**REACTOR COOLING WATER EXPANSION JOINT
BELLOWS: THE ROLE OF THE SEAM WELD IN FATIGUE
CRACK DEVELOPMENT (U)**

by S. L. West

Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

Other Authors:

D. Z. Nelson
(WSRC)
M. R. Louthan, Jr.
(WSRC)

A paper proposed for Presentation/Publication
at/in the 25th Annual Meeting of the International Metallographic Society
Denver, CO
08/02-05/93

This paper was prepared in connection with work done under Contract No. DE-AC09-89SR18035 with the U. S. Department of Energy. By acceptance of this paper, the publisher and/or recipient acknowledges the U. S. Government's right to retain a nonexclusive, royalty-free license in and to any copyright covering this paper, along with the right to reproduce and to authorize others to reproduce all or part of the copyrighted paper.

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.

**REACTOR COOLING WATER EXPANSION JOINT BELLOWS:
THE ROLE OF THE SEAM WELD IN FATIGUE
CRACK DEVELOPMENT**

S. L. West ¹, D. Z. Nelson ¹ and M. R. Louthan, Jr. ¹

ABSTRACT

The secondary cooling water system pressure boundary of Savannah River Site reactors includes expansion joints utilizing a thin-wall bellows. While successfully used for over thirty years, an occasional replacement has been required because of the development of small, circumferential fatigue cracks in a bellows convolute. One such crack was recently shown to have initiated from a weld heat-affected zone liquation microcrack. The crack, initially open to the outer surface of the rolled and seam welded cylindrical bellows section, was closed when cold forming of the convolutes placed the outer surface in residual compression. However, the bellows was placed in tension when installed, and the tensile stresses reopened the microcrack. This five to eight grain diameter microcrack was extended by ductile fatigue processes. Initial extension was by relatively rapid propagation through the large-grained weld metal, followed by slower extension through the fine-grained base metal. A significant through-wall crack was not developed until the crack extended into the base metal on both sides of the weld. Leakage of cooling water was subsequently detected and the bellows removed and a replacement installed.

¹Materials Technology Section, Savannah River Technology Center
Westinghouse Savannah River Company, Aiken, SC

BACKGROUND

The Savannah River Site (SRS) has five nuclear material production reactors (C, K, L, P and R) which were designed and built in the early 1950's, at the direct request of President Truman. These low temperature, low pressure reactors use heavy water as a neutron moderator and as the primary coolant for the reactor core and internal components. Heavy water is circulated through the reactor by six primary coolant loops. Each loop, and the reactor tank, is fabricated from austenitic stainless steel and contains piping, valves, a main pump, two heat exchangers, and expansion joints. The heat generated during nuclear operations is transferred from the heavy water to the secondary cooling water system through the heat exchangers. The secondary cooling water system also contains piping, valves, pumps and expansion joints.

The expansion joints in both the primary and secondary coolant systems are designed to reduce thermal stresses in the piping and to facilitate component replacement in, and alignment of, the systems. A typical expansion joint design is illustrated in Figure 1. Details differ among the various expansion joints because several different suppliers were used and design details differed among the manufacturers. The fabrication of all designs includes roll forming a cylinder from 1.25 mm thick (0.050 inch) austenitic stainless steel, longitudinal seam welding and cold expansion against dies to produce the convoluted bellows. The bellows are then formed to flanges and welded in position. However, regardless of the specific design, the convolutes are the thinnest portion of the pressure boundary in both the primary and secondary coolant systems.

Fatigue cracks in, and leakage from, the convolutes of an expansion joint have developed on several occasions during the 35+ years of reactor operations at Savannah River. In 1958, the joints were modified to reduce the tendency for fatigue and since that time approximately seven leaks have been detected in expansion joints in process water systems. In each case, the leaking expansion joint was replaced before reactor operations were resumed.

Nuclear materials production at Savannah River was temporarily halted in 1989 so that safety upgrades could be made to the reactors systems. The restart of the production reactors included hydraulic testing of the primary and secondary cooling systems of the K-reactor. During this testing, a crack developed in a convolute of an expansion joint in the secondary cooling water system. This crack provided a path for river water to leak from the bellows and necessitated both the

replacement of, and a failure analysis for, the expansion joint. This paper presents the metallurgical evaluation portion of that failure analysis.

FAILURE ANALYSIS TECHNIQUE

A crack in the third of sixteen convolutes of an expansion joint in the secondary cooling water system was discovered during restart testing of K-reactor. The circumferential crack, initially detected because of water accumulation in a sump, was approximately thirteen centimeters (five inches) long and was centered on an autogenous gas tungsten arc (GTAW) seam weld in the bellows, Figure 2. Testing was discontinued as soon as the leak was detected and the leaking bellows was located by a walkdown of the piping system. The installed length of the expansion joint and tie rods were measured before the bellows and the associated portions of the expansion joint, Figure 3, were removed from the cooling water system. The crack, even though it was approximately thirteen centimeters (five inches) long, was not opened significantly and closed tightly when the bellows was removed from the expansion joint assembly.

Figure 1. Schematic of Typical Expansion Joint Design.

Figure 2. Failure Site Centered on Seam Weld.

Figure 3. Expansion Joint Once Removed from Service. Arrow Indicates Position of Flange When Installed.

Penetrant testing of the bellows provided a crack indication in the ninth convolute of the same weld, Figure 4. This particular bellows had been fabricated with three longitudinal seam welds, whereas two is typical for this design. The remainder of the bellows, including the second and third seam welds, was free of crack indications. The crack from the third convolute and the crack indication from the ninth convolute were removed for metallurgical evaluation. The regions of interest were saw cut from the bellows after the cracked area had been wedged apart to prevent damage to the fracture surface during the removal process. The fracture surfaces of the through-wall crack from the third convolute were examined by both optical and scanning electron microscopy (SEM) techniques. The fracture surface of the partially through-wall crack from the ninth convolute was exposed for SEM observations by tensile loading to failure the section that contained the crack indication. Selected areas of the seam welds, bellows convolutes and other regions of the expansion joint were also examined by both optical and scanning electron microscopy. The tensile properties of various regions of the bellows material were also evaluated.

Figure 4. Dye Penetrant Indication at the Ninth Convolute Intrados.

METALLURGICAL OBSERVATIONS

The fracture surfaces of both the through-wall crack in the third convolute and the thumb nail crack in the ninth convolute indicated that the cracks were produced by fatigue processes. Cracking originated from microscopic ($200\text{ }\mu\text{m}$ {0.008 inch} diameter) regions of intergranular fracture in the heat-affected zone (HAZ) of the seam weld, Figure 5. The intergranular microcracks were caused by liquation in the HAZ of the autogenous GTAW seam weld, and are defined as HAZ liquation cracks [1]. The grain morphology in the weld fusion zone was typical of a procedure utilizing a "high" welding speed and producing a teardrop-shaped weld pool [2], Figure 6. Large grains grew epitaxially from the base material to the weld centerline at a constant angle with respect to the weld axis. This microstructural evidence indicates that the GTAW process was utilized effectively and the overall heat input was lower than for a slow welding speed (elliptical weld pool shape), which helped to minimize the size of the liquation zones, Figure 7. The liquation cracks initiated on the outer surface of the cylinder and penetrated approximately five to eight grains into the weld HAZ. Cold forming of the convolutes closed the microcrack responsible for the failure by placing the outer surface of the bellows in residual compression at the convolute intrados. A metallographic cross section of a potential microcrack is shown in Figure 8. Such microcracks were only observed near the outer surface of the bellows, which was the top surface of the weld. This may be attributed to a steeper temperature gradient on the back side of the weld from a chill block, fixture or purge gas. A steep temperature gradient would reduce the width of the partially melted region (liquid at grain boundaries) in the HAZ and the likelihood of cracks occurring [3].

The measurements from the as-installed bellows showed that the installation processes had stretched the bellows, removing the residual compressive stresses and placing the outer surfaces of the inner convolutes (intrados regions) in tension. Stretching of the bellows beyond a qualified limit was not recommended in the manufacturers installation specifications and this stretching, or improper installation of the bellows, was the root cause of the failure process. The microcracks themselves were so small as to be below the detection limit of standard non-destructive testing techniques and were found to be present in the bellows sections of other expansion joints with several years of service.

Figure 5. Intergranular HAZ Liquation Microcrack Initiation Site for Through-Wall Crack Propagation.

Figure 6. Grain Morphology of Fusion Zone Indicating Teardrop-Shaped Weld Pool (a) and Schematic of Moving Weld Pool (b) [2].

Figure 7. Microstructural Evidence of Liquation at Grain Boundaries in the Seam Weld HAZ (Small Arrows). Large Arrows Indicate Fusion Boundary.

Figure 8. Cross Section of Potential HAZ Liquation Microcrack. Arrow Indicates Fusion Boundary.

The improper installation practice increased the stress in the bellows convolutes and significantly reduced the number of fatigue cycles to failure. The fracture surface topography was typical of fatigue, Figure 9. Striations were apparent throughout the surface and, based on striation spacing, the fatigue fracture process was very rapid across the large grained microstructure typical of the weld fusion zone. Once the crack bridged the weld fusion zone, it grew circumferentially along the intrados of the convolute (outer surface), at approximately equal rates on either side of the weld. Based on the shape of the partially through-wall thumb nail crack, the predicted shape of the through-wall crack indicated it was approximately one to three centimeters (0.5 to 1.25 inches) long when it penetrated the wall of the bellows. At this point, the crack opening was not significant and little or no water leaked from the secondary cooling water system. Subsequent crack growth increased the crack opening and when the crack length reached approximately thirteen centimeters (five inches), the leak rate through the bellows was sufficient for detection through accumulation in a sump which was instrumented for such detection. Stains on the fracture surface of the thirteen centimeter (five inch) crack were also consistent with a lack of significant leakage from the initial through-wall crack portion.

The surface of the initial through-wall crack portion was covered with a light redish-brown film, indicating increased age relative to other portions of the crack. Additionally, on either side of the weld, stains were evident beyond the initial through-wall crack region at a depth about halfway through the wall, Figure 10. A major portion of the crack evidently grew from the outside surface around the circumference and was stable for some time before penetrating through-wall. The observed stains are consistent with the development of conditions which favored crevice corrosion within the crack [4,5]. Crevice corrosion conditions develop because of the depletion of dissolved oxygen within a stagnant fluid. Oxygen depletion of the water entrained within the crack requires both the lack of flow through the crack and the a tight fit between adjacent crack faces. These conditions can only develop if the crack was water filled, but non-leaking, for a significant period of time (weeks to months). These observations, coupled with the knowledge that the expansion joint had been in the reactor for approximately one year before the leak developed and that the crack initiation site was a pre-existing discontinuity in the weld HAZ, suggest that the crack growth rate was slow enough to assure that a full circumferential fatigue crack would not develop before leaking was detected.

Figure 9. Optical (a) and SEM (b) Micrographs of Fracture Surface Topography. Small Arrows Indicate Initiation Site and Double Arrows Indicate Fatigue Striations. Large Arrows Indicate Fusion Boundary (a) and Large Fusion Zone Grains (b).

Figure 10. Stains on Fracture Surface Distant from the Weld.

The tensile tests of the portions of the bellows convolutes demonstrated that neither the welding nor the liquation cracking of the HAZ reduced the strength of the bellows. Three types of flat, reduced section test samples were prepared: base metal samples, samples which had the seam welds parallel to the specimen axis, and samples which had the seam welds perpendicular to the specimen axis. Fabrication processes caused the strength of the bellows to be anisotropic. The ultimate strength of the steel in the direction parallel to the seam weld was 621 MPa (90,000 psi) while the ultimate strength perpendicular to the seam weld was approximately 586 MPa (85,000 psi). The seam weld was stronger than the base material and when tests were conducted on samples which had the seam weld perpendicular to the specimen axis, most of the deformation was remote from the weld and fracture took place in the base metal. The ultimate strength of these samples was slightly decreased by the welding process because of the constraint imposed on the base metal on either side of the weld. This base metal provided the weak link in the deformation and fracture processes and the ultimate strength of these samples was about 614 MPa (89,000 psi). When the seam weld was parallel to the specimen axis, the measured strength was increased because the specimen configuration forced deformation and fracture to occur in the weld metal. The ultimate strength of these samples was 752 MPa (109,000 psi). Optical and scanning electron microscopy of the fractured test samples failed to reveal any evidence of fracture initiation in the liquated regions of the weld heat-affected zones. All samples failed by microvoid coalescence processes and even the samples which had the seam weld parallel to the specimen axis displayed no evidence of failure related to intergranular microcracks, Figure 11.

Figure 11. Fracture Surface of Tensile Test Specimen. Arrows Indicate Fusion Boundary.

These tensile data, coupled with metallographic evidence that liquation induced microcracks are common to seam welds, demonstrate that the microcracks should not be a major problem if the bellows are installed properly. These data are also supported by the successful, long term operation of numerous expansion joint bellows of similar design also known to contain microcracks in weld heat-affected zones.

CONCLUSIONS

The metallurgical evaluations of the failed expansion joint bellows demonstrated that failure was by fatigue crack growth from intergranular microcracks which resulted from liquation cracking in the weld HAZ. However, the GTAW procedure was not at fault because the microcracks did not degrade the strength of the bellows. The root cause of the premature failure of the bellows was improper installation which placed the bellows convolute in tension and significantly reduced the fatigue life of the system. Even under these conditions, the fatigue crack developed slowly and was detected by cooling water leakage, thus preventing the development of conditions favoring the onset of rapid fracture in the bellows convolute.

Microstructural evaluation revealed that the GTAW parameters used would minimize the heat input and size of the liquation cracks for the process. In addition to proper installation and minimizing the number of welds, the fatigue life of these expansion joints could be improved by using a high energy density welding process such as laser beam welding to further reduce heat input. These steps would reduce the number and size of potential microcracks to act as fatigue crack initiation sites.

REFERENCES

- 1) B. Hemsworth, T. Boniszewski and N. F. Eaton, "Classification and Definition of High Temperature Welding Cracks in Alloys," **Metal Construction and British Welding Journal**, Vol. 1, p 273, 1969
- 2) W. F. Savage, "Solidification, Segregation and Weld Imperfections", **Welding World**, Vol. 18, p 89, 1980
- 3) W. F. Savage, E. F. Nippes and T. W. Miller, "Microsegregation in Partially Melted Regions of 70Cu - 30Ni," **Welding Journal**, Vol. 55, p 181s, 1976
- 4) M. G. Fontana and N. D. Greene, **Corrosion Engineering**, McGraw-Hill Book Co., p 41, 1978
- 5) **Metals Handbook**, Ninth Edition, Vol. 13, ASM International, p 110, 1987

END

**DATE
FILMED**

7 / 9 / 93