Feeder Bend Testing Project – A Decade in Review

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Abstract

The Feeder Bend Testing Project has been funded by CANDU Owners Group (COG) from 2003 to 2012 to support the safe operation of degraded feeder piping in Canadian CANDU plants. The present paper summarizes this multi-million dollar project from a variety of aspects: background, project management, test setup and results, achievements, and lessons learned.

Key Words: CANDU, Feeder, Wall Thinning, Cracking, Bend Testing, Burst

Acronyms

AECL:	Atomic Energy of Canada Limited	FBTP-3:	Feeder Bend Testing Project Phase 3
ASME	American Society of Mechanical Engineers	FFSG:	Fitness For Service Guidelines
CCT:	Cold Commissioning Test	FIJP:	Feeder Integrity Joint Project
CM&C:	Chemistry, Materials & Components	FISC:	Feeder Integrity Steering Committee
CNSC:	Canadian Nuclear Safety Commission	HCT:	Hot Commissioning Test
COG:	CANDU Owners Group	FWTP:	Feeder Welds Testing Project
CSA:	Canadian Standards Association	ID:	Insider Diameter
DMW:	Dissimilar Metal Weld	NPS:	Nominal Piping Size
FFS:	Fitness For Service	OD:	Outsider Diameter
FBTP:	Feeder Bend Testing Project	PLGS:	Point Lepreau Generating Station
FBTP-1:	Feeder Bend Testing Project Phase 1	PWSCC:	Primary Water Stress Corrosion
FBTP-2:	Feeder Bend Testing Project Phase 2	QA:	Quality Assurance

1. Introduction

1.1 Design of Feeder Pipes

Feeder pipes that connect the inlet and outlet headers to the reactor core in CANDU nuclear power plants are designed in accordance with NB-3000 of Section III of the ASME Boiler and Pressure Vessel Code (B&PV Code) [1], and are designated as Class 1 components in accordance with the CSA Standard N285.0 [2]. Rules for seismic loads on feeder piping are given in the CSA Standard CAN/CSA-N289.3 [3]. Feeders range from Nominal Pipe Size (NPS) of 1.5 (DN 40) through NPS of 3.5 (DN 90), with lengths from 20 feet (6 m) through 60 feet (18 m). Feeders in a number of the early reactor units, such as those at Pickering A, were procured to a specific inside diameter and not a standard Nominal Pipe Size. To date, all feeder pipes have been procured to either Grade B or Grade C of the SA-106 seamless carbon steel pipe specification. A typical CANDU feeder arrangement is shown in

Figure **1**. An example of a schematic of a feeder, and the idealization used in a feeder stress analysis, are shown in

Figure **2**.

1.2 Significant Feeder Degradation Events

A variety of degradation mechanisms have been observed in CANDU feeders. A chronological sequence of occurrences of these degradations is shown in Figure 3. These significant degradation events include:

- Wall thinning first detected in the extrados of outlet feeder bends at Point Lepreau Generating Station (PLGS) in 1996.
- Through-wall leak (Inside Diameter (ID) crack) from outlet feeder bend S08 at PLGS detected in 1997 and removed in 1998.
- Through-wall leak (ID crack) from outlet feeder bend K16 at PLGS detected and removed in 2001.
- Through-wall leak from repaired field weld in outlet feeder G09 at Gentilly-2 in 2003.
- Blunt flaw detected near the elbow weld in multiple Pickering Unit 1 (P1) outlet feeders in 2004.
- Long and deep Outside Diameter (OD) surface crack detected in outlet feeder bend D14 at PLGS and burst tested in 2005.
- The Alloy 600 to carbon steel Dissimilar Metal Welds (DMW) in Darlington feeders have been assessed to be at high risk to be susceptibly to Primary Water Stress Corrosion Cracking (PWSCC).

Figure 4 shows the images of some degradation mechanisms.

1.3 Feeder Life Extension Projects

To manage these degradation mechanisms and extend the life of feeder pipes, several feeder life extension projects have been implemented. These projects are presented in Figure 3 and include:

- Feeder Thinning Joint Project, initiated in 1996 to respond to the PLGS extrados wall thinning.
- Feeder Cracking Joint Project, initiated in 1997 to respond to the PLGS S08 cracking.
- Feeder Thinning Joint Project and Feeder Cracking Joint Project merged and formed Feeder Integrity Joint Project (FIJP) in 2001.
- Feeder Bend Testing Project (FBTP) was initiated in 2003 and the first commissioning test was conducted in 2003. Phase 1 of FBTP (FBTP-1) was completed in 2004 and Phase 2 of FBTP (FBTP-2) started in 2005.
- Feeder Fitness For Service Guidelines (FFSG) document was were developed in 2006 and issued for 3-year trial use in 2007.

- Feeder related R&D projects (FBTP and feeder cracking project) were transferred from FIJP to COG Chemistry, Materials & Components (CM&C) Research Program in 2007. In the same year, Phase 3 of FBTP (FBTP-3) started.
- Feeder Weld testing Project (FWTP), which was initiated in 2010 to response to risk of PWSCC in DMWs. In the same year, Revision 2 of FFSG was issued for 2-year trial use.
- FIJP and FBTP successfully completed their missions and will be closed by the end of 2012.

The focus of the present paper is the FBTP.

2. Project Management

It is clear from Figure 3 that FBTP spans from 2003 to 2012 and is divided into three phases. There was significant change in terms of project management in 2007 after the FBTP was transferred from FIJP to CM&C.

- Phase 1 (FBTP-1): this phase of FBTP was managed under FIJP and tested six nominal thickness specimens with through-wall axial crack in the intrados/cheek region of the bend observed in PLGS S08 under design loads at elevated temperature. The testing of through-wall cracks introduced the challenge of developing a viable high-temperature liner. AECL Sheridan Park (Technical Advisor) was responsible for the overall technical quality and Kinectrics (Test Contractor) was responsible for conducting the tests in accordance with AECL's specification. Both AECL and Kinectrics reported to FIJP directly and budgets were fully supported by the Feeder Integrity Steering Committee (FISC).
- Phase 2 (FBTP-2): this phase of FBTP was also managed under FIJP and tested seven thinned test specimens with through-wall cracks in the extrados and in the intrados/cheek region of the bend under bounding monotonic loads. The testing of thinned specimens introduced the challenge o developing a viable electro-chemical thinning process. AECL Sheridan Park was responsible for the overall technical quality and Kinectrics was responsible for conducting the tests per AECL's specification. Both AECL and Kinectrics reported to FIJP directly and budgets were fully supported by the Feeder Integrity Steering Committee (FISC).
- Phase 3 (FBTP-3): this phase of FBTP was managed under CM&C and tested eleven thinned test specimens with severe local thinning under bounding cyclic or monotonic loading. AECL Sheridan Park (and now Candu Energy Inc.) was responsible for the overall project (both technical and financial) and Kinectrics (as a subcontractor) was responsible for conducting the tests per AECL's specification. The change of project management was intended to reduce the overall cost of FBTP to be competitive with other R&D projects. The annual budget for the FBTP-3 was reduced in 2010/2011, 2011/2012 and 2012/2013 fiscal years per the directions from the CM&C Technical Committee.

A normal FBTP test includes the following steps (in the sequence of occurrence):

- AECL defined the scope of testing and developed the Technical Specification based on the given budget and the inputs from FIJP-FFS team (sometimes from CNSC staff).
- The Test Specification was reviewed and accepted by FIJP/CM&C.

- Kinectrics prepared the Project Specific Work Instruction (PSWI) for each test based on the approved Technical Specification.
- AECL reviewed and approved the PSWI and performed a walk down of the test setup at least one day before the test.
- Kinectrics performed the test with AECL witnessing the test and providing timely guidance for any unplanned scenarios. Any deviation from the Technical Specification was recorded in the lab notes.
- Kinectrics prepared the test memo with all test QA documents and AECL reviewed and accepted the memo.
- AECL assessed the impact of the test results on feeder life cycle management and prepared "quick look" report documenting the results and impact of the test.
- COG reviewed and accepted AECL's report.
- AECL presented the test results to all stakeholders: FIJP-FFS Team, FISC, CM&C Steel Working Group, CM&C Technical Committee, and the CNSC.

An important feature of FBTP was that a Cold Commissioning Test (CCT) and/or a Hot Commissioning Test (HCT) test were performed before any formal test for each phase of the testing program. The purpose of the commissioning tests were to demonstrate the ability to apply the loads and temperature to the test specimen in a controlled manner as stipulated in the Test Specification and refine the test procedure and modify the Technical Specification, if necessary. Usually, the first formal test for each Phase is a repeated HCT. The HCT results should not be credited in any structural integrity assessment unless the results are very close to the first repeat formal test.

Another important feature of FBTP was that it had a live Technical Specification throughout of the project. This is due to the fact that FBTP is a multiple year project; consisting of many tests with different flaw size and testing conditions. To take advantage of the lessons learned from completed test(s) and accommodate requests from the utilities for any emergent issues, it was necessary to periodically revisit the technical specification. A revised technical specification covering the tests to be conducted in a given year was issued to the Test Contractor at the beginning of each fiscal year.

It is important to note that the FBTP benefited greatly from independent technical audit of FBTP-1, which was commissioned by FISC in 2004.

3. Description of Test Setup and Results

Figure 5 summarizes the tests performed under FBTP. A typical test setup is shown in Figure 6. Note that the burst-pressure tests of three ex-service outlet feeders (PLGS-D14, PLGS-H12, OPG-P1B13E) were partially or fully funded by PLGS and OPG directly. The test setups for these three tests were also different because these three samples were irradiated and had to be tested in Kinectrics' low radiation lab. The test results for these three ex-service tests were all documented as COG reports.

The test specimens cover all existing feeder materials: normalized feeder elbows (prototypical of Bruce A and Pickering A feeders), stress relieved feeder bends (prototypical of Bruce B feeders), and warm-bent bends (prototypical of Darlington, CNG2 and PLGS feeders). The loadings included a combined bending moment and internal pressure loading or pressure loading only. Each test specimen had a unique flaw configuration that conservatively simulated a real field observation.

Typical specimens for each phase of FBTP are shown in Figure 7 for FBTP-1, Figure 8 for FBTP-2, and Figure 9 for FBTP-3. Figure 10 shows examples of the range of failures observed in Phase 3 of FBTP, where DEGB stands for Double Ended Guillotine Break. Extensive plastic deformation were observed in all specimens in spite of the measured low fracture toughness J_{Ic} from sub-sized compact toughness tests that varied from 13 kJ/m^2 to 30 kJ/m^2 at 265°C. The test of the ex-service feeder bend with a deep surface crack (<75%tw) demonstrated large margins against rupture [4]. The failure pressure for all burst-pressure tests of specimens with severe local thinning tested under FBTP-3 were at least 5 times the design pressure [5].

4. Achievements of FBTP

It is estimated that more than $5M dollars have been invested by the Canadian Utilities in the three phases of the FBTP. The successful outcomes from FBTP can be categorized into the following five aspects.

4.1 Training Young Nuclear Engineers

With the retirement of the baby-boomer generation, knowledge transfer is a pressing issue currently facing Canadian nuclear utilities and design organizations. FIJP has taken a pro-active approach in this aspect since its inception. Critical knowledge held by subject experts was identified and new hires (the first author of this paper) were assigned to work with subject experts (the second author of this paper). Sufficient funding and an easy working environment (allowing personnel to learn from both successes and mistakes) were provided to both subject expert and new hire during the first two years. Opportunities for continued training such as attending international technical conferences have been provided by both FIJP/CM&C and AECL. After 4 years of hard work, from both protégé and mentor, the second author retired in 2010 and the first author has become the subject expert.

Similar training program has also been taken by Kinectrics (Test Contractor). A new technician and engineer (the third author of this paper) have been working with subject experts (the fourth author of this paper) during the last two years.

FBTP also promoted cooperation with local universities. A group of students and a professor from the University of Toronto toured Kinectrics' Burst Testing Facility and witnessed one of the Phase 3 tests. One undergraduate student has selected the FBTP as his final year project.

4.2 Supporting Unit Restart

One of the most successful cases for supporting the restart was the PLGS-H12 ex-service burst-pressure test conducted during the PLGS 2006 outage. It took less than one month from removing the feeder bend section, shipping to Kinectrics, performing the testing, and completing the assessment. The test result together with a probabilistic safety evaluation provided a solid technical basis for returning the plant to service in a timely manner.

4.3 Enhancing Regulator's Confidence in FFSG

The development of the feeder FFSG has greatly benefited from the FBTP. Some articles of the FFSG are the direct outcome from the results of the FBTP. Most articles of the FFSG were indirectly supported by test results and the rationale have been documented in technical basis documents.

The FBTP has been identified by the CNSC staff as one of the critical conditions for the CNSC's acceptance of FFSG Revision 0 (and R1) for trial use by the Industry. A senior CNSC manager, CNSC staff, and utility representatives were invited to witness the FBTP-3-GL-C-5 test on 2008 November 13. The witnessing of the test enhanced regulator and utility confidence in the FBTP testing process. The test results have been cited by CNSC staff in various international technical exchange forums.

The application of the FFSG has made it possible for Canadian utilities to avoid unnecessary replacement of at least 300 feeders (256 for Darlington, 68 for Bruce B and 34 for Bruce A). Assuming an average cost of ~\$0.5M per feeder replacement, the total savings is more than \$150M and more than 2100 Rem in dose assuming 7 Rem per feeder replacement.

4.4 Maintaining Test Capability

Because of the constant funding from COG, some old equipment in the Kinectrics' Burst Test Facility was replaced. A stable team composed of Technical Advisor, Test Contractor and Technicians have worked together during the last decade providing a testing service to support Canadian utilities with any emergent technical issues, e.g., the burst-pressure testing of the three ex-service outlet feeders (PLGS-D14, PLGS-H12, OPG-P1B13E).

4.5 Promoting CANDU Reactor Technology

A series of papers have been published in the prestigious ASME Pressure Vessels and Piping Division Conferences [4], [5], [6], [7]. The tests results support the development of some Code Cases of ASME B&PV. International exposure helps to demonstrate that Canadian CANDU plants are being operated in safe and reliable manner.

5. Benchmarking with Other Testing Programs

Pressure tube, feeder pipe, and steam generator tube are three major components identified in CSA N285.4. There is a testing program for each of the three major components:

- Pressure tube burst-pressure tests are part of the pressure tube surveillance program. This program has been supported by the Fuel Channels Technical Committee since the 1980s. It seems unlikely that this test program will be terminated in near future.

- Steam Generator Tube Testing Project (SGTTP). This program has been funded by OPG since 1999. In total, over 450 tests have been completed to support the structural integrity assessment of degraded steam generator tubes subject to 9 different degradation mechanisms. This program is currently being funded at about $150K per year. It is unlikely that this program will be terminated in near future.
- Feeder Weld Testing Program (FWTP). This program has been funded by CM&C Technical Committee since 2010. The objective is to provide test data to support structural integrity assessment of repaired carbon steel weld and dissimilar metal weld in feeder pipe. The FWTP can be treated as the continuation of FBTP. A series of measures have been taken to minimize the cost: subcontracting tests to qualified contractors from the USA, cooperation with national laboratories in other countries, and teaming up with Canadian universities to apply for funding from the Natural Sciences and Engineering Research Council of Canada and Ontario Centres of Excellence.

6. Conclusions

The Feeder Bend Testing Project was a successful project. It provided a platform for training young nuclear engineers, supported unit restart, maintained a test facility, enhanced the regulator and utilities confidence in the Feeder Fitness For Service Guidelines, and promoted CANDU reactor technology nationally and internationally.

7. Acknowledgements

The authors sincerely acknowledge the full support from the Feeder Integrity Steering Committee, FIJP-FFS Team and Chemistry, Materials and Components Technical Committee during the last decade.

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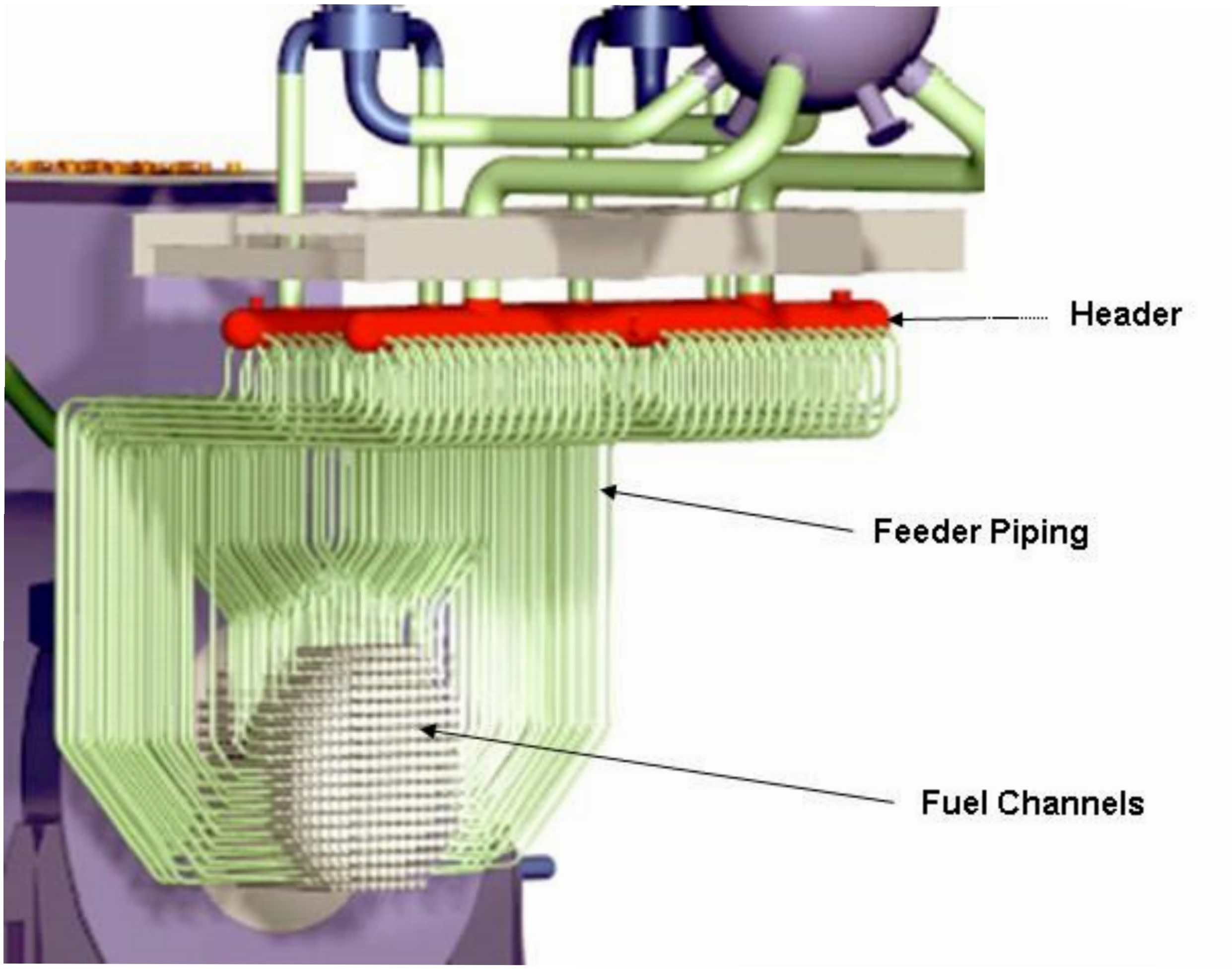


Figure 1: A Typical Feeder Arrangement

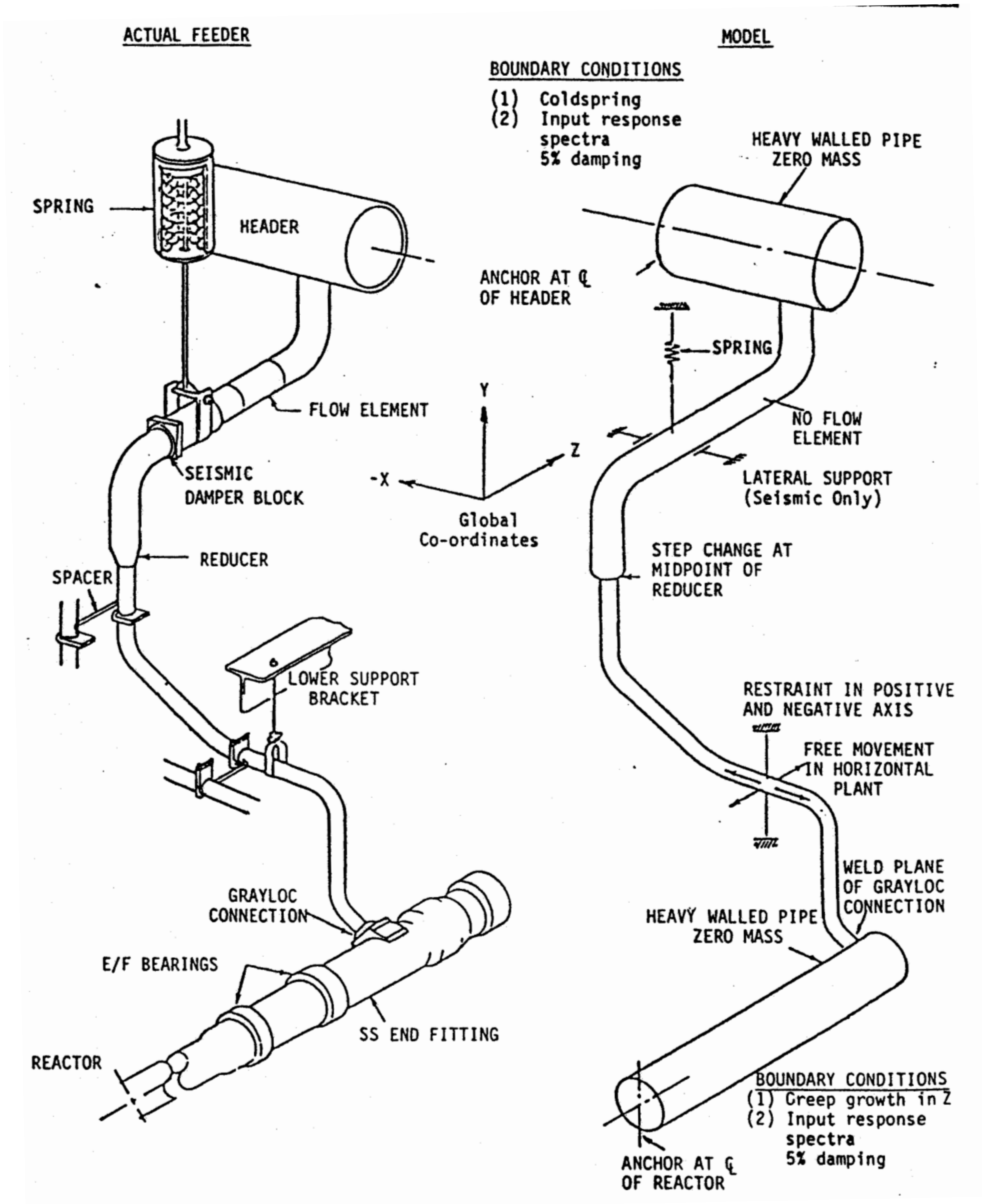


Figure 2: Physical Presentation and Mathematical Idealization of Feeder Pipes

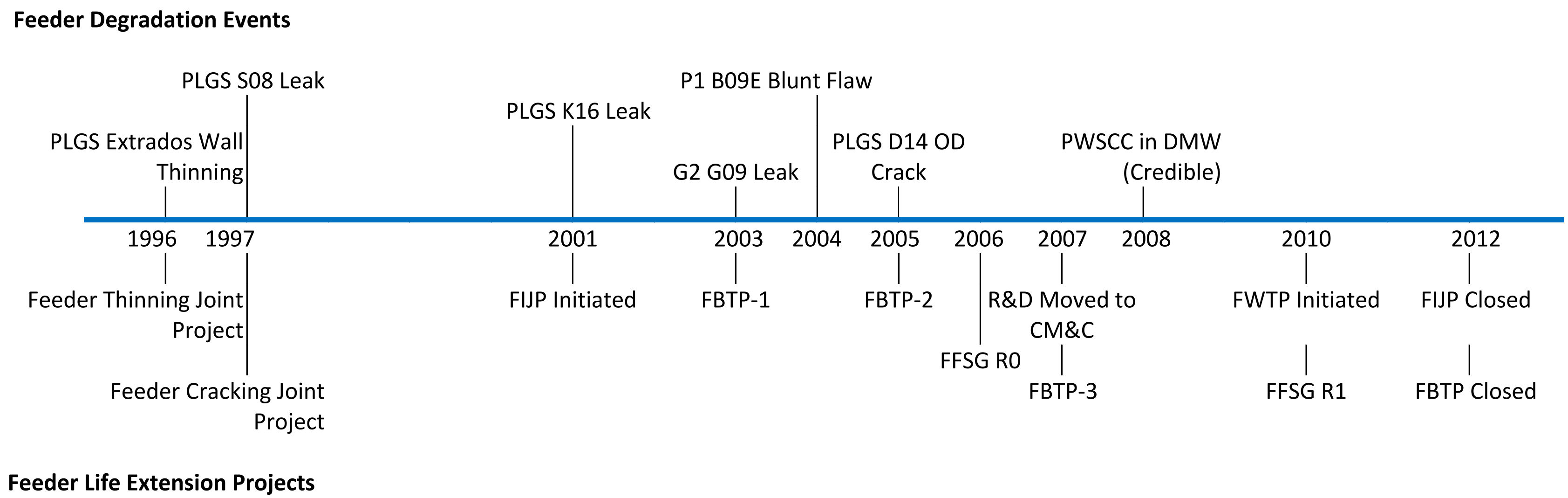
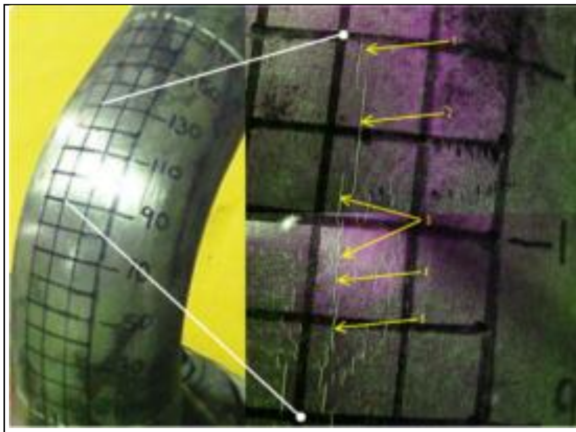
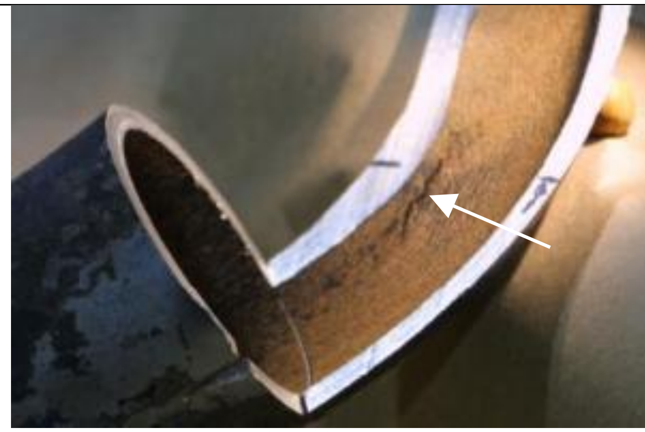


Figure 3: Feeder Degradations and Corresponding Life Extension Projects

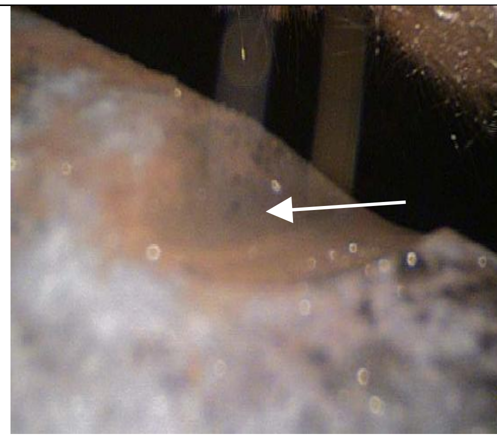


OD Crack at the Extrados of the Bend

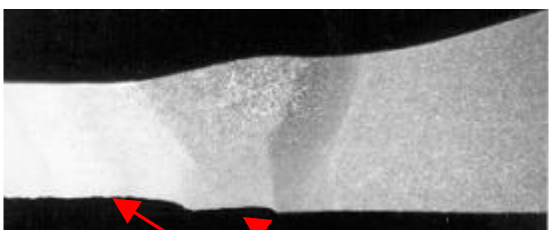


ID Crack at the Cheek/Intrados of the Bend

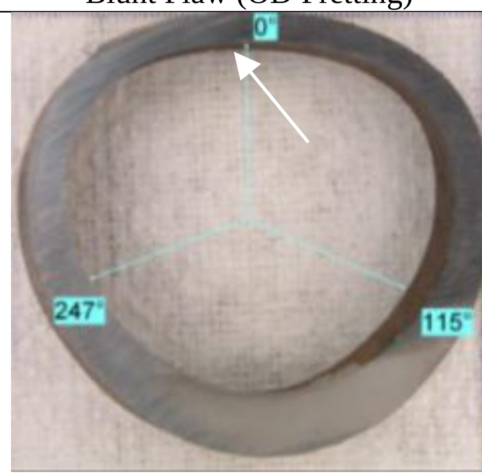
Repaired Field Weld Crack



Blunt Flaw (OD Fretting)



Grayloc Wall Thinning



Wall Thinning at the Extrados of the Bend

Figure 4: Images of Major Feeder Degradation Mechanisms

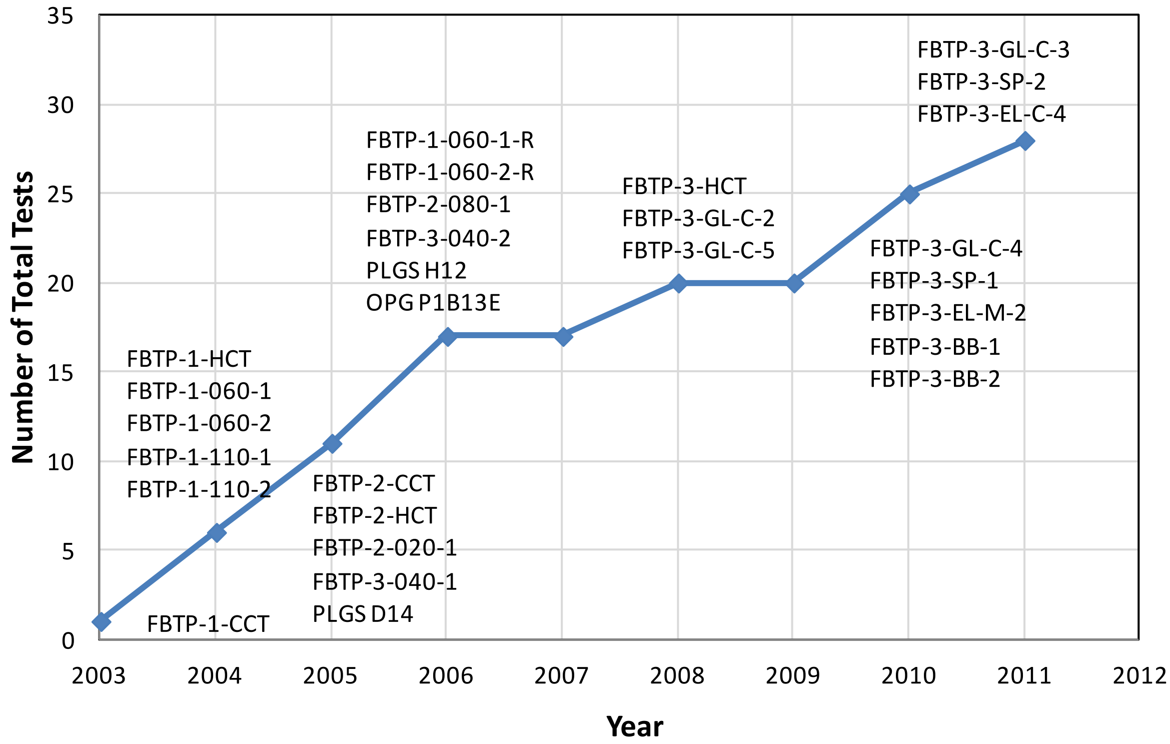


Figure 5: List of Tests Performed under FBTP

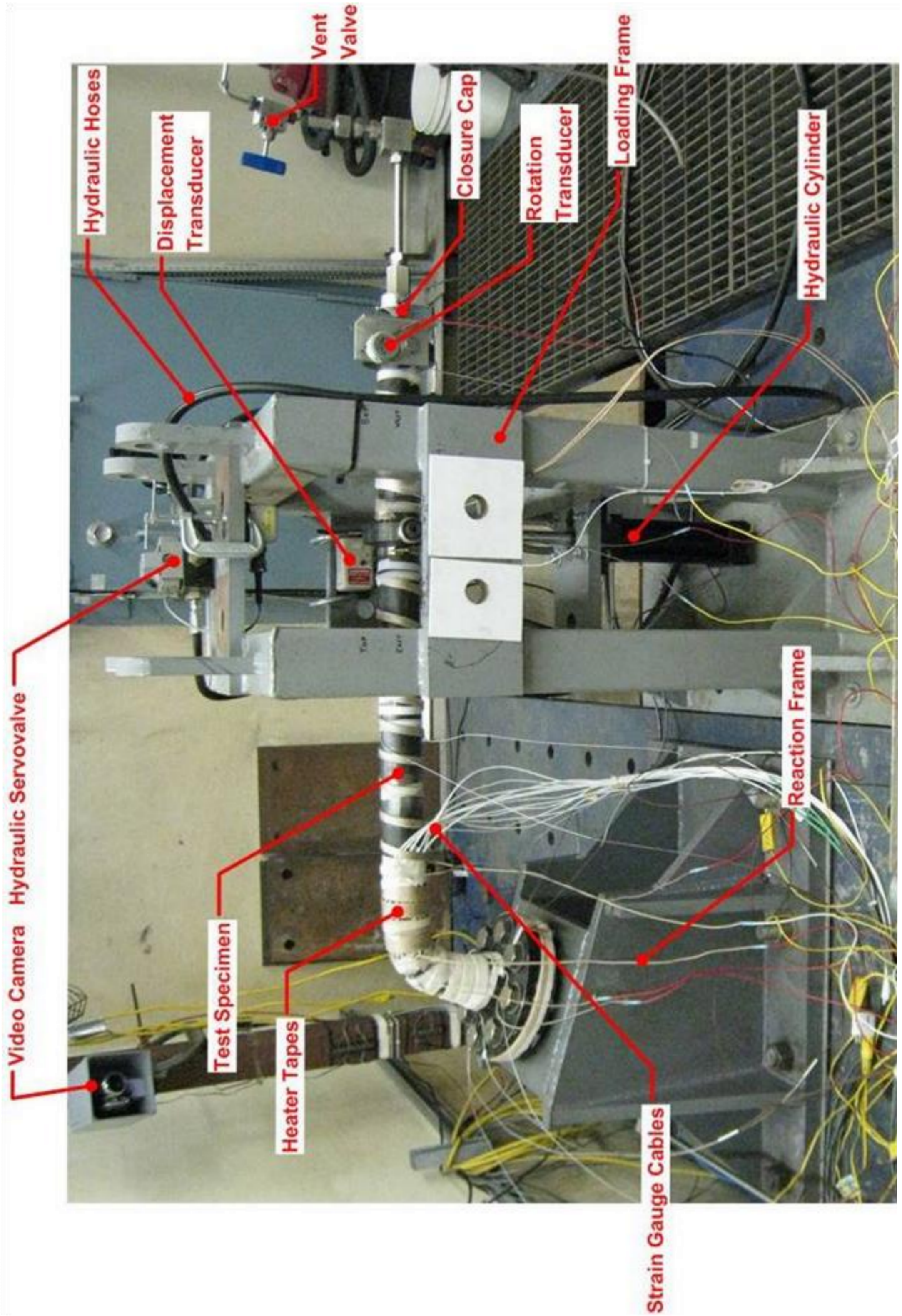
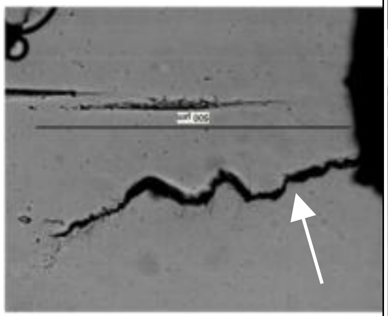
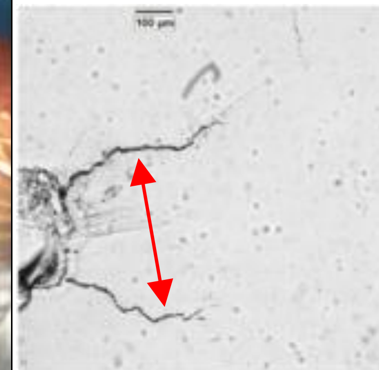


Figure 6: Typical FBTP Test Setup



Fatigue Pre-Cracking

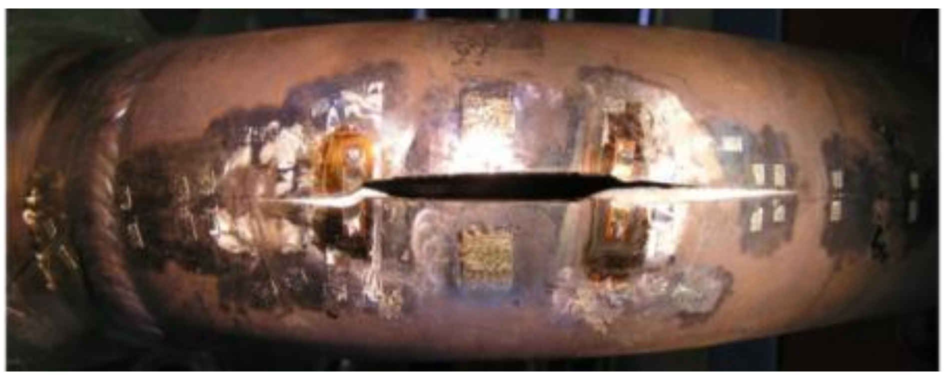
Specimen before Test



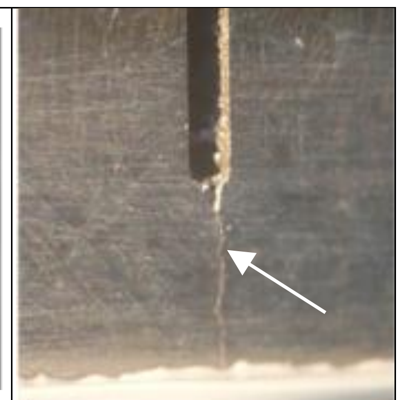
Fatigue Pre-Cracking

Figure 7: Test Specimen FBTP-1-060-1

EDM Slot



Specimen after Burst Test



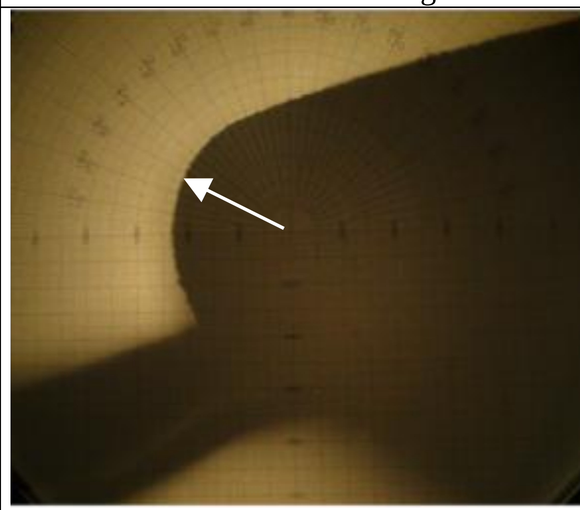
Fatigue Pre-Cracking

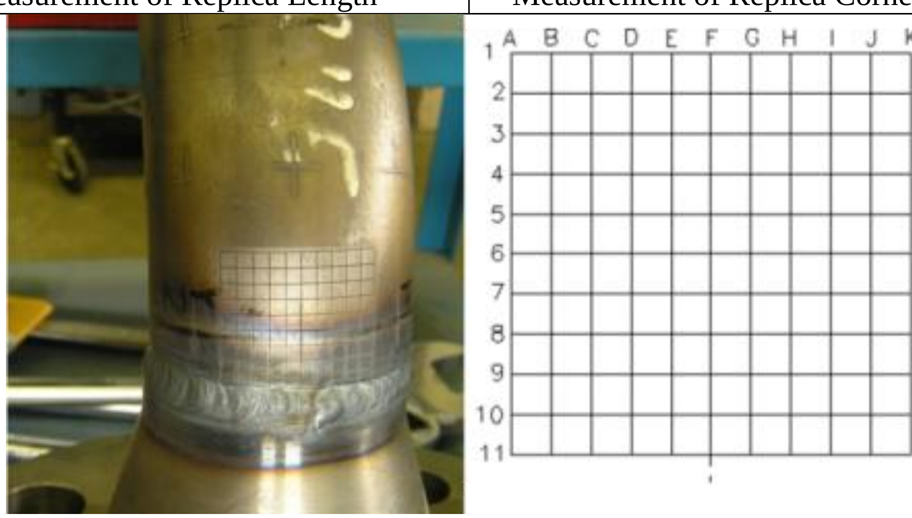
Figure 8: Test Specimen FBTP-2-040-1


Specimen on EDM Machine


EDM Local Thinning


Measurement of Replica Length


Measurement of Replica Corner Radius



OD Grids for Strain Measurement

Figure 9: Test Specimen FBTP-3-HCT

DEGB	Break	Rupture	Leak before Break

Figure 10: Mode of Failure of Specimens with Severe Local Thinning Tested under FBTP-3