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Age-Related Degradation of Westinghouse 480–Volt Circuit Breakers

Mechanical Cycling of a DS-416 Breaker
Test Results

Prepared by M. Subudhi, E. MacDougall, S. Kochis, W. Wilhelm, B. S. Lee

Brookhaven National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

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DEDICATION

This work is dedicated to the memory of our colleague and friend, Ed MacDougall who was responsible for the successful completion of this test program.

Authors

ABSTRACT

A DS-416 low voltage air circuit breaker manufactured by Westinghouse was mechanically cycled to identify age-related degradations. This accelerated aging test was conducted for over 36,000 cycles during nine months. Three separate pole shafts, one with a 60 degree weld, one with a 120 degree and one with a 180 degree were used to characterize the cracking in the pole lever welds. In addition, three different operating mechanisms and several other parts were replaced as they became inoperable. The testing yielded many useful results. The burning of the closing coils was found to be the effect of binding in the linkages that are connected to this device. Among the seven welds on the pole shaft, #1 and #3 were the critical ones which cracked first to cause misalignment of the pole levers, which, in turn, had led to many problems with the operating mechanism including the burning of coils, excessive wear in certain parts, and overstressed linkages. Based on these findings, a maintenance program is suggested to alleviate the age-related degradations that occur due to mechanical cycling of this type of breaker.

SUMMARY

After the McGuire event in 1987 relating to failure of the center pole weld in one of its reactor trip breakers, activities were initiated by the NRC to investigate the probable causes. During the last decade NRC has issued a number of information notices and bulletins pertaining to the problems encountered in Class 1E breakers. A review of operating experience suggested that the burning of coils, jamming of the operating mechanism, and deterioration of the contacts dominated the breaker's failures. Although failures of the pole shaft weld were not included as one of the generic problems, the NRC augmented inspection team had suspected that these welds were substandard which led them to crack prematurely.

This test program involved a commercial grade Westinghouse DS-416 air circuit breaker that is typically of the type used in nuclear power plants for class 1E applications. The test breaker under no electrical load was cycled mechanically over 36,000 cycles to accelerate the aging processes that could be attributed to breaker cycles. The test was conducted in accordance to the ANSI/IEEE Standard 37.50 (1981) for the life testing of circuit breakers. Three different pole shafts with approximate weld configurations of 60 degrees, 120 degrees, and 180 degrees in the center pole lever (#3) were used. In addition, three operating mechanism units, along with several other parts, were replaced as they became inoperable.

Based on the results the following conclusions were reached on the manufacturing, aging, and maintenance of Westinghouse DS-series breakers:

Manufacturing

– Pole shafts used in this test program were found to have substandard welds. This raises questions as to the effectiveness of the quality-assurance program that was followed during welding.

– Fracture of the trip shaft lever suggested that the incorrect electroplating procedures might have been followed.

– Newly purchased reset springs had sharper bends at the neck of the hooks than an older design, which led to early spring failures.

– Testing of the hardness of the oscillator surface showed a 30% reduction for the newly procured units.

Aging

– Wear, fracture, distortion, and normal fatigue dominated the aging process; with wear being the largest contributor.

– Excessive wear was evident in the ratchet wheel, holding pawls, oscillator, drive plate, motor crank and handle, cam segments, main roller, and the stop roller.

– Structural components and contact assembly parts indicated that there was little aging due to mechanical cycling.

– A pole shaft with a reduced size weld could fail at a cycle as low as 3000 cycles.

Maintenance

– The ultimate life of various breaker parts was found to be 10,000 cycles, except for the newly procured reset spring, which was 2000 cycles.

– One commercial grade lubricant was found to perform better than those recommended by the manufacturer.

– The current plant maintenance practices have not incorporated the experience of aging problems associated with the power-operated mechanisms.

– The scheduling of the breaker maintenance should be dependent primarily on the number of cycles experienced by the breaker, with some consideration given to time in service.

Recommendations

The following maintenance and manufacturing recommendations, obtained from the test results, should help mitigate aging problems.

– When procuring a new breaker or spare parts, careful attention should be given to their design adequacy (procure as safety related).

– For the indicator and reset springs, to minimize the damage to the surface and to reduce the tensile stresses on the inside surface of the bend area of the end hooks, it is recommended that a smooth transition bend should be made instead of a sharp bend.

– For the pole pin connecting the Phase A of the breaker contacts, smooth corners should be machined, free from surface defects.

– Improper welding practices at the pole shaft levers should be avoided.

– Assuming a factor of safety of 2, the life of a DS-416 (or DS-206) breaker is estimated to be 5000 cycles. Based on an assumption that a breaker, such as reactor trip, is typically subjected to 250 cycles annually, this translates to a breaker life of 20 years. The life of other Class 1E breakers should be determined according to their application and use.

– A method of tracking operating cycles of each Class 1E breaker should be implemented. A preferred method is a counter.

– At each surveillance testing interval the overall condition of the breaker should be visually inspected if possible.

– Every 50 or 100 cycles, an inspection program should be performed to check items that are vulnerable to aging.

– At each 250 cycles, the maintenance schedule should include an examination of all parts, lubrication at recommended points, and replacement of degraded components.

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The generosity of Mr. Jim Thomas of Duke Power in providing the refurbished DS-416 breaker from the Duke Power Plant, and Mr. Pete Morris and Mr. Chuck Geis of Westinghouse for visiting our facility and providing useful comments, are deeply appreciated.

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1. INTRODUCTION

The Westinghouse DS-series low voltage air circuit breakers are built with a steel frame, a very complex charging system, and a number of linkages, mechanical parts, and control devices. Some of these components are made out of age-sensitive materials and their aging is attributed primarily to environmental conditions and to service duty. The environmental conditions in a nuclear power plant are benign, and hence do not cause significant aging of the breaker components. Howerver, each duty cycle which consists of charging, closing and tripping the unit is responsible for degrading various components of the breaker. The arcing of power contacts during the closing and tripping often erodes and burns materials around the three contact assemblies and arc chutes. The mechanical cycling itself imposes wear on rubbing surfaces and linkages, causes sluggish operation of parts, cracking of overstressed components, and burning of electro-mechanical devices.

Understanding the aging of these breakers and defining appropriate methods to manage them without compromizing their safety functions are the primary goals of this testing program. The testing was conducted on a commercial grade breaker (there are no differences in manufacturing, design or material from nuclear grade) and the aging process was limited to mechanical cycling of the power-operated charging mechanism (most identified problems have been related to mechanical aspects of breaker operation).

1.1 Background

During the last decade, the issuance of numerous NRC information notices, bulletins, and generic letters has prompted the utilities and the regulators to re-examine the performance of this class of breakers in the nuclear power plants. After the McGuire event in 1987 relating to the failure of the center pole weld in a reactor trip breaker, several activities were started to determine the root cause. The results indicated that there were inadequate procedures for the manufacture of these pole shafts. In addition, the utilities were not given information on the life of various subcomponents; therefore, they are not replaced or refurbished in time to avoid impending failures. In addition, the maintenance programs among utilities are not uniform. One of such studies refers to volume 1 of this NUREG and the study relates to the Westinghouse DS-series (DS-206 and DS-416) breakers typically used in Class 1E applications in nuclear power plants. One specific application of concern to both the utilities and the NRC is the reactor trip breakers.

From an evaluation of operating experience (Ref. 1), the predominant subcomponents that frequently exhibited failures are the contact assemblies, operating mechanisms, and control devices such as closing coil, shunt trip attachment (STA) coil, and under-voltage trip attachment (UVTA) coil. The age of the breakers is characterized by the number of breaker cycles experienced, rather than the actual service life. Normal wear, overheating, and out of adjustment dominate the aging processes.

The study also verified that the burning of contact surfaces and erosion in the arc chutes as a result of arcing during closing and tripping the breaker are well understood by both the manufacturers and utilities. Therefore, in most plants these subcomponents are regularly cleaned or replaced depending on the service conditions. Failure data shows that some breaker failures are attributed to deteriorations of the contact point. However, maintaining the operating mechanism including all parts that are responsible for charging, closing, and tripping the breaker, has been a problem to the nuclear industry. Unlike other industries, the breakers used in this industry are typically subjected to many operating cycles due to the statutory, maintenance, and safety requirements. The lack of knowledge in predicting the life of various subcomponents within the breaker assembly, specifically the operating mechanism, leads to many of the failures reported by the plant. In addition, substandard parts and improper maintenance have exacerbated this problem.

1.2 Purpose

The purpose of this testing was to identify age-related degradation that occurs in the Westinghouse DS-series breakers that may impede their functions. In addition, maintenance practices to manage aging were evaluated so that the breaker could be refurbished or repaired before any impending failures.

Since the study on the Westinghouse DS-series breakers was promulgated by the McGuire reactor trip breaker event, one of the ancillary objectives was to confirm the fact that this incident, caused by the fracture of the center pole lever weld, was due to excessive breaker cycles on a substandard weld. These results were further analysed to assure the adequacy of the recommendations provided in the NRC bulletin 88-01 to remedy the problem of weld fracture.

Other objectives of the test program included determining the service life of various breaker subcomponents or predicting the remaining life of the breaker assembly, and recommending the frequencies and the types of maintenance activities.

1.3 Scope

To achieve the above objectives a commercial grade Westinghouse DS-416 circuit breaker was acquired for the testing. In addition, two operating mechanisms were purchased as commercial grade from Westinghouse; other spare parts for other subcomponents were procured from another vendor. For evaluating the weld characteristics in the pole levers, three pole shafts were purchased; one was cut to simulate a 60 degree weld size. Thus, the three test shafts represented the center pole lever welds of approximately 60, 120, and 180 degrees, respectively.

Before starting the program, a plan describing the details of the test program was written (see Appendix A). A test stand with a control panel was built to provide controls to the test set. Each of the pole shafts was instrumented with dynamic strain gages to indicate the forces on the welds during charging, closing, and tripping the breaker (see Appendix B). Thermocouples were installed on the closing coil to monitor its temperature.

The first test started with the pole shaft containing the sixty-degree center pole lever weld. Throughout the program the breaker was subjected to 500 and 1000 cycle maintenance. This protocol is in concurrence with the industry standard (ANSI/IEEE Standard C-37.50, 1981) for life testing of an electrical devices such as circuit breakers. The entire test program consisted of over 36,000 cycles of the original breaker unit over 9 months. The major events that occurred were detachment of weldments in the first pole shaft, cracking of weldments in the second and third pole shafts, and the break down of three separate operating mechanisms. Minor events including repairing or refurbishing other breaker parts such as broken springs, burnt motors and coils; a cracked shaft lever bar were also noted. The structural components and the main contact assemblies never needed replacement during this test.

Cracks in the welds of the pole shaft levers were closely monitored with dye-penetrant tests to characterize the growth of the crack. Following the complete separation of the welds from the shaft, each fracture surface was further subjected to metallurgical tests to determine the root cause and the mechanism. Broken hooks in the reset springs and complete fracture of a pole pin were also included in this examination. The results of the analysis of these failures are summarized in Appendix C.

Periodic maintenance activities during the testing were commensurate with typical plant practices including lubricating, cleaning, testing, and inspections. In fact, the BNL procedures were based on an operating plant maintenance procedures and the recommended programs by the Westinghouse Owners' Group for the reactor trip breakers (Ref. 2). The test plan in Appendix A contains such details.

During each maintenance period, all relevant parameters were measured and/or tested for the trending of the subcomponent degradation. These parameters included electrical tests (such as meggering the coil insulation), measurement of certain physical parameters inside the operating mechanisms, wear of rubbing surfaces, spring characteristics, and alignments of the pole levers and the pole contacts.

One of the limitations in this test program is the exclusion of the environmental effects, both from the external atmosphere and the heat generated from arcing of the contact points during closing and opening the breakers. The use of a commercial-grade breaker and its parts has been questioned regarding its lack of quality assurance. However, a close comparison of all parts and operation of the test breaker with the refurbished reactor trip breaker from the McGuire plant, and discussions with the manufacturer who visited the test facility and examined the breaker eliminated any doubts on its quality. From a technical point of view, the test breaker was built as well as a Class 1E breaker typically used in nuclear power plants.

This report is organized in six sections. Section 2 discusses the test program, and section 3 contains the test parameters periodically measured for monitoring the breaker's performance. Section 4 summarizes the test results for each component that indicated age-related degradation. An aging analysis of the breaker assembly is discussed in Section 5, including mitigation techniques that can counteract aging. Finally, section 6 provides the conclusions and recommendations for improving the reliability of circuit breakers.

2. DESCRIPTION OF THE TEST PROGRAM

A Westinghouse DS-416 low voltage power circuit breaker, originally manufactured as a commercial grade DSL-206 style breaker in February 1981 (Westinghouse Shop order 49Y7062), was acquired for life testing from a vendor who had a stock pile of these units originally bought for off-shore drilling. In addition, three pole shafts, two operating mechanisms, several control coils, two charging motors, a trip shaft, and other miscellaneous items were purchased. In contrast to the original plan, one breaker unit was cycled for the entire test duration with appropriate refurbishment of parts as needed. The life of each subcomponent within the test breaker was monitored. We note that the statistical sample size of events are limited based on one test set up, and hence, any conclusions drawn should not be construed as generic. However, these results when viewed with the frequent problems seen from the plant operating experience should provide a guideline in developing appropriate aging mitigation programs for this class of breakers.

As described in the test plan (see Appendix A), the original goals of this test program were to establish the causes for the failure of pole shaft weld similar to those of the McGuire reactor trip breaker, and to determine the adequacy of the recommended inspection criteria in the NRC bulletin 88-01. In addition, we planned to monitor the conditions of other breaker components to assess aging degradation that could affect the performance of the circuit breaker.

2.1 Test Set-up

Before the test, the circuit breaker was disassembled to measure all critical dimensions, inspected for any defects, and photographed (Figures 2-1 and 2-2). This formed the baseline for characterizing aging of subcomponents as the breaker was subjected to test cycles. The breaker was then assembled, lubricated, and adjusted, and tested for normal operation. With the exception of the pole shaft, all the parts used in the first breaker were the original ones. The pole shaft used in this test set-up was purchased separately and the center pole lever weld was cut and ground to leave an effective welding material for an approximately 60 degree weld in circumferencial length.

Later in the test, individual parts that had failed were replaced with new components. The operating mechanism was replaced as a single unit rather than as individual subcomponents. A second pole shaft was chosen with a weld size of approximately 120 degrees, and the third one had welds of about 180 degrees.

The breaker assembly then was mounted on a flat surface, leveled, and bolted down to the test table. The arc chutes were removed from the assembly for a clearer vision of the moving parts. Since the testing was limited to mechanical cycling, the arc chutes had no specific function.

A controller was designed and installed to automatically actuate the breaker for a predetermined number of cycles. This controller also was used to record the test cycles, stop and start the breaker, provide mountings for other meters and measuring devices, and, most importantly, harness all electrical connections to insure both electrical integrity and quick disconnects.

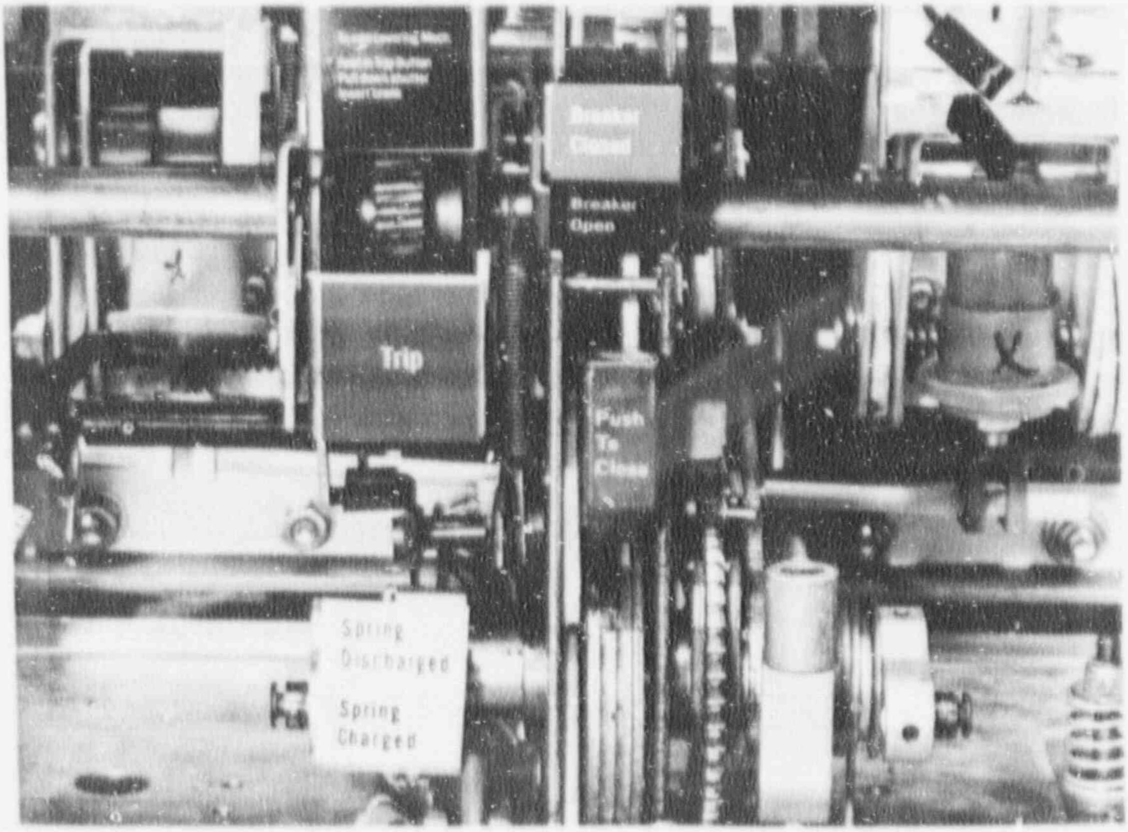


Figure 2-1. Westinghouse DS-416 Air Circuit Breaker

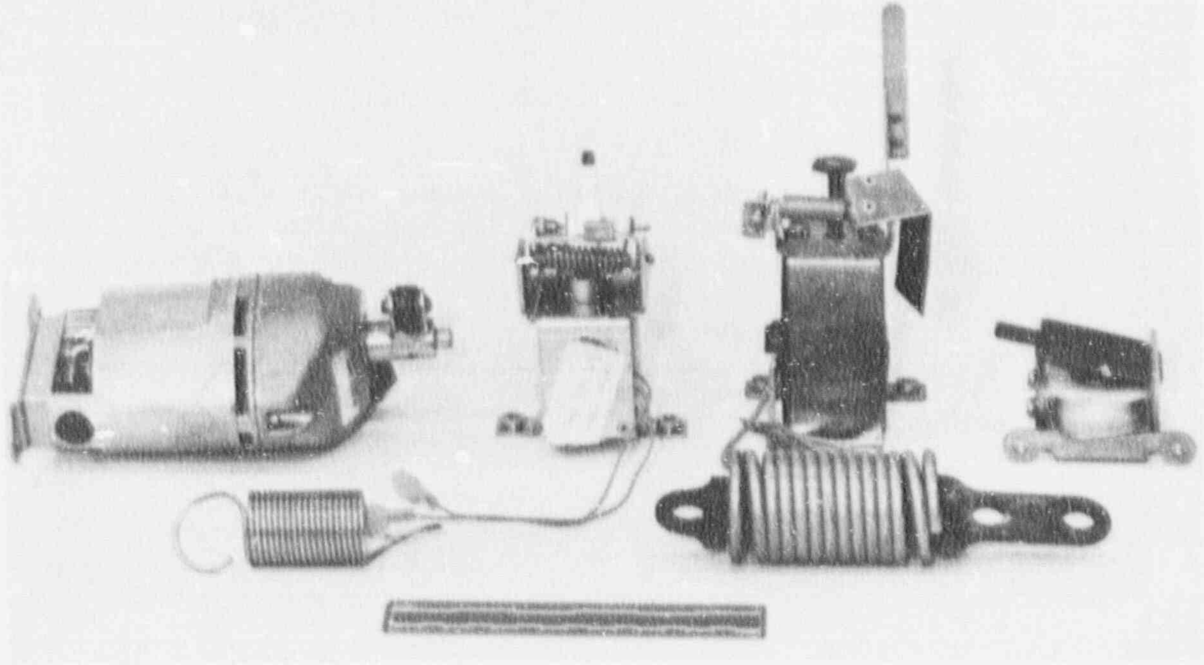


Figure 2-2. Miscellaneous Parts of a DS-Breaker

This controller was consisted of timing and logic circuitry connected to low power driver electronics sufficient to actuate the circuit breaker set and trip function. Figure 2-3 is schematic diagram of the controller. The logic in the circuitry permitted the controller to detect malfunctions. Other devices included in this controller were a timer for the shunt trip, a timer and a rectifier for the cycle counter, temperature recorder, thermocouples, indicator lights, toggle switches, fuses, and receptacles for 120 Vac. The test control panel contained the control equipment that was used for obtaining shaft torque through strain gages and the associated equipment.

Each pole shaft was instrumented with strain gage rosettes and the corresponding control equipment was connected to directly read the torque on the shaft at any instant. The details of this arrangement are given in Appendix A and some discussions of dynamic strain gage analysis in Appendix B.

Figure 2-4 shows the overall test set up of the breaker assembly, the controller, and other test equipment.

2.2 Test Equipment

One of the most complicated tasks in testing and monitoring the breaker performance is to instrument the breaker parts to measure their condition. The undervoltage trip attachment was energized for the entire test. The dropout voltage was measured periodically. The main electrical contacts also were monitored for dimensional stability. Furthermore, the main contacts were tested for contact and circuit resistances. Other tests included the coil resistance for the closing coil and its temperature. The shunt trip attachment was also tested for the tripping ability at 55% of the rated coil voltage.

Measurements were made of stresses (or Forces/Torques), clearances, spring stiffnesses, and distortions of the mechanical components. Other physical parameters measured included temperatures, cleanliness, wear, sluggishness, alignments, and cracks. The test plan gave details for obtaining such data.

With the exception of the measurement of torque on the pole shaft, other parameters required no elaborate instrumentation. The forces/torques on the center pole lever weld were monitored with strain gages mounted on the pole shaft between the #2 and #3 levers and by observing both static and dynamic stress signals displayed on an oscilloscope while the breaker was operating. The details were documented in four separate reports (Ref. 3) covering various phases performed by Alkem Research and Technology Inc: a summary is included in Appendix B.

The steps involved in monitoring forces on welds in the pole shaft were as follows:

- Assessing the strain measurement requirements
- Identifing and specifing the required strain gage components
- Developing a procedure for attaching the gages and testing
- Preparing instrumentation electronics for calibration, testing, and operating experiments

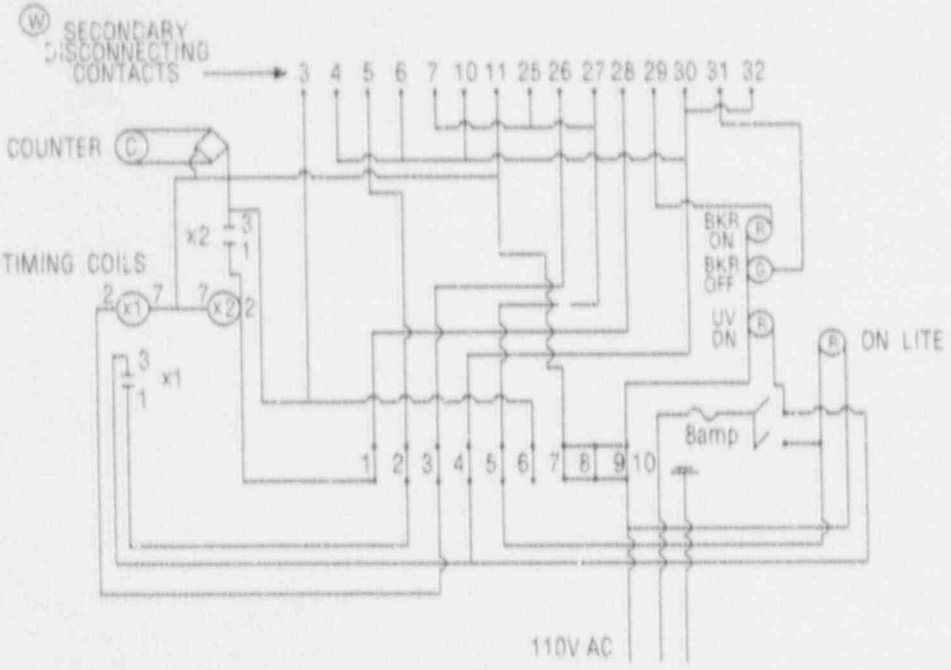


Figure 2-3. Control Circuit Diagram of the Automatic Controller

Figure 2-4. Experimental Setup for the DS-416 Testing

- Attaching gage clusters on the test shaft and electronically evaluating the quality of the signal for amplitude, signal-to-noise, and calibration
- Assessing results for guiding calibration sample
- Attaching the gage cluster to first breaker shaft, then testing and calibrating.
- Attaching the final gage cluster on test fixture
- Establishing electronic interfacing and monitoring.

The last three steps were repeated for every new shaft used in the program. Also, the entire arrangement was periodically checked for its accuracy and calibration. The equipment list used for this particular monitoring were:

- Oscilloscope Tektronix 2215
- Scope Camera Tektronix C5B
- Multimeter Backman 3010
- Precision Multimeter Hewlett Packard 3468A

Other test equipment and tools used for testing, measuring or manipulating the test parameters include;

- Megger HW Sullivan T2900 Biddle 212900
- Variac Techni Power W5MT3
- Calipers Mitutoyo 505-626-50 (Inside/Outside)
- Temperature Indicator Omega CN 9111
- Multimeter-Auto Ranging Keithley 168
- 1" Micrometer Mitutoyo No. 103-127
- Special Long Vernier Calipers Brown & Sharp 571
- Spring Scales A to 50 lbs
- Spring Scales B to 70 lbs
- Thickness Gauge Starrett # 66T

2.3 Test Procedure

The test was designed to be performed in divided segments for three separate breaker units, each containing a predetermined weld size of the center pole lever of the pole shaft. The life of each set up was to be limited by either the failure of the weld or 10,000 cycles, whichever occured first. This protocol was later modified to one breaker unit for the entire duration of the test and the breaker was refurbished with new parts as needed to bring it to its original condition. The program included three different pole shafts with different weld configurations, three similar operating mechanisms, and other components.

The test was conducted according to the life testing requirements of the ANSI/IEEE Standard C-37.50 (1981) on the circuit breakers. The close/trip period for breaker in between cycles was a minimum of two minutes. Every 500 cycles the breaker had a minor maintenance as outlined in the test plan. Thus, the condition of the test breaker was maintained in operationally ready condition throughout the life of the breaker. After every 1000 cycles several breaker tests were performed to obtain the component aging parameters discussed earlier. These parameters then were trended to determine the aging characteristics of the breaker component. Each time either the pole shaft or the operating mechanism was inoperable and replaced, the test breaker was examined, overhauled, photographed, and refurbished before its next test sequence.

Before the start of the test, the breaker was examined, baseline data for each subcomponent were measured, and it was tested for proper mountings and connections. These activities were completed when the breaker had already experienced about 27 cycles. The counting of cycles started at zero from the day the breaker was acquired from the vendor. The total number of cycles operated on the breaker was over 36,000. A list of all the events observed or experienced during the entire duration of the test was documented; the age of the breaker was characterized by the test cycle.

The shaft of the first two pole shafts with 60 and 120 degree welds in the center pole levers was examined during each 1000-cycle maintenance and tested with dye-penetrants for cracks in any of the seven welds on the shaft. The results were compared with the original baseline data and with previous readings for monitoring the crack growth between the shaft and the levers. The third shaft with an almost perfect weld (approximately 180 degree) was only examined pre- and post-testing for cracks. All breaker components that fractured during the test were further examined at the BNL Material Science Laboratory to determine the root causes and other metallurgical defects that had caused the component to fail. Appendix C summarizes these findings.

Each time the breaker failed to function, cycling was interrupted and the root cause was investigated. Depending on the severity of the problem, the breaker was repaired or refurbished to bring it back to operation.

3. MONITORING OF BREAKER PERFORMANCE

The overall integrity of the breaker was monitored by periodic inspections and tests of various structural, mechanical, and electrical components. Since this test was limited to mechanical cycling in a laboratory, most of the monitoring techniques were focussed on aging degradation induced by mechanical stresses. The age of a breaker component was characterized by the number of test cycles it had experienced before its impending failure.

Table 3.1 summarizes the effects of mechanical cycling on various components. In addition to operator-related problems, two conditions can induce degradation in the breaker; these are the environment of the surroundings and the heat generated by full load operation and the arcing process associated with the closing and tripping of the breaker. As discussed earlier, the environment in a nuclear power plant is relatively benign and, hence, considered to have minimal effect on the degradation of the breaker's component. The arcing of contacts affects the contact assembly, arc chutes, electrical sensors, and other electronic control devices. These problems are well recognized by the utilities as is evident from their maintenance programs; hence, aside from measuring contact dimensions and routine megger tests, they were not considered in this test program.

The components that were monitored during this test program included the welds of the pole levers on the pole shaft, various elements of the operating mechanism (such as springs and cam), breaker contact assembly, alignments of the breaker poles, and other miscellaneous devices such as the closing and shunt trip coils, UVTA coil , charging motor, the auxiliary switch and electrical connections.

3.1 Pole Shaft

The pole shaft is constructed of a round steel shaft and seven levers welded on to it. With exception to the levers 4 and 5 (see Figure 3.1), the other five levers are connected to the moving contact assemblies for the three poles. The #3 and #4 levers are also connected to the main drive link which, in turn, is connected to the operating mechanism via the main roller and cam assembly. The #5 lever is for the auxiliary switch drive link. Thus, when the breaker is closed, or tripped, the stored energy in the closing and/or opening springs rotates the pole shaft to the appropriate positions. Therefore, the welds on the shaft are subjected to torsional forces; weld #3 being the only lever connected to the charging mechanism and the pole, has the worst stress.

Strain gages were attached to the pole shaft and monitored dynamically to observe the changes in the torsional forces while changing the breaker states. The objective was to derive information indicating changes in performance and operation that can be correlated with initiation and growth of cracks in the welds (see Appendix B).

The initiation and growth of the cracks in all seven welds were monitored by performing dye-penetrant tests after each 1000-cycles of testing. Once the crack was initiated, this interval was adjusted to reflect its growth rate.

Table 3-1. Effect of Mechanical Cycling on Breaker Components

BREAKER COMPONENTS	STRESSORS	SIGNS OF AGING (SYMPTOMS)	COMMENTS
STRUCTURAL INTEGRITY			
Frame Assembly	Mechanical Vibration	Loose Fasteners, Distorted Structure	Environmental effect minimal, Switchgear cabinet not included in the test
MECHANICAL INTEGRITY			
Power Operated Mechanism*	Mechanical Stresses	Wear of Contact Surfaces, Distortions, Fractures, Misalignment	Heat effect due to arcing not included, Environmental effect minimal
Contact Assembly	Mechanical Stresses	Wear, Misalignment	Heat effect due to arcing not included, Periodic replacement of contacts mitigate other aging problems
Arc Chutes	None	None	Burning/erosion by heat due to arcing not included
ELECTRICAL INTEGRITY			
Amptector Trip unit	None	None	Not included in this test
Sensors	None	None	Not included in this test
Actuators	Mechanical/ Electrical Stresses	Coil Burning, Sticking Links, Insulation Degradation,	Environmental effect minimal

*This category includes the charging assembly, operating mechanism, and its tripping assembly. The charging assembly includes the motor, crankshaft, and associated parts. The triping mechanism includes the trip shaft, trip latch, roller constraining link, and STA. The cam assembly, main drive link, pole shaft, an oscillator and associated likages constitute the operating mechanism.

To characterize the life of a weld, we used three different shafts with 60, 120, 180 degree welds in the center pole lever. The first shaft, with a 60 degree weld, was prepared by grinding the excess welding material from the original weld. The second and third shafts were carefully chosen from other breakers so that no preparation was needed.

3.2 Power-Operated Mechanism

The power-operated mechanism is the primary element in charging, closing, and tripping the breaker (Figure 3.2). The terms identified in the figure are used throughout this report for referring to individual breaker components. This mechanism operates by a charging motor via a

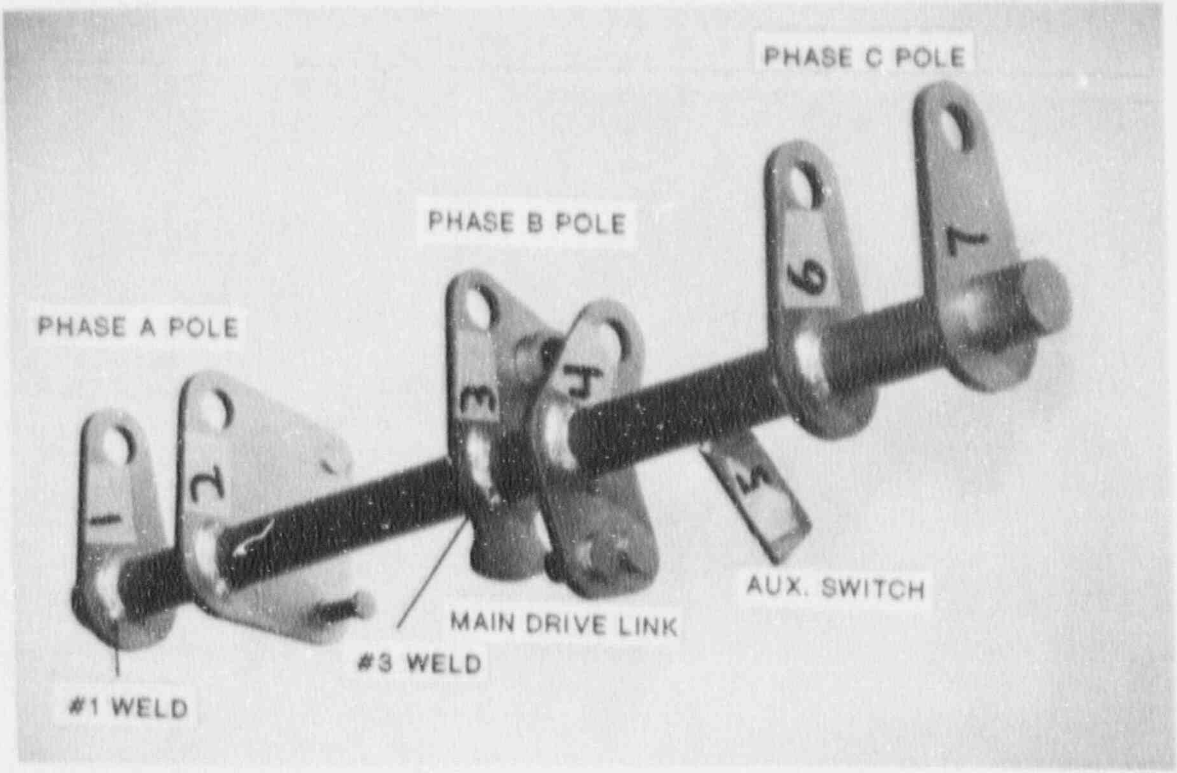
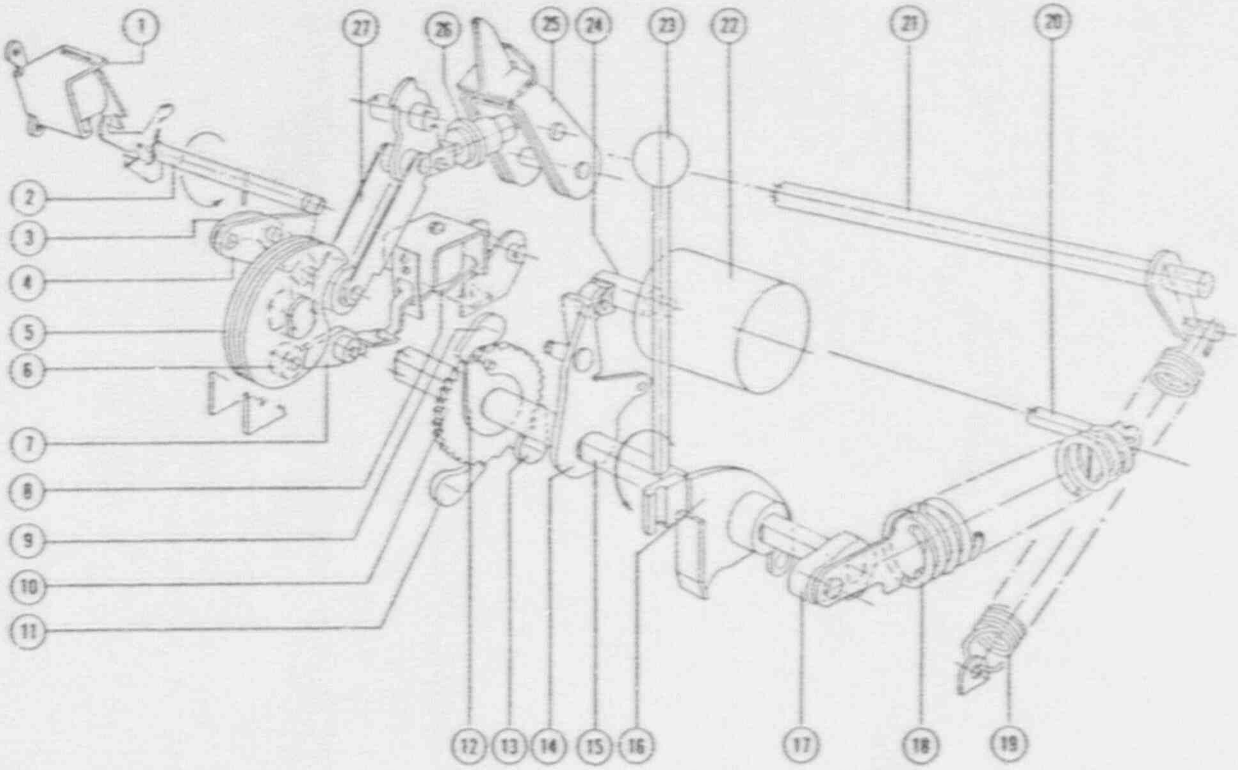


Figure 3-1. Pole Shaft with Seven Levers Welded on to it

ratchet wheel and oscillator arrangement. If power is lost this mechanism also can be operated by hand. The closing springs attached at both ends of the crank shaft are used as stored energy, while the ratchet wheel is cranked to rotate the close cam to a specific position. On command from the control unit, the spring release device is energized to close the breaker instantly to reduce arcing between the main contacts. At the same time, the main opening springs in each pole base assembly and one opening spring at one end (Phase C side) are charged by the movement of the pole shaft levers. The cam assembly is also connected to a trip shaft and associated control devices such as shunt-trip attachment and undervoltage trip attachment. To trip the breaker, the control devices rotate the trip shaft which rotates the cam to release the stored energy in the opening springs.

The aging of this assembly due to mechanical cycling predominates in degradation of the breaker. All moving elements of a breaker assembly are in some way connected to this power-operated mechanism. Thus, its failure or malfunction can lower the breaker's performance. Although this assembly is designed for the 40 years life of the plant, frequent cycling has resulted in premature failures due to its degradation.



1. SHUNT TRIP DEVICE
2. TRIP SHAFT
3. ROLLER CONSTRAINING LINK
4. TRIP LATCH
5. CLOSE CAM
6. STOP ROLLER
7. SPRING RELEASE LATCH
8. SPRING RELEASE DEVICE
9. OSCILLATOR PAWL
10. RATCHET WHEEL
11. HOLD PAWL
12. DRIVE PLATE
13. EMERGENCY CHARGE PAWL
14. OSCILLATOR
15. CRANK SHAFT
16. EMERGENCY CHARGE DEVICE
17. CRANK ARM
18. CLOSING SPRING
19. RESET SPRING
20. CLOSING SPRING ANCHOR
21. POLE SHAFT
22. MOTOR
23. EMERGENCY CHARGE HANDLE
24. MOTOR CRANK AND HANDLE
25. MOVING CONTACT ASSEMBLY
26. INSULATING LINK
27. MAIN DRIVE LINK

Figure 3-2. Details of the Power-Operated (Stored-Energy) Mechanism
(Close Spring shown in the Charged Position)

All bearing surfaces associated with this mechanism and those with other peripheral components were periodically examined and lubricated as a part of the 500 cycle maintenance schedule. The lubricant initially used was molycote BR-2 Plus, recommended by the manufacturer. Graphite grease was also applied, when needed, to the breaker auxiliary switch contacts (as recommended by the Westinghouse Owners Group).

When the breaker is being charged by the manual handle or the motor, force is transmitted to the ratchet wheel, and then to the close cam. Thus, the components experiencing excessive wear due to mechanical cycling are the motor crank and handle, ratchet wheel, oscillator pawl, emergency charge pawl, close cam, and stop roller. Regular inspection of these components for any sign of wear was conducted throughout the test. Distortion of linkages, changes in various clearances between elements of the operating mechanism, adjustments, alignments and change in tolerances were monitored for early signs of aging.

3.3 Other Components

In addition to the various elements of the power-operated mechanism and the pole shaft, other components become energized or activated during the cycling of the breaker. These components include the electrical and control devices, springs for storing energy, small springs providing mechanical control, the trip shaft and associated subcomponents, drive motor, and moving contacts. Most of these parts have moving elements and any resistance to their motion can lead to breaker malfunction.

The closing coil, shunt trip attachment coil, and UVTA coil were closely monitored for any unusual rise in temperature due to resistance heating. At the beginning of the test, all these control devices were 120 volts ac-powered, and later were replaced with 120 volts dc-powered coils to simulate most safety-related components in nuclear power plants. In addition, the insulation resistance of the coils was measured periodically for any breakdown.

The wear in carbon brushes in the charging motor was also monitored, along with the motor shaft attachment to the crank and handle.

The three large springs used for storing energy for closing and tripping the contacts were periodically tested for their spring constants at first. Later, when it was established that the aging of these components was inconsequential, testing was discontinued.

The attachments to the moving contact assemblies for the three poles were periodically checked for any change due to mechanical vibrations and impacts exerted upon them during each test cycle.

3.4 Breaker Contact Assembly

The three main poles of the DS-416 breaker are mounted on individual molded bases, which have the contact parts and sensors mounted on it. Each pole is connected with individual insulating bases and all are aligned within a welded frame. Detail discussions are included in Volume 1 of this report (Ref. 1).

Since the breaker was not tested for degradation caused by arcing at the contacts, only the overall condition of the three pole assemblies was inspected at each 1000 cycles for any change in their settings.

3.5 Alignments

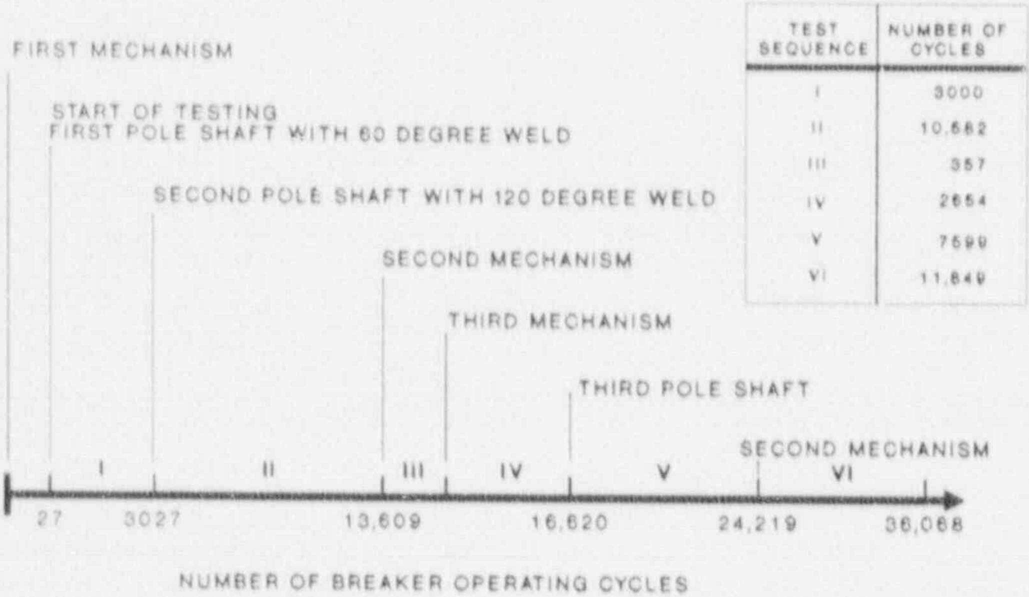
The alignment of the breaker pole assembly both at the pole shaft and the stationary poles was periodically inspected and, if needed, adjusted as part of the maintenance activity. The operating mechanism and its associated subcomponents were also checked against any misalignment during each maintenance.

4. TEST RESULTS

One of the problems that promulgated this study was the cracking in the welds of the pole levers to the pole shaft. Based on previous investigations and the utilities' responses to the NRC Bulletin, it was found that a large number of this class of breakers did not pass the inspection criteria (Ref. 1). Most failures were attributed to the lack of quality control in the welding process and/or excessive use in the plants. Our test results on the pole shaft are assessed to verify some of these conclusions and to characterize weld cracks as the breaker gets older.

Aging degradation in other breaker components is also analysed to determine the dominant aging mechanisms that can impede their function, and to assess their useful life so that appropriate maintenance can be performed on components with impending failures. In this section we discuss the operating mechanism and its peripheral components such as trip bars, charging elements, electrical motor, control coils and associated mechanical links. We also discuss aging in structural components, the wear and misalignment of the pole contact assembly, evaluation of the breaker maintenance practices, and anomalies and limitations.

Figure 4.1 illustrates the sequence of major events that took place during the nine months of the test. The first 27 cycles occurred during the pre-testing period with the first operating mechanism in place. Next, the first shaft with the 60 degree weld was installed on the third pole lever; the test then started with automatic cycling. The shaft failed after 3000 cycles of operation when the center pole lever was completely separated from the shaft; this period was designated as Test Sequence I. The test resumed with the second shaft with a 120 degree weld, but the operating mechanism remained the same. After 10,582 cycles (Test Sequence II) the operating mechanism failed. The second mechanism was installed and the test was resumed. Because of a burr on the crank shaft due to poor quality assurance during manufacture, the mechanism failed



TEST SEQUENCE	NUMBER OF CYCLES
I	3000
II	10,582
III	357
IV	2654
V	7599
VI	11,849

Figure 4-1. Sequence of Major Events in the Breaker Testing

after only 357 cycles (Test Sequence III). It was then replaced with the third mechanism for next 2654 cycles (Test Sequence IV). The defective unit was repaired and was kept for later use. At the end of this period, the second pole shaft was inoperable. In this case, the pole levers never separated from the shaft; however, cracks in the first and third welds had extended to 4mm in lengths causing misalignment between the five levers on the shaft. The second shaft was then replaced with a third unit containing a set of good welds and the test continued for another 7599 cycles (Test Sequence V), when the third operating mechanism failed. In the final Test Sequence VI the second mechanism was reinstalled and the test was continued for 11,849 cycles with the third shaft until the mechanism failed at 36,068 cycles. Table 4.1 lists the events that occurred during each Test Sequences.

4.1 Weld Evaluation in Pole Shaft

Three separate evaluations were performed to assess the weld failures on the pole shaft. Strain gage readings were analysed to develop dynamic properties of the charging/closing and opening torques on the pole shaft. The readings were compared with those produced by Westinghouse. Secondly, test results from the three shafts were evaluated to characterize how crack growth separated the weld material from the shaft. Finally, the effects of weld failure on other mechanical linkages and electrical devices were studied to determine root causes of the most frequent breaker problems.

4.1.1 Dynamic Forces on Welds

In 1987, Westinghouse presented their test results on actuation torque signatures for a set up involving five members of the linkages for opening and closing the breaker. The test was mounted on a table and was cycled in 90,000 simulated breaker operations over a series of tests; shaft actuation was solely through the pole shaft lever. Details of these tests are not available. However, the peak torques reported were +814 in-lb on closing and +614 in-lb on opening, and the range was +814 in-lb to −692 in-lb. The conclusion drawn from these tests was that a good 10% of an as-designed 180 degree weld would be adequate to function during its design life.

At the beginning of our test an effort was made to duplicate these torque signatures. This was not possible because the details of the Westinghouse tests were unavailable. It was not clear whether these torques were measured at the weld itself or an inch away from the weld as was the case at BNL. The durations for closing and opening the breaker were also different. These differences were later assessed to be due to the different set ups; BNL tested the entire breaker, while Westinghouse tested only five members mounted on a fixture on the test table. Thus, their test had more control on the movement of the pole shaft than that of BNL's tests. Furthermore, the reduced closing forces were due to the original design of the test breaker as a DSL-206 breaker. In spite of these differences, the profiles of the signatures exhibited similar characteristics.

Table 4.2 summarizes torques on the first pole shaft for the beginning and before failure cycles of the test breaker. The average closing torque range remained almost unchanged at 340 to 373 inch-lbs in the later part of the shaft life, while the opening torque range averaged more than doubled from 400 to 840 inch-lbs. This change in the tripping torque occured at about 2000 cycles on the shaft and the crack in the weld separation had grown to 3.18mm in circumference. Figures 4.2 and 4.3 illustrate the strain gage signatures for the torque on the shaft representing the beginning and final part of its life, respectively. Comparing these two figures, a change in

Table 4.1 Sequence of Events in the Breaker Testing

TEST SEQ.	DATE	CYCLE COUNTER READING	TEST CYCLE #	OPER. MECH. CYCLE #	POLE SHAFT CYCLE#	EVENTS
	February 1989		27			Pre-Test Cycles with First Operating Mechanism
I	3/2	998,683	57	57	30	First Pole Shaft Installed/Pre-Tests Performed
	6/15	998,806	180	180	153	Automatic Cycling Started
	6/22	999,653	1027	1027	1000	Crack Initiated, Size = 2.36 mm
	6/30	000,653	2027	2027	2000	Crack Grew to 3.18 mm
	7/18	001,153	2527	2527	2500	Crack Grew to 4.24 mm, Bent Pole Shaft Arm
	7/19	001,285	2659	2659	2632	Trip Mech. Jammed
		001,361	2735	2735	2708	Breaker would not Lock In
	7/20	001,480	2854	2854	2827	Breaker would not Trip
	7/21	001,653	3027	3027	3000 (Pole Shaft Life (60°Weld))	Center Pole Lever Weld Detached
II	8/1	001,653	3027	3027	0	Second Pole Shaft Installed/Test Resumed
	September '89 →					No Tests Performed
	10/18	009,370	10,744	10,744	7717	Oscillator Pawl Hung Up
	10/26	010,623	11,997	11,997	8970	Motor Brushes needed Cleanup. Crack Initiated in both Weld #1 and Weld #3. Crack Sizes #1:.69 mm, #3:.65 mm
	11/1	011,653	13,027	13,027	10,000	No Change in Crack Sizes
	11/8	012,235	13,609	13,609 (First Oper. Mech. Life)	10,582	Motor Completely Burned Out. First Mechanism Failed to Operate
III	11/14	012,235	13,609	0	10,582	Second Operating Mechanism Installed/Test Resumed
	11/17	012,592	13,966	357 (See Test Seq. VI)	10,939	Motor Cutoff Switch Cam Jammed Due to a Burr on the Crank Shaft. Mechanism was taken out for Repair

Table 4.1 Sequence of Events in the Breaker Testing (cont'd)

TEST SEQ.	DATE	CYCLE COUNTER READING	TEST CYCLE #	OPER. MECH. CYCLE #	POLE SHAFT CYCLE#	EVENTS
IV	11/27/89	012,592	13,966	0	10,939	Third Operating Mechanism Installed/Test Resumed
	11/30	013,594	14,968	1002	11,941	Cracks Grew by 1.75 mm in #1 Weld and by 0.55 mm < #3 Weld
	12/6	014,594	15,968	2002	12,941	Misalignment in the pole levers due to cracks in welds. Cracks grew by 1.05 mm in #1 weld and by 1.25 mm in #3 weld.
	12/8	015,246	16,620	2654	13,593 (Pole Shaft Life (120° Weld))	Broken Pin on Phase-A Pole. Pole Shaft Bent and Poles Misaligned
V	12/8	015,246	16,620	2654	0	Third Pole Shaft Installed/Test Resumed
	12/21	018,453	19,827	5861	3207	Trip Latch Spring Broke/Replaced
	1/2/90	022,377	23,751	9785	7131	Closing Coil Burnt/Replaced
	1/3	022,845	24,219	10,253 (Third Oper. Mech. Life)	7599	Operating Mechanism Jammed and Inoperable because of Excessive Wear and Distortion/Replaced Closing Coil Burnt/Replaced
VI	1/3	022,845	24,219	357 (See Test Seq. III)	7599	Second Operating Mechanism (After Repairing) Installed/Test Resumed
	1/4	022,950	24,324	462	7704	Motor Burnt/Replaced
	1/8	023,845	25,219	1357	8599	Broken Wire in the UVTA/Replaced
	1/9	023,980	25,354	1492	8734	Motor Brushes Needed Cleaning
	1/10	024,774	26,148	2286	9528	Broken Oscillator Spring/Replaced
	1/12	025,562	26,936	3074	10,316	Broken X-Washer on Right Closing Spring/Replaced

Table 4.1 Sequence of Events in the Breaker Testing (cont'd)

TEST SEQ.	DATE	CYCLE COUNTER READING	TEST CYCLE #	OPER. MECH. CYCLE #	POLE SHAFT CYCLE#	EVENTS
VI Cont'd	2/9/90	034,694	36,068	12,206 (Second Oper. Mech. Life)	19,448	Operating Mechanism Failed Cracks on #1 Weld 6.15 mm and on #3 Weld 10.5 mm
– END OF THE TESTING –						

Table 4.2: Torques on the First Pole Shaft During Closing and Tripping the Breaker

Test Cycles	Closing Torque Range in Inch-Lbs.	Opening Torque Range in Inch-Lbs.
165	260	440
258	380	365
259	380	310
348	380	390
349	310	390
519	320	430
808	310	440
999	380	410
	Average 340	400
2015	470	860
2115	415	910
2484	415	910
2648	390	780
2712	340	880
2804	340	830
2886	310	790
2992	310	780
	Average 373	840

the tripping torque is shown by a sharp peak in the signature. Also, the time taken to trip has increased from about 80 milliseconds to 110 milliseconds. However, the closing time, like the closing torque range, remains unchanged.

Figures 4.4 and 4.5 show similar torque signatures for the Test Sequence II where the first operating mechanism continued to operate and the second pole shaft replaced the first at 3027 test cycles. In this case, both closing and tripping torque amplitude ranges did not change significantly with the test cycles. However, as the operating mechanism started showing significant aging it induced noises with ragged waveshapes. The mechanism failed at 13,609 test cycles. Figure 4.6 represents torques after a new mechanism was installed and shows that the noise levels were reduced. But, as the second pole shaft started showing abnormal behavior due to cracks in its first and third welds, spikes in the tripping signatures reappeared, as discussed earlier (Figure 4.7). Subsequently, the second pole shaft was replaced by a third shaft which had relatively good welds.

4.1.2 Crack Growth in Welds

The first shaft with a 60 degree weld at the center pole lever (#3 in Figure 3.1) had a life of 3000 mechanical operating cycles. At the end of the test, the pole lever was completely detached from the shaft, as shown in Figure 4.8. A crack was first noted at one end of the weld where the weld material was taken out for experimental purposes. At that time the breaker had undergone 1000 operating cycles. Up until 2500 cycles, the effect of this crack was not noticed; at this point the pole shaft was bent. From then, until the end of the test, several problems associated with the

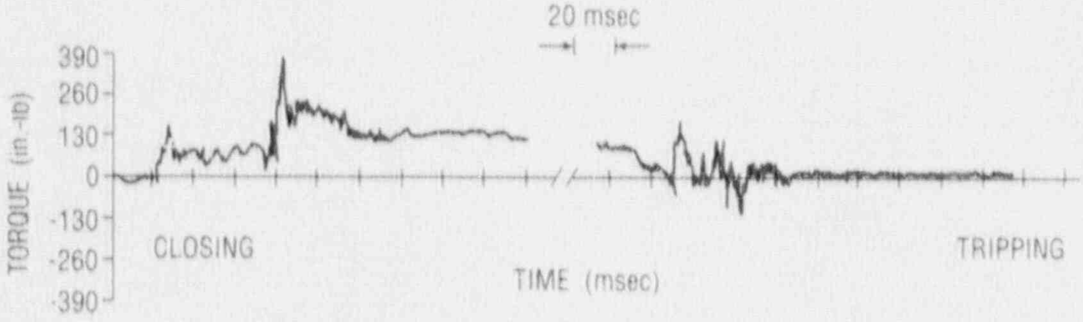


Figure 4-2. First Pole Shaft Torque Signature at 287 Test Cycles (Sequence I – Beginning)

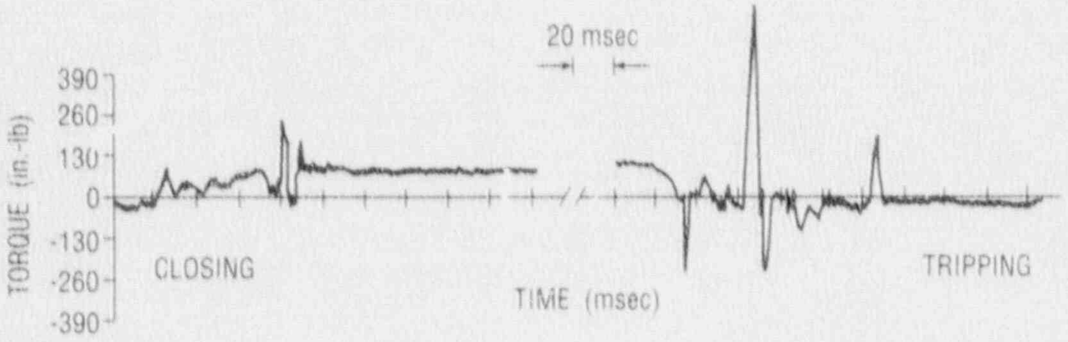


Figure 4-3. First Pole Shaft Torque Signature at 2854 Test Cycles (Sequence I – End)

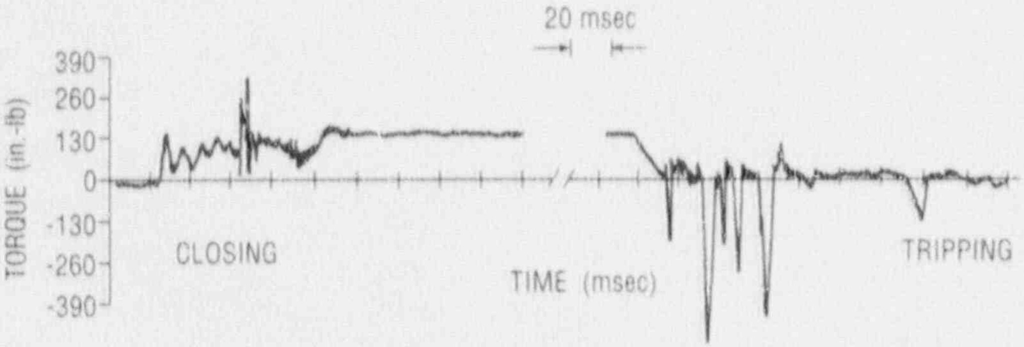


Figure 4-4. Second Pole Shaft Torque Signature at 3027 Test Cycles (Sequence II – Beginning)

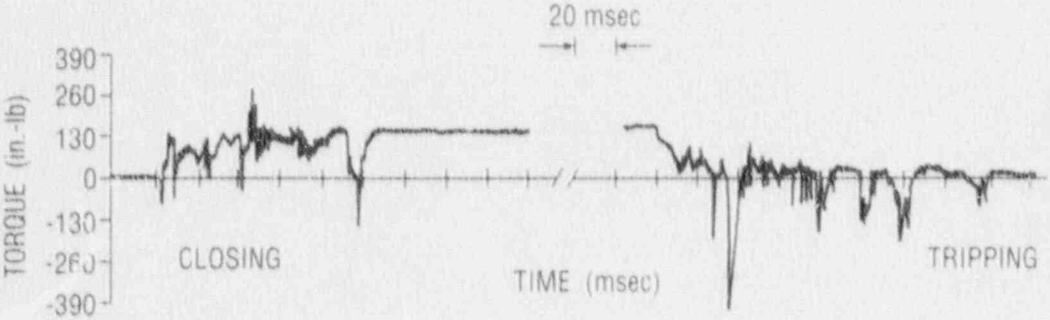


Figure 4-5. Second Pole Shaft Torque Signature at 13,500 Test Cycles (Sequence II – End)

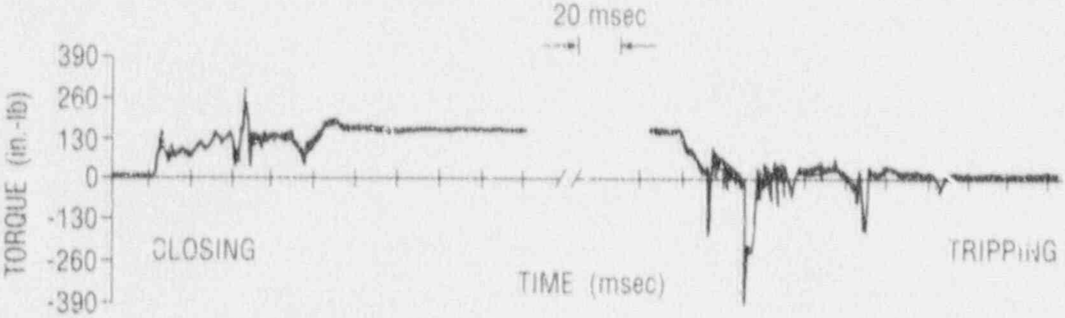


Figure 4-6. Pole Shaft Torque Signature at 13,966 Test Cycles (Sequence IV – Beginning)

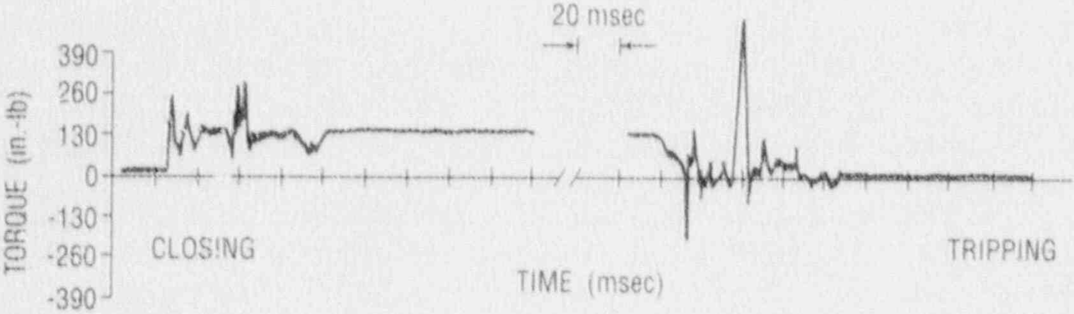


Figure 4-7. Pole Shaft Torque Signature at 15,968 Test Cycles (Sequence IV – End)

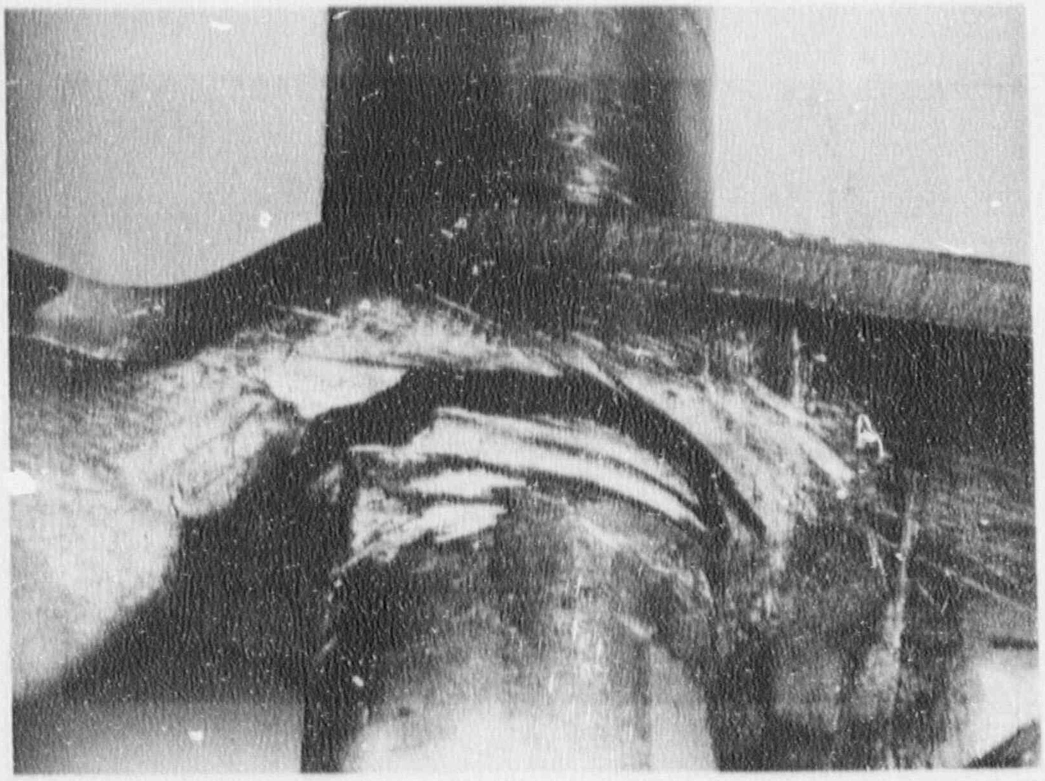


Figure 4-8. Complete Detachment of #3 Pole Lever at 3027 Test Cycle.

operating mechanism were observed, including jamming of the trip mechanism, failure of the breaker to lock in or trip, and sluggish operation.

The second pole shaft with a 120 degree weld size lasted for 13,593 cycles. Two cracks appeared at the levers #1 and #3 welds (see Figure 3.1) simulteneously after the shaft had undergone 8,970 operating cycles. Both cracks grew at almost same rate and reached to sizes of 2.5mm – 3.5mm before the misalignment between the five levers shown in Figures 4.9 and 4.10 caused the end of the shaft life. The event occurred when this pole shaft experienced 12,941 cycles. Problems associated with this misalignment caused the phase A pole pin to break. In between the period when the first cracks were noticed and the misalignment (8,970 to 12,941 pole shaft cycles), the first operating mechanism failed to operate and the motor burned out. In evaluating the data, we attributed these problems to the aging in the operating mechanism rather than to the two cracks on the shaft. These cracks never grew big enough to suggest that there was any change in the torque on the shaft, as was the case in the first shaft, nor did they induce problems with other components attached to the shaft. However, the misalignment caused by the shaft finally fractured the pin.

Metallurgical examinations of the fractured weld surfaces of the first shaft showed slag particles in the weld material (see Figure 4.11), that probably had become included during welding. The cracks in this weld started at these locations and later propagated to completely sepa-

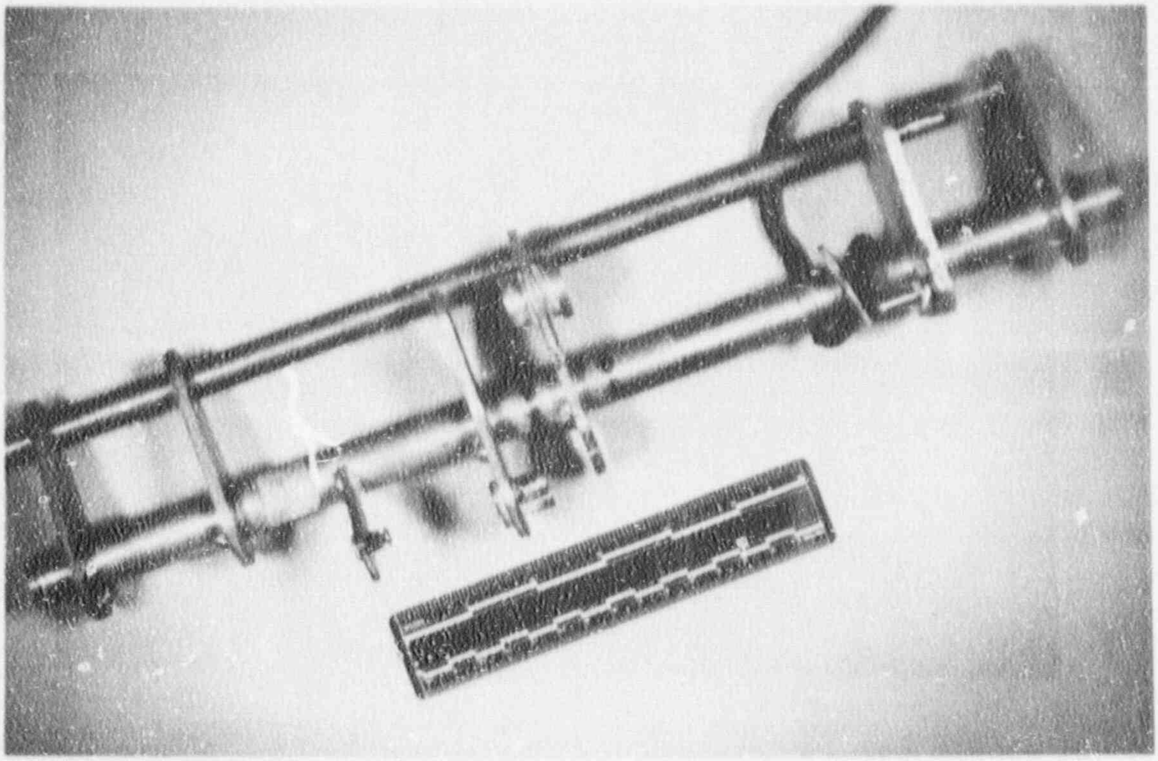


Figure 4-9. Misalignment of Pole Lever #1 from other Levers (#2, #3, #6, and #7).

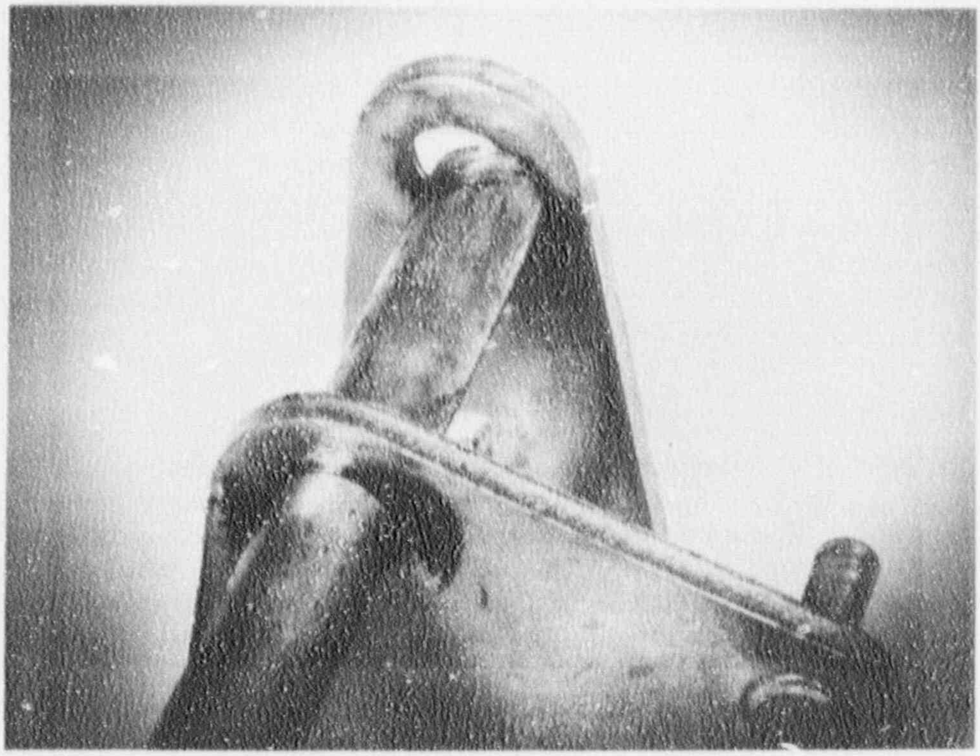


Figure 4-10. Demonstration of the Pole Lever Misalignment Caused by Cracks in Welds #1 and #3.

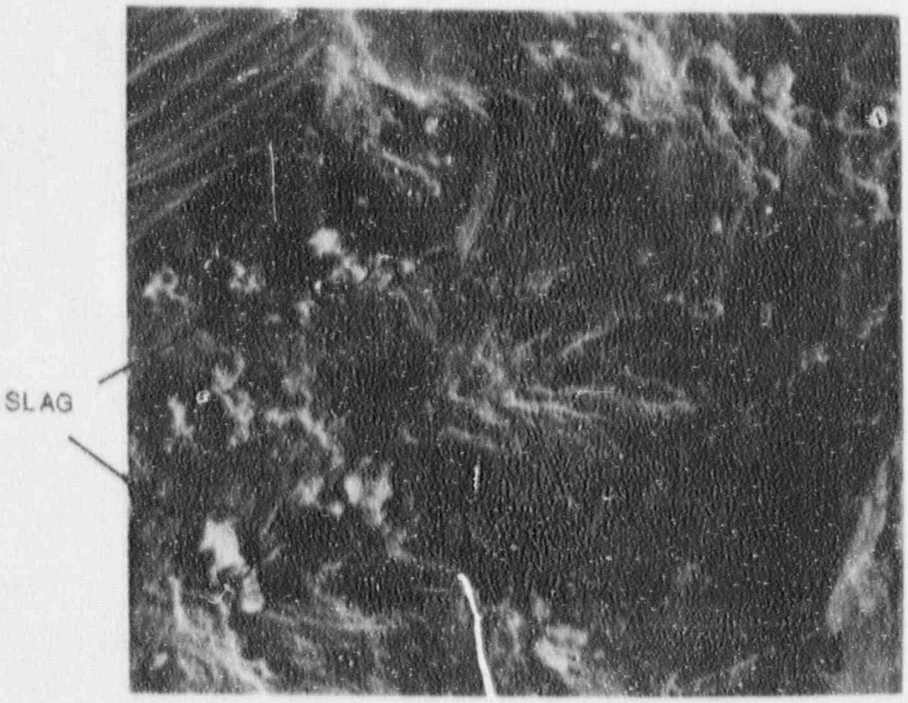


Figure 4-11. Failed Weld Showing Slag Inclusions (Marked in Circles)

rate the weld from the shaft. (Appendix C, section C.2.5 discusses more findings on this investigation.)

The third shaft had a set of good welds and had no problems for over 13,000 cycles. Small cracks associated with the pole shaft levers were observed for the rest of the test period. Surprisingly, the same #3 weld and #1 weld exhibited detachment from the pole shaft.

The crack growths in the first and second pole shafts are plotted in Figures 4.12 and 4.13. The plots show that after the cracks were first detected, another 1000 cycles passed before the growth rate increased significantly. The sharp change in the torque at 2000 cycle shown in Figure 4.12 is presumed to be the beginning of instability at the crack tips

4.1.3 Effect on Operating Mechanism

The operating mechanism is intimately connected to the pole shaft and, in fact, provides the energy stored by the opening or closing springs for rotating the shaft to its desired position. Hence, a misalignment between the five levers connected to the three pole assemblies, and/or the distortion in the shaft itself, caused faster degradation in other components associated with the operating mechanism or the contact assembly. Longer duration for closing or opening of the contacts caused coils to burn out. Larger forces on the main roller caused by the distorted shaft often increases the wear in the closing cam. These larger forces may also increase wear in the oscillator and ratchet wheel if the closing springs are charged when the main breaker contacts are closed and the pole base opening spring forces are added to the normal closing spring forces.

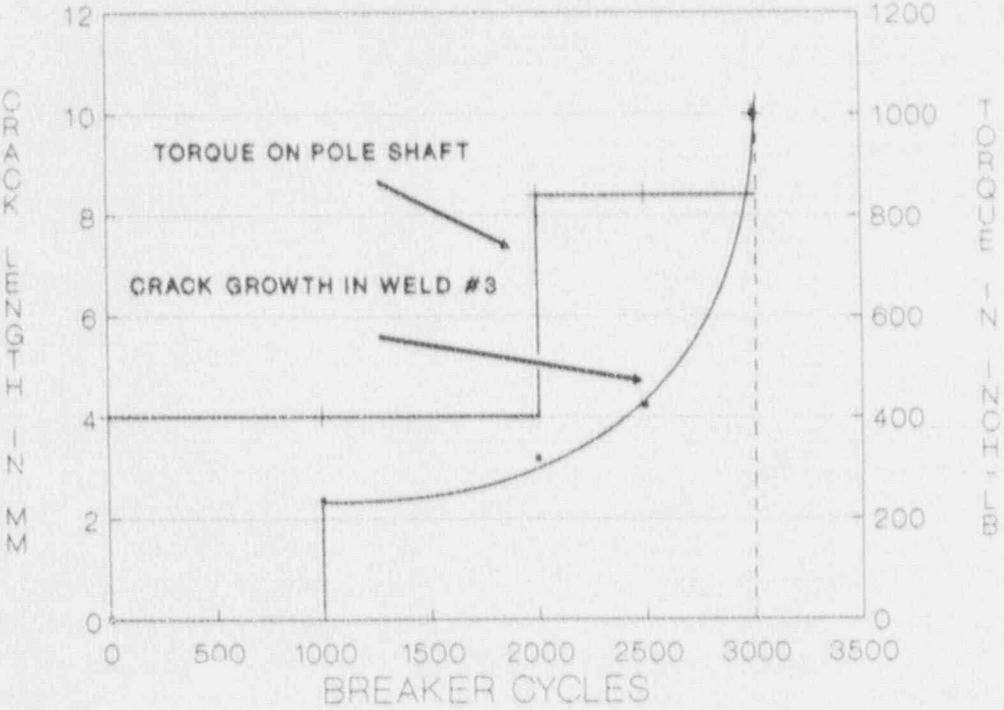


Figure 4-12. Failure of the First Pole Shaft Weld

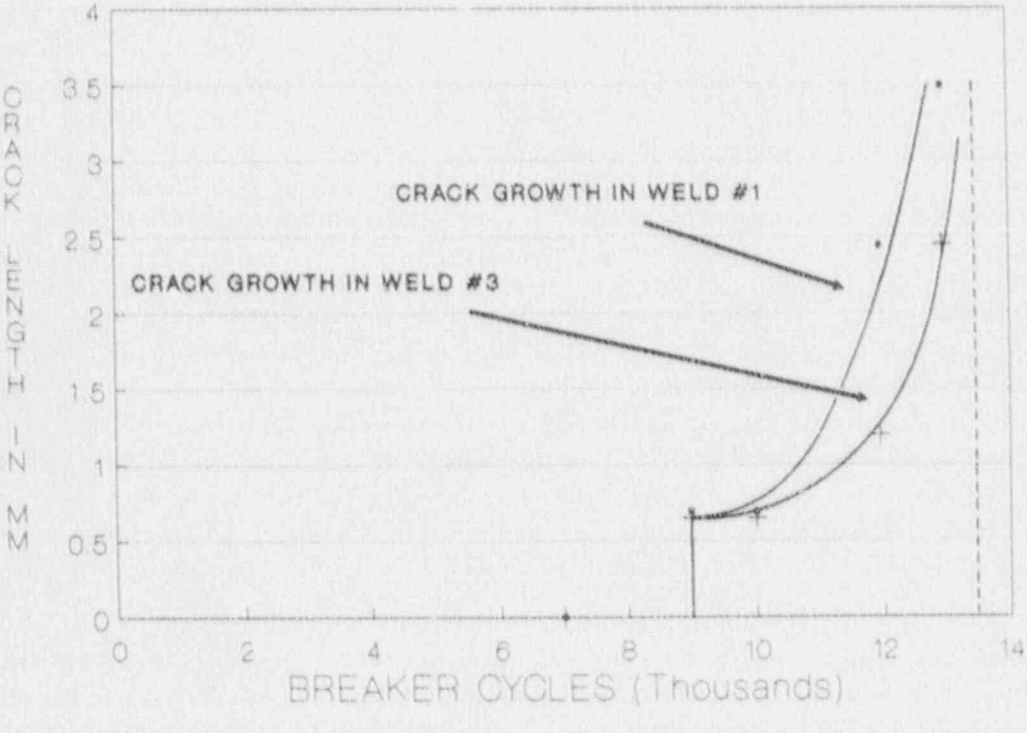


Figure 4-13. Failure of the Second Pole Shaft Weld

4.1.4 Summary of Results

The following conclusions are based on results related to the pole shaft:

- Cracks in the welds of shafts with substandard welds are primarily due to breaker operating cycles,
- Weld cracks of certain length can cause misalignment of pole levers, which further affect the performance of the operating mechanism, and
- Instability in cracks started at 2,000 cycles for the 60 degree weld, and at 10,000 for the 120 degree weld.

4.2 Operating mechanism

The operating mechanism is a mechanical component which controls the transfer of the motive power from the charging motor to the pole shaft and its levers. It consists of a levering shaft interlock for positioning within the breaker assembly, a cam arrangement for controlling the breaker operation, an oscillator and cranking mechanism for charging, and two closing springs to store the charged energy. In addition, it houses bearings for the trip shaft and motor shaft, and other linkages, springs, and mechanical components to assist the breaker operation. The cam provides motion to the pole shaft through the main drive link to move the poles to the desired positions.

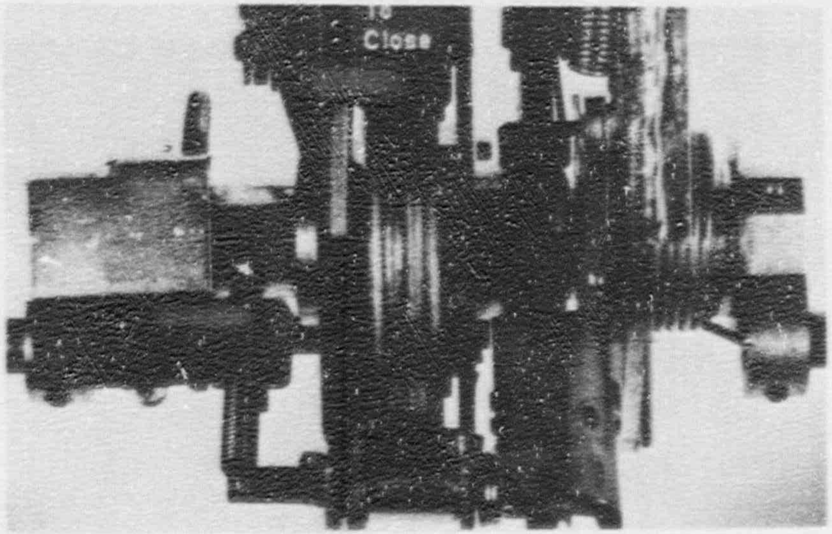
Aging of this component is primarily attributed to mechanical cycles. Its moving elements operate when the breaker operates. The operating mechanism is exposed to the environment for the life of the breaker. Because of the way this component operates surface wear, grooving, sluggishness, and distortion are the most dominant aging mechanisms.

Figure 4.14 shows the severity of aging as the first mechanism underwent test cycles: the wear on the four segments of the cam assembly increased with the number of cycles. In addition, the cam assembly loosened and developed a little play within its housing. Figure 4.15 shows grooving in the stop roller and on the cam itself that was seen after disassembling the cam assembly from the operating mechanism. It is also evident that the inner two plates were worn more than the two outer plates of the cam assembly.

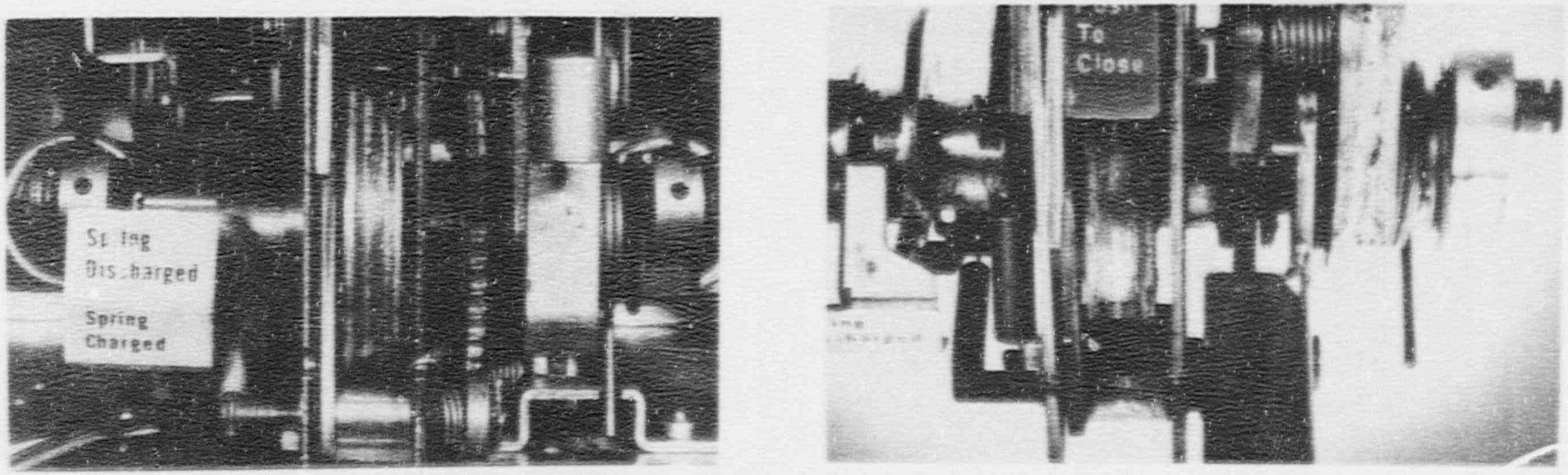
Other elements which were badly worn at the end of the life of the operating mechanism include the oscillator, oscillator pawl, and ratchet wheel. Figure 4.16 illustrates the wear on the oscillator by the motor crank handle for two different mechanisms. The wear on the first mechanism after 13,609 cycles is less severe than that of the third mechanism after 10,253 cycles. The first mechanism belonged to the original breaker and is presumed to have components manufactured in the seventies, whereas the second and third mechanisms were separately purchased from the current inventory and presumed to be built recently. Based on the Rockwell B hardness tests, the new oscillators were made out of softer material than the older units. Table 4.3 summarizes the hardness values for the three mechanisms used in this test program.

4.3 Contact Assembly

Erosion, burning, and deterioration of contact pressure typically are the dominant aging mechanisms caused by arcing during closing and opening the contacts. In addition, mechanical



Almost New
(<1000 Cycles)



After 4000 Cycles

End of 13,609 Cycles

Figure 4-14. Wear in the Cam Assembly

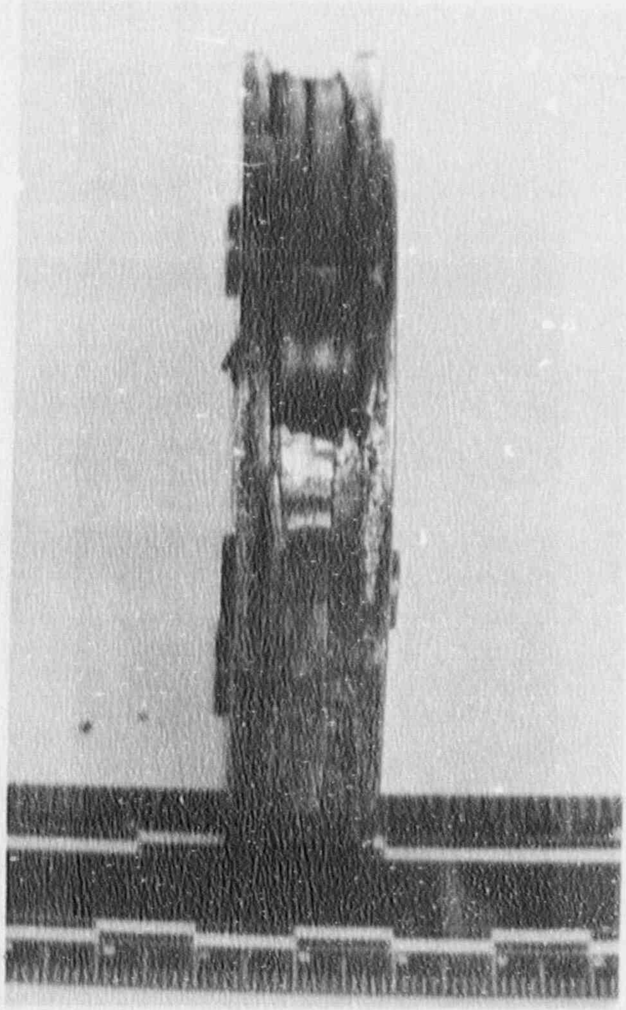
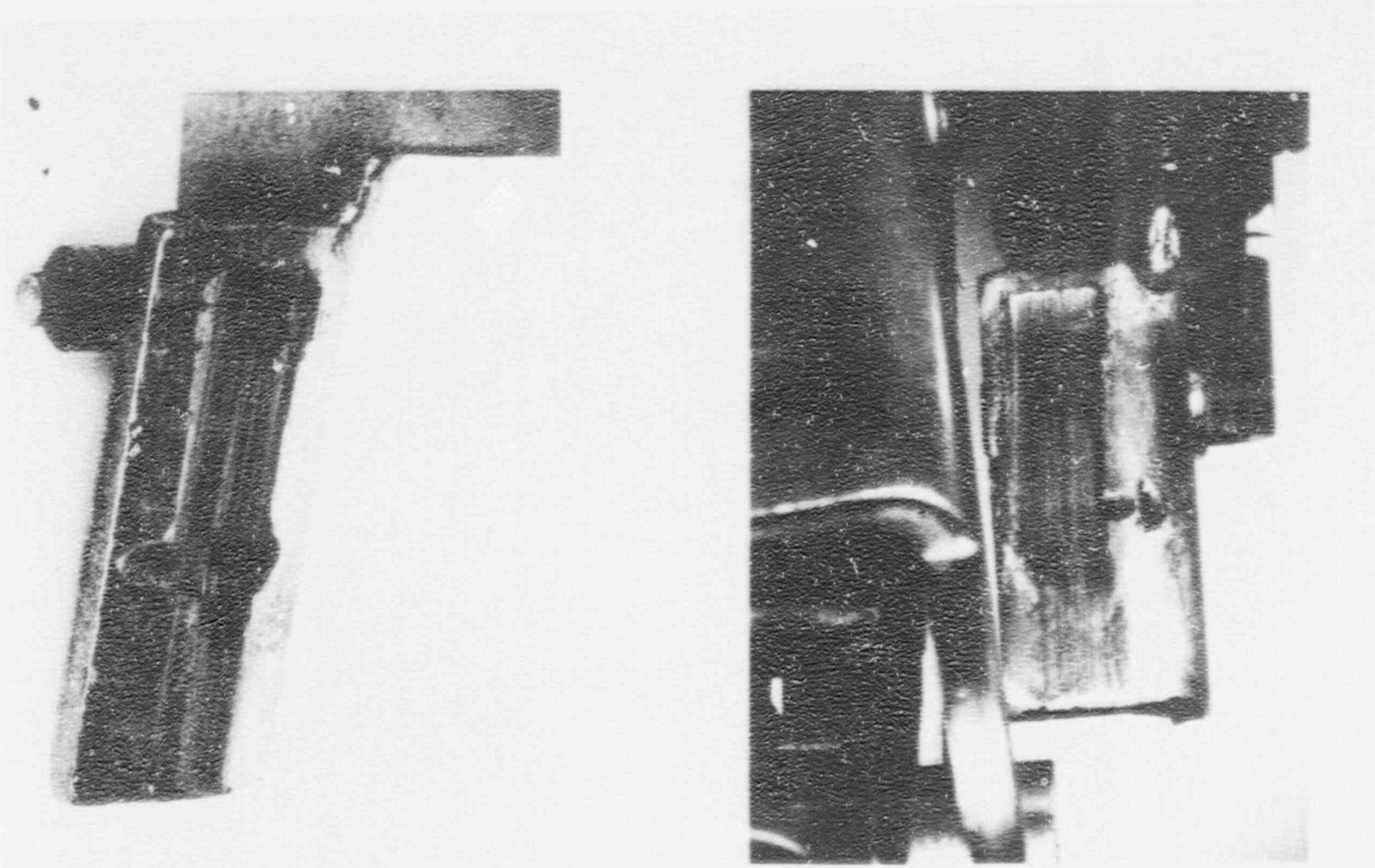


Figure 4-15. Severe Wear in Cam Segments and grooving in stop roller

cycling can cause looseness or maladjustment of each contact point as well as misalignments between the three phases. After each 1000 cycle maintenance, the contact resistance at each phase, the insulation resistance between the phases, and each contact dimensions 'A' and 'C' (see Figure 6.1, Vol. 1) were measured to monitor changes.

All readings for contact resistance remained within a range of 1 to 5 milliohms, below the allowable of 6 milliohms. Similarly, the insulation resistance between the poles as well as from each pole to ground were maintained at 5×10^{10} megohms or higher throughout the test and there was no deterioration in the insulating systems. The dimension 'A' was in the range of .05 -- .08 inches, which is well below the allowable value of .020 inches. Finally, the dimension 'C' varied within a range of .35 to .422 inches and never went above the allowable range of .42±.08 inches.



First Mechanism
(End of 13,609 Cycles)

Third Mechanism
(End of 10,253 Cycles)

Figure 4-16. Wear on Oscillator Surface

Table 4.3 Hardness Test Results on Oscillator

	Rockwall 'B' Hardness Number	
	Wear Surface	**Original Material Surface**
1st Mechanism	68.8	57.7
2nd Mechanism	45.8	38.7
3rd Mechanism	52.5	45.5

We conclude that the mechanical cycling of this class breakers alone does not adversely affect the contact adjustments.

4.4 Electrical Coils

The under-voltage trip attachment (UVTA), shunt-trip attachment (STA), and the closing coil were the three coils used in the test program. The UVTA was not used to operate the breaker, but was de-energized to trip the breaker in case of an under-voltage condition. The closing coil was used to close the contacts via the spring release attachments, and the shunt-trip coil was used to trip the breaker in a typical breaker test cycle. The coils in these two devices (STA and Closing Coil) are designed to withstand current flow for a very short time. Extended duration of current flow often damages the coil. With the exception of the first test sequence, dc coils were used, for the remaining test period.

There was no incidence of burn out or malfunction of the UVTA and STA coils during the test. However, the closing coil was burned out, as shown in Figure 4.17, after it had been through 20,724 cycles. Within another 468 cycles, a newly replaced coil burned again at the end of the test sequence V. These incidents were further investigated to determine the root causes of the coil failures. They both occurred when the then installed operating mechanism (third unit) was showing significant aging and was running sluggishly. The second coil burning occurred when the mechanism was completely jammed. Reviewing other indicators including insulation resistance, temperature rise, and binding of the interfacing mechanical linkages, no particular abnormal condition was found in these components prior to the coil failure. Thus, we concluded that these incidents were attributable to the mechanism whose aging caused the coils to remain energized for longer than they were designed to.

The temperature in the UVTA when energized remained unchanged between 33 to 38°F. Similar trends were also noticed for the STA and closing coils with the average rise in temperature being 4°F. Temperature readings were not useful in monitoring the condition of the coils.

Periodic measurements of resistance of these coils indicated no correlation of the coil resistance with its degradation rates.

The tripping threshold voltage of the STA coil was tested at each 1000 cycles. Each time the breaker was tested (go/no go) for tripping at a voltage of 55% of the rated value and no abnormal behavior was observed in its life.

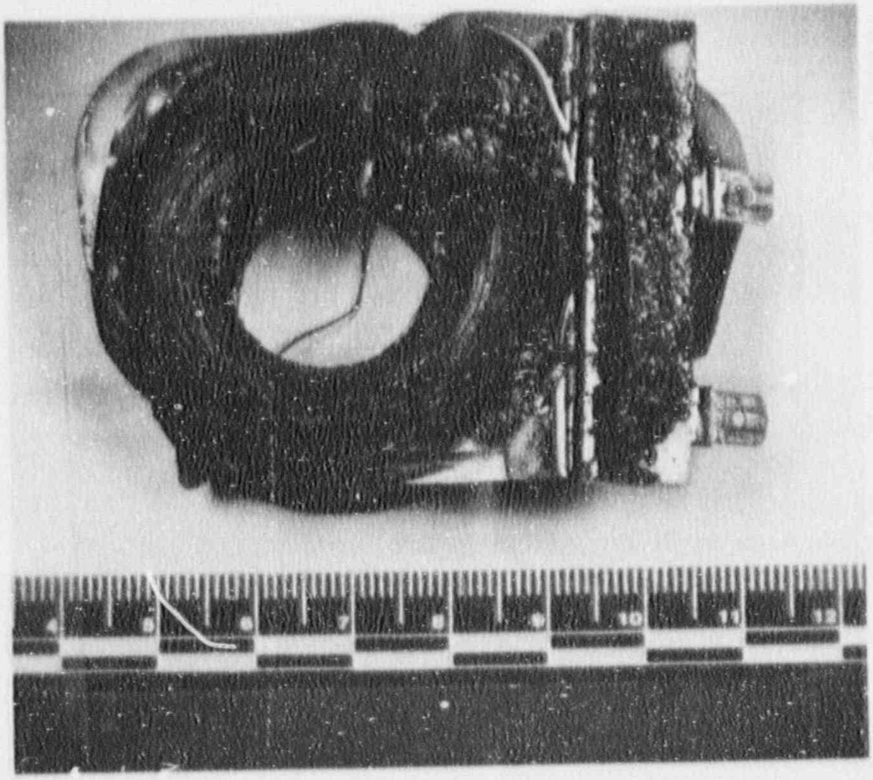


Figure 4-17. Burned Closing Coil After 20,724 Cycles

Finally, the test results of the dropout voltage of the UVTA coil were examined. Figure 4.18 shows the trend of this parameter with the breaker test cycles. Each data point represents the average of three measurements performed according to the maintenance procedure. The upper and lower limits for a successful operation of this device are also illustrated. It is interesting to note that for the entire life of this device all the measured values remained within these limits; for the first 10,000 cycles it was closer to the upper limit of 28.8 volts, while for the remaining life it was closer to the lower limit of 14.4 volts. The drop in dropout voltage at 10,000 cycles is not understood. However, degradation within the coil insulation by the ohmic heat may be the cause. Again, after this drop the trend remained unchanged for the rest of the coil life.

We conclude that aging in any of these three coils has minimal effects on breaker operation. However, the STA and closing coils are vulnerable to quick burnout due to excessive heat generated by an extended operation, which is primarily caused by the aging of various elements in the operating mechanism and the associated linkages whose binding or sluggish motion caused the coils to burn out instantly.

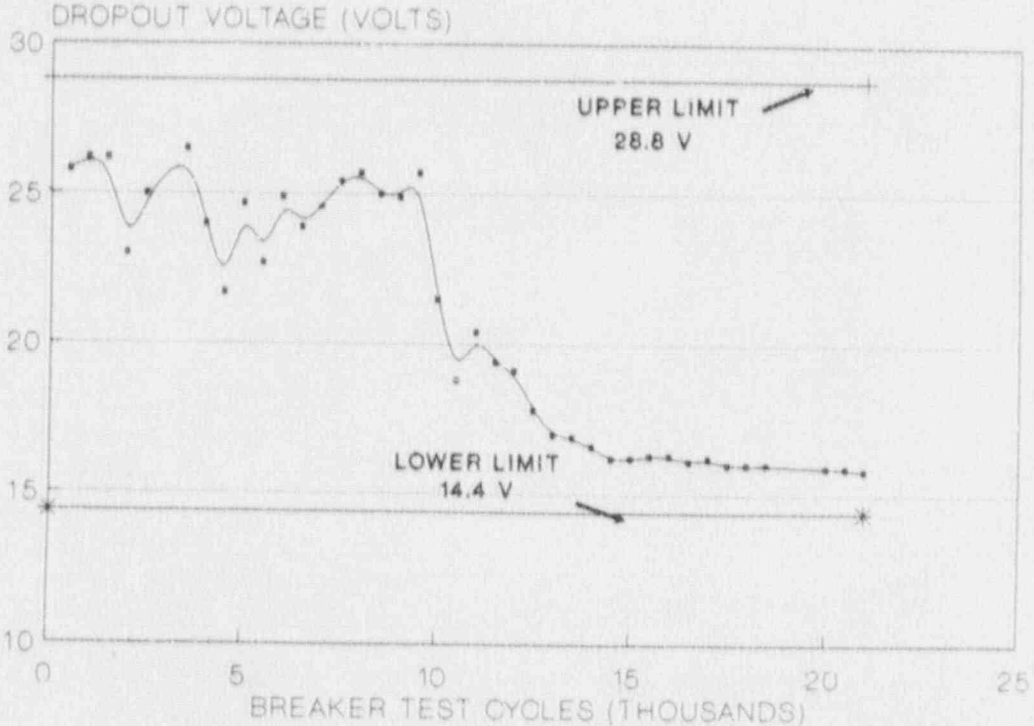


Figure 4-18. Dropout Voltage for the UVTA

4.5 Electrical Motor Assembly

The electric motor used to automatically charge the breaker on command from the controller was replaced twice during the test. The first time it took 13,609 cycles before the stator coil was completely burned (Figure 4.19). The second time it occurred again, in the same mode, after 10,715 cycles. In between, there were several problems associated with the carbon brushes, including cracking, uneven wear, and excessive carbon deposits on the armature contact surface (see Figure 4.20). The cracking of brushes was presumably due to poor manufacturing or to inclusion of foreign substances in the carbon. Uneven wear was due to spring adjustments on the brush holders and the wear of carbon was part of the normal condition when it rubbed against a metal surface. Throughout the test, the carbon settings were adjusted and the armature surfaces were cleaned for proper operation.

Figure 4.21 shows the motor crank and handle assembly. When the motor is energized this part of the motor assembly rubs against the oscillator surface (see Figure 4.16) and causes considerable wear on both surfaces. The grooves generated on the oscillator surface were caused by the metal surface of the motor assembly.

4.6 Trip Mechanism

This mechanism consists of the trip shaft, the roller constraining link, and the trip latch. The signal from either the UVTA or the STA is transfered to the cam assembly through this mechanism. The rotation of the trip shaft to an appropriate position causes the tripping. Two

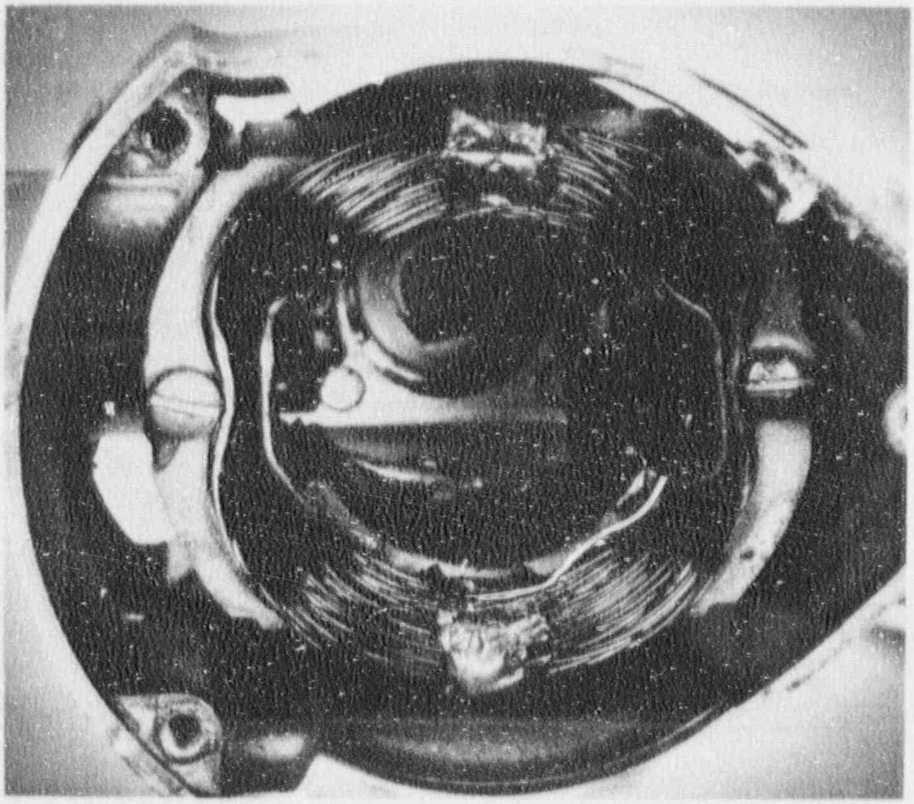


Figure 4-19. Degradation of the Insulation on the Motor Stator

small springs, which are very important for its operation, are the trip-shaft reset spring at the STA coil end of the shaft and the trip latch spring mounted vertically in the front of the trip latch. Both springs reset the trip shaft to the appropriate position; otherwise, the breaker follows the trip-free mode of operation and ignores the closing mode after a closing signal has been given. The trip-shaft reset spring is small and often gets lost during maintenance. No failure of this spring was noted during the test. However, the trip latch reset indicator spring broke once; details of its fracture are discussed later in the section on springs.

The fracture of the trip shaft lever is a mystery. This lever, attached to the trip shaft, is shown in Figure 4.22 showing a long crack. When we investigated the cause, it was found that this part of the trip shaft has no contact with any other force-transferring link or device. Fracture at the root of this lever was presumed to be due to a manufacturing defect or crack at the neck and the free vibration of this section during shaft rotation helped to propagate its failure.

Scanning electron microscope (SEM) examination revealed that cracks started at the sharply angled corner of the wing. Under vibratory motion of the bar, the crack propagated fast like a brittle fracture. Hydrogen embrittlement from the zinc electroplating process is suspected to be the cause. Hydrogen embrittlement can happen when electroplating is done improperly. The proper procedure includes relieving all stresses from the shaft before electroplating and

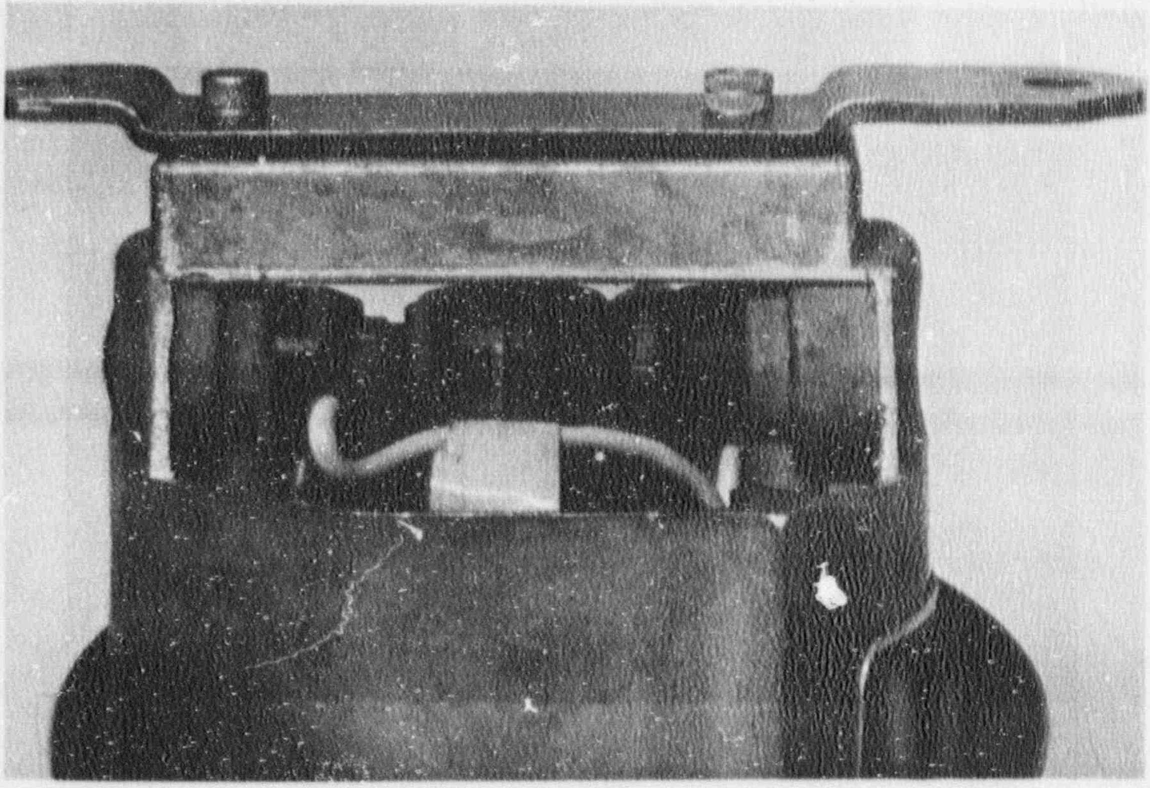


Figure 4-20. Carbon Deposits on Armature Contact Surface

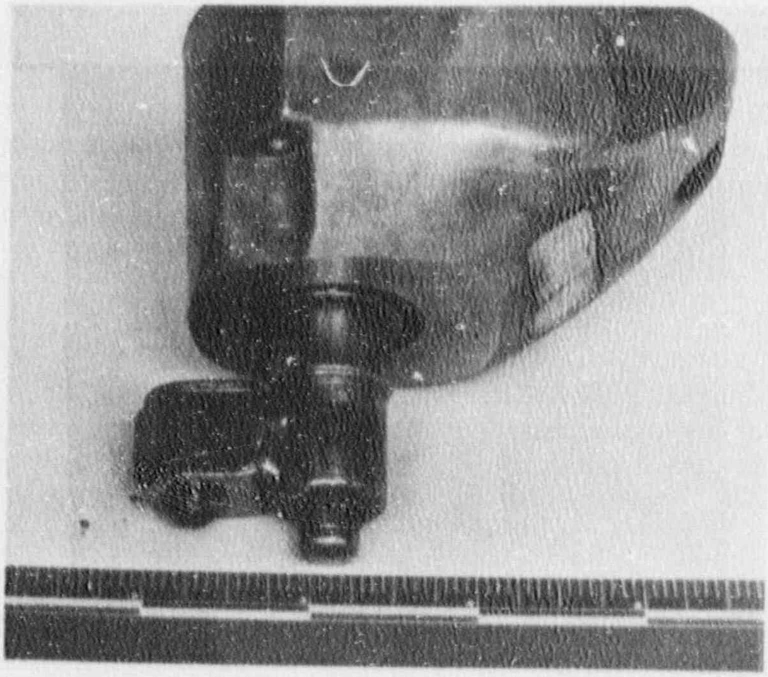


Figure 4-21. Wear on the Motor Crank and Handle

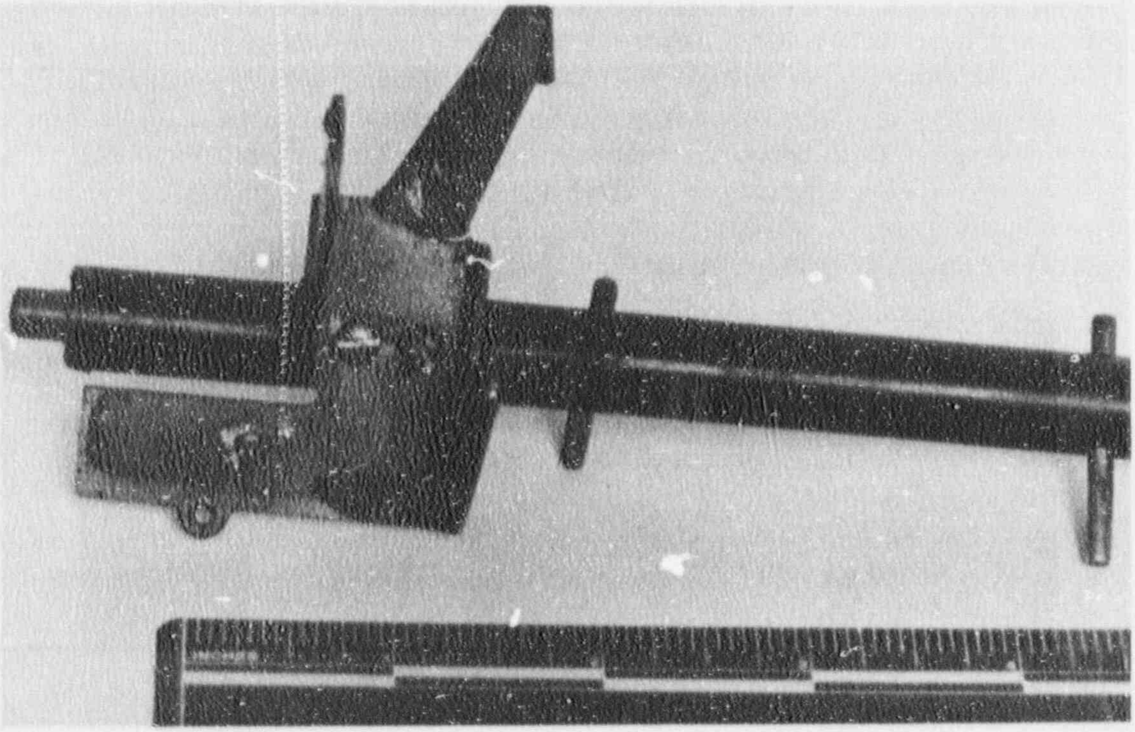


Figure 4-22. Fracture of the Wing on the Trip Bar

baking the part at a particular temperature after electroplating is completed. A detailed discussion of this procedure is presented in Appendix C, section C.2.4.

Wear in the roller constraining link was evident from the test. The sluggish motion of this link might cause a tripping problem to the breaker.

4.7 Main Drive Link Assembly

The main drive link is connected to the center pole lever (#3) at one end and to the cam via the main roller at the other end. Any motion of the cam guides the main roller to roll over the cam surface to appropriately position the main drive link. This link further provides the necessary force to the pole lever to generate a torque, which allows the pole shaft to rotate to the desired positions. Throughout testing the main drive link and the main roller were inspected for wear, distortion, and any mechanical problems.

The main roller had some minor wear on its outer surface. The main drive link itself did not cause any problems. However, when misalignment of the pole shaft occurred due to cracks in the (#1 & #3) welds, this link lost its alignment with the pole shaft, resulting in an abnormal motion of the main roller over the cam surface.

4.8 Mechanical Springs

There are two large closing springs on either side of the operating mechanism and one opening spring on the right side of the breaker. The former ones are charged during the breaker charge/close cycle. Once the breaker is closed, the latter spring remains in a charged position. When the breaker is tripped, all three springs remain in relaxed positions. In addition, there are several small springs used for positioning various indicators such as 'Breaker Closed', 'Trip', 'Spring Charged', 'Spring Discharged'. Figure 4.23 shows the broken trip indicator reset spring. There is another spring which is connected to the oscillator and experiences a large number of excursions while charging the breaker.

The three larger springs were originally tested for their spring constants, while all of them were periodically inspected for any distortion or change in spring characteristics. Table 4.4 summarizes the spring parameters measured during the testing.

During the test two different vintages of smaller springs were used for the trip indicator and the oscillator reset; one set came with the original breaker and the others were purchased from a current inventory for replacements. The older springs lasted over 13,000 cycles without any deterioration, while one of the newer springs failed after 5861 cycles and the second one after 2286 cycles.

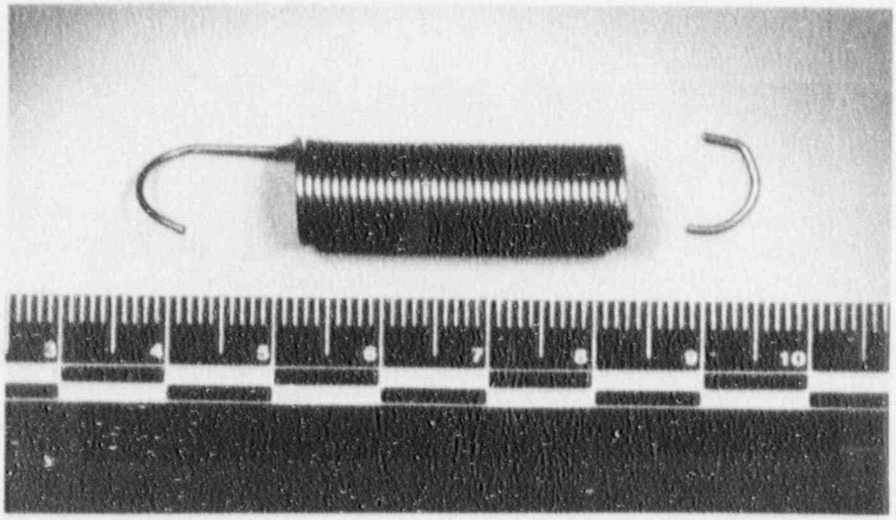


Figure 4-23. Broken Spring of the Trip Indicator Reset

Table 4.4. Spring Parameters

	Length in Inches	Outside Diam. in Inches	Inside Diam. in Inches	Wire Size in Inches	No. of Turns	Spring Stiffness Lbs/Inch	Acutaul Deflection/ Max. Allowed Deflections Inches
Closing Spring	3.4	1.9	1.5	.236	13	90	2.13/4.31
Opening Spring	2.05	1.25	1.03	.105	19	7	1.97/5.59
Indicator Spring	1.26	0.38	0.31	.032	39	0.8	2.23/4.30

Figure 4.24 shows the striation marks on the fracture surface of the indicator spring. This premature failure was probably due to excessive plastic deformation during the formation of the hook bend, supplemented by surface imperfection during the drawing process. A detailed discussion is provided in Appendix C, section C.2.1.

Similar imperfection was also noted from the fracture surface of the oscillator pawl reset spring. However, the bend in the neck of the hooks for the newer springs is much sharper than that of the older unit (Figure C-5). The crack started on the inside surface and grew slowly by fatigue. Appendix C, section C.2.2 further explains the causes for these spring failures.

A very tiny spring which is used to reset the trip bar is located at the STA end of the trip bar. This spring has a very important role in positioning the trip bar. During the test it was never bro-

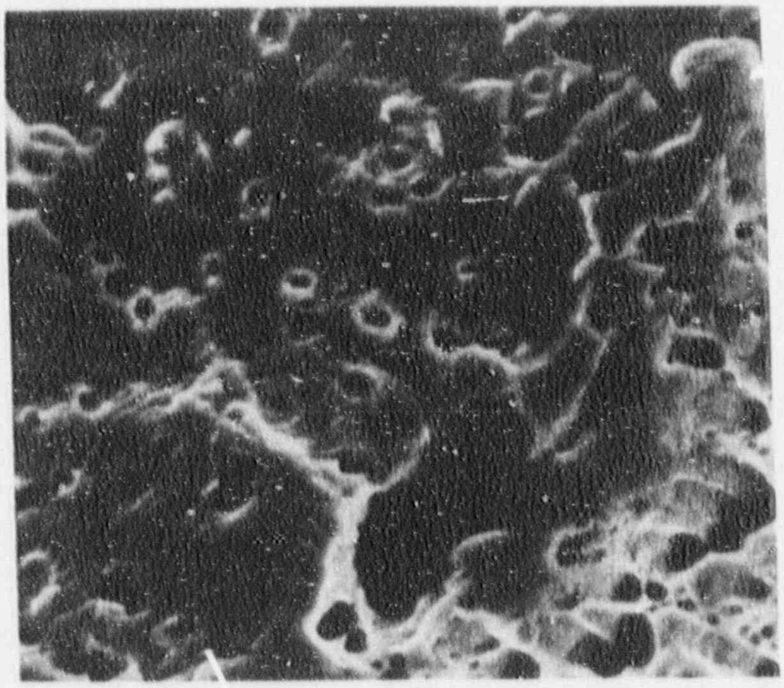


Figure 4-24. Striation Marks on Fractured Spring Surface

ken nor showed any age-related degradation. However, because of its size it was frequently lost during maintenance and installation.

4.9 Miscellaneous components

Several other components associated with the operating mechanism failed during this test. Figure 4.25 illustrates the conditions of some of these components taken from the first mechanism that exhibited significant aging after 13,609 cycles. These include worn pawls (emergency charge, hold, and oscillator) for the ratchet wheel, aged drive plate, and fractured pole shaft pin. Other components shown in this figure were discussed earlier.

The second pole shaft with a 120 degree weld in the #3 lever developed cracks in the #1 and #3 lever welds at about the same time. When these cracks became large at about 13,000 cycles, misalignment of the first two levers was noticed, as shown in Figure 4.10. This probably caused higher torque and bending moments on the phase A pole shaft pin which broke (see Figure 4.26) at 13,593 cycles. The metallurgical examination of the fractured surface revealed that the cracking of this pin was primarily due to an improper heat treatment of the stainless steel. Improper machining might have left raisers which initiated the crack under excessive bending moment and finally the crack propagated intergranularly to break the pin (see Appendix C, section C.2.3).

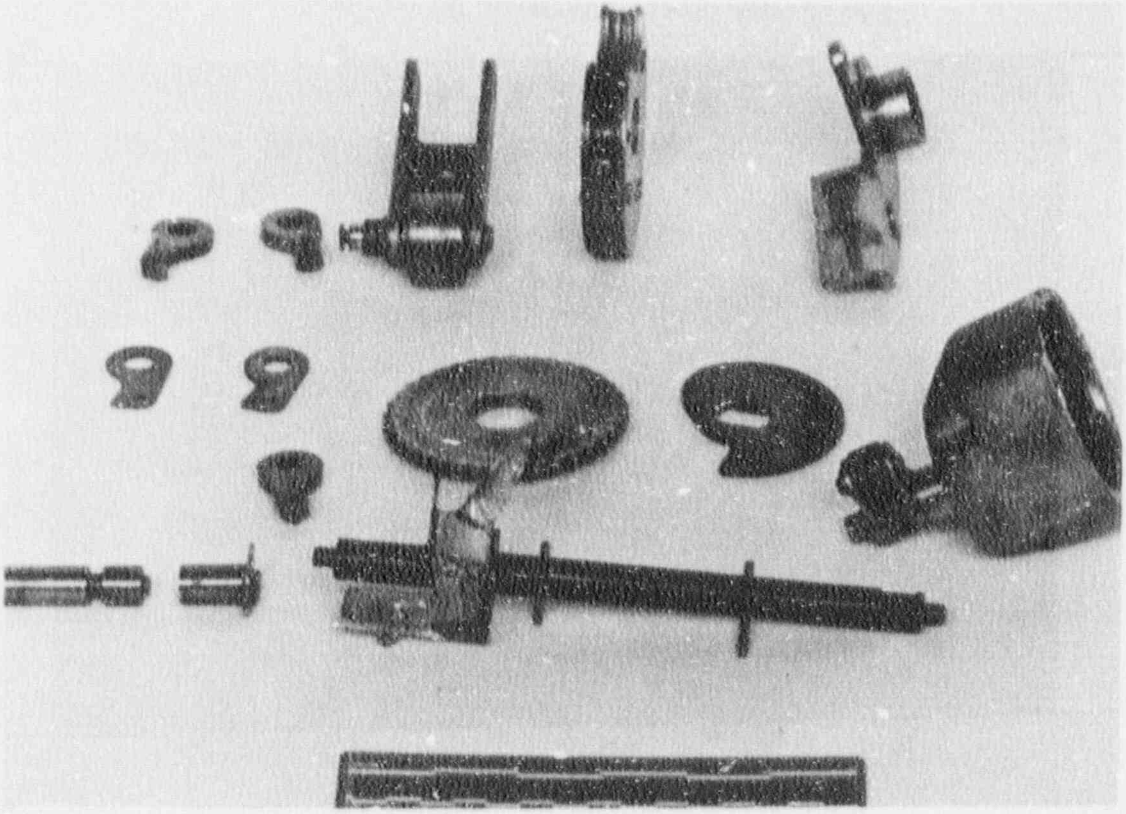


Figure 4-25. Aging in Various Breaker Components

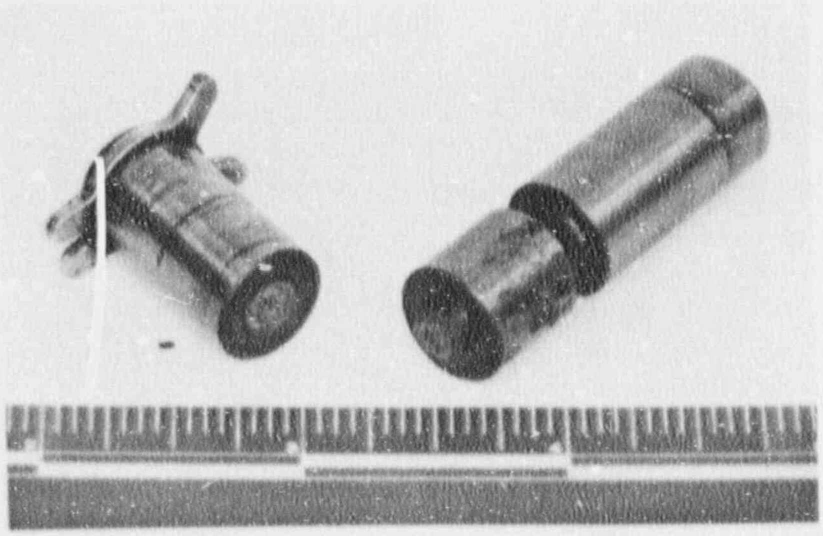


Figure 4-26. Fractured Phase A Pole Pin

The three pawl surfaces shown in Figure 4.27 were worn when rubbed against the ratchet wheel teeth. Because of this metal-to-metal contact, the wearout of these contact surfaces is excessive and after 10,000 cycles of breaker operation the pawls started slipping from the ratchet wheel, thus taking a longer time to charge the breaker.

X-washers taken out of the breaker assembly were found to be unusuable due to permanent deformations. Hence, these fasteners were generally replaced with new ones when the breaker was reassembled.

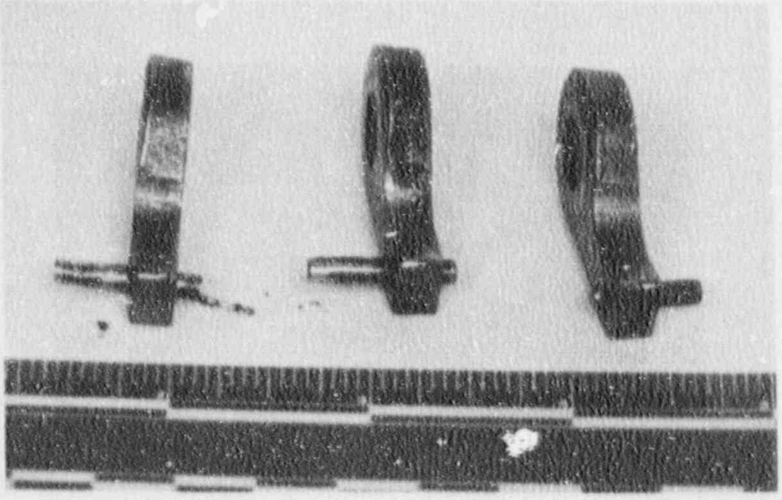


Figure 4-27. Wear in the Ratchet Wheel Pawls

5. AGING ANALYSIS OF BREAKER COMPONENTS

The overall performance of a breaker depends on the integrities of its structural, mechanical, and electrical components responsible for breaker operation, and the contact assemblies. Our results showed that the structural components and the contact assembly exhibited little aging due to mechanical cycling. On the other hand, the power-operated mechanism and associated components exhibited extensive aging degradation, and the levels of this degradation were proportional to the breaker operating cycles.

The heat due to normal full load current and arcing at the main and arcing contacts during closing and/or tripping has a significant effect on the life of various components in the contact assemblies. Aging due to this stressor is well understood by the breaker industry, and therefore, periodic adjustments of spring forces and replacement of erroded parts, surveillance testing of contact resistances, and cleaning of contact surfaces are typically included in the plant's preventive maintenance programs (see Volume 1). Although the effect of heat on the electrical devices within the operating mechanism assembly can be deleterious, because of the infrequent operation of the breakers, its impact on these devices is not particularly detrimental. Similarly, because the environment in nuclear power plants is relatively benign, its effect on breaker aging is minimal.

This section analyses the test data obtained from the mechanical cycling of the DS-416 breaker. Most discussions include life estimates of various breaker components (specifically those elements associated with the power-operated mechanism for charging, closing and tripping the breaker), predominant aging processes, failure modes, and possible mitigation programs.

5.1 Analysis of Test Results

The primary function of a circuit breaker is to close the contacts when supplying electric power to a component and to open the contacts to disconnect the power supply. Therefore, the breaker should be able to charge, close, and trip the breaker whenever needed, and the contacts should be able to transfer or break the electric power. This, in turn, requires that the three integrities (structural components, power-operated mechanism, and the contact assemblies) of the breaker should be maintained. The results from this testing, revealed significant aging in parts associated with the power-operated mechanism (Figure 5.1).

5.1.1 Pole Shaft and Levers

The failure of the pole shaft weld, which recently received a great deal of attention, is analysed separately. The strain-gage plots shown in Figures 4.2 through 4.7 suggest that the peak torques experienced by the pole shaft and the tripping time spans change with the age of the breaker. These torque signatures are influenced both by the pole lever weld cracks and aging of various parts within the operating mechanism assembly. Analysing the test results for the three test shafts, the following two failure modes are associated with pole shaft failures:

(1) If the quality of the weld in the lever #3 is very bad (i.e. an effective weld size less than 90 degree, or the presence of cleavages or slags in the weld), complete separation of the lever will occur.

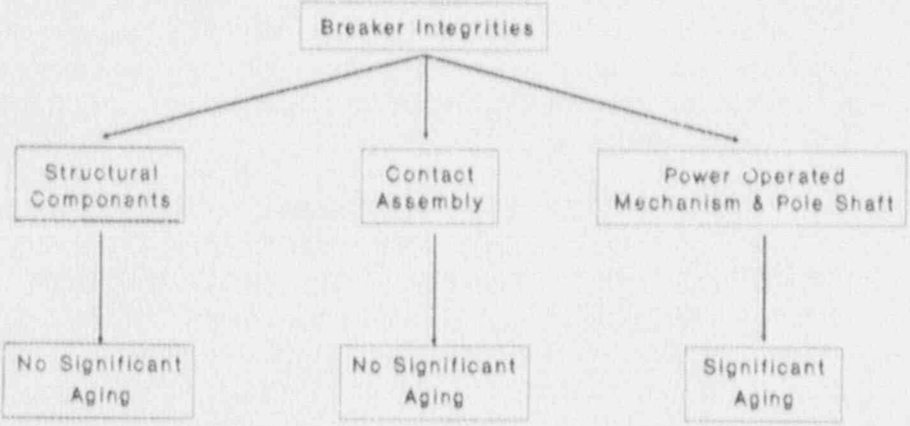


Figure 5-1. Aging Effects on Breaker Integrities Due to Mechanical Cycling

(2) If the quality of the weld in the lever #3 is normal (i.e. an effective weld size is at least 90 degree with some level of imperfection such as porosity), cracks in the #1 and #3 welds will develop.

In either mode, once the cracks reach a certain size the five levers on the pole shaft become misaligned. The torque transfered by the main drive link is then redistributed nonuniformly among the three poles via their associated pole levers (i.e. #1 and #2 for pole A, #3 for pole B and #6 and #7 for pole C).

The effects of the torque redistribution and the misalignment of pole levers, disrupts the bending moment on the pole pins connected between two adjacent levers supporting the insulating link and the moving contact assembly. Since the shaft is connected to one opening spring at the lever #7, phase A levers (#1 and #2) experience the largest torque while the phase C (#6 and #7) levers experience the least. However, the center pole (phase B) being the point where the main drive link is attached, experiences large enough torque to produce the largest weld cracks for the second and third test shafts. Table 5.1 gives the results relating to the pole shaft weld life.

The force on the main drive link and the connecting parts of the power-operated mechanism are also changed due to the cracks in the pole shaft weld. The two significant effects are the longer time of action during the tripping cycle, and the distortion of the linkages. These, in turn, lead to the burning of the motor winding and control coils. Figure 5.2 illustrates the sequential events that appear to have occurred as a result of weld cracking in the pole shaft.

Provided the welds on the pole shaft are good (as designed or passed NRC Bulletin 88-01 requirements), the life of the pole shaft can be well over 12,000 mechanical cycles. Thus, after complying with the NRC Bulletin inspection programs cracking in the pole shaft weld should not be a concern for safety. However, monitoring for possible cracks in the welds #1 and #3 during a breaker overhaul or maintenance would be a good practice.

Table 5.1. Evaluation of Life of Pole Shaft Weld

#3 Weld Size	No. of Mechanical Cycles		Failure Mode	Failure Cause
	Crack Initiated	Shaft Life		
60° Weld	1000	3000	Weld Separation	#3 Weld Cracked
120° Weld	8970	13,593	Misalignment of Pole Levers	Large Crack in #1 and #3 Welds
180° Weld	-	$19,448^+$	-	Cracks in #1 and #3 Welds

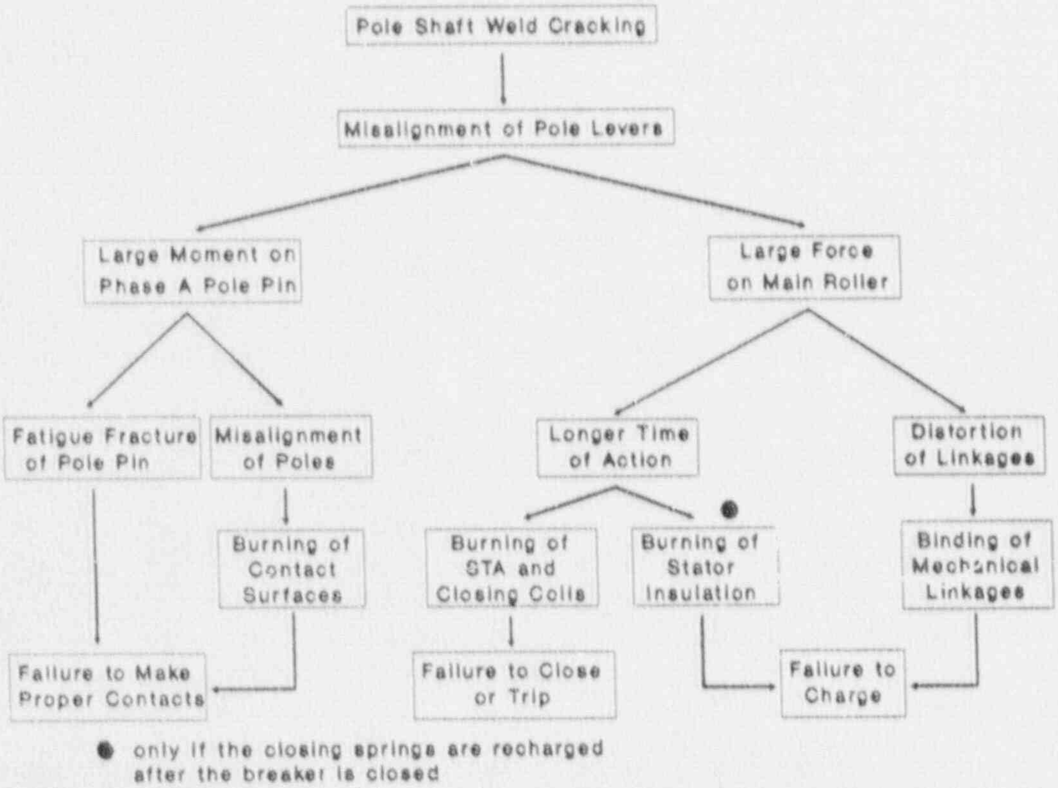


Figure 5-2. Cause and Effect Analysis of Failure of Pole Shaft Weld

5.1.2 Power-Operated Mechanism

The principal parts of a power-operated mechanism assembly, that have shown some aging due to mechanical cycling, are listed in three groups (Figure 5.3). Others, not included in this list, such as the closing and opening springs, crank shaft performed their design functions throughout the test. Group 1 components are responsible for charging the unit while the closing springs store the potential energy for closing the contacts, group 3 components are responsible for tripping the breaker, and group 2 components are responsible for closing the contacts and also providing controlled motion for the three operations (i.e. charging, closing, and tripping) of the breaker.

Table 5.2 summarizes the life estimates for the power-operated mechanism assembly. The two predominant modes of failure include the jamming of all linkages and the slipping of the

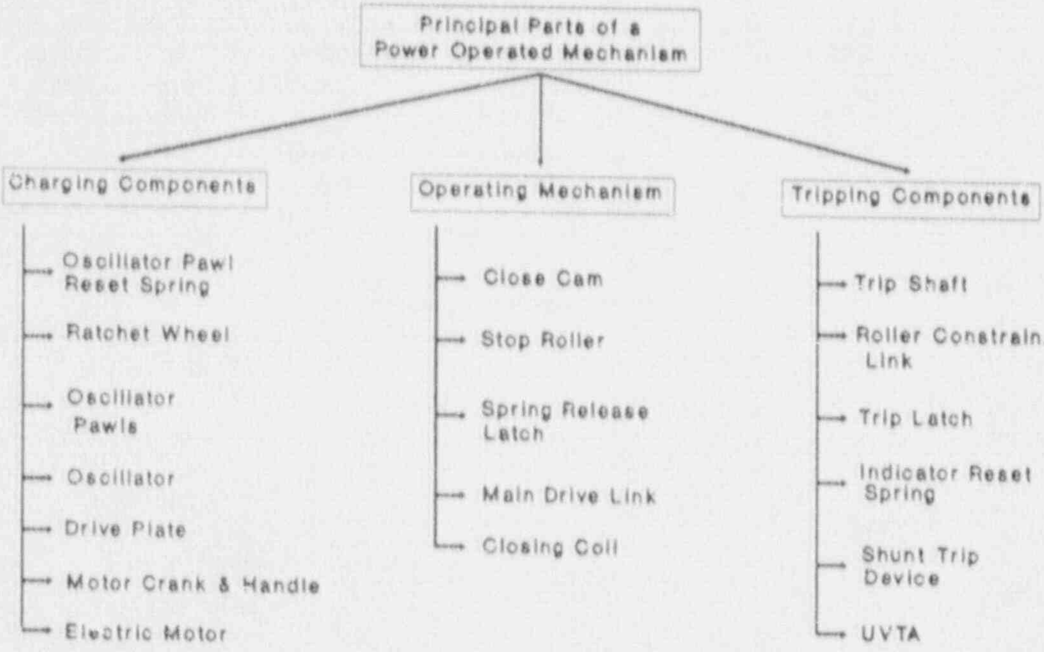


Figure 5-3. Principal Parts of a Power Operated Mechanism Vulnerable to Aging

crank shaft which prevented the breaker from charging. Based on the test results, the average life of this assembly is about 12,000 cycles. However, indications of aging were observed somewhere around 9500 cycles. These indications are presumed to reflect the synergic effects of parts of this assembly and the cracking of the pole shaft welds. Therefore, for the second mechanism where the pole shaft contained good welds, no particular early sign was noted until the final 500 cycles.

Excessive wear of the teeth in the ratchet wheel and the rounding of pawl and the drive plate edges caused the ratcheting action to slip when the electric motor began to crank. Futhermore, the grooving on the oscillator surface and wearing of the motor crank and handle caused irregular motion of the crank shaft. Finally, deterioration of insulation in the motor stator windings was a factor in the loss of motive power to the charging components. As a result of these aging problems, the breaker failed either to crank or to hold the ratchet wheel at its proper positions. Thus, eventually the breaker failed to rotate the cam assembly to appropriate posi-

Table 5.2. Operating Mechanism and Associated Components

Mechanism #	First Sign of Problems	O.M. Life	Failure Mode
1	10,744	13,609	Failed to Operate (Charge)
3	9,785	10,253	Jammed
2	–	12,206	Failed to Operate (Charge)
		Avg. 12,023	

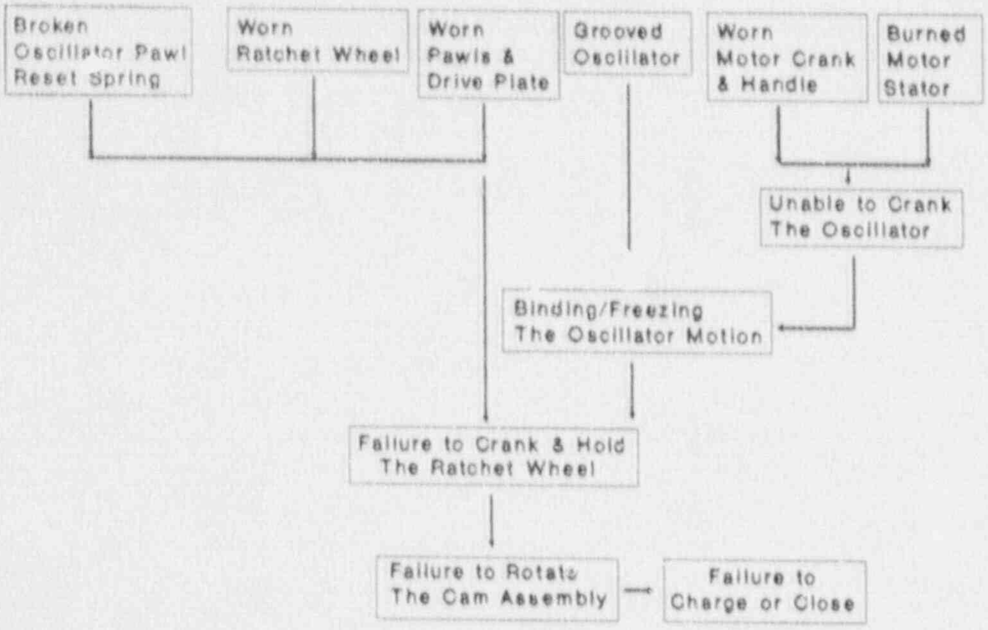


Figure 5-4. Cause and Effect Analysis of Parts Responsible for Charging the Breaker

tions. Figure 5.4 illustrates the root-cause analysis of parts associated with components responsible for charging the breaker.

For the parts within the operating mechanism, wear in the cam assembly and the stop roller reduced the ability of the cam to transfer appropriate control to the main drive link. The constant rolling action of the main roller over the cam surfaces, which can be further accentuated by the redistribution of forces on the main drive link by either failure of the pole shaft weld or misalignment, is primarily responsible for wear on the cam. The main roller attached to the main drive link showed some wear and distortion. Aging in all these components often leads to a binding force on the spring release latch which, in turn, leads to burning of the closing coil. Figure 5.5 shows the cause and effect analysis for this group of components.

Finally, among all parts within the tripping assembly, the roller constraining link or the trip latch indicated some wear. In addition, there are two small springs, one attached to the left end of the trip shaft, and the other linked to the 'trip' indicator plate. Both springs are used to reset the trip bar. Metallurgical examination of the fractured surfaces of the broken trip indicator spring revealed that because of the sharp bend at the ends, a high stress probably initiated the crack, which grew under cyclic action of this spring. Under these conditions, the trip shaft failed to reset the breaker. Although this never happened in this test program, dwelling of the trip shaft in one position could lead to burning of the STA coils. Figure 5.6 shows the root cause analysis for this group of breaker components.

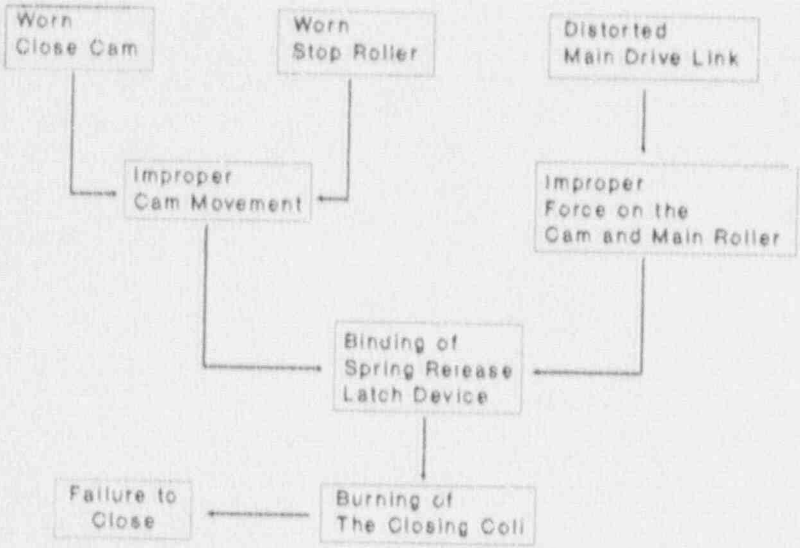


Figure 5-5. Cause and Effect Analysis of Parts in the Operating Mechanism

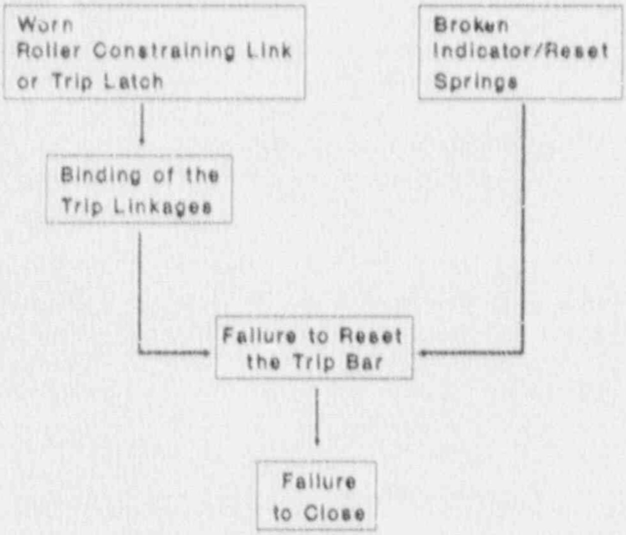


Figure 5-6. Cause and Effect Analysis of Parts in the Tripping Assembly

5.2 Mitigation of Aging Effects

After over 36,000 mechanical cycles, none of the structural components posed any problems. Good house-keeping of the area and the breaker cabinets should be adequate to maintain the structural integrity. However, a periodic inspection, and, if necessary, minor maintenance for the anchors, bolts, welds, and other fasteners should be considered in the plant PM program.

The contact assembly which includes the moving and stationary contacts exhibited no deterioration of contact resistance value, nor required alignments and adjustments of various tolerances/clearances. These parameters were monitored throughout the test for over 36,000 cycles and never needed any corrective action. Most of the contact problems are most likely attributed to the arcing of contacts while closing and/or tripping the breaker. Based on these premises the following activities are desirable for maintaining the contact integrity of a breaker:

- Periodic inspection and monitoring of contact assembly.
- Periodic cleaning of contact surfaces or replacement.
- Periodic adjustment of various tolerances for proper transfer of electric power.
- Replacement of badly burnt arc chutes.

Finally, several mechanical parts inside the breaker indicated aging problem during the test. The operating mechanism was replaced twice; thus the test was performed on three separate mechanisms. The first one came with the breaker, while the other two replacements were acquired from the spare parts inventory. Wear and fatigue are the leading causes of aging; binding and distortion are the next dominating factors. There were several occasions when cracking of certain parts, such as welds, springs and hooks caused the breaker to fail.

All subcomponents that cracked were subjected to metallurgical examinations to determine their root causes. The weld failures in the pole shaft levers were primarily due to substandard welds, attributed to the lack of proper quality assurance in the manufacturing process. Our test results suggest that cracks appear first in the #3 lever weld followed by the #1 weld. Therefore, it would be good practice to inspect the conditions of these two welds whenever there is an opportunity during a maintenance outage or annual preventive maintenance.

The breaking of spring hooks is presumed to be due to the design change in geometric shape of the hook. The older springs that came with the original breaker were still in good condition even after over 13,000 cycles. The newer parts failed twice after well below 5000 cycles. A close examination of the shape and the fractured surface indicated that high stress at the hook bends started cracks, which later propagated due to fatigue imposed by the compressive and tensile motions of the spring. To alleviate this problem, these springs should be replaced with new ones having smooth transitions at the neck of the hooks on either side of the spring, or periodically inspected for possible unusual deformation and replace every 2000 cycles.

Wear was evident in the following parts of the operating mechanism:

Ratchet Wheel
Holding Pawls
Oscillator Surfaces
Motor Crank and Handle
Closing Cam Segments
Stop Roller
Roller Constraining Link.

The deformation of parts include:

Main Drive Link
Main Roller
Mechanical Reset Springs
[illegible]ers
Pole Pins (Specifically Phase A)

The parts listed above should be periodically inspected for wear or deformation and replaced when needed. A good practice should include a complete replacement of the operating mechanism every 5000 cycles or 20 years, whichever comes first. All X-washers removed for disassemblying of the mechanism during maintenance should be replaced with new ones, since using the same washer again caused problems with loose or distored parts during testing.

The electrical and control devices within the breaker need periodic inspection and monitoring. None of the three coils (closing coil, shunt trip coil and undervoltage trip coil) showed any aging throughout the testing. The dc coils operated at a higher temperature than that of the ac coils due to ohmic heating. Each time a coil was burned, subsequent analysis revealed that binding of the mechanical linkages caused the current to flow for a longer period, leading to the failure. The dropout voltage in the UVTA coil showed one interesting result. This coil was energized for the entire duration of the test. As a result, the constant heating of the coil possibly degraded the insulation and the dropout voltage after 10,000 cycles changed from the upper limit value of 25 volts to the lower value of 16 volts; it remained at that level for the remaining life of the UVTA. It should be noted that this dropout voltage had never crossed the limits for safe operation.

All the above three coils should be periodically tested for insulation resistance, dropout/pickup voltage levels, and binding of the attached linkages. Also, bearings associated with some of these linkages should be properly lubricated as suggested by the manufacturer. Note that the insulation resistance value of a coil does not necessarily indicate any degradation that may be occuring, with the exception of degradation from moisture and dirt.

The charging motor burned out twice during the testing after a service life of over 10,000 cycles. In addition to typical electrical testing of the motor, it is good practice to replace this component every 5000 cycles or 10 years, whichever comes first. 10 year has been chosen because of the insulation degradation, which is affected not only by the heat but also by humidity and dirt. Cleanliness of the motor assembly should be considered in the motor maintenance program. The most frequent maintenance of the motor assembly is the cleaning of the armature that rubs against the carbon brushes. In addition, based on the test results the carbon brushes should be replaced every year or 250 cycles and the brush holder springs should be adjusted as needed.

Lastly, the test program used lubricants recommended by Westinghouse for the linkage bearings and the rubbing surfaces. The bearing lubricant (Molykote BR-2 by Dow Corning) was found to collect dust and contaminants. It was then replaced with Neolube #2 manufactured by the Harun Industry; this dry-film conducting lubricant was found to be better than the BR-2 type.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on the operating experience of Westinghouse DS-series breakers in the nuclear power industry we determined that the predominant cause of breaker failures is the burning of the control coils, specifically the closing coil. It was followed by other control devices, charging components, and the trip mechanism. Investigations of the failure of the pole shaft welds revealed that the weld cracks were caused by the substandard welding during the manufacturing process. Also, the weld cracks caused the control coils to burnout prematurely. This accelerated aging of a DS-416 breaker was conducted to better understand the interaction of various breaker components, to identify the aging processes within the breaker assembly, and to determine some realistic life assessment of various breaker parts. However, the test was limited to mechanical cycling only.

The test breaker was subjected to over 36,000 breaker cycles in a period of nine months. Three separate pole shafts were used; the first one with 60 degree, the second one with 120 degree, and the third one with 180 degree weld in the third lever. In addition, three operating mechanisms and several spare parts were replaced during the test. Recommendations provided in the ANSI/IEEE Standard C-37.50 (1981) on circuit breaker life testing were followed in choosing the cycle interval, maintenance frequency, and other relevant limitations. The periodic maintenance program was developed from the current industry practices, manufacturer recommendations, owners' group maintenance manual for the reactor trip breakers, and these test results.

6.1 Conclusions

This test provided results in three specific areas; manufacturing, aging, and maintenance of the breakers. Certain breaker parts were found substandard, apparently due to lack of adequate quality assurance during the manufacturing process. Additionally, one component was made out of different materials and the design of another part had been changed during the last decade. Aging of various parts is directly proportional to number of breaker cycles, instead of time. This particularly is true for breakers used in nuclear power plants because of the clean and benign enviromental condition. Finally, based on the operating experience and discussionsss with the plant maintenance engineers, current maintenance programs do not employ methodologies for life estimation of various breaker parts, for evaluation of lubricant type, or for aging mitigation.

6.1.1 Manufacturing and Spare Parts

During the test BNL purchased spare parts which included pole shafts, pole pins, operating mechanisms, charging motors, carbon brushes, all kind of springs, fasteners, and X-washers, closing coils, components for the charging system, and other miscellaneous parts. Based on the test and close examination of failed components, the following conclusions can be made:

- Comparing the three pole shafts, including the original one that came with the breaker, the components recently manufactured have much improved welds than those of an older unit. However, even the welds on the newer units exhibited cold working, porosity, multiple passes, and slag inclusion, which are unacceptable for nuclear applications. Note, these shafts were not made for class 1E application and were of commercial grade. However, no difference in their physical appearance was seen when compared with the RTB from the McGuire plant.

- The phase A pin had machined surface with sharply machined corners. These became the source of cracks which started under excessive bending moment due to the cracking of the pole shaft welds.
- Sharp-angled corners of the trip bar and improper electroplating probably led to the fracture of the trip bar wing.
- Both the trip indicator spring and the ratchet wheel pawl reset spring had broken hooks. The newer design had sharper bends at the neck of the hooks. The older units never failed even after over 13,000 cycles, while the newer units failed within 5000 cycles.
- The hardness testing of the oscillator surfaces indicated that the newer parts had a 30% lower hardness compared to that of the older oscillator material.
- The quality assurance program and the qualification program employed during the manufacturing process was ineffective, as evident from the parts procured for the test, as well as the utility responses to the NRC Bulletin 88-01 (Ref. 1).

6.1.2 Aging of Breaker Components

Aging due to breaker operation should be principally measured by the number of operating cycles, with some consideration given to time in service. As mentioned earlier, the breakers age significantly by operating cycles. Therefore, a method for registering the cycles should be in place for all class 1E breakers (an installed counter is preferred). The effect of arcing during the actual operation of a breaker was not considered in the following conclusions:

- Aging of structural components of the breaker was not evident from this test.
- Aging of the contact assembly due to the mechanical cycling was almost non-existent. Both the contact surfaces and the pole alignments did not change significantly during the test.
- Aging was evident in parts used for the power-operated mechanism and the pole shaft. Wear, fracture, distortion, and fatigue are the dominant aging mechanisms. There is a strong interrelationship in sharing the force being transmitted from the charging motor to the three pole movements. Therefore, any degradation in parts between the motor and the poles redistributes this force causing large unbalanced stresses in certain components.
- A well made pole shaft should not cause any problem for the life of a breaker (over 12, 000 cycles). The first cracks noted in the welds of the pole levers were #1 and #3. Once these cracks grew to a certain length (approximately a quarter the size of an effective weld length), the five levers connecting the three poles became misaligned and caused excessive moment on the pole A pin, leading to its complete fracture. Misalignment of the pole levers also caused binding and other problems within the operating mechanism assembly.
- Wear of the ratchet wheel, holding pawls, oscillator, drive plate, and the motor crank and handle dominated the aging of the charging system. The pawl reset springs had broken hooks. The electric motors burned out twice and the carbon brushes needed frequent maintenance.

- The operating mechanism itself exhibited excessive wear in its cam assembly and stop roller. Binding of the spring release latch device led to the burning of the closing coil. Distortion of the main drive link and its roller were the other aging problems.
- The tripping assembly had the fewest aging problems in the complete power-operated mechanism assembly. Other aging problems were minor wear of the roller constraining link and the trip latch and missing or broken hooks of reset springs.

6.1.3 Breaker Maintenance

Breakers in nuclear power plants operate in many different modes. The reactor trip breakers (RTBs) remain in the closed mode for normal operations, while other Class 1E breakers remain in either a closed or open mode. Many of them remain in one state for a long period while others operate very frequently, depending on the systems' needs (such as compressors, charging pumps). Most Class 1E breakers undergo surveillance testing for their operability check and/or channel checks. Again, the annual or semi-annual maintenance check prior to bringing them into operation adds more cycles to the breaker life. Therefore, aging of a breaker varies considerably, depending upon its application.

In 1983, the Westinghouse owners group issued an extensive maintenance manual for the reactor trip breakers. Similar documents are under development for other class 1E breakers.

Following is the list of items that were learned from this test program:

- Neither the manufacturer's operating manual nor the plant maintenance programs indicate the actual life of various parts of a breaker. For low voltage breakers ANSI-C37. 16-1980 defines the life of a DS-416 breaker as 4000 cycles and that of a DS-206 as 12, 500 cycles. The manufacturer recommends that the UVTA,STA, and closing coil with its spring release device should be replaced every 2500 cycles, while the amptector unit, which was not used in this test, had a qualified life of only 420 cycles.
- Based on the test results, the ultimate life estimates in terms of mechanical cycles for various breaker parts are:

DS-416 Breaker (if maintained)	10,000
Pole Shaft – very bad welds	3,000
– normal welds	10,000
– as designed welds	19,000
Operating Mechanism	10,000
UVTA, STA, Closing Coils	10,000
Electric Motor Assembly	10,000
Mechanical Reset Springs – New Type	2200/5800
– Old Type	10,000
Charging components	10,000

- Other items not listed above may be categorized in two groups. Parts like X-washers, carbon brushes, fuses, auxiliary contacts, wirings should be replaced each time they are taken out of the assembly. The degradation of contact assembly and arc chute depends on the breaker application. The other group including the structural components, closing and opening springs could have a longer life than the above list of components.

- Although evaluation of the type of lubricant which should be used in a breaker was not part of this test, several observations were made. The bearings and linkages, as noted in the Westinghouse Owner's Group maintenance manual, were lubricated by the Westinghouse BR-2 lubricant. However, this lubricant collected dust and contaminants. Therefore, a dry film conducting lubricant (Neolube #2: Huron Industry) was used during most of this test, which yielded better results than the original one. Also, on advice from the manufacturer, all rubbing surfaces were sprayed with Lubriplate 130 graphite-based grease, purchased from Westinghouse for reducing the wear. Later it was found that this spraying was not that effective in reducing wear on the rubbing surfaces.
- The present maintenance practices are found to be adequate for the contact elements and associated parts, but not for the power-operated mechanism parts. A monitoring program with a check list of all parts that are vulnerable to aging should be developed. Electrical coils are not the source of breaker problems as originally perceived. These devices, unfortunately, are subject to other mechanical problems that arise elsewhere in the operating mechanism assembly.
- Scheduling of breaker maintenance should primarily depend on the actual breaker cycles imposed by operation, testing, and maintenance.

6.2 Recommendations

The following recommendations should help utilities to develop their own maintenance programs that can mitigate aging problems in a Class 1E DS-series breaker. Some of the life estimates and schedules are based on a factor of safety of 2 to 3 to take into account: 1) the heat due to arcing which can expedite the aging process, and 2) other unknown factors can contribute to the breaker failures.

- In procuring a new breaker or spare parts for a breaker there should be an inspection program, and if necessary, analysis or testing to assure their design adequacy. This includes inspecting for geometric shape or size of the component, adequacy in fasteners (such as welds, bolts, pins), QA/QC or dedication documents qualifying the requirements, and their origins.
- The life of a breaker (either DS-416 or DS-206*) is estimated to be 5000 cycles or 20 years, whichever comes first. Here, it is assumed that a breaker, such as rector trip, charging pump, or compressor, is typically subjected to 250 cycles annually. The life of other Class 1E breakers for an overhaul or replacement interval should be determined according to their application and use.
- A method for registering the actual number cycles should be employed. An installed counter is the preferred method.

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*Note: Although not tested, the DS-206 breaker is included in this recommendation because of its similarity to the DS-416 breaker in design, construction and materials.

- In addition to monthly testing on breaker and/or channel operability, a visual inspection program should be developed to check the overall condition of the breaker while it is in place.
- Depending on the safety importance of the breaker, at every 50 to 100 cycles, inspection involving an extensive list of items that are vulnerable to aging should be conducted on each breaker. This might require pulling the breaker out of the cabinet, but not disassembling it.
- At each 250 cycles (For normal usage this is equivalent to an interval that ranges from annual to each refueling interval.) maintenance check on the breaker components should be performed. This might require removing the breaker from the cabinets and testing various parameters that assure the components operability and operational readiness. Degraded parts should be replaced with new units. Lubrication of parts identified by the manufacturer should be made at this time.

7. REFERENCES

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2. Westinghouse Owners Group Maintenance Manual, MPM-WOGRTSDS 416-01, Rev 0, November 30, 1986.
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APPENDIX A

LIFE TESTING OF WESTINGHOUSE DS-416 LOW VOLTAGE CURCUIT BREAKER: A TEST PLAN

E.A. MacDougall, W. Wilhelm, and M. Subudhi

ABSTRACT

The test plan for Life Testing of Westinghouse DS-416 low voltage circuit breakers is described in this report. During the last decade, several breaker failures, documented in various NRC information notices, bulletins, and plant operating experience data bases, have resulted from either malfunction or complete failure of breaker components. These components include failures of pole shaft welds, loss of spring tensions, burning of coils, and sticking of linkages. The purpose of this testing is to identify all age-related failure modes and to assess the condition of components, so that a maintenance program can be developed to alleviate breaker failures. The results of this test program will provide a measure of the individual life of breaker components, functional indicators to identify age-related degradation, and the time at which appropriate maintenance should be performed. Since most failures are attributed to the number of cycles that the breaker experiences, a relationship between cycles and failure will be established.

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A.1. INTRODUCTION

A.1.1 Background

The Westinghouse DS 416 low voltage power circuit breakers are used to interrupt power from the rod drive motor-generator set to the rod control cabinet on command from a reactor trip signal. Interruption of the power to the rod control cabinet causes the control rods to fall by gravity into the reactor core for a PWR, thereby causing reactor shutdown. In recent years, several reactor trip breaker (RTB) failures were attributed to the substandard welds on the pole shafts and to misalignment of the breaker closing mechanism. The cause of these failures was the lack of fusion during the welding process (i.e., lack of characteristic weld bead ripple, notches at the edge of the weld beads, and some evidence of base metal melting).

The welding of pole levers to the shaft is performed as a commercial grade item, and there are inconsistencies in the size, shape, and appearance (i.e., porosity and coldwork) of the welds. These difference are primarily due to the lack of quality assurance on the products, and inadequacies in the Class 1E qualification program.

The operating experience both in nuclear and non-nuclear facilities shows that pole shaft failures have not been the only problem associated with these DS-series breakers. Shunt trip or closing coil burning, charging motor malfunction, deterioration of power or control contact points, and failures of the trip latch mechanism far exceed the documented failures of the pole shaft welds. However, the root cause of these subcomponent failures were never analyzed. After the welds at the center pole shaft failed at the McGuire Nuclear Station in 1987, further testing revealed misalignment of the center pole shaft on the closing cam. This could allow a high current flow in the shunt coils for a longer time than their rated value, which is typically very short. (This could cause the coil to remain energized longer than its intermittent design rating). This might have led to burnout of these coils. Similar conditions may have caused premature failure of other control devices identified in the operating experience data bases. Therefore, problems with pole shaft welds may contribute to other breaker failures.

The premature failure of the pole lever welds are presumed to be due to the large number of trip cycles imposed on substandard welds. These cycles can impose large fatigue stresses in the interfaces of the weld-shaft material. Because of substandard welding, cleavages could occur, developing into cracks after frequent impact cycling. Crack propagation could continue with subsequent operation until fatigue failure occurred, causing the pole levers to detach from the shaft. Once the weld has been separated, the main link on the closing cam could cause other mechanical problems, such as being stuck to corners, and wear of cam surfaces. This would prevent the breakers from tripping on demand. Thus, we conclude that too frequent cycling of the breakers can cause fatigue at substandard welds, which could be a root cause of breaker failure.

A.1.2 Objective

The object of this testing program is to investigate and understand the failure modes associated with the Westinghouse DS-series circuit breakers (DS-206 and DS-416). These types of breakers are typically used in nuclear power plants for Class 1E application. During the life of a plant, they often undergo many test cycles as a requirement of plant technical specification and maintenance. In some cases, such as for charging pumps, the associated breakers experience a large number of trips during the operating mode of the system. The test program will effectively monitor all the major suspected locations and subcomponents of the circuit breaker that are candidates for failure, based on previously recorded failures. Since these breakers are located in a benign environment, aging due to environmental effects is assumed to be less critical.

The testing will use an automatic actuation through a laboratory controller for trip cycles, followed with scheduled routine inspections and recording of data. Such routine monitoring during the test is expected to reveal information on changes in performance and operation that can be correlated with the eventual failure or malfunction of the device.

Upon final destructive failure, a rigorous metallurgical inspection will be performed on the fracture surface to determine the mode of failure. Such information is expected to give important information for future predictions of failure in the breaker. Such information also could provide important technical data for improving breaker designs.

The test program will use at least three pole shafts with different weld configurations and defects. In each test set-up, initiation and propagation of cracks in the weld-base metal interface will be monitored as the breaker is subjected to accelerated aging due to cycling. It is anticipated that welds with substandard welds or cleavage defects will fail after fewer cycles than ones made in accordance with the design. The correlation of weld sizes with the number of breaker cycle could provide guidance for maintenance of these breaker models.

A.2. TEST SET-UP

To correlate the fracture characteristics of the substandard welding of pole shaft levers and the number of breaker operating cycles, three separate tests of a particular circuit breaker model will be conducted. Each test will provide information on the life of a breaker, (i.e., total cycles to fail) when furbished with a particular weld configuration, and on how the crack in the weld propagates with the operating cycles, leading to eventual failure of the weld. Performance of other mechanical components and electrical devices will be monitored throughout the test.

The first test will be performed on a DS-416 circuit breaker with the worst center-pole weld configuration (i.e., < 90 around the shaft circumference) and type (i.e., multiple pass). After examining the overall condition of the breaker assembly, decisions will be taken regarding the next test set-up. The third test will be repeated with a good (i.e., as designed) pole shaft.

Since most breaker failures have been mechanical ones, each assembly will be subjected to only mechanical cycling. There will be no current through the pole contacts, hence, no arcing will be considered.

A.2.1 Pre-Test Examination

Before testing, each circuit breaker will be disassembled to measure critical dimensions and for an overall inspection of all subcomponents (Figure A-1). This measurement includes certain base line data related to components characterizing the aging degradation as the breaker undergoes test cycles. The welds on the pole shaft will be carefully examined for defects (such

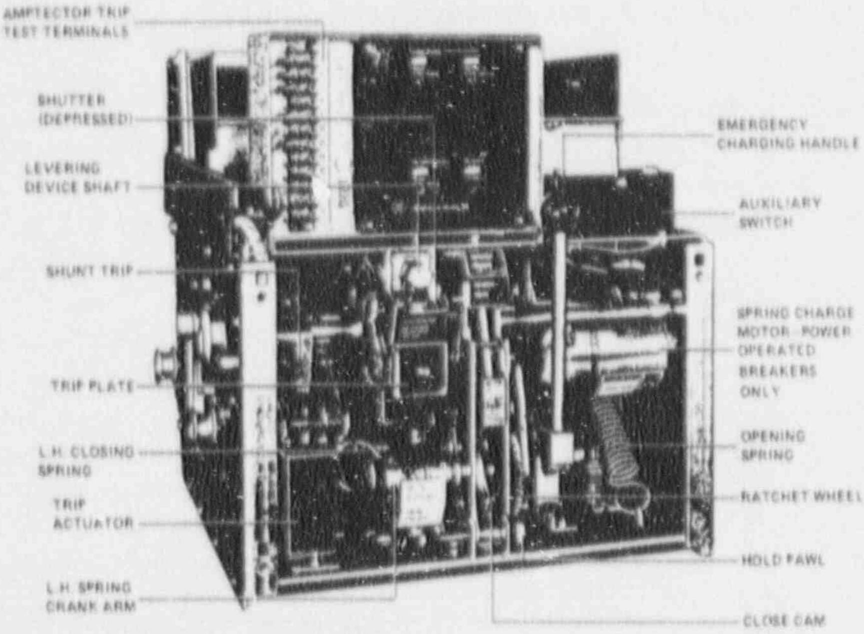


Figure A-1. DS-416 circuit breaker

as cleavages, welding induced defects, cracks) and photographed. The breaker will then be assembled and tested. All mechanical parts will be properly lubricated.

A.2.2 Mounting of Breaker on Test Stand

Since the environment of the breaker is not included in the parameters of this test, the circuit breaker will be mounted on a flat surface, leveled, and bolted down, so allowing visual inspection during operation and accessibility for measurements. The mounting arrangement in the stand will permit ease of access to expedite removal and installation. Wiring harnesses will be used to keep wire breakage to a minimum. Lockable connectors will also be used to insure both electrical integrity and quick disconnection and reconnection between service and inspection: this is important to expedite the examination in the limited time between cycle operation.

A.2.3 Breaker Control Actuator

To test the circuit breaker under operating conditions, it must be made to set and trip efficiently as many times as necessary to reach failure. Therefore, a controller will be used that automatically actuates the breaker for a pre-determined number of cycles. Also, in the event of a failure this controller will stop the process driving the breaker and will record the number of cycles at the time of the failure.

This controller will consist of timing and logic circuitry connected to low-power driver electronics sufficient to actuate the circuit breaker set and trip functions. In addition, logic will be included in the circuitry that permits the controller to detect malfunctions. This can be accomplished by using the breaker power contact terminals as a circuit interlock path for the logic.

If the breaker fails, two distinct conditions can be expected. Either the breaker will fail to close due to a malfunction in the actuator circuit, or the breaker will fail to open due to malfunction in the trip circuit. These conditions will be monitored by the logic in conjuction with the timing of the actuator. In the event of non-coincident condition, the logic will stop the test.

A.2.4 Inspection and Monitoring

Testing of the DS 416 circuit breaker will require both physical inspection and test monitoring using conventional and specially designed instruments. The inspection will primarily focus on mechanical integrity based on visual inspections, and any measured change in tolerance as an indication of wear and impending failure. Standard measuring techniques using calipers, feeler gages, and dial indicators will be used. The inspection will include investigations into weld integrity and dye penetrant examination of critical locations, such as welds and other areas expected to experience high dynamic stress loads such as bars, poles, and shafts.

Other monitoring will incorporate on-line techniques to better observe dynamic properties such as impact stress and temperature rise in suspected weak areas. Stress on the pole shaft will be monitored with strain gages configured to observe peak transient torque on the pole shaft, using an instrumentation amplifier interface and an oscilloscope. The temperature measurements will be centered around the trip solenoid. It will be accomplished with thermocouple instrumentation and recorded on charts to establish thermocouple instrumentation, temperature history, and any changes relative to that history.

Areas subject to stress testing are:

1) Impact torque measurements on the pole shaft weld during opening and closing cycles.

2) The identification of weld cracks as a function of weld size and number of weld cycles.

3) The quantification of growth in weld cracks with the number of operational cycles.

Any failure of other subcomponents, such as Shunt Trip Attachment (STA), closing springs, and trip latches will be monitored throughout the test. Appropriate maintenance of the breaker will be performed in accordance with ANSI/IEEE standards and Westinghouse instructions. From these test results, data will be obtained for developing guidelines for limiting operation depending upon specific weld sizes, condition, and other component problems.

A.2.4.1 Strain Gage Measurements

Instrumentation will be provided for assessing internal stresses in the subcomponents of the circuit breaker. The pole shaft is the most likely candidate for this instrumentation. Careful planning of the type and placement of the strain gage is critical for deriving useful and accurate information. Because of the operating characteristics of the breakers require spring loaded impact, the strain gage will have to register dynamic and static strain properties. Static operation will be primarily used to conform the calibrations.

The configuration of the strain gage array and the signal conditioning used in the instrumentation setup is also critical for proper operation and detection of dynamic event. It is anticipated that more than one strain gage will be required to measure the same critical area. This configuration most desirably would be a fully-compensated electrical bridge made from the component strain gages, that would provide the largest signal-to-noise ratio for good resolution, and stable temperature compensation for high accuracy.

A high-quality instrumentation amplifier with high common-mode rejection will be an important component to this configuration. An oscilloscope will also be required to record the dynamic events to compare with expectation, and as a method for comparing changes over the period of the test.

A.2.4.2 Monitoring of the Trip Solenoid Temperature

The solenoid trip circuit on the DS-206 and DS-416 has a high incident of failures. The failures have been associated with overheating and burnout of the coils. There is a reasonable probability that the burnout may be caused by associated mechanical failure which prevent the solenoid iron core from moving the trip actuator after it has been energized. This forces to coil to remain continuously excited in a locked position. Continuous duty exceeds the design limits of the coil and results in burnout.

In normal operation, this solenoid deactivates the circuit breaker, causing an interruption of power to the load. Under proper trip conditions, this trip solenoid experiences a surge of power for a fraction of a second, sufficient to provide the mechanical energy necessary to release the lock holding the contacter closed. After release is effected, power to the solenoid is also interrupted.

If a mechanical condition within the breaker causes additional resistance against the solenoid actuator, a prolonged reaction time could be expected. This change in reaction time will cause the solenoid to remain on for longer, causing the temperature to rise in the solenoid in proportion to the "on" time. In the extreme case of a jammed actuator, the coil in the solenoid could remain on continuously, causing it to burn up and, possibly, destroy itself.

A correlation can be proposed that relates a temperature rise in the coil as a possible precursor to impending mechanical failure (due to an increase in on-time duty cycle). To monitor any increase in duty cycle, a thermocouple temperature sensor will be attached to the circuit breaker trip solenoid to register effective critical on-time or period of excitation. This can be an important indicator of mechanical change within the solenoid mechanism trip circuit.

A.2.5 Test Equipment List

	Mfg. and Model No. (where available)
1) Control Actuator	
a) Training Device	
b) Cycle Connector	
c) Ammeter	
d) Switch	
2) Strain Gages and their Controls	
a) Strain Gages (micro-meas. div.)	125 Series
b) Instrumentation Amplifier	Meas. Group #
c) Oscilloscope	Phillips #3234
d) Camera	
e) Recorder	
f) Disconnects	
g) Cables	
3) Temperature Measuring Devices	
a) Thermocouples	Omega
b) Thermocouple Reference	Omega
c) Temperature Indicators	Honeywell
d) Temperature Recorders	Honeywell Electronik 19
4) Electrical Test Equipment	
a) Megger	
b) Portable Current Meter	
5) Crack Propagation Instrumentation	
a) Resistance Measurement Device	
b) Dye Penetrant	
6) Dimensional Measuring Devices	
a) Calipers	
b) Feeler gages	
c) Dial Indicators	
d) 7/16" Drill Bit	
7) Spring Constant Measuring Device	

A.3. TEST PROCEDURE

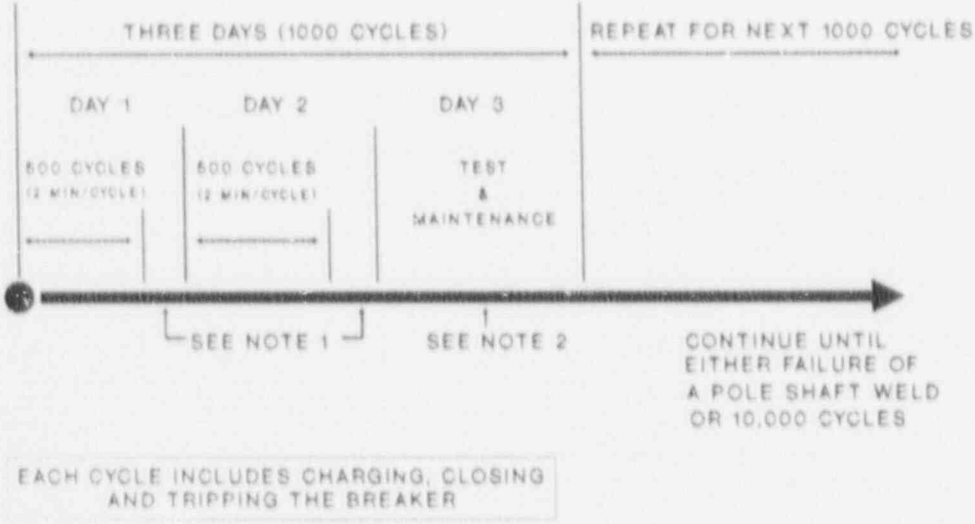
The breaker will be tested in divided segments until one of the welds on the pole shaft fails. A failure will be determined by the inability to either set or trip the breaker under normal conditions. ANSI/IEEE Standard C-37.50 (1981) on circuit breaker life testing will be used to determine the limits of these segments and also the time between each tripping cycle. After one test has been completed, all components of the breaker will be examined similar to the pre-test examination. The broken welds on the pole shaft will be removed and the fracture surfaces will be examined with a scanning electron microscope for metallurgical assessment.

A.3.1 Test Schedule

With a reset/trip period of two minutes and a 500-cycle limit, a test segment can be accomplished in approximately 17 hours. To accomplish the overall test mo[illegible]peditiously, the cycling and failure detection will be automated for unattended overnig[illegible]ation. Thus, it will be possible to exercise the greater number of cycles in the shortest t[illegible], while maintaining essentially the entire standard working day for dynamic measurements, tolerance measurements, and scheduled maintenance (see Figure A-2).

Testing is expected to start April 1989 and will continue on a five-day work week, so allowing about 1750 cycles per week. The 500-cycle test segment will be timed to start during the last two hours of the work day and terminate during the first hours of the following work day. Dynamic strain gage testing can thus occur while the breaker is in continuous operation.

The first set of strain gage tests will begin at the start of the segment in the afternoon and will be repeated again at the end of the 500-cycle period, allowing a comparison of the strain characteristics at the start and finish of the cycle.



NOTES

1. Normal Maintenance (as recommended by Manufacturer) such as lubrication, visual inspection.
2. Mechanical & Electrical Tests are performed. Cracks on the welds are examined.

Figure A-2. Testing Program for the Westinghouse DS Breaker

During the period between the end of the cycle and the start of the next, mechanical inspections and maintenance will be performed, and all data will be recorded and logged.

A.3.2 Scheduled Inspection

Inspections will be made after every 500 cycles. The inspections will consist of a predetermined list of operations designed to characterize the condition of the breaker at that stage of the test. Full characteristic testing and examination will occur before the start of the operational test period and at the end, defined by destructive failure.

Daily scheduled evaluations between cycles are intended for longer term characterization. They will be based on routine monitoring that includes dynamic measurements, collection of fixed data, and maintenance. Intermediate, unscheduled evaluations may also be required, based on changes warranting quantification of breaker properties at the point of observed change. The entire period of the test is defined to the point of failure and for the period after failure when the breaker components will be examined in the laboratory.

A.3.3 Scheduled Testing of Breaker Performance

Instrumented data to reveal physical changes will consist of dynamic measurements made during on-line operation and static measurements made during off times. The dynamic data will come from the strain gages and the temperature sensors. The strain gage information will be recorded on an oscillograph and temperature information on a strip chart recorder.

The dynamic stress characteristics will be recorded by photographing the face of the oscilloscope with the calibration screen illuminated. This will reveal all dynamic amplitudes on a calibrated time base. The photographs can be used to dissect the component stress peaks within the characteristic impact wave shape. They will also provide a record to compare with succeeding oscillographs as a function of time during active testing.

The recording of temperature data will be based on a much longer time, stretching over the 500 cycle segment. In the event of a temperature rise, the history of that rise can be correlated to the time of the event during that test segment. The solenoid is the most likely candidate for this test, but this does not eliminate other locations, such as the drive motor, for passable on-line temperature monitoring.

All other data will be obtained by the test operator. The data recorded by the operator will be based on manual measurements with standard gages and scales. All data will be recorded as magnitudes read from the gage with its respective calibration accuracy.

A.3.4 Unscheduled Failures and Abnormalities

We expect that during the test, other electrical and mechanical components will have degradations that were not detected in the previous scheduled test and maintenance outage. These may include distorted linkages, surface wear, burning of solenoid coils, jammed trip latches, and broken springs. In most cases, the testing will be stopped, appropriate parts will be replaced or repaired to return the breaker to normal conditions, and the test will then continue.

A.3.5 Metallurgical Examination After Failure

A thorough metallurgical inspection and analysis will be performed after failure by the Nuclear Waste and Material Technology Division of DNE. Optical microscopy and scanning election microscopy will be used on the fractures. Dye penetrant testing will be used on the pole shafts. General photographs and cross-section photographs will be presented in the final test report.

A.4. EVALUATION PROCEDURES

Four types of data are expected to be obtained at the end of the test program, namely, scheduled/unscheduled inspection data, scheduled/unscheduled maintenance data, scheduled/unscheduled test and monitoring data, and metallurgical data on weld cracks. Each data set will be analyzed, the cause of the failure mode of the breaker, the cause of the failure, the aging mechanism that should be mitigated, and mitigation guidelines. Data from the pre-test, during-test, and post-test periods will be analyzed together.

We believe that this test will reveal important information for future planning and design. The information will increase the likelihood of predicting incipient failure modes in the Westinghouse DS-series or similar circuit breakers.

From the data, recommendations will be offered highlighting methods for improving inspection procedures and mechanical design. Also, the test procedures may, in themselves, be a model for on-line monitoring for assuring higher degrees of safety through fault detection and subsequent direct inspecting and maintenance.

A.4.1 Evaluation of Inspection Data

Data from all phases of the test program will be analyzed to determine:

a) Age-related degradations in any device or component (wear, contamination, alignment, cleanliness, looseness).

b) Correlation of each mechanism with test cycles.

c) Identification of incipient, degraded, catastrophic performances.

A.4.2 Evaluation of Maintenance Data

This data will provide the information that correlates the lubrication problems of mechanical parts, life of control devices, distortion of mechanical linkages, weakening of spring stiffness, and other maintenance-related parameters with the test cycles. If any trend is shown in assessing the life (i.e., number of test cycles) of a particular component, this should indicate periodic failure of those components.

A.4.3 Analysis of Test and Monitoring Data

Degradations of various mechanical components and electrical devices will be monitored by any of the following test parameters:

a) Temperature
b) Insulation Resistance
c) Current Flow
d) Crack Initiation and Propagation
e) Impact Force on Welds
f) Resistance Across Cracks

These parameters will be evaluated to determine whether any can monitor the normal deterioration of various components. If not, then the times of replacement of these components will be determined. Both weld crack initiation and propagation will be analyzed to develop a correlation with the number of cycles.

A.4.4 Metallurgical Examination of Fracture Surfaces

Scanning Electron Microscopy (SEM) of crack surfaces will be used to determine:

a) fracture initiation mechanism and their causes.
b) fracture propagation and the forces that cause it to occur.
c) metallurgical defects in material selection or manufacturing process.

A.5. EXPECTED RESULTS

The results from this test program will, identify and characterize the following:

1) Life cycles for pole lever weld configurations.
2) Crack propagation rate for each weld configuration.
3) Life cycles for small control devices (STA, UVTA, solenoids).
4) Wear in closing cam by the main roller.
5) Characteristics of closing/opening spring.
6) Degradation and distortions of trip mechanism.
7) Evaluation of charging motor life.
8) Degradation (mechanical) of contact surfaces.

Recommendations will be developed to improve the existing plant maintenance activities for alleviating the problem of breaker failure, specifically for those used for Reactor Trips. Also, this will include predicting the life cycles of various breaker components which should be factored into the maintenance program for minimizing degradation and avoiding castrophic failure.

A.6. REFERENCES

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A.3) NRC IN 87-35, "Reactor Trip Breaker Westinghouse DS-416 Failed to Open on Manual Initiation."

A.4) NRC IN 88-44, "Mechanical Binding of Spring Release Device in Westinghouse DS-416 Circuit Breakers."

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APPENDIX B

DYNAMIC STRAIN GAGE ANALYSIS

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ABSTRACT

A history of failures in power plant circuit breakers associated with critical welds in the internal pole shafts was investigated. This paper describes the test, equipment and instrumentation and summarizes the preliminary results of testing of these breakers at Brookhaven National Laboratory. We describe the instrumentation including the use of a full-bridge strain gage sensor and instrumentation amplifier connected to an oscilloscope. The combination provided a sensitive instrument, capable of revealing subtle changes in the performance of the circuit breaker. The strain gages were attached to pole shafts and monitored dynamically. The observed changes in wave signature were recorded as a function of accumulated operating cycles. Complex changes in wave shape recorded on an oscillograph indicate patterns related to impending failure of the weld. The life expectancy measured as the number of circuit breaker open and closing cycles is compared with the failures of the weld and other components.

CONTENTS

ACKNOWLEDGMENTS

The authors are very grateful for the excellent technical support received from Mr. Steven Kochis and Mr. Antony Bono. Special thanks is also offered to Dr. Manomohan Subudhi, Mr. John Taylor, and Mr. James Higgins for their guidance and editorial support.

B.1. INTRODUCTION

The object of this testing program at Brookhaven National Laboratory is to investigate and understand the failure modes associated with the Westinghouse DS 416 circuit breaker, a common unit used in both conventional and nuclear power plants. This investigation was prompted by a history of failures associated with this series circuit breaker. A test program was created that included a series of instrumented tests to monitor the major stress areas associated with subcomponents in the circuit breaker. A subcomponent called a pole shaft mechanically links the various attachments in the circuit breaker and was identified as the critical component for investigation.

The object of the monitoring was to derive information indicating changes in perfomance and operation that can be used to predict destructive failure. The testing plan included subjecting the breaker to a continuous series of on-off operations designed not to exceed the manufacturer's specifications. This operation was accompanied by visual and instrumented monitoring at scheduled intervals during the test.

The on-line techniques proved useful for observing dynamic properties associated with impact stress, including monitoring dynamic torque at the time of opening and closing impact, and static rest torque at the opened and closed rest positions. We used a special strain gage configuration designed to observe peak transient torque on the shaft during impacts and static torques at rest. Auxiliary components were required, including an instrumentation amplifier, an oscilloscope and a digital voltmeter. Photographs were taken to aid observation and record the events.

B.2. STRAIN GAGE MEASUREMENTS

The strain gage is characteristically a low-level device with voltage output in the microvolt range. A full electrical bridge configuration was used that achieved 5 microvolt per inch-pound of torque. Because this small signal is below the noise threshold (about 300 uV) of the oscilloscope used, an external instrumentation amplifier was required to raise the signal levels and improve signal-to-noise ratio.

The ability to discern fine structure in the wave shape during real time related to the torque behavior of the pole shaft is important. This fine structure can reveal both critical dynamic torque amplitudes and frequency components that can effect crack initiation and accelerate their propagation. The instrumentation amplifier was carefully selected to meet this requirement.

B.3. STRAIN GAGE CONFIGURATION

Torque measurements require a strain gage configuration that responds to the strain associated with twisting. This is a two element gage in which the sensitive elements are positioned at an angle relative to each other. The gages are attached along the axis of the pole shaft so that the physical "twisting" of the shaft causes tension to one element and compression in the other, effecting their electrical resistance.

In the rotational mechanical forces associated with torque, a vectored stress is created on the surface and at a shallow angle relative to the line defined by the shaft's rotational axis. Under such conditions, this differential change in resistance is in proportion to the strain. Two such gages were used at strategic locations on the pole shaft creating a four-element active electrical bridge. Such a configuration offers full temperature compensation and twice the signal level compared with a single two-element configuration. The gage chosen for the application was mode EA-06-062TV-350 made by Micro-Measurements.

B.4. PROCEDURES FOR GAGE ATTACHMENT AND TESTING

In the investigation, a critical weldment attaching a lever to the pole shaft was suspected of premature failure. To determine the forces on this weld, a regional representative of the forces on the shaft and the weld was necessary. Therefore, it was important for the strain gages to be attached at some distance from the weld, so that the complex geometry associated with the mass of the weld did not distort the indication of dynamic torque.

The optimum location of the gages was in a clear span of shaft where there were no other mechanical connections. This position lies about five inches long between the critical weld under investigation and the furthest adjacent attachment. The gages were placed in a symmetrical position bisecting the location of the two adjacent welded attachments. There the strain gages directly indicate shaft torque from all forces influencing twisting at the point of attachment. The strain gages were bonded to the shaft with adhesives which, upon curing, physically transfer the relative surface motion of the shaft to the gage.

All cabling from the strain-gage bridge to the interfacing electronics was accomplished using techniques developed specifically for this application. Careful harnessing and routing of the cabling was necessary to avoid damage while cycling because of the heavy impact. The design was further complicated by the requirement for low electrical noise and quick disconnection, so that frequent disassembly and assembly could be accomplished for inspection without major rewiring.

B.5. INSTRUMENTATION ELECTRONICS

The electronics required for the experiment consisted of four subsystems:

1. A strain gage bridge cluster attached along the primary axis of the pole shaft with four active elements (see Figure B-1).
2. An instrumentation amplifier for raising the level of the strain-gage signal and for reducing common-mode electrical noises.
3. A regulated power supply for the strain-gage bridge and the instrumentation amplifier.
4. An oscilloscope to monitor the real-time dynamic data and a five-place digital volt meter for static measurements.

The resolution of the oscilloscope is limited to visual discrimination of the screen. In practice, this limits the accuracy to 2% of the full scale screen amplitude. Static measurements were

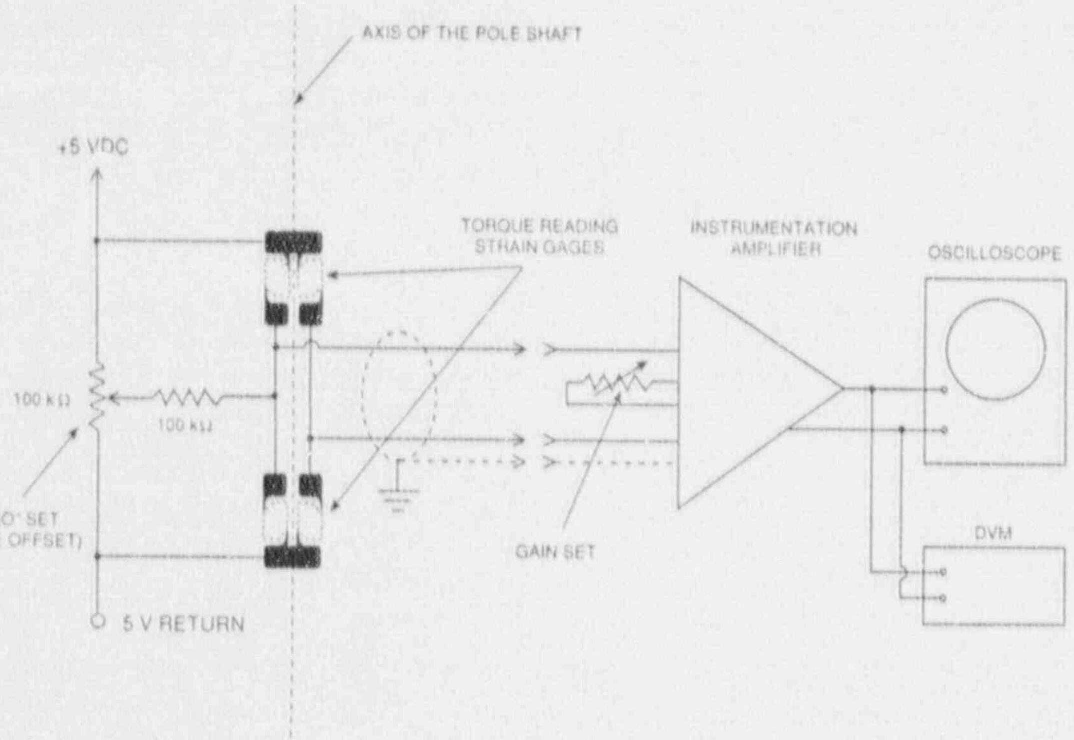


Figure B-1. Circuit Breakers Test Setup

more accurate because the digital output allowed as little as 0.01% change to be detected. It was useful for tracking the more subtle changes in statis "rest" torque.

The instrumentation amplifier (Analog Devices AD521) was chosen for its maximum signal-to-noise ratio of indicated strain. This circuit was constructed from component hardware and connected with low-noise cabling to the electrical strain-gage bridge. The combination yielded a low drift, high common mode signal rejection and wide frequency response.

By definition the instrumentation amplifier, essentially amplifies only the signals that are different at the output of the strain gage bridge. This system can amplify with a very high gain factor (up to 1000 times) the differential signal at the strain gage electrical bridge outputs, while rejecting signals common to both bridge terminals, referred to as common-mode noise. The AD521 has a common mode rejection ratio that measures as high as 110dB.

The relative high frequency response was also important for this monitoring application to show any detectable fast transient peaks that might influence crack initiation. This frequency response is a function of the gain factor applied to the amplifier, and drops in proportion to increases in gain. Similarly, the common-mode rejection ratio decreases with decreased gain, so it was important to optimize the gain factor for maximum performance. To this and, a compromise gain was chosen for the amplifier, (about 320) that allowed both a suitably high signal-to-noise ratio with good anticipated common-mode rejection and an acceptable frequency bandwidth (about 50 Khz).

Bench testing was performed before actual testing of the circuit breaker to insure that the operation of the connected instrumentation components complied with the expectations prescribed in the original design plan. Two overall tests were made to satisfy operation expectations, one with conventional gages mounted on standard steel sheets with all design connections used to assess all components operation, while the second included testing with a standard circuit pole shaft. All testing proved satisfactory, both at the component and the system level, and well within the boundaries of predicted results.

B.6. CALIBRATION

The calibration of the strain gage was ultimately performed with all design connections intact, as used in the circuit breaker test. This calibration was performed on the pole shaft in a special calibration fixture prepared at the Alkem facility.

The calibration fixture was designed to allow a predetermined and accurate measurement of static torque to the shaft while recording the output from the digital voltmeter. The output of the amplifier was adjusted for a gain factor corresponding to a compromise between good common-mode noise rejection and transient response, as evaluated by simulated impacting on the pole shaft in the bench-mounted test.

The bridge configuration was also electrically "zeroed" so that the pole shaft showed no torque at rest. Any non-zero torque shown in the instrumentation after installation in the circuit breaker would be indicative of static rest torque in the pole shaft either in the breaker closed or open position. This torque was also measured with the digital voltmeter. Drifting of this static rest torque during the test would indicate some internal changes. The recorded readings then were manually entered into a linear regression curve-fitting computer program to be analyzed and converted into a corresponding calibration graph. The graph shown in Figure B-2 incorporated two different pole shaft calibrations with good agreement, adjusted for gain corresponding to real static torque as applied to the pole shaft and indicated on a digital voltmeter. Such a calibration was made by installing the pole shaft in a fixture built at Alkem for this purpose. The fixture was designed to allow a predetermined and accurately measurable application of static torque to the shaft while recording the output from the digital voltmeter.

B.7. CIRCUIT BREAKER TESTING AND PRELIMINARY RESULTS

After completion of all electrical testing and callibration, the instrumented pole shaft was installed in the circuit breaker. The automatic set and trip controller permitted the circuit to be energized and tripped at two-minute intervals. Maintenance and inspection was performed after 500 cycles in accordance with the recommendations made by the manufacturer and developed by BNL.

The results of the experiment were relatively predictable. The dynamic torque wave form and amplitude correspond approximately to other data taken in earlier Westinghouse test. The BNL testing attempted to be more comprehensive by striving for more accuracy, resolution and a greater volume of accumulated data. Three pole shafts with different weld properties have been included in the test program to satisfy this requirement.

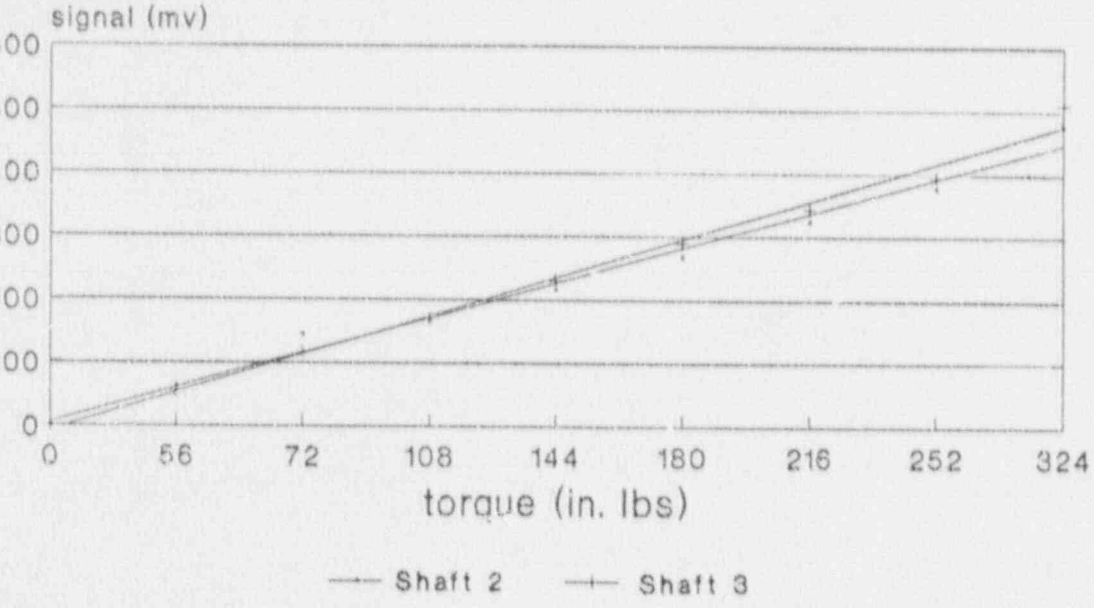


Figure B-2. Strain Gage Calibration – Shaft 2 and 3

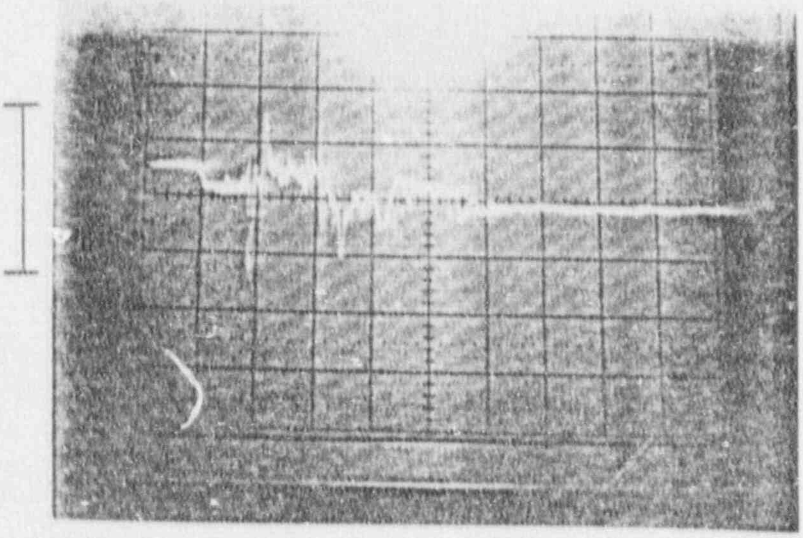
Other critical parts in the construction of the circuit breaker, including a drive motor, springs a trip solenoid, and various associated components are also being monitored for durability and cycle life, as shown by extreme wear and failure.

A characteristic change in the waveform was observed as a function of accumulated opening and closing cycles to the point of failure. The first pole shaft failed at 3027 cycles on July 21, 1989. At 2015 cycles, the oscilloscope photographs indicated a doubling of the "tripping forces" during the opening of the circuit breaker. These higher dynamic torques, in the range of 780 to 910 inch-pounds, remained high until the pole shaft failed.

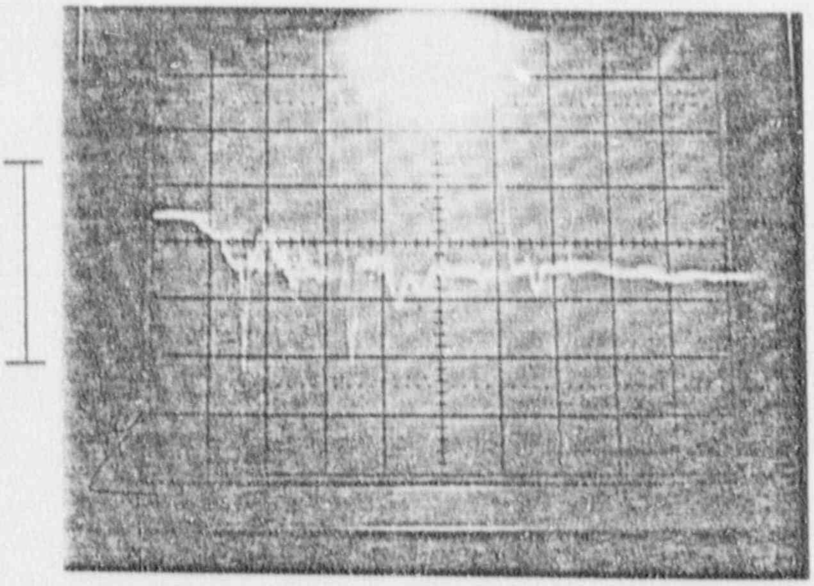
Figure B-3 shows the tripping forces on June 15, 1989, at 180 cycles; this oscilloscope photograph shows ±390 inch-pounds of torque and is typical of the results from June 15 to July 10. Figure B-3 also shows a photograph at 2735 cycles on July 19, 1989; the torque is ±830 inch-pounds which is typical of all photographs taken from July 11, 1989 until failure.

As part of the testing program, dye penetrant readings were made periodically. These tests revealed a 0.125 inch crack on the critical weld at 2000 cycles. This crack reached a length of 0.260 inches at 3000 cycles just before failing.

The first complete failure of the entire first mechanism occurred at 13,609 cycles on November 8, 1989. Before failure, dramatic changes occurred in the pole shaft torque as shown in the oscilloscope photographs. Figure B-4 shows a typical photograph of the torque prior to

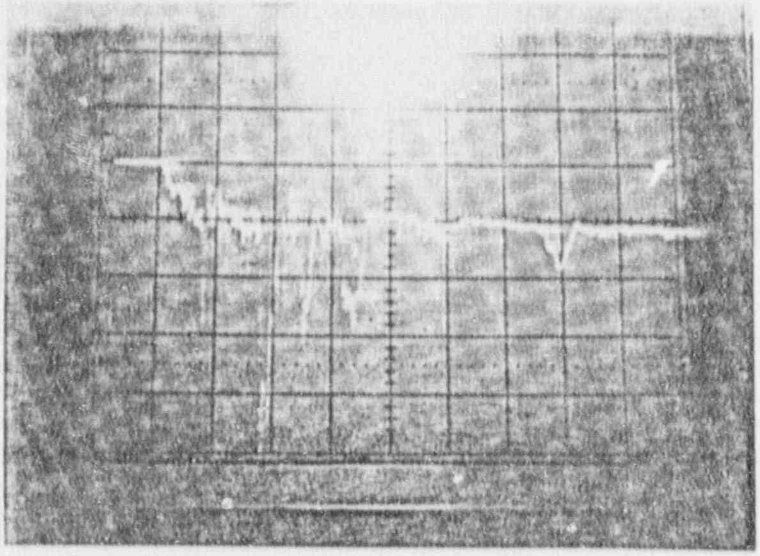


6/15/89 TRIPPING FORCES = ±390 in. lbs

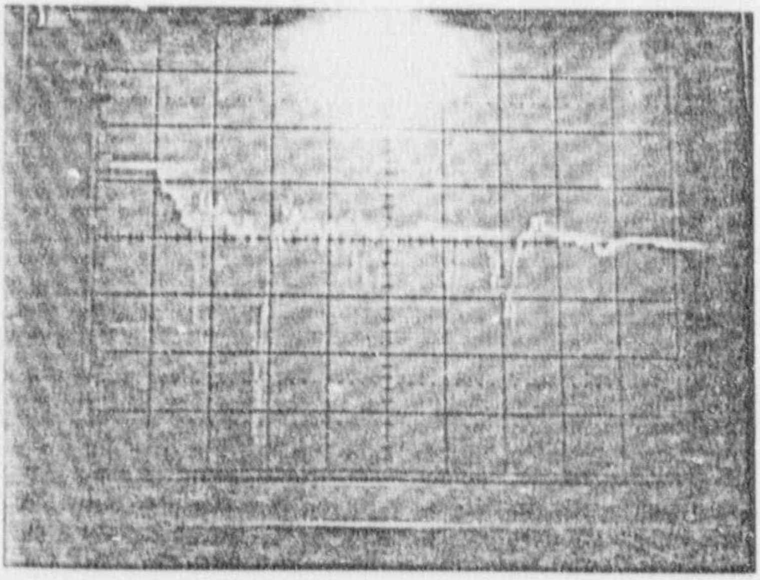


7/19/89 TRIPPING FORCES = ±830 in. lbs

Figure B-3. Tripping Forces – Pole Shaft 1



TYPICAL WAVE FORM - 10/31/89 - 12, 289 CYCLES



WAVE FORM - 11/8/89 - 13, 227 CYCLES

Figure B-4. Tripping Forces – First Mechanism

November 8, 1989. The end of the circuit breaker closing indicates a relatively stable torque waveform. The lower photograph shows a more ragged wave shape, typical of the pattern leading to failure.

We need a more detailed understanding of the entire waveshape and its changes as a function of cycle life. However, it can be safely said that there are progressive indications of wear, measured by changes in amplitude and frequency, that suggest impending failure.

These dynamic torque indications are a manifestation of changes in tolerance. The mechanisms attached to the pole shaft, as well as physical fatigue in the shaft, are being altered by the repeated impacts. As these tolerances increase the alignment of components attached to the shaft are altered, resulting in increased reactive forces on the shaft and its attachments. All these forces are transmitted through the shaft and are, therefore, observable with the strain gages. Such changes in fine structure were not observable in earlier Westinghouse testing. In future, this information should prove useful in guiding future designs of circuit breakers. The instrumentation approach will also provide a tool for validating the quality of these future designs in the interest of avoiding unpredictable failures.

B.8. SUMMARY AND CONCLUSIONS

The results of ongoing testing indicate that the approach used to better understand critical circuit breaker fatigue and failure modes is proving valuable. Measuring dynamic torque in the pole shaft in the DS series circuit breaker is a good indicator of normal forces on the shaft as well as changes leading to failure. The torque wave shape also is an indicator of what is occurring with other components coupled to the shaft.

Techniques developed from these studies can improve quality assurance and avoid the pitfalls of substandard designs and materials. These tests suggest a method that can predict failure many cycles before it occurs. The dynamic measurements shown of both maximum torque and characteristic torque waveform patterns indicated by the peaks and the complex frequencies. As a function of succeeding breaker cycles these changes are believed to be a signature of structural change and impending failure. These effects will be analyzed in more detail in the weeks ahead and reported in the near future.

The data collected, which was broadly predictive of failure in the circuit breaker pole shaft, offers the promise of being useful for a theoretical model of component wear and failure model. Also, the success of the experimental methods suggests that similar test may be beneficial for other mechanical components, such as pump shafts or load-bearing crane parts.

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B.6. U.S. Nuclear Regulatory Commission, "Reactor Trip Breaker Westinghouse DS-416 Failed to Open on Manual Initiation," NRC Information Notice 87-35, July 1987.

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APPENDIX C

METALLURGICAL EXAMINATION OF FAILED COMPONENTS

Bom Soon Lee

ABSTRACT

As a part of life testing program of Westinghouse DS-416 low voltage circuit breakers, analyses were conducted on failed parts to determine the possible causes for the failures. These parts included an indicator spring, an oscillator pawl reset spring, a phase A pole pin, a trip shaft lever, and a No. 3 weld on pole shaft #1. Recommendations are also made to help avoid premature failures of these parts in service.

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LIST OF FIGURES

ACKNOWLEDGEMENTS

The author thanks Dr. Manomohan Subudhi and Mr. Edward MacDougall for giving him an opportunity to work on this project. He also thanks Dr. Peter Soo for critical review of this report. Finally, Mr. Stephen Kochis and Mr. Robert Sabatini are acknowledged for their technical assistance.

C.1. INTRODUCTION

Westinghouse DS-416 low-voltage power circuit breakers are used in nuclear power plants to interrupt power from the rod drive motor-generator set to the rod control cabinet on command from a reactor trip signal. Interruption of the power to the rod control cabinet causes the control rods to fall by gravity into the PWR reactor core, thereby causing shutdown. This type of circuit breaker is built with a steel frame, a very complex charging system, several linkages, mechanical parts, and control devices.

During the lifetime of a power plant, the circuit breakers undergo many test cycles as a requirement of plant technical specification and maintenance. In recent years, several circuit breakers failed prematurely, and an aging test program was started at Brookhaven National Laboratory for the U.S. Nuclear Regulatory Commission to investigate and understand the failure modes of the Westinghouse DS-series circuit breakers.

As a part of this program, analyses were conducted on failed parts to determine the possible causes for the failures. The results are expected to lead to information useful for lifetime prediction of parts in a given circuit breaker. Such information could also provide important technical data for improved circuit breaker designs.

In this appendix, failures of the following five circuit breaker parts were analyzed, and recommendations are made to help avoid premature failures of these parts in the future:

1. Indicator Spring
2. Oscillator Pawl Reset Spring
3. Phase A Pole Pin
4. Trip Shaft Wing
5. No. 3 Weld on Pole Shaft #1

In conducting failure analyses, it is essential to have information on materials (compositions, specifications, etc.) and manufacturing processes of the parts. However, this information could not be obtained from Westinghouse despite several requests. Lack of this information was not considered serious since we could tentatively identify the materials in the current study.

C.2. FAILURE ANALYSES

C.2.1 Indicator Spring

C.2.1.1 Background

The indicator spring is a part of a breaker trip indicator as shown in Fig. 2.1 in the main text. When this spring fails, the indicator cannot provide correct information on the status of a breaker. More importantly, however, this spring is a part of the trip mechanism, and the breaker does not function when this spring fails. One indicator spring failed after 5,861 cycles of service, while the other spring did not fail after 13,000 test cycles.

Energy dispersive X-ray spectroscopy (EDAX) analysis showed that the composition of this material is mainly iron with some Cr and Ni. This spring shows slight ferromagnetism: thus, the material is most probably Type 301 stainless steel which contains some ferrite. Type 301 or 302 stainless steel is commonly used as a spring material since these steels are responsive to cold working (e.g., for Type 301 SS, annealed, yield strength: 276 MN/m^2, cold-worked yield strength: 966 MN/m^2).

C.2.1.2 Discussion

Figure 4.23 in the main text shows the failed indicator spring, and Fig. C-1 shows its fracture surface. It is quite clear that cracking started in the areas marked by arrows in Fig. C-1. Figure C-2 shows the transition from fatigue crack growth to final fracture (higher magnification micrograph of the area B in Fig. C-1). This scanning electron microscope (SEM) micrograph shows striation marks which indicate that fatigue crack growth preceded the final overload fracture. The final fracture surface contains "dimples", which show that this material is ductile.

Examinations of the wire surfaces of the bent area (where failure occurred) revealed some subtle differences between the inside surface (marked as I in Fig. C-1) and the outside surface (marked as 0 in Fig. C-1). The inside surface has shallow surface cracks (Fig. C-3 a), while this kind of cracking is absent on the outside surface although deep drawings marks are clearly visible as (Fig. C-3 b). These marks were formed when the wire was originally made. The shallow, longitudinal cracks on the inside surface were probably developed during the mechanical bending process to make the hook.

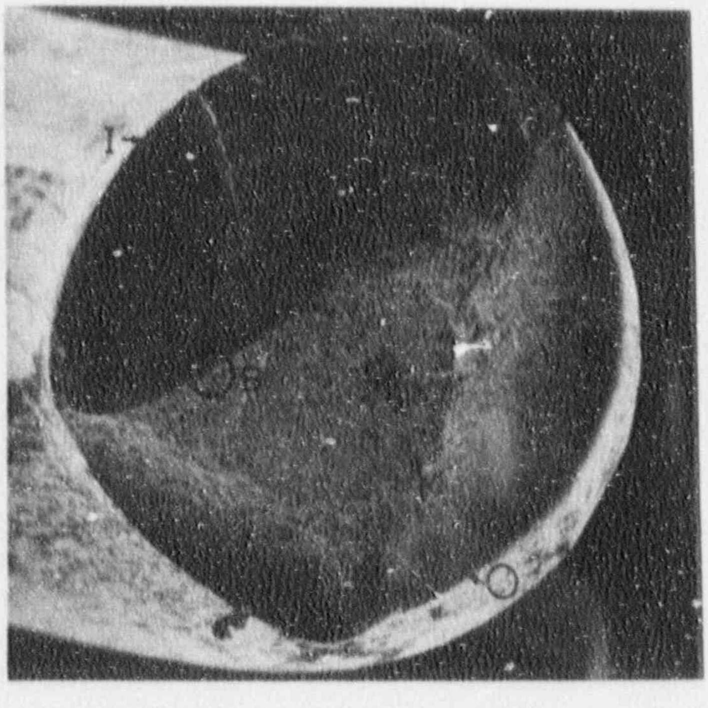


Figure C-1. SEM micrograph of the fracture surface of the indicator spring. Mag: 100x.

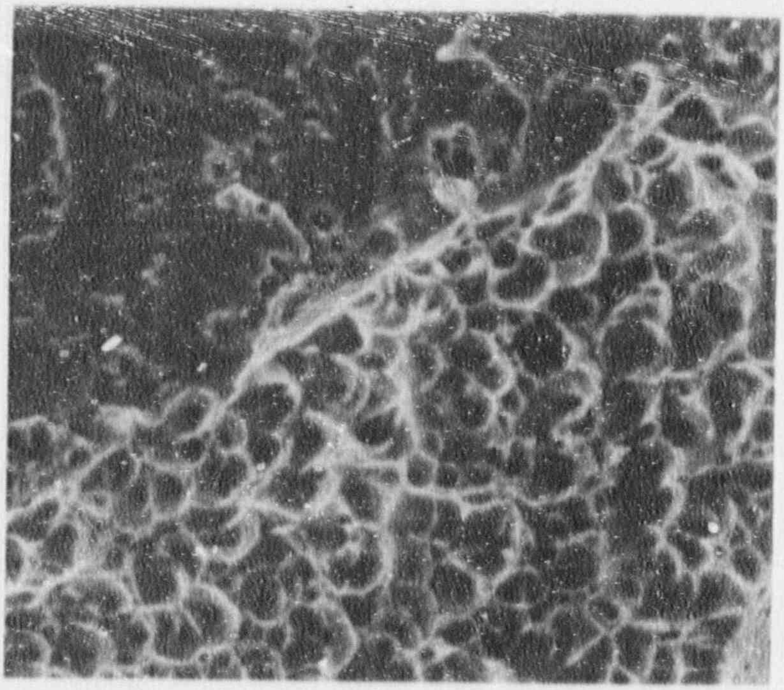


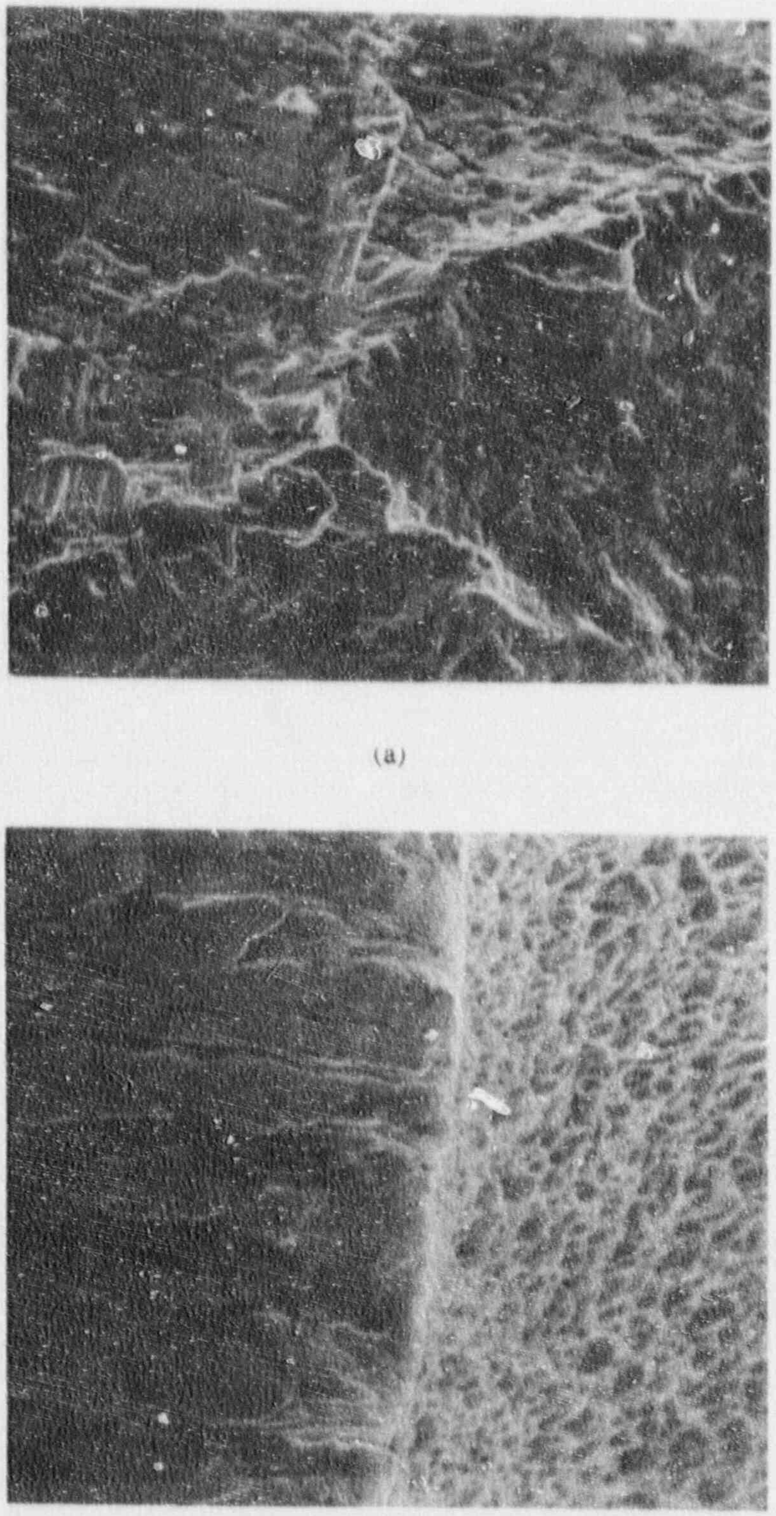
Figure C-2. SEM micrograph shows striation marks in the transition area from fatigue crack growth to final fracture. Mag: 2,000x.

In addition to some torsional stresses, the inside surface of a loaded spring experiences tensile stresses while the outside surface is under compressive stresses. Thus, any defects on the inside surface of the bent wire that are in normal direction to tensile stresses can initiate cracks, which then will grow due to cyclic stresses. Even in the absence of this type of defect, the surface defects in the longitudinal (axial) direction can initiate a transverse fatigue crack (ASM, 1975).

Figure C-4 a) shows that crack initiated at the upper right corner. As it grew it was stopped by the axial crack and continued on a different plane. Figure C-4 b) shows a secondary crack, which started from the same origin. Figure C-4 b) also shows plastic deformation on the wire surface caused by mechanical bending.

Thus, it is believed that a crack was initiated at an area of plastic deformation where the tensile stress and the potential for the surface defects were the highest. The crack initiation was followed by fatigue growth, which led to final overload fracture.

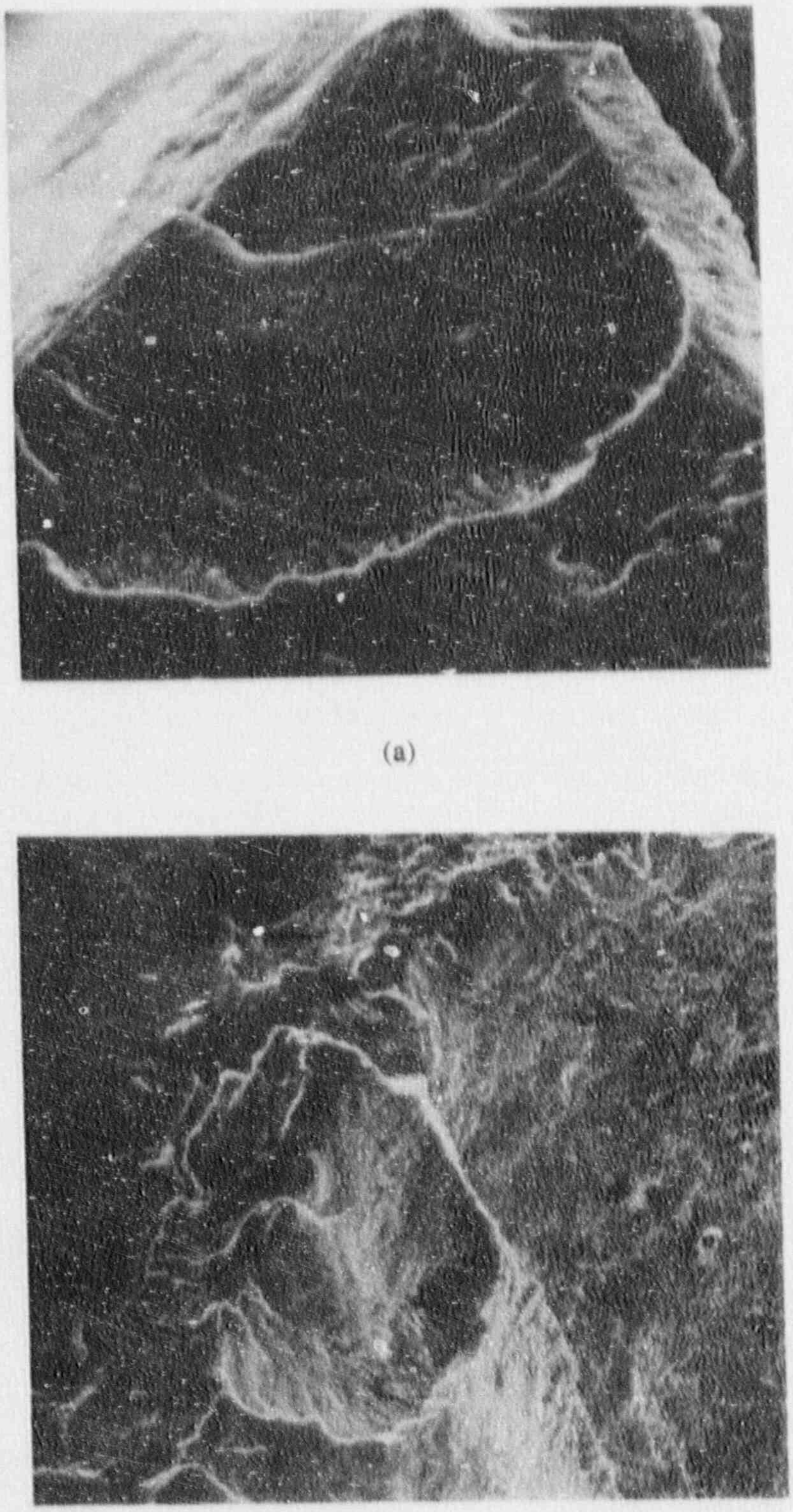
Another indicator spring did not fail even after 13,000 test cycles. This spring was also examined to see if there were any differences in surface conditions between the two springs. The inside surface of the bent area was examined for any transverse or longitudinal cracks, but none developed. The surface drawing marks are similar to those of the failed spring. Energy Dispersive X-ray Spectroscopy showed that the compositions of the two springs are identical.



(a)

(b)

Figure C-3. a)SEM micrograph shows axial surface cracks on the inner surface. Mag: 1,000 x.
b)SEM micrograph shows drawing marks on the outer surface. Mag: 1,000 x.



(a)

(b)

Figure C-4. a)SEM micrograph shows a crack initiation site. Mag: 2,000 x.
b)SEM micrograph shows a secondary crack formed from the same origin. Mag: 1,000 x.

C.2.1.3 Conclusions

Based on the examinations of the failed and unfailed springs, we conclude that one or more of the following causes may be responsible for the premature failure of one of the springs:

- Excessive plastic deformation during the formation of the hook bend,
- Surface imperfections due to the wire drawing process.

C.2.1.4 Recommendations

To minimize the damage to the surface and reduce the tensile stresses on the inside surface of the bend area near the hook, it is recommended that a shallow curve be made (see the unfailed spring in Fig. C-5, which is discussed in the following section) instead of a sharp bend.

C.2.2 Oscillator Pawl Reset Spring

C.2.2.1 Background

The function of this spring is to reset the oscillator pawl after each cycle of testing. It should be noted that this spring experiences a large number of vibrations in the process of resetting. One oscillator pawl reset spring failed after 2,286 test cycles, while the other spring did not fail even after 13,000 cycles. Both springs are shown in Fig. C-5.

EDAX analysis showed that this spring is made of carbon steel, and is plated with chromium and zinc. Because of the plating, the outside surface is relatively free of surface defects. Figure C-6 shows that the steel wire was cold worked (drawn and wound), and then was plated.

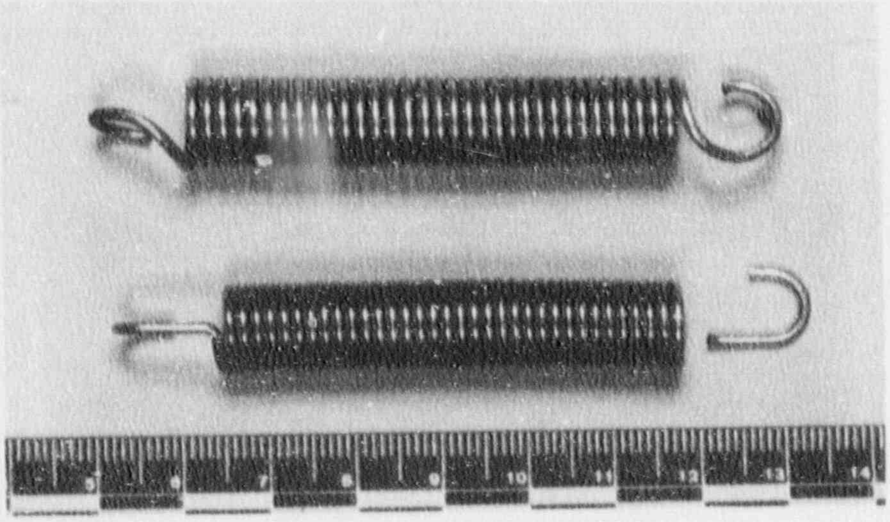


Figure C-5. Oscillator pawl reset springs

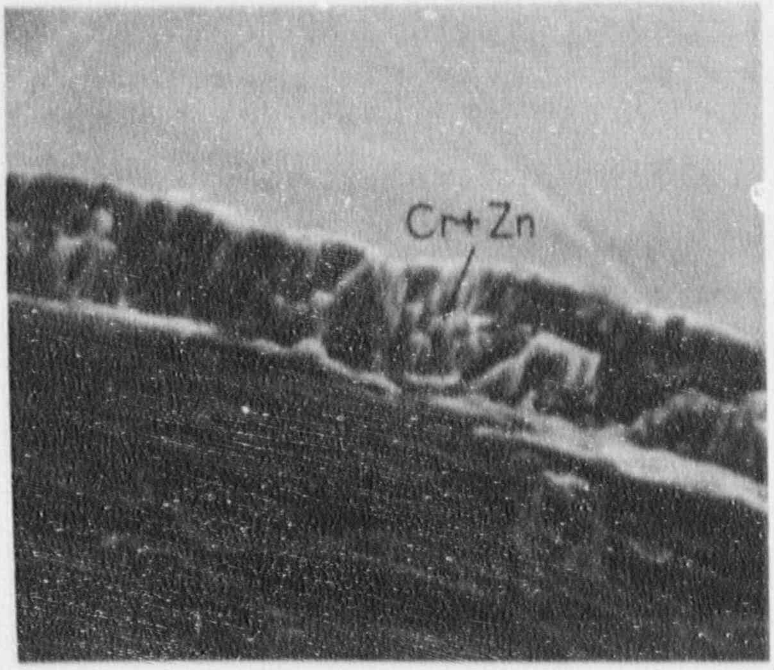


Figure C-6. SEM micrograph of the fracture surface that shows the surface coating. Mag.: 3,000 x.

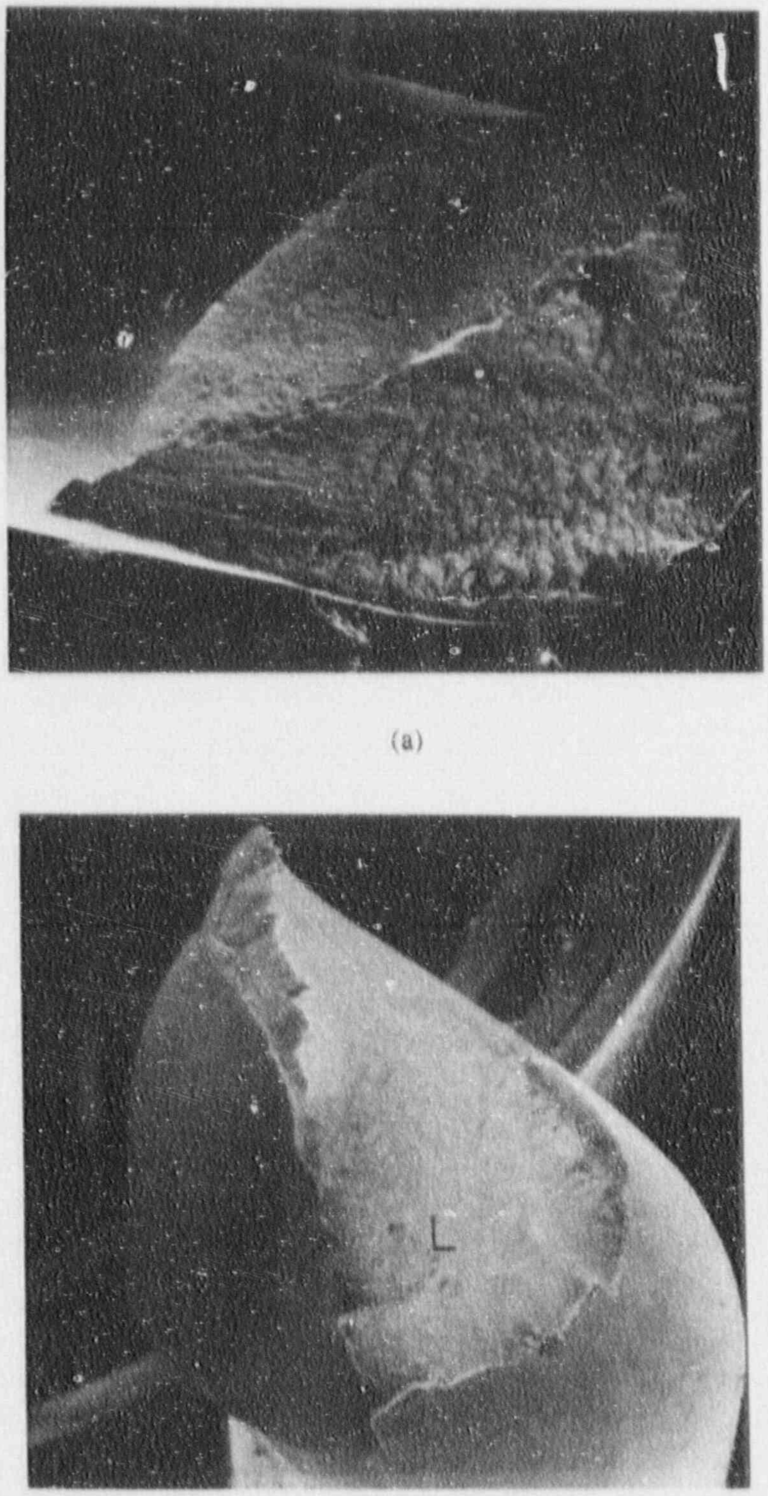
C.2.2.2 Discussion

As shown in the fracture surfaces in Fig. C-7 a) and b), the fracture occurred through complex processes. The area marked as U in Figures C-7 a) and b) is flat and smooth, which indicates slow fatigue crack growth. On the other hand, the area marked as L in these figures is rough and has many impact steps and longitudinal fractures (Fig. C-8). These longitudinal fractures and steps are typical of overload fracture-surface morphologies for wires that failed during laboratory reversed-bending fatigue tests [Shemenski, 1974].

Figure C-9 is a higher magnification SEM micrograph of the area marked as 01 in Fig. C-7 b), which shows river marks indicating the origin points of the crack. This crack propagated by fatigue growth. Area L in Fig. C-7 a) shows a small area marked as 02 which is smooth and flat. A higher magnification SEM micrograph of this area, Figure C-8, shows impact marks (smeared metal) which indicates that this crack existed before the final overload fracture.

It is known that reverse-bending fractures have two origins or two groups of origins, lying opposite to one another in cross-section [Naumann, 1969]. Thus, it is believed that two cracks started, one at 01 in Fig. C-7 b) and the other at 02 in the same figure, due to the reversed bending stresses. However, the crack initiated at 01 grew much faster than the one at 02 probably due to much higher tensile stresses experienced by the inside surface of the bend when the spring was loaded.

Figures C-10 a) and b) show a longitudinal (axial), splitting crack initiating at the front of the fatigue crack when the crack had propagated to a length as large as half the wire cross-



(a)

(b)

Figure C-7. SEM micrograph of the matching fracture surfaces. Mag.: a) 50x b) 43x.

Figure C-8. SEM micrograph of impact marks and steps. Mag.: 500x.

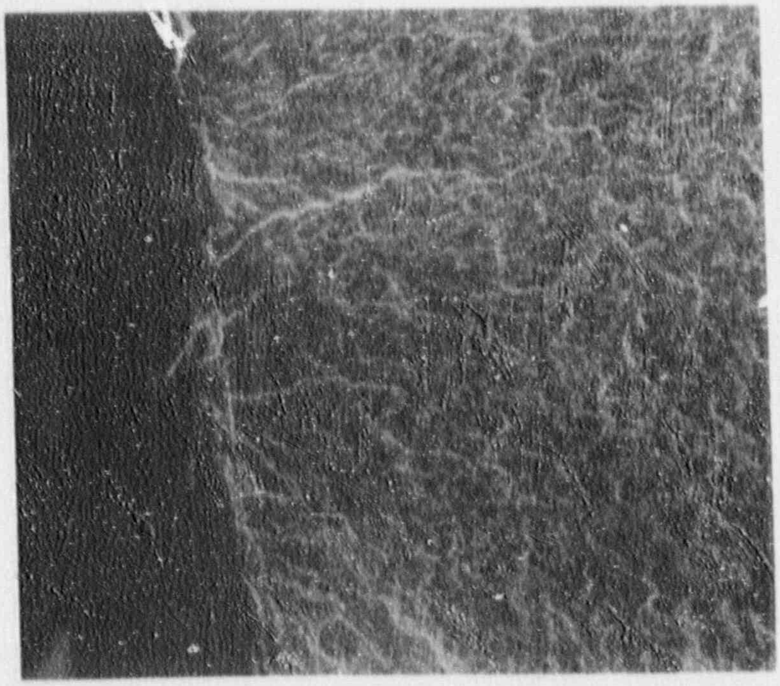
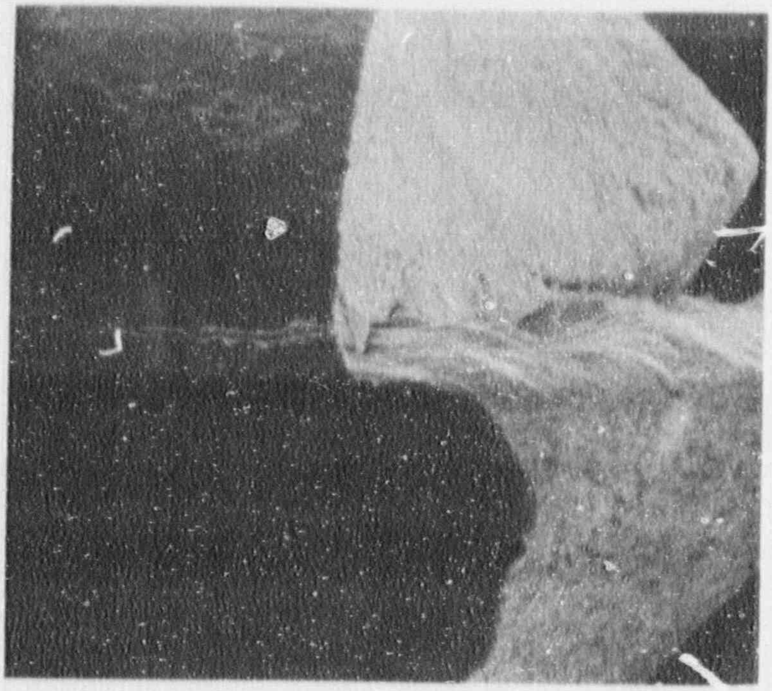


Figure C-9. SEM micrograph of the fatigue crack growth surface shows river marks. Mag.: 500x.



(a)

(b)

Figure C-10. SEM micrograph show longitudinal, splitting crack. Mag.: 100x.

section. Figure 10 b) also shows plastic deformation morphology that indicates torsional stresses. We believe that torsional stresses caused this axial crack. Also, the large number of vibrations after each test cycle may have contributed to the growth of this crack.

The final step of the failure was an overload fracture which produced step-like morphologies (Fig. C-8). This final fracture could have been preceeded by some fatigue growth of the crack that originated at 02 in Fig. C-7 a).

C.2.2.3 Conclusions

The crack initiated on the inside surface of the sharp bend formed to make the hook grew by fatigue until it covered about half the cross section of the wire. Because of the sharp bend, this initiation site must have experienced excessive tensile stresses when the spring was loaded. The next step was probably the development of a longitudinal, splitting crack caused by torsional stresses and a large number of vibrations after each test cycle. The final step of the failure was an overload fracture, which produced a step-like morphology.

C.2.2.4 Recommendations

As shown in Figure C-5, the spring that did not fail even after 13,000 test cycles has shallow curves in the hook area. On the other hand, the failed spring has sharp bends in the hook area. It is recommended that shallow curves be made instead of sharp bends when forming the hooks.

C.2.3 Phase A Pole Pin

C.2.3.1 Background

The phase A pole pin connects a drive link with a pole shaft through the pin holes in No. 1 and No. 2 levers which are shown in Fig. 3.1 in the main text. These levers are welded to the pole shaft by weld No. 1 and weld No. 2. During the aging tests, weld No. 1 deformed and caused a misalignment of the pin holes through lever No. 1 and lever No. 2, which generated bending and some torsional stresses in the pin, resulting in a failure after 13,593 cycles. The photograph of the failed pin is shown in Fig. 4.26 in the main text.

EDAX analysis showed elemental peaks for Fe and Cr, which suggests that this pin is made of ferritic stainless steel. EDAX analysis of the inclusions, revealed that these are complex manganese sulfides which are the typical inclusions for free machining stainless steel such as Type 430F stainless steel. Sulfur is commonly added to the stainless steels for better machinability.

C.2.3.2 Discussion

Figure C-11 shows the fracture surface of the pin. Because of rubbing between two surfaces it is not clear where the crack initiated. Several independent cracks may have started round the circumference and later joined to become one. Around the circumference (Fig. C-11), the pin was machined thus reducing the diameter which formed a sharp corner. This raises stress and is a likely place for a crack to start.

Figure C-12 a) – d) shows the fracture surface in a sequence moving inward from the surface. Figure C-12 c) shows that the fatigue crack propagated by intergranular cracking. Figure

Figure C-11. SEM micrograph of the fracture surface of the failed pin. Mag.: 21.5 x.

C-12 b) indicates that cleavage fracture was also involved in the earlier stage. Figure C-12 d) shows the manganese sulfide inclusions discussed above. Thus, we believe that the fatigue crack propagated along the circumference and inward by intergranular cracking; the most probable cause for this cracking may be chromium carbide precipitation along the grain boundaries.

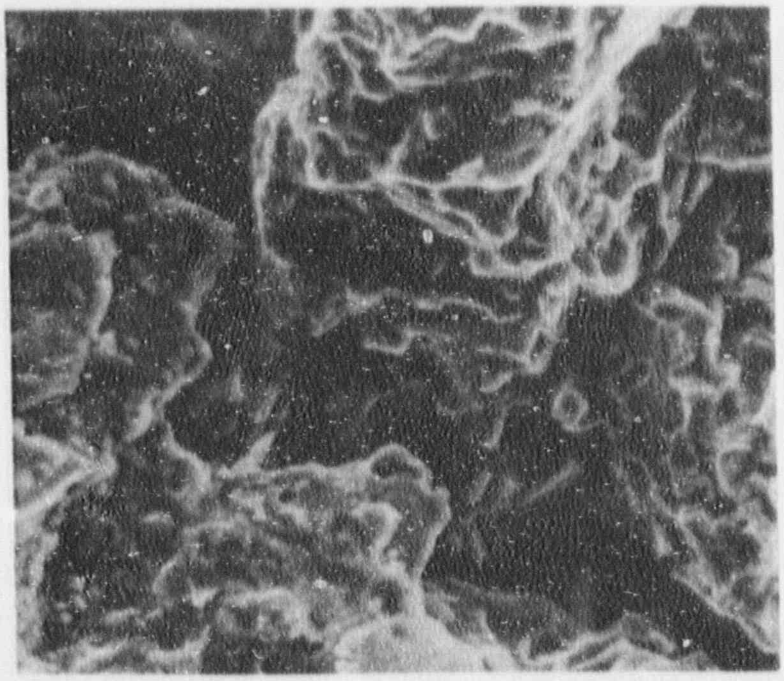
C.2.3.3 Conclusions

Due to bending and torsional stress caused by a misalignment of the pin holes, cracks at sharp machined corners, which propagated intergranularly. Thus, the main causes of the premature failure are believed to be the following:

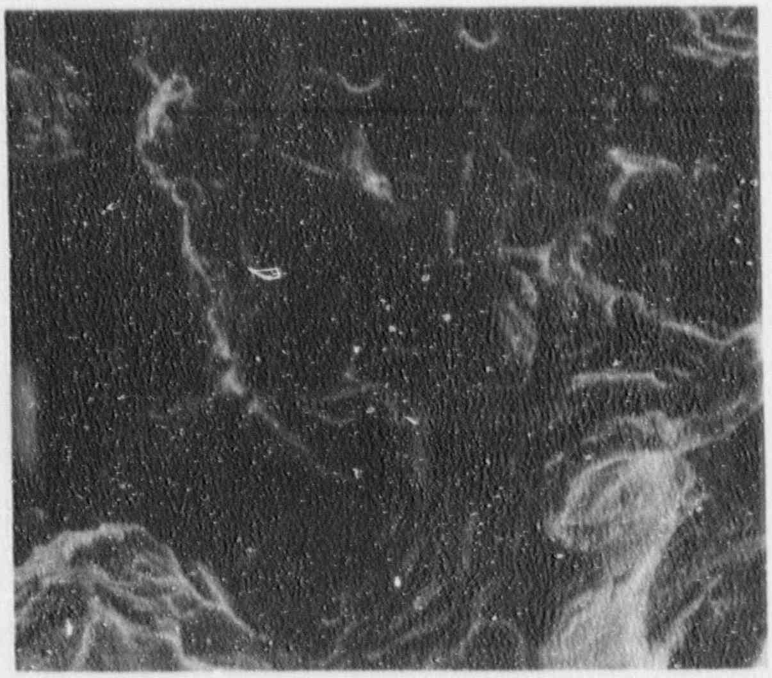
1. A defect in the weld No. 1 caused a misalignment of the pin holes, which, in turn, generated excessive bending and some torsional stresses in the pin.
2. The sharply machined corner (notch) acted as a stress raiser, and initiated a crack.

C.2.3.4 Recommendations

1. Improve the quality of welding.
2. Machine smooth corners or delete machining if possible.



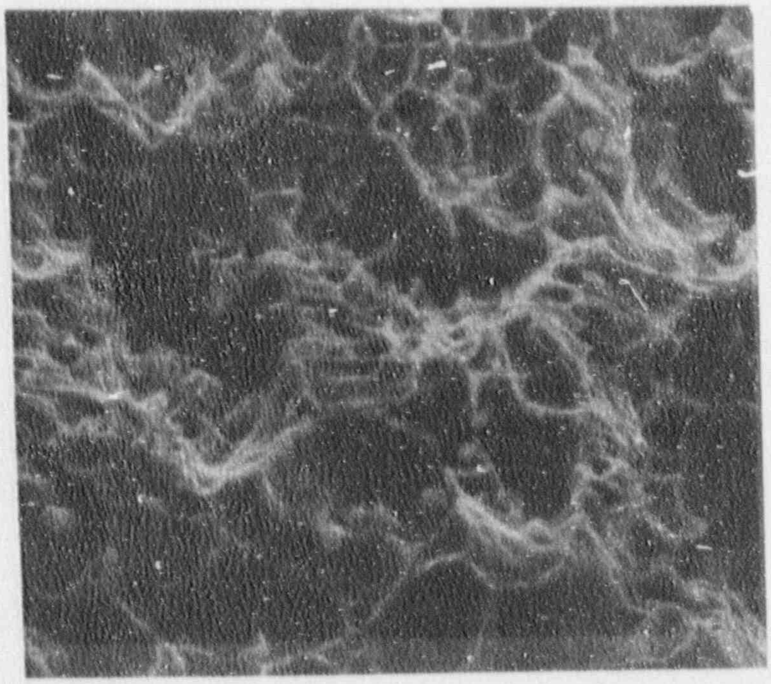
(a)



(b)

Figure C-12. SEM micrographs of the fracture surface of the drive link pin. Mag.: 2,000 x.

(c)



(d)

Figure C-12. SEM micrographs of the fracture surface of the drive link pin. Mag.: 2,000 x. (Cont'd)

C.2.4 Trip Shaft Lever

C.2.4.1 Background

The trip shaft lever is attached to the trip shaft as shown in Fig. 4.22 in the main text. EDAX analysis showed that this part is made from carbon steel plated with zinc and chromium. Steel hardware that must withstand indoor environments for more than 20 years is commonly electroplated with zinc (thickness >0.2 mil), which then is chromated to increase corrosion resistance and permanence of surface appearance [ASM, 1969]. It is believed that this trip shaft lever was formed from carbon steel, followed by zinc electroplating and chromate conversion coating.

C.2.4.2 Discussion

As shown in Fig. 4.22 in the main text, a large crack propagated from the sharply angled corner. Figure C-13 shows the fractured surface; the left side shows the fast fracture caused by is forced separation after testing which was carried out to separate the sample for visual and microscopial examination. The Figure clearly shows that the cracks initiated from the stress raiser on the right side. Figure C-14 shows parallel lines on the fracture surface, but these are not fatigue striations, but are caused by rubbing between two surfaces (see the deep gouging marks indicated by arrows). This SEM micrograph provides other important information. The surface of the fatigue crack on the left side extends beneath the abraded metal in the middle, which indi-

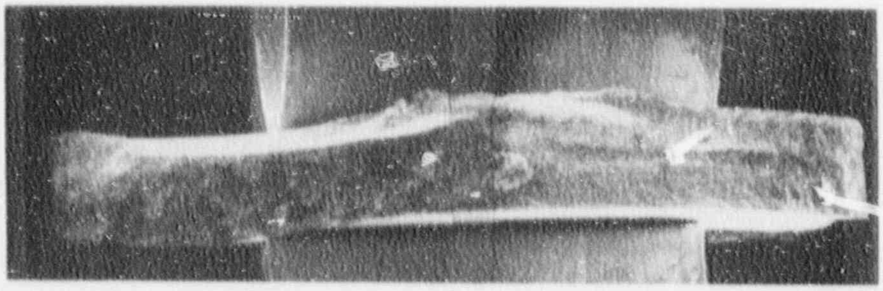


Figure C-13. SEM micrographs of the fracture surface of the trip shaft lever. Mag.: 15x.

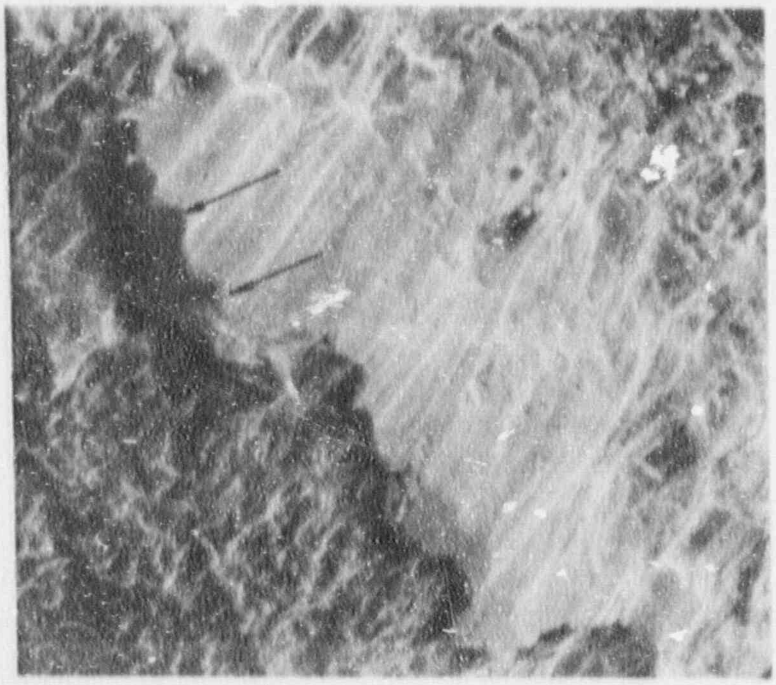


Figure C-14. SEM micrographs of the fatigue fracture surface of the trip shaft lever. Mag.: 100x.

cates that the fatigue cracks grew on both sides. Most probably, cracks started at both sides of the corners, and, at some point, consolidated into one big crack. Tearing continued inward due to vibration from cycling.

Figure C-15 shows the final fast fracture surface, which indicates that this material is brittle (see the cleavage fractures). Since this trip shaft lever was probably electroplated with Zn, hydrogen may have caused embrittlement. Hydrogen embrittlement is more likely to occur in cyanide zinc plating than in the plating of any other common metal, and it is known that application of some electrodeposited coatings decrease fatigue strength largely as a result of hydrogen embrittlement and failure to observe precautions during baking treatments [ASM, 1969]. Stressed parts should be relieved before electroplating, and after parts should be baked at 177 to 204°C for 3 to 24 hours, depending on the strength of the steel, to prevent hydrogen embrittlement.

C.2.4.3 Conclusions

Cracks started at the sharply angled corners, and propagated by cyclic impacts. The metal seems to be very brittle, and hydrogen embrittlement from zinc electroplating processes is suspected.

C.2.4.4 Recommendations

1. Check whether stress in the part was relieved before electroplating.
2. Check whether correct baking procedures were followed after electroplating.
3. Avoid sharply angled corners if possible.

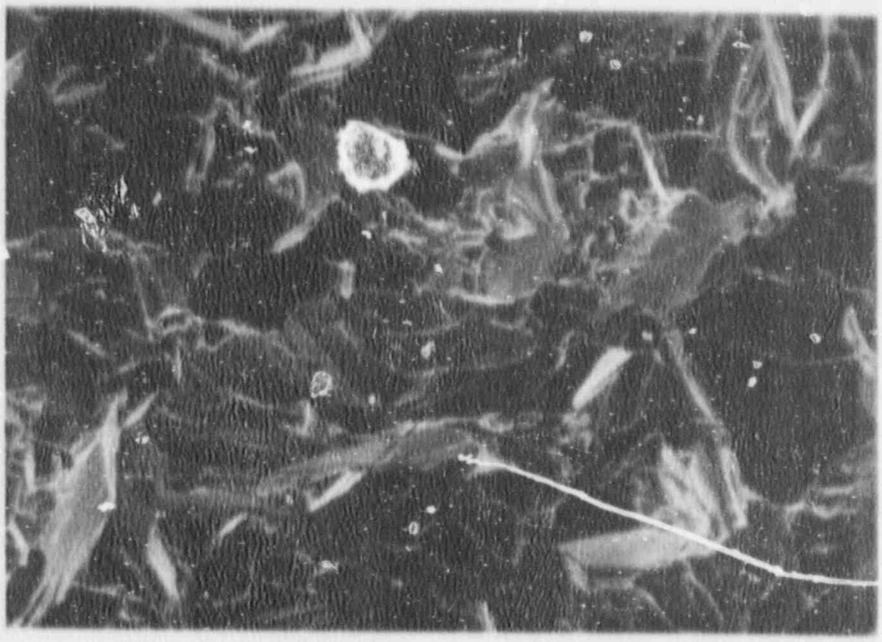


Figure C-15. SEM micrographs of the fast fatigue fracture surface. Mag.: 500x.

C.2.5 No. 3 Weld on Pole Shaft #1

C.2.5.1 Background

The No. 3 weld (60 degrees weld) shown in Fig. 3.1 in the main text failed causing the No. 3 lever to loose after 3000 test cycles. EDAX analysis of the weld shows that it is carbon steel.

C.2.5.2 Discussion

Figure C-16 shows the fracture surface with striation marks. The final fracture occurred on the left side of this picture, and it is clear the fatigue crack propagated from the right side to the left. This SEM micrograph also shows a welding defect which started a secondary crack. Figure C-17 shows the transition from fatigue crack growth to final fracture, suggesting that this weld is quite ductile. Chevron marks were observed (Fig. C-18), in the area which is in the right side direction from Fig. C-16. Chevron marks usually point to the origin of a crack. The area marked as O shows some nonmetallic particles which were analyzed with EDAX and shown to contain Si, S, Ca, Ti and Mn. It is believed that these are oxide slag particles. These slag particles may have initiated a crack which propagated by fatigue.

C.2.5.3 Conclusions

Slag particles inside the weld probably initiated a crack which propagated by fatigue, resulting in the failure of the weld.

C.2.5.4 Recommendations

The following actions are recommended to cure this problem:

1. Use correct welding techniques.
2. Use at least 120 degrees welding (see the main text for discussions).

Figure C-16. SEM micrograph of the fracture surface of the weldment. Mag.: 20x.

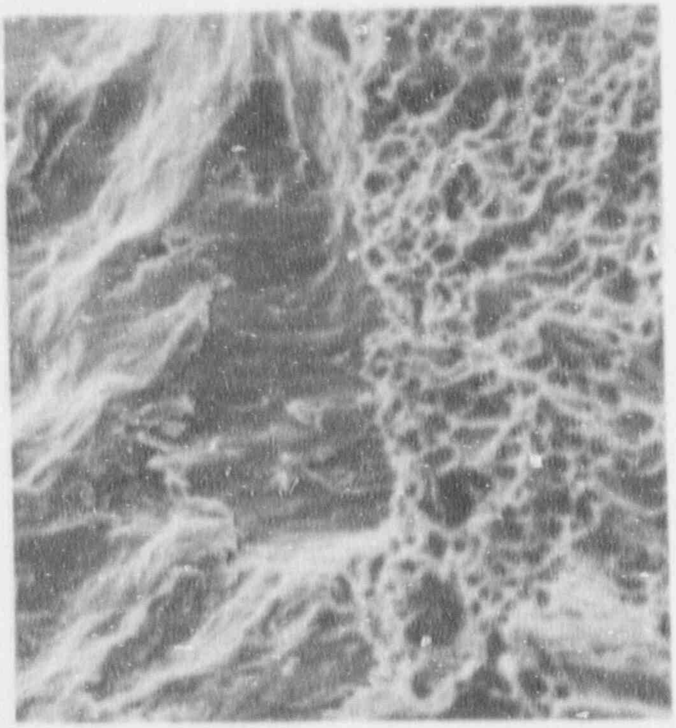


Figure C-17. SEM micrograph shows a transition from fatigue crack growth to final fracture. Mag.: 1,000 x.

Figure C-18. SEM micrograph shows chevron marks (V's) and the slag inclusions (marked with circles). Mag.: 100 x.

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11. ABSTRACT *(200 words or less)*

A DS-416 medium voltage air circuit breaker manufactured by Westinghouse was mechanically cycled to identify age-related degradations. This accelerated aging test was conducted for over 36,000 cycles during nine months. Three separate pole shafts, one with a 60 degree weld, one with a 120 degree, and one with a 180 degree were used to characterize the cracking in the pole lever welds. In addition, three different operating mechanisms and several other parts were replaced as they became inoperable. The testing yielded many useful results. The burning of the closing coils was found to be the effect of binding in the linkages that are connected to this device. Among the seven welds on the pole shaft, #1 and #3 were the critical ones which cracked first to cause misalignment of the pole levers, which in turn, had led to many problems with the operating mechanism including the burning of coils, excessive wear in certain parts, and overstressed linkages. Based on these findings, a maintenance program is suggested to alleviate the age-related degradations that occur due to mechanical cycling of a breaker.

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