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JANUARY 1994

THE B&W OWNERS GROUP

MATERIALS COMMITTEE

External Circumferential Crack Growth Analysis For B&W Design Reactor Vessel Head Control Rod Drive Mechanism Nozzles

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External Circumferential Crack Growth Analysis For B&W-Design Reactor Vessel Head Control Rod Drive Mechanism Nozzles

43-10190-01

by

K. K. Yoon

(See Section 7 for Document Signatures)

Prepared for

Duke Power Company
Entergy Operations, Inc.
Florida Power Corporation
GPU Nuclear Corporation
Tennessee Valley Authority
Toledo Edison Company

Prepared by

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EXTERNAL CIRCUMFERENTIAL CRACK GROWTH ANALYSIS
FOR B&W-DESIGN REACTOR VESSEL HEAD
CONTROL ROD DRIVE MECHANISM NOZZLES

1. Introduction

Only one out of approximately 2600 CRDM nozzles inspected to date revealed a leaking through-wall crack. This same nozzle also exhibited an indication of circumferential cracking on its outside surface. It is noted that development of circumferential cracking on the outside surface is only possible after establishment of a leak path for the primary water environment. Primary water can only reach the outside nozzle surface (during operation) when a through-wall crack is present. The predicted time, therefore, for external crack initiation and growth is in addition to the time for the internal surface crack growth to become a leaking through-wall crack.

Unmitigated circumferential crack growth from the outside surface of the nozzle potentially implies a completely detached upper portion of the nozzle thereby leading to the scenario of nozzle ejection. This addendum to the Safety Evaluation of B&W Design Reactor Vessel CRDM Nozzles provides an evaluation of this concern specifically for the stresses presented in reference 1.

2. External Circumferential Crack Growth

Upon examination of all axial stresses of the hillside CRDM nozzles in the B&W Owners Group plants, the maximum tensile outside stress was found at the top of the weld zone on the downhill side of the nozzle as shown in Figure 1 (Figure 2-8 in reference 1). This is also the location of the maximum stress gradient across the nozzle wall which ranges from a high tensile stress on the outside of the wall to a compressive stress on the inside. On the uphill side of the nozzle, there is a reduced tensile axial stress on the outside surface. The stress gradient at this location is significantly less as can be seen in Figure 2 (Figure 2-9 of reference 1). The average stress around the nozzle is relatively constant at approximately 20 ksi (Figure 3). The axial stresses are primarily comprised of secondary stresses resulting from the welding operation and thermal loading. The remaining portion of the total axial stress is comprised of pressure induced primary stresses. For an internal pressure of 2200 psi, the pressure induced stress in the axial direction is approximately 2 ksi and is insignificant compared to the residual welding stresses and thermal stresses. A rigorous three-dimensional finite element analysis, including crack growth with time, would demonstrate the effect of stress relief as a circumferential crack propagates through the nozzle wall. However, this would require an inordinate amount of computational effort. Instead, a simple but conservative crack growth analysis is presented here that treats the residual and thermal stresses as primary stresses and uses the crack growth rate equation presented in reference 1.

The worst-case stress profile is located on the downhill side and is shown in Figure 4. A cubic polynomial fit of the stress data resulted in a set of coefficients to be used for a stress intensity factor calculation using the Raju-Newman(2) solution for circumferential surface cracks (Figure 5). The outside surface of the nozzle was machined and most likely contains a small cold-worked layer. The welding operation recrystallizes this cold-worked layer in the heat affected zone and no additional machining is performed after welding. With this information, it can be argued that the crack initiation for the outer surface would take a longer time than the inside surface where the machining process, which was performed prior to welding and in some cases after welding, introduced a layer of cold-worked material. Therefore, a very small initial crack size was assumed (i.e., 1.0 mil) on the external surface of the nozzle. The resulting crack growth is given in Figure 6. This shows that a minimum of 6 years is required for a 1.0 mil crack to become a through-wall crack if all the applied stresses are primary stresses. In reality, considering the self-relieving nature of the residual stress, the crack would have arrested, probably ~50-60% through the thickness. As stated previously, the pressure stress is only 2 ksi. This translates into a stress intensity factor much lower than the threshold value for crack growth ($9 \mathrm{MPa}\sqrt{\mathrm{m}}$). This pressure stress is very low compared to the 90 ksi starting axial total stress at the outside of the nozzle.

Even if a through-wall circumferential flaw growth is possible, it would take more than 40 years for this flaw to grow circumferentially along the elliptical weld zone toward the uphill elevation. Here again, relief of the residual stress will prevent complete growth of the circumferential flaw. Therefore, it is concluded that there is no possibility for an external circumferential flaw indication to grow circumferentially to the point of becoming a safety concern.

3. Gross Leak-Before-Break: The Ultimate Safety Feature

If it is postulated that a circumferential crack propagates through-wall and grows circumferentially along the weld-nozzle interface region, the potential safety concern is detachment of the upper nozzle from the lower nozzle section and its ejection from the closure head. This event is not likely to happen due to the following reasons.

The first reason is as described above: more than 90% of the crack driving force is self-relieving residual stress. Upon opening of a crack, a significant part of the crack driving stress will be relieved so that either the crack growth rate is drastically reduced or the crack growth is terminated.

The second reason is due to a gross leak-before-break mechanism. The net section limit ligament is less than 10%. Postulating that a large portion of the nozzle cross-section contains a through-wall crack, there is ample room for leakage to occur before approaching the net section limit ligament as depicted in Figure 7. This will allow a detectable leakage of steam through this large crack, thereby providing ample warning to prevent the failure of the nozzle. Furthermore, when the limit load causes the remaining ligament to start to stretch, it would do so gradually and not be an instantaneous catastrophic failure since Alloy 600 is a very ductile material. In addition, evidence indicates that the nozzles are in an oval shape due to interaction with the closure head deformation. Therefore, there are gaps between the nozzle and the head that will provide sufficient leak paths for steam to escape with fairly large volume thereby providing leak detection. Sufficient contact area would also remain to resist any slippage due to the ovalized nozzle. The finite element analysis results indicate that the maximum gap is ~3.0 mils with an average of ~1.0 mil during a normal operation. This is an inherent safety feature that keeps the outside surface cracking from becoming a safety issue.

4. CRDM Nozzle Straightening

CRDM nozzle straightening was performed by B&W during the manufacturing process for various nozzles to fulfill a straightness tolerance of 0.0055 inch/foot. Manufacturing records only indicate the total number of CRDM nozzles that required straightening. There is no information available that indicates how far out of tolerance the nozzles were nor what means were used to straighten them. The straightening process typically involves permanent bending. It is believed that in the case of a CRDM nozzle, straightening was performed after welding to the closure head by pulling the top end of the nozzle to one side. This process would impart a very small permanent deformation to the CRDM nozzle, on the order of a mil, near the OD of the closure head. The shrink-fit portion of the CRDM nozzle at the top of the closure head serves as the fixed end of a cantilever beam. Therefore, it is concluded that the straightening procedures utilized during manufacturing would not affect the stress nor the deformation near the high stress weld zone.

5. Conclusions

Based on the above evaluation, it is concluded that the occurrence of nozzle detachment is physically impossible during the design life of the B&W-plants considered in this study.

6. References

1). BAW-10190P, Safety Evaluation For B&W Design Reactor Vessel Head Control Rod Drive Mechanism Nozzle Cracking, May 1993.

2). Raju, I. S. and Newman, J. C., "Stress Intensity Factor for Circumferential Surface Cracks in Pipes and Rods under Tension and Bending Loads," ASTM STP 905, 1986, pp.789-805.

7. Certification

This report is an accurate evaluation of the safety and consequences associated with the possibility of external circumferential primary water stress corrosion crack growth analysis for B&W-design CRDM nozzles.

KK Yoon 12/14/93

K.K. Yoon Date
Fracture Mechanics

This report was reviewed and was found to be an accurate description of the work reported.

AD Nana 12/14/93

A.D. Nana Date
Fracture Mechanics

Verification of independent review.

12/14/93

K.E. Moore Date
Materials and Structural Analysis

The document has been approved for release.

12/14/93

A.W. Robinson Date
Program Manager

Figure 1.

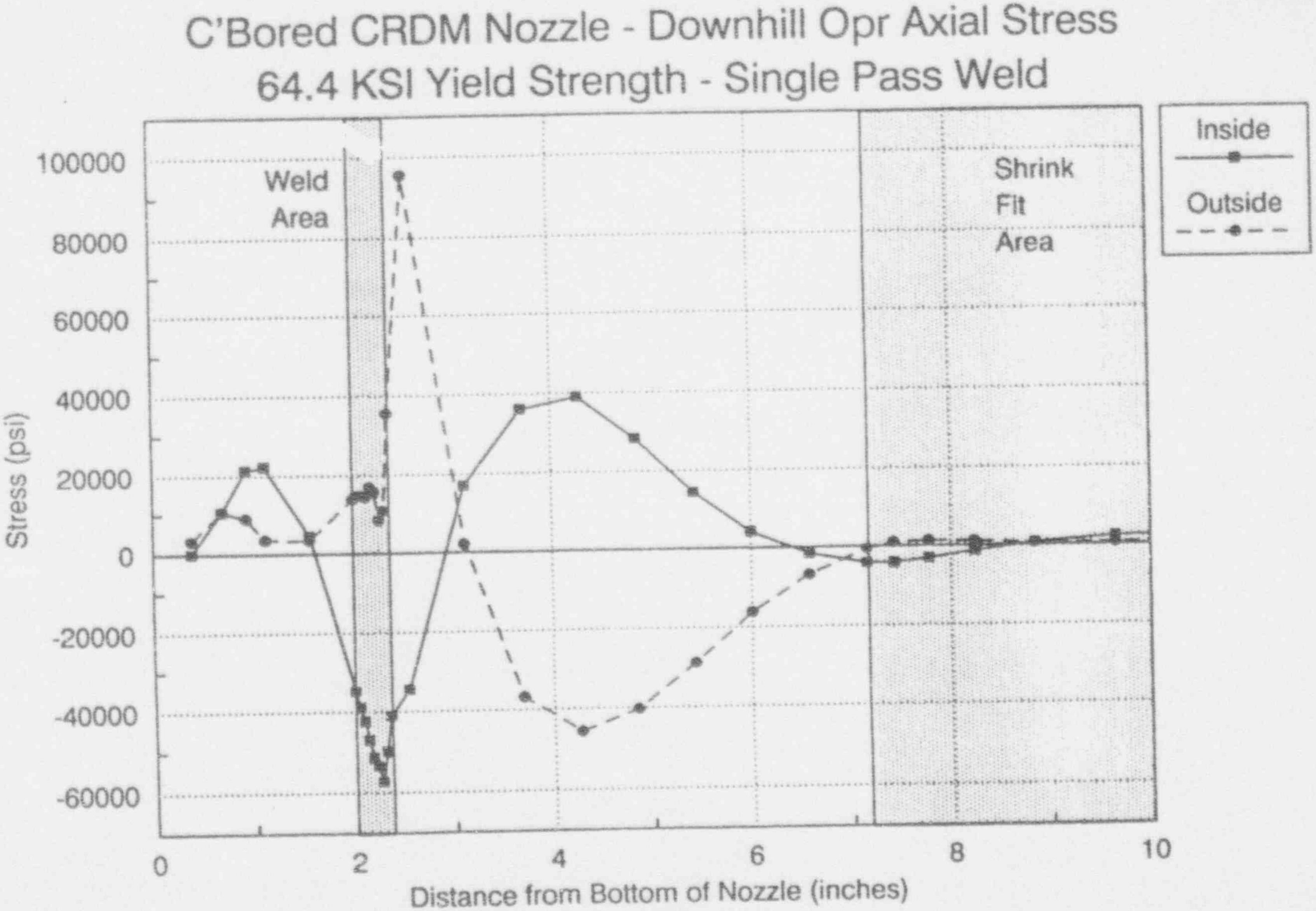

C'Bored CRDM Nozzle - Downhill Opr Axial Stress
64.4 KSI Yield Strength - Single Pass Weld
Weld
Area
Shrink
Fit
Area
Inside
Outside
100000
80000
60000
40000
20000
0
-20000
-40000
-60000
Stress (psi)
0
2
4
6
8
10
Distance from Bottom of Nozzle (inches)

Figure 2.

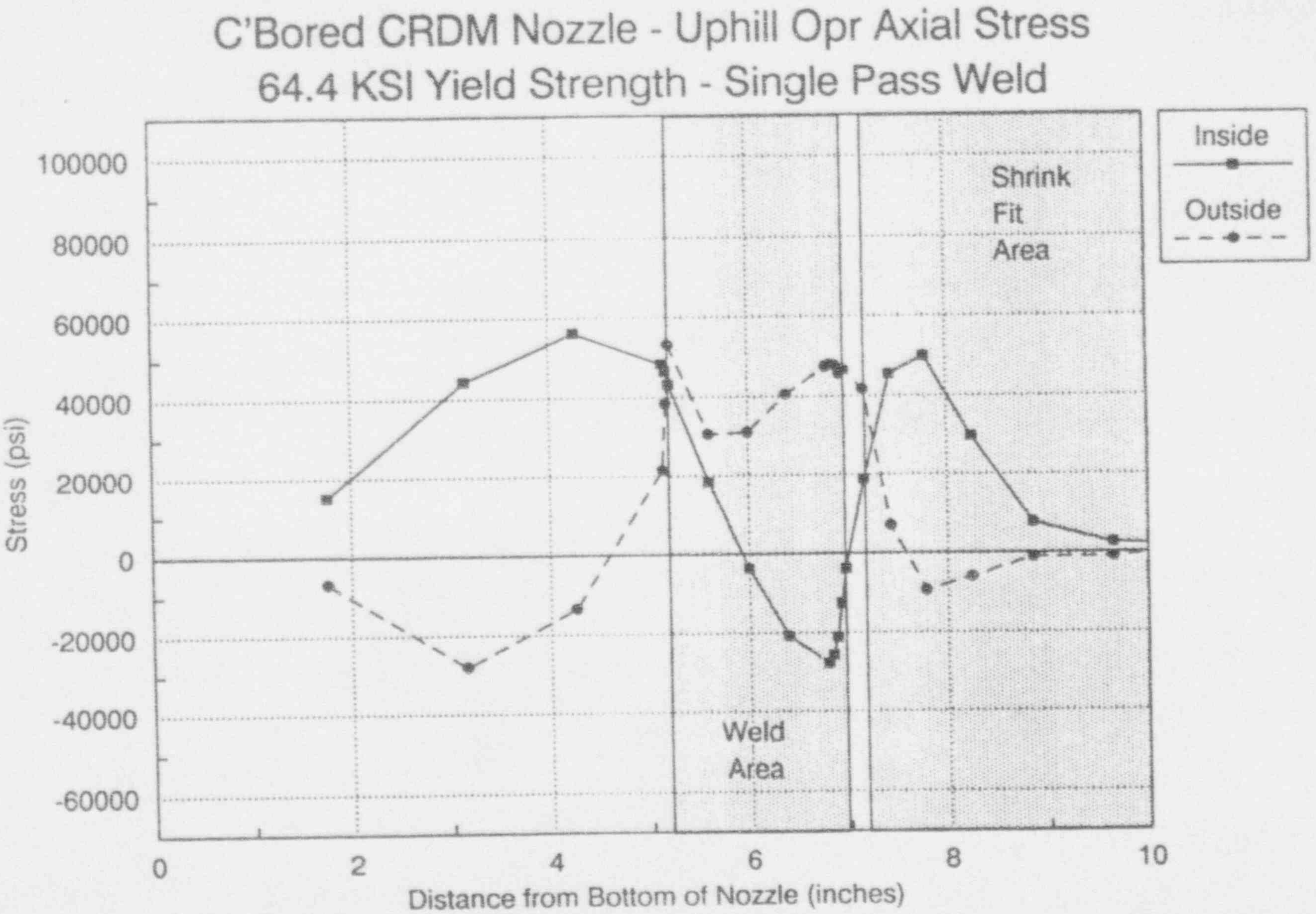
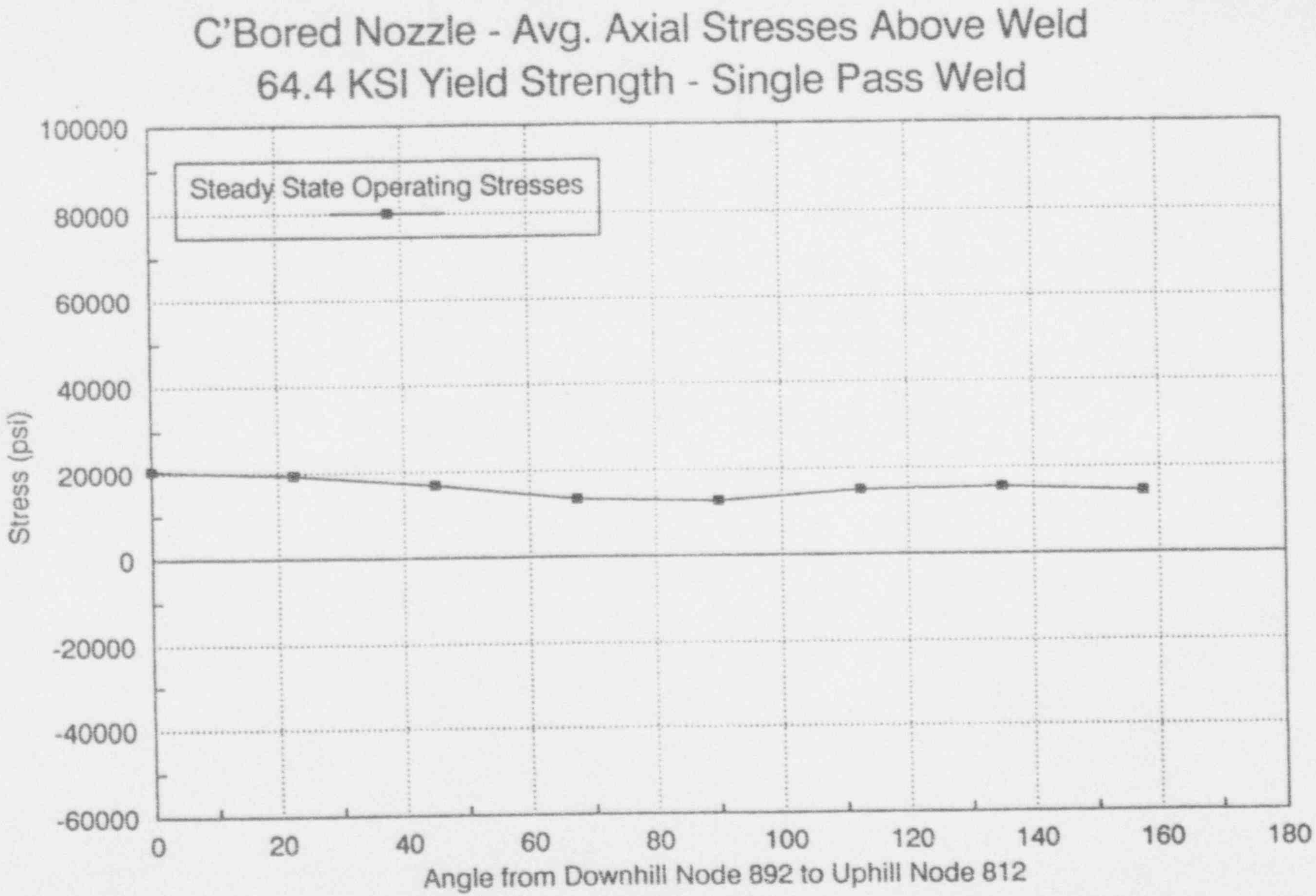

C'Bored CRDM Nozzle - Uphill Opr Axial Stress
64.4 KSI Yield Strength - Single Pass Weld
Stress (psi)
100000
80000
60000
40000
20000
0
-20000
-40000
-60000
0
2
4
6
8
10
Distance from Bottom of Nozzle (inches)
Shrink
Fit
Area
Weld
Area
Inside
Outside

Figure 3.



C'Bored Nozzle - Avg. Axial Stresses Above Weld
64.4 KSI Yield Strength - Single Pass Weld

Figure 4.

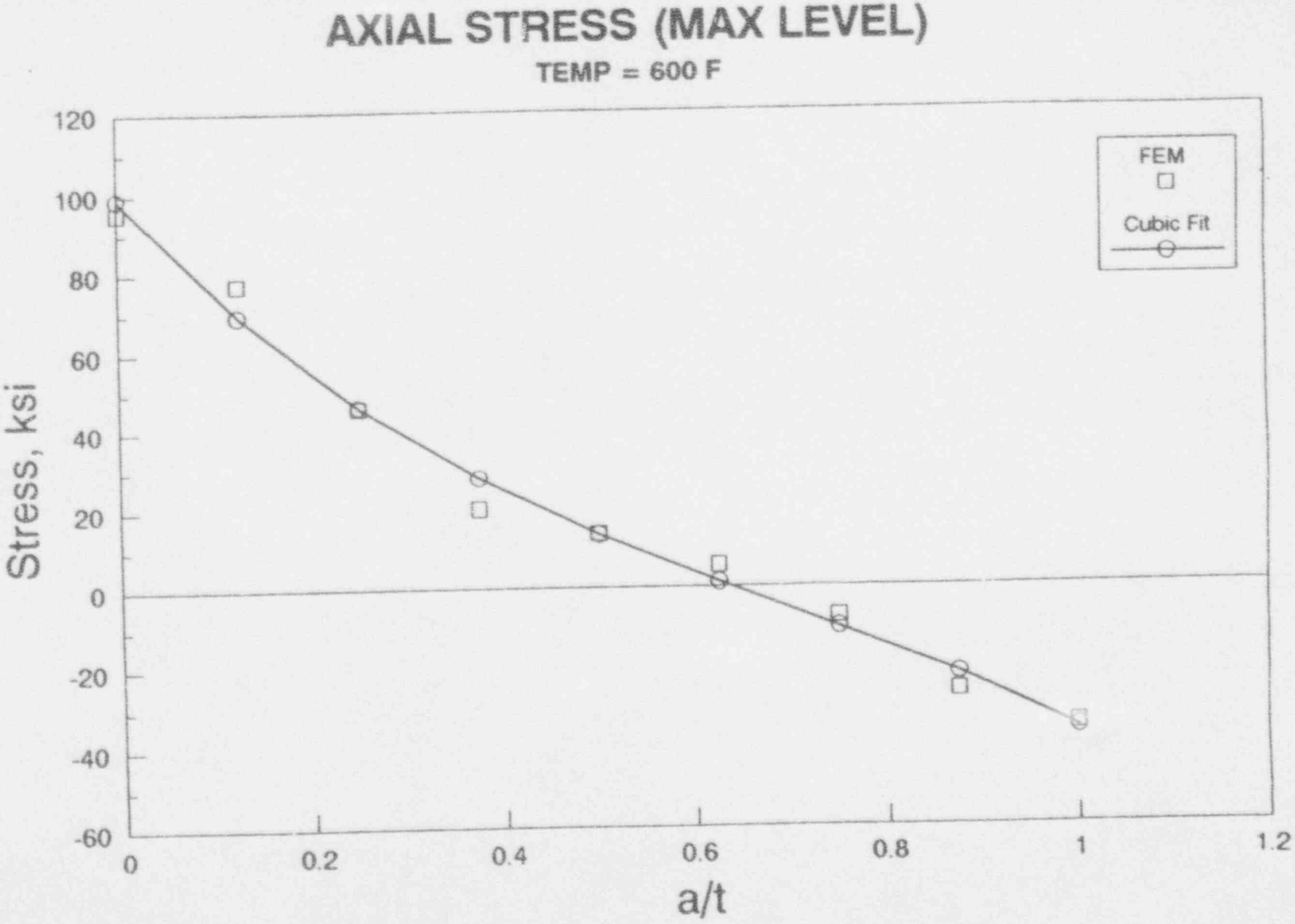

AXIAL STRESS (MAX LEVEL)
TEMP = 600 F
FEM
□
Cubic Fit
Stress, ksi
120
100
80
60
40
20
0
-20
-40
-60
0
0.2
0.4
0.6
0.8
1
1.2
a/t

Figure 5. External Circumferential Crack on a Cylinder (Ref. 2)

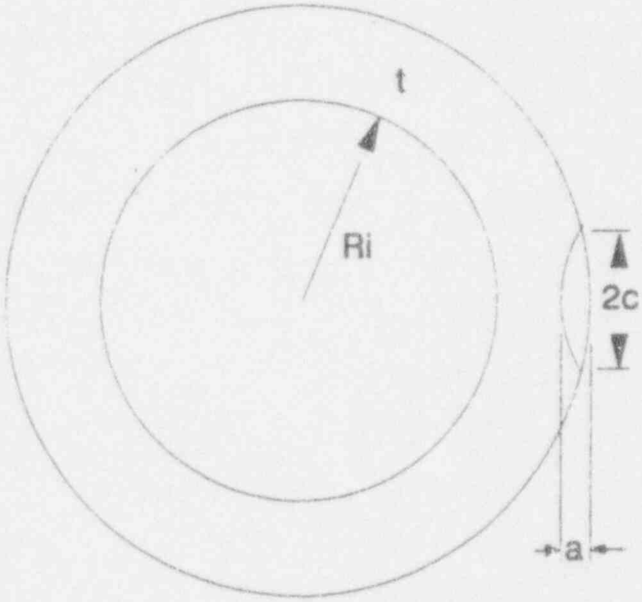
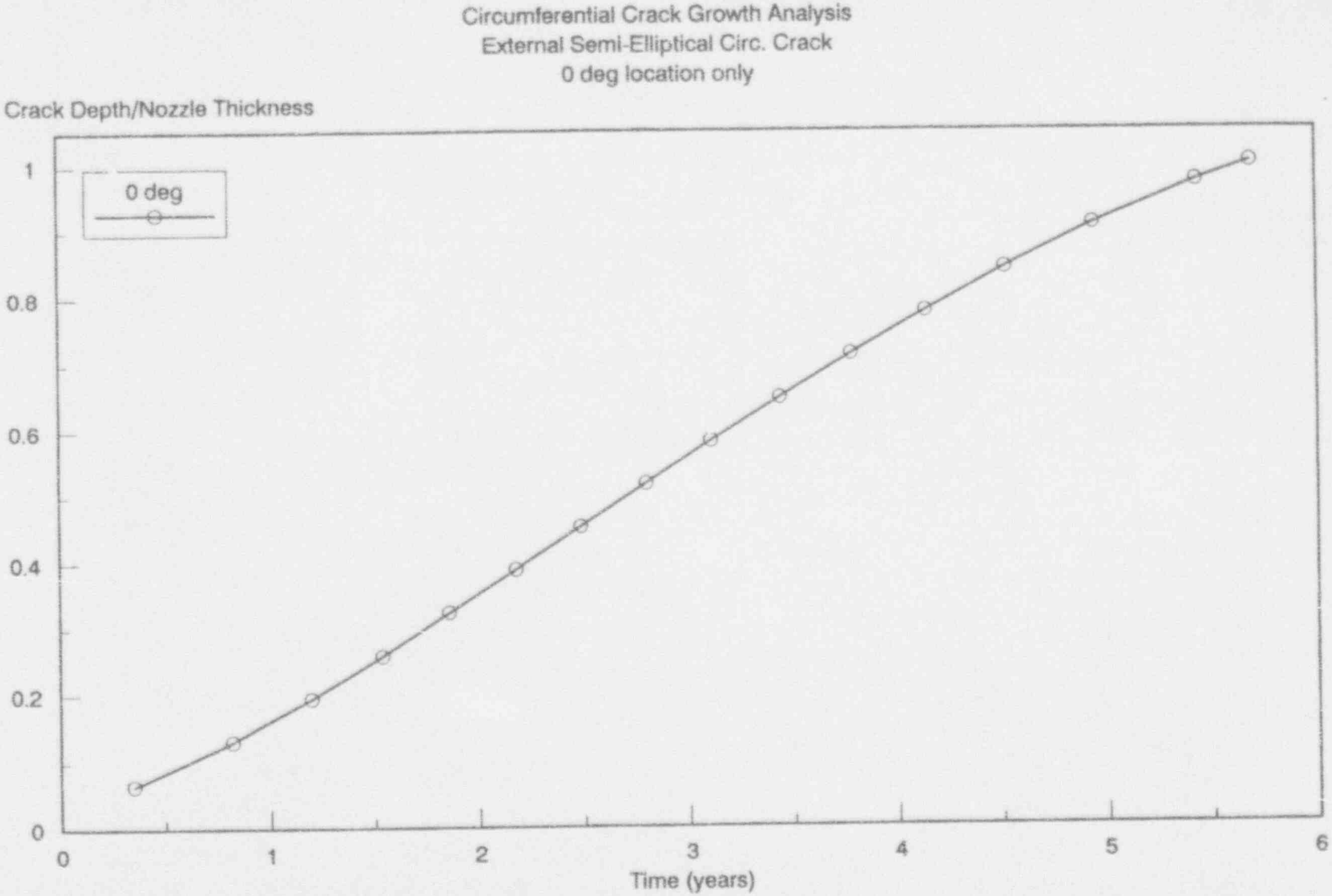
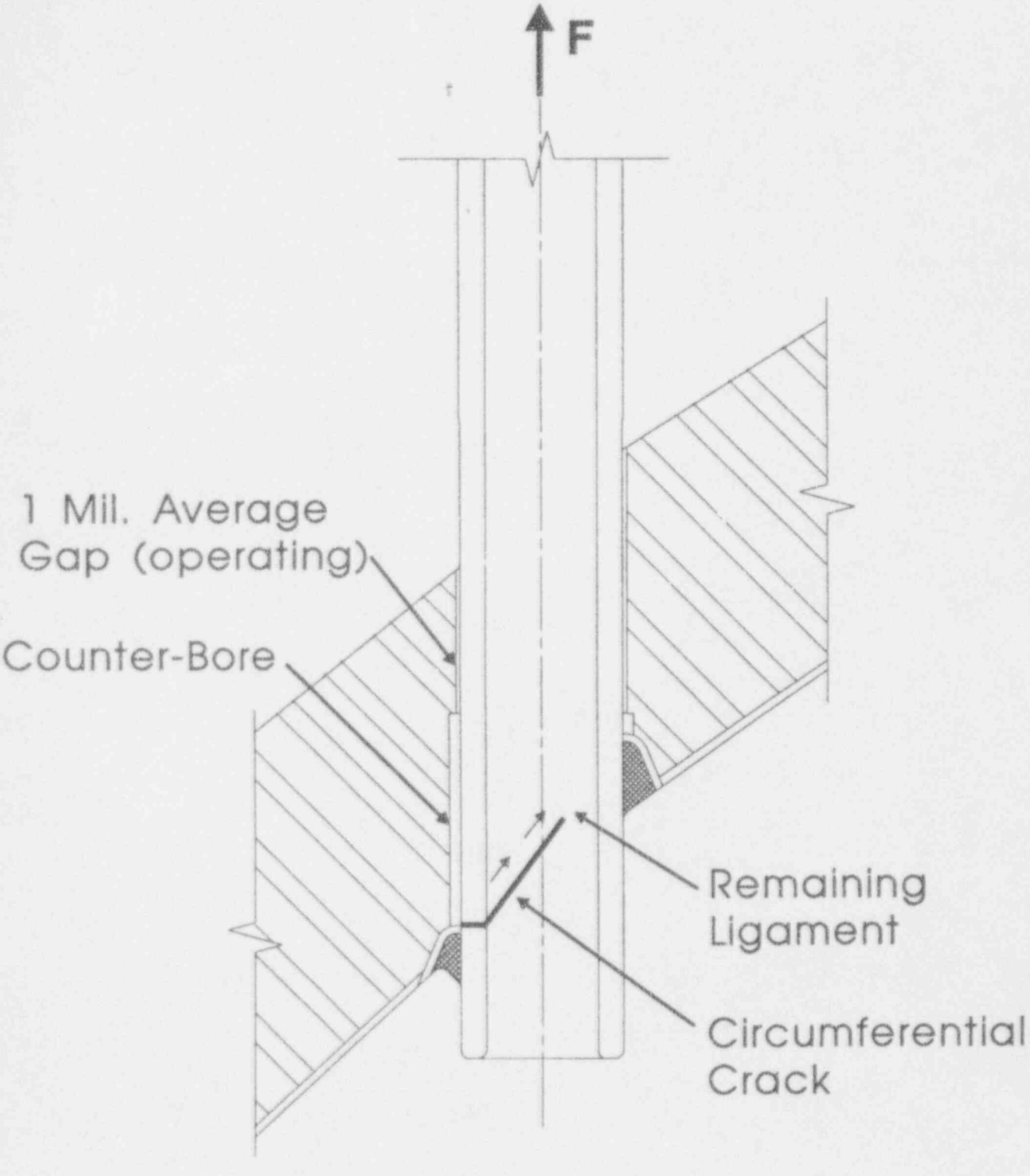


Figure 6.



Circumferential Crack Growth Analysis
External Semi-Elliptical Circ. Crack
0 deg location only
Crack Depth/Nozzle Thickness
0 deg
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
Time (years)

Figure 7. CRDM Gross Leak-Before-Break Geometry



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December 14, 1993
OG-1322

Mr. Morris Schreim
NUMARC
1776 Eye Street
Suite 300
Washington, DC 20006

Subject: B&WOG Safety Evaluation for CRDM Nozzle PWSCC

Reference: Addendum to B&WOG Report BAW-10190P Entitled, "External Circumferential Crack Growth Analysis for B&W Design Reactor Vessel Head CRDM Nozzles," dated December 1993

Dear Mr. Schreim:

Enclosed please find five (5) copies of the referenced report. Please submit this report addendum to the NRC on behalf of the B&W Owners Group (B&WOG). Note that this addendum applies to both the proprietary and non-proprietary versions of the B&WOG Safety Evaluation Report (BAW-10190P).

This addendum provides an evaluation of the following items:

- External Circumferential Crack Growth
- Gross Leak-Before-Break
- CRDM Nozzle Straightening

The following conclusions were reached from the evaluation of these items coupled with the evaluation provided in BAW-10190P:

- External Primary Water Stress Corrosion (PWSCC) is possible only after an ID-initiated axial crack propagates through-wall. The through-wall crack growth time for the axial cracking, presented in BAW-10190P is a minimum six years.

- An external circumferential crack would take a minimum of six years to propagate through-wall if the primary driving stresses were applied continuously. Since the crack driving stresses are primarily self-relieving residual stresses, the crack is predicted to arrest near the nozzle mid-thickness.

- Circumferential crack growth around the nozzle would take longer than the forty year design life. The growth is dependent upon continual application of the crack driving stresses. Here again, the driving stresses are self-relieving residual stresses that will allow crack arrest.
- Finite element results indicate the existence of a ≈1mil (average) gap between the nozzles and head. This gap will provide an ample leak path for detectable primary fluid leakage.
- Manufacturing deviations such as straightening do not significantly affect the stress distribution of the nozzle near the high stress weld zone.

Based on these conclusions, the B&WOG contends that the potential for circumferential cracking presents no immediate safety concern to the operation of B&W designed vessels. The overall conclusions presented in BAW-10190P remain unchanged with this addendum.

In the NRC's recent Safety Evaluation Report (SER), they also requested evaluation of two additional items. The items include:

- Ringhals weld cracking
- Enhanced leak detection systems

The B&WOG has not performed a comparison of the Ringhals weld cracking issue relative to the B&W designed vessels. Based on the data received to date, it is our understanding that this issue is fabrication-related and is not associated with PWSCC. Therefore, any discussion of evaluation of this issue should be handled separately.

The B&WOG has performed an evaluation of both on-line and off-line enhanced leak detection systems. The conclusions reached from this evaluation are that the current GL88-05 walkdown visual inspections of the reactor vessel head areas provide adequate leak detection capability. Copies of this evaluation will be made available to the NUMARC AHAC members for their use.

If you have any questions concerning the attachments please contact me at (510)964-8937, Dave Whitaker (DPCo) at (703)382-7246, or A. W. Robinson (BWNT)at (804)385-3290.

Sincerely,

AW Robinson for
D. F. Spond
Chairman
B&WOG Materials Committee

DFS/AWR/mcl

Attachment

cc: Steering Committee

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