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Switching Tests for the LCTF Protective Dump Circuit

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SWITCHING TESTS FOR THE LCTF PROTECTIVE DUMP CIRCUIT

by

W. M. Parsons

ABSTRACT

Each of the six coils in the Large Coil Test Facility (LCTF) has a separate power supply, dump resistor, and switching circuit. Each switching circuit contains five switches, two of which are redundant. The three remaining switches perform separate duties in an emergency dump situation. These three switches were tested to determine their ability to meet the LCTF conditions.

The power supply crowbar switch in the LCTF is required to close on 25 kA at a low voltage and to carry this current on a continuous basis. An oil cooled, high current bypass switch was successfully tested for over 200 make operations at 25 kA and run continuously for seven hours without excessive temperature rise.

The interrupter bypass switch in the LCTF is required to carry 23.2 kA continuously and to interrupt this current and divert it into a parallel connected dc interrupter. It must then withstand a 5 kV arc voltage generated by the dc interrupter followed by a 2.5 kV dump resistor voltage. More than 200 synthetic tests were performed at 25 kA and 10 kV. Almost 40 additional tests involving full current transfers and circuit breaker interruptions were also completed. Both sets of tests were done with and without oil in the switch.

The dc interrupter in the LCTF is typically required to divert 25 kA into a 0.1 Ω, 20 μH resistor. This commercially available switch was subjected to over 120 interruptions ranging from 5 to 28 kA. Although every interruption was successful, the breaker had considerable trouble interrupting currents with recovery voltages in excess of about 1.5 kV. Two interrupters connected in series improved performance at these higher voltages.

I. INTRODUCTION

The Large Coil Task (LCT) at the Oak Ridge National Laboratory (ORNL) will test an array of six superconducting tokamak toroidal field coils. The high energy and cost associated with each coil necessitates the use of a protective dump circuit in an emergency situation.[1] Five individual switches and a dump resistor comprise each protective dump circuit. Two of the five switches are redundant.

The three remaining switches are the power supply crowbar switch (PSCS), the interrupter bypass switch (BP), and the dc circuit breaker (DCCB). Both PSCS and BP are modified versions of a switch that was originally developed at Los Alamos for use in a high current vacuum interrupter system.[2] The redundant switches include another interrupter bypass switch and dc circuit breaker which are used as a secondary system if the primary system fails.

Figure 1 is a schematic of the protective dump circuit for a single coil.

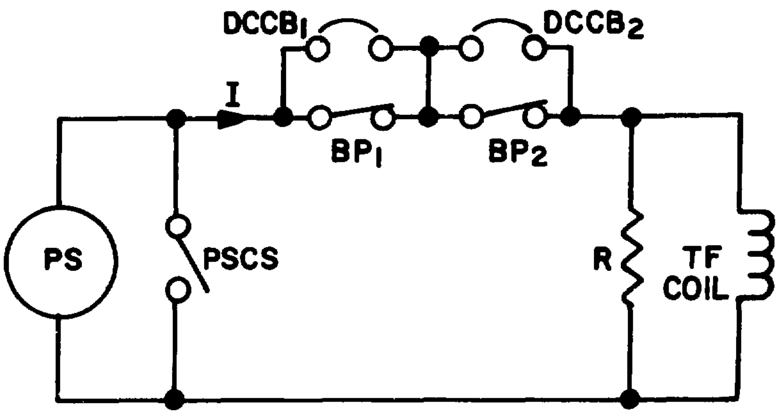


Fig. 1. Protective dump circuit.

The system operates as follows. All switches are initially closed except PSCS, and 90% of the current, I, flows through BP_1 and BP_2, while 10% flows through $DCCB_1$ and $DCCB_2$,. When a signal is received to initiate an emergency dump, a signal is given to PSCS to close and to the power supply to turn off. The closure of PSCS removes the output inductance of the power supply, thus easing the interruption duty of DCCB and also protecting the power supply from any voltage transients. When PSCS has closed, BP_1 begins to open. This transfers the full current into $DCCB_1$. When BP_1 has fully opened, $DCCB_1$ is given a signal to trip. The opening of $DCCB_1$ creates a high arc voltage and transfers all the current to dump resistor, R. If for some reason this transfer is not completed, redundant switches BP_2 and $DCCB_2$ then open in the same sequence as BP_1 and $DCCB_1$.

The six coils in the LCT operate at different maximum currents ranging from 14 to 24 kA. The dump resistor will be 0.1 ohms resulting in maximum recovery voltages ranging from 1.4 to 2.5 kV. Tests were conducted at currents ranging from 5 to 28 kA and are detailed in the following sections.

II. THE POWER SUPPLY CROWBAR SWITCH

The power supply crowbar switch has two basic duties--to close on or make currents as high as 25 kA and to carry this current on a continuous basis. A 25 kA temperature rise test was conducted when the switch was first installed in the test facility. The maximum temperature recorded was on a rocker contact, which rose 208° F over a 78° F ambient temperature. The circulating oil temperature reached 140° F. The transient temperature response for various points in the PSCS is included in Appendix A.

Figure 2 shows the circuit used to test the making ability of the crowbar switch. A dc current of 33 kA was established through the 20 μΩ resistor, R, with PSCS open. The switch was then closed. The relative resistance ratio of PSCS and R was such that 25 of the 33 kA flowed through PSCS after closing. The initial rate of current rise in PSCS was measured to be 1.25 MA/s. Figure 3 is an oscillogram of the current in R during a typical make operation. The power supply current, measured by SH_1, was essentially constant during the closure of PSCS. A total of 203 making operations was performed at three-minute intervals. No sign of contact bounce or excessive

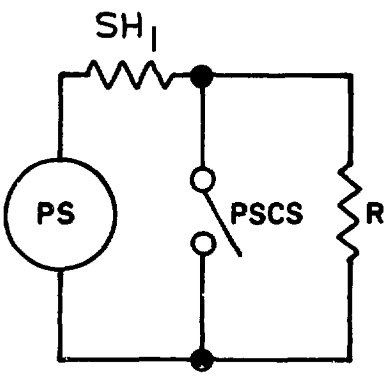


Fig. 2. Test circuit for power supply crowbar switch.

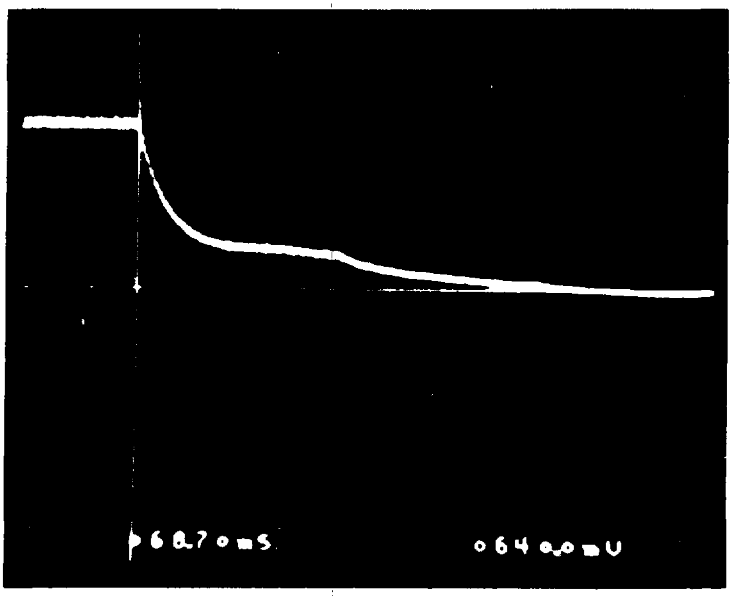


Fig. 3. Current in R during a typical make operation.

erosion was observed. At the conclusion of the make tests another temperature rise test at 25 kA produced a circulating oil temperature of 130° F. The detailed transient temperature measurement for this test is also included in Appendix A. This switch should be capable of more than 1000 operations before maintenance should be required. The erosion rate was low and the circulating oil remained clear throughout the 200 making operations.

III. THE INTERRUPTER BYPASS SWITCH

The interrupter bypass switch also has two basic duties, namely, to carry 23.2 kA continuously and to break this current and divert it into the parallel dc circuit breaker. The dc circuit breaker generates arc voltages as high as 5 kV while interrupting. After interruption the dump resistor generates a 2.5 kV voltage while absorbing the coil energy. Because the bypass switch is electrically parallel to both elements, it must not restrike under the voltages generated.

A. Initial Tests

The first 23.2 kA temperature rise test, performed when the contacts were new, produced a circulating oil temperature of 118° F. The detailed transient temperature response is included in Appendix A.

Several transfer operations were initially performed with the power supply as a current source. These tests showed the delay time, transfer time, and arc voltage of the bypass switch. Figure 4 is an oscillogram of the voltage across this switch during a transfer operation illustrating these three parameters. The average arc voltage was about 15 V, while the transfer time was 1.4 ms. The delay time was measured at 57.4 ms.

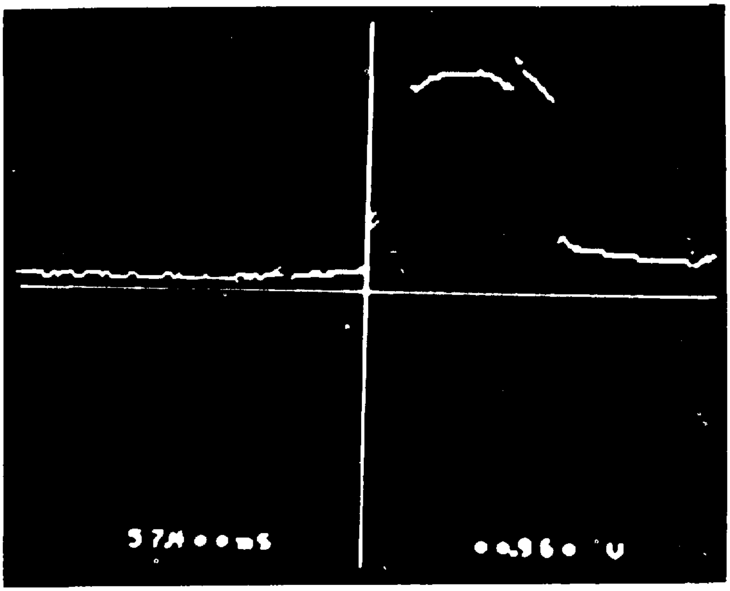


Fig. 4. Voltage across BP during transfer operation.

B. Synthetic Tests

Initially, full power transfer-interruption tests began with both DCCB and BP triggered independently. On the third test, noise triggered DCCB open before BP, and approximately 1 MJ was dissipated in an arc between the open contacts of BP. This prompted a modification, and a special limit switch was designed and mounted on BP. This switch was used to energize the trip coil of DCCB. While parts for this modification were being fabricated, a set of synthetic tests was performed on BP with the circuit shown in Fig. 5.

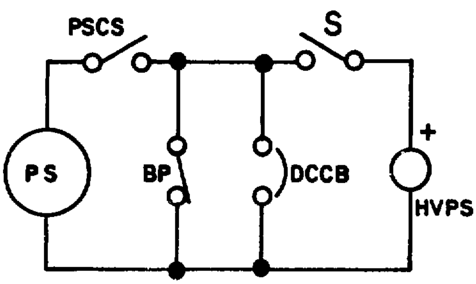


Fig. 5. Synthetic test circuit for BP.

Initially all switches except S were closed, and the power supply PS was set to 25 kA. BP was then opened to transfer the full current to DCCB, which then opened. Because of the limited energy stored in the inductance of the power supply loop, the arc in DCCB cleared before moving into the arc chute. PSCS then opened on zero current to provide isolation for the power supply. After a short delay, S was closed to place high voltage across BP. This was intended to simulate the high arc voltage that would have been generated by DCCB, had sufficient energy been stored in the power supply loop. For these tests, the high voltage power supply, HVPS, was set to 10 kV. Figure 6 is a diagram detailing this timing sequence with comparison to the actual voltage stresses that BP will see in LCTF. Figure 7 is an oscillogram of the voltage injection waveform as it was actually applied. BP successfully withstood this voltage waveform for 201 consecutive operations.

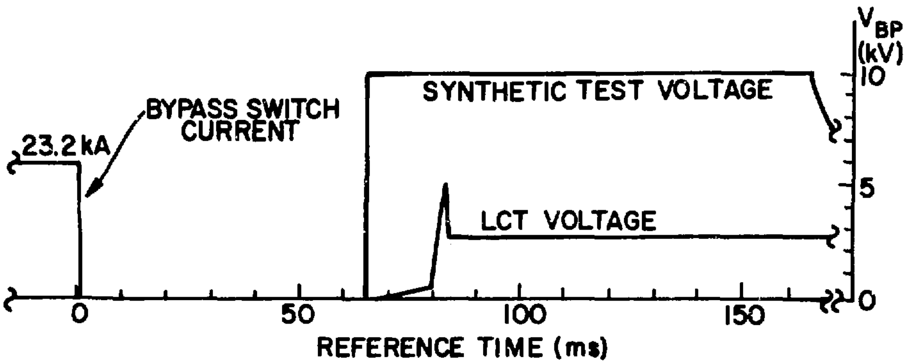


Fig. 6. Comparison of synthetic and anticipated voltage stresses on BP.

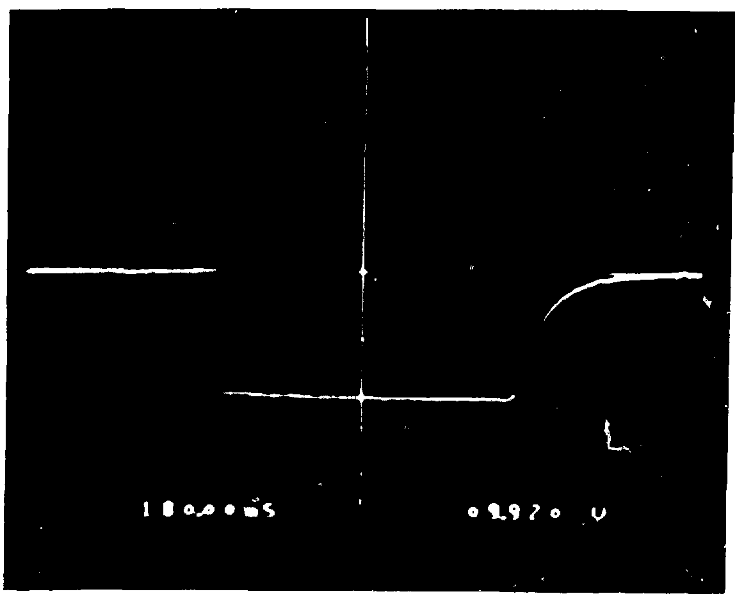


Fig. 7. Voltage injection waveform.

At the time these tests were taking place, the staff at ORNL was considering elimination of the silicone oil in BP. Appendix B discusses the problems associated with silicone oil. For this reason, the oil was drained from BP and 14 more operations were performed with the exact timing and voltage as in the previous tests. All were successful in withstanding the 10 kV. However, the contact area was blackened from these open air arcs. This blackening from metallic oxides could lead to tracking problems after many operations.

The air cylinder stroke was then reduced to half of its normal stroke and tests were rerun without oil. One breakdown appeared in four operations at this reduced stroke. An oscillogram of this breakdown in shown in Fig. 8.

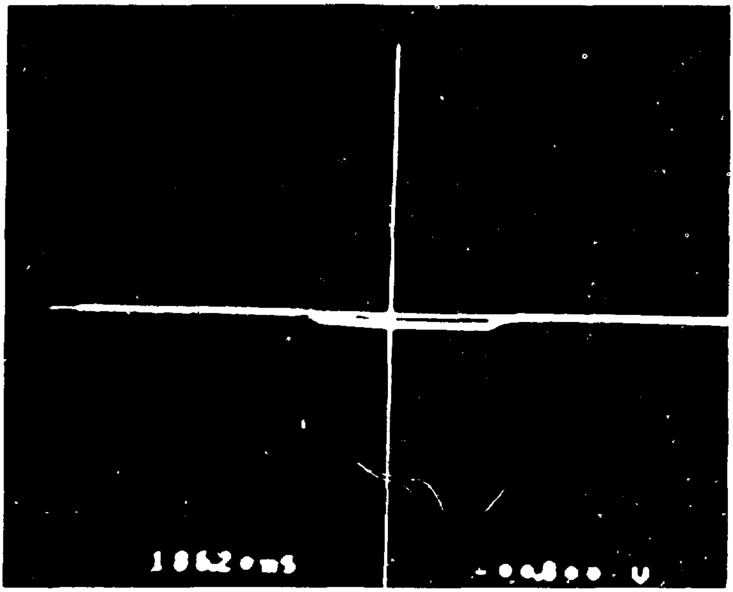


Fig. 8. Voltage breakdown at 10 kV with reduced stroke.

In conclusion it is felt that BP can operate safely in either air or silicone oil. If run in oil, the film deposition and gas generation problems in Appendix B should be noted. If run in air, increasd maintenance is recommended to remove the metallic oxides from the contacts and insulating surfaces resulting from open air arcing.

C. Full Power Tests

After the new limit switch mechanism was installed on BP, full power transfer and interruption tests proceeded. An inductor was charged to currents as high as 28 kA by a capacitor bank. This inductive current was distributed between BP and DCCB as described in the introduction. BP was then opened and transferred all the current to DCCB. DCCB then interrupted and diverted the inductive current into the dump resistor. Due to the current decay associated with the nonsuperconducting coil used in these tests, DCCB was opened before BP reached full stroke. This condition is more severe than

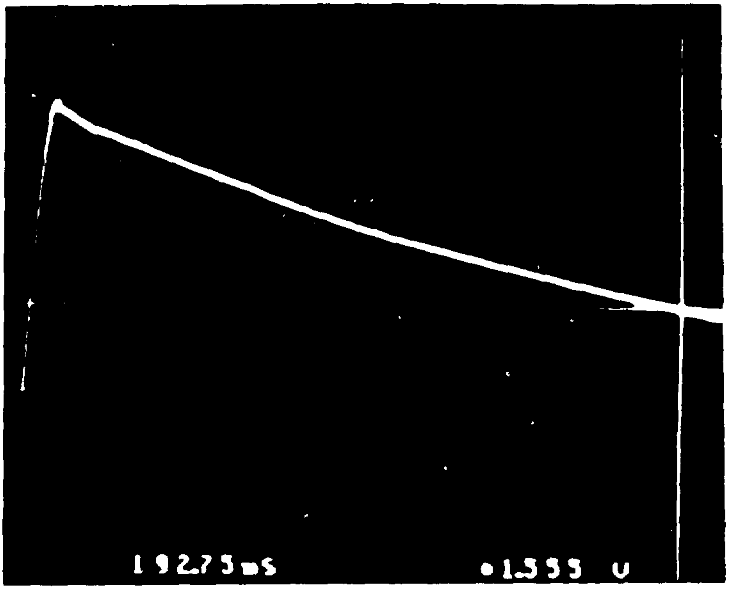
LCTF conditions, which will allow BP to be fully open before DCCB is tripped. For these tests, DCCB was tripped 15 ms after BP began to open. Because DCCB has a 20 ms delay and requires 10 ms to generate high arc voltages, the contacts on BP were 90% open when DCCB began to generate high arc voltage.

Tests were again performed with and without oil in BP. During the 20 tests with oil and 18 tests without oil, BP performed its transfer operaton and withstood the resulting recovery voltages successfully. Typical DCCB arc voltages ranged from 3.5 to 5 kV. Occasionally, inductive spikes at interruption caused voltage transients as high as 8.3 kV to appear across BP. The switch contacts examined after these test showed some erosion and pitting, although not severe.

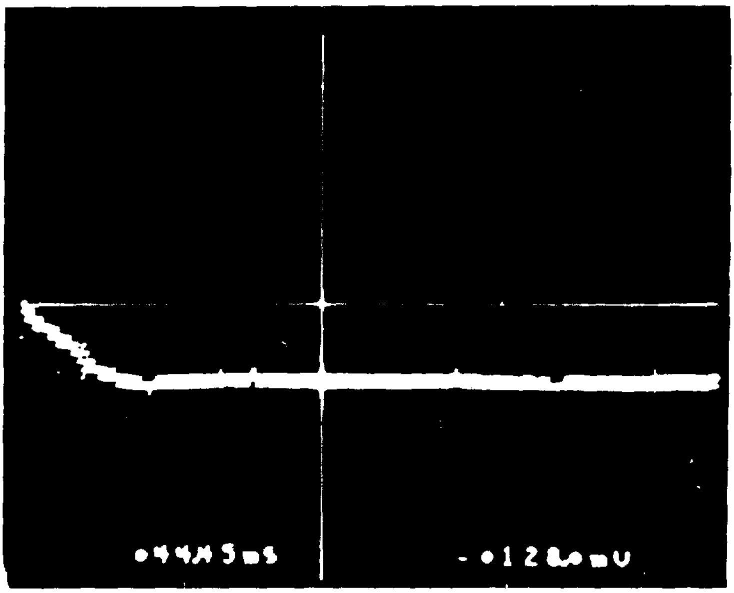
This switch, if run in oil, should be able to perform at least 1000 operations before maintenance of the contacts is required.

D. Failure to Transfer Test

A test was performed on BP to determine the maximum arc voltage generated by fully open contacts at high currents. This situation would occur if the parallel DCCB were opened before BP and current transfer became impossible. For this test, DCCB was held open, and the capacitor bank was discharged through BP as in the full power tests in section III.C. Contacts parted on 21 kA approximately 8 ms after current initiation. Figures 9a and 9b are the respective current and voltage waveforms for BP during this test. The peak arc voltage measured was 144 V, while the average voltage was about 130 V.



(a)



(b)

Fig. 9. Waveforms for BP arcing test.
a. Current.
b. Voltage.

IV. THE dc INTERRUPTER

The dc interrupter selected by ORNL for use in the LCTF was a Westinghouse type DMD, semi-high speed, air magnetic circuit breaker. This interrupter has a 4 kA continuous current rating, a 1.5 kV nominal voltage rating, and was equipped with a special 5 kV arc chute for this application.

Tests began with the circuit of Fig. 10. In this circuit DCCB and BP are initailly closed, S is open, and C is precharged. S now closes and C discharges through L. D_1 crowbars C when L has reached peak current and traps the inductive current in the circuit breaker leg. Now, BP opens to transfer the full current into DCCB, which then opens. The arc voltage of DCCB forces the current into R, which completes the protective dump operation. The value of C was 9.5 mF, L was either 3.7 or 4.5 mH, and R was varied between 60 and 170 mΩ to obtain different recovery voltages for a given current.

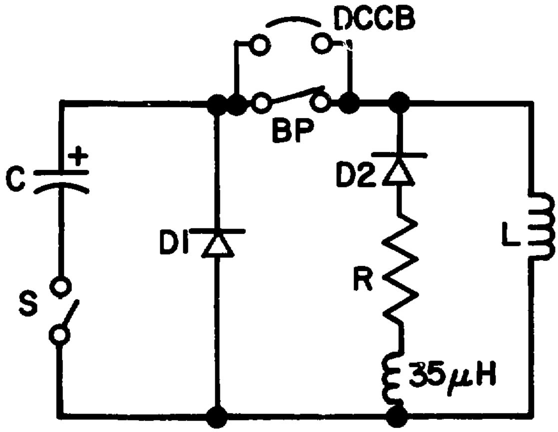


Fig. 10. Circuit breaker test schematic.

A. Tests on a Single dc Interrupter

Figure 11 shows current and voltage waveforms from a 7 kA, 1.5 kV interruption. BP opened at 7.5 ms to transfer current into DCCB, which interrupted at 42 ms. The peak arc voltage generated by DCCB was 1.9 kV, while the steady state recovery voltage was 1.5 kV.

Most of the tests run on a single interrupter did not involve a prior current transfer from BP. This allowed higher interruption currents to be achieved because BP did not need to reach full stroke.

Almost 100 interruptions were performed on a single dc interrupter with currents between 5 and 28 kA and recovery voltages ranging from 0.8 to 2.6 kV. All interruptions were successful. When the recovery voltage was under about 1.5 kV, interruptions were generally quite clean and very quick as shown in the current waveform of Fig. 11. When R was changed to higher values and produced recovery voltages greater than 1.5 kV, interruptions were not as clean or quick. Figure 12 shows the current and arc voltage waveforms for a 19.5 kA, 2460 V interruption. Each dip in the current waveform corresponds to

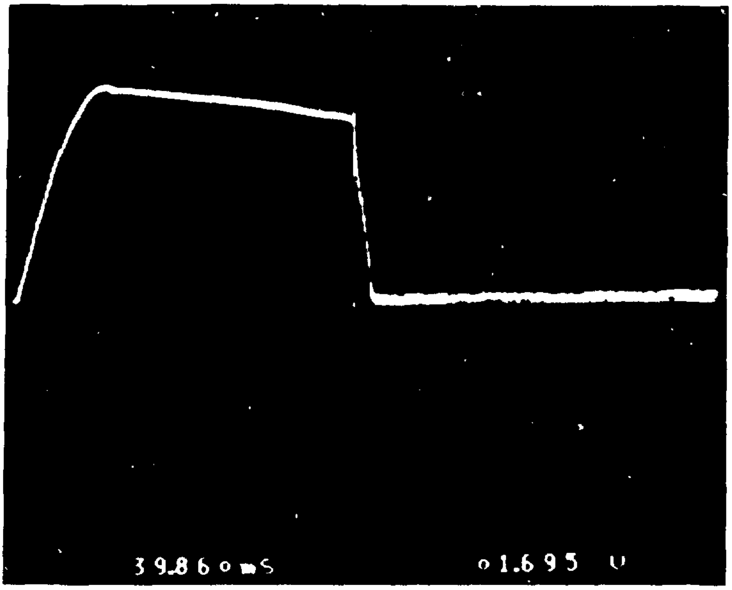


Fig. 11a. Breaker current from a 7 kA, 1.5 kV interruption with full transfer by BP.

Fig. 11b. Breaker voltage from a 7 kA, 1.5 kV interruption with full transfer by BP. Peak arc voltage is 1.9 kV.

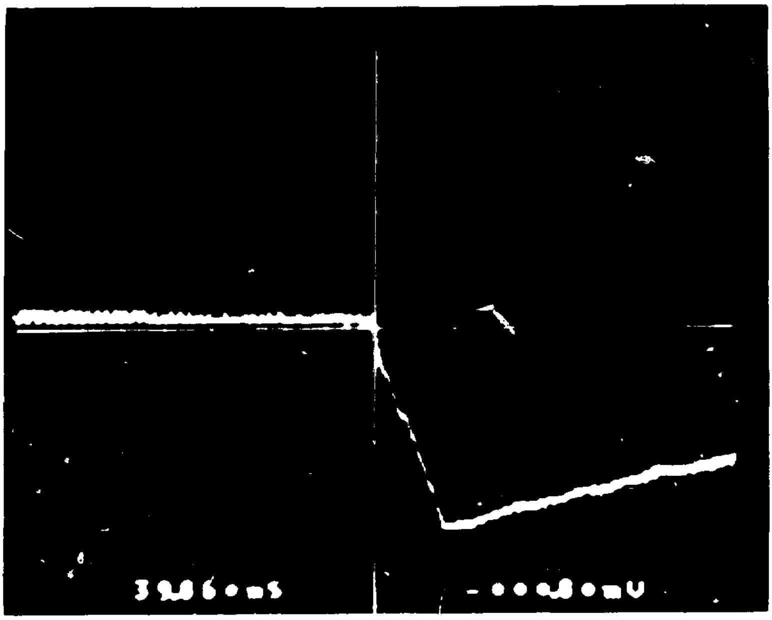
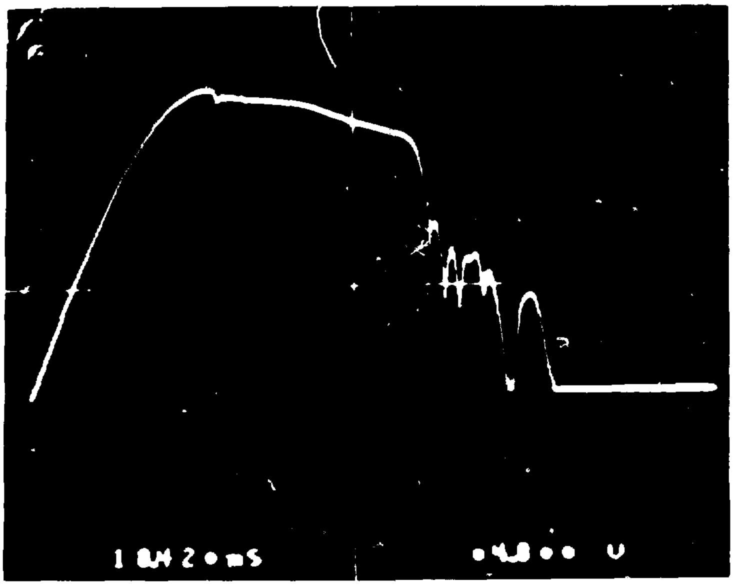


Fig. 11c. Resistor current from a 7 kA, 1.5 kV interruption with full transfer by BP. Transfer current is 5.5 kA.

a peak in the arc voltage waveform. The circuit breaker was probably restriking on the lower contacts while the primary arc was in the arc chute. This restrike effectively shorted the high voltage arc with a low voltage arc. The current then transferred from the parallel resistor back to the circuit breaker. The arc on the lower contacts then moved up into the arc chute and the process repeated. Eventually the breaker cleared, possibly due in part to the uprush of heated gas generated by the prolonged arcing process.

To verify that the restriking process was dependent on recovery voltage, a number of tests were conducted where R was reduced to lower the recovery voltage. Although the restriking process continued, the magnitude and frequency of restrikes was diminished. Compare the current waveform of Fig. 13, which had a 1.4 kV recovery voltage, to the current waveform of Fig. 12 with a 2.46 kV recovery voltage. Both interruptions were at the same current. This interruption was typical of the kind of improvement seen when the recovery voltage was lowered. To gather some statistical evidence related to recovery voltage influence, each test was analyzed for the number of loops or restrikes occurring during that interruption. These data are presented in Table I. In the entry X/Y, X is the number of tests performed at a given current and voltage level, and Y is the average number of loops or restrikes during the tests.



(a)

(b)

Fig. 12. Waveforms from a 19.5 kA, 2.46 kV interruption.
(Time scales are different.)
a. Breaker current.
b. Breaker voltage.

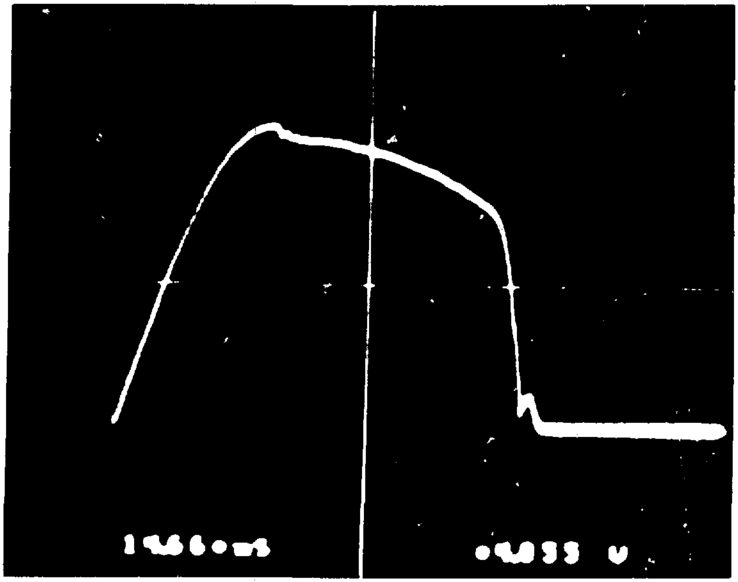


Fig. 13. Current waveform for a 19.5 kA, 1.4 kV recovery voltage.

TABLE I

RESTRIKE DATA FOR SINGLE INTERRUPTER TESTS
X/Y IS ENTRY WHERE X = NUMBER OF TESTS
AND Y = AVERAGE NUMBER OF RESTRIKES

Interrupted Current (kA)	Recovery Voltage (V)						
	750–1000	1000–1250	1250–1500	1500–1750	1750–2000	2000–2250	2250–2500
6–10	2/0	2/0	1/0	---	---	---	---
11–15	---	2/2	3/4	---	---	---	1/2
16–20	---	---	6/1.6	5/1.8	---	---	14/3.1
21–25	---	---	---	2/1	---	12/3.3	23/3.6
26–30	---	---	---	2/1.5	---	---	10/4.1

As can be seen in the table, the average number of restrikes increases significantly from left to right but only slightly from top to bottom. These trends indicate that the restriking is more dependent on high voltages than on high currents. Regardless of recovery voltage, restriking was somewhat more frequent with the high current interruptions.

B. Tests on Two dc Interrupters in Series

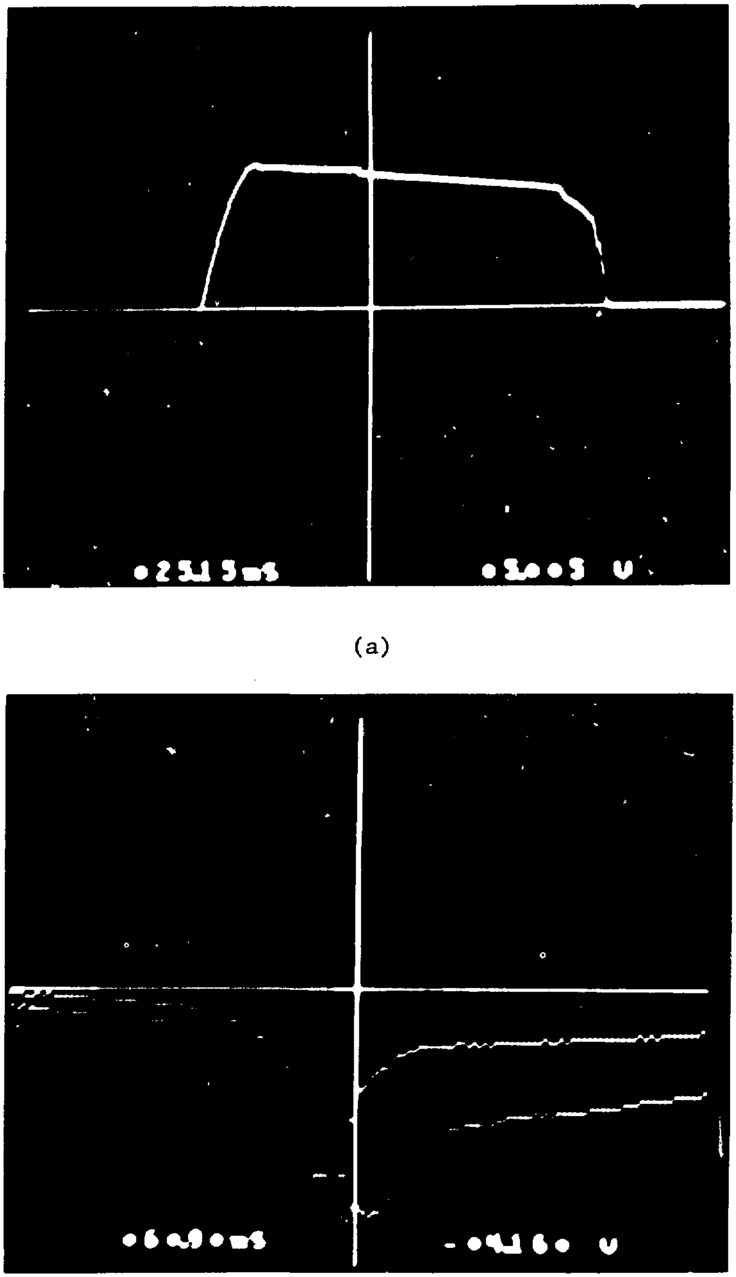
In an attempt to obtain high voltage, restrike free interruptions, the ORNL staff requested that two series connected dc circuit breakers be tested. Two sets of full current transfers and interruptions were performed at currents ranging from 3 to 20 kA. Peak currents were reduced slightly from previous tests due to the current decay while BP reached full contact separation. The two sets of tests differed in that oil was removed from BP for the second set. Because this did not affect the performance of the dc interrupters, the two test results are considered together for the remainder of this report.

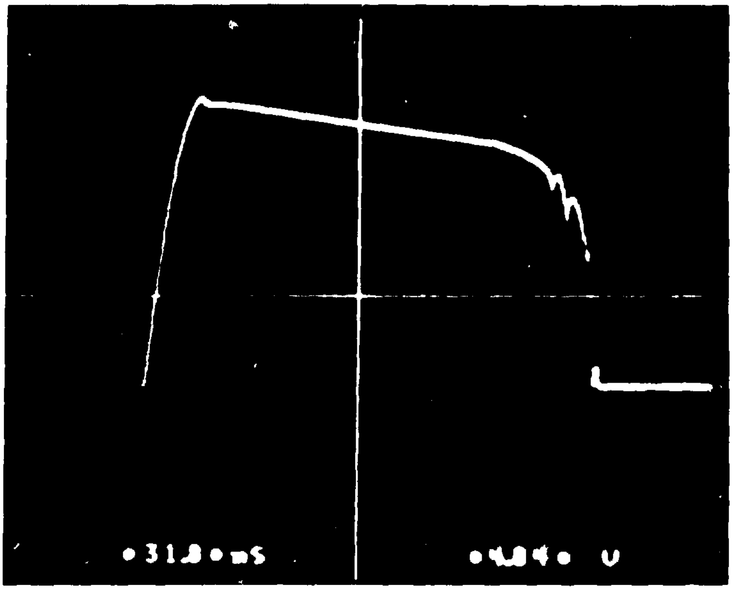
All the 38 interruptions in this set of tests were successful. However, the attempt to obtain restrike free interruptions at high recovery voltages was only partially successful due to the high jitter of the circuit breakers. When both interrupters opened simultaneously, interruption was quite good. Figure 14 shows the current and voltage waveforms for a 19.6 kA, 2.24 kV interruption where both interrupters opened simultaneously. The two traces on the voltage waveform are the midpoint and full voltage traces. Notice the even voltage sharing during and after the arcing process.

Simultaneous opening was achieved only about 25% of the time. The rest of the time, one of the breakers would open earlier than the other, and the restriking process would occur until the switch cleared or until the other breaker opened sufficiently to assist. Figure 15 is representative of such an interruption. Notice on the voltage waveform that the midpoint and full voltage traces cross. This is caused by one breaker not generating any arc voltage during interruption and not sharing any recovery voltage until the other breaker has already interrupted. Also notice that the restrike loops are fewer and smaller than those seen during tests on a single interrupter. Despite the mostly nonsynchronous openings, the bulk of these tests showed that the series connected interrupters had a positive effect in reducing the size and number of restrikes.

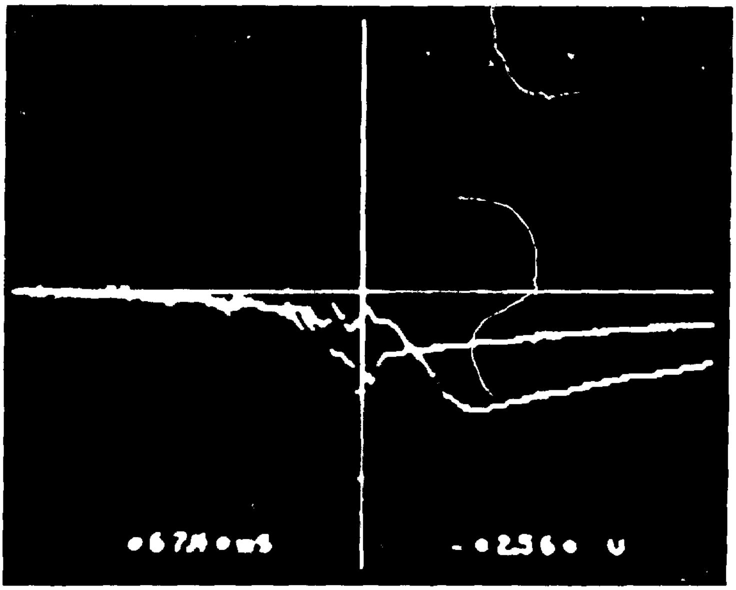
C. Comment on Application of a dc Circuit Breaker for Coil Protection

The requirements placed on an interrupter for coil protection are unlike the requirements for dc interrupters in standard applications. These interrupters are typically used to clear faults in traction motor service and are not used with a parallel resistor. In traction service, once the current has been reduced to a low level by the breaker's arc voltage, it cannot quickly rise again. If the breaker were to restrike, the new arc would be forced into the arc chute before the fault current had a chance to rise to significant levels. Indeed, NEMA standards specify the maximum di/dt for semi-high speed dc breakers to be 5.0 A/μs. The time measured for a typical restrike to reach full arc voltage was about 600 μs. In a traction system this would amount to a maximum restrike current of 3.0 kA. In the LCT application, however, the current in the system is essentially constant. When the breaker restrikes, the coil current can rapidly move from the parallel resistor back into the circuit breaker. This restrike di/dt was found to be as high as 25 A/μs. Because of this, restrikes frequently reached levels of





(a)



(b)

Fig. 15. Waveforms for a 19.4 kA, 2.4 kV interruption with both interrupters not opening simultaneously.
a. Breaker current.
b. Breaker midpoint and full voltage.

15 to 20 kA. The restriking process is not uncommon in traction applications, but because the magnitude is limited, the problem is not as severe.

If a significant inductance were added in series with the dump resistor, the restrike di/dt could be reduced. Calculations indicate that this inductor would have to be on the order of 0.5 mH to reduce the di/dt to 5 A/μs. This would be counter productive as initial current transfer to the resistor would be more difficult to accomplish. Also, 156 kJ of energy dissipation in the arc chute would be added at 25 kA. Because the breaker is only rated at 160 kJ, the device would be over stressed for energy absorption. In addition, restrikes probably would not be eliminated but simply reduced in magnitude. There may exist an intermediate optimum that results in minimum erosion for the interrupter; however, this minimum would be difficult to determine theoretically. The basic problem seems to arise from using the device at voltages greater than its normal rating.

V. CONCLUSIONS

The power supply crowbar switch and the interrupter bypass switch were both able to carry their continuous design currents of 25 and 23.2 kA and successfully perform their respective making and breaking duties. No adverse erosion was detected in either device after several hundred operations. These devices should be able to operate more than 1000 times before maintenance is required. In addition, the bypass switch was found to operate reliably with or without oil at twice the expected recovery voltage.

The dc circuit breaker had no failures to interrupt in any of the tests performed. Interruption currents ranged from 5 to 28 kA, while recovery voltages varied from 0.8 to 2.6 kV. Interruptions with recovery voltages greater than the 1.5 kV rating of the device were characterized by multiple restrikes before final current clearing.

Tests with two circuit breakers in series showed some improved current clearing time, although this improvement was strongly dependent on the simultaneous opening of both breakers. The simultaneous opening was achieved only about 25% of the time because of the jitter of the devices. A trend toward reduced restrike magnitude was exhibited even when the breakers did not open simultaneously.

VI. REFERENCES

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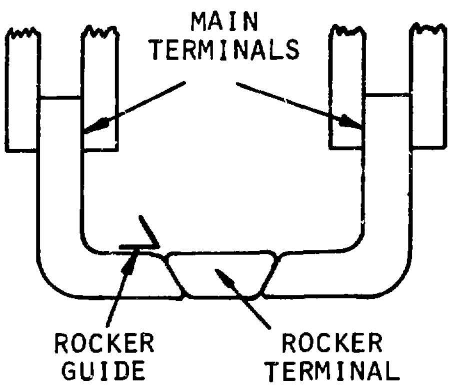
APPENDIX A

TEMPERATURE RISE TEST DATA ON BP AND PSCS

Figure A1 is the initial temperature rise test data for BP and PSCS at 23.2 and 25 kA, respectively. This test was performed before any make or break tests were done. Figure A2 is the temperature rise test for the same switches after approximately 200 make or break tests on each switch. The following references apply to the traces on Figs. A1 and A2 and include the maximum temperatures recorded.

Reference A1

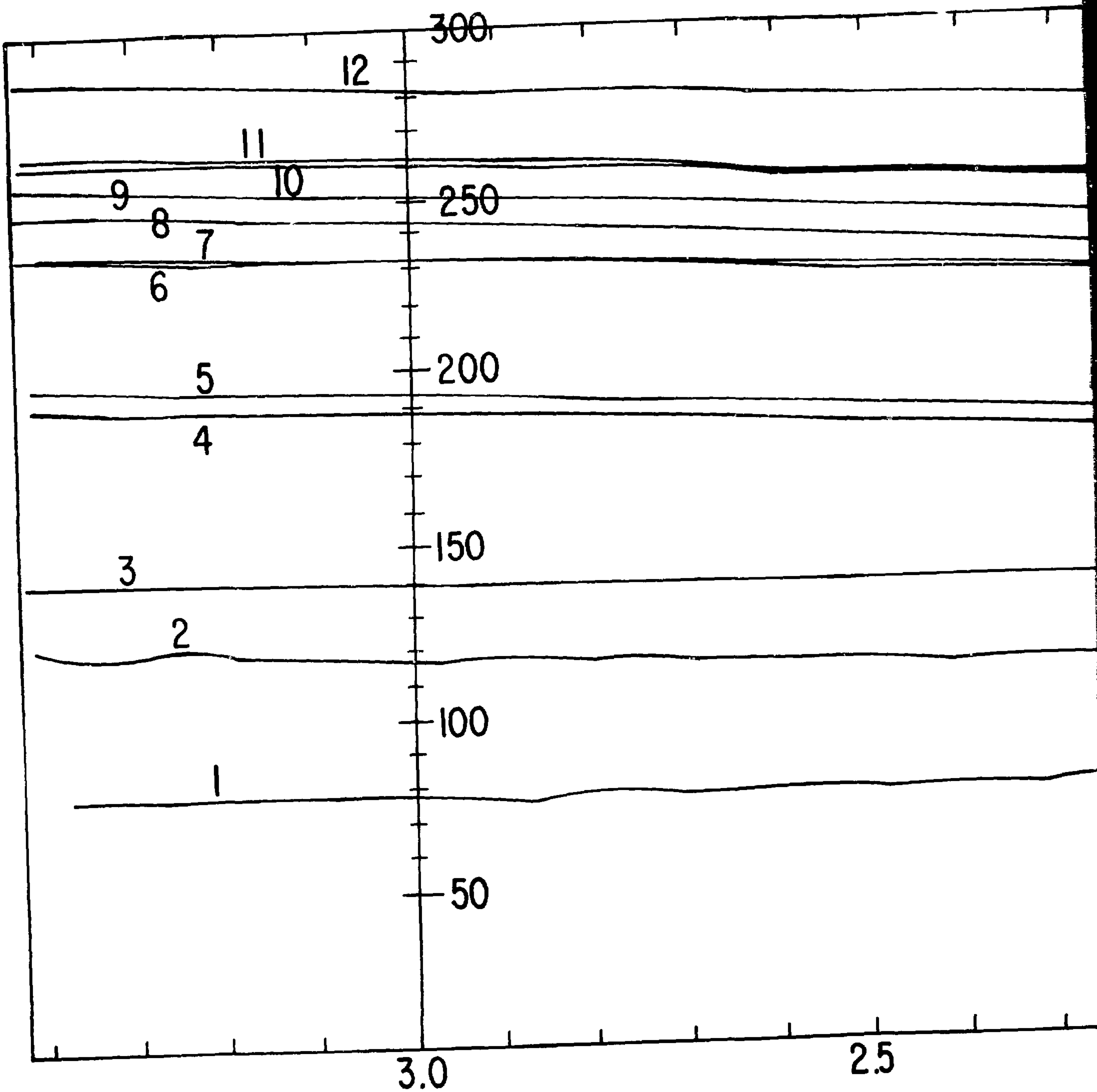
Trace	Description	Max. Temp. °F
1	ambient air	78
2	BP oil	118
3	PSCS oil	140
4	BP main terminal	190
5	BP main terminal	196
6	PSCS main terminal	234
7	BP rocker guide	234
8	PSCS main terminal	246
9	BP rocker guide	254
10	PSCS rocker terminal	262
11	PSCS rocker guide	264
12	PSCS rocker terminal	286



KEY

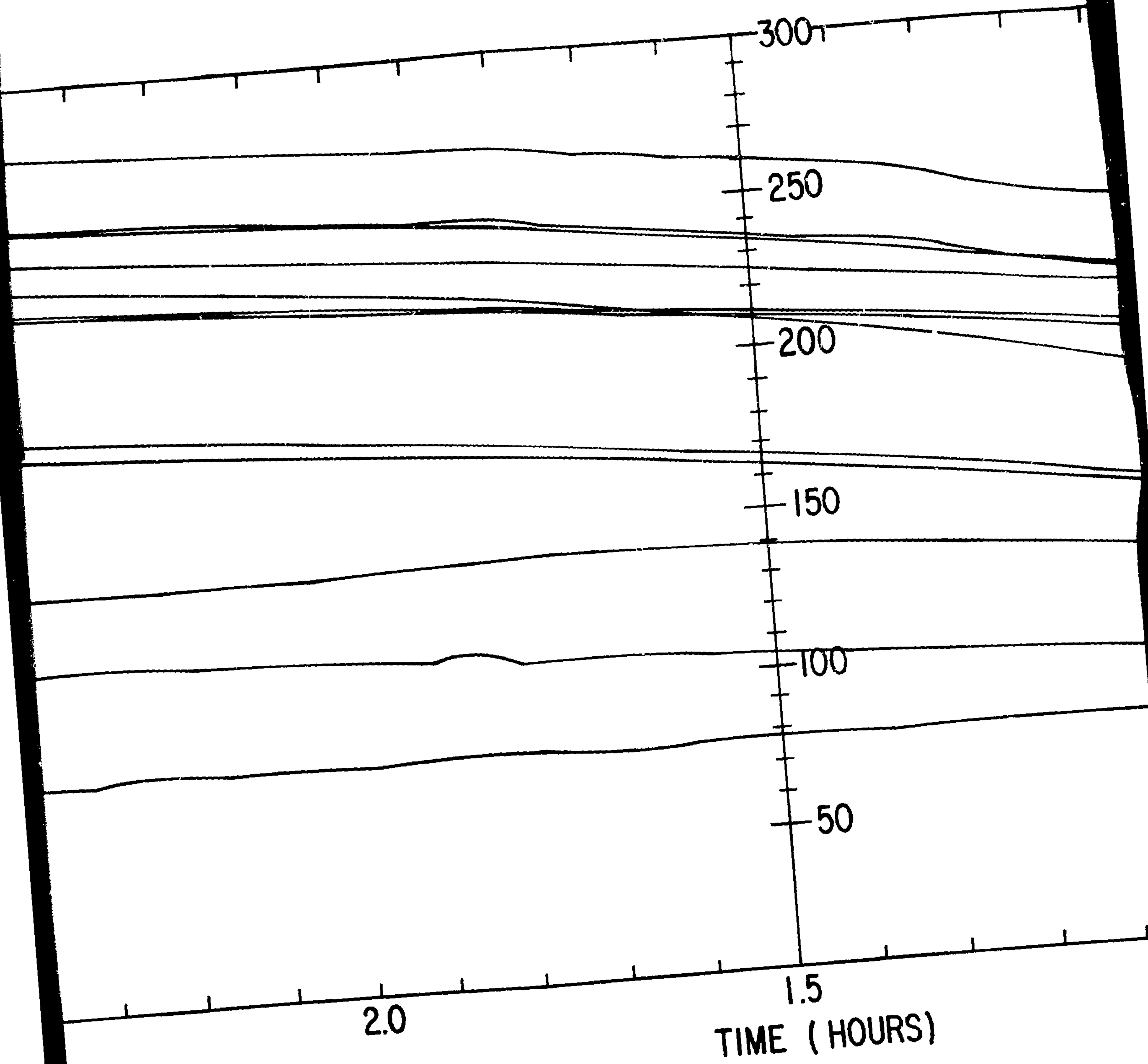
Reference A2

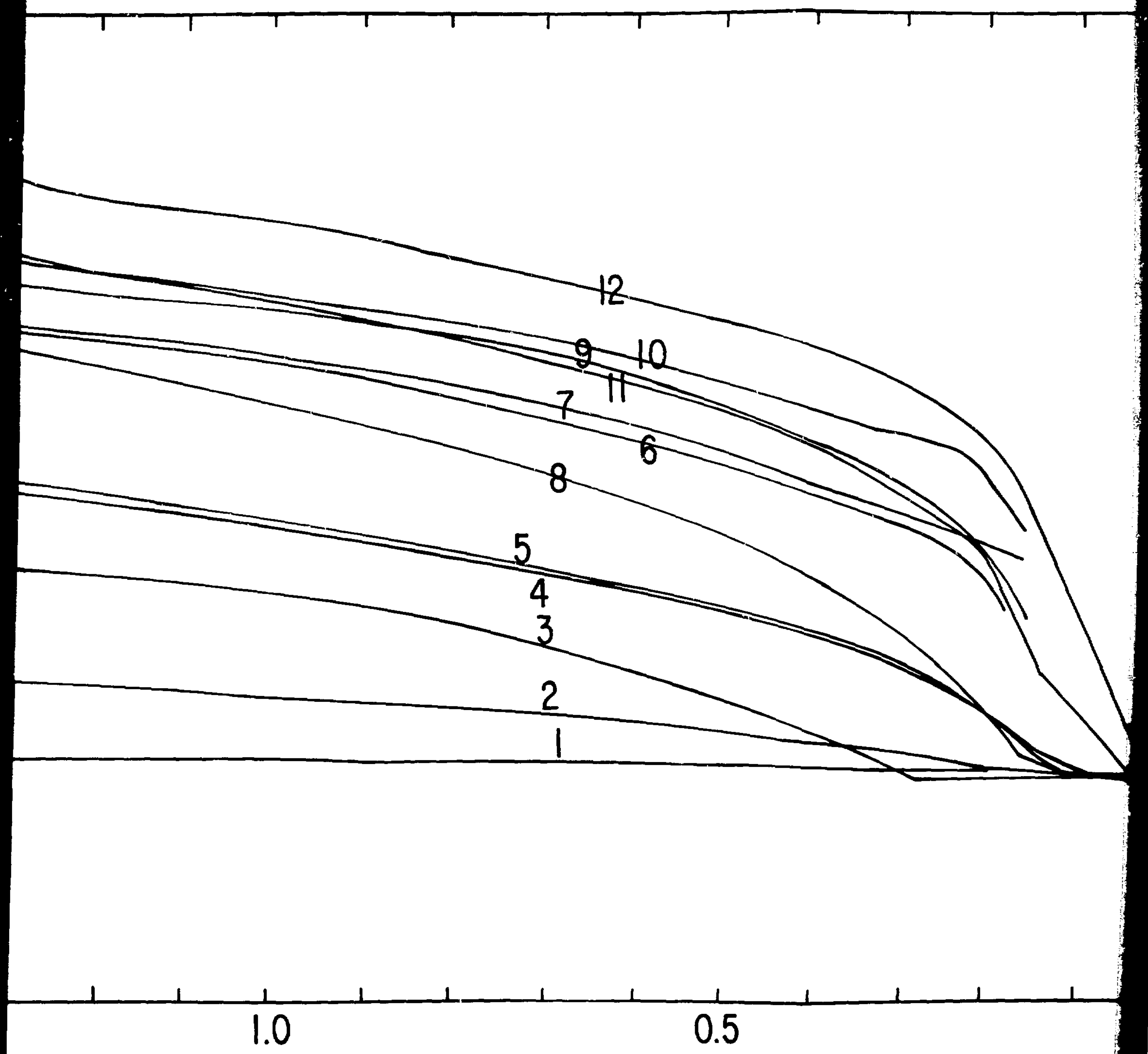
Trace	Description	Max. Temp °F
1	ambient air	86
2	BP oil	122
3	PSCS oil	128
4	BP rocker terminal	198
5	PSCS main terminal	210
6	BP main terminal	238
7	BP rocker guide	240
8	PSCS rocker terminal	250
9	PSCS rocker guide	266

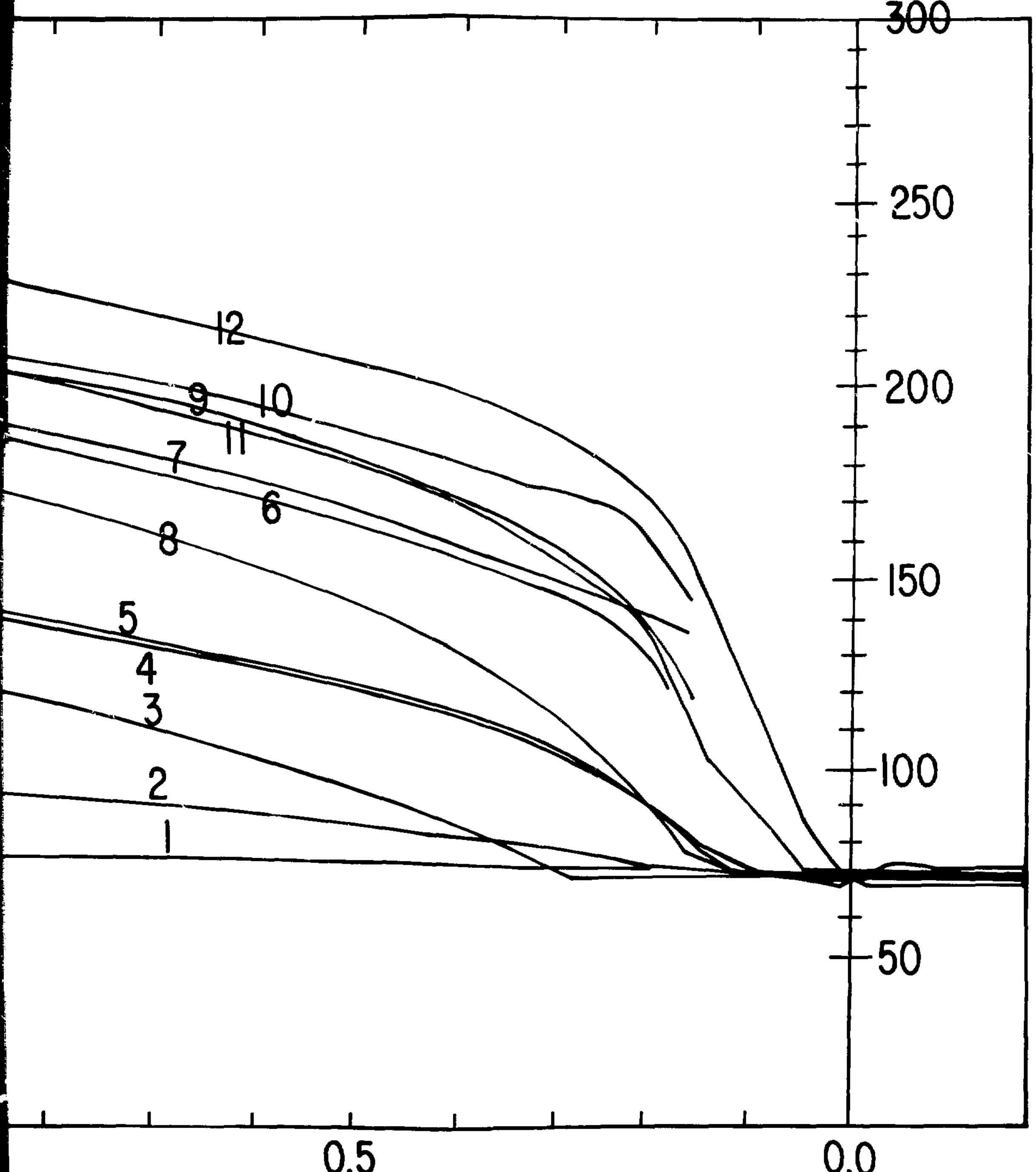


300
250
200
150
100
50
3.0
2.5
1
2
3
4
5
6
7
8
9
10
11
12

FIG. A-1




12
9
10
11
7
6
8
5
4
3
2
1
1.0
0.5


300
250
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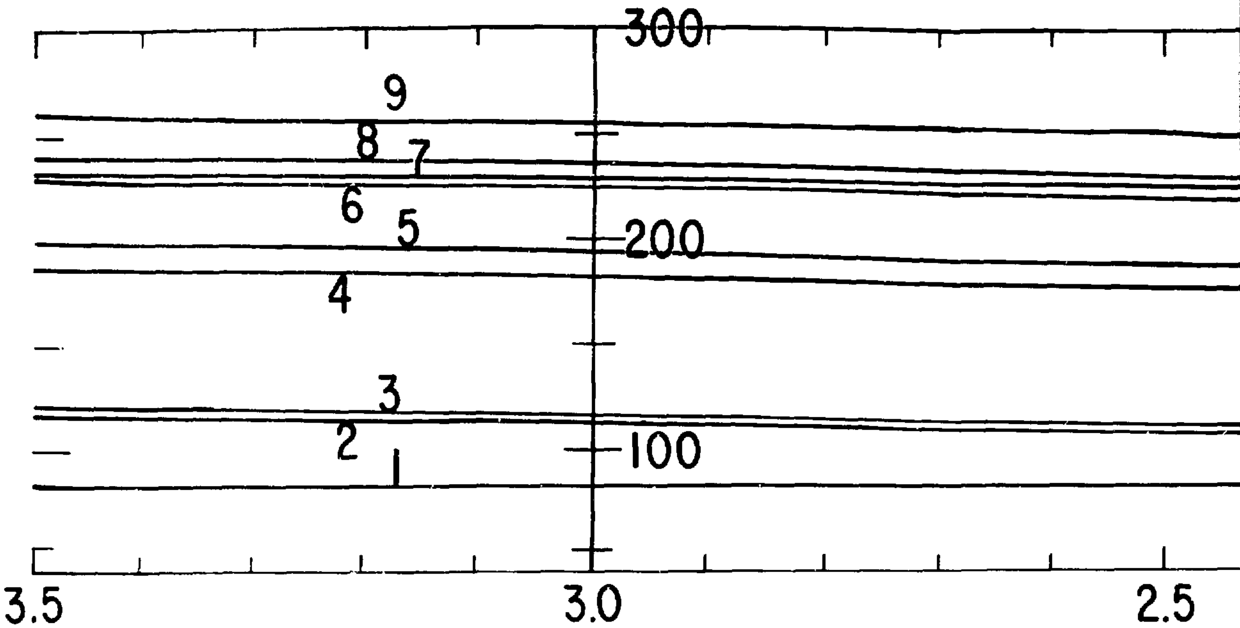

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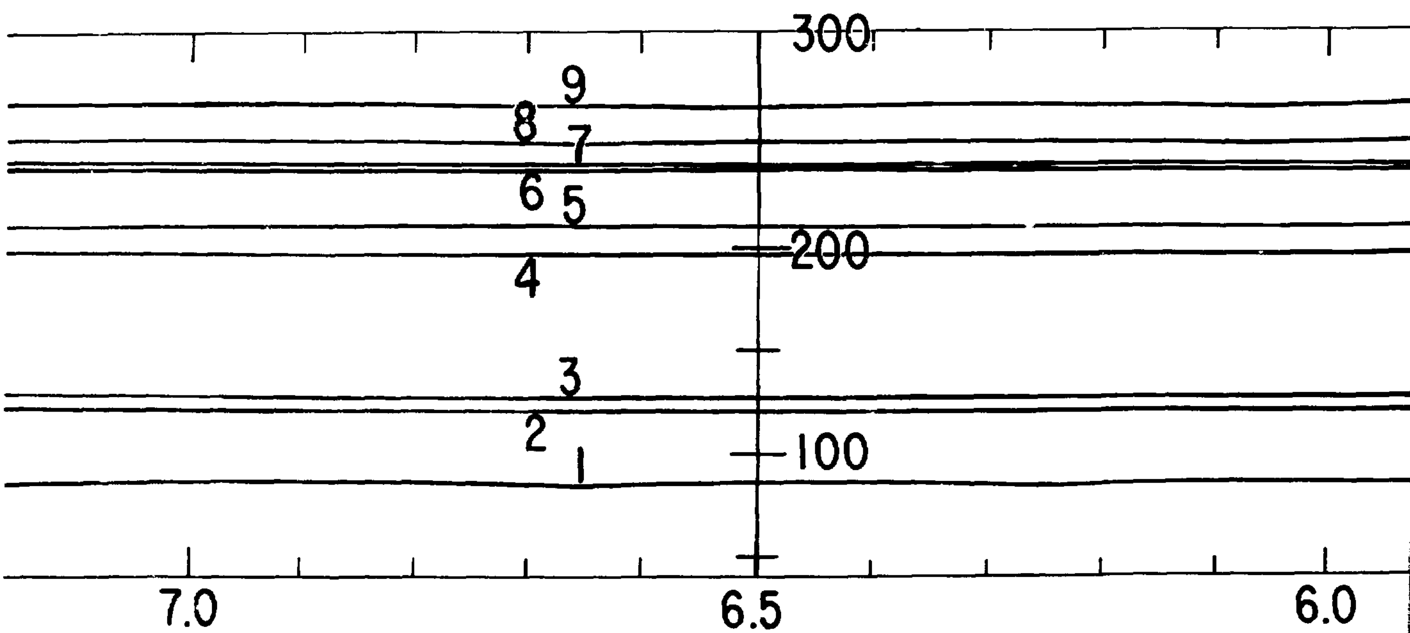

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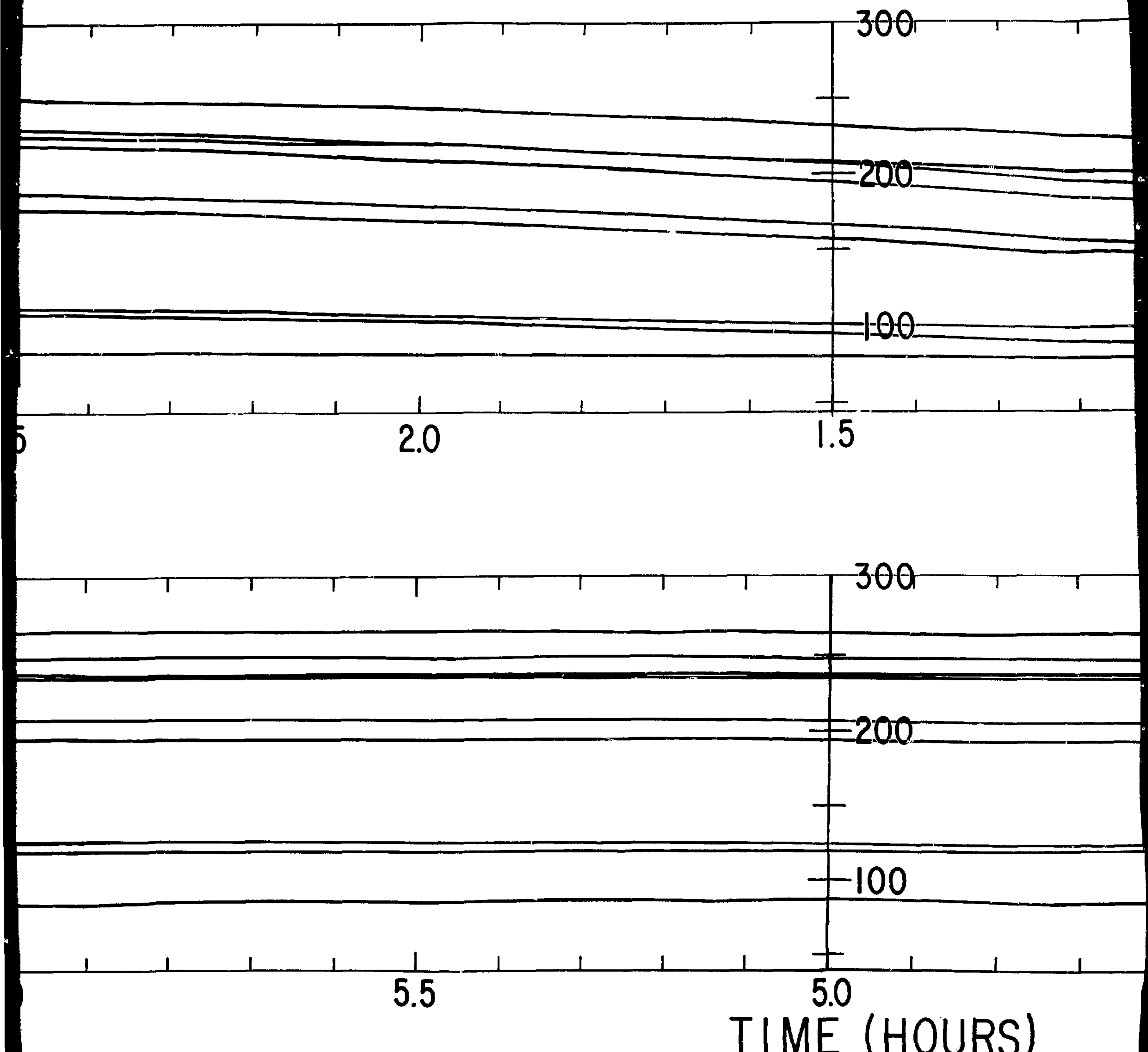
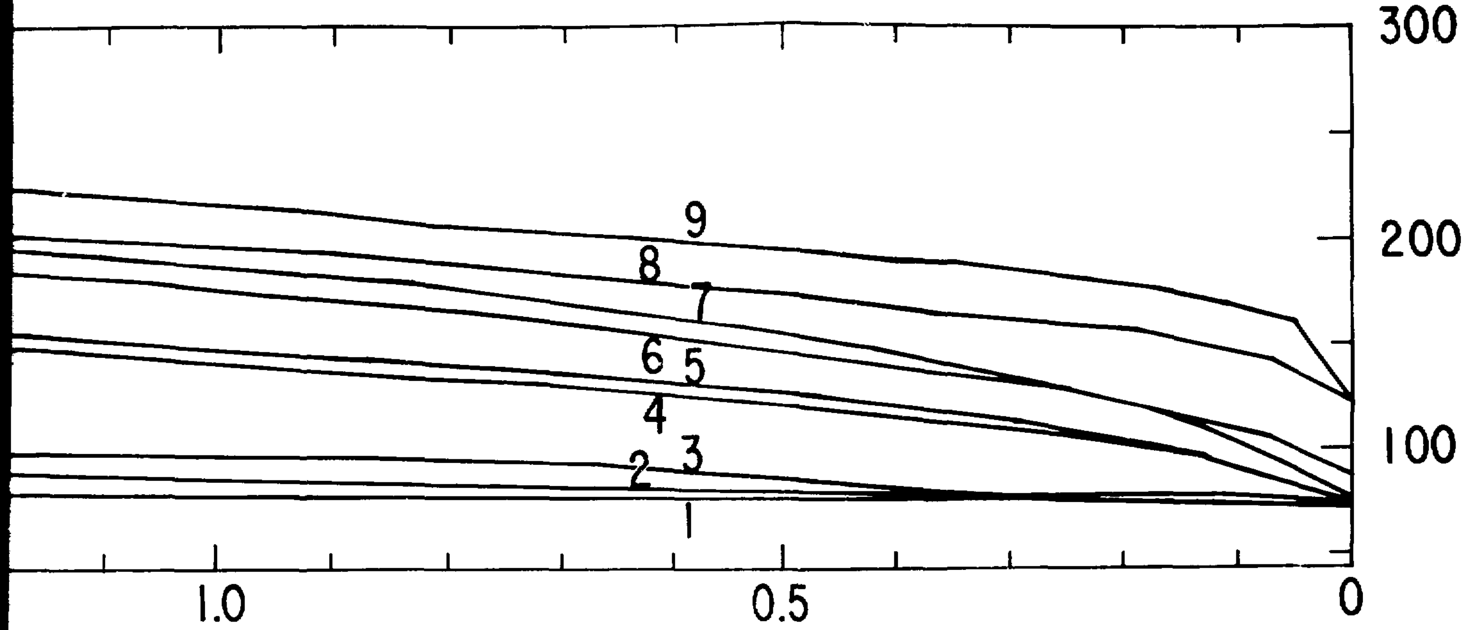
FIG. A-2

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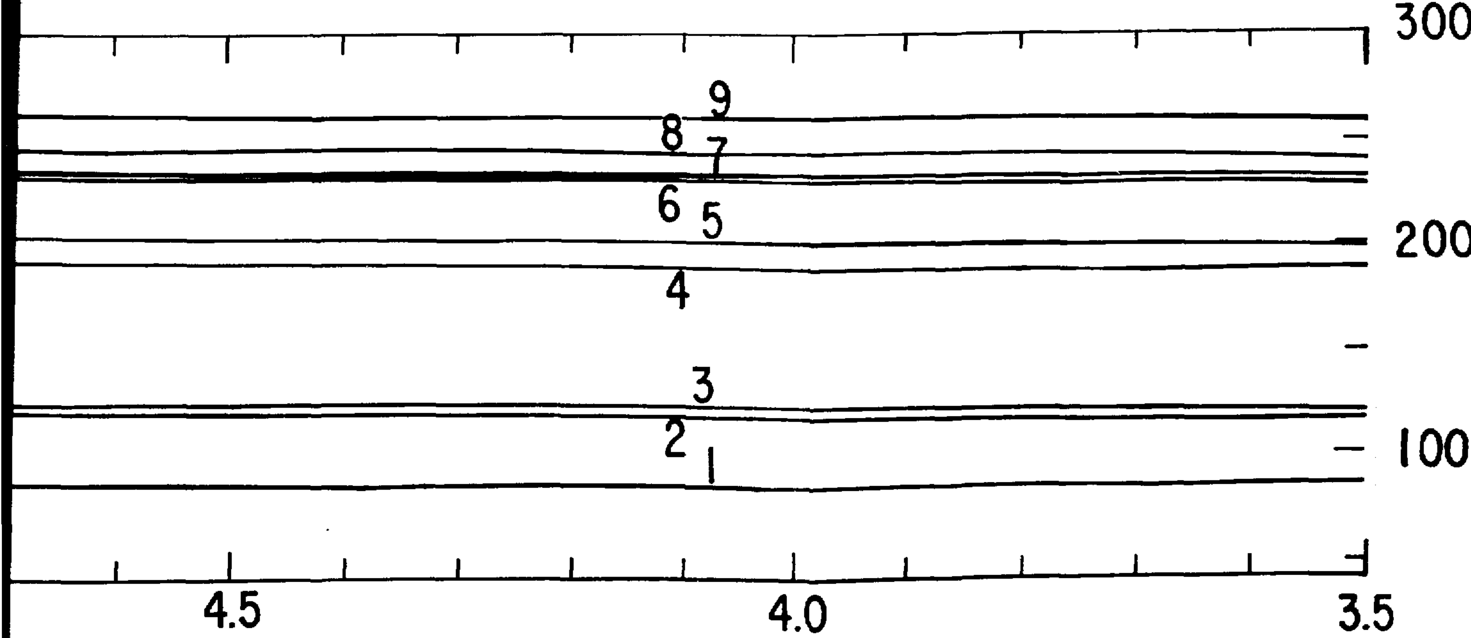
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100
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4.5
4.0
3.5

APPENDIX B

AREAS OF CONCERN ASSOCIATED WITH THE USE OF SILICONE OIL IN SWITCHES

There are two basic areas of concern associated with the use of oil in switches. They are the generation of explosive gas from submerged arcing in oil and the formation and growth of film between contact surfaces submerged in oil. The gas generation problem would result if BP or PSCS were triggered open inadvertently while conducting current. The film growth problem is inherent in the system even during normal operation.

Explosive gases, mainly hydrogen and methane, are generated as byproducts of decomposition when oil is exposed to an electric arc. Silicone oil generates more gas than mineral transformer oil. One literature source[B1] reports a gas evolution rate of 6 mℓ/A-s for 100 centistoke silicone oil. Using this figure, an arc at 25 kV would generate gas at the rate of 150 ℓ/s. Because silicone oil is not flammable in oxygen concentrations less than 80%, the primary hazard would be a gas explosion. Our recommendation is that the switch be equipped with either a suitable rupture disc that would remove the silicone oil during an unexpected pressure rise or a high volume ventilation system to remove any explosive gases from the area. Inert gas cover should be used with any contained or closed submerged oil switch.

Film growth on contact surfaces is a recognized problem in circuit breaker design and is primarily dependent on operating temperature. Lemelson[B2] suggests that the failure time for copper to copper contacts decreases by an order of magnitude when the operating temperature is raised from 40° C to 100° C. For this reason ANSI Standard C37.04 limits the hottest spot temperature for a silver alloy contact in a circuit breaker to 90° C. The hottest contact temperature in PSCS during the first heat rise test was 141° C. Lee[B3] indicates that the film may be partially removed by the surface shear action when the contacts are operated. Oil temperature should be periodically monitored in the LCTF switches as a precautionary measure and occasional switch operation performed to remove the film.

REFERENCES

B1. Frank M. Clark, Insulating Materials for Design and Engineering Practice, John Wiley and Sons, Inc., New York and London, 1962.

B2. K. Lemelson, "About the Failure of Closed Heavy Current Contact Pieces in Insulating Coil at High Temperatures", IEEE Trans., PHP, 9, No. 1 (March 1973).

B3. T. H. Lee, Physics and Engineering of High Power Switches, MIT Press, Cambridge and London, 1975.

APPENDIX C

PROBLEMS ENCOUNTERED WITH PROTOTYPE LCTF EQUIPMENT

The following is a summary of problems encountered with the equipment tested for use in LCTF.

1. The air cylinder on both BP and PSCS is mounted in elongated holes. During the test, one of these cylinders moved in its holes, making repositioning necessary. A set screw is recommended.

2. Twice during the tests, the air cylinder of BP stuck in a midpoint position and to change its positon by remote control was not possible. Movement was done manually. The problem seems to originate in the shuttle valve system.

3. Clearance needs to be allowed in front of DCCB. Plasma generated during an interruption caused a breakdown between conductors approximately 10 inches in front of the breaker. Clearance guidelines are usually supplied with this type of equipment.

4. The clearance on connections between BP and DCCB needs to be increased. Several busbars had to be wrapped with polyethelene to prevent breakdown.

5. If two DCCB's are used in series, a voltage grading network should be used. There was no steady state voltage sharing between the two tested until a 100 kΩ resistor was connected in parallel across each interrupter.

6. The timing of DCCB changes with erosion. Approximately 5 ms difference in contact parting time was noted after 100 operations.

APPENDIX D

TIMING MEASUREMENTS ON PROTOTYPE SWITCHES FOR LCTF

Table DI is a summary of the mean opening, closing, delay, and jitter times measured on new prototype LCTF equipment. The limit switches on BP and PSCS were used for their measurements, while the parting of the intermediate contacts on DCCB was used for its measurement. The jitter here is defined as the standard deviation from the mean.

TABLE DI

OPENING, CLOSING, DELAY, AND JITTER TIMES FOR LCTF SWITCHES

SWITCH	OPENING (ms)				CLOSING (ms)			
	DELAY	JITTER	COMPLETION	JITTER	DELAY	JITTER	COMPLETION	JITTER
BP(125 psi)	39.4	0.45	77.9	0.63	38.7	1.8	229.4	3.9
PSCS(125psi)	31.9	0.30	76.5	0.64	41.0	0.41	429.6	4.9
DCCB(125Vdc)	25.3	0.29	*	*	----	----	154.4	4.9

*The high jitter discussed in the text is given here.
This jitter was not apparent from this contact parting measurement.
The critical time is the time when the arc moves from the intermediate contacts into the arc chute.
The jitter for that process is approximately ± 3 ms.

APPENDIX E

PHOTOGRAPHS OF SWITCHES IN TEST FACILITY.

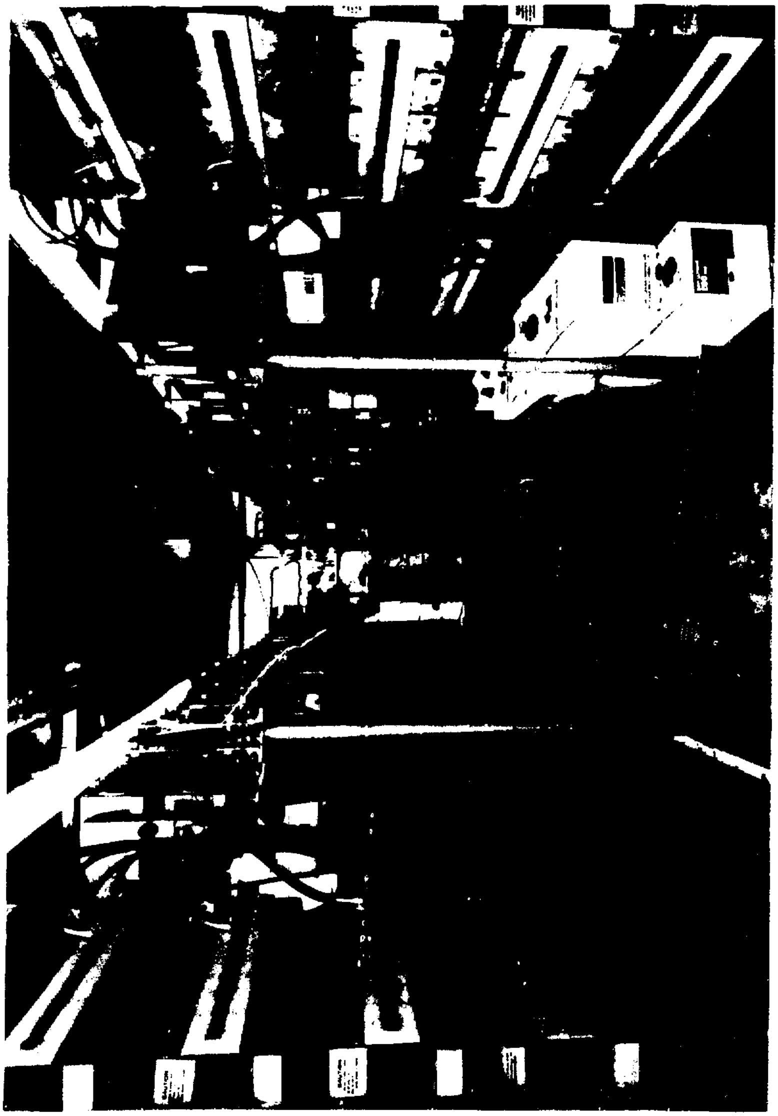


Fig. E1. Overview of test facility with the resistor on right and load coil in center.

Fig. E2. BP in foreground and PSCS in background.

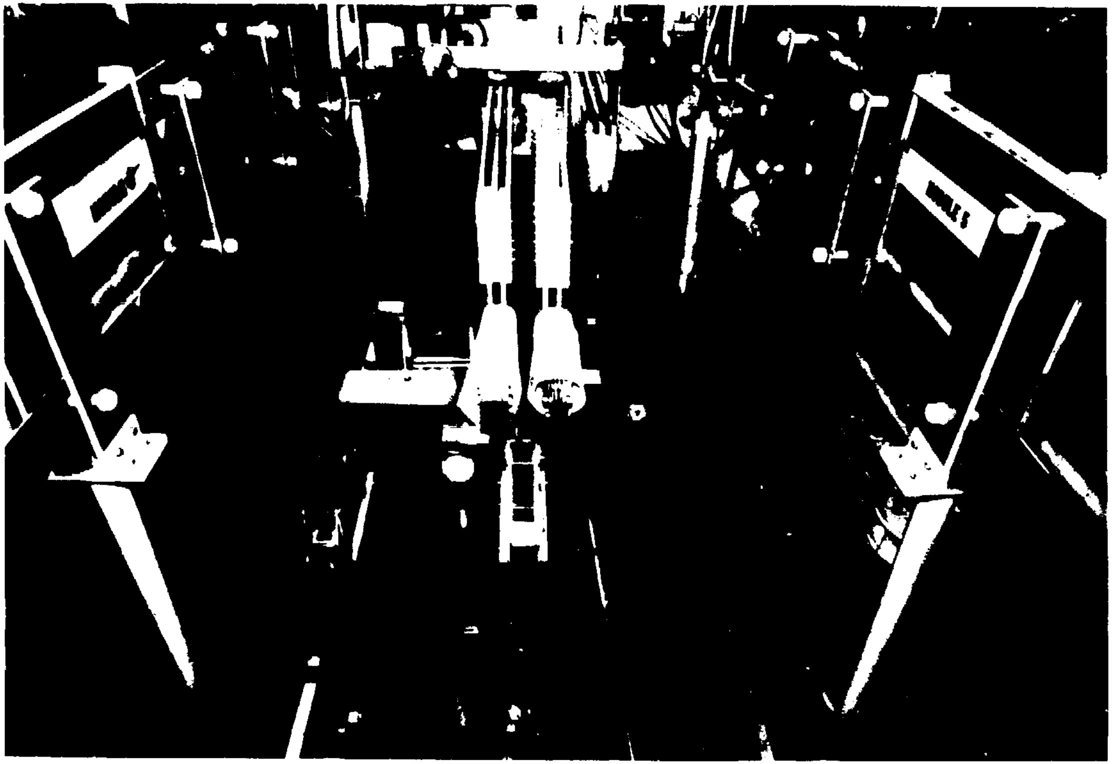
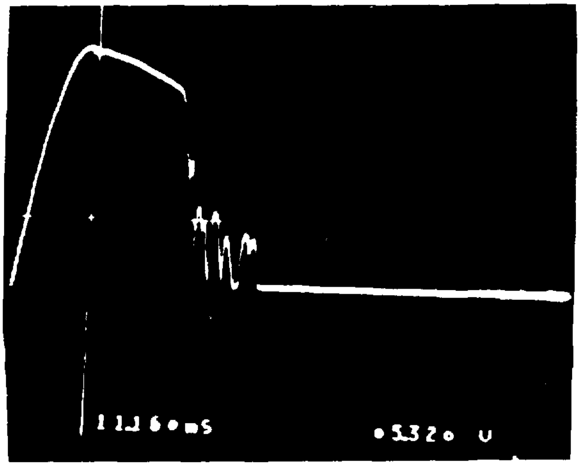


Fig. E3. Series connected DCCB's (lower), BP (middle), and PSCS (top).

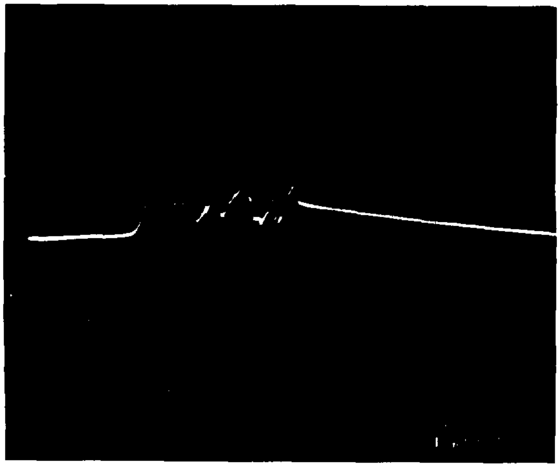
Fig. E4. Series connected DCCB's (left) and BP (right).

APPENDIX F

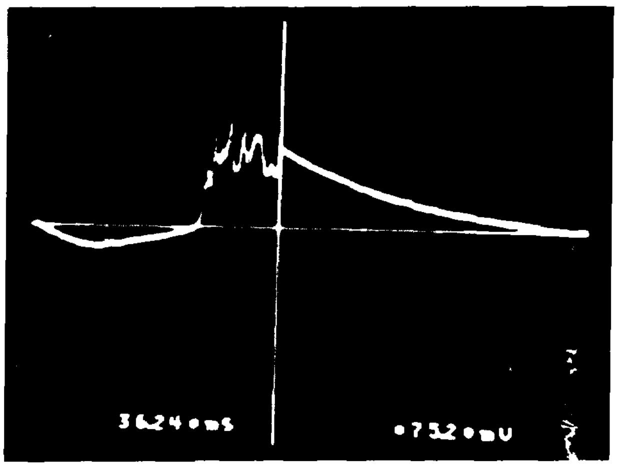
REPRESENTATIVE WAVEFORMS TAKEN DURING TESTS ON A SINGLE DC INTERRUPTER



a. Breaker current.
Peak current is 21 kA.

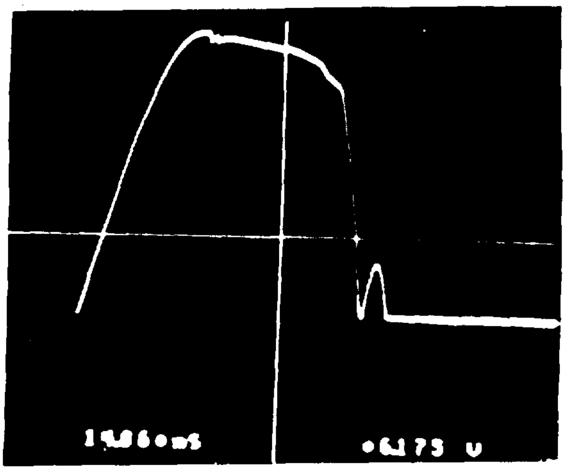


b. Breaker voltage.
Peak voltage is 5.8 kV.
Recovery voltage is 2.1 kV.

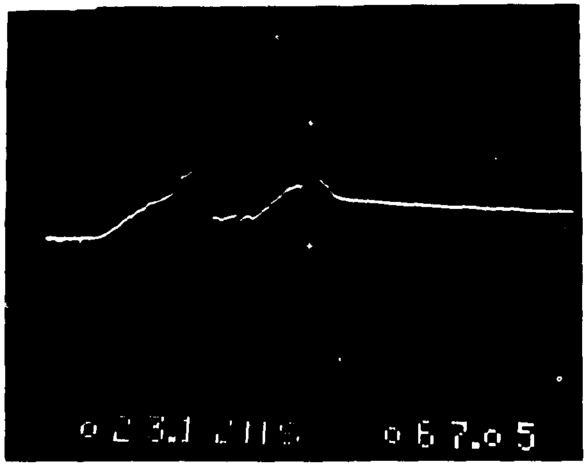


c. Resistor current. Transfer current is 13.5 kA.

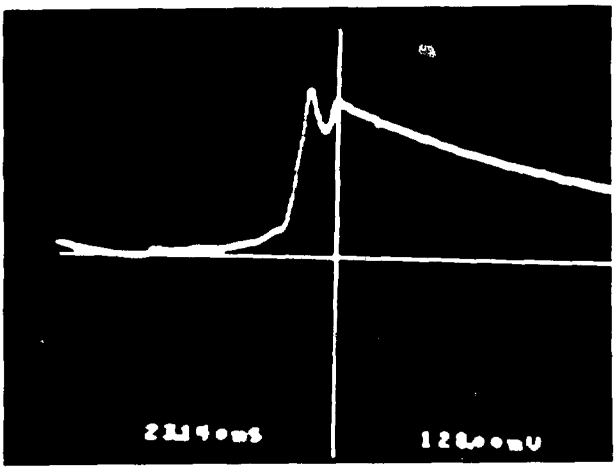
Fig. F1. Interruption at 2.1 kV showing multiple restrikes.
Time scales are different.



a. Breaker current.
Peak current is 25 kA.

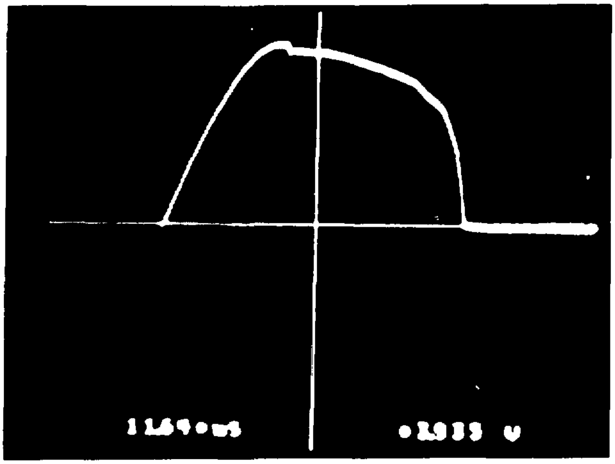


b. Breaker voltage.
Peak voltage is 6.7 kV.
Recovery voltage is 2.3 kV.

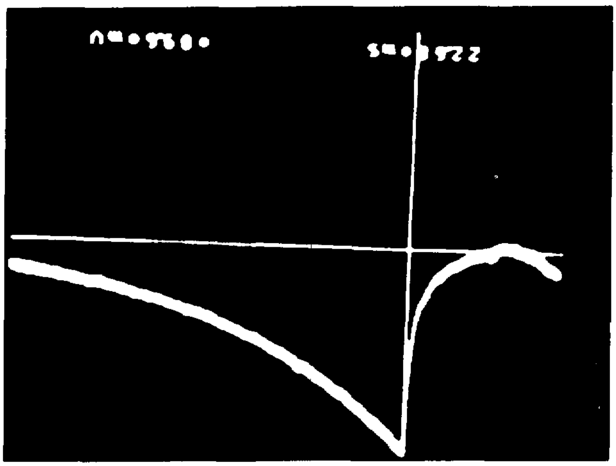


c. Resistor current. Transfer current is 23 kA.

Fig. F2. Interruption at 2.3 kV showing single restrike.
Time scales are different.

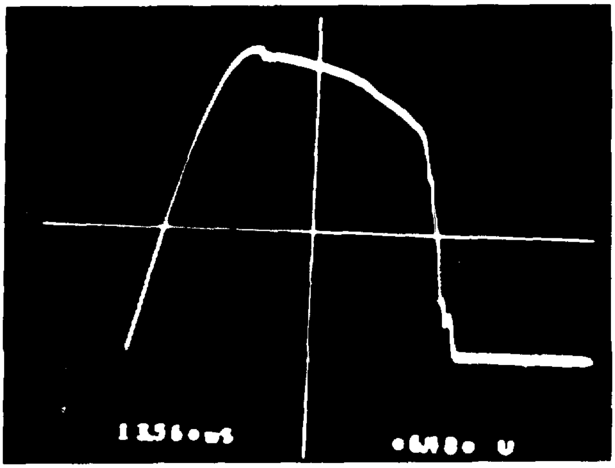


a. Breaker current.
Peak current is 16 kA.

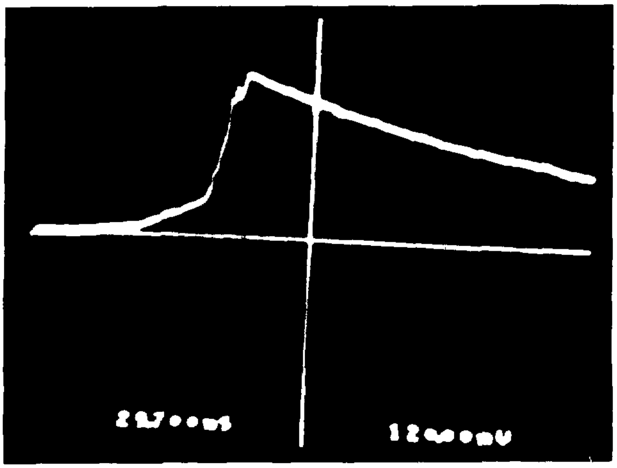


b. Resistor current.
Transfer current is 14 kA.

Fig. F3. Interruption at 1.1 kV showing no restrikes.
Time scales are different. Voltage waveform not available.

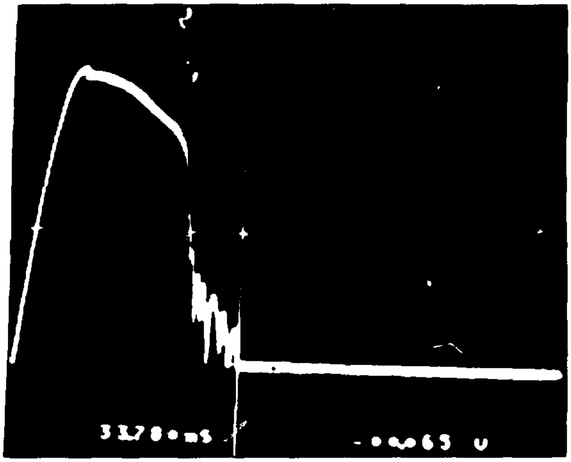


a. Breaker current.
Peak current is 26 kA.

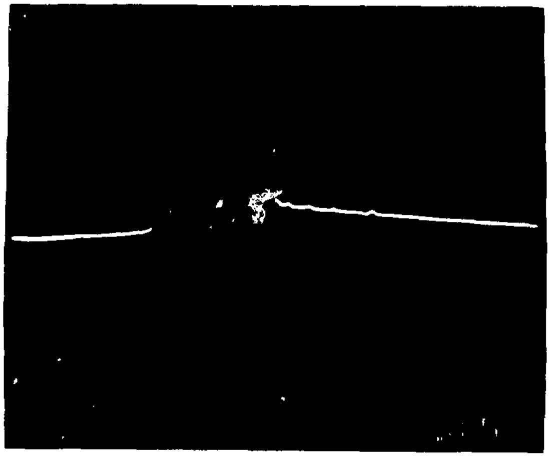


b. Resistor current.
Transfer current is 24 kA.

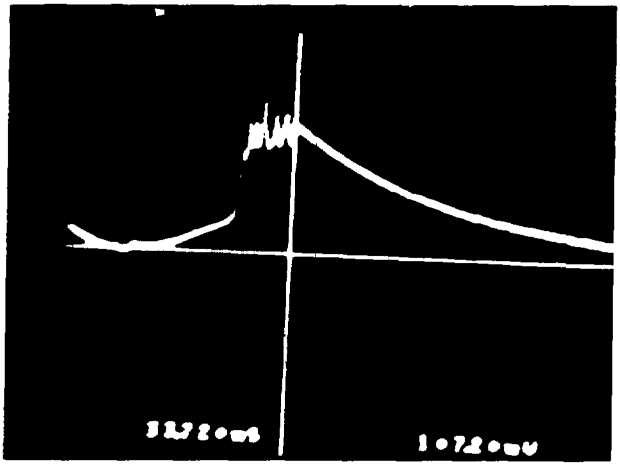
Fig. F4. Interruption at 1.6 kV showing no restriking, but some hesitation at current zero. Time scales are different. Voltage waveform not available.



a. Breaker current.
Peak current is 25 kA.



b. Breaker voltage.
Peak voltage is 5 kV.
Recovery voltage is 2 kV.



c. Resistor current. Transfer current is 23 kA.

Fig. F5. Interruption at 2.0 kV showing multiple restrikes.
Time scales are different.

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