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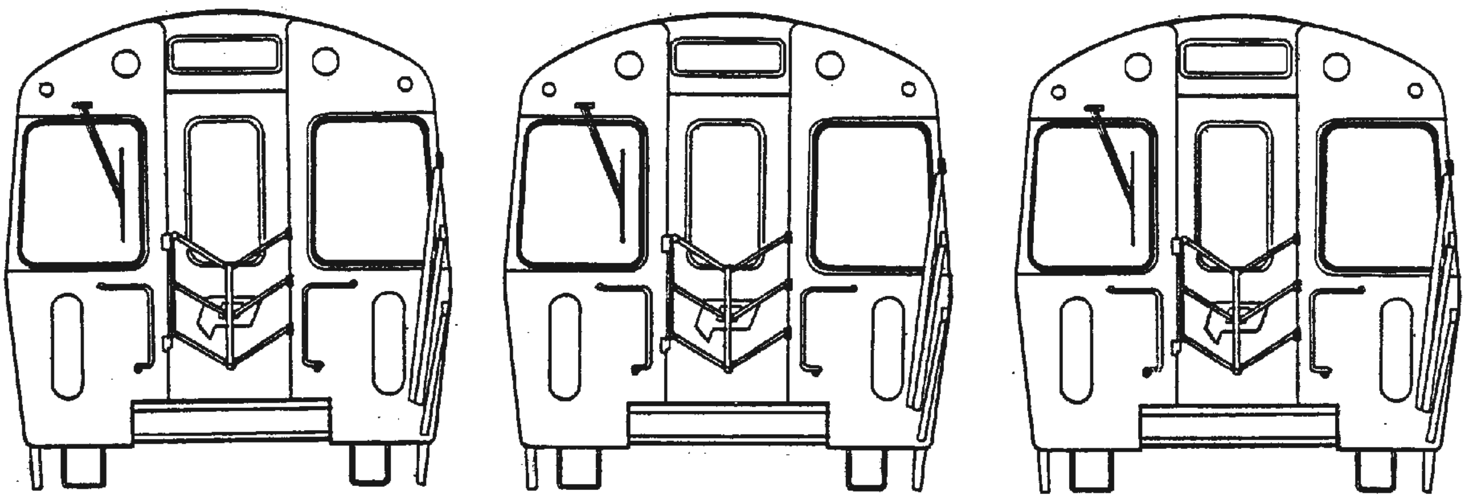
U.S. Department of Transportation
Urban Mass Transportation Administration

PATH Car Motor Controller Unit Investigation

Prepared by

Port Authority Trans-Hudson Corporation and
Parsons, Brinckerhoff, Quade & Douglas, Inc.

February 1985



UMTA Technical Assistance Program

NOTICE

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16. Abstract

This report describes the tests and analyses conducted to determine possible cause(s) of the motor controller fire on a PATH car. In addition, tests were made to determine possible cause(s) of the motor controller bolt erosion.

During the investigation, measurements were made of controller box temperature, voltages and currents while operating cars throughout the PATH system and also under stationary motor-plugging conditions. The measured parameters were analyzed and their causes and effects described in terms of their contribution to arcing. The report develops several fault trees and a description of arcing to show that this is the most likely phenomenon. The report also discusses the various components of the motor controller and their characteristics and performance. For this task, emphasis was placed on cables because the major fire load is the cable insulation.

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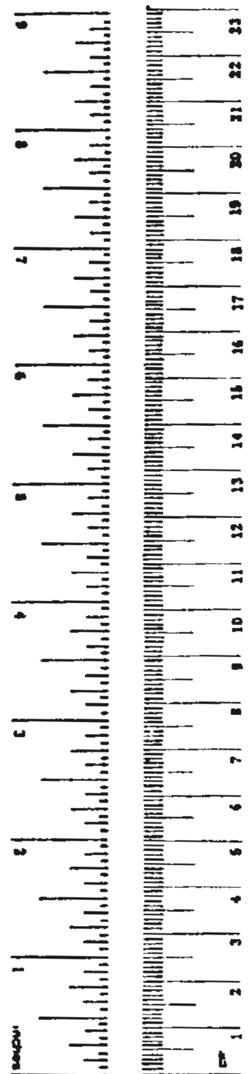
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

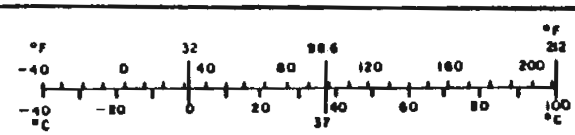
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



URBAN MASS TRANSPORTATION ADMINISTRATION

RESEARCH & DEVELOPMENT GRANT

PATH CAR MOTOR CONTROLLER UNIT INVESTIGATION

PROJECT NO. NY-06-0117

FEBRUARY 1985

PARTICIPATING AGENCIES

U.S. DEPARTMENT OF TRANSPORTATION
URBAN MASS TRANSPORTATION ADMINISTRATION (UMTA)
TRANSPORTATION SYSTEMS CENTER (TSC)
AMERICAN PUBLIC TRANSIT ASSOCIATION (APTA)
PORT AUTHORITY TRANS-HUDSON CORPORATION (PATH)
THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY
PARSONS, BRINCKERHOFF, QUADE & DOUGLAS, INC.

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This report was prepared by Vincent J. Petrucelly and Arvind Patel, Research and Development Division, Engineering Department, The Port Authority of New York and New Jersey. The section of the report by Parsons, Brinckerhoff, Quade and Douglas was prepared by Dr. John Marchetti. Contributions and recommendations from the PATH Car Equipment Division, Rail Planning Division, Way, Power and Structures Division, Transportation Division, Port Authority Engineering Department Design Division and Risk Management are gratefully acknowledged.

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PATH CAR MOTOR CONTROLLER UNIT INVESTIGATION

SUMMARY AND RECOMMENDATIONS

SUMMARY

This report describes the tests and analyses conducted to determine possible cause(s) of the Motor Controller fire on PATH Car 725. In addition, tests were made to determine possible cause(s) of the Motor Controller bolt erosion.

During the investigation, measurements were made of Controller box temperature, voltages and currents while operating Car 159 throughout the PATH system, and also under stationary motor-plugging conditions. The measured parameters were analyzed and their causes and effects described in terms of their contribution to arcing.

The most likely cause of the fire is an arc that contained sufficient energy to burn through metal parts and ignite internal combustible components. The report develops several fault trees and a description of arcing to show that this is the most likely phenomenon.

The report also discusses the materials of the Motor Controller, such as cables and components, and their characteristics and performance. For this task, emphasis was placed on cables because the major fire load is the cable insulation. Selection of cables and their overall performance weighting includes consideration of smoke emission, circuit integrity, toxicity, abrasion resistance, etc. Available information from the Transportation Systems Center (TSC) data bank, Factory Mutual publications and cable manufacturers literature was used to evaluate various cable insulating materials.

RECOMMENDATIONS

To control both the Controller box fire problem and the Controller box bolt erosion problem, it is recommended that all PATH Controller boxes should be insulated from the car body. In addition, a ground fault protection device is recommended, so that in the event that excessive ground currents are present, they can be quickly detected and interrupted. Further, establishment of optimum maintenance standards for ensuring a non-contaminated environment within the Controller box is recommended.

For the PATH system, smoke, circuit integrity and abrasion resistance are the most important cable parameters. It is recommended that field testing of Flexible Exane, BIW LS-3, GEXOL F and FX, and TEFZEL should be conducted prior to making a selection of one or more cables for future use in the maintenance of the Controller as well as other car equipment. Field testing of these cables would require at least a few years for evaluation.

PATH CAR MOTOR CONTROLLER UNIT INVESTIGATION

INTRODUCTION

A severe fire occurred in PATH PA Car 725 (Reference 1) on March 16, 1982. The cause of the fire was found to be electrical in origin but neither the initiating components nor the sequence of the fire progression could be specifically determined. The most severe damage was in the area of the Motor Controller, and it was most likely the source of the fire.

Immediately after the fire on March 16, PATH Vice President and General Manager, Francis A. Gorman, appointed a committee of Port Authority and PATH representatives to investigate every aspect of the fire and passenger evacuation. In its report, issued in May 1982, the Commitee listed findings and conclusions, and made recommendations. In accordance with the Committee's recommendation, PATH requested the American Public Transit Association (APTA) to establish a Task Force of representatives from transit systems and controller unit manufacturers. The task force met in January 1983. After reviewing the control group fire experiences of all the represented transit systems, it was apparent that controller fires present a hazard to all rapid transit systems. Each of the properties has instituted a program to rehabilitate controllers, but these programs vary depending on site-specific circumstances. Two working groups, on maintenance and design, were established by the Task Force. The efforts of each group are under way and a final report is in preparation. In addition, PATH received a grant from the Urban Mass Transportation Administration (UMTA) to conduct an investigation on the cause(s) of the Controller fire. The PATH proposal to UMTA is described briefly below. (The complete proposal appears in Appendix 9.)

PATH PROPOSAL

The work carried out under this contract consisted of five tasks, as follows:

Task 1 - Fault Tree Analysis, Temperature Measurement, and Failure Mode Effects Analysis (FMEA)

Task 2 - Coordination with Consultant

Task 3 - Material Investigation

Task 4 - Arcing

Task 5 - Administration

During the preliminary testing, information was developed that indicated that the test plan should be modified to include (a) voltages and currents in the "grounded"* or insulated Controller box under various operating conditions (such as accelerating or decelerating) and (b) use of a spark simulator in an attempt to induce arcing.

Tasks 1 and 4 were carried out by the Consultant, Parsons, Brinckerhoff, Quade and Douglas, Inc. and these are described in Appendix A and Appendices 1-5. Controller Operational Protocol, called for in Task 1, is presented in Appendix 8.

Tasks 2 and 3 were carried out by the Port Authority of New York and New Jersey. Task 3 is given in Appendix 6. Highlights of Tasks 1, 3 and 4 are given below.

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*"grounded" means connected to car body.

HIGHLIGHTS OF TASKS 1, 3, AND 4

Tasks 1 and 4 (Fault Tree Analysis, Temperature Measurement, Failure Mode Effects Analysis; Arcing)

Tasks 1 and 4 were planned with PATH approval by Parsons, Brinckerhoff, Quade and Douglas, Inc. (PBQ&D). The work was modified from that described in the Work Statement (PATH Proposal) as a result of actual test observations as well as various updated information on the Motor Controller. Specifically, controller temperatures were measured in one controller rather than four because the tests showed little variation in temperature in one car. Also, after controller box bolt erosion was discovered, it was deemed desirable to concentrate our investigation on the car that had a large amount of bolt erosion, on the basis that this car would be more likely to provide data on cause(s) of the fire. Accordingly, instead of several cars, only one car was tested for possible causes of the fire, and the test plan was expanded to include measurements of voltages and currents for both a "grounded" and floating motor controller box. Highlights of Appendix A are presented below:

The Controller box is supported by four 3/4 inch bolts. The box is coated with a sintered epoxy, about 0.030 inch thick, both inside and outside. Therefore, many of the PATH Controller cases are floating. If the Controller cases are connected to the car body, it is because the bolts fit snugly in the support holes and destroy the epoxy around the support holes. The Controller case potential on fleet cars is therefore indeterminate. Therefore, for the test, the Controller case for Car 159 was insulated from the car body, with provision for connecting to car body by means of relay-controlled shunts.

The test procedure consisted of operation of Car 159 throughout the PATH system while recording data on magnetic tape and a Visicorder Oscillograph. Results of the measurements are given below:

(1) Bolt currents of 1 to 2 milliseconds and as high as 90 amperes flow from the Controller box to the car body on the order of 18,000 pulses per day per car. These currents are induced in the box during interruptions of the collector shoe voltage when passing over a third rail gap, or by changes in propulsion motor current. These currents may be large enough to explain the observed bolt erosion over a period of years. There is no direct correlation between bolt erosion and Controller box fire. They are separate and distinct, although the method of protection for both may be identical or at least overlap.

(2) For the two-month test, no power arcs were observed within the main control group that could cause the fire that PATH has experienced.

(3) The use of a spark simulator (see Appendix 1, page 14), did not produce an arc, indicating that although the insulated Controller box stray capacitance results in spark-producing charging-discharging conditions, it does not in itself result in a high current arc.

(4) The eroded bolts were examined by a metallurgist. (See Appendix 5.) Results of the examination indicate that the bolts melted and resolidified due to electrical arcing. It would appear that

normal vibrational stresses present during operation of the car cause failure of the epoxy insulation and subsequent direct contact between the clearance hole and bolt. The current that produced melting may have been the observed 90 ampere, one millisecond pulses, and/or propulsion motor return currents. Further, the metallurgist states that:

"It would appear that initial torquing of the bolts was inadequate with respect to bolt pre-load. Normal service stresses were apparently greater than the bolt pre-load stress and mutual movement of the support package frame and support bolt occurred. This movement under normal service stresses caused failure of the epoxy insulator and subsequent electrical shorting. We suggest for your consideration that adequate torquing pre-loads be investigated with respect to the support package frame and insulator material."

Since none of the tests resulted in an arc sufficient to cause a fire, several reasonable hypotheses for fires caused by arcing have been developed that drew on Parson's test observations and some information developed by the University of Sherbrooke as reported in reference 12. (See Appendix 4 for Fault Tree Failure Mode Effects Analysis, and Appendix 7 for the tests conducted by the University of Shebrooke.)

Briefly, the Sherbrooke University tests show that an arc may be started by (a) overheating of adjacent cables of opposite polarity resulting in carbonization which encourages an arc to form between the cables even if the cables are not touching; (b) carbonization in general where voltages and currents are found that will encourage arcing, and (c) any condition equivalent to carbonization, such as grease, metal filings, moisture, dirty and tracked line switch mounting block, etc., which exists next to terminals or exposed conductors with sufficient energy to start and sustain an arc.

The two months of testing on Car 159 provided an understanding of what is happening on PATH cars with regard to the bolt erosion problem as well as the possible various causes and events leading to the Controller fire. The fault trees in Appendix 4 describe a number of reasonable hypotheses. For example, Figure 20 in Appendix 4 draws on the experience reported by the University of Sherbrooke combined with the charge-discharge phenomenon to provide a scenario where the sub-station breaker clears the fault. A similar scenario with severe arcing would exist if the sub-station breaker did not immediately clear the fault. This would occur if the arc currents were comparable to ordinary line currents so that the sub-station breaker remained closed for some time. (See "POWER ARCS" in Appendix 4.)

Temperature measurements and photocell readings did not reveal any unusual conditions in the Controller box.

The following discussion addresses some additional considerations not given in the PBQ&D report (Appendix A).

(a) PATH has experienced two major control group fires, both on PA3 cars. The dates of the fires were as follows:

Car 725 (PA3)	3/16/82
Car 761 (PA3)	12/19/82

Differences between PA1, PA2 versus PA3 are found in the Controller box coating (epoxy versus paint) and in spacing of components and cabling. Both PA3 cars were in service at least 10 years before the fires. Possible common cause(s) of the fires may be attributed to general wear, deterioration and accumulation of grease and metal particles.

(b) The PBQ&D report points out (Appendix A, Paragraph 2) that the "Henderson Shop personnel observed that the bolt nearest to the line switch usually shows the maximum erosion". A possible explanation for this observation is that a short duration arc develops from a power source (such as the line switch) and the arc current distributes itself throughout the box inversely to the box resistance. Since the bolt closest to the line switch would be in the path of the least resistance, it would show maximum erosion.

CONCLUSIONS OF TASKS 1 AND 4

The conclusions of the investigation follow.

(1) Bolt Currents of 1 to 2 milliseconds and as high as 90 amperes flow from the control group case to the car body on the order of 18,000 pulses per day per car.

(2) Normally, if the case were solidly connected to car body, there would be insufficient energy to cause the bolt erosion that has been experienced.

(3) The PATH car Controller boxes are not connected to car body and arcing at the bolts is possible by more than one means. Such arcing over a period of time (probably several years) can explain the bolt erosion.

(4) For the two-month test, no power arcs were produced within the Controller box that could cause the Controller fires that PATH has experienced. Such power arcs are not responsible for the bolt erosion problem since they happen too infrequently, wheras bolt erosion is a continuing phenomenon.

RECOMMENDATIONS OF TASKS 1 AND 4

(1) To control both the bolt erosion problem and the Controller box fire problem, all PATH Controller boxes should be insulated from the car body.

(2) A fast-operating line breaker, remotely mounted from the Controller box, should be installed on all PATH cars.

(3) The Controller box should be connected to the car body through a single lead* carrying a current detector that trips the remote line breaker.

As reported by Sherbrooke (reference 12), an arc may not operate the standard protecting devices. By adding a single lead, current detector, and fast operating line breaker (in addition to the standard line switch), any arcing to the Controller box will be detected and extinguished by the fast operating line breaker, even if the line switch fails to open.

In addition, even though the Controller box is insulated, no personnel shock hazard exists because the single lead maintains the box at car body potential.

The above recommendations are now under study and test. The final system will be designed by the car contractor for both PATH rehabilitated cars and new cars, with approval by the Engineer.

<u>TASK 3</u> (<u>Material Investigation</u>)

The Controller material investigation task examined three major areas as follows: Controller shell (box), components and wires/cables. The following factors play an important part in trouble-free operation of the Controller: spacing of the components, dissipation of heat generated within the Controller box, cleanliness of the Controller interior, maintenance of line switch contacts and other parts, and reliability of the arc-extinguishing mechanism.

* Note that the return propulsion motor currents do not pass through the single lead. Instead, they are routed through a separate return cable to the axle ground brush.

For this task, emphasis was placed on cables because the major fire load is the cable insulation. Selection of wires and cables would involve consideration of smoke emission, toxicity, circuit integrity, flexibility, flammability, water and oil resistance, abrasion resistance and corrosivity. Researchers have made studies to evaluate these parameters and establish rank order for some of the cables. However, more work in this area remains to be done. Selection of the wires/cables for the Controller would involve the following steps:

(1) Use the information published by research organizations and manufacturers.

(2) Establish priority weights for the above parameters.

(3) Consider design features of the Controller.

(4) Consider operating environment and degree of maintenance.

Originally, PA3 controllers used Hypalon cables, which was replaced by neoprene until about 1982. Presently PATH uses EXANE cable for replacement/repair purposes.

It is recommended that PATH conduct field tests prior to final selecton of Exane, BIW LS-3 GEXOL F (and FX), and TEFZEL, for future use in the maintenance of the Controller and other car equipment. Since the field testing would require an extended period, the results would not be available for the current car rehabilitation program. Further, establishment of optimum maintenance standards for ensuring a non-contaminated environment within the Controller box is recommended.

The complete Task 3 appears in Appendix 6, under "Material Investigation".

APPENDIX A

PATH RAIL VEHICLE PA CAR MOTOR CONTROLLER STUDY

PATH Rail Vehicle PA Car Motor Controller Study

**Parsons Brinckerhoff
Quade & Douglas, Inc.**

Parsons
Brinckerhoff

June 1984

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EXECUTIVE SUMMARY

Path car 159 was instrumented to determine the cause of motor controller bolt erosion discovered in late 1983, a severe problem that affected 90 percent of the PA car fleet. Additionally, the test program provided a further understanding and possible means of preventing control group fires since there existed the possibility that the two phenomena were somehow linked.

No linkage was found. In two months of testing, adequate data were obtained to show that bolt erosion is a continuing long-range problem due to the additive arcing of very short pulses of current. During the entire test period, no currents were found that might have led to a control group fire, despite considerable electric changes and fault simulation to a normally operating control group.

Althought not linked, the method of protection for both is identical. The control group must be insulated from the car body and a high-speed breaker must be added that is remote from the main group, with controlled bonding to the car body for use with a detection device.

1. INTRODUCTION

In mid-1983, PATH expressed concern about the serious bolt erosion taking place on the four bolts used to attach the Westinghouse cam controllers to the car body. These 3/4-inch-diameter bolts were, in many cases, practically eroded by what appeared to be electrical arcing.

PATH started a program of bolt inspection and replacement for the entire fleet. It soon became apparent that more than 90 percent of the cars showed evidence of this erosion.

The question arose whether there was any correlation between the bolt erosion problem and some serious controller fires that had occurred. To determine if a correlation existed, it was necessary to measure the magnitude of these currents, when and why they occurred, and to determine a solution that would prevent the bolt erosion and also reduce the likelihood of cam controller fires.

Parsons Brinckerhoff was retaianed by PATH to investigate this bolt erosion problem. A detailed investigation was begun on March 27, 1984 and completed on June 21, 1984. This report describes the tests performed, the conclusions reached, and the recommendations made.

2. INSTRUMENTATION DESCRIPTION

Car 159 was chosen as the test vehicle because the bolts found on this car were very severely eroded. Three of these bolts are shown in Appendix 1, Figure 13. The fourth bolt showed no erosion. Variations in erosion among the four bolts may be a random occurrence. However, Henderson Shop personnel observed that the bolt nearest to the line switch usually shows the maximum erosion. Designating this bolt as number 1, the remaining bolts are numbered 2, 3, and 4 in a counterclockwise direction when looking down on the main control group (see Figure 15).

The test plan was to insulate the main control group case from the car body and then make a connection around each corner of the case to replace the connection normally made by the bolts. This additional connection included a 150-ampere shunt and a 200-ampere magnetically operated switch. By this means, the case could either be floated or, by closing the switch, the current that would have passed to the car body through that particular bolt could be measured.

The mechanical and electrical arrangement is shown in Figure 16. The electrical path is simple: currents through the shunt and switch flow in opposite directions to cancel inductive effects. To achieve this, the connections to, and the size of, the switch had to be as equal as possible to the size of the shunt. Figure 16 shows them to be equal. In fact, they were made very nearly equal through the use of a Cutler-Hammer solenoid-operated aircraft switch with the profile required.

Normally bolted 1 inch below the car body, the control group case was lowered to 3 inches below the car body to provide room for the added supports and insulators.

The four 3/4-inch bolts that connect the main group to the car body do not guarantee that the control group case is solidly grounded* through the bolts. The Westinghouse control group case is coated with a sintered epoxy, approximately 0.030-inch thick, both inside and outside. Therefore, it is possible that many of the PATH control group cases are floating. If the control group cases are grounding, it is because the bolts fit snugly in the support holes. The epoxy on the inside of the support holes can be destroyed by the sharp edges of the bolt threads. The epoxy on the edges of the holes is weak and chips off easily. Any lateral forces against the bolts also aggravate the situation. The control group case potential on fleet cars is, therefore, indeterminate. It is neither positively grounded nor positively insulated and may shift from one condition to the other throughout a day's running.

* "grounded" is used throughout Appendixes A to 5 to mean "connected to car body."

As shown in Figures 14 and 15, the instrumentation measured the following parameters:

a. Total propulsion current.
b. Via photocells, the light caused by arcing from the line switch, J and S switches, and any cam controller contacts.
c. Bolt currents 1, 2, 3, and 4.
d. Temperature within the control group case.
e. Contral group case voltage.
f. Motor voltage.
g. Temperature of critical devices within the control group using stick-on temperature indicators close to the contact tips.

The photocells were added as a precautionary measure since it was not certain that switching around of the case potential might not cause an arc within the case that could not be extinguished.

A K-car line switch, controlled by an inside the car manually operated switch, was installed outside the control group. This switch could be opened in any emergency that might be indicated by the photocell light or total current.

3. TEST PROCEDURE

The test procedure consisted of running car 159 on the entire PATH railroad, recording all functions on an FM magnetic tape recorder at 15 inches/second, and later playing the data back into a six-channel Brush Recorder at 15/16 inch/second, where it could be viewed and analyzed. By this means, frequencies 16 times higher than the frequency limit of the paper and ink recorder could be seen.

A Phillips Analog 14 FM recorder with built-in compensation cards for playback and recording at all speeds was used. Recording and playback speeds could therefore be changed easily. The characteristics of the recorder are:

Tape Speed	Bandwidth	Playing Time
30 inches/second	0-10,000 Hz	11 minutes
15 inches/second	0- 5,000 Hz	22-1/2 minutes
3-3/4 inches/second	0- 1,250 Hz	1-1/2 hours
15/16 inch/second	0- 312 Hz	6 hours

The Analog 14 is a cassette recorder that uses 1/2-inch-wide computer-grade tape. Two cassettes were available, giving a total record time of 45 minutes with one cassette change.

An expansion ratio of 16 to 1 was chosen as a reasonable compromise between seeing some high-frequency inputs and analysis time. At a 16-to-1 ratio, 4 hours of train time require 64 hours of playback time for viewing the data before analysis.

The Analog 14 has a playback head just behind the record head that reads from the tape what has just been recorded. This playback feature is available on all 14 channels and was used to check the operation of the data channels.

Although an expansion ratio of 32 to 1 was available, it was not used because it would have lengthened the available data-taking time and prolonged the analysis time unnecessarily. Expansion in time means, for example, that a 3,200-Hz signal in real time could be slowed down to 200 Hz. The reverse process (compression) was also available. A 200-Hz signal can be compressed to 3,200 Hz.

A storage cathode-ray tube permitted the viewing of data flashes as they were being recorded.

Slight deviations from the original test plan were made as necessary. The only significant change was the removal of a common car ground for the bolt current circuits because it was more realistic to follow as closely as possible the path the current would take on a noninstrumented car.

4. DATA TAKING

On April 24, 1984, the first run around the Henderson yard was made to permit instrument adjustment and calibration. On April 25, 1984, with all instrumentation operating, an exploratory run of the entire railroad was made using what was to be the normal test consist -- a seven-car train carrying no passengers. With two cars cut out to simulate loading, car 159 -- the instrumented car -- operated as a "heavy car" by means of a bypass on the load weigh circuit. The test run included Hoboken, 33rd Street, the World Trade Center, and Newark.

It soon became evident that the currents involved were in the kilocycle range and that the expansion of 16 to 1 placed them beyond the writing capability of the Brush Recorder. At 1,000-Hz, the Brush Recorder would have an input of 62.5 Hz and have a 3-dB recording loss. The tests continued for several days using the Brush Recorder in the expectation that there would be sufficient low-frequency components to permit recording. When this did not occur, use of the Brush Recorder was discontinued. A four-channel visicorder was obtained and used as the instrument of final viewing. Now the FM recorder became the limit. At 5,000 Hz, the expansion dropped to 313 Hz, well within the capability of the visicorder galvanometers (estimated limit 2 kHz).

The visicorder datagraph limitation of a four-channel review did not create a problem. Sufficient running had been done to determine that the temperature, photocell data, and thermocouple data were slow-moving functions that did not need the passband of the FM recorder. The four bolt currents had been reduced to two, namely bolt 1 and bolt 4, by virtue of double ending the coaxial connections at the shunts. From May 1 to the last run on May 23, only three channels were used, the two bolt current channels and total current.

4.a. Photocell Data

The photocells were installed to observe the amount of light emitted by the various flashing contactors and to detect a fire within the control group. The sensitivity of the photocells was adjusted so that a 60-watt bulb at the end of the control group case would give a full-scale indication on the digital voltmeters at the other end of the case.

The light output within the box was first recorded on two of the Analog 14 channels. Recording was discontinued when very little flashing occurred. The output of the digital voltmeters was monitored visually throughout the testing period. No light was noted from the line switch (it operates within an enclosed arc chute). The J and S switches produced an output that was about 10 percent of full scale.

4.b. Temperature Data

As in the case of the photocell data, the thermocouple data were also recorded on the Analog 14. The voltage output of the copper constantan thermocouples was amplified by a factor of 100 in two channels of the isolating amplifier and then recorded on the 0.1-volt scale of the Analog 14. Here again the data were found to be slow moving and the recording was discontinued in favor of direct viewing on a digital readout device that accepted the output of the thermocouples without amplification.

In addition to temperature data from the thermocouples, the following units within the main group were marked with temperature indicators of 306°F and 263°F:

Line Switch
J Switch
S_1 and S_2
Power brake control (PBC) contactor

In no case were the temperatures exceeded.

The temperature within the main control group rose about 40°F above ambient after a 3-hour run. The temperature rise seems reasonable and actually may help to keep the main control group dry.

When these tests were begun, the control group case-to-ground resistance was measured as 300 megohms with the four bolt switches open (see Figure 15). This measurement was the leakage across the four pink support insulators. The resistance from +600 volts to control group case, essentially the leakage resistance within the main group, was 200 megohms. The high leakage resistance of a reasonably dirty control group was quite surprising. Even more surprising, after two days of rain, was that the resistance of the pink insulators dropped from 300 megohms to 30 megohms and the dirt within the control group maintained its value of 200 megohms, indicating that the inside of the main control group case stayed dry during the damp weather.

4.c. Motor Voltage

The original test plan included the measurement of motor voltage to determine if bolt currents were a function of car speed. No such correlation was found and the recording of this function was discontinued.

4.d. Bolt Current Data

From the early runs we concluded that:

a. Most bolt current was evident from Journal Square to Newark. The reverse downhill run provided little current through the bolts.

b. Relatively high frequency currents only were visible on a storage oscilloscope with a 10-megacycle passband (storage writing only 2 kHz).

The efforts were therefore concentrated on runs from Journal Square to Newark. Figures 1 through 10 are excerpts from one typical run recorded at 15 inches per second on magnetic tape, played back at 15/16 inch per second, and recorded on a visicorder with paper running at 0.1 inch per second. The following numbers apply to the trip from Journal Square to Newark shown on Figures 1 through 10:

Total trip time	=	564 seconds
Length of magnetic recording	=	705 feet
Playback time to visicorder	=	9,024 seconds
Length of visicorder record	=	75.2 feet
Playback time	=	2.5 hours

5. BOLT CURRENT ANALYSIS

In planning this test program, it was expected to detect bolt currents of appreciable energy content that would clearly explain the heavy erosion that had been observed on the bolts. Arcs from various energized portions of the main control group to the case and thence via the bolts to the car body were visualized. A few heavy currents, but not too many, were expected.

In two months of instrumented testing, the observations did not confirm the preconception. Instead, all that was recorded was a very large number of currents of fairly high amperes but of 1-millisecond duration or at the most 2 milliseconds.

These findings raise the following questions:

a. Can the total energy available from these short pulses explain the degree of bolt erosion observed? (See paragraphs 5.a and 5.b and Appendix 2.)

b. Are the high currents observed (as high as 90 amperes) real or are they errors of instrumentation? (See paragraph 7).

5.a. Significance of Measured Currents If No Arcing Is Assumed

A single recording taken between Journal Square and Newark was analyzed in detail.

1. 1,008 pulses of varying amplitude were counted and all were assumed to be of 0.001-second duration.

2. By taking into account their varying amplitudes, a graphic integration was made to arrive at the following number:

40 average ampere-seconds/bolt/trip

PATH operating personnel estimated that a car may make as many as 18 trips/day but also as few as 2 trips/day. A factor of 9 was arbitrarily assigned to arrive at the average number of trips per day.

40 x 9 = 360 average ampere seconds/bolt/day

or

36 average ampere-hours/bolt/year

Bolts in firm contact with the car body and the control group case could pass this electricity (coulombs) with absolutely no disfiguration of the bolts and with totally negligible heating. This was the condition under which the data were taken.

From this analysis, the measured currents are of no consequence in explaining bolt erosion and are not significant in explaining the control group fires that have obtained.

5.b. Significance of Measured Currents If Arcing Is Assumed

At this point in the test program, it was realized that the grounding of the control group case may not be solid and that the potential for arcing between the control group case and bolt is real.

The decision was to build contacts that would open and close around the bolt positions at random in order to simulate as closely as possible a normal uninstrumented car that would have an enclosed arc in the interface between the bolt and the control group case.

As a preliminary step in this investigation, an adjustable spark gap inside the car was provided at the instrumentation position, and through it the control group case was tied to ground. The gap spacing was adjusted to about 0.002 inch. An oscillation of the control group case voltage between ground and +250 volts resulted. An observation with a 25-kilovolt 100-megohm probe showed that the control group case capacitance was charging from +600 volts to a case voltage determined by the relative leakage resistance of 200 and 300 megohms. It then discharged through the arc to ground. When the arc extinguished, the process was repeated.

Clearly, if an oscillation of this nature could result with such high-leakage resistance within the group and such low control group case to ground capacitance (the case had been lowered from the car body an additional 2 inches), it was necessary to determine what it might be in a standard car and with a more reasonable internal leakage resistance. The leakage resistance was set at 0.5 megohm and the normal case capacity was simulated with added capacitance. The result was a much stronger spark and voltage swings of the case from +600 to -200 volts. At 200 volts below ground, there was a voltage resonance phenomenon that could not be localized. Details are provided in Appendix 3.

Consider the 1,008 pulses of 0.001-second duration and assume that they do not tie solidly to ground but rather impinge on the bolt in an arc with 10 volts across the arc.

There are 40 average ampere-seconds/bolt/trip (Appendix 2):

$$40 \times 10 = 400 \text{ watt-seconds/bolt/trip.}$$

There are approximately 1,000 pulses/bolt/trip:

$$\frac{400}{1000} = 0.4 \text{ watt second/pulse}$$

Each pulse is of 0.001-second duration:

$$\frac{0.4}{0.001} = 400 \text{ watts/pulse}$$

The 400 watts is a considerably high rate of doing work, particularly when it impinges on a small section of the bolt at a time.

The above calculation is somewhat optimistic. Not all of the current pulses will reach the bolt through an arc. It is, nonetheless, a clear indication that bolt erosion may be an electrical arcing phenomenon that could well erode the bolts over a period of time.

A secondary conclusion may be drawn at this point, namely, that there is no correlation betweeen bolt erosion and control group fires. They are separate and distinct, although their cures may be identical or at least overlap.

The oscillatory arcing described in Appendix 3 is energy that is added to the estimate of 400 watts/pulse.

6. BOLT CURRENT CATEGORIES

Bolt currents can be divided into five basic categories:

1. Power arcs from +600 volts to control group case.
2. High-frequency pulses associated with current changes di/dt.
3. High-frequency pulses associated with third-rail gaps or shoe arcing.
4. Locally generated currents in the vicinity of the main control group.
5. Currents due to charging and discharging the control group case capacity.

6.a. Power Arcs from +600 Volts to the Control Group Case

This bolt current category is the only one that can be associated with control group fires although it occurs infrequently. A large percentage of power arcs occur on the load end of the line switch and are cleared by the line switch. The line switch is limited to being reset three times. If the arc appears on the high side of the line switch, or at the switch contacts, then nothing will clear the fault unless the car happens to be close to a power substation whose breakers may clear the fault. In some cases, a faulty blowout coil or an improperly fitted arc chute prevents the line switch from clearing the fault and an internal electrical fire may occur in the main group. In serious cases, the fire, aided by compressed air, continues to burn even though the electrical arc may have been extinguished. When a power arc occurs, it contributes to bolt erosion. It is not, however, the main cause of bolt erosion. Bolt erosion has been much more widespread relative to power arcs. More than 90 percent of the fleet has been seriously affected. Bolt erosion is a slow, continuing, phenomenon that occurs independently of the more violent but infrequent power arc.

6.b. Bolt Currents Associated with di/dt

Appendix 1, Figures 1 through 10, give evidence of bolt currents that are associated with changes in propulsion currents. Of 1,008 currents monitored, 305 were those that occurred with changes in propulsion current, either as large steps or the smaller steps of resistance change by the cam controller. Steps up in current gave larger responses than current reductions. The difference can be attributed to the fact that dynamic brake current was not monitored.

The recording equipment was bilateral, i.e., it recorded both positive and negative currents. The record shows that practically all of the currents are positive. This means the currents were flowing from the control group case to car body and negative return.

It has been noted by many observers that the bolt hole in the control group case, although it shows evidence of the arcing, does not lose as much metal as the bolts. This observation substantiates the hypothesis that arc currents are involved. In a dc arc, metal is transferred from the negative electrode to the positive electrode. Therefore, one would expect the bolt to give up material and the case to build it up. Pender's Electrical's

Engineers Handbook (4th edition, Page 3-25) states: "An arc is an incandescent vapor bridge consisting of material impelled from a negative to a positive electrode." Pender's 2nd edition, page 53, has an interesting description of the use of a dc arc by the Pennsylvania Railroad.

"An application of this was made by the Contractors of the Pennsylvania Railroad (East River tunnel) who used a carbon rod one foot long and one inch in diameter, bolted to a copper rod, provided with an asbestos shield, one foot in diameter. The operators worked with asbestos masks and aprons and dark-colored eye glasses.

"Direct current was used, the carbon electrode being connected to the positive and the steel to be cut to the negative feeders. The current was varied by means of water rheostats, the voltage at the tool varying between 45 and 60 volts. The current varied from 250 to 400 amperes per tool for burning off rivet heads and light section plates and from 600 to 800 amperes for burning plates 4 inches thick. The best results were obtained with 40 volts, 600 amperes and a 1/2 inch to 3/4 inch arc. A fair day's work (8 hours) removed 300 rivet heads, although a record of 350 was reached. In the same time 4 feet 6 inches of 4 inch plate could be burned off."

6.c. Bolt Currents Associated with Third-Rail Gaps or the Arcing of Collector Shoes

These bolt currents are really quite similar to di/dt currents. The only difference is that current is cut and then reapplied as a result of third-rail conditions rather than by command of the motorman. They exceed in quantity the disturbances associated with normal running of the train and are sporadic in their timing. The disturbances encountered in crossing the Hackensack River Bridge is a perfect example of this type.

6.d. Locally Generated Bolt Currents

On the first day's run, it was observed that, with all bolt switches open, approximately 50 volts was developed between bolt 1 and bolt 4. When the bolt switches were closed, the voltage dropped to 15 volts. This indicates that a voltage was generated across the length of the control group case. Later recordings substantiated this hypothesis because currents are seen to leave the case on one end and return on the other end. This is due to a locally generated voltage in the control group case. All of the heavy current leads that enter or leave the case are clamped to the underside of the top steel plate. The circular lines of magnetic flux around these conductors can easily cut longitudinal filaments of this cover. This induces a voltage along the case that, once it enters the car body, must return to the case with opposite polarity and simultaneous timing.

There are not many of these currents (122 out of 1,008), and they seldom are greater than 30 amperes. Insofar as bolt erosion is concerned, they are not very important.

6.e. Bolt Currents Due to Charging and Discharging Control Group Case Capacity

Bolt currents of this type exist, but depend entirely on the existence of an arc to be effective. This type of arc was produced on a spark gap brought inside the car body on a very long lead. In a normal car, the spark occurs right at the interface of the case and bolt and is expected to be much more vigorous, not only because no long leads would be involved but also because the spark would be operating in a closed environment with the arc gases and vapors self-contained. Appendix 3 discusses this condition in greater detail. At the present time, this type of bolt current is important, particularly when a dirty main group has been subjected to considerable moist weather and its leakage resistance is at approximately 10,000 ohms. High rates of capacity charge can also take place where a carbonized path of low resistance exists in some insulation of the group. The energy involved is always $1/2\ CE^2$, but the rate at which it is delivered to the bolts can become very high.

7. DATA VALIDATION

The significance of the current passing during an arc was discussed in paragraph 5(b). Until now it has been assumed that the measurements taken were valid. During the testing on car 159, the validity of the data being acquired was continually checked. However, when the measurement of 1-millisecond pulses is involved there is always room for error. Without the compression and expansion capabilities of the magnetic recording, the data could not have been obtained at all. Furthermore, it is certain that frequencies higher than 5,000 Hz are available under the car and that the Analog 14 had insufficient bandwidth to record them. The following precautions were taken:

1. All recording instruments were floating and tied to the shunts in order to prevent ground loops.

2. Isolating power transformers with electrostatic shields were used on the recorders and oscilloscope.

3. Single-ended connection to the shunts was changed to a double-ended connection so that an electrostatic shield existed on both the information wire and the reference wire.

4. Shorts at the amplifier inputs reduced the amplitude of the data by about 40 percent, indicating that the shunt was acting as a low-impedance source.

5. The possibility of the leads picking up stray signals was verified at the Henderson Shops. The information leads were removed from the shunt and shorted together. No signal was transmitted through the shorted leads when the motors were plugged. See Figure 12, Appendix 1.

It is difficult to take measurements of the type reported herein on a rapid transit car with all currents returning to the rails through undetermined paths in the car body, and switching direction rapidly as a function of which collector happens to be making the best contact at the time. If a future test were to be made, a separate set of coaxial signal cables should be attached to a single terminal of the shunt (the reference side) and this signal should be recorded on a separate channel of the magnetic tape recorder. Then, in reading the data, the difference between these two would be the true voltage across the shunt. Another recommendation would be to change the shunts from 150 amperes to 10 amperes for a 50-millivolt output. The heavy currents of short duration would do no harm, but the signal-to-noise ratio would be improved.

8. CONCLUSIONS

1. Bolt Currents of 1 to 2 milliseconds and amperes as high as 90 flow from the control group case to the car body on the order of 18,000 pulses per day per car.

2. Normally, if the case were solidly grounded, there would be insufficient energy to cause the bolt erosion that has been experienced.

3. The PATH car control groups are not grounded and arcing at the bolts is possible by more than one means. Such arcing over a period of time (probably several years) can explain the bolt erosion.

4. This two-month test observed no power arcs within the main control group that could cause the control group fires that PATH has experienced. Such power arcs are not responsible for the bolt erosion problem since they happen too infrequently, whereas bolt erosion is a continuing phenomenon.

9. RECOMMENDATIONS

1. To reduce and/or control both the bolt erosion problem and the main control group fire problem, all of the PATH main control group cases should be insulated from the car body.

2. A fast-operating line breaker, remotely mounted from the main control group, should be installed on all PATH cars.

3. In order to detect the escaped current that causes erosion of the tie bolt and/or main control group fires, the insulated main control case should be connected to a grounded single lead. A current detector should be magnetically coupled to the single lead and electrically connected to a reed relay that actuates the high speed circuit breaker. The high speed circuit breaker is to respond when the escaped current exceeds 125 amperes for a duration longer than 500 milliseconds. Both the current amplitude and duration should be adjusted to minimize false alarms.

If these recommendations are adopted, bolt erosion cannot take place since no arcing can occur with a solidly grounded control group case. The grounded case is still capable of accepting fault currents due to a number of possibilities -- open arc chute, destroyed blow-out coil, or screwdriver accidentally left in the main control group -- however, it cannot cause a control group fire that goes undetected since a detection circuit is provided and a remote breaker can clear the fault. An ancillary advantage of using a fast operating breaker to clear the fault on the car is that the railroad will not be tied up by tripping a station breaker as has occurred in the past.

These recommendations are the same as those made independently by Mr. Tom Di Genaro of the Port Authority in a memorandum to Mr. William Fellini dated February 21, 1984. These recommendations have been included in Parsons Brinckerhoff's suggestions for the PATH rehabilitation program.

Preliminary planning for this investigation included a task of instrumenting four cars as part of this test. This planning was based on an assumption that temperature increases generated by heat-producing components within the main control group could be a significant factor in causing the fires that had occurred.

After installation of heat-measuring instrumentation in the first car and collection of temperature data, it became obvious from the lack of heat build-up that hot spots in the main control group were not contributing to this problem.

Based on this early test data, it was decided to expand the scope of the investigation and extensively instrument one car with shunts, visicorder recording equipment, an oscilloscope, and spark-generating equipment in order to run an in-depth study, covering a larger search of possible causes of these fires.

APPENDIX 1

FIGURES 1 THROUGH 17

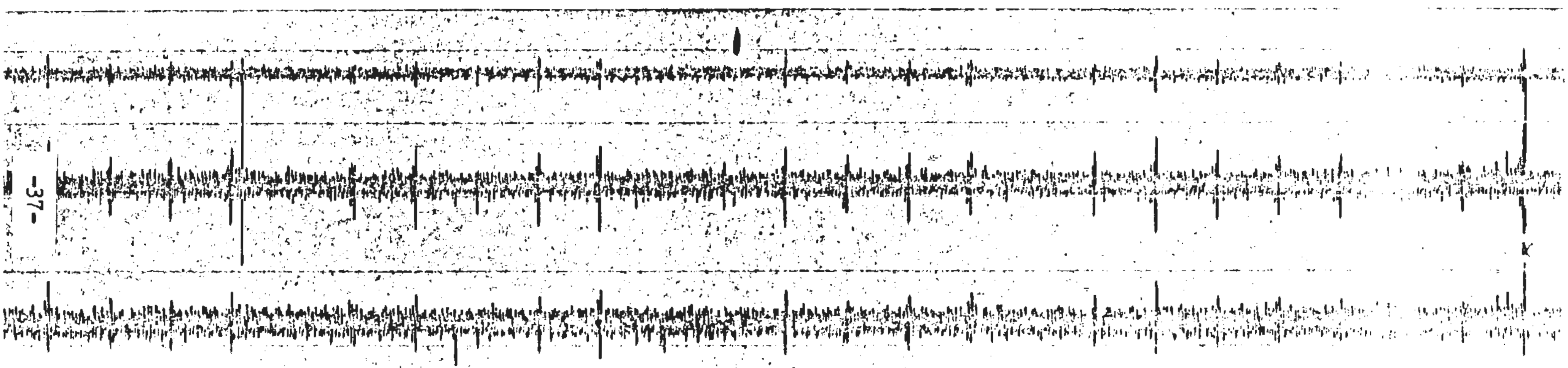

FIGURE 1 - GENERAL NOISE LEVEL OF BOLT CURRENTS

LEAVING JOURNAL SQUARE FOR NEWARK

(See Figure 2 for trace details)

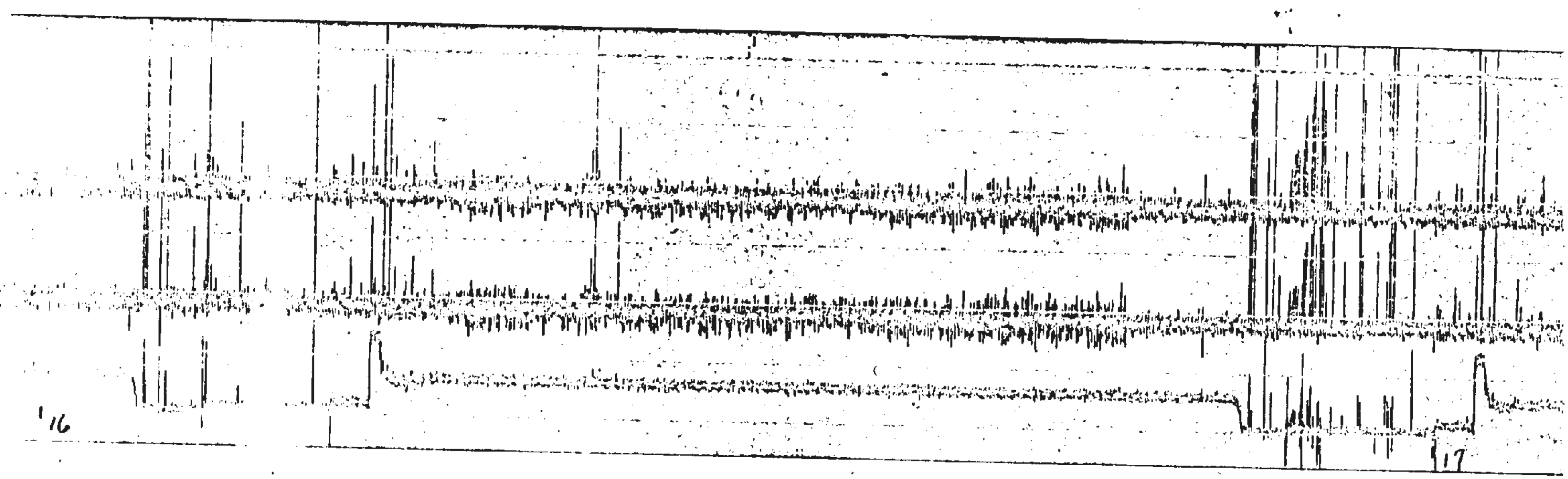

FIGURE 2 - 123 SECONDS OUT OF JOURNAL SQUARE
BOLT CURRENT VS. PROPULSION AMPERES
AT HACKENSACK RIVER BRIDGE

Upper trace - Bolt 4 current (one inch = 60 amperes)
Middle trace - Bolt 1 current (one inch = 60 amperes
Lower trace - Propulsion amperes (one inch - 700 amperes)

- Positive bolt currents indicate currents from main group to ground

- Time scale - one inch = 0.625 seconds in real time

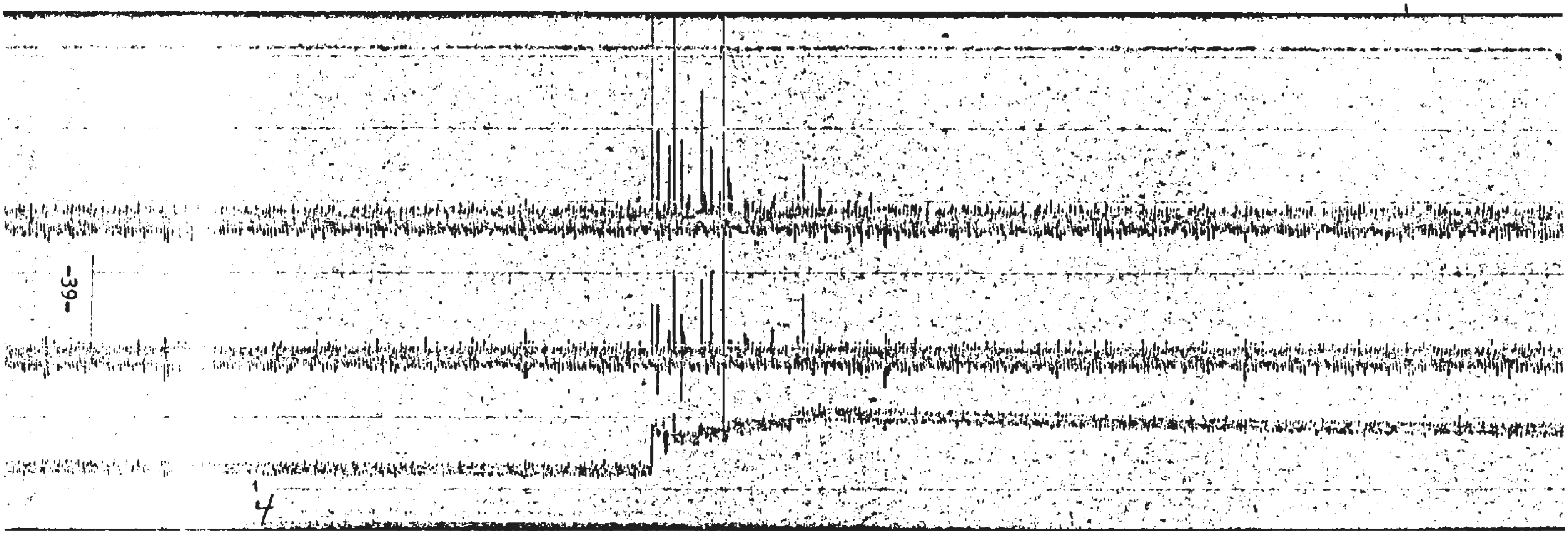

FIGURE 3 - 32 SECONDS OUT OF JOURNAL SQUARE

BOLT CURRENTS VS. PROPULSION CURRENT

FOR AN APPLICATION OF POWER

(See Figure 2 for trace detail)

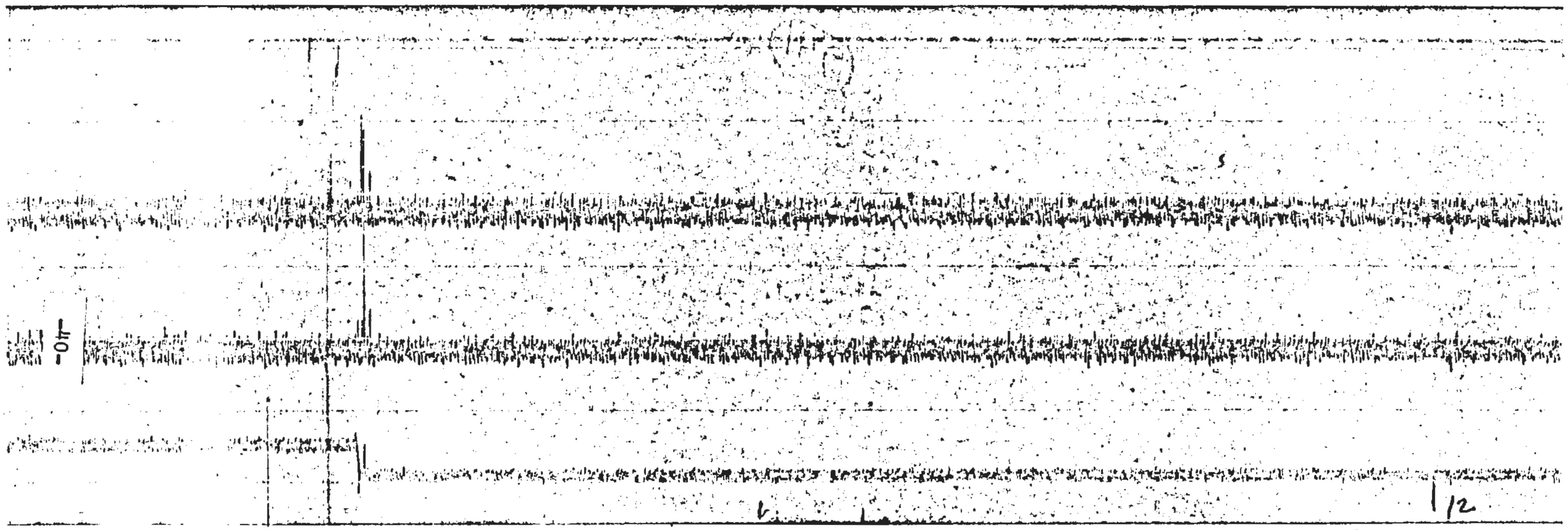

FIGURE 4 - 87 SECONDS OUT OF JOURNAL SQUARE

A TYPICAL POWER REDUCTION

(See Figure 2 for trace details)

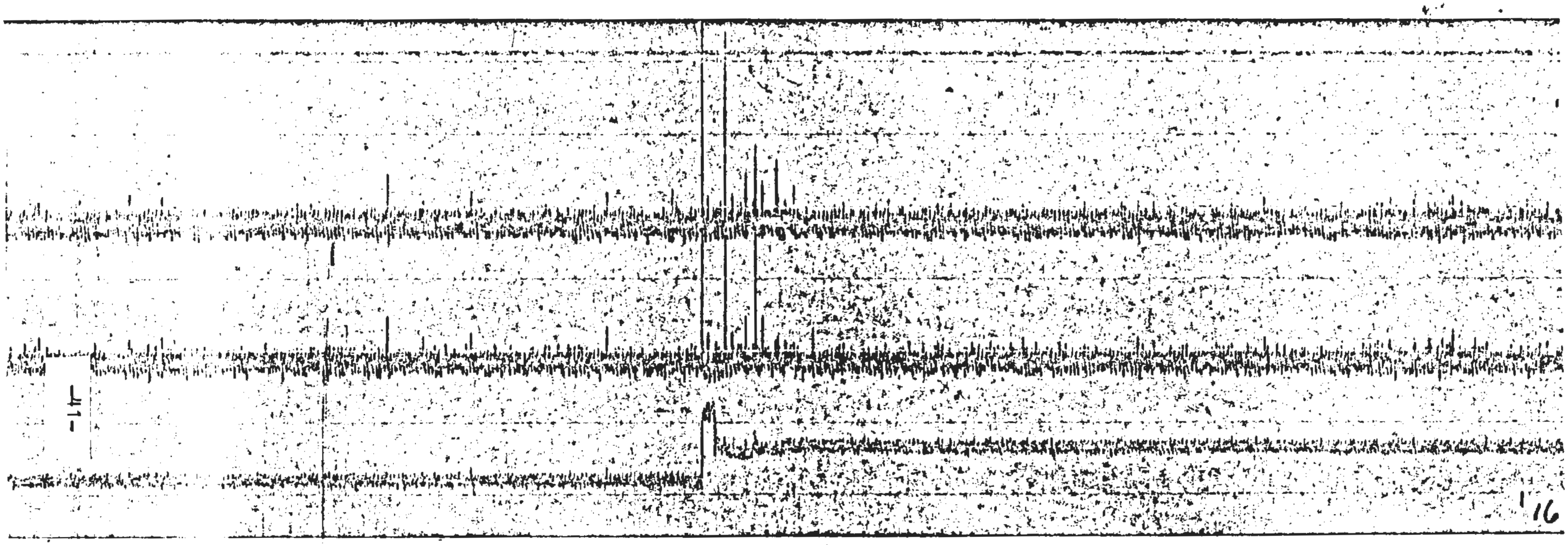

FIGURE 5 - 117 SECONDS OUT OF JOURNAL SQUARE

A TYPICAL POWER APPLICATION

(See Figure 2 for trace detail)

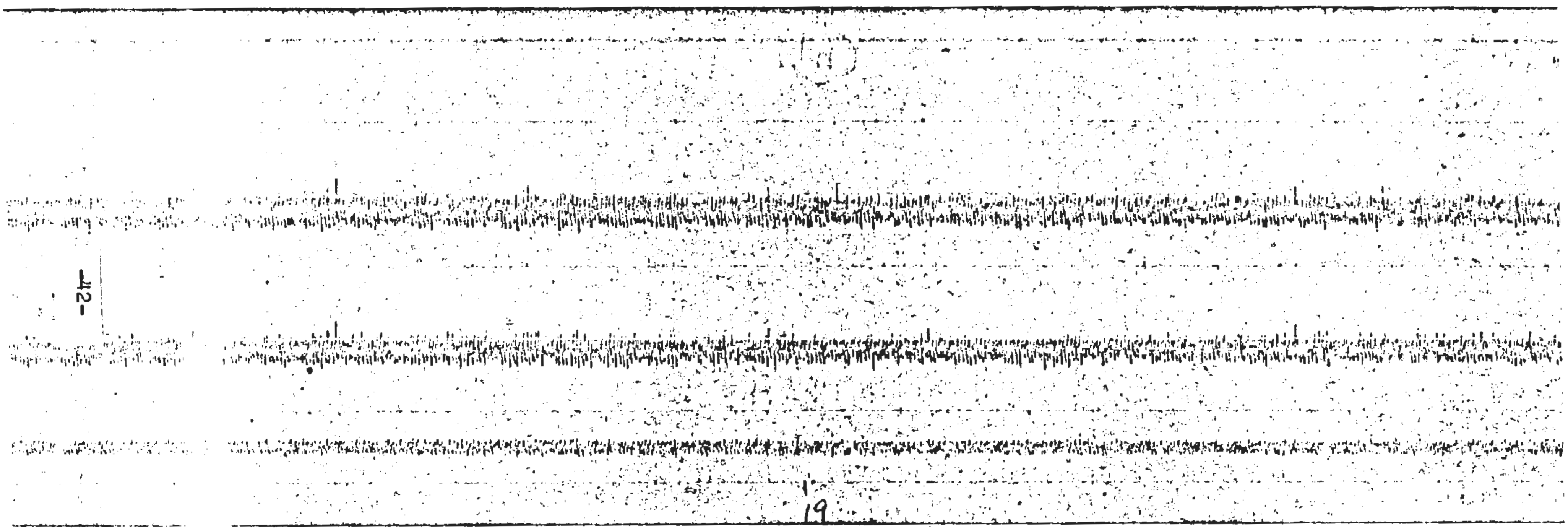

FIGURE 6 - 143 SECONDS OUT OF JOURNAL SQUARE

- Cruising at steady speed and no bolt currents
- A considerable amount of data between Journal Square and Newark is this quiet

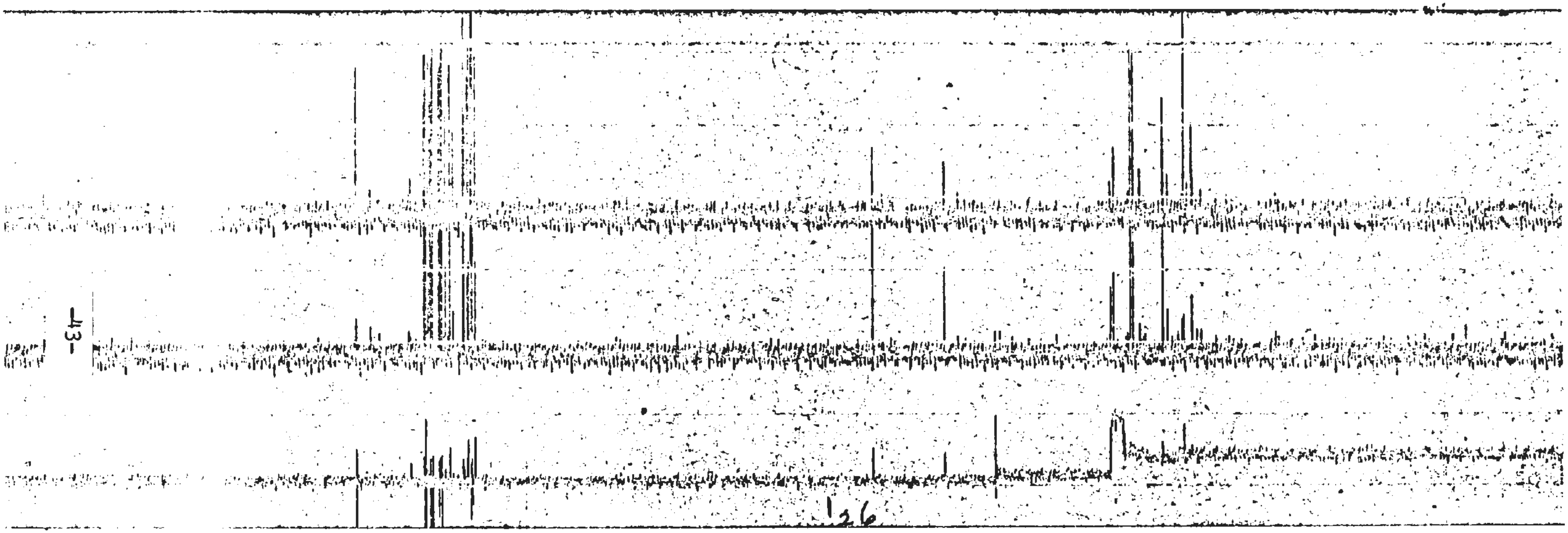

FIGURE 7 - 195 SECONDS OUT OF JOURNAL SQUARE

(See Figure 2 for trace detail)

- An example of collector arcing followed by a power application

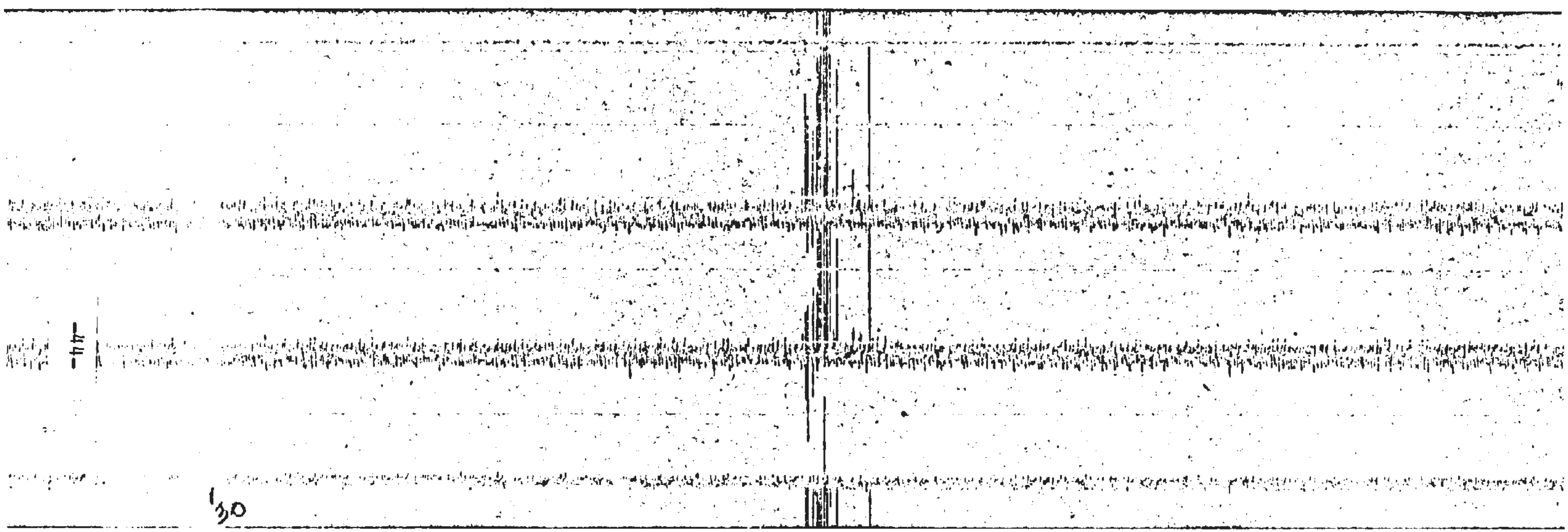

FIGURE 8 - 228 SECONDS OUT OF JOURNAL SQUARE

(See Figure 2 for trace details)

- An example of collector arcing

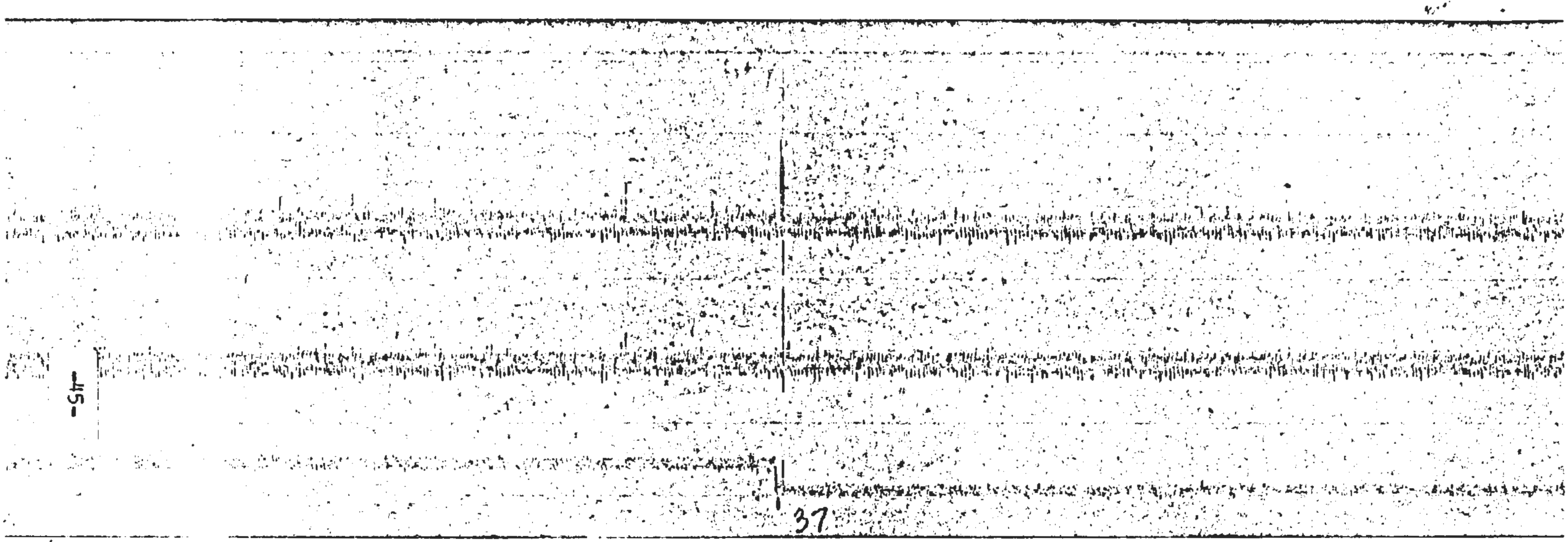

FIGURE 9 - 278 SECONDS OUT OF JOURNAL SQUARE

(See Figure 2 for trace detail)

- An example of power reduction

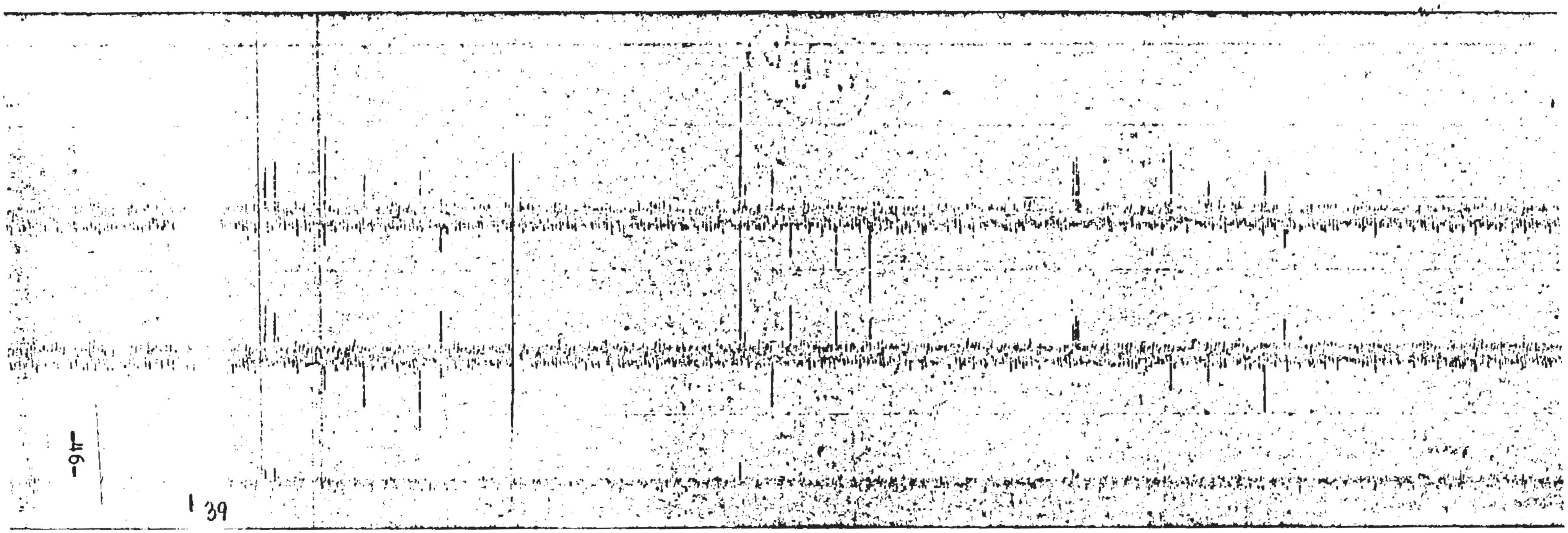

FIGURE 10 - 295 SECONDS OUT OF JOURNAL SQUARE

(See Figure 2 for trace detail)

- An example of positive and negative simultaneous bolt currents

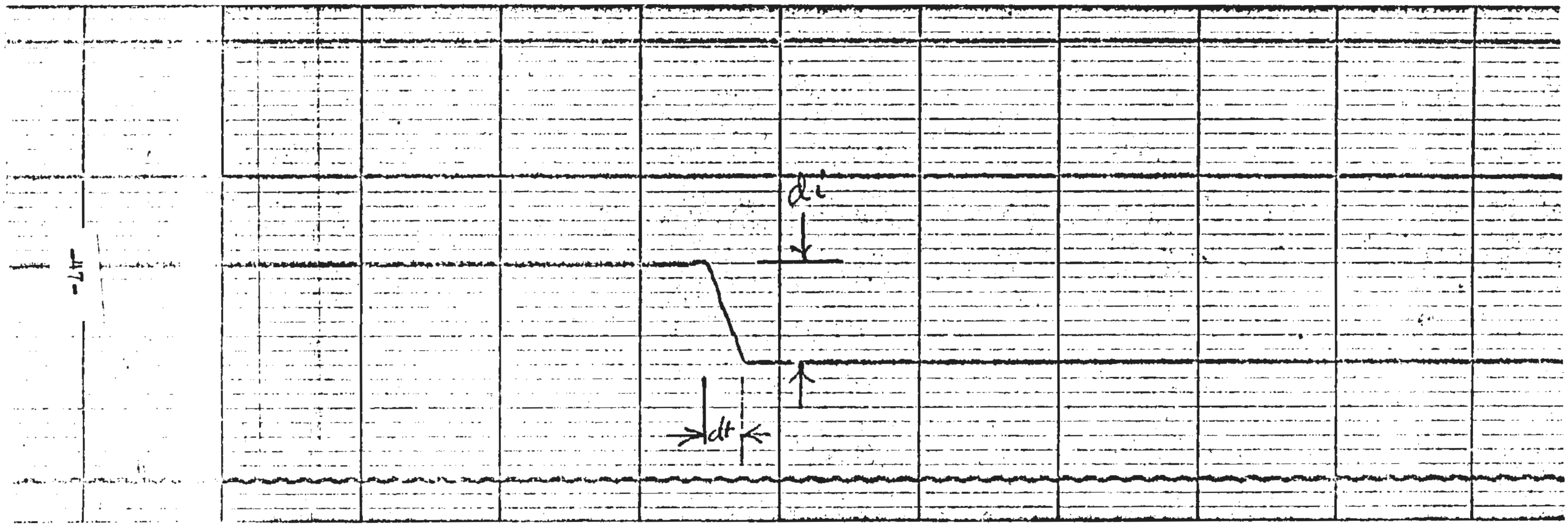

FIGURE 11 - MEASUREMENT OF AMPERES PER SECOND ON CURRENT DECAY

di = 280 amperes
dt = .025 seconds
di/dt = 11200 amperes per second

- This measurement made statically at Henderson Shops

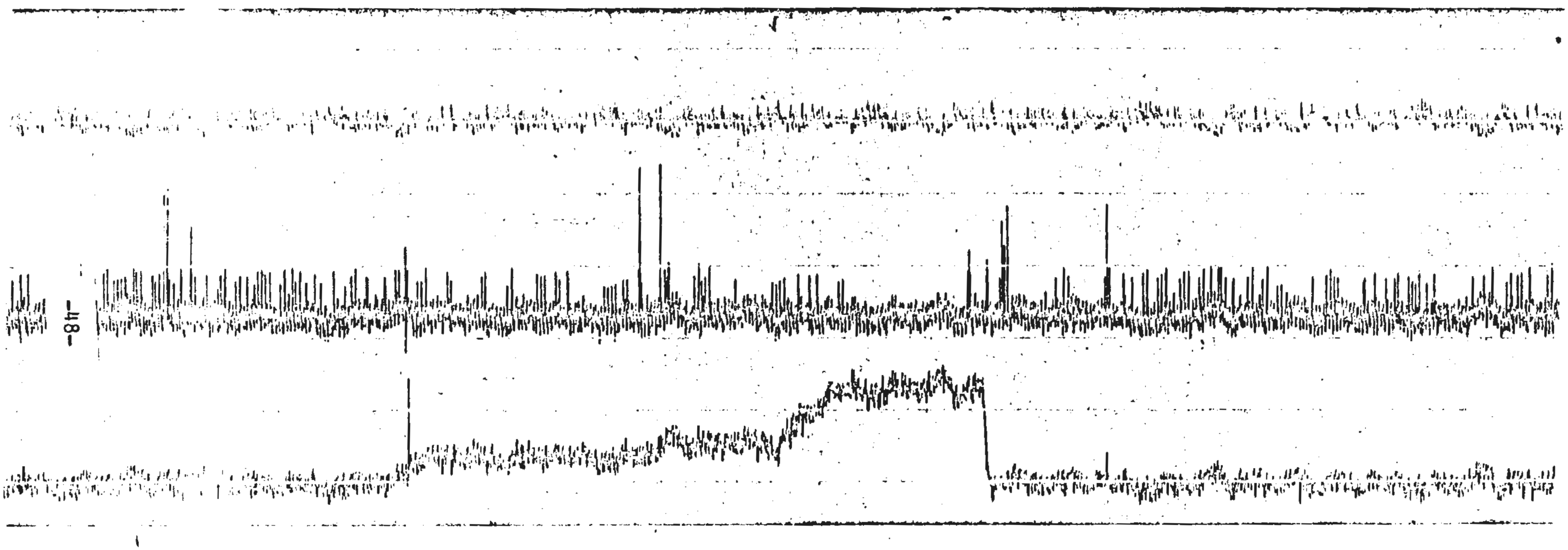

FIGURE 12 - INSTRUMENTATION CHECK

- Bolt 4 leads disconnected from shunt
- Bolt 1 leads connected
- This test made statically at Henderson Shops to show there was no pickup in leads

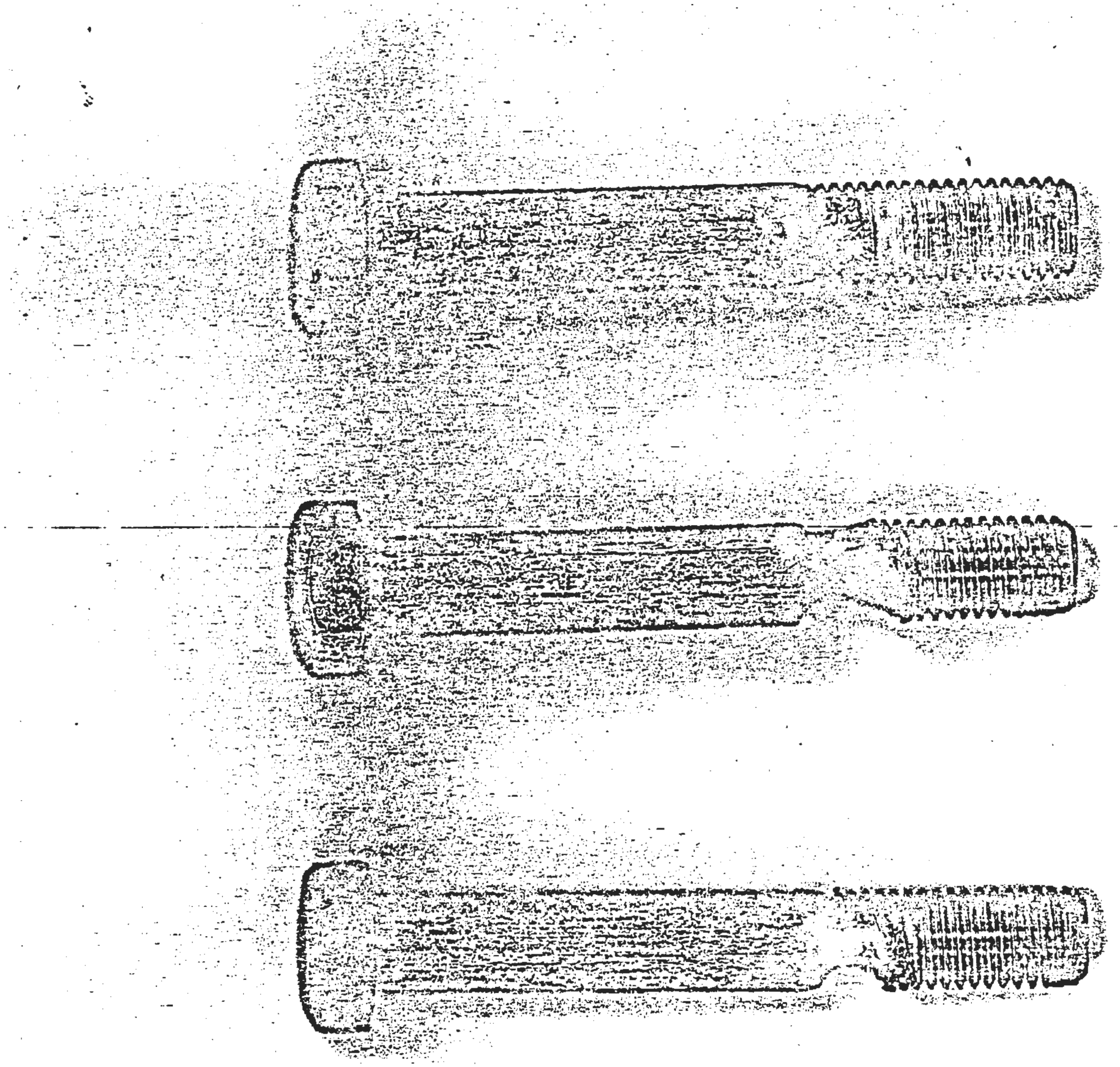

FIGURE 13

HANGER BOLTS FROM MAIN GROUP OF CAR 159

- Note cutting of bolts occurs at interface between bolt and the top metal of main group.

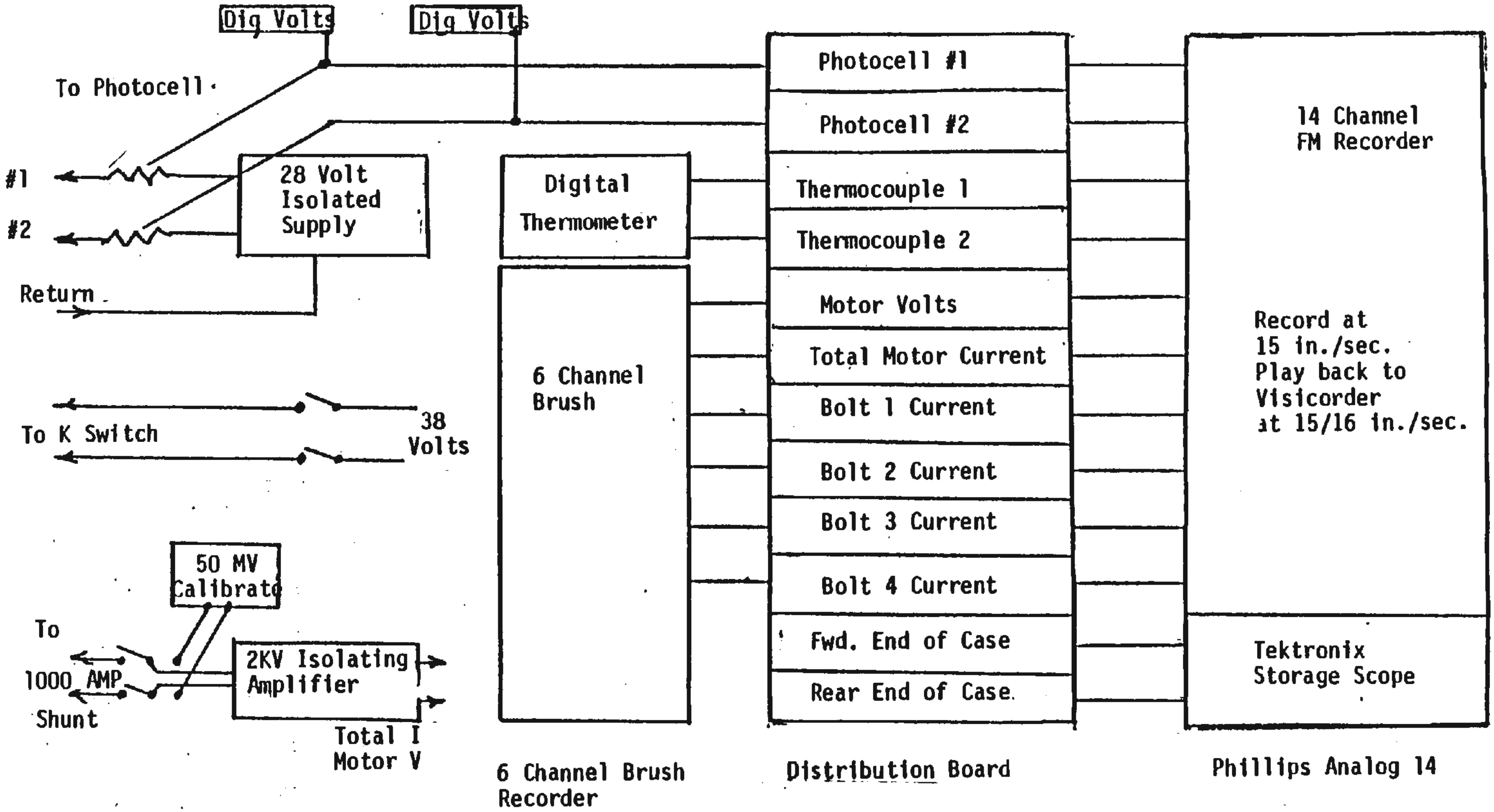

FIGURE 14. IN-CAR INSTRUMENTATION

Note: This is a one-line diagram. Actual wiring is more complex and generally in coaxial cable.

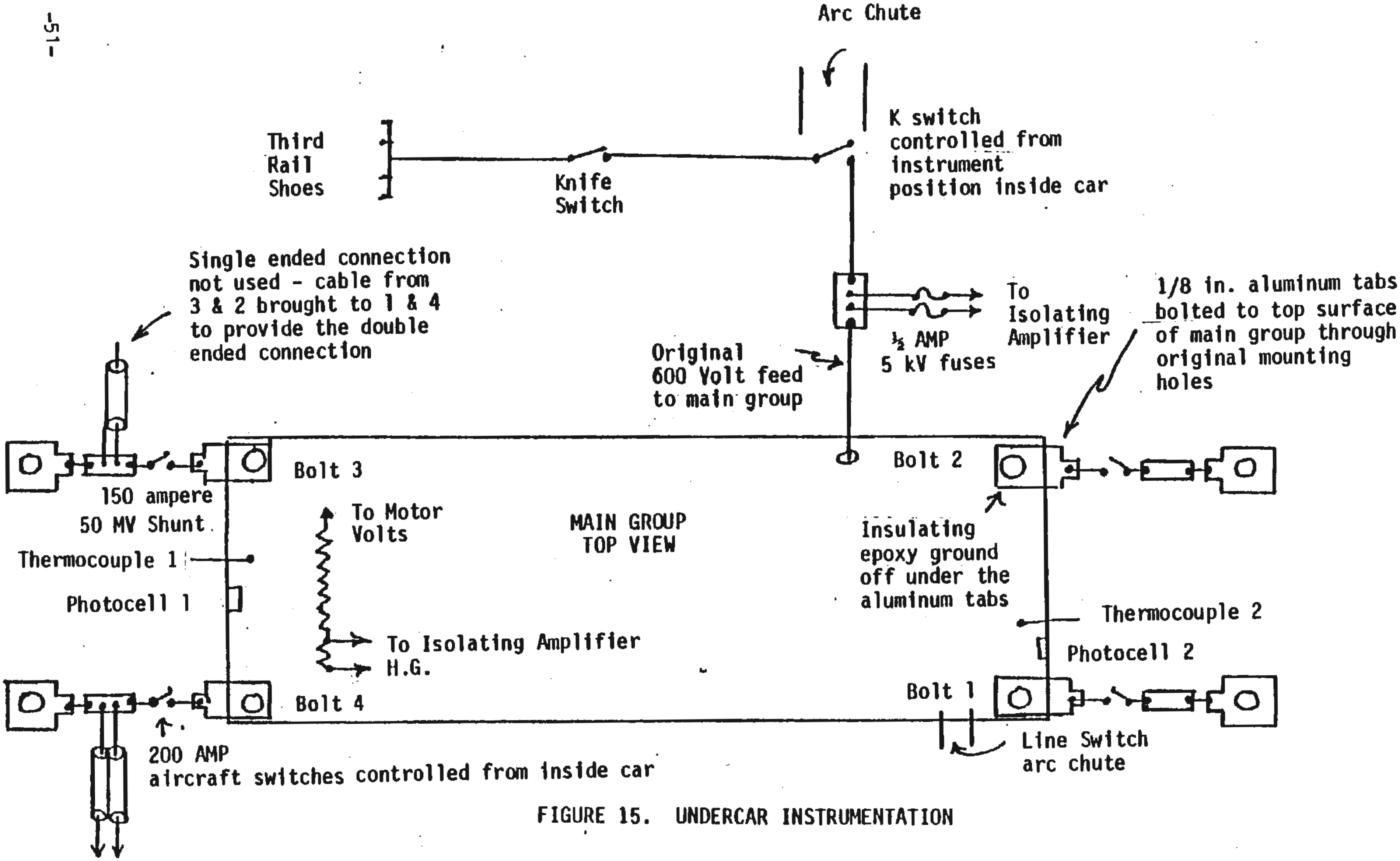

FIGURE 15. UNDERCAR INSTRUMENTATION

Note - Outboard aluminum tab folds over around the switch and shunt connection. Thus the same hole in car body is used for the ground connection.

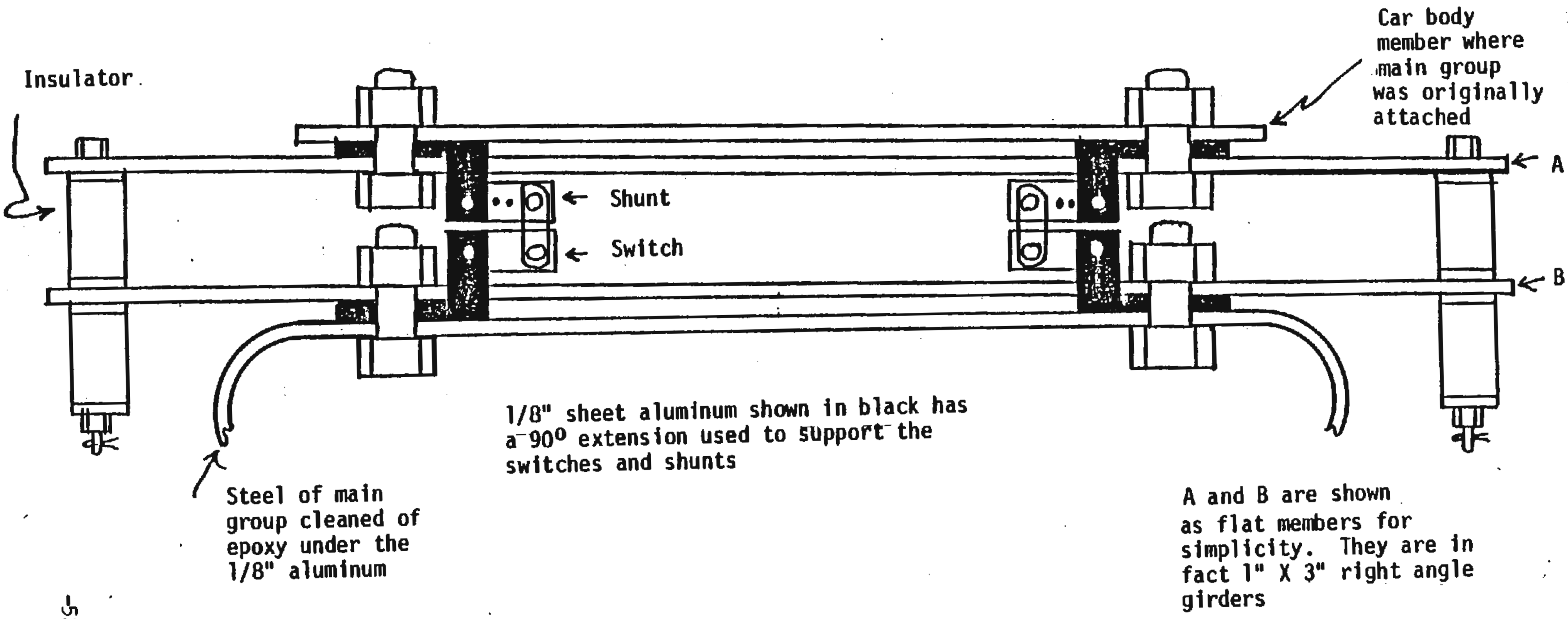

FIGURE 16. METHOD USED TO INSULATE THE MAIN GROUP OF CAR 159

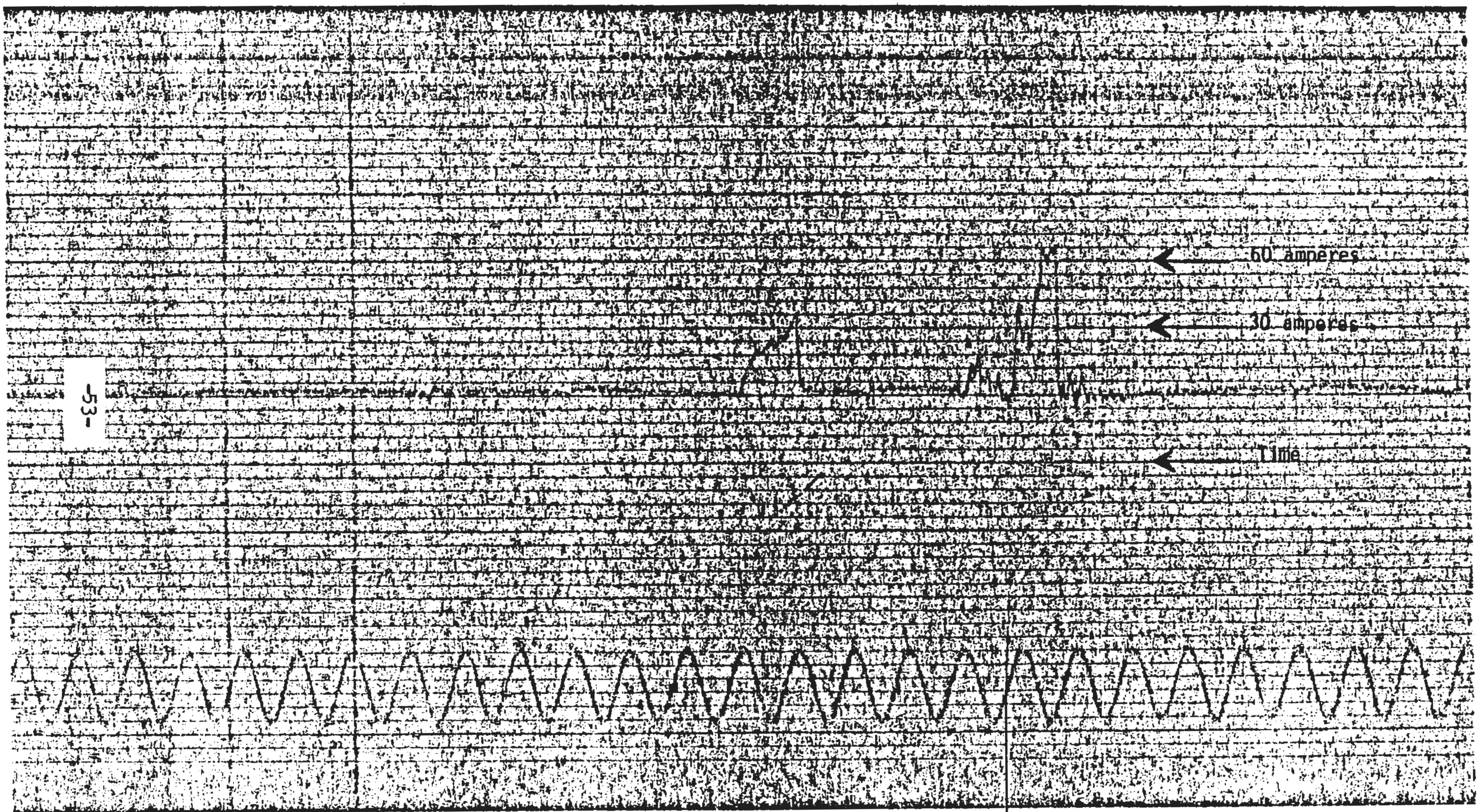

FIGURE 17

- Two bolt currents taken at randon from magnetic tape
- Timing Wave 960 HZ

APPENDIX 2

DETAILED ANALYSIS OF A RUN FROM

JOURNAL SQUARE TO NEWARK

On approximately 75 feet of visicorder data, the bolt currents were counted and grouped into three categories:

1. di/dt currents: Those that occurred from changes in propulsion current initiated by the motorman.

2. Arcing currents: Those that occurred due to changes in current initiated by rail gaps or shoe arcing.

3. Plus or minus currents: Those that were simultaneous but were complementary between bolt 1 and bolt 4.

The count was made in separate amplitudes of 6-ampere increments:

Amplitude in Amperes	Number of di/dt	Number of Arcing	Number of $\pm$	Cross Totals
12	8	12	16	36
18	31	31	20	82
24	42	41	26	109
30	47	62	60	169
36	20	15		35
42	18	52		70
48	19	68		87
54	13	54		67
60	42	56		98
66	21	91		112
72	5	50		55
78	14	13		27
84	18	34		52
90	7	2		9
	305	581	122	1008

To determine the ampere-seconds, a step integration yielded the following number of pulses times the currents they developed times 1 millisecond.

Figure 17, which shows two expansions of bolt currents, indicate that the assumption of a 1-millisecond interval and a square pulse is conservative.

36	x	12	x	0.001	=	0.432		
82	x	18	x	0.001	=	1.476		
109	x	24	x	0.001	=	2.616		
169	x	30	x	0.001	=	5.07		
35	x	36	x	0.001	=	1.26		
70	x	42	x	0.001	=	2.94		
87	x	48	x	0.001	=	4.176		
67	x	54	x	0.001	=	3.618		
98	x	60	x	0.001	=	5.88		
112	x	66	x	0.001	=	7.392		
55	x	72	z	0.001	=	3.960		
27	x	78	x	0.001	=	2.106		
52	x	84	x	0.001	=	4.368		
9	x	90	x	0.001	=	0.810		
						40.812	average	ampere-seconds

The 40.812 represents the count for bolts numbers 1 and 4. Taking into account the return trip plus the run from the World Trade Center, the ampere-seconds were arbitrarily doubled.

Therefore:

40 average ampere-seconds/bolt/per trip
x 9 trips a day
360 average ampere-seconds/bolt/day
x 360 days/year
129,600 average ampere-seconds/bolt/year
÷ 3,600 seconds
36 average ampere-hours/bolt/year

APPENDIX 3

THE CHARGING AND DISCHARGING OF THE CONTROL GROUP CASE CAPACITANCE

The control group case capacitance was charged through a 500,000-ohm resistor, and a charging time of 0.002 second was observed on test car 159.

Therefore: $R = .5 \times 10^5$ ohms

$T = 0.002$ second

$C =$ Capacitance

To determine the capacitance of the control group case:

$$C = \frac{T}{R} = \frac{0.002}{5 \times 10^{-5}} = \frac{2 \times 10^{-3}}{5 \times 10^{-5}} = 0.4 \times 10^{-8} \text{ farads}$$

$$C = 0.4 \times 10^{-2} \text{ microfarads}$$

This is the capacitance of the instrumented control group case on car 159, which has been lowered from about 1 inch to 3 inches, and is mounted to the car frame on insulators.

To calculate the capacitance of the control groups on the rest of the PATH cars, which are at 1 inch from the underframe, start with the known 0.004 microfarad and introduce the difference with the following proportion:

C is directly proportional to Area x Spacing x K

K is the dielectric constant

Capacitance of the control groups closer to the underframe is:

$$C = 0.004 \times \frac{3}{1} = 0.012 \text{ microfarad}$$

The control groups on the remaining PATH cars are mounted to the underframe of the car with four bolts passing through four aluminum blocks. Each control group has an epoxy coating on the inside and outside of the case with a combined thickness of 0.03 inch. (See Figure 18.)

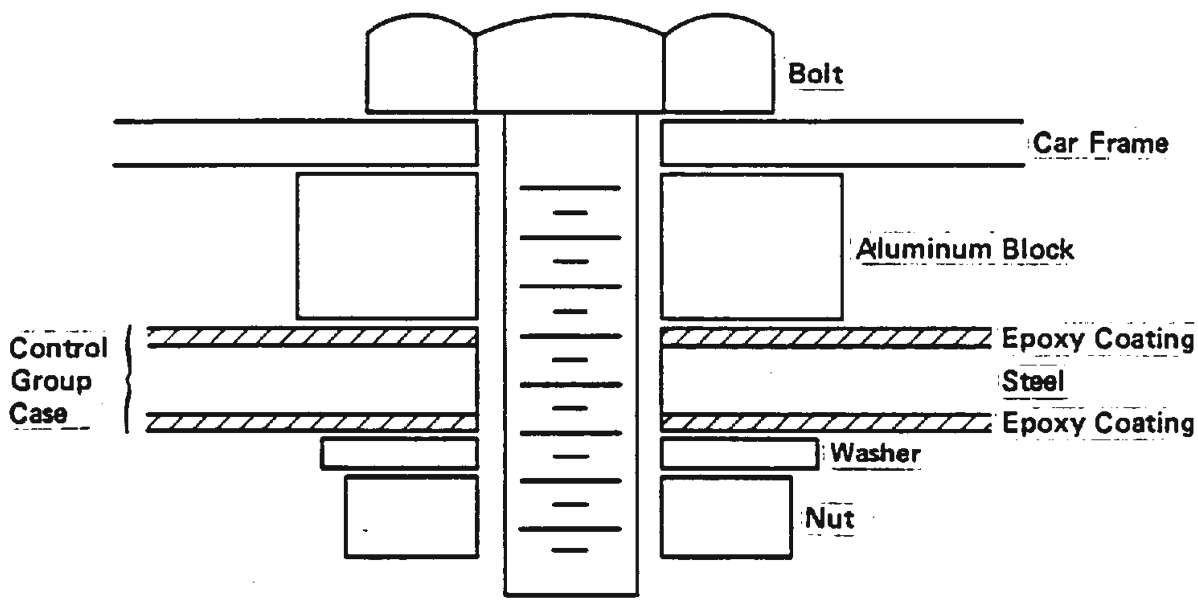

FIGURE 18. CONTROL GROUP MOUNTING BOLT

Area of each aluminum block = 4 x 4 = 16 in.^{2}

Area of each washer = $\underline{3\ \text{in.}^2}$

19 in.^{2}

Total area of four assemblies = 19 x 4 = 76 in.^{2}

Total area of the top of the control group = 20 x 50 - 1,000 in.^{2}

Dielectric constant K for the epoxy coating is estimated at 6. The additional capacitance due to this mounting arrangement is:

$$C = 0.004 \times \frac{76}{1{,}000} \times \frac{3}{0.03} \times 6$$

$$= 0.004 \times 0.076 \times 100 \times 6 = 0.182 \text{ microfarad}$$

Therefore the total capacitance between the control group case and the frame of the standard PATH car is:

0.012 + 0.182 = 0.194 microfarad

The energy in this capacity is:

$$1/2\ CE^2$$

$$= 1/2 \times 0.194 \times 10^{-6} \times (600)^2$$

$$= 0.0349 \text{ watt-second/pulse}$$

The data taken on a standard car shows a pulse duration of 0.001 second, therefore the energy delivered to the bolt is:

$$\frac{0.0349 \text{ watt-second/pulse}}{0.001 \text{ second}} = 34.9 \text{ watts/pulse}$$

If, under very wet conditions, the charging resistance drops to 10,000 ohms:

$$T = R \times C$$
$$T = 10{,}000 \times (0.194 \times 10^{-6})$$
$$T \approx 0.002 \text{ second}$$

The 35-watt pulse can impinge on the bolt approximately 500 times per second.

APPENDIX 4

FAULT TREE ANALYSIS AND FAILURE MODE EFFECTS ANALYSIS (FMEA)

Fault Tree Analysis and Failure Mode Effects Analysis (FMEA) are two complementary methods of describing a sequence of events without the complexity of a completely verbal description. By the use of a block diagram sequencing of events, together with the logic symbols "and" and "or," a visual presentation results that tells the story quickly.

Fault Tree Analysis is a deductive procedure in which hazards are identified and then analyzed as to their potential causes.

Failure Mode Effects Analysis (FMEA) is an inductive procedure in which potential malfunctions are identified and then analyzed as to their possible effects.

During the two months of testing conducted on car 159, an understanding of what is happening on PATH cars with regard to the bolt erosion problems, as well as the various causes and events leading to cam controller fires, has evolved.

They are described in Figures 19 through 24:

Figure 19.	Failure Mode Effects Analysis (FMEA) -- Open Blow-Out Coil and Flashed Motor
Figure 20.	Failure Mode Effects Analysis (FMEA) -- Carbonized Path and Capacitive Charging and Discharging
Figure 21.	Fault Tree -- Bolt Erosion
Figure 22.	Fault Tree -- Aluminum Erosion
Figure 23.	Fault Tree -- Blow-Out Coil of Line Switch
Figure 24.	Failure Mode Effects Analysis (FMEA) -- Arc Chute Damaged or Open Controller Doors

Both bolt erosion and aluminum erosion are the result of arcing at the bolt-case interface or the bolt-aluminum spacer interface.

In general, there are more cases of bolt erosion than of aluminum erosion. This is due to the fact that given the construction of the cam controller case, it is more likely that the bolt is insulated from the case rather than electrically tied to the case.

In the recommendations given in paragraph 9 of the report, the solution of this problem is provided by insulation of the case, as well as by insuring that no electric currents can pass through the bolts.

The power supplied to the bolts in each pulse was calculated in Appendices 2 and 3 as 400 watts/pulse for di/dt pulses and 35 watts/pulse for capacitive discharge.

The latter number of 35 watts/pulse was calculated assuming the decay of the charge took place in 1 millisecond. A later more careful measurement in the PATH research laboratory gave 0.050 millisecond as the time of discharge. Therefore, a revised number for capacitive discharge power is 700 watts/pulse.

POWER ARCS

Although in two months of testing no evidence of power arcing was seen, the power arcs must exist. When they do occur, they also contribute to bolt erosion since again, due to the construction, any currents that flow from case to ground must flow through the bolts. There is no other path.

There are three types of power arcs:

1. Those that occur from cam controller to ground and can be cleared by the line switch.

2. Those that are so high in current that they trip a substation breaker before any serious damage is done to the cam controller. A

power arc will always do some damage. If cleared quickly, the damage will be repairable.

3. Those that go undetected for several minutes and continue to arc. By the time they are cleared, the cam controller has been totally destroyed. The fire department must be called to extinguish the residual fire of the burning insulation.

To better understand the power of an electrical arc, one should be aware of the temperatures involved:

Electric arc temperature = 6,500°F
Aluminum melts at 1,348°F
Copper melts at 1,983°F
Stainless steel melts at 2,606°F

The only difference between type 2 and type 3 power arcs is the speed of clearing the fault. Faults of type 2 result in tieing up the railroad while (by radio) power is reapplied several times. If the fault location is not quickly found and cleared by opening the knife switch at the car in trouble, a type 2 fault can easily escalate to type 3.

Type 3 faults are the most dangerous in terms of car damage. They go undetected for minutes. Smoke from the car is usually the first sign of this form of trouble.

Type 3 faults, although of long duration, usually end by tripping the substation breaker.

An example of a type 3 power arc eventually becoming a type 2 is as follows:

An arc that draws 600 volts at 400 amperes starts in the cam controller; 240 kilowatts is being delivered to the main control group case. The fuse does not clear at this level of current and the substation line breakers detect no abnormality.

The 240 kilowatts continue to be delivered to the main control group case. The fiberglass covers quickly disappear, and everything that can burn is ignited. By this time there is metal melting. Molten metal will provide a bridge from +600 volts to ground which now can carry several thousands of amperes. This happens quickly, the car fuse cannot respond fast enough, and the substation breaker clears the fault. The cam controller by this time is totally destroyed.

This is probably what happened in the fire on car 725.

Some failure modes are as follows:

1. Excessive resets into a heavy motor fault.

2. Foreign object in the control group case, such as a piece of metal vibrated loose or a tool accidentally left in the case.

3. Carbonized path glows then starts a flaming arc from +600 volts to ground. This is a thin arc, limited by the resistance of the carbonized path. It is moved by the varying magnetic fields until it strikes a solid +600 volts and becomes a power arc.

4. Damaged blow-out coil.

5. Missing or damaged arc chute gasket.

6. Open control group doors.

7. Badly pitted contact tips on cam controller that partially connect (arcing). On opening of the cam there is sufficient ionized air in the vicinity of the contacts to sustain the arc, which can either melt itself clear or spread to a more vital location.

8. Heavy accumulations of dirt.

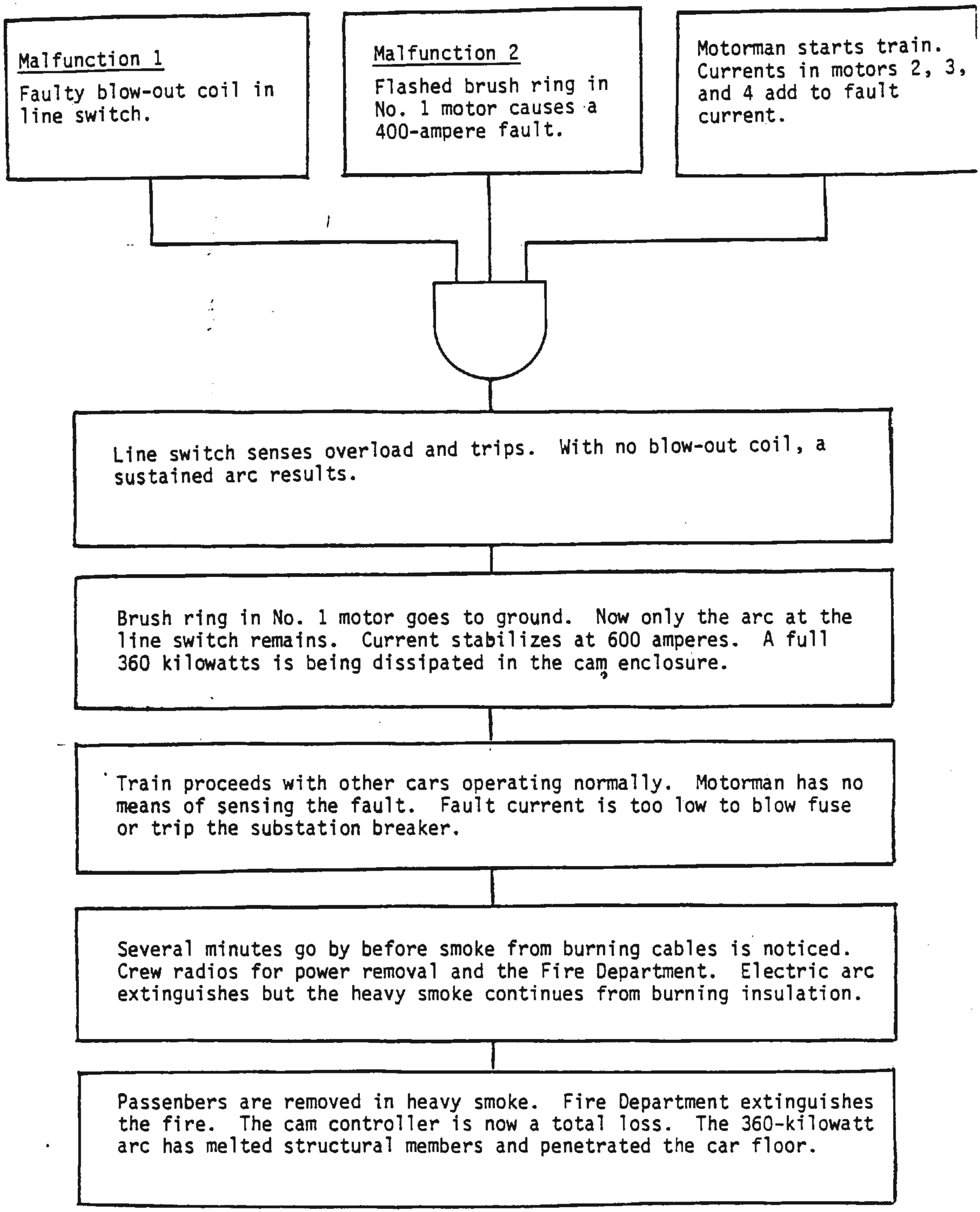

FIGURE 19. FAILURE MODE EFFECTS ANALYSIS (FMEA) - OPEN BLOW-OUT COIL AND FLASHED MOTOR

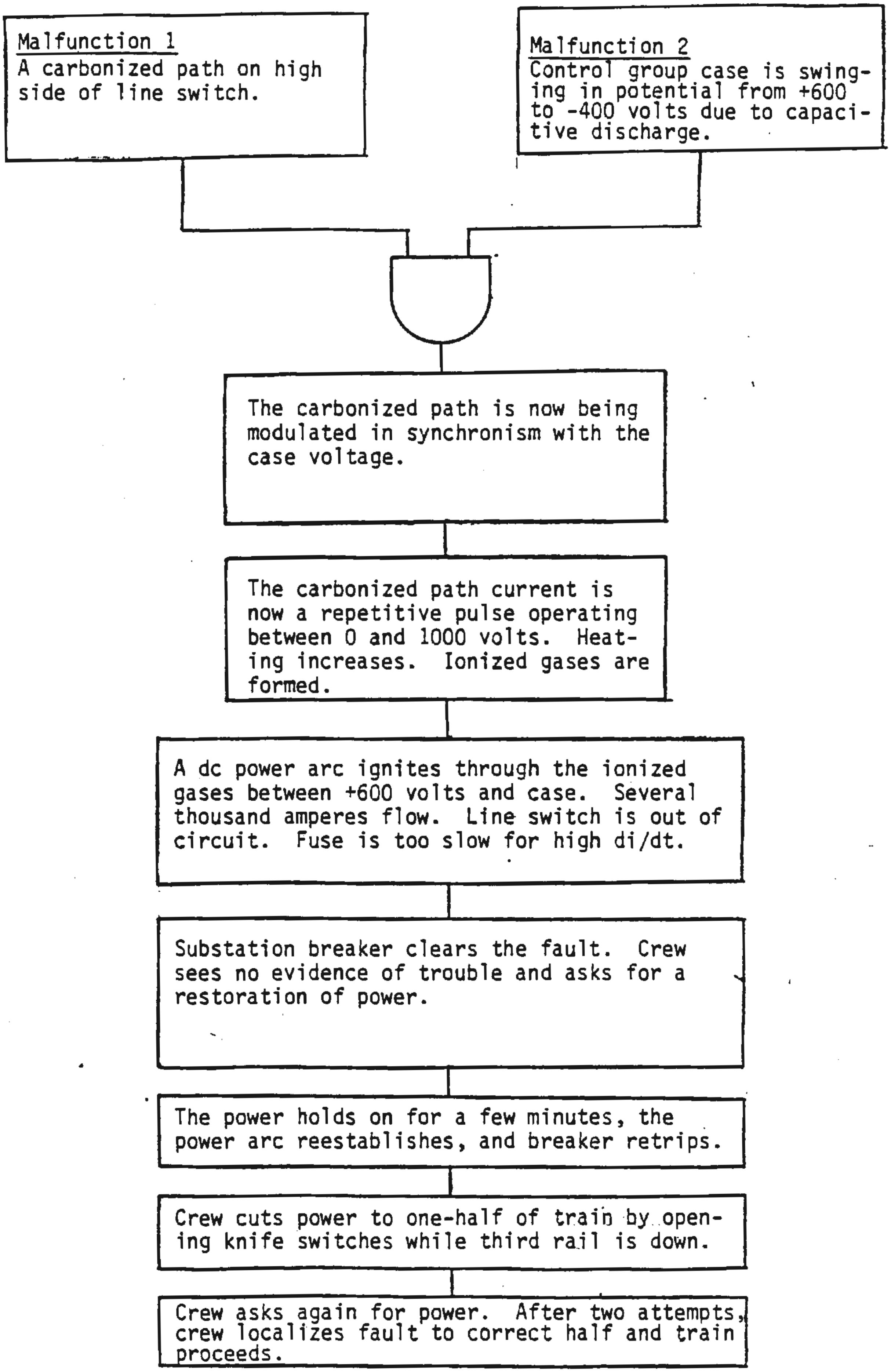

FIGURE 20. FAILURE MODE EFFECTS ANALYSIS (FMEA) - CARBONIZED PATH AND CAPACITIVE CHARGING AND DISCHARGING

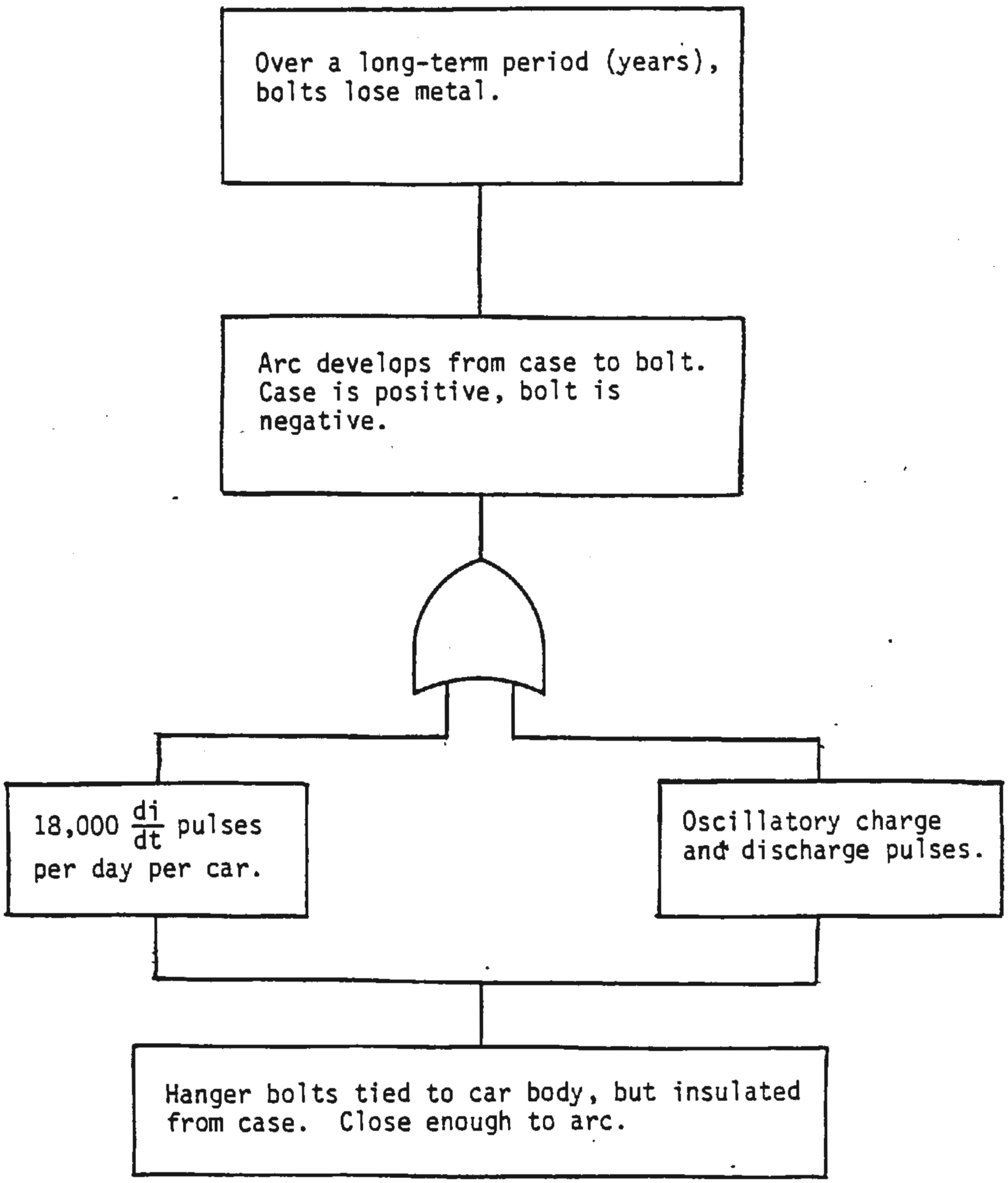

FIGURE 21. FAULT TREE - BOLT EROSION

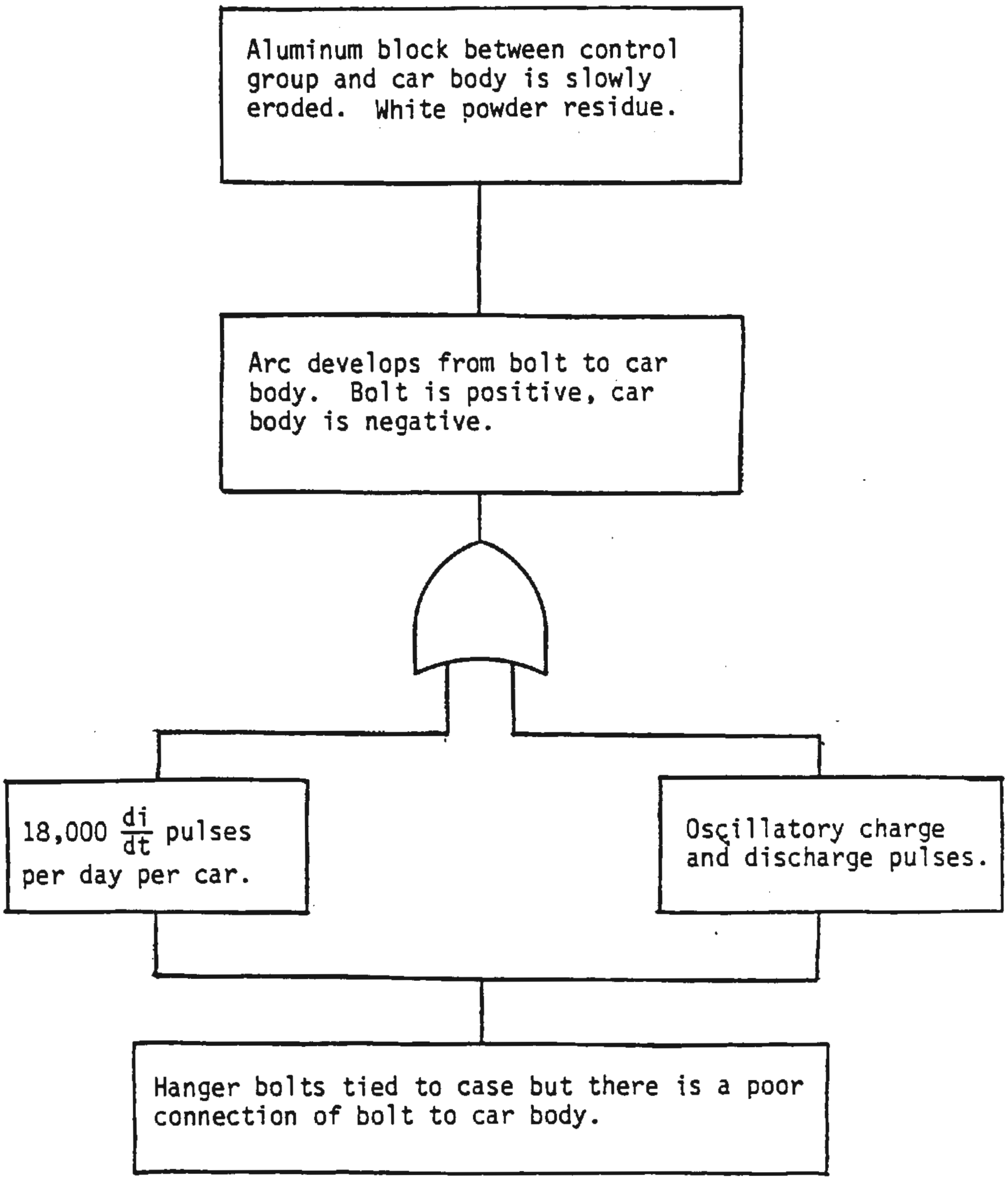

FIGURE 22. FAULT TREE - ALUMINUM EROSION

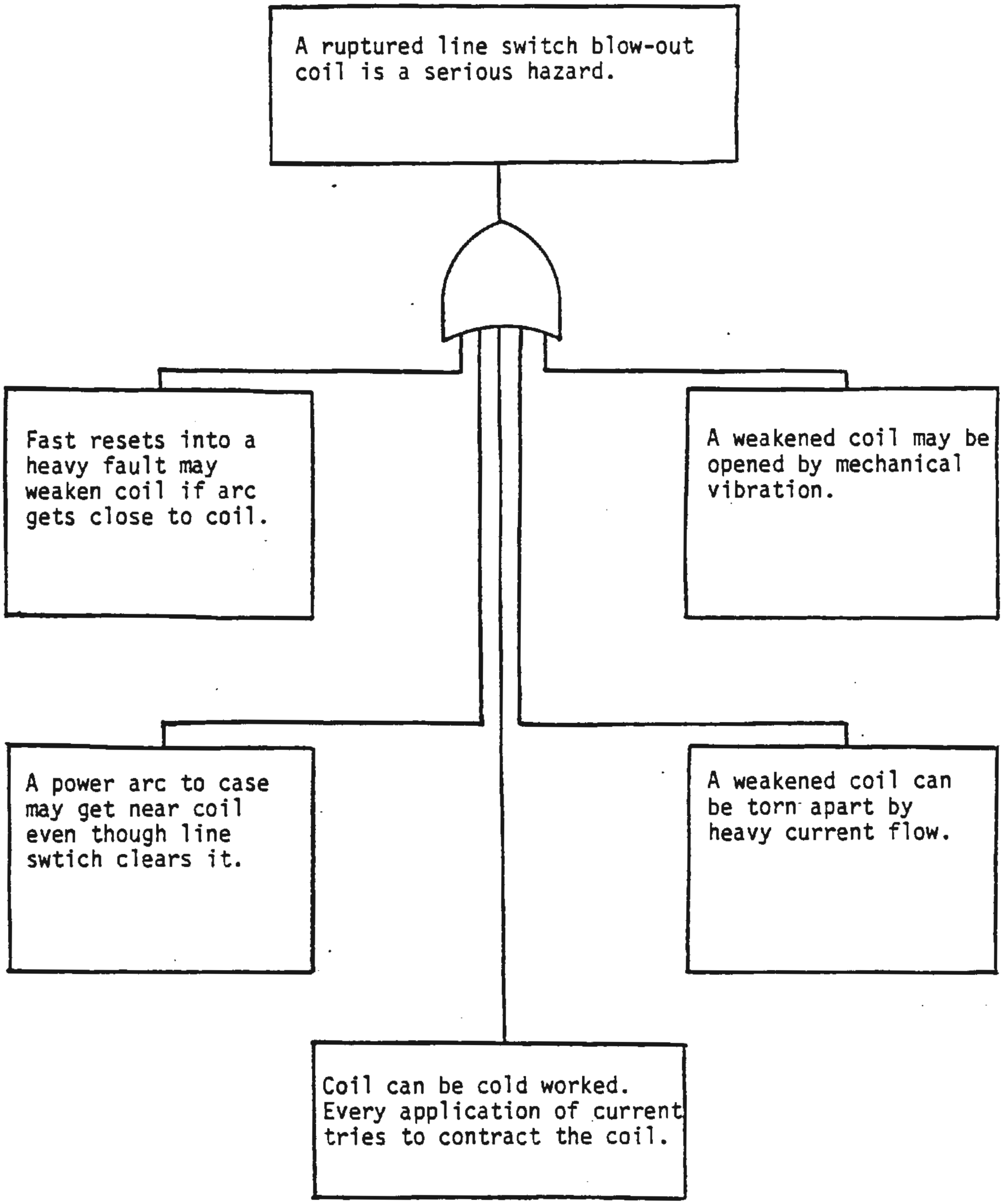

FIGURE 23. FAULT TREE - BLOW-OUT COIL OF LINE SWITCH

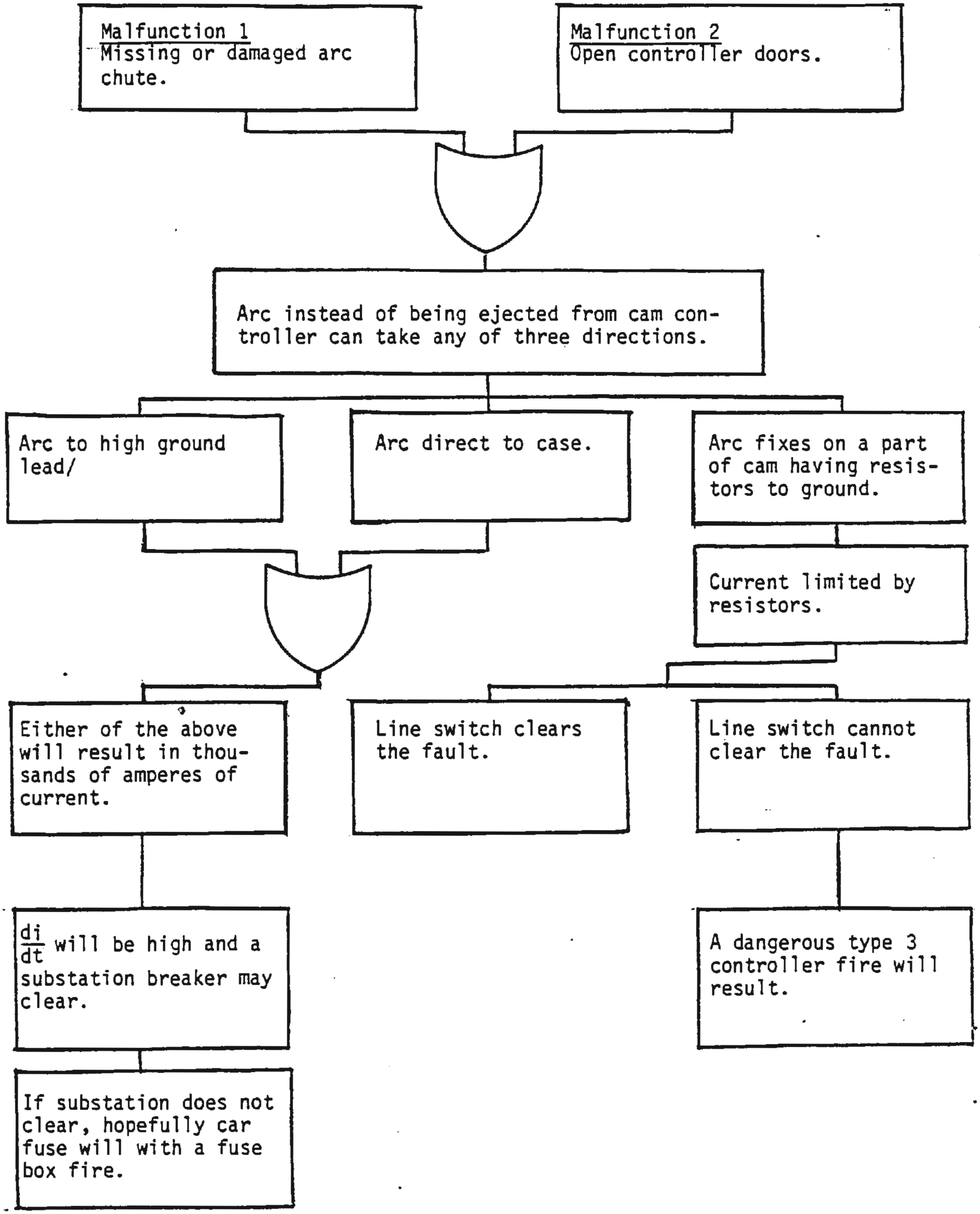

FIGURE 24. FAILURE MODE EFFECTS ANALYSIS (FMEA) - ARC CHUTE DAMAGED OR OPEN CONTROLLER DOORS

APPENDIX 5

METALLURGICAL REPORT ON MOUNTING BOLTS

REPORT NO. M-7715

EXAMINATION OF CONTROL PACKAGE SUPPORT BOLTS - PATH CAR 159 - TYPE C CAR

PARSONS BRINCKERHOFF QUADE & DOUGLAS, INC.

Lucius Pitkin
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Metallurgical and Chemical Consultants
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REPORT

July 27, 1984

Report No. M-7715

Your P.O. letter 7/16/84

Parsons Brinckerhoff Quade & Douglas, Inc.
One Penn Plaza
250 West 34th Street
New York, N.Y. 10119

Attention: Mr. Jack F. Forman
Project Manager

Subject: EXAMINATION OF CONTROL PACKAGE SUPPORT BOLTS
PATH CAR 159 - TYPE C CAR

Two 3/4 in. diameter by 5 in. long galvanized hexagon head bolts were submitted to Lucius Pitkin, Inc. for metallurgical examination.

The bolts had been threaded for approximately one inch with ten threads per inch. For approximately 180 degrees around and 1/2 in. long, the threads adjacent to the bolt shank had been wasted resulting in a relatively smooth straw-colored surface appearance. The remaining threads and shank exhibited a uniform bright, clean zinc galvanize coating. Radial markings paced 120 degrees apart on the head indicated the bolt to be manufactured to ASTM: A 449.

Fig. 1 is a photograph showing the submitted control package support bolts in the as-received condition.

A small section of the straw-colored wasted area of the bolt was prepared for scanning electron microscopy. Examination revealed the surface to contain numerous relatively small spheroids and contour markings characteristic of melting and rapid solidification as would occur from electrical arcing. The surface condition of the bolt in the straw-colored area showing the metal spheroids is shown in Fig. 2.

A longitudinal section through the wasted area was prepared for metallographic examination. It was observed that the wasted area at the surface was found to consist of melted and resolidified metal exhibiting an untempered martensite microstructure. No evidence of foreign materials was observed in the melted and resolidified area.

The general microstructure of the bolt material away from the melted zone was found to consist of tempered martensite typical of a quenched and tempered steel.

Figs. 3A, 3B and 3C are photomicrographs showing the microstructure exhibited by the bolt in the melted and resolidified area.

An energy dispersive X-ray analysis in the wasted area exhibiting the straw-colored melted and resolidified metal showed the element iron to be present, no other elements were detected. Fig. 4 is a energy dispersive X-ray spectrum of this area.

A hardness survey was performed on a damage-free area of the shank below the galvanize coating. Hardness was found to be Rockwell C 29. Based on standard conversion charts for steel, this hardness is equivalent to an approximate ultimate tensile strength of 132,000 psi, well above the minimum specified tensile strength of 120,000 psi as specified in ASTM: A 449.

* * *

Results of our examination indicate the submtted control package support bolts to have undergone melting and resolidification due to electrical arcing. It would appear that normal vibrational stresses present during operation of the car caused failure of the epoxy insulator and subsequent direct contact between the support package frame and support bolt.

Repeated contact between the support package frame and the support bolt caused local electrical arcing producing temperatures greater than 2600 F, the approximate melting temperature for carbon steel.

It would appear that intial torquing of the bolts was inadequate with respect to the bolt preload. Normal service stresses were apparently greater than the bolt preload stress and mutual movement of the support package frame and support bolt occurred. This movement under normal service stresses caused failure of the epoxy insulator and subsequent electrical shorting.

We suggest for your consideration that adequate torquing preloads be investigated with respect to the support package frame and insulator material.

Respectfully submitted,

LUCIUS PITKIN, INC.

A. J. Vecchio
Vice President &
Asst. Chief Metallurgist

AJV/mm/4

Lucius Pitkin
incorporated

Parsons Brinckerhoff Quade & Douglas, Inc.
Attn.: Mr. Jack F. Forman

July 27, 1984
M-7715

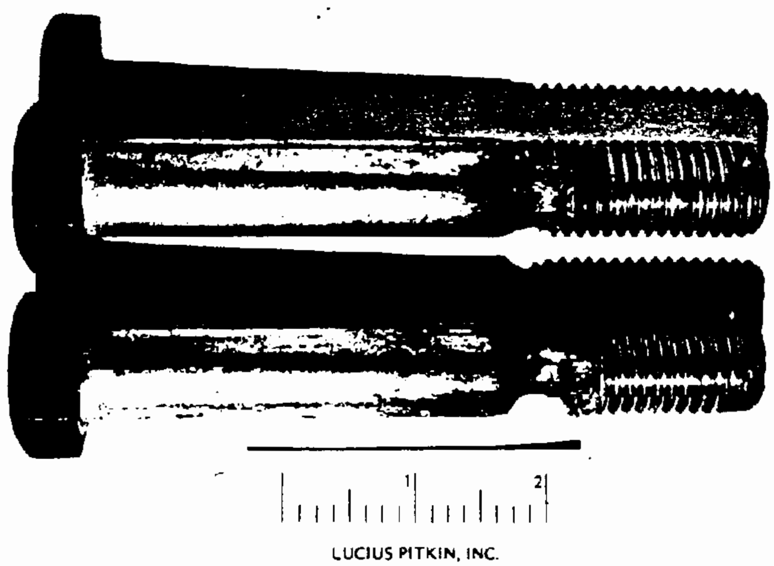

Fig. 1 SUBMITTED SUPPORT BOLTS - AS RECEIVED

Photograph showing the submitted support bolts in the as-received condition. It can be seen that wastage occurred at several threads adjacent to the shank of the bolt. This location corresponds to the support package frame.

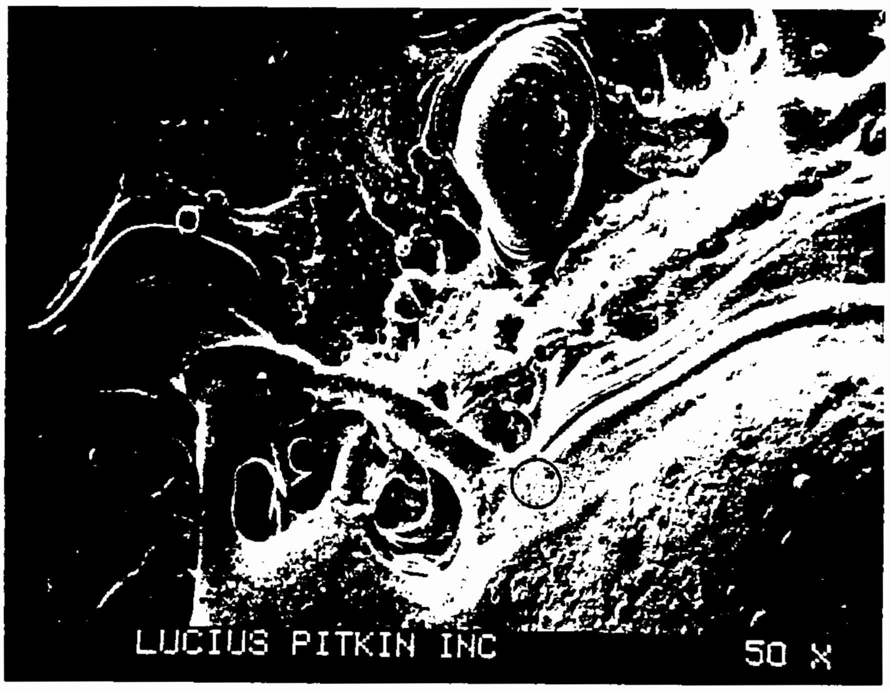

Fig. 2 SCANNING ELECTRON MICROGRAPH 50 X

Scanning electron micrograph showing the wasted area of one of the bolts which contains numerous relatively small spheroids and contour markings characteristic of melting and rapid solidification as would occur from electrical arcing.

The circle shows the area which was analyzed by energy dispersive X-rays to determine the presence of surface elements.

Figs. 3A, 3B and 3C — MELTED AND RESOLIDIFIED METAL

Fig. 3A is a photomacrograph showing the melted and resolidified zone.

Figs. 3B and 3C show the melted and resolidified microstructure exhibited in the wasted area. It is apparent in Fig. 3C that three layers of microstructure are present:

layer 1 is a melted and resolidified zone
layer 2 is a heat-affected zone of untempered martensite resulting from very high temperatures and fast cooling
layer 3 is the general microstructure of the bolt material which consists of uniformly tempered martensite

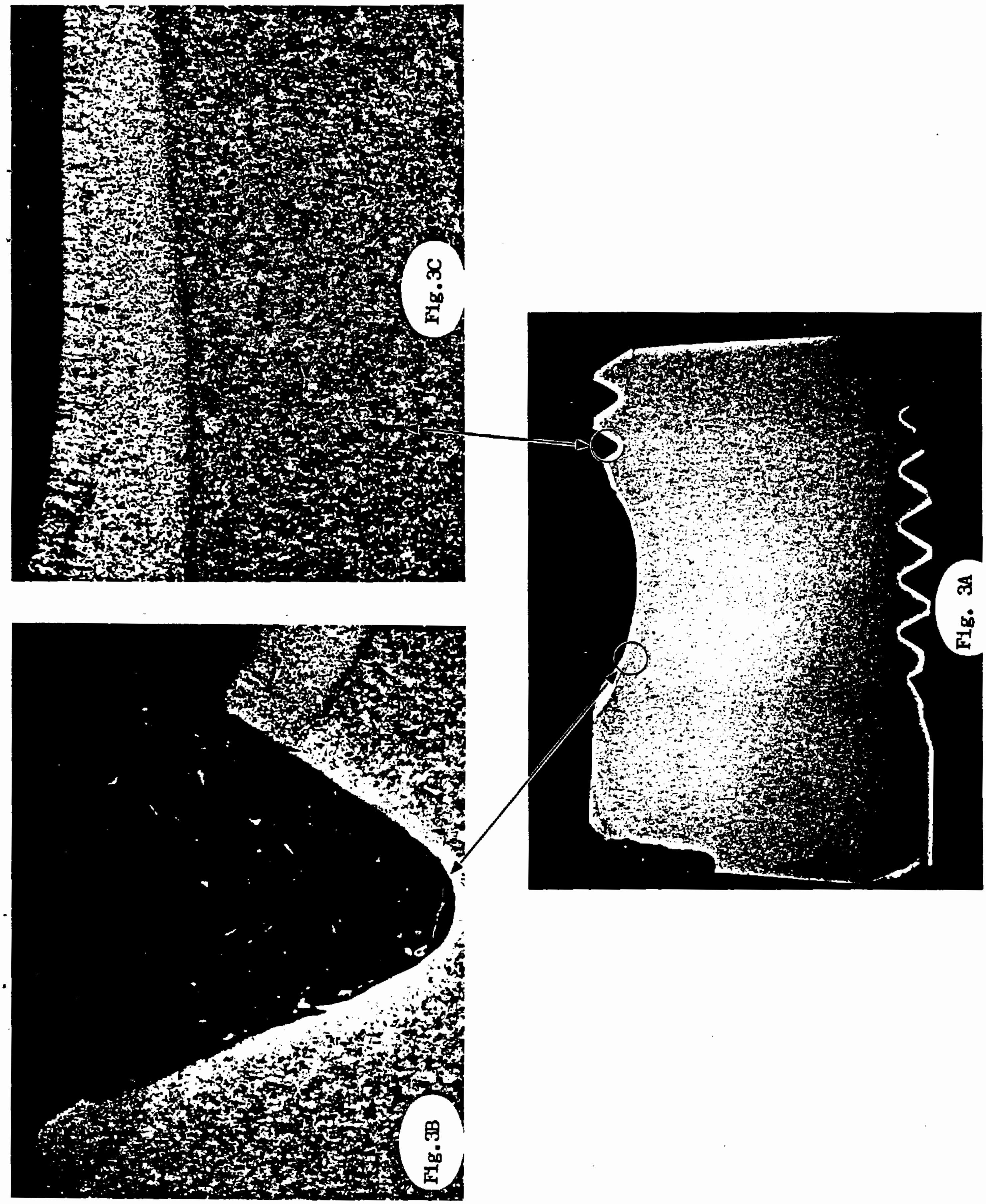
Fig.3C
Fig.3B
Fig. 3A

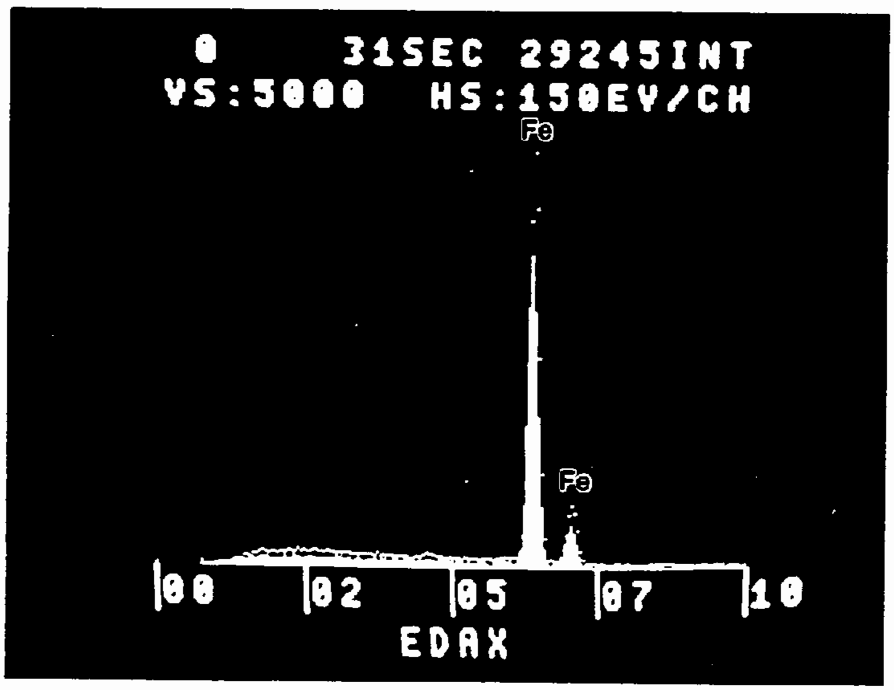

Fig. 4 ENERGY DISPERSIVE X-RAY SPECTRUM

Energy dispersive X-ray spectrum of the melted straw-colored wasted area of the bolt. Only the element iron is present on the surface.

APPENDIX 6

TASK 3 - MATERIAL INVESTIGATON

TASK 3 - MATERIAL INVESTIGATION

The Controller Material Investigaton task has been divided into three major groups, as follows:

(1) Controller shell (box)

(2) Components, e.g. blow-out coil, main switch, 'J'-resistor, and supporting elements for cables and components.

(3) Wires and cables.

PATH PA-1, -2 and -3 cars use Westinghouse cam controllers. These cars are 12 to 17 years old.

3.1 CONTROLLER SHELL:

The controller shell consists of a metallic box and a fiberglass cover. The metallic boxes for both PA-1 and PA-2 cars are coated with epoxy while the metallic box for the PA-3 car is painted inside and out. The Controller box cover uses a combustible resin and is supplied with a combustible gasket. The gasket takes a permanent set allowing dust penetration (Reference 2). The Control box cover metal hinges are not insulated. (NOTE: G.E. uses silicone insulating material for the NYCTA control box hinges.)

The Controller box has a rectangular arc chute opening. Westinghouse recommended 26 inches clearance for the arc. However, due to space restrictions, only 18 inches of space is available under the PATH cars. The arc, if formed, would project directly towards an electric component (motor) of the car. To protect this component, fiberglass shields were retrofitted under the cars in the path of the arc. During a car fire the shield has been destroyed.

3.2 COMPONENTS:

The major components consist of cam and cam follower, 'J'-resistor, main switch, blow-out coil, hinges, pneumatic piping, bolts, nuts and miscellaneous hardware. These components are made of copper, steel and plastic. Detailed material information on the components is not available because of their proprietary nature. Arc generation, arc extinction, heat build-up and heat dissipation would depend not only on properties of these materials but also on spatial arrangement of the components. Evaluation of the controller design is not included in the scope of this project. It is understood that close proximity of cables and components in a motor Controller has created fire related problems in the LIRR commuter trains. The problem was solved by improving spacing of the components. The PA-3 car Controller box component spacing is almost identical to PA-1 and PA-2 Controller boxes.

Method of component attachment, interior and exterior environment of the controller and level of maintenance should be considered when designing spatial arrangements for the components. Vibration may affect the alignment of the moving parts. Caked steel dust has been found in the Controller box, and this may increase possibility of electrical malfunctions. Interval between cleaning of the Controller box interior may also affect the proper function of the Controller box.

The PATH cam Controller uses a plastic cam operating against a rolling cam follower. NYCTA (N.Y. City Transit Authority) has learned that when a sliding cam follower is used, the plastic cam wears less compared to the rolling cam follower. PATH Controller pneumatic piping (rubber hoses) which supply air to the Controller has no air fuses. In case of fire, a ruptured hose may supply air to the fire. PATH is retrofitting the existing PA cars with air fuses and future PATH cars will be provided with the air fuses. PATH Controller air regulator does not have a gage. For PA-4 cars, Westinghouse has proposed a quick disconnect plug for inserting an air gage as an assist in maintenance of the air system.

Proper function of the line switch operation is very desirable. A specific standard is necessary for maintenance of the line switch tip contacts. The present PATH switch is pneumatically operated. An all electric line switch would eliminate the pneumatic system and therefore may be worth considering. A blow-out coil is located behind the line switch and on the opposite end of the arc chute. In both PATH car fires a part of the blow-out coil was damaged as though a "slicing" action had occurred. Because of the heat generated it may be desirable to locate the 'J'-resistor outside the Controller box. For PA-4 cars, the 'J' resistor will be external to the Controller box.

3.3 WIRES AND CABLES:

For this task, emphasis was placed on cables because the major fire load is the cable insulation. Selection of cables requires careful consideration and appropriate weighting of several parameters associated with safety, performance, durability and cost. Evaluation and rating of most of the cable insulating materials are listed in UMTA reports (References 3, 4, 5, 6).

The Association of American Railroads (AAR) has recommended a specification for single conductor 600 V. cables for locomotives and car equipment (Reference 7). The recommended list includes physical and electrical properties of generic insulating/jacketing materials.

Generally more than one standard or test method is used by the cable manufacturers to specify their products. Therefore, it would be difficult to make a comparison among various cables for their specified performance. To overcome this difficulty, TSC designed a new set of standard tests (e.g., vertical flame test, etc.) and cables/wires were tested using the standard tests. The results of the tests are reported in References 3 through 6. These references also contain information from the TSC data bank. Following are the important characteristics of cable insulation materials:

flammability; smoke emission; circuit integrity; toxicity; water and oil resistance; dielectric strength; tensile strength; cold bend; ozone resistance; temperature and voltage rating; aging; heat distortion; minimum bending radii; corrosivity; abrasion resistance; thermal cycling

Cables may have insulation or insulation and jacketing. The commonly used insulation and jacketing materials for single conductor wire and multi-conductor cables were tested by Meyer, et al, at Boeing Commercial Airplane Company for U.S. Department of Transportation (Reference 5). Their findings and relative ranking of cables/wires for flammability, smoke emission, circuit integrity and overall ranking based on the three criteria are listed in Tables 1 and 2.

Boeing also conducted tests on insulation materials for insulation resistance, dielectric strength, abrasion resistance and dynamic cut-through resistance. Relative rankings of these properties are listed in Table 3.

Under UMTA Technical Assistance Program, Tewarson, et al, at Factory Mutual Research Corporation, conducted tests for representative wire/cables for the following parameters:

- ignition; electrical failure; corrosivity of fire products generated from wires and cables; smoke, toxic and corrosive compound generation; fuel vapor generation and light obscuration

See Reference 3. Appendix 6.1 contains definitions of these parameters. Table 4 lists general relative rankings of wires and cables. The tests show the following:

(1) Performance and characteristics of the cables and wires are not only a function of the generic nature of the insulation/jacket materials but also depend on the additives, size and construction of the wires and cables.

(2) As the size of the wires and cables is increased, relative ranking for ignition, flame spread, heat, light obscuration and electrical failure decreases due to enhanced charring at the surface.

(3) For the above seven parameters, the relative importance may vary according to the operating environment and maintenance of the cars.

3.3.1 TOXICITY:

Relative inhalation toxicity of the gases produced by thermal degradation of insulation material is a very important parameter for selecting wire/cables. Toxicity is a complex subject and not clearly understood. Factory Mutual Research of Norwood (Reference 9) and Aviation Toxicology Laboratory at FAA Civil Aeromedical Institute (Reference 6) have made extensive studies of toxicology of insulation materials. Two approaches have been taken by the researchers:

(1) Toxicity measured as the ability of a given amount of insulation material to incapacitate or kill laboratory rats. (See Table 3.)

(2) A more useful parameter would be toxicity based on a worst case performance at a given temperature for equal lengths of insulation from equal gage wire materials. (See Table 6.)

Very limited toxicity data is available for wires/cables. Toxic hazard depends not only on material of decomposition (Reference 8) but also rate of burning (mass loss rate). In case of a transit car the toxic hazard depends upon rate at which thermal energy is transferred to the specimen and the ratio of oxygen consumption rate to the rate at which oxygen can be replaced in the gaseous environment immediately surrounding the thermal decomposition process. Thus it is seen that there is an immediate need to design and conduct parametric studies that would examine critically the relative effect of changes in each of these areas on toxic hazard index.

Furthermore, Crane, et al (Reference 4), states that:

"We feel confident about the correspondence between rodent and human dose-response relationships for the systemic toxic gases (such as CO, HCH and hydrogen sulphide) and anesthesia-like effect (hydrocarbons and ethers).....however, there could be serious problems with the use of rodents in evaluating the effect on humans of irritant gas components of smoke."

The above discussion shows that since toxicity is a complex subject it may be prudent for an engineer making cable selection to use the available toxicity information and defer any judgement on biological and physiological aspects for untested materials and compounds.

Boeing and Factory Mutual studies do not include the following parameters:

ozone resistance; aging; thermal cycling; heat distortion; oil and water resistance

Wire and cable manufacturers however, may provide data on these properties.

After obtaining data and ranking of the cables and wires, an important question arises:

How should weighting be assigned to all these parameters to get a composite rating for a particular cable or wire?

A transit property may estimate relative weightings and assign a number or range of numbers to each of the physical properties described above. For example, a subway transit system may attach more importance to smoke rating and less importance to water resistance as compared to a surface transit system. Until a rational approach is developed, a combined hazard index for wire and cable may be estimated by the transit operators based on their experience, operating environment and level of maintenance. Selection of better quality cables and wires may become a developmental process. The transit property may compare the specifications of the existing wires/cables in use with other cables in the market and after assigning proper weighting of the parameters, it can determine desirability of adopting new cables.

3.4 PATH MOTOR CONTROLLERS

PA-1, -2 and -3 cars use two generations of Westinghouse motor Controllers. The original Westinghouse Controller cable specifications are not available for PA-1 and PA-2 cars. PA-3 car controllers used Hypalon cables/wires. PATH had used neoprene insulated cables CL 903 for replacement in the Controller until about 1982. Presently PATH uses EXANE cable 16 AWG through 4/0 AWG for replacement/repair purposes.

We contacted the following cable suppliers to obtain cable specifications:

(1) Pirelli Cable Corporation, Union, NJ

(2) The Okonite Company, Ramsey, NJ

(3) Champlain Cable Corporation, Winodski, VT

(4) General Electric Company, Bridgeport, CT

(5) The Kerite Company, Seymore, CT

(6) Anaconda-Ericsson, Inc., Indianapolis, IN 46240

(7) Raychem Corporation, Menlo Park, CA

(8) Harbour Industries, Inc., Selburne, VT

(9) BIW Cable Systems, Inc., Boston, MA

(10) American Insulated Wire Corporation, Pawtucket, RI

(11) ITT Surprenant, Clinton, MA

(12) Kabelwerke Friedrich C. Ehlers, Hamburg, Germany

Table 7 is a summary of the cable specifications supplied by the manufacturers (suppliers). Some of the information was obtained over the telephone and therefore not documented.

As a result of our discussion with various transit properties and organizations, the following information was obtained:

(1) Exane and LOSMOKE cables are more popular in the transit industry. However, other cables are available that might as well fit the need of the transit properties. The cable selection process by the transit industry could be significantly improved.

(2) Teflon has high abrasion rating. However, NYCTA used EFP-TEFLON for transit car power cables which cracked. The studies showed that the resins used in the cable insulation had "memory" and thermal cycling due to surges in the currents created circumferential cracking. We have no information on improvement of the resins for the particular cables.

(3) TEFZEL cables are used in the Montreal Transit System. TEFZEL claims low smoke rating and flammability.

(4) ELODUR (German) cables have very high temperature rating (800° C). However, water and oil resistance and flexibility parameters are not available in the brochure.

(5) Budd specifies Exane cables for the motor controller.

(6) BIW LOSMOKE cables have better smoke rating than Exane. However, Exane has better abrasion rating.

(7) The cable insulation "curing" is done by an irradiation or a chemical process. Manufacturers of both the processes claim superiority over the other.

CONCLUSIONS OF TASK 3

It is concluded that there are a number of brand names available for PATH which includes BIW LS-3, Flexible Exane, GEXOL F (and FX), TEFZEL etc. However selection of a particular cable would involve careful weighting of various parameters of the cables and cost. Field testing of more than one selected cable may involve extended time and monitoring costs.

RECOMMENDATIONS OF TASK 3

As stated in the report, PATH is implementing several improvements for the Controller. Additional recommendations follow:

(1) The arc chute shield requires further investigation to improve mechanical strength and durability.

(2) After consideraton of the cost and material inventory policy, PATH may conduct a field study of two or more of the following cables for the Controller as well as other car wiring: Exane, BIW LS-3, GEXOL F and FX, and TEFZEL.

APPENDIX 6.1

DEFINITIONS OF CABLE/WIRE TEST PARAMETERS*

Ignition Parameter - The ignition parameter (IP) is defined as the inverse of the ignition energy (time to ignition multiplied by external heat flux applied to the sample). By measuring time to ignition as a function of the external heat flux applied to the sample, IP is calculated and plotted as a function of the external heat flux. From the data, critical heat flux, below which ignition is not expected to occur, can also be determined.

Electrical Failure Parameter - The electrical failure parameter, EP, is defined as the inverse of energy required for electrical failure; where energy is equal to the product of time to electrical failure and external heat flux applied to the sample.

Corrosivity of The Fire Products Generated From Wires And Cables - Corrosivity was defined in terms of the cumulative corrosion to mild steel as a function of time per unit concentration of the water-soluble corrosive compounds.

Fuel Vapor Generation Parameter - The fuel vapor generation parameter (VP), is defined as the ratio of the generation rate of fuel vapors to the external heat flux applied to the sample. Thus, VP is the amount of fuel vapors generated per unit amount of heat received by the sample.

*See Reference 3.

Heat Generation Parameter - The heat generation parameter (HP) is defined as the ratio of actual heat release rate to the external heat flux applied to the sample. Thus, HP is the amount of heat produced per unit amount of heat received by the sample.

Smoke, Toxic And Corrosive Compounds Generation Parameter - The smoke, toxic and corrosive compound generation parameter (CP) is defined as the ratio of the generation rate of smoke or toxic or corrosive compound to the external heat flux applied to the sample. Thus, CP is the amount of smoke or toxic or corrosive compound generated per unit amount of heat received by the sample.

Light Obscuration Parameter - The light obscuration parameter (LP) is defined as the ratio of the optical density per unit path length corrected for dilution of smoke to the external heat flux applied to the sample.

TABLE 1

RANKING OF SINGLE CONDUCTOR MATERIALS*

Insulation Material	Ranking						
		Smoke Emission		Circuit Integrity		Overall Ranking	
	Flammability	After 4 Min.	Maximum	4 Min. Base	20 Min. Base	4 Min. Base	20 Min. Base
Asbestos	1	1	3	3	3	1	1
Mica	3	5	5	2	2	2	2
Kapton	2	3	2	6	6	4	3
Teflon (PTFE)	4	2	1	7	7	5	4
Tefzel (Polyimide)	7	4	4	9	9	7	5
Silicone Rubber	8	8	9	1	1	3	6
Tefzel	6	7	6	8	8	6	7
EPR	9	9	7	4	4	9	8
Halar	5	6	8	11	11	8	9
Polyester	11	11	10	12	12	10	10
Polyethylene	13	10	11	13	13	11	11
Polyolefin	12	12	12	5	5	12	12
PVC	10	13	13	10	10	13	13

* For definitions and test method details see Reference 5.   Rank 1 = better than Rank 2, etc.

TABLE 2

RANKING OF MULTICONDUCTOR CABLES*

Cable Insulation Description	Ranking						
		Smoke Emission		Circuit Integrity		Overall Ranking	
	Flamm-ability	After 4 Min.	Maximum	Using 4 Min. Base	Using 20 Min. Base	4 Min. Base	20 Min. Base
Teflon (FEP)-Mica/Teflon	3	1	2	1**	4	2	1
Kapton/Kapton	1	2	1	2	9	1	2
Synthetic Rubber/Neoprene	2	9	5	1**	1**	7	3
Silicone Rubber/Glass Braid	7	5	4	1**	1**	4	4
Synthetic Rubber/Neoprene (1)	10	10	8	1**	2	9	5
Halar/Halar	8	3	3	3**	10	5	6
Tefzel-Mica/Tefzel	6	4	7	1**	7	3	7
Polyethylene/Neoprene	5	8	9	1**	3	8	8
Polyolefin/Polyolefin	11	7	6	1**	5	10	9
Polyethylene/Polyethylene	4	6	10	1**	6	6	10
Polyolefin/Polyolefin (another manufacturer)	9	11	11	1**	8	11	11

*Reprinted from Reference 5.

**Exceeds Base Time.

(1) Proprietary Compound.

Rank 1 = better than Rank 2, etc.

TABLE 3

RANKING OF INSULATION MATERIALS*

Material	Insulation Resistance	Dielectric Strength	Abrasion Resistance	Dynamic Cut-through
Teflon	1	8	2	6
Tefzel	2	5	3	4
Polyolefin	3	2	1	2
Kapton	4	10	4	1
Polyester	5	7	7	3
Polyethylene	6**	4	8**	7**
Silicone Rubber	7	9	5	-
PVC	8	3	6	5
Thermoplastic		1**		
EPR		6**		
Halar		11**		

*For definitions and test method details, see Reference 5. Most of the cables passed cold bend tests.

**Very small samples.

Rank 1 = better than Rank 2, etc.

TABLE 4*
GENERAL RELATIVE RANKING OF REPRESENTATIVE WIRE AND CABLE
SAMPLES USING ETHYLENE PROPYLENE/HYPALON SELECTED
ARBITRARILY AS A REFERENCE SAMPLE

	Relative Combustibility Ranking						
Insulation/Jacket Materials	Ignition/ Flame Spread	Electrical Failure	Corrosion	Fuel Vapors	Heat	Carbon Monoxide	Light Obscuration
EPR/FR/Hypalon	1.0	1.0	1.0	1.0	1.0	1.0	1.0
EPDM/Hypalon	0.87	1.6	1.1	0.95	1.0	0.19	1.6
EPDM/Hypalon	0.87	2.5	N	N	N	N	N
EPR/Hypalon	0.82	NF	N	0.59	0.62	0.88	0.65
XLPO,FR/None	0.62	2.6	1.2	N	N	N	N
EPR/Low Smoke PO	0.58	2.1	N	N	N	N	N
EPR/XLPO,RF,Smoke Suppress.	0.56	2.2	0.54	N	N	N	N
XLPO/None	0.49	2.1	1.1	N	N	N	N
Mica-Mat,Gemex Tape/XLPO	0.49	1.6	N	N	N	N	N
EPR/Neoprene	0.49	0.30	N	0.35	0.89	0.083	0.26
XLPO/None	0.43	NF	N	N	N	N	N
EPR,FR,Low Smoke/XLPO	0.38	1.6	0.51	1.2	2.1	0.40	1.7
EPR/Low Smoke PO	0.34	0.30	N	N	N	N	N
XLPO/None	0.34	2.9	1.4	N	N	N	N
EPR/XLPO,FR,Smoke Suppress.	0.31	NF	N	0.57	1.3	0.11	0.22
EPR,FR,Low Smoke/XLPO	0.27	NF	N	0.62	1.2	0.21	0.40
EPDM/PO	0.26	NF	N	N	N	N	N
Polyrad XLPO/None	0.23	1.1	0.97	N	N	N	N
XLPO/None	0.23Z	0.40	N	0.43	0.83	0.25	0.38
EPR,FR,Low Smoke/XLPO	0.22	NF	N	0.59	0.83	0.11	0.30
Silicone,Low Smoke/PO	0.19	0.80	0.79	N	N	N	N
XLPO,FR/None	0.18	0.30	N	0.46	0.85	0.19	0.28
Silicone,Low Smoke/PO	0.17	0.50	N	0.95	0.92	1.3	1.1
Polyrad XLPO/None	0.17	0.40	N	0.81	1.2	0.88	0.92
EPR,FR,Los Smoke/XLPO	0.17	NF	N	0.46	0.59	0.060	0.17
Halar (ECTFE)	NI	1.1	N	N	N	N	N
	0.10	—	N	0.65	0.35	0.053	0.24
Halar (ECTFE)	NI	2.4	N	N	N	N	N
	N	—	3.4	N	N	N	N
Teflon (PTFE)	NI	NF	N	N	N	N	N
	0.078	0.50	N	1.1	0.56	1.1	0.00083
Teflon (PTFE)	NI	0.50	3.5	N	N	N	N
Kapton/Teflon (FEP)	NI	NF	N	N	N	N	N
ZeroHal	N	N	0.090	N	N	N	N

Samples in vertical configuration; forced normal air flow in the F M Small-Scale Combustibility Apparatus.
Ranking based on parameters for ignition, generation of combustible vapors, heat, and carbon monoxide, light obscuration, and corrosivity. Higher ranking of each parameter higher relative hazard is expected in fire.
Sample used as a reference for comparative purposes only.
Under simulated conditions of flame and external radiation for large-scale fire conditions, achieved by increasing oxygen concentration well above ambient value and also applying external heat flux.
For wavelength 0.624 of the light source (visible range)
N: Not tested.
NI: No ignition occurred.

TABLE 5

MATERIAL TOXICITY RANK-ORDER BASED ON
EQUAL WEIGHTS OF MATERIALS

Rank*	Material
1	Sil/Glass Braid
2	Silicone/PO
3	PE/Al/PVC/Grease
4	PVC
5	PE/Cu Shield
6	EPR/Neoprene
7	Exane
8	PE/Cu Shield
9	Teflon
10	EPR/Hypalon
11	Prop/Cloth/Neoprene
12	Halar
13	Tefzel
14	Kapton

*Rank 1 least toxic. Tests conducted using laboratory rats.

Data taken from Reference 6.

TABLE 6

RANK-ORDER EVALUATIONS OF TOXICITY
FOR EQUAL LENGTHS OF INSULATION
FROM EQUAL-GAUGE WIRE ASSEMBLIES*

Rank**	Insulation Material	No. of Conductors Per Assembly	AWG
*	(EPR/Hypalon)	1	14
1	(Silicone/PO)	1	12
2	(Halar)	1	12
3	(XLPO)	1	12
4	(EPDM/Hypalon)	1	12
5	(EPR/XLPO)	1	12

*Only those wire assemblies containing equal-gauge conductors are ranked as to relative toxicity.

**Rank 1 is least toxic; relative rank is based on the calculated response time for that quantity of insulation from one meter of wire. All materials in this series were of the single conductor type.

Data taken from Reference 4.

TABLE 7

COMPARISON OF PARAMETERS FOR TRANSIT CABLES

	Insulation	Temp. Rating	Smoke Generation (Ds)*		Stability in Water		Abrasion Resistance	Remarks
			Insulation	Jacket	Insulation	Jacket		
BIW LS-3 0.6/2.0 kv	Silicone rubber XLPO jacket	125°C	4 Min:50 Max (flaming & non-flaming)	4 Min:50 Max (flaming & non-flaming)	168 hrs. at 70°C - 10 mg/in max absorption	168 hrs. at 70°C - 35 mg/in absorption	-	Non-halogenated
PYRO-FLODUR 0.6/1.0 kv	Silicone rubber XL elastomer compound	800°C (3 hrs)	Low smoke less than 0.1 of PVC	Low smoke less than 0.1 of PVC	Not known	Not known	-	Non-halogenated
FLEXIBLE-EXANE 2.0 kv	Polyolefin	110°C	4 Min (12 AWG) 100 Max (non-flaming) 200 Max (flaming)	4 Min (12 AWG) 100 Max (non-flaming), 200 Max (flaming)	ICEA-S-61-402: 5 mg/sq in	ICEA-S-61-402: 5 mg/sq in	7,428-11,876 scrapes (Test similar to UL.)	PATH (in use)
AMERICAN WIRE CL 903 0.6 kv	Neoprene	90°C	-	-	-	-	-	PATH (used until 1982)
AMERICAN WIRE 9528 0.6/2.0 kv	EPR Hypalon (jacket)	90°C	-	-	-	-	-	-
GEXOL F (AND FX) 2.0 kv	Cross-linked Polyolefin	125°C	4 Min:200 Max	4 Min:200 Max	ICEA EM-60**: 3.0%	ICEA EM-60**: 3.0%	GE MAT 122-A: 1150 cycles	No chlorine content
ANACONDA LSNH EP-PO 0.6/2.0 kv	EP insulation XLPO jacket	90°C	4 Min (12 AWG): 4 (non-flaming) 21 (flaming)	4 Min 150 (flaming), 150 (non-flaming)	ICEA EM-60: 10%	ICEA EM-60: 10%	UL 719: 1000-2000 cycles	Non-halogenated

*Ds = Specific optical density NFPA 258 or ASTM 622.
**ICEA = EM-60: percentage increase in capacitance (1-14 day).

APPENDIX 7

ARCING PHENOMENA

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ARCING PHENOMENA

(1) <u>ELECTRIC ARC DESCRIPTION</u>

Reference (10) describes an electric arc as follows:

"An electric arc is an incandescent vapor bridge consisting of material electrically impelled from a negative to a positive electrode. A spark is also an incandescent vapor bridge, but differs from an arc in not depending upon the electrodes for its material medium. The establishment and maintenance of an arc require the expenditure of energy for the latent heat of evaporation of the electrode and for the motion of the vapor stream. As no energy can be expended for these purposes until a current flows, an arc cannot start spontaneously. The following expedients are, therefore, adopted to start arcs:

(1) Bringing the electrodes into contact with each other and separating them after the current has commenced to flow.
(2) Stressing the dielectric between the conductors by overvoltage until it breaks down electrically and becomes conducting.
(3) Using a subsidiary arc to furnish the initial vapor bridge.

"A peculiarity of the carbon arc is that, with any particular length of arc, if the current is increased the difference of potential across the carbons will decrease. This occurs continously up to a certain point, when in the open arc the voltage drops quite suddenly. If the current is still increased the voltage will again become steady at a much lower value. Between the values before and after the drop the arc is unstable and emits a hissing sound. In inclosed arcs the hissing point is absent and the curve is continuous.

"The relation between the drop of potential across the arc and the current flowing through it depends upon whether the arc is in the steady state corresponding to the current flowing or whether the current has been changed without giving time to the vapor column and electrodes to accommodate themselves to the new strength of current. Let v be the drop of potential across an arc, and i be the current flowing. If the current is decreased at a rate rapid enough so that a steady state is not set up, then dv/di is the resistance of the arc to the rapidly changing current. Throughout ordinary ranges of frequency (less than 100 kHz) the ratio dv/di is negative. Thus the a-c resistance of an arc is negative and is a function of the current."

(2) COHERER EFFECT

The Coherer effect was discovered by Sir Oliver Lodge, who found that when electrical oscillations occurred between metallic particles in poor contact, the resistance of the particles fell to a very small amount. See reference (11).

Thus, if metallic particles are present in the motor controller box, electrical pulses or sparks (oscillations) may cause the particles to cohere, thereby providing a path for an arc to form.

(3) UNIVERSITY OF SHERBROOKE TESTS

The work of Professor Beland of the University of Sherbrooke is described in reference (12) as follows:

"If one creates a short circuit on a 120/240 volt circuit with fuses or circuit breakers of 15, 30, or 100 amperes, one cannot melt the conductors more than superficially. However, if a live cable is put into a fire of some intensity, one observes the following:

(a) The insulation is gradually melted or consumed depending on its nature.

(b) When the insulation is partly destroyed, some small spurious arcs begin between the conductors. This part of the phenomenon occurs randomly and in some cases, is absent.

(c) Eventually, an arc is started between the conductors, without physical metallic contact between them. This arc is similar to the one obtained in electric arc welding. These events occurred systematically using cables such as metallic or non-metallic sheathed cables, extension and lamp cords of different sizes, makes and kinds."

Beland states that: "A short circuit is not very likely to start a fire. In a short circuit, although the current might be very high (hundreds or thousands of amperes), the voltage is low (fraction of a volt). Therefore the available power is small. Furthermore, the protecting device will open the circuit in a very short time so that total energy is extremely small and very unlikely to start a fire, or even to melt inches of conductor."

In addition Beland points out that:

"An arc can have a very high energy in a small volume and reach temperatures of several thousand degrees as seen in arc welding. The current is much lower than in the case of the short circuit because of the limiting effect of the arc itself. Because of this limited current, the voltage is close to the power source voltage and, depending on the current, the arc can last for quite a long time. The power and energy in the arc are sufficient to melt the conductor over an appreciable length."

APPENDIX 8

CONTROLLER OPERATIONAL PROTOCOL

APPENDIX 8

CONTROLLER OPERATIONAL PROTOCOL

The Controller box contains a Line Switch and Overload Relay, a Reverser, a Series-Parallel Controller, a Power Brake Controller, a Cam Controller, a Limit Relay, a J Contactor and Resistor, and S1 and S2 Contactors. Major items are described below.

LINE SWITCH AND OVERLOAD RELAY

The Line Switch conducts current to the motors from the +600 volt third rail shoe. The Overload Relay is set to open the Line Switch in the event of an overload, and is set to operate at 1200 amperes.

REVERSER

The Reverser acts to reverse the motor fields with respect to the armatures to cause the motors to rotate in a direction opposite to the previous direction of rotation.

SERIES-PARALLEL CONTROLLER

The Series-Parallel Controller acts to connect all four motors in series at starting or to connect them in series-parallel during running, where two motors on one truck are in series with each other, and these are connected in parallel with the other two series-connected motors of the other truck.

POWER BRAKE CONTROLLER

The Power Brake Controller operates in conjunction with the Line Switch. It closes before the Line Switch closes, and opens after the Line Switch opens. It is normally used as a "power" to "brake" controller.

During braking, the motors are connected as generators. The output of the "generators" is fed to a braking resistor bank, which provides a braking force to decelerate the train. Greater braking effort is obtained by shorting out the braking resistor in steps.

Note that the output of the first motor on a truck excites the field of the second motor on the truck, and the output of the second motor excites the field of the first motor. This "cross-excitation" provides stabilizing and equalization of "generator" output.

CAM CONTROLLER

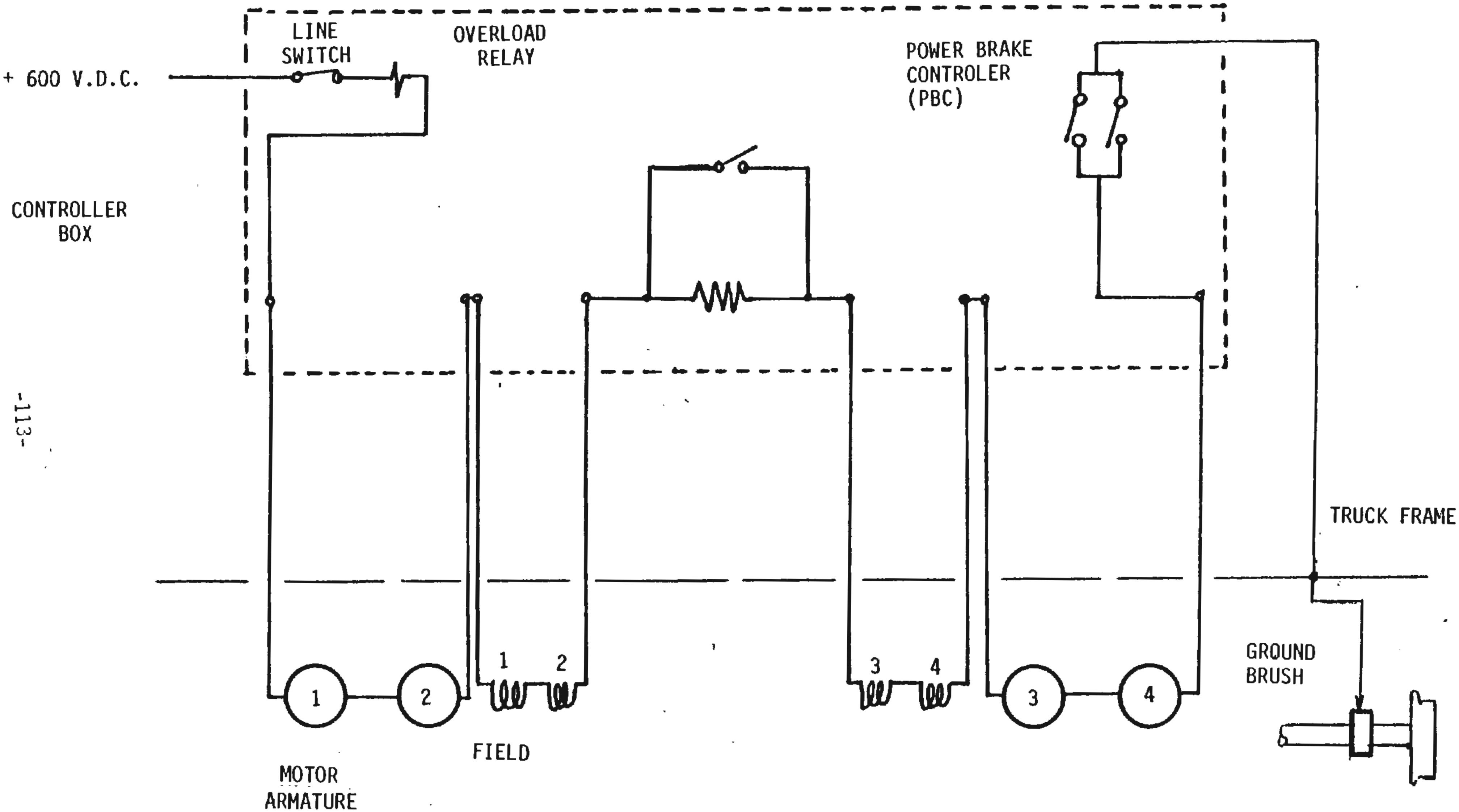
The Cam Controller consists of cam switches and interlocks. The cam switches are connected in the accelerating resistor circuit, the braking resistor circuit and the traction motor field circuits.

LIMIT RELAY

The Limit Relay acts to maintain the desired acceleration and braking currents of the car. It performs these functions by controlling the voltage to the Cam Controller which inserts or cuts out resistance to the traction motor circuits in acceleration or brake.

CONTROLLER DIAGRAM

Figure 1 is a simplified diagram of the high current portions of the Controller box for the case where the car is starting up. All four motors and fields are connected in series, and maximum resistance is in the motor circuit. A similar diagram applies during running, except that two motors of one truck are in series and these are connected in parallel with the two series-connected motors of the other truck. The Power Brake Controller (PBC) and Line Switch remain the same for both starting and running. Some arcing effects at the Controller box metal hinge (about 8" from the PBC) has been observed, possibly caused by inadvertent opening of the PBC contacts before the Line Switch opens.



PATH PA-3 CAR

SIMLIFIED STARTING DIAGRAM - FOUR MOTORS IN SERIES

FIGURE 1

APPENDIX 9

PATH PROPOSAL AND WORK STATEMENT

APPENDIX 9

PATH PROPOSAL AND WORK STATEMENT

INTRODUCTION

At 7:10 a.m. on March 16, 1982, the Motorman on the 7:03 a.m. PATH train from Hoboken, New Jersey to 33rd Street in Manhattan reported to the PATH Trainmaster that he believed there was something burning in the second car of his (seven car) train. The Motorman had stopped the train in accordance with standard procedure. The train had just crossed under the Hudson River into New York and was approximately 50 feet west of the Morton Street emergency exit and 1500 feet west of the nearest station, at Christopher Street in Manhattan. At 7:12 a.m., a power outage occurred in the tunnel section where the train was located. Following an attempt to restore power and a report by the Motorman that he thought the problem had been solved, the Trainmaster requested the Motorman to proceed to Christopher Street to discharge passengers.

At 7:20 a.m., the Motorman reported that he had not been able to move the train and that the smoke was getting heavy. He was given permission by the Trainmaster to begin evacuation through the Morton Street emergency exit. The evacuation proceeded slowly from the front of the train; it was hampered by the use of a narrow emergency ladder from the train to the tracks, by the heavy smoke, and by the steep circular stairs in the exit shaft.

New York Fire and Police Department personnel arrived at the street level entrance to the Morton Street emergency exit at 7:30 a.m.

but the Fire personnel were unable to get down the stairway because passengers evacuating the train were ascending the stairs. Accompanied by PATH Police, the New York Fire Department personnel proceeded to the Christopher Street station, where they entered the tunnel. Passengers in the rear cars of the train on the other side of the fire car from the emergency exit, were unable to pass through the train because of the heavy smoke. PATH police reached the rear car of the train at 8:01 a.m., and assisted those passengers through the train and up the emergency exit. By 8:07 a.m. all passengers were off the train and the fire was extinguished by New York Fire Department personnel. By 8:17 a.m., all passengers were out of the tunnel.

Of the approximately 400 passengers on the train, 80 were treated for smoke inhalation; of the 80, 55 were taken to area hospitals and of these, two were admitted. Six PATH employees and police officers were taken to the hospital and four were admitted. The longest hospital stay was one week. There were no fatalities.

THE INVESTIGATION

Immediately after the fire, on March 16, PATH Vice President and General Manager, Francis A. Gorman, appointed a committee of Port Authority and PATH representatives to investigate every aspect of the fire and passenger evacuation. The Committee's charge was to: 1) determine the cause of the fire; 2) document the evacuation of passengers and the response of PATH staff and other emergency forces to the scene; 3) evaluate the adequacy of PATH's standard operating procedures and the extent to which they were adhered to in the incident; 4) identify any corrective measures required; and 5) report its findings and recommendations to the Vice President and General Manager as soon as possible.

The Committee interviewed a number of passengers who were on board the fire train, as well as PATH personnel and PATH police involved, and members of the New York Fire Department who responded to the fire. Transcripts of radio and telephone conversations were reviewed, together with the defect/maintenance history of the fire car and PATH's car maintenance procedures. A consultant, Lucius Pitkin, Inc., was retained to conduct metallurgical tests on some of the under-car equipment in the fire car. A separate investigation of the incident was conducted by the National Transportation Safety Board.

In its report, issued in May 1982, the Committee listed nineteen findings and conclusions. Among these were determinations that manpower and response and adherence to procedures was good, with the major exception of a 13 minute delay in notifying the New York Fire Department when the Motorman first reported the smoke condition. The established procedures is - and was, at the time of the fire - for the Trainmaster to request the Police to advise the Fire Department immediately. The committee found that the new tunnel lighting was very useful, but that on-train emergency lighting needed improvement. It also determined that the emergency rescue equipment initially on the scene was inadequate, that the evacuation ladder slowed the evacuation and the emergency exit both slowed the evacuaion and prevented police and fire personnel from reaching the train quickly.

Regarding the cause of the fire, the Committee found it to be electrical in origin but concluded that "neither the initiating components nor the sequence of the fire progression could be specifically determined." However, the most severe damage was in the area of the motor controller, and the Committee concluded that the controller was most likely the source of the fire.

CONTROLLER UNIT INVOLVEMENT

The fire destroyed the motor controller as well as all power and control cables and air lines in the vicinity of the controller. The car floor and under-frame structure were also damaged and a 11 x 14 inch hole burned through the car floor in the area above one end of the controller. The controller, which directs operation such as speed, direction and braking, is comprised of a number of components. Of these, the power brake controller, the series parallel controller and the cam controller sustained the most damage. The aluminum channel sections which support the motor controller were also severely damaged. A survey revealed that power and control wiring beyond the area of the controllers was also damaged.

COMMITTEE RECOMMENDATIONS

Based on its findings and conclusions, the Committee made 21 recommendations in its report. Several of the recommendations concerned the reevaluation of existing procedures or institution of new procedures, including: the termination of all train operations on the system during passenger evacuation, to avoid moving more smoke into the fire area; re-instruction for all Control Center and Police personnel; and evaluating the adequacy of emergency response staffing. These have all been acted upon, and PATH is preparing a manual of routine and emergency operating procedures. A number of other recommendations concerned providing better or additional equipment for emergency evacuation. These include redesigning tunnel wall-mounted and car-borne evacuation ladders and making all ladders more accessible; designing a light-weight evacuation ramp; eliminating an energy-saving feature which shut down emergency lights; improving the communication systems in PATH tunnels and further training for operational staff. In addition, work is continuing on two projects underway prior to the fire - the installation of an emergency tunnel ventilation system to remove smoke and provide fresh air, and the construction of new emergency access/egress stairways.

With regard to fire protection and prevention in the cars themselves, the Committee made four major recommendations. Two which related to fire barriers were: (1) continue studies to determine the need for additional protection for the power and control cables and air lines in the vicinity of the motor controller; and (2) insert a fire retardant material between the car's under-floor surface and control and power cables. In response, barriers have been installed and valves are presently being installed which will close off the air supply in the vicinity of the controller during a fire. With regard to the motor control group, the Committee advised that inspections be made more detailed; expanded inspections were instituted a week after the fire. The Committee called for a study of the design of motor controller units, including the feasibility of installing heat sensors or alarms. It also recommended "an industry-wide review of the fire safety aspects of the controller units."

<u>APTA TASK FORCE</u>

In accordance with the Committee's recommendation, PATH requested the American Public Transit Association (APTA) to establish a Task Force of representatives from transit systems and controller unit manufacturers. The Task Force, funded by the Transit Development Corp., Inc., met in January 1983. Its two main purposes were: (1) to identify the extent of control group fires, review preventive maintenance, rebuilding and repair programs; and (2) identify design, construction and maintenance practices for controls.

After reviewing the control group fire experiences of all the represented transit systems, it was apparent that controller fires present a hazard to all rapid transit systems. Each of the properties has instituted a program to rehabilitate controllers, but these programs vary depending on site-specific circumstances. Two working groups, on maintenance and design, were established by the Task Force. The efforts of each group are under way and a final report is in preparation.

PATH PROPOSAL - SUMMARY

While the findings of the Task Force are expected to be of benefit to PATH as well as to other rapid transit systems, PATH also determined that an in-depth study of its own controller equipment would yield valuable information. This approach was consistent with one of the recommendations of the PA/PATH Committee which investigated the PATH fire, and it builds upon both the work of the APTA Task Force and work undertaken at the Washington Metropolitan Area Transit Authority (WMATA).

The PATH study will involve five tasks. Task 1, to be performed by Parsons Brinckerhoff Quade & Douglas, Inc. (Parsons), will involve the development of "fault trees" for the controller unit, based on likely malfunctions. The task will also include a failure mode and effects analysis (FMEA) as input to the fault trees. Parsons will also install thermocouples on four controllers to measure actual temperatures experienced in the controller unit, information which is believed to be critical to the safe and proper operation of the controller. Task 2 will involve PATH's on-going review of Parsons' work and coordination with them. Task 3 will identify the controller unit materials and their properties to determine whether or not the best material is in use. This task will be performed by the Transportation Systems Center (TSC). The work in Task 4, to be performed by Parsons, focuses on another major problem associated with possible controller malfunction. Arcing from the control box to the car body causes severe erosion of the body of the mounting bolts. The final task, Task 5, includes task coordination, PATH costs and out-of-pocket expenses for travel, report typing and report reproduction.

The nature of the controller problem is unknown and thus the solution to the problem - and even whether one exists, short of total redesign and replacement - is also unknown. For this reason, the implementation of the project's recommedations cannot be planned until the causes and solutions are determined. While implementation is outside of the scope of this project, to the extent possible, PATH will plan to implement the study's findings.

SCOPE OF WORK

The PATH controller fire incident occured on a PA-3 car. This series car was in revenue service for about ten years without any kind of similar situation developing. The other series (PA-1 and PA-2) cars in the PA car fleet are older and have not experienced any kind of controller incident approaching the magnitude of the car #725 fire. The present PA series fleet numbers 248 cars, of which 158 are PA-1's, 44 are PA-2's, and 46 are PA-3's. The PA=1 and PA-2 series each have an "A" type and a "C" type. All PA-3 cars are "A" type. The propulsion - control system is essentially the same Westinghouse Electric Corporation equipment in all three series of cars.

While PATH is fortunate in that it had only one serious failure, the preliminary report of the APTA Task Force confirms that controller system failure is not unique. Every rapid transit property has experienced controller failure to some degree. However, only "band-aid fixes" have been developed for these problems.

WORK STATEMENT

Following is PATH's detailed Work Statement.

TASK 1 - FAULT TREE ANALYSIS, TEMPERATURE MEASUREMENT AND FMEA

A thorough understanding of the motor controller functions and sequencing is central to resolution of the problems being experienced. This understanding can be achieved by considering the controller as the sub-system whose function is to switch the large currents and high voltages involved when the cam sequences and circuits are initiated by positioning of the master controller handle.

The work in this task is sub-divided into four phases. The first phase of this Task 1 activity will be to study the normal operational protocols of the controller. This will involve review of the pneumatic, electrical, and mechanical components and their operation and sequencing in response to the master controller. The work will also include analysis of the spatial relationships among components, cabling, etc. within the motor controller box, and in the undercar areas adjacent to it. The second phase involves a Failure Mode and Effects Analysis (FMEA). Several system and sub-system malfunction conditions will be assumed and the effects of each failure mode will be analyzed to determine which failure conditions are most likely.

The object of the third phase will be a determination of actual temperatures developed in a controller. This effort will complement tests made on the WMATA system. WMATA made temperature determinations at cable locations exterior to the controller box and in various resistor grid locations. By contrast, this effort will be directed toward temperature determinations within the controller box itself, under operating conditions.

Insofar as PATH has five different types of PA cars, it is intended to make temperature determinations on each type. However, since the PA-1 and PA-2 purchases were (except for cosmetic changes) the same cars, only one PA-1 "A" car, one PA-1 "C" car, one PA-2 "A" car, and one PA-2 "C" car may be sampled. In addition, three PA-3 cars may be sampled (all PA-3 cars are "A" cars) in order to provide valid sampling data.

Working with Parsons, it is anticipated that temperature determinations will be made by use of heat sensitive labels to record the maximum temperatures that are reached, and the locations where they are experienced. Because this determination does not record the rate of temperature rise, duration of temperature, or even peak temperature, its use is limited to establishing controller box areas for which further testing is warranted.

These high temperature areas of interest will then be subject to further tests, with installation of thermal sensors connected to recorders in order to obtain a time/temperature history. PATH intends to install these devices in approximately five locations, dependent upon results of the heat sensitive label applications. The thermal sensor leads will be run up to a non-operating cab in which temperature conditions in the motor controller box will be monitored and recorded. These five locations will be tested on four cars, for a total of 20 thermocouples.

It is not anticipated that these temperature tests will record either excessive temperatures or an incipient failure condition. What is expected, however, are indications of the potential for a failure to develop in the future. These possible downstream failures may be heralded by rate of temperature rise, temperature levels that are reached, and most importantly, the length of time high ambient temperatures are maintained.

The fourth phase of task activity will be to utilize likely malfunction scenarios developed in the FMEA. Several most likely fault trees will then be developed and analyzed as to their causes.

The purpose of this phase is to develop several credible scenarios based on malfunction conditions derived from the Failure

Mode and Effects Analysis (FMEA). Fault tree analysis will be logical event sequences that can result in fire hazards. The result of the FMEA, the temperature measurements discussed above, and the findings in Task 3, Determination of Material Characteristics, will be used in the fault tree analysis.

The product of Task 1 will be a report prepared by Parsons that summarizes conclusions and recommendations, integrating them with the conclusions of Task 4, Arcing.

Parsons Brinckerhoff Quade and Douglas, Inc. (Parsons), an engineering/planning consultant, has been retained by PATH to undertake an extensive review of PATH's car fleet and to make recommendations regarding the purchase of new vehicles and the overhaul of existing cars. Parsons began this work in March, 1983 and their report is scheduled to be completed by December, 1983. A new contract is being written for additional work and will include the motor controller investigation. It is appropriate that Parsons be retained to perform Task 1.

Parsons' analysis includes a determination of the useful life of PATH's 250 PA-series cars without overhaul, and the costs and benefits of overhaul. This includes performing a detailed assessment of the car materials and components to improve the cars' systems. As part of its study, Parsons is evaluating the car wiring and the fire retardancy of the cars' insulation.

In the ten months that Parsons has been performing the PATH car evaluation, they have accumulated a wealth of knowledge regarding PATH's car fleet. Their evaluation has included examining nine fire-damaged cars, including car number 725, damaged in the March 16, 1982 fire. Parsons is thus intimately familiar with all aspects of PATH's PA-series cars, including the contoller unit, fire prevention and retardancy considerations and the specific fire damage to the motor controller unit fire car. The work performed by Parsons during this time represents a significant resource of accumulated knowledge about PATH's car equipment which would be time-consuming and costly for another consultant to acquire. Their performance of this task will result in timely completion of this important aspect of the study.

Fire safety is a major concern of PATH. Engaging Parsons to perform this work would, in addition to the reasons stated above, allow PATH to accelerate this aspect of the safety programs and to enhance the system safety as quickly as possible.

TASK 2 - COORDINATION WITH CONSULTANT

Task 2 includes all PATH and Port Authority staff coordination with the consultant, Parsons Brinckerhoff Quade & Douglas. Staff work involves assisting in the development of test plans, reviewing and approving them, including the identification of locations for the temperature testing and mnonitoring equipment. This includes preliminary temperature determination for subsequent location of thermocouples. Task 2 also includes internal staff review and approval of Parsons' final report for Tasks 1 and 4.

TASK 3 - MATERIAL INVESTIGATION

One important area for investigation of controller failures is whether materials or components are used that are marginal for their application. This may be the result of environmental conditions within the undercar controller box which, over a period of time, cause degradation of electrical and/or physical properties of materials and components otherwise satisfactory.

This task will determine the characteristics of representative materials and ocmponents in the controller box. In achieving this, PATH anticipates that it will work closely with the UMTA Transportation Systems Center (TSC). It is understood that TSC's date bank is available, as a resource, to identify these characteristics.

In addition, as part of this task effort, it is intended to contact the Factory Mutual Research Corporation (FMRC) to find out what information is available in its library that relates to material and components.

Results of material investigation will confirm the suitability of materials for their use in the controller. This investigation will identify the materials used in PATH's controller, both as supplied by the Original Equipment Manufacturer (OEM) and utilized by PATH as part of routine maintenance, i.e., wire and cable changeout. The appropriate electrical and physical characterristics will be tabulated, along with the actual design environment conditions established through discussion with the OEM and as a result of the temperature determinations and the malfunction conditions described in Task 1.

TASK 4 - ARCING

During the course of the PA car inspection program, it was discovered that arcing has been occurring in the area of the control box clearance holes and control box mounting bolts, causing severe wear to the body of approximately half of the bolts inspected. While it is apparent that the arcing occurs over a period of time and that the bolts are not damaged by one continuous arc, it is not clear what starts the arcs or what extinguishes them. Parsons' investigation of several of the PATH cars involved in fires indicates that the area adjacent to the line switch (in the controller) must have experienced tremendous heat and that in one case, continuous arc burned a hole through the metal case. In this task, Parsons will measure the voltages and currents that exist during a fault occurrence, and will investigate the line switch as the possible source of the problem. While the damage caused by arcing is a specific known problem, the cause of the arcing is undetermined. It is clear, however, that the solution of the arcing problem may well be a significant step toward the avoidance of control group fires.

TASK 5 - ADMINISTRATION

This final task will be used to accumulate all PATH staff costs other than those directly associated with the consultant's work. This will include administration and coordination of Tasks 1, 3 and 4, out-of-pocket costs for travel, temperature sensors and typing and reproduction of the final report.

The project is expected to take approximately one year to complete. The data collection, analytical work and temperature test program will extend over nine months.

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