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Revision 0

EVALUATION OF QUAD CITIES PENETRATION BELLOWS ASSEMBLIES LEAKAGE RATES

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EXECUTIVE SUMMARY

Flexible metallic bellows in Pressure Suppression System line 1-1605-18"-LX at Unit 1 penetration X-25 were found to have flaws during the Q1R11 outage Integrated Primary Containment Leak Rate Test (IPCLRT). Although the X-25 flaws resulted in higher than historical IPCLRT leakage, the "as-left" IPCLRT leakage was within permissible limits. The X-25 bellows were replaced during the Q1R11 outage significantly increasing the IPCLRT margin.

CECo requested NUTECH prepare calculations to assess the impact of potential flaw growth during the next eighteen month fuel cycle following Q1R11, and the resulting leakage.

This report discusses the following subjects:

- History of bellows at Quad Cities
- Background information relative to Penetration X-25
- Method of analysis
- Major assumptions
- Results
- Conclusions

NUTECH's assessment has resulted in the following conclusions:

- If the flawed bellows at penetration X-25 had been left in place and all identified flaws grew by 3/16", the predicted leakage rate contributed by X-25 during the next "as-found" IPCLRT would be within IPCLRT allowables.
- If there is a bellows which currently is not leaking through its outer surface, but is postulated to have 200 flaws emerge at the start of the cycle and grow to 3/16" at the end of the cycle, the predicted leakage rate during the next "as-found" IPCLRT would be within IPCLRT allowables.

PURPOSE

This report documents the results of NUTECH's evaluation of Quad Cities flexible metallic bellows leakage and its affect on primary containment leakage rate (see Attachment 1 for bellows sketch). NUTECH has evaluated the leakage characteristics of bellows with transgranular stress corrosion cracking (TGSCC) flaws that could have grown during one fuel cycle. The evaluation consists of a finite element model of the bellows assembly (Attachment 2) and a leakage flow calculation (Attachment 3). The evaluation addresses the following questions:

1. Will the leakage from a "worst-case" bellows assembly, modeled after the removed X-25 penetration bellows, also be within limits, allowing for crack growth due to TGSCC, and calculating leak rates for the IPCLRT at the end of the next fuel cycle?

2. Will the potential leakage from remaining bellows assemblies due to TGSCC be within 10CFR50 Appendix J limits until the next Integrated Primary Containment Leak Rate Test (IPCLRT)?

HISTORY OF BELLOWS AT QUAD CITIES

Since 1984, CECo has been implementing an aggressive program of inspection and replacement (when required) for Primary Containment flexible metallic bellows elements. Four bellows assemblies have been replaced at Quad Cities Station and one has been permanently removed at Dresden Station due to indications of increasing leakage rates. In addition, several other bellows assemblies were replaced as part of the Dresden Unit 3 reactor recirculation system piping replacement effort in 1987. In 1990, CECo developed a comprehensive plan to improve bellows performance and life expectancy by identifying failure mechanisms and implementing inspection programs to identify if, and when future failures might occur.

There are two basic replacement methods that have been utilized: a) a like-for-like approach in which the existing bellows elements are removed and replaced with components which are essentially identical to the originals, and b) a "clam shell" replacement in which the original bellows elements are removed and replaced with new elements which are assembled in-situ, thus avoiding the need to remove the process pipe. CECo has qualified the latter replacement method by prototype test, as required by ASME Code Case N-315.

Over the years, CECo has performed several (1984, 1990 & 1991) metallurgical examinations to evaluate bellows failures at both Quad Cities and Dresden Stations. In each of these investigations, failure of the bellows elements was attributed to TGSCC. No evidence of fatigue crack growth however been observed. The corrosive species responsible for crack initiation

has recently been identified as chlorides, fluorides and sulfides. The source of this material has been variously attributed to initial fabrication, original construction, or to other mechanisms that could be occurring during plant life which would result in the transport and concentration of these materials on the bellows surfaces. It has been consistently observed that TGSCC initiates on the bellows inner surface.

BACKGROUND OF X-25 PENETRATION

During the Q1R11 IPCLRT, the flexible metallic bellows at penetration X-25 exhibited significant leakage. Upon further inspection, it was determined that there were flaws (crack-like indications and pinholes) in the bellows. A special test, performed to determine the amount of leakage from the X-25 bellows assembly, revealed that the leakage rate was 137.4 scfh. The bellows was determined to be unrepairable and a replacement bellows was installed. Metallurgical examination of the removed bellows determined that the cause of the flaws is TGSCC. The removed bellows was inspected for flaw length, width, orientation, and quantity.

CECo personnel performed PT inspections of six other bellows assemblies and found two minor surface indications in one of the bellows. Although the X-25 bellows was leaking during the IPCLRT, the IPCLRT was successfully completed with adequate "as-left" leakage margin.

METHOD OF ANALYSIS

NUTECH constructed a finite element model to evaluate the response of bellows elements with varying size flaws to applied loads. The model reflects the latest data assembled by field personnel and at Argonne National Lab for the X-25 bellows. (See Table 1 for bellows flaw data.) The model was subjected to loads experienced during the IPCLRT (pressure). Crack propagation due to TGSCC attack over the course of one fuel cycle was also included.

The model was used to calculate the extent of flaw opening (i.e., fish-mouthing) under pressure. The geometry of the resulting flaw opening was used to perform a separate leakage flow calculation.

The leakage flow calculation utilized an orifice as a model, taking into account the flaw area calculated by the finite element model (see Attachment 3 for details of the flow model). Flow rates were calculated for a range of flaw lengths that envelope the observed flaws on penetration X-25. Calculated flows are as follows:

1. First, the leakage model was baselined utilizing the known X-25 bellows leakage (137.4 scfh). Actual flaw sizes, configuration and number as indicated by field personnel/Argonne Lab, were utilized in the model as

the initial condition (pre-test). Input from the finite element model was then used to calculate flaw area under the IPCLRT condition. Leakage flow was calculated and compared to the known leakage.

2. A second finite element model of the X-25 bellows was used to reflect flaw growth over the span of one fuel cycle. The new flaw area was calculated under IPCLRT conditions. From this data, leakage flow at the end of the fuel cycle was calculated.

3. A third model was used to reflect a large number of hypothetical subsurface flaws that pinhole immediately after plant start-up and grow over a fuel cycle to result in 3/16" flaws. This model was then subjected to the IPCLRT condition to obtain flaw areas and the combined leakage rate for these small flaws was determined.

Finally, the leakage information calculated was compared to the recent IPCLRT data and LLRT requirements to assess the impact of flawed bellows in the various configurations described above.

INPUT DATA

The following conditions were used as input to this analysis:

- IPCLRT Conditions
  Pressure: 48-50 psig
  Temperature: 80-100°F

In addition, data on bellows flaws as reported from the Station and from the Argonne inspections is presented in Tables 1 and 2, and Attachment 4. The input is summarized in the following assumptions/design inputs.

MAJOR ASSUMPTIONS/DESIGN INPUT

1. The crack growth rate used is 3/16" per fuel cycle (18 months). (This rate was derived from two sources: a) an independent fracture mechanics analysis performed by others for CECo used the results of a recent EPRI Report (RP-5064S) on stress corrosion crack growth rates to predict 0.1864 inches per cycle, b) the largest observed flaw on X-25 would have grown at a rate of 0.1832 inches per cycle if flaw initiation started in 1977 - the date when leakage was first detected.) This rate is used to predict flaw size at the end of a fuel cycle. Failure analysis results indicate that the crack propagation is due to the TGSCC process only and that no mechanical fatigue is involved.

2. Flaw orientation has been assumed to be predominantly in the axial direction. This is supported by the results of PT and visual examination of the bellows.

3. Flaws are assumed not to interact with each other. The TGSCC mechanism is non-preferential and therefore can initiate randomly on the material surface. Since the flaw size (width) is very small, and the flaws grow axially, the probability of flaws joining together is negligible.

4. Each flaw (other than pinholes) is modeled as a rectangularly shaped flaw with tapered ends. See Attachment 5 for finite element model drawings.

5. Only the outer ply of the two-ply bellows is modeled. The inner ply is assumed to behave with the actions of the outer ply and the flaw is assumed to have the same configuration on both the inner and outer plies. This assumption is conservative for the flow model because the flow losses attributable to the inner bellows are being ignored.

6. Movements of the drywell will not affect the width of the flaws. This is justified due to the axial orientation of the flaw and that deflection of the drywell at Penetration X-25 is in the lateral direction. These bellows assemblies are tandem-style, which effectively translate lateral displacement to axial displacement. Therefore, drywell lateral motion is equated to an axial movement of the bellows. The lines of force due to axial displacement at the bellows are parallel to an axial flaw and therefore do not contribute to changes in flaw shape.

7. The contribution of leakage from the pinholes is small when compared to the total leakage due to flaws in the bellows assembly. This is supported by the evaluation made in Attachment 3 and actual observed leakage during snoop testing of the X-25 bellows.

RESULTS

- The analytical result predicted by the flow model for the leakage rate through the X-25 bellows assembly at IPCLRT conditions was approximately 44.7 SCFH. The relative contribution of leakage rates predicted by the model from the various flaw sizes considered corresponds with the observed bellows leakage during the test. Therefore, the model is representative of the bellows with respect to its prediction of relative leakage rate to flaw size.

  Due to the nature of the crack geometry, size, and superposition across a curved surface, it is difficult to determine the actual flow area through the flaw. Also, because of the irregular form of the flaw, the flow is not fully developed. For these two reasons, the flow model results were correlated to the actual bellows test data by proportioning model results up to the test data.

  It can be observed that the relationship between mass discharge through flaws, as predicted by the model, and flow

area is approximately linear at similar test conditions. This observation can lead one to conclude that an accurate prediction of flow increase due to crack growth can be obtained by multiplying the observed or measured leak rate by a ratio of the increased flow area to the original flow area. Therefore, using this argument, increases in flaw areas (calculated from Attachment 2) will result in a leakage flow rate of 215 SCFH at the end of a fuel cycle. Similarly, the leakage flow rate for the growth of a number of pinholes over a fuel cycle was calculated to be 78.6 SCFH.

- The leakage flow calculations for each case result in flows that are within the Safety Limit at the end of the next fuel cycle. Results are tabulated below:

CASE	CALCULATED LEAKAGE RATE	CALCULATED FLOW (WT%/DAY) [1]	PREDICTED IPCLRT MARGIN (App. J) [2]	PREDICTED SAFETY MARGIN [3]
1. X-25 IPCLRT Condition	215 SCFH	(a) 0.44 wt%/day	(b) -0.02 wt%/day	0.23 wt%/day
2. 3/16" Pinholes IPCLRT Condition	78.6 SCFH	0.16 wt%/day	0.26 wt%/day	0.51 wt%/day

IPCLRT Margin was calculated by the following method:

IPCLRT Result (0.6096% wt/day) - As found X-25 data (0.2808% wt/day) = Adjusted IPCLRT Result (0.3288% wt/day)

Maximum Allowable Leakage (% wt/day)

10CFR50 Appendix J Limit	0.75% wt/day	
Safety Limit	1.00% wt/day	(489.6 SCFH)

The Appendix J Limit represents the maximum allowable "As-Left" condition after IPCLRT performance while the Safety Limit represents the Technical Specification Operability Limit.

[1] Calculated Leakage Rate (SCFH) x $\frac{0.25\ wt\%/day}{122\ SCFH}$ = (a) wt%/day

[2] 0.75% wt/day - 0.3288% wt/day = 0.4212% wt/day (Adjusted IPCLRT Margin)
0.4212% wt/day - (a) = (b)

[3] 1.0% wt/day - 0.3288% wt/day = 0.6712% wt/day
0.6712% wt/day - (a) = (b)

CONCLUSIONS

Primary Containment integrity will be maintained within the maximum allowable leakage limits assuming:

- the possibility of flaws in another penetration bellows assembly,
- leakage similar to that of the replaced X-25 bellows, and
- flaw growth for one fuel cycle.

Additionally, Primary Containment leakage integrity will also be maintained assuming:

- a bellows assembly has 200 subsurface flaws,
- pinholes form at the beginning of the fuel cycle, and
- the pinhole flaws grow by means of TGSCC to a length of 3/16" at the end of the fuel cycle.

TABLE 1

Bellows Assembly Flaw Data[1]

Flaw Length	Flaw Width	Quantity
1.7"	0.010"	1
0.5"	0.001"	3
0.187"	0.001"	36
0.001"	0.001"	200

(1) Reference NUTECH Communication Records TJW-91-056 and RWR-91-024. Note that the original data transmitted to NUTECH [RWR-91-024] stated that there are nine (9) 0.5" flaws and thirty (30) 3/16" flaws. The latest data from field observations [TJW-91-056] indicate that there are 4 major leaks. In addition to the large flaw, 3 leaks were felt by hand. Therefore, 6 flaws in the 0.5" category have been re-assigned to the 3/16" category because they did not exhibit significant leakage as did the major leaks.

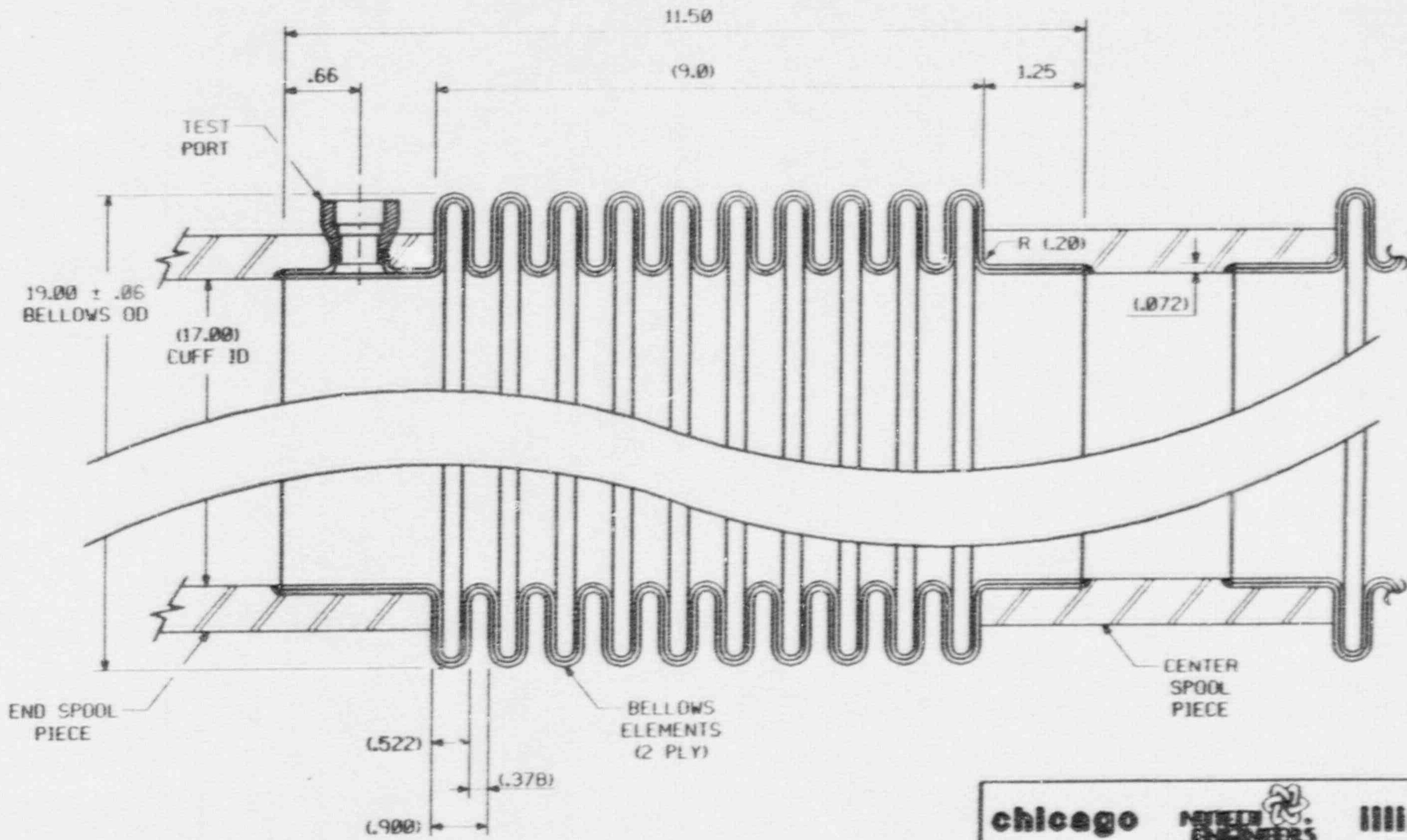
TABLE 2

Summary of Bellows Flaw Model Loading Data

	Load Case	Description	Initial Flaw Length	Flaw Growth	Quantity	Plant Condition	Flaw Orientation
1.	Baseline	Bellows Model Using As-found X-25 Flaw Data [See Table 1] at IPCLRT Conditions.	1.7" 0.5" 0.187"	None None None	1 3 36	IPCLRT (48 psig @ 90°F)	Axial Axial Axial
2.	Worst Case Bellows during IPCLRT	Bellows Model Using X-25 Flaw Data with 3/16" Growth for Each Flaw at IPCLRT Condition.	1.7" 0.5" 0.187" 0.001"	0.187" 0.187" 0.187" 0.187"	1 3 36 200	IPCLRT (48 psig @ 90°F)	Axial Axial Axial Axial
3.	Pinholed Bellows during IPCLRT	Bellows Model Using TGSCC Crack Growth for a Large Quantity of Pinholes at IPCLRT Conditions.	0	0.187"	200	IPCLRT (48 psig @ 90°F)	Axial

Attachment 1

QUAD CITIES BELLOWS
ASSEMBLY SKETCH



chicago illinois

BELLOWS ASSEMBLY SKETCH

ATTACHMENT 1

Attachment 2

QUAD CITIES BELLOWS FINITE ELEMENT MODEL CALCULATION

NUTECH ENGINEERS
A Pacific Nuclear Company

CALCULATION PACKAGE

FILE NO: COE118.0200.01
PROJECT NO: COE-118
CALC. NO: COE118.0200.01

PROJECT NAME:
Quad Cities Nuclear Power Station Unit #1

CLIENT:
Commonwealth Edison Company

CALCULATION TITLE:

Determination of Longitudinal Crack Areas and Perimeter Lengths for the Quad Cities Unit 1 Bellows at Penetration X-25

PROBLEM STATEMENT OR OBJECTIVE OF THE CALCULATION:

See Page 3

DOCUMENT REVISION	AFFECTED PAGES	REVISION DESCRIPTION	PROJECT ENGINEER APPROVAL/DATE	NAME AND INITIALS OF PREPARERS & CHECKERS
0	1-41	Initial Issue	Paul Berg 3/26/91 [illegible] 3/27/91	Paul D. Berg PDB [illegible]

QPNE 3-2.1.1
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INTRODUCTION

The purpose of this calculation is to determine areas and perimeters of various cracks in a bellows convolution of the Quad Cities Unit 1 X-25 penetration type. The areas and perimeters will be determined for use in leakage calculations that will in turn be used to evaluate the condition of bellows.

Longitudinal (axial) cracks on a bellows convolution have been modeled using finite element methods and are of three basic dimensions. The dimensions utilized are based on flaws that were observed on the X-25 bellows that has recently been replaced, and include:

1) 1.7" long, 0.010" wide
2) 1/2" long, 0.001" wide
3) 3/16" long, 0.001" wide

(Ref. 9)

The cracks will also be modeled such that each will grow 3/16" in length over a fuel cycle (Ref.#), which brings the total number of dimensions modeled to six. In addition to the different dimensions, two different conditions for the bellows will be used to find areas and perimeters, which are:

1) Initially Measured, Undeflected Condition
2) Integrated Leak Rate Test Conditions (48 psig, 90°)
(Ref. 8)

The first undeflected condition areas are calculated only to provide a comparison to the deflected areas, not as input to the flow calculations.

A final summary of the results is presented on Table 1.

METHODOLOGY

A finite element model composed of plate elements formulated in three dimensional space was used to represent the X-25 type bellows. Symmetry in the axial and circumferential directions was utilized such that a 90° model of a half convolution cross section comprised the model (see Figures 1 and 2). Boundary conditions at the edges of the half convolution cross section and the 0° and 90° model edges simulate the bellows convolution.

The cracks are placed near the 45° point where the mesh is considerably more dense than other areas in the model. The cracks were assumed to be at the crest of the bellows (Refs. 9 and 10) which dictates modeling only half the crack length (i.e., the middle of the crack is open at the top of the symmetric model).

The crack geometries are obtained from Reference 9. Three initial geometries are used that are representative of the "as-found" conditions in bellows X-25. Cracks of 1.7 inches, 0.5 inches and 3/16 inches are modeled with thicknesses of 0.010", 0.001" and 0.001" respectively. Models with these cracks were then loaded with 48 psig (Ref. 8) internal pressure to simulate conditions during the Integrated Leak Rate Test (ILRT).

The three crack geometries were then lengthened by 3/16" to represent TGSCC growth over the course of a fuel cycle. Also, a pinhole model of zero length was assumed to grow 3/16". These new crack geometries were then loaded again with ILRT conditions.

The various geometry and loading combinations brought the total number of finite element computer runs to six. Three "pre-growth" ILRT runs and three "growth after fuel cycle" ILRT runs. After each run, the widened crack areas and perimeter lengths were determined by geometric means on the deflected (loaded) model. Deflected crack widths at various points were determined as well as associated deflected lengths along the cracks. These were combined to obtain deflected areas and perimeters of the cracks. These areas and perimeters are summarized in Table 1. Also included in Table 1 are the undeflected (unloaded) crack areas and perimeters for comparitive use.

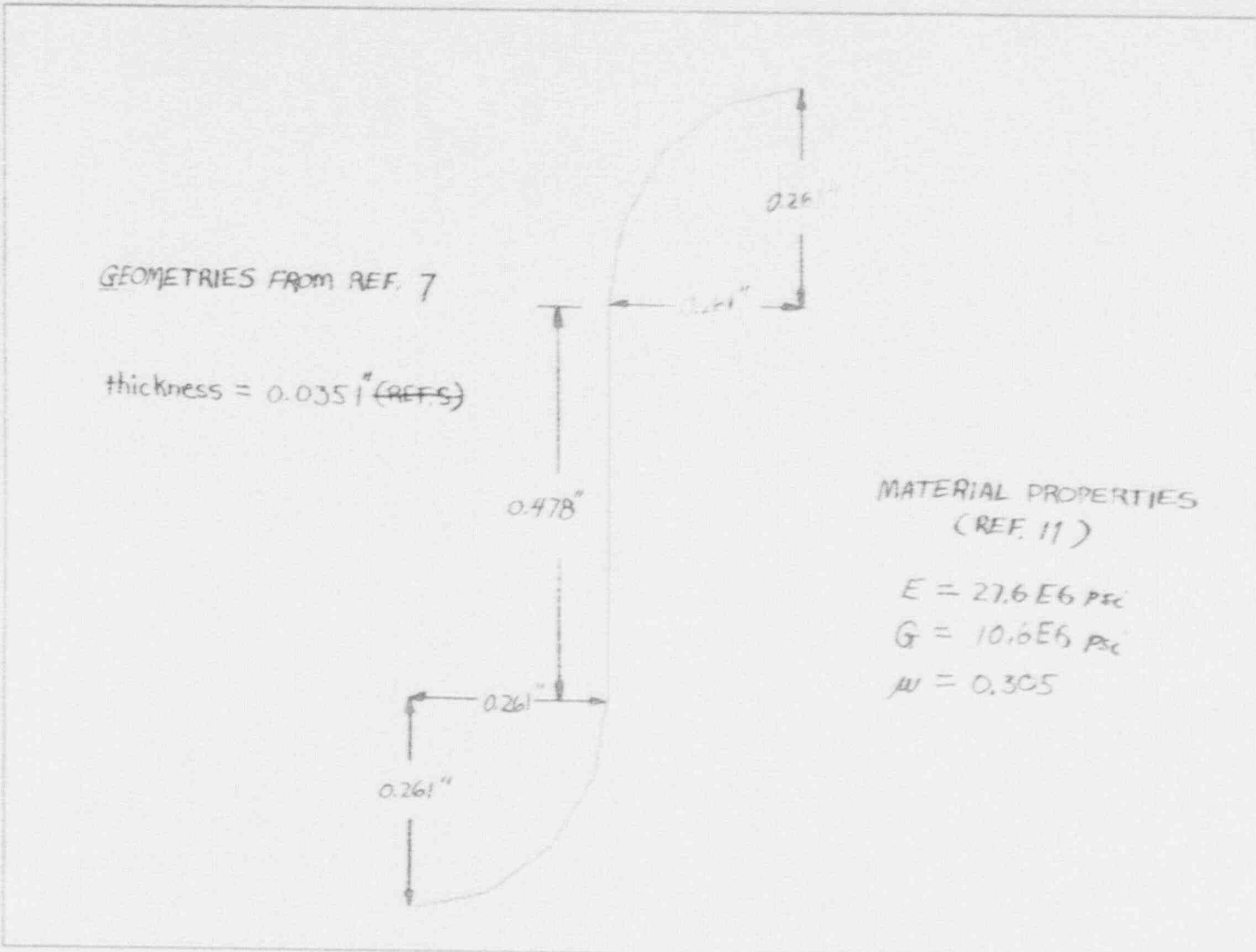

FIGURE 1 - SIDE VIEW OF MODEL CROSS SECTION WITH GEOMETRIES AND MATERIAL PROPERTIES

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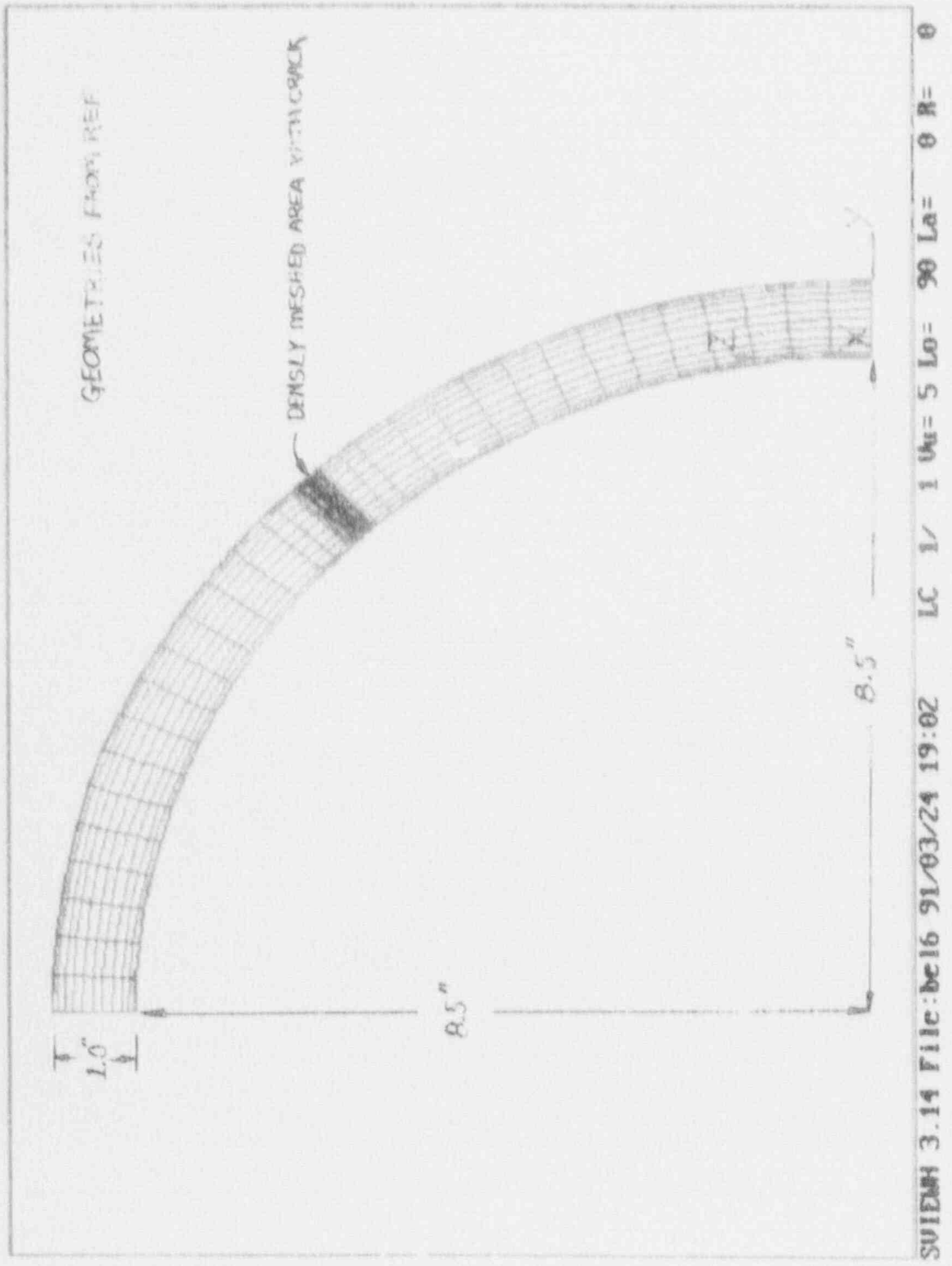

FIGURE 2 - TOP VIEW OF MODEL WITH GEOMETRIES

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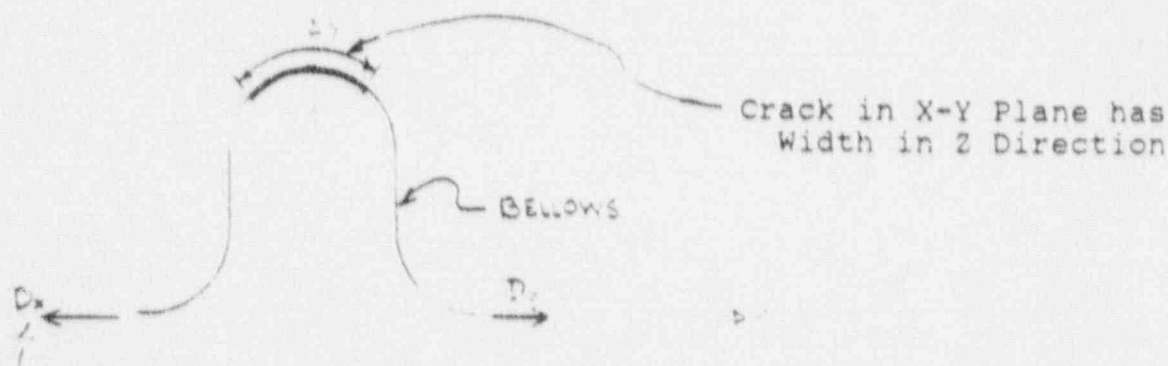
ASSUMPTIONS

1. The bellows was in its undeflected stress free state during the initial measurement of the crack size and was at an ambient temperature of 90°F.

2. The cracks are assumed to be rectangular in shape except near the ends where they taper to a point.

3. The bellows' convolutions behave as the outer ply only since the inner ply will not resist pressure as leakage progresses.

4. Movements of the drywell will not effect the width of the longitudinal crack; therefore, effects on area from these displacements will be negligible.



Equivalent Axial Movement

Effective displacement in X-direction does not effect Z-direction crack width.

5. The bellows' convolutions behave as a linear elastic model.

6. The crack dimensions are approximate (Ref. 13).

7. The effects of the phantom cracks due to symmetry boundary conditions has a negligible effect on the crack areas and perimeters due to the small size of the crack compared to the bellows diameter.

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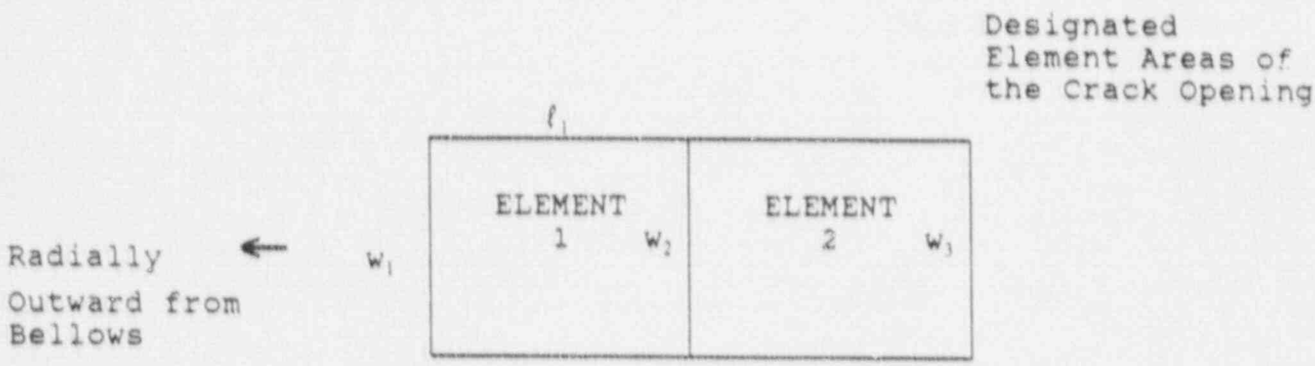
DETERMINATION OF CRACK AREAS AND PERIMETER LENGTHS

The following calculations determine crack areas and perimeter lengths for the various conditions described earlier. The crack areas are calculated by summation of the smaller elements (rectangles and triangles) shown in Figures 3 through 8. The rectangular elements areas are approximated as follows:



Area of Element 1 = $\ell_1 \times w_1$

Since w_1 is slightly larger than w_2, the area for Element 1 is slightly conservative. However, since the widths do not vary by concernable amounts. The calculated areas are adequate values for the intended purpose of these calculations. The triangular elements are calculated using basic geometric principals and are precise.

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Calculation for 3/16" x 0.001" Crack with Constant Length

Initial Conditions:

Note: The following lengths and widths are retrieved from the undeflected Algor model (see reference 1). See page 11 for designation of the Element Numbers.

Element Number	Length l	Width w
$i := 1 .. 2$		
1 2	$l := \begin{bmatrix} 0.050918 \\ 0.025459 \end{bmatrix}$ in	$w := \begin{bmatrix} 0.001123 \\ 0.001134 \end{bmatrix}$ in
3	$L3 := 0.025466$ in	$W3 := 0.001140$ in

Calculation of the Area of the Crack Opening:

$a_i := w_i \, l_i$ $\qquad a = \begin{bmatrix} 0.000057 \\ 0.000029 \end{bmatrix}$ in^2

ai = Area of each rectangular element for i th element

a3 = Area of triangular element

Where, $d := L3 \cos\left[\operatorname{asin}\left[\frac{W3}{L3 \; 2}\right]\right]$

$a3 := d \, \frac{W3}{2}$ $\qquad a3 = 0.000015$ in^2

A = Total area of crack opening $\qquad A := ((\Sigma a) + a3) \, 2$

$A = 0.000201$ in^2

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $\qquad P := ((\Sigma l) + L3) \, 4$

$P = 0.407$ in

Calculation for 3/16" x 0.001" Crack with Constant Length

ILRT Conditions:

Note: The following lengths and widths are retrieved from the deflected Algor model (see reference 1). See page 11 for designation of the Element Numbers.

Element Number	Length l	Width w

$i := 1 .. 2$

1 2	$l := \begin{bmatrix} 0.050912 \\ 0.025467 \end{bmatrix}$ in	$w := \begin{bmatrix} 0.001176 \\ 0.001179 \end{bmatrix}$ in
3	$L3 := 0.025467$ in	$W3 := 0.001175$ in

Calculation of the Area of the Crack Opening:

$a_i := w_i \, l_i$ $\qquad a = \begin{bmatrix} 0.00006 \\ 0.00003 \end{bmatrix} \text{in}^2$

ai = Area of each rectangular element for i th element

a3 = Area of triangular element

Where, $d := L3 \cdot \cos\left[\operatorname{asin}\left[\frac{W3}{L3 \cdot 2}\right]\right]$

$a3 := d \, \frac{W3}{2}$ $\qquad a3 = 0.000015 \text{ in}^2$

A = Total area of crack opening $\qquad A := ((\Sigma a) + a3) \cdot 2$

$A = 0.00021 \text{ in}^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $\qquad P := ((\Sigma l) + L3) \cdot 4$

$P = 0.407$ in

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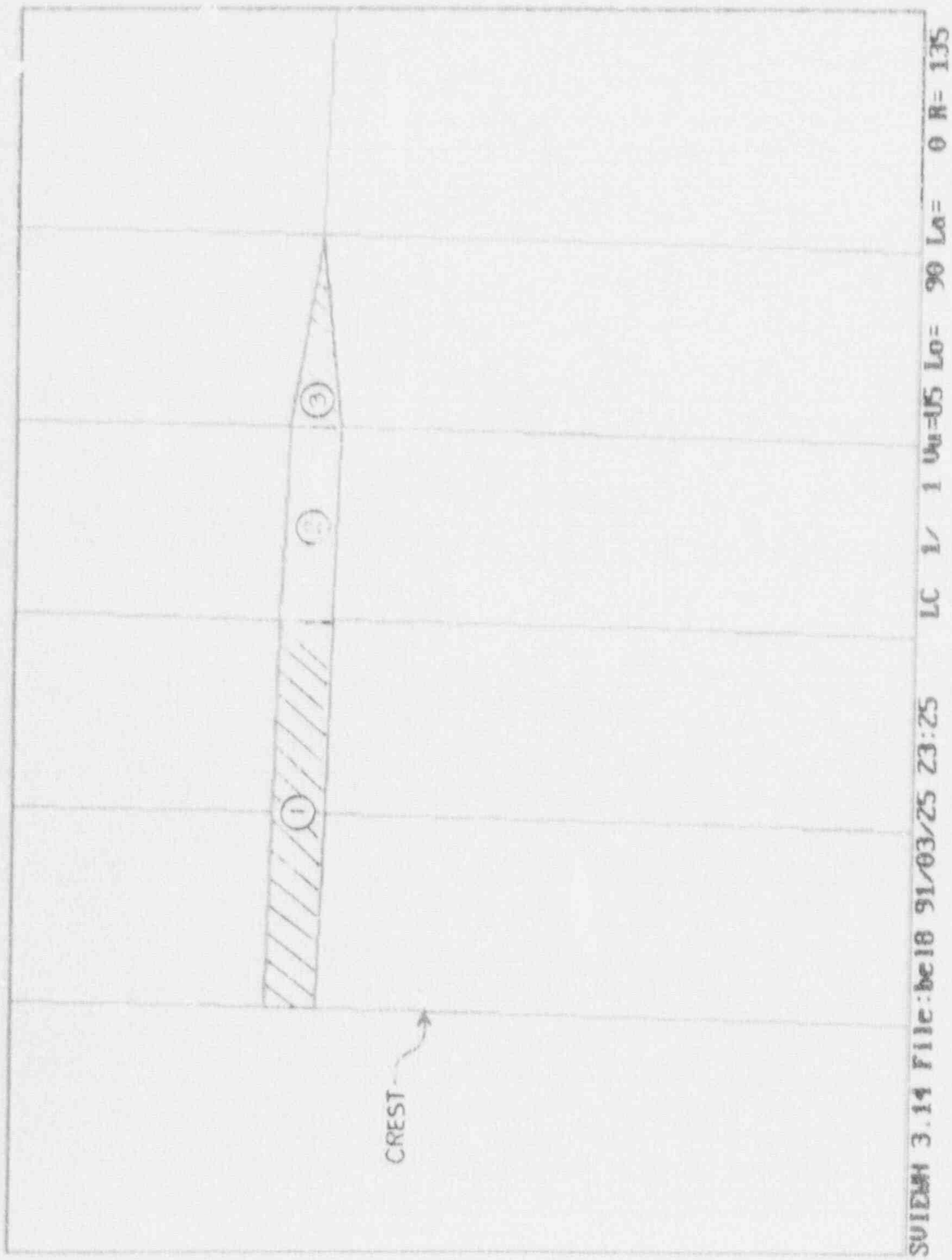

FIGURE 3 - DESIGNATION OF ELEMENT CRACK AREAS FOR 3/16 INCH CRACK

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Calculation for 0.500" x 0.001" Crack with Constant Length

Initial Conditions:

Note: The following lengths and widths are retrieved from the undeflected Algor model (see reference 2). See page '. for designation of the Element Numbers.

Element Number	Length l	Width w

$i := 1 .. 5$

Element	Length	Width
1	0.050918	0.001123
2	0.050919	0.001134
3	0.050919	0.001147
4	0.050919	0.001143
5	0.050917	0.001140

$l := [0.050918, 0.050919, 0.050919, 0.050919, 0.050917]^T$ in $\quad w := [0.001123, 0.001134, 0.001147, 0.001143, 0.001140]^T$ in

6 $\quad L6 := 0.025467$ in $\quad W6 := 0.001226$ in

0.500" x 0.001" with Constant Length, Initial Conditions

Calculation of the Area of the Crack Opening:

$a_i := w_i \cdot l_i$

ai = Area of each rectangular element for i th element

$$a = \begin{bmatrix} 0.000057 \\ 0.000058 \\ 0.000058 \\ 0.000058 \\ 0.000058 \end{bmatrix} in^2$$

a6 = Area of triangular element

Where, $d := L6 \cos\left[\operatorname{asin}\left[\frac{W6}{L6 \cdot 2}\right]\right]$

$a6 := d \frac{W6}{2}$

$a6 = 0.000016 \; in^2$

A = Total area of crack opening $A := ((\Sigma a) + a6) \cdot 2$

$A = 0.00061 \; in^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $P := ((\Sigma l) + L6) \cdot 4$

$P = 1.12 \; in$

Calculation for 0.500" x 0.001" Crack with Constant Length

ILRT Conditions:

Note: The following lengths and widths are retrieved from the deflected Algor model (see reference 2). See page for designation of the Element Numbers.

Element Number	Length l	Width w

$i := 1 .. 5$

Element	Length	Width
1	0.050916	0.001426
2	0.050915	0.001423
3	0.050915	0.001418
4	0.050914	0.001373
5	0.050910	0.001319

$$l := \begin{bmatrix} 0.050916 \\ 0.050915 \\ 0.050915 \\ 0.050914 \\ 0.050910 \end{bmatrix} \text{ in} \qquad w := \begin{bmatrix} 0.001426 \\ 0.001423 \\ 0.001418 \\ 0.001373 \\ 0.001319 \end{bmatrix} \text{ in}$$

6 $L6 := 0.025473 \text{ in}$ $W6 := 0.001327 \text{ in}$

0.500" x 0.001" with Constant Length, ILRT Conditions

Calculation of the Area of the Crack Opening:

$a_i := w_i \cdot l_i$

$a = \begin{bmatrix} 0.000073 \\ 0.000072 \\ 0.000072 \\ 0.00007 \\ 0.000067 \end{bmatrix} in^2$

ai = Area of each rectangular element for i th element

a6 = Area of triangular element

Where, $d := L6 \cdot \cos\left[\operatorname{asin}\left[\frac{W6}{L6 \cdot 2}\right]\right]$

$a6 := d \cdot \frac{W6}{2}$

$a6 = 0.000017\ in^2$

A = Total area of crack opening $A := ((\Sigma a) + a6) \cdot 2$

$A = 0.000742\ in^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $P := ((\Sigma l) + L6) \cdot 4$

$P = 1.12\ in$

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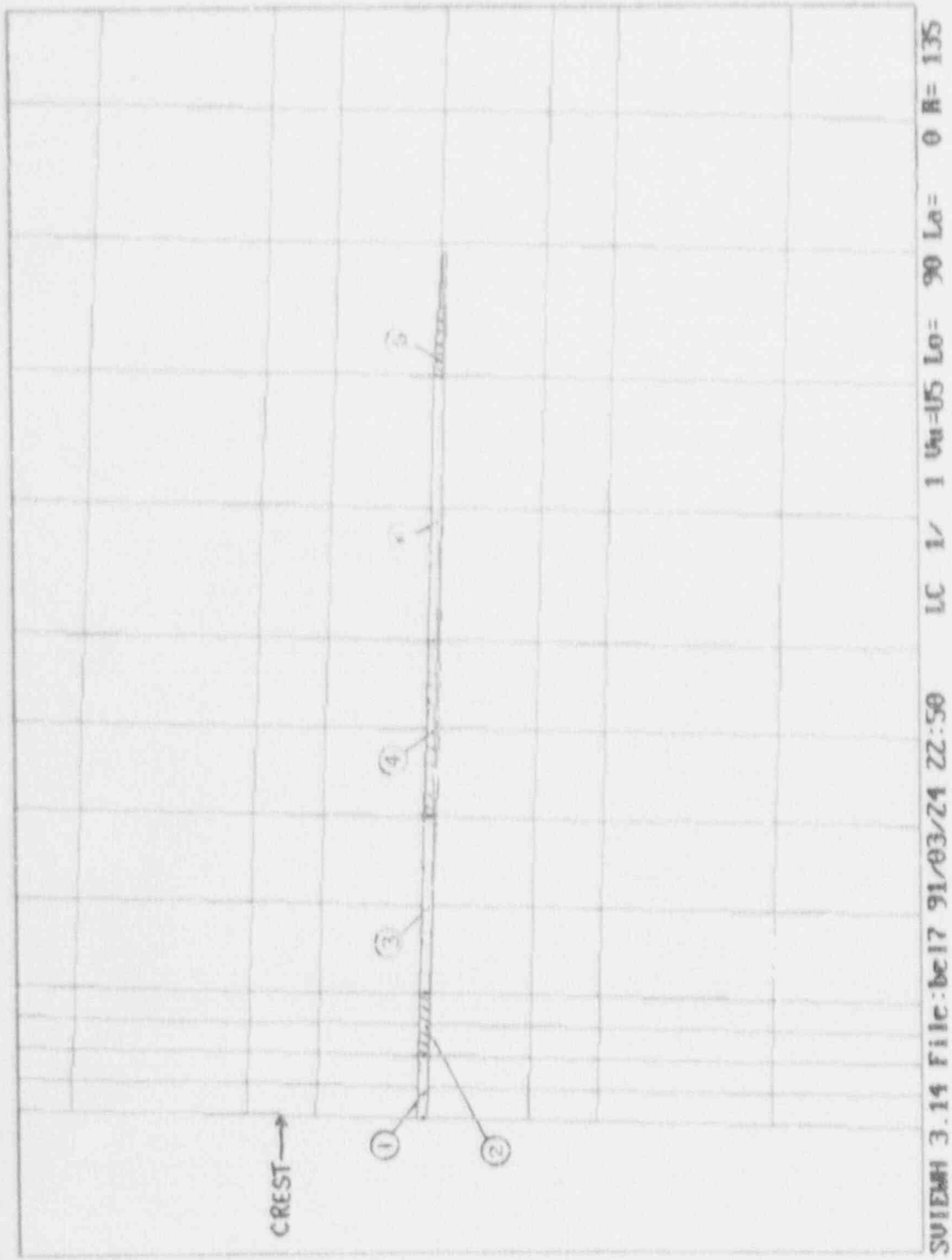

FIGURE 4 - DESIGNATION OF ELEMENT CRACK AREAS FOR 1/2 INCH CRACK

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Calculation for 1.700" x 0.010" Crack with Constant Length

Initial Conditions:

Note: The following lengths and widths are retrieved from the undeflected Algor model (see reference 3). See page 1 for designation of the Element Numbers.

Element Number	Length l	Width w
1	0.050919	0.010000
2	0.050918	0.010000
3	0.050919	0.010000
4	0.050919	0.009700
5	0.050918	0.009941
6	0.050919	0.010001
7	0.050919	0.010000
8	0.050918	0.010000
9	0.059750	0.009999
10	0.059750	0.009999
11	0.059749	0.010000
12	0.059751	0.010000
13	0.059749	0.010000
14	0.059751	0.010000

i := 1 ..14

l := [column above] in   w := [column above] in

15   L15 := 0.119604 in   W15 := 0.010000 in

1.700" x 0.010" Crack, Initial Conditions

Calculation of the Area of the Crack Opening:

$a_i := w_i \, l_i$

ai = Area of each rectangular element for i th element

$$a = \begin{bmatrix} 0.000509 \\ 0.000509 \\ 0.000509 \\ 0.000494 \\ 0.000506 \\ 0.000509 \\ 0.000509 \\ 0.000509 \\ 0.000597 \\ 0.000597 \\ 0.000597 \\ 0.000598 \\ 0.000597 \\ 0.000598 \end{bmatrix} in^2$$

a15 = Area of triangular element

Where, $d := L15 \cos\left[\operatorname{asin}\left[\frac{W15}{L15 \; 2}\right]\right]$

$a15 := d \, \frac{W15}{2}$

$a15 = 0.000597 \; in^2$

A = Total area of crack opening $A := ((\Sigma a) + a15) \; 2$

$A = 0.016475 \; in^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $P := ((\Sigma l) + L15) \; 4$

$P = 3.542 \; in$

Calculation for 1.700" x 0.010" Crack with Constant Length

ILRT Conditions:

Note: The following lengths and widths are retrieved from the deflected Algor model (see reference 3). See page 1 for designation of the Element Numbers.

Element Number | Length l | Width w

i := 1 ..14

Element Number	Length l (in)	Width w (in)
1	0.050918	0.014814
2	0.050919	0.014785
3	0.050918	0.014749
4	0.050921	0.014621
5	0.050918	0.014488
6	0.050923	0.014343
7	0.050919	0.014198
8	0.050920	0.013941
9	0.059749	0.013687
10	0.059746	0.013333
11	0.059742	0.012977
12	0.059740	0.012616
13	0.059736	0.012240
14	0.059735	0.011843

15 L15 := 0.119622 in W15 := 0.011415 in

1.700" x 0.010" Crack, ILRT Conditions

Calculation of the Area of the Crack Opening:

$a_i := w_i \cdot l_i$

ai = Area of each rectangular element for i th element

$$a = \begin{bmatrix} 0.000754 \\ 0.000753 \\ 0.000751 \\ 0.000745 \\ 0.000738 \\ 0.00073 \\ 0.000723 \\ 0.00071 \\ 0.000818 \\ 0.000797 \\ 0.000775 \\ 0.000754 \\ 0.000731 \\ 0.000707 \end{bmatrix} \cdot in^2$$

a15 = Area of triangular element

Where, $d := L15 \cdot \cos\left[\operatorname{asin}\left[\frac{W15}{L15 \cdot 2}\right]\right]$

$a15 := d \cdot \frac{W15}{2}$

$a15 = 0.000682 \cdot in^2$

A = Total area of crack opening $A := ((\Sigma a) + a15) \cdot 2$

$A = 0.022335 \cdot in^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $P := ((\Sigma l) + L15) \cdot 4$

$P = 3.542 \cdot in$

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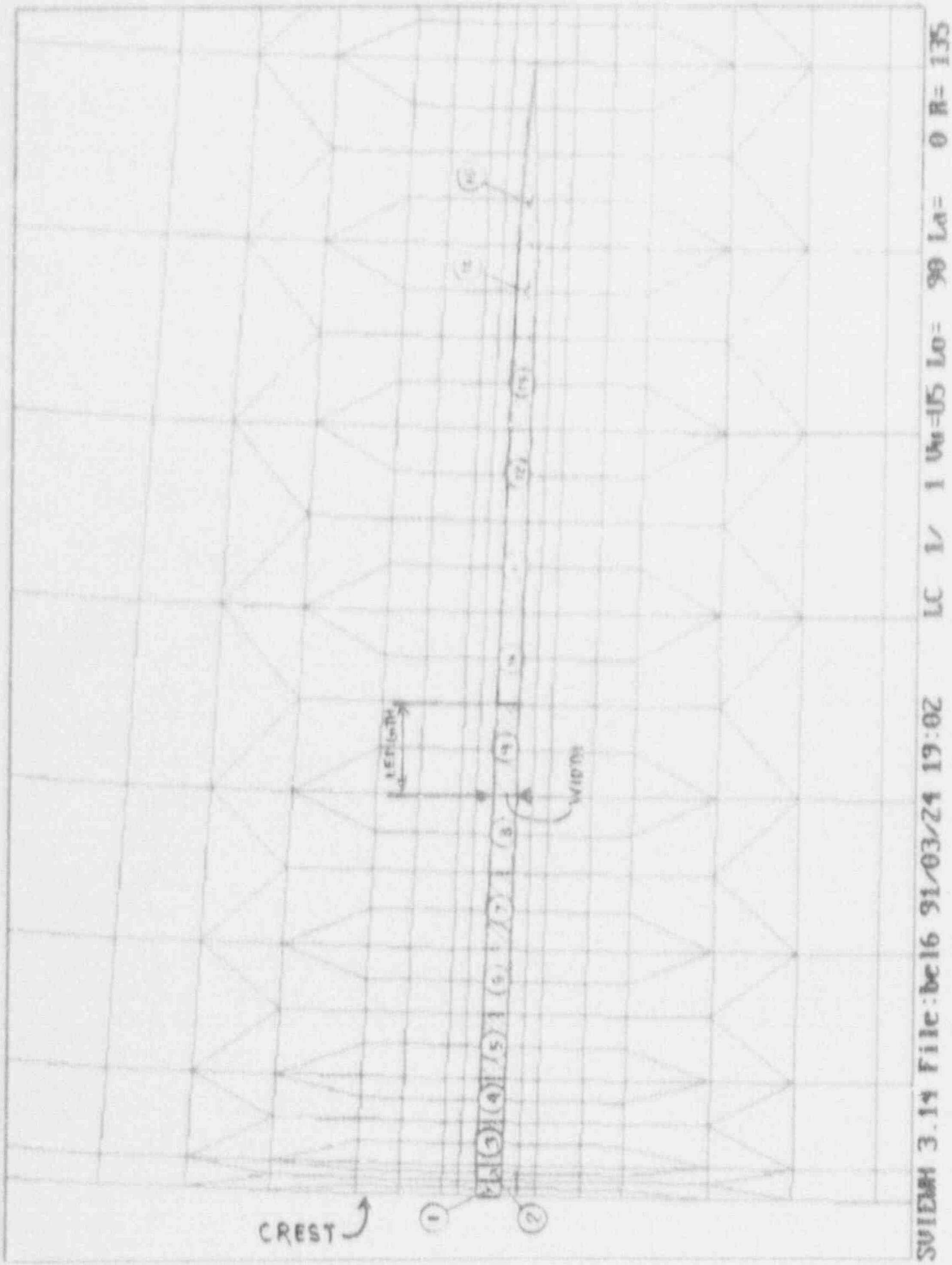

FIGURE 5 - DESIGNATION OF ELEMENT CRACK AREAS FOR 1.7 INCH CRACK

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Calculation for Pinhole with a 3/16" Growth (x 0.001" Wide)

Initial Condition:

Values for area and perimeter are equal to 3/16" x 0.001" crack with constant length. See page 9 of this calculation.

ILRT Condition:

Values for area and perimeter are equal to 3/16" x 0.001" crack with constant length. See page 10 of this calculation.

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Calculation for 3/16" x 0.001" Crack with 3/16" Growth

Initial Conditions:

Note: The following lengths and widths are retrieved from the undeflected Algor model (see reference 4). See page for designation of the Element Numbers.

Element Number	Length l	Width w

$i := 1 .. 4$

1
2
3
4

$$l := \begin{bmatrix} 0.050918 \\ 0.050919 \\ 0.050919 \\ 0.025459 \end{bmatrix} \text{ in} \qquad w := \begin{bmatrix} 0.001124 \\ 0.001134 \\ 0.001147 \\ 0.001143 \end{bmatrix} \text{ in}$$

5 $\quad L5 := 0.025466 \text{ in} \qquad W5 := 0.001141 \text{ in}$

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3/16" x 0.001" with 3/16" Growth, Initial Conditions

Calculation of the Area of the Crack Opening:

$a_i := w_i \, l_i$

$$a = \begin{bmatrix} 0.000057 \\ 0.000058 \\ 0.000058 \\ 0.000029 \end{bmatrix} \text{in}^2$$

ai = Area of each rectangular element for i th element

a5 = Area of triangular element

Where, $d := L5 \cos\left[\operatorname{asin}\left[\frac{W5}{L5} \cdot \frac{}{2}\right]\right]$

$a5 := d \, \frac{W5}{2}$

$a5 = 0.000015 \text{ in}^2$

A = Total area of crack opening $A := ((\Sigma a) + a5) \, 2$

$A = 0.000434 \text{ in}^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $P := ((\Sigma l) + L5) \, 4$

$P = 0.815 \text{ in}$

Calculation for 3/16" x 0.001" Crack with 3/16" Growth

ILRT Conditions:

Note: The following lengths and widths are retrieved from the deflected Algor model (see reference). See page 27 for designation of the Element Numbers.

Element Number	Length l	Width w

i := 1 ..4

Element	l (in)	w (in)
1	0.050914	0.001292
2	0.050914	0.001292
3	0.050914	0.001287
4	0.025456	0.001244

5 L5 := 0.025470 in W5 := 0.001213 in

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3/16" x 0.001" with 3/16" Growth, ILRT Conditions

Calculation of the Area of the Crack Opening:

$a_i := w_i \cdot l_i$

$$a = \begin{bmatrix} 0.000066 \\ 0.000066 \\ 0.000066 \\ 0.000032 \end{bmatrix} in^2$$

ai = Area of each rectangular element for i th element

a5 = Area of triangular element

Where, $d := L5 \cdot \cos\left[\text{asin}\left[\frac{W5}{L5 \cdot 2}\right]\right]$

$a5 := d \cdot \frac{W5}{2}$

$a5 = 0.000015\ in^2$

A = Total area of crack opening $A := ((\sum a) + a5) \cdot 2$

$A = 0.000488\ in^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $P := ((\sum l) + L5) \cdot 4$

$P = 0.815\ in$

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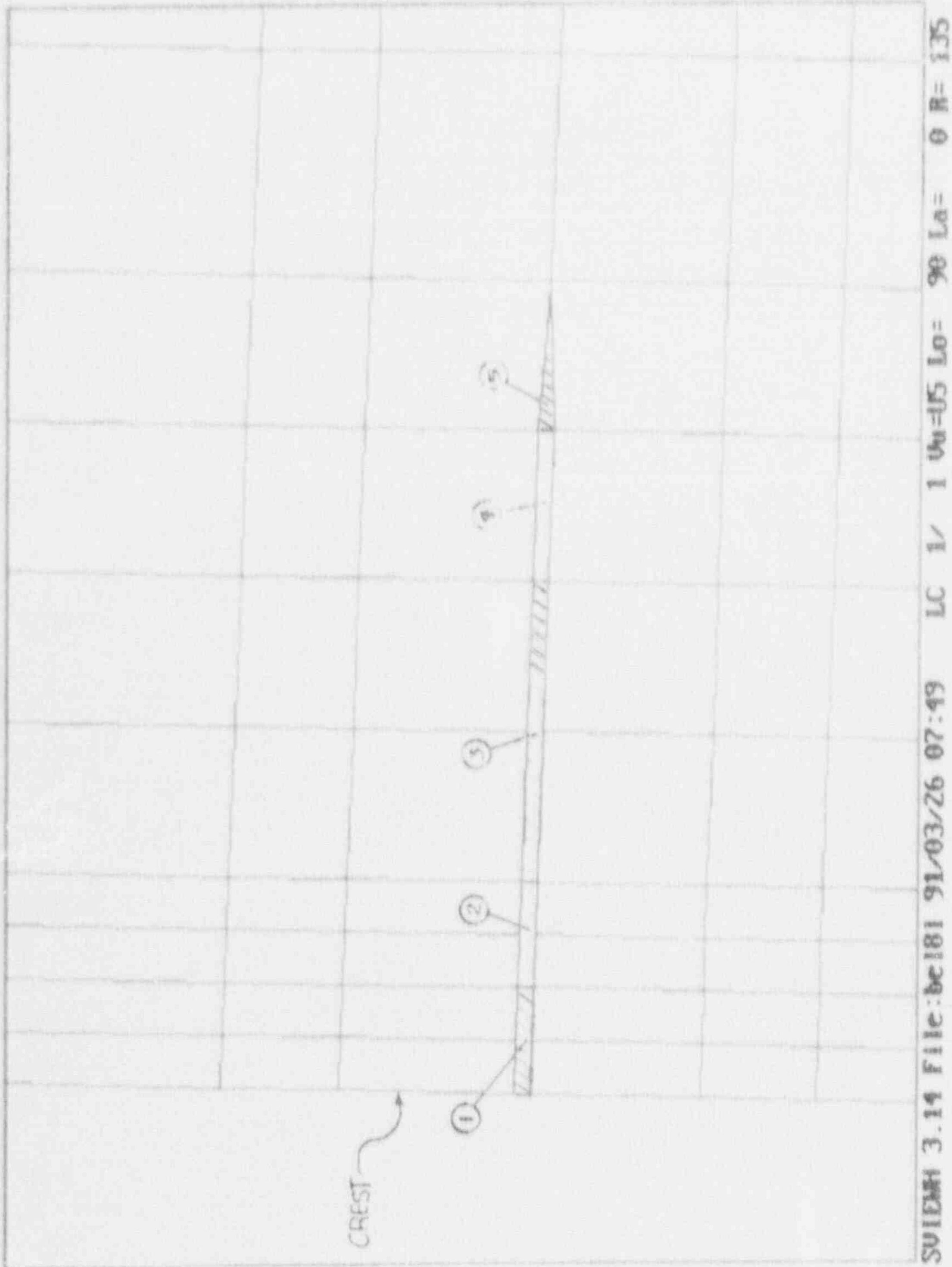

FIGURE 6 - DESIGNATION OF ELEMENT CRACK AREAS FOR 3/16 INCH CRACK WITH 3/16 INCH GROWTH

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Calculation for 0.500" x 0.001" Crack with 3/16" Growth

Initial Conditions:

Note: The following lengths and widths are retrieved from the undeflected Algor model (see reference 5). See page 81 for designation of the Element Numbers.

Element Number	Length l	Width w

$i := 1 .. 7$

Element Number	Length l (in)	Width w (in)
1	0.050918	0.001123
2	0.050919	0.001134
3	0.050918	0.001147
4	0.050919	0.001143
5	0.050919	0.001140
6	0.050918	0.001226
7	0.025460	0.001226

8 $L8 := 0.025467 \text{ in}$ $W8 := 0.001224 \text{ in}$

0.500" x 0.001" with 3/16" Growth, Initial Conditions

Calculation of the Area of the Crack Opening:

$a_i := w_i \, l_i$

ai = Area of each rectangular element for i th element

$$a = \begin{bmatrix} 0.000057 \\ 0.000058 \\ 0.000058 \\ 0.000058 \\ 0.000058 \\ 0.000062 \\ 0.000031 \end{bmatrix} in^2$$

a8 = Area of triangular element

Where, $d := L8 \cdot \cos\left[\operatorname{asin}\left[\frac{W8}{L8 \cdot 2}\right]\right]$

$a8 := d \cdot \frac{W8}{2}$

$a8 = 0.000016 \text{ in}^2$

A = Total area of crack opening $A := ((\Sigma a) + a8) \cdot 2$

$A = 0.000798 \text{ in}^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $P := ((\Sigma l) + L8) \cdot 4$

$P = 1.426$ in

Calculation for 0.500" x 0.001" Crack with 3/16" Growth

ILRT Conditions:

Note: The following lengths and widths are retrieved from the deflected Algor model (see reference 5). See page 32 for designation of the Element Numbers.

Element Number	Length l	Width w
1	0.050917	0.001567
2	0.050917	0.001563
3	0.050917	0.001558
4	0.050916	0.001512
5	0.050913	0.001461
6	0.050916	0.001480
7	0.025455	0.001398
8	L8 := 0.025474 in	W8 := 0.001346 in

i := 1 ..7

$$l := \begin{bmatrix} 0.050917 \\ 0.050917 \\ 0.050917 \\ 0.050916 \\ 0.050913 \\ 0.050916 \\ 0.025455 \end{bmatrix} in \qquad w := \begin{bmatrix} 0.001567 \\ 0.001563 \\ 0.001558 \\ 0.001512 \\ 0.001461 \\ 0.001480 \\ 0.001398 \end{bmatrix} in$$

$L8 := 0.025474$ in $W8 := 0.001346$ in

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0.500"x 0.001" Crack with 3/16" Growth, ILRT Conditions

Calculation of the Area of the Crack Opening:

$a_i := w_i\, l_i$

ai = Area of each rectangular element for i th element

$$a = \begin{bmatrix} 0.00008 \\ 0.00008 \\ 0.000079 \\ 0.000077 \\ 0.000074 \\ 0.000075 \\ 0.000036 \end{bmatrix} in^2$$

a8 = Area of triangular element

Where, $d := L8 \cos\left[\operatorname{asin}\left[\frac{W8}{L8\ 2}\right]\right]$

$a8 := d\,\frac{W8}{2}$

$a8 = 0.000017\ in^2$

A = Total area of crack opening $A := ((\Sigma a) + a8)\ 2$

$A = 0.001036\ in^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $P := ((\Sigma l) + L8)\ 4$

$P = 1.426\ in$

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FIGURE 7 - DESIGNATION OF ELEMENT CRACK AREAS FOR 1/2 INCH CRACK WITH 3/16 INCH GROWTH

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Calculation for 1.700" x 0.010" Crack with 3/16" Growth

Initial Conditions:

Note: The following lengths and widths are retrieved from the deflected Algor model (see reference 6). See page 17 for designation of the Element Numbers.

Element Number	Length l	Width w
1	0.050919	0.010000
2	0.050919	0.010000
3	0.050918	0.010000
4	0.050919	0.009970
5	0.050918	0.009941
6	0.050919	0.009970
7	0.050918	0.010001
8	0.050920	0.010000
9	0.059749	0.010000
10	0.059750	0.009999
11	0.059750	0.009999
12	0.059749	0.010000
13	0.059750	0.010000
14	0.059749	0.010000
15	0.059751	0.010000
16	0.059749	0.010000

i := 1 ..16

l := [above vector] in   w := [above vector] in

17   L17 := 0.101960 in   W17 := 0.010001 in

1.700" x 0.010" Crack with 3/16" Growth, Initial Conditions

Calculation of the Area of the Crack Opening:

$a_i := w_i \cdot l_i$

ai = Area of each rectangular element for i th element

$$a = \begin{bmatrix} 0.000509 \\ 0.000509 \\ 0.000509 \\ 0.000508 \\ 0.000506 \\ 0.000508 \\ 0.000509 \\ 0.000509 \\ 0.000597 \\ 0.000597 \\ 0.000597 \\ 0.000597 \\ 0.000598 \\ 0.000597 \\ 0.000598 \\ 0.000597 \end{bmatrix} \cdot in^2$$

a17 = Area of triangular element

Where, $d := L17 \cdot \cos\left[\operatorname{asin}\left[\frac{W17}{L17 \cdot 2}\right]\right]$

$a17 := d \cdot \frac{W17}{2}$

$a17 = 0.000509 \cdot in^2$

A = Total area of crack opening $\quad A := ((\Sigma a) + a17) \cdot 2$

$A = 0.018713 \cdot in^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $\quad P := ((\Sigma l) + L17) \cdot 4$

$P = 3.949 \cdot in$

Calculation for 1.700" x 0.010" Crack with 3/16" Growth

ILRT Conditions:

Note: The following lengths and widths are retrieved from the deflected Algor model (see reference 6). See page 37 for designation of the Element Numbers.

$i := 1 .. 16$

Element Number	Length l	Width w
1	0.050918	0.016992
2	0.050919	0.016945
3	0.050918	0.016891
4	0.050921	0.016711
5	0.050919	0.016528
6	0.050922	0.016304
7	0.050918	0.016081
8	0.050921	0.015733
9	0.059747	0.015387
10	0.059745	0.014928
11	0.059741	0.014469
12	0.059737	0.014007
13	0.059734	0.013536
14	0.059730	0.013051
15	0.059728	0.012547
16	0.059725	0.012011

(l := [above column] in, w := [above column] in)

17 $L17 := 0.101989$ in $W17 := 0.011426$ in

1.700" x 0.010" Crack with 3/16" Growth, ILRT Conditions

Calculation of the Area of the Crack Opening:

$a_i := w_i \, l_i$

ai = Area of each rectangular element for i th element

$$a = \begin{bmatrix} 0.000865 \\ 0.000863 \\ 0.00086 \\ 0.000851 \\ 0.000842 \\ 0.00083 \\ 0.000819 \\ 0.000801 \\ 0.000919 \\ 0.000892 \\ 0.000864 \\ 0.000837 \\ 0.000809 \\ 0.00078 \\ 0.000749 \\ 0.000717 \end{bmatrix} in^2$$

a17 = Area of triangular element

Where, $d := L17 \cos\left[\operatorname{asin}\left[\frac{W17}{L17 \cdot 2}\right]\right]$

$a17 := d \, \frac{W17}{2}$

$a17 = 0.000582 \, in^2$

A = Total area of crack opening $A := ((\Sigma a) + a17) \, 2$

$A = 0.027759 \, in^2$

Calculation of the Perimeter of the Crack Opening:

P = Perimeter of opening $P := ((\Sigma l) + L17) \, 4$

$P = 3.949 \, in$

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SUMMARY

The results are listed in Tables 1a and 1b. The significant results are the ILRT conditions only. Initial areas and perimeters are added for comparative purposes. It should be noted that the "Pre-Growth" 3/16" condition and the "Growth After Fuel Cycle" condition is the same.

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TABLES 1a AND 1b

AREA SUMMARIES

"PRE-GROWTH" CONDITIONS		
Crack Length/Loading	**Area (in^2)**	**Perimeter (in)**
3/16" Initial	2.01 E-4	0.407
3/16" ILRT	2.10 E-4	0.407
0.5" Initial	6.10 E-4	1.12
0.5" ILRT	7.42 E-4	1.12
1.7" Initial	16.5 E-3	3.54
1.7" ILRT	22.3 E-3	3.54

(1a)

"GROWTH AFTER FUEL CYCLE" CONDITIONS		
Crack Length/Loading	**Area (in^2)**	**Perimeter (in)**
* 0" + 3/16" Initial	2.01 E-4	0.407
* 0" + 3/16" ILRT	2.10 E-4	0.407
3/16" + 3/16" Initial	4.34 E-4	0.815
3/16" + 3/16" ILRT	4.88 E-4	0.815
0.5" + 3/16" Initial	7.98 E-4	1.43
0.5" + 3/16" ILRT	10.4 E-4	1.43
1.7" + 3/16" Initial	18.7 E-3	3.95
1.7" + 3/16" ILRT	27.8 E-3	3.95

(1b)

*Also listed for "Pre-Growth" Conditions.

REFERENCES:

1. Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 3/16" x 0.001" Crack at ILRT Conditions." Dated 3/25/91, 1:25 P, File No.: COE118.0200.01.

2. Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 1/2" x 0.001" Crack at ILRT Conditions." Dated 3/24/91, 10:50 P, File No.: COE118.0200.01.

3. Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 1.7" x 0.010" Crack at ILRT Conditions." Dated 3/25/91, 8:36 P, File No.: COE118.0200.01.

4. Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 3/16" x 0.001" Crack at ILRT Conditions." Dated 3/26/91, 7:49 A, File No.: COE118.0200.01.

5. Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 1/2" x 0.001" Crack with 3/16" Growth at ILRT Conditions." Dated 3/25/91, 9:45 P, File No.: COE118.0200.01.

6. Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 1.7" x 0.010" Crack with 3/16" Growth at ILRT Conditions." Dated 3/25/91, 8:36 P, File No.: COE118.0200.01.

7. Pathway Bellows Drawing "18" Tandem Expansion Joint Assembly; Quad Cities Unit 1 & 2, Item X-25" Drawing No. 8052, Rev. 0, File No.: COE118.0160.

8. Updated FSAR for Quad Cities Unit #1, NUTECH Library.

9. NUTECH Communication Record by Ray Rosten, "Meeting on Quad Cities Bellows Leakage." Dated 3/22/91, No. RWR-91-024, File No.: COE118.0001.

10. System Materials Analysis Department Report on Inspection of the X-25 Drywell Penetration Bellows at Quad Cities Station, No. M-1243-91 dated 3/12/91, File No.: COE118.0160.

11. Mark's Standard Handbook for Mechanical Engineers 7th Ed.

12. Computer Program Verification Document, File No. QA SJ0.SOFT.165.9.0.

13. Nures - Algor Finite Element Analysis Software, Version 9.0, File No. 2.165.9.0.

Attachment 3

QUAD CITIES BELLOWS
LEAKAGE FLOW CALCULATION

NUTECH ENGINEERS A Pacific Nuclear Company	**CALCULATION PACKAGE**	FILE NO: COE118.0200.02 PROJECT NO: COE-118 CALC. NO: COE118.0200.02

PROJECT NAME:	CLIENT:
Quad Cities Nuclear Power Station Unit #1	Commonwealth Edison Company

CALCULATION TITLE:

Determination of Flow Rate Through Observed and Postulated Cracks.

PROBLEM STATEMENT OR OBJECTIVE OF THE CALCULATION:

The objective of this calculation is to determine the flow rate through an observed crack, postulated pinhole cracks and projected cracks (after growth) in the X-25 penetration bellows at Quad Cities Unit 1 during ILRT conditions. Leak rates are calculated from an analytical model, representing compressible, choked flow through a thick walled orifice located in a wall of infinite area with a discharge coefficient based upon crack wall roughness.

DOCUMENT REVISION	AFFECTED PAGES	REVISION DESCRIPTION	PROJECT ENGINEER APPROVAL/DATE	NAME AND INITIALS OF PREPARERS & CHECKERS
0	1-3[illegible]	Initial Issue	W S Kwong David DeGrak 3-27-91	David DeGrak DPD Sonja C. Schullmoeller SCS

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1.0 PURPOSE

This calculation will attempt to quantify the leakage through the observed cracks in bellows penetration X-25 at Quad Cities Unit 1. Additionally, the calculation will determine a worst case leak rate to be expected through postulated "pinhole" cracks. Finally, the calculation will determine the leak rate during ILRT conditions after the observed cracks have been allowed to grow 3/16" in length.

2.0 METHODOLOGY

Modeling the leakage through the observed cracks will be attempted utilizing an analytical method based upon compressible, choked flow through a thick walled orifice located in a wall of infinite area with a discharge coefficient based upon crack wall roughness. Thermodynamic and hydraulic parameters utilized within the models are based upon conditions inside the bellows during the integrated leak rate test (ILRT) at 49 psig and 90°F. The resistance coefficients were calculated utilizing measured crack geometries and quantities such as crack opening under load determined by finite element methods. The model results will be benchmarked against a cumulative measured crack leakage flow rate from bellows penetration X-25 at Quad Cities Unit 1 of 137.4 SCFH. The analytical method will be applied to the 3 major crack sizes in an attempt to predict the observed flow rate. This model was selected because of its accurate representation of actual flow conditions and geometries.

Section 4 of this calculation will present the results of the leakage rates through the cracks predicted by the analytical method for three different populations of crack sizes. The three crack sizes based on length are:

1.7 inches
0.5 inches
3/16 (.1875) inches

Section 5 of this calculation will determine the worst case leak rate expected from the cracks characterized geometrically as "pinholes". This section uses two analytical methods to model the "pinholes" which bound the flow regimes (i.e. laminar and turbulent, choked). The method giving the largest flow rate is selected.

Section 6 of this calculation will present a methodology along with a justification for scaling the measured leak rate through observed cracks during a recent ILRT to a future ILRT. The future ILRT will be performed at the end of a fuel cycle where the leakage is postulated to occur through a similar population of cracks as observed above that have been allowed to grow a specified amount as predicted by fracture mechanics.

3.0 NOMENCLATURE

NOMENCLATURE

Q_o = Volumetric flow rate outside the bellows

G = Mass flow rate

t_1 = Temperature inside the bellows

P_o = Pressure outside of bellows

P_1 = Pressure inside of bellows

a = Crack area

D_h = Hydraulic diameter

A_h = Hydraulic area

R_a = Wall/crack roughness

f = Friction factor

l = Depth of crack

w = Width of crack

n = Polytropic index

C_d = Flow discharge coefficient

C = Temperature in degrees Celsius

ρ_o = Density of air at standard temperature and pressure

ρ_1 = Density of air inside bellows

μ = Absolute viscosity

k = Specific heat ratio

v_s = Sonic velocity

Re = Reynolds number

R = Ideal gas constant

AP_{ratio} = Actual pressure ratio

CP_{ratio} = Critical pressure ratio

λ = Friction coefficient

4.0 ANALYTICAL MODEL UTILIZING COMPRESSIBLE FLOW THROUGH A THICK WALLED ORIFICE LOCATED IN A WALL OF INFINITE AREA

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BASELINE CALCULATION FOR ILRT CONDITIONS

I PURPOSE

The purpose of this calculation is to determine flow rate through various postulated cracks in the X-25 bellows at Quad Cities Unit 1.

II ASSUMPTIONS

1. The area at the entrance to the crack is equal to the area at the exit of the crack.

2. The most restrictive losses occur at the outer bellows ply, therfore the annulus between plys is at ILRT pressure and all losses can be attributed to one bellows ply.

3. Due to the irregular shape of the crack opening, all the models will utilize an area based on the hydraulic diameter of the opening.

4. The model used for this calculation is based on compressible, choked flow through a thick-walled orifice located in a wall of infinite area.

III INITIAL CONDITIONS

1. Pressure and temperature in the containment is a constant at 49 psig and 90F, respectively per reference 1.

2. Pressure and temperature outside the containment are at standard atmospheric conditions.

3. The calculation has been performed three times for crack lengths of 1.7, 0.5, and 0.1875 inches. In addition, an idealized flow rate (i.e., discharge coefficient = 1.0) for the 1.7 inch crack was calculated.

4. A uniform wall thickness of 0.0351 inches exists for all cracks.

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IV CALCULATION

For the 1.7 inch crack

A. Determination of Flow Conditions

The following is a list of parameters to be used in throughout this calculation.

$P_1 := 49\ psig$ ILRT guage pressure (Ref 1)

$P_0 := 0\ psig$ guage pressure (outside containment)

$P_{atm} := 14.7\ psia$

$P_1 := P_1 + P_{atm}$ $P_1 = 63.7\ psia$ ILRT abs. pressure

$P_0 := P_0 + P_{atm}$ $P_0 = 14.7\ psia$ Abs. pressure (outside cnt.)

$P_1 = 4.3932 \cdot 10^5\ Pa$ $P_0 = 1.0138 \cdot 10^5\ Pa$

$\rho_1 := 0.313\ \frac{lb}{ft^3}$ $\rho_1 = 5.01\ \frac{kg}{m^3}$ Density @ 90 F & 49 psig (Ref 2)

$l := 0.035\ in$ $l = 8.89 \cdot 10^{-4}\ m$ Bellows wall thickness (Ref 9)

$R_a := 5 \cdot 10^{-6}\ m$ Wall Roughness (Ref 7)

$t_1 := 305.37\ K$ ILRT containment temperature (Ref 10)

$R := 287\ \frac{m^2}{sec^2 \cdot K}$ Gas Constant (Ref 10)

$\mu := 1.87 \cdot 10^{-5}\ Pa\ sec$ Absolute Viscosity @ 90F, 32.2C (Ref 5)

$k := 1.4$ Ratio of constant pressure to constant volume (ReRef

Next, the conditions for choked flow to exist will be checked by comparing the actual pressure ratio to a critical pressure ratio.

Critical Pressure Ratio (for compresible nozzle flow):

$$CP_{ratio} := \left[\frac{2}{k+1}\right]^{\frac{k}{k-1}} \qquad CP_{ratio} = 0.5283$$

(Ref 5, page 348)

Actual Pressure Ratio:

$$AP_{ratio} := \frac{P_0}{P_1} \qquad AP_{ratio} = 0.2308$$

CP > AP , therefore the flow is choked. (Ref 5, page 348)

Due to the crack configuration, a hydraulic diameter will be calculated in order to determine the Reynold's number for the flow through the crack.

Hydraulic Diameter Determination:

$a := 22.335 \cdot 10^{-3}\ in^2$	$a = 1.441 \cdot 10^{-5}\ m^2$	Crack Area (Ref 3)
$p := 3.542\ in$	$p = 0.09\ m$	Crack perimeter (Ref 3)
$D_h := 4 \cdot \frac{a}{p}$	$D_h = 6.4067 \cdot 10^{-4}\ m$	Hydraulic dia (Ref 4)
$A_h := \pi \cdot \frac{D_h^2}{4}$	$A_h = 3.2237 \cdot 10^{-7}\ m^2$	Area based on hydraulic dia. (Ref 4)

B. Calculating the discharge coefficient for a thick-walled deep orifice

The discharge coefficient (Cd) will be determined from the coefficient of fluid resistance (f). The coefficient of fluid resistance will be determined using Table 2-2 of Reference 6, the Reynold's number (Re), the relative wall roughness (Rr), and friction coefficient (λ).

Since the flow has been determined to be choked, the velocity of the medium is sonic. Thus, the velocity (Vs) through the crack is:

$$V_s := \left[k \cdot R \cdot t_1\right]^{0.5} \qquad V_s = 350.2823 \frac{m}{sec} \qquad \text{(Ref 5, Eq 11.3)}$$

Reynold's Number:

$$Re := \rho_1 \cdot V_s \cdot \frac{D_h}{\mu} \qquad Re = 6.0124 \cdot 10^4 \qquad \text{(Ref 5, page 153)}$$

Relative Roughness:

$$R_r := \frac{R_a}{D_h} \qquad R_r = 0.0078 \qquad \text{(Ref. 6, page 80)}$$

Based on the ratio of the wall thickness or crack depth (l) to the hydraulic diameter, the initial coefficient of fluid resistance (fo) can be obtained from Reference 6.

$$Ratio := \frac{l}{D_h} \qquad Ratio = 1.3876$$

Therefore, $f_0 := 1.62$ (Ref 6, page 174)

The friction coefficient (λ) is the friction resistance of a segment of relative unit length and can be obtained from Table 2-2 of Reference 6.

$\lambda := 0.032$ (Ref 6 page 80)

Coefficient of fluid resistance:

$$f := f_0 + \lambda \cdot \left[\frac{1}{D_h}\right] \qquad f = 1.6644 \qquad \text{(Ref 6 page 174)}$$

Discharge Coefficient (accounting for losses in the nozzle):

$$C_d := \frac{1}{f^{0.5}} \qquad C_d = 0.7751 \qquad \text{(Ref 6, page 35)}$$

C. Mass Flow Rate (for choked flow):

$$G := C_d \cdot A_h \cdot \left[\frac{2}{k+1}\right]^{\frac{1}{k-1}} \cdot \left[\left[\frac{2 \cdot k}{k+1}\right] \cdot \rho_1 \cdot P_1\right]^{0.5} \qquad \text{(Ref 6, page 35)}$$

$$G = 2.5383 \cdot 10^{-4} \frac{kg}{sec}$$

$$\rho_0 := 0.0764 \frac{lb}{ft^3} \qquad \rho_0 = 1.2229 \frac{kg}{m^3} \qquad \text{(Ref 2, 0 psig, 60 F)}$$

$$Q_0 := \frac{G}{\rho_0} \qquad Q_0 = 2.0757 \cdot 10^{-4} \frac{m^3}{sec}$$

$$Q_0 = 26.3686 \frac{ft^3}{hr}$$

Final Flow (Standard)
For 1.7" Crack

D. Maximum Flow Rate for Idealized Conditions

For idealized flow conditions, the disharge coefficient is assumed to be 0. The resulting idealized flow rate (without exit losses) would represent the maximum flow rate as modeled in this calculation.

$$C_d := 1.0$$

$$G := C_d \cdot A_h \cdot \left[\frac{2}{k+1}\right]^{\frac{1}{k-1}} \cdot \left[\left[\frac{2 \cdot k}{k+1}\right] \cdot \rho_1 \cdot P_1\right]^{0.5}$$

$$G = 3.2748 \cdot 10^{-4} \frac{kg}{sec}$$

$$Q_0 := \frac{G}{\rho_0} \qquad Q_0 = 34.0186 \frac{ft^3}{hr} \quad \text{(Standard)}$$

For the 0.5 inch Crack

For the 0.5 inch crack, steps A, B, & C will be repeated to calculate it's respective flow rate. All variables not specifically listed remain unchanged from those used in the 1.7 inch crack flow rate calculation above.

A. Determination of Flow Conditions

Critical Pressure Ratio:

$$CP_{ratio} := \left[\frac{2}{k+1}\right]^{\frac{k}{k-1}} \qquad CP_{ratio} = 0.5283$$

Actual Pressure Ratio:

$$AP_{ratio} := \frac{P_0}{P_1} \qquad AP_{ratio} = 0.2308$$

CP > AP , therefore the flow is choked.

Hydraulic Diameter Determination:

$a := 7.42 \cdot 10^{-4}\ in^2$ $\quad a = 4.7871 \cdot 10^{-7}\ m^2$ Crack Area - (Ref 3)

$p := 1.12\ in$ $\quad p = 0.0284\ m$ Crack edge - (Ref 3)

$D_h := 4 \cdot \frac{a}{p}$ $\quad D_h = 6.731 \cdot 10^{-5}\ m$

$$A_h := \pi \frac{D_h^2}{4} \qquad A_h = 3.5584 \cdot 10^{-9} \, m^2$$

B. Calculating the discharge coefficient for a thick-walled deep orifice

Fluid Velocity:

$$V_s := \left[k \cdot R \cdot t_1 \right]^{0.5} \qquad V_s = 350.2823 \, \frac{m}{sec}$$

Reynold's Number:

$$Re := \rho_1 \cdot V_s \cdot \frac{D_h}{\mu} \qquad Re = 6.3168 \cdot 10^3$$

Relative Roughness:

$$R_r := \frac{R_a}{D_h} \qquad R_r = 0.0743$$

Coefficient of Fluid Resistance:

$Ratio := \frac{l}{D_h}$ $Ratio = 13.2075$

Therefore, $f_0 := 1.55$ (Ref 6 page 174)

$\lambda := 0.0831$ (Ref 6 page 80)

NOTE: It is necessary to perform an interpolation/extrapolation for the values of R_r and Re to obain λ from Table 2-2.

$f := f_0 + \lambda \left[\frac{l}{D_h}\right]$ $f = 2.6475$

$C_d := \frac{1}{f^{0.5}}$ $C_d = 0.6146$

C. Mass Flow Rate (for choked flow)

$$G := C_d A_h \left[\frac{2}{k+1}\right]^{\frac{1}{k-1}} \left[\left[\frac{2\,k}{k+1}\right] \rho_1 P_1\right]^{0.5}$$

$G = 2.2215 \cdot 10^{-6} \frac{kg}{sec}$

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$\rho_0 := 0.0764 \cdot \frac{lb}{ft^3}$ $\rho_0 = 1.2229 \cdot \frac{kg}{m^3}$

$Q_0 := \frac{G}{\rho_0}$ $Q_0 = 1.8166 \cdot 10^{-6} \frac{m^3}{sec}$

Final Flow For 0.5" Crack $Q_0 = 0.2308 \cdot \frac{ft^3}{hr}$ (Standard)

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For the 0.1875 inch crack

For the 0.1875 inch crack, steps A, B, & C will be repeated to calculate its respective flow rate. All variables not specifically listed remain unchanged from those used in the 1.7 inch crack flow rate calculation above.

A. Determination of Flow Conditions

Critical Pressure Ratio:

$$CP_{ratio} := \left[\frac{2}{k+1}\right]^{\frac{k}{k-1}} \qquad CP_{ratio} = 0.5283$$

Actual Pressure Ratio:

$$AP_{ratio} := \frac{P_0}{P_1} \qquad AP_{ratio} = 0.2308$$

CP > AP , therefore the flow is choked.

Hydraulic Diameter Determination:

$a := 2.1 \cdot 10^{-4}\ in^2 \qquad a = 1.3548 \cdot 10^{-7}\ m^2$ Crack Area - Ref 3

$p := 0.407\ in \qquad p = 0.0103\ m$ Crack perimeter Ref 3

$D_h := 4 \cdot \frac{a}{p} \qquad D_h = 5.2423 \cdot 10^{-5}\ m$

$$A_h := \pi \frac{D_h^2}{4} \qquad A_h = 2.1584 \cdot 10^{-9}\ m^2$$

B. Calculating the discharge coefficient for a thick-walled deep orifice:

Fluid Velocity:

$$V_s := \left[k\ R\ t_1\right]^{0.5} \qquad V_s = 3.5028 \cdot 10^{2}\ \frac{m}{sec}$$

Reynold's Number:

$$Re := \rho_1\ V_s \frac{D_h}{\mu} \qquad Re = 4.9196 \cdot 10^{3}$$

Relative Roughness:

$$R_r := \frac{R_a}{D_h} \qquad R_r = 0.0954$$

Coefficient of Fluid Resistance:

$$Ratio := \frac{l}{D_h} \qquad Ratio = 16.9583$$

Therefore, $f_0 := 1.55$ (Ref 6, page 174)

$\lambda := 0.0964$ (Ref 6, page 80)

NOTE: It is necessary to perform an interpolation/extrapolation for the values R_r and Re to obtain λ from Table 2-2.

$$f := f_0 + \lambda \left[\frac{l}{D_h}\right] \qquad f = 3.1848$$

$$C_d := \frac{1}{f^{0.5}} \qquad C_d = 0.5604$$

C. Mass Flow Rate (for choked flow):

$$G := C_d\, A_h \left[\frac{2}{k+1}\right]^{\frac{1}{k-1}} \left[\left[\frac{2\,k}{k+1}\right] \rho_1\, P_1\right]^{0.5}$$

$$G = 1.2286\ 10^{-6}\ \frac{kg}{sec}$$

$\rho_0 := 0.0764 \frac{lb}{ft^3}$ $\rho_0 = 1.2229 \frac{kg}{m^3}$

$Q_0 := \frac{G}{\rho_0}$ $Q_0 = 1.0047 \cdot 10^{-6} \frac{m^3}{sec}$

Final Flow
For 0.1875" Crack $Q_0 = 0.1276 \frac{ft^3}{hr}$ (Standard)

V. SUMMATION OF LEAK RATES

CRACK SIZE (inches)	VOLUMETRIC FLOW RATE (ft^3/hr)	NO. OF CRACKS	RELATIVE VOLUME (ft^3/hr)
1.7	26.3686	1	26.3686
0.5	0.2308	3	.6927
0.1875	0.1276	36	4.5936
Pinhole	0.0658	200	13.16
	(see Calc. COE118.0200.02, Section 5)		

Total w/Pinholes

$$Q_T = (26.3686) + .6927 + 4.5936 + 13.16$$
$$= 44.815 \ ft^3/hr$$

Total w/out Pinholes

$$Q_T = (26.3686) + .6927 + 4.5936$$
$$= 31.655 \ ft^3/hr$$

1.7 in. crack percentage of total w/Pinholes

$$\frac{26.3686}{44.815} \times 100\% = 58.8\%$$

1.7 in. crack percentage of total w/out Pinholes

$$\frac{26.3686}{31.655} \times 100\% = 83.3\%$$

0.1875 in. crack percentage of total w/out Pinholes

$$\frac{4.5936}{31.655} \times 100 = 14.5\%$$

VI. CONCLUSION

The objective of this calculation was to determine the flow rate from the postulated cracks in the X-25 bellows. The success with which this was accomplished can only be realized by carefully considering the results for each crack in relation to the total leakage, as well as the basis for the governing assumptions.

Section V tabulates the resulting flow rates for varying crack size and the respective number of cracks found. The most important determination made from this data is that the large (1.7 inch) crack contributes almost 59% of the total leakage if pinhole leakage is considered and over 83% of total if the pinholes are neglected. The next largest contributor of measurable size is the family of 0.1875 in. cracks, which are responsible for just 14.5% of the total leakage w/out pinhole leakage. Since the number of pinhole leaks is an approximation based on a quadrant average, it is reasonable to neglect it in prediction of overall percentage of leak rates.

The significance of the large cracks contribution to the total leakage indicates that any future predictions of leakage may be approximated based on the large cracks alone given that ratio of the number of the small cracks ($L \leq 0.5"$) to the number of the large cracks is ≤ 10. Additionally, a worst case bounding value of leakage through the large crack (1.7") was calculated. Section IV.D calculates the flow rate based on an ideal fluid resistance coefficient (C_d) of 1. The resulting flow rate increases 24% over the actual predicted value.

The differences that exist between the measured flow rate of 137.4 ft^3/hr and the theoretical values do not invalidate the model used for this analysis. It must be noted that the irregular outline of the cracks do not lend themselves to accurate prediction of areas. Also, due to the nature of the crack geometry, it is reasonable to assume that flow profiles are not fully developed. These two facts suggest that the actual flow area be corrected in some manner. This calculation accounts for these effects by utilizing a flow area based on the hydraulic diameter of the openings. Results from calculations utilizing the actual crack were considerably higher than the measured leakages. Although lower than the measured values, the calculation yields reproducible leakages, representing the varying percentage of leakage contribution from the various crack sizes.

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5.0 ANALYTICAL MODEL FOR FLOW RATE THROUGH "PINHOLE" CRACKS UTILIZING LAMINAR AND TURBULENT COMPRESSIBLE FLOW

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PURPOSE

To conservatively determine the flow rate from Transgranular Stress Corrosion Cracks (TGSCC) with a geometry described as "Pinholes."

INPUT/ASSUMPTIONS

1. "Pinholes" modeled conservatively as a thick walled circular orifice in an infinite wall with a throat diameter D = 0.001 in. = 0.0000254 m (Ref. 12).

2. Discharge Coefficient, C_d, for orifice chosen ideally high at 1.0.

3. Integrated Leak Rate Test (ILRT) Conditions Apply

$$\text{Inside Containment, Pressure, } P_1 = 49 \text{ psig} = 4.39 \times 10^5 \frac{N}{m^2} \text{ (abs.)}$$

$$\text{Temperature, } T_1 = 90°F = 550°R \qquad \text{(Ref. 1)}$$

$$\text{Density, } \rho_1 = 0.313 \frac{lb}{ft^3} = 5.01 \frac{Kg}{m^2} \qquad \text{(Ref. 2)}$$

$$\text{Ratio of Specific Heats for air } k = 1.4 \qquad \text{(Re[illegible]}$$

4. Number of Pinhole Cracks, N = 200 (Ref. 12)

5. Sonic (Choked) Flow

CALCULATION

For sonic conditions, the mass flow rate is given by

$$G = C_d a\left(\frac{2}{k+1}\right)^{\frac{1}{(k-1)}} \sqrt{2\frac{k}{k+1}\ \rho_1 P_1} \qquad \text{(Ref. 6)}$$

where a is the orifice throat area $= \frac{\pi}{4}(.0000254m)^2 = 5.07 \times 10^{-10} m^2$

$$G = 1.0 \cdot 5.07 \times 10^{-10}\left(\frac{2}{1.4+1}\right)^{\frac{1}{(1.4-1)}} \sqrt{\frac{2 \cdot 1.4}{1.4+1}\ 5.01 \cdot 4.39 \times 10^5}$$

$$G = 5.15 \times 10^{-7}\ \frac{Kg}{sec}$$

Volumetric flow rate at standard conditions, Q_o

density of air at standard conditions, $\rho_o = 1.222\ \frac{kg}{m^3}$

$$Q_o = \frac{G}{\rho_o} = \frac{5.15 \times 10^{-7}}{1.222} \cdot \left(\frac{1}{.3048}\right)^3 \cdot 3600 = 5.36 \times 10^{-2}\ SCFH$$

Total (Worst Case) Leak Rate from all "Pinholes"

$$Q_{T_o} = N \cdot Q_o = 200 \cdot 5.36 \times 10^{-2} = 11\ SCFH$$

Now try laminar flow:

For laminar flow, the mass flow rate is given by

$$G = \frac{g\pi D^4}{256\ \mu \ell} \cdot \frac{1}{RT_1}\,[P_1^2 - P_0^2] \qquad (Ref.\ 14,\ Section\ 3.2.2)$$

where:

g is the gravitational conversion constant = 32.2 $\frac{lbm \cdot ft}{lbf \cdot sec^2}$

D is the pinhole throat diameter = 0.001 in = 0.0001 ft.

P_1 is the inside Bellows Pressure = 49 psig = 63.7 $\frac{lb_f}{in^2}$ = 9,172.8 $\frac{lb_f}{ft^2}$

P_0 is the standard atmospheric pressure = 14.7 psia = 2,116.8 $\frac{lbf}{ft^2}$

μ (at 90°F) is the viscosity of gas = 0.0187 centipoises = 1.256 x 10^{-5} $\frac{lbm}{ft \cdot sec}$ (Ref. 2)

ℓ is the length of the leak path = 0.035 in = 0.0029 ft (Ref. 9)

R is the gas constant = 53.34 $\frac{ft\ lbf}{lbm\ ^\circ R}$ (Ref. 8)

T_1 is the inside Bellows Temperature = 90°F = 550°R (Ref. 10)

$$G = \frac{32.2(\pi)(4.82 \times 10^{-17})(79,659,417.60)}{256(1.256 \times 10^{-5})(.003)(53.34)(550)} = 1.42 \times 10^{-6} \frac{lbm}{sec}$$

$$units = \frac{lbm}{sec}$$

$\rho_0 = .0764 \frac{lbm}{ft^3}$ at $t = 60°F$ and atmospheric pressure (Ref. 2)

volumetric flow rate at standard conditions, Q_0

$$Q_0 = \frac{G}{\rho_0} = \frac{(1.37 \times 10^{-6})}{.0764} \cdot 3600 = .0646\ SCFH$$

$$Q_{T_0} = N \cdot Q_0 = 200 \cdot 0.0646 = 13\ SCFH$$

CONCLUSIONS

For determining the flow rate from the "pinholes," the laminar flow case gives a larger flow rate than the turbulent flow case.

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6.0 PREDICTION OF LEAKAGE RATES AT ILRT CONDITIONS DUE TO CRACK GROWTH AFTER ONE FUEL CYCLE

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PURPOSE

The purpose of this section is to determine a relationship between volumetric flow rate and crack area. Once the relationship is defined, the hypothetical volumetric flow rate for the postulated increased crack growth will be determined.

METHODOLOGY

The flow through the 1.7" crack during ILRT condition was calculated to be approximately 26.4 SCFH and for each of the medium size cracks with a length of 0.5 inches, was predicted to be approximately 0.231 SCFH. For the 3/16" cracks during ILRT condition, the flow was calculated to be approximately .128 SCFH. Additionally, the flow through the 200 pinhole flows was conservatively estimated at 13 SCFH total.

Using the observed crack population (Reference 12) modified by Reference 13, the flow through all cracks can be calculated as follows:

$$Q_{TOT} = Q_{1.7} + 3\ Q_{0.5} + 36\ Q_{3/16} + Q_{TOTAL\ PINHOLES} \quad \text{where } Q = \frac{G}{\rho_0}$$

(The subscripts correspond to the four different crack lengths.)

$$= 26.4 + 3\ (.231) + 36\ (.128) + 13 = 44.7 \text{ SCFH}$$

This total does not match the observed ILRT flow rate of 137.4 SCFH. Because each of the flow rate contributions from the different crack sizes came from the same correlation (except the pinhole leak rate), the assumption is made that each calculated crack flow rate deviates from the actual by the same constant of proportionality which is 137.4/44.7 = 3.07.

Adjusted with the proportionality constant, the actual leak rate through the crack is more closely represented by the following values:

CRACK SIZE	CALCULATED LEAK FOR CRACK SCFH	SEALED LEAK PER CRACK SCFH	NUMBER OF CRACKS	TOTAL LEAKAGE FOR EACH CRACK SIZE SCFH ($Q_{TOTAL\ BEFORE\ GROWTH}$)
1.7"	26.4	81.0	1	81.0
0.5"	0.231	.709	3	2.13
3/16" or .1875"	0.128	.393	36	14.11
Pinholes	0.065	.200	200	40.00
			TOTAL MEASURED	137.3≈ 137.4 SCFH

The expression used to determine the mass discharge through a crack is given by (Reference 6):

$$G = c_d A_h \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{2k}{k+1} \rho_1 P_1}$$

It is apparent from this expression that the last two parameters are independent of the crack size. Furthermore, comparison of G between ILRT tests at the same containment conditions allows ρ_1 and P_1 to be treated as constants. The two remaining parameters C_d and A_h were tabulated as follows:

	1.7"	0.5"	3/16" = 0.1875"
C_d	0.775	0.613	0.562
A_h (m^2)	3.22×10^{-7}	3.56×10^{-9}	2.2×10^{-9}
$C_d A_h$	2.4987×10^{-7}	2.182×10^{-9}	1.236×10^{-9}

where C_d is proportional to the square root of depth/hydraulic diameter of the crack. As shown in this table, % changes in C_d are small compared to % changes in A_h (for changes in corresponding crack lengths). This result is depicted by the change in the product of $C_d A_h$ as it more closely follows the percent change in A_h than that of C_d.

Therefore, one can conclude that the change in mass flow discharge through the crack varies nearly linearly with the change in A_b or D_b^2. Since the volumetric flow rate, Q_0, is directly proportional to the mass flow discharge, one can conclude that Q_0 also varies nearly linearly with the change in A_b or D_b^2. Hence, as an approximation, one can use the percentage change in area of the cracks after one fuel cycle to predict the appropriate leak flow rate as follows.

$$Q_{Total\ After\ Growth} = Q_{Total\ Before\ Growth} + Q_{Total\ Before\ Growth}\ (\%\ \text{change in area})$$

In order to prevent accumulated error from change in C_d, the above expression must be utilized per crack size.

The precent change in area per crack size is given by:

$$\%\ \textit{change in area} = \frac{\textit{Area after Growth - Area before Growth}}{\textit{Area before Growth}}$$

From Ref. 1 and 2:

INITIAL CRACK SIZE	AREA BEFORE GROWTH (in^2)	AREA AFTER GROWTH (in^2)	% CHANGE IN AREA
1.7"	22.3×10^{-3}	27.8×10^{-3}	.247 or 24.7%
0.5"	7.42×10^{-4}	10.4×10^{-4}	.402 or 40.2%
3/16" or 0.1875	2.10×10^{-4}	4.88×10^{-4}	1.32 or 132%
Pinhole	*	2.10×10^{-4}	*

*Area before growth of pinhole for this evaluation is taken as approximately 0 in^2.

Over a fuel cycle, the cracks are postulated to grow 3/16" (Ref. 12).

Therefore:

CRACK SIZE BEFORE GROWTH	CRACK SIZE AFTER GROWTH	$Q_{TOTAL\ AFTER\ GROWTH}$ SCFH
1.7"	1.89"	101
0.5"	0.688"	2.97
3/16" or 0.1875"	0.375"	32.7
Pinhole	0.1875"	78.6*
	SCALED TOTAL	215 SCFH

*This value represents the scaled leakage through a 3/16" crack calculated previously multiplied by 200 cracks.

Therefore, the predicted total measured leak rate after crack growth is 215 SCFH.

CONCLUSION

Analytically, it has been shown that the volumetric flow rate varies nearly linearly with the hydraulic area (for with the hydraulic diameter squared).

7.0 REFERENCES

nutech
Chicago, Illinois

PROJECT QUAD CITIES NUCLEAR POWER STATION UNIT #1 FILE NO. COE118.0200.02

OWNER COMMONWEALTH EDISON COMPANY

CLIENT COMMONWEALTH EDISON COMPANY

REFERENCES:

1. "Temporary Procedure 6653", Bellows Leakage Measurements; dated 3/4/91; Nutech file No. COE118.0160.
2. Cranes Technical Paper No. 410.
3. Nutech Calculation COE118.0200.01, "Determination of Longitudinal Crack Areas for the Quad Cities Unit 1 Bellows at Penetration X-25".
4. Marks Standard Handbook for Mechanical Engineers, Eighth Edition.
5. Introduction of Fluid Mechanics, Second Edition, J. John and W. Haberman; Prentice Hall.
6. Handbook of Hydraulic Resistance, Second Edition, 1970, Nutech file No. COE118.0160.
7. Calculation of Leak Rates Through Cracks in Pipes and Tubes, EPRI Research Project 1757-19, NP-3395. Nutech file no. COE118.0160.
8. Fluid Mechanics, Second Edition, F. M. White, 1986 McGraw-Hill, Inc.
9. Drawing 8052, "Pathway Bellows Drawing 18", Tandem Expansion Joint Assembly; Quad Cities Units 1 & 2", Rev. 0, Nutech file no. COE118.0160.
10. Reactor Containment Building Integrated Leak Rate Test, Quad Cites Nuclear Power Station Unit 1, dated November 14-15, 1989; 04 83H/02142, Nutech file no. COE118.0160.
11. CEGB 376/047, "Simple methods for predicting Gas Leakage through Cracks", D. J. Ewing, MA, PhD; Central Electricity Generating Board.
12. Meeting on Quad Cities Bellows Leakage, Nutech Communication Record RWR-91-024, dated March 22, 1991; Nutech file no. COE118.0001.
13. Nutech Communication Record TJW-91-056; "Drywell Penetration X-25 Bellows Replacement COE-118", dated March 25, 1991; Nutech file no. COE118.0001.
14. Document No. TID-20583;" Leakage Characteristics of Steel Containment Vessels and the Analysis of Leakage Rate Determinations", 1964;Nutech File No. COE118.0160.

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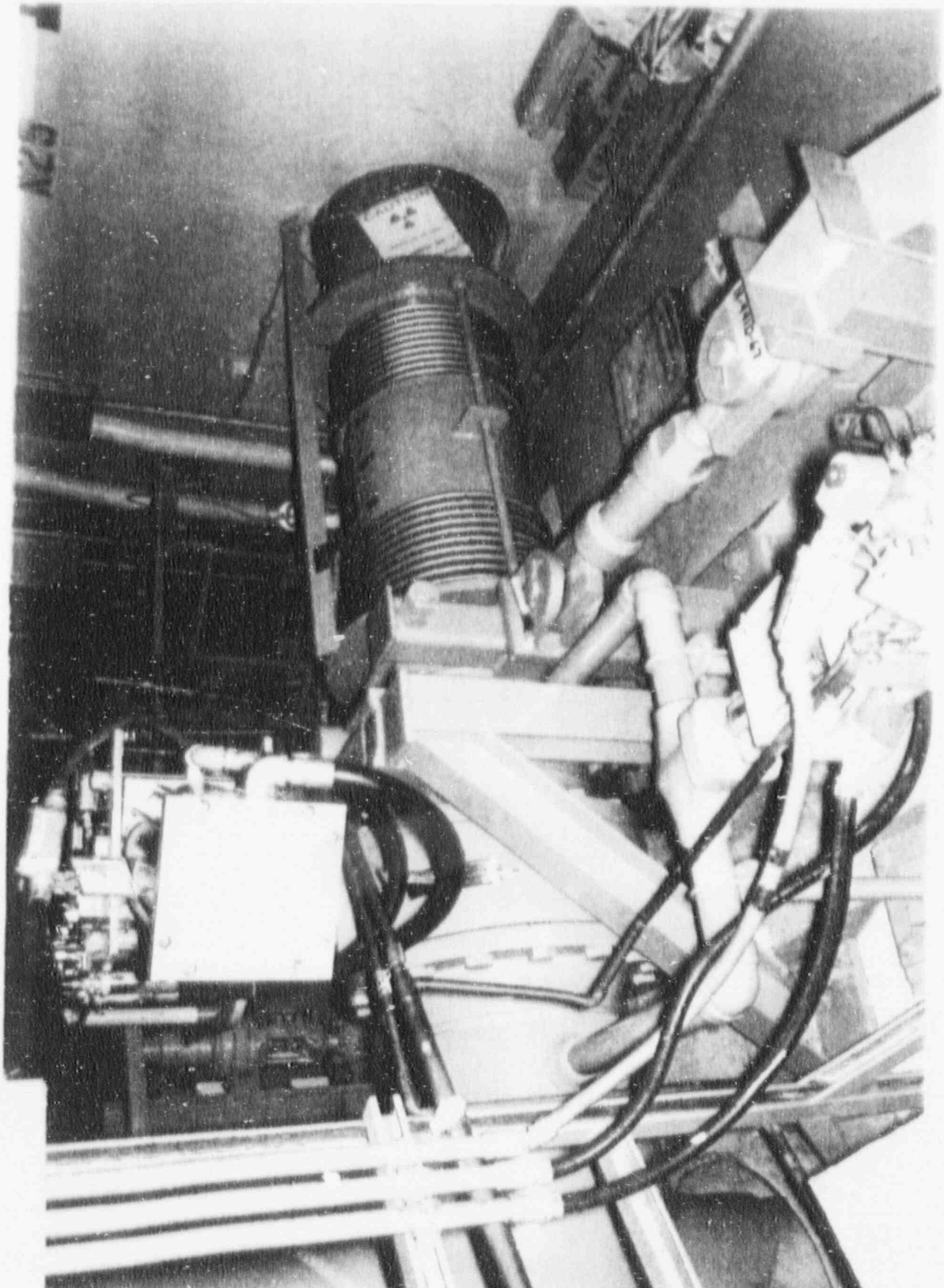
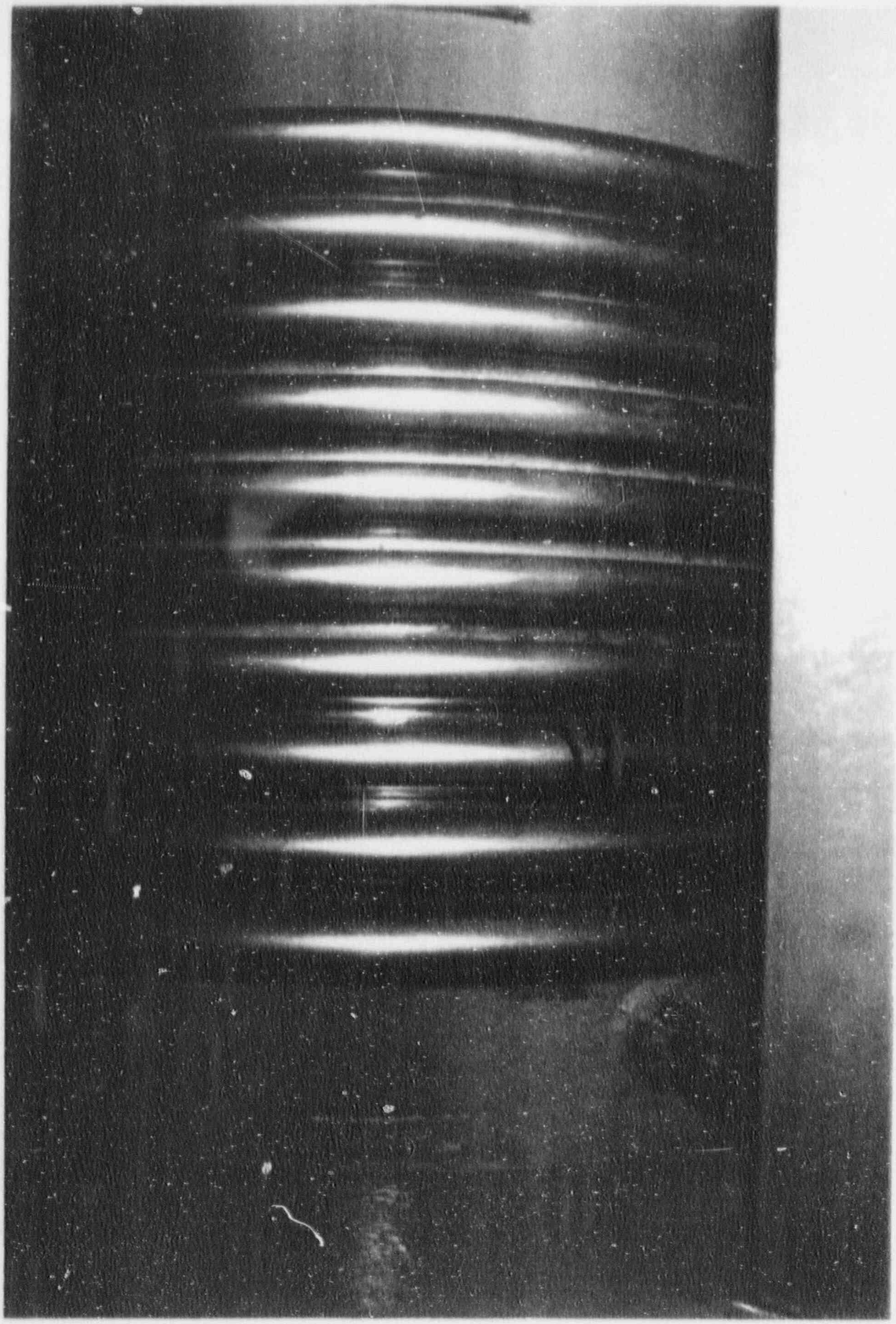
PREPARED BY/DATE	DPD/3-27-91					OF 37
CHECKED BY/DATE	SCS/3-27-91					

Attachment 4

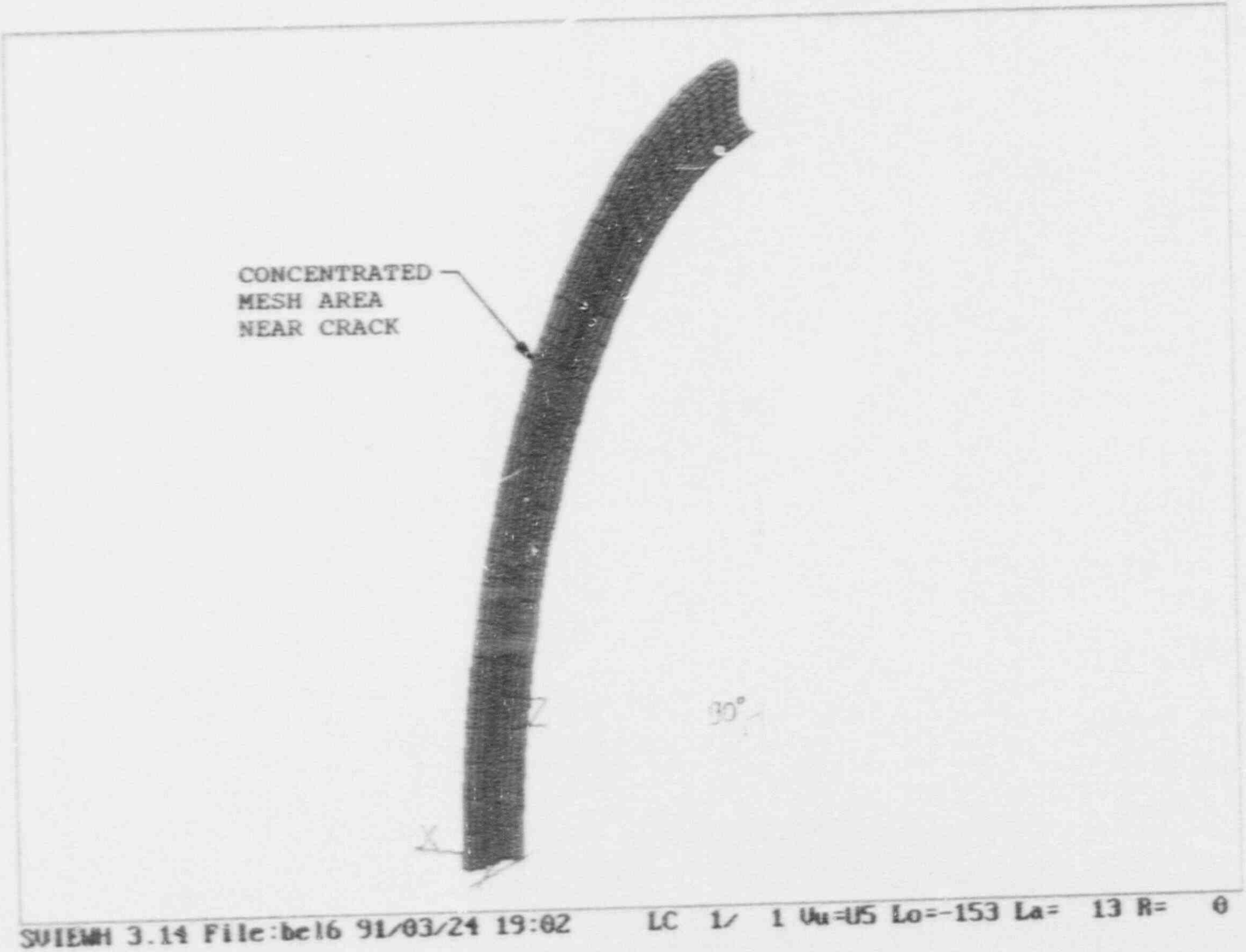
COMMONWEALTH EDISON COMPANY
PHOTOGRAPHS OF X-25
BELLOWS



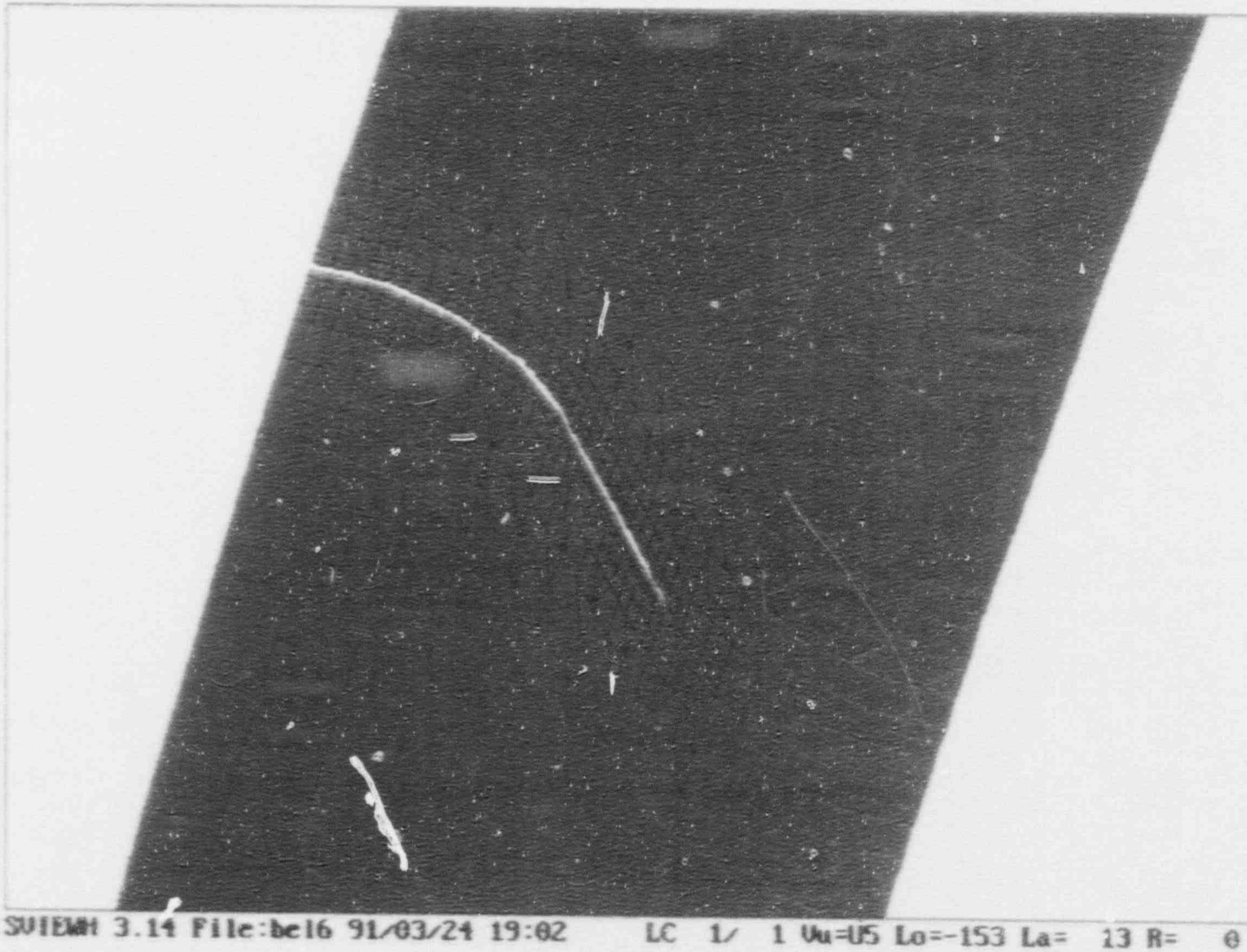


Attachment 5

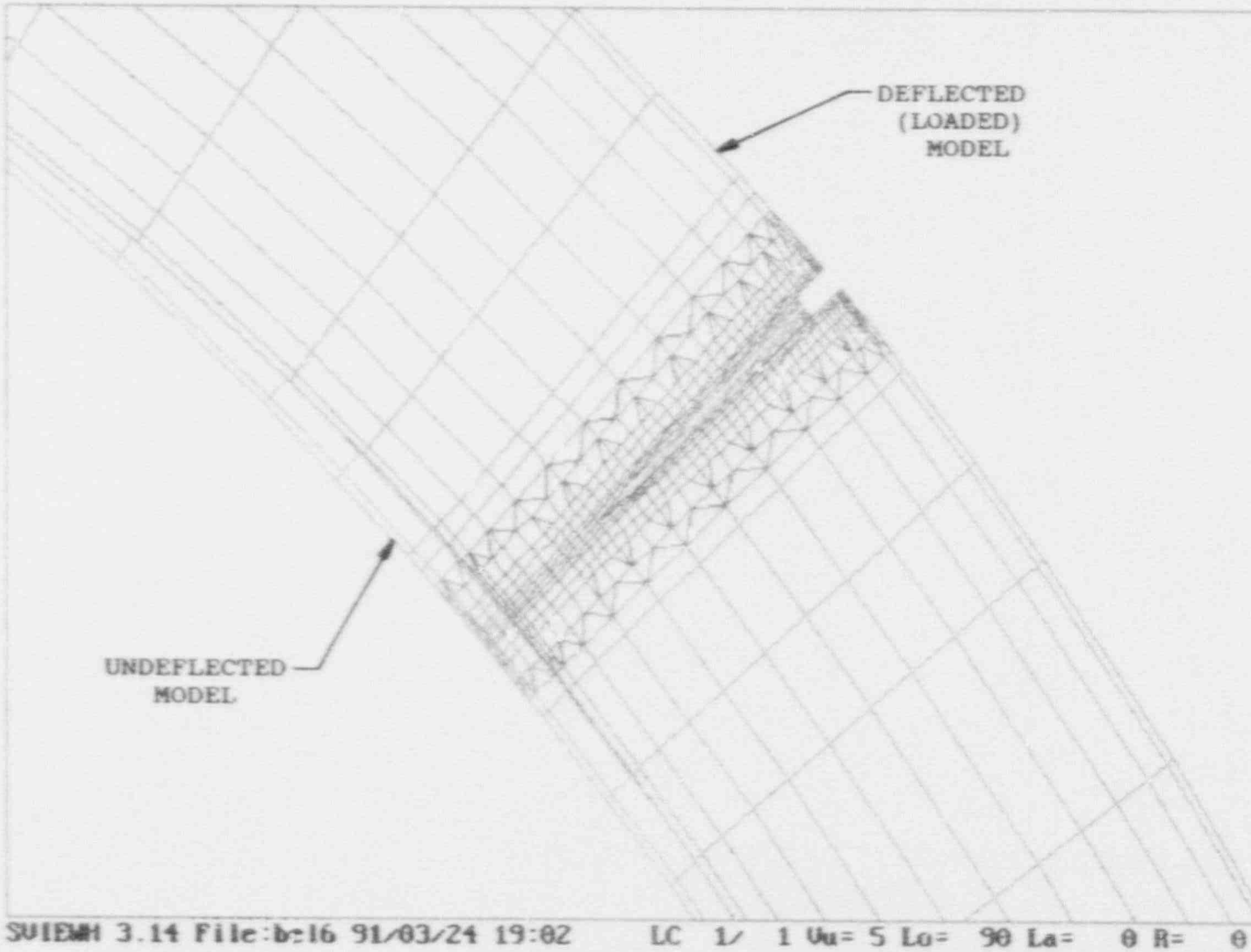
FINITE ELEMENT MODEL
DEPICTING BELLOWS DETAILS



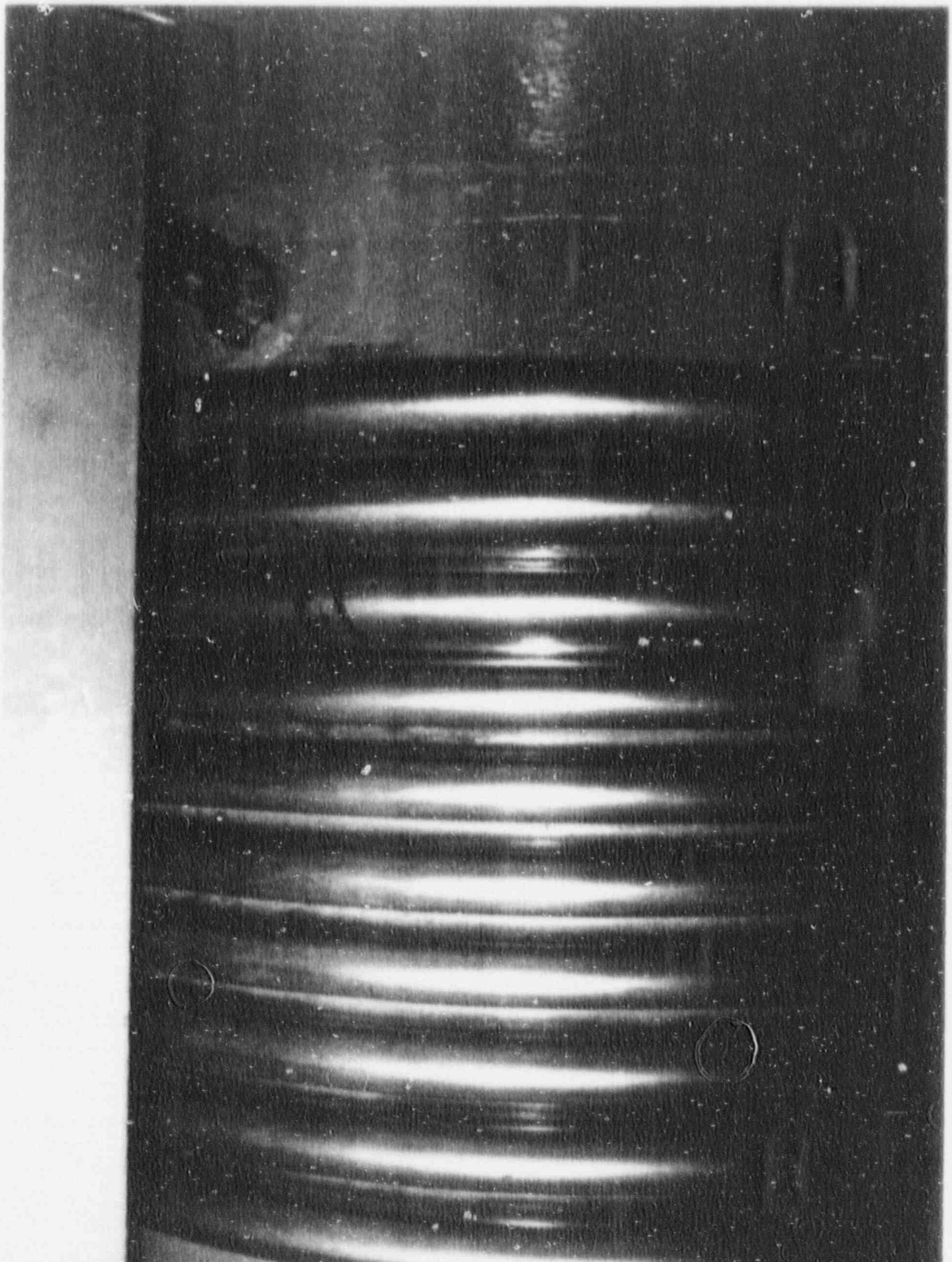
OBLIQUE VIEW SHOWING QUARTER MODEL OF HALF CONVOLUTION



OBLIQUE VIEW CLOSE-UP SHOWING 1.7" X 0.01" CRACK

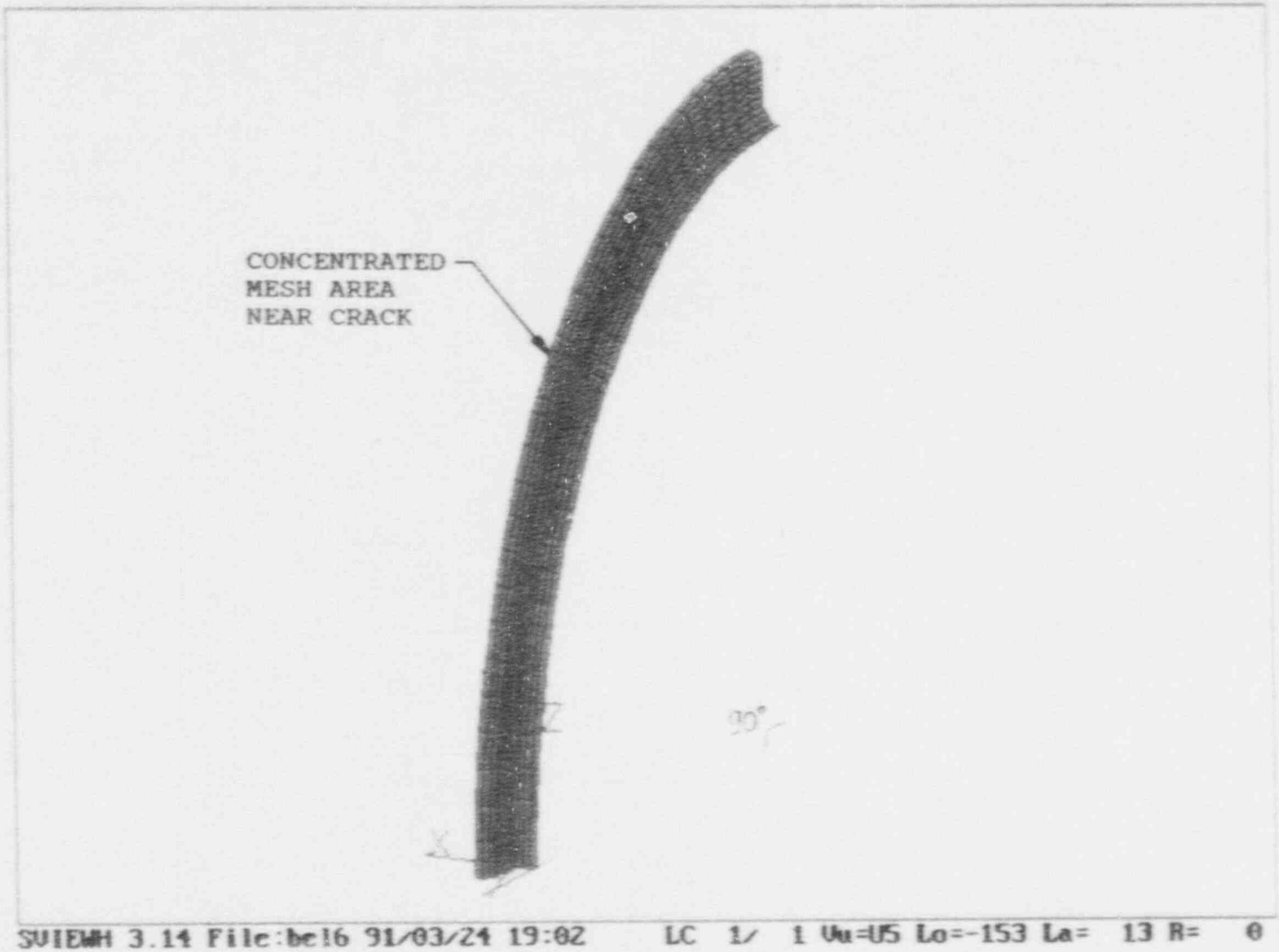


SIDE VIEW CLOSE-UP SHOWING CRACK EXPANSION DUE TO LOADING

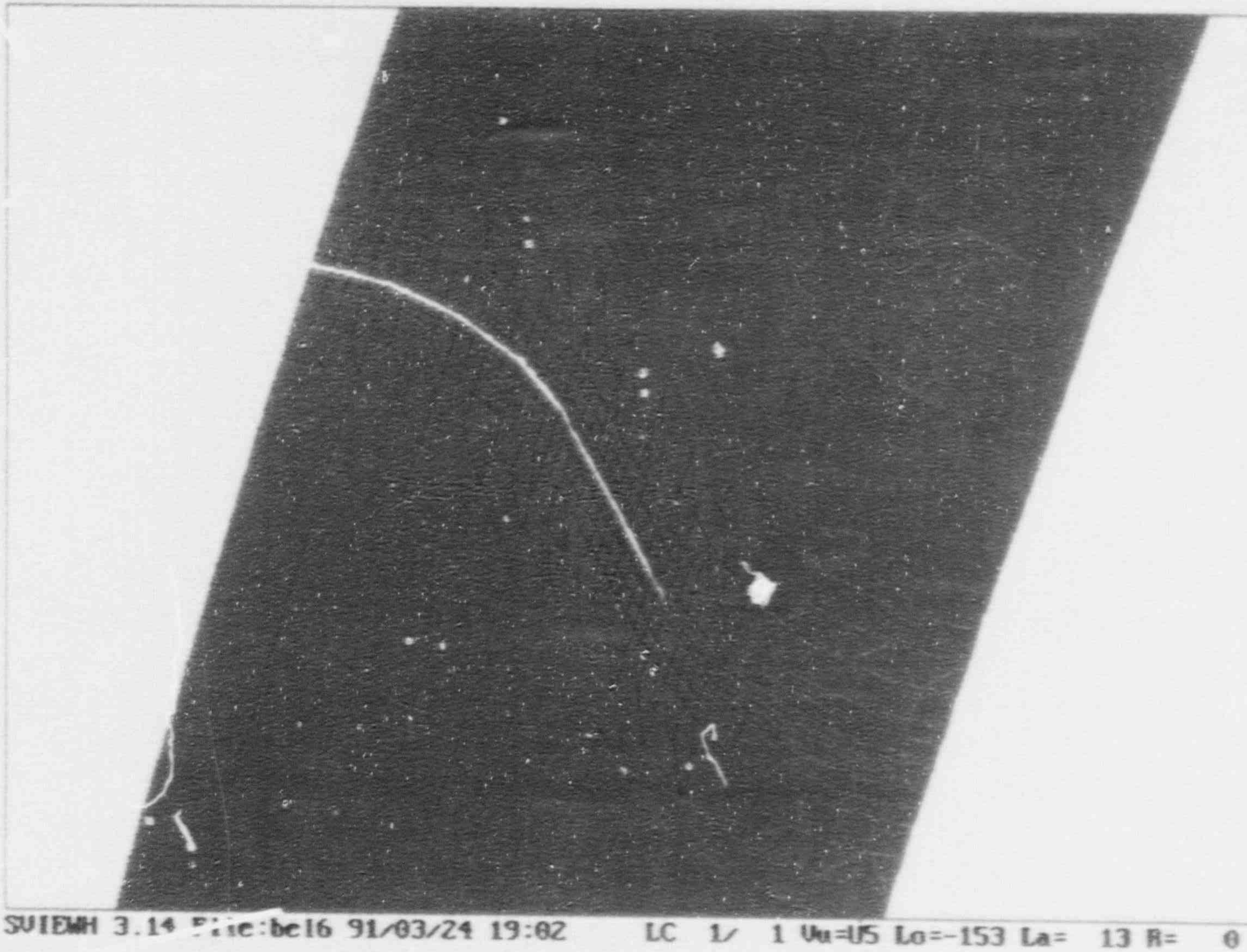


Attachment 5

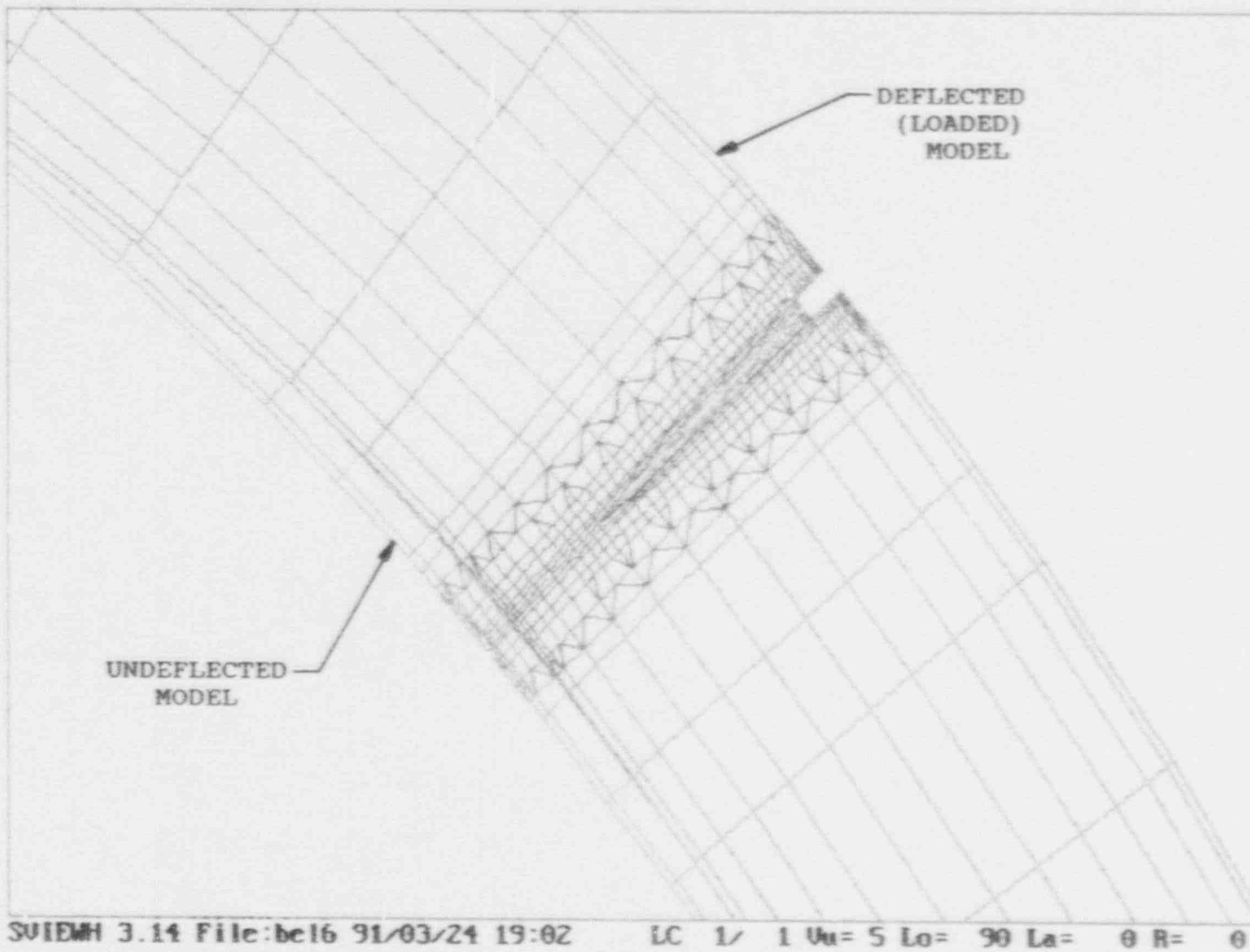
FINITE ELEMENT MODEL
DEPICTING BELLOWS DETAILS



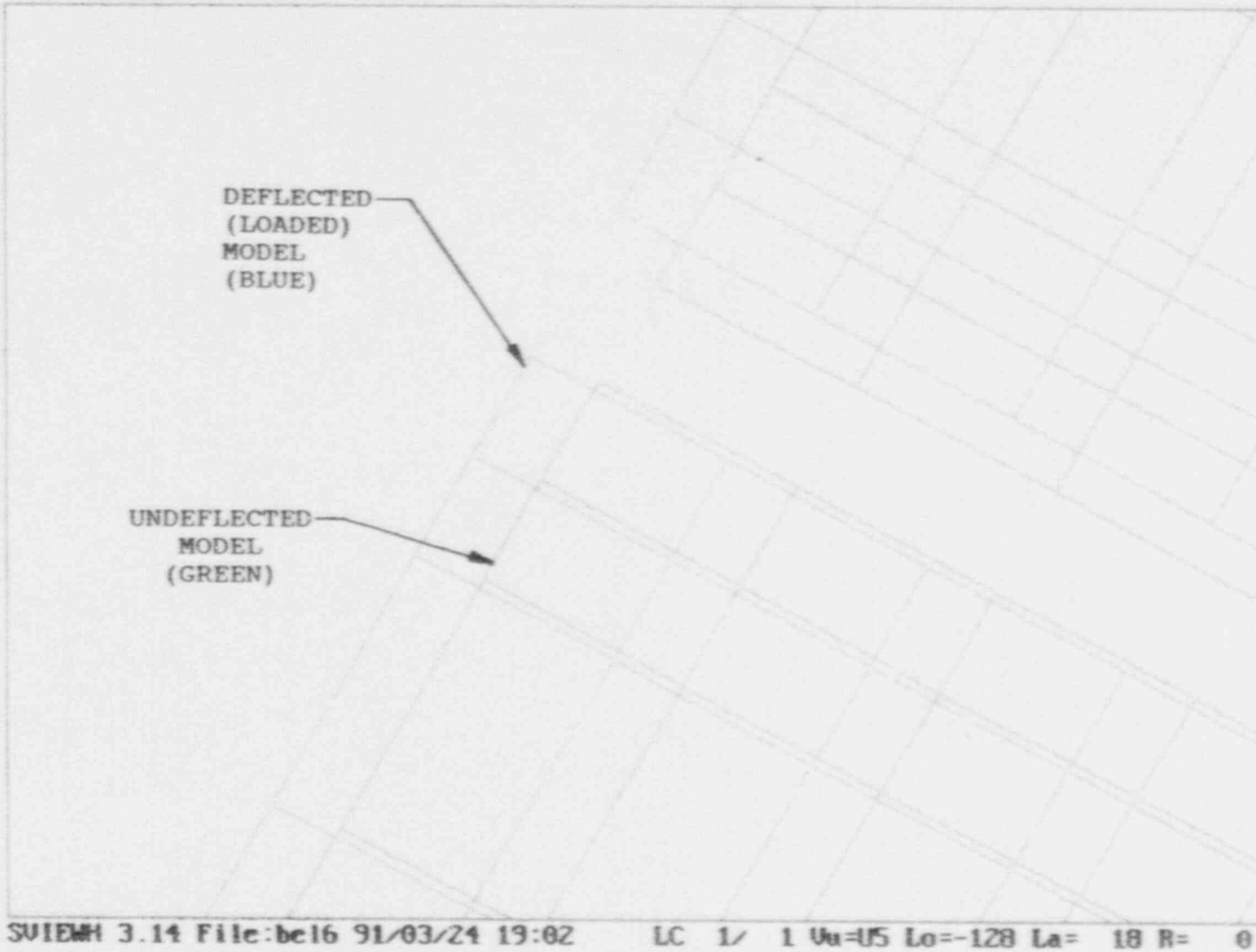
OBLIQUE VIEW SHOWING QUARTER MODEL OF HALF CONVOLUTION



OBLIQUE VIEW CLOSE-UP SHOWING 1.7" X 0.01" CRACK



SIDE VIEW CLOSE-UP SHOWING CRACK EXPANSION DUE TO LOADING



OBLIQUE VIEW EXTREME CLOSE-UP SHOWING CRACK EXPANSION DUE TO LOADING

Attachment 6

DESIGN INPUT LOG

DESIGN INPUT LOG

Unique Document No: COE-118
File No: COE118.0150
Revision No: 0
Date: 3/26/91

Client: Commonwealth Edison Company Project No: COE-118 Project Name: Quad Cities Bellows Leakage

Document No.	Title or Subject	Des. Input? Y/N	Rev. or Date	File Number	Responsible PE Approval	Date
Miscellaneous						
	Mark's Standard Handbook for Mechanical Engineers, Eighth Edition	Y	1970		[signature] PDB	3/27/91 3/26/91
	Mark's Standard Hadbook for Mechanical Engineers, Seventh Edition	Y				
	Handbook of Hydraulic Resistance, Second Edition, Revised and Augmented; I.E. Idelchik; Hemisphere Publishing Corporation	Y		COE118.0160	[signature]	3/27/91
	Introduction to Fluid Mechanics, Second Edition, J. John and W. Haberman; Prentice-Hall, Inc.	Y		COE118.0160	[signature]	3/27/91
	Standards of the Expansion Joint of Manufacturer's Association, Inc., Fifth Edition, including 1985 Addenda	Y	1980	NUTECH Library	PDB	3/26/91
	Fluid Mechanics, Second Edition, Frank M. White, McGraw-Hill Book Company	Y	1986	COE118.0160	[signature]	3/27/91
0483H/0219	Reactor Containment Building Integrated Leak Rate Test	Y	11/14/89	COE118.0160	[signature]	3/27/91 3/26/91
M-1243-91	System Materials Analysis Department Report on Inspection of the X-25 Drywell Penetration Bellows at Quad Cities Station	Y	3/12/91	COE118.0160	PDB	
CR 87946	Design Report Articulated Expansion Joint per ASME Boiler and Pressure Vessel Code Section III, Class MC	Y	3/05/91	COE118.0160	Jeffrey A. [signature] for PDB	3-27-91

* Asterisk designates preliminary input data

DESIGN INPUT LOG

Unique Document No: COE-118
File No: COE118.0150
Revision No: 0
Date: 3/26/91

Client: Commonwealth Edison Company **Project No:** COE-118 **Project Name:** Quad Cities Bellows Leakage

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Document No.	Title or Subject	Des. Input? Y/N	Rev. or Date	File Number	Responsible PE Approval	Date
	Temporary Procedure 6653, Bellows Leakage Measurements	Y	3/04/91	COE118.0160	[illegible]	3/27/91
	Updated FSAR for Quad Cities	Y		NUTECH Library	[illegible]	3-27-91
Meeting Notes						
RWR-91-024	Meeting on Quad Cities Bellows Leakage	Y	3/22/91	COE118.0001	[illegible]	3-27-91
Papers						
CEGB 376/047	Simple Methods for Predicting Gas Leakage Flow Through Cracks	Y			[illegible]	3-27-91
	Crane's Technical Paper No. 410	Y			[illegible]	3-27-91
	Crane's Technical Paper No. 410M	Y			[illegible]	3-27-91
	Fracture Mechanics Evaluation (unapproved copy)	Y	3/14/91	COE118.0160		
NP-3395	Calculation of Leak Rates Through Cracks in Pipes and Tubes EPRI Research Project 1757-19	Y		COE118.0160	[illegible]	3-27-91
TID-20583	Leakage Characteristics of Steel Containment Vessels and the Analysis of Leakage Rate Determinations	Y	1964	COE118.0160	[illegible]	3-27-91
Calculations						
COE118.0200.01	Determination of Longitudinal Crack Areas for the Quad Cities Unit 1 Bellows at Penetration X-25	Y	0	COE118.0200.01	[illegible]	3-27-91

* Asterisk designates preliminary input data

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Client: Commonwealth Edison Company Project No: COE-118 Project Name: Quad Cities Bellows Leakage

Document No.	Title or Subject	Des. Input? Y/N	Rev. or Date	File Number	Responsible PE Approval	Date
Telecons						
CJJ-91-006	Characterization of Observed Crack in X-25 Bellows Elements	Y	3/25/91	CWE053.0001	Jeffrey A. Treiber for PDB	3-27-91
TJW-91-056	Drywell Penetration X-25 Bellows Replacement COE-118	Y	3/25/91	COE118.0001	[signature]	3-27-91
Drawings						
8052	Pathway Bellows Drawing 18" Tandem Expansion Joint Assembly; Quad Cities Units 1 & 2 Item X-25	Y	0	COE118.0160	[signature]	3-27-91
Computer Models						
	Quad Cities Unit #1, Bellows at Penetration X-25 with 3/16" x .001" Crack at ILRT Conditions	Y	3/25/91	COE118.0200.01	Jeffrey A. Treiber for PDB	3-27-91
	Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 3/16" x 0.001" Crack at ILRT Conditions."	Y	3/25/91	COE118.0200.01	Jeffrey A. Treiber for PDB	3-27-91
	Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 1/2" x 0.001" Crack at ILRT Conditions."	Y	3/24/91	COE118.0200.01	Jeffrey A. Treiber for PDB	3-27-91
	Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 1.7" x 0.010" Crack at ILRT Conditions."	Y	3/25/91	COE118.0200.01	Jeffrey A. Treiber for PDB	3-27-91

* Asterisk designates preliminary input data

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Document No.	Title or Subject	Des. Input? Y/N	Rev. or Date	File Number	Responsible PE Approval	Date
	Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 3/16" x 0.001 Crack with 3/16" Growth at ILRT Conditions."	Y	3/26/91	COE118.0200.01	Jeffrey A. Treiber for PDB	3-27-91
	Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 1/2" x 0.001" Crack with 3/16" Growth at ILRT Conditions."	Y	3/25/91	COE118.0200.01	Jeffrey A. Treiber for PDB	3-27-91
	Algor Computer Model "Quad Cities Unit #1: Bellows at Penetration X-25 with 1.7" x 0.010" Crack with 3/16" Growth at ILRT Conditions."	Y	[illegible]	[illegible]118.0200.01	Jeffrey A. Treiber for PDB	3-27-91
	Computer Program Verification Document, Algor Finite Element Software, Version 9.0	Y	0	QASJO.SOFT.2.165.9.0	Jeffrey A. Treiber for PDB	3-27-91
	Nures - Algor Finite Element Analysis Software, Version 9.0	Y	0	2.165.9.0	Jeffrey A. Treiber for PDB	3-27-91

* Asterisk designates preliminary input data