Westinghouse Non-Proprietary Class 3

Westinghouse Energy Systems

WCAP-14435

Structural Integrity Evaluation for the Feedwater Nozzle Safe-end Region of the Kewaunee Nuclear Plant

July 1995

W. H. Bamford
A. L. Thurman
D. E. Prager

Reviewed by: P. L. Strauch

Approved by: S. A. Swamy, Manager
Structural Mechanics Technology

Approved by: J. L. Houtman Manager
Steam Generator Design and Analysis

WESTINGHOUSE ELECTRIC CORPORATION
Nuclear Technology Division
P. O. Box 355
Pittsburgh, Pennsylvania 15230

m:\2187w.wpf:1b-072695

EXECUTIVE SUMMARY

This flaw evaluation handbook has been prepared to address flaw indications which were found when performing Section XI ultrasonic examinations of Steam Generator (SG) nozzle-to-pipe welds at the Kewaunee Nuclear Power Plant (KNPP) during the 1995 refueling outage. The 1A and 1B SG Feedwater nozzle-to-pipe welds have been proactively examined since 1979, following repair/replacement activities due to cracks in the counterbore region. No recordable indications had been detected during these earlier examinations. The tables and charts provided herein allow the evaluation of any indication discovered in the 1A and 1B SG FW nozzle-to-pipe welds without further fracture mechanics calculations. The fracture analysis work was performed in accordance with Appendix A of Section XI and is documented in this report. Use of this handbook will allow the acceptability (by analysis) of larger indications than would be allowable by only using the standards tables in Section XI of the ASME B&PVC. This report also provides the background and technical basis for the handbook charts. This handbook was prepared utilizing KNPP plant specific operation information and supplemented with applicable crack growth data from previous industry experience.

The flaw indications will be ultrasonically inspected during the 1998 refueling outage in accordance with the reexamination requirements of paragraph IWC-2420 of Section XI. These areas will also be ultrasonically examined prior to 1998 at a frequency beyond the code rules, to the extent practical to monitor the growth rate of the flaw indications, thereby ensuring the continued integrity of the FW system. Furthermore, a temperature monitoring system has been designed and is scheduled to be installed and functional prior to startup, following the 1995 refueling outage. This system will monitor the outer pipe wall circumferential temperature profile caused by fluctuating Auxiliary Feedwater flow during scheduled plant startups and shutdowns. Data collected from the temperature monitoring system will be incorporated as applicable into the flaw evaluation analysis following reexamination of the 1A and 1B SG nozzle-to-pipe welds tentatively scheduled for the next planned refueling outage.

This handbook combines the multi-disciplinary methods of fracture mechanics, inservice inspection and temperature monitoring to ensure the structural integrity of the FW nozzle-to-pipe welds at KNPP. This integrated approach will ensure that any flaw growth is properly evaluated and that the 1A and 1B SG FW nozzle-to-pipe welds are repaired prior to exceeding the allowable flaw size derived from Appendix A of Section XI.

[

TABLE OF CONTENTS

1.0 INTRODUCTION

This report presents the results of the Westinghouse plant specific evaluation for the feedwater nozzle to pipe welds at Kewaunee. For purposes of this report, the term "flaw" has the same definition as used in Section XI of the ASME Code (Reference 9).

Descriptions of the Westinghouse engineering evaluations and associated results are presented in Sections 4.0 through 7.0 of this report. Section 4.0 determines the load conditions acting on the feedwater nozzle to pipe welds which are used in the fatigue evaluations of Section 5.0 and the crack growth analysis in Section 6.0. [

]a,c,e

Section 5.0 provides the results of the feedwater nozzle to pipe welds stress and fatigue evaluations for Kewaunee. [

]a,c,e

The fracture mechanics and fatigue crack growth evaluations performed for Kewaunee are presented in Section 6.0 of this report. This section evaluates the integrity of the nozzle to pipe weld region, during further service, based on the stress analyses reported in Section 5.0.

2.0 INSPECTION HISTORY

2.1 HISTORY AND BACKGROUND

Steam generator feedwater nozzle-to-pipe cracking has been a recurring problem in the nuclear industry. As a result of a through-wall leak at the D.C. Cook plant in 1979, the USNRC issued Bulletin 79-13 requesting PWR plants to perform examinations of the feedwater nozzles and adjacent feedwater piping. In response to these events, Kewaunee Nuclear Power Plant (KNPP) performed radiography (RT) of these areas and detected linear indications in the feedwater nozzle-to-pipe welds of both steam generators. Ultrasonic (UT) examination characterized the depth at these indications to be approximatoly 20 mils. The indications were determined to be at or near the inside surface; however, no firm conclusions could be made as to whether the indications were cracks, fitup mismatch or discontinuities. High cycle fatigue was suspected to be the cause of cracking in this region. Typical industry practice at this time was to replace the feedwater piping adjacent to the nozzle with an essentially identical transition piece. Several factors were considered which led to the decision te replace the sections of feedwater piping with the indications. First, several other plants had also found cracks near their nozzles. Second, secondary plant activities extended the planned outage length, and ample time would be available to cut out the pipe for a physical examination. Third, replacement piping was available on site; consequently, no delays were anticipated in reconstructing the FW piping. And fourth, very little information was available at that time to accurately estimate crack growth. Upon removal of the suspect piping, visual examination confirmed cracking of the nozzle-to-pipe weld next to the weld root, in the base metal adjacent to the root, and in the counterbore region on the pipe side of the weld. The failure mechanism was identified as high cycle fatigue.

Since the repair and addition of a new transition piece at both steam generater feedwater nozzle-to-pipe welds in 1979, KNPP has performed ASME Section XI required UT examinations each period and augmented RT examinations each refueling outage, except for 1985 and 1987 (see Table 2-1). No recordable indications were found using UT, although intermittent geometry was detected. Likewise, RT has not shown evidence of cracking.

TABLE 2-1				
YEAR	Steam Generator 1A FW-W29		Steam Generator 1B FW-W57	
	UT	RT	UT	RT
1979	X	X	X	X
1980	X	X	X	X
1981		X		
1982		X		
1983	X	X	X	X
1984		X		X
1985				
1986	X	X	X	X
1987				
1988		X	X	X
1989		X		X
1990		X		X
1991		X		X
1992	X	X		X
1993		X	X	X
1994		X		X
1995	X	X		X

SUMMARY OF NDE PERFORMED IN 1995

During the 1995 refueling outage, Steam Generator 1A nozzle-to-pipe weld FW-W29 was examined using manual UT (0°, 45°, and 60° transducers) and magnetic particle testing as scheduled in the KNPP Third Interval ISI Plan. UT examination detected low amplitude indications on the ID surface of the pipe approximately 0.4-0.5" from the weld root in the base metal on the pipe side of the weld. Per the requirements of paragraph IWC-2430, the 1995 refueling outage ISI Program was expanded to ultrasonically examine 1B SG feedwater nozzle-to-pipe weld FW-W57. UT examination of the B SG FW nozzle-to-pipe weld also detected low amplitude indications on the ID surface of the pipe approximately 0.4" to 0.5" from the weld in the base metal on the pipe side of the weld as shown in Figure 2-1 below.

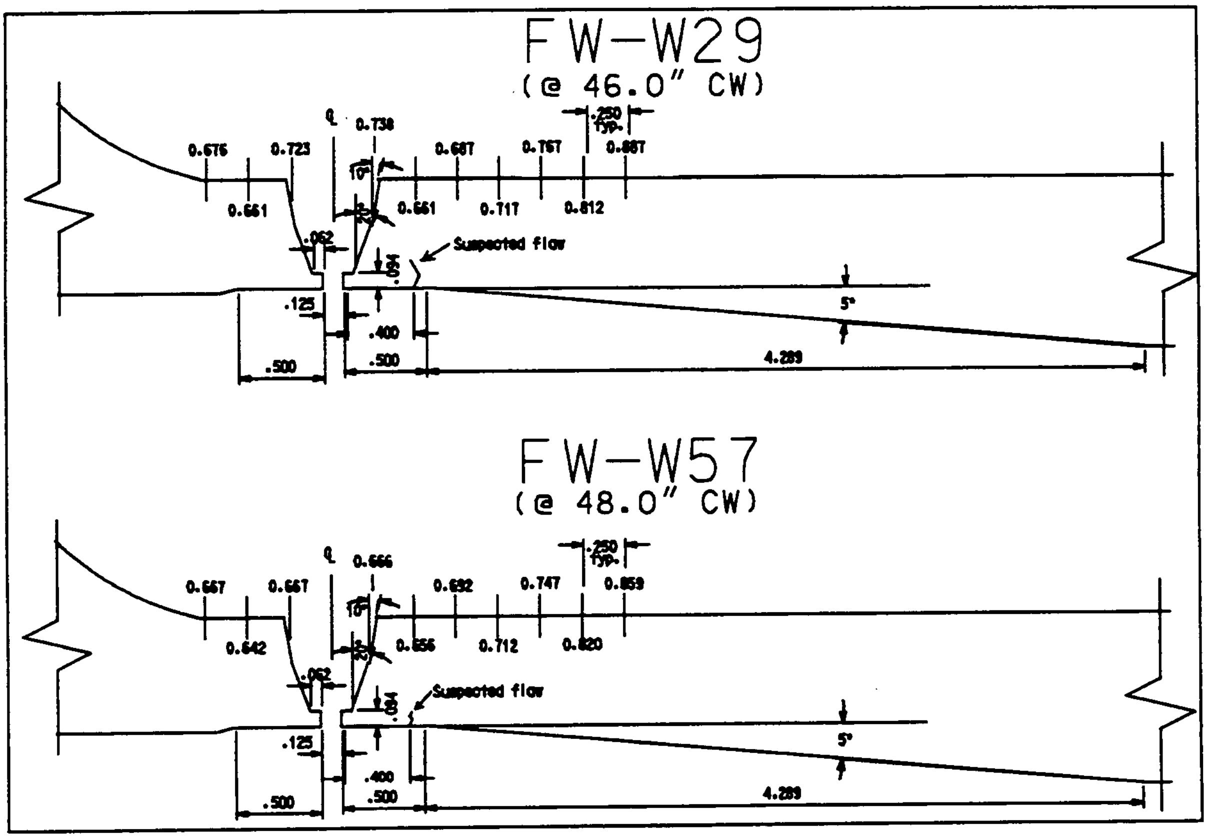


Figure 2-1: KNPP 1A and 1B SG FW Nozzle-to-Pipe Weld Configuration

Additionally, both the 1A and 1B SG FW nozzle-te-pipe welds were radiographed and no evidence of cracking could be detected. The 1989 edition of ASME Section XI requires recording and investigation of any indication of a suspected flaw and all indications which are not determined to be of geometrical or metallurgical origin that produce a response equal to or greater than 20% of the distance amplitude curve (DAC). In an effort to characterize the indications, automated UT was performed on the suspect areas using 45° and 60° shear wave transducers. Several other manual UT sizing techniques were also utilized in sizing the indications including, tip diffraction, multipulse observation, full V-path corner reflection, and refracted high angle longitudinal wave. These techniques have been demonstratod and are recommended by EPRI and Performance Demonstration Initiative. A combination of these techniques was used to size the indications. The appropriate technique selected for sizing was based on the depth range for which it is most reliable.

These low amplitude indications were not required to be recorded in the past according to the rules of the 1980 W81 edition of Section XI. The 1980 W81 edition of Section XI required indications to be recorded if they produced a response equal to or greater than 50% of the distance amplitude curve (DAC).

2.2 DETECTION AND CHARACTERIZATION

This section describes the actions taken for detection and characterization of all flaw indications. Refer te Table 2-2 and Table 2-3 for details.

TABLE 2-2

NONDESTRUCTIVE EXAMINATION AND EVALUATION FOR STEAM GENERATOR 1A WELD NO. FW-W29

1989 ASME SECTION XI EXAMINATION

PERFORMED MANUAL UT USING 2.25 MHZ 0,45S, AND 60S DEGREE(S) TRANSDUCERS. DETECTED INDICATIONS AT TDC ~20.0" LONG AND AT BDC ~6.0" LONG. SCANNING WAS PERFORMED AT +12DB. AMPLITUDE LEVELS WERE < 60% DAC AT REF.

AUGMENTED/SUPPLEMENTAL

PERFORMED RADIOGRAPHY EACH REFULEING OUTAGE EXCEPT FOR 1985 AND 1987 SINCE REPLACEMENT IN 1979. RADIOGRAPHY HAS BEEN TYPICALLY PERFORMED USING KODAK M FILM. KODAK R FILM WAS ALSO USED IN 1984 AND 1995 FOR GREATER SENSITIVITY. RADIOGRAPHY HAS NOT SHOWN CONCLUSIVE EVIDENCE OF CRACKING.

SUPPLEMENTAL (IWC-3200)

UTILIZED OTHER EXAMINATION TECHNIQUES (IWA-2240) TO DETERMINE THE CHARACTER OF THE FLAW (I.E., SIZE, SHAPE AND ORIENTATION).

ULTRASONIC IMAGING
(LMT PROC. UT-83 REV. 1 & UT-84 REV. 1)

PERFORMED AUTOMATED EXAM ON SUSPECT AREAS UTILIZING 45S AND 60S DEGREE(S) TRANSDUCERS WITH RETENTION OF DATA EVERY 0.10" IN THE X-DIRECTION (CIRC.) AND 0.04" IN THE Y-DIRECTION (AXIAL) WITH A 0.375" DIA. ELEMENT, ULTRASONIC LEVEL II AND III EXAMINERS WITH EPRI IGSCC DETECTION, QUALIFICATION, AND THERMAL FLAW FAMILIARITY. REFER TO TABLE 2-4.

ULTRASONIC FLAW SIZING
(LMT PROC. UT-73 REV. 3)

UTILIZED SEVERAL MANUAL SIZING TECHNIQUES FOR DETERMINATION OF THRU-WALL DIMENSION. PROCEDURES AND PERSONNEL QUALIFIED AT EPRI AND PDI. TECHNIQUES INCLUDED:
- ID CREEPING WAVE
- TIP DIFFRACTION, PATT/ATT
- TIP DIFFRACTION, SPOT/RATT
- MULTIPULSE OBSERVATION, MOST
- FULL VEE-PATH CORNER REFLECTION
- REFRACTED HIGH ANGLE LONGITUDINAL WAVE

EACH TECHNIQUE HAS A SPECIFIC DEPTH FOR WHICH IT IS MOST RELIABLE, THEREFORE, A COMBINATION OF TECHNIQUES WAS USED IN FINAL FLAW SIZING.

FLAW SIZING ANALYSIS

INDICATIONS WERE EVALUATED IN ACCORDANCE WITH IWB-3514. SEE TABLE 2-6 FOR FINAL SIZE OF INDICATION.

1980.fmk

TABLE 2-3

NONDESTRUCTIVE EXAMINATION AND EVALUATION FOR

STEAM GENERATOR 1B WELD NO. FW-W57

1989 ASME SECTION XI EXAMINATION

PERFORMED MANUAL UT USING 2.25 MHZ 0,45S, AND 60S DEGREE(S) TRANSDUCERS. DETECTED INDICATIONS AT TDC ~8.0" LONG AND AT BDC ~3.0" LONG. SCANNING WAS PERFORMED AT +12DB. AMPLITUDE LEVELS WERE < 60% DAC AT REF.

AUGMENTED/SUPPLEMENTAL

PERFORMED RADIOGRAPHY EACH REFULEING OUTAGE EXCEPT FOR 1985 AND 1987 SINCE REPLACEMENT IN 1979. RADIOGRAPHY HAS BEEN TYPICALLY PERFORMED USING KODAK M FILM. KODAK R FILM WAS ALSO USED IN 1984 AND 1995 FOR GREATER SENSITIVITY. RADIOGRAPHY HAS NOT SHOWN EVIDENCE OF CRACKING.

SUPPLEMENTAL (IWC-3200)

UTILIZED OTHER EXAMINATION TECHNIQUES (IWA-2240) TO DETERMINE THE CHARACTER OF THE FLAW (I.E., SIZE, SHAPE AND ORIENTATION).

ULTRASONIC IMAGING
(LMT PROC. UT-83 REV. 1 & UT-84 REV. 1)

PERFORMED AUTOMATED EXAM ON SUSPECT AREAS UTILIZING 45S AND 60S DEGREE(S) TRANSDUCERS WITH RETENTION OF DATA EVERY 0.10" IN THE X-DIRECTION (CIRC.) AND 0.04" IN THE Y-DIRECTION (AXIAL) WITH A 0.375" DIA. ELEMENT. ULTRASONIC LEVEL II AND III EXAMINERS WITH EPRI IGSCC DETECTION, QUALIFICATION, AND THERMAL FLAW FAMILIARITY. REFER TO TABLE 2-5.

ULTRASONIC FLAW SIZING
(LMT PROC. UT-73 REV. 3)

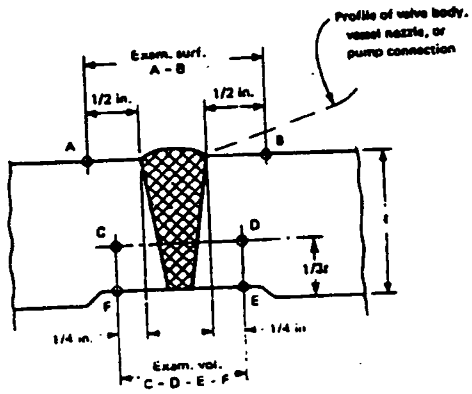
UTILIZED SEVERAL MANUAL SIZING TECHNIQUES FOR DETERMINATION OF THRU-WALL DIMENSION. PROCEDURES AND PERSONNEL QUALIFIED AT EPRI AND PDI. TECHNIQUES INCLUDED:
- ID CREEPING WAVE
- TIP DIFFRACTION, PATT/ATT
- TIP DIFFRACTION, SPOT/RATT
- MULTIPULSE OBSERVATION, MOST
- FULL VEE-PATH CORNER REFLECTION
- REFRACTED HIGH ANGLE LONGITUDINAL WAVE

EACH TECHNIQUE HAS A SPECIFIC DEPTH FOR WHICH IT IS MOST RELIABLE, THEREFORE, A COMBINATION OF TECHNIQUES WAS USED IN FINAL FLAW SIZING.

FLAW SIZING ANALYSIS

INDICATIONS WERE EVALUATED IN ACCORDANCE WITH IWB-3514. SEE TABLE 2-6 FOR FINAL SIZE OF INDICATION.

The ASME code ultrasonic examination method utilized for this work is detailed in KNPP Procedure QCP-913 and includes the area of examination as the inner one-third thickness of the weld and one quarter-inch of base metal from the circumferential butt weld. The examination volume is depicted below per Section XI Figure IWC-2500-7.



Procedure QCP-913 was used to detect flaw indications. This procedure is capable of detecting flaw indications oriented both parallel and transverse to the weld. A combination of transducers were utilized for detection: 2.25 MHZ 0°; 2.25 MHZ 45°(S); and 2.25 MHZ 60°(S). Scanning in the circumferential and axial directions at a minimum of 6 DB above reference sensitivity for any suspect areas with a minimum 10% overlap assured proper coverage per the code. Decreased scanning speed and oscillation were used to increase the detection capability for flaws.

Manual ultrasonic examination of FW-W29 (performed for purposes of detection) resulted in the following two indications:

Indication	% DAC	Max Amp Position	Length
No. 1	60	2.50"	20"
No. 2	60	26.50"	8"

Supplemental examinations were performed to further characterize the flaw.

With two suspect flaws identified in Weld No. FW-W29, the scope of the 1995 ISI Program Plan was expanded to include a similar weld (FW-W57) on the other steam generator. The manual UT examination of FW-W57 (performed for purposes of detection) resulted in the following two indications:

Indication	% DAC	Max Amp Position	Length
No. 1	25	6.5"	8"
No. 2	25	25.6"	3"

Additionally, radiography was performed on both of these welds. This proactive supplemental examination was performed using Kodak M film. Additional/supplemental radiography was performed using more sensitive Kodak R film. No evidence of cracking could be detected with this volumetric technique.

Automated ultrasonic examinations were performed per Procedure QCP-913 with retention of data every 0.10" in the x-direction (circumferential) and 0.04" in the y-direction (axial) with the same search element parameters and industry recommended scanning parameters.

The results from the supplemental automated ultrasonic examinations for Train A and B are documented in Table 2-4 and Table 2-5, respectively.

TABLE 2-4

Steam Generator 1A

Weld FW-W29

SUPPLEMENTAL AUTOMATED UT DATA

UT SCAN	FLAW IND NO.	POSITION L1	POSITION Lm	POSITION L2	LENGTH (1)	HEIGHT (a)	THICKNESS (t)
45A5	1	------------------->		1.2	15.50"	0.15"	0.650"
	2	1.6	1.7	1.9	0.30"	0.15"	0.650"
	3	2.6	2.8	3.0	0.40"	0.15"	0.650"
	4	3.6	4.3	9.2	5.60"	0.15"	0.650"
	5	11.2	11.4	11.5	0.30"	0.09"	0.650"
45B5	1	20.7	20.7	21.1	0.40"	0.10"	0.650"
	2		22.4		SPOT	0.10"	0.650"
	3	23.6	24.2	------->	3.80"	0.10"	0.650"
45C5	1	------------------->		27.4	3.80"	0.10"	0.650"
	2	28.0	28.6	30.8	2.80"	0.10"	0.650"
	3	36.7	38.3	------->	15.50"	0.15"	0.650"
45D5	1	-------------------------------->			15.50"	0.15"	0.650"
45A2	1	------------------->		2.0	4.0"	0.15"	0.650"
	2	3.4	4.3	4.9	1.50"	0.15"	0.650"
	3	5.8	6.1	6.6	0.80"	0.15"	0.650"
	4		10.7		SPOT	0.15"	0.650"
	5	12.3	12.3	12.5	0.20"	0.15"	0.650"
45B2	1	13.2	13.8	14.6	1.40"	0.09"	0.650"
	2	14.9	16.4	16.7	1.80"	0.09"	0.650"
	3	17.3	18.9	19.3	2.00"	0.09"	0.650"

TABLE 2-4 (cont.)

Steam Generator 1A

Weld FW-W29

SUPPLEMENTAL AUTOMATED UT DATA

UT SCAN	FLAW IND NO.	POSITION			LENGTH (1)	HEIGHT (a)	THICKNESS (t)
		L1	Lm	L2			
	4		20.8		SPOT	0.10"	0.650"
	5	21.4	22.0	22.2	0.80"	0.10"	0.650"
	6		22.5		SPOT	0.10"	0.650"
	7	24.3	24.4	------->	4.10"	0.10"	0.650"
45C2	1	------------------>		28.4	4.10"	0.10"	0.650"
	2		28.6		SPOT	0.10"	0.650"
	3	29.3	31.1	33.5	4.20"	0.10"	0.650"
	4	34.1	34.3	35.0	0.90"	0.15"	0.650"
	5	36.0	36.3	37.1	1.10"	0.15"	0.650"
	6	37.5	37.7	------>	10.90"	0.15"	0.650"
45D2	1	------------------->		48.4	10.90"	0.15"	0.650"
	2	49.0	50.1	------>	4.00"	0.15"	0.650"

TABLE 2-4 (cont.)

Steam Generator 1A

Weld FW-W29

SUPPLEMENTAL AUTOMATED UT DATA

UT SCAN	FLAW IND NO.	POSITION			LENGTH (l)	HEIGHT (a)	THICKNESS (t)
		L1	Lm	L2			

-------------------> Flaw Continues Through Additional Scan Areas.

UT Scan Notes: Circumference is dissected into 12.80" segments, each segment is denoted by a scan number such as (45A5).

- 45 denotes angle

- A, B, C or D denotes segment

- 2 or 5 denotes scan direction, 2 against & 5 with flow

A = 0.00" - 12.80"

B = 12.80" - 25.60"

C = 25.60" - 38.40"

D = 38.40" - 51.00"

TABLE 2-5

Steam Generator 1B

Weld FW-W57

SUPPLEMENTAL AUTOMATED UT DATA

UT SCAN	FLAW IND NO.	POSITION L1	POSITION Lm	POSITION L2	LENGTH (l)	HEIGHT (a)	THICKNESS (t)
45A5	1	5.3	5.5	5.8	0.50"	0.08"	0.650"
	2	9.9	10.7	10.9	1.00"	0.08"	0.650"
45B5	1	19.3	19.8	19.8	0.50"	0.06"	0.650"
45D5	1	39.7	40.2	42.2	2.50"	0.09"	0.650"
	2	43.1	45.4	46.2	3.10"	0.09"	0.650"
	3	48.4	50.2	50.5	2.10"	0.04"	0.650"
45A2	1	0.8	1.0	1.0	0.20"	0.08"	0.650"
	2	2.7	3.1	3.5	0.80"	0.08"	0.650"
	3	6.1	6.4	6.7	0.60"	0.08"	0.650"
45B2	1	13.2	13.3	13.6	0.40"	0.06"	0.650"
	2	17.5	17.6	18.3	0.80"	0.06"	0.650"
	3	19.9	20.1	21.3	1.40"	0.06"	0.650"
	4	22.2	24.8	25.5	3.30"	0.09"	0.650"
45C2	1	25.9	27.9	28.7	2.80"	0.09"	0.650"
	2	29.7	31.6	31.7	2.00"	0.09"	0.650"
	3	36.1	36.4	36.8	0.70"	0.09"	0.650"

TABLE 2-5 (cont.)

Steam Generator 1B

Weld FW-W57

SUPPLEMENTAL AUTOMATED UT DATA

UT SCAN	FLAW IND NO.	POSITION			LENGTH (1)	HEIGHT (a)	THICKNESS (t)
		L1	Lm	L2			
45D2	1	38.6	39.3	40.9	2.30"	0.09"	0.650"
	2		41.7		SPOT	0.09"	0.650"
	3	42.9	44.1	46.3	3.40"	0.05"	0.650"
	4	46.8	48.3	51.0	4.20"	0.05"	0.650"

UT Scan Notes: Circumference is dissected into 12.80" segments, each segment is denoted by a scan number such as (45A5).

- 45 denotes angle

- A, B, C or D denotes segment

- 2 or 5 denotes scan direction, 2 against & 5 with flow

A = 0.00" - 12.80"

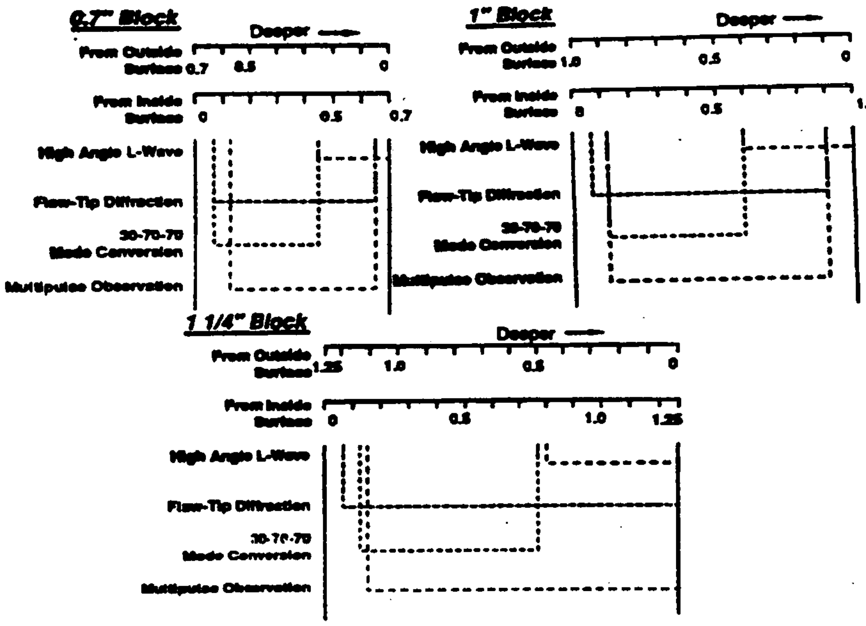
B = 12.80" - 25.60"

C = 25.60" - 38.40"

D = 38.40" - 51.00"

2.3 ULTRASONIC FLAW SIZING

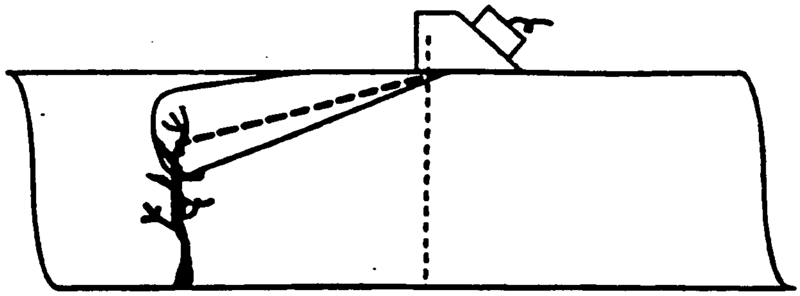
Upon characterization of the suspect areas as planar flaws connected to the inside surface of the piping, several techniques as recommended by EPRI and suggested by PDI were used for determination of the flaw height dimension. No single sizing technique is able to give accurate and repeatable flaw size information in all cases. Variables such as flaw size, component wall thickness, weld geometry, grain structure and attenuation, plus interactions with the flaw indication and ultrasound must all be taken into consideration. The variability of the mentioned factors requires a multiple approach in terms of complementing methods.



The above figure illustrates depth reliability from inside and outside surfaces of a component for ultrasonic flaw sizing for various techniques.

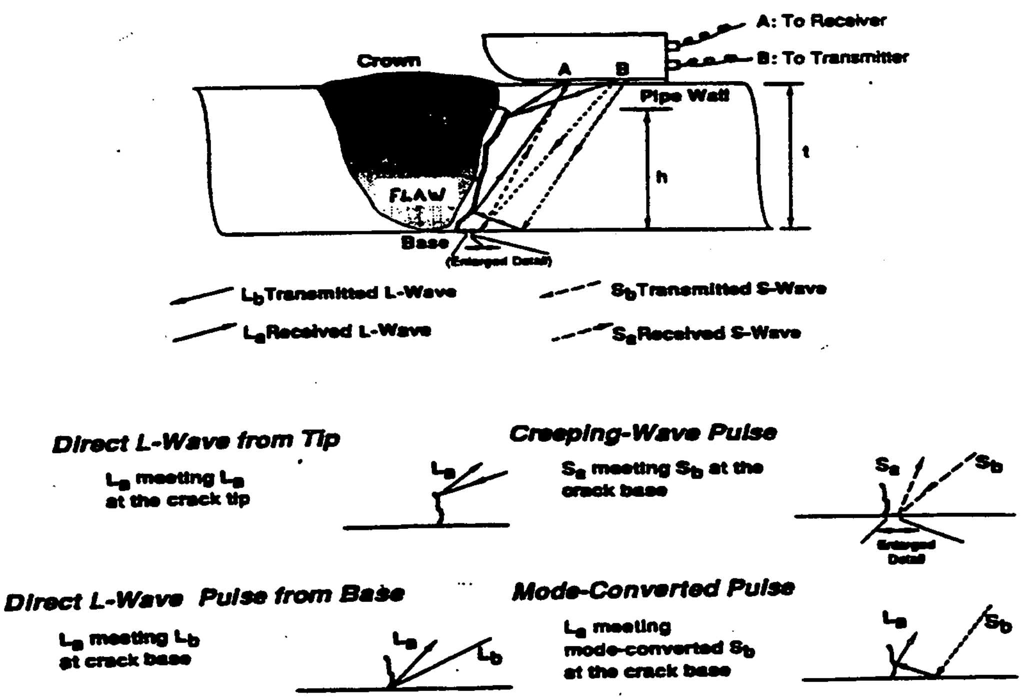
Each of these techniques is further described as follows.

A. High-Angle Refracted Longitudinal Wave Technique: Hi-Angle RL



This method uses a high angle longitudinal wave. The wave, in conjunction with its beam spread, is used to scan the outer surface of a component for flaws which have propagated close to the outside surface of the component delivering a reflected response as measured on a calibrated CRT screen range.

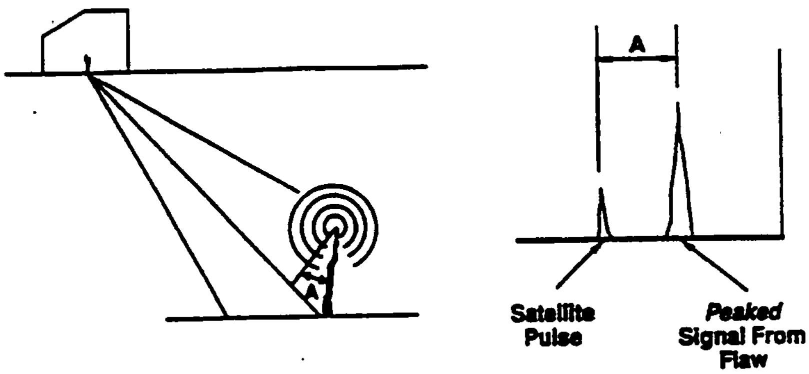
B. Multipulse Observation Technique:



This technique is used primarily for mid-wall surface connected flaws which range from 20% to 80% in depth. Results are obtained by subjecting the area of interest to multiple shear and longitudinal waves and simultaneously displaying the absolute and comparative readings on a CRT. This allows the examiner the ability to determine absolute flaw height from flaw tip La by comparing the response from crack face and crack base.

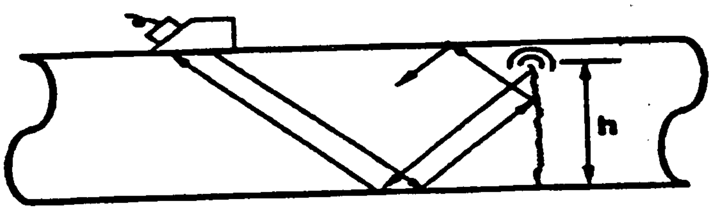
C. Tip Diffraction Technique: PATT/ATT

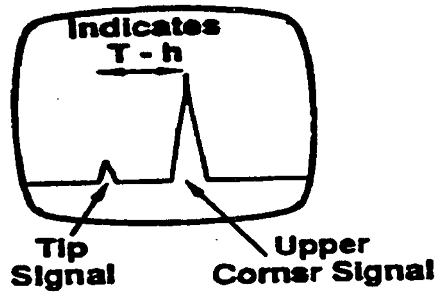
Tip Diffraction Technique: SPOT/RATT



This technique is used primarily for shallow flaws which are within the inner 25% of the wall thickness. The flaw tip diffraction method takes advantage of an ultrasonic signal generated by the interaction of the ultrasonic beam with the flaw. This method has a unique advantage in that the diffracted wave originates at the flaw tip. By observing the arrival time (PATT/SPOT) of this signal, it is possible to deduce the location of the flaw tip.

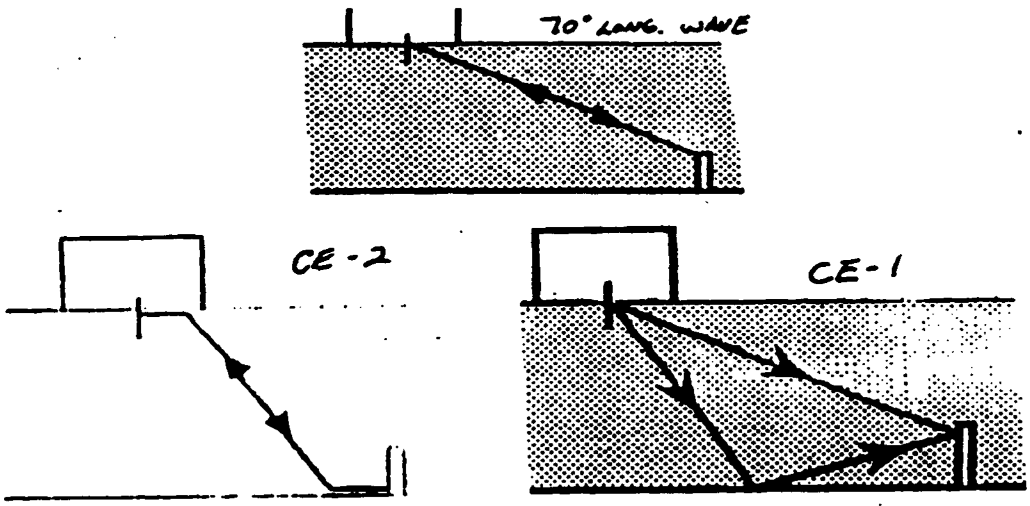
D. Full-VEE Corner Method Technique: FULL-VEE





This technique is primarily used for very deep flaws that extend near the outer or scanning surface. This technique employs a single element 45° shear wave search unit. A corner reflection is obtained at the full-VEE path position similar to that at the half-VEE path position. The sound beam is reflected at the flaw face and is reflected via the outside surface back to the search unit enabling the examiner to determine flaw height.

E. 30-70-70 Mode Conversion Method Technique: ID Creeping Wave



The 30-70-70 mode conversion method provides a qualitative measurement of height for flaws extending 10% to 90% thru-wall. This method employs the use of a 70° longitudinal wave, a 35° direct shear wave (CE-1), and a 31.5° indirect shear wave (CE-2, ID creeping wave) simultaneously. Generally, the ID creeping wave technique is a qualitative sizing measure which allows the examiner to classify ID connected flaws as shallow, mid-wall or deep. Finite flaw depth information is obtained by other sizing techniques.

Multiple techniques were used to ensure accurate sizing of flaw indicators from the 1A and 1B SG FW nozzle-to-pipe welds. Sizing results are as follows:

TABLE 2-6

Final Flaw Size Information for 1995 UT Inspection

of 1A and 1B SG FW Nozzle-to-Pipe Welds

Indication No.	Percent DAC	Length (l)	Height (a)	Thickness (t)	Aspect Ratio $\left(\frac{a}{l}\right)$	Actual Flaw $\left(\frac{a}{t}\right)$
Weld FW-W29						
1	60%	51.0"	0.15"	0.65"	0.01	23.08%
Weld FW-W57						
1	25%	51.0"	0.09"	0.65"	0.01	13.85%

2.4 REEXAMINATION PLAN

Paragraph IWC-2420 of Section XI requires that areas containing flaw indications be reexamined during the next inspection period listed in the schedules of the inspection program as described in Table IWC-2412-1. The current refueling outage represents the first of two refueling outages of the first inspection period (i.e. 1994 to 1997) of the third inspection interval. Because KNPP operates within an 18-month fuel cycle, there will not be a refueling outage in 1997. Accordingly, the next required reexamination to satisfy the Section XI reexamination requirements is in spring 1998. The Section XI permitted time interval between reexaminations is consistent with the fatigue evaluation which shows that the flaw indications are not expected to exhibit significant growth between now and the first refueling outage of the second inspection period. Although Section XI does not require reexamination until the next inspection period, Wisconsin Public Service Corporation plans to continue proactively inspecting the SG feedwater nozzle-to-pipe welds. The examination methods to be employed between now and the first refueling outage of the second inspection period will likely include both radiography and ultrasonics. Tentative re-examination plans include both radiography and automated ultrasonic examination of the train A and B nozzle-to-pipe welds in 1996.

3.0 DESCRIPTION OF KEWAUNEE PLANT OPERATIONS

3.1 SUMMARY OF OPERATIONAL HISTORY TO DATE

A summary of plant evolutions was developed through a search of operations data, logs, process computer outputs, etc. (reference 2). In order to limit the scope of this records search, it was assumed that at least a 150 degree differential temperature between the steam generator (S/G) and the feedwater supply is needed to be significant for the purpose of this analysis.

Therefore, plant conditions of cold shutdown (200 degrees F) are not considered germane since the largest temperature difference with cold feedwater of 70 degrees F would be less than 150 degrees.

Similarly, at the other extreme, plant conditions above 5% power are not considered because the main feedwater will provide a full pipe at 5% flow with warmer water from the condenser hotwell which will preclude differential temperatures of interest.

Plant conditions falling in between the above extremes were reviewed and the data tabulated. In cases where the warmer main feed or condensate were used during shutdown evolutions, a smaller differential temperature could be justified, but no credit was taken and 70 degree auxiliary feedwater was assumed.

The parameters of interest during the qualified plant conditions which were identified since 1979 are displayed in the following tables 3.2 through 3.5.

Two other evolutions were conservatively estimated for this study. Auxiliary feedwater flow has been used to cool the AFW header and reseat the AFW check valves at the Steam Generators when conditions of back leakage were identified. This condition generally occurs when AFW is secured after main feedwater is established. These cycles are therefore not occurring under plant condition of interest.

[

][a,c,e]

Lastly, in addition to the startup and shutdown events identified in Tables 3-1 through 3-3, there were occasions which required maintaining hot shutdown condition for extended periods during which the S/G level was controlled using a batch fill method (level was allowed to recede to 25% and auxiliary feedwater started to restore level to 50%). [

]a,c,e

TABLE 3-1 **Reactor Trips and Plant Restarts**	
Number of Evolutions Since 1979	[ ]a,c,e
Average Duration of Evolution (hours)	[ ]a,c,e
Total of All Evolutions (hours)	[ ]a,c,e
Average AFW Flow Throughout Evolution (gpm)	[ ]a,c,e
Total AFW Throughout All Evolutions (gal)	[ ]a,c,e
AFW Flow Range During Evolution (gpm) (AFW Pump Design is 240 gpm)	[ ]a,c,e
Typical Number of AFW Flow Initiations (per SG) in One Evolution	[ ]a,c,e
Total Number of AFW Flow Initiations (per SG) in All Evolutions	[ ]a,c,e
Average Temperature Differential (°F) (Assume RCS at 547°F and AFW at 70°F) (Assume	[ ]a,c,e

[

]a,c,e

Data is for each SG.

TABLE 3-2 **Plant Startups from Cold Shutdown to 5% Plant Load**	
Number of Evolutions Since 1979	[ ]a,c,e
Average Duration of Evolution (hours)	[ ]a,c,e
Total of All Evolutions (hours)	[ ]a,c,e
Average AFW Flow Throughout Evolution (gpm)	[ ]a,c,e
Total AFW Throughout All Evolutions (gal)	[ ]a,c,e
AFW Flow Range During Evolution (gpm)	[ ]a,c,e
Typical Number of AFW Flow Initiations (per SG) in One Evolution	[ ]a,c,e
Total Number of AFW Flow Initiations (per SG) in All Evolutions	[ ]a,c,e
Average Temperature Differential (°F) (90% of AFW Initiations Occur at Delta T of 477°F)	

Remarks: [

]a,c,e

Data is for each SG.

TABLE 3-3 Plant Shutdown from 5% Load to Cold shutdown Condition	
Number of Evolutions Since 1979	[ ][a,c,e]
Average Duration of Evolution (hours)	[ ][a,c,e]
Total of All Evolutions (hours)	[ ][a,c,e]
Average AFW Flow Throughout Evolution (gpm)	[ ][a,c,e]
Total AFW Throughout All Evolutions (gal)	[ ][a,c,e]
AFW Flow Range During Evolution (gpm)	[ ][a,c,e]
Typical Number of AFW Flow Initiations (per SG) in One Evolution	[ ][a,c,e]
Total Number of AFW Flow Initiations (per SG) in All Evolutions	[ ][a,c,e]
Average Temperature Differential (°F) (Linear during the cooldown, however higher flows occur at the higher delta Ts, as more flow is needed to supply the cooldown.)	[ ][a,c,e]

Remarks: [

][a,c,e]

Data is for each SG.

TABLE 3-4 AFW Full Flow Surveillance Testing		
Number of Evolutions Since 1979:	SP05B-253	[ ]a,c,e
	SP05B-284	[ ]a,c,e
Average Duration of Evolution (min)	SP05B-253	[ ]a,c,e
	SP05B-284	[ ]a,c,e
Total of All Evolutions (hours)		[ ]a,c,e
Average AFW Flow Throughout Evolution (gpm)	SP05B-253	[ ]a,c,e
(See Remarks)	SP05B-284	[ ]a,c,e
Total AFW Throughout All Evolutions (gal)		[ ]a,c,e
AFW Flow Range During Evolution (gpm)		[ ]a,c,e
Typical Number of AFW Flow Initiations (per SG) in One Evolution		[ ]a,c,e
Total Number of AFW Flow Initiations (per SG) in All Evolutions		[ ]a,c,e
Average Temperature Differential (°F) (RCS at 547°F and AFW at 70°F)		[ ]a,c,e

[

]a,c,e

Data is for each SG.

TABLE 3-5 Steam Generator Crevice Flushing Evolutions	
Number of Evolutions Since 1979 (cycles) (Six procedures with an average of 11 cycles each)	[ ]a,c,e
Average Duration of Cycle (AFW Refill) (min)	[ ]a,c,e
Total of All Evolutions (AFW Refills) (hours)	[ ]a,c,e
Average AFW Flow Throughout Evolution (gpm)	[ ]a,c,e
Total AFW Throughout All Evolutions (gal) (Each cycle raised SG level 3% WR (681 gal))	[ ]a,c,e
AFW Flow Range During Evolution (gpm) (Maximum flow allowed was 100 gpm)	[ ]a,c,e
Typical Number of AFW Flow Initiations (per SG) in One Evolution	[ ]a,c,e
Total Number of AFW Flow Initiations (per SG) in All Evolutions	[ ]a,c,e
Average Temperature Differential (°F) (Flushing performed with RCS at 300°F and AFW at 70°F).	[ ]a,c,e

[ ]a,c,e

Data is for each SG.

TABLE 3-6 **Summary of Flows, Hours of Operation, and Temperature Cycles**	
Total Number of Cycles	[ ]a,c,e
Total of All Evolutions (hours)	[ ]a,c,e
Average AFW Flow per Evolution (gpm)	[ ]a,c,e
Total AFW for All Evolutions (gal)	[ ]a,c,e
Average Differential Temperature for All Evolutions (°F) (90% occurred at 477°F)	[ ]a,c,e

Notes:

(1) [

]a,c,e

(2) Data is for each SG.

3.2 FEEDWATER MONITORING SYSTEM

Following the discovery of planar indications in the Steam Generator nozzle-to-pipe welds during the 1995 refueling outage, Wisconsin Public Service Corporation initiated plans to install a monitoring system to track the circumferential temperature profiles caused by fluctuating auxiliary feedwater flow at the counterbore region of each steam generator feedwater nozzle-to-pipe weld. The monitoring system will be installed and functioning to collect data during startup after the 1995 refueling outage. Data will generally be collected at scheduled plant shutdowns and startups, during periods of high system delta T (between the S/G and feedwater). At other times, such as steady state power operations when the delta T is low, data will not be collected to minimize data storage. In addition, the plant will log the date, time interval, and approximate AFW flow rates for each time the AFW pumps are operated above approximately 200°F, i.e., intermediate shutdown conditions and above. The circumferential temperature profiles from the monitoring data will be used to determine the stratification history and confirm analytical assumptions made in the flaw evaluation analysis. Plant specific monitoring data will be incorporated into the flaw evaluation analysis following future re-examinations of the steam generator feedwater nozzle-to-pipe welds. A schematic of the data acquisition system is shown in Figure 3-1. The resulting data will be analyzed to determine the sequence of reference stratification profiles (see Section 4) and ΔT's experienced by the feedwater nozzle and adjacent piping during typical hot standby and low power operation at Kewaunee.

To determine which of the reference profiles most closely matches a measured temperature distribution, a dimensionless temperature ratio is first defined by:

$$Ø = (T - T_c) / (T_h - T_c)$$

Where

T = Temperature at intermediate point on pipe wall

T_h = Temperature at top of pipe

T_c = Temperature at bottom of pipe

In terms of the thermocouple (T/C) data for the nozzle location: Thermocouples will be placed every 30° around the circumference from the top to the bottom of the pipe. T_1 corresponds to the top of the pipe and T_7 to the bottom. T corresponds to T_2, T_3,

T_4, T_5,or T_6; T_h to T_1 and T_c to T_7. The temperatures on the outside surface for each of the reference profiles at the locations of the T/C's will be tabulated and the corresponding Ø's calculated.

A measure of how well the T/C data for a temperature distribution match one of the reference profiles is given by:

$$\varepsilon = [(Ø_2 - Ø_2(\text{ref}))^2 + (Ø_3 - Ø_3(\text{ref}))^2 + \ldots + (Ø_6 - Ø_6(\text{ref}))^2]^{1/2}$$

The smaller the value of ε, the closer the match between the T/C data and the reference profile. Thus the reference profile which yields the smallest ε is the appropriate one to assign to that temperature distribution. Repeating this process for each set of T/C data assigns a reference profile to each temperature distribution.

All data supplied by WPS will be processed to determine the sequence of reference stratification profiles and ΔT's experienced by the feedwater nozzle and adjacent piping during typical hot standby and low power operation at Kewaunee. The fatigue and crack growth evaluations of Sections 5 and 6 will be repeated if needed using the Kewaunee stratification data.

The configuration and location of the thermocouple for the 1A and 1B steam generator feedwater nozzle-to-pipe welds are illustrated in Figure 3-2 and Figure 3-3, respectively. The design specifies a total of 12 thermocouples, per nozzle-to-pipe weld region, located circumferentially at 30 degrees increments around the feedwater pipe.

Installation of thermocouples at 30 degree increments provides redundancy should failure of an individual thermocouple occur. Omega type J thermocouples, model number XCIB-J-4-1-10, will be utilized for this application. These thermocouples are capable of monitoring temperatures to 1400°F. Actual monitoring temperature is expected to range from ambient to about 547°F. The heat transfer of carbon steel in this pipe thickness range is high enough to permit accurate measurement of the pipe inner diameter temperature using externally mounted thermocouples. The response time from two Omega Type J thermocouples were measured in the laboratory between 30°F and 210°F; the response times range between 7 and 8 seconds and are satisfactory for this application.

Each thermocouple is enclosed in an inconel sheath. The thermocouple will be attached to carbon steel straps/hoseclamps with inconel tack welds. The carbon steel straps or hoseclamps will be used to mount the thermocouple to the exterior surface of the feedwater system piping, taking care to properly insulate the area against heat loss due to thermal convection or radiative heat transfer. The inconel sheath, carbon steel straps/hoseclamps, and inconel tack welds are all compatible with the feedwater line material. Signals from the thermocouple will be input to the data acquisition system.

The data acquisition system is not part of the plant process computer. Signals from the thermocouple will not be input to any of the plant control or protection logic. All of the signals will be sent to Rustrack Ranger II dataloggers which will be located inside containment. The datalogger units will be installed in a weatherproof, heavy-duty, fiberglass enclosure and seismically mounted to prevent movement under normal, accident, and seismic conditions. The dataloggers will be powered from a non-safety related AC receptacle. The data acquisition system will assign an identification code, time, and date to each temperature measurement. Each datalogger is capable of collecting approximately six days of data at the desired two minute sampling rate. Collection of temperature data will be accomplished by periodically downloading to a portable personal computer.

A laptop personal computer will be periodically taken into containment to download temperature data that is electronically stored on the datalogger units. Data will be temporarily stored on the hard drive of the laptop PC until it is transferred to the network computer system for processing, i.e., plotting, trending, and evaluation.

a,c,e

Figure 3-1. Schematic of Feedwater Monitoring System

a,c,e

Figure 3-2. Steam Generator 1A Piping Configuration and Thermocouple Locations

a,c,e

Figure 3-3. Steam Generator 1B Piping Configuration and Thermocouple Locations

4.0 LOAD CONDITIONS

The feedwater nozzle/elbow assembly is subjected to several types of loads during its service. The load conditions usually considered for an analysis of the feedwater nozzle and elbow include:

1. Pressure - acting on the inside surface of the nozzle and attached piping.
2. Nozzle piping loads - three components of force and moment, transformed to act at the end of the piping.
3. Thermal stratification profiles - six temperature profiles based on field measurements from several operating steam generators. These occur during auxiliary feedwater addition when the plant is in a hot standby condition or operating at low power levels.
4. System thermal transients - unit loading (0% to 100% power), unit unloading (100% to 0% power), large step load decrease, and loss of power are analyzed to umbrella the significant system transients.

[

][a,c,e] Thermal stratification is a concern during the following operating conditions at Kewaunee: intermediate shutdown, hot shutdown, and low-power operation. Piping loads are relatively constant, and therefore contribute little to either fatigue usage or crack growth. System thermal transients such as plant heatup, large step load decrease, and the upset transients occur much less frequently than the varying stratification levels produced by the auxiliary feedwater additions during hot standby. They also make a relatively minor contribution to the fatigue usage and crack growth at the nozzle/piping junction. Pressure stresses at the nozzle/piping weld are on the order of 10 ksi, and will vary during plant operation. In the evaluations to follow, the pressure stresses are combined with the thermal stratification stresses, and the plant operating transients are represented by umbrella transients in the fatigue usage and crack growth calculations.

All the loadings, including dead weight, thermal expansion, and seismic, have been included in the fracture evaluation and chart construction described in Section 6. A search of Kewaunee operational and maintenance records did not reveal any occurrences of bubble collapse water hammer in the entire history of operation. therefore water hammer loads were not included in the flaw evaluation.

4.1 THERMAL STRATIFICATION

During normal plant operation a series of temperature measurements have been taken around the feedline pipe circumference in the vicinity of the feedwater nozzle/pipe weld for several steam generators that have experienced thermal stratification [ ]a,c,e. Temperatures have been measured during reactor heatup, hot standby, and variation between zero and 20 percent power. The measurements were taken on the inside surface of the pipe as well as on the outside surface.

Analysis of the data for the above series of measurements indicates that the stratified temperature distributions may be grouped into basic profiles corresponding to different levels of the interface between the hot and cold fluids.

Flow tests have been performed [ ]a,c,e to provide detailed fluid temperature profiles for various interface levels in the feedwater nozzle. These profiles, modified to account for the heat transfer between the metal and fluid which the test could not model, were combined with the above plant data to determine six basic temperature profiles. These profiles are assumed to be at steady state conditions because of their long durations observed during the tests.

[

]a,c,e

A summary of the hot standby periods for Kewaunee taken from Reference 2 is provided in Table 3-6. [

]a,c,e Auxiliary feedwater injection during these periods is typically trickle flow [ ]a,c,e, where feedwater flow is controlled manually by the operators to balance the steam flow. Flow rates are usually less than 100 gpm. These conditions are relatively moderate compared to those for other plants.

Stratification data are not available for Kewaunee steam generators at the present time. (There are plans, however, to obtain such data during the next fuel cycle as described in Section 3). Data from another plant may be used, however, if the other plant has operated in a manner similar to the way Kewaunee has operated during hot standby periods. After sixteen years of operation since the pipe had been replaced, no cracking had been found at the nozzle/pipe joint after numerous careful inspections, until the latest outage. [

]a,c,e

The Kewaunee operating data have been compared to the operating data for other plants for which stratification data are available. Table 4-2 contains a comparison of the stratification data collected during 1979-80 [ ]a,c,e for four plants with an elbow attached to the feedwater nozzle. [

]a,c,e

4.2 THERMAL TRANSIENTS

Feedwater injection during the various system thermal transients causes through-wall temperature gradients to develop in the feedwater nozzle and piping. The limiting thermal transients during which the feedwater fills the nozzle and piping are unit loading, unit unloading, large step load decrease, and loss of power conditions. These transients umbrella the remaining significant thermal transients specified in References 4 and 5.

Table 4-3 lists the Normal and Upset transients and Test conditions affecting the feedwater nozzle based on the duty cycles specified in References 4 and 5. The pressure variations during these transients are included in the fatigue and crack growth evaluations in Sections 5 and 6. [

]a,c,e

The limiting thermal transients and the conditions which they envelope are as follows:

Unit Loading - Reference 4 specifies 18,300 cycles of unit loading during the 40 year design objective of the steam generator. The increasing feedwater temperature and flow rates which occur during unit loading are judged to umbrella the loadings experienced by the nozzle during the more gradual heatup (200 cycles) and 10% step load increase (2000 cycles) transients. (20,500 total cycles of this umbrella transient are anticipated during a 40 year design objective).

Unit Unloading - Reference 4 specifies 18,300 cycles of unit unloading during the 40 year design objective of the steam generator. The decreasing feedwater temperature and flow rates which occur during unit unloading are judged to umbrella the loadings experienced by the nozzle during the more gradual cooldown (200 cycles) and 10% step load decrease (2000 cycles) transients. (20,500 total cycles of this umbrella transient are anticipated during a 40 year design objective).

Large Step Load Decrease - Reference 4 specifies 200 cycles of large step load decrease with steam dump during the 40 year design objective of the steam generator.

Loss of Power - The upset transients all exhibit rapidly decreasing feedwater temperatures (approximately 400°F in 150 seconds). This transient (40 cycles) is used as the enveloping transient for loss of load (80 cycles), reverse flow (80 cycles), and reactor trip (400 cycles) load conditions. A total of 600 cycles of this enveloping condition is postulated for the 40 year design objective of the steam generator.

Table 4-1. Surface Temperatures for the Elbow Reference Profiles

a,c,e

Table 4-1. Surface Temperatures for the Elbow Reference Profiles (Cont.)

a,c,e

Table 4-2. Stratification Profile Comparisons

a,c,e

Table 4-3. Normal, Upset and Test Conditions

Kewaunee Nuclear Plant (Design Specification)

a,c,e

[ ]

Table 4-4. Umbrella Transients for Various Periods of Operation

a,c,e

a,c,e

Figure 4-1. Stratification Profiles 1 and 2 for Feedwater Nozzle and Piping

a,c,e

Figure 4-2. Stratification Profiles 3 and 4 for Feedwater Nozzle and Piping

a,c,e

Figure 4-3. Stratification Profiles 5 and 6 for Feedwater Nozzle and Piping

5.0 FEEDWATER NOZZLE STRESS AND FATIGUE ANALYSIS

The stresses used for the evaluation of the feedwater nozzle to pipe welds at Kewaunee were obtained from [

]a,c,e. Figure 5-1 contains the drawing for the feedwater nozzle.

Figure 5-2 shows the 3-D finite element model developed for the [ ]a,c,e analysis. Figure 5-3 is an enlarged view of the nozzle/elbow weld region.

[

]a,c,e

The region to be evaluated is the root of the nozzle-pipe weld counterbore on the pipe side, which is where the indications have been found. Seven analysis points through the thickness are considered on the pipe side of the weld (ASN's 61-73). Refer to Figure 5-5 for the locations of these ASN's. They are listed in Table 5-1.

An elbow was attached to the nozzle in the [ ]a,c,e analysis. The Kewaunee nozzles typically have a run of horizontal pipe ranging from approximately two to seven feet followed by a 90° elbow welded to the nozzle. The stratification stresses at the Kewaunee nozzle weld counterbore shonld therefore be less than those calculated in [ ]a,c,e. [

]a,c,e

An additional source of conservatism exists on the pipe side of the counterbore. The actual weld geometry was modeled in the [ ]a,c,e analysis, and this introduced an additional stress concentration on the pipe side of the counterbore. The combination of a 90° elbow attached directly te the nozzle with the additional stress concentration in the [ ]a,c,e model results in the Kewaunee pipe counterbore stresses being at least twenty percent less than those calculated in [ ]a,c,e. This is confirmed in Table 5-2, [

]a,c,e. The stratification stresses from [ ]a,c,e are therefore reduced by twenty percent for this evaluation of the pipe counterbore.

5.1 STRATIFICATION CYCLES

The [

]a,c,e

[

]a,c,e

5.1.1 Procedure For Counting Stratification Cycles

The stratification data [ ]a,c,e were used to select the stratification cycles for this analysis. In this evaluation, the stresses produced by each profile occurrence at each of the nodes to be evaluated are used to select those profile types and their associated top-to-bottom temperature differences which cause local maxima or minima in the stress history at a given node during the period for which data were available. In particular, the selection process consists of the following steps:

1. Form a list of profile types and associated ΔT's in the order in which they occurred.

2. For each entry on this list, scale the dominant stress component from the appropriate unit load results for the node being evaluated by the scale factor determined previously.

3. Test for a local maximum or minimum stress. If so, save the profile type and ΔT for later use.

4. Group the local maxima and minima from step (3) by profile type and sort by increasing ΔT.

The above procedure is carried out for each node evaluated to obtain stress histories like those shown in Figure 5-6 for a node at the top of the pipe counterbore (3405). Note that there are two regions identified on this figure. The first two-thirds of the plot occurred during the period of the test identified to be a normal hot standby condition. The second period occurred during unit loading when the feedwater flow rate was increasing to provide more steam for rolling the turbines. The horizontal axis for this plot represents the sequence of profiles selected above.

Knowing the elapsed times during the test period for each type of stress cycling permits a refinement of the selection process described above. The complete stratified cycle selection approach used in this evaluation consists of the following steps for each node evaluated:

For a given period of plant operation,

1. Separate the data into two groups, one for hot standby conditions and one for low power operation.
2. Follow steps (2) to (4) above for each set of data, arriving at two lists of events which produced local extremas of stress sorted by profile type and ordered in ΔT.
3. Determine the number of occurrences of each unique ΔT during the period of plant operation by multiplying the number obtained for the corresponding data collection period by the ratio of the length of time during operation to the length of time during the data collection.
4. Reduce the number of ΔTs for each profile to a manageable number (four) by minimizing the mean square error between the full list of ΔTs and the new ΔTs. [

]a,c,e

[

]a,c,e

[

]. a,c,e

5.2 THERMAL TRANSIENTS

Stresses were calculated at several times during each transient based on temperature differences between the inside surface and the average temperature at key sections as well as on temperature differences between adjacent parts of the nozzle. The times at which stresses were calculated for each transient are listed in Table 5-5. The thermal transient stresses used in the fatigue and crack growth evaluations are those that result in a maximum or minimum at the pipe counterbore.

5.3 STRESS AND FATIGUE ANALYSIS

Fatigue usages have been calculated for operation to date and for the next fuel cycle. The highest fatigue usages occur at the top of the section at the pipe counterbore and are 0.33 for operation to date and 0.03 for the next eighteen month fuel cycle.

Table 5-6 lists the fatigue usages calculated for each section around the circumference at the pipe counterbore for operation to dato as well as for the next fuel cycle. Table 5-7 lists the load conditions for the node (3405) with the highest fatigue usage in that region, and Table 5-8 contains a summary of the detailed fatigue calculations for that node.

5.4 STRESSES AND CYCLES USED IN CRACK GROWTH EVALUATION

Stresses through the thickness, load combinations, and the number of cycles for use in the fatigue crack growth program, [ ]^{a,c,e} have been generated for the operating periods of interest for each of the sections listed in Table 5-1. The dominant stress components were the axial stress for the counterbore. Accordingly, the flaw orientations considered in the fatigue crack growth analysis were circumferential. Tables 5-9 and 5-10 illustrate the type of data supplied for input to [ ]^{a,c,e}. Table 5-9 provides the stresses at a section near the side of the nozzle for each of the load conditions (Note: the load conditions and their number of cycles are identical to those used in the fatigue evaluation for the same location). The load condition combinations and number of cycles, ranked by severity, are listed in Table 5-10.

5.5 SUMMARY AND CONCLUSIONS

The fatigue usage factor is an indicator for crack initiation. When the usage reaches a value of 1.0, a fatigue crack may initiate at that location. Once a crack has started, fatigue usage calculations are no longer appropriate at that location. Instead, a fatigue crack growth evaluation applies. When usage factors greater than 1.0 are calculated, the magnitude of the usage factor may be used to estimate when a crack initiated.

The highest usage factors at the counterbore are calculated for the top and sides of the section. As is shown in Section 6, the section 60° from the top of the pipe counterbore is the location with the highest potential for crack growth, not the top of the pipe. This occurs because crack growth is driven by high tensile stresses, while fatigue is based on stress ranges. Figure 5-6, which plots the stratification stress history for the top of the pipe counterbore, demonstrates that compressive stresses contribute to most of the stress ranges at that location, resulting in high usage factors but low crack growth. The usage factors at the side of the pipe counterbore are much less than those at the top, indicating a low potential for crack initiation. Since the calculated usage factors for operation to date at this location are less than 1.0, environmental factors such as high oxygen levels or low pH values in the feedwater probably contributed to the indications observed in the current outage. On the other hand, since over sixteen exams have been done since 1979 with no findings except the most recent results discussed here, the possibility exists that this may be a mis-call due to geometry. Nonetheless, the most limiting indication sizing results have been used in the flaw evaluations, to be discussed in Section 6.

Table 5-1. Analysis Sections for Fatigue and Crack Growth Evaluations

a,c,e

Table 5-2. Thermal Stratification Stresses: Comparison Of Straight Pipe To Elbow Axial Stresses

a,c,e

Table 5-3. Kewaunee Stress History For Node 3405

a,c,e

Table 5-3. Kewaunee Stress History For Node 3405 (Cont.)

a,c,e

Table 5-3. Kewaunee Stress History For Node 3405 (Cont.)

a,c,e

Table 5-4. Occurrences of Profile 3 For Node 3405

a,c,e

Table 5-5. Times for Calculating Transient Stresses

a,c,e

Table 5-6. Kewaunee Fatigue Usage for Pipe Counterbore Region

a,c,e

Table 5-7. Normal and Upset Load Conditions for Node 3405
Operation to Date

a,c,e

Table 5-8. Fatigue Usage for Node 3405 - Operation to Date

a,c,e

Table 5-9. Load Condition Stresses For Crack Growth Evaluation

a,c,e

Table 5-10. Load Condition Summary for Input to FCG

a,c,e

a,c,e

Figure 5-1. Series 51 Feedwater Nozzle Dimensions

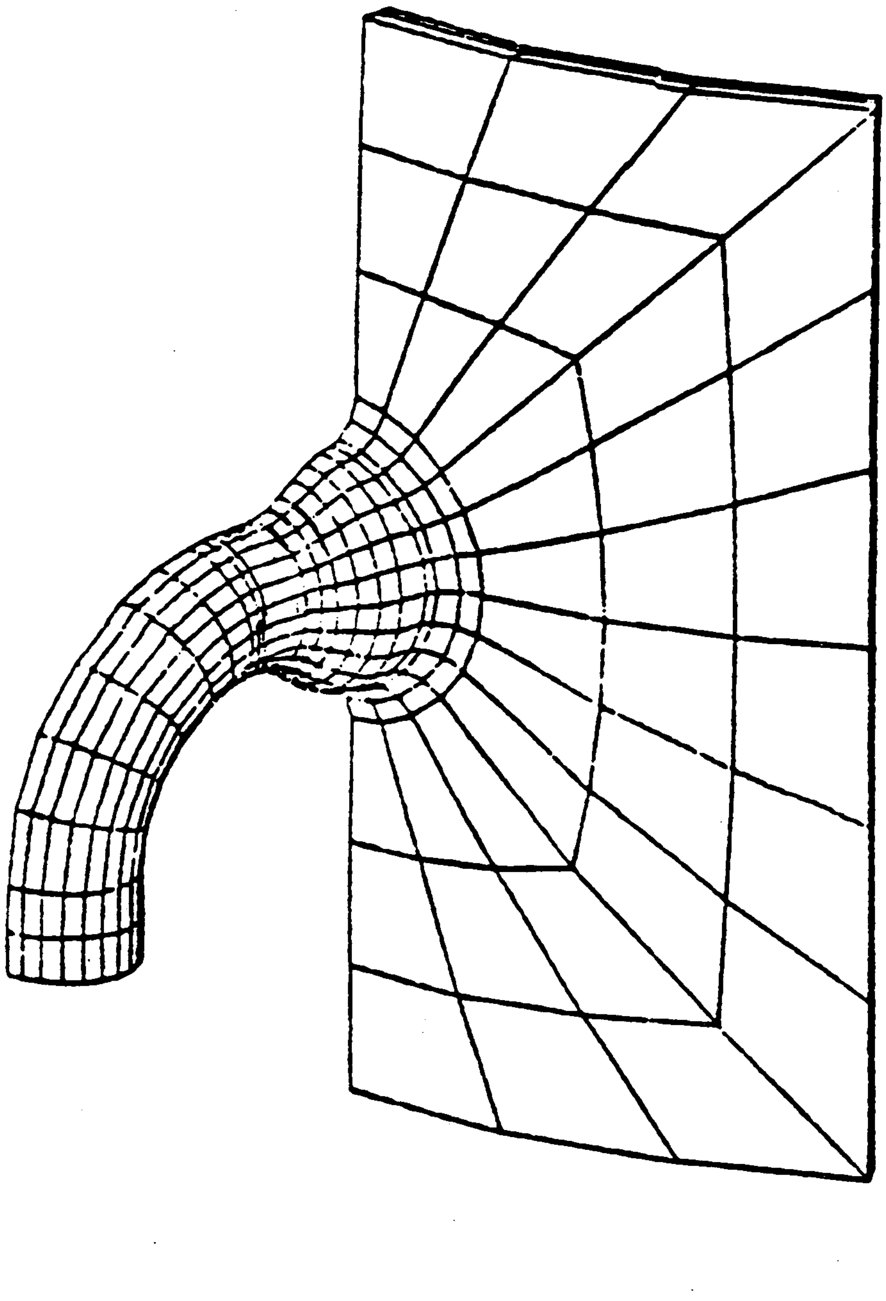


Figure 5-2. Feedwater Nozzle Finite Element Model [ ]a,c,e

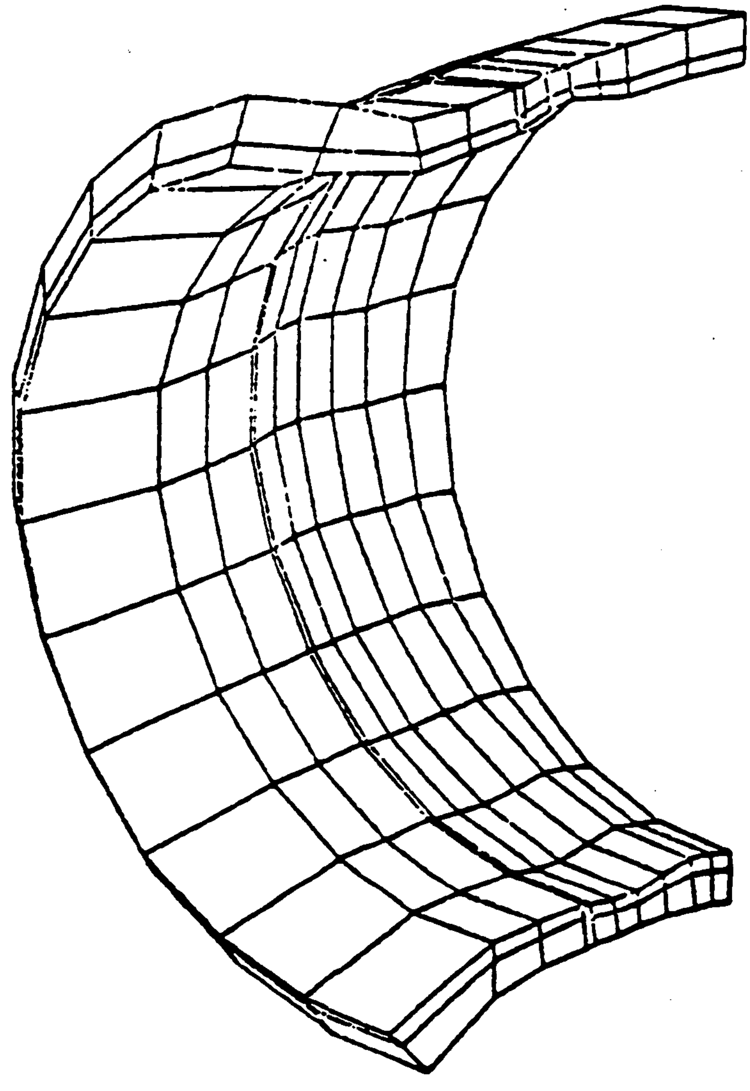


Figure 5-3. Weld Counterbore Region of FEM in Figure 5-3

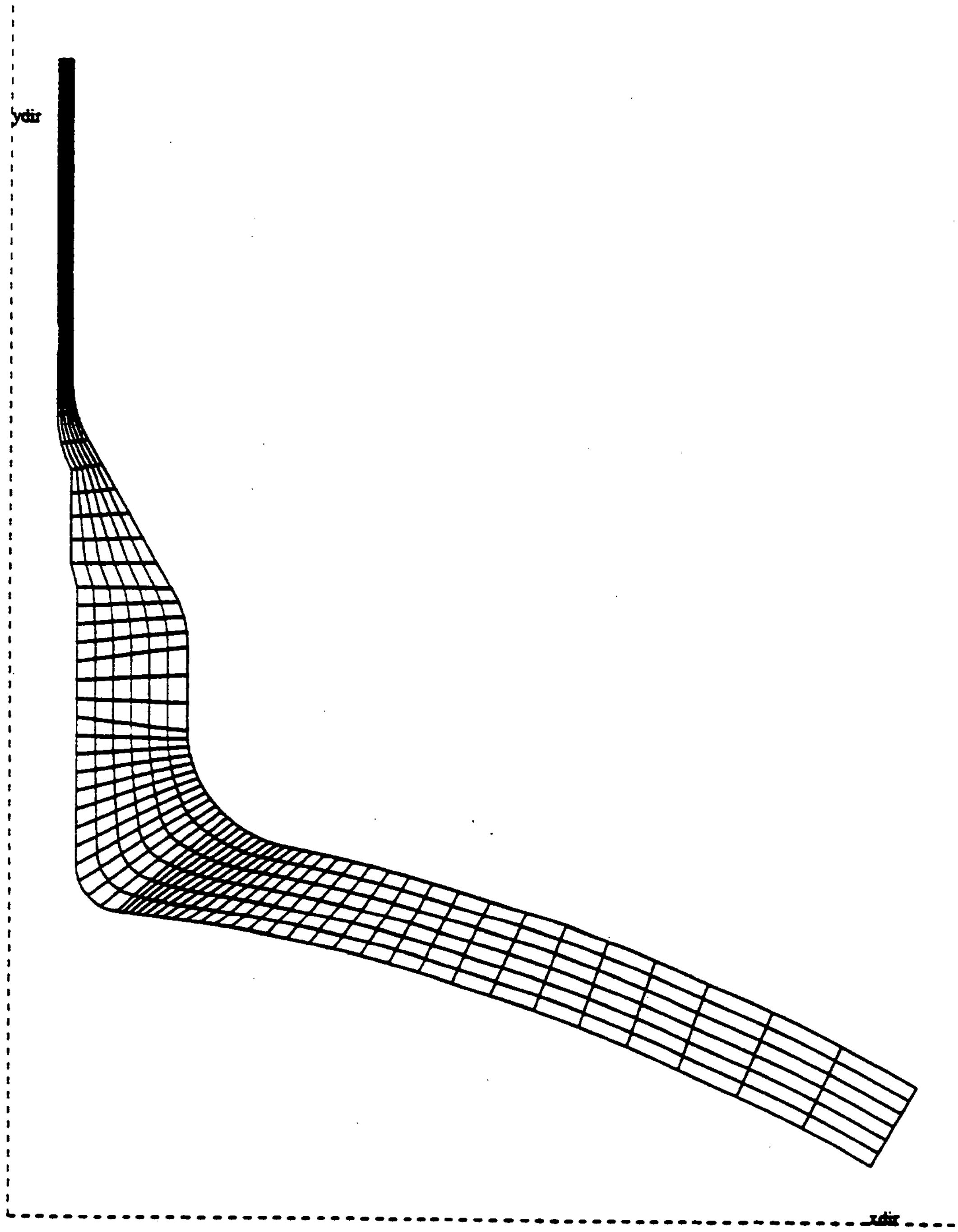


Figure 5-4. 2-D Finite Element Model for Thermal Transient Analysis

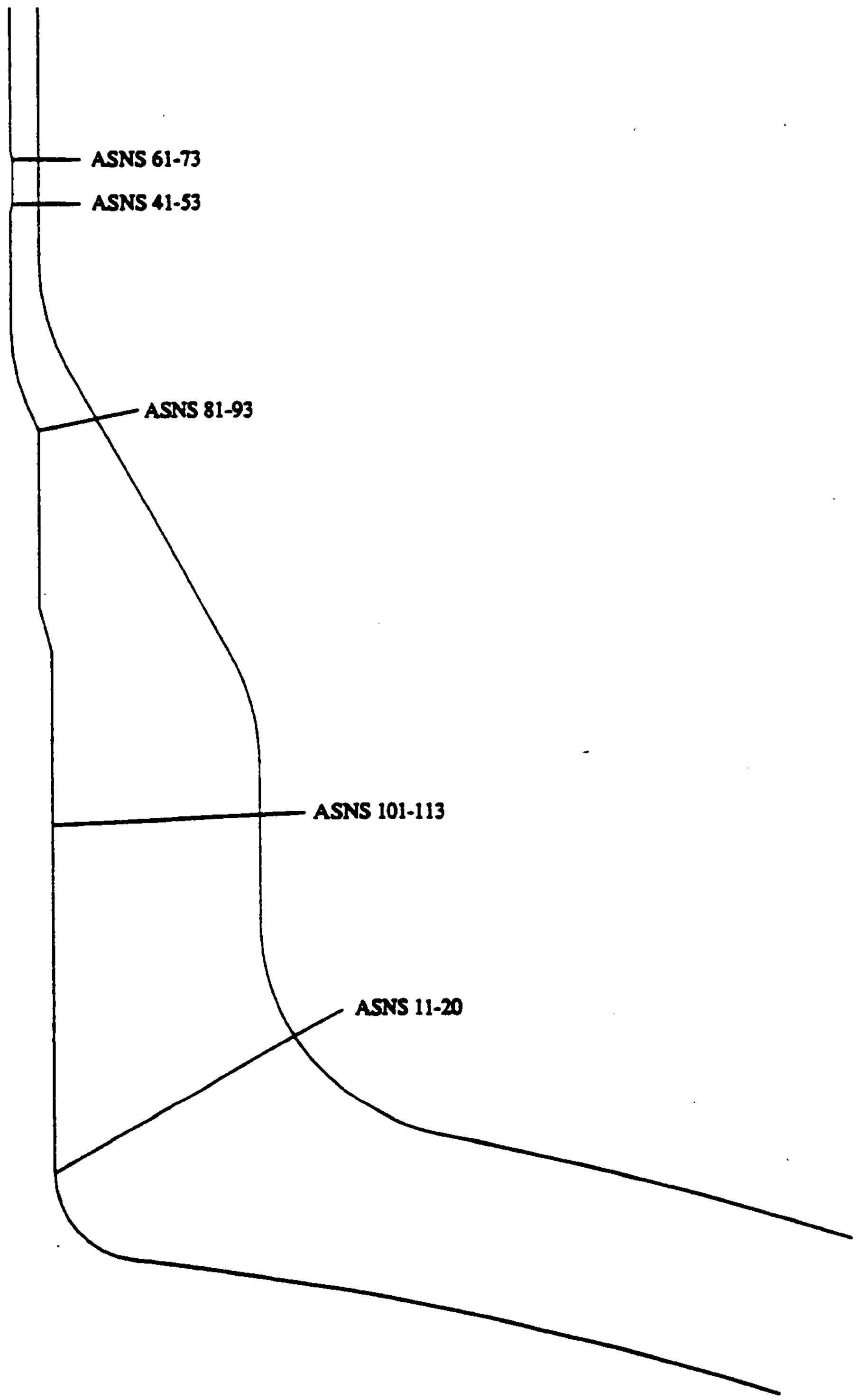


Figure 5-5. Locations of ASN's for Fatigue Evaluations

a

Figure 5-6. Stratification Stress History Model Results for the Top of Counterbore

6.0 FRACTURE MECHANICS EVALUATION

6.1 INTRODUCTION

This analysis examines the feedwater nozzle safe-end region of the Kewaunee steam generators (See Figure 5-1 for the dimensions used in the analysis). Fracture mechanics evaluations have been performed incorporating the 3-D finite element stress results from Section 5 based on stratification temperature profiles in the region and cyclic occurrences [

]^{a,c,e} of those profiles. The goal was to study their effects on the structural integrity of the nozzle safe-end region for both steam generators. These results were then used to generate flaw evaluation charts and crack growth rate curves which provide the largest flaw sizes that could remain acceptable during operation without repair. The fracture evaluations were performed in accordance with the guidelines of Section XI of the ASME Code [Reference 9]. For purposes of this report, the term "flaw" has the same definition used in Section XI.

6.2 ANALYSIS APPROACH

6.2.1 Stress Intensity Factor Calculations

One of the key elements of the fatigue crack growth calculations is the determination of the driving force or stress intensity factor (K_I). This was done for each of the feedwater nozzle stress profiles using expressions available from the literature. In all cases the stress intensity factor utilizes a representation of the through wall stress profile (determined in Section 5) rather than a linearization. This is necessary to provide the most accurate determination possible of the crack growth, and is particularly important for consideration of conditions where the stress profile is generally nonlinear and often very steep. The stress profile perpendicular to the flaw plane is represented by a cubic polynomial:

$$\sigma(x) = A_0 + A_1\frac{x}{t} + A_2\left(\frac{x}{t}\right)^2 + A_3\left(\frac{x}{t}\right)^3 \qquad (1)$$

where

x = the coordinate distance into the wall

t = wall thickness

σ = stress perpendicular to the plane of the crack

A_0, A_1, A_2, A_3 = coefficients of the fit to the stress profile

Analyses were carried out for a range of surface flaw shapes, including a continuous flaw, to conservatively represent the range of flaw sizes which might be observed by ultrasonic testing.

[

]a,c,e

[

]a,c,e

6.2.2 Fracture Toughness

Another key element in the fracture evaluation is the fracture toughness of the material. The fracture toughness for ferritic steels has been taken directly from the reference curves of Appendix A, Section XI [ ]. In the transition temperature region, these curves can be represented by the following equations:

$$K_{Ic} = 33.2 + 2.806 \exp[0.02\,(T - RT_{NDT} + 100°F)] \tag{5}$$

$$K_{Ia} = 26.8 + 1.233 \exp[0.0145\,(T - RT_{NDT} + 160°F)] \tag{6}$$

where K_{Ic} and K_{Ia} are in ksi$\sqrt{\text{in}}$. K_{Ia} is based on the lower bound of crack arrest critical K_I values measured as a function of temperature, while K_{Ic} is based on the lower bound of static initiation critical K_I values measured as a function of temperature. These values are determined based on the reference nil ductility temperature (RT_{NDT}) as it relates to the temperature in the region being evaluated.

The upper shelf temperature regime requires utilization of a shelf toughness which is not specified in the ASME Code. A value of 200 ksi$\sqrt{\text{in}}$. has been used here. This value is consistent with general practice in such evaluations, as shown for example in Reference 12, which provides the background and technical basis for Appendix A of Section XI.

The other key element in the determination of the fracture toughness is the value of RT_{NDT}, which is a parameter determined from Charpy V-notch and drop-weight tests. Information for material chemistry and initial RT_{NDT} is not available for this region, and so a conservative value of RT_{NDT} = 60°F has been used.

6.2.3 Section XI Flaw Evaluation Approach for Ferritic Piping

The feedwater nozzles are made of ferritic material (either SA-508 Class 2 or SA-508 Class 3). The connecting pipe is also ferritic (SA-106 Grade B). The load carrying capacity of flawed ferritic piping can vary significantly within the LWR operating temperature range. This temperature dependence results in three distinct regions, each requiring a different fracture mechanics analysis technique. Rapid, nonductile failure is possible for ferritic materials at low temperatures, but at higher temperatures and under some loading conditions higher ductility leads to two other possible modes of failure, plastic collapse or ductile tearing. The second mechanism can occur when the applied J integral exceeds the J_{Ic} fracture toughness, and some stable ductile tearing occurs prior to failure. If the ductile tearing mode of failure is dominant, the load carrying capacity can be less than that predicted by the plastic collapse mechanism.

The flaw evaluation for the feedwater nozzle to pipe weld (counterbore) region was carried out using paragraph IWB-3650 of ASME Section XI and Appendix H. A screening criterion is available in Appendix H to determine which of the above failure modes would be expected. Specifically it involves calculations of the parameters for a deformation plasticity failure assessment diagram (DPFAD). Figure 6-1 illustrates how the DPFAD distinguishes between failure modes. The vertical axis, K_r, represents the ratio of the flaw driving force to the material fracture toughness, while the horizontal axis, S_r, is the ratio of the applied stress to the stress at a reference limit load. The ratio of K_r' to S_r', where the ' indicates that this is the coordinate value for a given stress level, determines whether linear elastic fracture mechanics (LEFM), elastic plastic fracture mechanics (EPFM), or limit load analysis should be used.

As indicated in Figure 6-2, the first step in applying the screening procedure is to define the material toughness, J_{Ic}, at the temperature of interest for the evaluation. The yield stress, σ_y, of 27.1 ksi and the stress intensity, S_m, of 18.1 ksi were obtained from ASME Section III Appendix I, and were used for the calculation since the screeniug criterion parameters defined in Appendix H-4000 are based on these values. The screening criteria (SC) values were obtained using the following:

$$SC = K_r' \;/\; S_r' \tag{7}$$

where

K_r'	=	$[1000K^2 / (EJ_{Ic})]^{1/2}$
S_r'	=	$(P_b + P_e) / \sigma_b$
K	=	calculated stress intensity factor
E	=	Young's Modulus
P_b	=	primary bending stress
P_e	=	pipe expansion stress
σ_b	=	bending stress

The above screening sequence was applied on an iterative basis once for the loads associated with the normal/upset conditions using an initial flaw size of 0.15 inches. The SC value obtained was 0.376, indicating that the governing failure mode is EPFM, or ductile tearing.

Since the SC value is between 0.2 and 1.8, the failure mode for the feedwater nozzle to pipe weld region is concluded to be the intermediate one, ductile tearing, or elastic plastic fracture (see Figure 6-2).

The loading conditions which were evaluated for comparison with the screening criteria and for determining the allowable flaw sizes included thermal expansion (normal and upset), pressure, deadweight and seismic (OBE and SSE) loadings. The forces and moments for each condition were obtained from Reference 13. Residual stresses were not used in this portion of the evaluation, in compliance with the Code guidelines. The stress due to pipe loadings was calculated using the following equations:

$$\sigma = P_m + P_b \tag{8}$$

$$\sigma = \frac{F_x}{A} + \frac{1}{Z}\,[M_y^2 + M_z^2]^{1/2} \tag{9}$$

where

P_m = membrane stress loading

P_b = bending stress loading

F_x = axial force component (membrane)

M_y, M_z = moment components (bending)

A = cross-section area

Z = section modulus

The section properties A and Z at the weld location were determined based on the minimum pipe dimensions.

The following load combinations were used:

A. Normal/Upset - Primary Stress

Pressure + Deadweight + OBE

B. Emergency/Faulted - Primary Stress

Pressure + Deadweight + SSE

C. Expansion Stress - Secondary Stress

i) Normal Thermal

ii) Upset Thermal

D. Normal/Upset - Total Stress

i) Pressure + Deadweight + OBE + Normal Thermal

ii) Pressure + Deadweight + Upset Thermal

E. Emergency/Faulted - Total Stress

i) Pressure + Deadweight + SSE + Normal Thermal

ii) Pressure + Deadweight + Faulted Thermal

In D and E above, load combination (i) is the governing case.

6.3 FATIGUE CRACK GROWTH ANALYSIS METHODOLOGY

The analysis procedure involves postulating an initial flaw at start of life and predicting the flaw growth due to an imposed series of loading transients. Start of life in this analysis is the present inspection. The input required for a fatigue crack growth analysis is basically the information necessary to calculate the parameter ΔK_I (range of stress intensity factor), which depends on the geometry of the crack, its surrounding structure and the range of applied stresses in the crack area. Once ΔK_I is calculated, the growth due to a particular stress cycle can be calculated by equations given in Section 6.3.1. This incremental growth is then added to the original crack size, and the analysis proceeds to the next cycle or transient. The procedure is continued in this manner until all of the analytical transients predicted to occur in the prescribed period of operation have been analyzed.

The transients considered in the analysis are the design transients contained in the equipment specification in addition to the thermal stratification transients which occur during hot standby operation, as shown in Tables 4-3 and 4-4 of Section 4. These transients are distributed equally over the plant operating life, with the exception that the preoperational tests are considered first.

Faulted conditions are not considered because their frequency of occurrence is too low to affect fatigne crack growth.

6.3.1 Crack Growth Rate Reference Curves

The crack growth rate curves used in the analyses were taken directly from Appendix A of Section XI of the ASME Code. Water environment curves are used for all inside surface flaws.

For water environments the reference crack growth curves are shown in Figure 6-3; growth rate is a function of both the applied stress intensity factor range, and the R ratio (K_{min}/K_{max}) for the transient.

For 0.25 < R < 0.65,

$$\frac{da}{dN} = (1.02 \ x \ 10^{-6}) \ \Delta K_I^{5.95} \qquad (\Delta K_I < 19 \ ksi\sqrt{in.})$$

$$\frac{da}{dN} = (1.01 \ x \ 10^{-1}) \ \Delta K_I^{1.95} \qquad (\Delta K_I \geq 19 \ ksi\sqrt{in.})$$

where $\frac{da}{dN}$ = Crack Growth rate, micro-inches/cycle.

For R > 0.65

$$\frac{da}{dN} = (1.20 \ x \ 10^{-5}) \ \Delta K_I^{5.95} \qquad (\Delta K_I < 12 \ ksi\sqrt{in.})$$

$$\frac{da}{dN} = (2.52 \ x \ 10^{-1}) \ \Delta K_I^{1.95} \qquad (\Delta K_I \geq 12 \ ksi\sqrt{in.})$$

For R ratios between these two extremes, interpolation is recommended.

6.4 FATIGUE CRACK GROWTH RESULTS

6.4.1 Prediction Of Future Flaw Growth

A range of initial flaw sizes were used to insure that the results of future UT findings were enveloped and crack growth calculations were made to assess the effects of additional operation. [

]a,c,e Operating conditions to date were based on the previous years of operation for the nozzle to pipe welds. Although this could affect the cyclic impact on the crack growth calculations, the cycles to date are conservatively imposed with minimal impact. [

]a,c,e Figure 6-4 illustrates the results of this crack growth analysis for a range of initial flaw sizes for the pipe counterbore region, for the highest stressed circumferential location.

This crack growth is significantly less for other locations around the circumference, which have lower stresses. An example is shown in Figure 6-5 for the mid side location of the pipe, the second highest stress location. [

]a,c,e

To understand the impact of the calculated future crack growth it must be compared to the allowable flaw size as calculated using the criteria defined in ASME code Section XI. The calculated allowable flaw size for each region is dependent on the flaw shape and the maxinmm stresses which occur there. The allowable flaw depth for a range of flaw shapes, including the effects of future fatigue crack growth, is developed in the next section.

6.4.2 Development Of Flaw Evaluation Charts

To examine the sensitivity of the nozzle to pipe weld region to the presence of flaws, a flaw evaluation chart was prepared for the pipe counterbore region, as shown in Figure 6-6. This chart provides a graphical presentation of the largest allowable flaw for selected periods of operation. The charts include the effects of fatigue crack growth, so a flaw which is found can be plotted directly, with no calculations necessary. The construction of a typical chart is discussed in detail in Appendix A.

Figure 6-6 shows the flaw evaluation chart for the pipe counterbore region at the highest stress circumferential location. Results are presented for operating periods up to 12 years, and covering a complete range of flaw shapes, from semi-circular ($a/\ell = 0.5$) to continuously long ($a/\ell = 0$). Note that even for 12 years of operation (8 - 18 month fuel cycles) the allowable flaw depths to meet Section XI requirements are quite large.

6.5 SUMMARY AND CONCLUSIONS

This work has shown that cracks in the feedwater nozzle region are not predicted to grow very fast, for a number of reasons. The fatigne usage was calculated to be low, and the water enviroument is well-controlled. Kewaunee plant has a feedwater system (condenser, feedwater heaters, moisture separator reheaters) composed entirely of stainless steel. Phosphates were eliminated from the secondary water during the first fuel cycle, and since initial startup in-line chemistry monitors have been operated, with alarm set points based on vendor recommendations, EPRI gnidelines and plant experience.

[

]a,c,e

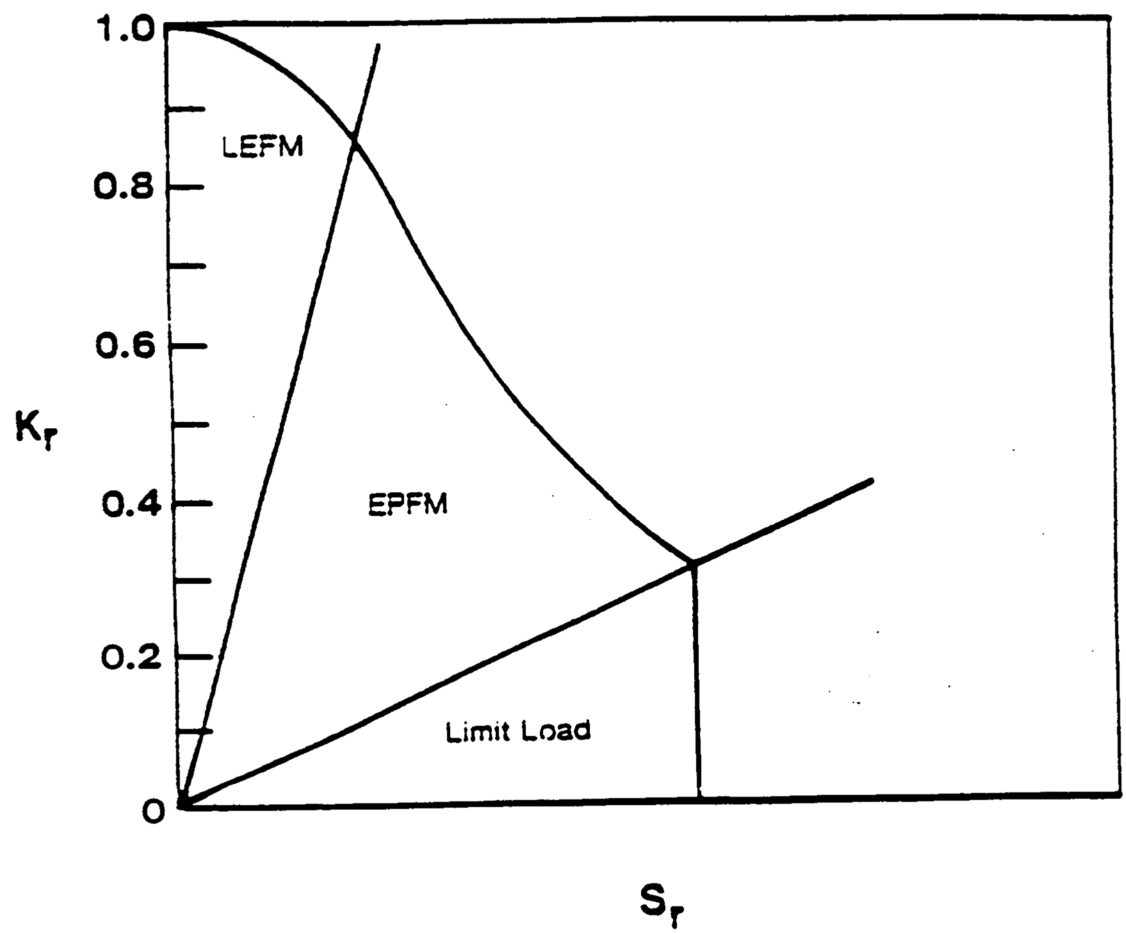


Figure 6-1. Illustration of Screening Criteria for Flaw Evaluation in Section XI, Paragraph IWB-3650 and Appendix H

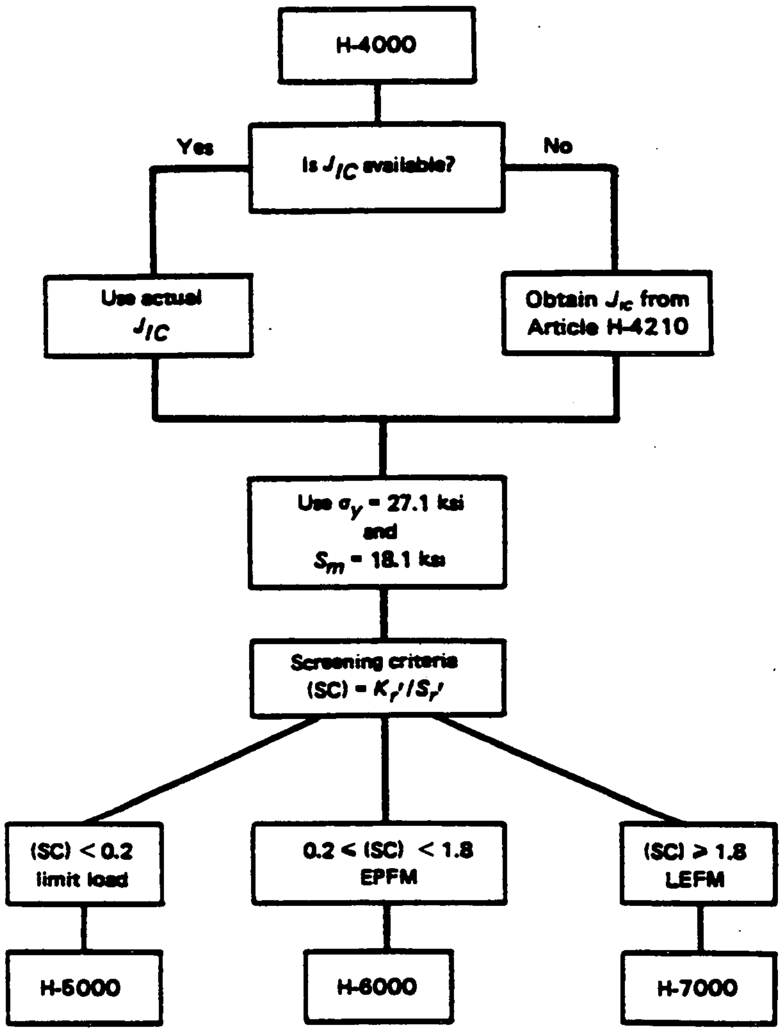


Figure 6-2. Screening Criteria Flow Chart for Identifying the Failure Mode and Associated Analysis Method

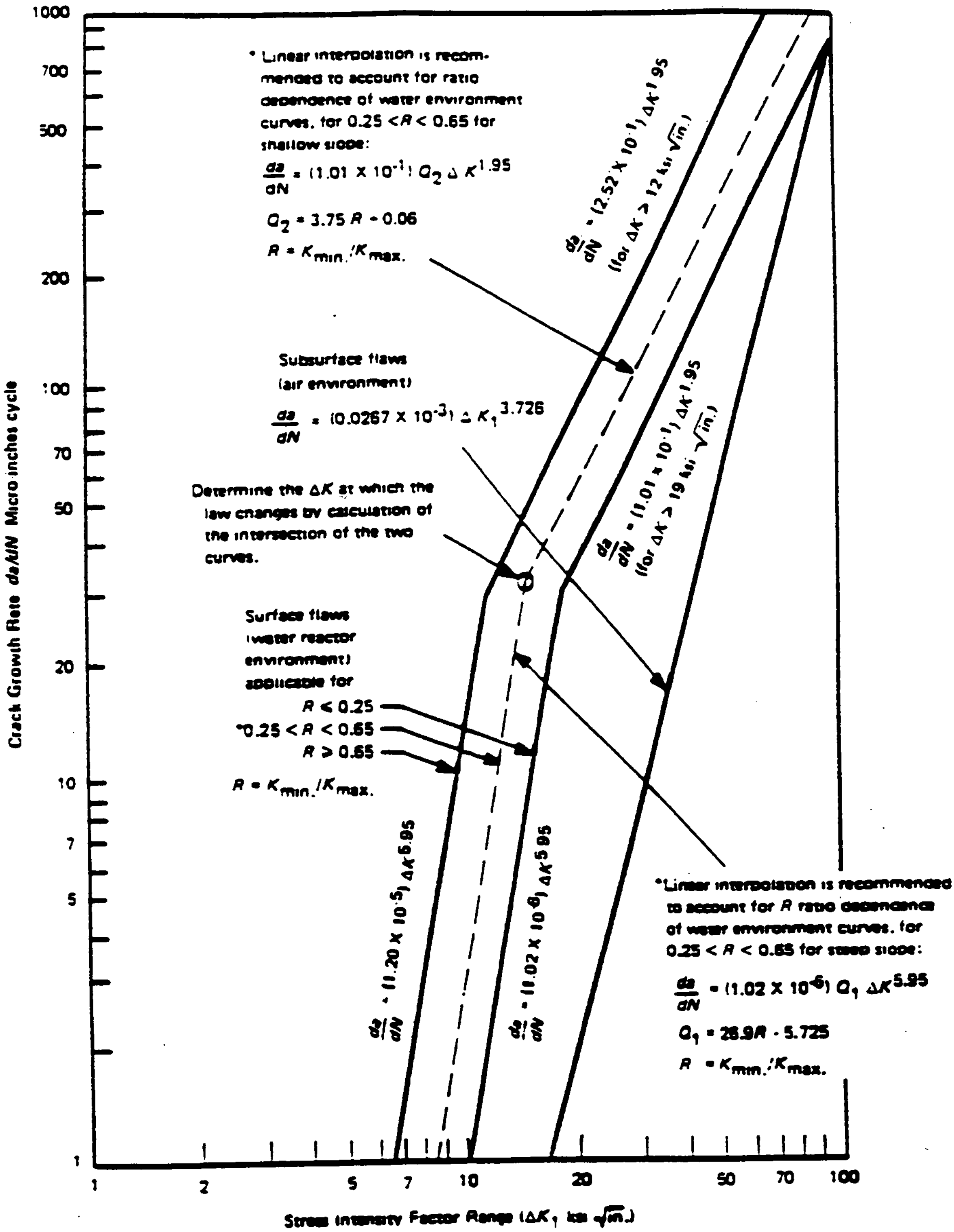


Figure 6-3. Reference Fatigue Crack Growth Curves for Carbon and Low Alloy Ferritic Steels [Reference 9]

[a]

Figure 6-4. Results of Crack Growth Calculations for Flaws Postulated in the Pipe Counterbore Region: Maximum Stress Location

a,c,e

Figure 6-5. Results of Crack Growth Calculations for the Counterbore Region: Second Highest Stress Location

a,c,e

Figure 6-6. Allowable Flaw Depth Chart, Pipe Counterbore Region

7.0 DISCUSSION AND CONCLUSIONS

This report has presented the results of the Westinghouse plant specific evaluation for the 1A and 1B SG feedwater nozzle-to-pipe welds at Kewaunee.

Stresses were based on pressure and stratification stresses from analyses performed for the feedwater nozzle cracks at other plants, plus thermal transient stresses. The thermal stratification data collected in 1979 and the operating history data supplied by WPS were combined to develop the load conditions to be used for the fatigue and crack growth evaluations. The resulting fatigue usages were then determined at key locations.

The fatigue usage factors calculated for the various operating periods are consistent with the radiography results observed at Kewaunee between 1979 and 1995 which showed no evidence of cracking. Yearly inspections have been conducted since the repair/replacement activities in 1979, with no indications reported until the 1995 inspection. This history suggests that the 1995 findings may be artifacts, but the evaluation reported here has used the largest of the flaw characterizations of the 1995 inspection for conservatism in estimating the acceptable period of future operation.

[

]a,c,e

Therefore, it may be concluded that the indications in the Kewaunee Nuclear Plant counterbore regions will be acceptable by a wide margin for the next few years of operation. To ensure that this evaluation is valid, thermal monitoring of both feedwater lines is planned for the next fuel cycle, after which this evaluation will be revisited using the actual plant-specific data.

8.0 REFERENCES

1. Charles A. Tomes (WPS), Inspection History for Kewaunee Nozzle/Pipe Welds for Steam Generators "A" and "B", April 24, 1995.

2. Webb, T. (WPS), "Transmittal of Kewaunee Operating History Data for Periods of Cold Feedwater Addition", April 19, 1995.

3. [

]a,c,e

4. "Reactor Coolant System Series "51" Steam Generator", General E-Spec G-677164, Rev. 1, Westinghouse NES, December 18, 1969.

5. "Wisconsin Public Service Corporation Kewaunee Project Reactor Coolant System 51 Series Steam Generator", Addendum E-Spec 677031, Rev. 4, Westinghouse NES, March 20, 1975.

6. Hu, M. H., Houtman, J. L., and White, D. H., "Flow Model Test for the Investigation of Feedwater Line Cracking for PWR Steam Generators", ASME Paper 81-PVP-4, June, 1981.

7. [

]a,c,e

8. [

]a,c,e

9. ASME Boiler and Pressure Vessel Code, Sections III and XI, including Appendices, 1989 Edition.

10. Raju, I. S. and Newman, J. C., "Stress Intensity Factor Influence Coefficients for Internal and External Surface Cracks in Cylindrical Vessels," in *Aspects of Fracture Mechanics in Pressure Vessels and Piping*, ASME publications PVP, Vol. 58, 1982.

11. Buchalet, C. and Bamford, W. H., "Stress Intensity Factors for Continuous Surface Flaws in Reactor Pressure Vessel," *Mechanics of Crack Growth*, ASTM STP590, pp. 385-402, 1976.

12. Marston, T. U., Editor, *Flaw Evaluation Procedures: ASME Section XI*, EPRI Special Report No. EPRI-NO-719-SR, August 1978.

13. Fax from T. Webb (WPS) to D. Prager, "Pipe Support Summary for Kewaunee", April 19, 1995.

APPENDIX A DEVELOPMENT OF FLAW EVALUATION CHARTS

A-1 INTRODUCTION

The 1995 inspection of the Kewaunee feedwater nozzles safe-ends revealed indications in the region for each of the plant's two loops. To examine whether this region and the other nozzle regions could remain operable for the next fuel cycle, a fracture mechanics analysis has been completed. This analysis shows the largest crack size which is acceptable without repair for various periods of future operation.

In order to make the fracture evaluations performed here useful for future inspections of this region, this Appendix describes the development of a flaw evaluation chart for surface flaws in the pipe counterbore region. [

]a,c,e

A-2 EVALUATION OF INDICATIONS USING THE FLAW CHARTS

A-2.1 Evaluation Procedure

The evaluation procedures for ferritic piping contained in ASME Section XI are clearly specified in paragraph IWB-3650. [

]a,c,e

[

]a,c,e

A-3 SURFACE FLAW EVALUATION

The acceptance criteria for surface flaws have been presented in Section 6 of this report.

[

]a,c,e

A-3.1 Fatigue Crack Growth

[

]a,c,e

A-3.2 Allowable Flaw Size Determination

[

]a,c,e

Screening Criteria

[

]a,c,e

[

]a,c,e

Allowable Flaw Determination

[

]a,c,e

[

]a,c,e

A-3.3 Typical Surface Flaw Evaluation Chart

[ ]a,c,e

[

]a,c,e

A-3.4 Procedure for the Construction of a Surface Flaw Evaluation Chart

[

]a,c,e

[

Step 1

Step 2

Step 3

]a,c,e

[

Step 5

]a,c,e

Step 6

Plot a/ℓ vs. a/t data from the standards of Table IWB-3514-1 of Section XI as the lower curve of Figure A-2.

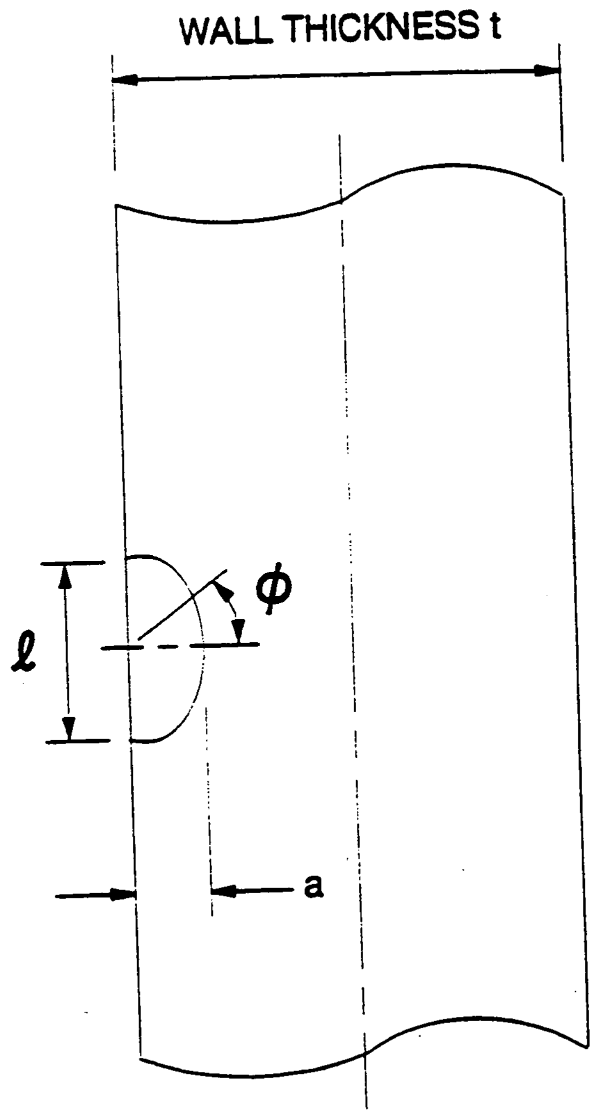
The values of Table IWB-3514-1 for Code editions up until the 1989 edition are:

Table A-6. Code Values of a/ℓ vs. a/t

Aspect Ratio a/ℓ	Surface Indication a/t, %
0.00	10.6
0.05	11.35
0.10	12.46
0.15	13.86
0.20	14.58
0.25	14.58
0.30	14.58
0.35	14.58
0.40	14.58
0.45	14.58
0.50	14.58

The above six steps complete the procedure for the construction of the surface flaw evaluation charts for 4 years of operating life. Crack growth results for 8 and 12 years were used to construct separate curves for those operating periods, and all three of these curves are found in Figure A-2.

The allowable flaw depths for surface flaws in ferritic steel pipes conservatively are limited to 75 percent of the section thickness. In some cases, allowable flaw depths greater than 75 percent of the wall thickness can be calculated, but these values are not used in the evaluation charts and they are terminated at 75% of the thickness.



TYPICAL SURFACE
FLAW INDICATION

Figure A-1. Geometry and Terminology for Various Flaw Types

a,c,e

Figure A-2. Evaluation Chart for Feedwater Pipe Counterbore Region Surface Flaws

APPENDIX B ALLOWABLE FLAW SIZE CALCULATION

a,c,e

a

a,c,e

a,

18