SUMMARY OF FIELD EXPERIENCE FOR ACOUSTIC EMISSION MONITORING OF SEAM-WELDED HIGH ENERGY PIPING

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Abstract

The structural integrity of seamed fossil high energy piping has become a major safety and O&M issue again with five recent failures of seam-welded superheat link piping segments since 1992, two of them catastrophic. Advanced methods of inspecting piping welds with Ultrasonics, such as Time Of Flight Diffraction and Focused / Phased Arrays, is pushing back the envelop of detection to earlier stages of creep damage. But these are still very expensive and involve considerable logistics planning and downtime to perform. EPRI has sponsored development activities since 1986 to mature the utilization of a real-time online evaluation method for seam-welded piping: Acoustic Emission (AE). Guidelines were published in 1995, and over 30 full scale tests have been performed to develop a database and correlate results with other established evaluation methods.

Tests to date have shown high sensitivity to early stage creep damage. Successful double-blind testing with advanced ultrasonsic inspection methods has proven both the reliability and sensitivity of the AE technique. The economics of the method are highly favorable. Only small areas of insulation need to be removed every 15-20 ft to weld “waveguides” to the piping surface. These form a linear location array along the length of piping, providing global coverage of the piping system. Testing is performed online with normal peak loading and load cycling. No outage schedule is required to perform the AE examination. Results will be presented showing that the AE method

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has become a reliable and economical field evaluation tool for seamed high energy piping.

Seam-Welded Piping Issues

Ever since the catastrophic failures of seam-welded, hot reheat (HRH) piping at Southern California Edison's Mohave plant in 1985, and Detroit Edison's Monroe plant in 1986, utility companies have been carefully considering the need for periodic inspections of critical piping to guard against creep-induced failures. Figure 1 illustrates the creep damage mechanisms associated with seam-welded, high energy piping. A number of serious defects in seamed piping were removed after inspections in the late 1980's, and for a number of years there were no more catastrophic failures.

Beginning in 1992, however, there have been five known failures of seam-welded superheat (SH) link piping supplied with CE boilers. Two of these have been catastrophic: Virginia Power's Mt. Storm Unit 1 in June 1996, and Kansas City Power & Light's Hawthorne Unit 5 in August 1998 (Figure 2). No loss of life occurred in either of those two failures, but the cost of repairs and loss of power generation is of critical concern to utility companies in this age of growing competition. All failures of SH link piping have occurred on units with accumulated service time of 125,000 to 200,000 hrs. Compounding the problem of inspection is the inaccuracy of supplied documentation, which may not reflect the true alloy content and method of fabrication. The Hawthorne SH link piping was not known to be seam-welded. The general aging of fossil plants will continue to raise concerns about the safety of operating seamed high energy piping systems. Even seamless piping systems have had problems, including failures of circumferential welds, and the through-wall creep failure of a seamless SH bend that had been improperly fabricated. Current strategies for effectively managing the safety and life of seam-welded piping are based upon periodic inspection of the weld area for evidence of inservice damage.

Inspection Issues

The normal inspection process is arduous: wait for a scheduled outage, remove insulation from large areas of piping, and conduct ultrasonic (UT) inspections inch by slow inch. Certain areas, such as welds under hanger attachments and at floor penetrations, are not typically inspected due to the additional costs of access. In some cases, the inspections have not produced reliable results. The through-wall failure in a Sabine HRH elbow in 1992 was preceded by UT inspections five and three years before failure. The Mt. Storm SH link piping failure in 1996 was preceded by UT inspection 14 months prior to failure. The lack of a predictable re-inspection interval to avoid this type of failure has become problematic on top of the high inspection costs and plant downtime. In addition many utilities are going to extended outage schedules, limiting the time and interval available for periodic off-line inspections.

More sensitive UT techniques using Time-of-Flight (TOFD) and Focused Array (FATS) have come to fore in the past two years as reliable methods of pushing back the envelope of detection of creep-induced defect conditions; but these are even more expensive to apply as general survey methods than conventional multi-angle, pulse-echo UT inspections. Conventional stress and materials analysis methods are only marginally useful in predicting location and timing of the development of creep damage. Changing conditions on the line with time may alter the effectiveness of hangers, and general relaxation effects change stresses from the original installed condition. Peaked weld geometries, welding materials, methods and post-weld heat treatment add an additional range of variables to the prediction of when and where. A physical test that could inexpensively locate areas of potential damage---while the unit is in operation--- would offer the best safety and cost solution to the problem of seam-welded piping management. That technology is acoustic emission monitoring, and the results to date are very encouraging.

Acoustic Emission Monitoring

Acoustic emission (AE) has been used extensively in the past twenty years in the petrochemical, nuclear, and aerospace industries, and has been incorporated into a variety of society inspection codes and practices (ASME, ASTM, ASNT). Aerial manlift vehicles on the T&D side of electric utility companies have been routinely inspected with AE since the early 1980's (ASTM F914-85). Acoustic emission is an attractive alternative to conventional inspection. Its principal features as applied to high energy piping are:

1. It is a passive monitoring technique, which listens for the high frequency sounds of material failures (degradation). The detected energy comes from sound waves generated by growing flaws.
2. Emission sources can be "source-located" within a few inches on linear lengths of piping by time-of-arrival techniques, similar to seismology.
3. It is a global inspection. Any defect growing in the metal path can be detected and located. This includes seam, closure, and hanger welds, drains, vents, etc.
4. Instrumentation of the line is minimal. Removal of 1 ft^2 of insulation every 15-20 ft along to length of the line is required to install AE Waveguides. These are ¼" diameter stainless steel rods welded to the pipe surface, with a platform for mounting the AE sensor at the other end (Figure 2). Welding is allowed by ASME B31.1 code either offline or during plant operation. Both manual welding and stud-welding attachment are practiced.
5. Testing is performed online, while the plant is operating and load cycling. Feedback is real-time, and does not require an outage to perform testing.
6. After initial setup and calibration of equipment, monitoring can be conducted remotely via modem communication. 1-2 weeks of monitoring is required for a typical 500-ft piping system.
7. Direct inspection costs are only 10-30% of that required for ultrasonic inspection, and no plant downtime is required. This allows more frequent testing (3 yrs

average) than would be practicable or affordable with UT, and increases the safety margin for early detection of problems.

Equipment and AE Testing Set-up

The process of AE monitoring applied to piping systems starts with installation of piezoelectric transducers on thermal stand-offs (or waveguides) along the length of the piping. Spacing intervals for the sensor are typically 15-18 ft, and installation of the sensors does not require full removal of piping insulation. Acoustic emissions generated in the piping structure are detected by the sensors and relayed to the data acquisition system. A schematic of the hardware set-up is shown in Figure 3.

Data Evaluation and Correlation

During startups, shutdowns, and normal operation, the piping system is a rich source of acoustic events which are detected by the sensor array on the piping. By evaluating time of arrival differences at two sensors, the source of the emission can be located. Some of the detected emissions are associated with processes that are not of concern with regard to pipe integrity. These sources include steam flow noise and mechanical friction. The acquired data is accordingly filtered to focus on sources associated with inservice damage. Figure 4 provides an illustration of the processing that is used to correlate AE sources with weld damage. The ongoing field testing is populating the database with which more refined and quantitative assessments can be made from the AE information. The current application of AE monitoring is undertaken as a screening tool to identify areas for follow-on inspection with quantitative techniques.

Field Testing Program

Several years ago EPRI began investigating AE testing to quickly screen large areas of piping while a plant is on line, then come back later for a closer look with conventional UT examination methods. Beginning in 1991 with a joint R&D program with Pacific Gas & Electric, EPRI charted the course for the development of a reliable field procedure. That program produced the EPRI Acoustic Emission Monitoring Guidelines (2), a comprehensive guide to seam-welded HRH line inspection. It was demonstrated in double-blind testing in 1994 on PG&E's Potrero Unit 3 HRH line, where the results from AE testing and conventional UT were successfully corroborated.

From 1995-1998 an extensive field testing program was undertaken to build a database of results performed to the EPRI Guidelines criteria. These were used to verify the methodology, refine evaluation criteria, and compare the results with other inspection/evaluation methods. Thirty inspection programs have been conducted to date on both HRH and SH seam-welded piping systems for twelve different utility companies. Table 1 provides a summary of these inspections and follow-on results to date. Some of these have included Tailored Collaboration projects between EPRI and its member utilities, including Central & Southwest (Central Power & Light and West Texas Utilities), American Electric Power, Kentucky Utilities, Illinois Power, United Illuminating, and Sierra Pacific Power. Other companies have started their own inspection programs, including PG&E, Oklahoma Gas & Electric, Grand River Dam Authority, Northern Indiana Public Service Co, and Entergy.

A typical inspection of 500 ft of HRH piping with UT will often require extensive scaffolding, complete insulation removal and reapplication, and 2-3 weeks of plant downtime. This can easily run into the $300K range for this length of piping. Often time is spent evaluating material conditions that do not represent active defect sources (original welding flaws, plate laminations, e.g.). An AE test program will typically cost <$60K for the same coverage. AE only detects active (growing) flaw sites, and therefore focuses the priorities for follow-on inspection. This can lead to findings that would otherwise be ignored or not pursued aggressively enough. Several examples of this occurred during AE testing programs.

In the original proof-of-method AE test on PG&E's Potrero Unit 3 HRH line, several defect conditions were found that would otherwise not have been noted without the AE testing. These included a cracked saddle weld in a hanger support, cracks in a cast elbow, and ID-connected thermal fatigue cracking in the parent material adjacent to a spool closure weld. None of these defects was a serious structural threat, but the sensitivity of the AE technique was established. The following subsections summarize some specific results from the testing program.

Central Power & Light Tests

An early AE test using the EPRI guideline approach was the inspection of Central Power & Light's Joslin Unit 1 HRH line in April 1997. A series of AE sources was being source-located at a mechanical hanger location on the bottom of the line. Plant manager Tom Buller was shown a dramatic demonstration of the sensitivity of the AE technique during online testing. After emission was detected with increasing load (pressure) on two previous peak load cycles, another test was conducted while he and other CPL employees watched the AE system graphics displays. There was also a heterodyned audio output which allowed listening to the normally high frequency (400 kHz) sensor output in the audible range. As load was increased in steps, the CPL personnel observed the increasing rate of emission being located at the hanger position, and could audibly detect the pops and crackles of defect growth above the background flow noise. During the following outage, the hanger strap was removed and the indications verified in the seam weld by both manual and automated (multi-angle pulse echo and Time-of-Flight) UT inspection. In a normal inspection scenario, the hanger would not have been removed. Using AE source location to direct follow-up inspection averted a potentially serious future problem.

Central & Southwest Manager Wes Hull leads a group formed to evaluate high energy piping in CS&W's member companies. Based on the Joslin test and five others conducted on CPL and WTU units, his group has determined that AE can be used as a reliable screening method for the remainder of CS&W's 43 fossil units.

American Electric Power Tests

Two tests were conducted on the largest fossil units in N. America, AEP's Gavin Units 1 & 2. Gavin Unit 1 was the subject of another double blind test with UT inspection in the summer of 1996. The lower 500 ft of the dual-line, 1200-ft HRH piping system was inspected first with both manual and Time-of-Flight UT during a planned outage. This was followed by online AE testing for several weeks during peak load cycling operation. AE detected two areas of activity on elbow closure welds, and two minor areas of activity on turbine leads. The closure weld indications correlated with OD-connected shallow cracks that had been visually ground out during the outage. The two areas on the turbine leads also matched UT indications. The pattern of intermittent indications, and length of line affected, matched up well between the UT and AE methods. None of these indications was an immediate structural problem. A spool piece with a high density of plate laminations in another turbine lead was flagged as a potential problem by AEP. But the AE results showed nothing of significance going on in this structure, and future costs for re-inspecting this area with UT on a regular basis can be averted. Testing of the full 1200 ft of Gavin Unit 2 in 1997 revealed no significant AE indications anywhere on the line. The estimated cost savings on this line by using AE screening in place of conventional UT inspection was $500K, not counting potential lost power generation.

Kentucky Utilities Tests

Two significant inspection programs were conducted at Kentucky Utilities Ghent Unit 1 and Brown Unit 3 in 1997. Several exit elbows in the HRH link piping at Ghent were found to have highly active AE sources during startup and subsequent online AE monitoring. Manual UT inspection confirmed all five indicated areas of activity. Weld repairs were conducted to remove most of the indicated weld material. AE Monitoring was performed after weld repair. The two elbows that had been repaired by through-wall removal of weld metal showed a 95% reduction in AE activity to very low levels. The SH link piping was also monitored on this unit, and showed no significant activity. Such was not the case at Brown Unit 3.

The seam-welded SH link piping leads (12-ft vertical segments) were monitored at KU's Brown Unit 3 during an unit restart following the Spring outage in 1997. Both leads were observed to have active AE sources in areas below the penthouse roof. These areas were similar to the location of a through-wall failure on a SH link at Alabama Power's Gaston plant in 1992. Monitoring was performed during online operation again in Feb. 1998, prior to an outage when the links were scheduled for replacement. Similar AE activity was observed in the suspect area. One of the leads was removed and sent to the EPRI NDE Center in Charlotte, NC for further analysis. A phased-array automated UT inspection was performed on the seam weld, and significant indications were observed in a 24-inch long area matching the AE source location results. A 3" plug sample was taken for metallographic analysis. No cracking was evident with normal metallography, so the specimen was sent to Materials & Mechanical Engineering in Austin, TX (division of Hartford Steam Boiler) for further analysis. A reliable method of early creep detection is a method known as cryo-cracking. It is capable of identifying the condition when damage still exists as isolated cavitation around carbides and inclusions in the weld Heat Affected Zone (HAZ). The specimen is scored at the desired analysis location, submerged in liquid nitrogen to supercool the material, then impacted to break the material along the preferred plane. Careful examination under SEM magnifications of 5000x is required to observe the fine structural detail of the fracture surface. The cryo-cracking examination identified evidence of early-stage creep cavitation in the weld centerline (Figure 5). These sophisticated UT and metallographic methods confirmed that AE had identified a developing problem well ahead of the appearance of microcracking, which later would coalesce into a major crack. This added perhaps years to the early detection of the problem, and allowed the utility to remove a future hazard on a reasonably planned schedule.

Illinois Power Tests

Another recent AE monitoring program at Illinois Power's Baldwin and Wood River plants identified potential creep problems in several seam-welded elbows and bends. Structural Integrity Associates (Silver Spring, MD) was contracted to perform Time-of-Flight (TOFD) and Focused Array (FATS) UT inspection on one of the clamshell elbows on Baldwin Unit 1. They found evidence of early-stage creep cavitation in the midspan extrados weld of the elbow, in the location the AE results had predicted. This result matched well with the expectations of the AE monitoring, which identified this area as a low-activity source. The utility now knows where the bellwether indicators are on the line, and the approximate level of damage it represents. Periodic future inspections or metallographic examination can be used to plan a replacement or repair schedule consistent with the company's operating objectives.

Conclusions

Acoustic emission has proven its worth in these and other test programs. Approximately 30% of lines tested have shown no significant findings, and most others have shown only minor activity at suspect locations. The majority of seam weld findings have been in elbows and bends, followed by hanger locations on horizontal line segments. These are known to be higher stressed areas, and offer further validation of the AE methodology. The correlation with follow-on nondestructive inspection has been very good, better than 90% for suspected seam weld sources. The economics of inspection and relative certainty of detection at an early stage of creep damage should be increasingly attractive to companies attempting to manage their piping systems in a climate of reduced capital and O&M spending.

References

1. *Guidelines for the Evaluation of Seam-Welded High Energy Piping,* Palo Alto, CA: Electric Power Research Institute, September 1996. TR-104631.

2. *Acoustic Emission Monitoring of High-Energy Piping, Volume 1: Acoustic Emission Monitoring Guidelines for Hot Reheat Piping,* Palo Alto, CA: Electric Power Research Institute, November 1995. TR-105265-V1.

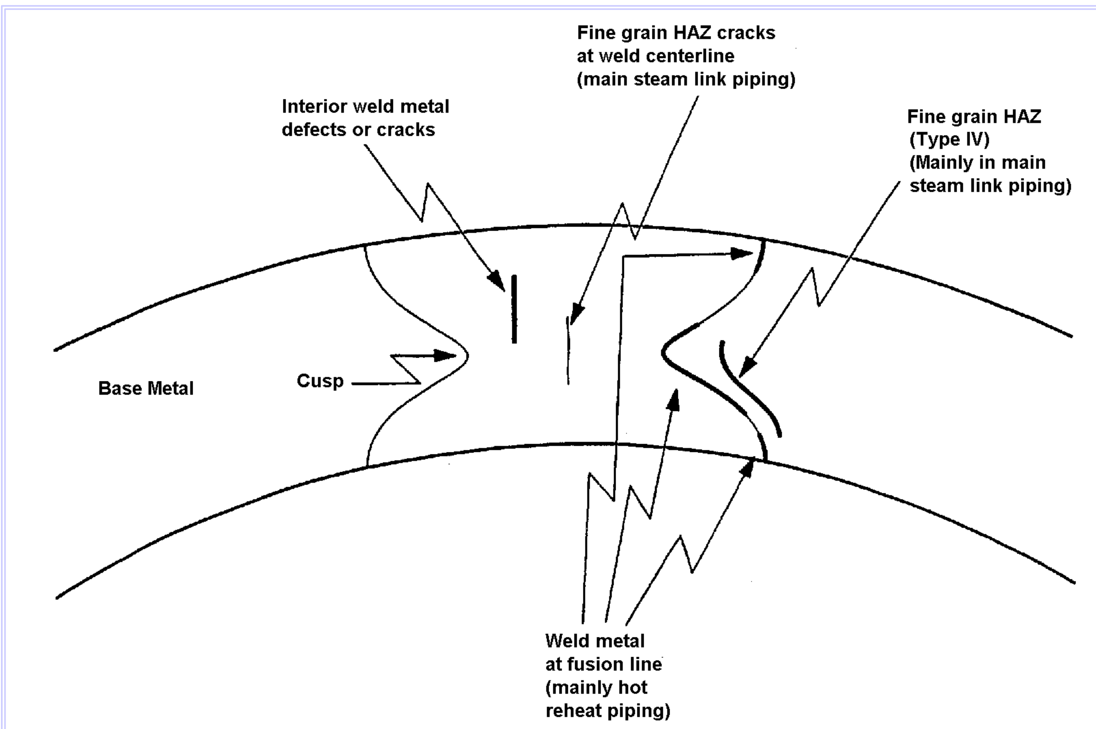

Figure 1. Typical high-temperature creep cracking defects occuring in seam-welded fossil piping systems constructed of P11 or P22 grade steels (1).

Figure 2. Photograph of seam-welded pipe failure at Hawthorn Unit 5.

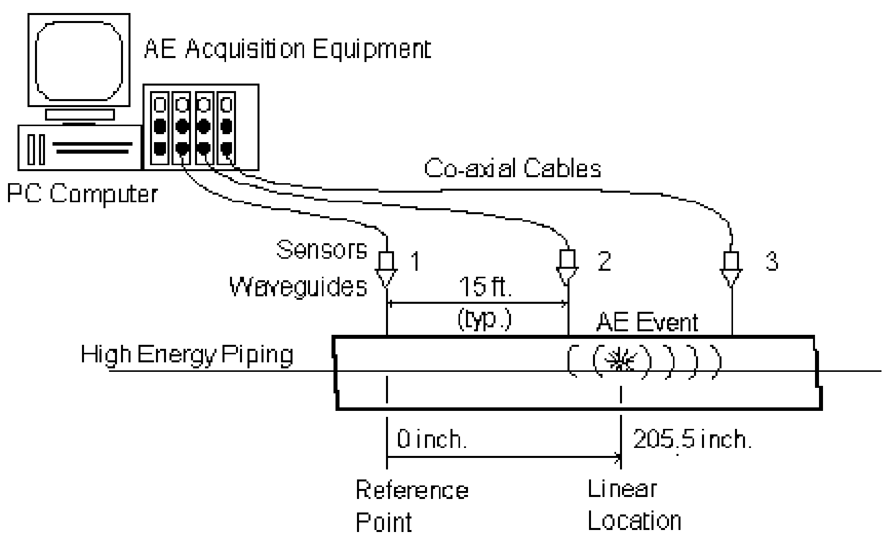

Figure 3. Schematic of typical computer-based acoustic emission data acquisition system connected to piping sensors.

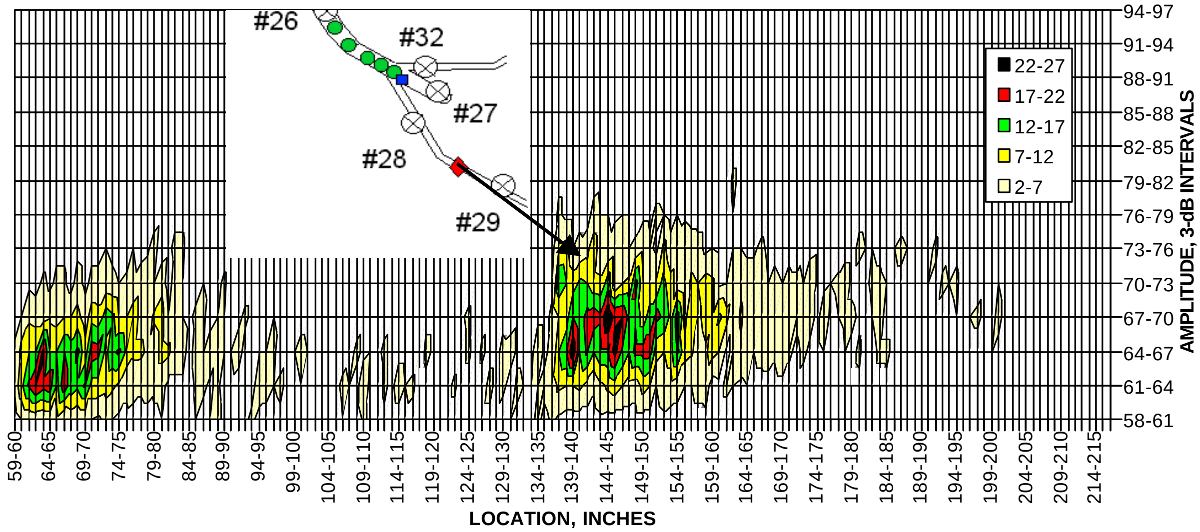

Figure 4. Example of event clusters of AE to identify significant sources for follow-up investigation.

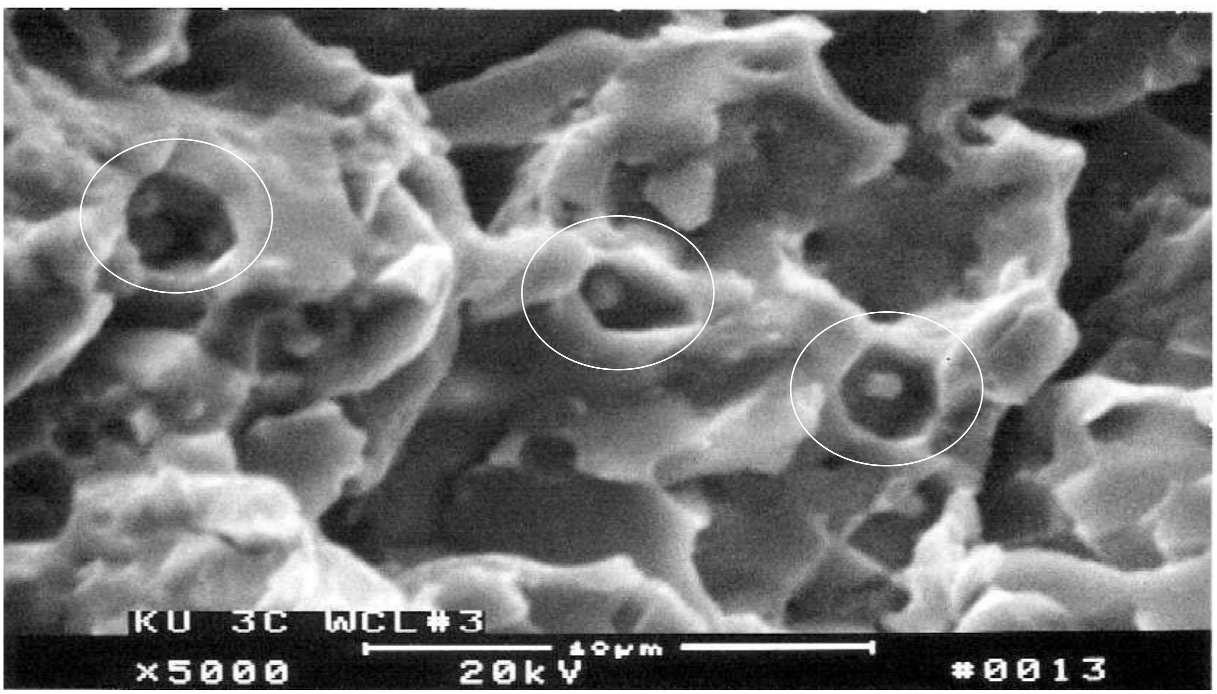

Figure 5. SEM micrograph showing early stage creep damage in the centerline region of a seam-welded SH link pipe.

Table 1. Summary of AE Tests on Seam-Welded, High Energy Piping. 12/98

Station and Unit	AE Indications	Verified by	Comments
Potrero 3 HRH	2 East lead elbows	Automated UT & RT	One elbow inspected. Near-ID linear indications, porosity in elbow. Not sure seam welded. On lower neutral axis. Associated with casting defects (shrinkage porosity)
	Hanger attachment on horizontal segment.	Visual	Cracked saddle weld. Repaired. No AE after repair.
	Closure weld at East lead elbow.	Manual UT	Circ weld cracking (minor).
Montour 1 HRH	Minor indications in turbine lead bend and near horizontal hanger support.	100% UT Time of Flight.	No significant findings. Turbine lead bend later removed.
Nueces Bay 6 HRH	NSF		No inspections planned.
Gavin 1 HRH, partial.	2 elbow closure welds, shallow OD cracks, one of them 270° around circumference.	MT	Lower 500' of line double blind UT to ERPI specs, both manual and TOFD. Circ. weld cracks ground out <u>prior</u> to AE testing.
	2 indications, turbine leads, in seam.	Manual, TOFD UT	Manual UT confirmation of strongest sources (near ID, discontinous over 30" from shallow elbow to hanger--matches AE locations). TOFD confirmation of other source (midwall, discontinuous, past horizontal elbow).
Pittsburg 6 HRH	Several hanger positions, closure welds at piping intersections.		No inspection yet.
Coal Unit 2 HRH	7 Cracked stantions (Hanger attachments) in fillet welds. Cooldown only--no online indications.	MT	Some manual UT of seam welds around hanger, bend locations. No findings confirm AE online results.
E.S. Joslin HRH	3 seam weld indications under and near hangers.	Manual, automated UT	Manual and automated UT confirmation (Multi-angle shear and TOFD)--midwall indications. One indication removed. Cryo-cracking analysis by M&M Engrg (Austin, TX) confirms early stage creep cavitation in weld.
	3 circ weld indications.	Manual UT	Minor indications.
Ghent 1 HRH link piping	4 elbows, formed. In-seam indications. One in-seam indication in horiz. segment past elbow.	Manual UT	UT indications in all five areas. HRH link elbows match pattern, severity predicted by AE. All repaired. East lead elbows repaired through-wall show 95% reduction in AE activity. Material sample shows no evidence of cracking. Cryo-cracking investigation pending.
Ghent 1 HRH	4 elbows, one other near hanger on horizontal segment. In-seam indications.	Automated UT (P-Scan)	Results pending.
Ghent 1 SH Links	NSF		No inspection planned.

Station and Unit	AE Indications	Verified by	Comments
Valmy 2 HRH	Several hanger positions.	UT	Double blind UT on lower half of line. 2nd AE test (Dec 97) duplicated findings of first test (Apr 97). Inclusions, cracking in repair weld near hanger on vertical segment during 2nd UT inspection. Additional AE tests June 98, Jan 99, July 99.
Brown 3 HRH, SH Links	2 main steam leads, in-seam indications.	Automated UT (phased array)	Material removed during Spring 98 outage. One section to EPRI for investigation. No findings with EPRI multiangle procedure. UT phased array finds indications in SH seam weld matching AE locations. Cryo-cracking analysis by M&M Engrg (Austin, TX) shows early stage creep cavitation in mid-weld fusion zone.
Lon C. Hill 4 HRH	Lower level seam weld indications at turbine deck, and batwing hanger indications.	Manual UT, MT	Inspection during 3/98. UT confirmed multiple discontinous laminar indications in seam weld at turbine deck location. Batwing hanger indication during startup and cooldown only. Multiple OD-cracks to 3" found in batwing hanger welds (MT).
Horseshoe Lake 7 HRH	5 Elbows, seam weld sources.	Manual UT	Midwall indications to 1" long. No materials investigation to date.
	Batwing hanger attachment welds.	MT	OD cracks on both hanger and pipe wall sides. AE during online and startup, not on cooldown.
Mustang 4 HRH	NSF		
Coal Unit 1 HRH	Rigid hanger. Hanger in bend. Y-block outlet welds.	MT	Cracks in hanger stantion weld on bend. Found by AE on startup only.
Gavin 2 HRH	NSF		No inspection planned.
New Haven Harbor HRH	3 hangers, including one rigid support.		No UT findings near rigid hanger. Other inspections pending.
Schahfer 15 HRH	Elbow seam weld.		No inspection yet.
Oklaunion HRH	Reducer closure weld or drain line near waveguide.	Visual	Cracking in drain line fillet weld.
Wood River 4	2 large radius bend seam welds.		No inspection yet.
Navajo 2	Clamshell elbows.	UT (Time-of-Flight & focused array)	Prior inspection verified creep damage with UT. Elbows monitored with AE among lowest ranking damage with UT.
Baldwin 1	4 HRH radiused bends, bends in turbine leads, Y-block welds.	UT(focused array)	One clamshell inspected with Time-of-flight(TOFD) and Focused Array (FATS) ultrasonics. FATS confirmed early stage creep damage in midwall of extradose weld.
Baldwin 2	4 HRH radiused bends, bends in turbine leads, Y-block welds.		No inspection yet. Two highest ranking bends recommended for focused array UT.
Victoria 5	1 radiused bend.		No inspection yet.
Victoria 6	Upstream closure weld on bend.		No inspection yet.
Ghent 4	NSF		No inspection planned.

Station and Unit	AE Indications	Verified by	Comments
Horseshoe Lake 6	Minor indications in 7 bends and at one batwing hanger.		No inspection yet.
Hennepin 2	Minor indications in 3 bends and one fixed (batwing) hanger.		No inspection yet.

NSF - No Significant Findings

All tests performed to EPRI AE

Guidelines standards (Nov 1995)