., as-built profiles, in order to better understand the results.
- Additional engineering is needed to quantify and characterize the phenomenon implied by the test results.

Current & Future Actions

- Discuss the burst test issue with the staff on 7/6.
- The information presented should:
  - Summarize current knowledge — Today.
    - All modes of degradation — Ongoing.
  - Extent of the issue — Appears to be limited to specific morphology.
  - Plan for resolution — Following slides.

Specific Issues to be Addressed

- Burst pressure dependence on pressurization rate.
- Effects on industry test procedures.
- Effects on industry evaluation models.

Industry Burst Evaluation Program

- HYPOTHESIS —Hold time may affect the burst pressure of some flawed tubes.
- Program Overview
  - Characterize the phenomenon to deal with the implications.
  - Verify and develop an understanding of the existing hold-time data.
  - Assess implications on existing burst test databases and CMOA analyses.

Program Details — Verification

- Verify and document the ANO EDM burst tests.
  - Review the test procedures and test conduct.
  - Examine raw data (pressure vs. time histories).
  - Characterize specimen appearance by test.
  - Measure & compile as-built depth profiles.
  - Perform fractographic analysis of surfaces.
  - Examine tensile test data for rate effect.

Program Details — Database

- Compile a database of loading rate and hold time effects evident from existing test data.
  - Information available from W, W-CE, FTI, PNL, and ANL.
  - Test procedures.
  - Burst test results.
  - Pressure time records.

Program Details — Significance

- Do the results provide evidence of an unanticipated phenomenon?
  - What is the phenomenon?
- Implications for ODSCC & PWSCC ARCs.
- Implications for CMOA evaluations.
  - Past & present.
  - Look at each model of degradation and the supporting test data.
- Effect on the EPRI Flaw Handbook.

Program Conduct & Schedule

- Program initiation on July 6, 2000.
- Requests to industry vendors and national laboratory personnel for information
- Targeted completion by end of August.
- Results will be presented to the staff.

ANO 2 Burst Testing Results

1.0 Introduction

The following paper describes the current status of work being done to address the burst pressure test phenomenon observed on ANO test data. It is a "work in progress" and will be developed further as study progresses.

2.0 Background

At the ANO 2 2P99 inspection in November 1999, SG B tube R72C72 was pressure tested in situ to evaluate the burst pressure and leakage potential for the indication. The maximum pressure attained during the test was 4147 psi as corrected for the pressure drop due to leakage flow in the test equipment and for instrumentation error. The test was performed as a whole tube test, as contrasted to use of a localized test employing a bladder, and the maximum test pressure was limited by the flow capacity of the test equipment. The test results were considered to be effectively inconclusive because three times the normal operating primary-to-secondary pressure difference, $3\Delta P$, was not reached and at the same time information was not available to demonstrate that the burst pressure of the tube had been reached. To determine whether or not the R72C72 tube burst pressure is greater than or equal to $3\Delta P$, a series of EDM notch surrogate specimens were fabricated and pressure tested. The flaws in the test specimens were made using EDM techniques to simulate the single, eddy current (ECT) estimate of the R72C72 indication profile with adjustments to match in situ testing leakage behavior. The adjustments consisted of making the ligaments thicker and adjusting some flaw depths. Separate series of pressure tests were conducted to identify both the leak (ligament tearing) and burst resisting capability of the EDM notched tube specimens.

In a meeting between Entergy and the NRC staff on June 8, 2000, information was presented comparing burst pressures obtained following ligament tearing with standard burst pressure test results obtained using a foil reinforced bladder with pressurization rates on the order of 2000 psi/s (in accord with industry guidelines). The results from the ligament tearing and burst pressure testing were as follows:

1) Ligament tearing pressure tests of the EDM specimens demonstrated ligament tearing pressures significantly below the value of $3\Delta P$ for the ANO 2 plant SGs. Ligament tearing tests were performed using very slow pressurization rates (on the order of a few psi/minute and including hold

ATTACHMENT 4

times of several minutes) in order to achieve tearing of a portion of the crack without opening the whole crack.

2) Burst pressure tests performed on specimens that had been previously pressurized to ligament tearing did not result in demonstrating a burst pressure in excess of the ligament tearing pressure. The burst pressures following ligament tearing were found to be less than the burst pressures obtained using the industry standard burst pressure test techniques. These tests were performed per EPRI guidelines [1] using a foil reinforced plastic liner to prevent loss of pressure through the simulated flaw opening.

3) Burst pressure tests performed on non-previously tested specimens exhibited burst pressures significantly in excess of the ligament tearing pressures. Burst pressures in excess of three times the normal operating pressure differential, 3ΔP, for the ANO 2 plant SGs were measured for several of the specimens. The burst pressure tests were performed using a pressurization rate of about 2000 psi/s. The specimens were also lined with a bladder which was reinforced with a lubricated brass foil patch prior to testing.

4) Subsequent fractography, material testing and flaw depth profiling have not yet been performed on the EDM specimens to determine if the results are truly indicative of a previously unknown effect of the pressurization rate on the fracture, i.e., ligament tearing, for complex shaped planar, axial flaws. This activity has been authorized by the EPRI SGMP and should be completed in approximately one month.

The ANO 2, R72C72 indication was about 1.4 inches long with two deep sections separated by a shallower ligament, such that when that ligament tore, the resulting throughwall length did not permit a higher burst pressure than the ligament tearing pressure. If these test results are confirmed to indicate a pressurization rate or hold time influence on burst pressures, it is expected to affect only long and near throughwall cracks (likely significantly longer than an acceptable length for a throughwall flaw such as about 0.7 inch).

During a SGTF telephone conference on June 20, 2000 [2], the NRC staff expressed the opinion that the results indicate that if the pressure was raised slowly, and if hold times were included in the pressurization process, the tubes would have failed at pressures significantly lower than 3ΔP. The NRC staff also opined that the rapid increase in pressure used for the burst tests did not allow time for ligament failures to occur, thus artificially elevating the measured burst pressure of the EDM notch surrogate specimens. The industry position is that the cause of the apparent anomaly is not fully understood and that there is a significant library of laboratory and field in situ test results available that do not exhibit a similar pressure ramp

rate dependence. During that same SGTF telephone conference, the NRC staff indicated that this issue may have safety concerns as it raises questions about the adequacy of analytical burst models and of the results of similar laboratory tests that were used as a basis for several voltage based alternate repair criteria. If the laboratory tests are flawed, i.e., if a pressure ramp rate dependency has been overlooked, the validity of the data used to support the ARCs could be questioned and so could the operability of the steam generators at plants that have implemented the ARCs. The staff noted that they think this could affect eight to ten plants.

In summary, the pressurization rate associated with the use of industry standard procedures for burst testing was thought to not significantly affect the test result. However, the results from the testing program conducted using the R72C72 EDM notch surrogate specimens indicates that the standard test pressurization rates may lead to a higher burst pressure results than would be obtained from tests conducted in a quasi-static manner. This raises the following issues:

1. Is the burst pressure of degraded tubing a function of the pressurization rate used to test the tubing?

2. Should changes be made to industry test procedures to account for the potential dependence of the burst pressure on the pressurization rate?

3. Are there industry evaluation models that were empirically derived or qualified using data which might be pressurization rate dependent, e.g., data used for the ODSCC ARC?

4. Do the industry evaluation models need to be modified to account for the potential dependence of the burst pressure on the pressurization rate, i.e., to account for the potential for ligaments to tear prior to burst, thus reducing the burst pressure?

It is industry's current position that there is enough other information regarding testing ramp rates to demonstrate that a significant concern relative to the suitability of the data developed to support industry developed burst correlations and/or models should not exist. Industry is proceeding with a systematic approach aimed at developing an understanding of the ANO test program results and implications relative to the results from other test programs.

3.0 Discussion

The ANO 2 test results do present an unexplained difference relative to the results of SG tube burst testing that has been performed during the last quarter century. Specific tests have been performed to verify that the testing processes do not result in

an artificial increase in the burst pressure from strain-rate effects. However, the issue here is whether or not there is some other time-dependent phenomenon active when a complex crack profile is involved. The testing database mostly consists of throughwall slits and rectangular shaped profiles for developing analytical models for predicting burst pressure. However, burst data at different pressurization rates for pulled tubes, laboratory generated flaws and more complex EDM profiles exists and is interspersed in the test database with no apparent existence of the anomaly observed in the ANO testing.

4.0 Industry Standard Burst Testing

During the last 25 years a large number of burst tests have been performed under a variety of conditions and for a variety of degradation morphologies. Testing performed since 1995 likely conforms to the guidelines presented in Reference 1. If the tubes are not degraded, the burst pressure will be on the order of 10 to 12 ksi and the hoop strain at burst on the order of 20%. Given that yielding does not occur until a pressure of about 5 ksi is reached, the plastic strain accumulates in as little as five seconds. The rate is about 0.04 in/in/sec and is not at variance with results from standard tensile tests. The results for a variety of conditions of degraded tubing are summarized in the following paragraphs. This summary is not considered complete and the industry recommended follow-on program will endeavor to supplement this discussion. However the data presented in this paper indicates a consistent trend regarding the impact of pressurization rate.

4.1 Throughwall Cracking

The definitive work on measuring the burst pressure of SG tubes with throughwall cracks was performed by Laborelec (Paul Hernalsteen) [3]. In addition to performing multiple tests on laboratory specimens to investigate the effect of various test parameters, a series of specimens were tested to failure using the large capacity pumps at the Schelle fossil power plant in Belgium. The tests were performed without benefit of any lining to prevent leakage from the specimens. The pressure was gradually raised until unstable crack extension was attained. The results from those tests over a wide range of crack lengths confirmed the supposition that burst pressures were greater than had been reported by Westinghouse [4] from tests conducted at high rates and using a plastic bladder to prevent leakage prior to crack extension. They also confirmed that burst pressures were slightly lower than had been reported by others [4], including Laborelec, that used a metal foil, like stainless steel, to line the plastic bladder to prevent its expulsion through the crack opening.

Other testing performed by Laborelec [3] did confirm that burst pressures could be artificially increased by about 15% by increasing the pressurization rate by three orders of magnitude, say 200 psi/s to 200000 psi/s. Hernalsteen also reported

reductions in measured burst pressure by about 5% by decreasing the pressurization rate from say 200 psi/s to 20 psi/sec, but concluded that the result was due to *creeping* deformation of the liner and foil and not extension of the crack in the tube specimen.

A typical pressure versus time history for a Laborelec laboratory test is shown on Figure 4 and that for one of the tests performed at Schelle is on Figure 5. The pressurization rates from those specific tests are also illustrated on the figures. It is apparent that relatively slow pressurization rates were actually achieved during the tests. The pressure versus time histories from the other Schelle tests have been requested from Laborelec. The EPRI database curve for throughwall cracking is shown on Figure 6 along with the Schelle data. In fact, the Schelle data were included in the database for the regression analysis. The Laborelec laboratory and Schelle data are expected to be free from rate effects because the tests are conducted rather slowly. The close correlation of their results with the EPRI results shown in Figure 6 indicates that the EPRI database for throughwall cracks is also free from rate effects.

Additional data were reported by EdF [5] for throughwall cracks with lengths of 0.276" (18 & 435 psi/s), 0.591" (18 to 234 psi/s), and 1.18" (17 to >242 psi/s). The results of these tests demonstrate that there is no dependence of the burst pressure on the pressurization rate within the range of rates tested.

Finally, the data reported by the Battelle National Laboratory in Reference 6 were obtained at a rate of 30 psi/s. These burst test results are not at variance with data obtained from other test programs at other laboratories, including Westinghouse, Combustion Engineering and Framatome.

4.2 Part-Throughwall Cracking

Data for a variety of tube sizes and various depth rectangular notches were reported in Reference 6. These data were obtained at pressurization rates of about 30 psi/s at 600 °F and have been used with results from other test programs from other laboratories, including Westinghouse, which typically use significantly higher pressurization rates.

Data for 0.250" long EDM notches from 60 to 90% deep at pressurization rates of "Quasi-steady" to 3200 psi/s indicate no significant dependence on the ligament tearing pressure for 7/8" diameter by 0.050" thick Alloy 600 MA SG tubes [7].

Testing performed for the Combustion Engineering Owner's Group (CEOG) of laboratory environmentally generated, long deep flaws did not produce results similar to the ANO test program. Additional study on part throughwall cracks is ongoing by the SGMP to find out if pressurization rates have an effect.

4.3 ODSCC ARC Burst Tests

Burst tests of model boiler and pulled tube specimens were, and continue to be, performed at several different laboratories in at least three countries, the United States, Belgium and France. Although the testing procedures were different the test results were similar. Tests performed in the US were at a pressurization rate of about 1500 to 2000 psi/s, while those in France were at a maximum of 500 psi/s and those in Belgium were most likely performed at a rate of about 200 psi/s [1].

The US and Belgian results were quite similar, despite being at the most different pressurization rates, while the French burst test results were uniformly of 425 psi higher on average than the US and Belgian results. The implication here is that there is no effect of the pressurization rate. Leak rate testing was performed for significant hold times at 600 °F at 3000 psi without observing any time dependent effects.

The ODSCC voltage limits are 1.0 and 2.0 V for plants with 3/4" and 7/8" diameter tubes respectively. The burst resistance of tubes subject to the ARC is illustrated on Figures 8 and 9 for 3/4" and 7/8" diameter tubes respectively. The average burst pressure for tubes with ODSCC indications is about 7500 psi regardless of the size of the tubing [6]. This result is to be compared to an imposed pressure during a postulated SLB event of about 2560 psi with a criterion value of about 3600 psi. Therefore, the margin to tube burst during postulated accident conditions is adequate for both tube sizes.

4.4 PWSCC ARC and Other Burst Tests

Testing programs similar to those for ODSCC ARC applications have been conducted at multiple laboratories, e.g., see References 9 and 10, for PWSCC cracked tubes. The tests were of both laboratory specimens and pulled tube sections. The results from the different laboratories were not discernibly different, implying no noticeable effect of pressurization rate. However, not as much information is known about test differences for PWSCC specimens as for ODSCC specimens. Further information is being developed.

5.0 In Situ Test Experiences

In situ tests are typically performed at slow pressurization rates. An informal survey of in situ test procedures indicates that some plants include a hold time at maximum pressure when performing in situ testing (the typical hold time for the plants surveyed to date is 1 minute for structural tests and 5 minutes for leakage measurements). There are approximately 700 in situ tests in the EPRI database representing a large variation in flaw characteristics. While this is not definitive

evidence of hold time effects since the tests were not run to tube failure, it is a good indication of the capability of the tubes at operating plants to withstand differential pressures up to 3 times normal steady state operation under the present steam generator inspection techniques.

6.0 Resolution Activities

A project has been initiated to study the significance of ANO pressure test results. This project consists of the following tasks:

- Verify and document all aspects of the ANO specimen burst tests to ensure that the results are accurate and evidence of a real physical phenomenon,
- Compile a database of loading rate and hold time effects for completed tests, and
- Evaluate the significance of ANO specimen burst test data including a characterization of the phenomenon and the implications of the effect on tube burst models and ARCs

This project is scheduled for completion by the end of August. The need for additional work will be evaluated at that time.

7.0 Conclusions to Date

The results from the previous discussions indicate no significant dependence of the burst pressure of SG tubes on pressurization rate for throughwall cracks and slits.

For part-throughwall cracks and slits, the effect, if any, appears to be limited to a narrow range of flaw characteristics.

For ODSCC ARC specimens and PWSCC specimens (although the review here were not as extensive as for the ODSCC specimen data) the effect appears to be of less concern due to the small crack lengths allowed by the criteria.

For the EDM notch profiles tested, the results indicate the possibility that some crack shapes with slow pressurization rates and / or hold times may result in lower burst pressures than the data included in industry burst pressure correlations. Fast and slow pressurization rate tests, as described above, have previously been performed for throughwall cracks, and uniform depth cracks, and long axial cracks with no significant differences observed in the resulting burst pressures. Based on these results, no effects of pressurization rate had been expected prior to the

initiation of the test program, and, although the ANO 2 tube EDM notch surrogate test results may be indicative of an effect that has not been previously noticed, it is concluded that actions to be taken to resolve the questions raised by this single set of test results should be conducted systematically. There does not appear to be any immediate operability concern because of the diverse mix of test results without a similar indication of anomalous low burst pressure behavior.

As previously noted, a systematic program intended to lead to a definitive understanding of the ANO 2 test results is currently in progress. The results will be presented to the NRC staff as they become available.

8.0 References

1. NSD-EPRI-0646, "EPRI Guidelines for Leak & Burst Testing of SG Tubes," Westinghouse Electric Company, Madison, PA (July, 11, 1994).
2. Riley, J., "SG News," electronic mail to distribution, NEI, Washington, DC (June 21, 2000).
3. Hernalsteen, P., "The influence of Testing Conditions on Burst-Pressure Assessment for Inconel Tubing," IJPVP, **52**, pp. 41-57 (1992).
4. TR-105505, "Burst Pressure Correlation for Steam Generator Tubes with Throughwall Axial Cracks," EPRI, Palo Alto, CA (October 1997).
5. NP-6865-L, "Steam Generator Tube Integrity Volume 1: Burst Test Results and Validation of Rupture Criteria (Framatome Data)," EPRI, Palo Alto, CA (June 1991).
6. NUREG/CR-0718, "Steam Generator Tube Integrity Program Phase 1 Report," U.S. Nuclear Regulatory Commission, Rockville, MD (September 1979).
7. Diercks, D., "Steam Generator Tube Integrity Program Monthly Progress Report for January 2000," Argonne National Laboratory, Argonne, IL (March 1, 2000).
8. NP-7480-L, "Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, Addendum 3, 1999 Database Update," prepared by Westinghouse Electric Company for EPRI, Palo Alto, CA (May 1999).
9. AES 96112906-1Q-2, "Aptech Axial Crack Burst Pressure Methodology," prepared by Aptech Engineering Services for the CEOG Steam Generator Task Force, Sunnyvale, CA (December 1997).
10. WCAP-15128 (Proprietary), Revision 2, "Depth-Based SG Tube Repair Criteria for Axial PWSCC at Dented TSP Intersections," Westinghouse Electric Company, Madison, PA (February 23, 2000).

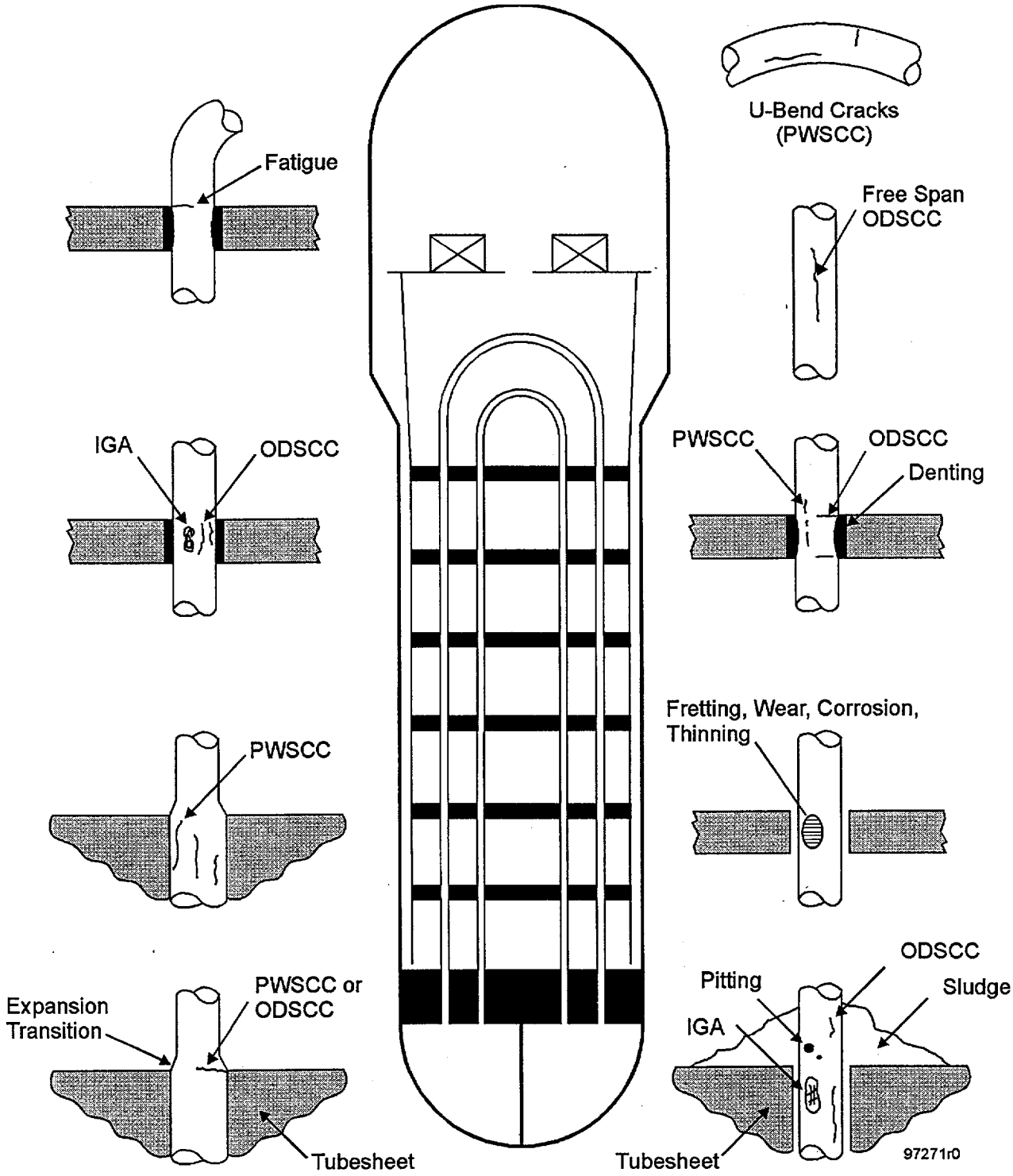


Figure 1: Typical locations of SG degradation

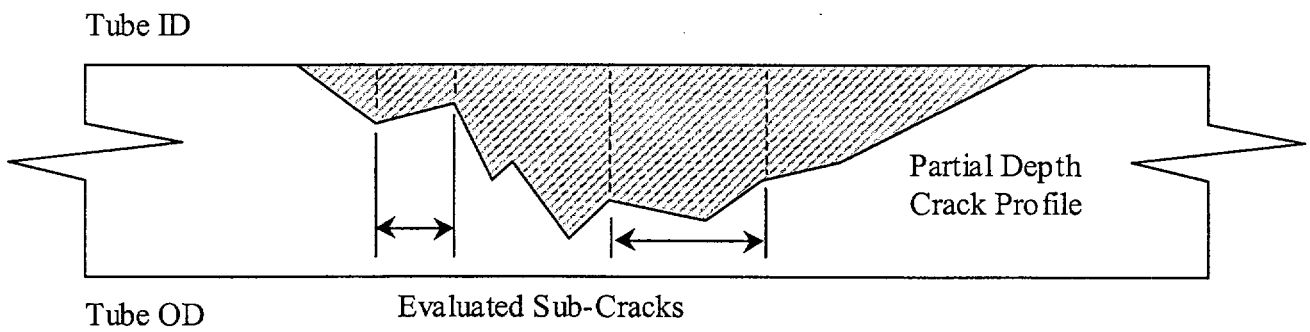


Figure 2: Representative part-throughwall axial crack profile.

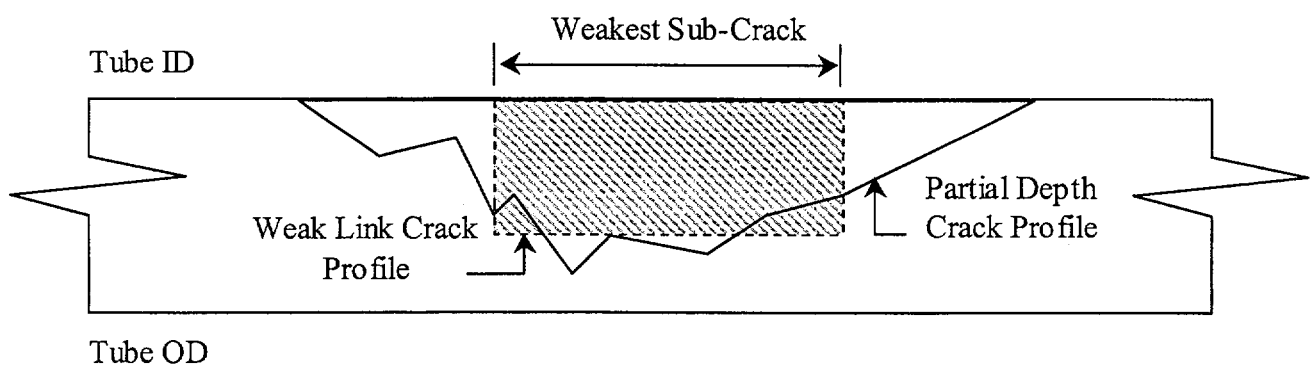


Figure 3: Representative part-throughwall axial crack profile with the effective rectangular profile shown.

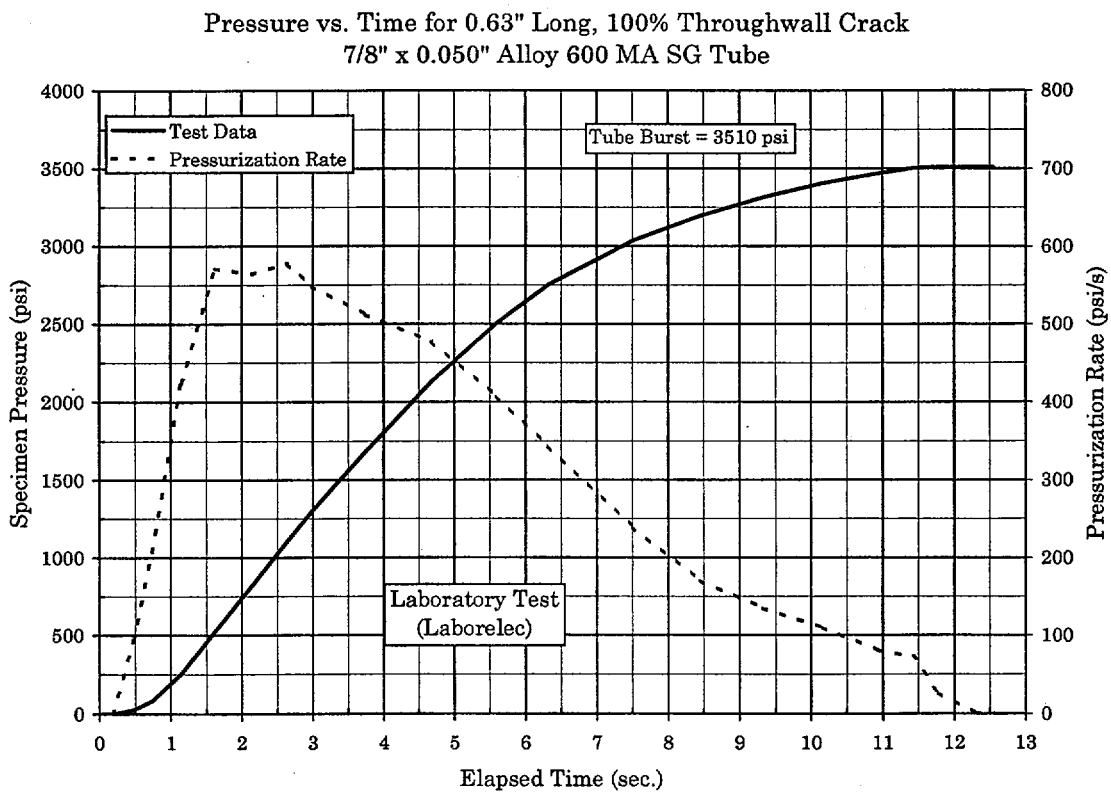


Figure 4: Pressure vs. time plot for Laborelec laboratory test.

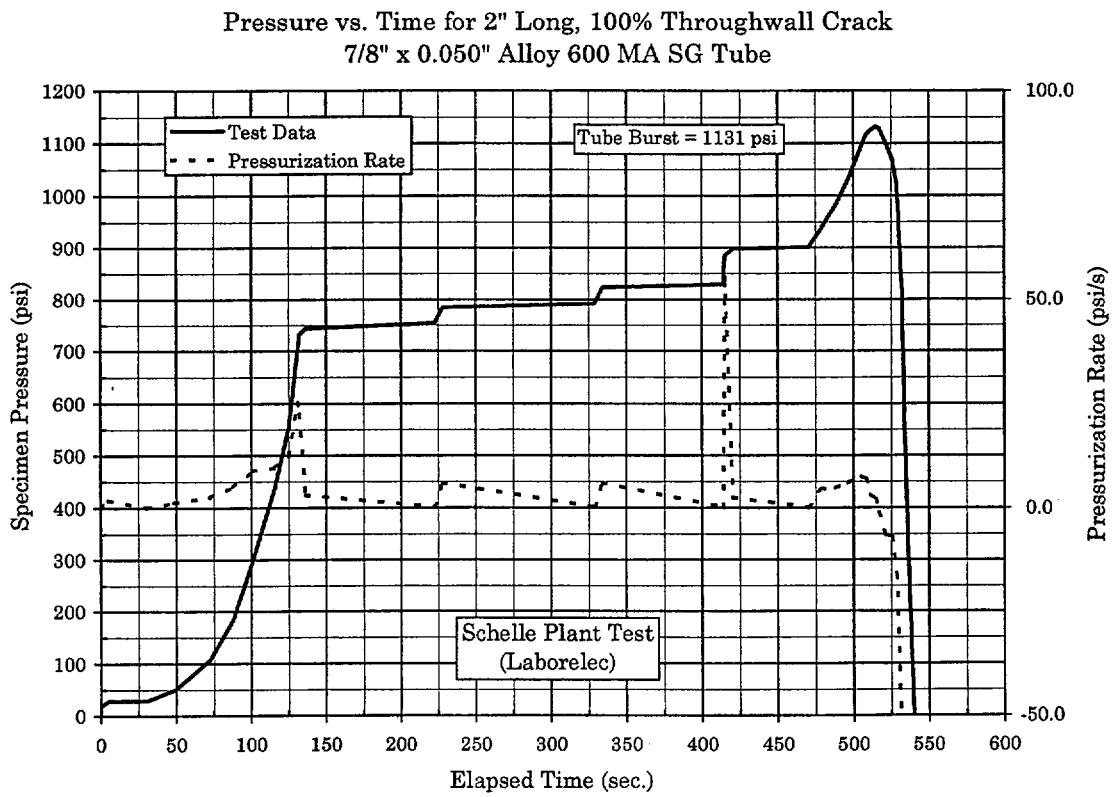


Figure 5: Pressure vs. time plot for Laborelec Schelle test

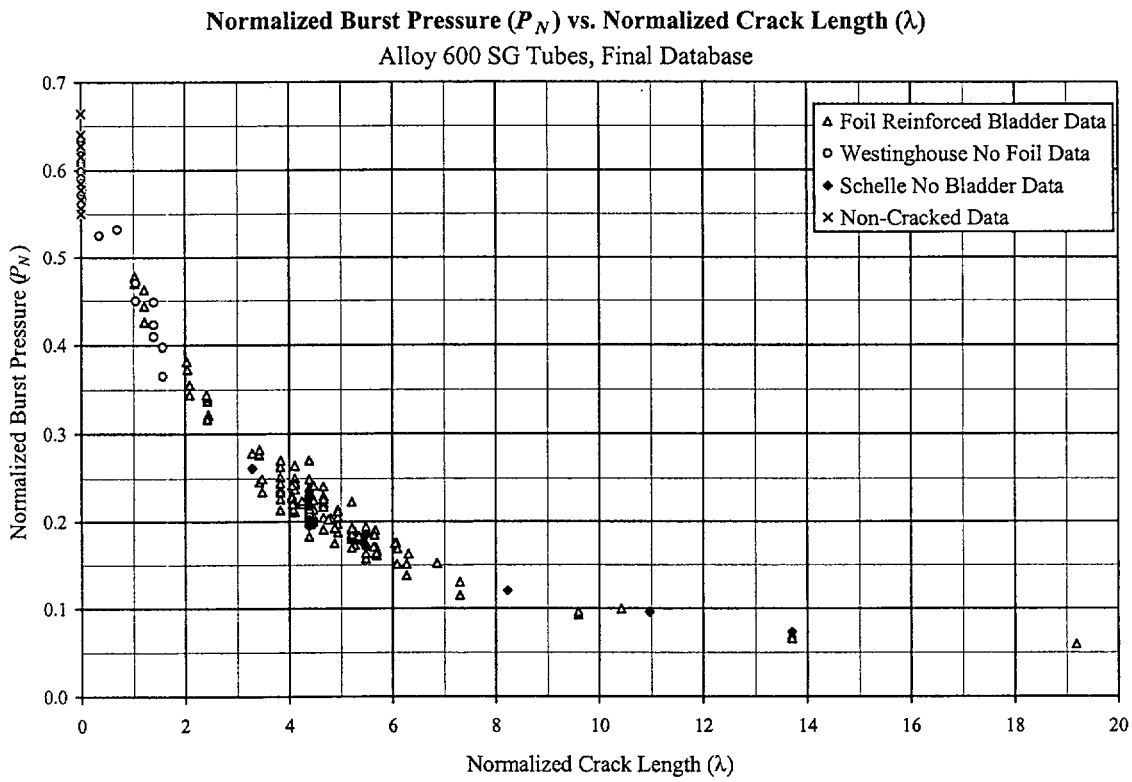


Figure 6: Throughwall Crack Burst Pressure Database [4]

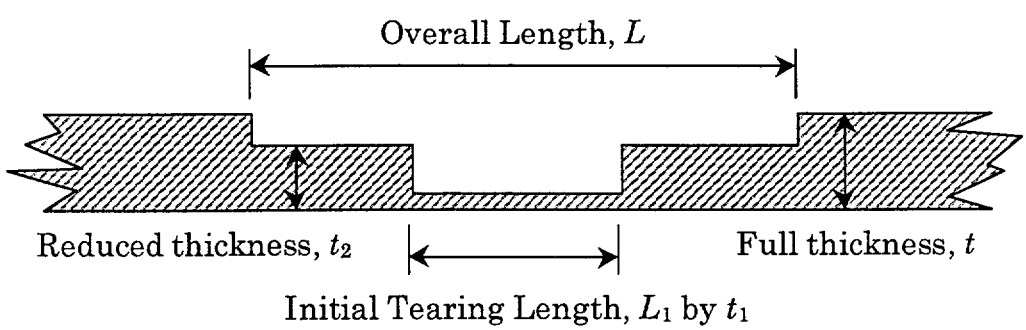


Figure 7: Idealization of a PTW crack by multiple rectangular sections.

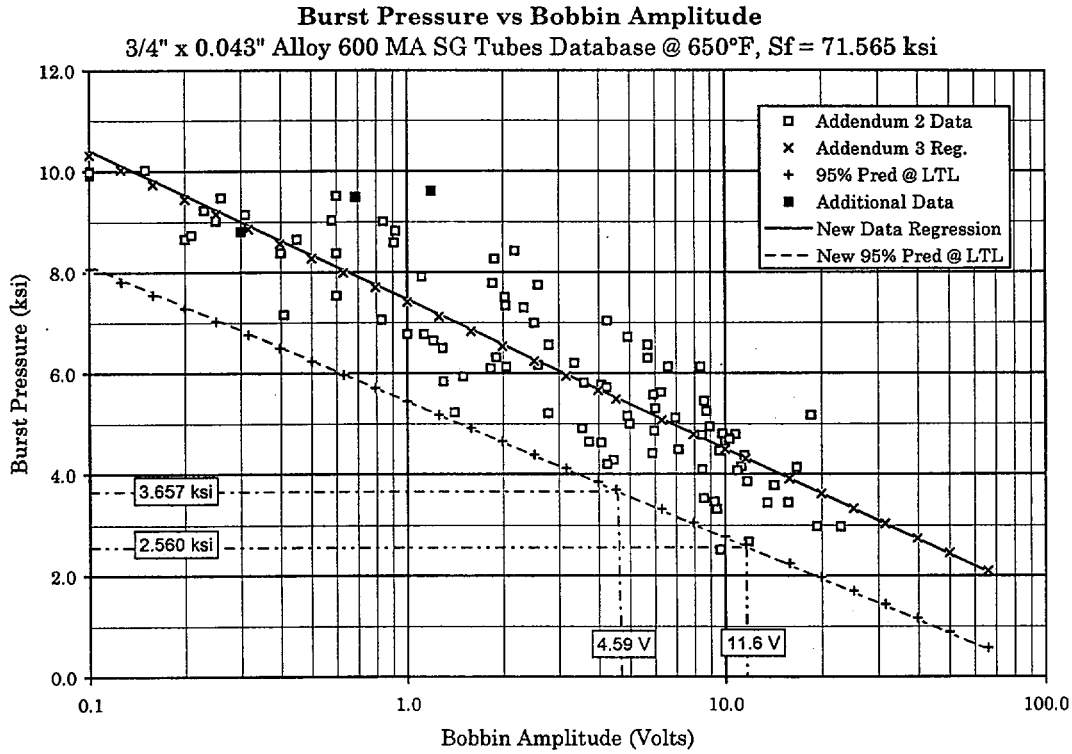


Figure 8:

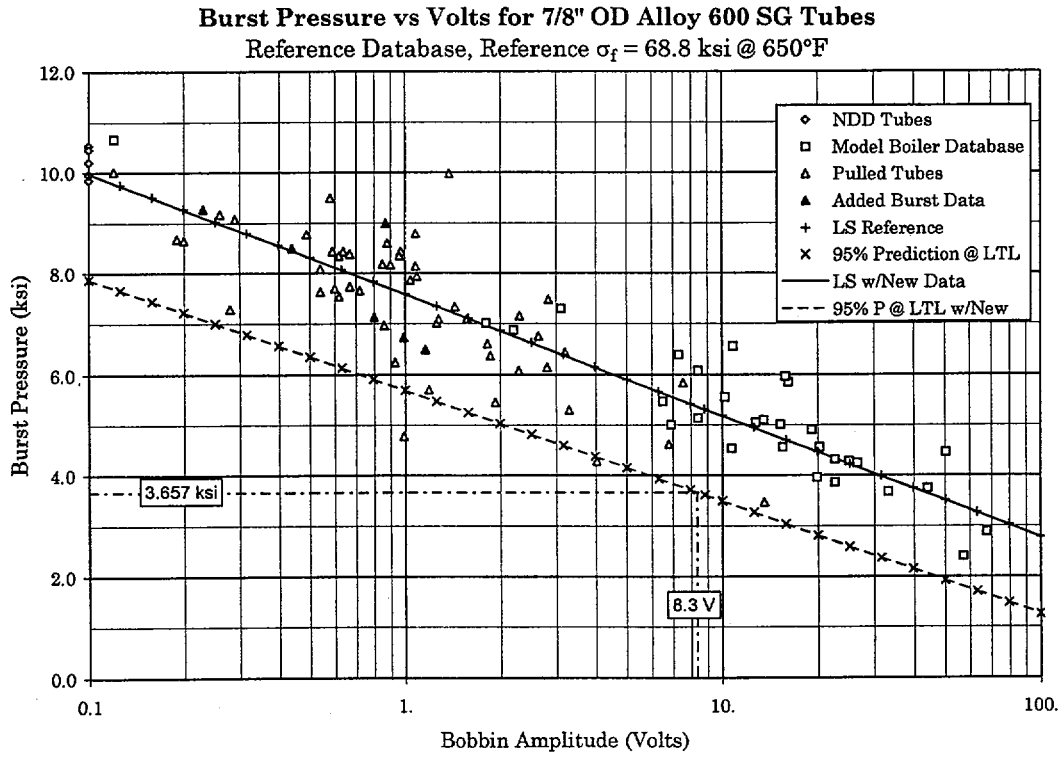


Figure 9: ODSCC ARC fir 7/8" diameter tubes.

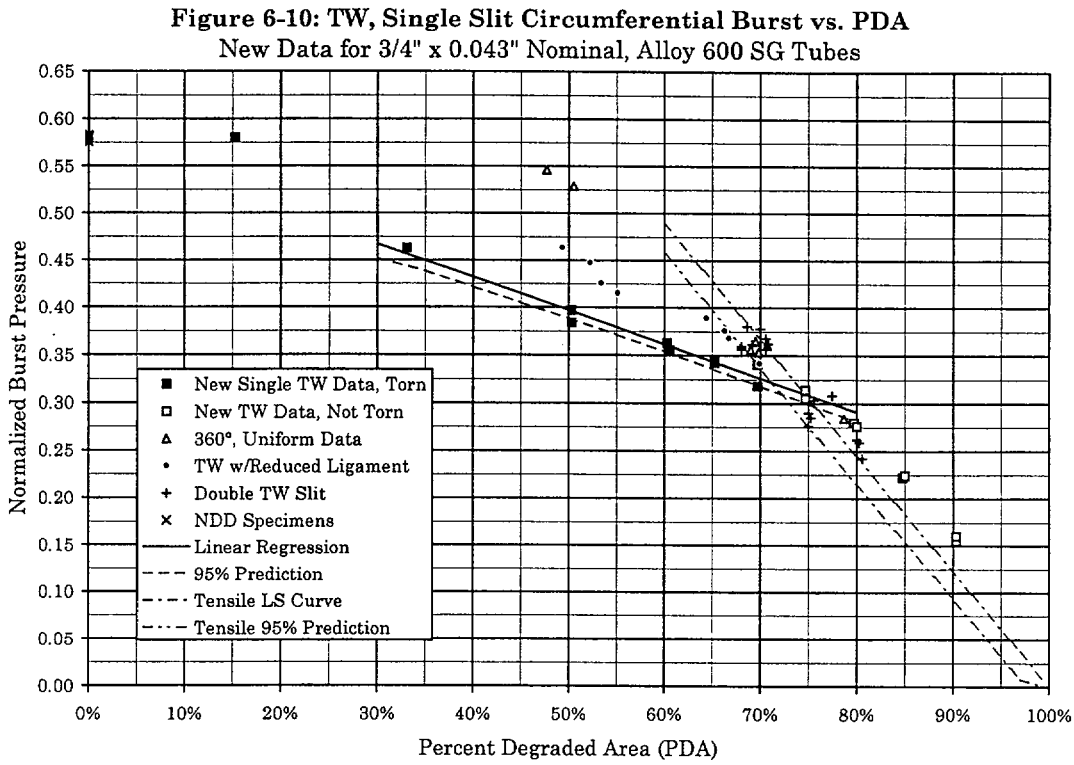


Figure 10: Circumferential model for burst.

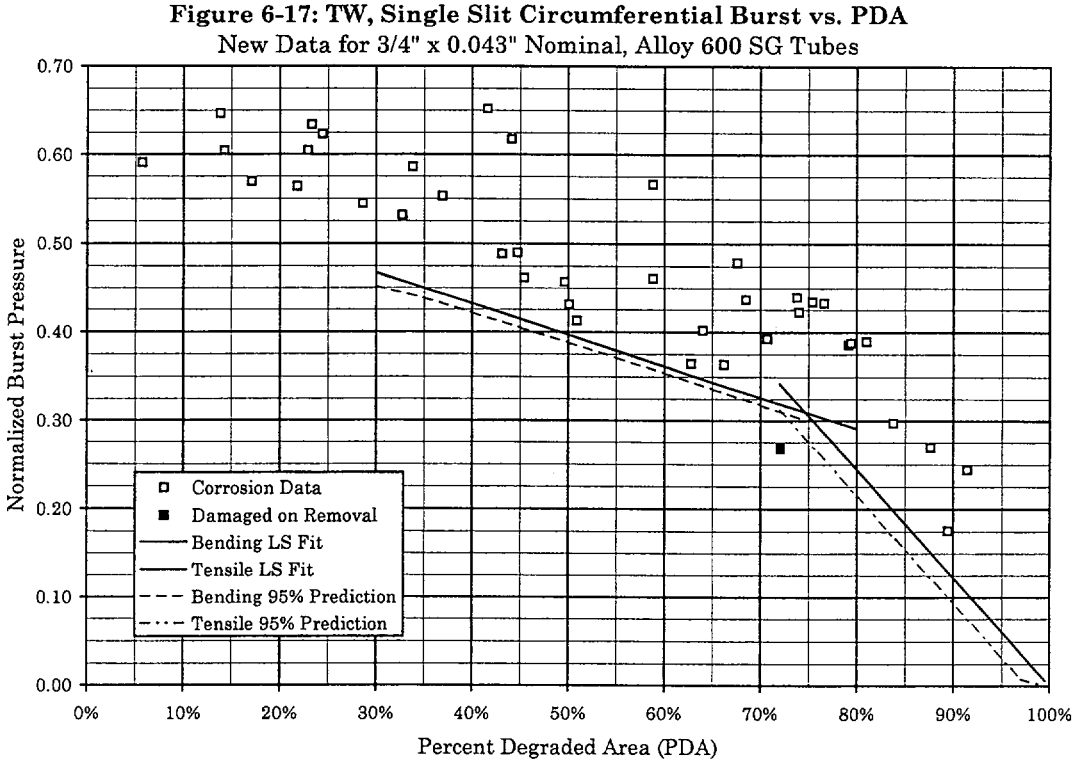


Figure 11: Circumferential model relative to pulled tube data

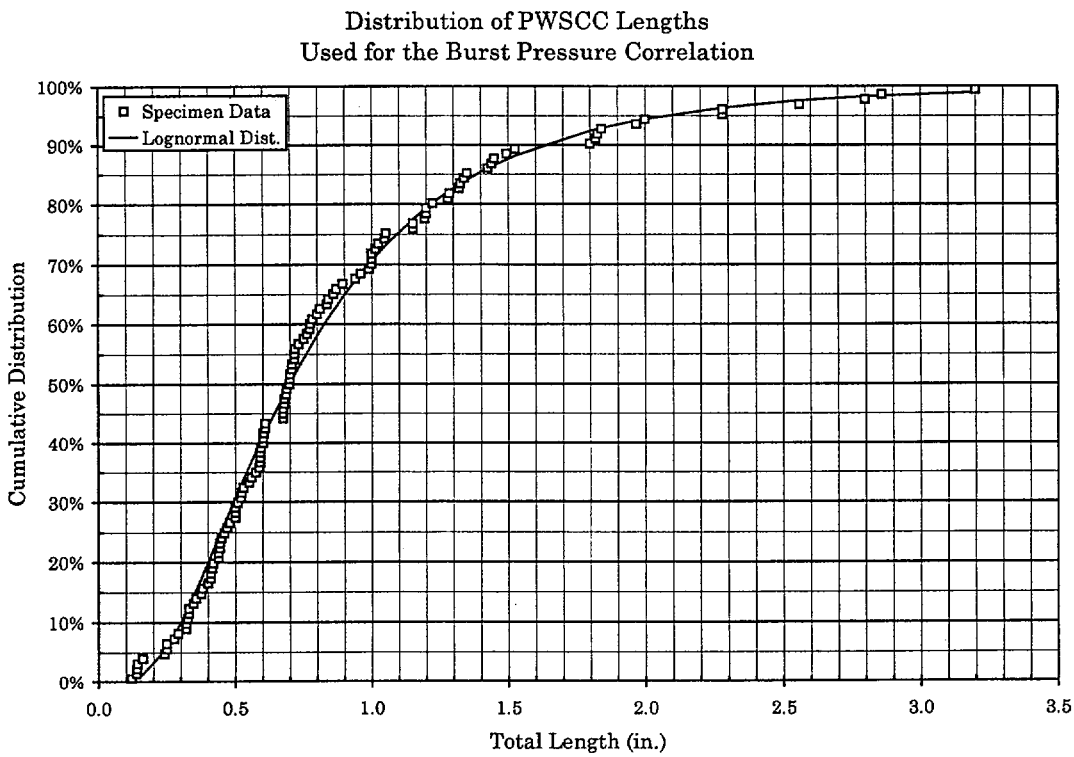


Figure 12: Distribution of lengths of indications used in the development of the PWSCC burst model.