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Flaw Tolerance Evaluation
Quad Cities Units 1 and 2
Feedwater Nozzles

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Table of Contents

List of Tables

List of Figures

1.0 BACKGROUND

Cracking in feedwater nozzles due to thermal sleeve bypass leakage was a problem discovered in BWRs in the mid 1970's. The thermal sleeves in the original nozzle designs were installed with a nominally tight fit, which permitted small (but not insignificant) amounts of bypass leakage of feedwater between the sleeve and the nozzle (see Figure 1-1). This is not a serious concern during normal operation because the feedwater is heated to a temperature not too much lower than the reactor temperature. However, under low power and hot standby operation, the feedwater is not heated, and there is a significant temperature differential between reactor and feedwater temperatures approaching 500°F. Bypass leakage of this relatively cold feedwater past the sparger inlet thermal sleeves resulted in severe thermal cycling within the nozzles of many BWR's, subsequently leading to the initiation and propagation of inside surface thermal fatigue cracks [1].

To address this concern, Commonwealth Edison installed new, triple sleeve feedwater spargers in the Quad Cities Nuclear Station. This sparger design, illustrated in Figure 1-2, incorporated an interference fit at the inboard seal, and piston ring sealing devices on both the inboard and outboard seals to prevent thermal sleeve bypass leakage. The stainless steel cladding was also removed from the nozzle as part of this modification to improve its fatigue resistance [2].

Design analyses for the modified spargers at Quad Cities [3,4] were conducted using conservative assumptions regarding degradation of the thermal sleeve fits and piston ring seals, such that several seal refurbishments were predicted to be required during the plant lifetime to ensure that a leakage-free condition would be maintained. The seal refurbishment interval is approximately consistent with the required interval for internal PT examination of this type of sparger (9 fuel cycles or 135 startup/shutdown cycles) specified in the NRC response to this cracking concern, NUREG-0619 [5].

To address the seal degradation issue, Commonwealth Edison installed a leakage monitoring system (LMS) on the feedwater nozzles [6] to monitor the bypass leakage past the thermal sleeve. The objective of the LMS is to provide indication of changes in bypass leakage, thus assisting in decisions relative to nozzle inspection and sparger replacement. As illustrated in Figure 1-3, the LMS employs thermocouples attached to the top and bottom of the nozzles to record the temperature history at these predetermined locations. An analytical correlation between the recorded temperatures, reactor temperature, feedwater temperature and flow rate, is used to predict the leakage rate on a continuous basis [7,8]. The LMS indicates that little or no bypass leakage is occurring in any of the Quad Cities nozzles at this time.

NUREG-0619 allowed that the in-vessel PT requirement discussed above could be modified (or eliminated entirely), if a utility implements effective bypass leakage monitoring and effectively qualifies an alternative, ultrasonic inspection approach for the nozzles. The alternative inspection approach also includes a requirement for fracture mechanics evaluation to demonstrate that the maximum possible defect that could be missed by the inspection would not grow unacceptably during the period of future operation until the next scheduled inspection. The purpose of this report is to document the fracture mechanics evaluation, using plant specific design and loading information for the Quad Cities nozzles, and reflecting the current results of the plant bypass leakage monitoring system.

Structural Integrity Associates (SI) has developed the **FatiguePro** analysis and monitoring system that has the ability to perform transient thermal stress and fracture mechanics analysis for any arbitrarily defined set of thermal transients using a personal computer [9]. Such analyses are accomplished through the use of transfer matrices and a Duhamel Integral (Green's Function) thermal analysis approach. In its basic form, the software uses actual transient data from a plant computer to monitor fatigue and predict fatigue usage and/or crack growth. In this report, the **FatiguePro** software is specifically tailored to perform crack growth analyses of hypothetical cracks in the feedwater nozzles at the Quad Cities plant. A specially customized, off-line version of the program is used to evaluate a number of

different initial crack sizes in the feedwater nozzles for two assumed rates of bypass leakage. In performing this evaluation, conservative design-basis transients are input to the program in an off-line mode to simulate projected future operation (in lieu of monitoring based on actual plant data). The design basis transients used in the evaluation are compared to transients actually measured by the **FatiguePro** system in 1988, and shown to be conservative.

In Section 2.0 of this report, thermal boundary conditions, i.e., heat transfer coefficients and temperature distributions for various thermal sleeve bypass leakage cases are determined. These boundary conditions are used in a transient thermal stress analysis in Section 3.0. An analysis of pressure load is also discussed in this section. In Section 4.0, a fracture mechanics evaluation is performed to determine the transfer functions for a unit step change in feedwater temperature utilizing the stress transfer functions obtained from Section 3.0. Section 5.0 discusses the implementation of the **FatiguePro** software and the design transients used in the evaluation. Resulting crack growth rates are compared to the ASME Code Section XI [13] allowable flaw size to establish an acceptable period of continued operation between inspections for the nozzles. Section 6.0 provides a summary and conclusions.

Table 1-1

Summary of Quad-Cities Monitoring Results

Unit	Nozzle	Indicated Leakage[1] gpm	Observations
1	N4A	≈ 0.01	Recent trends indicate no significant seal performance degradation.
1	N4B	<0.01	There is no trend of significant seal performance degradation.
1	N4C	<0.02	There is no trend of significant seal performance degradation.
1	N4D	<.03	There has been no trend of significant seal performance degradation since 1987.
2	N4A	≈ 0.03 Ave. 0.3 Max.	There has been no degradation indicated by a long term trend. One sensor is indicating low in most recent data.
2	N4B	≈ 0.03 Ave. 0.1 Max.	Prior to 1990, there was a trend of performance degradation that has held steady since then.
2	N4C	≈ 0.02 Ave. 0.07 Max.	Pre-1993 data indicated possible leakage, that is recently not observed.
2	N4D	≈ 0.02 Ave. <0.03 Max.	There is a slight trend of decreased seal performance.

Note: 1. Based on revised LMS leakage correlation. [8]

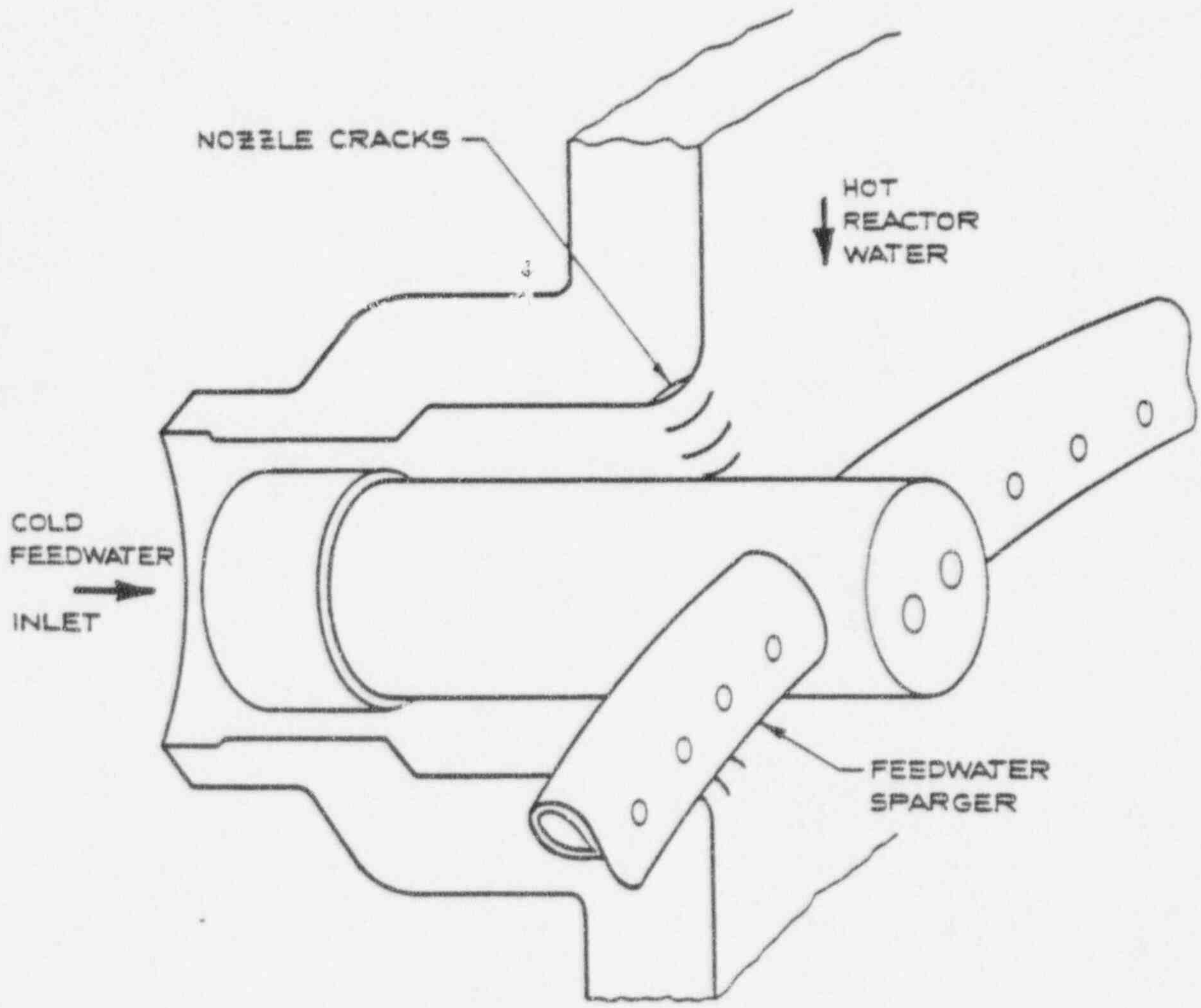


Figure 1-1. Original Single-Sleeve Feedwater Nozzle/Sparger Arrangement

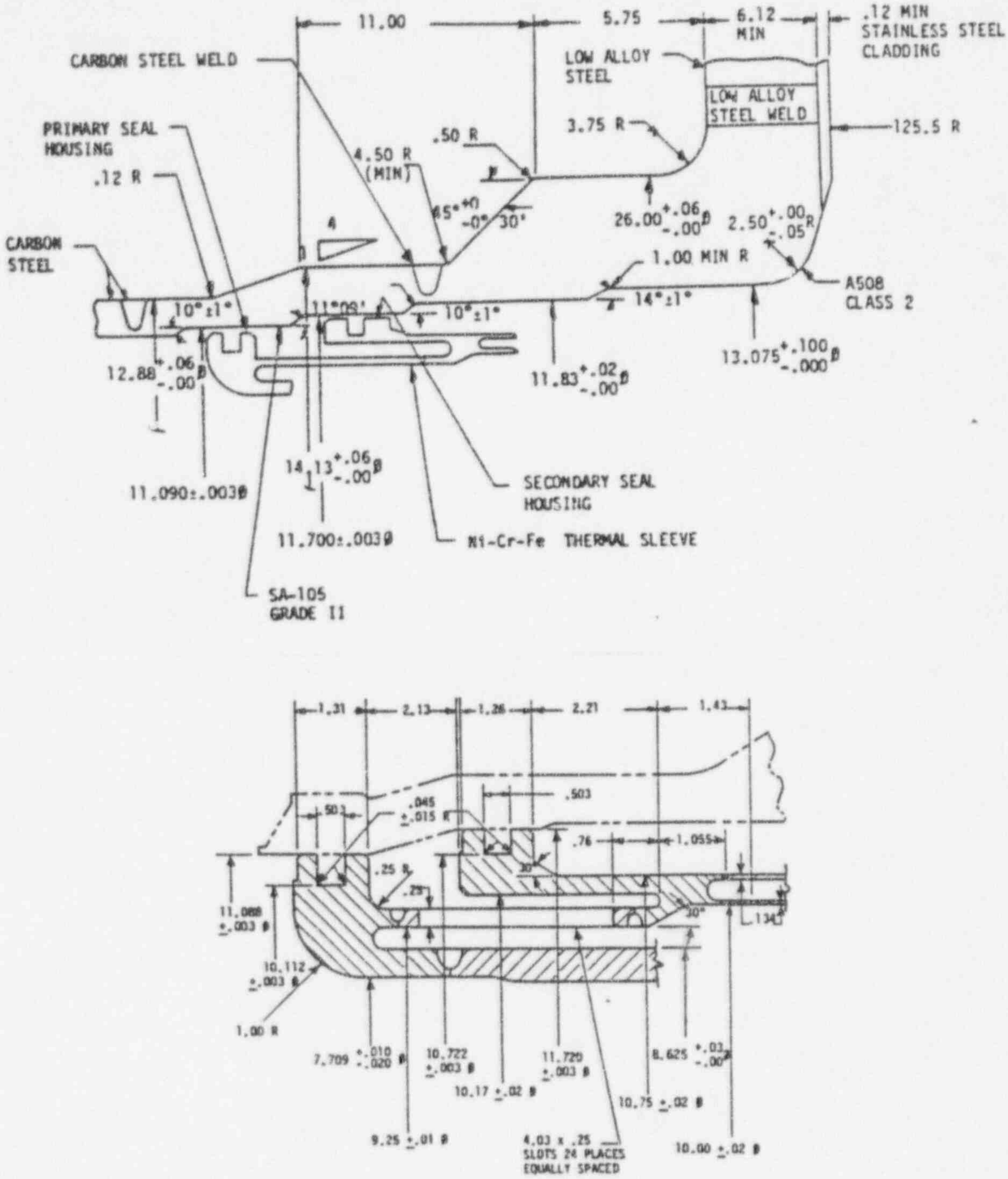


Figure 1-2. Triple Sleeve Feedwater Nozzle/Sparger Arrangement Currently Installed at Quad Cities 1 and 2

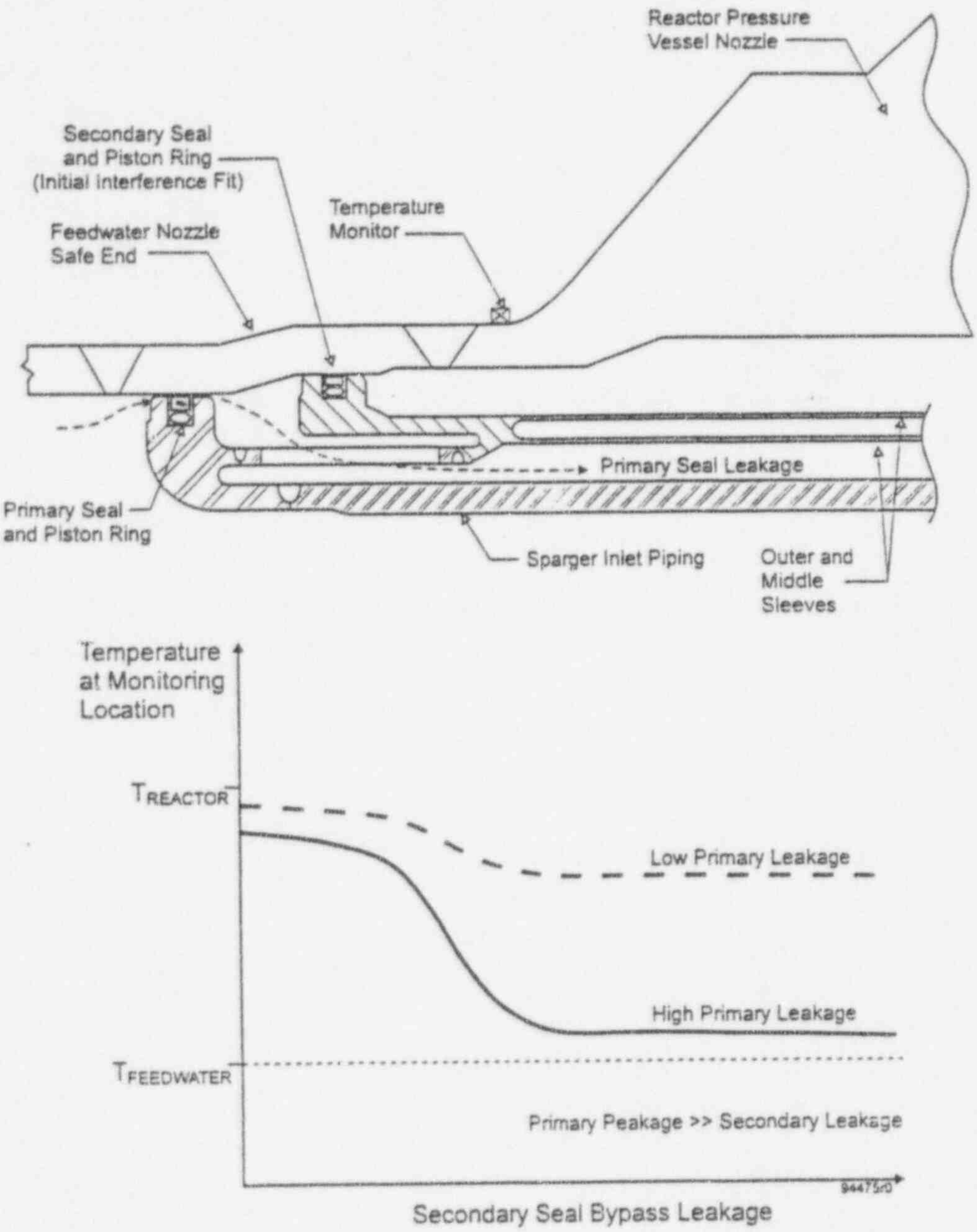


Figure 1-3. Conceptual Illustration of Bypass Leakage Monitoring System

2.0 HEAT TRANSFER ANALYSIS

2.1 Technical Approach

Using the ANSYS finite element model described in Section 3.0, transient thermal stress analysis of the nozzle was conducted. Using boundary conditions described in Section 2.2, heat transfer runs were made to establish Green's functions for a 1°F feedwater temperature change. Using these Green's function, the **FatiguePro** program can provide temperature, stress and fracture mechanics parameters for any arbitrary transient applied at the nozzles. By simply changing Green's functions, this analysis approach can be used to address any defined set of boundary conditions.

2.2 Heat Transfer Boundary Conditions

Two transient thermal stress cases were identified for analysis, based on various assumed bypass leakage rates. These cases, and their associated thermal boundary conditions are identified as the low leakage case and the high leakage case in Table 2-1. The low leakage case bounds the maximum predicted leakage in Table 1-1. The high leakage case assumed a nominal leakage rate of 1.0 gpm. The thermal conditions are specified for various nozzle inside surface locations identified in Figure 2-1. The convective boundary conditions for a unit step change in feedwater temperature are applied as a step δT along the inside surface of the nozzle in accordance with the following formula:

$$\delta T = 1 - T_{Normalized}$$

where: $$T_{Normalized} = \frac{T_{inside} - T_{FW}}{T_{reactor} - T_{FW}}$$

T_{inside} = nozzle inside surface local temperature, °F

$T_{reactor}$ = reactor temperature, °F

T_{FW} = feedwater temperature, °F

Case 1. - Low Leakage Case (0.381 GPM)

This case represents a step change in feedwater temperature at the design basis leakage rate taken from Ref. [2]. The magnitude of the δT along the nozzle inside surface reflects variation of the bypass leakage flow temperature due to sensible heat being added to the leakage fluid as it progresses through the annular region between the nozzle and the thermal sleeve. The fluid temperatures are consistent with the minimum annulus temperatures reported in Ref. [1]. The heat transfer coefficients are bounding valves and considerably exceed these based on classical heat transfer formulae for laminar and turbulent flow based on the specified leakage flow rates.

In actual fact, leakage rates during conditions of low feedwater flow rate would be expected to be proportionately less than measured by the LMS during full-power operation. This reflects another conservatism in the analysis.

Case 2. - High Leakage Case (1.0 GPM)

This case uses the same bounding heat transfer coefficients as Case 2, but uses predicted δT values that account for higher secondary seal leakage rate, (and therefore less heating of the bypass leakage fluid). Since bounding heat transfer coefficients were specified for the low leakage case, no adjustment was required for the effects of increased flow. This case is consistent with the leakage rate much higher than expected in the Quad Cities thermal sleeves, which is much greater than the current maximum leakage rates being measured by the LMS [8]. This case is presented to show sensitivity of crack growth rates to increased leakage rates.

Table 2-1

Heat Transfer Boundary Conditions for Various Regions of the Quad Cities Feedwater Nozzles

Case		A	B	C	D	E	F	G	H	I	J
Low Leakage (0.381 GPM)	Fluid Temp. °F	100	100	100	212.5	280	347.5	460	460	505	550
	δT	1	1	1	0.75	0.6	0.45	0.2	0.2	0.1	0
	h (BTU/ft²-°F-hr)	6700	1500	525	800	1153	1500	3000	3000	3000	1000
High Leakage (1.0 GPM)	Fluid Temp. °F	100	100	100	116.6	156.7	208.4	372.2	460	505	550
	δT	1	1	1	0.963	0.874	0.759	0.395	0.2	0.1	0
	h (BTU/ft²-°F-hr)	6700	1500	525	800	1153	1500	3000	3000	3000	1000

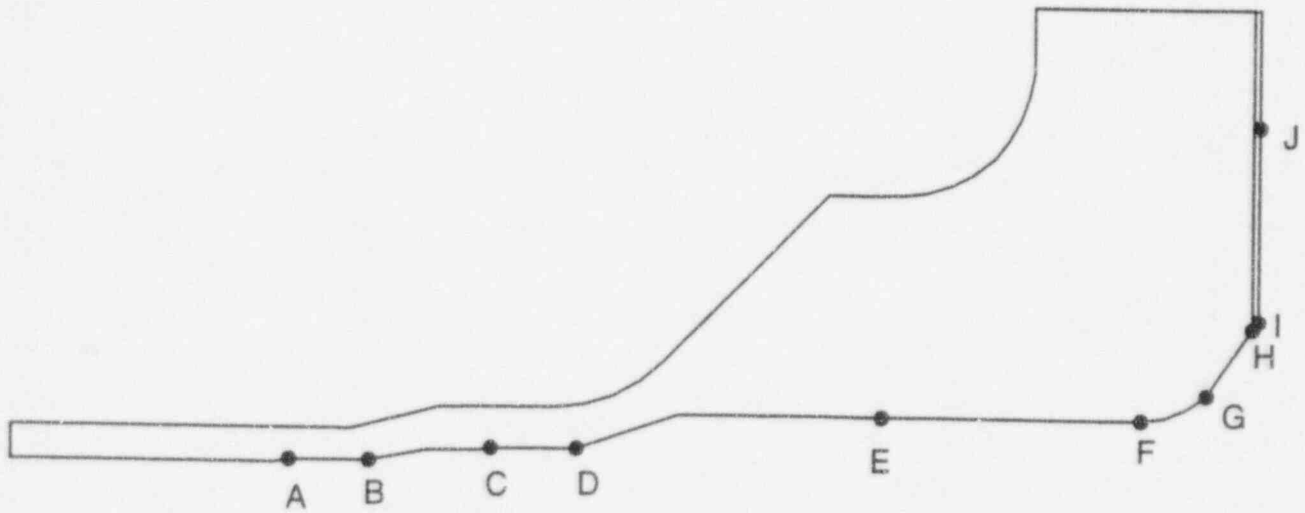


Figure 2-1. Thermal Regions for Quad Cities Feedwater Nozzles

3.0 FINITE ELEMENT STRESS ANALYSIS

3.1 Feedwater Nozzle Thermal Stresses

The heat transfer coefficients and the temperature distributions for the two cases discussed in the previous section were used as boundary conditions for finite element stress analysis of the nozzle to determine stress response of the nozzle to a 1 °F step change in feedwater temperature. This response, at the most highly stressed sections in the nozzle, constitutes the stress Green's Functions which will be used to calculate nozzle stress distributions in the **FatiguePro** program. These through-wall stress distributions are used to determine stress distribution coefficient Green's Functions, as will be discussed in Section 4.0 of this report describing the fracture mechanics analysis.

The stress locations of interest have been selected as the highest stressed locations in the nozzle blend radius and bore regions, and correspond approximately to the locations in which cracking has been observed in BWR feedwater nozzles in the past [1]. The finite element model, employing a cylindrical geometry, used for this analysis is illustrated in Figure 3-1, with details of the nozzle blend radius and bore locations for which the Green's Functions are to be determined, shown in Figures 3-2. The temperature boundary conditions and heat transfer coefficients used in the finite element model, for the cases considered in the evaluation, are as described in Section 2.0.

The thermal stress analysis was performed using the ANSYS computer code [10]. The analysis process consisted of imposing the boundary conditions for a 1 °F step change in feedwater temperatures for the bypass leakage cases considered. The material properties used for the evaluation were obtained from the ASME Code [13] and are shown in Table 3-1. Material identifiers for the various locations in the model are shown in Figure 3-3.

The maximum stresses on the inside elements in the blend radius and the bore regions for the 1°F step change are shown in Figures 3-4, for the low leakage case. This distribution is

fairly typical of the high leakage cases, and therefore these inside surface elements provide an indication of which sections in the blend radius and the nozzle bore that the maximum thermal stresses should occur.

A thermal transient analysis for uniform heatup and cooldown of the nozzle inside surface was not conducted. The transient stresses and stress intensities for these conditions are small compared to those for the feedwater transients.

3.2 Pressure Stresses

It was also necessary to perform static finite element analyses to predict the pressure stresses in the nozzles, since these stresses must be superimposed upon the thermal stresses to determine the total stress at the limiting locations.

The pressure stress analysis was performed using the same ANSYS finite element model as had been used for the thermal analyses. A unit inside surface pressure of 1000 psi was assumed in the analysis for the nozzle. The stress distribution for the inside elements of the nozzle for this pressure loading case is illustrated in Figure 3-5.

Reactor vessel pressure is one of the inputs provided in the **FatiguePro** model. The input pressure is used to scale the finite element results to determine pressure stress distributions at the sections of interest. The scaled pressure stress throughwall distributions at each location are then combined with the associated thermal stress distributions for the two limiting thermal stress sections (bore and blend radius) for evaluating the effects of combined loadings.

Table 3-1

Material Properties

Mat. No.	Part	Material	E (psi)	α^* (in/in-°F)	TC (Btu/hr-ft-°F)	Cp (Btu/lbs-°F)
1	Nozzle	SA-336 F1	2.80E+07	7.18E-06	25.1	0.119
2	Safe-End	SA105 Grade II	2.83E+07	7.18E-06	28.38	0.121
3	Vessel Cladding	SS 304	2.70E+07	9.46E-06	9.81	0.125
4	Vessel	SA-302 Gr. B	2.80E+07	7.12E-06	28.99	0.121

Property values are at 300° F

*Average value from 70 to 550° F

Figure 3-1. Finite Element Model for Quad Cities Feedwater Nozzle

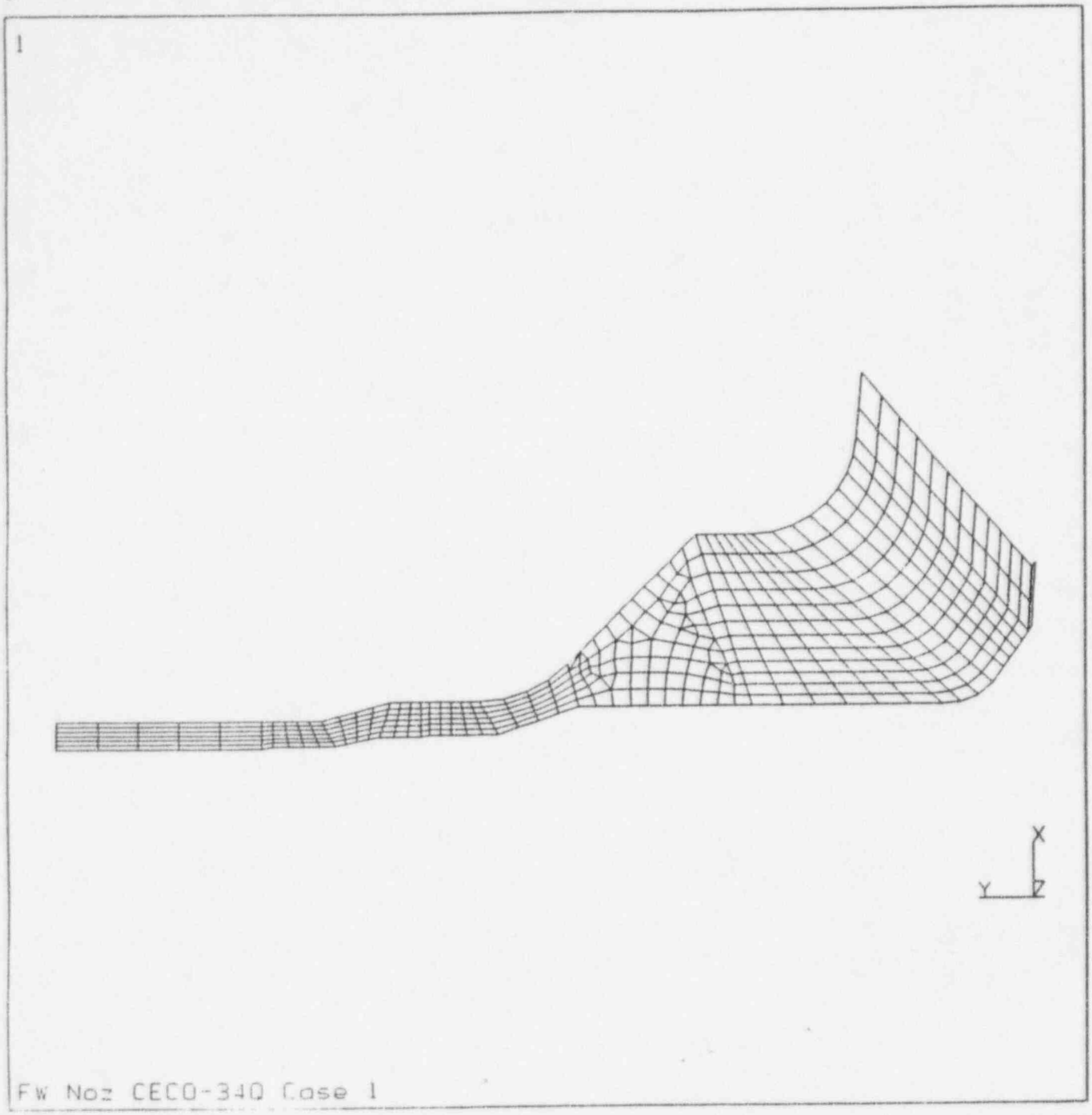
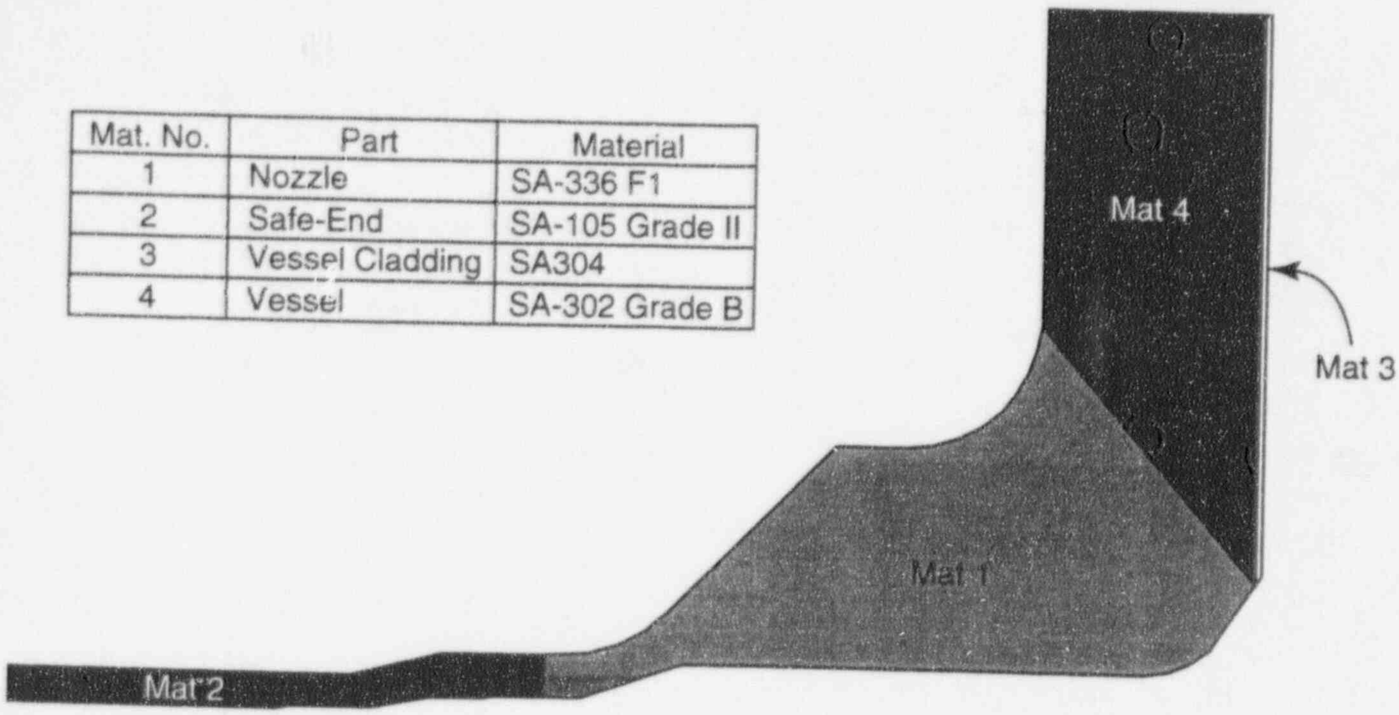


Figure 3-2. Details of FEM - Nozzle Blend Radius and Bore Region



Mat. No.	Part	Material
1	Nozzle	SA-336 F1
2	Safe-End	SA-105 Grade II
3	Vessel Cladding	SA304
4	Vessel	SA-302 Grade B

For analysis purposes, the interface between the vessel and nozzle materials was modeled between elements as shown. In view of the similarities between the properties of materials No. 1 and No. 4, this assumption will not significantly affect the results.

Figure 3-3. Material Property Locations in Finite Element Model

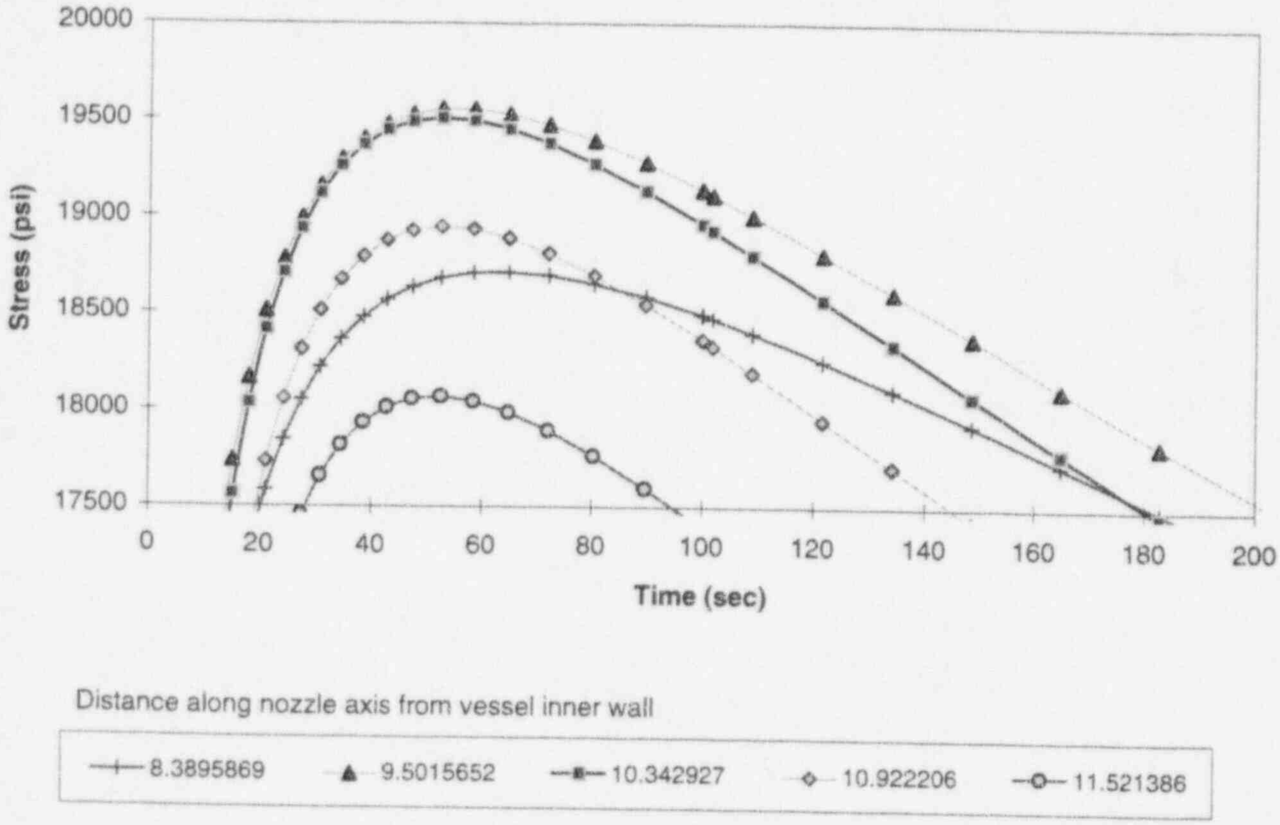


Figure 3-4. Maximum Inside Surface Stresses - Low Leakage Case

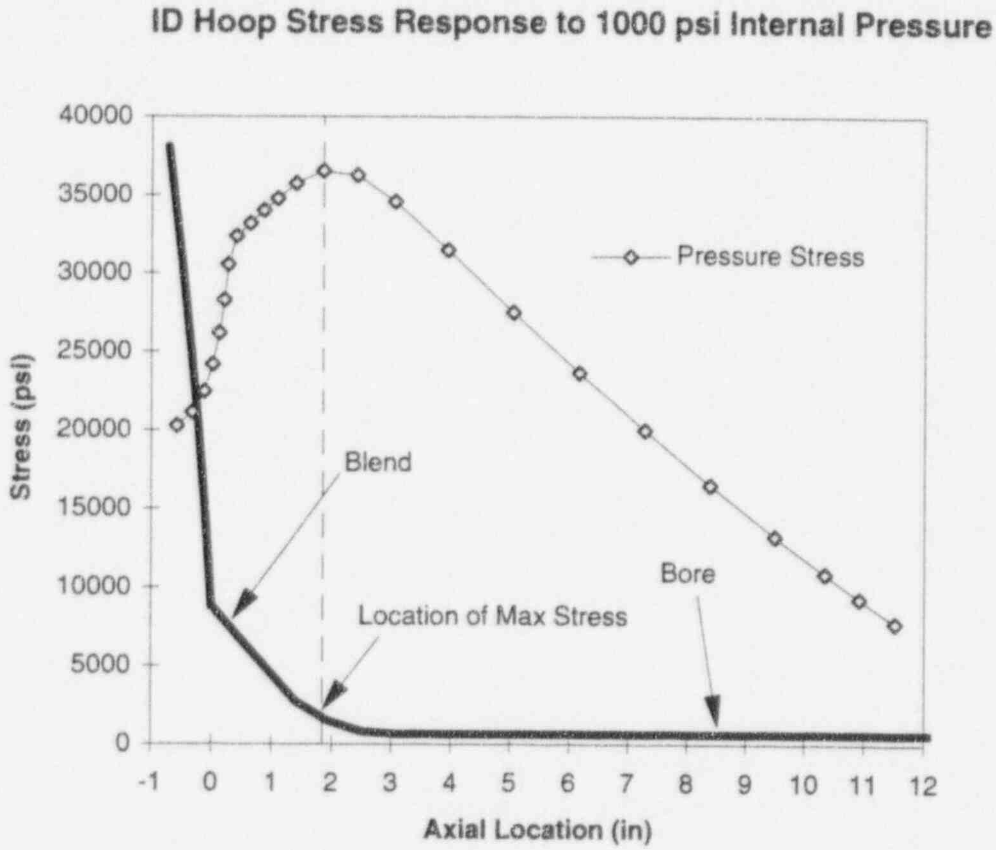


Figure 3-5. Maximum Inside Surface Stresses - Pressure Loading Case

4.0 FRACTURE MECHANICS ANALYSIS

The end objective of this evaluation is to predict growth of hypothetical flaws in the feedwater nozzles. Fatigue crack growth calculations for flaws under a specified set of loads are commonly performed using linear elastic fracture mechanics (LEFM) techniques consistent with Appendix A of ASME Code Section XI [13]. The component geometry and stress state through the component wall are used to determine the stress intensity at the flaw location, and the flaw growth resulting from a stress cycle is predicted as a function of the stress intensity K, usually by means of a "Paris Law" type of crack growth correlation of the form:

$$da/dN = C\ (\Delta K)^n \tag{1}$$

where:

- a is flaw depth
- N is stress cycles, and
- C,n are experimentally determined parameters related to the material and environment, and where C may be a function of K_{min} / K_{max}.

The stress intensity K is a function of the through-wall stress distribution, and the stress intensity range between two extreme (K_{max} - K_{min} or ΔK) is the controlling variable in the crack growth law.

In order to compute stress intensity factors for hypothetical cracks in the Quad Cities feedwater nozzles, the complete through-wall stress distributions at the limiting sections in these nozzles, as determined from the finite element analyses described in Section 3 were used. These stress distributions were represented as third order polynomial functions of distance from the inside surface of the nozzles (Figure 4-1). These functions are of the form:

$$\sigma(x,\ t) = C_0(t) + C_1(t)\,x + C_2(t)\,x^2 + C_3(t)\,x^3 \tag{2}$$

where:

$\sigma(x,t)$ is the through-wall hoop stress distribution

C_0, C_1, C_2, C_3 are time dependent stress coefficients

x is distance from the inside surface.

As discussed in Section 3.0, the thermal stress at each location through a section of the component (blend radius or bore region) is a function of time during the thermal stress transient. The polynomial coefficients are therefore also time dependent. The time dependent coefficients were determined by performing a third order curve fit of the through-wall hoop stress distribution at the limiting sections in the feedwater nozzles for each time step following the unit step change in the transient thermal stress finite element analyses conducted for these nozzles. This curve fit process produced Green's Functions describing the time behavior of each of the coefficients, for each nozzle and leakage cases analyzed in Section 3.0. The stress coefficients for the feedwater nozzle cases are shown in Figures 4-2 through 4-4 for the bore and blend radius region for each of the three cases analyzed in Section 3.0. Note that these are defined for a unit 1°F step change of feedwater temperature. (See Table 4-1 for units.)

Pressure stress coefficients for the 1000 psi case analyzed are given in Table 4-1. These must be scaled to the actual reactor pressure and added to the above thermal coefficients.

Once the polynomial stress coefficients are known, the stress intensity for a nozzle blend radius or bore region crack can be expressed as follows:

$$K_I(t) = \sqrt{\pi a}\,[0.706\ C_0(t) + 0.537\ (2a/\pi)\ C_1(t) + 0.448(a^2\ /2)\ C_2(t) + 0.393\ (4a^3/3\pi)\ C_3(t)] \quad (3)$$

where:

a is the crack depth as defined in Figure 4-1, and

C_0, C_1, C_2, C_3 are time dependent stress coefficients defined above.

This is a standard stress intensity factor expression for nozzle corner cracks subjected to non-linear through-wall stress distributions. It has been verified by comparisons to experimental results and was shown to produce good crack growth predictions up to 70 percent of nozzle thickness [11,12]. Although the bore region location was not at the corner, analysis showed that the corner crack model produced conservative results by comparing it to a model for a cylinder with a finite length ($a/\ell = 0.5$) crack.

Table 4-1

Polynomial Stress Function Coefficients for

1000 psig Internal Pressure

Coefficient	Bore	Blend Radius
C_0 (psi)	15,144	58,747
C_1 (psi/in)	-3,110	-9,295
C_2 (psi/in^2)	409	871
C_3 (psi/in^3)	-32.2	-29.3

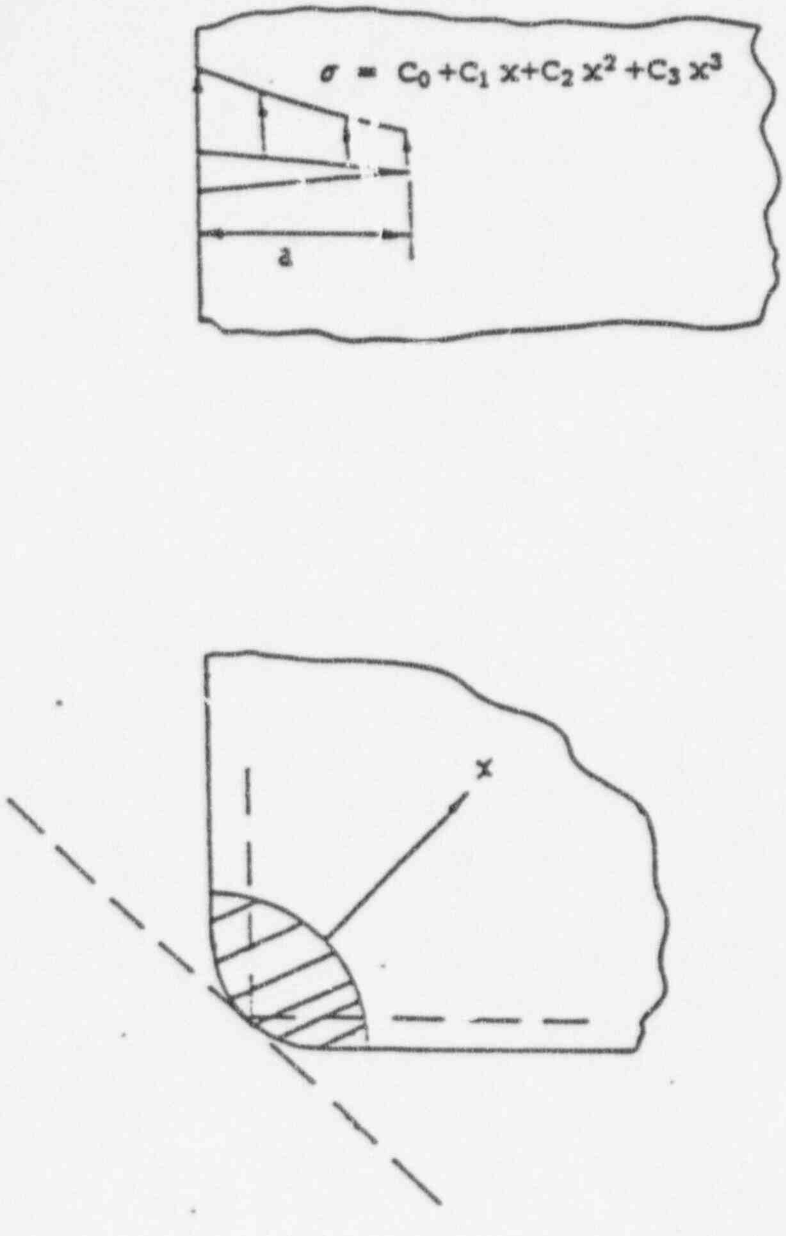
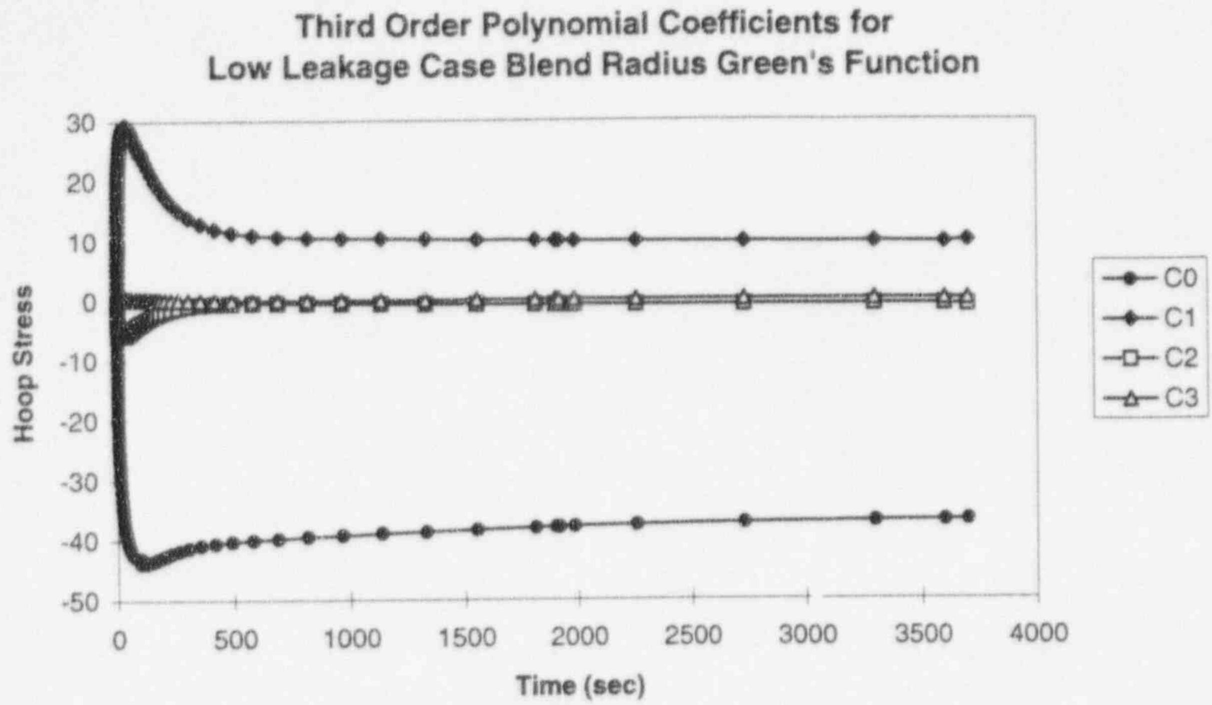


Figure 4-1. Simulated 3-D Nozzle Corner Crack Model



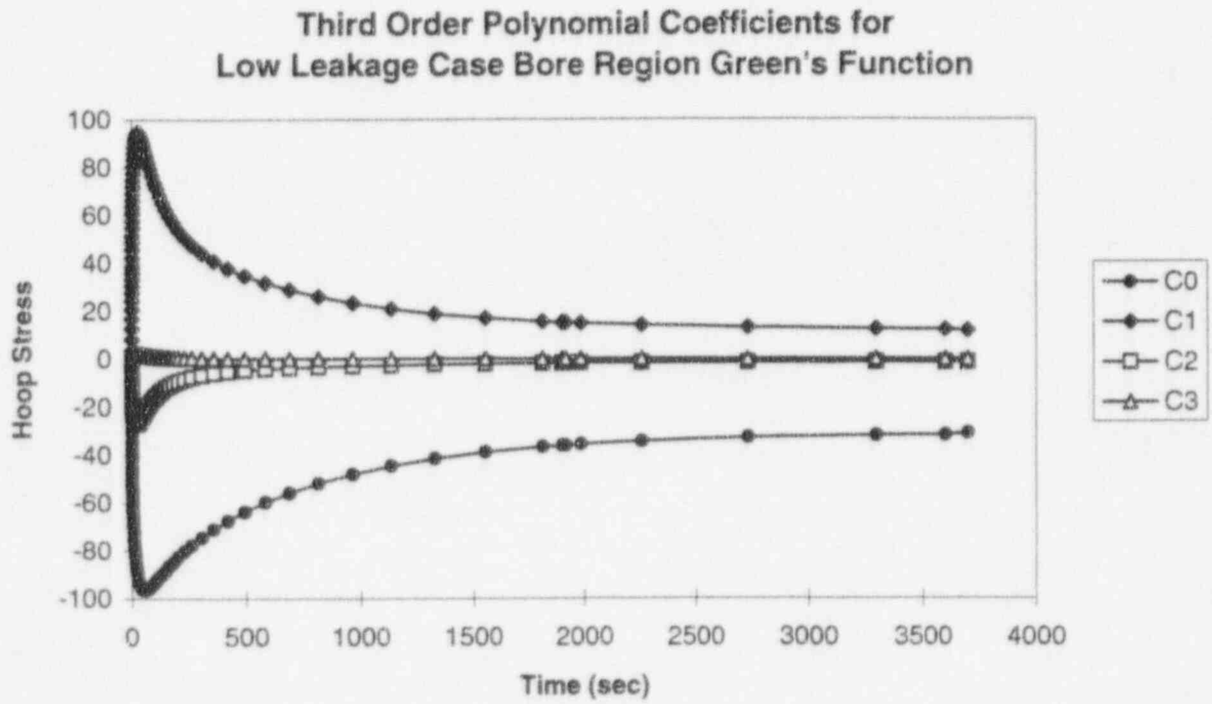
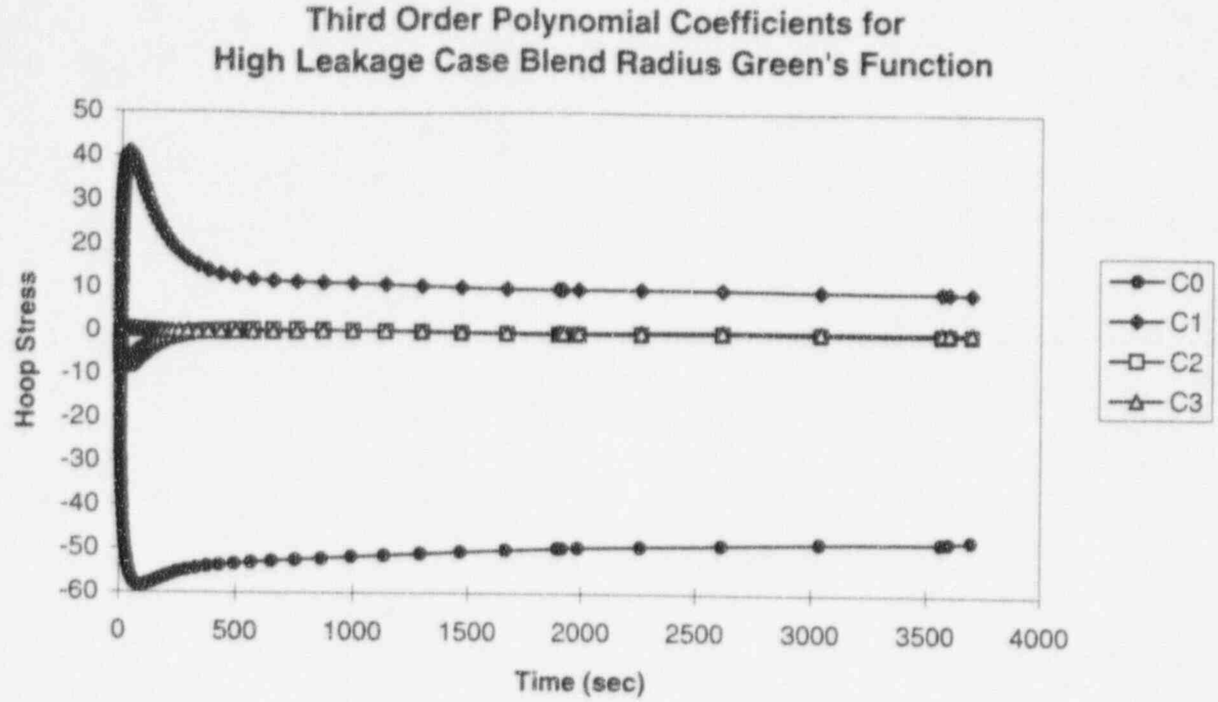


Figure 4-2. Hoop Stress Coefficients for Low Leakage Case - Bore and Blend Radius Regions



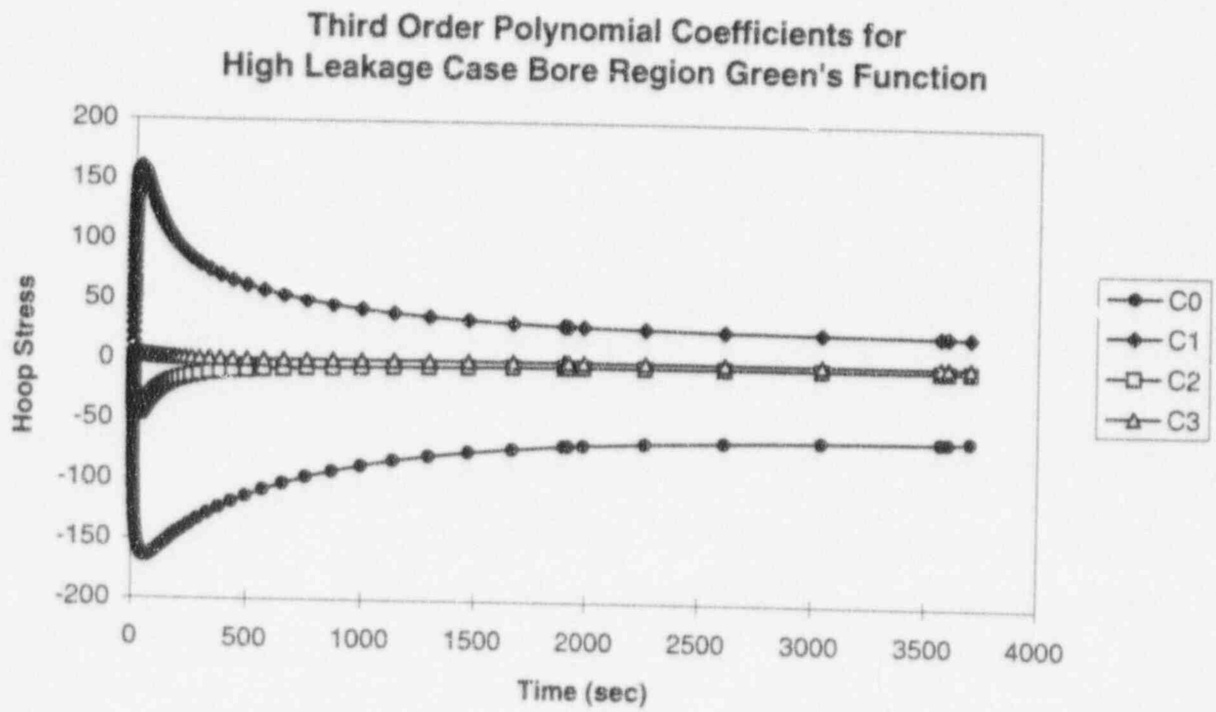


Figure 4-3. Hoop Stress Coefficients for High Leakage Case - Bore and Blend Radius Regions

5.0 DAMAGE ASSESSMENT METHODOLOGY

The previous sections discuss the various aspects of the stress analysis which were performed to support the development of the **FatiguePro** stress intensity factor prediction system for the feedwater nozzles at Quad Cities. The purpose of this **FatiguePro** application is to provide a convenient method for predicting the stress intensity factor time history of hypothetical cracks for any applied set of flow rate, pressure and temperature conditions. This section discusses the damage assessment techniques used to perform this evaluation.

5.1 Design Transient Definition

The fatigue crack growth rate at a location is a function of the magnitude and frequency of the stress cycles experienced at that location. For feedwater nozzle locations, these depend on the number and magnitude of heatup-cooldown and feedwater flow transients which the nozzle experiences. The design basis thermal events for the Quad Cities feedwater nozzles are defined in Reference 2. These include the following design transients which terminate or initiate flow to the feedwater nozzles, and significantly affect the temperatures at the nozzles:

	Event	Number of Cycles
1.	Startup and Turbine Roll	200
2.	Loss of Heaters	70
3.	Interruption of Feedflow (+ Scrams)	280
4.	Safety Valve Blowdown	1
5.	Normal Operation	20000
6.	Reduction to Zero Power	198
7.	Hot Standby	2600
8.	Shutdown	198

For purposes of simulating feedwater nozzle operation in a crack growth analysis, it is necessary to combine these events into an equivalent set of events that can be counted during plant operation. The standard cycles that may be counted for feedwater nozzles are those corresponding to the "startup-shutdown" transient, which includes a shutdown and return to power following the shutdown, and is counted the same whether the plant is shut down to a hot standby mode (as in a mid-cycle scram) or to cold shutdown for refueling or extended maintenance. Each such event involves a turbine roll and typically some period of time in hot standby (upon the restart). Therefore, from the above transient list, it is conservatively assumed that the plant will undergo 200 such startup-shutdown cycles, with 2600/200 or 13 hot standby feedwater injection cycles per event. This cycle is defined by reactor pressure, reactor and feedwater fluid temperatures, and feedwater flow rate changes with time. It will also be conservatively assumed that each scram results in a shutdown and will also have 13 feedwater injections. Figure 5-1 illustrates both the reactor pressure and fluid temperature contributors to the cycle definition. The feedwater flow is illustrated in Figure 5-2. The remainder of the design basis cycles indicated above are assumed to be encompassed within this "startup-shutdown" cycle definition. (The normal operational cycles are not significant from the standpoint of feedwater nozzles, and the loss of feedwater heater and interruption of feedflow scram events are assumed to be conservatively counted as one of the above startup/shutdown events).

In 1987 and 1988, an on-line version of the **FatiguePro** monitoring system was installed at the Quad Cities plant for a four month trial period. During this period, there were a total of three startup-shutdown and/or scram events. As illustrated in Figure 5-3, however, these events involved considerably fewer stress cycles than the design basis assumption assumed for this analysis (one turbine roll plus 13 hot standby events per startup/shutdown). Counting the cycles experienced during the **FatiguePro** monitoring yields an average of about 5 feedwater events per startup-shutdown, with a maximum of 6 (during the Jan 11 scram and Jan. 15-16 startup). Therefore, the startup-shutdown cycle assumed for purpose of this analysis is very conservative with respect to number of cycles. Actual rates of temperature change are also much less severe than the design basis rates. Thus, much slower rates of

crack growth would be predicted if actual feedwater cycling condition were taken into consideration.

5.2 Fatigue Crack Growth

Once a crack has been initiated in a component, its propagation is driven by magnitude and frequency of the stress cycling, including an effect of the stress distribution through the wall of the component. As discussed in Section 4.0, fatigue crack growth is a function of changes in the stress intensity factor K, which is itself a function of the time dependent through-wall hoop stress distribution. The methodology used to compute fatigue crack growth for the Quad Cities crack growth evaluation is described in the following paragraphs.

Using the methods described in Sections 2 through 4 of this document, the stress intensity factor is calculated as a function of time based on design condition plant pressure and temperature operating conditions. In summary, the **FatiguePro** program uses simulated values of plant temperature, pressure, and flow history to calculate resulting through-wall stress distribution transients. These are in turn used to calculate K as a function of time for the feedwater nozzle blend radius and bore regions. The program is run assuming that a hypothetical crack of depth $a_{initial}$ exists that is a conservative estimate of the depth of flaw which could be missed by external ultrasonic examination of the nozzle. During each hour of operation, **FatiguePro** calculates the incremental crack growth which would be predicted from the input transients, by using the calculated ΔKs for that hour with the crack growth law of Figure 5-3, which is built into the program. At the end of each hour, the program updates the flaw depth to reflect any predicted growth during the hour, and the analysis proceeds to the next hour. Since K is a function of crack depth, the stress intensity factors calculated during subsequent hours are based upon the updated crack depth from previous hours.

In the **FatiguePro** calculations used herein, the crack size remains essentially constant for the small number of transients considered for each startup shutdown cycle. Thus the

evaluation of actual crack growth for a large number of cycles was based on an alternate calculation. This required only that separate **FatiguePro** runs be made to determine the stress intensity factor history for each of a range of initial crack sizes.

5.3 Determination of Crack Growth Rates for Quad Cities Feedwater Nozzles

The **FatiguePro** software can be used with any selected transients to determine the stress intensity factor history for the two leakage conditions considered in this evaluation. A conservative design transient was chosen in this evaluation to determine the stress intensity transient history at various crack sizes for various design transients. It is observed for the purpose of this evaluation that the design transients for Quad Cities were conservatively bounded by two simple transients as illustrated in Figures 5-1 and 5-2. The first is startup to full pressure followed by turbine roll and then depressurization to zero pressure. The second transient involves a hot standby injection in which the feedwater flow is initiated 6 times per hour for a total of 13 injections following FW termination. These two transients were combined in order to determine the stress intensity ranges (ΔK) using the **FatiguePro** software. Four separate evaluations were made for each assumed leakage rates with initial crack sizes of 0.25, 0.50, 0.75 and 1.0 inches. These runs determined the ΔK ranges for the startup/shutdown and the hot standby injection as a function of crack size.

The ΔK transients for the two cases in the blend radius and the bore regions are shown in Figures 5-5 and 5-6 for a 0.5 inch initial crack size. Review of Figure 5-5 and 5-6 confirms that there are only two important parts of the transients. Pressurization plus the initial injection of feedwater flow produces the maximum ΔK range. The following feedwater heatup, and subsequent steady state operation, do not produce a ΔK cycle, and are thus unimportant. The second important ΔK is that due to hot standby flow cycling where on/off feedwater injection can alternately cause significant stress cycling in the nozzle.

A summary of the stress intensity factor ranges for the various leakage cases for the blend radius and bore regions are shown in Table 5-1[1]. For use in crack growth calculations, a relationship between ΔK and the crack size (a) of the following form was developed from the values shown in Table 5-1.

$$\Delta K = \sqrt{A + Ba + Ca^2} \tag{4}$$

Table 5-2 shows the values of A, B and C for the various cases. To evaluate ΔK ranges for other transient combinations, the values of ΔK may be linearly ratioed as follows:

For pressure P,

$$\Delta K_P = \frac{P \cdot \Delta K_{p=1025}}{1025} \tag{5}$$

For the startup/shutdown cycle with startup turbine roll step change of T_{tr} at pressure P:

$$\Delta K_{su/sd} = \frac{T_{tr} \cdot (\Delta K_{su/sd=502} - \Delta K_{p=1025})}{502} + \Delta K_P \tag{6}$$

Note that this linearly corrects the temperature step change portion of the startup/shutdown cycle and then recombines the pressure portion. Additional pressurization after turbine roll would not increase the ΔK range since the transient response peak would be past.

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[1]These were determined based on a feedwater temperature of 50°F and a reactor temperature of 552°F at turbine roll, and with a feedwater temperature of 100°F and reactor temperature of 552°F during hot standby. Pressure was assumed to be 1025 psig during both transients.

For the hot standby injection transients at ΔT_{hs} (between reactor temperature and feedwater temperature) with ΔP_{hs} between the feedwater initiation and termination portions of the transient.

$$\Delta K_{hs} = \frac{T_{hs} \cdot \Delta K_{hs=452}}{452} + \frac{\Delta P_{hs} \Delta K_{p}=1025}{1025} \qquad (7)$$

The results of the evaluations with the above conditions are included in Figures 5-7 through 5-9 conservatively assuming 90 psi pressure cycling during hot standby. These figures present predicted crack depth versus number of Startup/Shutdown cycles for various initial flaw sizes of 0.25, 0.5, and 0.75 inches, for the assumed low and high leakage rates (0.38 and 1.0 GPM). These results may be compared to the allowable flaw size results calculated in Section 5.4 below to determine an acceptable period of continued operation between nozzle inspections.

5.4 Allowable Flaw Size

The allowable flaw size for the various leakage cases considered in this evaluation are determined from the provisions of the ASME code Section XI, IWB-3610 and IWB-3611 [13]. The flaw size is limited to one-tenth of the critical flaw size for normal operating and upset conditions as determined from linear elastic fracture mechanics.

The determination of the critical flaw size requires a comparison of the applied stress intensity versus crack size with the fracture toughness of the material. The intersection of these two curves represent the critical flaw size. The applied stress intensity versus crack size plots for all of the bounding turbine roll transients considered in this evaluation were determined using Structural Integrity software **pc-CRACK** [13] and are shown in Figure 5-10. For the temperatures during reactor operating conditions, the fracture toughness for reactor vessel grade low alloy steel is approximately 200 $ksi\sqrt{in}$, consistent with the value used in

since all the applied stress intensity curves are below the fracture toughness curve. Based on Section XI requirements, the allowable flaw size is limited to one-tenth of the thickness of the nozzle (8.9 inches blend radius and 6.12 bore region) resulting in an allowable flaw size of 0.89 inches for the blend radius and 0.612 inches for the bore.

Table 5-1

Stress Intensities for Startup/Shutdown and Hot Standby

Transient	a (in)	Stress Intensitty Factors, $K_{min}/K_{max,}$ ΔK (ksi-in$^{0.5}$)			
		0.38 GPM Case		1 GPM Case	
		Blend Radius	Bore	Blend Radius	Bore
Startup/ (1) Shutdown	0.25	0/42.5	0/36.5	0/46.7	0/55.9
		42.5	36.5	46.7	55.9
	0.5	0/58.2	0/47.4	0/63.9	0/72.1
		58.3	47.4	63.9	72.1
	0.75	0/69.2	0/53.4	0/76.0	0/80.7
		69.2	53.4	76	80.7
	1	0/77.9	0/56.9	0/85.7	0/85.5
		77.9	56.9	85.7	85.5
Hot Standby	0.25	28.9/41.0	2.8/31.1	28.6/44.6	-1/46.8
		12.1	28.3	16.0	47.8
	0.5	40.4/56.2	5.2/40.5	40.2/61.1	0.9/60.6
		15.8	35.3	20.9	59.7
	0.75	48.9/66.9	7.4/45.8	48.7/72.7	3.0/68.1
		18.0	38.4	24.0	65.1
	1	55.5/75.2	9.6/49.0	55.3/81.6	5.2/72.5
		19.7	39.4	26.3	67.3
Pressure (1025 psi)	0.25	0/29.6	0/9.4	0/29.6	0/9.4
		29.6	9.4	29.6	9.4
	0.5	0/41.0	0/13.0	0/41.0	0/13.0
		41	13	41	13
	0.75	0/49.3	0/15.5	0/49.3	0/15.5
		49.3	15.5	49.3	15.5
	1	0/55.9	0/17.5	0/55.9	0/17.5
		55.9	17.5	55.9	17.5

(1): Includes pressure ΔK that is lis'ed separately above

Table 5-2

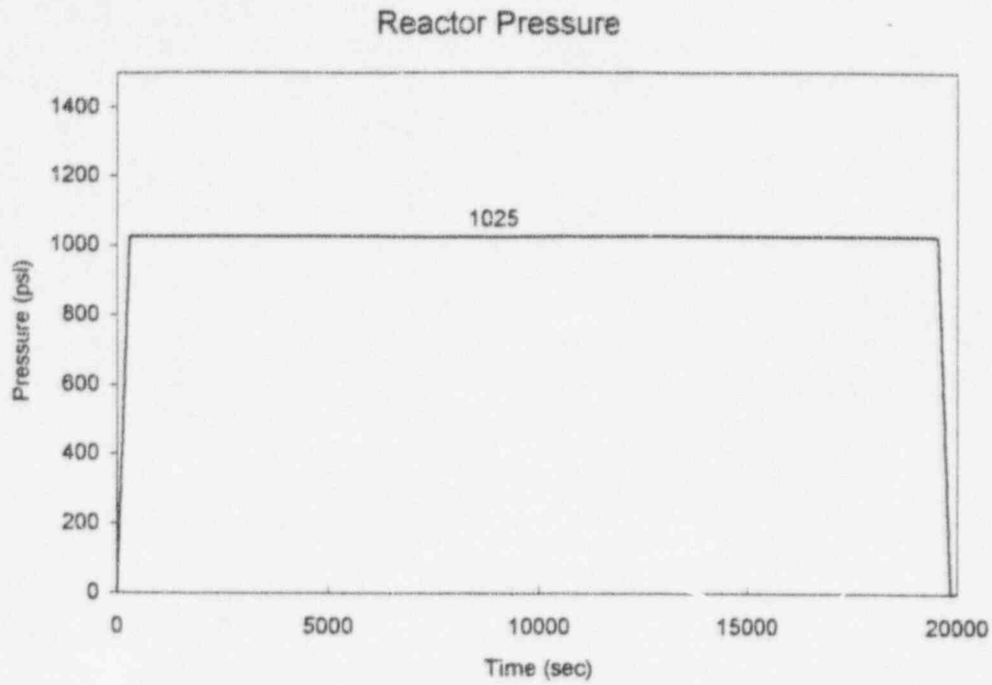
Curve-Fit Coefficients for Stress Intensities Versus Crack Size

Coefficients		0.38 GPM Case		1 GPM Case	
		Blend Radius	Bore	Blend Radius	Bore
Startup/ (1) Shutdown	A	9.1886	20.143	15.1957	54.1817
	B	7482.9	5714.51	8952.87	13390.27
	C	-1435.2	-2516.7	-1639.23	-6186.99
Hot Standby	A	3.2297	21.5434	5.3897	64.8317
	B	602.662	3411.82	1049.63	9653.21
	C	-221.154	-1900.47	-368.27	-5248.51
Pressure (1025 psi)	A	1.8406	0.164	1.8406	0.164
	B	3600.47	367.596	3600.47	367.596
	C	-478.89	-61.84	-478.9	-61.84

(1): Pressure ΔK included

$$\Delta K = \sqrt{A + Ba + Ca^2}$$

ΔK = Stress intensity range (ksi$\sqrt{\text{in}}$)
a = crack size (in.)
A,B,C = power law coefficients.



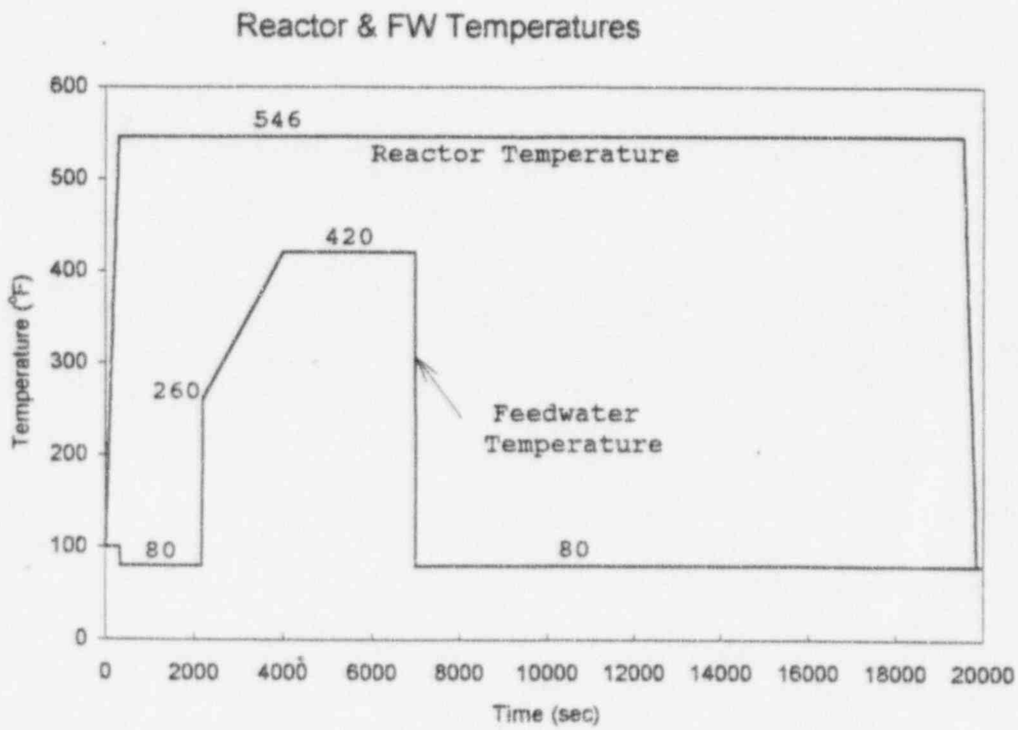


Figure 5-1. Equivalent Startup-Shutdown Cycle used for Crack Growth Analysis

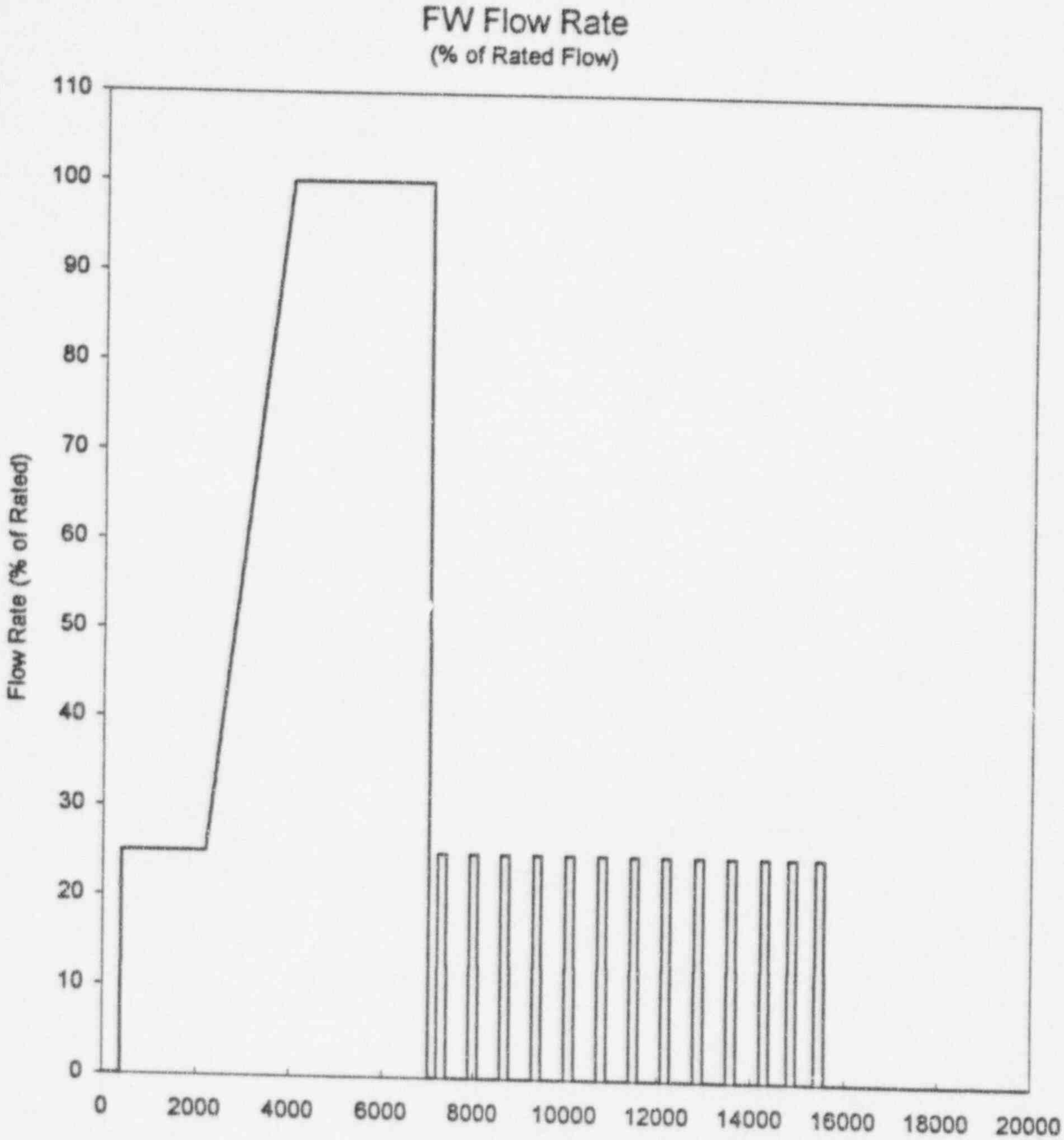


Figure 5-2. Equivalent Startup-Shutdown Cycle used for Crack Growth Analysis

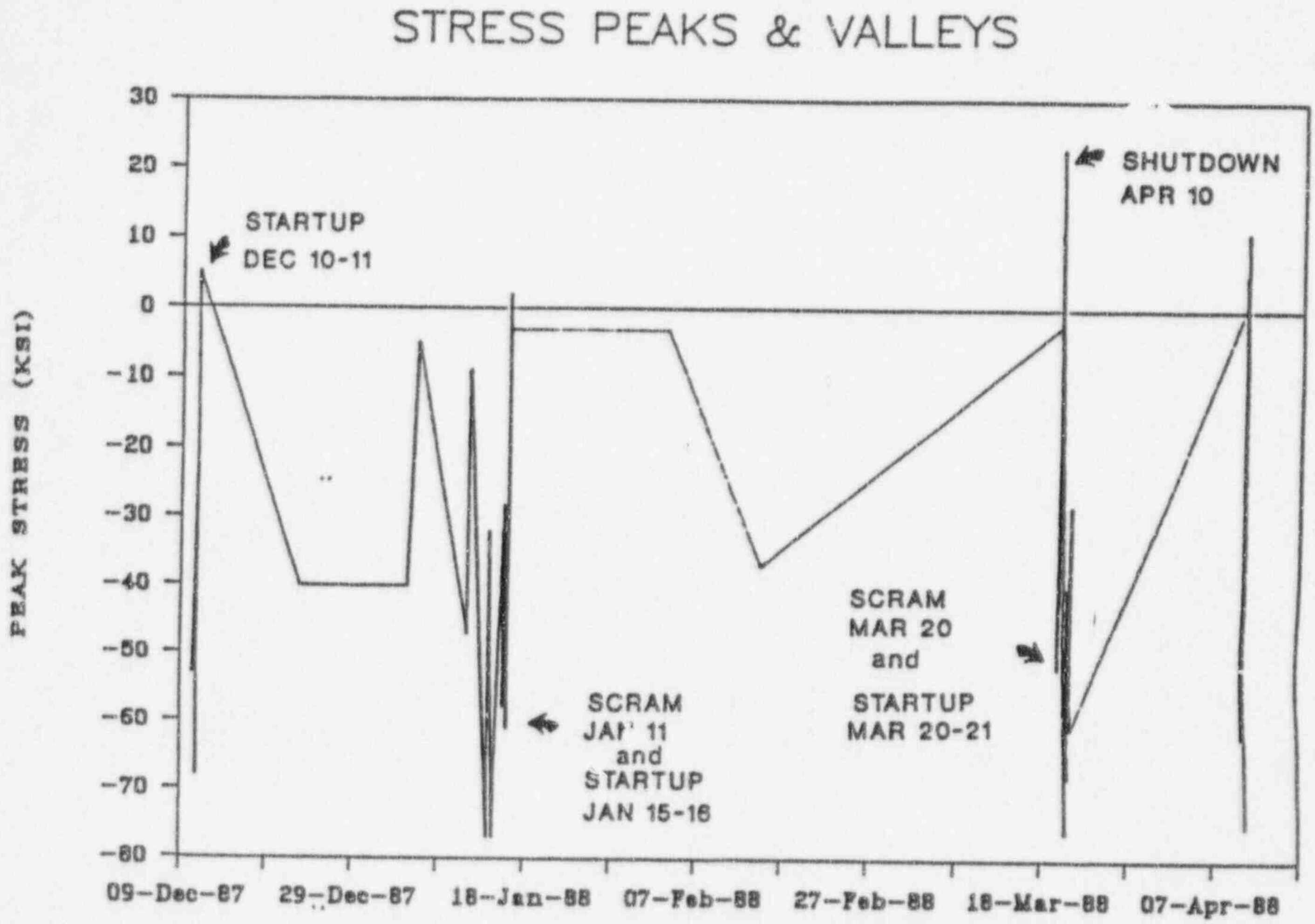


Figure 5-3. Startup-Shutdown Cycles as Monitored by the **FatiguePro** System

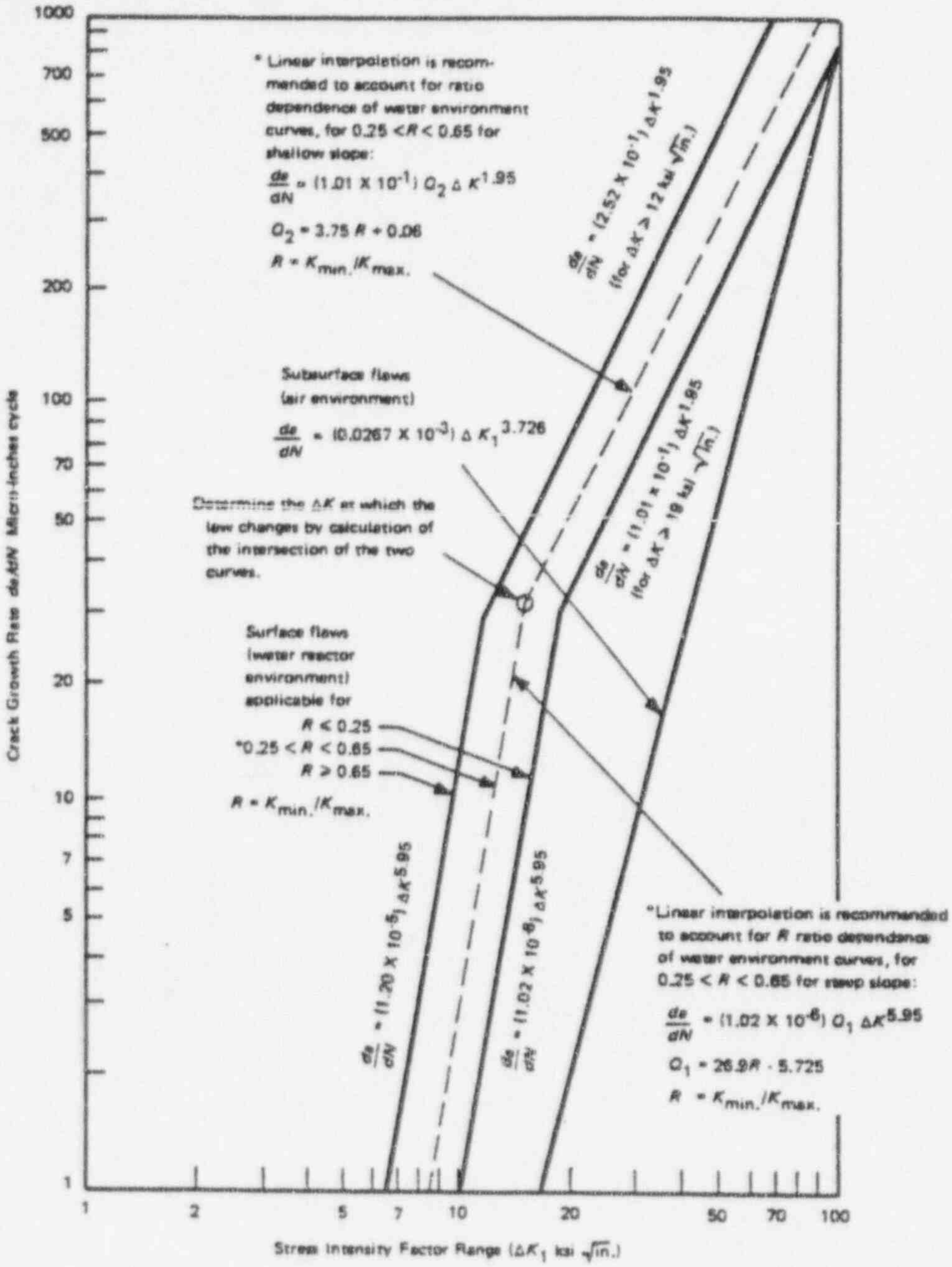


FIG. A-4300-1 REFERENCE FATIGUE CRACK GROWTH CURVES FOR CARBON AND LOW ALLOY FERRITIC STEELS

Figure 5-4. ASME Section XI Crack Growth Law [13]

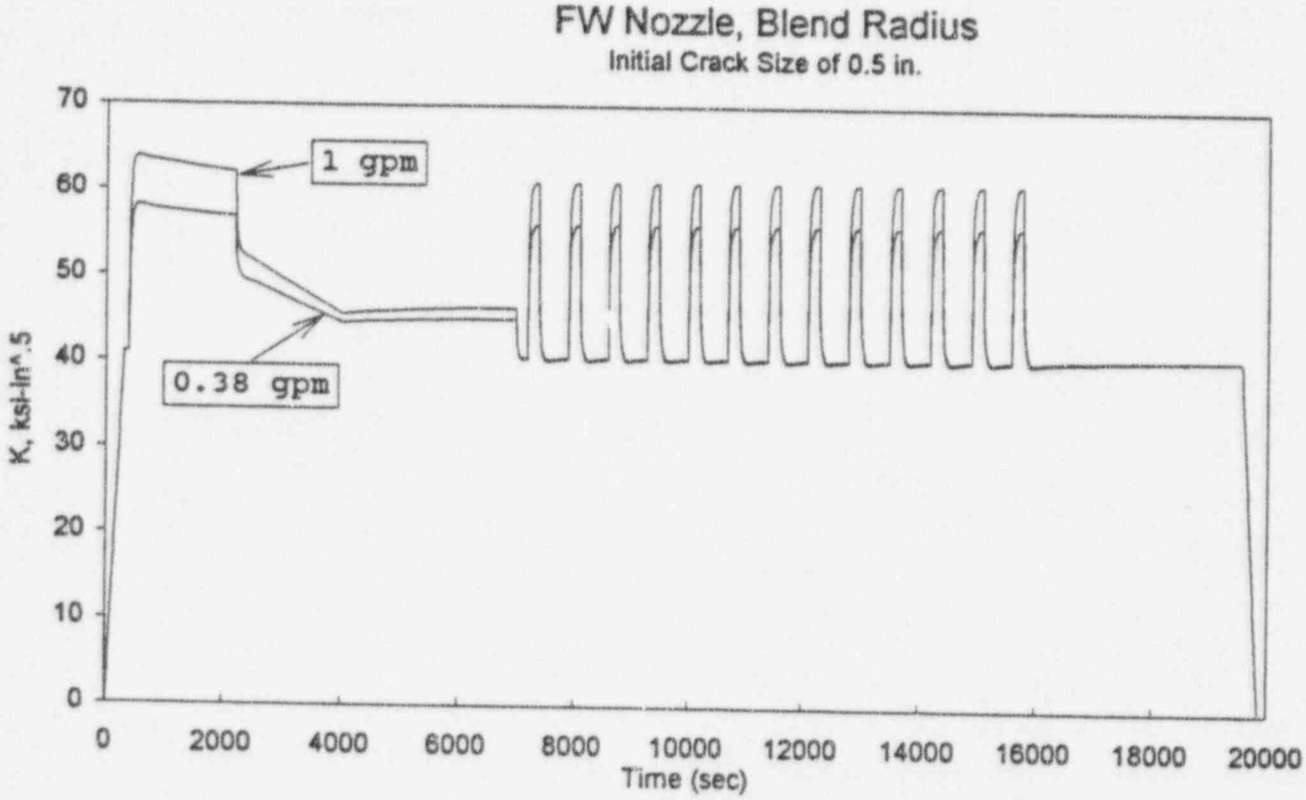


Figure 5-5. Stress Intensity Factor for Assumed Startup-Shutdown Transient - Blend Radius

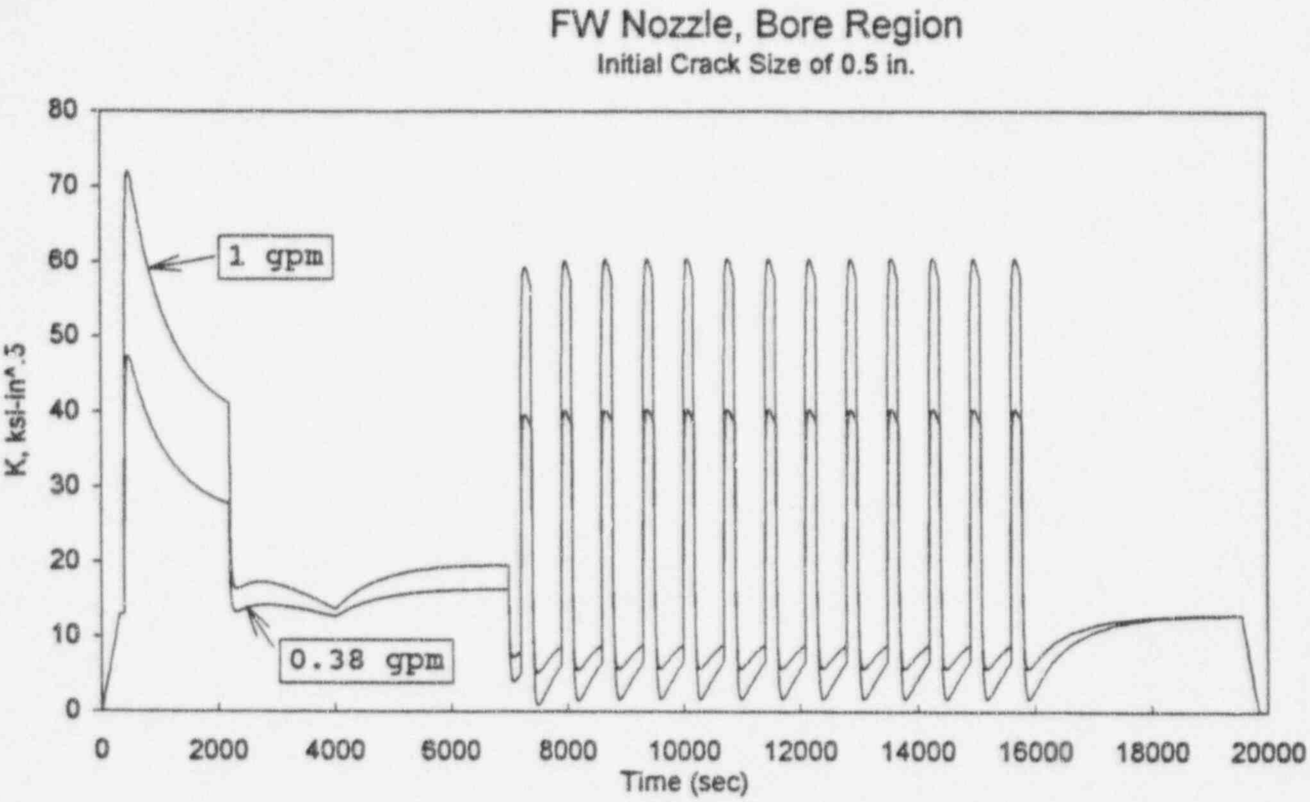


Figure 5-6. Stress Intensity Factor for Assumed Startup-Shutdown Transient

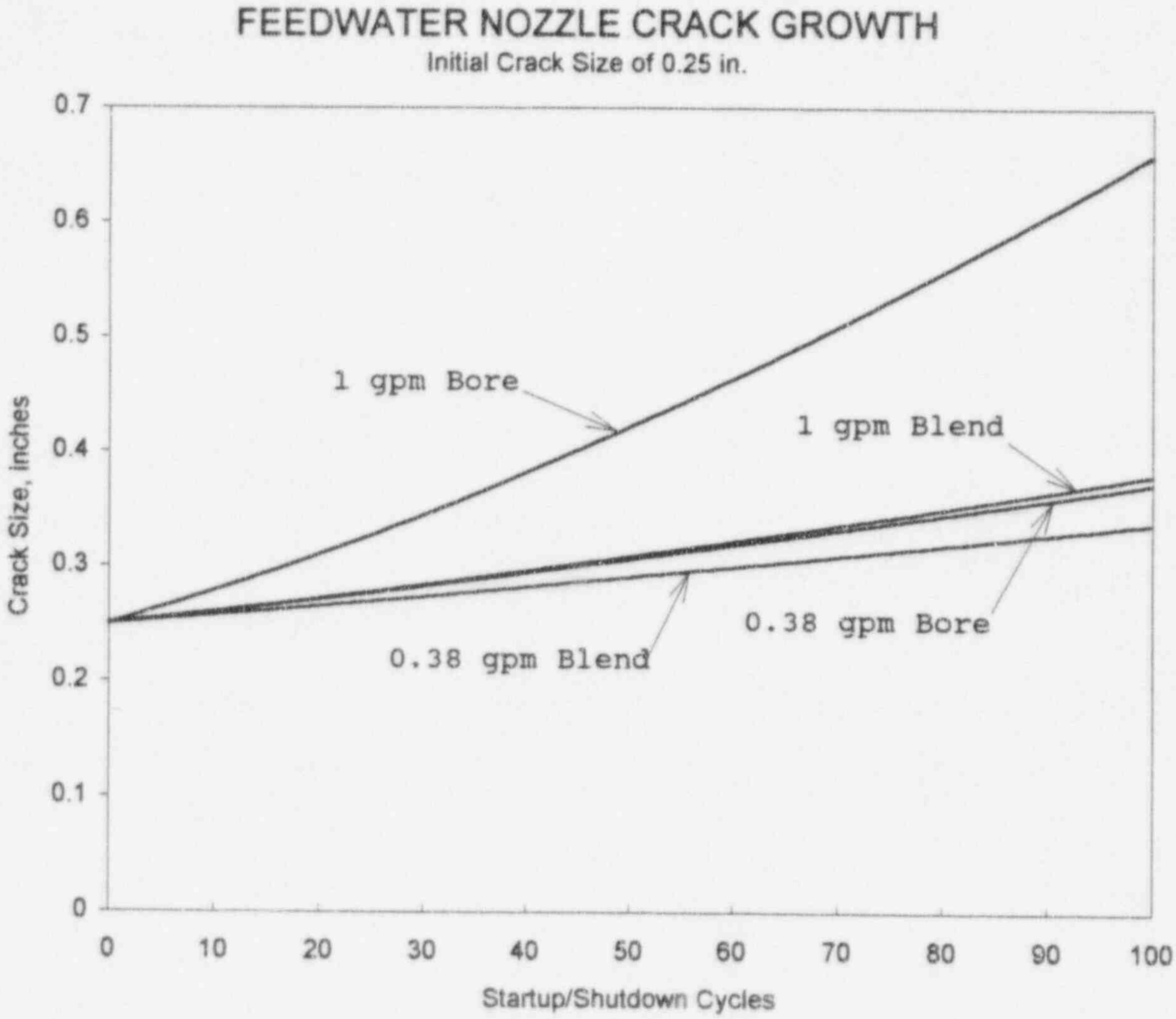


Figure 5-7. Fatigue Crack Growth Results (Initial Crack Size = 0.25")

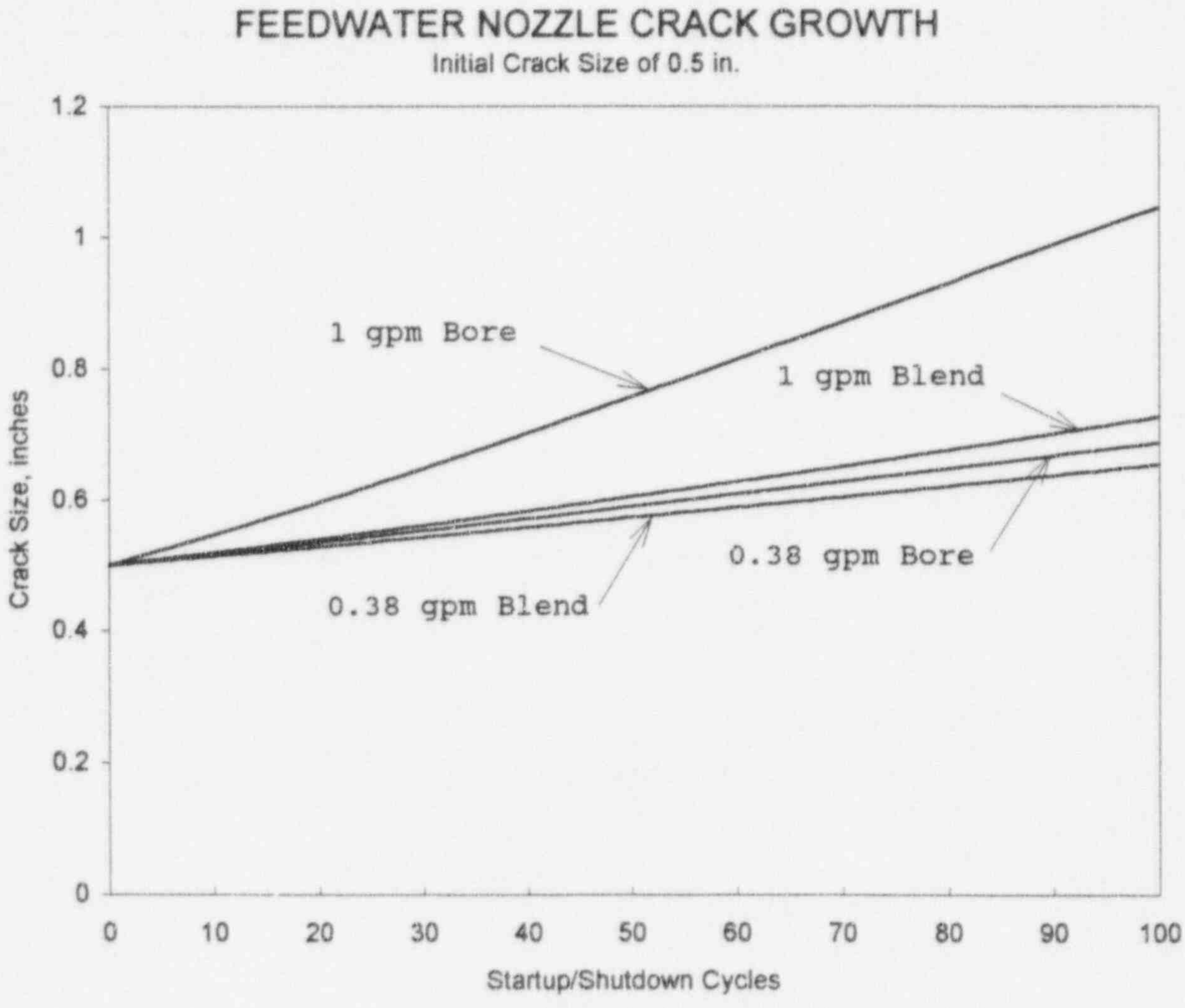


Figure 5-8. Fatigue Crack Growth Results (Initial Crack Size = 0.5")

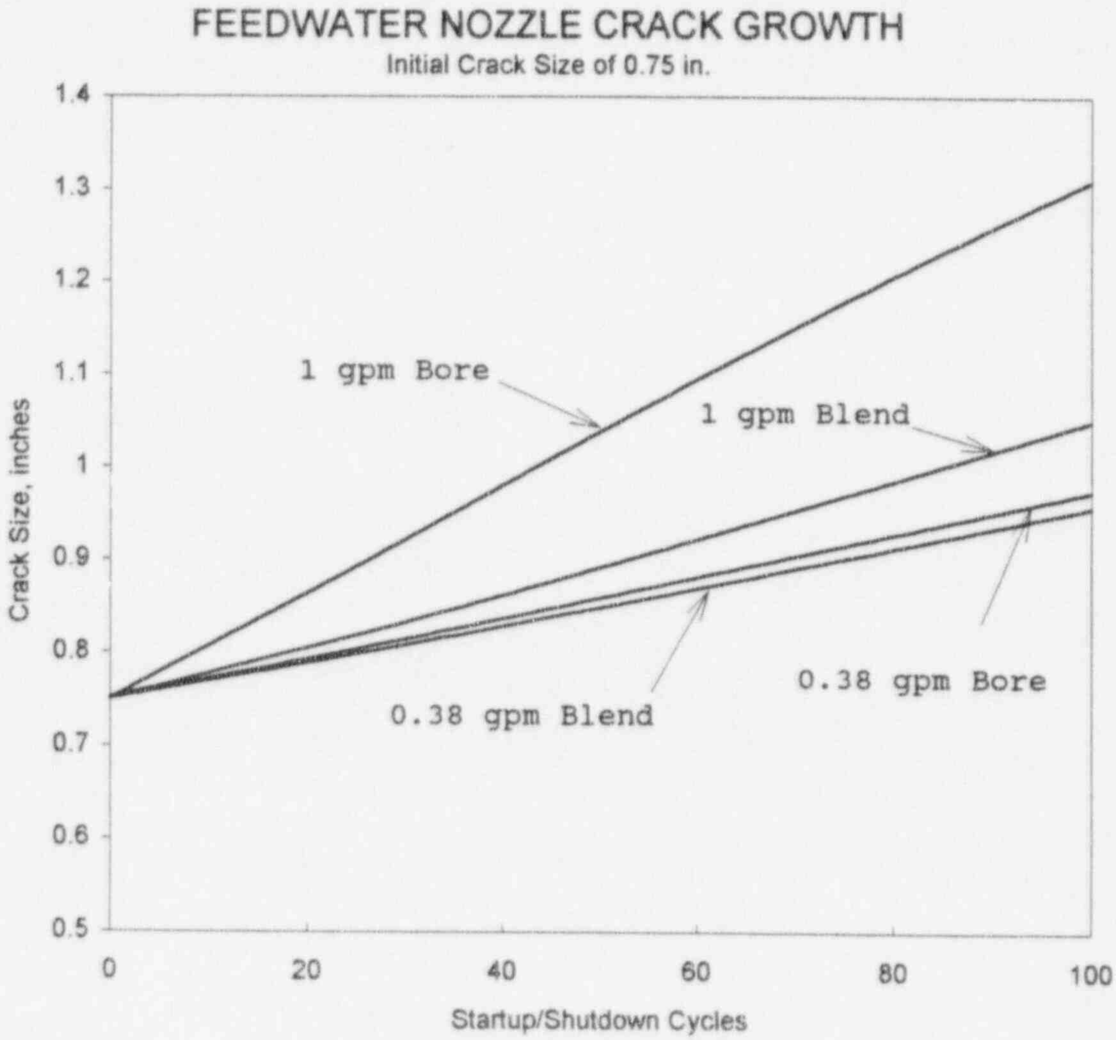


Figure 5-9. Fatigue Crack Growth Results (Initial Crack Size = 0.75")

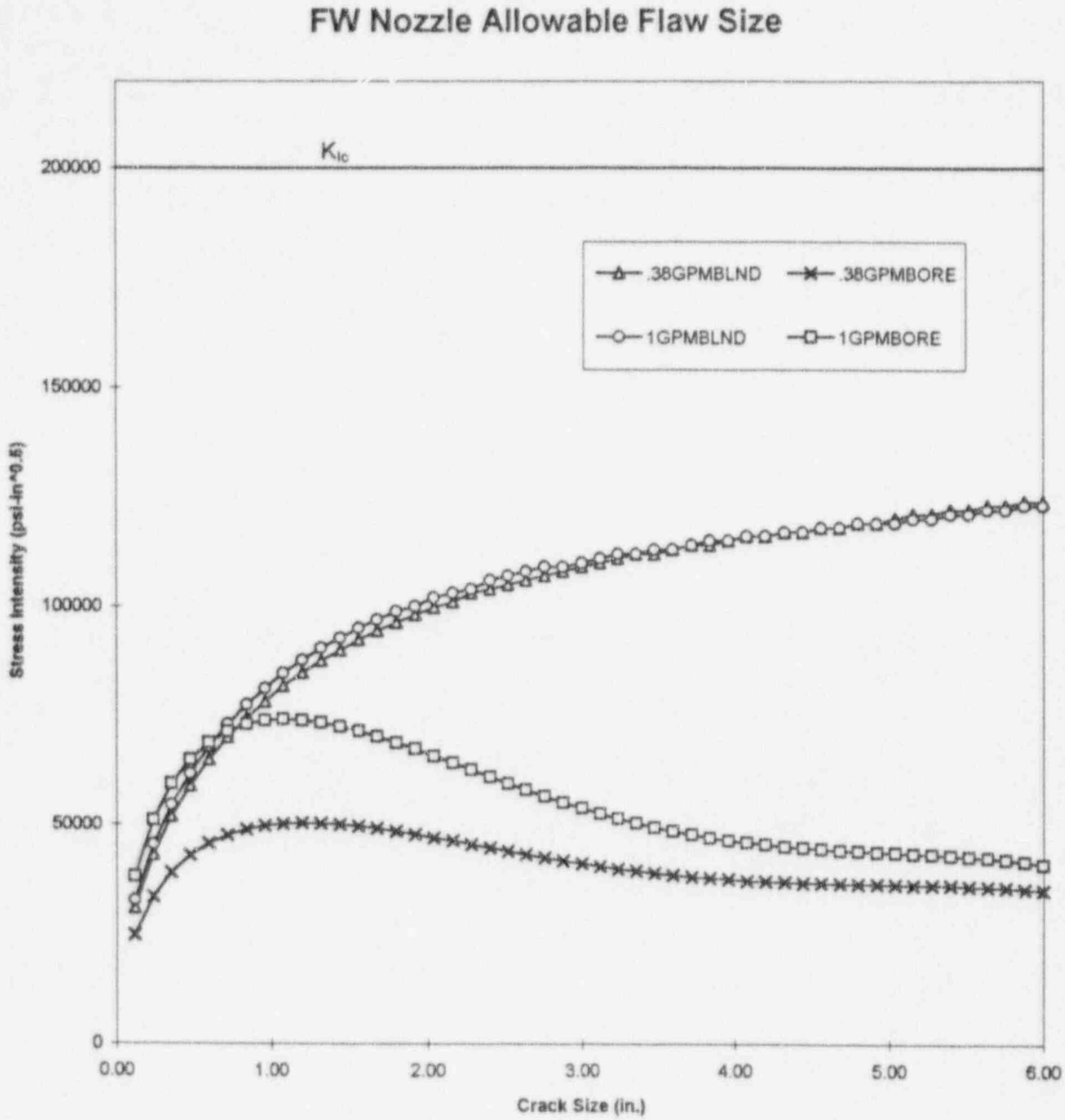


Figure 5-10. ASME Section XI Allowable Flaw Size Determination

6.0 SUMMARY AND CONCLUSIONS

This report presents the results of fatigue crack growth and critical flaw size calculations for the Quad Cities Unit 1 and 2 reactor vessel feedwater nozzles. The analyses consider two critical sections of the nozzle, one in the nozzle inside blend radius to the vessel, and the other in the nozzle bore region. These sections correspond to the maximum pressure and thermal stress locations in the nozzle, respectively. Stress and stress intensity factors for these locations in the nozzle were developed using the EPRI **FatiguePro** methodology and software. The software was then used to analyze a conservative set of design cycles for the nozzle, which can be correlated with plant startup/shutdown or scram cycles. Critical flaw sizes and ASME Section XI allowable flaw sizes were also determined for both locations.

The results of the analyses are presented in Table 6-1, in terms of the number of startup/shutdown or scram cycles required for flaws of various depths to reach the ASME Section XI allowables. The following observations may be drawn from these results:

1. The critical flaw size is equal to the nozzle wall thickness at both locations. Therefore, in accordance with ASME Section XI requirements, the allowable flaw size is equal to one-tenth of the thickness, or 0.89 inches in the blend radius and 0.612 inches in the bore region.

2. Assuming a 0.25 inch initial flaw size, and thermal cycling which bounds the current maximum expected bypass leakage rate of 0.38 GPM (from the bypass leakage monitoring system installed on the nozzles), the crack will not exceed the Section XI allowables at either location for greater than 100 of the assumed design-basis cycles, which corresponds to approximately one half of the design number of cycles. The 0.25 inch flaw size is consistent with minimum detectability levels of the upcoming ultrasonic inspections of the nozzles using current day technology.

3. Even assuming a larger initial flaw size of 0.5 inches, the nozzles have considerable remaining life (> 70 startup/ shutdown cycles for the 0.38 GPM leakage case).

4. Even when assuming the higher-than-expected bypass leakage rate of 1.0 GPM for the triple sleeve spargers installed at Quad Cities, reasonable remaining life still exists for the 0.25 inch initial flaw size (> 90 startup/shutdown cycles).

Based on these results, it is concluded that continued operation with the existing feedwater nozzle/spargers is acceptable, assuming that the upcoming ultrasonic examinations yield results within these limits. In the event that larger flaws are observed, the **FatiguePro** system could be used to track crack propagation based on actual plant transient operating conditions. In any event, it is recommended that thermal sleeve bypass leakage continue to be monitored using the installed leakage monitoring system.

Table 6-1

Analysis Results

Initial Flaw Size Assumption (in.)	Allowable Remaining Startup/Shutdown Cycles	
	0.38 GPM Leakage	1.0 GPM Leakage
<u>Blend</u>		
0.25	> 100	> 100
0.5	> 100	> 100
0.75	69	48
<u>Bore</u>		
0.25	> 100	92
0.5	72	25
0.75	0	0

7.0 REFERENCES

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