FATIGUE CRACKING OF ALLOY 600 IN SIMULATED STEAM GENERATOR CREVICE ENVIRONMENT

G. Ogundele* and O. Lepik*

ABSTRACT

Investigations were carried out to generate fatigue life (S-N) and near-threshold fatigue crack propagation (da/dN) data to determine the environmental influence on fatigue behavior for Alloy 600 in air, deionized water and in simulated Bruce Nuclear Generating Station "A" crevice environments under appropriate loading conditions. In the low cycle fatigue regime, the simulated crevice environment did not affect the fatigue life of Alloy 600 under the applied loading conditions. The near-threshold fatigue crack growth rates of Alloy 600 in the simulated crevice environment were significantly lower compared to either pure water or air environments and is believed to be the result of higher crack closure in the crevice environment.

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INTRODUCTION

The Bruce Nuclear Generating Station A (BNGS-A) consists of four 760 MWe reactor units, each equipped with eight recirculating steam generators (SGs). Each steam generator has 4200, 0.5 inch (12.7 mm) nominal outside diameter (OD) tubes. The tubing material is mill-annealed Alloy 600. Tubes were made in a four-stage draw reduction process with interstage annealing at 954°C (1750°F). After degrease and pickle, a final hydrogen furnace anneal was conducted at 1093°C (2000° F) [1]. The annealed tubes were then straightened, outside surface -ground, cold bent, and assembled into the tube bundle. The completed bundles were then heat-treated to relieve the stresses at the carbon steel closure welds at a nominal temperature of 607°C (1125°F). Heat was applied to the lower half of the vessel while the upper portion of the bundle shell was insulated. Tube temperature at the U-Bend region reached 538°C (1000°F) which is not enough to change tubing microstructure or sensitize the material [1,2].

The cracking of Alloy 600 SG tubes have been reported at BNGS-A[1-3]. Metallurgical examination of removed leakers identified high cycle, low stress amplitude fatigue due to flow induced vibration as the most likely cause of failure. The observed cracks were circumferentially oriented, and secondary side initiated [3]. Between 1990 and 1991, more cracking that was most likely fatigue-related initiated from stress corrosion cracks, and resulted in several forced outages in BNGS-A Units 1 and 2. Other plants have also experienced circumferential cracking attributable to corrosion fatigue. This cracking was diagnosed to have resulted from small amplitude vibrations combined with the transport of impurities into the upper region of the SGs [4-6]. Tube vibration measurements in operating steam generators have also shown that the cyclic stresses (< 34MPa peak to peak) were too low to account for the nucleation and propagation by fatigue alone, without a simultaneous action of an aggressive environment [7].

Numerous studies have been carried out to characterize the fatigue life behavior and fatigue crack growth rate characteristics of Alloy 600 in various environments [5,6,8,9]. However, the database is particularly limited for environments that can occur locally in steam generators such as at deposit-covered U-bend supports and tube support plates. It is well known that non-volatile solute impurities concentrate in crevices and under deposits in SGs. These limitations are underscored by the difficulties experienced in determining the causes at stations that have experienced fatigue failures.

As part of the development of generic CANDU steam generator fitness for service guidelines, an experimental program was initiated and sponsored by the CANDU Owners Group (COG). The objective is to gain a better understanding of the interaction of fatigue, corrosion fatigue, and stress corrosion cracking of Alloy 600 at BNGS-A. In this test program, the fatigue life (S-N), and fatigue propagation rate (da/dN) of Alloy 600 in air, deionized water and in simulated Bruce NGS-A crevice environments under appropriate loading conditions were investigated.

EXPERIMENTAL DETAILS

Test Environment

The laboratory test environment developed to simulate a representative BNGS-A SG crevice environment consisted of the following chemistry: 0.15 M Na_2SO_4, 0.3 M NaCl, 0.05 M KCl, 0.15 M $CaCl_2$, ~ 0.5 mole SiO_2 (as solid), and ~ 100 ppm Pb (added as PbO). These concentration levels are based on a comprehensive evaluation of the crevice chemistry and is presented elsewhere[10]. Deaerated conditions were used for the testing.

Test Material

The material used for the test program was obtained from a 25.4 mm thick hot-rolled plate (heat number NX8844) that was initially produced for EPRI to simulate as closely as possible tube material characteristics under EPRI Task RP5511-02. In order to simulate the temperature cycle experienced by BNGS-A tubing at the U-bend, the plate material was heat-treated at 540°C for 5 hours. The chemical composition is given in Table 1. The carbon content of this heat (0.067%) is high compared to most Alloy 600 tube materials. However, it was considered appropriate for the scope of work intended, as the heats in BNGS-A SG tubing materials have higher than usual carbon contents and some individual heats have equivalent carbon contents or even exceed this level. Mechanical properties for the heat-treated plate material are given in Table 2 and the microstructure is shown in Figure 1.

Test Procedure

Fatigue Life Data

Tensile test specimens, having reduced gauge sections, were machined with the axis coincident with the rolling direction of the plate material. The gauge section of the specimens (8 mm) was polished to 600 grit. The strain-controlled air fatigue tests were performed in accordance to ASTM E 606-92 using a computer-controlled servohydraulic mechanical testing machine. The environmental fatigue tests were performed under stroke control because of the difficulties encountered in the instrumentation. However, the strain level were correlated with actual strain at the gauge section of the samples. The test apparatus used for the environmental tests is shown in Figure 2. Details of the test apparatus and experimental procedure are described elsewhere[11]. Baseline (air) tests were conducted using the following parameters: strain amplitude 0.3%, 0.6%, 1.1%; mean strain 0, 0.1%, 0.15%, at room temperature (~ 23°C). This was followed by tests in the simulated BNGS-A crevice environment at different temperatures. All tests were conducted at a frequency of 0.5 Hz under a sine waveform. The fatigue life reported in this investigation was defined as the number of cycles to 25% load drop across the specimen.

Near-threshold Fatigue Crack Propagation Data

Tests were performed in accordance to ASTM E647-95 [12]. Compact tension C(T) specimens were used having a width and thickness of 30 mm and 4 mm, respectively. Specimens were machined from the wrought plate material in the L-T orientation with the plane of crack growth normal to the longitudinal direction of the plate and crack growth in the transverse direction. Crack length was monitored continuously by using either the elastic unloading compliance or d.c. potential drop method. Crack growth rates were generally calculated over 0.2 mm increments and were determined by a modified secant method. Using this approach the crack length increment to establish da/dN spans the adjacent first and third a versus N data points with ΔK based on the crack length midway through the increment.

The near-threshold fatigue crack propagation tests were conducted on a standard servo-hydraulic closed-loop mechanical test machine. The testing system was fully automated and controlled by a computer. A decreasing ΔK schedule was used to obtain near-threshold crack growth data. Using this method the stress ratio R is held constant while K_{max} is exponentially decreased according to the following control algorithm:

$$K = K_o \exp[C(a-a_o)]$$

where K_o is the initial stress intensity factor at the start of the test, a_o is the initial crack length and C is the normalized K-gradient (-0.08 or -0.10 mm^{-1}).

Baseline tests were performed in laboratory air at room temperature (~23°C) and 305°C. These tests were conducted using a sinusoidal waveform over a range of frequencies from 30 to 45 Hz. Tests in an aqueous environment were conducted in an autoclave at 300°C at a loading frequency of 8 Hz. These tests were carried out in de-ionized deaerated water or water having the BNGS-A crevice chemistry, but without the addition of lead. Water was either circulated through the autoclave by a low flow (3 ℓ/h) recirculating high temperature flow loop or was left stagnant in the autoclave. The concentration of dissolved oxygen in the autoclave influent water was maintained below 20 ppb.

RESULTS AND DISCUSSION

Fatigue Life Data

The fatigue life of Alloy 600 in air at 25°C is shown in Figure 3. The present results compares well with fatigue life data from other sources [6,13]. It is important to note that these data from references 6 and 13 were generated using test parameters that are different from the present program.

The results in BNGS-A crevice environment combined with the air data are shown in Figure 4. As can be seen, there appears to be no effect of environment on the fatigue life. The reason for the absence may be due to the following: (a) strain rate levels are extremely high such that the corrosion fatigue process was dominated entirely by mechanical factors, and (b) the environment is not aggressive enough to cause any acceleration in fatigue damage.

Near-Threshold Fatigue Crack Propagation Data

The results of the near-threshold fatigue crack propagation tests in air are shown in Figure 5. A small increase in growth rates was observed with increasing temperature in the near-threshold regime. Crack growth rates increased with increasing stress ratio and were attributed to an absence of crack closure at the higher R-ratios of 0.7 and 0.8, which was apparent from measurements of specimen compliance.

Figure 6 shows the results of the tests conducted at 300°C in the water environments at a stress ratio of 0.1. At the test frequency of 8 Hz used in this study the near-threshold crack growth rates were lower in the water environments than in air. The crack growth rates were significantly lower in the simulated crevice environment and are believed to be the result of higher levels of crack closure. Although crack closure was not measured in the water tests, the crack in the specimen tested in the crevice environment was plugged with silica and salt deposits, suggesting that a form of closure similar to oxide-induced closure [14] was operative. Under these conditions, a small portion of the tensile loading cycle would only be transmitted to the crack tip, thereby reducing the effective ΔK at the crack tip. Results of the test conducted at a stress ratio of 0.8 in the simulated crevice environment (see Figure 7) show a similar reduction in crack growth rates in the near-threshold regime.

CONCLUSIONS

In the low cycle fatigue regime and under the test conditions used in this study, the simulated BNGS-A crevice environment did not affect the fatigue life of Alloy 600. The near-threshold fatigue crack growth rate behaviour of Alloy 600 in the simulated BNGS-A crevice environment was significantly lower compared to either pure water or air environments and is believed to be the result of higher crack closure in the crevice environment.

REFERENCES

1. N. Simpson, "Bruce A Steam Generator Tubing History", Attachment 17 - "Bruce A Root Cause of Cracking - Summary Report 1"- December 1995

2. M. A. Clark, "Task III - Effect and Determination of Microstructural Factors" - Attachment 16 - " Bruce A Root Cause of Cracking - Summary Report 1" - December 1995

3. P.J. King et al., "Stress Corrosion Cracking Experience in Steam Generators at Bruce NGS", Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems, San Diego, Ca. pp 233-240, Pub. TMS, August 1-5 1993.

4. S. J. Green and J.P.N. Paine, "Steam Generator Materials - Experience and Prognosis", pp. 53-68, Proc. of the 1st Int. Symp. on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Myrtle Beach, South Carolina, August 22-25, 1983.

5. R.J. Jacko and L.E. Willertz, "The Corrosion Fatigue Performance of Ni-Cr-Fe Alloy 600 Under Typical Steam Generator Conditions", ibid, pp. 775-808, 1983.

6. R.J. Jacko, "Fatigue Performance of Ni-Cr-Fe Alloy 600 Under Typical Steam Generator Conditions", EPRI Report Number NP2957, Westinghouse Electric Corporation, March 1983.

7. R.S. Pathania, Memorandum to G.F. Taylor, AECL on EPRI Workshop on Corrosion Fatigue and Localized Corrosion in Steam Generators, June 15, 1979.

8. A. Boateng, J.A. Begley, and R.W. Staehle, "Corrosion Fatigue of Type 304 Stainless Steel and Inconel 600 in a Boiling (150°C) Concentrated Caustic Solution", Met. Trans. A, Vol. 14A. pp. 67-73, January 1983.

9. H.M. Shalaby, P. Zhao, G. Cragnolino and D.D. MacDonald, "Corrosion Fatigue Behavior of Alloy 600 in High-Salinity Brine", Corrosion, Vol. 44, No. 12, pp. 905-915, 1988.

10. M. Mirzai, C. Maruska, S. Pagan, O. Lepik, G. Ogundele, M. D. Wright, and G. Kharshafdjian, "Stress-Corrosion Cracking/Corrosion Fatigue/Fatigue in Alloy 600", Proc. 8th Int. Symp. on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Vol. 1, pp. 11-18, August 10-14, 1997.

11. G. I. Ogundele and J. Schaefer, Test apparatus for corrosion fatigue, In preparation.

12. ASTM Standard Test Method for Measurement of Fatigue Crack Growth Rates, ASTM Standard E647-95, 1997, Vol. 03.01, pp. 557-593.

13. S-N Data WG of PVRC Autumn Meeting, October 7-9, 1996, at Columbus, OH. Fatigue Life of Stainless and Alloy 600 in PWR Primary Water

14. S. Suresh and R.O. Ritchie, Engineering Fracture Mechanics, Vol. 18, 1983, p. 785.

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Table 1 Chemical Composition of Alloy 600 Plate Material

Element	**Mill Analysis**	**Check analysis**
Carbon	0.069	0.045
Nickel	Balance	73.6
Chromium	14.97	15.5
Iron	8.26	8.8
Copper	0.22	0.21
Cobalt	0.04	0.052
Titanium	0.29	0.29
Aluminum	0.27	0.27
Manganese	0.26	0.24
Molybdenum	0.15	0.17
Silicon	0.24	0.25
Phosphorus	0.009	< 0.0005
Sulfur	0.0005	0.006

Table 2 Mechanical properties of Alloy 600 Plate Material heat-treated for 5 hours at 540°C

Temp.	0.2% Yield Stress (MPa)	UTS (MPa)	Elongation (%)	(%)Reduction in Area
RT	336	693	47	59
300°C	264	633	49	56

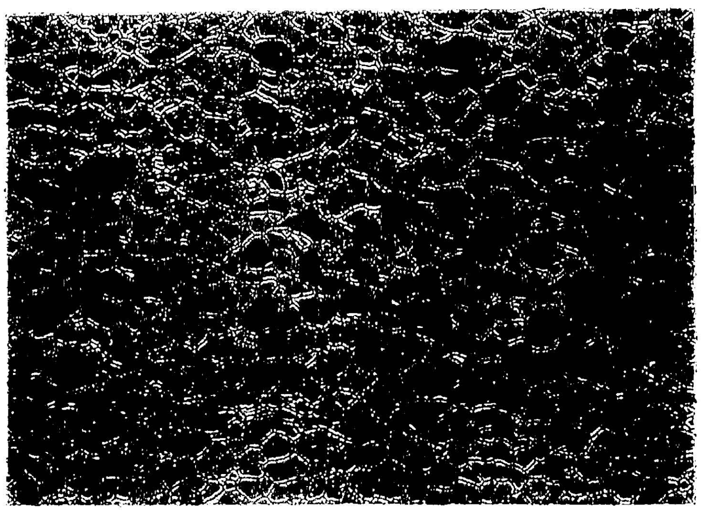

Figure 1 Microstructure of Alloy 600 plate material

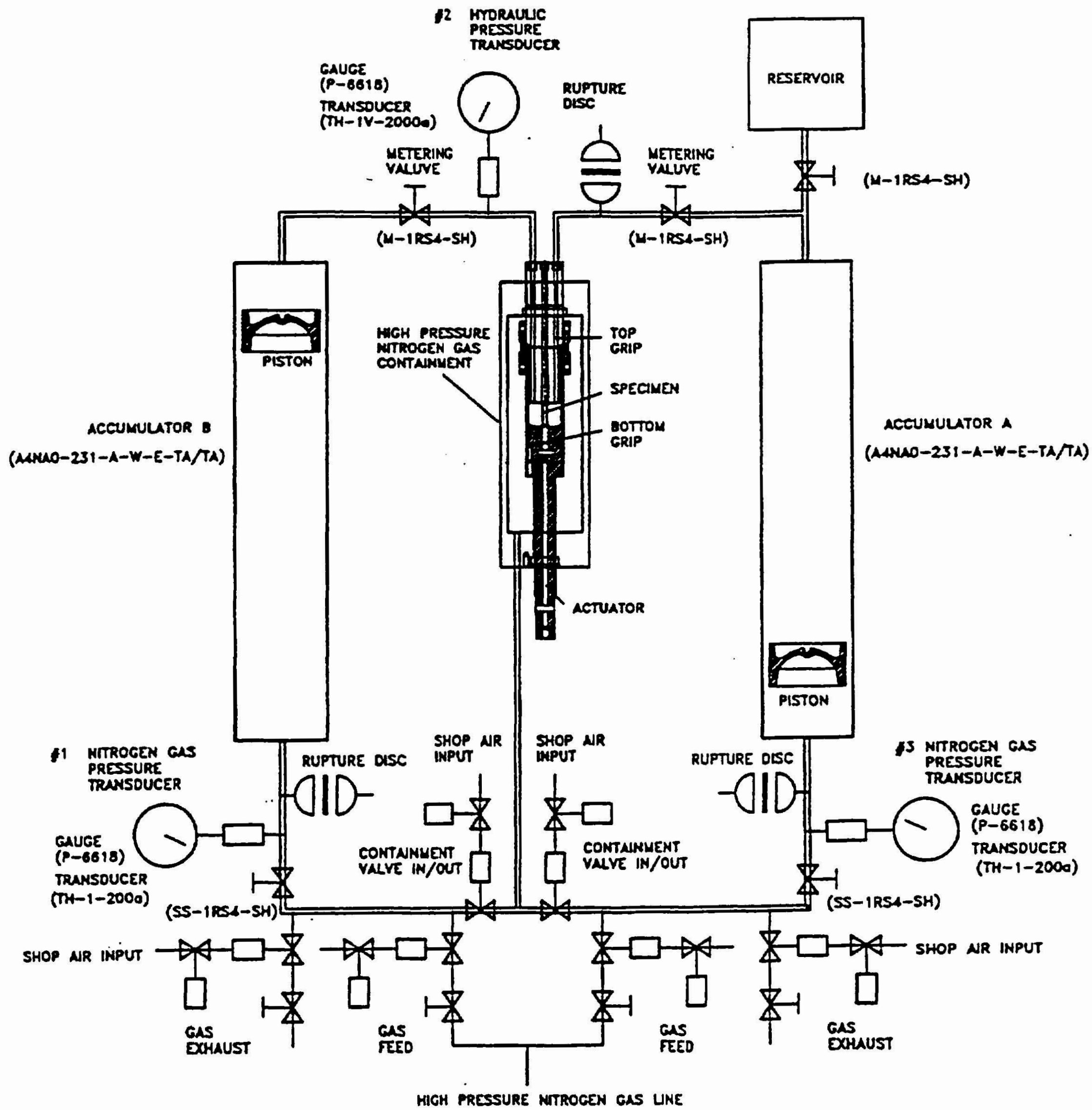

Figure 2 Test apparatus for the environmental tests

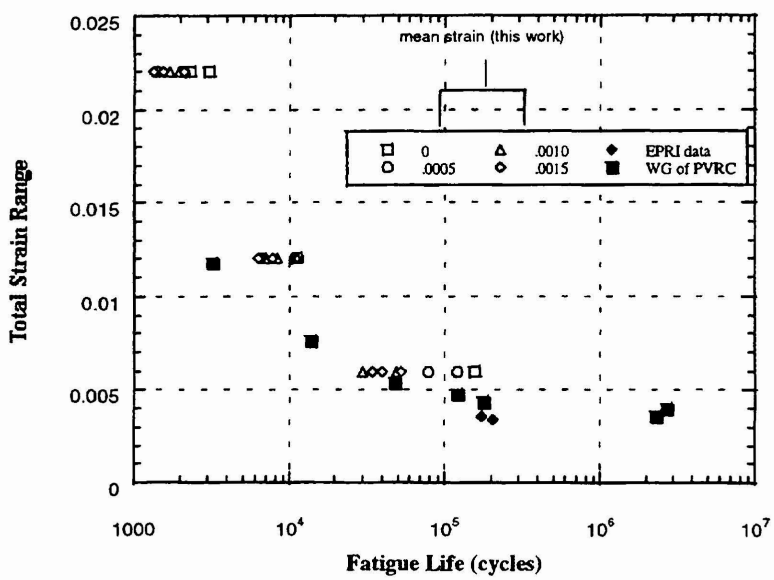

Figure 3
Strain vs life data for Alloy 600 in air at 25% load drop (~ 23°C)

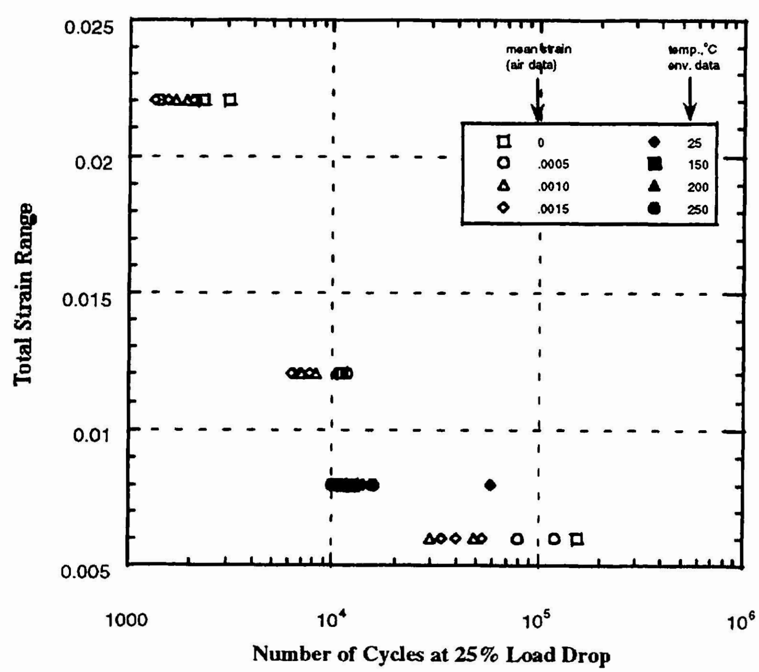

Figure 4
Strain vs life data for Alloy 600 in air and in simulated BNGS-A crevice environment

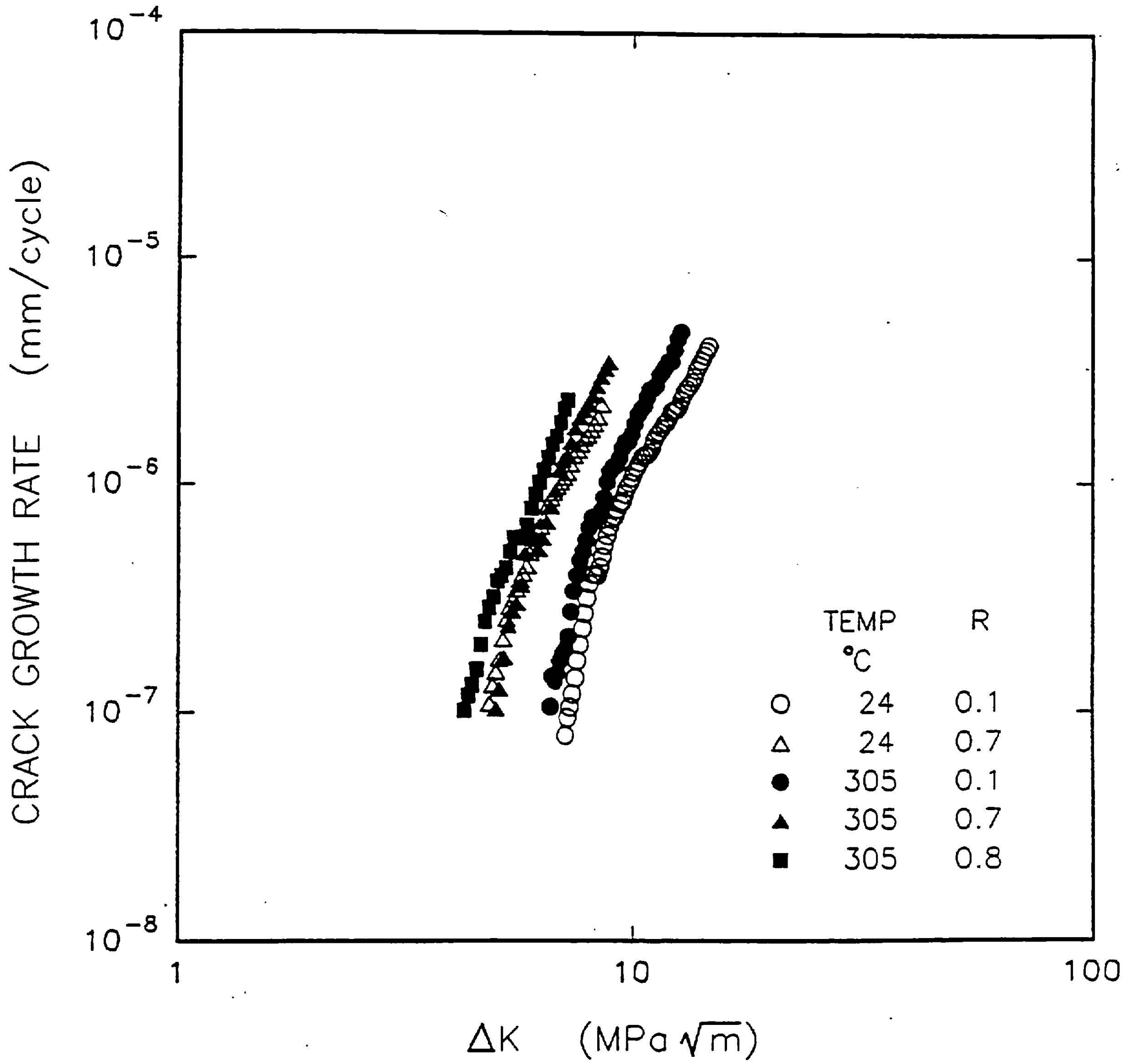

Figure 5
Fatigue crack growth rates in Alloy 600 in air at 24 and 305°C

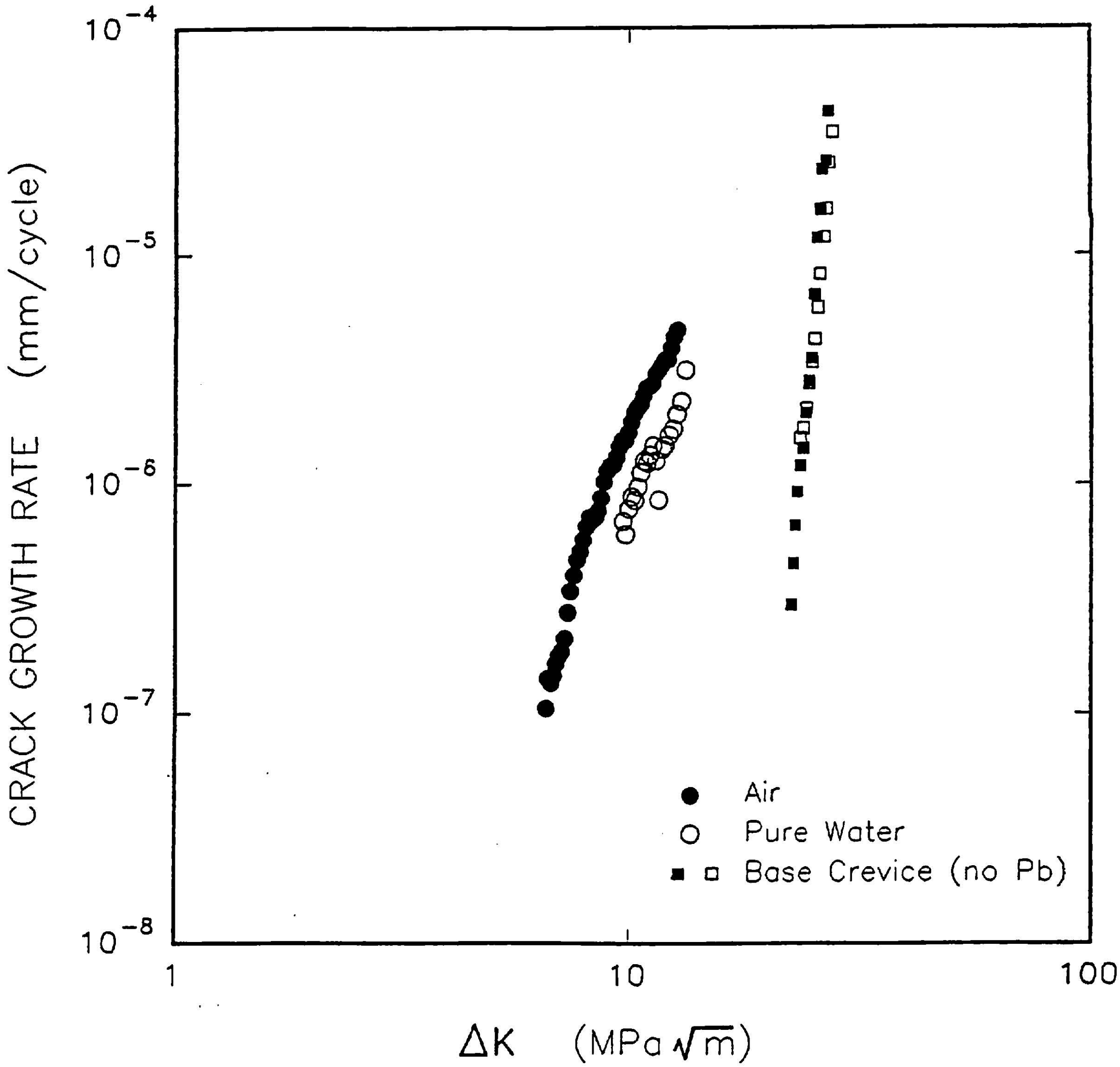

Figure 6
Comparison of crack growth rates in Alloy 600 in de-ionized water, simulated BNGS-A crevice water and in air at R=0.1. Air data at 305°C, water data at 300°C

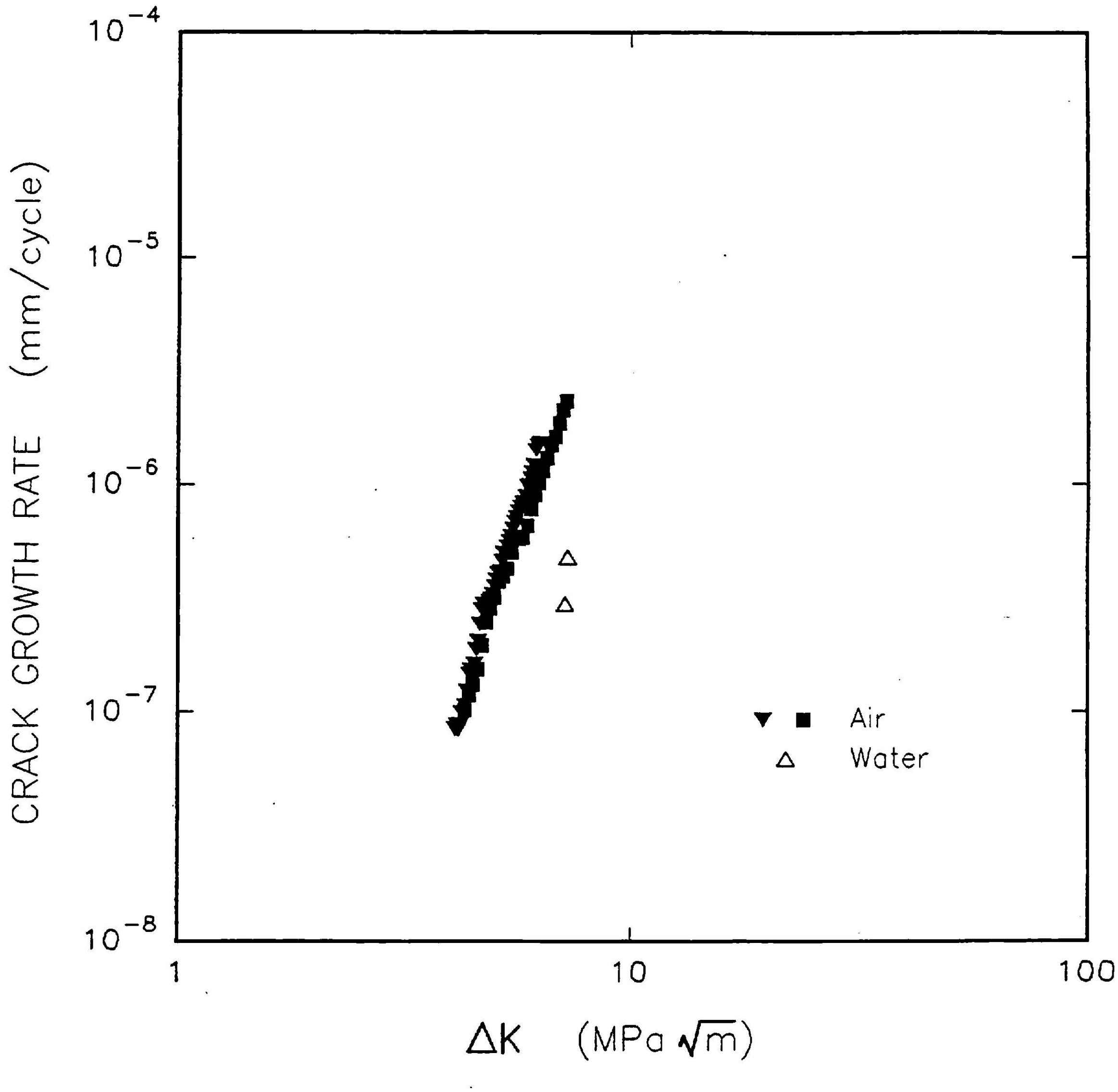

Figure 7
Comparison of crack growth rates in Alloy 600 in simulated BNGS-A crevice water and air at R=0.8. Air data at 305°C, water data at 300°C

DISCUSSION

Authors: G. Ogundele, O. Lepik, Ontario Hydro Technologies

Paper: Fatigue Cracking of Alloy 600 in Simulated Steam Generator Crevice Environment

Questioner: J. Gorman

Question/Comment:

Please explain what is meant by "greater crack closure" with environment.

Response:

Cracks that were grown in the simulated crevice environment were full or plugged with deposits which we believe promoted higher levels of crack closure that reduced the effective ΔK at the crack tip.

Questioner: M. Wright

Question/Comment:

You noted a pronounced crack closure effect resulting in reduced crack growth rates. In the context of fitness-for-service calculations, would you expect to be able to take credit for this or is this merely an observation?

Response:

Further study in other environments would be required before the information reported could be incorporated in fitness-for-service calculations.

Questioner: R. Garg

Question/Comment:

(1) Does your work make comparison to actual inspection results to validate your work?
(2) The work is done for Bruce A I-600 tubing. This unit is now shut down. Do you intend to continue your work which could be used?

Response:

To the first part of your question, any comparison would be limited to the fracture surface morphology. This we found quite similar in our preliminary results. We did not perform an extensive fractography.

For the second part, we are continuing our investigation on Alloy 800.

Questioner: K. Bagli

Question/Comment:

Gabriele, as you are aware Bruce-A has a serious lead ingress problem. Did you do any tests with lead and how do these results differ from those with the non-lead EPRI test specimens?

Response:

No. We did not study the effect of lead. The amount of lead (as PbO) in the simulated crevice environment was the only level used in the $\Delta\varepsilon$-N investigation. As indicated in the presentation, the lead was excluded in the CGR tests.

Questioner: F. Vaillant, EDF

Question/Comment:

Why do you use such high frequencies to investigate an environmental effect on CGRs of Alloy 600?

Response:

In fact, the frequency at U-bend due to FIV has been estimated to be >30 Hz. That's why the CGR tests were performed at the range selected. We recognize the significance of frequency in studying environmental effects; consequently, we performed the $\Delta\varepsilon$-N at 0.5 Hz and even lower in future tests.