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Failure Analysis Study of a Cracked Superheater Outlet Header

by

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ABSTRACT

This paper addresses the results of a detailed failure analysis study conducted to determine the cause of severe bore hole and ligament cracking found in a radiant superheater outlet header, on the Unit No. 1 boiler at the Big Cajun II station of Cajun Electric Power Cooperative.

Background information, including the discovery of the cracking, and the subsequent actions, including safety considerations taken by the owner, consisting of interim assessments, reduced operating conditions and ultimate component replacement is presented.

The primary focus of the paper is on the comprehensive failure analysis study, which included a series of review, metallurgical, analytical and mechanical testing tasks. The metallurgical and mechanical testing tasks were performed on metal sections and samples taken from the original header. The metallurgy includes a determination of the crack morphology, and a distribution analysis of the microstructure. Failure analysis calculations were done involving creep and fatigue considerations, to the loading conditions derived from plant operating records. The failure evaluation used the EPRI developed Boiler Life Evaluation and Simulation System (BLESS) computer program.

INTRODUCTION

A detailed failure analysis study has been performed in order to determine the cause of severe internal bore hole and ligament cracking in a radiant superheater outlet header, on the number one boiler at Big Cajun II station. See Figure 1 for a side elevation sketch of the boiler.

The study consisted of a series of review, metallurgical, analytical and mechanical testing tasks. The metallurgical and mechanical testing tasks were performed on samples machined from a section of the cracked header and consisted of the following items.

METALLURGICAL EVALUATION

- Macro photographs of representative cracks in the header internal ligaments.
- Determination of the microstructure of the header material at O.D., I.D. and through wall locations.
- Distribution analysis of the microstructure. Scanning electron microscopy using X-ray diffraction and microprobe techniques.
- Determination of the crack morphology.
- Alloy analysis of the header material.
- Hardness testing at O.D./I.D. locations.
- Chemical analysis of the scale present in the cracks.

MECHANICAL TESTING

- Tensile testing of specimens at room temperature and at 950°F.
- Fracture toughness, J_{IC} tests using three-point bend specimens.

The tensile and fracture toughness testing results, from the degraded material specimens, have been compared to results previously obtained from testing of virgin material. The header material is ASTM SA335-P22 (2).

Riley and Cajun records have been researched in order to establish the input parameters for the failure analysis tasks. This information included the temperature, pressure and steam flow values associated with steady state and transient boiler operating conditions.

A series of failure evaluations have been done to the loading conditions from the review of operating records, using the Boiler Life Evaluation and Simulation System (BLESS) computer program (4). This program has been developed by the Electric Power Research Institute (EPRI), and it is used for the evaluation of critical boiler header and steam piping components.

Background

During a forced outage of the Unit 1 boiler in September of 1992, extensive internal bore-hole and ligament cracking was discovered in the radiant superheater outlet header. Based on the results of a comprehensive engineering evaluation of the cracked header, the unit was returned to service, with derated and base loaded operating conditions until such time as the header could be replaced. The header was replaced in April of 1993. A complete description of these items, relative to the cracked header, is presented in the Reference (3) paper.

Cajun Electric Power Cooperative's Big Cajun II Units 1 and 2 are identical 560 MW Riley Stoker Turbo boilers, which burn low-sulphur western coal. Each unit was designed to operate at 2620 psig, 1005/1005°F, with a steam flow capacity of 4.3 million lbs/hour. The units began commercial operation in 1980-81. Since that time, Unit 1 has logged approximately 85,000 hours of operation, with over 200 starts. Both boiler units were originally designed to be base loaded. However, as is the case with many such designed boilers, the units are subjected to daily load cycling from 35 to 100 percent of full load capacity.

The boilers utilize a split-header design for the outlet of the radiant superheater comprised of two 45 foot headers positioned end-to-end across the full width of the boiler. The headers are constructed from SA335 P22 (2¼% chromium 1% molybdenum) low alloy steel, 20" O.D. x 3.5", nominal wall. They are located in the penthouse enclosure at the top of the boiler.

In September of 1992, Unit 1 was forced out of service due to a failed terminal tube on the East radiant superheater outlet header. This was the first known creep related terminal tube failure on Unit 1. During this forced outage, more bulged and swollen tubes were discovered. In addition, several minor cracks in the tube to header welds were found. When the tube which had failed in service was cut away from the header, severe cracking was discovered in the tube bore holes at that section. The cracks originated at the inside surface of the header and ran in a circumferential path through the ligament field between the tube bore holes. Less severe cracks ran longitudinally along the axis of the header.

Video inspection of the header internals revealed cracks in adjacent tube row ligament fields. Even with a moderate layer of scale on the inside of the header, the longitudinal cracks were plainly visible with sharp, clean edges that appeared brittle in nature. The circumferential cracks were less visible and oxide filled. Based on the preliminary video data, the worst cracking appeared to be in the tube bundles adjacent to one of the header outlet nozzles. Less serious cracking was seen in the ligament fields of at least five other tube rows. Ultrasonic shear wave testing was used to determine the depth of the cracks in the worst areas. The deepest ligament crack, in the circumferential direction, as measured from the I.D. of the header towards the O.D. was 1.7 inches. The header nominal thickness at this point was 3.5 inches, leaving 1.8 inches of sound ligament wall.

An extensive analytical and testing program was undertaken to assess the severity of the header cracking. Concurrent stress analysis and fracture mechanics studies were performed, for the deepest crack location, to determine the fitness for service of the header. See the Reference 6 and 7 reports. The stress analysis study utilized a Code (1) acceptable method for demonstrating that even with the presence of extensive cracking, a gross overstressing of the circumferential ligament field would not occur. This method is described in Reference 9. The fracture mechanics evaluations addressed two aspects of failure. First, failure along the bore hole circumferential ligaments due to plastic instability (collapse due to loss-of-section); and second, fracture resulting from ductile crack extension (crack instability). In order to provide some material property data for the fracture mechanics evaluation, tensile and fracture toughness testing was performed on specimens taken from "new" SA335 P22 header material.

The conclusions from both of the analytical studies were that the header would leak before break, and that the unit could operate, with derated operating pressure and temperature values and no cyclic or load swing duty, for a six month period until a replacement header could be fabricated and installed. The imposed reductions in temperature and pressure resulted in a 35 percent capacity unit derating of approximately 185 megawatts. Subsequently, the cracked header was removed and the replacement components installed in the Spring of 1994, during a four week unit outage.

Failure Analysis Study

A series of review, metallurgical, analytical and mechanical testing tasks have been performed to determine the cause of the internal header cracking. As part of the metallurgical and mechanical testing, specimens and samples were cut and machined from a seven inch long whole piece of the cracked header, received at Riley. See Figure 2.

Metallurgical Evaluation

From the sample piece of radiant superheater outlet header, sections were cut from the region with indications of cracks. The section of interest was at the inboard region of the header (centerline of boiler). Figure 2 shows the ring section of the header selected for metallurgical evaluation. The section was subjected to visual, macroscopic, and microstructural analysis with selected hardness tests performed. The chemical composition of the header was also analyzed in order to verify the alloy type as SA335 P22. Further examination of the header sample was undertaken by the use of a scanning electron microscope with electron microprobe facilities.

Figure 4 shows the designation of the tube nipple connections. These nipples were labeled A through P according to the original drawing. Indications of cracks were noted at the edge of the bore holes in the region bounded by tubes E through H, and B through P. These cracks were longer in the circumferential direction than the longitudinal direction. Figure 3 shows detail of the cracks observed at bore hole F. Further inspection showed radial superficial cracks at the I.D. surface adjacent to the bore hole. More detailed visual inspection within the bore hole revealed longitudinal cracks which did not originate or end at the I.D. surface of the header.

All the major cracks observed in the header section were measured for length using calibrated calipers. The results are shown in Figure 5. The longest cracks were associated with bore holes E and F. These bore holes are at the front of the header and were connected to tubes which formed the leading edge of the radiant superheater header assembly, and therefore would have been at the highest temperature. Limited or little evidence of cracking was observed for bore holes N through J which correspond to the central section of the superheater assembly. The connected tubes would be at lower temperatures than tubes connected to bore holes E through H and B, A, and P. Indeed, no cracking was observed in bore holes O, N, M, L, K, and J. This pattern was observed with other ligament fields during the fiberscopic examination. Also, during the original assessment the deepest crack was measured by ultrasonics to be 1.7", between bore holes E and F. Mechanical measurements of the sample piece in the laboratory show this depth value to be 1.5".

Microstructural Examination

Following the visual and dimensional investigation sections were cut from the header from both the I.D. and the O.D. adjacent to bore hole G. The sections were mounted, polished, etched and examined using light and electron microscopy. In the case of the I.D. section which included a crack, electron microprobe analysis was used to determine the chemical composition of the scale at the tip of the crack. The results of the analysis are listed in Table 1 and are the average of a total of 11 individual points. Correlating the points analyzed with the features observed with the SEM showed that the oxide corresponded to iron oxide (probably magnetite) with some chromium oxide present. However, at the interface between the oxide wedge and the base metal there was a definite partially oxidized interface.

TABLE 1

Chemical Composition of Oxide Present in Crack (Average of 11 points analyzed).

Element	Wt%
Sodium	0.2
Magnesium	0.1
Aluminum	0.0
Silicon	0.5
Phosphorus	0.0
Sulfur	0.5
Chlorine	0.2
Potassium	0.0
Calcium	0.0
Chromium	2.7
Iron	79.2
Nickel	0.1
Oxygen	16.1*

* Oxygen by difference

Figure 6 shows the microstructure at the I.D. including the morphology associated with a typical crack. The structure has been fully spheroidized, presumably during service. Some creep damage was observed. Investigation of the crack morphology shows a thick oxide-filled crevice. The crack tip shows the propagation was transgranular, which is typical of thermal fatigue. There was some evidence of creep damage at the crack tip along with some oxidation at the interface between the oxide wedge and the base metal.

The microstructure at the O.D. is shown in Figure 7. The structure is similar to that observed at the I.D. (Figure 6), that is a spheroidized microstructure with some evidence of creep.

The metallurgical mounts were also examined using scanning electron microscopy in the backscattered imaging mode. The advantage to the use of SEM is the high magnifications possible combined with the chemistry sensitive contrast achieved with backscattered imaging. With this technique, holes or voids will appear black compared with the bright background of the base metal. Furthermore, oxidized or corroded metal will have a different contrast than intact material. Comparison of the SEM micrographs of the I.D. and O.D. sections showed that the I.D. had more voids than the O.D. Figures 8 and 9 show details of the crack observed at the I.D. of bore hole G, using backscattered imaging. The layered structure of the scale is clearly evident. Also, there is a distinct corrosion interface between the scale and the base metal.

It should be noted that the extent of creep damage, while measurable, would be considered to be Wedel-Neubauer (5) Type A. That is, the I.D. region of the header in the location of the circumferential cracks was at the initial stages of creep.

Hardness Testing

Hardness testing was performed on a section of the header adjacent to bore hole G. The testing was performed using a Rockwell instrument at selected points 1/8" apart from the I.D. to the O.D. The measurements were made on the Rockwell B scale. The results show that there was a definite decrease in hardness from the I.D. to the O.D. The values ranged from about 71.0 R_B at the I.D. to 68.0 R_B at the O.D. (lower values were observed at the first and last locations respectively and assumed to be associated with the surface and not the base metal)

Chemical Composition Data

The results of the chemical analysis of the header in the proximity of bore hole G are listed in Table 2. The data shows that the material conforms to the chemical requirements of SA335 P22 material.

TABLE 2

Chemical Composition of Header

COMPONENT	%
Carbon	0.12
Chromium	2.50
Molybdenum	1.13
Nickel	0.16
Phosphorus	0.022
Sulfur	0.018
Manganese	0.44
Silicon	0.38

Mechanical Testing

Mechanical Testing, in the form of tensile and fracture toughness tests, has been completed for samples taken from the received piece of header. The results, from the testing of degraded material, are compared to those from testing done on samples from new SA335 P22 material, from the Reference 6 report, as shown in Tables 3 to 6.

Tensile Testing

Six tensile specimens were machined from the degraded header material and tested at 70°F and 950°F. The results are tabulated below:

TABLE 3

Tensile Testing of Degraded SA335 P22 Material

Specimen No.		Sy (ksi)	Su (ksi)	RA (%)	EL. (%)	E_t (in/in)
1	(70°F)	24	63.5	72.3	31.5	1.284
2	(70°F)	24	65	72.3	30.6	1.284
3	(70°F)	(invalid test - break out of gage length)				
4	(70°F)	24	68	71.9	30.6	1.269
5	(950°F)	--	40	65.3		1.058
6	(950°F)	--	38	65.7	--	1.070

Similarly, four tensile specimens taken from virgin header material were tested in November of 1992. These results are tabulated as follows:

TABLE 4

Tensile Testing of New SA335 P22 Material

Specimen No.		Sy (ksi)	Su (ksi)	RA (%)	EL. (%)	E_t (in/in)
1	(70°F)	36.5	73	68	29.5	1.135
2	(950°F)	--	58.5	67.8	23.2	1.133
3	(70°F)	39	74.5	69.3	29	1.180
4	(950°F)	--	58.5	64.2	24.1	1.027

Note that for both cases yield values and elongation at 950°F could not be reliably determined since gage length displacement (strain) could not be monitored with conventional displacement transducers. The true strain at fracture, E_t is calculated from $E_t = Ln\ 1$ (1-RA).

Fracture Toughness Testing

Fracture toughness (J_{IC}) tests were performed for four specimens of the degraded material, using three-point bend specimens in accordance with ASTM E-813 (8). The test results are tabulated below:

TABLE 5

Fracture Toughness Testing of Degraded SA335 P22 Material

Specimen No.	Toughness Values (in-lb/in²) J_{max}	J_q
1	589	333
2	1200	420
3	(Not Used)	
4	762	304

Similarly, four three-point bend specimens taken from virgin material, were tested for fracture toughness in November of 1992. The results are tabulated as follows:

TABLE 6

Fracture Toughness Testing of New SA335 P22 Material

Specimen No.	Toughness Values (in-lb/in²) J_{max}	J_q
2	2000	767
3	877	550
4	621	456
1	(used in test setup)	

For both cases, the material behavior was such that all of the E-813 requirements for the J_{IC} test could not be satisfied. However, it is believed that useful J_{IC} levels have been determined. The tables present the maximum J-value just prior to initial crack extension (J_{max}) as calculated using the equations of E-813. The J-value at the point of crack extension would be somewhat higher. Also tabulated is the J_q value determined using the power curve fit procedure of E-813. Note that the validity requirements could not be met because most of the data points fell outside of the exclusion zones on the J versus crack extension plots. However, crack initiation was clearly observed during the tests and is readily evident from the plots.

As expected the tensile and fracture toughness properties for the header material, in service for 85,000 hours, are lower than those of the new material. The comparative results show a nominal 36% loss in yield strength, 11% loss in ultimate tensile strength and a 27% loss in fracture toughness for the material in service. The appropriate mechanical property values, including those for degraded material, have been used as inputs to the applicable analytical cases, using the BLESS program, as described herein.

Review of Records

Riley and Cajun available records have been reviewed in order to determine accurate input parameters for the analytical tasks. This data included numbers of operating hours at different loads, numbers and types of boiler startup and shutdown events, and their associated component temperature, pressure and steam flow rate values. The Unit 1 boiler began commercial operation in 1980. It has logged 85,000 hours of operation with over 300 starts to date. Typical daily operation consists of load swings from 100 to 35 percent of full capacity.

Records for the first few years of operation were sparse; however, during the first two years of operation, Units 1 and 2 experienced severe steam temperature control problems. Outlet steam temperatures ran as much as 200°F above design. The installation of additional steam attemperation, along with control system modifications, improved temperature control considerably. main and reheat steam temperatures could be operated at design, while radiant superheater outlet steam temperature continued to run approximately 100°F above design.

Failure Analysis

A series of failure evaluations have been performed utilizing the unique features of the BLESS (4) computer program.

The BLESS Code provides the capability to perform remaining life estimates of high-temperature headers and piping. The code is capable of performing deterministic or probabilistic remaining life estimates for header ligaments and girth and longitudinal welds in both headers and piping. In the case of ligaments, the code performs an approximate stress analysis based on header geometry and time variation of pressure, temperature and flow rates. Crack initiation and growth due to creep/fatigue and oxide notching are considered. Failure probabilities as a function of time are generated by Monte Carlo Simulation. The code greatly facilitates the life assessment of elevated temperature boiler components by eliminating the need for finite element stress and temperature analyses and utilizing recent developments in nonlinear creep/fatigue crack growth.

Two primary scenarios were investigated in the failure evaluation using the BLESS Code. The first set of simulations were run from the beginning of plant operation, and for the probability of header crack initiation and growth. A simulation of the first two years of operation, with 1200°F temperatures, was modeled. The deterministic results from this simulation were used as inputs to the next simulation from two years of operation until the present time, a period of twelve years.

The load cases considered in the analysis, based on representative modes of boiler operation, are listed as follows:

1. Cold start to full load - 28 hours
2. Low load operation
3. Medium load operation
4. Full load turbine trip - 6 hour recovery
5. Full load operation
6. Shutdown to cold condition - 16 hours
7. Steady operation - derated conditions
8. Steady operation - higher temperatures
9. Steady operation - normal temperatures
10. Steady operation - lower temperatures
11. Shutdown - normal to hot - 5 hours
12. Hot start - 6.5 hours
13. Steady operation - lower pressure, high temperature
14. Steady operation - lower pressure, normal temperature
15. Derated operation - non steady
16. Normal operation - full pressure

The results from these simulations show that for the first two years of operation, a crack was initiated after 9,060 hours in service. At this time, the creep damage factor was 0.225, and the fatigue damage factor was 0.002. After two years or 17,500 hours in service, the cracks depth is determined to be 0.094".

The deterministic results from the second simulations, years three to fourteen, using the inputs from the first simulation show a postulated crack depth of 0.323 inches after 85,000 hours of operation. Obviously, this value is much lower than the 1.51" measured crack depth. It is most probable that the median property values were not appropriate, or that some number of unknown but significant load cases have not been input to the program. Quite possibly these unaccounted for load cycles, occurred during the early years of operation for which accurate records were not found. The probabilistic results for this case confirm some of the uncertainties in the analysis. For the probability analysis, 5000 simulations were run, and the first ten results reported. These results indicate failure or crack depth equal to 1.7 inches, for three of the simulations. The results also show that after 85,000 hours of operation there is a 16% probability of failure.

Figure 10 shows the probability of failure versus time for two cases, namely with and without the initial 0.09" deep crack.

The next set of simulations using BLESS, deals with continued operation of the boiler with an existing ligament crack, 1.7 inches deep (from the U.T. measurement). For these cases, different temperatures were simulated at normal and derated pressure values, for steady state operation. Also, cycling operation at normal pressure was investigated.

The results are shown graphically in Figure 11, as probabilities of failure over a future two years of operation. For the cyclic operation case, failure is postulated to occur after further 17,048 hours at a crack depth of 2.36 inches, which is 70% of the wall thickness value. For the steady state case at 1030°F, failure is postulated to occur at 33,027 hours, at the crack depth of 2.36 inches.

Summary

A detailed failure analysis study has been completed for the cracked radiant superheater outlet header of the Big Cajun II, Unit 1 boiler. The study involved a series of review, metallurgical, analytical and mechanical testing tasks as described herein. Specimens taken from a piece of the header have been used for the microstructural and mechanical testing tasks.

Originally, the bore hole and ligament cracking was discovered in September, 1992. At that time, detailed stress analysis and fracture mechanics evaluations were performed in order to assure safe operation for a six month period of time. In the Spring of 1993 the headers were replaced, as described in the Reference 3 paper.

The results from the current comprehensive failure study confirm that the cracking was due to the combined effects of creep and fatigue. The recorded overtemperature conditions experienced during the first two years of service have been confirmed by the presence of Type A creep voids in the microstructure, adjacent to the ligament crack in the metallurgical sample. The crack tip shows the propagation was transgranular and contain thick oxide scale, which are indicative of thermal fatigue. The deterministic analytical results, using the BLESS program, confirm the creep damage but not that for fatigue. This probably indicates that some number of unknown, but significant load (cycling) cases from the early years of operation, were not input to the analysis. However, the results of the probabilistic analysis, which considered 5,000 simulations, show a 16% probability of failure in 85,000 hours of operation, including a postulated three failures for the first ten simulations.

Based on the analytical work completed for the failure study, the BLESS computer program has proven to be a very valuable and versatile tool, using state of the art techniques for the investigation of the cause and propagation of cracking in the header.

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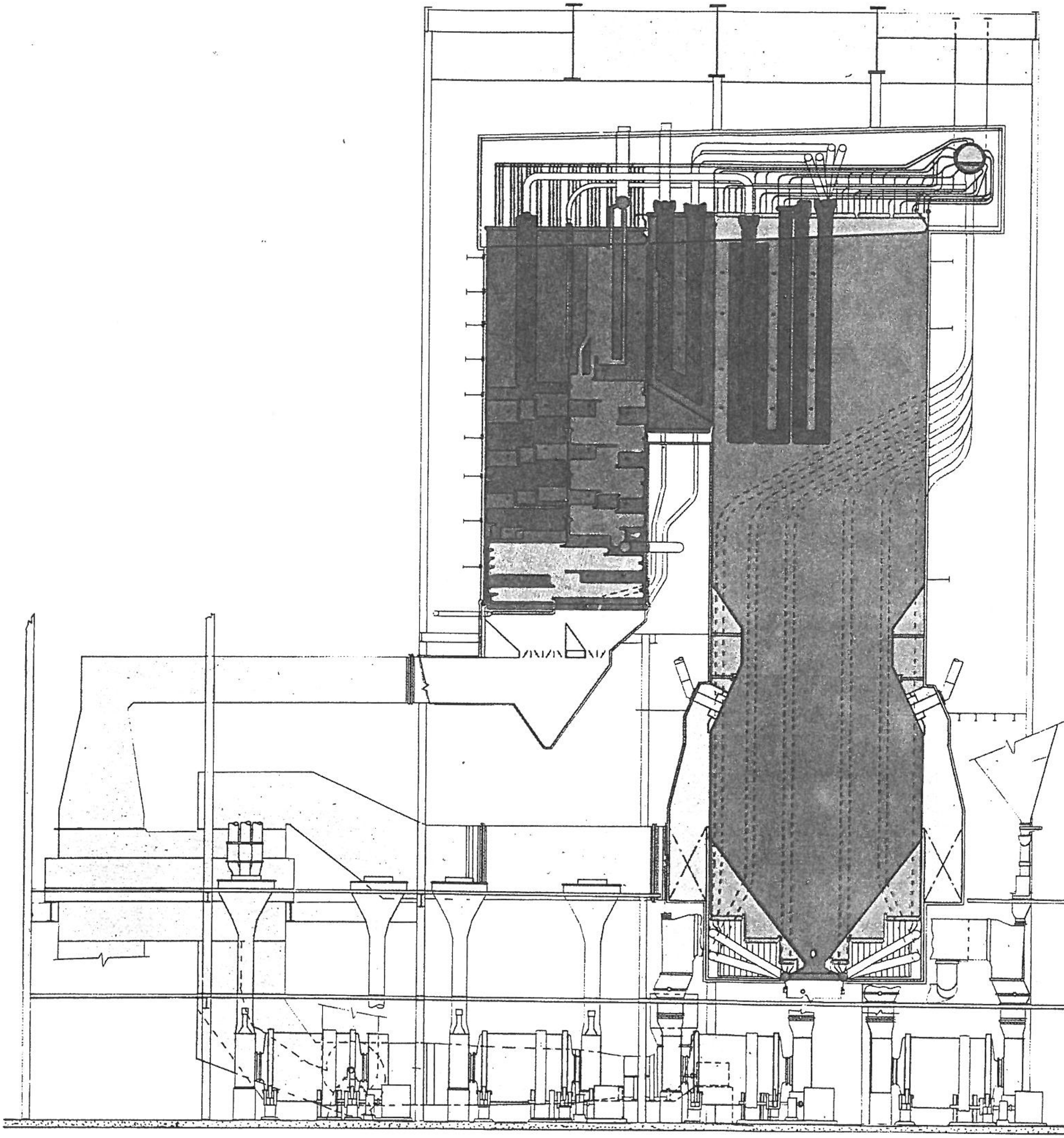
9. B. P. Holbrook and J. P. King, "Recent Experience in the Inspection and Assessment of Boiler Header and Steam Drum Cracking", presented at the Third EPRI Conference on Fossil Plant Inspections, August, 1991, Baltimore, Maryland.



BIG CAJUN NO. 2
UNITS NO. 1 & 2
New Roads, Louisiana
Cajun Electric Power Cooperative, Inc.

Two 4,300,000 lbs per hour — 2950 psig design — 2620 psig operating — 1005/1005F
Fired by Pulverized Coal
Bovay Engineers, Inc. and Burns & Roe, Inc., Consulting Engineers

75034
75038

FIGURE 1

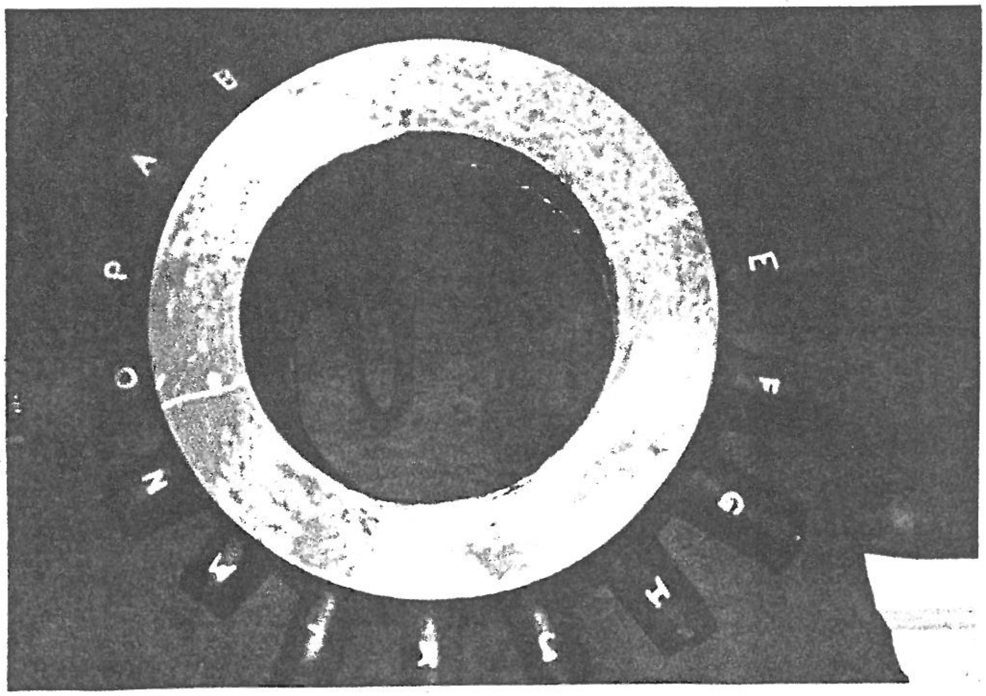


FIGURE 2
Section of East Header removed for evaluation.
Note designation of nipples/bore holes.

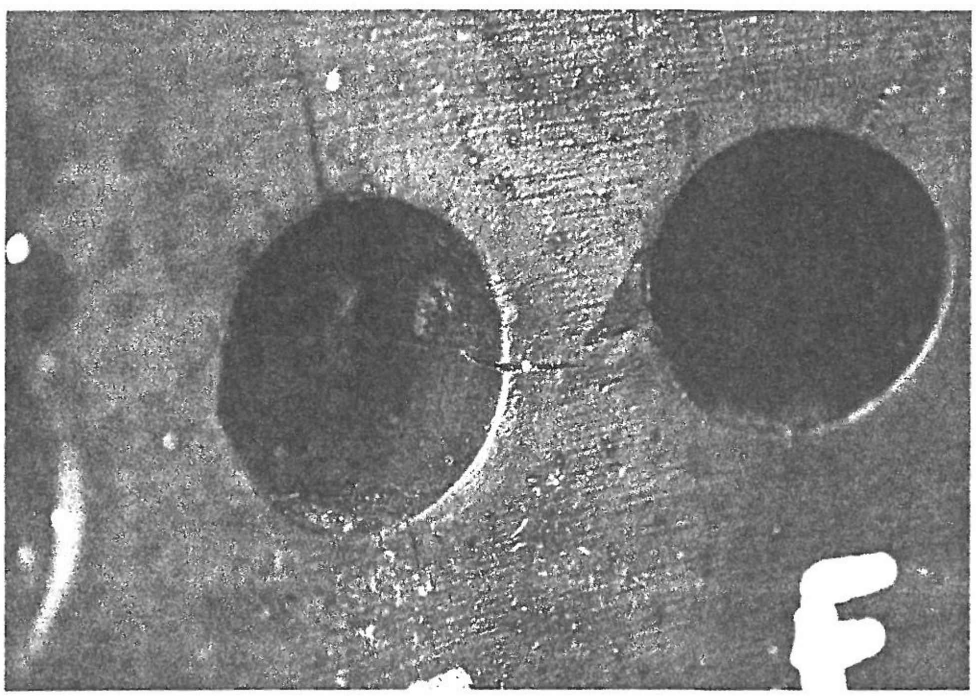
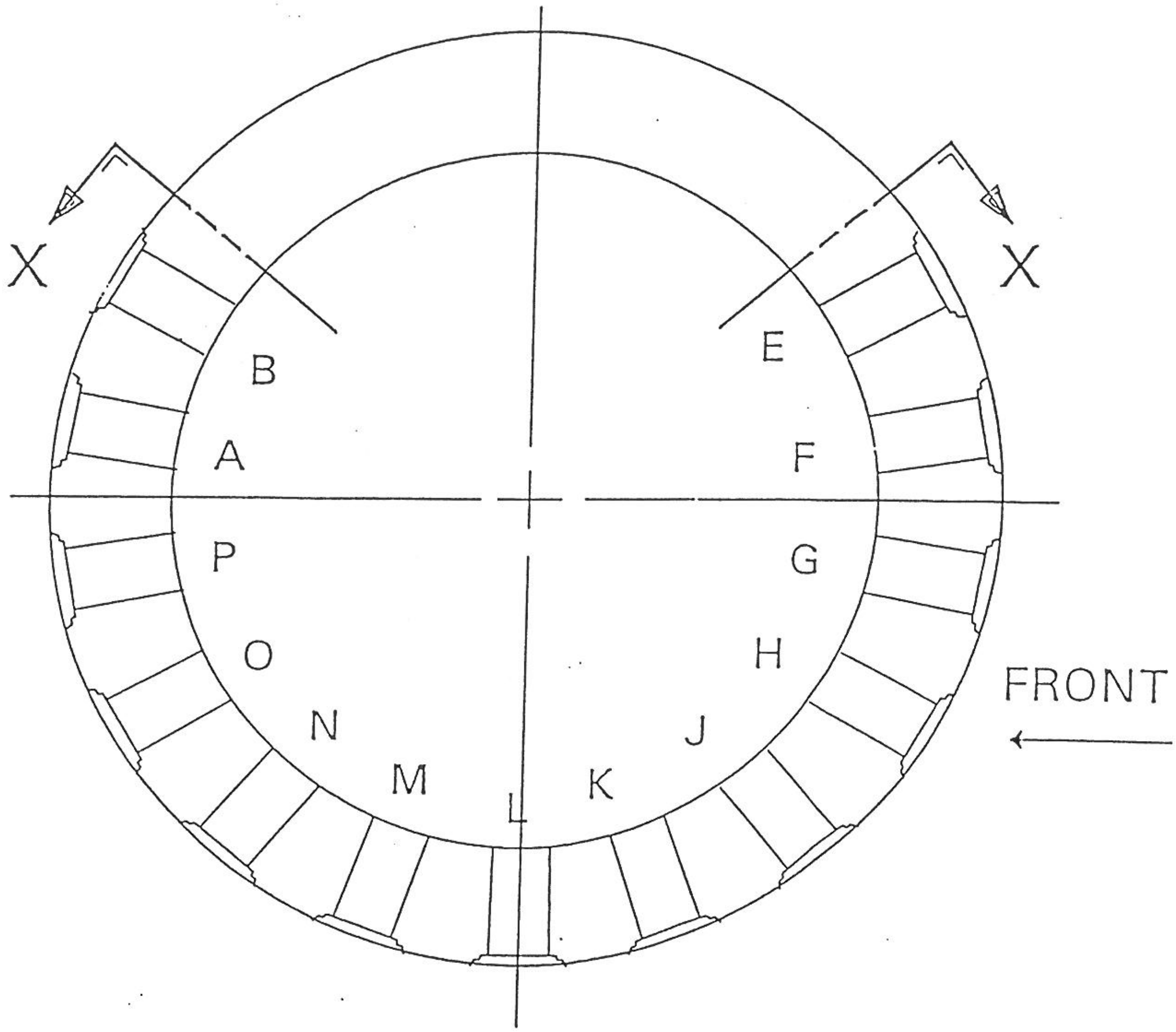


FIGURE 3
Macrophotograph of crack present between bore holes E & F.
Note deep crack in bore hole E.



LEFT HAND SIDE VIEW

FIGURE 4
SCHEMATIC OF EAST HEADER SHOWING DESIGNATION OF BORE HOLES. SEE FIGURE 5 FOR SECTION X-X.

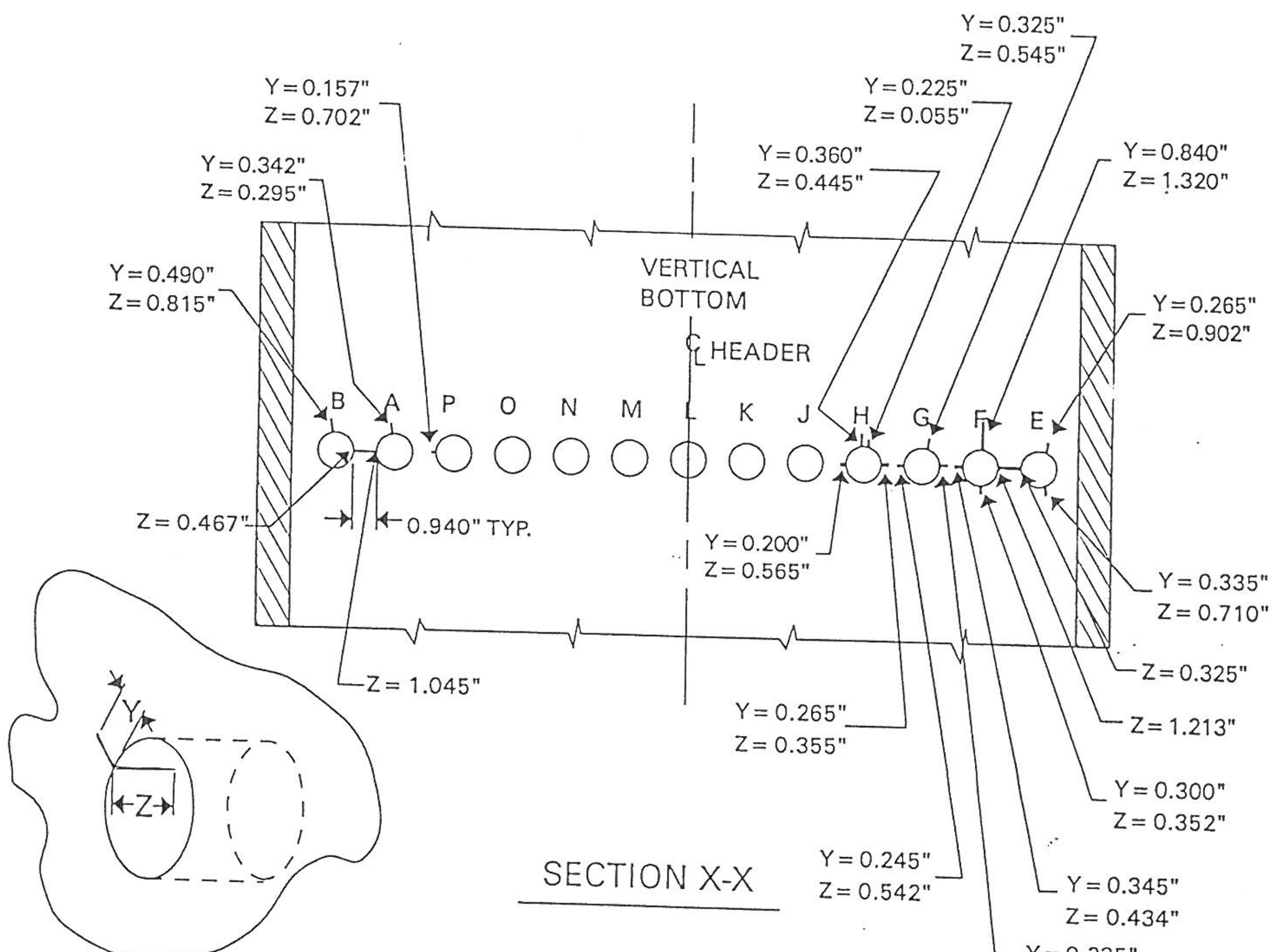


FIGURE 5

SECTION SHOWING PLAN VIEW OF SECTION X-X. CRACKS OBSERVED ARE INDICATED TO SCALE. CRACK LENGTH MEASUREMENTS ARE INCLUDED.

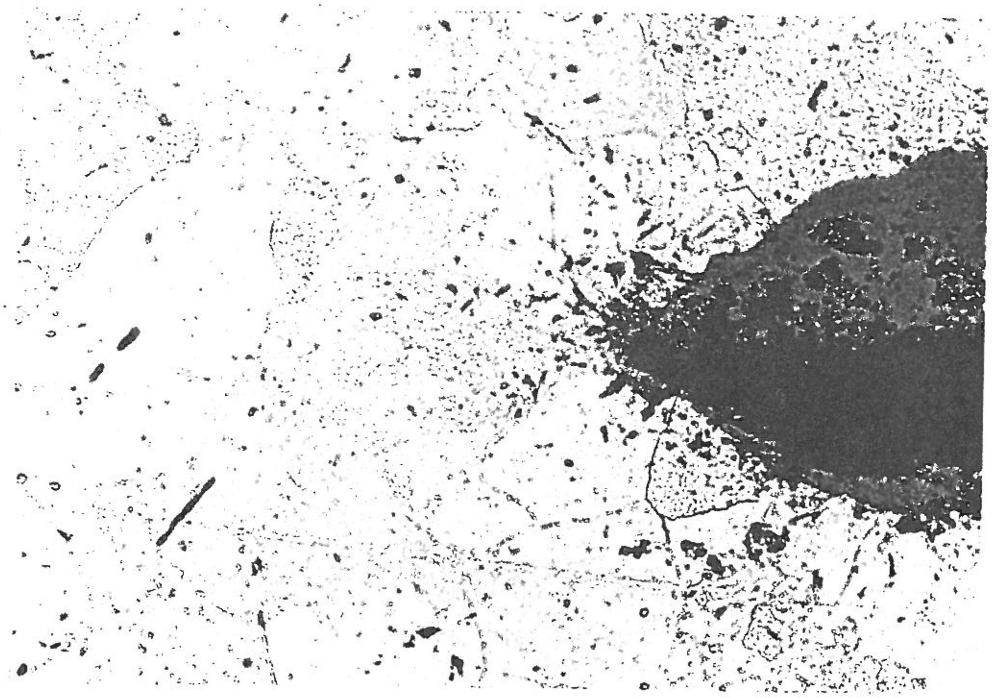


FIGURE 6
Microstructure at tip of crack present at I.D. (bore hole G).
Note transgranular propagation and spheroidized carbides. Some isolated creep voids are present 400X

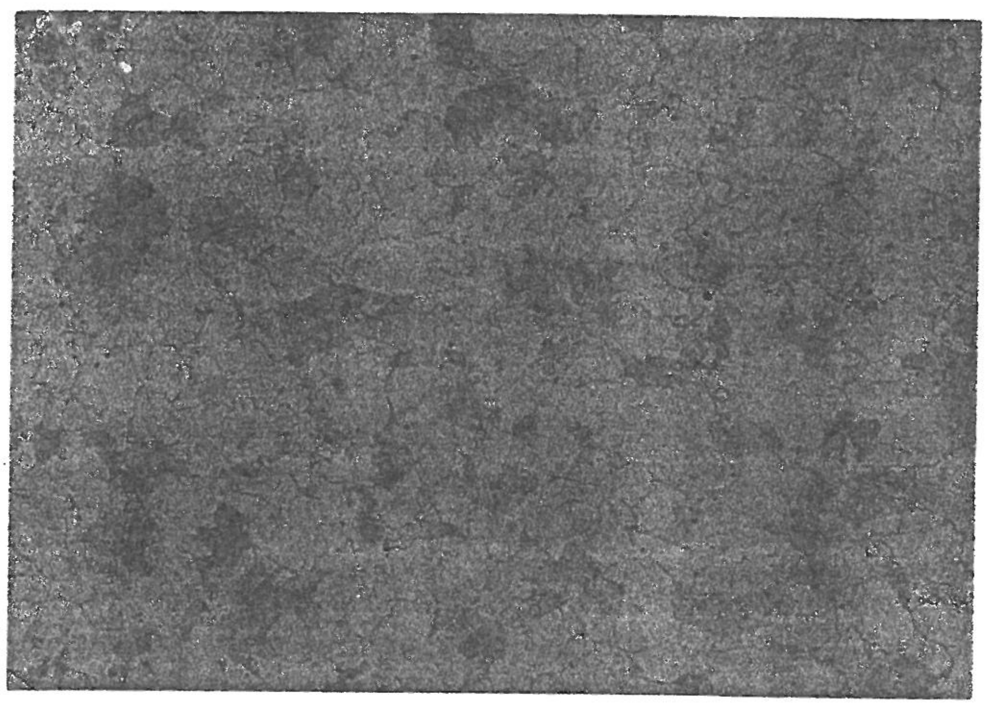


FIGURE 7
Microstructure at O.D. of section adjacent to bore hole G.
Some creep voids are present 400X

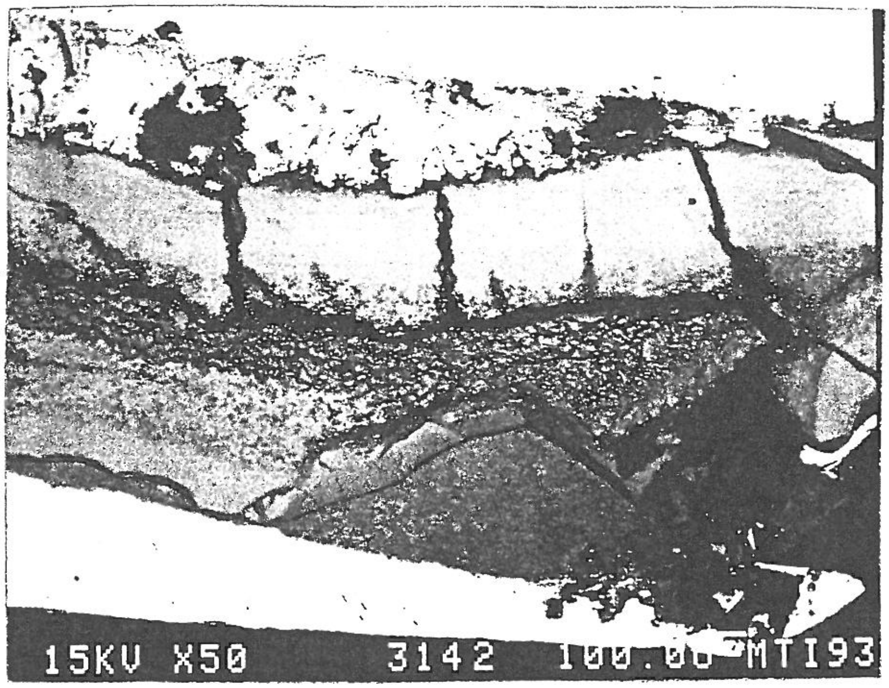


FIGURE 8

SEM (BEI) image of oxide-filled crack in bore hole G. Note different layers and the partially oxidized interface between dense scale and base metal. 50X

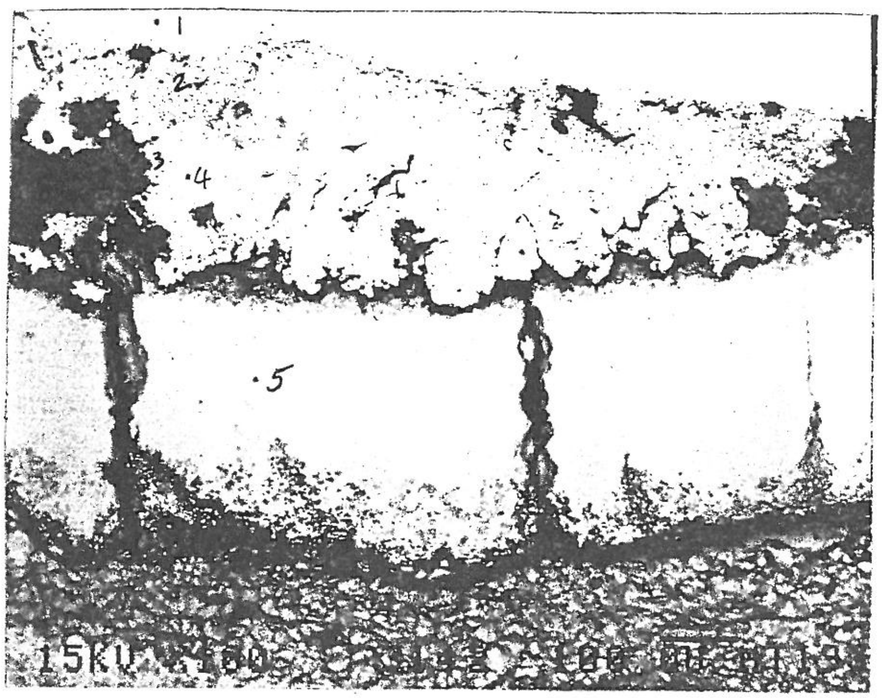
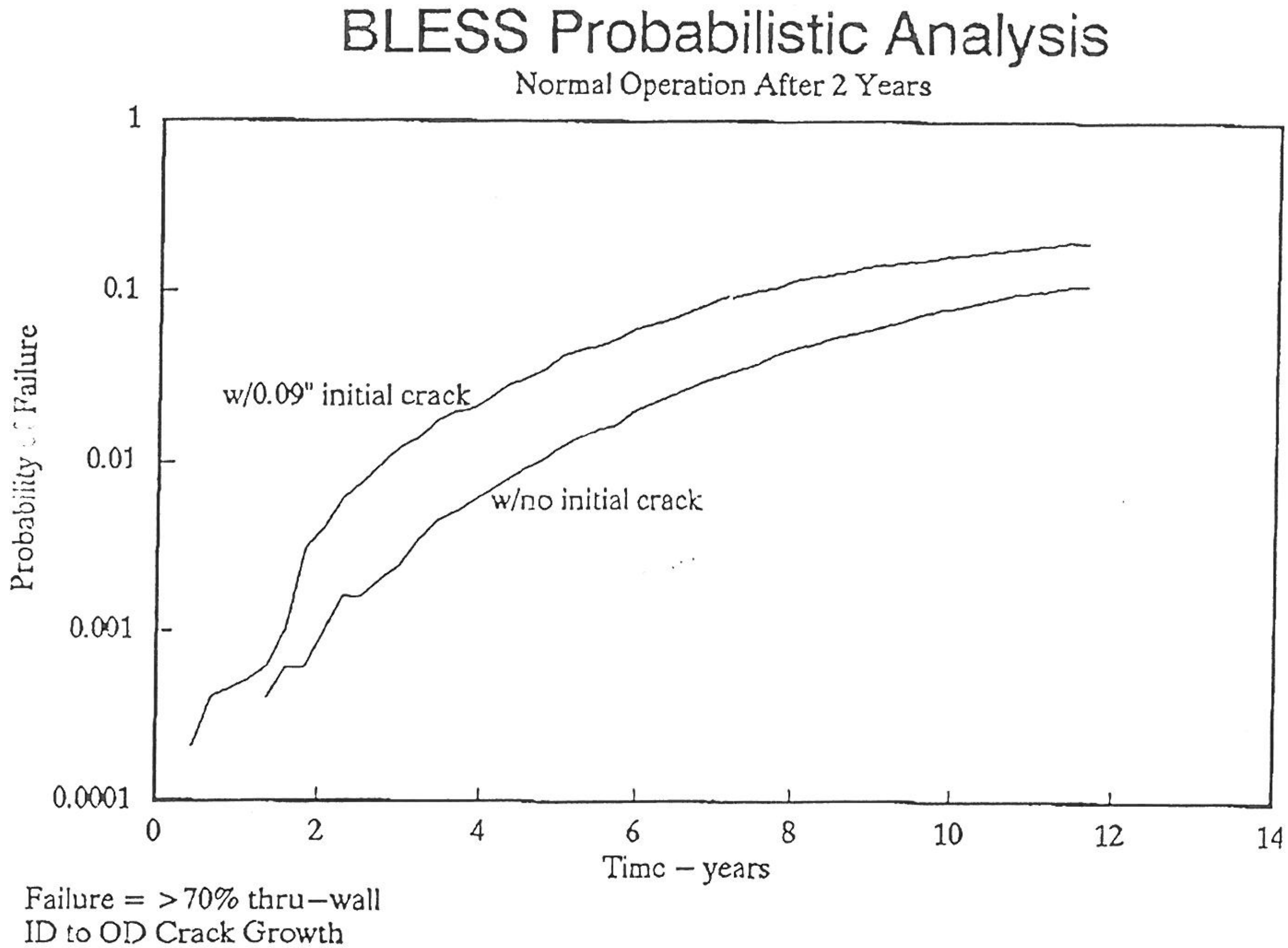


FIGURE 9

SEM (BEI) detail of Figure 8 showing interface region between scale and base metal. 100X



<u>FIGURE 10</u>
Probabilities of failure after fourteen years
(85,000 hours) of operation.

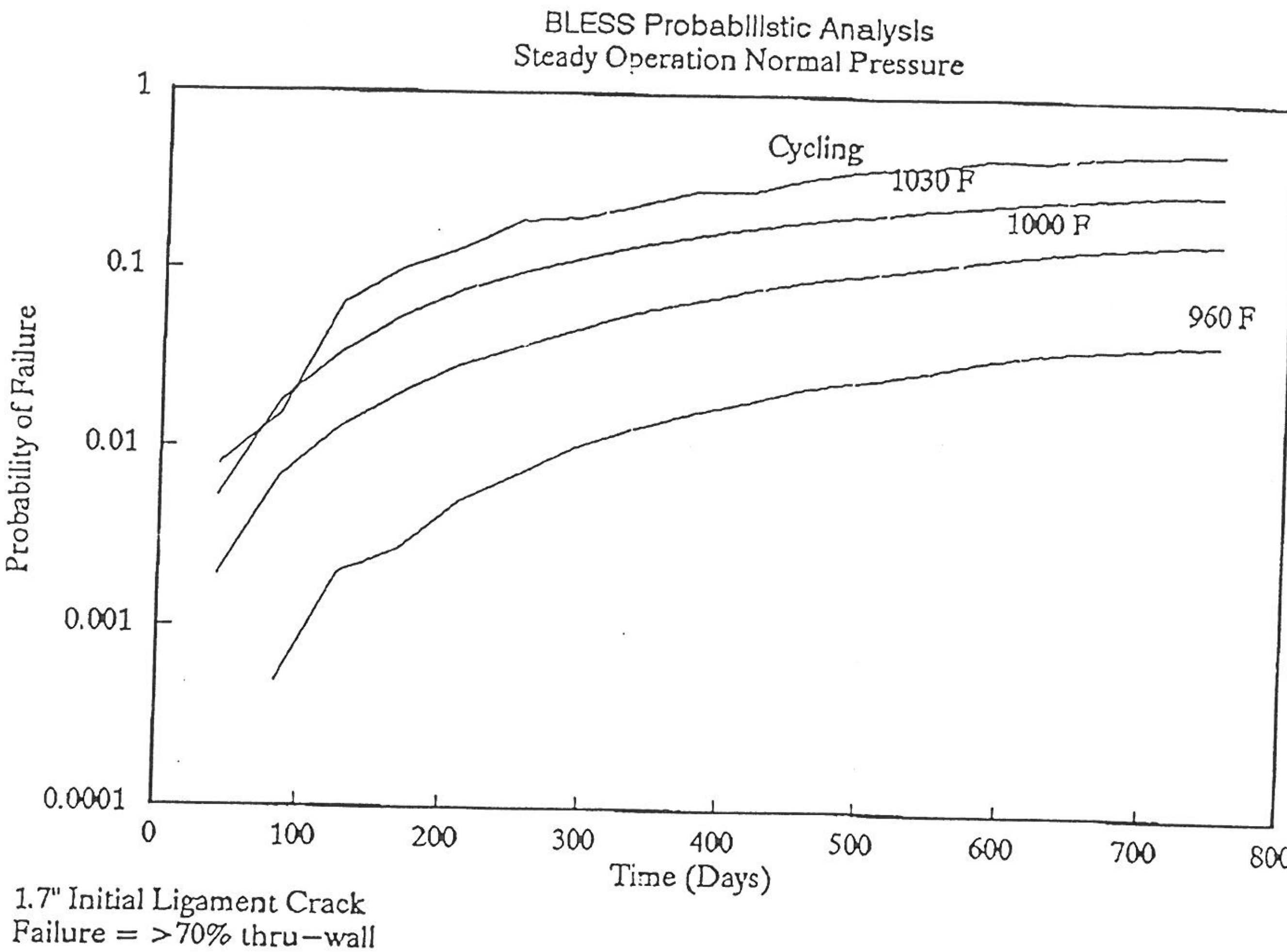


FIGURE 11
Probabilities of failure for additional two years of operation, after crack discovery.