Attachment 3

Aptech Report AES 00033958-1-1

Structural Integrity Evaluation of Axial Outside Diameter Stress Corrosion Cracking at Eggcrate Supports for Arkansas Nuclear One Unit 2 Under Severe Accident Conditions

April 2000 AES 00033958-1-1

Prepared for

Entergy Operations, Inc.

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Structural Integrity Evaluation of Axial Outside Diameter Stress Corrosion Cracking at Eggcrate Supports for Arkansas Nuclear One Unit 2 Under Severe Accident Conditions

Prepared By

Brian W. Woodman
Peter S. Jackson

APTECH ENGINEERING SERVICES, INC.

Prepared For

Entergy Operations, Inc.
Route 3, Mail Box 137-G
Russellville, Arkansas 72801

Attention: Mr. Dan Meatheany

APTECH ENGINEERING SERVICES, INC.
1282 REAMWOOD AVENUE □ SUNNYVALE □ CA 94089
POST OFFICE BOX 3440 □ SUNNYVALE □ CA 94089-3440 □ (408) 745-7000 □ FAX (408) 734-0445
HOUSTON, TX □ (281) 558-3200 □ CHARLOTTE, NC □ (704) 865-6318
ST. LOUIS, MO □ (636) 394-2653 □ WASHINGTON, DC □ (301) 868-4899

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Section 1
INTRODUCTION

An assessment of Arkansas Nuclear One Unit 2 (ANO-2) steam generator tube integrity for axial outside diameter stress corrosion cracking (ODSCC) at eggcrates was previously performed by Aptech Engineering Services, Inc. (APTECH) (1) for normal operating temperatures. The tube failure mechanism modeled in that work was tube rupture under high differential pressure loading, specifically steam line break (SLB) and three times normal operating differential pressure (3Δp) conditions.

This report addresses the structural integrity of steam generator tubes with axial ODSCC at eggcrates under the postulated conditions that may exist for thermal transients that are beyond the plant's licensing basis; so-called Severe Accident conditions. This report supplements that described previously for the case of these thermal transients. In these transients, the steam generator tubing is subjected to temperatures exceeding 1100°K leading to the possibility of a different failure mechanism: creep rupture.

An extensive study of failure behavior of internally pressurized flawed tubes at high temperature has been performed by Argonne National Laboratory (ANL) (2). That study included an evaluation of computational models for use in predicting failures of flawed and unflawed Alloy 600 tubes under high temperature conditions. Two basic modeling approaches are considered. The first uses a conventional static burst pressure approach in which the effects of high temperature exposure are modeled by a decrease in material flow stress. This model assumes a temperature history independence. Failure is predicted when the defect characteristic stress first exceeds the temperature dependent flow stress.

The second model is a true creep rupture model in which a linear time/fraction damage rule is applied. This model computes a damage integral over the temperature/stress history of the transient to determine a time to ligament rupture for a specific defect. The creep rupture model uses the standard Larson-Miller parameter as the basis for the actual computations.

The ANL work also described test programs in which specimens were subjected to various high temperature conditions including temperature ramps. The creep rupture model was found superior in predictive capability vis-à-vis the flow stress model. The creep rupture model was unambiguously recommended for usage in the evaluation of structural integrity for axial cracks in steam generator tubes during severe accidents.

The creep rupture model was consequently chosen for the evaluation of the ANO-2 steam generator tubing in this evaluation in spite of the additional computational complexity of the required transient analysis. The end-of-cycle (EOC) depth/length distributions generated for the analysis of normal operating temperature were utilized as input for this severe accident creep rupture analysis. A Monte Carlo simulation model [SASIM] was developed to perform creep-rupture-based probabilistic evaluations for three ANO-2 severe accident scenarios. The temperature/pressure histories for the transients were provided by Dr. Mark Kenton of Creare, Inc. The probabilities of numbers of ligament failures prior to hot-leg rupture for each transient are summarized in the results section of this report.

The possible effects of these hypothetical conditions on the structural integrity of degraded steam generator tubes were not considered in the original licensing basis. In general, they represent much more severe conditions than are traditionally evaluated for routine operational assessments to comply with industry initiatives and Nuclear Regulatory Commission (NRC) recommendations and requirements.

Section 2
CREEP-RUPTURE MODEL

2.1 INTRODUCTION

The probabilistic model for assessing the structural integrity of axial cracking at eggcrates for ANO-2 is fundamentally similar to that developed by ANL (2 through 4). This model extends the conditions that are considered for structural integrity to those that are associated with so-called Severe Accident conditions.

This section describes the fundamentals of the creep-rupture model that was used by APTECH to perform the structural integrity assessment. The following section describes the severe accident transient conditions that were used to calculate the creep-rupture damage and ultimately to predict the time to failure for affected tubes. An overview of the simulation model is then provided followed by a summary of the results of the assessment.

The basic creep-rupture failure model that was applied is:

$$\int_0^{t_f} \frac{dt}{t_R(T, m_p \sigma)} = 1$$

where,

T_f	=	Time to failure
T	=	Temperature (°K)
M_p	=	Magnification factor
σ	=	Net section stress

2.2 LARSON-MILLER PARAMETER

To predict the creep-rupture time to failure for a specific tube, the Larson-Miller parameter was used. Reference 2 cites the following equations that relate the Larson-Miller Parameter (P_{lm}) to the local stress, σ:

$$P_{lm} = \begin{cases} 24.3 \pm 0.7 - 0.3 \ln \sigma & \sigma \le 5.7 \text{ ksi} \\ 23.2 \pm 0.7 - 2.4 \ln \sigma & \sigma > 5.7 \text{ ksi} \end{cases}$$

The time to creep-rupture is then easily calculated as:

$$t_R = 10^{\left(\frac{P_{lm}}{T}\right)-15}$$

where T is expressed in °K and the time to creep-rupture is expressed in hours.

2.3 LIGAMENT TEARING MODEL

It is well-known that the failure pressure for straight sections of unflawed tubing of inner radius R is determined by the relationship:

$$p_b = \bar{\sigma} \ln\left(1 + \frac{t_{wall}}{R}\right)$$

which for small values of the ratio of the wall thickness to the inner radius is well approximated by:

$$p_b = \frac{\bar{\sigma} t_{wall}}{R_m}$$

$$\bar{\sigma} = k(\sigma_y + \sigma_u)$$

where R_m is the mean radius and the flow stress constant k is such that $0.5 \leq k \leq 0.6$.

In the case of steam generator tubing with axially oriented through-wall flaws, the plastic collapse failure model of Erdogan predicts the pressure required to cause unstable ductile failure in terms of the burst pressure of an unfailed tube, p_b, and the bulging factor, m:

$$
\begin{aligned}
p_{cr} &= \frac{p_b}{m} \\
&= \frac{\bar{\sigma} t_{wall}}{m R_m}
\end{aligned}
$$

$$m = 0.614 + 0.481\lambda + 0.386e^{-1.25\lambda}$$

$$\lambda = \frac{0.91L}{\sqrt{R_m t_{wall}}}$$

L = total crack length

In the case of part-through wall axial flaws, APTECH's burst pressure model is based on the so-called EdF burst pressure equation; the basis for this model is discussed in considerable detail in Reference 5. To be consistent with the approach followed by ANL in References 2 to 4, Kiefner's model, as modified by ANL (2), was used to predict the pressure required to fail the remaining ligament for a part-through wall axial flaw of depth, d:

$$p_{sc} = \frac{p_b}{m_p}$$

$$= p_b \left(\frac{1 - \dfrac{d}{t_{wall}}}{1 - \alpha \dfrac{d}{m t_{wall}}} \right)$$

$$\alpha = 1 + 0.85\left(\frac{d}{t_{wall}}\right)^2 \left(1 - \frac{1}{m}\right)$$

m_p is a magnification factor to account for tearing of the remaining ligament.

These equations were used to evaluate the structural integrity of axial flaws at the eggcrates in the ANO-2 steam generators for the postulated conditions of three severe accident transients that are briefly described in the Section 3.

2.4 MAGNIFICATION FACTOR FOR NONUNIFORM CRACKS

For a crack with a nonrectangular profile, such as that shown in Figure 2-1, a structural equivalent length and depth must be obtained. This is done in an analogous process to that used by APTECH for the normal temperature burst computations (5). In the creep rupture case, the objective is to find the equivalent rectangular section which maximizes the computed value of m_p rather than minimizing the burst pressure as computed by the Framatome equation. Since the sensitivities of the respective equations are different with regard to depth and length, it is expected that the structural equivalent rectangle for m_p could be different than that computed for the Framatome equation.

The basic descriptor of a crack in the APTECH simulation methodology consists of three values. The first is the defect maximum depth which is physically the peak depth of the defect. The second is the structural equivalent length which is the length of the rectangle as shown in Figure 2-1. The third is the structural equivalent depth as shown in Figure 2-1. The last two of these descriptors are mathematically related to the minimization of the Framatome equation. In practice, the length of defects as measured in the field is used as a conservative surrogate in the simulation process for the Framatome structural length.

Given only this information, a process was developed to compute an equivalent structural rectangle for the maximization of m_p. Given that the value of m_p approaches infinity as cracks approach 100% through-wall, even for very short cracks, a minimum segment length of 0.25 inch was chosen as a starting point. The remaining crack length is divided into 200 increments. An assumption is made that the average depth of the crack varies linearly over the Framatome structural length. Computations of mp are made for each sequential area and the maximum value is recorded. Figures 2-2 and 2-3 show the comparison between the Framatome and m_p equivalent rectangle for a tent shaped crack and an elliptical crack.

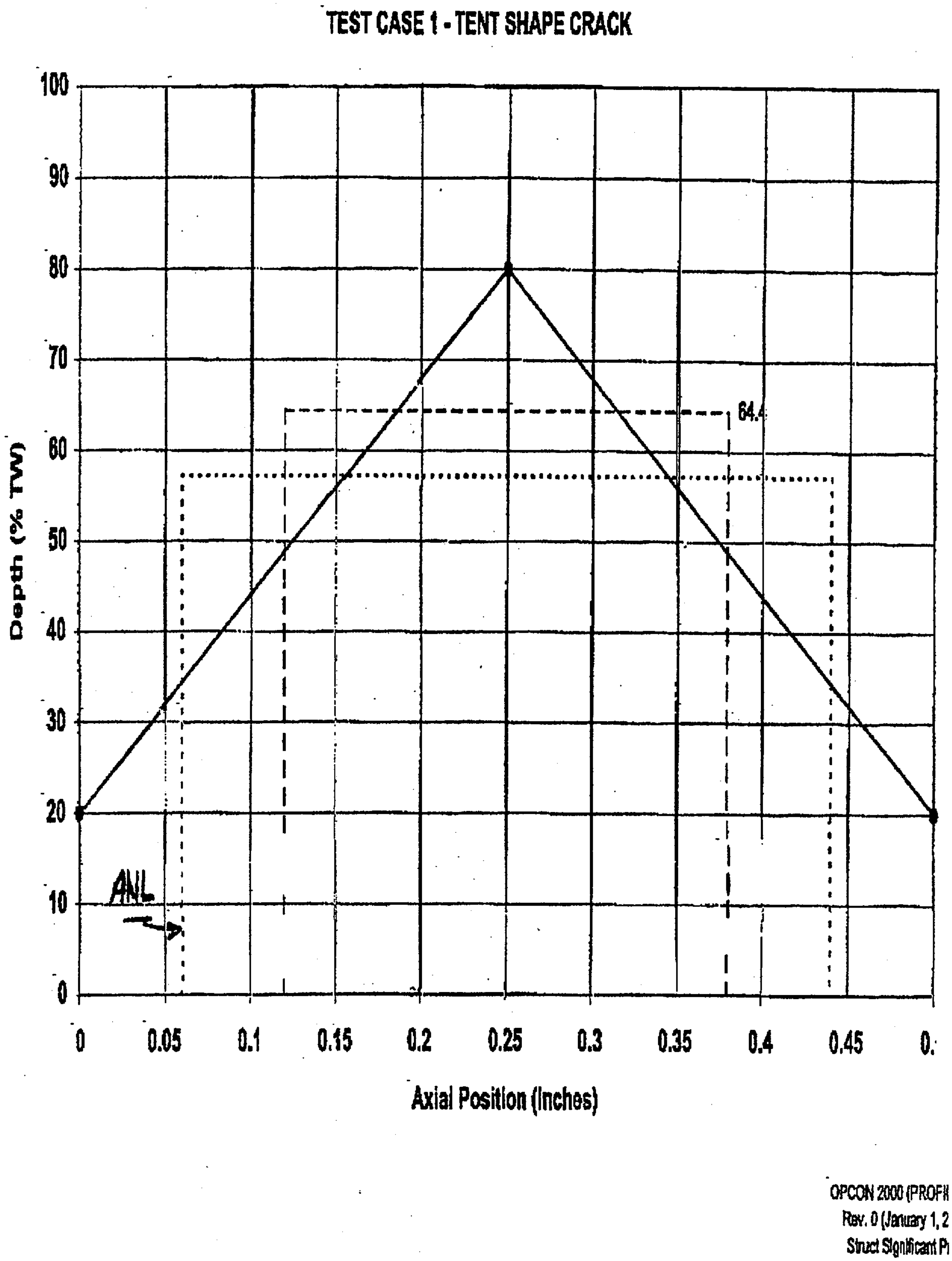

Figure 2-1 — Test Case 1 — Tent Shape Crack.

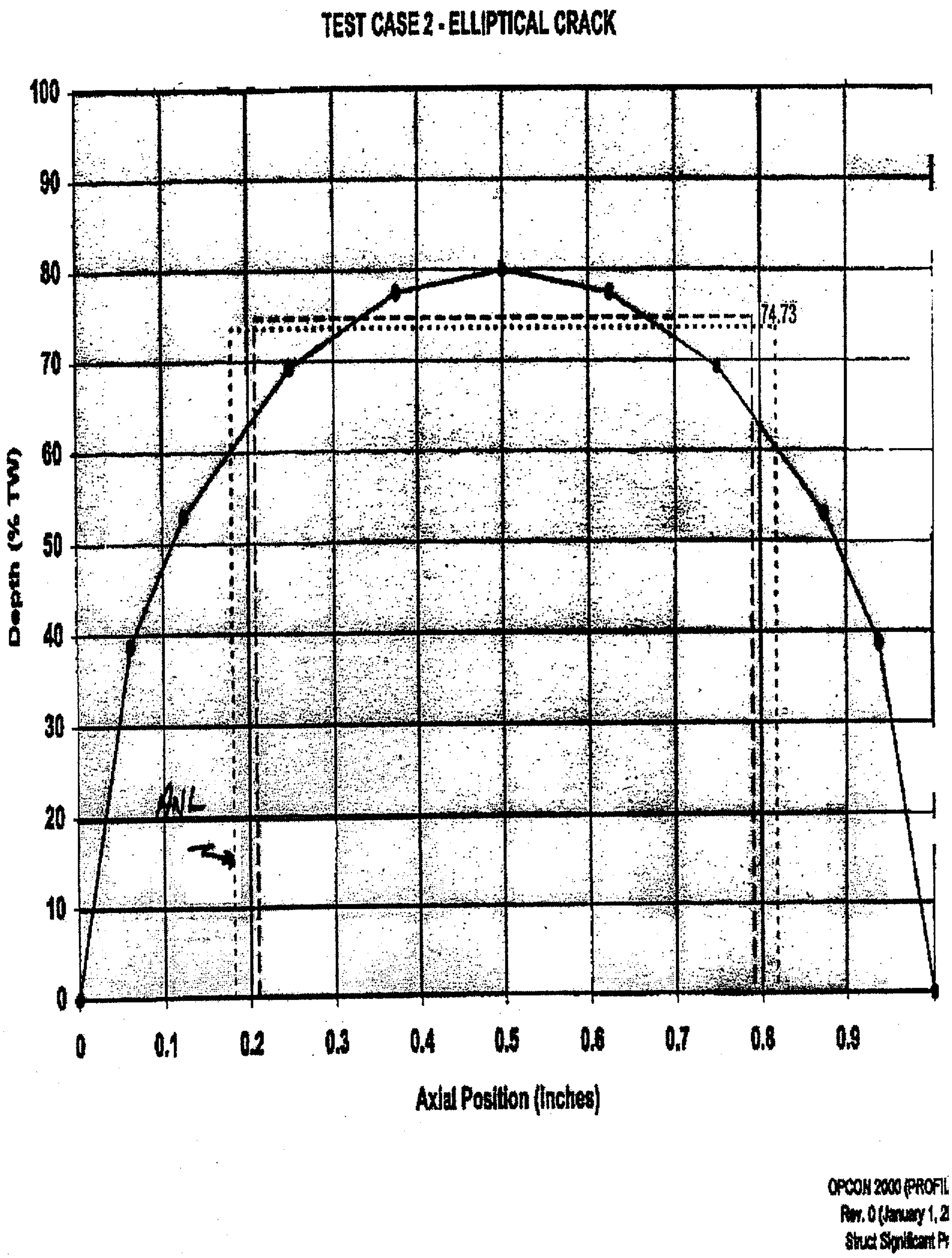

Figure 2-2 — Test Case 2 — Elliptical Crack.

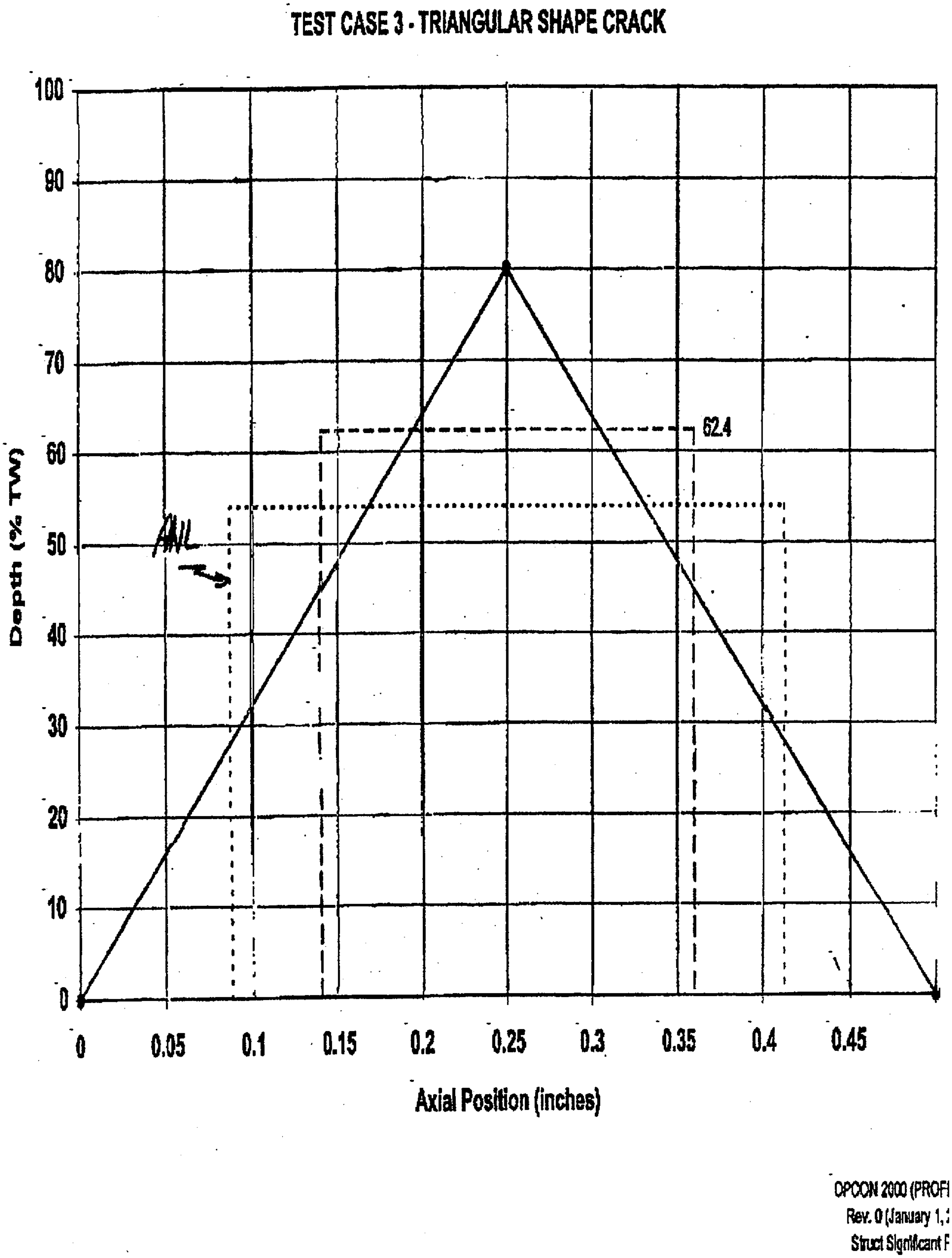

Figure 2-3 — Test Case 3 — Transgranular Shape Crack.

Section 3
ANO-2 SEVERE ACCIDENT TRANSIENTS

Three Severe Accident transients were evaluated by Creare using MAAP (6) on a best-estimate basis. These three transients resulted in the median times to hot leg failure listed in Table 3-1. The times to failure and the corresponding temperature and pressure transients were used to perform the probabilistic assessment that is described in the next section.

The pressure and temperature histories associated with each of these transients are provided in Figures 3-1 through 3-6. It should be noted that each of these transients represents an almost constant differential pressure over the course of the event, accompanied by a temperature ramp. This makes the choice of the creep-rupture model most appropriate. In the evaluation of these transients, the figure of merit for the analysis is the number of segments failing prior to hot leg failure.

Table 3-1

PREDICTED TIMES TO HOT LEG FAILURE

Transient	Time-to-Failure (hour)
H/D/H	0.827
H/D/L	0.799
M/D/L	0.849

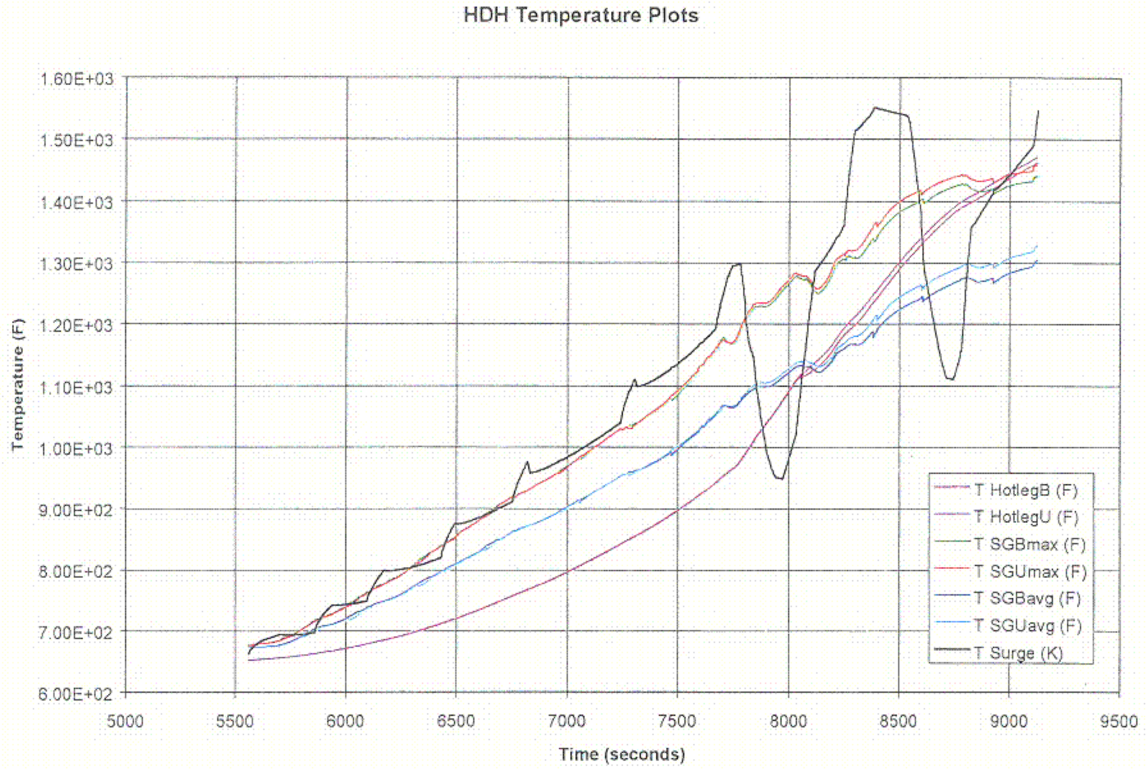

Figure 3-1 — H/D/H Temperature Transient.

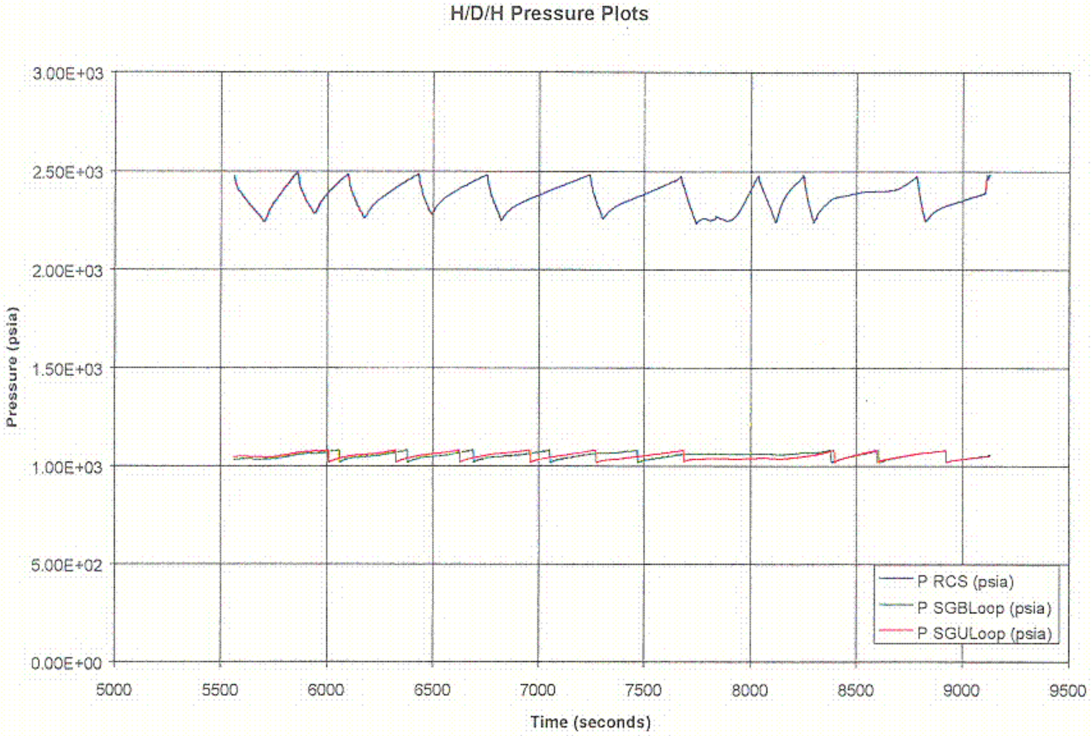

Figure 3-2 — H/D/H Pressure Transient.

C2

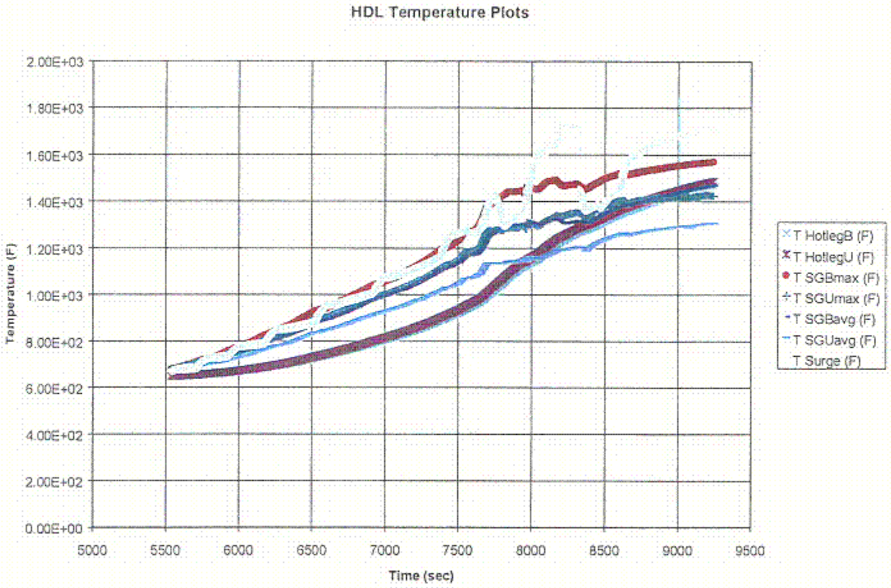

Figure 3-3 — H/D/L Temperature Transient.

C3

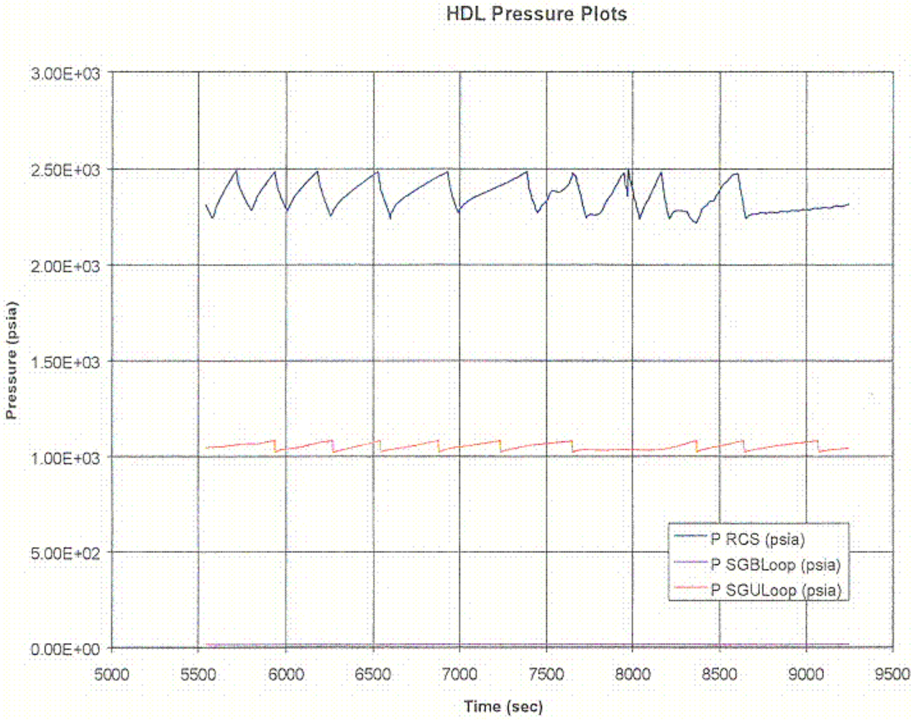

Figure 3-4 — H/D/L Pressure Transient.

c4

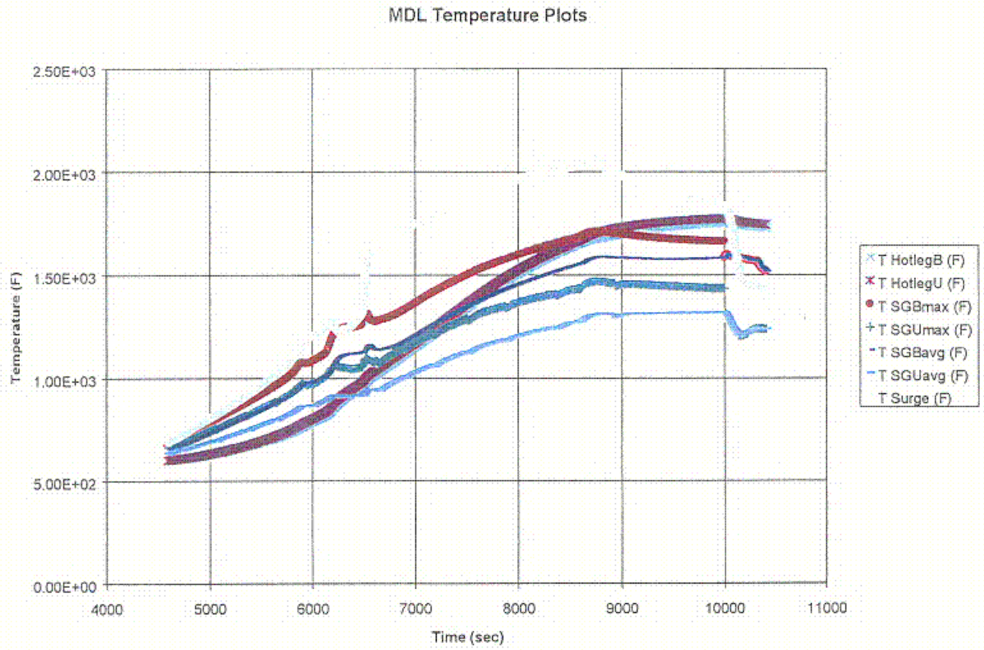

Figure 3-5 — M/D/L Temperature Transient.

C5

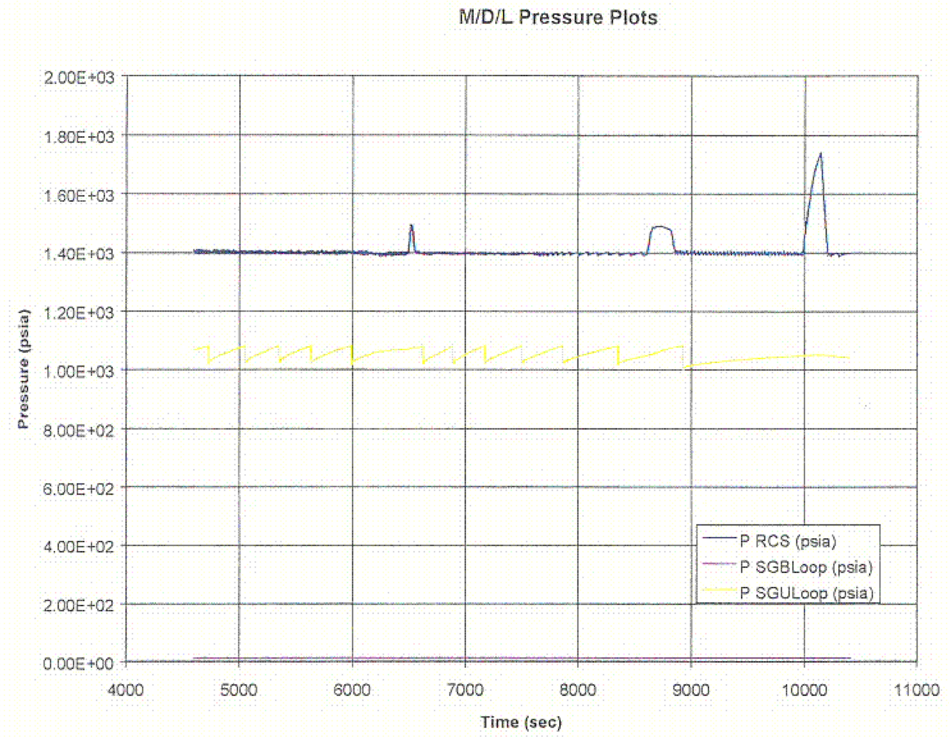

Figure 3-6 — M/D/L Pressure Transient.

C6

Section 4
SIMULATION MODEL

Figure 4-1 illustrates the general elements of the structural integrity assessment calculations that were performed for the ANO-2 steam generator tubes under postulated severe accident conditions. Four computer programs were used to calculate required inputs and to perform the simulation of the probability of ligament tearing under these conditions. The first, referred to as OA1 in Figure 4-1, was used to develop the predicted flaw size (maximum depth and structurally significant depth and length) cumulative probabilities for ANO-2 (1) after a specified period of operation following the most recent mid-cycle inspection. The cumulative distributions of flaw size are then input, with basic tube geometry information and the temperature, pressure transients calculated with MAAP (6) to the MP2 code.

MP2 calculates the probability distribution of the magnification factor, mp, in accordance with the methodology outlined in Section 2. MP2 essentially performs a deterministic computation to compute the mp values and failure times for the input crack distribution and selected transient. MP2 constrains the m_p optimization routine and a creep-rupture integration routine. The best estimate Larson-Miller parameter representation is used in the analysis. The SASIM1 program uses the failure time distribution computed in MP1 to evaluate the distribution of the number of ligament failures prior to hot leg rupture. SASIM1 is a straightforward Monte Carlo simulator.

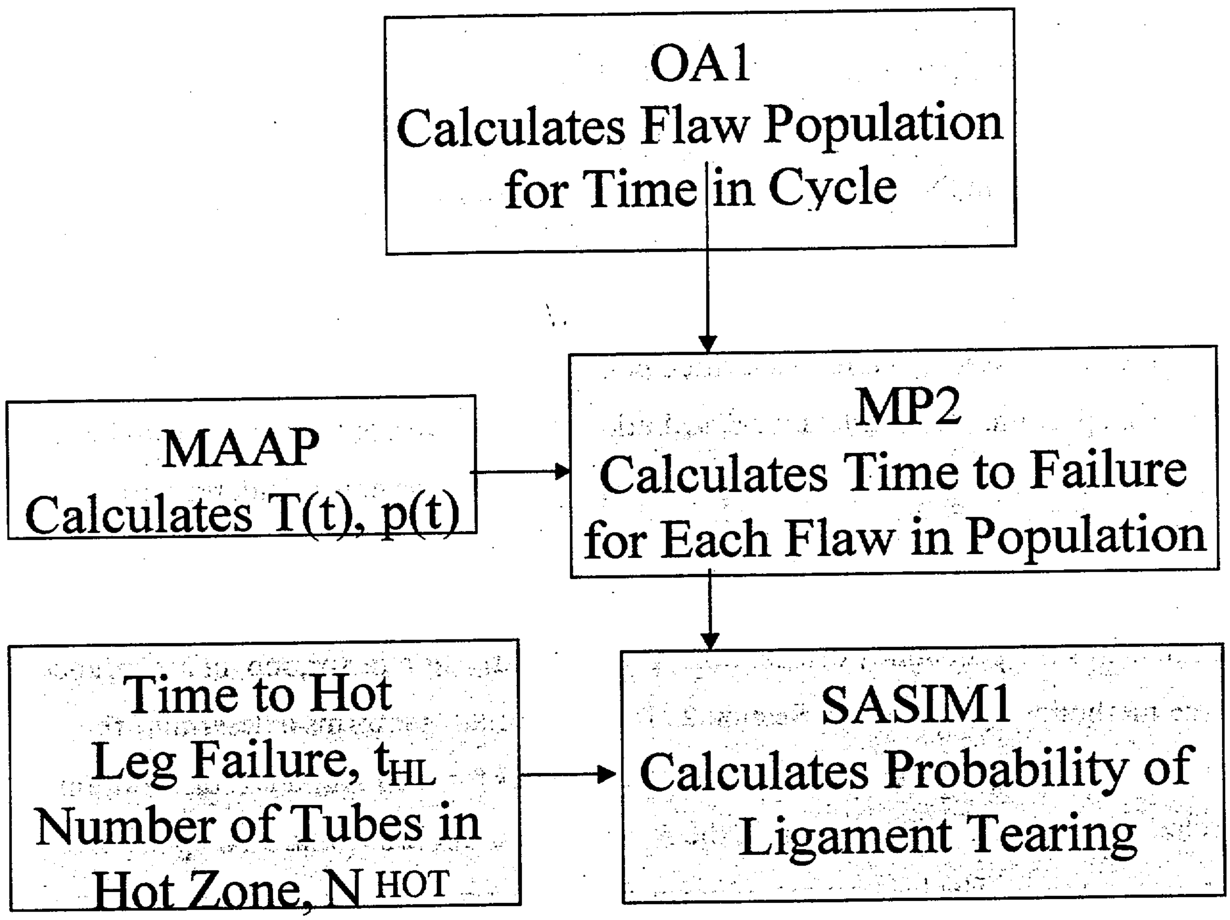

Figure 4-1 — General Elements of Structural Analysis for Severe Accident Transients.

Section 5
RESULTS

The simulation model described in Section 4 was used to evaluate the three severe accident scenarios for ANO-2 at projected EOC conditions for axial ODSCC degradation at eggcrate intersections in the most affected steam generator. In all cases, a total defect population of 150 was assumed. Of these, 50% were assumed to be in the hot region of the generator. For the most limiting transient (HDL), a two-part computation was performed. A small fraction (10%) of the total population was allocated to the hottest region. The remaining 40% of the hot region defects were assigned to a less hot region.

The results of the analysis are shown in Tables 5-1 through 5-3 for the transients analyzed.

Table 5-1

ANO-2 EOC14 RESULTS FOR HDH ACCIDENT CONDITIONS

Number of Tubes with Ruptured Remaining Ligament, N	Probability of N, P(N), %
0	97.9
1	2.0
2	< 0.1

Table 5-2

ANO-2 EOC14 RESULTS FOR MDL ACCIDENT CONDITIONS

Number of Tubes with Ruptured Remaining Ligament, N	Probability of N, P(N), %
0 n	85.75
1	13.16
2	0.99
3	0.01

Table 5-3

ANO-2 EOC14 RESULTS FOR HDL ACCIDENT CONDITIONS

Number of Tubes with Ruptured Remaining Ligament, N	Hottest Region (15 Tubes) Probability of N, P(N), %	Hot Region (60 Tubes) Probability of N, P(N), %
0	1.73	46.74
1	7.64	36.18
2	17.59	12.93
3	23.91	3.36
4	21.86	0.66
> 5	27.27	0.14

REFERENCES

1. Woodman, B.W. and Jackson, P.S., "Structural Integrity Evaluation of Axial Outside Diameter Stress Corrosion Cracking at Supports for Arkansas Nuclear One Unit 2 During Cycle 14 Post Mid-Cycle Operation," APTECH Report AES 99113855-1-1 (February 2000).

2. Majumdar, S., Shack, W.J., Diercks, D.R., Mruk, K., Franklin, J., and Knoblich, L., "Failure Behavior of Internally Pressurized Flawed and Unflawed Steam Generator Tubing at High Temperatures – Experiments and Comparison with Model Predictions," Argonne National Laboratory Report NUREG/CR-6575 (March 1998).

3. SGTR Severe Accident Working Group, "Risk Assessment of Severe Accident-Induced Steam Generator Tube Rupture," U.S. Nuclear Regulatory Commission Report NUREG-1570 (March 1998).

4. Chavez, S.A., Atwood, C.L., Ellison, P.G., and Jones, J.L., "Estimating Structural Failure Frequency of Degraded Steam Generator Tubes," ASME/JSME 4th International Conference on Nuclear Engineering, Vol. 5 (1996), p. 411.

5. "APTECH Axial Crack Burst Pressure Methodology," Aptech Engineering Services, Inc. APTECH Report AES 96112906-1Q-2, August 1999, Revision 1.

6. Kenton, M. (Creare) to Lloyd, M. (Entergy – ANO), Subject: Data Files, e-mail Tue, 21 Mar 2000 15:18:29 – 0500.

Business Units:

- Fossil Power Services, Nuclear Power Services, Petrochemical Oil & Gas, Legal & Insurance Litigation, Industrial

Headquarters
1282 Reamwood Avenue, Sunnyvale, California 94089
Post Office Box 3440, Sunnyvale, California 94088-3440
Phone: 408-745-7000, Fax: 408-734-0445, Toll Free: 800-477-2228
Email: aptechsu@ix.netcom.com, Website: www.aptech-eng.com

Offices
Houston, TX, 281-558-3200
Charlotte, NC, 704-865-6318
St. Louis, MO, 314-394-2653
Washington, DC, 301-868-4899

APTECH Engineering Services, Inc.

Attachment 5

Affidavit for EPRI Report TR-107623

EPRI

AFFIDAVIT

RE: EPRI Report TR-107623, Volume 1

I, JOHN BATEMAN, being duly sworn, depose and state as follows:

I am a Director of the Science & Technology Division at the Electric Power Research Institute ("EPRI") and I have been specifically delegated responsibility for the Reports listed above that are sought under this affidavit to be withheld (the "Reports") and authorized to apply for their withholding on behalf of EPRI. This affidavit is submitted to the Nuclear Regulatory Commission ("NRC") pursuant to 10 CFR 2.790 (a)(4) based on the fact that the Reports consist of trade secrets of EPRI and that the NRC will receive the Reports from EPRI under privilege and in confidence.

The basis for which the Reports should be withheld from the public is set forth below:

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>
> (1) Derives independent economic value, actual or potential, from not being generally known to the public or to other persons who can obtain economic value from its disclosure or use; and
>
> (2) Is the subject of efforts that are reasonable under the circumstances to maintain its secrecy.

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I have read the foregoing and the matters stated therein are true and correct to the best of my knowledge, information and belief. I make this affidavit under penalty of perjury under the laws of the United States of America and under the laws of the State of California.

Executed at 3412 Hillview Avenue, Palo Alto, being the premises and place of business of the Electric Power Research Institute:

April ~~11~~ 12, 2000

John Bateman

Subscribed and sworn before me this day: April ~~11~~ 12, 2000

Sumi Yamashita, Notary Public

SUMI YAMASHITA
COMM. # 1265539
NOTARY PUBLIC-CALIFORNIA
SANTA CLARA COUNTY
COMM. EXP. MARCH 31, 2004