ARCING FAULTS ON DIRECT CURRENT TROLLEY SYSTEMS

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ABSTRACT

This paper discusses tests that have been conducted to evaluate arcing short circuit faults on direct current trolley systems. Arcing faults supplied by single and multiple power sources and limited by various impedances were studied. Data were recorded to compare various system behavior during arcing faults. The instrumentation, test procedures, electrode material and other factors affecting arcing faults are described. The results are systematically evaluated and are compared to present Federal Regulations. Areas of further study and research are also presented.

INTRODUCTION

Trolley systems are used extensively in the mining industry to transport coal and mining supplies in underground coal mines. Fires which are caused by short circuit faults in trolley systems can increase the risk of serious injury or death to those persons working underground. Since the enactment of the Federal Coal Mine Safety Act of 1952, a total of 115 fires (Figure 1) involving trolley systems were formally investigated by Health and Safety personnel of the U.S. Bureau of Mines (1952-1970) and Mining Enforcement and Safety Administration (1970-1977), now the Mine Safety and Health Administration. During this 25-year period, 38 persons were killed and 25 persons were injured by fires involving trolley systems. In the 8-year period from 1970-1977, a total of 22 fires occurred involving trolley systems resulting in 11 injuries and 12 fatalities. Nine fatalities were caused by one fire in 1972.

Fire hazards associated with trolley systems can be reduced by the proper installation, maintenance and protection of trolley systems. Section 75.1001, Title 30, Code of Federal Regulations, Part 75, requires that trolley wires and trolley feeder wires be provided with overcurrent protection. They are also required to be supported on insulators and not in contact with combustible materials, roof or ribs. Presently, overcurrent protection is considered adequate if the affected circuit will be properly deenergized upon the occurrence of a short circuit at any location in the trolley system. In short circuit analysis of trolley systems, a bolted fault is assumed in order to calculate the current(s) that would flow at any given location.

The mining industry has had little information on the relationship between bolted fault current and the expected fault current during an arcing fault. Arcing faults have been called high-resistance faults, and the value of arcing fault current was sometimes assumed to decrease to values which would not be detected by conventional overcurrent devices. Thus, the cause of some fires associated with trolley systems has been attributed to such high-resistance faults. Also, the cause of some trolley fires

DATA ON COAL MINE FIRES RELATED TO TROLLEY CIRCUITS

INVESTIGATED 1953-1977

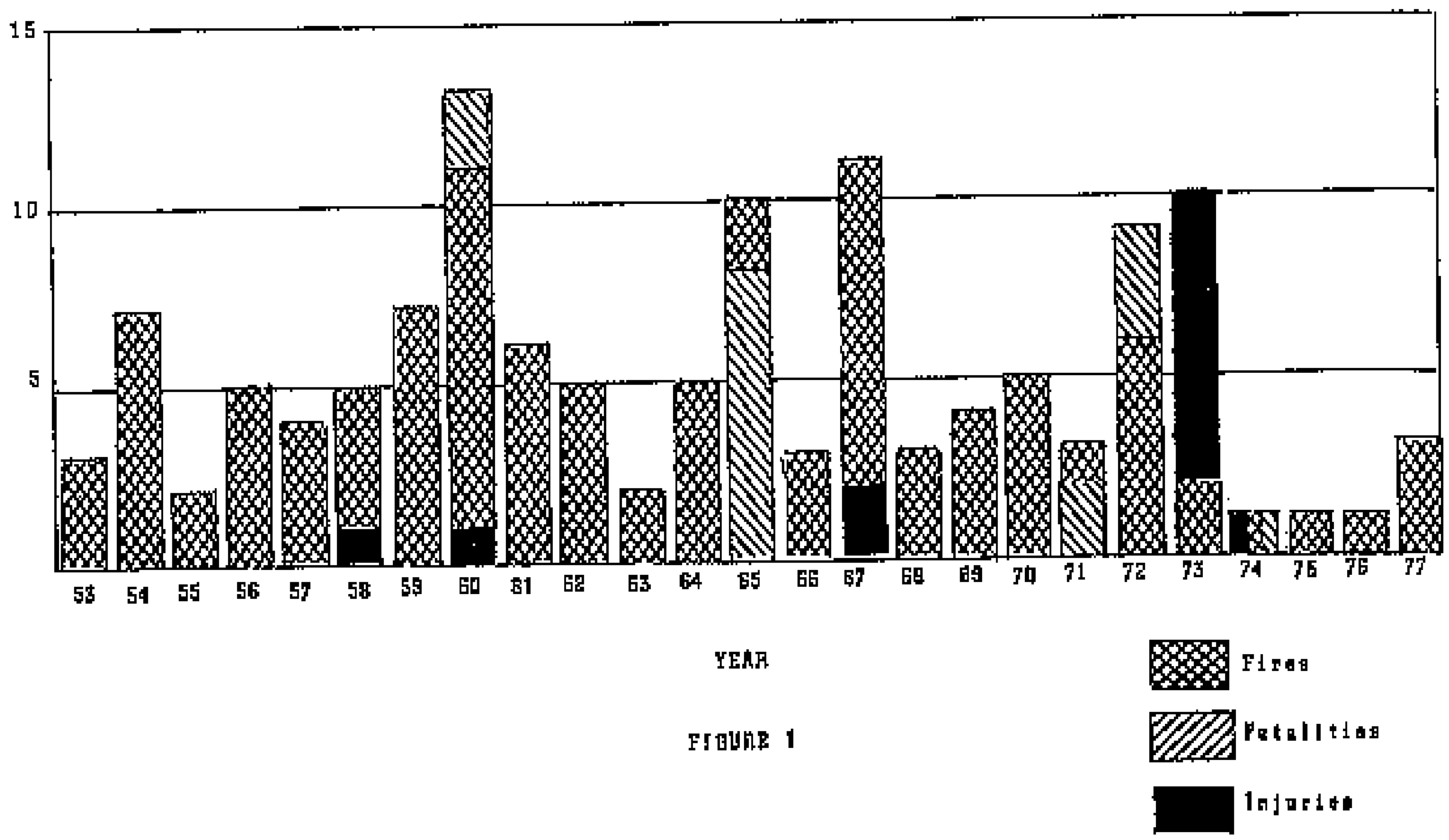


FIGURE 1

has been attributed to low-current faults due to insulation failures such as contaminated insulators. Both arcing faults and insulation failures are conditions which are undesirable and are capable of igniting coal and other combustible materials. Insulation failures are usually long-term conditions and fires resulting from such failures can be prevented by proper design and maintenance of trolley systems. Thus, they will not be treated in this paper. Arcing faults on the other hand, can occur instantaneously as a result of falls of roof, dislodged steel roof supports, haulage vehicle derailments, etc.

In order to obtain additional information on the relationship and characteristics of arcing faults, Mine Safety and Health Administration (MSHA) personnel performed various tests to simulate arcing faults on trolley systems. One of the main reasons for performing these tests was to determine the relationship between the current during bolted fault conditions and the expected current during arcing faults for known circuit parameters. Once this relationship is determined, the present short circuit analysis method for trolley systems can be modified to include the effect of arcing faults.

TEST PROCEDURES

Several series of arcing fault tests were conducted at a central mine shop in northern West Virginia. The shop facility utilizes a 1500 kVA bank of transformers to transform 23 kV to 2300/4160 V. An unregulated 500 kW rectifier and an induction regulated 1000 kW rectifier were used to convert 4160 Vac, three-phase power to 300 Vdc for the tests. Circuit protection was provided for the dc output by the installation of a panel mounted circuit breaker rated continuously for 4000 A. A remote-controlled contactor rated at 900 A continuous was used to initiate the arcing tests. Current was controlled by resistors rated at 1000 A for 12 sec. Circuit inductance was provided by using one of two air core inductors constructed of multiple turns of No. 4/0 and No. 2 AWG insulated wire. Figure 2 shows the setup of the testing circuit.

The arc electrodes were installed within a 2 x 2 x 4 ft. wooden box to insure safety of personnel and equipment. Standard trolley wire clamps installed on bell-type insulators were used to support the electrodes. This configuration elevated the electrodes approximately 6 in. above the bottom of the test box.

Cooper and steel electrodes were used in various configurations in order to simulate typical faults which are likely to occur in underground coal mines. Lengths of 9 section (400 MCM) trolley wire were used as the copper electrodes. Reinforcing bars of ½ in. diameter were used for the steel electrodes. The following configurations were tested:

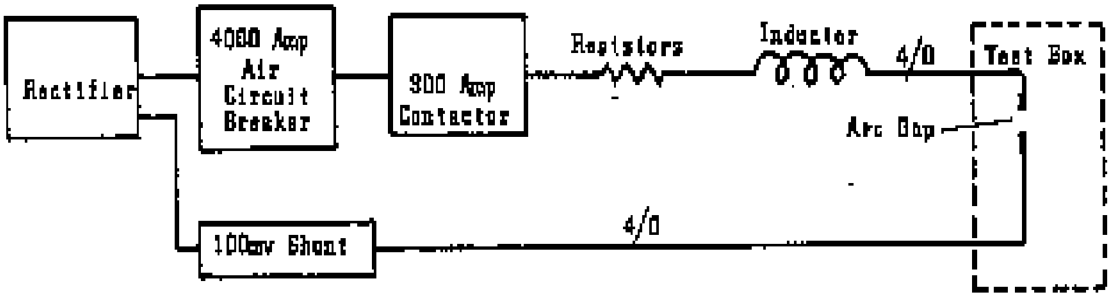
	Electrode	Polarity
	(+)	(-)
Electrode MaterIal	Copper	Copper
	Copper	Steel
	Steel	Copper
	Steel	Steel

The initial arc gap was varied from 3/16 in. to 6 in. with the majority of the tests being performed in the 3/8 in. to 1 in. range. Arcs were initiated by bridging the arc gap with several strands of a 19 strand No. 12 AWG wire. The wire bridging the arc gap evaporated and allowed an arc to be established. The electrodes were placed end to end to prevent immediate blowout of the arc [1].

Most circuit interrupting devices are usually capable of detecting and deenergizing a fault within 0.2 sec. Therefore, successful arcs were considered to be achieved whenever an arc lasted 0.2 sec. (12 cycles at 60 Hz) or longer.

During each test the arc voltage and supply voltage were measured using high-voltage isolation amplifiers to attenuate the high-voltage signals to levels providing adequate trace deflections on the oscillograph. During the tests which contained external inductance, the voltage across the inductor was measured in a similar manner. Arc current was measured with an appropriate shunt in conjunction with an isolation amplifier which increased the low-voltage signal from the shunt to a level for adequate oscillograph deflection.

In the third series of tests which were performed during the spring of 1978, the power of the arc was measured using an analog device which multiplied the arc voltage and arc current signals to the oscillograph giving a signal which was recorded on the oscillograph.



TEST CIRCUIT

Figure 2

TESTS

Approximately 100 arcing tests were conducted between June 1977, and July 1978. Forty-two of these tests were conducted with an initial gap of about 3/8 in. (0.953 cm). The time constant of the test circuit was varied from approximately 0.0 ms to 16.6 ms by the addition of air core inductors. The time constant of a trolley circuit depends on the total inductance and resistance of the circuit. When the trolley circuit is such that the inductance and resistance of rectifier, the time constant of the circuit can be approximated by the time constant of the circuit conductors. This will usually be the maximum time constant that can be obtained for any given configuration of the circuit conductors. The minimum time constant that can be obtained will be that of the rectifier source. A typical 300 Vdc trolley circuit for a large track haulage mine can have a time constant of approximately 25 ms while the time constants of various sizes of rectifiers described in reference [2] are less than 4 ms.

Seventy-six tests were conducted with negligible inductance with the current being varied from about 350 A to 2500 A during bolted conditions. The arc gap was changed from 3/16 in. (0.48 cm) to 6 in. (15.24 cm). Of the 76 tests conducted without inductance, 23 were conducted with an initial arc gap of 3/8 in. Consistent results were obtained when the tests were conducted with this gap length.

When an inductance of 3.85 mH was used in 7 tests, the time constant of the circuit varied from 9 ms to 16.6 ms. Time constants between 5 ms and 8 ms were obtained when an inductance of 1.64 mH was used in 14 tests. An inductance of 0.17 mH was used in 4 tests to achieve time constants between 0.5 ms to 1 ms.

A list showing system parameters is given in the following chart for arc tests conducted with initial gaps of 3/8 in.

OBSERVATIONS

Over 100 arcs were investigated with various circuit parameters. Current was varied from 300 A to 2400 A with initial arc gaps ranging from 3/16 in. to 6 in. A large number of the tests were conducted with copper electrodes and an initial arc gap of 3/8 in. The following observations pertain to such arcs:

1. Both arc current and arc voltage contained high frequency components at currents below about 800 A. As inductance was introduced into the circuit, the high frequency components of the arc current were reduced substantially. However, the high frequency components of the arc voltage were not reduced. Thus, it appears that large changes of arc voltage will result from relatively small changes in arc current at low arc currents.

2. The value of arc voltage remained relatively constant for arc currents about 800 A. For arcs with gaps of 3/8 in., the value of arc voltage was approximately 50 V. This value remained essentially constant even for various combinations of copper and steel electrodes.

3. Once an arc was established, the arc gap increased sufficiently to extinguish the arc. The maximum length of the gap after the arc self-extinguished was approximately 1.5 in. When

a steel cathode was used with a copper anode, the arc gap increased to a maximum of approximately 2 in. When steel was used for both electrodes, the arc gap increased to approximately 3 in.

4. Arcs in which steel was used for both electrodes, appeared more violent than arcs initiated with copper electrodes or copper and steel electrodes.

5. In the majority of the tests conducted the current reached bolted values before the arc was established. However, in at least one test, the arc was established before the current reached bolted value (See Figure 7). This was due to the small strands of wire bridging the gap melting before the bolted value was obtained. Thus, it is apparent that the maximum setting of overcurrent devices on trolley systems should be at values below the available bolted values.

Figure 3 shows a relationship between arc voltage and arc current for arcs having a 3/8 in. gap. The arc will usually operate at the intersection of this curve and the resistance load line of the circuit. The current will stabilize at a fixed point on the curve and the arc will dissipate a relatively constant amount of power. The load line may intercept the characteristic curve in two locations as shown in Figure 4 but only one point is stable. The stable operating location is the point with the lowest arc voltage. Also, the arc voltage versus are current characteristic curve will shift upward as the gap increases in length [3].

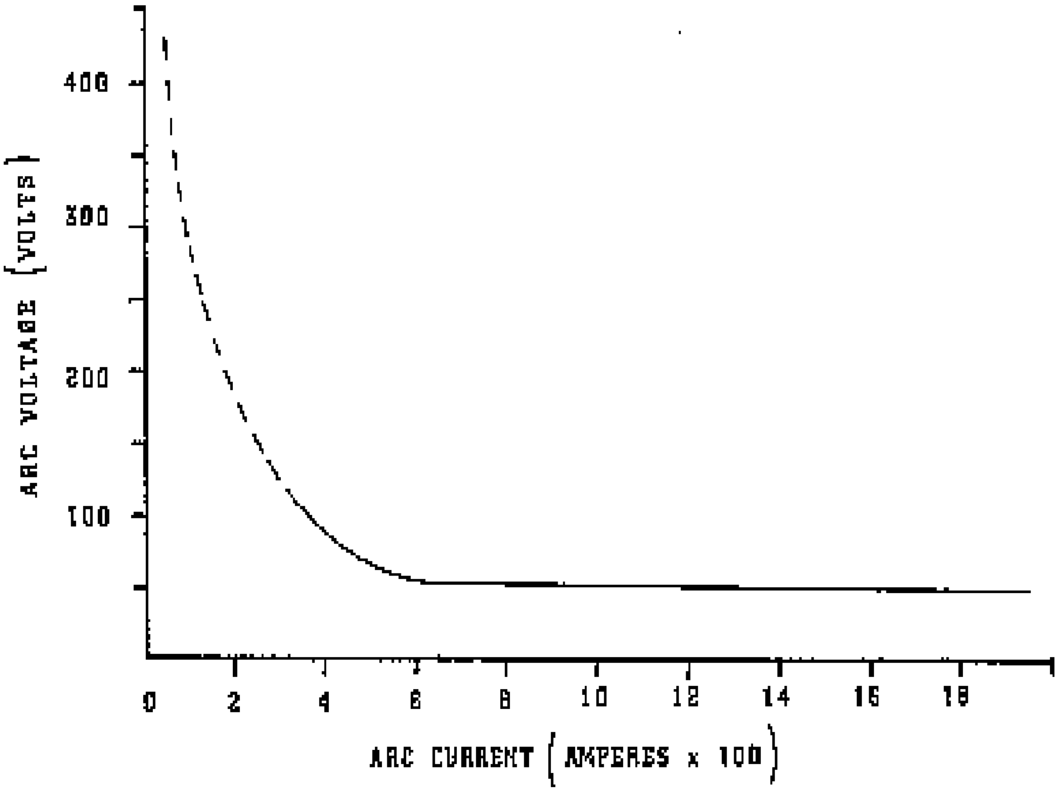


Figure 3

ARCING FAULT DATA (3/8 INCH GAP)

Test	System Voltage (Volts)	System Resistance (Ohms)	System Inductance (mH)	Bolted Fault Current (Amps)	Arc Current (Amps)	Arc Voltage (Volts)
A13	325	0.90	0.0	338	225	
A14	325	No Data	0.0	No Data	No Data	
B5	325	0.60	0.0	500	375	75
B6	325	0.60	0.0	500	375	75
B12	325	0.40	0.0	725	550	No Data
C5*	325	0.30	0.0	975	750	75
C6*	325	0.30	0.0	1000	750	75
C10	325	0.20	0.0	1380	1200	58
C11	325	0.20	0.0	1380	1200	50
F3	325	0.36	1.64	850	675	55
F4	325	0.36	1.64	840	650	50
G1	325	0.31	0.17	950	800	50
G2	325	0.51	0.17	950	780	65
G3	325	0.39	3.85	770	550	75
H1	325	0.39	3.85	775	580	50
H2	325	0.23	3.85	1100	1000	60
I1	325	0.23	3.85	1100	1020	50
I2	325	0.20	1.64	1270	1200	50
I3	325	0.20	1.64	1300	1200	50
I4	325	0.16	0.17	1700	1400	50
I5	325	0.16	0.17	1700	1500	50
J1	325	0.15	0.0	1750	1400	50
J2	325	0.15	0.0	1900	1600	50
J3**	325	0.15	0.0	1800	1500	50
J4**	325	0.15	0.0	1650	No Data	No Data
K1**	325	0.15	0.0	1800	1500	50
K2**	325	0.15	0.0	1800	1500	50
K3**	325	0.20	1.64	1400	1200	50
K4**	325	0.20	1.64	1400	1150	67.5
K5**	325	0.20	1.64	1400	1200	50
L1***	325	0.20	1.64	1400	1150	50
L2****	325	0.20	1.64	1400	1200	62.5
M1****	325	0.20	1.64	1380	1240	48
M2***	325	0.15	1.64	1750	1550	50

* Are extinguished in less than 0.25 a

** Electrodes - Copper (+) and Steel (-)

*** Electrodes Copper (-) and Steel (+)

**** Both electrodes steel

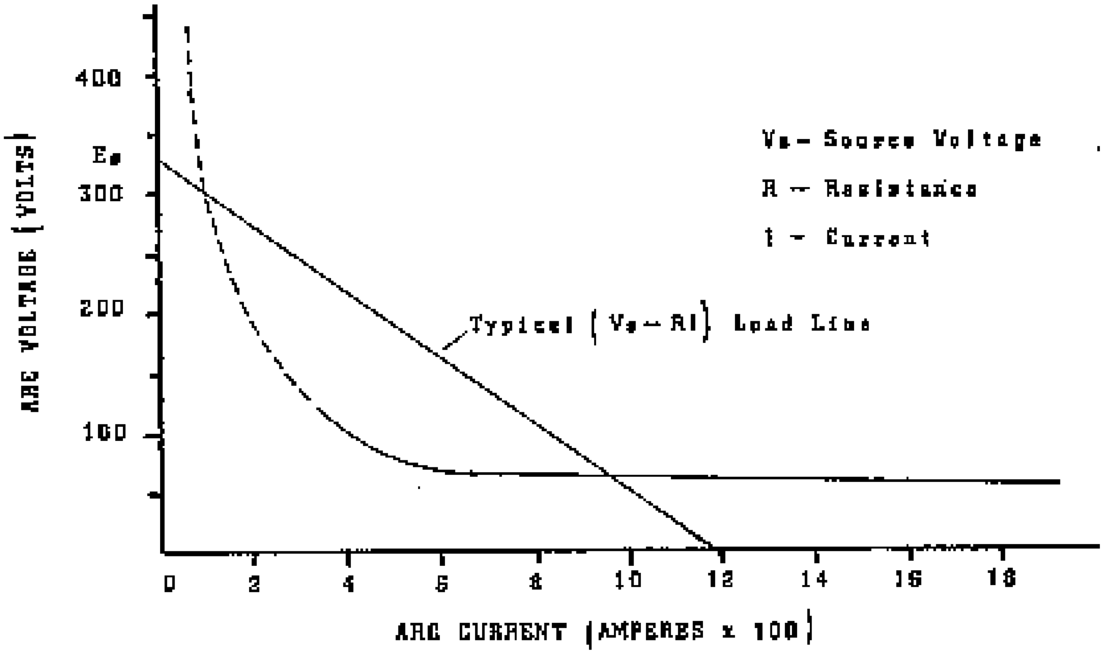


Figure 4

As mentioned above, the value of arc current is dependent upon the arc gap and the load line of the circuit. In circuits containing two or more sources, the arc current is dependent upon the total current flowing in the arc. Thus, as a cource is disconnected from the circuit, a new load line must be obtained to determine the next value of arc current. The load line which should be used for circuits containing multiple sources can be obtained by using Thevinin's equivalent voltage and resistance of the circuit.

Figure 5 through 11 in the appendix are typical oscillographs obtained during the arcing fault tests.

FUTURE RESEARCH

The preliminary research to determine the characteristics of dc arcing faults was not sufficient to recommend specific changes in the requirements for short circuit protection for underground trolley systems. There is a need for conducting future research on dc arcing faults to determine the complete relationship between arc voltage and arc current for all faults above 100 A, including the effects of high intensity arcing as described in reference [4]. Also, surveys at various mines should be conducted to determine typical time constants and inductances of the trolley systems.

In addition, the following are areas which should be thoroughly studied to determine their effects on dc arcing faults:

1. Constant arc gaps

2. Arcing faults contaminated by coal and other combustible materials

3. Ignition of coal and other combustible materials by dc arcs

4. Various methods of initiating dc arcs

5. Methods of detecting arcing faults

REFERENCES

[1] Lawrence E. Fisher, “Resistance of Low-Voltage a.c. Arcs” IEEE Transactions on Industry and General Applications, Vol. IGA-6, No. 6 November/December 1970.

[2] D.A. Paice, A.B. Shimp, and R.P. Putkovich, “Circuit Breaker Development and Application” Phase 1 Research Report Westinghouse Electric Corporation NTIS PB 248 31 O/AS.

[3] Cobine, J.D., “Gaseous Conductors” McGraw-Hill 1941 pp. 371-378.

[4] Samuel Korman, “High Intensity Arcs” International Science and Technology June 1964 pp. 90-98.

APPENDIX

Figures 5 and 11 show typical oscillographs of the tests performed during 1977. The oscillographs have been reduced to approximately 75 percent of their original size for reproduction purposes.

Figure 5

Test	C10
Supply Voltage	325 Vdc
Bolted Current	1380 A
Time Constant	0.0 ms
(+) Electrode	Cu
(-) Electrode	Cu
Average Current	1100 A
Time of Test	0.62755 s

Figure 6

Test	F-3
Supply Voltage	325 Vdc
Bolted Current	850 A
Time Constant	4.29 ms
(+) Electrode	Cu
(-) Electrode	Cu
Average Current	650
Time of Test	3.025 s

Note: Arc voltage contains high frequency components at lower values of current.

Figure 7

Test	H2
Supply Voltage	325 Vdc
Bolted Current	1100 A*
Time Constant	13-14 ms
(+) Electrode	Cu
(-) Electrode	Cu
Average Current	1000 A
Time of Test	2.4545 s

Note: Arc voltage fairly constant 60V

*Maximum value of available current not obtained.

Figure 8

Test	I2
Supply Voltage	325 Vdc
Bolted Current	1270 A
Time Constant	6.41 ms
(+) Electrode	Cu
(-) Electrode	Cu
Average Current	1200 A
Time of Test	2.215 S

Note: Arc voltage contains high frequency components as the current drops to about 850 A.

Figure 9

Test	K4
Supply Voltage	325 Vdc
Bolted Current	1400 A
Time Constant	7.06 ms
(+) Electrode	Steel
(-) Electrode	Cu
Average Current	1150 A
Time of Test	1.7765 s

Figure 10

Test	L-2
Supply Voltage	325 Vdc
Bolted Current	1400 A
Time Constant	7.06 ms
(+) Electrode	Steel
(-) Electrode	Steel
Average Current	1200 A
Time of Test	5.325 s*

*Arc did not self extinguish - contactor opened to deenergize the test circuit.

Figure 11

Same as Figure 10. Starts at 0.4s and ends at 0.55s

Notes: (1) 470 A change in arc current in 6.25 ms (Time constant 7.06 ms).

(2) Maximum arc voltage - 495 Vdc

(3) Inductor voltage becomes negative for large changes in current.

Test C10 Copper Electrodes (3/8 in. Gap)

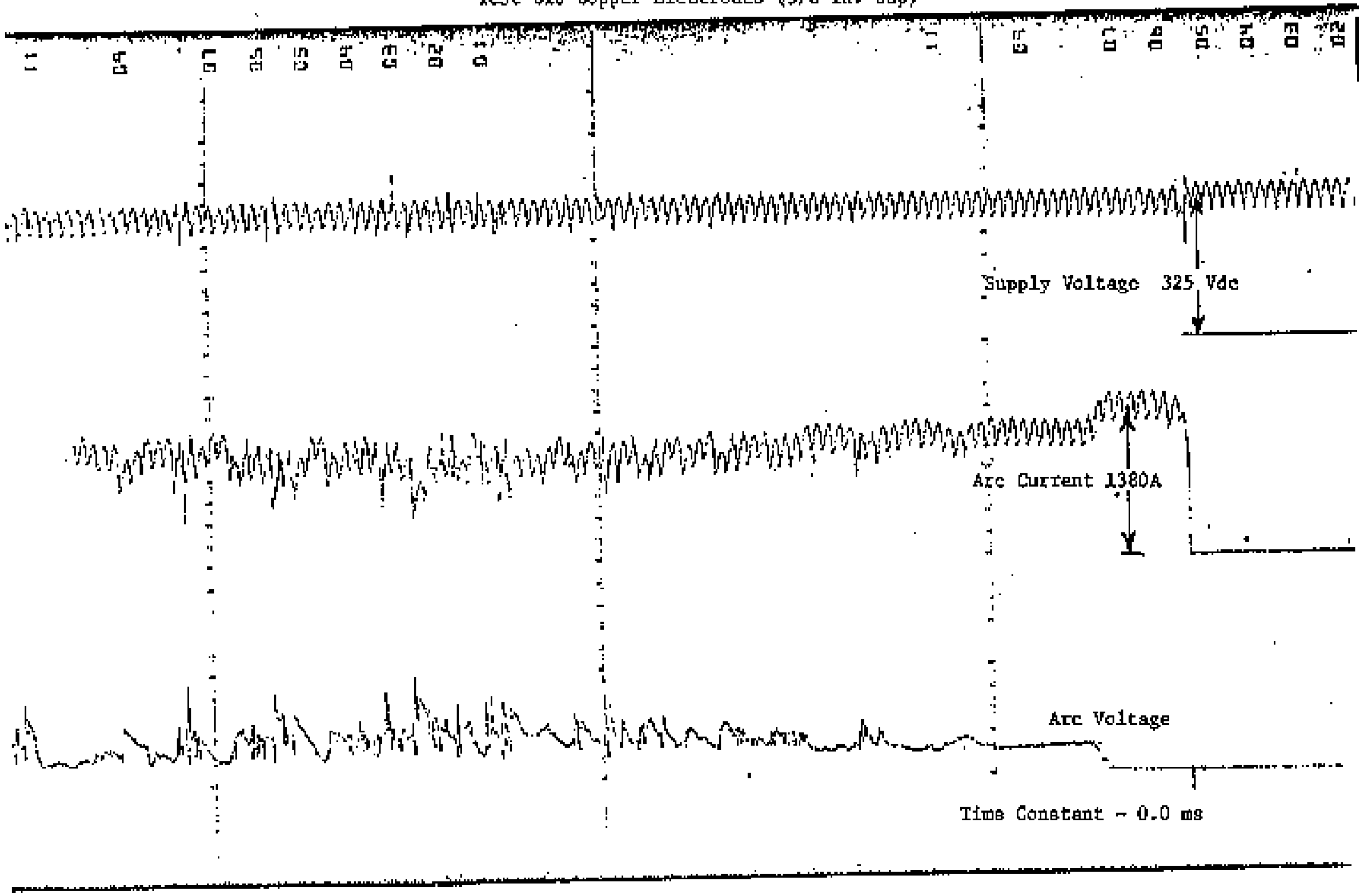


Figure 5

Test F-3 Copper Electrodes (3/8 in. Gap)

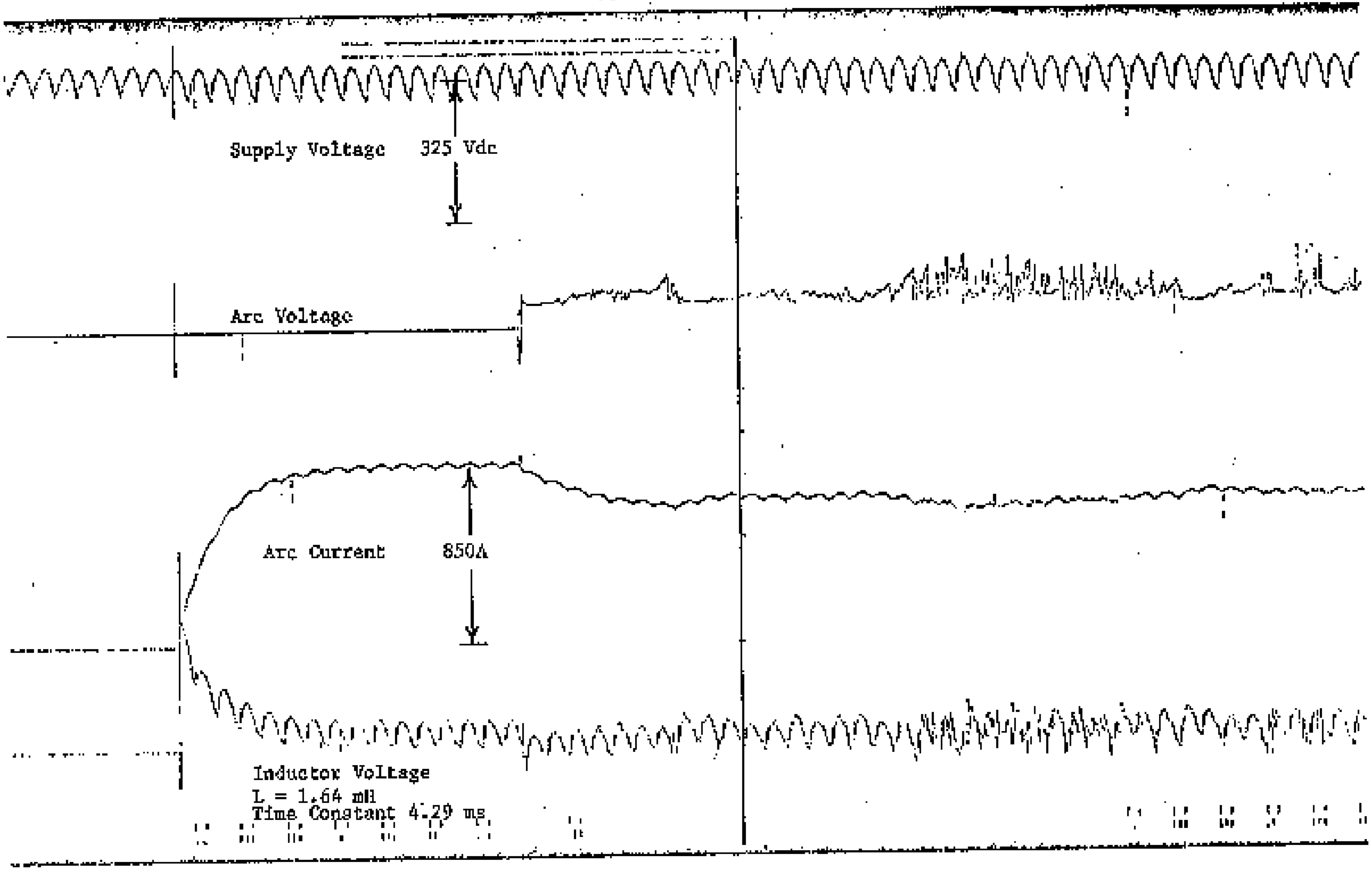


Figure 6

Test H-2 Copper Electrodes (3/8 in. Gap)

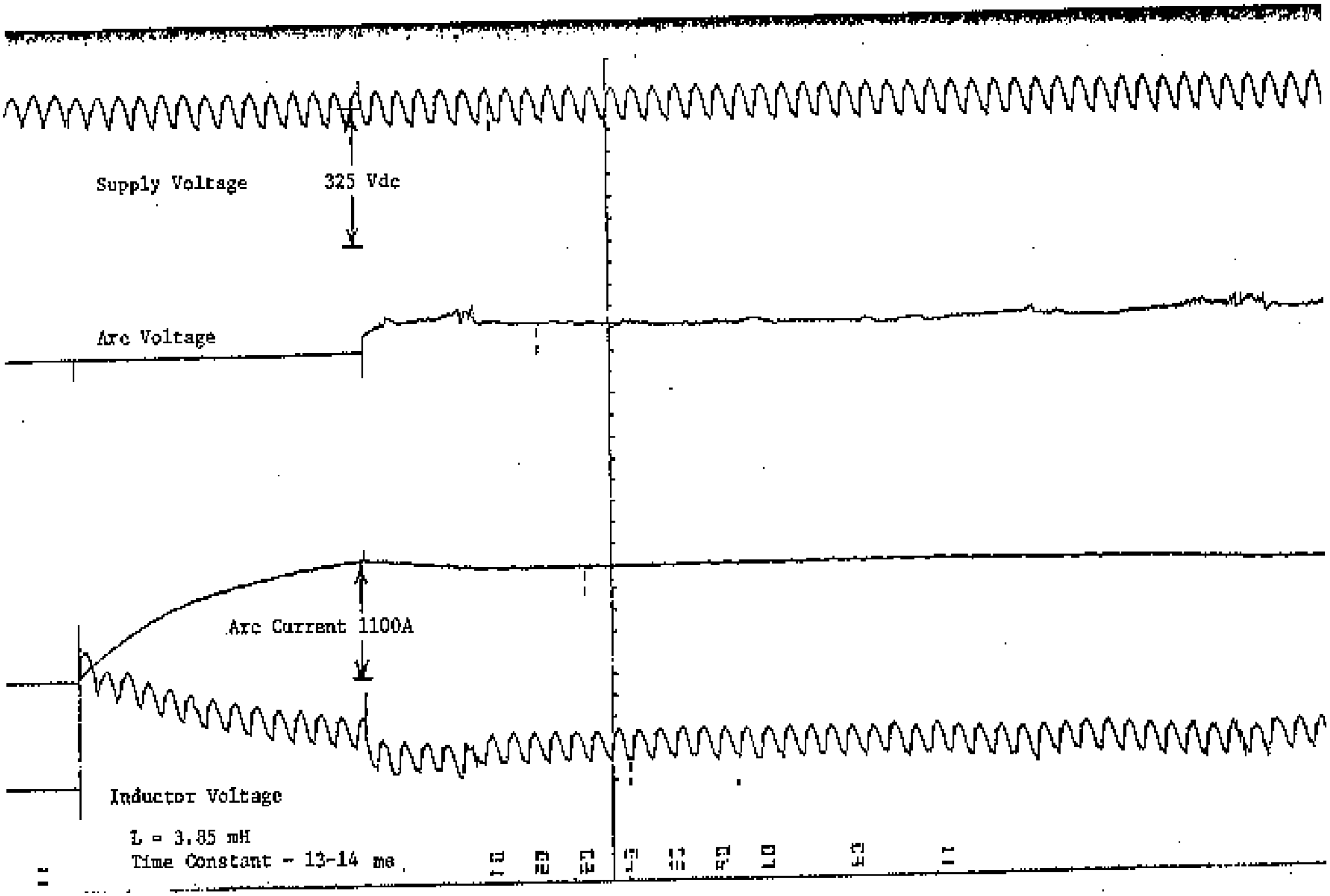


Figure 7

Test I2 Copper Electrodes (3/8 in. Gap)

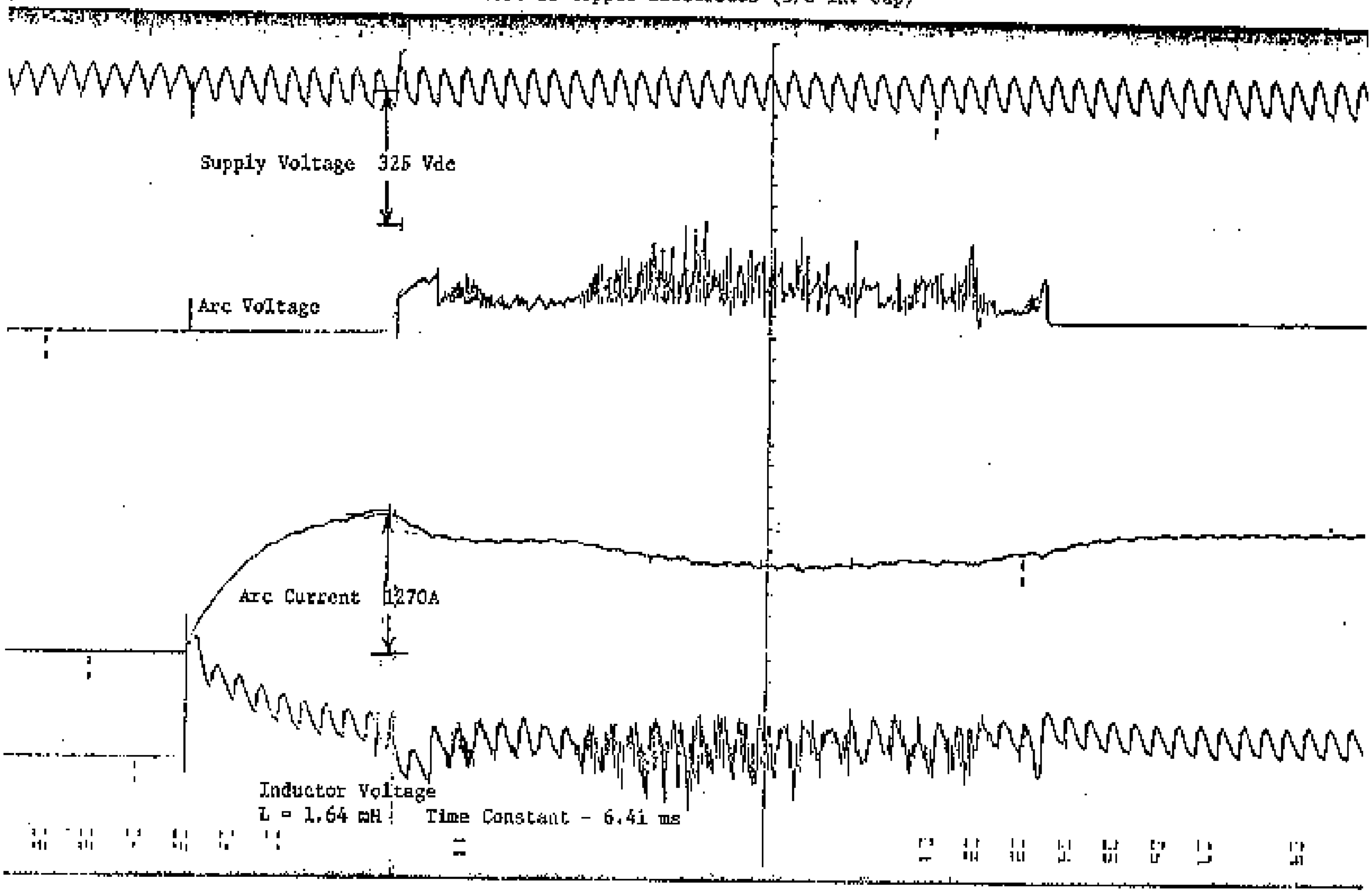


Figure 8

Test I2 Copper Electrodes (3/8 in. Gap)

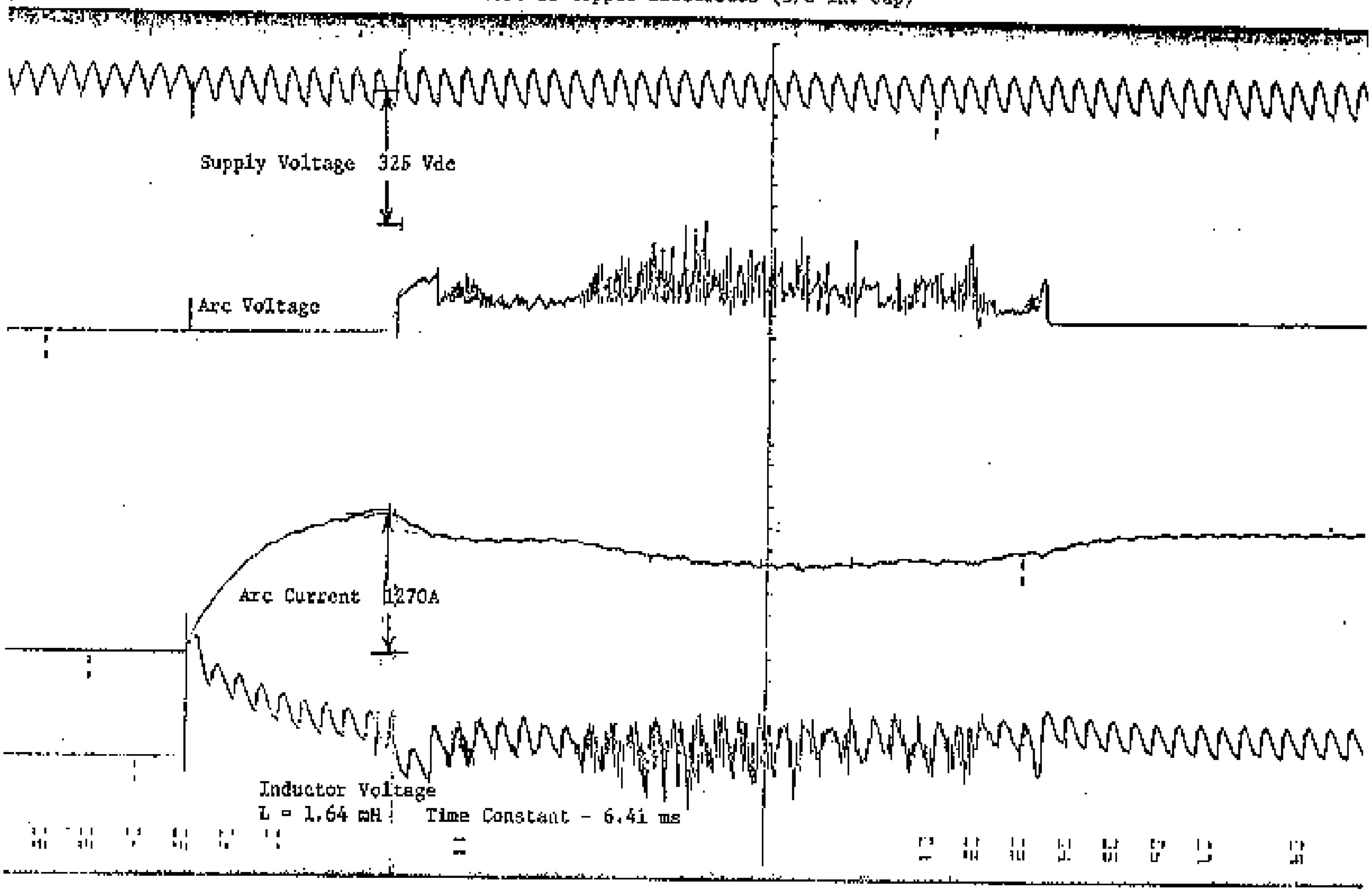
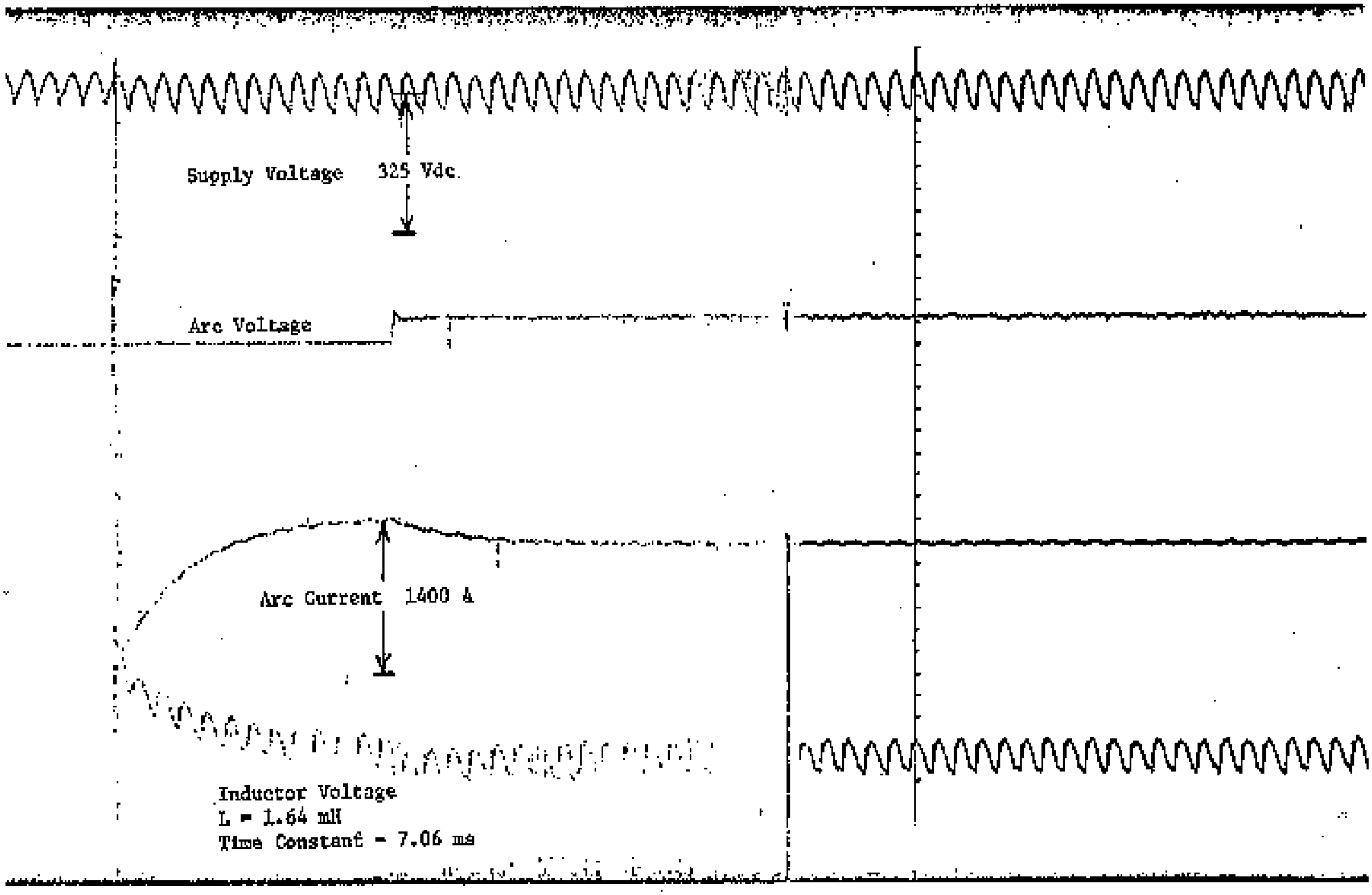


Figure 8

Test L-2 Steel Electrodes (3/8 in. Gap)



Test L-2 Continued - Steel Electrodes

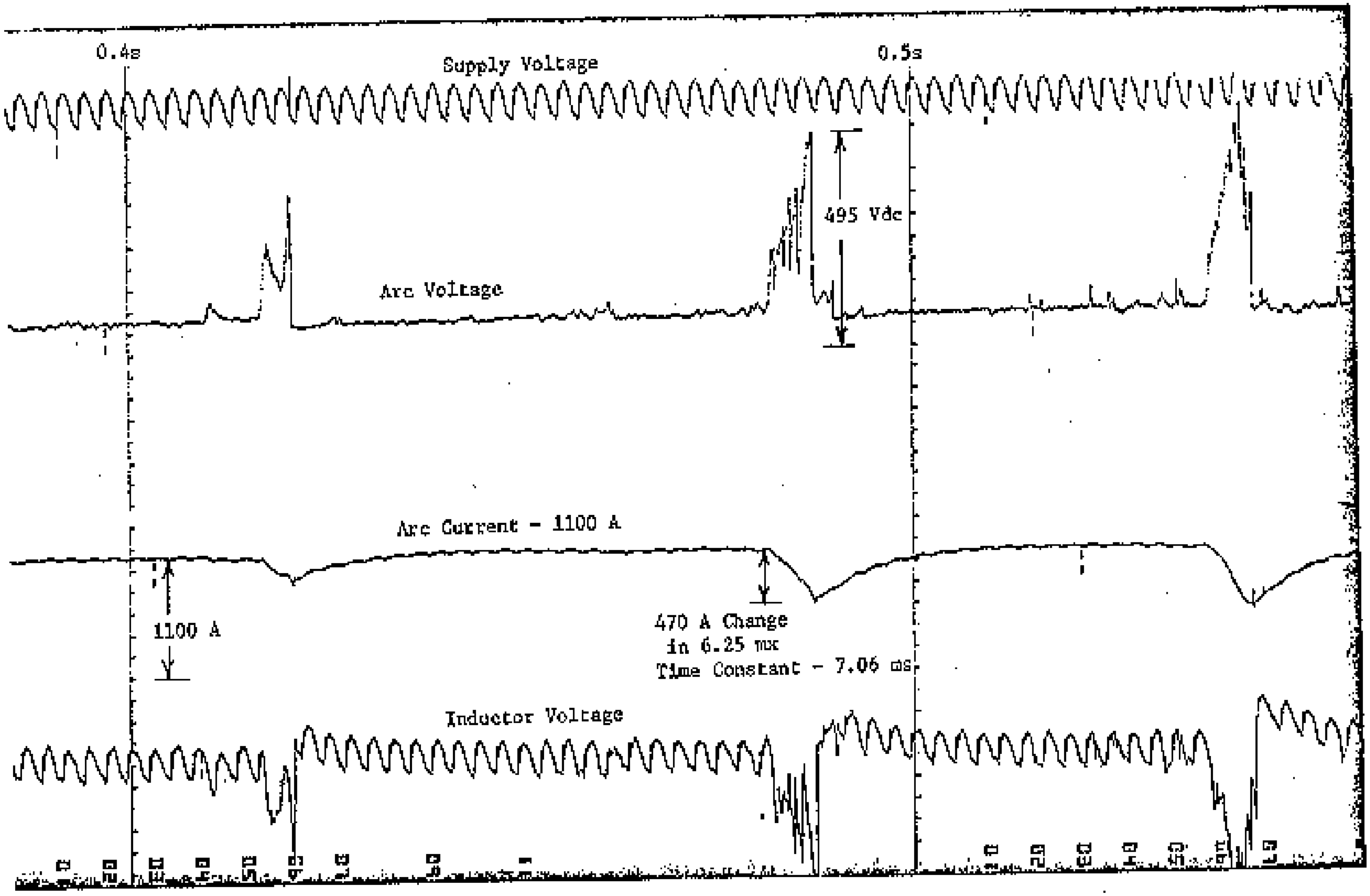


Figure 11