June 28, 1988

Docket Nos.: 50-369
and 50-370

Mr. H. B. Tucker, Vice President
Nuclear Production Department
Duke Power Company
422 South Church Street
Charlotte, North Carolina 28242

Dear Mr. Tucker:

SUBJECT: TECHNICAL REPORT REGARDING MCGUIRE 2 REACTOR TRIP BREAKER FAILURE AND METALLOGRAPHIC ANALYSES OF WELDS ON THE CATAWBA REACTOR TRIP BREAKER POLE SHAFT (TACS 65955/65956)

Enclosed for your information is a final technical report by our contractor, Franklin Research Center (FRC), entitled "Investigation of Trip Breaker Failure at McGuire Unit 2." The report explains the mechanical binding which kept the McGuire 2B reactor trip breaker (RTB) from opening July 2, 1987, discusses Westinghouse's inspection recommendations of September 11, 1987 for Westinghouse Owners Group members, and identifies issues and concerns other than those associated with pole shaft welds. It also includes certain recommendations made prior to the December 1, 1987 revision to the Westinghouse technical bulletin and considered by the NRC prior to issuance of NRC Bulletin 88-01.

Appendix A of the enclosure presents the results of the metallurgical investigation of the Catawba RTB pole shaft that you provided the NRC. Results of this investigation aided in our understanding of the limitations of in-situ, visual inspections of pole shaft welds to detect cracks and was instrumental in the decision reflected in the revised Westinghouse technical bulletin and NRC Bulletin 88-01 that welds not possessing the intended length and leg dimensions should receive continuing periodic inspections.

If you have questions, contact me at (301) 492-1442. Your cooperation in this matter is appreciated.

Sincerely,

Original signed by:

Darl Hood, Project Manager
Project Directorate II-3
Division of Reactor Projects I/II

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

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F-6177-5

Investigation of Trip Breaker Failure at McGuire Unit 2

NRC Docket No. 50-370	FRC Project No. 6177-005
NRC Contract NRC-05-86-168, Task EL-305	FRC Report F-6177-5
FRC Group Leader: H. M. Fishman	NRC Group Leader: D. S. Hood

Submitted to

U.S. Nuclear Regulatory Commission
Division of Reactor Projects
Project Directorate II-3
Washington, DC 20555

June 15, 1988

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FOREWARD

This report was prepared by Franklin Research Center (FRC), division of Arvin/Calspan, under a contract (NRC-05-86-168, Task Order EL-305), with the U.S. Nuclear Regulatory Commission (Office of Nuclear Reactor Regulation) for independent assessment and analysis.

The principal author of this report is the former Task Leader, Mr. Gary J. Toman. Dr. Laurence Leonard contributed the metallurgical analysis reported in Appendix A. The report was reviewed and revised by Mr. Howard M. Fishman, the current Task Leader.

During the performance of the technical assistance task concerning the failure of a Westinghouse reactor trip breaker at the McGuire Unit 2 Plant [1], FRC provided the NRC with data and recommendations that were incorporated in an NRC Information Notice No. 87-35, Supplement 1 [2] and an NRC Bulletin No. 88-01 [3].

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1. INTRODUCTION

On July 2, 1987, the 2B reactor trip breaker (RTB) of the McGuire Unit 2 plant failed to open on electrical command. It had jammed mechanically. On July 3, 1987, Duke Power Company personnel observed a second jamming of the RTB during investigation of the problem; however, the jamming of the RTB was overcome before the cause of the jamming was determined. On July 7 through 9, 1987, further attempts were made to have the jammed condition recur in the presence of the NRC Augmented Inspection Team. However, the circuit breaker did not jam during multiple operations even with purposeful attempts to put the RTB mechanism in an unfavorable position with regard to tripping. NRC Information Notice No. 87-35 [1] reported this potentially significant safety problem. Thereupon, it was determined that the RTB should be shipped to the Nuclear Services Integration Division (NSID) of Westinghouse for further evaluation. During the evaluation at the McGuire plant, it was determined that the weld between the center-pole lever and the pole shaft of the RTB had completely separated. It was believed that this weld failure was related to the jamming of the RTB, but the exact relationship was not known.

This report describes the failure evaluation at NSID; discusses the recommendations [4] made by Westinghouse on September 11, 1987 to Westinghouse Owners' Group members with DS-type circuit breakers; critiques Westinghouse's presentation to the NRC on September 23, 1987; and provides recommendations for further actions regarding DS-type circuit breakers. In addition, an independent analysis by FRC of the weld joints is presented.

2. SUMMARY OF FAILURE EVALUATION AT NSID

On August 24 through September 1, 1987, an evaluation of the failure of the McGuire 2B RTB (No. 24Y98508, #4) took place at Westinghouse's NSID facility in Monroeville, PA. The RTB was tested in the as-received condition, starting with basic measurements of key components, which were compared to those of an operable circuit breaker. After initial evaluation, the RTB was cycled 42 times with various means employed for tripping the RTB (undervoltage trip, shunt trip, and manual operation); no failure to trip occurred. Then, the RTB was partially disassembled, and the roller on the main drive link was found to have been striking the right-hand (viewed from rear of RTB) side frame plate. The weld between the pole shaft and center-pole lever was observed to be completely broken, which allowed the roller end of the main drive link to be skewed to the right (viewed from rear) and the roller axis to be canted counterclockwise approximately 3 to 5 degrees.

To allow further evaluation of the operation of the RTB, the racking (levering) mechanism, charging motor, and the undervoltage trip attachment were removed from the RTB and the remaining portions of the mechanism were returned to operating condition. Then, the RTB was operated approximately 15 more times. Some operations were performed with shims between the roller and side of the drive link in an attempt to cancel the effects of wear. No failure to trip occurred. Spring tension was applied to the side of the main drive link to force it harder against the side frame plate. The circuit breaker still tripped. An attempt to force the roller higher onto the cam (above top dead center) also failed to prevent tripping.

The right side plate and the roller were then replaced to put the RTB in a less worn condition. The RTB was operated, and the new roller was observed to strike the side plate upon closing. At the 22nd cycle, the RTB failed to open. The closing cam was observed to have not completely rotated by 18 degrees (The closing springs were not completely discharged.). The trip shaft was completely free of the trip latch. The edge of the trip latch had moved approximately 1/16 inch above the lower edge of the trip shaft, indicating that the trip latch had operated. The roller of the main drive link was found to be wedged between the right side frame plate and the left-hand cam segment of the closing cam. The roller was not canted about its axis as far as it had been in past closings (it was now riding 1 to 2 degrees counterclockwise). The condition of the roller with respect to the cam edge was photographed via fiber optics to record the jammed condition.

After deliberation by the evaluation team, a lever was used to relieve the pinching of the roller by the cam and side plate and thus free the roller. The failure was replicated twice more by manipulation of the closing cam and the roller on the main drive link. During the first replication, the constraining link was removed to verify that the failure was not partially or fully related to binding in the trip latch bearing (evaluation of the bearing in the original side plate had revealed damage to the trip latch bearing). During the second replication of the failure, the roller was released from the bound condition by operating the manual charging lever. This verified that further rotation of the closing cam caused the roller to be pushed out of the jammed condition as had occurred during the failure to open in service at the McGuire plant.

In an attempt to determine if the failure of the pole shaft weld was necessary to allow jamming to occur, two additional pole shafts were installed in the circuit breaker. Both had center-pole levers that were out of alignment in a condition similar to the failed pole shaft lever. The two were selected from a batch of 18 pole shafts that were available at NSID where the failure evaluation was being performed. Multiple attempts were made to cause the RTB to fail to open; none were successful. Although the roller could be forced to rest between the cam edge and the frame, the roller would not bind.

3. DISCUSSION OF FAILURE MODE

Figure 1 provides a labeled view of the RTB mechanism. Item 2 is the close cam, item 15 is the main roller, item 3 is the roller constraining link, and item 19 is the side frame plate (only partially shown). Figure 2 shows the position of the RTB mechanism with the RTB closed. The rear of the RTB is at the right in both figures. Figure 3 conceptually shows the roller pinched between the side frame plate and the left cam segment as viewed from the rear of the RTB. To actually observe the area where the pinching occurs, the arc chutes must be removed and inspection mirrors or fiber optics must be used.

The roller becomes pinched during the closing action. As the closing cam rotates, the edge of the roller is caught between the outer laminate of the cam segment and a spacer (see Figure 4). Continued rotation of the cam causes the roller to straighten in a clockwise rotation about its axis. This action causes the edge of the roller (marked "W" in Figure 4A) to attempt to separate the cam and the side plate. However, the cam and side plate are not free to move and therefore pinch and bind the roller. When the trip latch is released, allowing the constraining link (item 3, Figure 1) to be free, the binding or jamming of the roller prevents the roller from rolling down the cam face to allow the circuit breaker to open. The jamming of the roller also prevents full discharge of the closing springs, leaving the closing cam 18 degrees from the fully rotated position.

Upon removal of the original right side frame plate, the trip latch bearing was found to have a broken edge. The concern that binding of the trip latch was partially causing the jamming was alleviated during the second jamming of the RTB when the constraining link was removed and the RTB remained jammed. Binding of the crank shaft on which the close cam is mounted could also have partially caused the binding. However, the crank shaft was found to be free and turning properly when the RTB mechanism was disassembled. Elimination of trip latch and crank shaft binding confirmed that the sole cause of the failure was pinching of the roller between the edge of the close cam and the right side frame plate.

The failed attempts to jam the circuit breaker with pole shafts having unbroken center-pole-lever welds showed that both the lateral displacement of the roller end of the main drive link and a 3- to 5-degree canting (cocking) of the axis of the roller were necessary for jamming to occur. The pole shafts with unbroken welds did permit the lateral displacement, even allowing the roller to strike the side frame; but they did not permit sufficient axial rotation (uncocking) of the roller for it to become jammed between the cam and side plate. However, the pole shafts selected in this attempt to jam the circuit breaker were new and, as such, had not experienced the wear that could allow the necessary 3- to 5-degree canting of the roller axis.

4. DISCUSSION OF WESTINGHOUSE RECOMMENDATIONS FOR EVALUATION OF WELD DEFICIENCIES

In addition to the failure of the center pole lever-to-pole shaft weld on the McGuire 2B RTB, three similar weld failures are known to have occurred on DS-type circuit breakers. One occurred at a Duke hydroelectric power plant approximately 14 years ago and the two others occurred at nuclear plants within the last year. In one case, the circuit breaker failed to close when both the center-pole lever and anti-bounce lever to pole-shaft welds failed.

In response to an NRC request, Westinghouse developed inspection recommendations [4] for Westinghouse Owners Group members to use on DS-type breaker pole-shaft welds. The basic recommendation is to perform a weld inspection with the pole shaft in place in the circuit breaker and the top bracket removed from the RTB. Although removal of the top bracket improves the visibility of the weld on the center-pole lever, the weld is still located between the two side frame plates that are 1 inch apart and the weld is approximately 3 inches below the top of the plates. Thus, assessment of the weld is difficult, especially because a closed crack may be difficult to observe visually under the best of conditions.

Westinghouse recommended short-term evaluations at the next surveillance. The criteria for short-term acceptance of the three pole-lever welds are as follows:

1. Completely separated welds: remove the circuit breaker from service.
2. Cracked weld: remove the circuit breaker from main RTB service and use it only as a reactor trip bypass breaker until the weld condition is corrected.
3. Excluding the ends of the weld, which may show evidence of a cold start, the weld should have at least 3/16-in fillet for 90° continuously around the pole shaft. If the fillet is less than 3/16 in, then the weld must have at least a 1/8-in fillet for 120° continuously around the pole shaft. If these dimensions are not met, then the RTB should only be used as bypass RTB until the weld condition is corrected.

The long-term actions, to be performed at the next refueling outage according to the Westinghouse letter, are to inspect the remainder of the welds on the pole shaft excluding the stop lever welds, to replace the pole shaft if necessary, and to check the alignment of the breaker mechanism. In the alignment check, it must be verified that the roller on the main-drive link is riding on the two outside cam segments and, while the breaker is in the closed position, not in contact with either side-frame plate.

The Westinghouse letter further states that the short- and long-term inspection criteria for the DS-416 apply to the DSL-416 and DS-420. The timing of the inspections of the DS-206 and DSL-206 circuit breakers, which Westinghouse claims are less stressed, is left to the utilities, but must be performed on or prior to the next refueling outage.

5. FRC COMMENTS ON WESTINGHOUSE RECOMMENDATIONS

The recommendations contained in the Westinghouse letter of September 11, 1987 [4] have many shortcomings. It is clear from the letter that a circuit breaker with a completely severed weld should be removed from service. However, according to Westinghouse, welds with cracks that are not completely broken or are shorter than 90° (3/16-in fillet) or 120° (1/8-in fillet) may be used as a bypass RTB. No criteria are given for just how degraded these welds must be to be considered inadequate for bypass service, and no reasoning is provided for stating that an RTB with a degraded weld is acceptable for bypass service. Is 10° of weld acceptable? Is 90° of cracking acceptable? At present, the criteria merely state that if the weld is not completely severed, the circuit breaker is acceptable for a bypass RTB. This is not a logical assumption. In addition, Westinghouse claimed that the 180° weld originally specified had a conservatively calculated safety factor of 3.5. This value was never substantiated either in the letter or in the subsequent presentation on September 23, 1987.

Complete inspection criteria for the weld are not provided in the letter. Neither enough information nor a specific standard required for use in the inspection are given. During a meeting between Westinghouse and the NRC, held on September 23, 1987 in NRC offices in Bethesda, MD, Westinghouse personnel stated that a lack of fusion would be grounds for rejection of a weld and would require corrective action. However, the Westinghouse letter does not have any such requirement. During the meeting, the selection of 90° of continuous weld was described by Westinghouse as being acceptable for permanent use. The original design required at least 180° of weld with a 3/16-in fillet. The 180° weld design had been proven to be adequate by a 4000-cycle qualification test. The new 90°/120° weld acceptance criteria are based on static analyses and derating factors that do not take dynamic loads and fatigue fully into account and do not account for stress concentrations at the edges of cold starts in the welds. The visual inspection criteria given in the Westinghouse letter allow cold starts even though there is no way of telling if good fusion has occurred after the cold start. No qualification testing has been performed with welds that are 90°/120° long that have cold starts (i.e., no breaker is known to have been cycled 4000 or more times with such a weld).

The calculations of working and failure torque presented at the September 23, 1987 meeting indicated that the working torque for the 180° 3/16-in weld is 1230 in-lb. The formulae used are valid for a total of 180° arc length of symmetrically placed welds, not for the one-sided weld configuration specified by Westinghouse. No explicit formulae are presented in the AISC handbook [6] for partial arc fillets, but the calculation methodology that should be used is similar to that described in the section for Eccentric Loads on Weld Groups. The load capacity of partial arc fillets is significantly less than the arc length ratio times the capacity for an all-around circular weld. Other loading effects, such as bending in the weld due to misalignment of the roller, were neglected in the Westinghouse analysis.

Experimental validation data were presented by Westinghouse to indicate that, under dynamic conditions and without electrical load, the torque on the weld is less than the allowable. The experiment involved putting strain gauge rosettes, wired to measure shear, on the shaft on each side of the lever and closing and opening the RTB. The calibration and the data reduction techniques described were incorrect and the torque data for the weld were meaningless, but not necessarily unconservative. This was pointed out to Westinghouse at the meeting. It may be possible for Westinghouse to reinterpret the data and derive meaningful dynamic weld torque information.

To demonstrate that a 1/8-in fillet could be used for 120°, Westinghouse performed a static load test. The weld configuration was a ground-down 3/16-in weld. Such a modified weld may have fewer surface irregularities than a fillet with an 1/8-in bead, and may be significantly stronger than the weld it is intended to simulate.

In addition to problems with weld acceptance criteria, the 4000-cycle qualification limit is being approached by some RTBs. The estimated number of cycles on the McGuire 2B RTB that failed is between 2500 and 3500 cycles. Westinghouse states that some test circuit breakers have been cycled to at least 10,000 cycles; however, it must be assumed that these circuit breakers had 180° welds unless the pole shafts are available and can be inspected to determine weld condition and length.

6. OTHER ISSUES AND CONCERNS

The observed damage to the latch bearing is the result of the torsional forces on the constraining link and trip latch caused by the unwanted lateral displacement of the roller end of the main drive link. The lateral displacement could be caused by the breaking of the center-pole-lever weld or by the center-pole lever not being fully perpendicular to the pole shaft. It is possible that another type of failure could occur due to the misalignment of main drive link and roller if the damage to the trip latch bearing progresses and binds the trip latch pivot pin.

During inspection of the RTB components, damage was noted on the surfaces of the closing cam. The cam in the McGuire RTB is composed of four steel segments that are sandwiched together and held by three rivets. The two outer segments are heat-treated steel; the two inner segments are non-hardened steel. The surface of the segments is supposed to be of uniform shape except in the area of the stop roller that is fixed in a hollow in the two center segments. However, on the McGuire RTB, the two outer segments are slightly larger than the inner segments, providing the edge for the roller to catch upon.

The cam had also been mushroomed by the drive link roller in a number of areas. Of key concern was mushrooming in the area of the stop roller (item 1 in Figure 1). The stop roller holds the mechanism in readiness for release of the closing latch. The extreme mushrooming impeded rotation of the stop roller. It is possible that continued mushrooming could totally prevent stop-roller operation, which could prevent closure of the circuit breaker upon demand. While not of concern for an RTB, a failure-to-close condition would be of concern for DS-type circuit breakers used in safety applications requiring energization of the connected loads.

Eighteen new pole shafts were evaluated by Westinghouse for use in the RTB to determine the importance of a broken weld to a jamming condition. The welds on the center-pole lever are supposed to extend a minimum of 180° around the surface of the shaft. Because of the geometry of the adjacent anti-bounce lever, the center-pole-lever weld must be made in two segments: one approximately 120° and the other approximately 60°. It was noted that approximately half of the pole shafts had only the 120° segment of the weld and that some of these welds appeared to lack fusion to the base metal of the lever and/or shaft. It should also be noted that the weld that failed on the McGuire RTB also was only 120° long and appeared to have a lack of fusion for more than two-thirds of its length. These conditions were probably key to its failure.

From a metallurgical examination of welds on a shaft that had not failed, but which had been removed from service because of apparent defects, FRC found that the defects were more extensive than visually evident. However, FRC found no in-service cracking that had propagated from pre-existing defects. This analysis is detailed in Appendix A.

7. CONCLUSIONS

The McGuire 2B RTB failed to open due to pinching of the main roller between the raised edge of the closing cam and the right-hand side plate. Both lateral displacement of the roller end of the main drive link and axial rotation of roller are necessary to allow jamming. Some pole shafts without broken welds will allow the lateral displacement and even allow the roller to strike the side plate. However, a new pole shaft without broken welds would not allow sufficient axial rotation for jamming to occur. It may be possible that 3000 or more cycles could cause wear that would allow the necessary axial rotation.

A raised edge on the close cam is necessary to allow jamming. In addition, the distance between the inner surface of the cam edge and the side frame plate must be nearly the same as the width of the roller.

Other failure modes may also be developing in the DS-416 circuit breakers. If the roller hits the right-hand side frame plate (viewed from back of circuit breaker), the linkage exerts a lateral force on the constraining link and the trip latch that could result in trip latch bearing damage. Ultimately, such bearing damage could jam the trip latch and prevent the circuit breaker from opening. (On September 23, 1987, Westinghouse personnel discounted this theory, but presented no formal evaluation of the problem.)

In addition, a failure-to-close condition could occur due to the mushrooming of the cam if it causes binding of the stop roller. Such binding would prevent operation of the close release mechanism.

With respect to weld acceptance criteria, a detailed weld inspection standard is needed for evaluating the welds on the pole shaft. The standard must be either an existing industry standard or one specifically prepared for the pole shaft welds. The inspectors need to know exactly how to judge the welds and what is or is not acceptable. It is doubtful that an adequate inspection of the weld can be made with a pole shaft still in the circuit breaker, especially an inspection of the center-pole-lever weld. The restricted space and viewing angle do not allow proper inspection. Even the use of dye-penetrant inspection may not be feasible with the pole shaft still in the circuit breaker, because of inaccessibility to properly prepare the surfaces (a multi-step process).

The reduction of acceptable welds to the 90°/120° arc length recommended by Westinghouse has not been proven acceptable by either qualification testing or sound engineering analysis.

8. RECOMMENDATIONS

- The inspection of pole-shaft welds is highly desirable. However, at present, insufficient information has been provided to the users of the circuit breakers to perform uniform inspections. A weld inspection standard must be specified or a complete inspection guide provided.

- There is no established basis for permanent usage of 90° and 120° welds. A qualification program should be performed for breakers with pole shafts with 90° and 120° welds. If welds with cold starts are to be allowed for unrestricted use, then the qualification specimens must contain welds of 90° and 120° having cold starts.

- For interim usage of the 90°/120° welds, Westinghouse should compute allowable torques based on proper formulae with conservative stress concentration factors. In addition, it is suggested that the dynamic strain gauge measurements be either remade or properly reevaluated, establishing the dynamic torque history during opening and closing of an RTB for use in fatigue calculations.

- Since some circuit breakers are approaching the qualification limit of 4000 cycles, refurbishment criteria must be established or the qualification limit must be extended by retest or verification that cycling test data exist. The qualification limit for 180° and 90°/120° welds must be established.

- With respect to restriction of the stop roller by the mushrooming of the edges of the close cam segments, inspection criteria should be added to maintenance procedures for all Class 1E DS circuit breakers. Remedial actions should also be specified.

9. REFERENCES

1. NRC Information Notice No. 87-35, "Reactor Trip Breaker, Westinghouse Model DS-416, Failed to Open on Manual Initiation from the Control Room," July 30, 1987.

2. NRC Information Notice No. 87-35, Supplement 1, "Reactor Trip Breaker, Westinghouse Model DS-416, Failed to Open on Manual Initiation from the Control Room," December 16, 1987.

3. NRC Bulletin No. 88-01, "Defects in Westinghouse Circuit Breakers," February 5, 1988.

4. Westinghouse letter from H. C. Walls to the Westinghouse Owners' Group (WOG) that use its Models DS-416, DSL-416, DS-420, DS-206 and DSL-206 switchgear in Class 1E service, dated September 11, 1987.

5. "Instructions for Low-Voltage Power Circuit Breakers, Types DS and DSL," Westinghouse Electric Corporation, Instruction Bulletin 33-790-1E, September, 1979.

6. "Manual of Steel Construction," Eighth Edition, American Institute of Steel Construction, Inc. (AISC).

1. Stop Roller
2. Close Cam
3. Roller Constraining Link
4. Pivot Pin
5. Trip Latch
6. Trip Shaft Latching Surface
7. Trip Shaft
8. Pole Shaft
9. Center Pole Lever
10. Pole Lever Pin
11. Moving Contact Arm
12. Stationary Arcing Contact
13. Moving Contact Pivot Pin
14. Main Drive Link
15. Main Roller
16. Spring Release Latch
17. Insulating Link Adjusting Stud and Locknut
18. Insulating Link
19. Mechanism Side Frame
20. Hardened Latch Surfaces

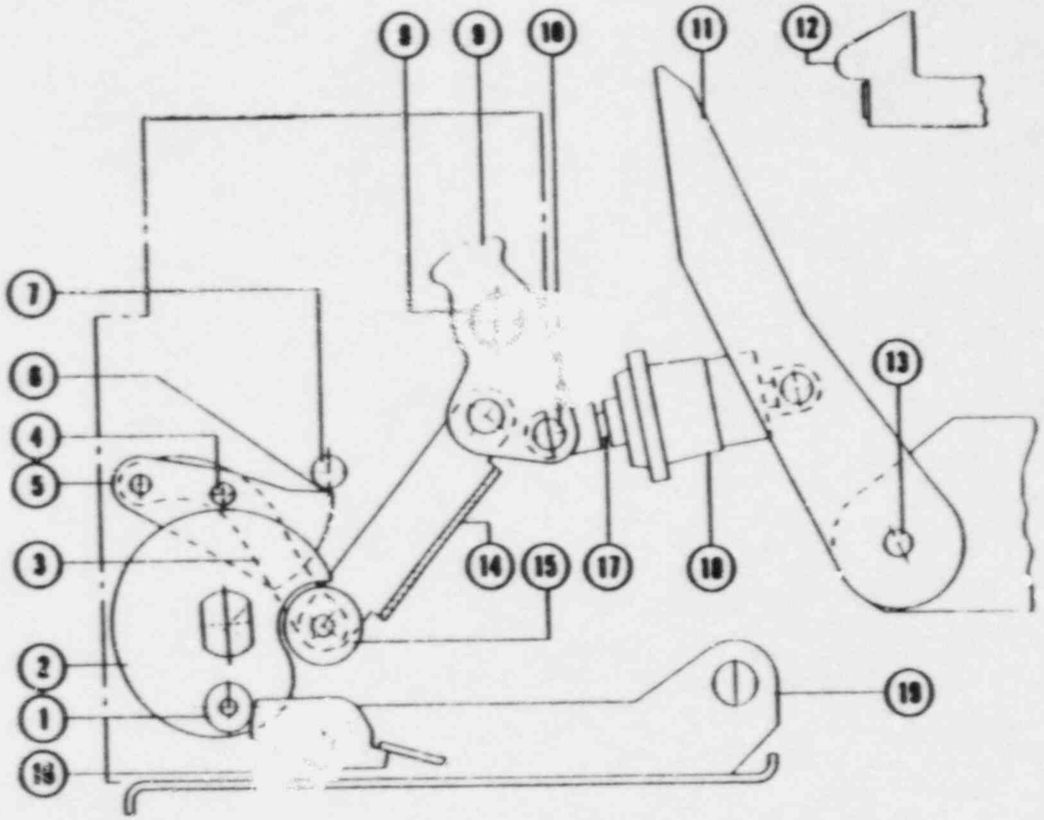


Figure 1. Linkages of DS-416 Breaker Mechanism Shown with CB Open and Springs Charged (Source: Reference 5)

F-6177-5

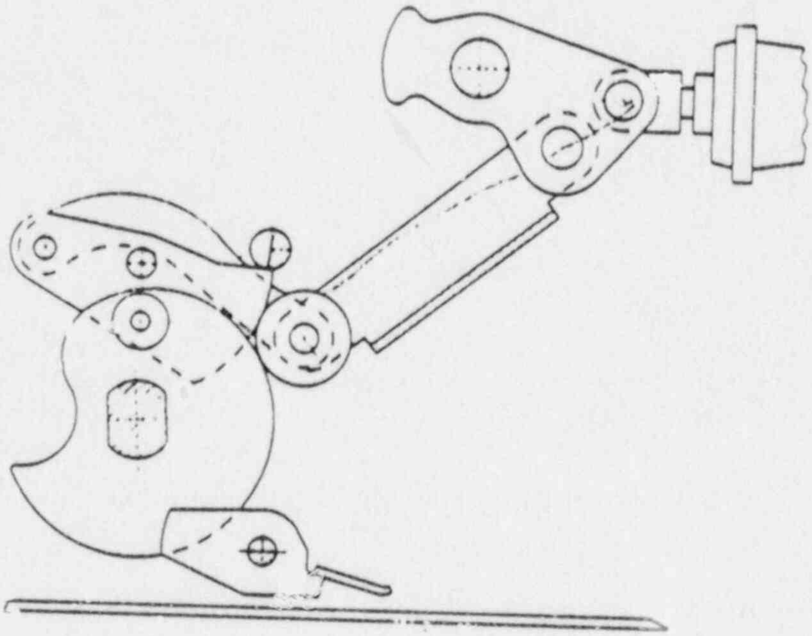


Figure 2. Position of Mechanism with RTB Closed (Source: Reference 5)

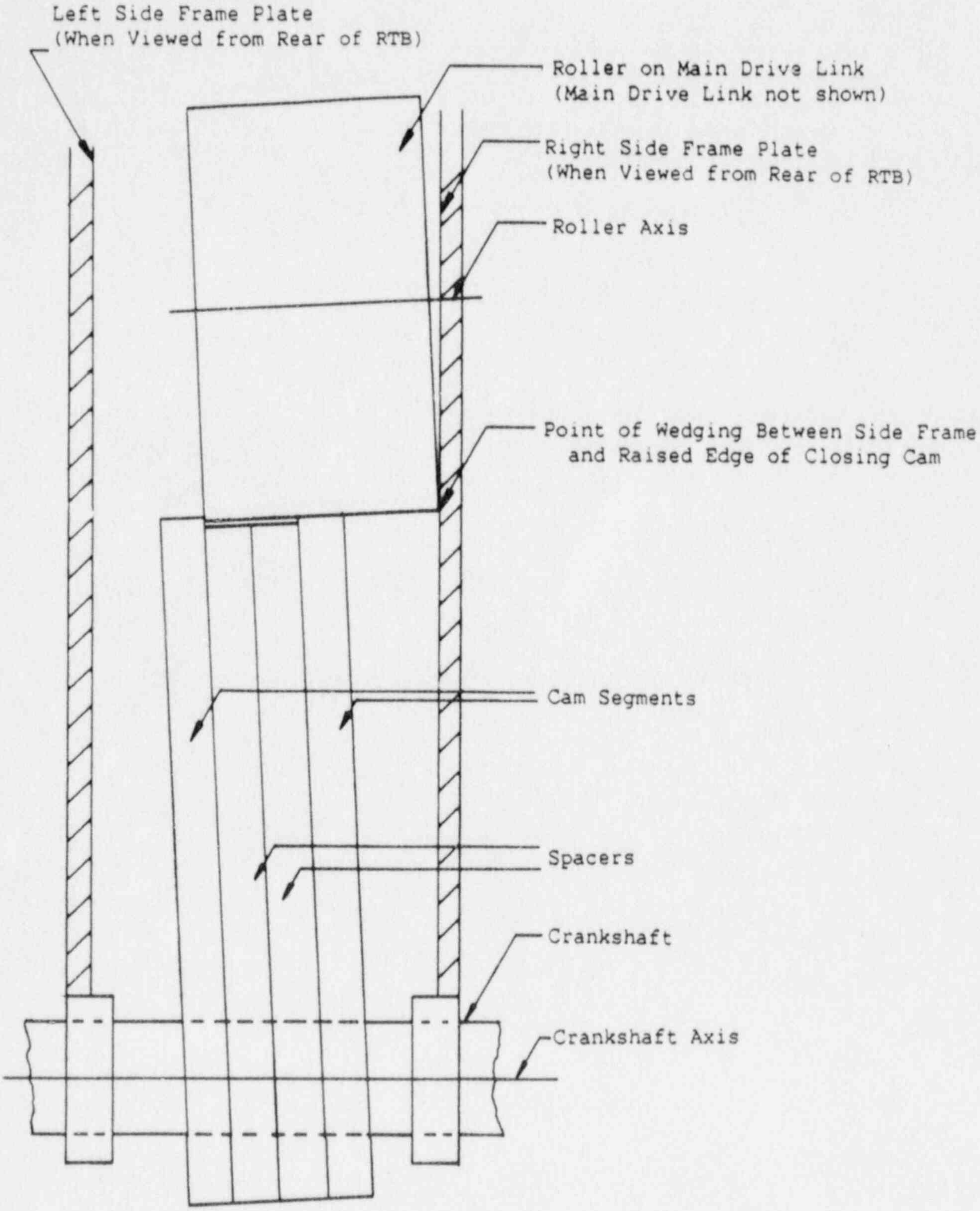
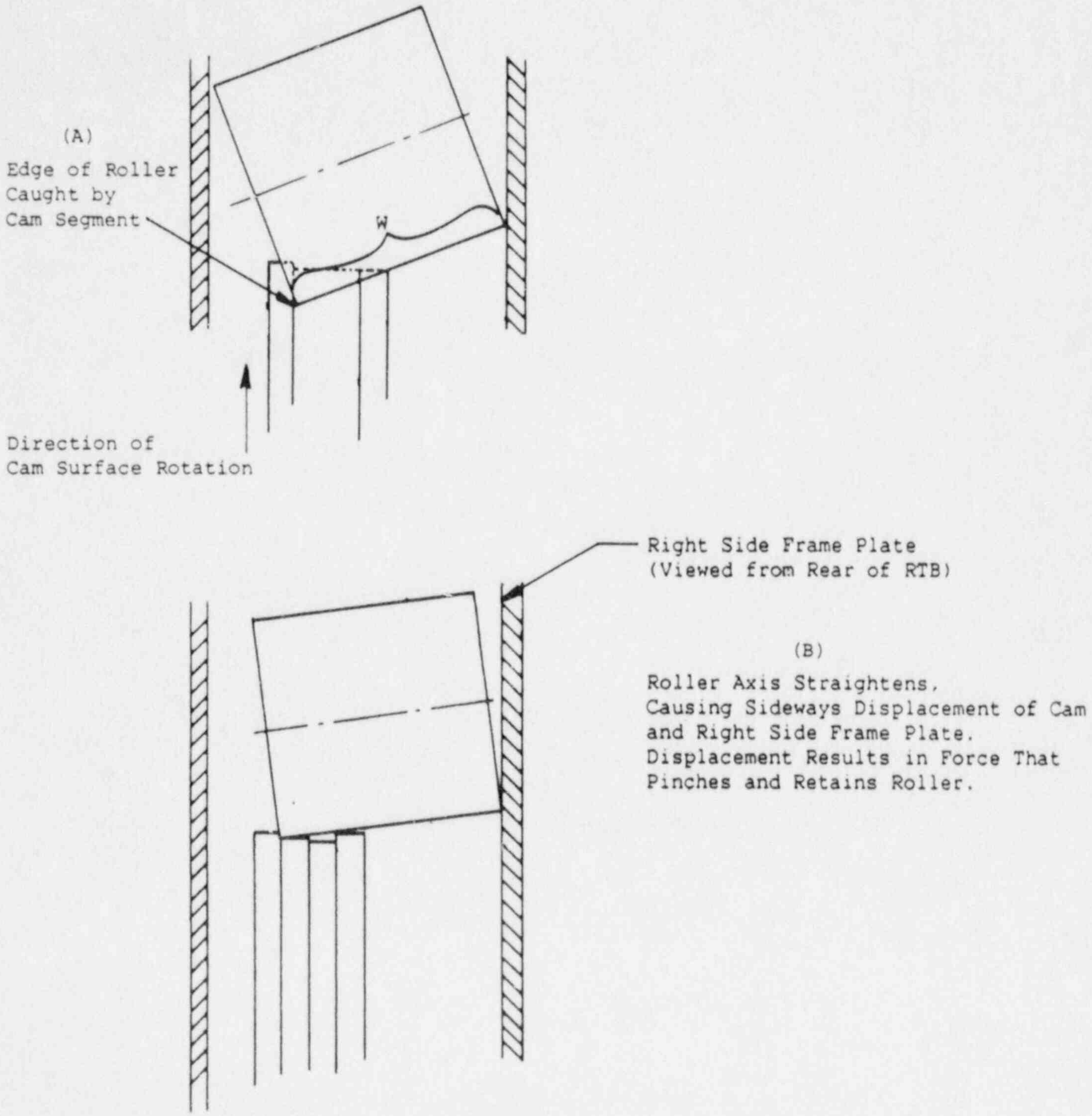


Figure 3. Roller Wedged Between Left Cam Segment and Right Side Frame Plate
(Conceptual Drawing, Not Fully to Scale)



Roller Axis Straightens, Causing Sideways Displacement of Cam and Right Side Frame Plate. Displacement Results in Force That Pinches and Retains Roller.

Figure 4. Binding of Roller

APPENDIX A

ANALYSIS OF WELD JOINTS ON A REACTOR TRIP BREAKER POLE SHAFT

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November 30, 1987

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1. INTRODUCTION

An earlier investigation of a reactor trip breaker (RT[illegible]ction at McGuire Unit 2 on July 2, 1987, determined that there had be[illegible]e of the fillet weld forming the center-pole lever to pole shaft ([illegible]oint. A metallurgical investigation of the weld attributed the failure t[illegible]ubstandard welding (i.e., porosity, lack of fusion, inadequate extent of welding). As a result, other such in-service pole shafts were inspected for similar defects. A shaft at the Catawba Nuclear Power Plant exhibited lack of fusion (LOF) in the CP/PS weld, and there appeared to be a crack in the anti-bounce lever to pole shaft (AB/PS) weld. This shaft assembly was forwarded to the Franklin Research Center (FRC) for an independent assessment of the weld integrity and quality. For each weld joint, it was of interest to determine the total extent of LOF and cracking, both on the surface and below the surface down to the weld root; the degree of difficulty or magnification required in detecting each crack; and when and why each crack had formed and whether it had been propagating as a function of the number of service load cycles.

As described and discussed below, optical and scanning electron microscope (SEM) and metallographic analyses were conducted to accomplish the evaluation. Based upon the results obtained, several conclusions are presented.

2. ANALYSES AND DISCUSSION

A segment of the pole shaft on which the two levers of primary interest (CP and AB) were fastened is shown in Figure 1. Dye penetrant residue from plant site testing of the welds was present at surface irregularities and at the LOF on the CP/PS joint at the weld start location, as shown in Figure 1. However, the dye did not highlight any cracks to such an extent that they were visually apparent. Using a binocular microscope with magnifications up to 40X, it was determined that there was a crack extending from the LOF into the weld on the CP/PS weld start, as pointed out in Figure 2; and there was a crack at the finish end of the fillet weld on each lever, as shown in Figures 3 and 4. The AB crack was open wider than the CP one; therefore, once it was detected under the microscope, it was possible, knowing its location, to observe it visually. In addition to the preceding defects, there was a highly irregular weld geometry at the start of the AB/PS weld, making it difficult to determine the presence, if any, of LOF and/or cracks.

Optical microscope inspection revealed no evidence of cracking on the other lever-to-pole shaft joints and, since it was reported that these levers experienced less severe service than the CP and AB levers, no further evaluations of them were conducted. However, the samples were retained should further analyses be deemed appropriate.

The CP/PS and AB/PS weld joint regions were then cut from the assembly so that more detailed evaluations could be conducted in the SEM. The crack stemming from the LOF at the start end of the weld on the CP/PS joint was clearly evident on the surface of the weld in Figure 5, but this did not necessarily mean that the cracking extended through the weld and/or into the adjacent lever face down to the bottom of the joint. The possibility of LOF extending into a crack also existed on the start end of the AB/PS weld, as shown in Figure 6, but again the defect depth could not be defined. The cracks on the surfaces of the finish ends of the CP/PS and AB/PS weld joints were also readily apparent in the SEM, as presented in Figures 7 and 8, with the termination of surface cracking in each case unclear, owing to highly irregular surface morphology, the tightness of the cracks, and, possibly, flaking of zinc and chromate coatings. Futhermore, the subsurface extent of cracking was again in question.

Accordingly, to better determine the total extent of each crack or LOF defect and, hence, the approximate length of intact weld joint, the welds were cross sectioned and step-wise reground and microscopically studied until cracking was eliminated. The approximate angular length of each weld around the circumference of the shaft was measured at each step of sectioning and polishing, and the final values are given in Table 1.

The first section through the CP/PS weld start was made where the surface LOF appeared to end and the surface crack begin, i.e., a little to the right of the right-hand arrow in Figure 3. As shown in Figure 9, this sectioning revealed that at the weld start, the weld had never been fused to the lever. On the metallographically prepared cross section of the weld, i.e., the plane approximately normal to the weld surface and near the beginning of the crack in Figure 2, a surface crack extended from the surface down to and along the face of the lever, following the heat-affected zone along a very shallow fused layer of the lever face, as shown in Figure 10. With successive repolishings it was found that the crack continued this path and that it had progressed to about the same distance around the shaft both at and below the top weld surface. In the last stage of polishing, shown in Figure 11, the plane of polish had become tilted away from the top of the weld, resulting in the crack being present only at the top of the weld. From the observations on the cross sections, it was not possible to ascertain whether the crack had propagated in service from the LOF initiator or if the crack, as the LOF, was already present after fabrication.

The AB/PS joint at the weld start was also subsequently ground and polished. Since the observations of the surface indicated only a short length of a defect, this shaft lever joint was initially sectioned only to the weld start. As shown in Figure 12, at the start of the weld its profile was highly irregular and there was some LOF to the lever face at the top of the weld. The surface crack-like defect evident in Figure 6 was found to be limited to this LOF, as shown in Figure 12 and, after further polishing, in Figure 13.

Both the CP/PS and AB/PS weld joints at the finish ends of the welds were sectioned near the termination of the surface cracks so that, if cracking had gone all the way through the joints, samples of mating crack surfaces could be obtained for fractographic analysis. The surface morphology would indicate the mode of fracture and, thus, the likely time of occurrence, i.e., during fabrication and/or in service.

There are several factors that could have initiated and/or propagated cracks in the welds and several possible sequences of events. Stresses in a weld would be expected to be large at the weld end, owing to mechanical restraint and thermal effects from withdrawal of the welding arc, and these stresses could have induced cracking during cooling, resulting in a ductile tearing fracture surface morphology. Also, residual stresses coupled with any hydrogen picked up during zinc plating could have led to hydrogen embrittlement cracking in the weld after plating, with brittle facets on the fracture surfaces.

Cyclic loads in service applied to a weld with both residual stresses and the stress-concentrating configuration inherent in the terminated weld also could have both initiated and propagated a fatigue crack. Fatigue fracture surfaces have characteristic striations or a morphology that closely follows the solidification pattern of a weld. Alternatively, the service usage could have fatigue-propagated a crack that had been initiated in fabrication.

The sectioning of the finishing ends at the CP/PS and AB/PS welds resulted in a separation of each of the lever and shaft segments. The mating fracture surfaces of both joints were entirely in the welds and, on a macroscopic scale, they had a highly irregular morphology, reflecting the solidification pattern inherent in the weld metal, as shown in Figure 14. The mating fracture surfaces of the CP/PS joint were bright, whereas those of the AB/PS were darkened and did not brighten with ultrasonic cleaning. Energy dispersive X-ray analysis (EDXA) in the SEM did not not detect zinc on either the AB or CP weld fractures except for a very thin plating layer at the surface, indicating that the cracks either had not been present prior to the plating or, if present, the plating had not deposited within them.

The fine scale details of the fracture surfaces did indicate that cracking had occurred in both the CP and AB welds while the weld metal had been hot. As shown in Figure 15, on the AB weld there was a fine-scale, ductile dimpled rupture, characteristic of high temperature fracture, on each of the mating fracture surfaces. Accordingly, the darkening of the fracture surface in

Figure 15 was likely the result of oxidation that occurred during cooling of the weld. Since the ductile tearing fracture mode was present on the entire fracture surface from the end of the weld to the cut, if any in-service fatigue cracking had occurred, it would have been limited in extent to the very short remaining length of crack beyond the sectioning cut.

The shiny appearance of the CP weld fracture stemmed from rubbing or smearing of the mating faces of the crack, as shown in Figure 16. In the undisturbed areas of the fracture surfaces, the morphology was the same as that on the AB weld fracture surfaces, i.e., ductile dimples. Therefore, this cracking had also most likely formed during fabrication. The rubbing over of the dimpled fracture could have occurred during the hack-saw sectioning through the joint or from cyclic opening and closing of the crack during service. Although there was no fatigue growth evident on the fracture faces exposed by the sectioning, such propagation of the limited length of crack beyond the sectioning cannot be ruled out.

The metallographic cross sections of the finish ends of the welds, prepared after the primary sectioning discussed above, revealed that in both the CP and AB welds the cracks were confined to the welds themselves and extended from the weld metal surface down to the roots of the joints, as shown in the example in Figures 16 and 17. In the CP weld, a change in direction of the crack within the weld metal corresponded with a change in microstructure from a columnar grain structure at the top of the weld to a more equiaxed grain structure near the root. At the latter location, the cracking evident in Figure 18 was intergranular, but EDXA of the grain boundaries at the crack did not determine any embrittling species. In particular, there was no indication that copper from the welding electrode contributed to a liquid copper grain boundary embrittlement during welding or cooling following welding. However, since the limit of detectability by EDXA is about 0.5%, the results cannot rule out an embrittlement contribution to the weld cracking at the location shown in Figure 18. It should also be kept in mind that the initial sectioning had not exposed any embrittlement on the fracture surface. Since the fracture surface observed represented the majority of the cracking, the absence of embrittlement indicated that high temperature ductile tearing was the primary cracking mode at the finish ends of the welds.

The inspection of similarly fabricated, but unused, pole-shaft units to confirm that cracks are introduced during fabrication of this assembly, and periodic, microscopic inspections of similar units in service, could help to resolve the critical question of whether or not cracks are propagated with time. Such information is deemed critical in defining the criteria for a weld joint that is suitable for continued operation without a chance of a failure. For example, if, in this case, it had been possible to conclude that there had been no fatigue propagation of any cracks and no LOF after fabrication, then, as reported in Table 1, a weld length as short as 65° or less, would appear adequate on CP/PS joints, whereas 86° or less, would suffice on AB/PS joints subjected to similar service as the shaft studied in the investigation.

3. CONCLUSIONS

Based on the findings of the study, the following conclusions are reached:

1. There were several defects on the pole shaft assembly and not all of these were visually apparent. Therefore, in situ inspection of in-service shafts will not be adequate to detect defects of the type identified in the report, i.e., lack of fusion (LOF) and weld cracks. After shafts are removed from service, inspection with a microscope (up to 20X) should reveal the presence and extent of all weld defects, since subsurface cracking corresponded with surface cracking, and since LOF at the surface equaled or exceeded that below the surface.

2. The majority of the reduction of the effective weld length by defects had occurred during fabrication. LOF at the weld starts and weld cracking at the weld ends were present before the shaft assembly was put into service. Any service-induced cracking that had propagated from the defects would have been limited to short lengths not exposed by the sectioning at the center-pole (CP) weld start and at both the weld ends of the CP and anti-bounce (AB) levers.

3. Inspection of unused, as-fabricated similar assemblies is required to define whether defects are, in general, inherent in the assembly and, if so, to what extent.

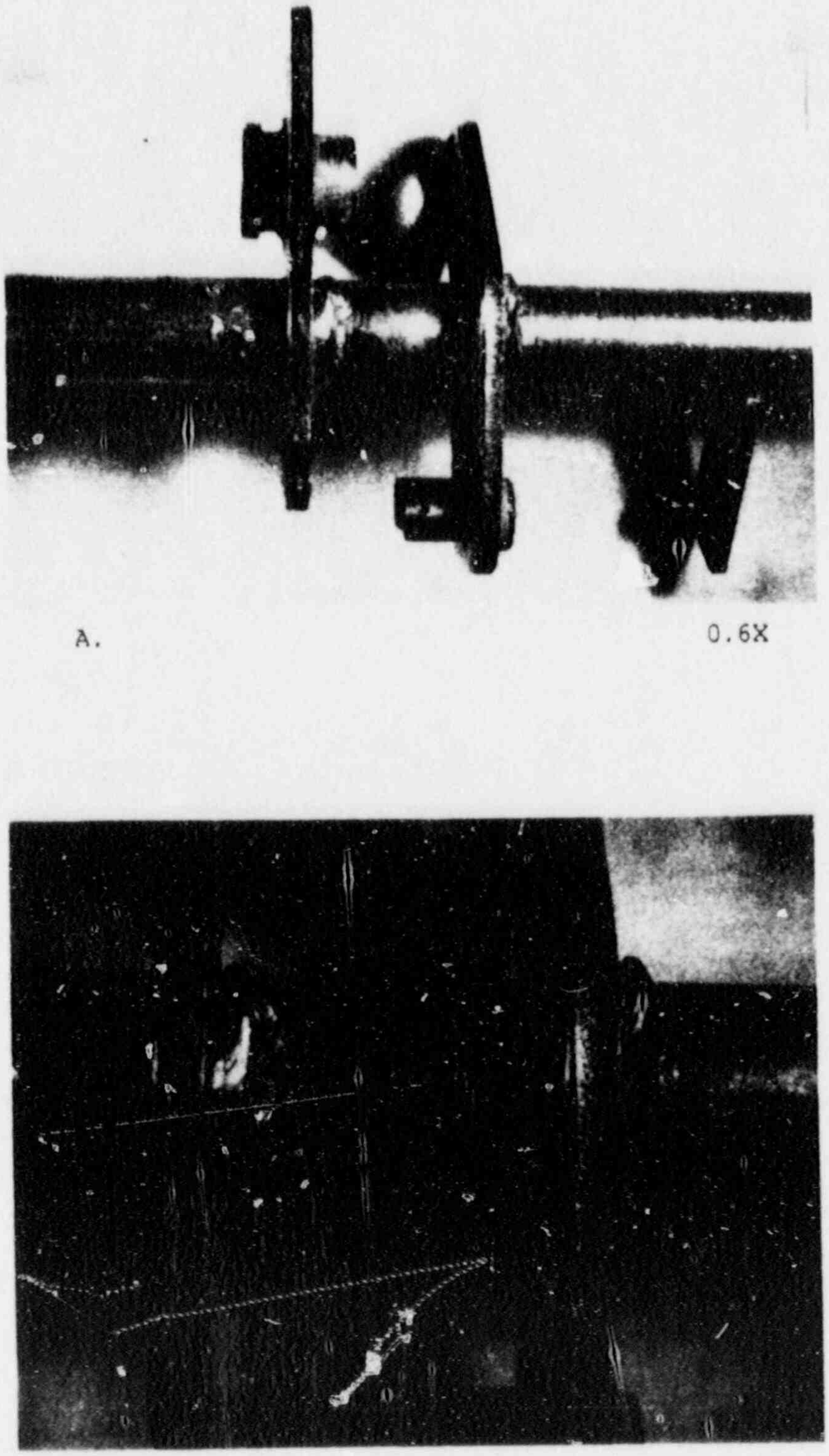
4. If in-service assemblies can be identified as defective, careful periodic observations of cracks and/or fractographic analyses after removal from service can resolve whether or not in-service cracking propagates from fabrication-induced defects.

Table 1. Weld Length Measurements

	Lengths (1)	
	Center Pole to Shaft	Anti-Bounce to Shaft
As welded (2)	143	186
Minus start end crack or LOF	136	163
Minus finish end crack	65	86

---

1. In degrees of arc around the shaft.
2. Not including gross lack of fusion (LOF) on the center-pole to pole-shaft joint.



A. 0.6X

B. 1.6X

Figure 1. Macrographs showing the shaft and the center-pole (left) and anti-bounce (right) levers. The arrow points to a gap, or lack of fusion, between the weld and the center-pole lever.

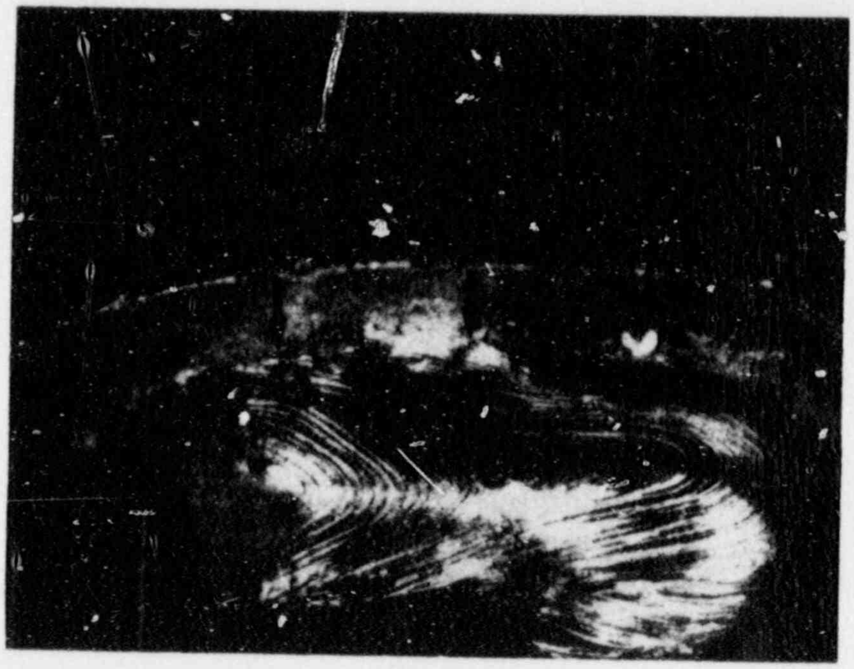
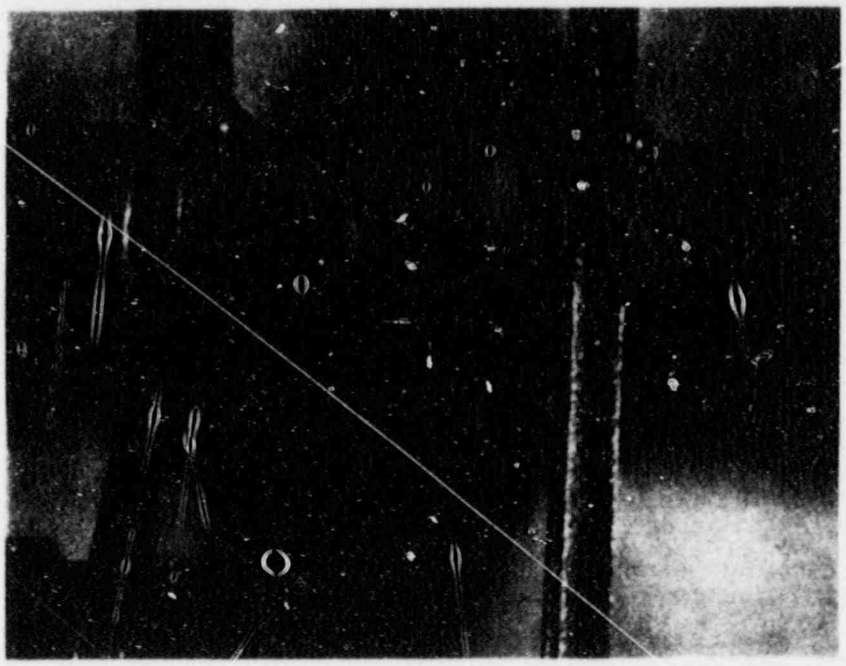
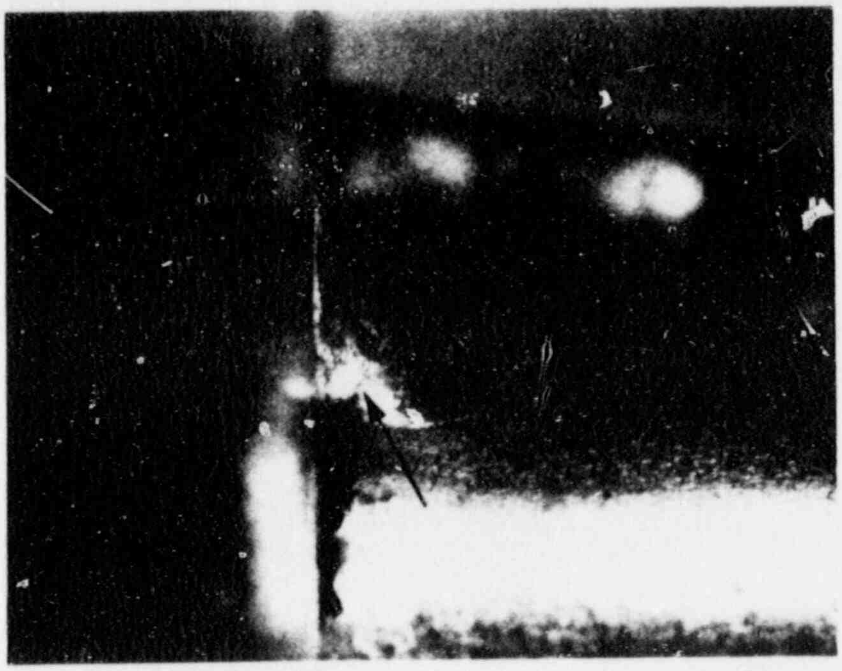


Figure 2. Macrograph showing the end of the weld on the center-pole lever. There is a gap between the weld and the lever, i.e., lack of fusion, which was darkened by the dye penetrant and which extends to a crack in the weld. The arrows indicate the portion of this crack shown in an SEM micrograph in Figure 5.



1.6X

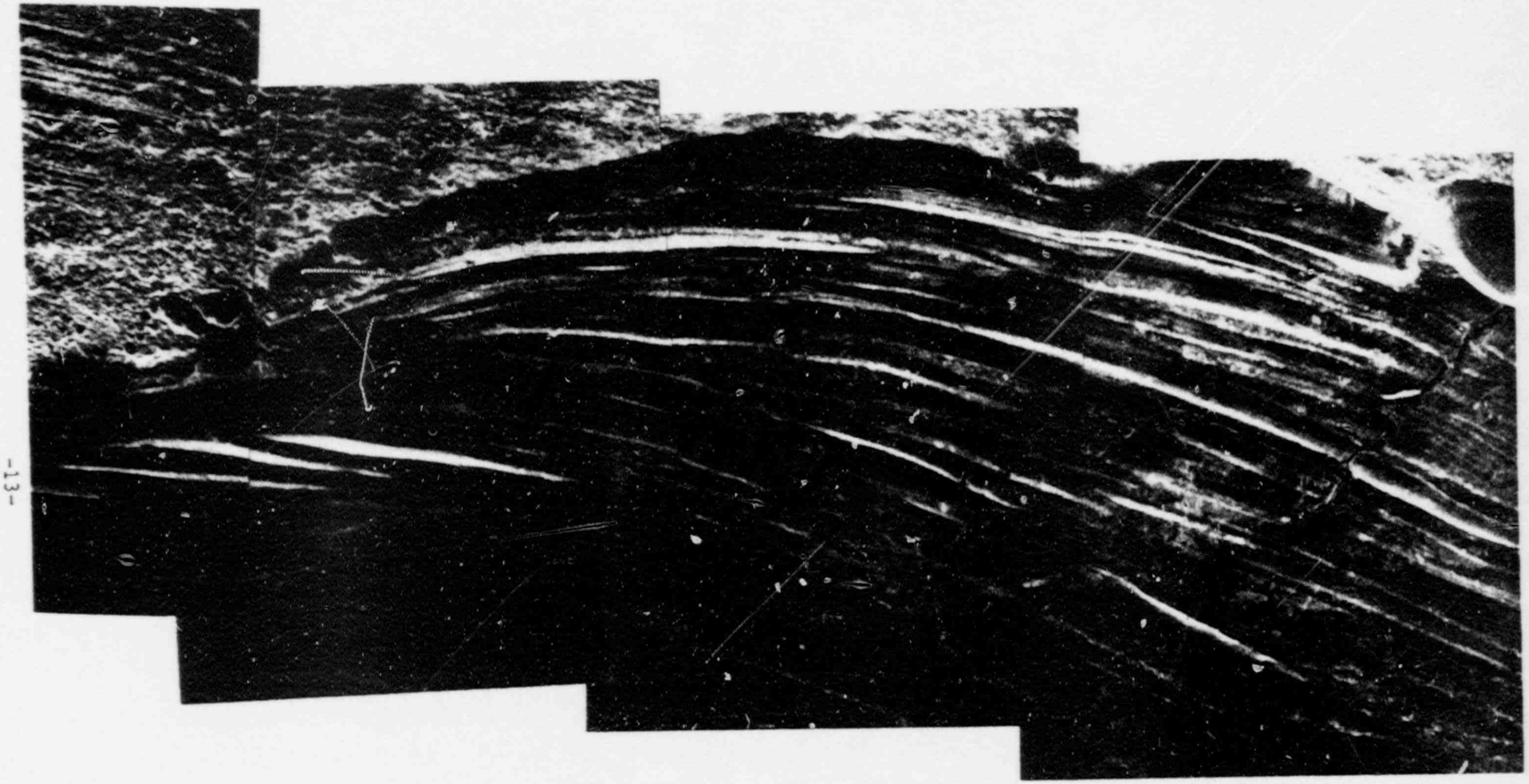
Figure 3. Macrograph showing the shaft and the center-pole (left) and anti-bounce (right) levers and the finishing ends of the fillet welds. A crack in the anti-bounce weld is barely visible at the arrow. Both welds are shown at higher magnification in Figures 4, 7, and 8.



A. Anti-Bounce 5X

B. Center-Pole 5X

Figure 4. Macrograph showing the finishing ends of the fillet welds. In each weld, a crack, as indicated by an arrow, originated at the crevice at the end of the weld.



50X

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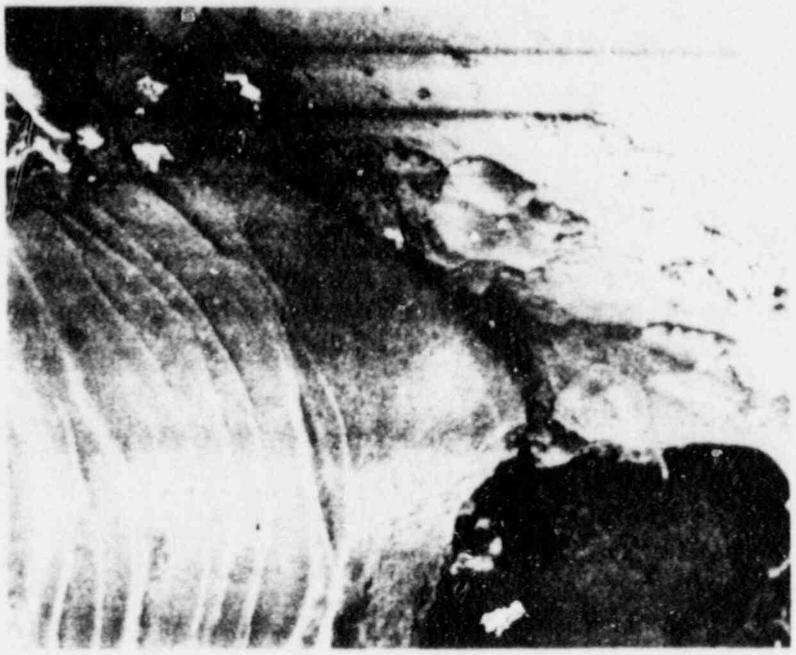
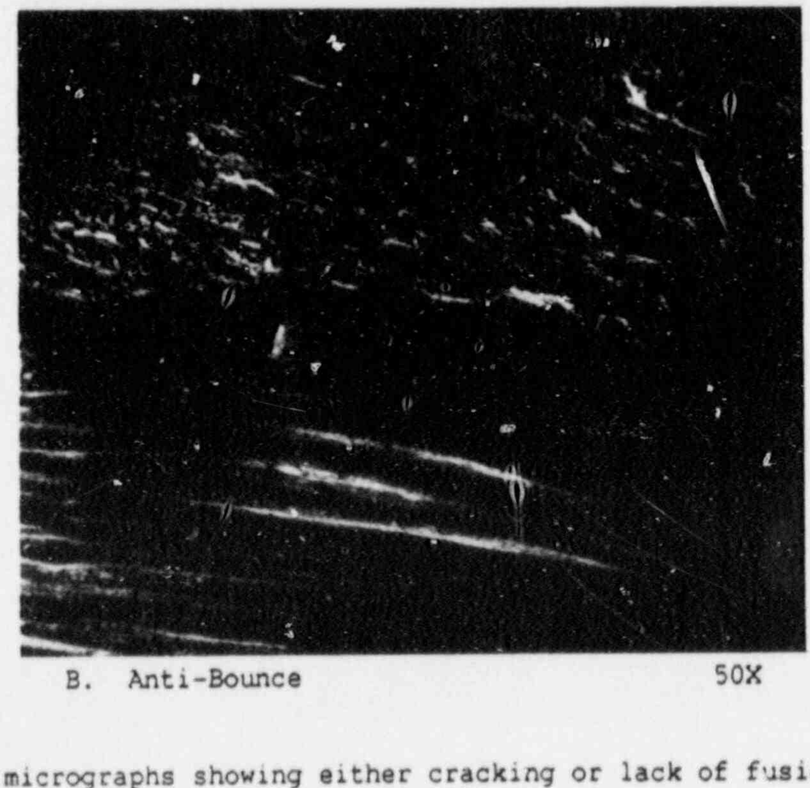
Figure 5. Composite SEM micrograph showing cracking in the weld adjacent to the center-pole lever, as indicated in the macrograph in Figure 2.



A. Anti-Bounce 50X



B. Anti-Bounce 50X

Figure 6. SEM micrographs showing either cracking or lack of fusion along the weld to anti-bounce joint. A shows the starting end of the weld, whereas B shows a region a short distance farther along the weld.

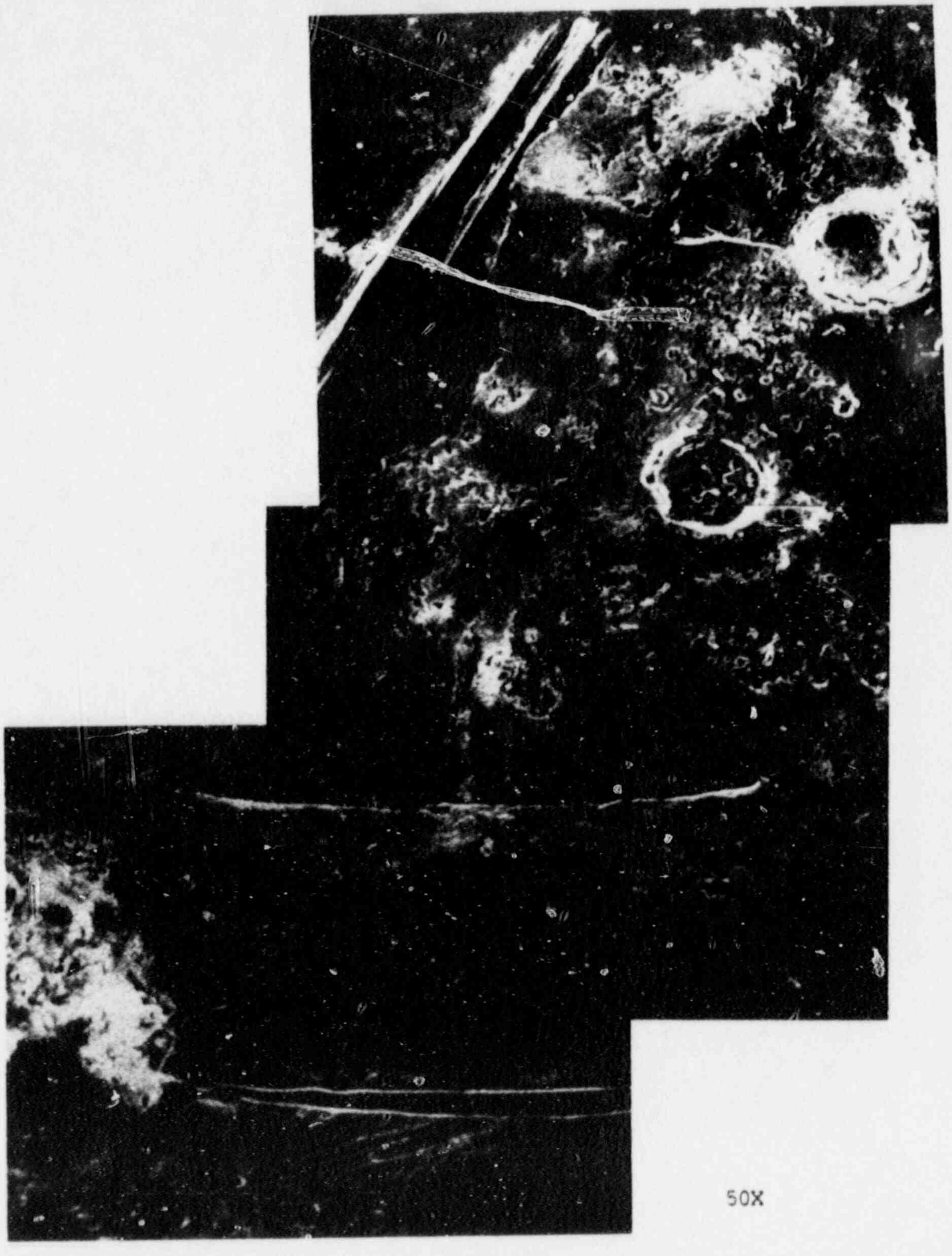
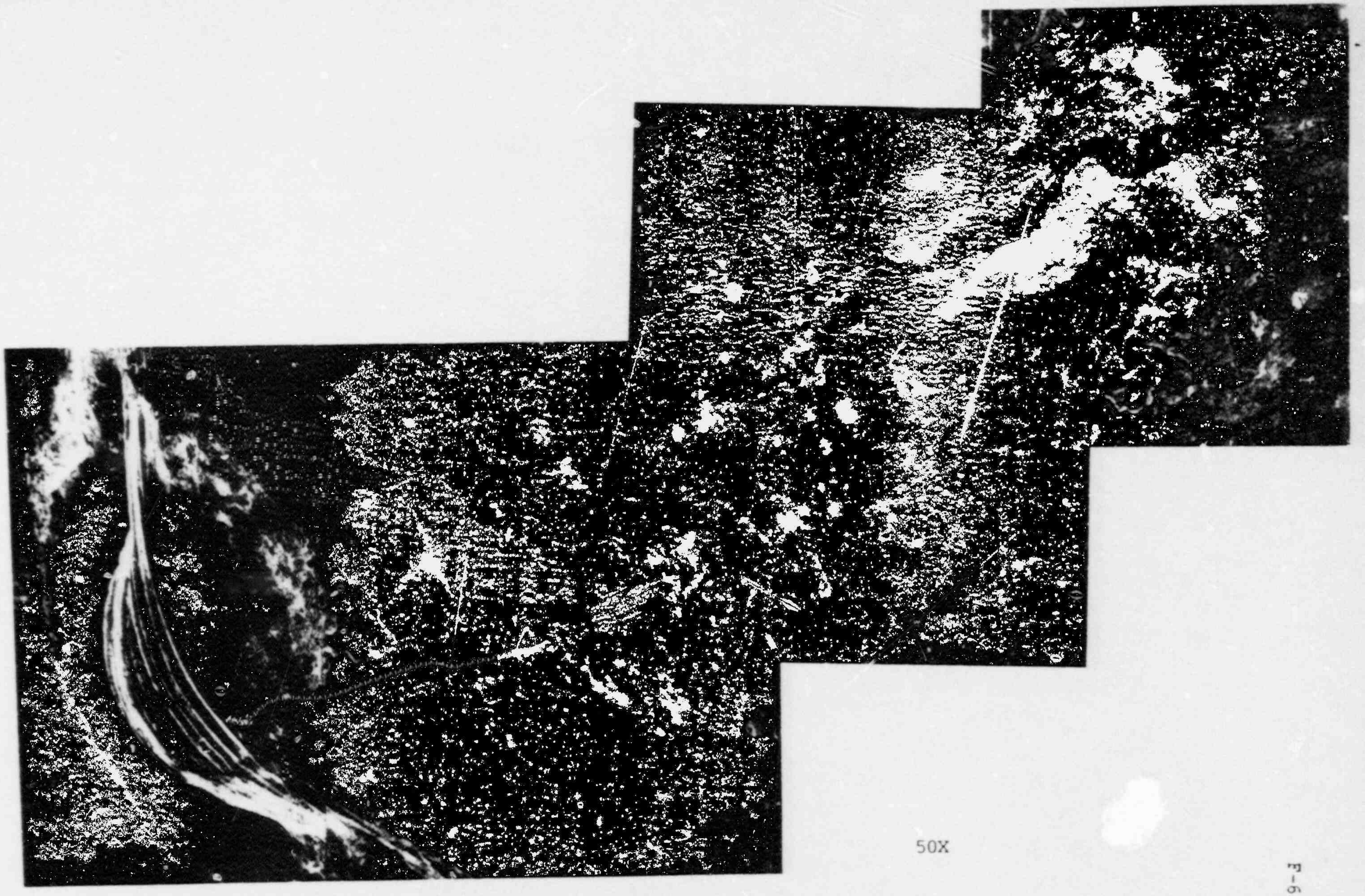
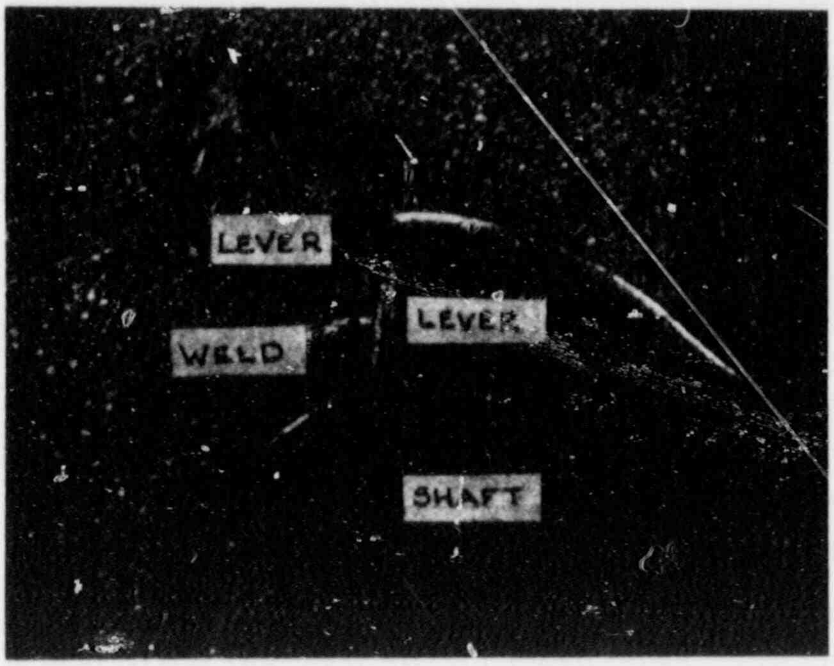


Figure 7. Composite SEM micrograph showing cracking on the finish end of the center-pole lever to shaft fillet weld previously shown in Figure 4. This crack was less pronounced than a similar one on the anti-bounce lever shown in Figure 8. Each crack had initiated at the end of the weld and had progressed through a dimpled area on the surface. It is difficult to define the end of the crack at bottom left.



F-6177-005

Figure 8. Composite SEM micrograph showing the crack at the end of the anti-bounce lever/shaft fillet weld. The crack, which is outlined by dye penetrant residue, had started at the end of the weld (at the upper left) and progressed through a dimple on the weld (near the center of the figure). The end of the crack at bottom left is difficult to define, even at 50X in the SEM.



3X

Figure 9. Macrograph showing the center-pole lever to shaft joint after the region of the joint had been cut from the pole shaft assembly and the joint was cross sectioned where there appeared to be a lack of fusion at the lever (see Figures 1 and 2). The lever segment, top right, separated during the cross sectioning, revealing a darkened area (arrow) where the weld metal had abutted but not fused with the lever.

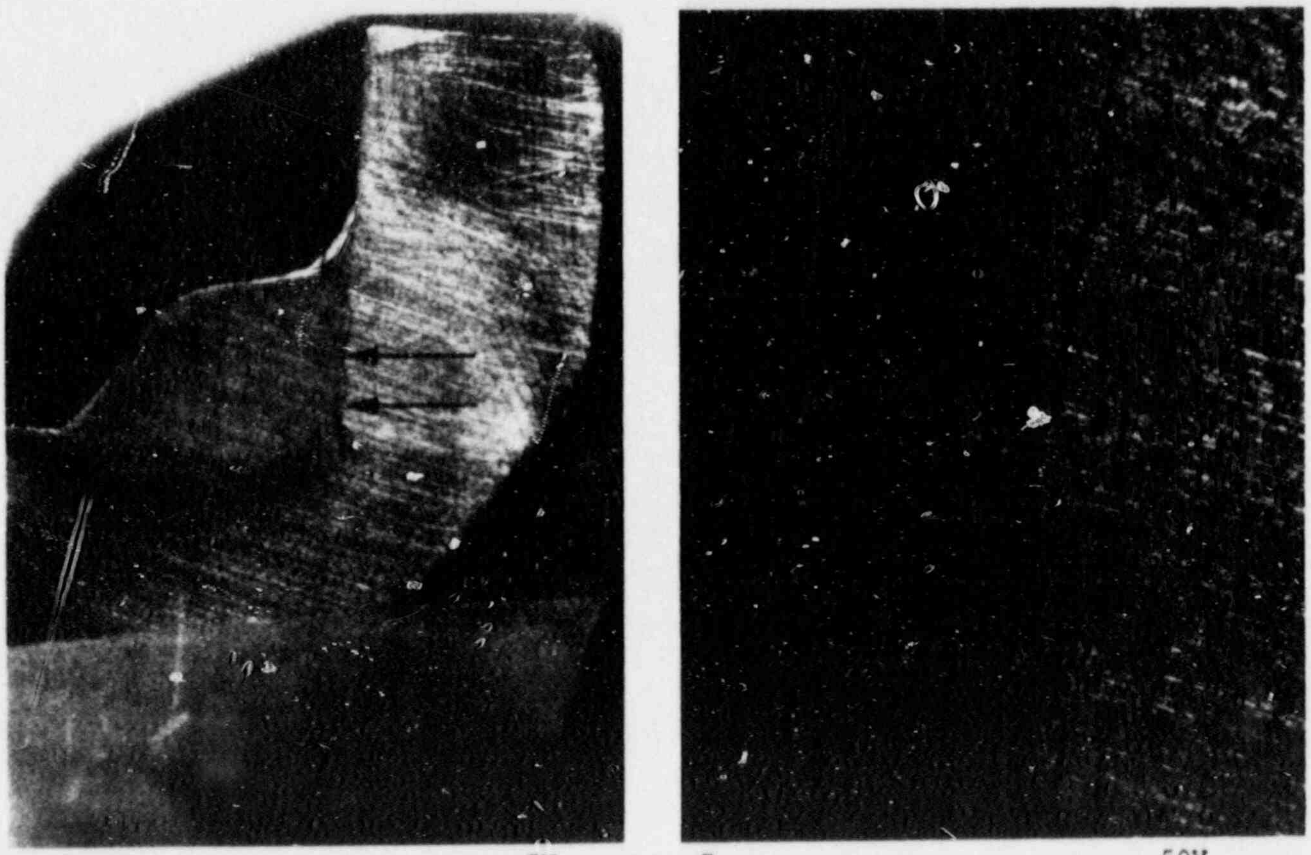
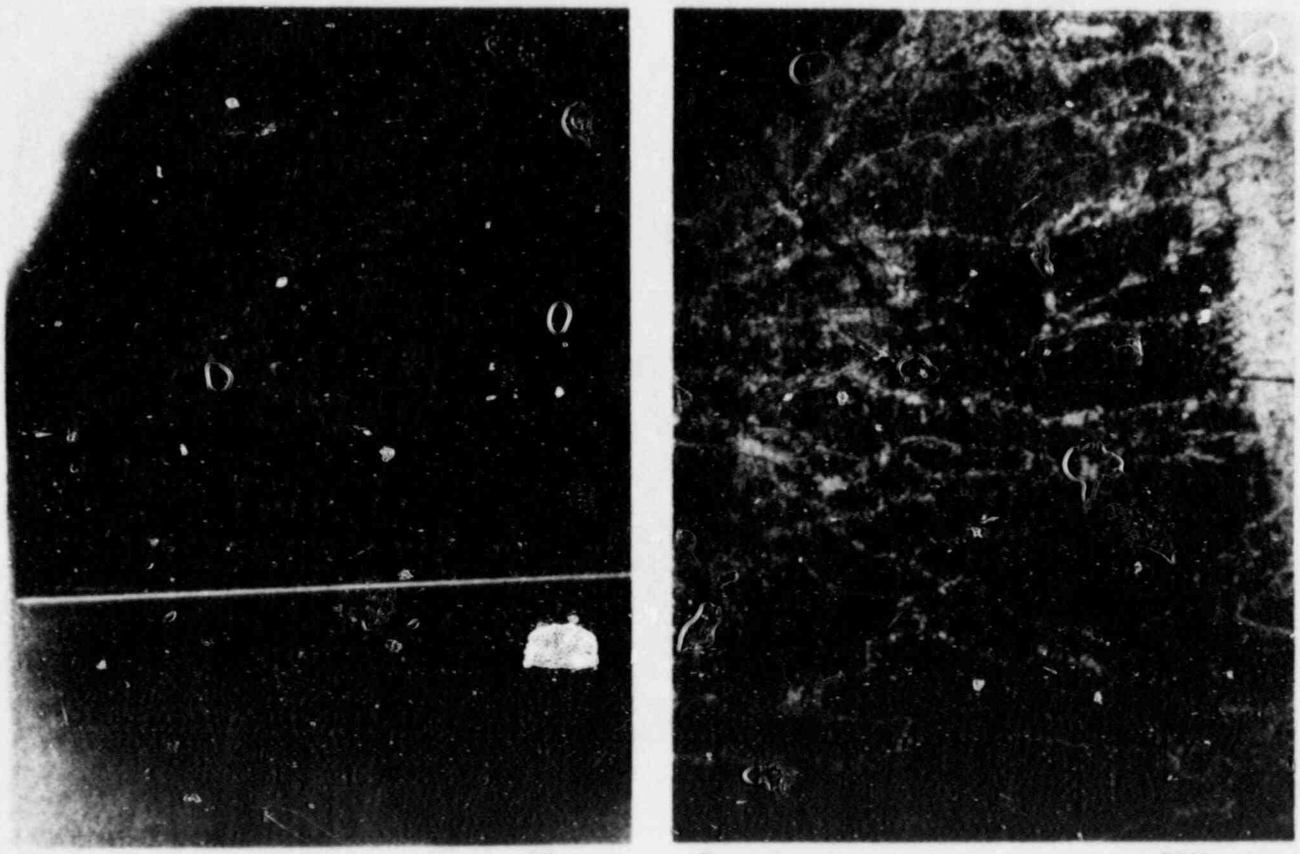


Figure 10. Macrograph and micrograph showing a cross section of the center-pole to pole-shaft weld after the cut face in Figure 9 was ground, polished, and etched. The arrows in A indicate the location of the crack in B. At the depth of this cross section along the weld, there clearly is a crack extending through the weld at the free surface down into the heat-affected zone of the lever. Also, there is very shallow fusion into the lever.

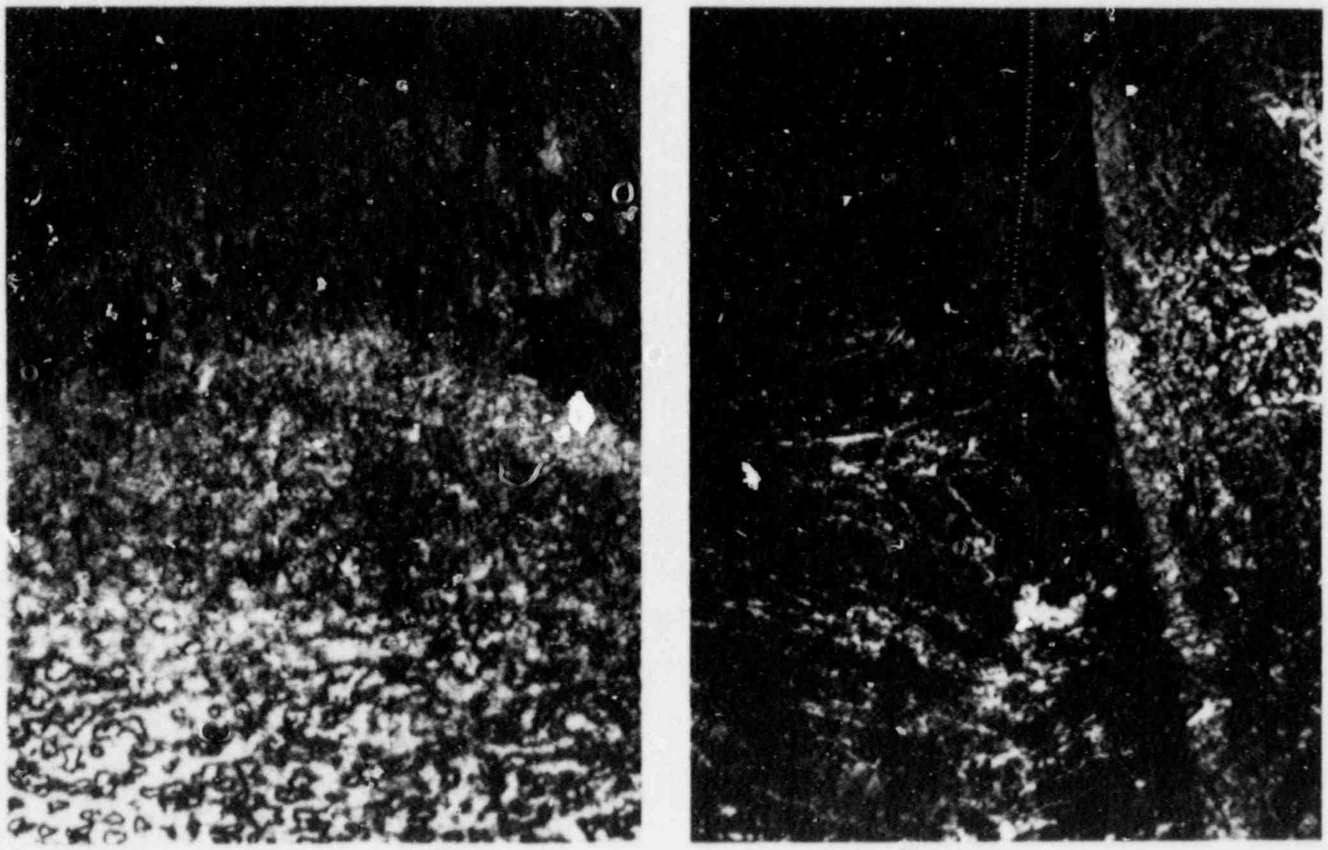


A. 7X B. 50X

Figure 11. Macrograph and micrograph showing the cross section of Figure 10 after repolishing. The crack, not visible at 7X, but indicated with an arrow in A, now extends from the free surface down into the weld. Also evident is a greater fusion depth into the lever, some porosity in the weld metal, and some scratches (straight lines) on the polished surface.

6.5X

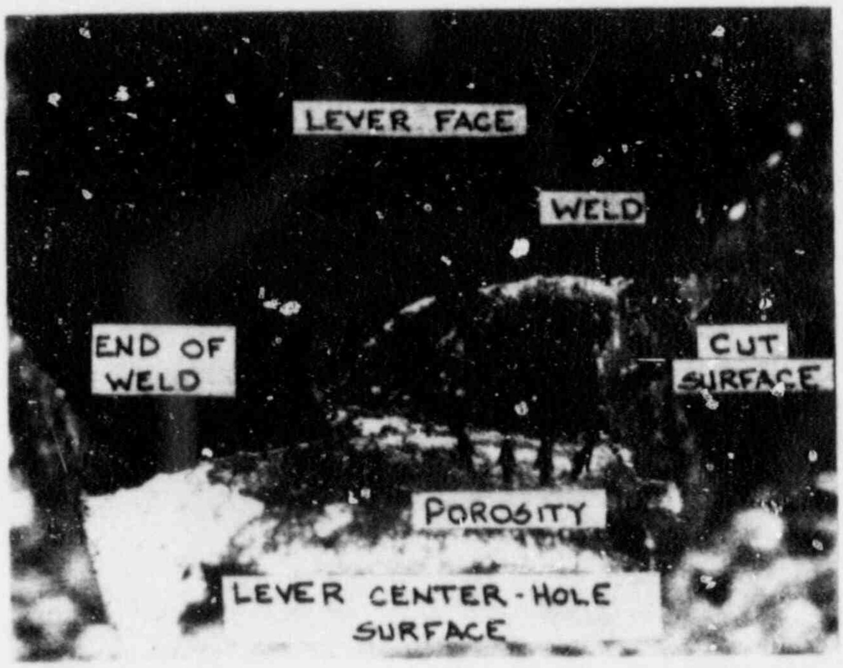
Figure 12. Macrograph showing a metallographically prepared cross section of the anti-bounce lever to shaft weld near the weld start shown in Figure 6. There is shallow fusion into the lever and a line of no fusion (arrow) at the toe of the weld on the lever.



A. Shaft 100X

B. Anti-Bounce Lever 100X

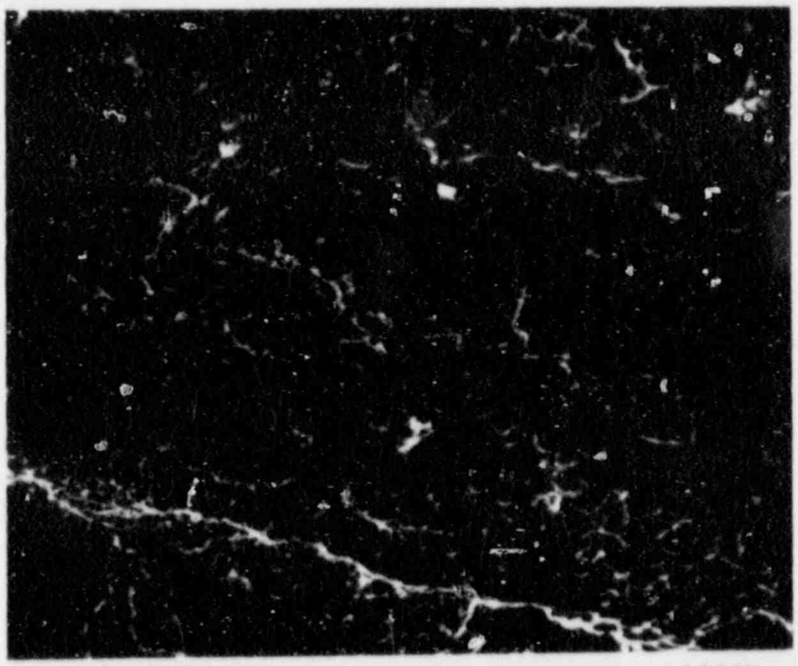
Figure 13. Micrographs showing the weld of Figure 12 after repolishing. Some lack of fusion at the lever is still present at the lever face and there is some porosity in the weld at the shaft.



9X

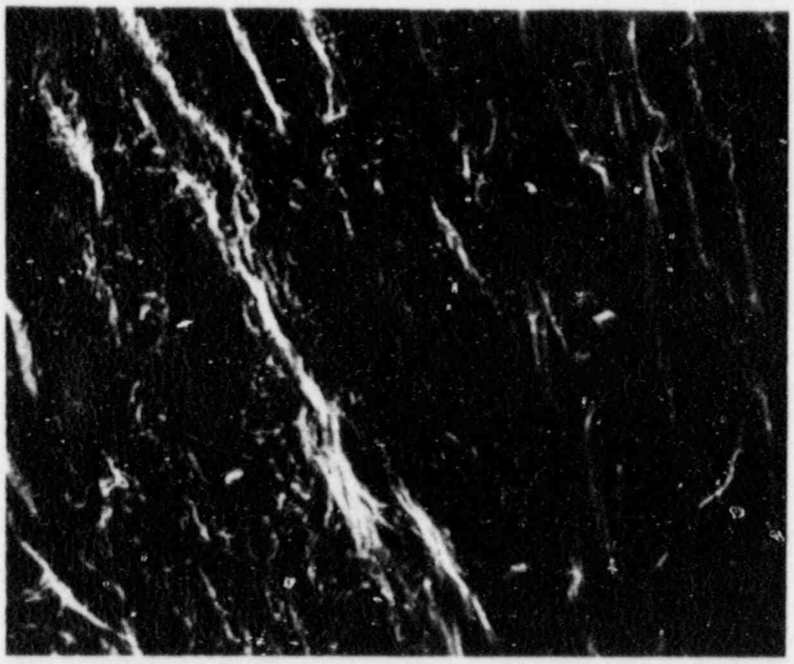
Figure 14. Macrograph showing one of the mating fracture surfaces exposed by sectioning near the termination of the surface crack on the finishing end of the AB/PS weld. The rough fracture surface, which reflects the solidification pattern of the weld, was darkened, apparently from high temperature exposure following cracking during cooling of the weld.

A. Anti-Bounce 300X

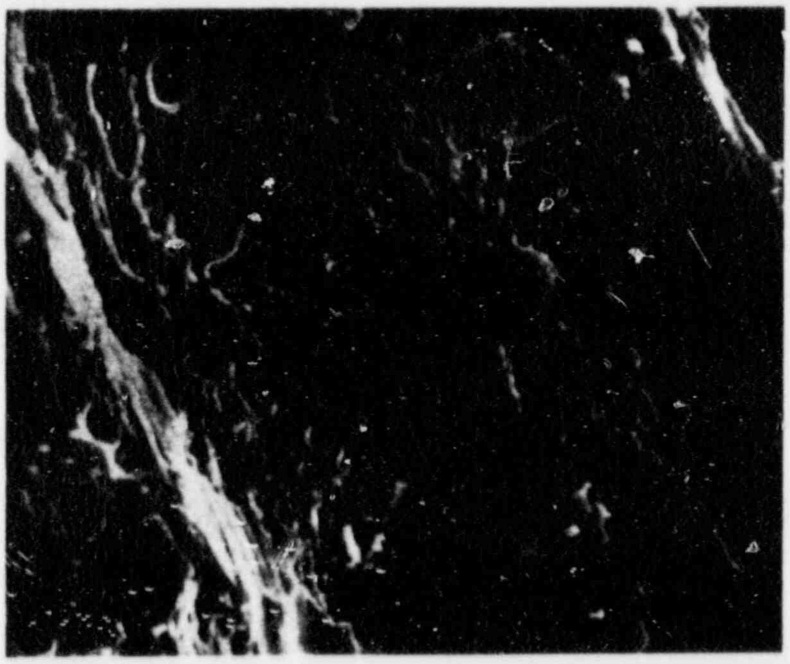


B. Anti-Bounce 1000X

Figure 15. SEM micrographs showing a representative area on the weld fracture surface exposed by sectioning near the termination of the surface crack shown in Figures 4A and 8. Essentially the entire fracture surface morphology is ductile dimpled tearing.



A. Center-Pole 300X



B. Center-Pole 1000X

Figure 16. SEM micrographs showing a representative area on the fracture surface exposed by sectioning near the termination of the surface crack shown in Figures 4B and 7. Partially masked by pronounced smearing (on the right) is ductile tearing similar to that on the anti-bounce cracked weld joint in Figure 15.

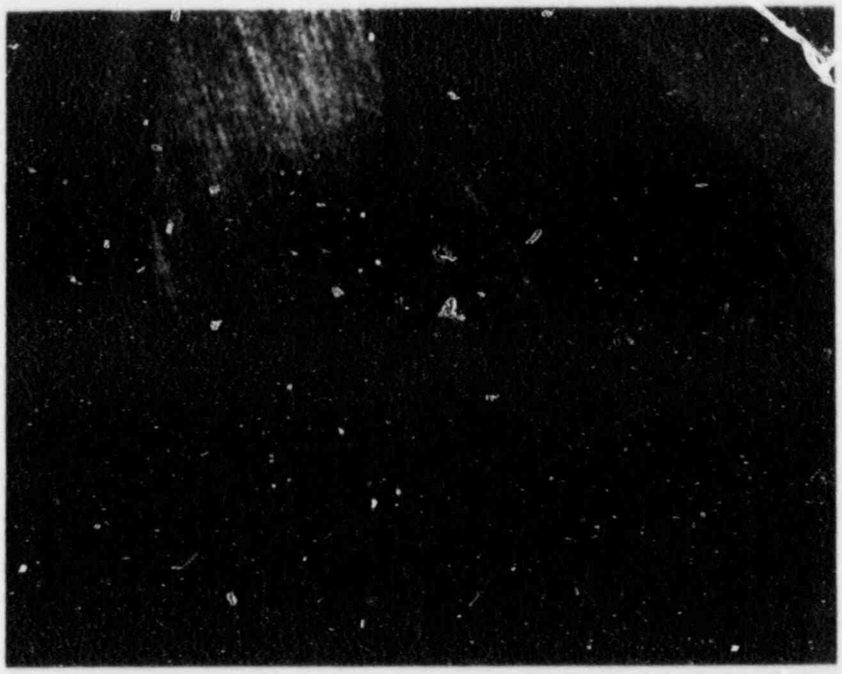


Figure 17. Macrograph showing a metallographically prepared cross section of the center-pole to pole-shaft weld after sectioning and grinding to a depth of about 80% of the surface length of the crack in Figure 7. In this cross section, the crack runs between the two arrows from the weld surface to the bottom of the joint. In this section, the etching delineated a different microstructure at the root of the weld, indicating that a root pass had preceded the bulk of the weld. The crack, shown at higher magnification in Figure 18, had a sharp change in direction at this structural change.

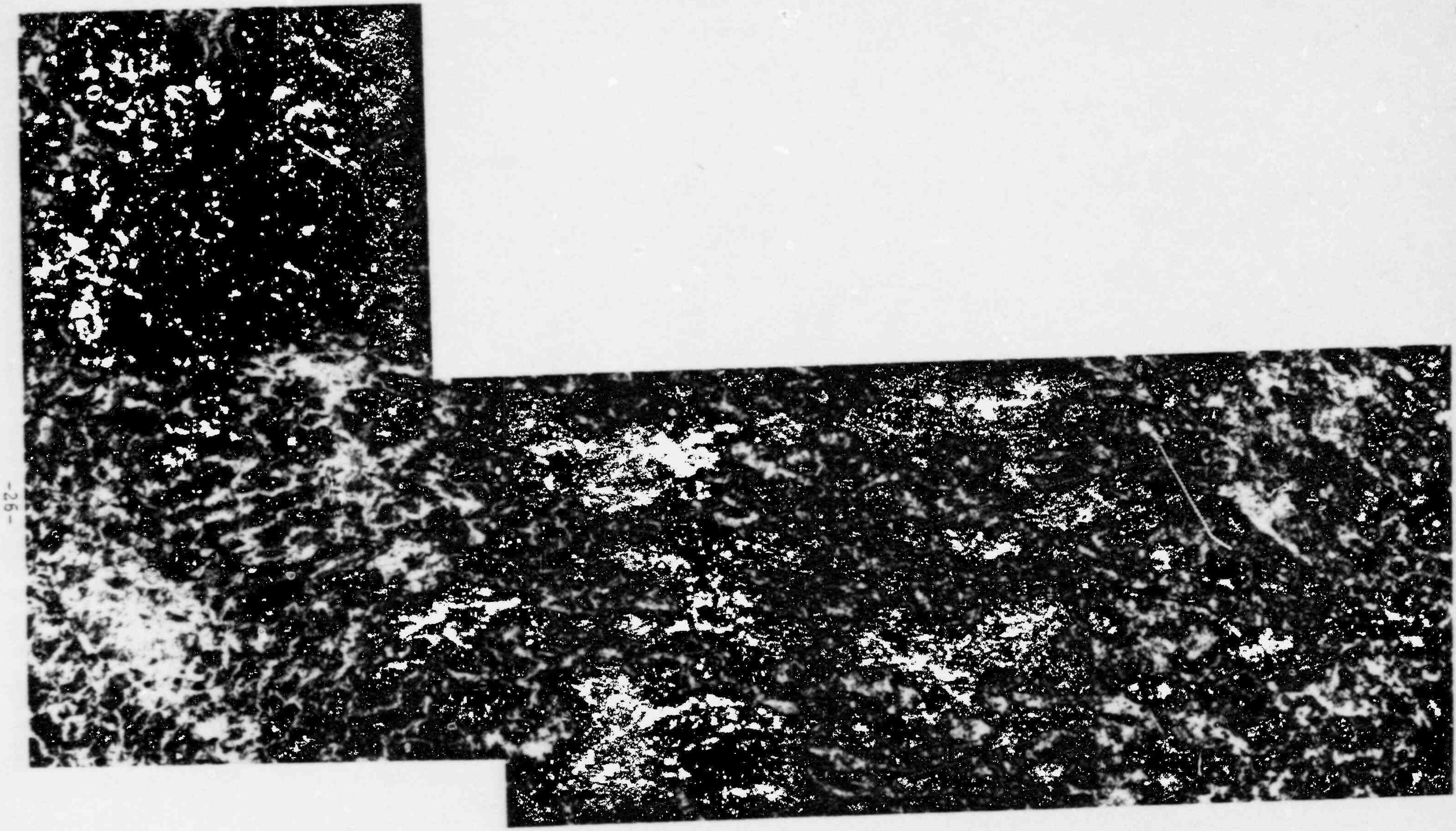


Figure 18. Composite micrograph showing a metallographically prepared cross section of the center-pole to pole-shaft weld after polishing the section in Figure 17 a little deeper. The crack, which was so tight at this location that it could not be delineated at 7X magnification, extended from the surface to the root of the weld, with a sharp change in direction near the root at the upper left. The black spots are either etching effects or porosity.

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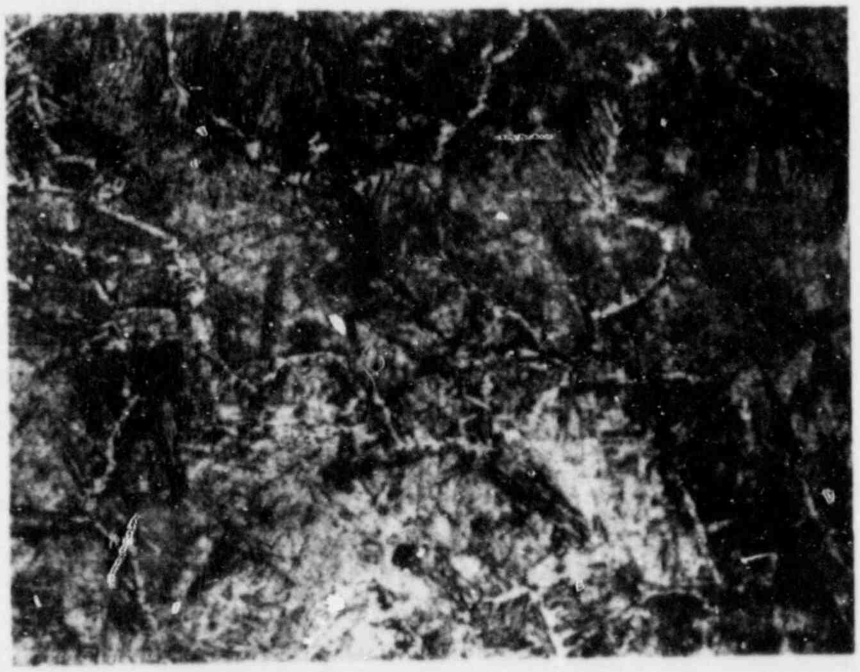

Figure 19. Micrograph showing a metallographically prepared cross section near the root of the anti-bounce lever to pole-shaft weld at the end of the surface cracking shown in Figure 8. At this stage of sectioning, about 1/2 inch of the circumferential length of the finishing end of the weld had been ground away.