COMMONWEALTH EDISON

ZION STATION UNITS 1 AND 2

STEAM GENERATOR GIRTH WELD REPORT

DECEMBER, 1990

Unit 1 Inspection Results and Repair Details

General

During the fall 1989 refueling outage for Zion Unit 1, ultrasonic examination (UT) was performed on the steam generator D upper shell to transition cone girth weld. During the course of this examination, indications were detected which exceeded the allowable standards of IWC-3000 (Table IWB-3511-1 of the ASME Boiler and Pressure Vessel Code, 1980 Edition with Addenda up to and including the 1981 Winter Addenda). These indications were detected using 45 degree and 60 degree shear wave, 2.25 MHz transducers while scanning perpendicular to the weld. The total population of indications included both surface and subsurface reflectors. Based on these results, the extent of the UT was expanded to include the girth welds in the other three steam generators.

The number of recorded UT indications (>20% of the distance amplitude curve) totaled 17, 21, 9 and 34 for steam generators A, B, C and D respectively. Based on the UT detection data, many of the indications were classified as surface indications. Magnetic particle examinations (MT) were performed on specific portions of the inner surface of all four steam generators to verify the existence of the surface classified indications. All confirmed surface indications were removed either by grinding and blending or as a boat sample to permit additional study by metallography. New baseline UT examinations were made of all repaired areas. All subsurface indications were characterized using supplemental UT techniques (5.0 MHz angle beam transducer and/or 0° L transducer) in accordance with paragraph IWB-3200 of ASME Section XI. Those indications which exceeded 50% DAC and did not meet the acceptance criteria of Table IWB-3511-1 were dispositioned by fracture evaluation in accordance with ASME Section XI, IWB-3600.

Steam Generator A

The following table lists the UT data:

Dim. (2a)	Dim. (l)	Dim. (S)	Value (Y)	Surf./Sub.	Ampl. (% DAC)
0.18"	0.85"	0.08"	0.89	Sub.	25
0.25"	2.70"	0.06"	0.48	Sub.	126
0.35"	0.75"	0.02"	0.00	Surf.	178
0.24"	1.00"	0.02"	0.00	Surf.	56
0.52"	0.50"	0.35"	1.00	Sub.	35
0.24"	1.60"	0.02"	0.00	Surf.	35
0.35"	0.80"	0.27"	1.00	Sub.	100
0.53"	0.60"	0.09"	0.00	Surf.	40
0.29"	1.38"	0.08"	0.55	Sub.	316
0.54"	0.90"	0.08"	0.00	Surf.	85
0.81"	0.90"	0.04"	0.00	Surf.	80
0.36"	2.30"	0.20"	1.00	Sub.	60
0.60"	0.80"	0.58"	1.00	Sub.	60
1.68"	0.60"	0.31"	0.00	Surf.	60
1.33"	0.50"	0.00"	0.00	Surf.	50
0.34"	2.10"	0.09"	0.53	Sub.	25
1.02"	0.90"	0.01"	0.00	Surf.	75

Three indications were confirmed by MT. Two were removed by grinding and blending and the other was removed as a boat sample. One of the UT indications appeared as two indications when examined by MT and both were removed by grinding and blending.

The following table lists the dimensions of the excavated areas required to completely remove the indications, without blending:

Length	Width	Depth
2.00"	0.60"	0.35"
4.10"	0.90"	0.25"
3.00"	1.20"	0.30"

Four of the subsurface classified indications exceeded 50% DAC and did not meet the acceptance standards of Table IWB-3511-1. These indications were dispositioned as acceptable by fracture evaluation in accordance with ASME Section XI, IWB-3600.

Steam Generator B

The following table lists the UT data:

Dim. (2a)	Dim. (1)	Dim. (S)	Value (Y)	Surf./Sub.	Ampl. (% DAC)
0.31"	0.60"	0.08"	0.52	Sub.	32
0.37"	1.70"	0.52"	1.00	Sub.	50
0.61"	2.20"	0.23"	0.75	Sub.	25
0.31"	0.70"	0.08"	0.52	Sub.	36
0.23"	1.00"	0.03"	0.00	Surf.	32
0.35"	0.90"	0.68"	1.00	Sub.	25
0.12"	0.40"	2.59"	1.00	Sub.	25
0.29	0.40"	0.73"	1.00	Sub.	28
0.23"	1.60"	0.03"	0.00	Surf.	32
0.59"	1.20"	0.31"	1.00	Sub.	25
0.23"	0.90"	0.03"	0.00	Surf.	36
0.41"	0.80"	0.43"	1.00	Sub.	32
0.23"	0.90"	0.09"	0.78	Sub.	100
0.23"	0.70"	2.65"	1.00	Sub.	50
0.70"	0.60"	0.31"	0.89	Sub.	50
1.05"	0.50"	1.95"	1.00	Sub.	30
0.20"	1.40"	0.58"	1.00	Sub.	25
0.59"	3.70"	0.78"	1.00	Sub.	25
0.87"	1.30"	0.58"	1.00	Sub.	50
0.36"	0.80"	0.14"	0.78	Sub.	45
0.71"	1.20"	1.20"	1.00	Sub.	25

One indication was confirmed by MT and was removed by grinding and blending.

The following table provides the dimensions of the excavated area required to completely remove the indication, without blending:

Length	Width	Depth
1.00"	0.40"	0.25"

Two of the subsurface classified indications exceeded 50% DAC and did not meet the acceptance standards of Table IWB-3511-1. These indications were dispositioned as acceptable by fracture evaluation in accordance with ASME Section XI, IWB-3600.

Steam Generator C

The following table lists the UT data:

Dim. (2a)	Dim. (l)	Dim. (S)	Value (Y)	Surf./Sub.	Ampl. (% DAC)
0.35"	2.80"	0.26"	1.00	Sub.	28
0.29"	0.50"	0.96"	1.00	Sub.	28
0.23"	1.00"	0.03"	0.00	Surf.	158
0.12"	0.40"	1.48"	1.00	Sub.	63
0.08"	0.30"	2.10"	1.00	Sub.	63
0.34"	0.80"	0.29"	1.00	Sub.	50
0.24"	0.80"	2.18"	1.00	Sub.	28
0.44"	0.90"	0.03"	0.00	Surf.	112
0.35"	0.50"	1.48"	1.00	Sub.	79

Two indications were confirmed by MT and were removed by grinding and blending.

The following table lists the dimensions of the excavated areas required to completely remove the indications, without blending:

Length	Width	Depth
1.30"	0.45"	0.25"
1.20"	0.35"	0.15"

Three of the subsurface classified indications exceeded 50% DAC. All three met the acceptance standards of Table IWB-3511-1.

Steam Generator D

The following table lists the UT data:

Dim. (2a)	Dim. (l)	Dim. (S)	Value (Y)	Surf./Sub.	Ampl. (% DAC)
0.23"	0.30"	0.62"	1.00	Sub.	32
0.31"	1.70"	0.57"	1.00	Sub.	36
0.38"	0.60"	0.57"	1.00	Sub.	28
0.21"	0.60"	1.36"	1.00	Sub.	28
0.19"	1.00"	0.02"	0.00	Surf.	45
0.19"	0.90"	0.02"	0.00	Surf.	100
0.06"	0.10"	0.02"	0.67	Sub.	55
0.34"	1.50"	0.96"	1.00	Sub.	100
0.12"	1.10"	0.61"	1.00	Sub.	28

Dim. (2a)	Dim. (l)	Dim. (S)	Value (Y)	Surf./Sub.	Ampl. (% DAC)
0.18"	0.90"	0.09"	1.00	Sub.	32
0.19"	1.40"	0.08"	0.84	Sub.	126
0.15"	0.80"	0.03"	0.00	Surf.	28
0.19"	1.20"	0.02"	0.00	Surf.	63
0.18"	1.00"	0.08"	0.89	Sub.	141
0.29"	0.80"	0.21"	1.00	Sub.	32
0.24"	1.60"	0.03"	0.00	Surf.	32
0.42"	0.40"	0.0[illegible]	0.00	Surf.	50
0.23"	0.50"	0.03"	0.00	Surf.	40
0.31"	1.10"	0.02"	0.00	Surf.	178
0.19"	0.60"	0.08"	0.84	Sub.	105
0.24"	2.20"	0.03"	0.00	Surf.	40
0.09"	0.20"	0.16"	1.00	Sub.	55
0.19"	0.80"	1.36"	1.00	Sub.	25
0.17"	0.50"	1.32"	1.00	Sub.	32
0.24"	1.10"	0.03"	0.00	Surf.	60
0.30"	0.60"	0.67"	1.00	Sub.	50
----	Spot	----	----	----	25
0.12"	0.20"	1.49"	1.00	Sub.	63
0.65"	0.50"	0.51"	1.00	Sub.	40
0.67"	4.88"	0.09"	0.00	Surf.	100
0.46"	0.75"	1.05"	1.00	Sub.	25
0.47"	0.63"	0.45"	1.00	Sub.	100
0.66"	0.50"	0.02"	0.00	Surf.	140
0.29"	0.63"	0.44"	1.00	Sub.	50

Eight indications were confirmed by MT and were removed by grinding and blending. Two of the repair locations contained multiple indications.

The following table lists the dimensions of the excavated areas required to completely remove the indications, without blending:

Length	Width	Depth
2.20"	0.90"	0.25"
1.70"	0.70"	0.20"
TOO SMALL TO BE MEASURED		
2.30"	0.60"	0.20"
2.30"	0.80"	0.38"
2.60"	0.80"	0.35"
6.45"	0.75"	0.50"
2.90"	0.90"	0.35"

Three of the subsurface classified indications exceeded 50% DAC and did not meet the acceptance standards of Table IWB-3511-1. These indications were dispositioned as acceptable by fracture evaluation in accordance with ASME Section XI, IWB-3600.

Unit 2 Inspection Results and Repair Details

General

During the spring 1990 refueling outage for Zion Unit 2, ultrasonic examination (UT) was performed on the steam generator D upper shell to transition cone girth weld. During the course of this examination, indications were detected which exceeded the allowable standards of IWC-3000 (Table IWB-3511-1 of the ASME Boiler and Pressure Vessel Code, 1980 Edition with Addenda up to and including the 1981 Winter Addenda). These indications were detected using 45 degree and 60 degree shear wave, 2.25 MHz transducers while scanning perpendicular to the weld. The total population of indications included both surface and subsurface reflectors. Based on these results, the extent of the UT was expanded to include the girth welds in the other three steam generators.

The number of recorded UT indications (>20% of the distance amplitude curve) totaled 6, 21, 8 and 22 for steam generators A, B, C and D respectively. Based on the UT detection data, many of the indications were classified as surface indications. Magnetic particle examinations (MT) were performed on specific portions of the inner surface of all four steam generators to verify the existence of the surface classified indications. All confirmed surface indications were removed either by grinding and blending or as a boat sample to permit additional study by metallography. New baseline UT examinations were made of all repaired areas. All subsurface indications were characterized using supplemental UT techniques (5.0 MHz angle beam transducer and/or 0° L transducer) in accordance with paragraph IWB-3200 of ASME Section XI. Those indications which exceeded 50% DAC and did not meet the acceptance criteria of Table IWB-3511-1 were dispositioned by fracture evaluation in accordance with ASME Section XI, IWB-3600.

Steam Generator A

The following table lists the UT data:

Dim. (2a)	Dim. (l)	Dim. (S)	Value (Y)	Surf./Sub.	Ampl. (% DAC)
0.34"	0.70"	0.73"	1.00	Sub.	36
0.17"	0.80"	0.09"	1.00	Sub.	50
0.04"	0.40"	0.05"	1.00	Sub.	56
0.32"	1.90"	0.00"	0.00	Surf.	28
0.10"	0.90"	0.32"	1.00	Sub.	28
0.41"	1.00"	0.26"	1.00	Sub.	45

Two indications were confirmed by MT. One was removed by grinding and blending and the other was removed as a boat sample.

The following table provides the dimensions of the excavated area required to completely remove the indication, including blending:

Length	Width	Depth
3.00"	2.50"	0.31"

Two of the subsurface classified indications exceeded 50% DAC. Both met the acceptance standards of Table IWB-3511-1.

Steam Generator B

The following table lists the UT data:

Dim. (2a)	Dim. (l)	Dim. (S)	Value (Y)	Surf./Sub.	Ampl. (% DAC)
0.40"	0.40"	0.28"	1.00	Sub.	25
0.51"	1.00"	0.13"	0.51	Sub.	45
0.25"	0.60"	0.02"	0.16	Surf.	32
0.23"	0.80"	0.04"	0.35	Surf.	45
0.36"	0.60"	0.03"	0.17	Surf.	32
0.36"	2.70"	0.03"	0.17	Surf.	71
0.36"	2.70"	0.03"	0.17	Surf.	63
0.19"	0.80"	0.02"	0.21	Surf.	71
0.27"	3.80"	0.06"	0.44	Sub.	40
0.25"	3.80"	0.18"	1.00	Sub.	32
1.88"	1.20"	0.06"	0.06	Surf.	32
1.88"	1.20"	0.06"	0.06	Surf.	40
0.32"	1.10"	0.09"	0.56	Sub.	79
0.32"	1.10"	0.09"	0.56	Sub.	71
1.21"	2.50"	0.18"	0.30	Surf.	63
1.21"	2.50"	0.18"	0.30	Surf.	100
0.92"	1.50"	0.06"	0.13	Surf.	50
0.69"	3.10"	0.04"	0.12	Surf.	100
0.69"	3.10"	0.04"	0.12	Surf.	36
0.87"	2.80"	0.13"	0.30	Surf.	40
0.40"	1.40"	0.14"	0.70	Sub.	36

Seven indications were confirmed by MT and were removed by grinding and blending. One repair location contained multiple indications.

The following table lists the dimensions of the excavated areas required to completely remove the indications, including blending:

Length	Width	Depth
2.50"	1.75"	0.38"
1.63"	1.50"	0.25"
2.00"	1.75"	0.25"
1.75"	2.38"	0.31"
3.25"	4.25"	0.56"
2.00"	2.50"	0.25"
11.00"	2.75"	0.44"

Two of the subsurface classified indications exceeded 50% DAC and did not meet the acceptance standards of Table IWB-3511-1. These indications were dispositioned as acceptable by fracture evaluation in accordance with ASME Section XI, IWB-3600.

Steam Generator C

The following table lists the UT data:

Dim. (2a)	Dim. (l)	Dim. (S)	Value (Y)	Surf./Sub.	Ampl. (% DAC)
0.53"	1.30"	0.01"	0.04	Surf.	63
0.17"	1.00"	0.04"	0.47	Sub.	79
0.51"	0.90"	0.02"	0.08	Surf.	32
0.41"	1.70"	0.47"	1.00	Sub.	36
0.44"	0.90"	0.05"	0.23	Surf.	25
0.26"	1.00"	0.01"	0.08	Surf.	32
0.24"	1.00"	0.09"	0.75	Sub.	32
0.32"	0.40"	0.10"	0.63	Sub.	25

Seven indications were confirmed by MT and removed by grinding and blending.

The following table lists the dimensions of the excavated areas required to completely remove the indications, including blending:

Length	Width	Depth
3.50"	2.50"	0.38"
2.50"	2.25"	0.25"
5.50"	2.50"	0.44"
2.50"	1.75"	0.25"
1.25"	1.00"	0.13"
3.50"	2.25"	0.13"
8.75"	2.00"	0.50"

One subsurface classified indication exceeded 50% DAC. It met the acceptance standards of Table IWB-3511-1.

Steam Generator D

The following table lists the UT data:

Dim. (2a)	Dim. (l)	Dim. (S)	Value (Y)	Surf./Sub.	Ampl. (% DAC)
0.21"	1.10"	0.17"	1.00	Sub.	25
0.12"	0.80"	0.07"	1.00	Sub.	40
0.12"	1.30"	0.07"	1.00	Sub.	25
0.15"	1.30"	0.04"	0.53	Sub.	36
0.27"	0.90"	0.08"	0.59	Sub.	79
0.12"	0.70"	0.13"	1.00	Sub.	56
0.23"	0.90"	0.02"	0.17	Surf.	32
0.40"	0.70"	0.43"	1.00	Sub.	63
0.47"	0.60"	0.49"	1.00	Sub.	50
0.12"	1.00"	0.06"	1.00	Sub.	36
0.34"	0.70"	0.78"	1.00	Sub.	25
0.29"	2.20"	0.02"	0.14	Surf.	100
1.27"	1.00"	0.03"	0.05	Surf.	79
0.85"	1.05"	0.55"	1.00	Sub.	32
2.10"	1.20"	0.12"	0.11	Surf.	36

Dim. (2a)	Dim. (l)	Dim. (S)	Value (Y)	Surf./Sub.	Ampl. (% DAC)
0.41"	1.30"	0.19"	0.93	Sub.	32
0.42"	0.70"	0.21"	1.00	Sub.	79
0.35"	3.60"	0.02"	0.11	Surf.	56
1.02"	0.90"	0.31"	0.61	Sub.	56
1.01"	3.20"	0.27"	0.53	Sub.	40
1.01"	3.20"	0.27"	0.53	Sub.	71
0.61"	1.00"	0.68"	1.00	Sub.	36

Nine indications were confirmed by MT and removed by grinding and blending.

The following table lists the dimensions of the excavated areas required to completely remove the indications, including blending:

Length	Width	Depth
1.50"	1.00"	0.13"
1.25"	1.00"	0.06"
1.50"	1.00"	0.13"
1.00"	1.00"	0.13"
0.75"	0.75"	0.13"
1.75"	1.00"	0.19"
3.00"	2.00"	0.44"
2.50"	2.50"	0.38"
1.50"	1.50"	0.06"

One subsurface classified indication exceeded 50% DAC and met the acceptance standards of Table IWB-3511-1. Six subsurface classified indications exceeded 50% DAC and did not meet the acceptance standards of Table IWB-3511-1. These indications were dispositioned as acceptable by fracture evaluation in accordance with ASME Section XI, IWB-3600.

One boat sample was taken in an attempt to capture a subsurface indication for additional study by metallography.

Unit 1 Metallurgical Examination

General

A metallurgical evaluation was performed on a boat sample removed from the upper shell of steam generator A. The purpose of removing the boat sample was to determine the cause of the linear indications found on the ID surface of the steam generator, in the area of the girth weld.

The boat sample that was removed contained one linear indication. The indication measured 5/8" in length and 0.353" in depth (estimated by UT). The sample was removed approximately 5" above the centerline of the girth weld and was located entirely in the base material. Conventional grinding techniques were used to remove the 2" long x 1/2" wide x 7/16" thick boat sample.

Metallurgical Evaluation by SRI International

The as-removed boat sample is shown in Figure 1. The surface indication which appeared as a crack measured 5/8" in length and appeared filled with oxide. Several deep pits were observed at random locations on the surface of the sample.

To evaluate the crack morphology, it was decided to have SRI in Menlo Park, California, perform the Fracture Surface Topography Analysis (FRASTA) method on the crack surfaces. The FRASTA method was developed by SRI to characterize the fracture surface morphology using computer aided topography mapping.

The FRASTA procedure permits reconstruction of the crack morphology. Stereophotographic images of the two halves of the sample which made up the crack surfaces are created using a scanning electron microscope. These images are then digitized which permits the sample and the crack to be reassembled by computer simulation. The goal of the computer simulation is to permit identification of the crack initiation point and to define the crack propagation characteristics.

The sample was downsized (as shown in Figure 2) by sectioning it into three pieces. This was done so that SRI could perform the FRASTA method on the largest portion of the crack tip. The remaining sections of the sample were evaluated by CeCo. After the sample was sectioned at SRI, the crack depth was measured to be 0.220".

The largest section of the sample was fractured open at -320^{o}F to examine preexisting crack surfaces. An examination of the crack surfaces revealed a heavily oxidized appearance with a configuration similar to a "thumbnail" shape (refer to Figure 3). Radial markings observed on the crack surface appeared to emanate from the base of a large surface pit.

Scanning Electron Microscopy (SEM) was performed at SRI on the conjugate crack surfaces. One of the surfaces, as shown in Figure 4, exhibited a heavily oxidized texture and adjacent to the crack tip there was a change in the oxide morphology. This region was narrow (approximately 400 microns), less oxidized and had a flat fracture appearance (refer to Figure 5). Numerous secondary cracks in this region that were observed were fissures in the oxide caused during the fracturing process of the sample.

Energy Dispersive X-ray Spectroscopy (EDS) of the crack surface oxide revealed a predominant Fe K $_{(alpha)}$ peak, with no other elements reported. SRI has completed the FRASTA evaluation. The results were inconclusive and did not reveal anything which would alter the present hypotheses regarding the girth weld cracking phenomenon, which are discussed in the conclusions sections of this report.

Metallurgical Evaluation by CeCo

The remaining portion of the sample was evaluated by CeCo's materials analysis group.

The sample was prepared for metallographic examination and the cross-section of the entire sample (approximately 3/8" away from one end of the crack) is shown in Figure 6. A 1/16" layer of weld deposit was discovered on the steam generator ID surface of the sample. This weld deposit appeared uniform in thickness. An EDS of the weld metal revealed an Fe K $_{(alpha)}$ peak and a smaller Ni K $_{(alpha)}$ peak. The chemical composition of the steam generator shell base material was verified to meet the requirements of ASME SA-533, Grade A, Class 1 material.

The crack exhibited minor branching and appeared to have initiated at the base of a corrosion pit (refer to Figure 6). The crack surfaces were oxidized and the crack tip, shown in Figure 7, was transgranular and filled with oxide. These types of features are indicative of corrosion fatigue crack propagation. While the FRASTA evaluation was unable to quantitatively define crack growth rates, the crack growth rates were found to be slow in the weld material, slightly increased in the heat affected zone (HAZ) and slowed again in the base metal. The cracks appeared to become blunted in the base metal and may become arrested there.

Microhardness tests of the weld metal, HAZ and steam generator shell base metal were performed on the sample. The microhardness of the weld metal (using a 300 gm load) ranged from 230-250 Vickers. The microhardness of the steam generator base metal HAZ ranged from 370-385 Vickers, and the steam generator shell base metal ranged from 194-200 Vickers. The microstructure of the steam generator shell base material consisted of tempered bainite.

Conclusions

The indication removed as a boat sample from steam generator A was identified as a corrosion fatigue crack that initiated and propagated from the base of an oxide filled pit.

The hardness of the HAZ beneath the weld deposit was exceptionally high. This implies that this area was not adequately tempered. The reason for the presence of the weld metal at this location is under review as described in the summary section.

The factors contributing to corrosion fatigue crack propagation in the vicinity of the girth weld cannot be unequivocally established based on the results of this one sample.

SYSTEM MATERIALS ANALYSIS DEPARTMENT REPORT
ON
METALLURGICAL EVALUATION OF A BOAT-SHAPED SAMPLE
FROM
ZION 1A STEAM GENERATOR

Figure 1. The boat-shaped sample as-removed from the 1A S/G at Zion Station. The arrow indicates the location of the surface flaw. Note the extent of pitting attack on the surface of the sample.

Figure 2. The portion of the boat-shaped sample after it was sectioned at SRI for the FRASTA evaluation.

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ON
METALLURGICAL EVALUATION OF A BOAT-SHAPED SAMPLE
FROM
ZION 1A STEAM GENERATOR

Figure 3. View of one of the crack surfaces showing an oxidized texture and 'thumbnail' shaped appearance.

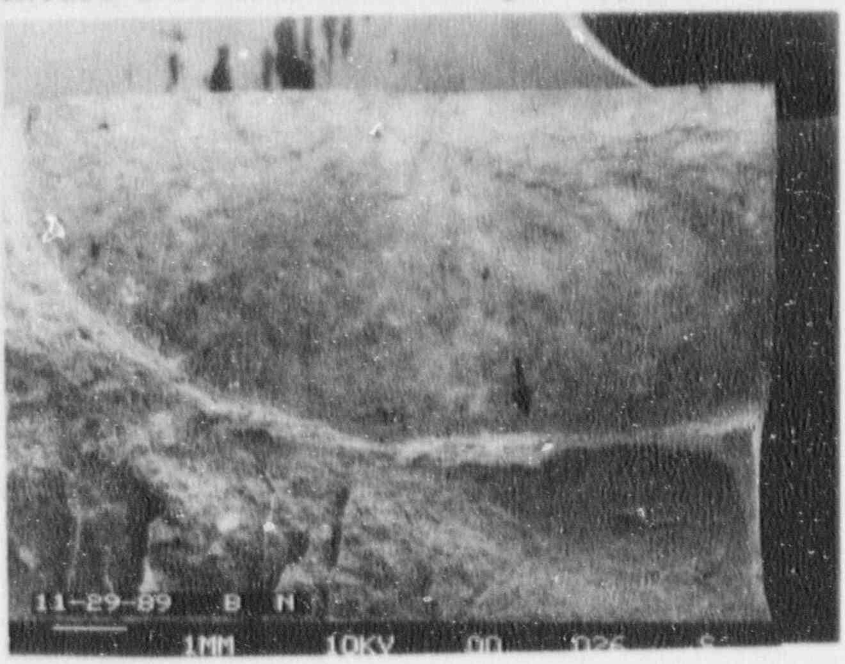

Figure 4. Scanning electron micrograph (SEM) showing the crack surface morphology and crack tip region (arrow).

SYSTEM MATERIALS ANALYSIS DEPARTMENT REPORT
ON
METALLURGICAL E"ALUATION OF BOAT-SHAPED SAMPLE
FROM
ZION 1A STEAM GENERATOR

Figure 5. SEM photograph showing the narrow, flat fracture region at the crack tip (arrow).

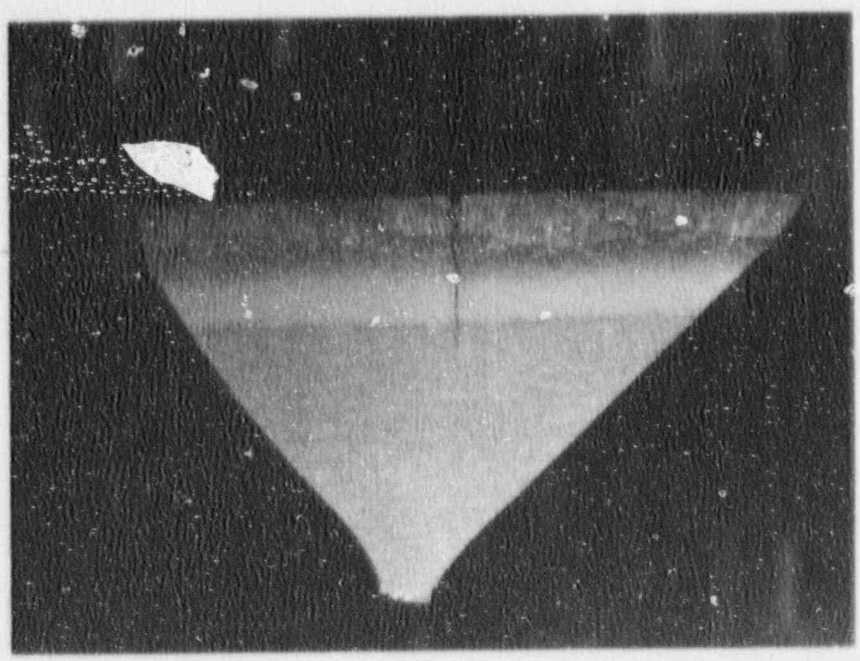

Figure 6. Cross-section of the crack-containing sample showing the crack location, corrosion pit and weld deposit.

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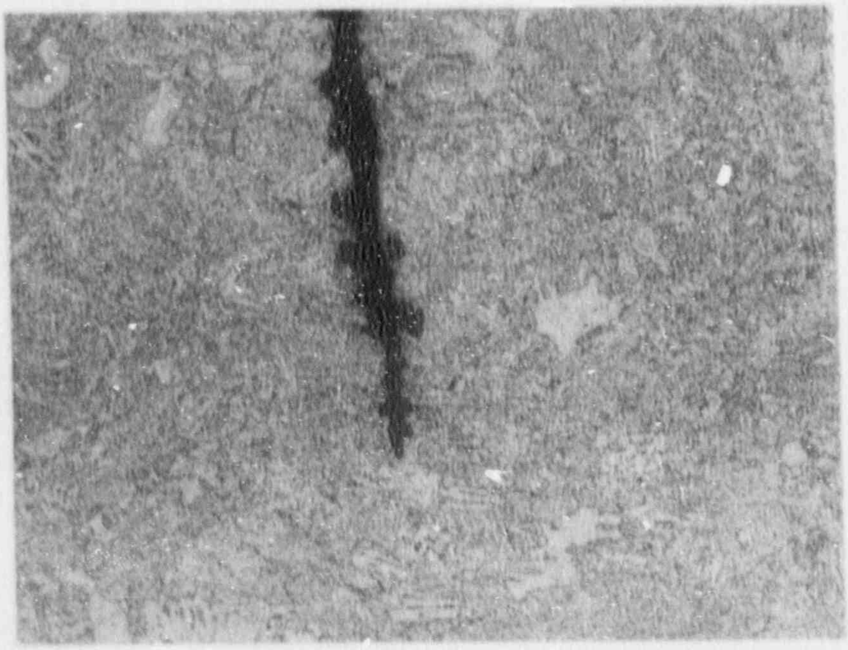
FROM
ZION 1A STEAM GENERATOR



400 x   Figure 7   etched: 2% Nital

Photomicrograph showing the transgranular crack morphology and oxide-filled crack tip. These features are characteristic of corrosion fatigue crack propagation.

Unit 2 Metallurgical Examination

General

One boat sample was removed from both the A and D steam generators for metallurgical evaluation. The sample from steam generator A contained a surface indication. The sample from steam generator D was taken in an effort to capture a subsurface indication. The purpose of removing the boat samples was to gather additional information in an effort to determine the cause of the linear indications found in the girth weld area.

Metallurgical Evaluation by CeCo

The boat sample removed from the A steam generator is shown in Figure 1. Visual examination of the sample revealed a 1/2" long crack, which upon closer examination was a series of corrosion pits that linked-up. The crack was linear and filled with oxide. Also, the surface of the boat sample representing the ID of the steam generator had a uniform layer of oxide (magnetite).

The sample was cross-sectioned at a location approximately 1/4" from one end of the crack to examine the crack morphology. This revealed the crack had propagated from the base of the corrosion pits into the heat affected zone (HAZ) and base metal of the steam generator shell. The crack depth was approximately 0.150". The corrosion pits which preceded the crack measured 0.020" to 0.030" in depth in the girth weld metal, as shown in Figure 2. The crack morphology was predominantly transgranular with a minor amount of branching at the crack tip, as shown in Figure 3.

The steam generator ID surface of the boat sample and the crack surfaces were oxidized. An analysis of the oxide using energy dispersive x-ray spectroscopy (EDS) revealed a predominant peak of iron, no other elements were found. The remainder of the ID surface of the sample contained random corrosion pits that were filled with oxide and measured 0.002" to 0.010" in depth.

Microhardness tests of the girth weld metal, HAZ and the steam generator shell base metal were performed on the sample. The hardness of the weld metal was 209 VHN, the HAZ was 360 VHN and the shell base metal was 190 VHN.

The microstructure in the HAZ consisted of coarse, slightly tempered martensite and bainite. The steam generator shell microstructure consisted of fully tempered bainite.

The sample from the D steam generator was similar in size to the sample from the A steam generator, except it was intended to contain a subsurface flaw and had an orientation perpendicular to the girth weld. The sample is shown in Figure 4. Visual examination of the sample surface (representing the ID surface of the steam generator) revealed random corrosion pits measuring up to 0.010" in depth and a uniform deposit of oxide (magnetite).

To determine the location of the subsurface flaw, this sample was longitudinally sectioned and the cut surfaces were examined by the wet fluorescent magnetic particle test method. This examination revealed no flaws or cracks on the cut surfaces.

The sample was then prepared for metallographic examination. After several attempts at surface grinding to various depths, no subsurface indications were found.

Microhardness testing was performed on the girth weld, HAZ and the steam generator shell base metal. The results of the microhardness tests revealed a hardness of 200 VHN for the weld, 330 VHN for the HAZ and 190 VHN for the base metal. The girth weld and HAZ microstructures are shown in Figure 5.

Conclusions

Metallurgical analysis of the D steam generator sample revealed no subsurface indication. The surface of the sample corresponding to the steam generator ID contained random corrosion pits 0.002" to 0.010" in depth in the girth weld metal.

Metallurgical analysis of the A steam generator sample revealed the crack initiated and propagated from the base of a series of corrosion pits that had linked-up in service. It was determined that the crack was linear, exhibited a transgranular crack morphology and was partially filled with oxide. A minor amount of branching was observed at the crack tip. The crack depth was measured at 0.150".

The analysis performed on a sample from Zion Unit 1 in 1989 and the results obtained from this investigation imply the girth weld cracks are caused by an environmentally assisted cracking mechanism. Two failure mechanisms are probable, corrosion fatigue and transgranular stress corrosion cracking. For each crack mechanism the contributor to crack propagation is the corrosive environment. The corrosion pits observed on the steam generator ID surface and the predominant iron peak observed in the oxide (based on an EDS analysis) imply the source of this corrosive environment is oxygenated water.

Structural Analyses

Analyses were performed using finite element and conventional analysis techniques. The analysis of the reference, unrepaired geometry was performed using a finite element model representation of the transition cone and short segments of the shell above and below the cone. This analysis used a Westinghouse computer program to perform a combined heat transfer/thermal stress analysis. A separate Westinghouse computer code was used to perform the ASME Code evaluation, including checks of the applicable stress limits. The analysis of the repaired geometry utilized conventional analysis techniques to modify the finite element results for the reference geometry to account for the presence of the repair locations.

Based on the analysis results, the repaired girth weld regions for both units satisfy the applicable ASME Code stress and fatigue limits.

Fracture Mechanics Evaluations

As described earlier, the subsurface classified indications which exceeded 50% DAC and did not meet the acceptance standards of Table IWB-3511-1 were dispositioned by fracture mechanics evaluations in accordance with ASME Section XI, IWB-3600. The fracture evaluation criteria and the complete technical basis for their construction has been provided by Westinghouse in WCAP-12045, "Background and Technical Basis: Handbook on Flaw Evaluation for the Zion, Byron and Braidwood Units 1 and 2 Main Coolant System, November 1988." The flaw evaluation charts are contained in Westinghouse WCAP-12047, "Handbook on Flaw Evaluation for Zion Units 1 and 2 Steam Generators and Pressurizers, November 1988" and have been independently verified to be applicable to the upper shell to transition cone weld, using the most up to date portrayal of the upper shell to transition cone stress analysis. All indications dispositioned in this fashion were found to be acceptable.

Summary

The root cause evaluation into the steam generator girth weld cracking phenomenon is continuing. It appears likely that a number of variables combine to initiate the condition and the various ways in which they interrelate contribute to accelerating the progress of the phenomenon at different rates for different plants.

CeCo is reviewing all available historical fabrication data as well as operational issues such as water chemistry control and layup procedures in an effort to isolate the root cause and take actions to mitigate the phenomenon. The experience gained from the Zion efforts are being applied to CeCo's other PWR's.

CeCo also continues to review all industry data and experience for impact on the phenomenon as it applies to Zion station.

A broader scope industry program is under way at EPRI. CeCo will be participating in this program and will review any resulting recommendations for application and implementation at its PWR's.

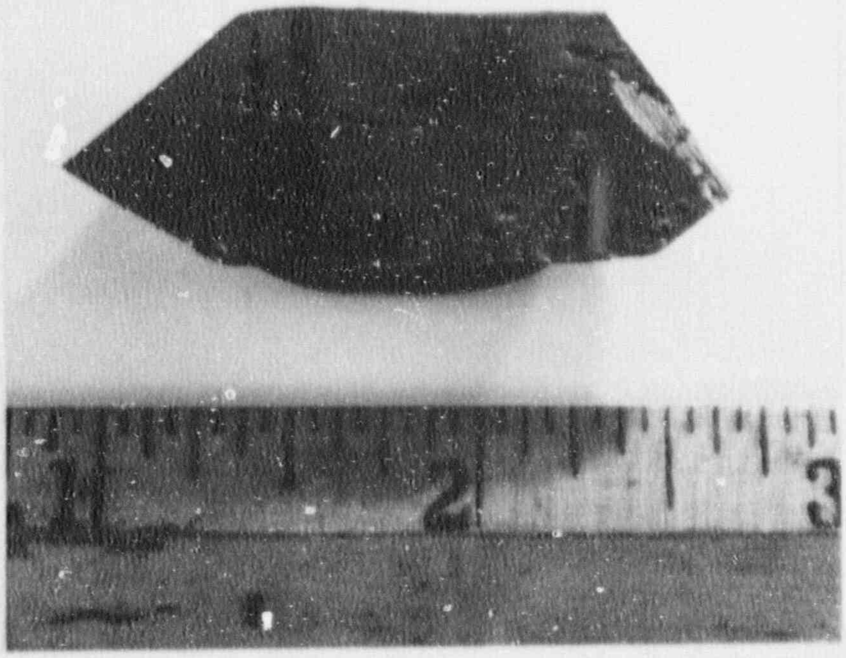


Figure 1
Sample removed from the Unit 2, 'A' S/G at Zion Station. The crack on the ID surface is indicated by the arrow. Note the corrosion pits on the sample surface.

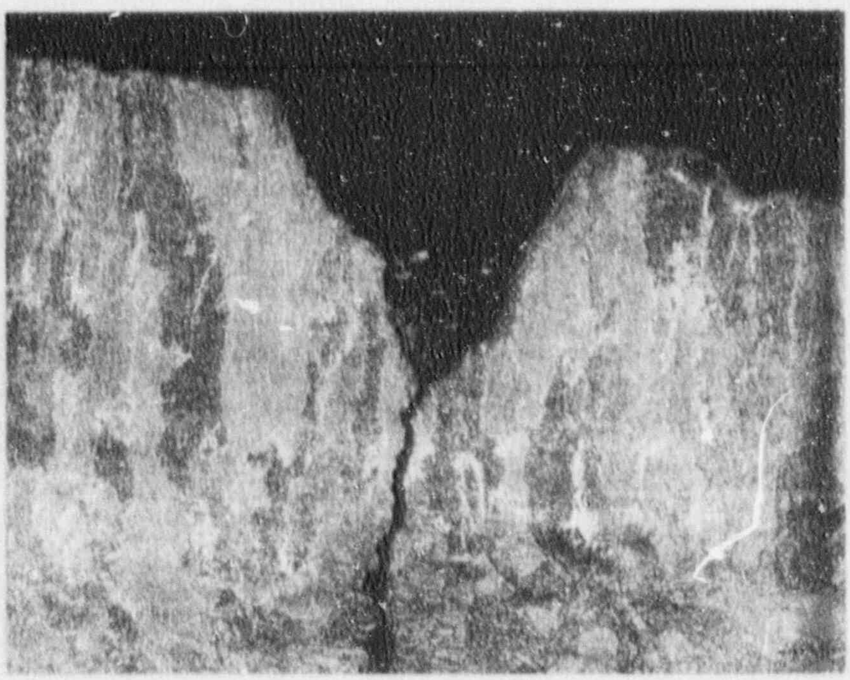


Figure 2
Photomicrograph showing the crack at the base of a surface pit. The pit is located in the girth weld (50 x mag, etched: 2% Nital).

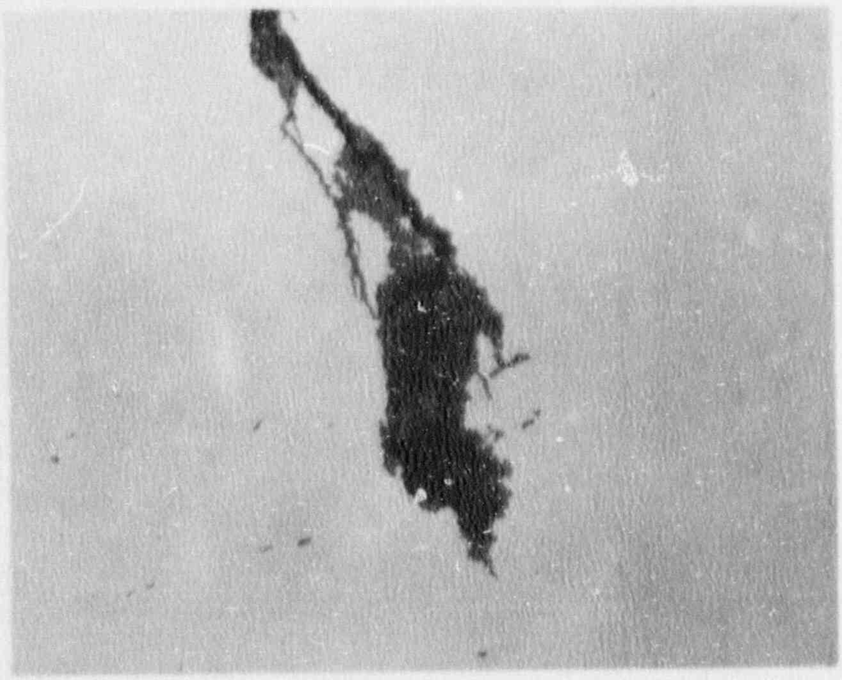


Figure 3
Photomicrograph showing the local corrosion and branching at the crack tip (200 x mag, unetched).

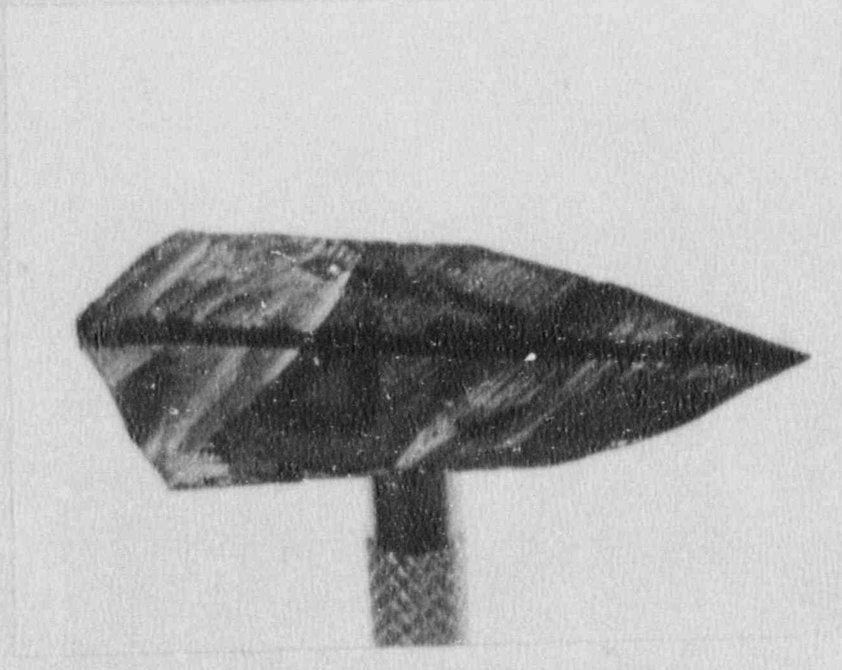


Figure 4
The as-received sample from the Unit 2 'D' steam generator at Zion Station. The sample measures 2.5" in length x .150" in depth.

Figure 5
Photomicrograph showing a section of the girth weld fusion zone in sample 2D. The HAZ microstructure consisted of slightly tempered martensite and bainite. (50x Mag., etched: 2% Nital)