NORTH ANNA #1 STEAM GENERATOR
ROW 9 COLUMN 51
TUBE FAILURE ANALYSIS

by

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Final Report

c/18

INTRODUCTION

On July 15, 1987 a leak occurred in the "C" Steam Generator of the North Anna Unit 1 nuclear power plant. The source of the leak was determined to be the rupture of the tube in the Row 9 Column 51 position. The author was retained as a consultant by the NRC Staff to help in the evaluation of the failure and to provide input with respect to the vendor (Westinghouse) and utility (Virginia Electric Power Company) analysis of the failure and proposed solution to the problem.

The author attended three meetings between the NRC staff, VEPCO, and Westinghouse personnel and received all VEPCO and Westinghouse reports related to the incident. Table 1 lists meeting dates and locations. Table 2 lists the reports that were received and reviewed.

AUTHOR'S QUALIFICATIONS

The author's resume is attached as Appendix 1. The author holds a joint appointment in the Departments of Nuclear Engineering and Materials Science and Engineering at the Massachusetts Institute of Technology as Associate Professor. The author has conducted extensive research in the areas of corrosion fatigue and stress corrosion cracking of nickel-base alloys, in particular, alloy 600, in high temperature aqueous systems. The fatigue crack growth data from the author's laboratory represents the only such data available in the literature.

QUESTIONS TO BE ADDRESSED:

The following questions were addressed as part of the analysis:

(1) What was the mode of failure?

(2) Was the vendor/utility analysis of the failure adequate?

(3) Are the proposals for avoiding future failures likely to be successful in their goals?

(4) Are there any additional areas of concern that have not been addressed in the vendor/utility analysis?

Failure Mode

Based on analysis of fracture surfaces it is proposed that failure was by crack initiation and propagation by fatigue in the aqueous environment of the secondary side of the steam generator. The necessary cyclic stress was provided by flow induced vibration. Initiation was facilitated by the presence of a high mean tensile stress associated with denting of the R9C51 tube in the upper support plate. Abnormally large vibrational amplitudes were the result of: (1) the absence of antivibration bars and, (2) the presence of a fluid elastic instability.

After examination of micrographs of fracture surfaces, the author concurs with the contention that failure was caused by fatigue. The presence of clearly identifiable fatigue striations as well as other features associated with fatigue failures, leaves no doubt.

With respect to the source and magnitude of the alternating stresses, further discussion will be presented in a subsequent section.

Vendor Utility Analysis

The vendor/utility analysis of the tube failure consisted of a number of major tasks. Among these were the following:

(1) Identification of the cause of failure

(2) Analysis of the failure scenario

(3) Identifiction of mitigation measures.

The identification of cause of failure was discussed in the previous section. The failure scenario consisted of two distinct phases: (1) initiation and (2) propagation. A major conclusion of the analysis indicates that the failure process was dominated by the initiation phase. Available crack propagation data indicates that once initiation has occurred, through wall penetration can occur in as little as a few hours with tube failure occurring in as little as 6 hours. Based on this analysis any mitigation scheme must be aimed at extending the time to initiation. Proposed mitigation measures will reduce the amplitude of tube vibrations and, hence, will extend the time to initiation.

The vendor's analysis is based on the observed failure made of corrosion fatigue. The assumption is then made that the failure initiated in a region of high tensile stress just above the seventh support plate. The high tensile stress (approaching yield) is calculated as a result of the high (exceeding yield) compressive stress generated in the support plate region due to tube denting, which was observed for this tube.

Using the observed time to failure and an estimate of the initial ΔK (stress intensity factor range) from striation spacing measurements a stress amplitude for the initiation phase was estimated. A reduced stress amplitude is calculated assuming a large effect of mean stress on fatigue strength.

Subsequent to initiation, crack growth rates are estimated based on striation spacing and literature data. From these rates, crack opening angles and, hence, leak rates are calculated as a function of time. Vibrational stresses are calculated to result from fluid/elastic sources.

In general, the above analysis is consistent with in-service and fracture surface observations. The type of calculations necessary for the analysis and the assumptions made with respect to the mean stress effect on initiation and fluid/elastic calculations normally would result in a large uncertainty in any calculated results. However, the field observations, especially fracture features such as striation spacings and morphology, tend to pin down the initial ΔK and subsequent crack growth rates which provide a bench mark for the analysis. Fracture features near the crack origin have been observed, by the author, in laboratory specimens for the exact conditions of service in North Anna 1 and are consistent with an initial ΔK of approximately 4KSI$\sqrt{}$ in.

The high mean stress, assumed to exist as a result of tube denting in the support plate region, is calculated to reach approximate yielding levels in the region of crack initiation. As an independent estimate of what stress levels would be consistent with the presence of a small thumbnail crack and a reasonable estimate of the maximum stress intensity factor of 4KSI $\sqrt{}$ in which is assumed based on fractographic evidence the far field stresses were calculated using a model for K developed by Parks and Chen (1).

Parks and Chen have recently completed K calculations for a thin wall tube with a thumbnail crack initiating from the exterior which, at least for very small crack depths, reasonably represents our conditions. Figure 1 shows a schematic of the tube and Figure 2 shows the crack geometry. Figure 3 shows the K solution as a function of crack parameters for various crack depths. The solutions for K do not include effects of bending so the solution is only applicable for very shallow crack depths where the axial stress gradient is small. Figure 4 shows the solution for K_{max} ($\phi/(\pi/2) = 1$) as a function of depth. If we extrapolate back to a depth of 0.0025" ($a/t = 0.05$) a far field stress of 57 KSI is calculated if one assumes an initial K_{max} of 4KSI $\sqrt{}$ in. This stress is consistent with the contention that yield conditions existed in the surface region prior to initiation.

This calculation is consistent with the vendor's assumption of a mean stress approximating yield at crack initiation.

The estimated stress amplitude at initiation of from 4-10KSI was arrived at by independent estimates of minimum and maximum values that are consistent with observation. Striation spacings in the region just before slant fracture began indicated an approximate ΔK of 50 KSI √ in. In order for this to be the xase a back extrapolated stress amplitude at initiation of 10 KSI maximum was calculated. If the stress amplitude was higher an unphysical stress history during crack propagation would result. In particular, the stress intensity factor range would have to decrease as the crack propagated for constant amplitude loading - an impossibility.

The lower limit for the stress amplitude range was arrived at by back extrapolation from a just through wall crack. At the point of wall penetration a ΔK effective of 9.3 KSI in is calculated based on striation spacing observations with a correction for the effect of mean stress. Back extrapolation of this to initiation, using a single edge notch model results in a far field stress amplitude of 6.3 KSI. This is reduced to 4 KSI to account for uncertainties in the use of the single edge notch model, the assumed R ratio (P_{min}/P_{max}) of 0.5, and the fact that one is using long crack data to judge behavior of small cracks.

The above calculation and estimates are consistent with the author's calculations above and ΔK values which are consistent with fractography. A high mean stress most likely existed with a superimposed 4-10 KSI (most likely closer to 4 KSI) stress amplitude at initiation. This resulted in an approximate ΔK, during initial stages of crack growth, of approximately 4KSI √ in.

Based on initial stress intensity factor ranges above, the vendor's calculation of penetration times and failure times are consistent. Table 3 shows the author's estimates of the maximum and minimum times to failure for a range of ΔK values. These times bracket the vendor's more rigorous calculations.

In conclusion, based on the assumptions made, the vendor's analysis is adequate. However, the possible effect of Intergranular Attack (IGA) in the region of the failure has not been considered as a factor. The factor will not affect the overall conclusions with respect to failure mode or solution but will be discussed further later.

(1) Parks, D.M., Chen, B.S., "Stress Intensity Factors for Surface-Flawed Plates and Shells: The Line-Spring Model," Unpublished MIT Report.

Mitigation Techniques

With the assumption that tube vibration was the source of the fatigue stresses, the solution consisting of generator modifications to reduce the stress amplitude by reducing vibration is an adequate solution and will result in an extension of the time to crack initiation. Since the process is initiation dominated, this should extend the tube life significantly.

Additional Comments/Areas of Concern

The effect of mean stress on cyclic life was assumed to be represented adequately by the relationship proposed by Smith et. al.(2). Smith at. al. propose a relationship of the form

$$\sigma_a \cdot \sigma_{max} = C$$

where σ_a is the cyclic stress amplitude and σ_{max} is the maximum stress during a cycle. This formulation results in a severe mean stress effect - more so than those proposed by others such as Goodman [$S_a/S_f + S_m/S_u = 1$], Gerber [$S_a/S_f + (S_m/S_u)^2 = 1$], Soderberg [$S_a/S_f + S_m/S_y = 1$], or Morrow [$S_a/S_f + S_m/\sigma_f = 1$] where

S_a = alternating stress amplitude

S_f = fatigue limit

S_m = mean stress

S_u = ultimate tensile stress

S_y = tensile yield stress

σ_y = true fracture stress

(3). While the Smith et. al. relationship provides for a reasonable reconciliation of the field observations and the analytical calculations, data reported by Jacko et. al. (4) for alloy 600 tubing in AVT water indicate that the mean stress effect is minimal in nominal AVT environments and is adequately represented by a Goodman functional form for faulted AVT chemistry conditions. If this data is a reasonable representation of in-service conditions one would expect a less severe mean stress effect. It must be pointed out, however, that the mean stress effect data reported by Jacko et. al. is quite limited and covers a range of mean stresses significantly less than those calculated to exist in the situation of interest.

If we were to assume a less severe mean stress effect and, at the same time, assume that the cyclic stress amplitude at initiation was between 4-10 KSI then, for this to be the case, another mechanism or mechanisms would have had to contribute to initiation. Two possibilities would be IGA and degraded local chemistry. In the author's opinion, the most likely cause of a reduction in fatigue strength would have been the presence of IGA. IGA was observed in the region of failure. If IGA is present, there is no reason to believe that the presence of IGA cracks will not affect the fatigue strength of the material. The effect of surface finish on fatigue life is well known. If IGA does play a role then this additional factor will warrant close observation of other generators that, while they may not have such a high degree of denting or vibration, may still have IGA. As IGA progresses in these generators, an increase in probability of fatigue crack initiation from the IGA cracks will occur. The presence of IGA will result in initiation at a lower level stress and hence ΔK. For this set of conditions a lower mean stress and/or smaller vibrational stress may be required. Unfortunately, no data exists that would show more clearly the effect of IGA on crack initiation. For this reason and the above discussion, the author recommends that other generators be closely monitored in the future to see if such an effect may exist.

(2) Smith, K.N., Watson, P., and Topper, T.H., "A Stress-Strain Function for the Fatigue of Metals", Journal of Metals, JMLSA, Vol. 5, No. 4, Dec. 1970, pp. 767-778.

(3) Fuchs, H.O., Stephens, R.I., Metal Fatigue in Engineering, Wiley & Sons, 1980.

(4) Jacko, R.J., et. al., "Fatigue Performance of Ni-Cr-Fe Alloy 600 Under Typical PWR Steam Generator Conditions", EPRI Report NP-2957, March 1983.

Table 1

Meetings Attended

09/02/87	Meeting at Westinghouse - Pittsburgh, PA
09/10/87	Meeting at NRC - Bethesda, MD
09/21/87	Meeting at NRC - Bethesda, MD

Table 2

Reports Received

1. "North Anna 1 Steam Generator Tube Rupture," Trip Notes for meeting held 07/20-07/23/87, H. F. Conrad, USNRC staff.

2. "North Anna Unit 1 July 15, 1987 Steam Generator Tube Rupture Event Presentation," Virginia Electric Power Company, July 29, 1987, Revision 0.

3. Westinghouse slide presentation material for 09/02/87 meeting in Pittsburgh, PA.

4. Westinghouse slide presentation material for 09/10/87 meeting in Bethesda, MD.

5. VEPCO slide presentation material for 09/10/87 meeting in Bethesda, MD.

6. STD-7.2.4-7126, "North Anna 1 S/G Tube Rupture and Remedial Actions Technical Evaluation," Westinghouse Electric Corporation, Nuclear Energy Systems, 09/13/87.

7. STD-7.2.4-1226 Addendum, 09/21/87.

8. "North Anna Unit 1 July 15, 1987 Steam Generator Tube Rupture Event Report," Revision 1, September 15, 1987.

Table 3

$\Delta K_{penetration}$ (KsI$\sqrt{in}$)	ΔK_{growth} (KsI$\sqrt{in}$)	$t_{penetration}$ (hrs)	t_{growth} (hrs)
4	4	42	833
7	15	0.2	4.2
7	20	0.2	1.3

$da/dn = 3.17 \times 10^{-11} \Delta K^4$

frequency = 40 Hz

total circumferential growth 0.96" (1/2 80% of circumference)

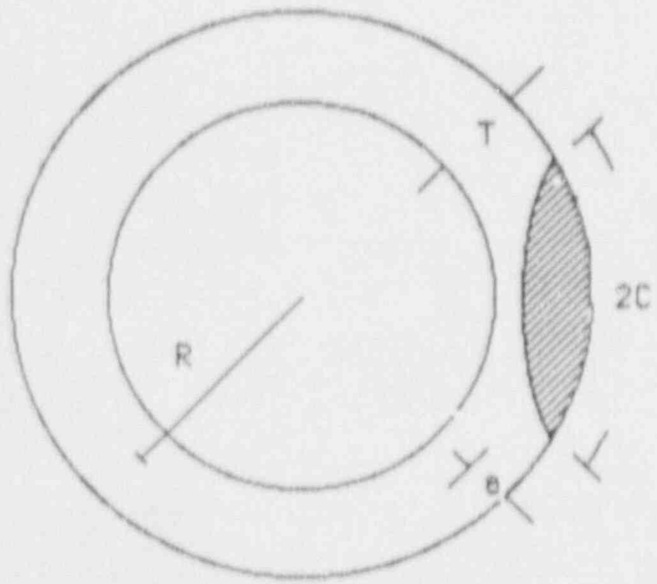

Figure 1

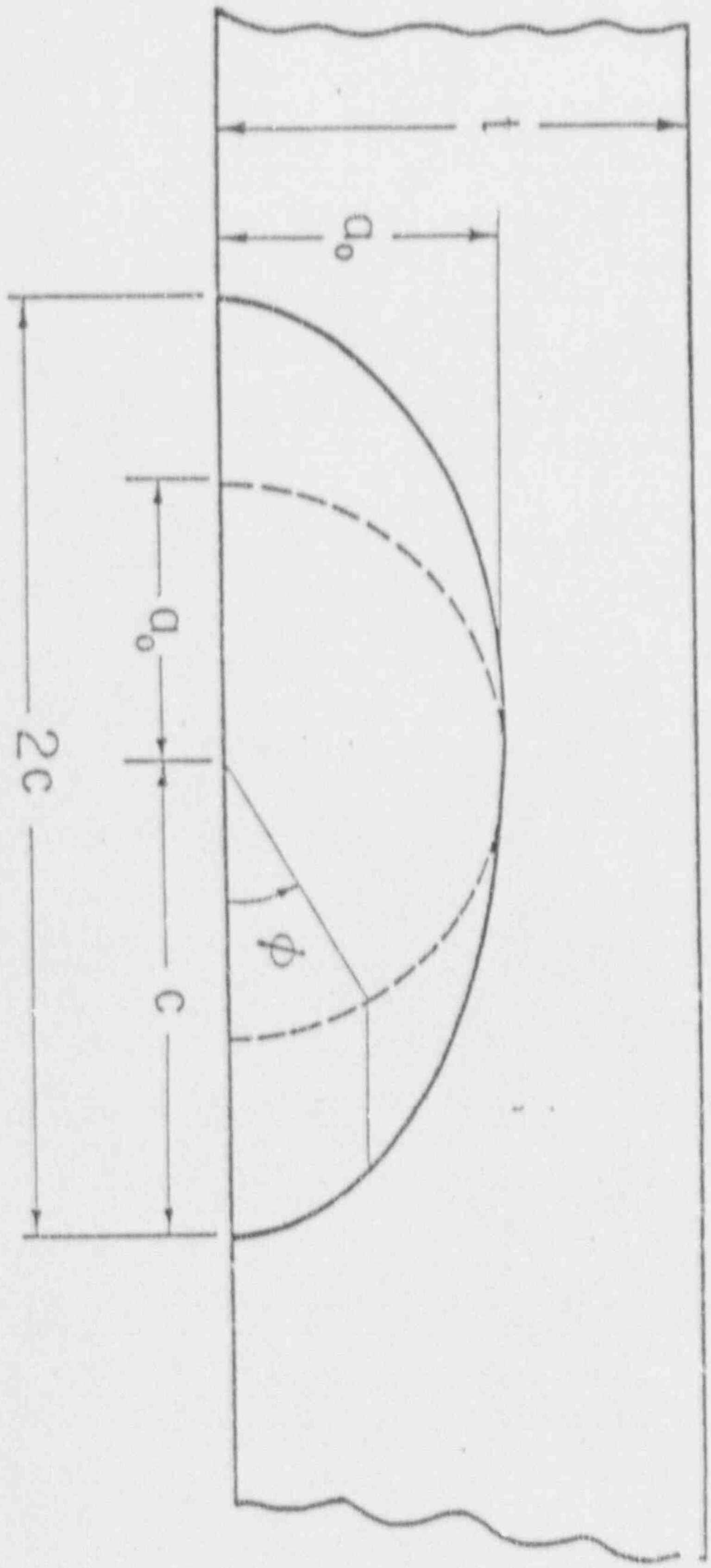

Figure 2.

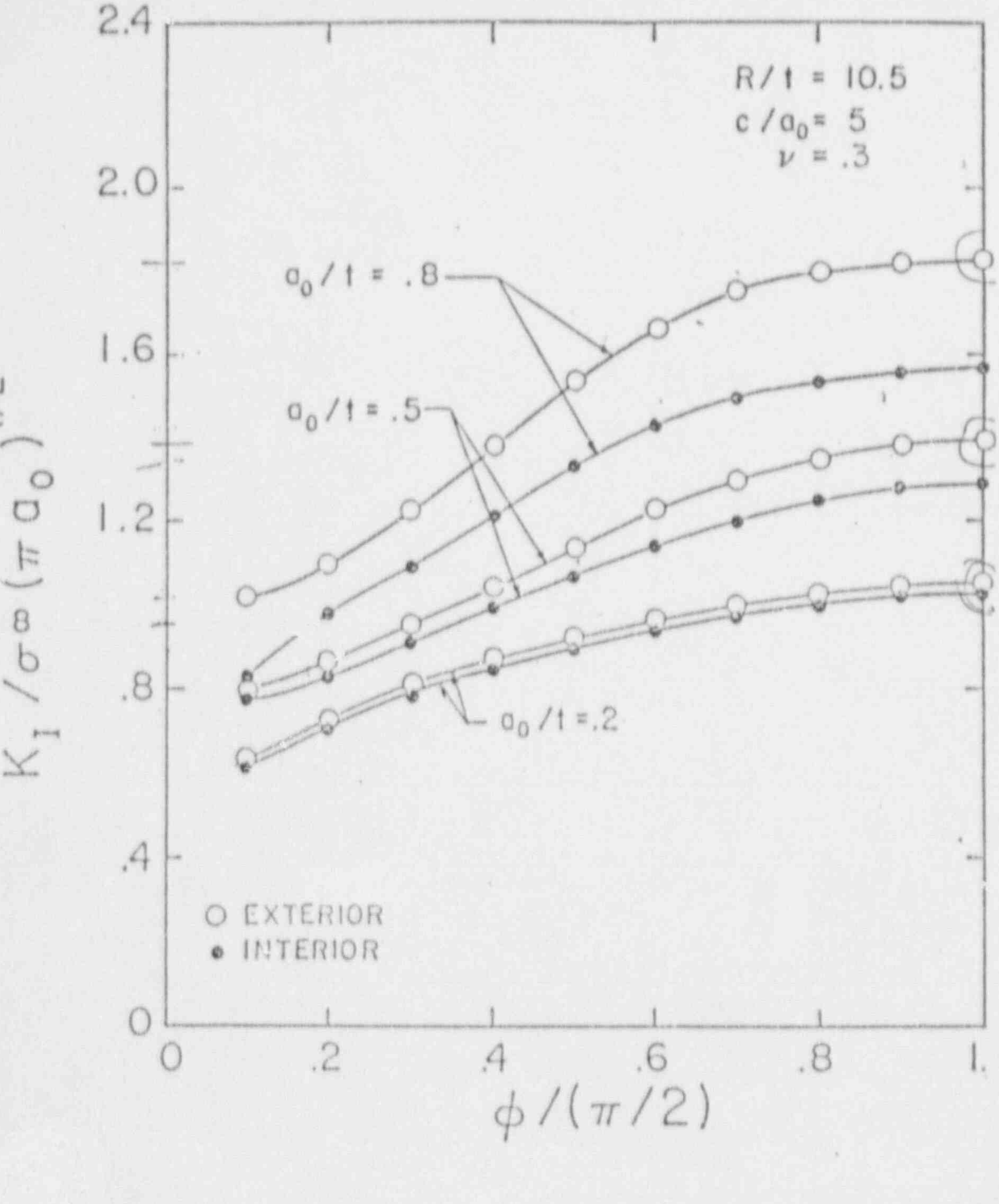
R/t = 10.5
c/a0 = 5
ν = .3
a0/t = .8
a0/t = .5
a0/t = .2
O EXTERIOR
• INTERIOR
K_I / σ^∞ (π a0)^1/2
φ/(π/2)
2.4
2.0
1.6
1.2
.8
.4
0
.2
.4
.6
.8
1.

Figure 3.

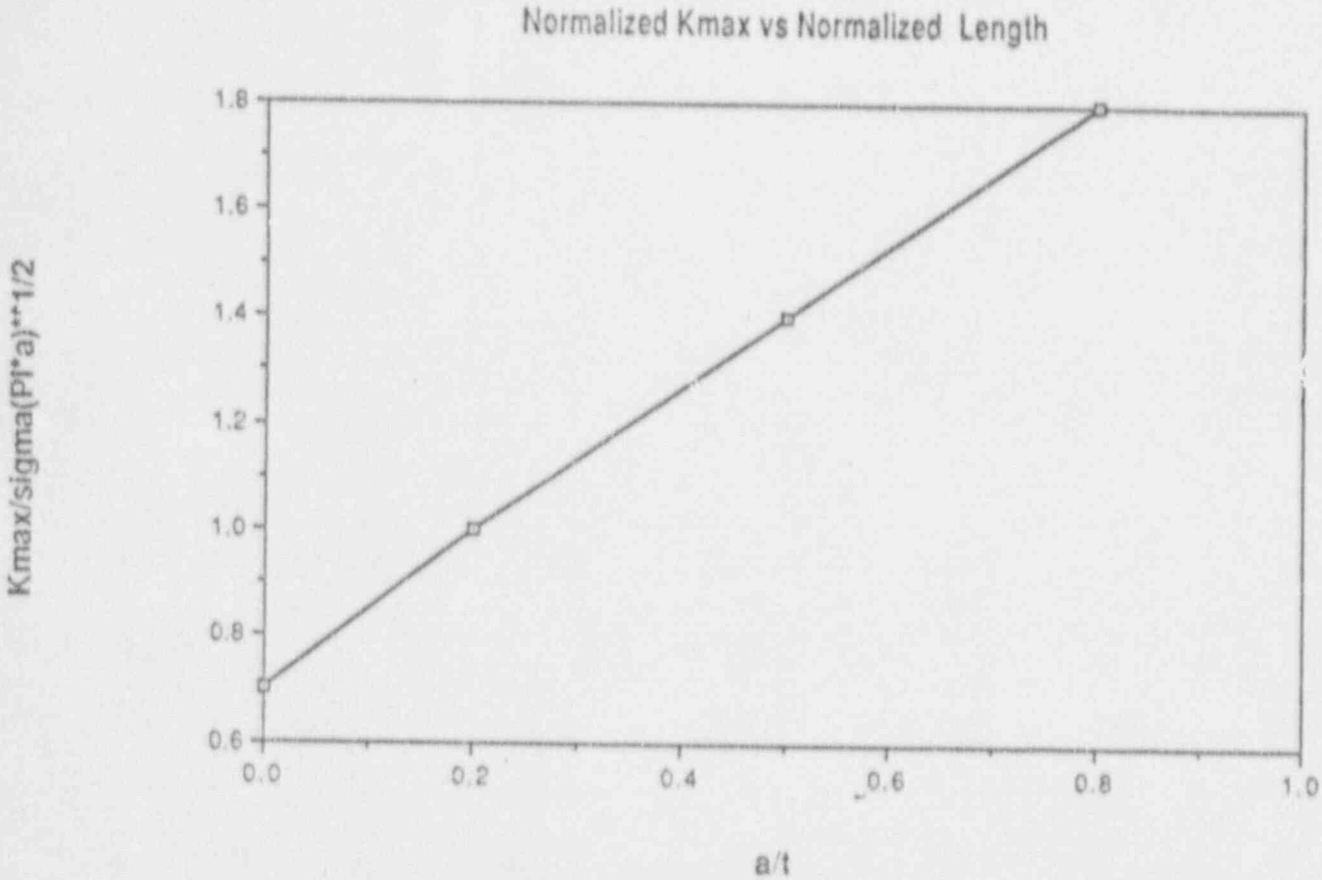
Normalized Kmax vs Normalized Length
Kmax/sigma(PI*a)**1/2
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.0
0.2
0.4
0.6
0.8
1.0
a/t

Figure 4.

APPENDIX 1

October 06, 1987

Professor Ronald George Ballinger

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Title

Associate Professor, Department of Nuclear Engineering and Materials Science and Engineering, Massachusetts Institute of Technology

Education

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Sc.D. degree in Nuclear Materials Engineering titled "Corrosion Fatigue of Nickel Base Alloys for Nuclear Applications," February 1982.

S.M. degree in Materials Science, February, 1978.

S.M. degree in Nuclear Engineering, September 1977. Thesis title: "The Anisotropic Mechanical Behavior of Zircaloy-2 " (Both degrees)

WORCESTER POLYTECHNIC INSTITUTE

S.B. degree in Mechanical Engineering, with high distinction, February, 1975. Emphasis in Materials Science.

Organization and Society Memberships

President, MIT Student Section, American Nuclear Society, 1977-78.

Vice-President, MIT Student Section, American Nuclear society, 1976-77

Member, Tau Beta Pi
Associate Member, Sigma Xi
Member, Pi Tau Sigma
Member, American Nuclear Society
Member, American Society for Metals
Member, National Association of Corrosion Engineers
Member, The Electrochemical Society
Member, American Society for Testing and Materials

Awards and Prizes

Metallurgy and Materials Science Prize, 1973, Sponsored by the Boston Section of the AIME and given in honor of Professor Morris Cohen.

1971-72 CRC Engineering Science Achievement Award, Worcester Polytechnic Institute.

Prof. R.G. Ballinger

Awards and Prizes	1975 George Eastman Award for Outstanding Graduate Class of 1975, Worcester Polytechnic Institute
	1985 MIT ANS Outstanding Professor Award
	1985 MIT Graduate Student Council Teaching Award
Research Interest	Mechanical behavior of structural materials with emphasis on corrosion fatigue and stress corrosion cracking behavior in high temperature aqueous environments. Applications of state-of-the-art experimental and analytical techniques to data acquisition and analysis. High temperature aqueous electrochemical analytical and measurement techniques. Application of advanced statistical techniques for materials optimization.
	Fuel cycle analysis with respect to materials selection and performance. Application of advanced deterministic and statistical techniques to the analysis of nuclear fuel performance.
	Material performance at low temperatures for superconducting and structural applications.
Professional Experience	Associate Professor, Department of Nuclear Engineering and Materials Science and Engineering, MIT. 1987-present.
	Assistant Professor, Department of Nuclear Engineering and Materials Science and Engineering, MIT. 1982-1987.
	Member, International Cyclic Crack Growth Review Group.
	Member, International Cooperative Working Group on Irradiation Assisted Stress Corrosion Cracking.
	Entropy Ltd., South Great Road, Lincoln, MA. Consultant on Nuclear Fuel Performance Modeling. 1978-present.
	Chairman, SPEAR Fuel Rod Reliability Code Workshop, Lincoln, MA, September 25 & 26, 1980.
Military Service	U.S. Naval Nuclear Power Program: Most Advanced rating, E-6. Served as Engineering Watch Supervisor on an operating nuclear submarine. Three years as instructor and Leading Petty Officer, M-Division at the SIC Naval Reactor Prototype.
Background	Born and raised in West Hartford, Connecticut.
References	Furnished upon request.

JOURNAL PUBLICATIONS

R. G. Ballinger, and R. M. N. Pelloux, "The Anisotropic Mechnanical Behavior of Zircaloy-2," Third International Conference on Mechanical Behavior of Materials, Cambridge UK, August 1979, Vol. 2, pp 685-695.

R. G. Ballinger, W. G., Dobson, R. R. Biederman, "Oxidation Reaction Kinetics of Zircaloy-4 in an Unlimited Steam Environment," J. Nuc. Materials, 62, 2, 3, November 1976.

W. G. Dobson, R. R. Biederman, R. R. Biederman, R. G. Ballinger, "Zircaloy-4 Oxidation in Steam under Transient Oxidizing Conditions," ASTM, STP 663, 1977.

G. S. Was, H. H. Tischner, F. L. Hall, R. M. Latanision, R. G. Ballinger and R. M. N. Pelloux, "Effects of Heat Treatment on Segregation and Precipitation of Trace Elements in Inconel 600," presented by Environmental Fracture Session 1, Fall Meeting of TMS-AIME, Milwaukee, September 1979.

R. G. Ballinger and R. M. N. Pelloux, "The Effect of Anisotropy on the Mechanical Behavior of Zircaloy-2," J Nucl. Materials, 97, No. 3, April 1981.

R. G. Ballinger (contributor), R. Christensen (ed.), "SPEAR Fuel Reliability Code General Description," Research Projects 971-1 971-2, 700-3 Interim Report, Electric Power Research Institute, Palo Alto, CA, March 1980.

R. G. Ballinger, R. Christensen, R. Eilbert, S. Oldberg, E. Rumble and G. S. Was, "Clad Failure Modeling Progress," Fifth International Conference on Zirconium in the Nuclear Industry, August 1980.

R. G. Ballinger, R. M. Latanision, W. C. Moshier, and R. M. N. Pelloux, "The Role of Uncertainty in the Measurement of Crack Length by Compliance Techniques," International Conference on Subcritical Crack Growth, Freiberg (W. Ger.), May 13-15, 1981, pp 261-285.

R. G. Ballinger et al., "Fission Gas Release and Fuel Reliability at Extended Burnup", Topical Meeting on LWR Extended Burnup, Fuel Performance and Utilization, Williamsburg, VA, April 4-8, 1982, pp 4-35.

C. K. Sheeks, W. C. Moshier, R. G. Ballinger, R. M. Latanision and R. M. Pelloux, "Fatigue Crack Growth of Alloys X-750 and 600 in Simulated PWR and BWR Environment," International Symposium on Environmental Degradation of Materials in Nuclear Power Systems, Myrtle Beach, S.C., August 22-25, 1983.

R. G. Ballinger, W. C. Moshier, K. N. Siebein, R. M Latanision, "A Study of the Thermal Aging Behavior in Alloy 600 Tubing," 9th International Congress on Metallic Corrosion, Toronto, Canada, June 3-7, 1984, pp 265-273

C. K. Sheeks, R. G. Ballinger, R. M. Latanision, "Fatigue Crack Growth Inconel Alloy x-750 in Simulated PWR and BWR Environments," 9th International Congress on Metallic Corrosion, Toronto, Canada, June 3-7, 1984, pp 310-316.

R. G. Ballinger, G. E. Lucas, R. M. Pelloux, "The Effect of Plastic Strain on the Evolution of Crystallographic Texture in Zircaloy-2, "Journal of Nuclear Materials, 126 (1984), pp 53-69.

R. G. Ballinger, "Corrosion Fatigue Testing in Aqueous Environment at High Temperatures and Pressures," Invited Article for MTS Closed Loop Magazine, MTS Systems Corporation, Minneapolis, NM.

R. G. Ballinger, J. W. Prybylowski, C. K. Elliott, "Effect of Processing History and Chemistry on the Structure of Nickel Base Superalloys," Second International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Monterey, CA, Sept. 9-12, 1985.

J. W. Prybylowski, R. G. Ballinger, "The Influence of Microstructure on Environmentally Assisted Cracking of Alloy 718", Corrosion, 43, No.2 (1987), pp 111-117.

C. K. Elliott, R. G. Ballinger, J. W. Prybylowski, "Corrosion Fatigue Behavior of Alloy X-785 in High Temperature Aqueous Systems", in press.

K. Hosoya, R. Ballinger, J. Prybylowski, I.S. Hwang, "The Role of Microstructure in Enviromentally Assisted Cracking of Nickel-Base Alloys," Corrosion, in press.

R. G. Ballinger, W. M. Morra, J. L. Martin, M. O. Hoenig, "Low Coefficient of Expansion Structural Materials Development for Conductor Applications," Ninth Annual Cryogenic Structural Materials Workshop, Reno, NV, October 6-8, 1986.

J. W. Prybylowski, R. G. Ballinger, "An Overview of Advanced High Strength Nickel Base Alloys for LWR Applications," EPRI Workshop on Advanced High Strength Materials for LWR Internal Applications, Clearwater Beach FL, March 12-13, 1986.

Books

R. G. Ballinger, The Anisotropic Mechanical Behavior of Zircaloy-2, Garland Publishing Co., Inc., New York, 1979.

LECTURES/SEMINARS GIVEN

Environmentally Assisted Fatigue Cracking of Nickel-Base Alloys for Nuclear Applications, MIT Industrial Laision Program Symposium on Corrosion, December 2, 1982.

Fatigue in Nickel Base Alloys - Seminar given at Framatome, Paris, France, March 28, 1983.

Corrosion Fatigue in Alloy X-750, Seminar given at Cruesot Loire Laboratories, Firminy france, 3/29/83.

Thermal Behavior of Nuclear Fuel Rods, Thermal-Hydraulic Design and Safety for Light Water Reactors, Center for Advanced Engineering Study, MIT, May 16-21, 1983.

Advanced Fuel Design and Performance, Short Course given at Westinghouse Electric Corporation, Water Reactor Divisions, July 11, 1983.

Pattern Recognition Techniques for Alloy Development, Seminar given at TRW Inc., Caldwell Laboratories, Uclid, Ohio, July 12, 1983.

"Fracture in Nickel-Base Alloys in Nuclear Power System Environments", Seminar given at Worcester Polytechnic Institute, March 29, 1985.

Professor Ronald George Ballinger

Professor Ballinger is an Associate Professor at the Massachusetts Institute of Technology with a joint appointment in the Departments of Nuclear Engineering and Materials Science and Engineering. Professor Ballinger's areas of specialization are as follows: (1) Environmental Effects on Material Behavior; (2) Nuclear Fuel (including cladding) Performance and Analysis; (3) Advanced Statistical Techniques for Experimental Design and Analysis, and (4) the Development of Advanced Materials for Cryogenic Structural Applications. Professor Ballinger is the author of several papers in the above areas and is a member of the International Cyclic Crack Growth Review Group which is charged with the development of an understanding of the behavior of reactor pressure vessel steels with regard to fatigue, stress corrosion cracking and corrosion fatigue. Professor Ballinger is also a member of the International Cooperative Working Group on Irradiation Assisted Stress Corrosion Cracking which is charged with the development of an understanding of this phenomena.

Professor Ballinger is active in nuclear fuel cycle analysis and is co-author of sophisticated fuel performance analysis codes. Professor Ballinger teaches several courses dealing with materials selection and performance in the nuclear fuel cycle. Professor Ballinger is a member of several professional societies and has consulted extensively in the above areas and is an expert in failure analysis related to these areas.