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Analysis and Resolution of Dye-Penetrant Indications in AISI-304 Alloy Cladding of Reactor Coolant System Elbows

Duke Power Company
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BABCOCK & WILCOX
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I. INTRODUCTION

In the course of the piping system modifications incidental to the installation of a replacement coolant pump at Oconee Unit 1, Duke Power, the straight section of the B-67 clad piping assembly was returned to the Mt. Vernon Works of the Babcock & Wilcox Company for rework. In the course of this rework a routine dye penetrant examination revealed some indications in the cladding. The affected cladding was removed by machining and replaced by welding in Mt. Vernon.

In order to assure that the balance of the cladding in the Oconee Unit 1 piping system did not show a similar condition, a complete reinspection of all of the cladding in the Oconee Unit 1 coolant piping system was initiated.

This report is addressed specifically to the work done with relation to the cladding on the twenty-six clad elbows of the coolant piping system; the investigation and findings of the problem with respect to manufacturing and non-destructive testing; and the corrective actions taken with respect to the Oconee Unit 1 coolant system elbows and manufacturing processes. An accompanying report, BAW-1363 addresses the work relating to cladding on the straight sections of the coolant system piping.

II. DESCRIPTION OF ELBOW PROBLEM

As a result of the detection of dye penetrant indications in the straight length of the B-67 coolant piping assembly returned for modification to Mt. Vernon Works from the Duke Power Company Oconee Unit 1, it was decided to conduct a 10% reinspection of the elbow cladding at the job site. This work was started on September 3, 1970, under the direction of Mt. Vernon Quality Control Organization. Since additional indications were noted on the cladding during this examination, a decision was made on September 14, 1970, to conduct a 100% examination of the clad surface of all of the elbows in the coolant piping system.

The clad surface of all of the elbows was reground to a finer finish to permit the detection of very small indications. Results of the penetrant examination are summarized below.

Table 1. Initial 10% Reinspection of Elbow Clad Surface

Loop	Type elbow	Elbow reference number	Results	Date
A-57	45°	8	PT - OK	9/11/70
	90°	7	PT - Reject[(a)]	9/11/70
B-41	45°	5	PT - Reject[(b)]	9/13/70
	90°	6	PT - Reject[(b)]	
B-67	45°	10	PT - Reject[(c)]	9/13/70
	90°	9	PT - Reject[(c)]	

[(a)] Micro-fissures in the 90° elbow; refer to Figure 7 for a more detailed description, refer to paragraph IV. A. 3 for repair procedure.

[(b)] Non-relevant surface indications—cleared OK with minor regrinding and re-examination.

[(c)] Micro-fissuring in the 90° elbow and surface indications in the 45° elbow. The 45° elbow was PT - OK at retest on 9/14/70. On 9/15/70 the 90° elbow was ground to clear the indications in three locations. The depth of grinding required to clear the indications was as follows:

Location 1 — 0.057 in.
Location 2 — 0.080 in.
Location 3 — 0.071 in.

At this point the deepest area was probe ground with a small burr grinder to base metal and measured with a dial depth indicator to determine the thickness of cladding remaining in this area. The thickness of sound cladding left was 0.126 in. thick. It was then decided to remove all of the indications by grinding since required minimum thickness is 0.125 in. The repair work started on September 15, 1970.

Table 2. 100% Reinspection of Elbow Clad Surface

Loop	Type elbow	Elbow reference number	Results	Date
B-45	90°	13	PT - OK	9/15/70
	45°	12	PT - OK	
B-40	45°	17	PT - OK	9/15/70
	45°	18	PT - OK	9/15/70
A-67	90°	23	PT - OK	9/15/70
A-32	90°	16	PT - OK	9/16/70
A-33	90°	3	PT - OK	9/16/70
A-67	45°	24	PT - OK	9/16/70
B-57	90°	25	PT - OK	9/16/70
	45°	26	PT - OK	9/16/70
B-46	45°	21	PT - OK	9/18/70
	90°	22	PT - OK	9/18/70
A-24-1	90°	1	PT - OK	9/18/70
	90°	2	PT - OK	9/18/70
B-40	90°	19	PT - Reject[a]	9/21/70
A-24-2	90°	14	PT - OK	9/22/70
	90°	15	PT - OK	9/22/70
B-45	45°	11	PT - OK	9/22/70
B-41	45°	4	PT - OK	9/23/70
B-46	45°	20	PT - OK	9/[illegible]/70

[a] Rounded indications in a 4" × 9" area which exceeded acceptance standard. The elbow was PT-OK after regrinding and re-examination on 9/21/70.

Summarizing the extent of the problem, the inspection detected several minor surface indications on B-40 90° elbow, B-41 45° and 90° elbows, and B-67 45° elbow, with more extensive indications on the 90° elbows in the B-67 and A-57 assemblies. As shown above, the indications on the B-41 90° and 45° elbows, and the B-67 45° elbow were non-relevant and will not be discussed elsewhere in this report. Relevant indications described above are defined as micro-fissures as discussed in section III of this report. See Figure 6, Reactor Coolant Loop Isometric, for elbow reference numbers and locations.

III. INVESTIGATION AND FINDINGS

A. Investigation of Manufacturing Aspects

Elbow Manufacturing — In order to provide large elbows for coolant piping systems, Babcock & Wilcox developed a manufacturing method many years ago which consists of hot-forming two elbow halves and subsequently welding these half-elbows together. This type of manufacturing is routine and all of the process steps involved here are well known and understood by B&W manufacturing personnel.

The process for manufacturing the clad elbows for the Oconee project varies from the standard manufacturing process for elbows by the introduction of two major process changes:

1. These elbows are manufactured from carbon steel plate which has been explosively clad with AISI 304 plate material.
2. The process includes quenching and tempering steps after forming and before welding the elbow halves together.

To ensure a high quality product, the surface of the cladding is inspected by dye-penetrant examination at duPont prior to shipment to B&W. After quenching the elbow halves, the surface of the cladding is again subjected to a dye-penetrant examination at B&W with records being kept of the inspections. In the course of further fabrication of the elbows, portions of the cladding adjacent to weld seams are again examined by dye-penetrant procedures.

B. Investigation of Oconee Unit 1 Problem and Definition of Problem

The preceding manufacturing outline indicates that the cladding in coolant system elbows has received two complete and several partial dye-penetrant examinations in the course of fabrication. Despite the very careful examination during fabrication, very small indications were found in the elbows during inspection of material that had been shipped to Oconee. In order to quickly define and assess the magnitude of the problem, a 100% re-inspection of the clad elbows at Oconee was carried out. At this time it was recognized that the indications, if present, would likely be very small and difficult to detect. Since normal surface preparation had not proven adequate for the detection of these small indications, the entire surface of all of the elbows at Oconee was carefully ground to provide a more favorable surface for the location of indications by dye-penetrant examination. The work was done under the direction of competent B&W NDT experts. As discussed in section III-E of this report, the indications were defined as micro-fissures, called fissures occasionally throughout this report.

The nominal cladding thickness is specified to be 1/4-in., and in order to ensure that the cladding thickness in the areas that were ground in the course of corrective work would still meet minimum cladding thickness requirements of 1/8-in., the entire clad surface was subjected to an eddy-current testing program. A special instrument had been designed and built by B&W for this type of testing and was utilized for the work.

Only two of the 26 elbows at Oconee showed any micro-fissures in the course of dye-penetrant examination. The other 24 elbows were completely clear and free of dye-penetrant indications except for minor surface indications in the B-40 elbow. These B-40 indications were very shallow and generally round in shape and did not appear like fissures but rather like surface impressions which could have occurred during manufacturing. This observation indicates that a general problem was not evident but rather a problem that was specific to only two of the elbows at Oconee. The other 24 elbows appeared to be completely free of micro-fissures.

C. Investigation of Manufacturing History — Barberton

In order to determine whether the two elbows showing penetrant indications (as discussed in B above) had experienced any different treatment in the course of their manufacture which would account for the different behavior, an additional concentrated search of the process and inspection data at Barberton was initiated. This review indicated that during the fabrication of the first elbows for the Oconee contract, some difficulties were experienced with the accidental impregnation of iron into the stainless cladding surface during the hot pressing operation. Shop practice at that time permitted the use of a dilute copper sulphate etchant (Strauss solution) to identify areas of iron contamination. The records not only indicate that dilute Strauss solution was used to identify iron contamination on the clad surface, but there is evidence that a bottle of full-strength Strauss solution was inadvertently sent to the shop to assist in the detection of the free iron. This strong corrodent was used on the first few elbows and later recalled and replaced by less aggressive material. There is reason to believe that the defective elbows noted at Oconee were treated in this manner. The composition of the copper sulphate etchant used for free iron determination is listed below:

8 g $CuSO_4 \cdot 5H_2O$
500 cc H_2O
2 to 3 cc H_2SO_4 conc.

Conventional Strauss solution has the following composition:

10 g $CuSO_4 \cdot 5H_2O$
100 cc H_2O
10 cc H_2SO_4 conc.

Records also indicate that a 10% nitric acid solution was used in an effort to remove contamination from the A-57 elbow. There is considerably less evidence that nitric acid was also used on the B-67 elbow; however, there is a probability that this was indeed the case, although no specific written reference was noted in the records.

In the proceedings of the Second International Congress on Metallic Corrosion held in New York on March 11-15, 1963, S. P. Rideout of Savannah River reports an incident where sensitized AISI 304 was damaged in the course of efforts to provide an ultra-clean surface. To this end, the surface was treated with a 8-20% nitric acid solution to which a small amount of hydrofluoric acid had been added. It is reported that these components developed intergranular fissuring later, perhaps not dissimilar in kind but more serious in magnitude than what was found in the two elbows at Oconee.

The preceding history provides a plausible rationale which could readily account for the fissuring in the cladding of the isolated two elbow units at Oconee. The fact that the incident involved only two of the 36 elbows at the job site lends support to the supposition that the unauthorized use of harsh chemicals on two of the units eventually resulted in the clad fissuring noted at the job site.

It was fortunate that the problem of iron contamination of the clad surface was solved soon after manufacturing for the Oconee Unit 1 contract began. The solution consisted of replacing carbon steel spacer bars with stainless steel spacer bars during the heating cycle and developing an effective technique to remove the scale with an air blast prior to pressing the half-elbow. The use of etchants to outline iron contamination was no longer necessary, and the use of these reagents was discontinued in Barberton.

D. Investigation of Manufacturing History — Mt. Vernon

At the completion of fabrication of clad elbows for Oconee Unit 1, it was decided to move elbow fabrication to B&W's Mt. Vernon, Indiana, plant. Barberton retained only the shape-cutting of the explosively clad plate and the hot-pressing of the elbow halves. All remaining operations were transferred to Mt. Vernon.

It would be unreasonable to assume that transfer of the work to Mt. Vernon would totally eliminate the problem, particularly since at the time of the transfer, the problem had not been identified and some of the work saw partial fabrication in Barberton and was completed in Mt. Vernon.

A review of the fabrication history of the remaining elbows now in production in Mt. Vernon indicates that over 100 of these units have been fabricated. Only three complete elbows and one half elbow showed any indication of this type of clad fissuring, and in each case the extent of the affected area was considerably less than 1% of the elbow surface. The indications discovered in Mt. Vernon are considered similar in kind to the elbow indications at Oconee, but several orders of magnitude less in degree. The indications in each case were ground out with the exception of a few metallographic samples that were removed from the affected area for laboratory examination.

Mt. Vernon had also used a dilute Strauss solution to identify iron contamination; however, this practice had been discontinued. In the course of removing the cladding adjacent to the weld seams, removal of clad residue from air arc cutting, back gouging, etc., 5% HNO_3 is reported to have been used to identify residual stainless cladding, to permit its removal by grinding.

These data, then, suggest the probability that the isolated fissuring of the Mt. Vernon-fabricated elbow sections could have resulted from the inadvertent exposure of the clad surface to harsh corrodents in a manner similar to the Barberton experience. Only two of the 3-1/2 elbows that showed fissuring were quenched and tempered in Mt. Vernon. The other 1-1/2 units had been processed in Barberton.

E. Laboratory Examination

Concurrent with the corrective work at the site, B&W's Alliance Research Laboratory conducted a metallographic investigation of the samples received from affected areas in elbows found in Mt. Vernon as well as some of the cladding material provided by Barberton. Metallographic examination of the surface of the cladding material in the as-received condition indicates this material to be annealed AISI 304 with a perfectly normal microstructure, as shown in Figure 1. Typical chemical analyses of the AISI 304 cladding used for the Oconee Unit 1 elbow cladding are shown in Table 3. In the course of processing the plate into an elbow in the B&W shops, the cladding material is heated to about 2000F. This is followed by slow cooling. The slow cooling from elevated temperature results in almost complete precipitation of the carbides in an intergranular manner. Figure 2 shows the structure of the explosive cladding at 90X under polarized light. Figure 2A illustrates the structure under normal illumination. In order to illustrate that the carbide precipitation does not adversely affect the mechanical properties of the cladding, bend specimens were prepared from the excess material of one of the elbows after complete processing. The bend specimen indicates the material to be sound and ductile, as would be expected from this material. A typical bend specimen is shown in Figure 2B. Figure 3 depicts the microstructure from the bent portion of the bend specimen. The cold work produced by the small amount of elongation involved in bending is reflected in this photomicrograph. Figure 3A illustrates the same structure under polarized light. Typical fissures found in specimens removed from areas that showed dye-penetrant indications are shown in Figures 4 and 5. Figure 4 is a view of a fissure in the unetched condition at 100X, and Figure 4A shows an etched view of the same fissure. Figure 5 shows another fissure in the unetched condition, and Figure 5A shows the same view after etching. It is by these findings that the indications are defined as micro-fissures.

It is interesting to note that the isolated fissures that were found in Mt. Vernon as well as the fissures ground out of the B-67 elbow at the Oconee site were all found to lie in a band formed between the cladding surface and a parallel plane 1/8-in. below the surface. Thus, removal of the fissures by grinding the B-67 elbow leaves an adequate thickness of cladding that was completely unaffected by the fissuring; this fact is important only in that shop and field rework is minimized.

Records of the field repair of the A-57 elbow indicate that some of the fissuring extended beyond the 1/8-in. laminar band down to the carbon steel base metal, requiring additional clad overlay and heat treatment. Figure 7 shows a map of the dye-penetrant indications and their extent.

IV. CONCLUSIONS OF INVESTIGATIONS

A. Corrective Action to Oconee I Coolant System

As pointed out in section II, there were actually three elbows that were not PT acceptable after the initial examination and 100% re-examination. They were as follows:

1 — 90° elbow in B-40 assembly.
1 — 90° elbow in B-67 assembly.
1 — 90° elbow in A-57 assembly.

Repairs to each of the above listed elbows were made in the field at the Oconee Nuclear Station, as follows:

1. B-40 Elbow — This elbow contained only one small area approximately 4 by 9 in. The indications were probed until PT cleared and depth reading revealed the deepest indication was 0.075 in. The area was blend-ground to a 3 to 1 taper, and re-PT cleared. No further action was required on B-40 elbow.

2. B-67 Elbow — This elbow required grinding of 100% of the surface to be cleared. The grinding has been completed, and the entire surface checked for cladding thickness with the eddy-current instrument. All areas were at least 1/8-in. thick except two small areas. One area was a small depth probe area, and the other was a spot 1/4 by 1/2 in. with 1/16-in. clad thickness remaining. These two areas were within 2 in. of a field weld, and were repaired as part of the back-cladding process, and stress-relieved with the field weld. All heat-affected areas were PT clear after stress relief.

3. A-57 Elbow — This elbow also required repair on 100% of the surface. The indications were deeper in this elbow than in the others. There were a number of scattered areas in which grinding to base metal was required in order to clear the PT. Much larger areas had remaining thickness of less than 1/8-in., as indicated by the eddy-current instrument. The total surface of A-57 elbow is presently having a layer of clad weld overlay applied to ensure cladding greater than 1/8-in. thick. The welding is being done in accordance with standard B&W procedures. After welding, the surface will be ground smooth; the entire elbow will be stress-relieved, followed by UT for bond and a 100% PT.

The information given with regard to the A-57 elbow is not consistert with that given to AEC Compliance during earlier discussions, in that AEC was advised that none of the PT indications that had been found were deeper than 1/8 in. The deeper indications were determined following the discussions with AEC Compliance.

B. Corrective Action to Manufacturing Processes and Quality Control Improvements

The occurrence of a manufacturing problem such as the one described here usually represents financial as well as schedule losses to the manufacturer and the customer, but it also provides a lesson that can prevent similar occurrences in the future if properly heeded. The effectiveness of the lesson is best evaluated by the quality and extent of the corrective action instituted to avoid repetition of the problem. The following corrective action has been taken by Babcock & Wilcox:

1. The use of harsh etchants to evaluate the presence of free iron or stainless steel residuals has been discontinued.

2. B&W has instituted a program where the clad surface of the elbow will be dye penetrant inspected after every major operation to assure freedom from this type of indication in the end product and assure detection and correction of the problem at the earliest possible time in the manufacturing process.

3. Mt. Vernon has effected an intensive operator training program using the dye penetrant technique. The men see about 80 hours of classroom and practical demonstration work as part of the B&W training program, and in addition are qualified dye penetrant inspectors in strict accordance with the provisions of Section III Appendix IX of the ASME Code. Qualification is in accordance with the provisions of SNT-TC 1A which is the standard upon which the ASME Code relies. This involves another 10 - 30 hours of intensive training. Actual samples of unacceptable production work such as those discussed herein are used as visual aids.

4. B&W initially attempted to have DuPont supply the clad plate as ELC material; however, until recently, DuPont was not in a position to supply the ELC cladding. They have now agreed to supply

future plate with AISI 304 ELC cladding. The use of the ELC cladding provides greater resistance to this particular type of fissuring.

V. SUMMARY

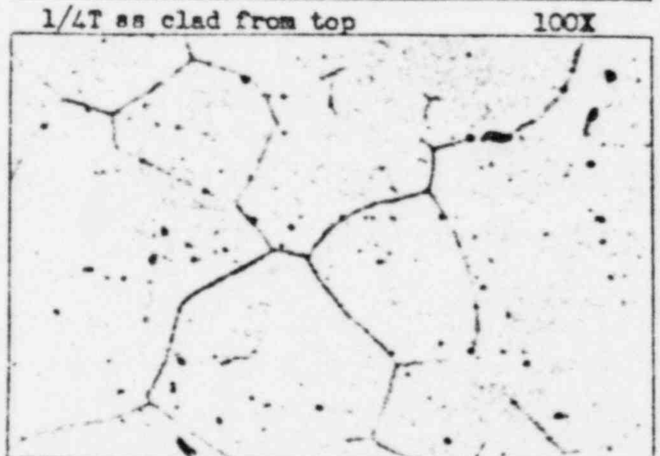
B&W's actions towards the solution of this problem will succeed in completely eliminating the micro-fissures in cladding from the current Oconee Unit 1 pipe elbows, as well as from those for all future jobs. The very careful training of B&W operators, together with better control of the manufacturing processes, should guarantee sound cladding in future components, and certainly the thorough examination and corrective work conducted at the Oconee job site provides adequate assurance that the problem there has been solved. In this connection, it is important to recognize that the cladding of these elbows is not considered part of the structure in terms of the elbow's ability to withstand operating stresses. From a design point of view, the carbon steel carries the entire load. Thus the cladding does not contribute to the integrity of the pressure boundary but rather provides a surface protection for the carbon steel.

The extensive investigations, surface examinations, and field rework as discussed throughout this report makes possible the final conclusion that the reactor coolant system integrity has not been jeopardized in any way and that the reactor coolant system is 100% sound for operation with respect to the investigations and repairs reported here.

Table 3. Chemical Composition of AISI-304 Cladding for Oconee Unit 1 Elbows Typical Analyses (by weight)

Clad heat No.	C	Mn	P	S	Si	Cr	Ni	Co
67768	0.048	1.17	0.030	0.027	0.57	18.38	9.12	0.10
67673	0.057	1.04	0.016	0.021	0.62	18.80	9.20	0.09
67758	0.057	1.10	0.028	0.021	0.64	18.27	9.09	0.10
47667	0.062	1.12	0.018	0.027	0.59	18.52	9.18	0.09
57736	0.033	1.08	0.015	0.017	0.59	18.23	9.48	0.09
37810	0.031	1.26	0.013	0.022	0.38	18.32	9.37	0.10
37783	0.058	1.10	0.021	0.029	0.49	18.61	9.05	0.09
43435	0.052	1.48	0.024	0.029	0.46	18.80	9.31	0.10
67735	0.053	1.12	0.017	0.011	0.52	18.02	9.17	0.10

1/4T as clad from top 100X



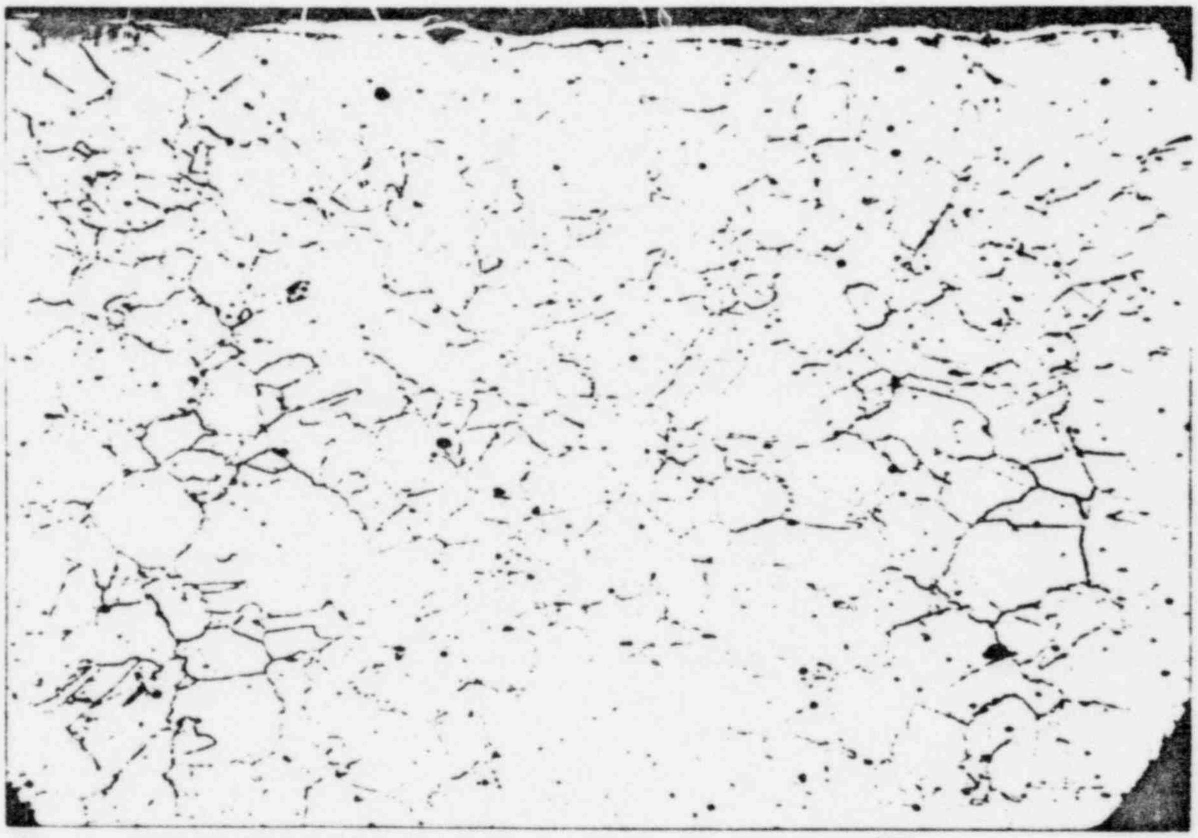
1/4T as clad from top 500X

Figure 1 Structure of Explosive Cladding as Received

Oxalic Acid

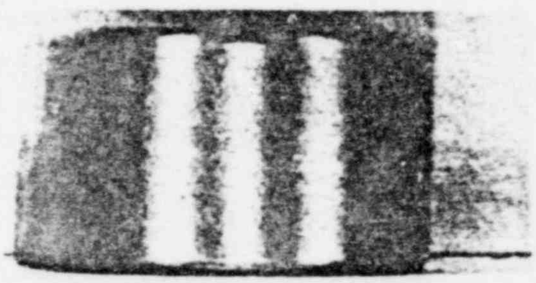
90X

Figure 2 Structure of Explosive Cladding after Thermal Treatments During Elbow Fabrication Before Bend



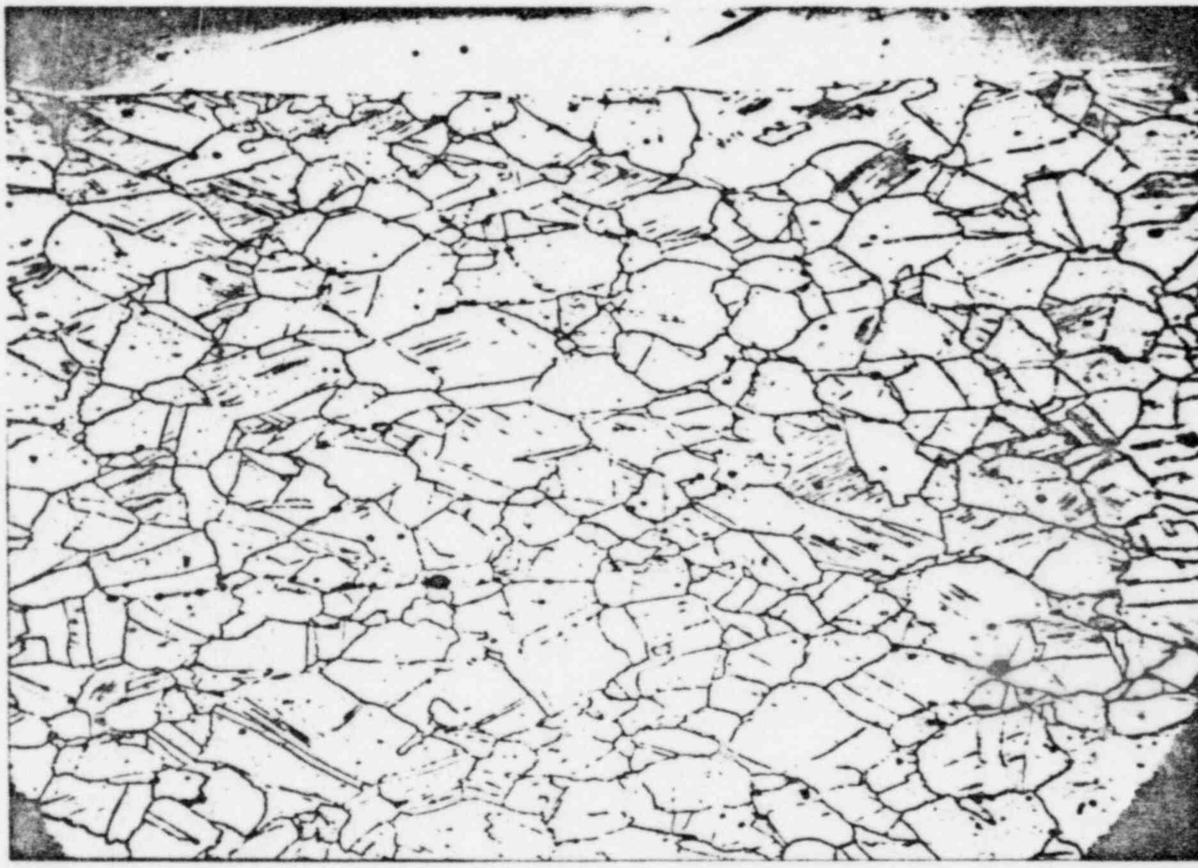
Oxalic Acid 90X

Figure 2A Structure of Explosive Cladding after Thermal Treatments During Elbow Fabrication Before Bend



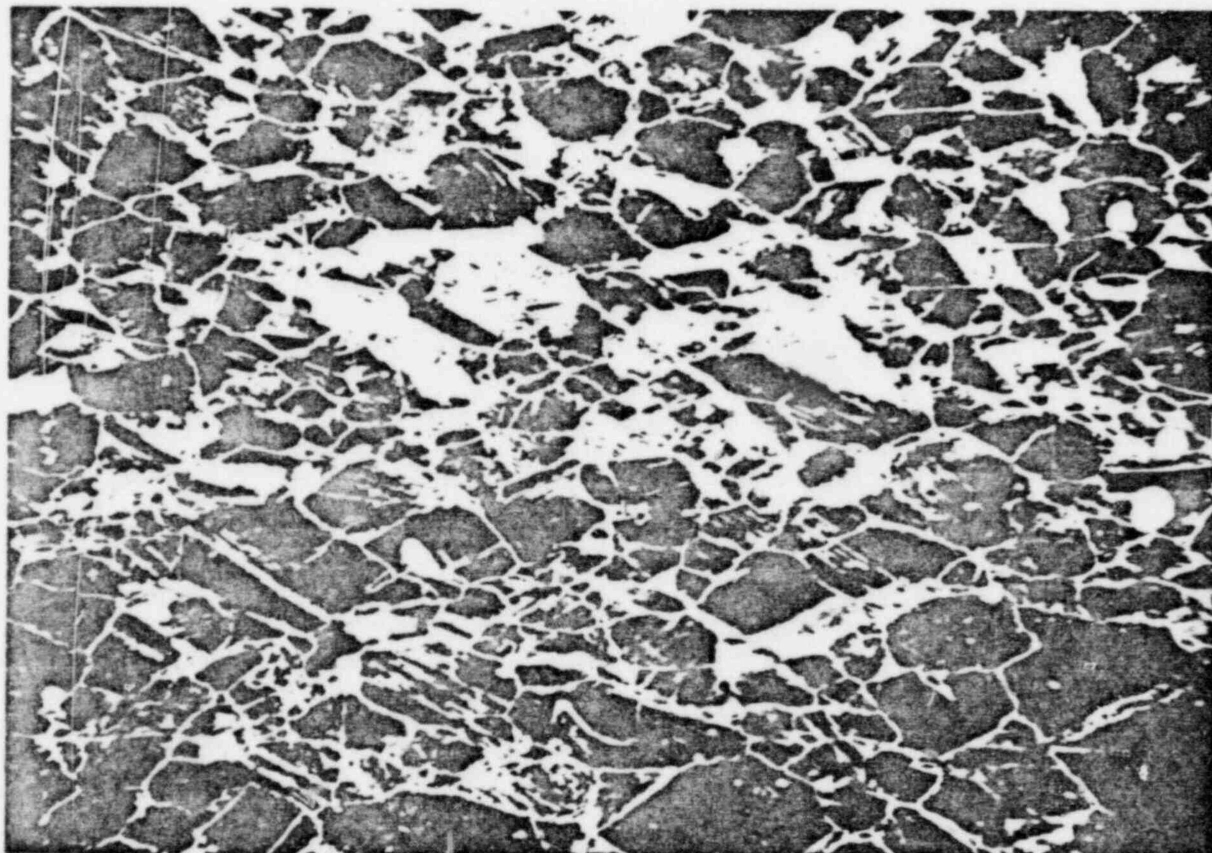
1X

Figure 2B - Bend Specimen of Explosive Cladding After Thermal Treatments During Elbow F-brication.



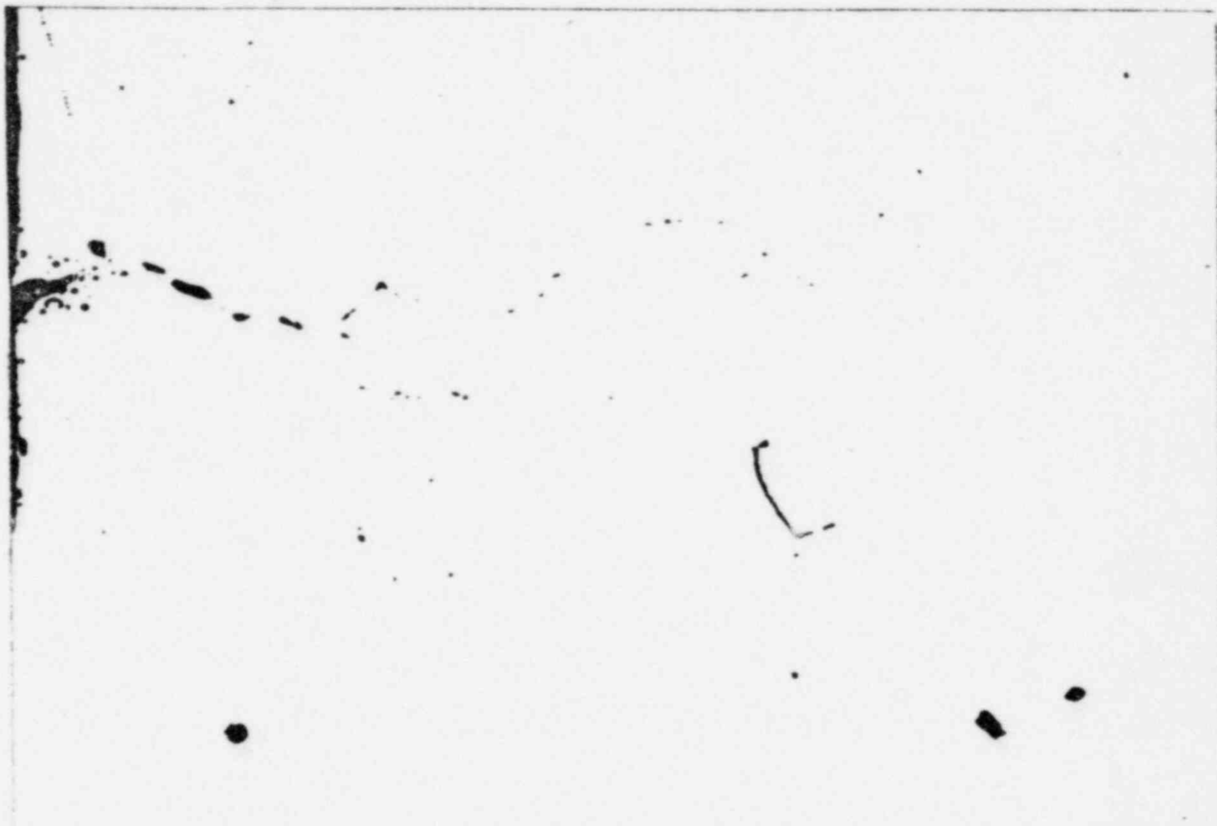
Oxalic Acid 90X

Figure 3 Structure of Explosive Cladding After Bend Test to Evaluate Room Temperature Ductility



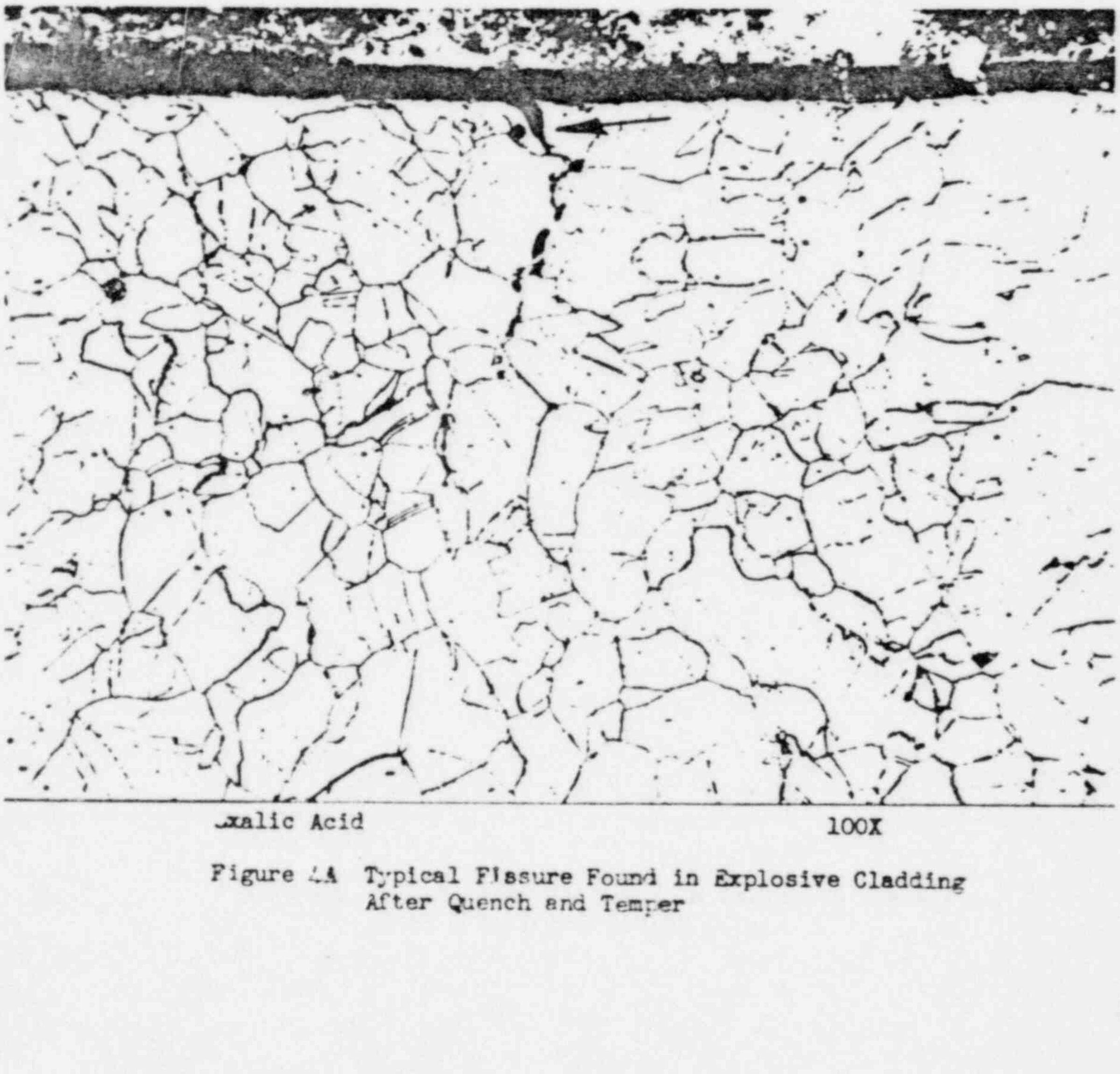
Oxalic Acid 90X

Figure 3A Structure of Explosive Cladding After Bend Test to Evaluate Room Temperature Ductility



Unetched 100X

Figure 4 Typical Fissure Found in Explosive Cladding After Quench and Temper



.xalic Acid 100X

Figure 4A Typical Fissure Found in Explosive Cladding After Quench and Temper

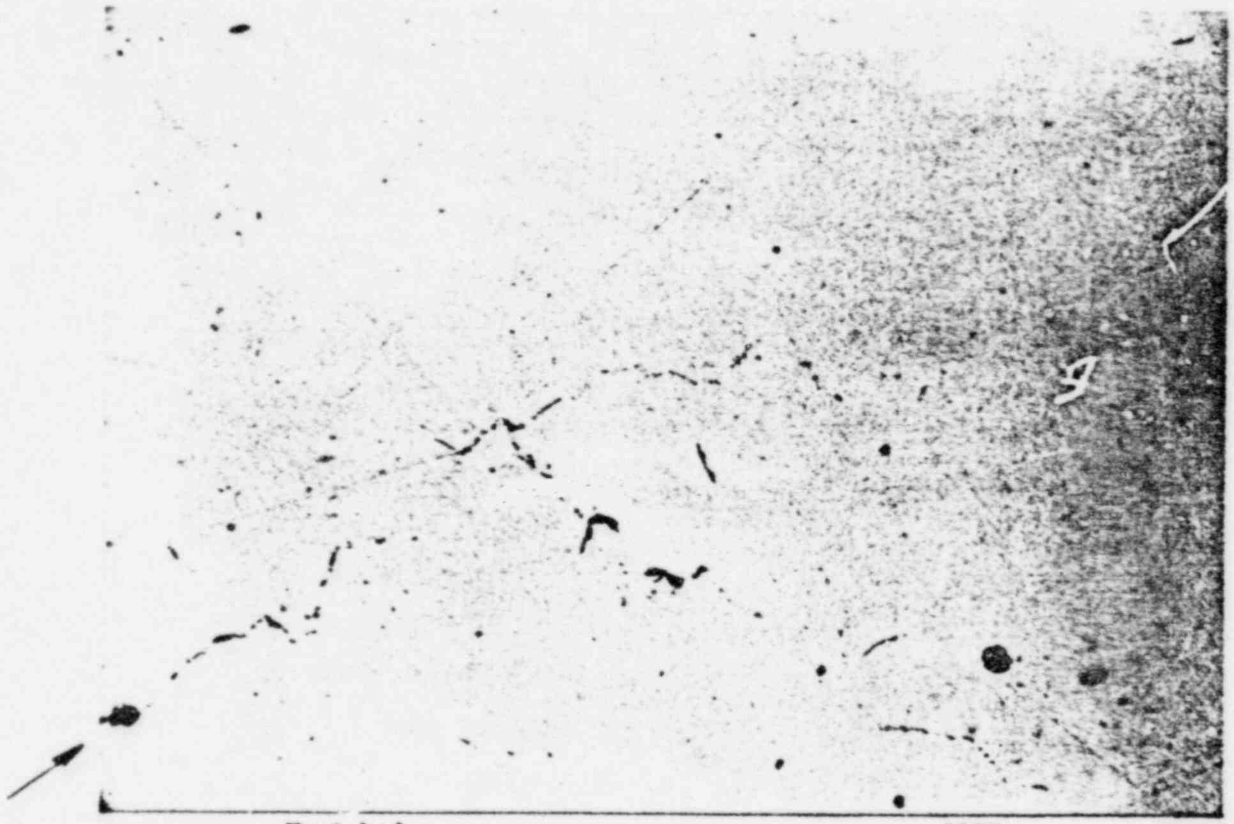
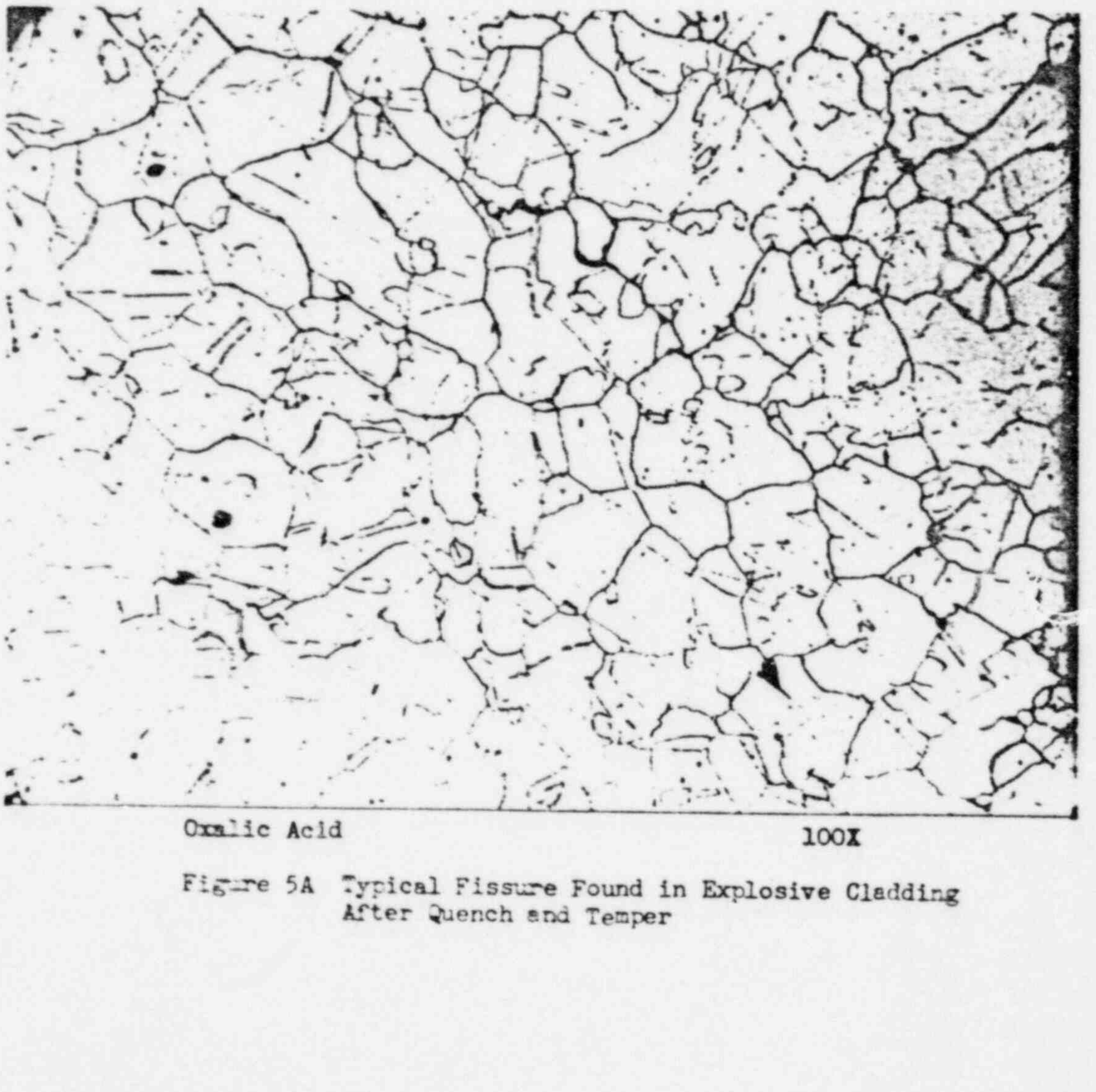
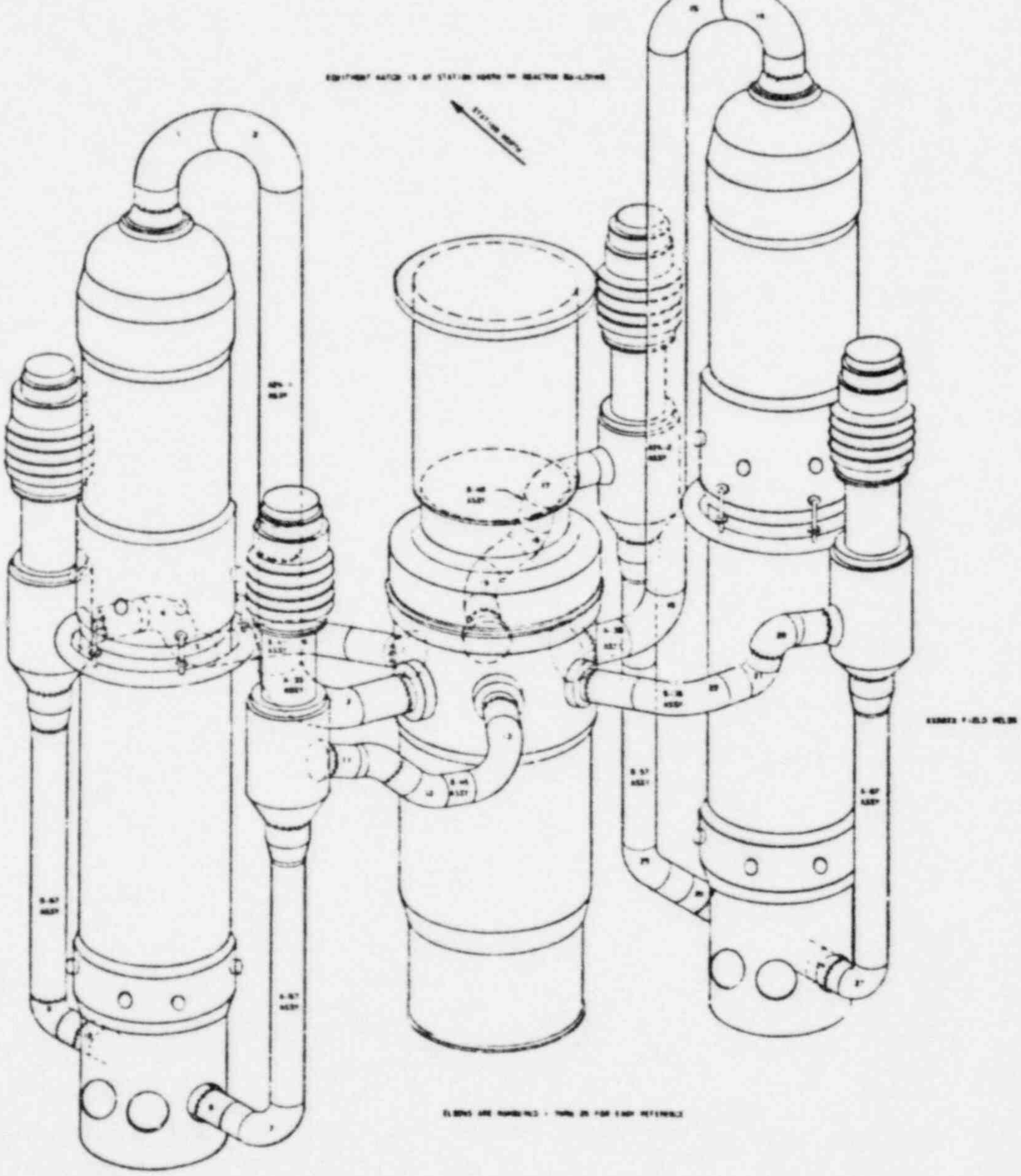


Figure 5 Typical Fissure Found in Explosive Cladding After Quench and Temper



Oxalic Acid 100X

Figure 5A Typical Fissure Found in Explosive Cladding After Quench and Temper



REACTOR COOLANT LOOP ISOMETRIC

Figure 6