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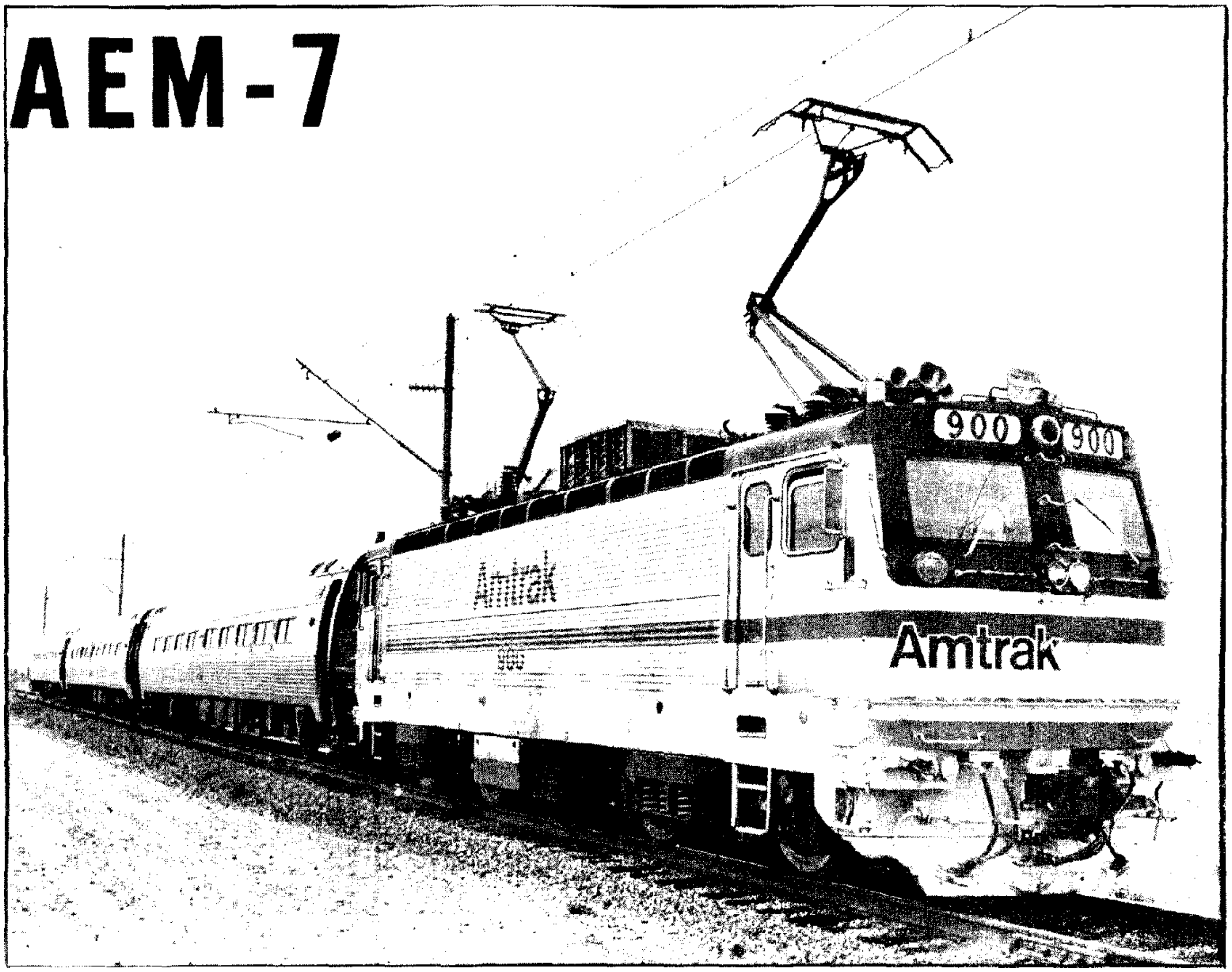
Federal Railroad Administration

AEM-7



ELECTRIC LOCOMOTIVE TESTING AT THE TRANSPORTATION TEST CENTER

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FRA/TTC-81/08		

4. Title and Subtitle

AEM-7 Electric Locomotive Testing
at the Transportation Test Center

5. Report Date

6. Performing Organization Code

7. Author(s) Peters, A. John; Washburn, Raymond P.; Kovacs, Paul E.; Grebenc, James W.

8. Performing Organization Report No.
TTC-15

9. Performing Organization Name and Address

Transportation Test Center
P.O. Box 11449
Pueblo, CO 81001

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address

U. S. Department of Transportation
Federal Railroad Administration
Office of Intercity Programs-RRI-1
400 7th St., S.W.
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report, FY79-81

14. Sponsoring Agency Code
DOT

15. Supplementary Notes

Dynalectron Corporation, Operations and Maintenance Contractor, Federal Railroad Administration, Transportation Test Center, Pueblo, Colorado, Contract No. DOT-FR-67001. Completed under Contract DTFR-80-C-20016, Boeing Services International.

16. Abstract

This report describes the tests conducted at the Transportation Test Center (TTC) on the first production AEM-7 locomotive, AMTRAK 900. These tests, which were conducted between April 1980 and May 1981, were to evaluate the locomotive characteristics on 25 kV 60 Hz and 12.5 kV 60 Hz voltage supplies, and to examine the locomotive reliability under high speed operating conditions.

The accelerated Northeast Corridor (NEC) schedules (2 hrs 40 min from New York to Washington, D.C., and 3 hrs 40 min from Boston to New York) were used for the Endurance Test Operations. A route simulator programmed with the Train Performance Calculation (TPC) predicted speed/time profile was used to prompt the locomotive engineer. A train consist of between four and eight cars was used for the test. The actual trip times and energy consumed were measured.

Major problems were experienced with the locomotive pantographs, truck assemblies wheel bearings, traction motors, and ground brush assemblies. A new phase break operating procedure was initiated to significantly reduce the AMFLEET car light flicker. It was found that the locomotive could meet the NEC accelerated schedule while using less energy than predicted. The total mileage accumulated at the TTC was 156,200 miles.

17. Key Words	18. Distribution Statement
Phase break, pantograph, catenary, route simulator, trip time, power factor, power consumption, current harmonics, electric locomotive, light flicker.	This document is available to the public through the: National Technical Information Service 5285 Port Royal Road Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	363	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The authors wish to thank the following organizations for their cooperation and assistance throughout the AEM-7 test program.

Federal Railroad Administration, Northeast Corridor Project Office
Federal Railroad Administration, Office of Research and Development
National Railroad Passenger Corporation (AMTRAK)
General Motors, Electromotive Division
Allmänna Svenska Electriska AB (ASEA)
Japanese National Railways

In particular, the support provided by the following individuals was much appreciated.

M. C. Gannett	(FRA/OR&D)
K. M. Watkins	(AMTRAK)
T. Kawazoe	(JNR)
J. W. Marchetti	(J.W. Marchetti and Associates)
J. Harrison	(Bechtel, Inc.)
L. Wedin	(ASEA)
W. P. McCutchon	(FRA/TTC)

Finally, the authors also wish to acknowledge the efforts of both the full time members of the test team and the part time support groups at the TTC who contributed to the success of the program.

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LIST OF ACRONYMS AND SHORTENED NAMES

AAR	Association of American Railroads
ABB	Air Blast Breaker
ACSR	Aluminum Conductor, Steel Reinforced
ACT 1	Advanced Concept Train
AMFLEET	National Railroad Passenger Corporation (fleet indentifier)
AMTRAK	National Railroad Passenger Corporation (corporate name)
APL	Auxiliary Power Load
ASEA	Allmänna Svenska Elektriska AB (corporate name)
BICC	British Insulated Callander Construction
BR/BW	British Rail/Brecknell Willis (Ringsdorff-BR/BW in U.S.A.)
CCW, CW	Counter Clockwise, Clockwise
CT	Current Transformer
CWR	Continuously Welded Rail
CSB	Center Services Building
ECAC	Electromagnetic Compatibility Analysis Center
EMD	Electromotive Division (General Motors)
FAST	Facility for Accelerated Service Testing
FRA	Federal Railroad Administration
FRAS	Failure Reporting and Analysis System
GEP	Great Extension Pantograph (Main stage, tr. from French)
GM	General Motors
HEP	Head End Power
IRIGB	Interrange Instrumentation Group (B Type Time Code)
LEP	Low Extension Pantograph (Second stage, tr. from French)
LOC	Loss of Contact
NEC	Northeast Corridor
NECPO	Northeast Corridor Project Office
NECIP	Northeast Corridor Improvement Project
OCB	Oil Circuit Breaker
OIP	Office of Intercity Projects
OR&D	Office of Research and Development
PT	Potential Transformer
PTACV	Prototype Air-Cushioned Vehicle
RAPT	Radial Axle Passenger Truck
RTT	Railroad Test Track
SEPTA	Southeastern Pennsylvania Transportation Authority
SNCF	Société Nationale de Chemin de fer Française (French National Railways)
SOAC	State-of-the-Art Car
TDT	Train Dynamics Track
TGV	Turbotrain très Grande Vitesse (high speed train)
TMM	Traction Motor Module
TPC	Train Performance Calculations
TSC	Transportation Systems Center
TTC	Transportation Test Center
TTT	Transit Test Track
UV	Ultra Violet (Arc Detector)
VC/PB	Voltage Change/Phase Break

ABBREVIATIONS, SYMBOLS, AND METRIC EQUIVALENTS

a.c.	Alternating current
B	Magnetic flux density
dB	Decibel
dBA	Decibel, A-weighted
d.c.	Direct current
°F	Degrees (°F-32) 5/9 = °C
ft	Feet
G	Gauss
g	Gravitation force constant
h,hr	Hour(s)
H	Magnetic field strength
hp	Horsepower = 746 W or 550 ft lbs/sec
Hz	Hertz
If	Field current
",in	Inch = 2.54 cm
kA	Kiloamps
kV	Kilovolt
kW	Kilowatt
kW hr	Kilowatt hour
λ	Lambda = effective conicity
lb	Pounds = .45359 kg
lb ft	Pounds feet (torque)
m	Meter
mi	Mile = 1.6129 km
mi/h	Miles per hour
min	Minutes
ms	Milliseconds
MVA	Mega volt amps
MW	Megawatts
N	Armature speed
#	Number
ϕ	Phi = Reference angle for polar coordinate system
Ω	Omega (Ohms) = unit of electrical resistance (Impedance)
P	Input Power
PSD	Power Spectral density
psi	Pounds per square inch
RMS	Root-mean-square
rpm	Revolutions per minute
%	Percent
s,sec	Seconds
U	Armature voltage
V	Velocity
V/A	Volts per amp
VA	Volt amps
VAR	Reactive power
W	Resistive power
yd	Yard

EXECUTIVE SUMMARY

Introduction

During 1979, the Railroad Test Track (RTT) at the Transportation Test Center (TTC), Pueblo, Colorado, was electrified as part of a project funded by the Northeast Corridor Office of Intercity Programs. The purpose of this project was to provide a facility for the evaluation of electric vehicles in support of the Northeast Corridor (NEC) Improvement Project.

A series of pantograph current collection performance tests were carried out in 1980 in order to check the current collection performance of the RTT catenary system. These were followed by a further series of pantograph tests aimed at evaluating the effect of temperature change on the Style 1 and Style 3 catenary designs. Also, the electrical characteristics of the catenary and substation were determined, after which the electrified RTT was considered ready for electric locomotive testing.

The first production AEM-7 locomotive, AMTRAK 900, was delivered by General Motors to AMTRAK in February 1980. After acceptance testing on the NEC by AMTRAK and General Motors, this unit was delivered to the TTC for further extensive testing.

Test Objectives

The test on the NEC had been designed to fully evaluate the AEM-7 locomotive on a line voltage supply of 11 kV 25 Hz. The tests at the TTC were designed to augment the NEC tests by first evaluating the locomotive characteristics on voltage supplies of 25 kV 60 Hz and 12.5 kV 60 Hz, then evaluating the reliability of the locomotive design during the Endurance Test. The major objectives of the Characteristic Test included:

- The measurement of the electrical energy requirements of the locomotive.
- The measurement of the harmonic content of the catenary current.
- The measurement of the locomotive transformer inrush and starting currents.
- The evaluation of the operation of the locomotive over phase breaks.
- The examination of the operation of the locomotive at the high and low limits of the catenary voltage.

The endurance test was originally planned to accumulate 250,000 miles in approximately 36 weeks, a very optimistic target. Included in the detailed objectives of the endurance tests were:

- The determination of the capability of the AEM-7 locomotive to consistently maintain the 2 hour 40 minute New York-to-Washington schedule and the 3 hour 40 minute Boston-to-New York schedule.

- The examination of the long term reliability of the locomotive systems and components under high speed operation.

- The evaluation of the locomotive maintenance procedures.

- The examination of the reliability of the locomotive voltage change/phase break control system under repeated operation.

- The measurement of the effect of wheel wear on the locomotive ride.

Based on a policy of continually upgrading the test plan as problems arose, additional test objectives were added during the course of the test program. These included:

- The evaluation of modifications to the Faiveley DS 11 pantographs, the standard units for the AEM-7 locomotive.

- The evaluation of the British Rail/Brecknell Willis (BR/BW) High Speed Pantograph.

- The evaluation of alternative phase break designs and operational procedures to eliminate AMFLEET car light flicker and locomotive auxiliary rotating machinery shutdown at phase breaks.

- The evaluation of traction motor brush material and brush pressure.

- The measurement of ground brush return current distributions.

- The measurement of dead line loss of contact and pantograph arcing of the Faiveley DS 11 and BR/BW pantographs on the RTT catenary systems including a section of graded catenary to simulate a bridge approach.

Participating Organizations

A number of organizations were involved in the total test program. These included General Motors and ASEA (the joint manufacturers and designers of the locomotive), AMTRAK (the official purchaser of the locomotive), and NECPO (the sponsor of the NEC improvement project). The program was coordinated by the Federal Railroad Administration's Office of Research and Development (FRA/OR&D), and conducted by the Transportation Test Center (TTC). In addition, a number of equipment manufacturers and consultants provided information and assistance during the test program.

The Characteristic Test Results

The measurement of transformer inrush currents proved to be more difficult than first envisaged. Initially, inrush currents were monitored by opening and closing the locomotive main breaker with the locomotive stationary. After a large number of breaker operations during which no large inrush currents were measured, this test method was abandoned. An alternate method of monitoring the transformer current during a large number of phase break operations was adopted. This not only provided the maximum inrush current levels over a large number of samples, but also provided a statistical measure of inrush current occurrence under varying operating conditions. The maximum inrush currents measured during this survey were:

- 600 A at 12.5 kV 60 Hz.
- 400 A at 25 kV 60 Hz.

The locomotive energy requirements, the catenary current harmonic content, and the operation at the catenary high and low voltage limits were all investigated using the data from a series of acceleration tests.

The major findings of the energy related tests were:

- The maximum power drawn by the locomotive (measured at the pantograph) was 6.71 MW at a speed of 56 mi/h. The maximum power factor was 0.83 which was attained at a speed of 95 mi/h.

- The relative magnitudes of the AEM-7 primary current harmonics are substantially independent of both locomotive speed and RMS current level.

- The AEM-7 continued to operate over the +10% to -25% of nominal voltage range on both 12.5 kV 60 Hz and 25 kV 60 Hz supplies. However, below the -25% level severe traction power reduction was noted. At the -35% level, the battery charger ceased to function and the auxiliary voltage dropped from the nominal 440 V to 375 V.

The Endurance Test

The Endurance Test operations were set up to accumulate mileage as quickly as possible under simulated revenue service conditions. The simulated service was designed to comply with mandatory schedules for actual NEC operations from:

Washington, D.C. to New York	2 hours, 40 minutes, and
New York to Boston	3 hours, 40 minutes.

A computerized route profile simulator was programmed with the route speed profile based on Train Performance Calculation (TPC) outputs. By using the locomotive speed signal as a reference, the unit provided a digital display for the necessary posted speed information based on accumulated distance with advance warning of the necessary speed change.

To evaluate the ability of the AEM-7 to meet the profile trip times, a representative sample of the run times was averaged for each of the simulated route profiles. In all cases the average measured trip time was within the TPC predicted time (based on a six car consist). The actual consist size varied between four cars and eight cars. A summary of the trip time data is given below with the TPC time in parentheses.

Boston-New York	3 hrs, 25 min, 0 sec (3 hrs, 27 min, 30 sec)
New York-Washington (two stops)	2 hrs, 25 min, 15 sec (2 hrs, 30 min, 02 sec)
New York-Washington (five stops)	2 hrs, 35 min, 52 sec (2 hrs, 36 min, 39 sec)

The measured energy consumption data for the simulated profiles were averaged in a similar fashion. The energy consumption data showed that the actual average energy used to complete a profile on the RTT was approximately 73% of that predicted in the TPC. For example, the average energy consumption for a series of six car profiles (New York - Washington, two stops) was 5568 kW hrs compared with a TPC prediction of 7858 kW hrs. While some of the difference may be explained by the dissimilarity in gradient profile between the NEC and the TTC and the number of cars in the consist using head end power, it is also probable that some of the coefficients used in the TPC do not represent the vehicles in the consist.

The routine maintenance schedules provided by AMTRAK and General Motors proved to be adequate and easy to implement. However, the major maintenance effort resulted from unscheduled repairs caused by equipment failures. The major equipment failures, which were mainly of mechanical components, included pantographs, traction motors, truck yoke and shock absorber assemblies, wheel bearing, and axle brush assemblies.

In general, the electronic equipment proved to be very reliable, the only exception being the YMX 125 K interface cards. Since the main purpose of these cards was to translate the locomotive protective monitoring circuit outputs into logic system alarm and lockout signals, a number of protective circuit malfunctions resulted. These included the failure of the 12.5 kV interlock circuit to prevent the energization of the locomotive on 25 kV with the 12.5 kV configuration selected.

Failures and Special Investigations

Special Investigations covered five main topics, namely:

- Traction motors
- Pantographs
- Phase Break Operations
- Ride Quality and Wheel Wear
- Axle Brush Currents

The traction motor investigation resulted from a series of motor flashovers and commutator damage which culminated in a substantial repair of all four traction motors. The cause of the motor flashovers was diagnosed as an incompatibility between the original grade of traction motor brushes and the commutator. For the remainder of the Endurance Test a number of brush material grades and brush pressure combinations were tested.

The results of the brush material and pressure tests were inconclusive, although the increase in brush pressure did noticeably improve the motor commutation performance. In all cases the commutator surface film proved to be unstable, reacting to changes in maximum operating speed, consist length, traction motor RMS current, and climatic conditions. None of the AEM-7 locomotives on the NEC were experiencing the same degree of commutator damage, so the problem was indentified at the TTC but left to long term service experience on the NEC to provide a solution if and when the problem arises there.

A major investigation of pantographs resulted from two structural failures of the Faiveley DS 11 pantographs on AMTRAK 900 in July 1980. The second failure resulted in a catenary dewirement in which approximately three miles of catenary were pulled down or damaged. Excessive lateral flexibility motion of the pantograph had been noted during the initial speed upgrade of the locomotive. Subsequent measurement of the pantograph head lateral displacement, using high speed movie techniques, indicated a maximum peak-to-peak amplitude of 9.75". Several modifications were initiated by Faiveley, S. A., to reduce the lateral flexibility and improve the current collection performance without success. However, a lightweight collector shoe modification did show promise until structural failure of the collector strip occurred.

After the two Faiveley pantograph failures, a prototype BR/BW High Speed pantograph was temporily installed. A significant improvement in current collection performance resulted from the pantograph substitution, and the lateral flexibility displacement of the BR/BW unit was measured as 0.5" peak-to-peak amplitude. The prototype BR/BW unit was retained as one of the locomotive pantographs until an increased reach model was available.

The 'stretched' version of the BR/BW pantograph was designed to conform to the AEM-7 locomotive mounting arrangement and the NEC wire height specifications. This unit was installed on AMTRAK 900 by the TTC. After aerodynamic testing and adjustments as specified by the manufacturer, the unit was evaluated for current collection performance and lateral flexibility. It was found that the current collection performance was acceptable (this was later confirmed by dead line tests) and the maximum peak-to-peak displacement amplitude was 1.0". After 34,000 miles of relatively trouble free operation, the 'stretched' unit was returned to the NEC with AMTRAK 900 for further service evaluation.

Another aspect of the TTC test involved an extensive evaluation of alternative phase break negotiation techniques. The AEM-7 locomotive is equipped with the necessary control system to negotiate voltage and phase changes using manual selection in the cab. AMTRAK 900 was further equipped with the modified General Electric automatic phase break negotiation system which is controlled by track mounted magnetic targets. The two aspects of phase break operations extensively tested at the TTC were:

- The reliability of the automatic phase break negotiation system.
- Investigation of phase break negotiations with the locomotive main breaker closed.

The reliability of the automatic system was excellent with only one failure and no malfunctions in approximately 5,000 operations, of which 1,000 were actual voltage changes. However, slight modification to the magnet spacing proposed by Louis T. Klauder and Associates was necessary to accommodate the AEM-7 logic response time for 120 mi/h operation.

For section breaks and phase change phase breaks, negotiation with reduced power was investigated. For this purpose a new type of phase break was used with improved arc control. It was found that for speeds above 40 mi/h the locomotive could successfully negotiate the phase break with 20 A at 25 kV and 50 A at 12.5 kV being drawn through the pantograph. This was sufficient power to maintain the locomotive auxiliaries and the car Head End Power, thus eliminating light flicker. Below 40 mi/h for phase changes, and for all voltage changes it was necessary to open the locomotive main breaker. This method of operation was tested for approximately 6,000 phase break operations including 500 actual phase changes without malfunction or significant phase break damage.

To accommodate the new method of operation, the phase break was much longer than conventional units. Consequently, extra care was needed in the initial set up. Immediately after installation of the original phase break extensive pantograph carbon damage was sustained until the phase break was carefully readjusted.

Soon after Endurance Test operations commenced it was noted that a higher rate of wheel wear was taking place than expected. It was also noted that the locomotive developed short bursts of truck hunting on the curved sections of track, although the oscillations were quickly damped out. Ride quality and wheel profile measurements were used to investigate this phenomenon. The data collection started at the first wheel reprofiling and then at approximately 20,000 mile intervals until the end of the program. The ride quality data demonstrated that the ride on the curved section of track was dominated by the truck kinematic frequency. At vehicle speeds between 110 and 120 mi/h the kinematic frequency became coupled very strongly with the Faiveley pantograph lateral frequency and contributed to the pantograph excessive lateral displacement amplitudes and subsequent structural failures. However, the lateral natural frequencies of both BR/BW units were high enough to avoid strong dynamic coupling with the kinematic frequency.

The wheel wear data indicated that the wheel flanges wore very rapidly over the first 2,000 miles of running. Thereafter, the rate of wear slowed down. It was the initial wear that developed the effective conicity to generate the kinematic frequency motion of the trucks on curves. The wheel wear rates were considered unique to operations on the RTT due to the uniform rail profile and high proportion of curved track, but the modest conicity developed by wheel wear could easily be repeated on the NEC.

The final aspect of the special investigations involved the measurement of the primary return current distribution among the four axle brush assemblies. The measurements were made using current transformers attached to the individual ground brush cables, and the total current was measured by a current transformer on the locomotive transformer ground cable. The current distributions were measured under various operating conditions including acceleration, coasting, slow speed, and high speed. It was found that under all operating conditions the current distribution among the axles was erratic but there was no evidence that current was bypassing the axle brush assemblies and passing through the bearings under the operating conditions tested.

Conclusions and Recommendations

The main conclusions drawn from the test program were:

- Transformer inrush currents should not be a problem on 60 Hz frequency operation since the inrush current peak level does not exceed the normal full load current values.

- The peak power factor value of 0.83 measured at the TTC on the 60 Hz supply is a slight improvement on the 0.81 value measured on the NEC at 25 Hz.

- The locomotive can be operated satisfactorily over the +10% to -25% supply voltage range. At -35% of the nominal supply voltage the propulsion power was severely limited and the battery charger ceased to function; therefore, the locomotive cannot satisfactorily be operated at this level for extensive periods.

- The operating temperatures in both the cab and equipment room were during high ambient temperatures. A level of 145° F was measured in the Y2 electronic cabinet interior.

- Based on TTC profile simulations it is concluded that the locomotive capable of meeting the Washington-to-New York and New York-to-Boston mandated schedules hauling a consist of six AMFLEET cars, provided at least three traction motors are operational. With four motors operational the locomotive was able to meet the mandated schedule between Washington and New York hauling a consist of eight cars.

- The measured energy comsumption data for the simulated profiles was 73% of that predicted by the Train Performance Calculations. The differences were probably caused by a combination of the method used to calculate energy in the TPC and differences between the assumed and actual resistance coefficients.

- The traction motor flashovers resulted from poor commutation. The exact cause of the commutation problems could not be indentified.

- The mechanical reliability of the locomotive should be improved by the redesign of such items as the truck yokes, shock absorber end bushings and brackets, and traction motor blower bellows. Many of these redesigned items have already been incorporated.

- The wheel bearing failure on AMTRAK 900 resulted from lubrication film breakdown due to the use of inferior quality grease. No firm evidence of electrical damage was apparent from the inspection of the other wheel bearings.

- While the primary current distribution among the individual ground brush assemblies was erratic, there was no evidence of overall system malfunction of the ground brush arrangement.

- The standard Faiveley DS 11 pantograph was unacceptable for operation on the RTT catenary system at speeds above 100 mi/h. The current collection performance was judged to be inadequate and the lateral flexibility displacements excessive.

- The British Rail/Brecknell Willis high speed pantograph gave acceptable performance on the RTT catenary at speeds up to 120 mi/h.

- The locomotive automatic voltage change/phase break negotiation equipment functioned satisfactorily. The traction power rampdown system was also successful.

- Head End and Auxiliary Power could be maintained across the Kupler 'modified' phase break at speeds above 40 mi/h for all electrical configurations except voltage changes. Below 40 mi/h either manual or automatic breaker open negotiations must be made.

- The AMFLEET car light flicker problem was almost totally eliminated by powered operation over the phase breaks.

- Special care is required in setting up and maintaining the Kupler 'modified' phase break due to its increased length. Where possible, a double structure support should be used to stabilize the unit.

- The kinematic frequency of the AEM-7 locomotive trucks on the RTT curves coupled closely with the lateral natural frequency of the Faiveley DS 11 pantograph, resulted in large lateral deflections of the pantograph head; this contributed to the pantograph structural failures.

- The TTC test program, coupled with the testing and mainline service experience on the NEC combined to provide one of the most extensive tests carried out on any newly introduced service locomotive.

The following recommendations were also made:

- Further evaluation of the traction motor commutator life should be carried out during early service life of the locomotive on the NEC.

- All mechanical design changes initiated during the combined test at the TTC and NEC early service should be incorporated in all locomotives including AMTRAK 900.

- The BR/BW pantograph should be subjected to NEC service evaluation before consideration as an alternative to the DS 11 unit.

- Faiveley, S. A., should be encouraged to continue with their efforts to improve the performance of the DS 11 by providing a mechanically reliable lightweight head.

- Coasting of phase breaks with partial power at speeds above 40 mi/h should be adopted where possible for NEC operation to reduce the instances of car light flicker and auxiliary equipment cycling.

- Careful installation procedures should be adopted for all high speed phase breaks on the NEC.

1.0 INTRODUCTION

During 1979, an electrified overhead catenary system and substation were installed on the Railroad Test Track (RTT) at the Transportation Test Center (TTC), Pueblo, Colorado. This project was funded by the Northeast Corridor Project Office, NECPO (now called the Office of Intercity Programs), to provide a facility for the evaluation of rail vehicles and components under controlled conditions in support of the Northeast Corridor (NEC) improvement project.

Prior to locomotive testing a series of preparatory tests was carried out during 1980 to evaluate the electrical characteristics of the RTT catenary system, the current collection performance of the catenary designs, and the current collection performance of three pantograph designs. The electrical characterization of the catenary and substation (appendix A) was intended to check the ampacity (current carrying capacity) of the catenary, and the relay settings for the substation. The pantograph and catenary current collection performance tests[1*] were carried out using dead line testing procedures. In all, three pantograph designs were tested:

- The Faiveley single stage pantograph (17MCP1A5).
- The Faiveley dual stage prototype (DS 12).
- The British Rail/Brecknell Willis (BR/BW) high speed prototype.

With the exception of the BR/BW test, which was funded by the TTC as part of a separate proposal, the preparatory test program was funded by NECPO through the Federal Railroad Administration's Office of Research and Development (FRA/OR&D).

To provide high-speed service on the Northeast Corridor AMTRAK procured forty-seven electric locomotives from General Motors, Electromotive Division (EMD). These locomotives, type reference AEM-7, were based on the ASEA (Sweden) RC-4 locomotive, but were designed by General Motors to conform to the Association of American Railroads (AAR) buff load standards. However, the ASEA electrical equipment was retained in the design, and the unit was designed with a maximum operating speed of 125 mi/h.

The first unit, AMTRAK 900 (Figure 1-1) was delivered to AMTRAK at Wilmington, Delaware in February 1980. After acceptance testing by AMTRAK and General Motors on the NEC, AMTRAK 900 was transferred to the TTC for further extensive testing. The TTC testing was funded by NECPO through the FRA/OR&D.

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*References are listed on page 251

FIGURE 1-1. THE AEM-7 LOCOMOTIVE, AMTRAK 900.

2.0 TEST OBJECTIVE SUMMARY

2.1 CHARACTERISTIC TESTS

A full evaluation of the locomotive power systems on a voltage supply of 11 kV 25 Hz had been carried out during the test program[2] on the NEC. The main objective of the characteristic tests at the TTC was to repeat the evaluation on voltage supplies of 25 kV 60 Hz and 12.5 kV 60 Hz. Of special interest were temperatures of critical components, electrical energy requirements, inrush and starting currents, operation of the locomotive over phase breaks, and pantograph arcing.

2.2 ENDURANCE TEST

The endurance test was originally planned for a mileage accumulation of 250,000 mi in approximately 36 weeks. This target was based on the optimistic assumption that no locomotive failures would occur and that only routine maintenance would be required. Based on the original plan, the main objectives of the endurance test was to determine the capability of the locomotive to meet the 2 hour 40 minute schedule from New York to Washington and the 3 hour 40 minute New York to Boston schedule. The test was therefore structured to provide long term reliability data on the locomotive traction and auxiliary power systems, examine the effect of wheel and rail wear on locomotive ride, and to determine the reliability of the locomotive automatic voltage changeover equipment.

2.3 ADDITIONAL TESTS (ENDURANCE)

Based on a policy of continually upgrading the test plan, as problems developed or new requirements arose, any necessary changes were incorporated in the test objectives after the technical and financial approval had been received from FRA/OR&D. Major investigations added were the modified DS 11 and 'stretched' BR/BW pantographs, auxiliary power interruptions at phase breaks, traction motor brush and commutator life, and ground return current.

2.4 ADDITIONAL TESTS (PANTOGRAPH CURRENT COLLECTION PERFORMANCE)

The problems experienced with the Faiveley DS 11 pantograph renewed interest in the pantograph tests carried out before the arrival of the AEM-7 at the TTC. These earlier tests were augmented by a series of special tests including the installation of a graded catenary section. Evaluations were made of the effect of catenary tensions on the Faiveley DS 12 current collection performance and the current collection performance of the BR/BW high speed prototype (European Reach) pantograph. Both live and dead line measurement techniques were used in these evaluations.

3.0 PROJECT MANAGEMENT

3.1 PARTICIPATING ORGANIZATIONS

The principal organizations participating in the AEM-7 test program are presented in Figure 3-1. The solid lines represent the formal lines of communication along which recommendations and decisions were processed. The dotted lines represent informal lines of communication used only to exchange technical information. These informal communications were particularly useful to expedite fault correction and furnish vital spare parts. The main function of each participating organizations is outlined below.

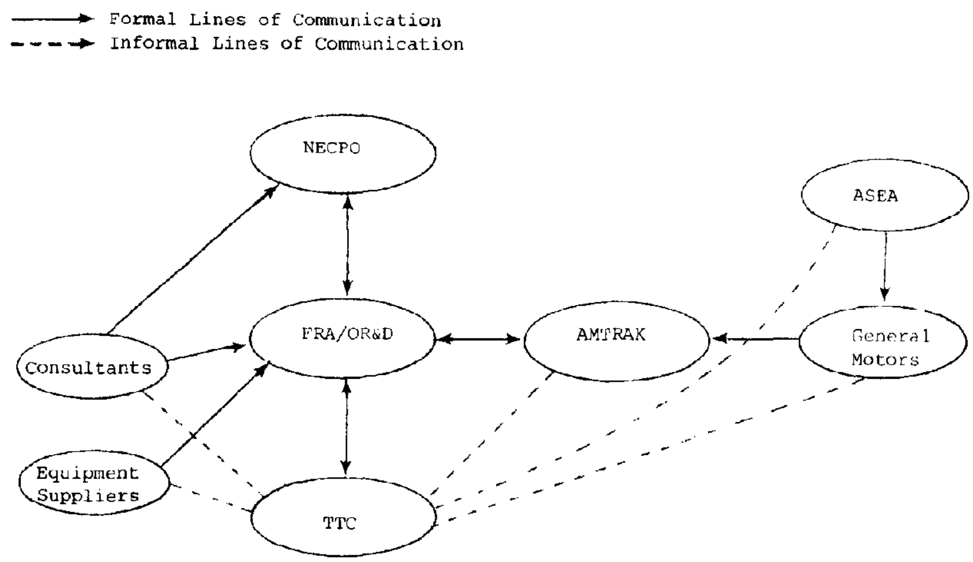

FIGURE 3-1. THE PARTICIPATING ORGANIZATIONS.

3.1.1 Northeast Corridor Project Office

The Northeast Corridor Project Office was responsible for coordinating and funding the Northeast Corridor Improvement Project (NECIP). In the context of the AEM-7 locomotive test program, NECPO provided the funding for the tests and the technical approval of the program.

3.1.2 Federal Railroad Administration Office of Research & Development

The FRA/OR&D provided the Program Manager, who was responsible for the coordination of the project. His function included acting as the liaison

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between the TTC and the other participating organizations. All recommendations and decisions regarding the test program were handled by the Program Manager. He was also kept informed of all technical interchange among the other organizations.

3.1.3 ASEA

Allmänna Svenska Elektriska AB (ASEA of Sweden) was responsible for the locomotive system design, and the supply of the major components for the locomotive manufacture. They also provided the field support engineers for fault investigations.

3.1.4 General Motors, Electromotive Division

General Motors EMD was the official manufacturer of the locomotive. All warranty and failure information was channeled to EMD. All locomotive modifications were in turn initiated by EMD and incorporated with the technical support of EMD personnel. During the early stages of the test program EMD engineers provided advice to the TTC on instrumentation hookups for the AEM-7 power and control systems.

3.1.5 AMTRAK (National Railroad Passenger Corporation)

As the agency responsible for operating the NEC, AMTRAK was the official purchaser of the AEM-7 locomotives. They were responsible for the acceptance of the locomotives, the approval of maintenance schedules, and subsequent operations. In the case of unit #900, AMTRAK supervised the NEC test program, approved the TTC test plan, and supervised the initial operations, operator training, and testing at the TTC. Throughout the test program, they retained responsibility for the locomotive equipment, approving all changes and modifications wherever they were instigated. This arrangement provided configuration control, and protected the locomotive warranty agreement with EMD.

3.1.6 Transportation Test Center

The TTC was solely responsible for the technical supervision and conduct of the test program, providing the Test Manager, Program Coordinator and Chief Test Engineer. The TTC maintained the locomotive and cars for the consist in accordance with AMTRAK and the AAR approved maintenance procedures.

Changes to the test plan were submitted by the TTC to the Program Manager (FRA/OR&D) for approval. Changes instigated by any of the other participating agencies were submitted through the Program Manager. Informal exchanges of technical information between the TTC and other organizations were permitted provided that no unapproved changes in the test plan were involved.

3.2 EQUIPMENT MANUFACTURERS AND CONSULTANTS

In addition to the organizations mentioned above, certain equipment manufacturers and consultants provided a direct input to the test program as listed below:

- Technical Monitoring

J.W. Marchetti & Associates	(characteristic tests)
Japanese National Railways	(locomotive life tests)
Transmark	(locomotive trucks)
Electrak	(graded catenary)
Bechtel, Inc.	(train performance)

- Equipment Supply

Kupler Corporation (Karl Pfisterer, West Germany)	(phase breaks)
Electrak (Balfour Beatty, England)	(phase breaks)
Faiveley, France	(pantographs)
Ringsdorff (Brecknell Willis, England)	(pantographs)

4.0 DESCRIPTION OF TEST FACILITIES

The TTC site layout plan (Figure 4-1) shows the relative locations of the test facilities. The test track complex consists of three major test loops:

- The Facility for Accelerated Service Testing (FAST) and Train Dynamics Track (TDT)
- The Transit Test Track (TTT)
- The Railroad Test Track (RTT)

Only the RTT will be described in detail, although other facilities were occasionally committed to the AEM-7 program for non-test use.

4.1 THE RAILROAD TEST TRACK

The RTT forms the outer perimeter of the test track complex. It is approximately 13.5 mi in length and is designed and maintained for a maximum speed of 125 mi/h over its entire length. Rail access from the maintenance building on the east side of the RTT to the other test areas necessitates crossing the RTT. Dedication of the RTT to the AEM-7 program for 16 hours per day interfered with the Transportation Test Center train logistics moves. This problem was partly overcome by operating the AEM-7 at night.

Location reference around the RTT is provided by marker boards positioned at 1,000 ft intervals with the location number displayed, prefixed by the letter R. The marker boards on the RTT do not start at zero. The RTT datum point at the frog angle of the South Wye access switches to the Central Services area is assigned location R4 + 108.8 as a result of the original track survey. The station numbers, starting with R5, increase in magnitude in a clockwise direction until, at R75 + 409.3, the datum point at the South Wye is once more reached. Only marker boards R5 through R75 appear on the RTT.

A 1.4 mi long turnaround loop, commonly known as the Balloon Track, leads off the east side of the RTT. This track, together with the RTT was electrified as part of the NECPO funded program.

4.1.2 Curvature and Gradients

Since the RTT is a closed loop, 71% of the track is curved. All curves on the RTT are identical, being of 50 minute (6875 ft radius) curvature. The constant radius curved track superelevation is six inches ($\simeq 6°$) resulting in a curve balance speed of 105 mi/h. Details of the curve locations are given in Table 4-1.

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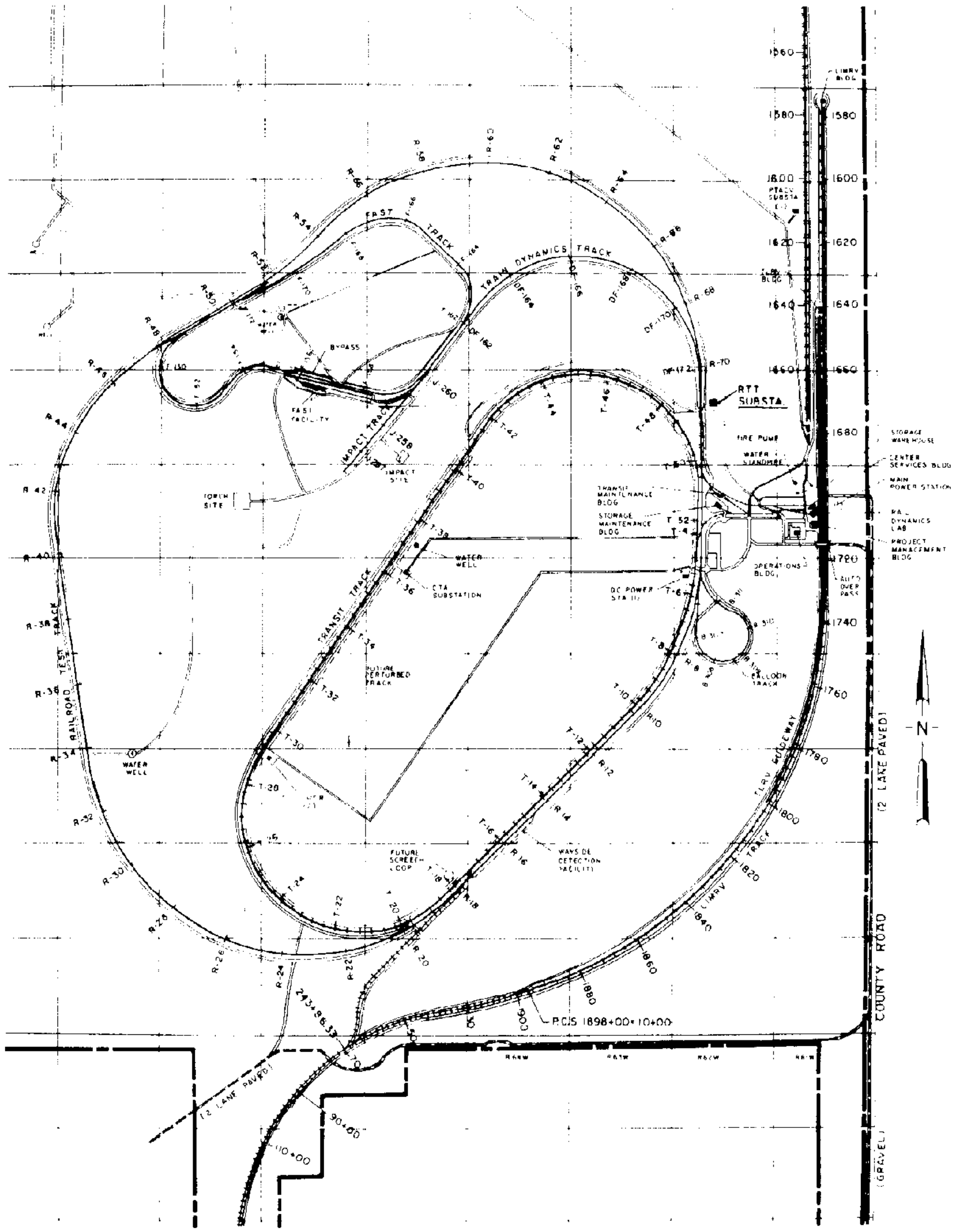


FIGURE 4-1. THE TTC TEST TRACK LAYOUT.

TABLE 4-1. RTT CURVED TRACK DETAILS.

RTT Location (clockwise)		Track	
Start	Finish	Alignment	Common Name
R4+630	R11+230	Curved	East Curve
R11+230	R18+141	Tangent	East Tangent
R18+141	R33+510	Curved	South Curve
R33+510	R39+154	Tangent	West Tangent
R39+154	R48+106	Curved	West Curve
R48+106	R50+846	Tangent	FAST Tangent
R50+846	R53+546	Curved	FAST or Reverse Curve
R53+546	R53+746	Tangent	Short Tangent
R53+746	R70+846	Curved	North Curve
R70+846	R4+630	Tangent	Core Area

The maximum gradient on the RTT is 1.47%. This is approximately the same as the maximum 'open route' gradients on the New York-to-Washington section of the NEC. The difference in height between the north curve (the RTT high point) and the south curve (low point) is 175 ft. A summary of the RTT track gradients is given in Table 4-2 for the clockwise direction of travel.

4.1.3 RTT Construction

The RTT is constructed of 136 lb/yd rail on 7"x9"x9'0" hardwood cross ties at a nominal spacing of 19 1/2". The rail is fixed to the ties with standard 14" tie plates and 6" x 5/8" track spikes. The tie plates are A-punch, 4-hole plates with 4 spikes per plate both tangent and curve.

The track bed consists of a 10" layer of upper ballast on a 12" layer of lower ballast on a 6" subbase. Where necessary a 3 ft deep moisture density control zone is also provided below the subbase. The superelevation on curves is provided by the upper ballast layer. No superelevation is permitted in the lower ballast or subbase layers. The ballast shoulders on both tangent and curved track must extend to a minimum distance of 12" beyond the tie end and be level with the top of the ties. The maximum permitted slope of the upper ballast shoulders is 2:1 (30° to the horizontal).

TABLE 4-2. RTT TRACK GRADIENTS.

RTT Location (Clockwise)		Gradient (%)
Start	Finish	+ rising/- falling
R4+109	R8+400	-0.5004
R8+400	R13+600	-1.4665
R13+600	R19+600	-0.2605
R19+600	R24+300	-0.0008
R24+300	R27+600	+0.8285
R27+600	R32+000	+0.1591
R32+000	R37+400	+0.1342
R37+400	R41+200	+0.1342
R41+200	R43+900	+1.0148
R43+900	R46+800	+0.6662
R46+800	R56+700	+0.3402
R56+700	R60+400	+0.1622
R60+400	R64+000	-0.2778
R64+000	R67+500	+0.7914
R67+500	R72+200	-0.6150
R72+200	R74+600	-1.3100
R74+600	R75+409	-0.5004
R75+409	(start)	

A combination of jointed rail and continuously welded rail (CWR) is used (Table 4-3). The sections of jointed track are based on the 39 ft rail length staggered joint layout. One section of track near the FAST switches utilizes a welded/jointed combination where the welded rails are jointed at 150 ft intervals.

TABLE 4-3. RTT RAIL LAYOUT.

RTT Location		Rail Type
Start	Finish	
R4+661	R35+500	CWR
R35+500	R48+550	39 ft jointed rail (staggered)
R48+550	R59+000	150 ft welded/jointed
R59+000	R71+200	CWR
R71+200	R4+661	39 ft jointed rail (staggered)

Since the RTT forms the outer perimeter of the test track complex, numerous turnouts are required for the test tracks and central services area access. Originally, ten switches were incorporated in the RTT layout, concentrated in three areas. This number was reduced to nine during the early part of the AEM-7 program. The main concentration of switches is in the core area between station R70 and R6 where there are five. All switches on the RTT conform to the No. 20 turnout design. Table 4-4 presents the location, the designation number, and the configuration (facing or trailing) for a clockwise direction of travel.

The track is aligned and maintained to FRA Class 6 standard. This includes all switch and grade crossing installations. The normal maximum operational speed for the entire loop is 125 mi/h.

4.2 CATENARY

4.2.1 Catenary Designs

Five different catenary designs are used for the electrification of the RTT and the balloon track:

- Styles 5 and 5X, compound catenary,
- Style 1, compound catenary,
- Style 3, compound catenary,
- Style 5A, simple catenary,
- Style 5T, trolley wire.

TABLE 4-4. RTT TURNOUT DETAILS.

Switch #	Point of Switch	Facing/Trailing (Clockwise)	Access
302	R4+109	Trailing	Central Services Area (South Wye)
602B	R4+200	Facing	Transit Test Track
301	R4+500	Facing	Balloon Track
503	R14+700	Facing	Wayside Test Facility (North Access)
503	R17+684	Trailing	Wayside Test Facility (South Access)
501	R18+286	Facing	TTC Access Track
305B	R48+250	Facing	FAST Access (South) (Removed 7/80)
307B	R49+150	Trailing	FAST Access (North)
304	R71+200	Trailing	Train Dynamics Track
303	R73+200	Facing	Central Services Area (North Wye)

A summary of conductor sizes and tensions for each style is given in Table 4-5. A brief description of each is given in the text below, and each is illustrated in Figure 4-2.

TABLE 4-5. RTT CATENARY CONDUCTOR DETAILS.

Catenary Type	Contact Wire	Auxiliary Wire	Messenger Wire	Return Wire
Style 5,5X	4/0 grooved	7/0.0833	19/0.0833	2/0 ACSR*
Style 1	336 MCM grooved	4/0 grooved	5/8" copper weld	2/0 ACSR
Style 3	4/0 grooved	4/0 grooved	5/8" steel 7/8" steel	2/0 ACSR
Style 5A	4/0 grooved	-	19/0.0833	2/0 ACSR
Style 5T	4/0 grooved	-	-	2/0 ACSR

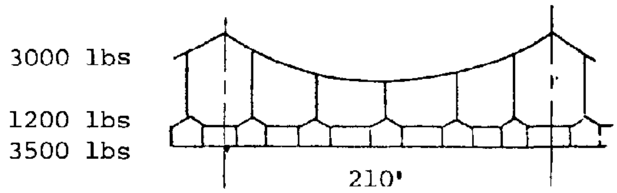
* Aluminum Conductor, Steel Reinforced

a. Styles 5 and 5x. The style 5 catenary is a lightweight compound catenary design based on the proposed system for the new electrification between New Haven and Boston on the NEC.[3] The term "compound" refers to a 3-conductor design of catenary in which an intermediate conductor (auxiliary messenger) is suspended from the main messenger by a second set of hangers. The resultant catenary has a substantially uniform mechanical compliance over the span length.

The Style 5 catenary on the RTT is supported and registered by a single pole and cantilever support structure (Figure 4-3). The majority of the poles are galvanized steel broad flange beams; however, a short section between R56 and R59 has concrete poles for comparison. The maximum support spacing (span length) on the Style 5 catenary is 210 ft. The tension on the conductors is maintained by balance weights at either end of the catenary section. Catenary terminated in this fashion is called "fixed tensioned equipment." The section between each set of balance weights is called a tension section.

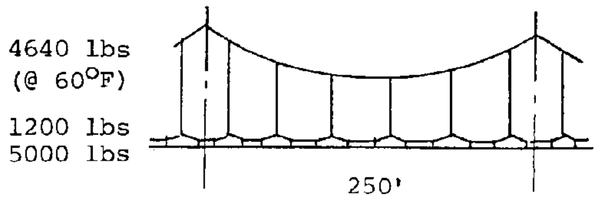
The Style 5X catenary is identical to the Style 5 except that the maximum span length has been increased to 250 ft. This equipment was the alternative for the test length and was not used during the AEM-7 program.

b. Style 1. The Style 1 catenary is a compound system based on the existing catenary between Washington and New York on the NEC. It uses much heavier conductors at much higher tensions than the Style 5, and the conductor



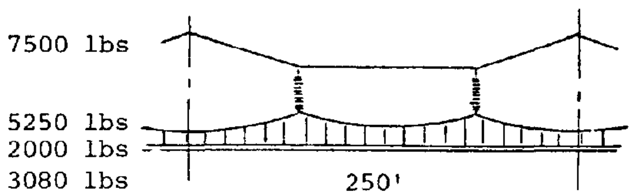
(5X= 250" in Test Section)

Compound Catenary, Style 5, (5X), Proposed New Haven to Boston



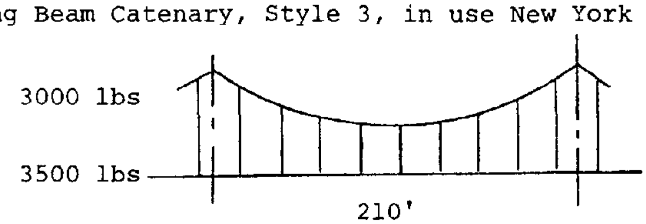
(NEC 270')

Compound Catenary, Style 1, in use Washington to New York

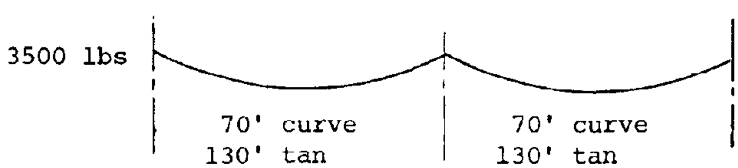


(NEC 306')

Hanging Beam Catenary, Style 3, in use New York to New Haven



Simple Catenary, Style 5



Trolley Style 5T

FIGURE 4-2. OVERHEAD CONTACT SYSTEMS.

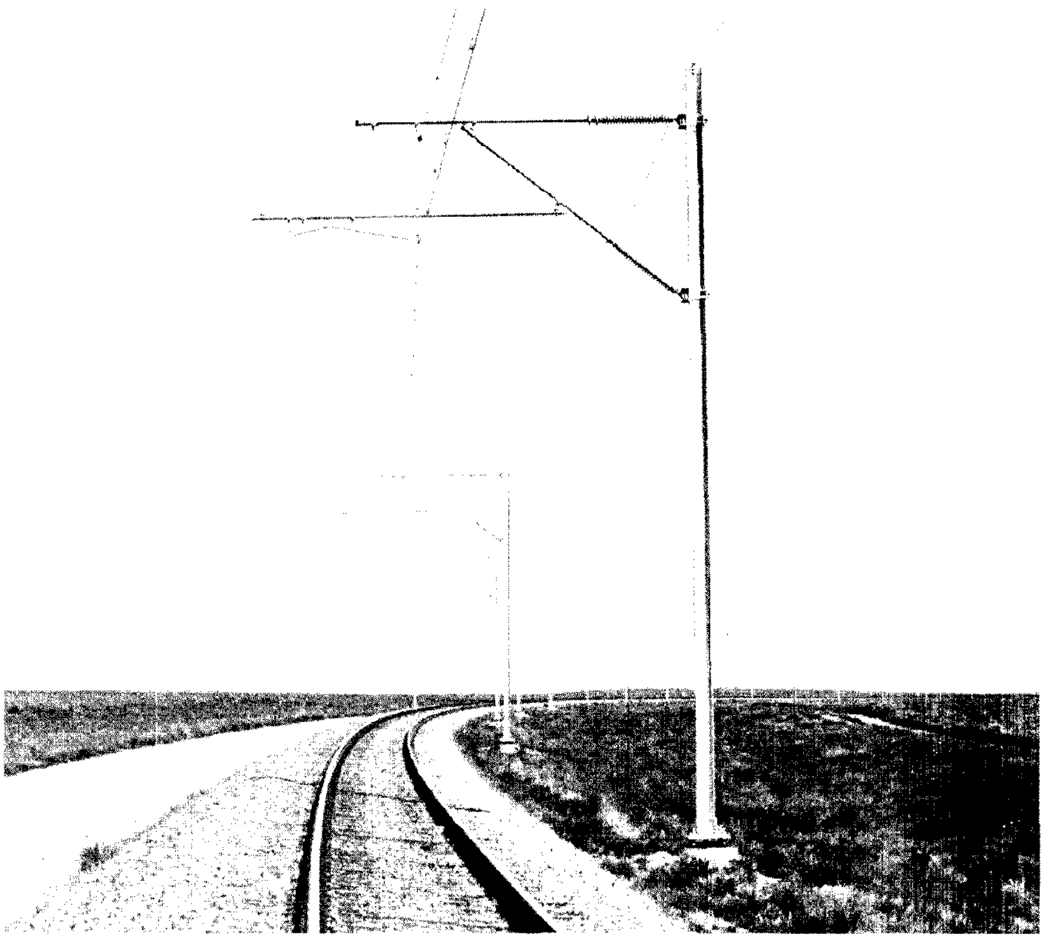


FIGURE 4-3. TYPICAL SINGLE POLE AND CANTILEVER SUPPORT.

tensions are variable because the termination of the conductors in the original design is fixed with no balance weights. However, the RTT system is equipped with balance weights, which can be fixed to simulate the original equipment termination, or allowed to float in order to simulate the fixed tensions at different ambient temperatures. Balance weight controlled tensions representing 60°F were used throughout the AEM-7 program.

c. Style 3. The Style 3 catenary on the RTT is also representative of the existing NEC catenary design, used between New York and New Haven. Its across-track hanging beam construction supports a compound catenary (similar to the Style 5) from a beam which is in turn supported by an along-track support wire. For the single track design at the TTC, the support wire is arranged longitudinally parallel to the track over the track center line. Like the Style 1, the Style 3 is fixed-terminated, but balance weights are incorporated in the RTT system to simulate various ambient temperatures. Again balance weight controlled tensions were used during the AEM-7 program, this time the simulated temperature was 30°F.

d. Style 5A. The Style 5A catenary is a simple catenary design (Figure 4-2) in which the contact (trolley) wire is suspended directly from the messenger by hangers. At the TTC, this equipment is used to blend the slow speed Balloon Track Single trolley wire equipment into the high speed RTT Style 5 equipment. The Style 5A simple catenary is normally used for medium speed (30 to 90 mi/h) applications.

e. Style 5T. The Style 5T trolley wire is the simplest basic system employed for electrification. It is a single contact wire, directly supported by a pole and cantilever without the use of a messenger wire. It is designed for very low speed operation (less than 40 mi/h). It is used only on the Balloon Track.

4.2.2 Test Length

The major portion of the RTT, between stations R39 clockwise to R33 + 500 is equipped with the lightweight Style 5 catenary. However, the 1-mi section between R33 + 500 clockwise to R39 on the west tangent is set up as a special test length. Here the support structures are broad flange beam portal frames spanning the track and adjacent roadway (Figure 4-4), spaced for 250 ft spans. Two sets of cantilevers are used, one hinged to the east side upright of the portal, the other on a transfer roller system on the bridge of the portal.

The east side cantilevers are used to support two half-tension sections of style 5X lightweight catenary. This equipment was stored flat against the east side portals (Figure 4-4) for the duration of the AEM-7 test.

The cantilevers on the transfer system are used to support one half-tension section in the Style 1 and Style 3 catenary designs. The Style 1 system is at the south end of the test length; the Style 3 system is at the north end. When not in use, this equipment is stored over the roadway. For the AEM-7 test program the Styles 1 and 3 catenary systems were in use.

4.2.3 Support Structure Identification

In keeping with normal electrification practice each support structure on the RTT catenary system is assigned a unique number, called the structure number. The main purpose of the structure number is to provide an easy means by which maintenance personnel and locomotive engineers can report catenary faults.

The structure numbers are in turn based on the number of the Tension Section (the length of catenary between a pair of balance weight assemblies). The assigned structure number is in a two part format. For example structure number 10/17 refers to the 17th structure in Tension Section number 10. The

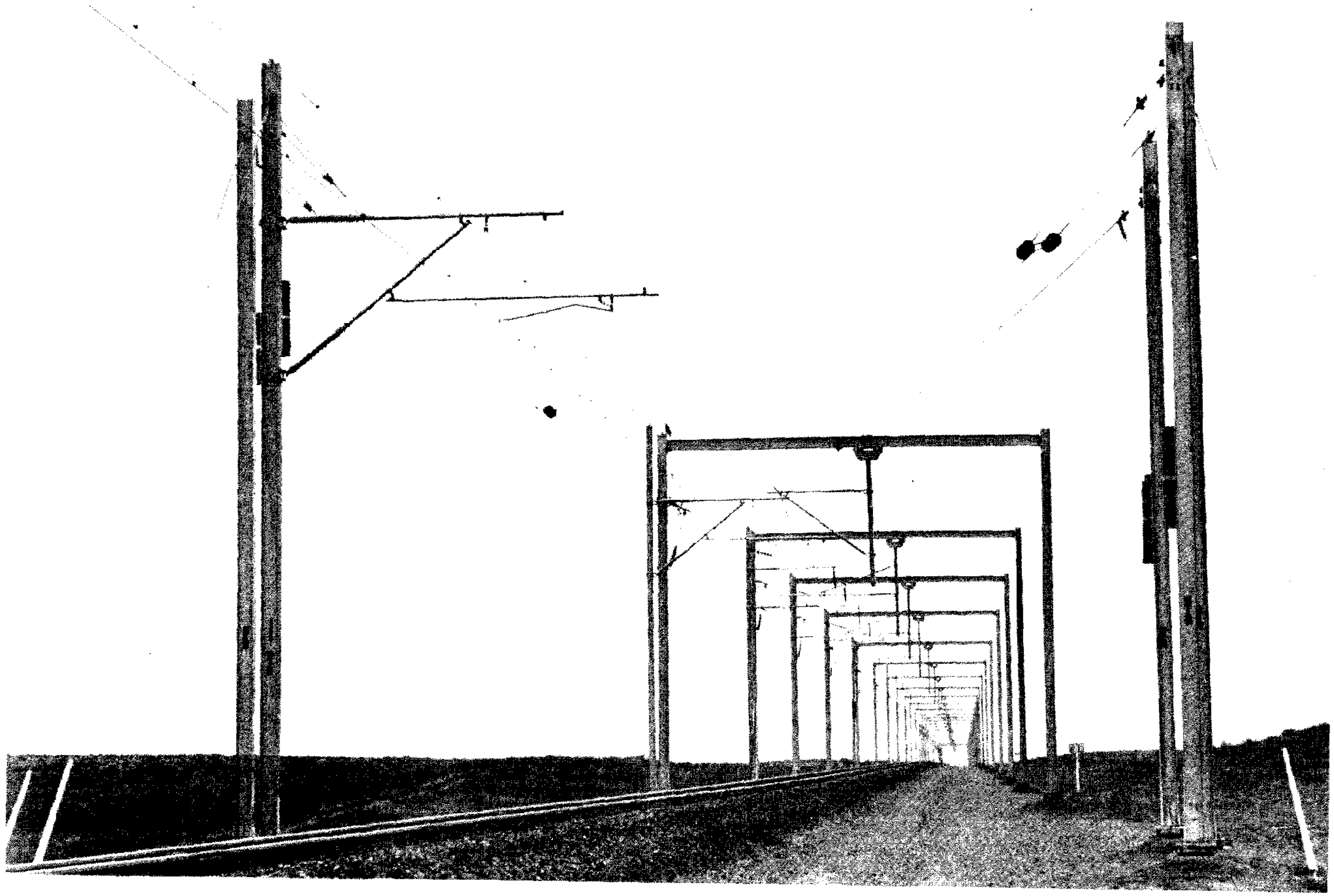


FIGURE 4-4. PORTAL FRAME TEST LENGTH.

number is stencilled on the structure so that it is clearly visible from the cab of an approaching locomotive.

4.2.4 Phase Breaks

Phase breaks are incorporated in the catenary system in order to provide electrical isolation between sections while at the same time maintaining mechanical integrity of the contact wire to allow passage of the pantograph.

In general, phase breaks consist of two insulated runners in the contact wire separated by a short section of contact wire forming the center section. Skids or gliders normally provide a smooth transition from the contact wire to the insulated rods to prevent pantograph head damage. The skids also form the base of the arcing horns. The total installation length is normally 12 to 15 ft.

Several design options are available for the center section of the phase breaks. In Europe, the phase break center section is normally grounded, when used with commercial frequency installations. On 16 2/3 Hz installations the section can be ungrounded or grounded through a fuse. In Japan some phase break installations[4] have one 8 m (26 ft) long insulated rod with no center section at all.

During the AEM-7 test program four different phase break designs were used in the RTT catenary system. A brief description of each will follow.

a. The BICC Ceramic Bead Insulator Phase Break. The original phase break installation at the RTT substation (station R70 + 800) consisted of the British Insulated Callandar Construction (BICC) ceramic bead insulator phase break. This unit (Figure 4-5) consisted of two insulated runners, each made up of a pair of rods with a lateral separation of approximately 6" and a length of 38". Each rod was manufactured of ceramic beads bonded onto a glass fiber center with teflon spacers separating the beads.

   The BICC phase break was designed for a maximum speed of 90 mi/h, although careful set up and testing during the dead line tests[1] resulted in a 120 mi/h installation. It should also be noted that the BICC phase break was designed specifically for a grounded center section installation with an arc trap to divert an arc to ground rather than arcing horns to extinguish the arc.

b. Kupler Phase Break (Standard Unit). During the RTT catenary construction the decision was made by the NECPO to use a Kupler phase break at the second location, R33 + 031. This unit, designed by Karl Pfisterer, Stuttgart, West Germany, for the German Federal Railways, is manufactured under license by Kupler Corp., Branford, CT.

   The Kupler phase break (Figure 4-6) is similar in design to the BICC unit. However, the installation length is reduced by omitting the contact wire between the two sets of runners and grounding the center through a central set of gliders and arcing horns. The total installation length is

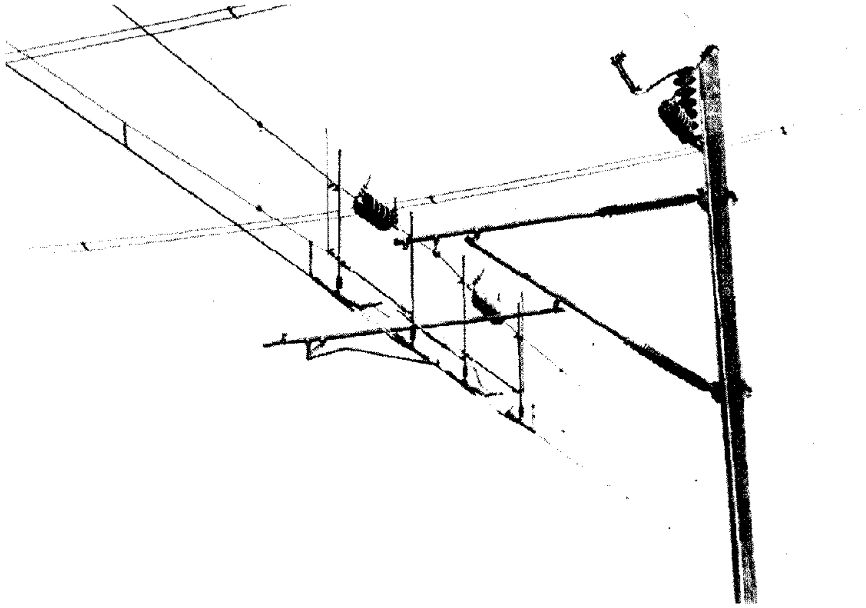


FIGURE 4-5. BICC CERAMIC BEAD INSULATOR PHASE BREAK.

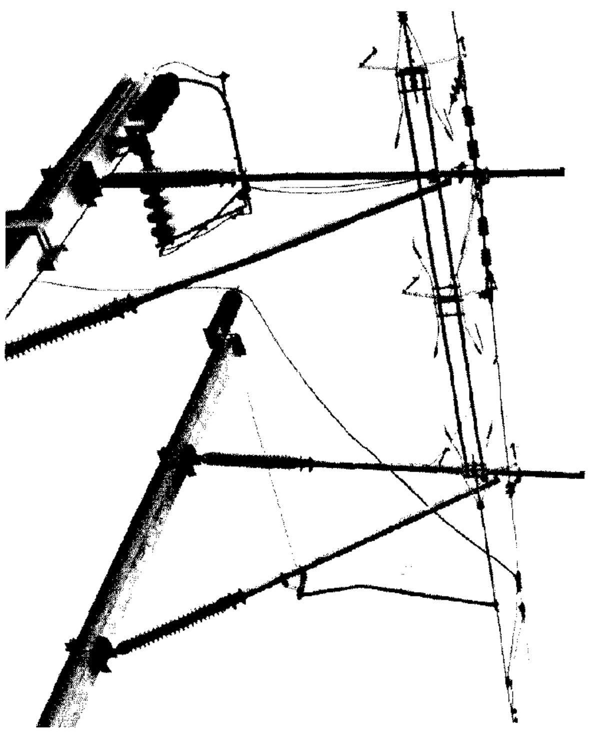


FIGURE 4-6. KUPLER PHASE BREAK (STANDARD UNIT).

2.5 m (8 ft). The insulated runners are constructed of a pair of Teflon coated glass fiber rods. The gliders are manufactured of bronze.

c. The Balfour Beatty Phase Break. The BICC phase break at station R70 + 800 was replaced in July 1980 by a Balfour Beatty High Speed phase break (Figure 4-7). This unit, which had been successfully tested in South Africa, also consisted of a pair of insulated runners separated by a short section of contact wire. The runners were manufactured of a special self-cleaning material developed by Balfour Beatty, Ltd., Liverpool, England. Unlike the BICC unit the Balfour Beatty phase break incorporated arcing horns for arc control rather than arc traps for fault current control.

d. Kupler Phase Break (Improved Unit). In January 1981 the Balfour Beatty phase break was replaced by an improved Kupler phase break. This substitution was made in response to a requirement for a modified phase break operation procedure for the NEC.

Based on the original Pfisterer phase break design, this unit was designed to allow a locomotive to pass over it without powering down. It consists of two Teflon coated fiberglass insulated sections approximately 8 ft long separated by a short section of trolley wire (Figure 4-8). The overall installation length (including end fittings) is 21 ft.

Some detailed design changes have been made between the improved and original Pfisterer units. First, sheds have been incorporated at each end of the insulated runners, to provide protection against rainwater bridging the insulator. Second, turnbuckles have been provided in the support cables to aid in the setting up process.

For the center section of the phase break provision is made to float or ground the center by means of a switch. A third alternative is a high speed fuse unit, provided to interrupt a maximum fault current of 40 kA. The fuse is intended to interrupt and limit a phase-to-ground fault before the substation protective breaker opens to interrupt the whole distribution system. The manner in which this is accomplished is as follows: at the point where the waveform of the fault current through the fuse reaches the 25 A level the fuse element starts to rupture. The current continues to rise until the element ruptures, at which time the current is interrupted. The manufacturer claims that for a fault current with a peak of 40 kA the current would be interrupted before reaching 10 kA on the first half cycle. Since the substation main breaker would not have operated until after the first three cycles, it would not react to the fault.

After the fuse has blown, the phase break center is not grounded until a new fuse element is fitted. The significance of this will be discussed later in section 11.0 under the title of Phase Break Operations. This unit has been retained in the RTT catenary.

4.2.5 RTT Substation

a. General Description. The RTT traction substation was designed as a

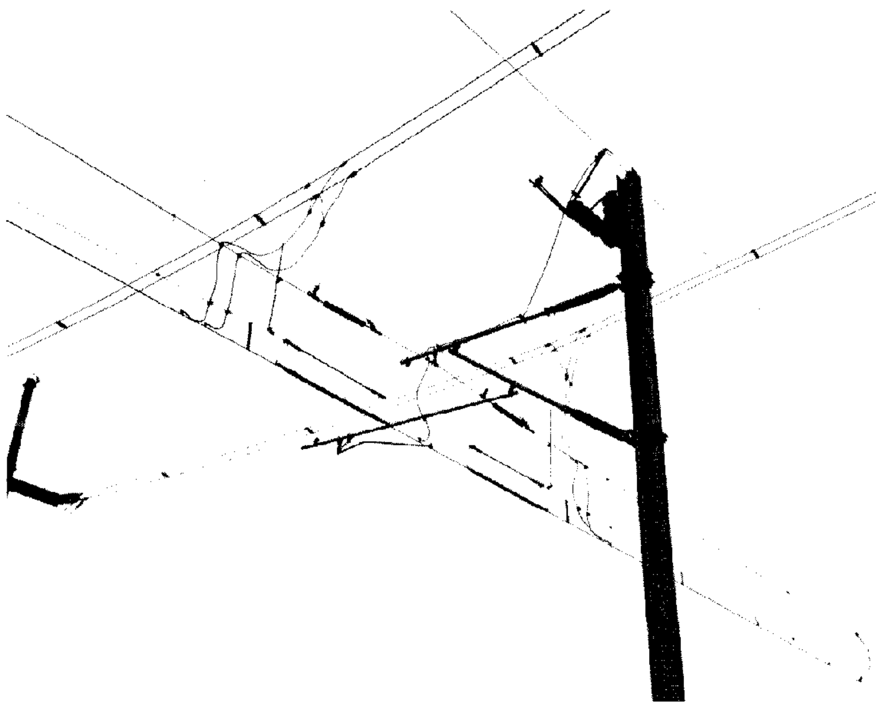


FIGURE 4-7. BALFOUR BEATTY HIGH SPEED PHASE BREAK.

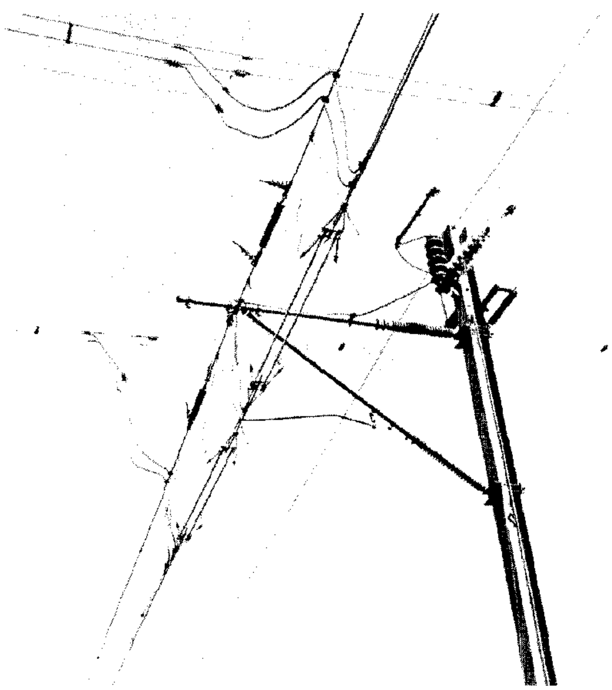


FIGURE 4-8. KUPLER PHASE BREAK (IMPROVED UNIT).

typical single feed electrified railroad substation. However, its power rating, three selectable voltages, and some of its metering are unique in order to provide a latitude in test capability. Otherwise, the station layout and components are similar to those used for electrified railroads.

b. Substation High Voltage Supply. The incoming power supply for the substation is a spur transmission line from the TTC site substation. All three transmission line phases are supplied to the substation. The line voltage is 115 kV and the line capacity is 25 MVA. A schematic diagram of the substation is presented in Figure 4-9.

The 3-phase power lines entering the substation are protected by lightning arrestors. However, only phases A and B are presently used for traction power, with Phase C being retained for possible extensions. Two potential transformers for line voltage measurement and metering, and a 50 kVA house power supply transformer are connected between the relevant phases and ground. The first substation disconnect switch, #312, connects the two lines containing the two current transformers to the incoming supply. The first motorized circuit switcher, #313, connects the main power to the transformer. Switcher #313 is designed to open under relay action in the event of a transformer fault or the operation of certain key interlocks. In general, it is not designed to open as first line protection for a catenary fault.

c. Main Transformer. The main transformer was specially designed for the TTC to provide three voltages with tap changers on both the primary and secondary windings. This was to allow testing of traction units at nominal voltages of 12.5 kV, 25 kV, and 50 kV. The secondary taps allow testing over the -35% to + 10% nominal voltage range in 5% steps.

The transformer is rated at 16 MVA for normally (convection) cooling, and 21.3 MVA for forced-air cooled operation. The transformer input is 1-phase 115 kV to the primary winding. The transformer output consists of four 12.5 kV secondary windings which are taken directly to a large selector switch where they may be paralleled for 12.5 kV, series-paralleled for 25.0 kV, and series-connected for 50.0 kV operation. A tertiary winding, rated at 7.2 kV, 833A, is provided for future harmonic filters and power factor corrections, if required. This winding was used during catenary testing (appendix A) to provide a special low voltage source. Standard instrumentation to protect the transformer include sensors for winding temperatures, gas pressure, oil temperature, and gas composition analysis. Differential relaying protects the transformer in the event of internal faults, and keyed interlocks prevent changing any taps with the transformer energized.

d. Catenary Feed Arrangement. The catenary system is fed from the transformer by means of the #315 oil circuit breaker (OCB), as shown in Figure 4-9. The feed to each half of the catenary system, separated by the two phase break installations at R33 + 033 and R70 + 800, is controlled by switches #314-1 and #314-3. Each is a manual disconnect switch with an interlocked grounding switch on the catenary side. Switcher #314-1 controls power to the south leg of the catenary, and switcher #314-3 controls power to the north leg of the catenary. Key interlocks prevent

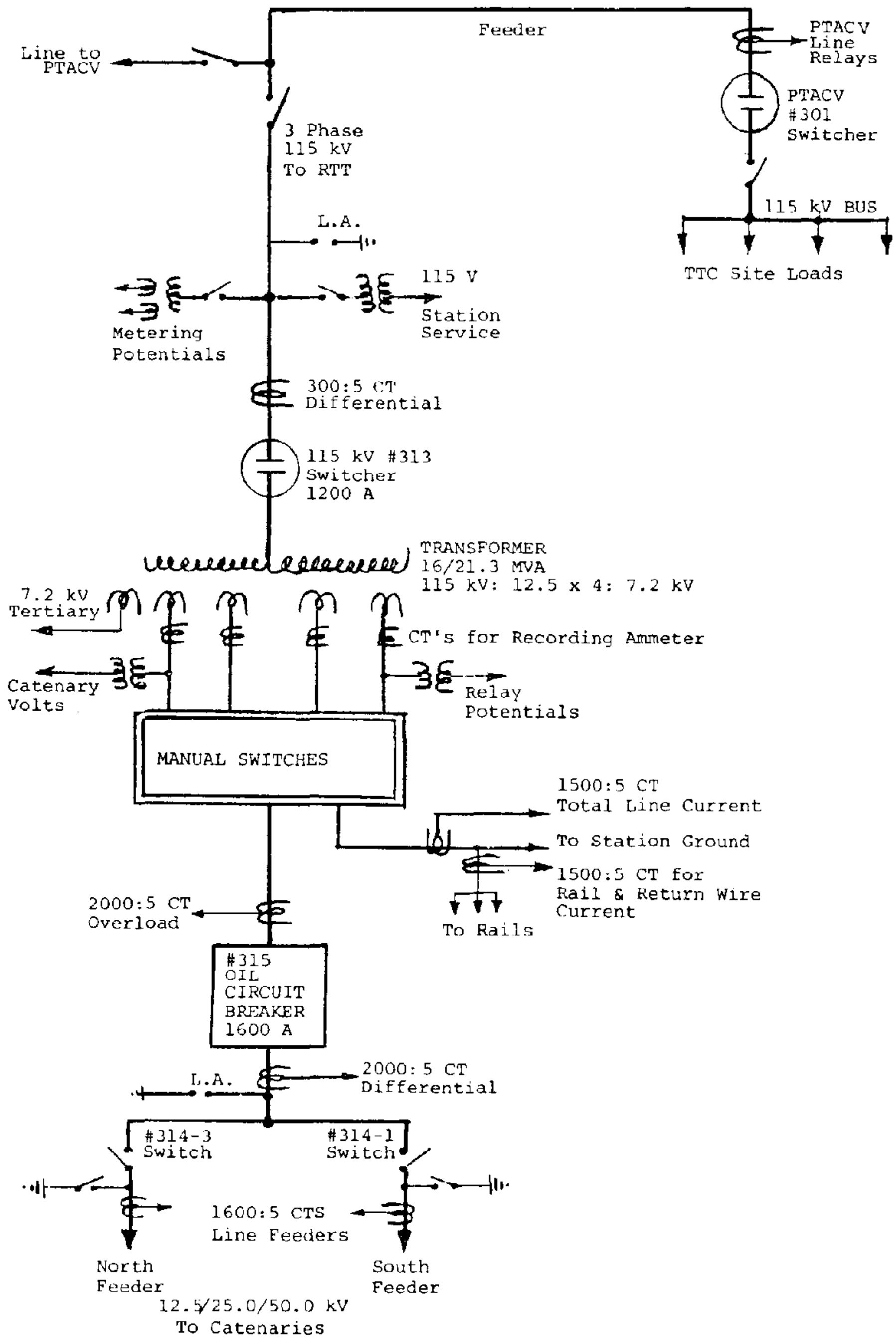


FIGURE 4-9. SCHEMATIC DIAGRAM OF THE RTT SUBSTATION AND FEEDER.

each of the feeder switches from being in the closed position if the corresponding grounding switch is closed. No interlocking is provided between switchers #314-1 and #314-3, and one may be grounded while the other is in the feed-through position. A bypass switch is located at station R33 to allow use of the catenary in a loop configuration. The bypass switch is interlocked to prevent operation with the OCB closed.

Each catenary feeder has a current transformer for over-current detection, operating the OCB #315 on overcurrent. The short circuit catenary over-current is 5.5 kA at 25 kV and 11 kA at 12.5 kV. The OCB is rated at 115 kV with a 22 kA interrupt capability. The catenary is further protected by a distance relaying system. The catenary is rated at 640 A.

e. Substation Monitoring. The substation data indication and recording are controlled by five panels in the control room enclosure. The two left panels display the complete metering of the 115 kV incoming power and control of the 115 kV switcher, #313. Recording meters are used for 115 kV incoming voltage, current, reactive power (VAR), resistive power (W), and power factor(Cos ϕ). In addition, a watt-hour meter measures energy consumed.

The next two panels display and contol the transformer secondary output. Indication of catenary voltage, recording of catenary current, and the #315 OCB control are on the third panel. The total transformer current and the two rails plus the ground wire return current are indicated separately. The protection relays are also installed in substation panels #3 and #4.

f. Catenary Electrical Characterization and Substation Relay System Checkout. After initial acceptance of the substation a series of tests was carried out to determine the electrical characteristics of the catenary and to make comparisions with the design return current path. In addition, the substation relaying system was evaluated, some of which was done using the AEM-7 as the base load. Discrepancies were found in the relaying system, and in the catenary. This work is fully reported in appendix A.

g. The Dual Voltage Feed System. One of the major features of the AEM-7 locomotive is its ability to operate on different line voltages. During the test planning stage it was recognized that one of the more important aspects of the test program would be the extensive checkout of the locomotive dual voltage capability. Since this was not possible with the existing substation configuration, a permanent modification to the substation was approved by the NECPO in April 1980.

The dual voltage feed arrangement was designed to provide a line voltage of 25 kV to the south half of the RTT catenary and 12.5 kV to the north half. The bypass switch across the phase break at station R33 + 033 must be in the open position for dual voltage operation.

Figure 4-10 shows the dual voltage configuration. To provide the necessary voltage outputs the main transformer secondary winding switch rack was modified to allow one pair of windings to be series connected

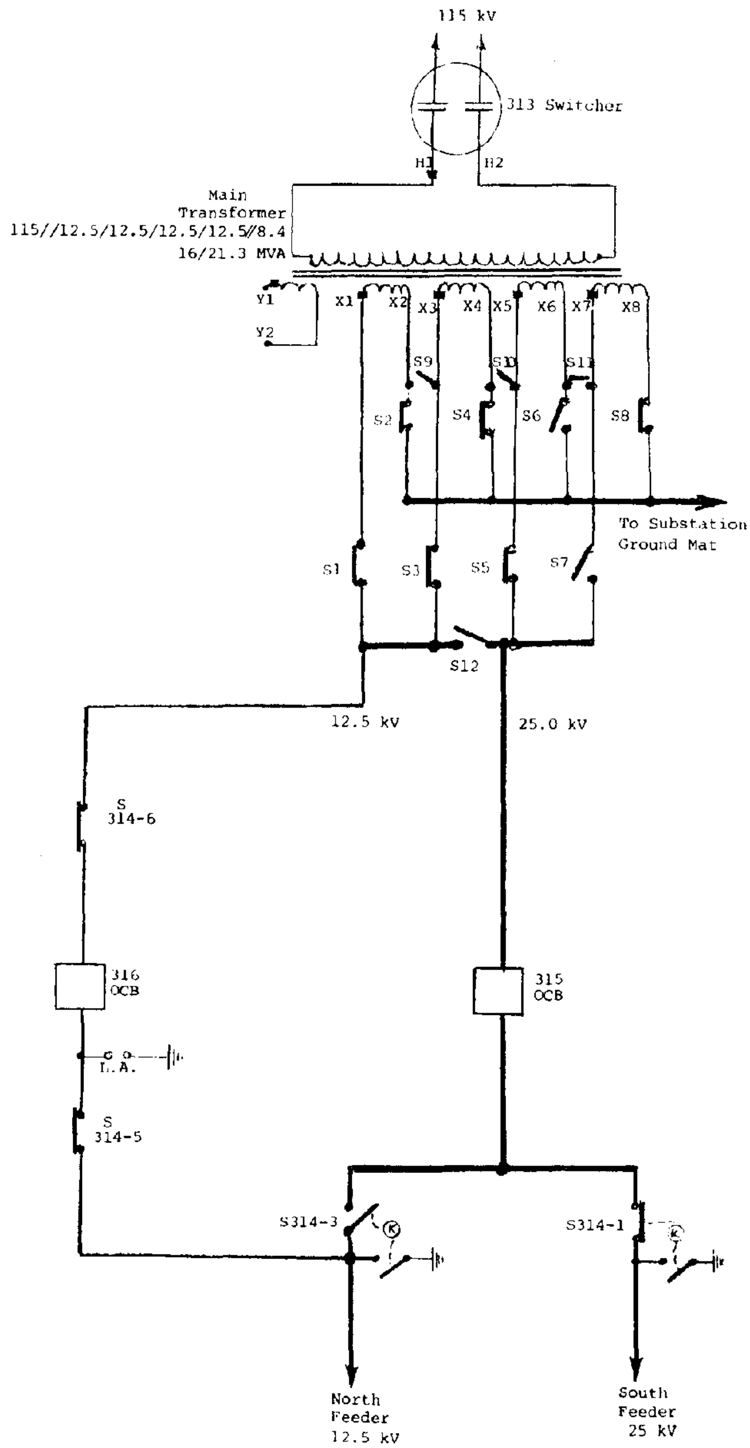


FIGURE 4-10. DUAL VOLTAGE CONFIGURATION.

while the other pair were parallel connected. The series windings were then fed to OCB #315 and switcher #314-1 to provide 25 kV to the south half of the catenary system. An extra switcher, #S12, was provided in the switch rack to isolate the output from each pair of windings. A second OCB, #316, complete with lightning arrestor was added, along with a pair of isolation switchers, #314-6 and #314-5. The output from #316 was connected through #314-5 to the catenary side of original catenary north feed switcher, #314-3. With switcher #314-3 in the open position a 12.5 kV supply to the north half of the catenary could be controlled by OCB #316. A picture of the modified substation is shown in Figure 4-11. The necessary controls and relaying modification were installed in substation control panel #5. The new OCB is rated at 25.8 kV and has an interrupt current level of 11 kA.

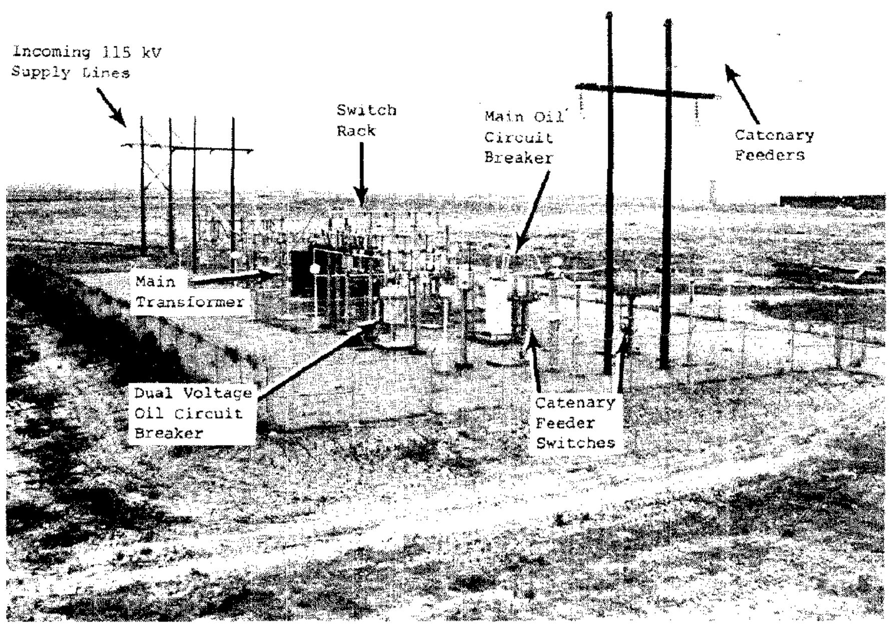


FIGURE 4-11. GENERAL VIEW OF THE RTT SUBSTATION.

h. <u>The Dual Phase Feed System</u>. During the test program a temporary modification for the RTT catenary system was found to be necessary. To provide a realistic phase break operation a phase change was required. Since only one transformer was available, only in-phase and out-of-phase voltages were possible.

Unlike the dual voltage system the dual phase arrangement was a temporary hook up; however full relay protection was retained. The feed arrangement is shown in Figure 4-12. As with the dual voltage arrangement the transformer secondary windings were utilized in two pairs. The 'south' pair were connected in series to provide 25 kV and fed through OCB #315 to the south half of the catenary system. The 'north' pair of windings were also connected in series to provide 25 kV, but temporary cables were manufactured to reverse the polarity within the switch rack. The normal bus-bars were temporarily removed. Clearance and cable support were provided by a temporary stand-off insulator.

The 12.5 kV lightning arrestor on OCB #316 was temporarily replaced by a 25 kV unit. To provide full relay protection the polarity of the north half current transformer tapping for the differential relay had to be reversed. In addition, the reverse current relay was temporarily disabled.

Thus two 25 kV out-of-phase RMS voltages were supplied to the two halves of the catenary system through the two OCB's (#315 and #316). This resulted in a 72 kV peak voltage across the phase breaks at each half cycle.

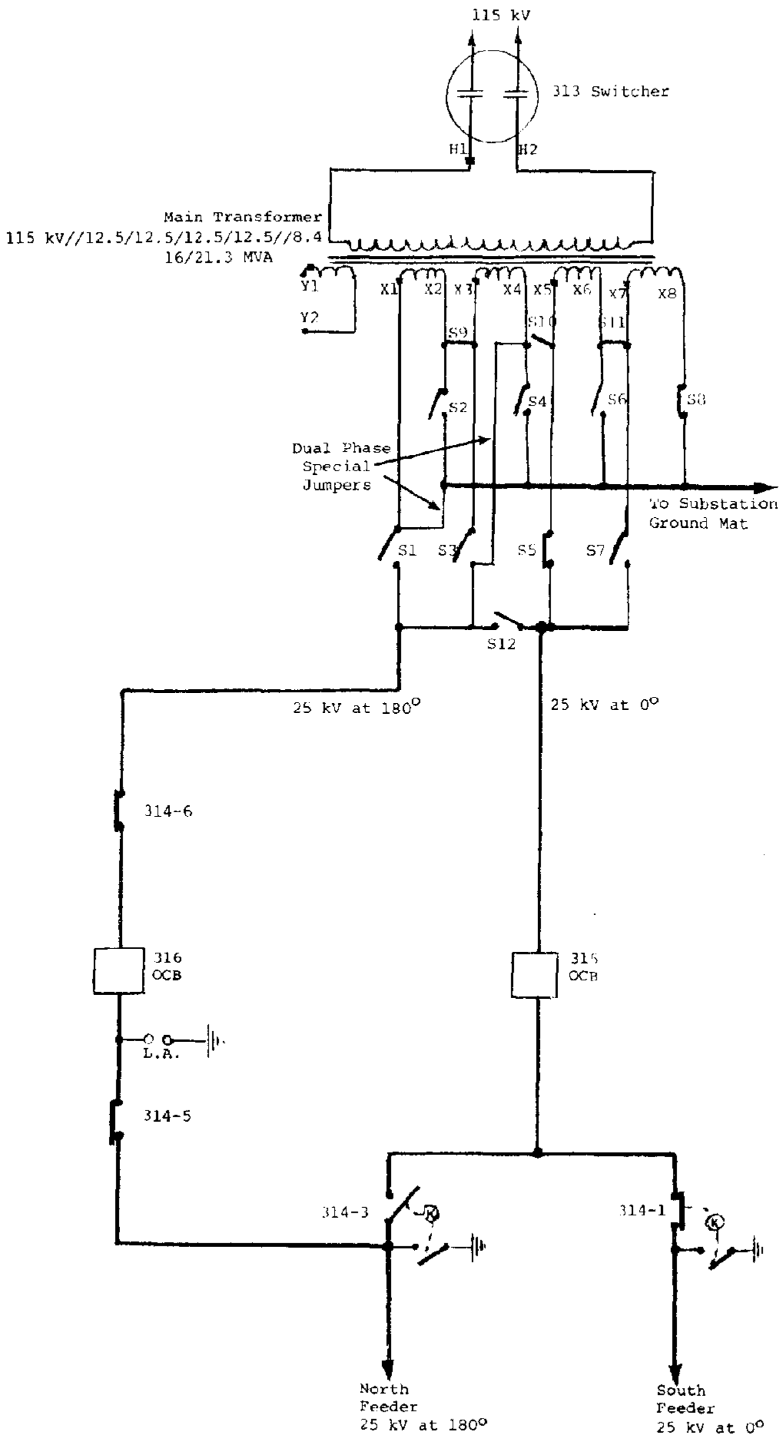


FIGURE 4-12. DUAL PHASE CONFIGURATION.

5.0 AEM-7 LOCOMOTIVE SYSTEM DESCRIPTION

5.1 GENERAL DESCRIPTION

The AEM-7 electric locomotive was built by General Motors (Electromotive Division) for AMTRAK under license from ASEA, Sweden. Although the AEM-7 is a passenger locomotive, its design is based on the RC and RM series of thyristor controlled passenger/freight locomotives built by ASEA for the Swedish State Railways. The RC series locomotives, starting with the RC1 (1967) through the RC4, and the latest RM units were designed to operate on 15 kV 16 2/3 Hz. Some major design changes were necessary to produce the AEM-7 as a passenger locomotive, i.e.:

- The trucks were improved to permit 125 mi/h operation
- A second static inverter was included to provide 440 V 3-phase power for the cars (Head End Power)
- Primary voltage changeover equipment was incorporated to permit operation on 11 kV 25 Hz, 12.5 kV 60 Hz, and 25 kV 60 Hz.

Main Specifications of the AEM-7 locomotive are:

Axle Arrangement	Bo-Bo
Number of axles	4
Wheel Diameter (New)	51.2 in.
Total Length	613.8 in
Truck Center Pin Distance	307.1 in
Truck Wheel Base	108.7 in
Total Wheel Base	415.8 in
Nominal Weight	200,000 lbs
Axle Load	50,156 lbs
Maximum Speed	125 mi/h
Continuous Power (at the rail)	5,300 hp
Short Term Rated Power (at the rail)	7,600 hp
Head End Power (HEP) Rating	500 kW
Maximum Tractive Effort	29,000 lb ft @ 75 mi/h
Maximum Starting Tractive Effort	51,500 lb ft
Gear Ratio	85:36

5.2 LOCOMOTIVE HIGH VOLTAGE EQUIPMENT

A line diagram of the locomotive high voltage current is shown in Figure 5-1. The main components are described below.

5.2.1 Pantograph

The locomotive is normally equipped with two Model DS 11 pantographs

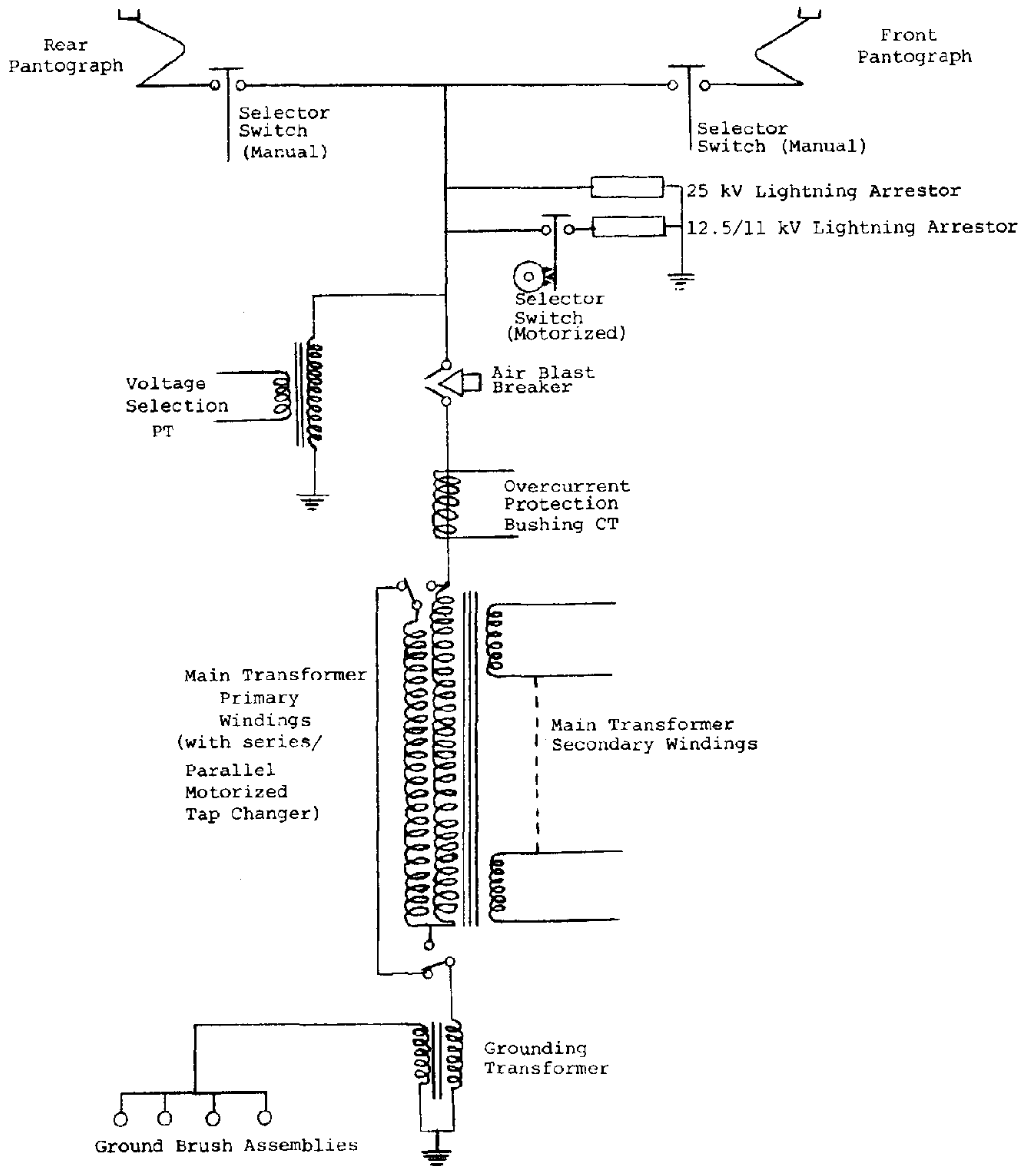


FIGURE 5-1. SCHEMATIC DIAGRAM OF THE AEM-7 LOCOMOTIVE HIGH VOLTAGE EQUIPMENT.

supplied by Faiveley, S.A., France. The Faiveley DS 11 pantographs have two superimposed air and spring raised and spring lowered stages. The lower stage applies a damped constant raising force that reacts to low-frequency, high-amplitude variations in the catenary system. The upper stage applies a decreasing raising force and reacts to high frequency, small amplitude irregularities in the contact wire. The main objective of the design was to minimize the effective dynamic mass of the head (collector shoe) in order to increase the dynamic frequency response operating range.

Pantograph Data

Max Current Collecting Extension	126 in
Max Mechanical Extension	134 in
Static Uplift Force	20 to 29 lb ft
Lockdown Force	150 lbs
Minimum Pressure for Raising	75 psi
Rated Pressure for Operating	100 psi
Maximum System Pressure	145 psi

5.2.2 Main Circuit Breaker

The main circuit breaker, which isolates the locomotive equipment from the pantograph, is an Electro-pneumatically controlled Air Blast Breaker (ABB) located on the locomotive roof. It is connected to either of the pantographs through individual manually operated disconnect switches, (Figure 5-2). The continuous rated current for the breaker is 630 A, with a breaking capability greater than 250 MVA. The ABB is equipped with two pressure guards. One prevents the breaker from closing if the air pressure to the ABB is less than 71 psi. The other opens the breaker if the air pressure falls below 54 psi.

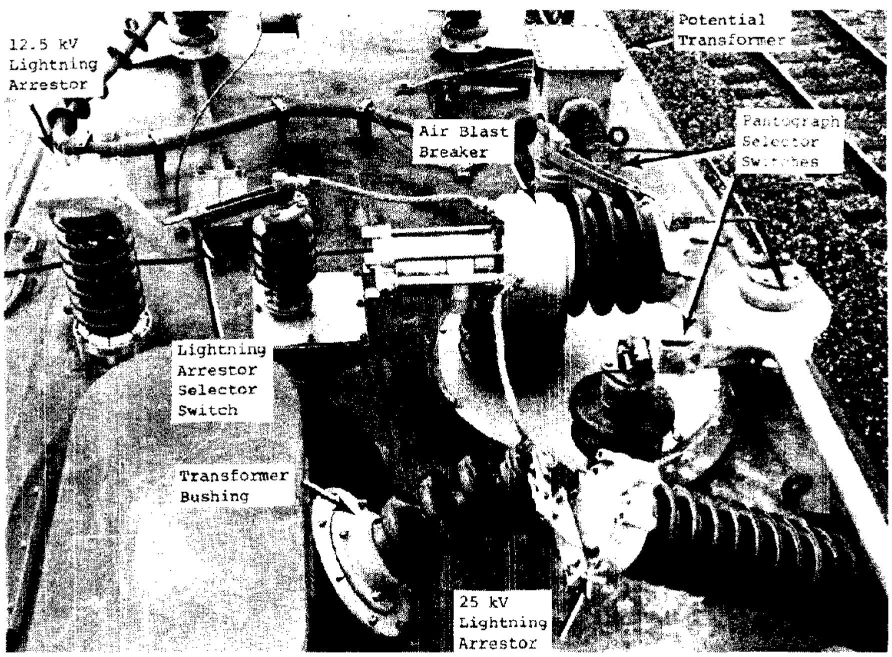


FIGURE 5-2. GENERAL VIEW OF THE AEM-7 LOCOMOTIVE HIGH VOLTAGE ROOF EQUIPMENT.

5.2.3 Lightning Arrestors

Two lightning arrestors are connected to the bus-bar between the main circuit breaker and the high voltage bushing. The purpose of the lightning arrestor is to limit the surge over-voltage on the primary side of the main transformer and to provide first line over-voltage protection for the entire locomotive including the thyristor convertor. The lower voltage arrestor has a motorized switch in series. Both arrestors are connected to the supply when the locomotive is operating at 11 kV or 12.5 kV. The lower voltage arrestor switch is open while operating at 25 kV.

5.2.4 Potential and Current Transformers

High voltage equipment protection is provided by a potential transformer (voltage) and a bushing current transformer (current). The potential transformer (PT), which is connected to the pantograph side of the ABB, provides the voltage and frequency measurement by which the voltage/frequency changeover equipment selects its setting. The PT output circuity provides backup protection against over- and undervoltage.

The current transformer (CT) is contained within the high voltage bushing through the locomotive roof to the main transformer. The output from the CT is used to drive current relays to provide the first line of overcurrent protection.

5.2.5 Main Transformer

The main transformer has two primary windings with nine secondary windings. The transformer primary windings are connected in series for 25 kV operation and in parallel for 11 kV or 12.5 kV operation by means of a motorized tap changer. The control for the tap changer motor is provided by the locomotive changeover equipment.

The outputs of two sets of two windings of the secondary are rectified and regulated by thyristor controlled convertor bridges and smoothed by reactors to provide d.c. to the traction motors. Two sets of two windings provide power for the Head End Power and an auxiliary power convertor. One winding supplies power for the traction motor field convertor. The main transformer windings and the smoothing reactors for the rectified outputs are contained within a welded steel tank which is equipped with a circulating oil pump system that supplies silicon cooling oil at a flow rate of 1 m^3/min. The oil is circulated through the windings of the transformer and reactors to a forced air cooled, externally mounted radiator. Overtemperature and low pressure protection are provided for the cooling oil system. Electrical ratings of windings are tabulated below.

Main Transformer Data

	Primary	Primary
Windings	11 kV 25 Hz	12.5 kV, 25 kV 60 Hz
	Secondary	Secondary
Convertor - Armature	4x508 V	4x577 V
- Field	1x112 V (center tapped)	1x128 V (center tapped)
Head End Power	2x451/508 V	2x513/577 V
Auxiliary	2x451	2x513

5.2.6 Grounding Transformer and Ground Brush Assemblies

The main transformer primary current returns to the running rails through the grounding transformer and ground brush assemblies. The grounding transformer is a 1:1 ratio current transformer, the primary winding of which is connected between the main transformer primary winding low voltage output and locomotive underframe. The secondary winding of the grounding transformer is connected between the ground brush assemblies and the locomotive underframe. This circuit forces the total ground brush current to equal the primary current and effectively connects the low voltage side of the transformer primary winding directly to the axles, eliminating underframe currents.

The ground brush assemblies consist of spring loaded brushes on slip rings attached to one end of each axle. The whole assembly is contained in a grease-proof enclosure inside the axle box cover. The grounding transformer forces the traction return current to flow through the axle brushes to protect the wheel bearings from electrical damage.

5.3 LOCOMOTIVE PROPULSION AND AUXILIARY POWER SECTIONS

5.3.1 Auxiliary Power Load Convertor

The Auxiliary Power Load convertor is designed to convert the single phase a.c. power from the main transformer output at either 25 Hz or 60 Hz to a 3-phase supply used to drive the locomotive auxiliary machines. The convertor consists of three main parts:

- The thyristor controlled rectifier produces full-wave rectified d.c.
- The d.c. link filter smooths the d.c.

- The thyristor chopper controlled inverter chops the d.c. to form three-phase a.c. at 60 Hz frequency.

The APL is controlled by a set of input and output contactors. The system is designed to allow the direct starting of three-phase motors. However, the locomotive loads are divided into four groups to allow sequenced starting at 2 second intervals. The APL specification is as follows:

Ratings

Input voltage		2 x 451 V $^{+10\%}_{-20\%}$	25 Hz
	or	2 x 513 V $^{+10\%}_{-20\%}$	60 Hz
Output voltage		440 V ± 2% 3-phase 60 Hz	
Output power		175 kVA at 0.8 power factor	

5.3.2 Head End Power Convertor

The Head End Power convertor is similar in design and function to the APL. However, its power rating is higher. In addition to supplying house power to the cars, the HEP supply can be used to power the locomotive auxiliaries in the event of APL failure. The HEP supply specification is as follows:

Ratings

Input		451 V + 508 V $^{+10\%}_{-20\%}$	25 Hz
	or	513 V + 577 V $^{+10\%}_{-20\%}$	60 Hz
Output voltage		480 V ±2% 3-phase 60 Hz ± 1.6%	
Output power		625 kVA at 0.8 power factor	
Overload capacity		10% overload for 1/2 h per 1 h.	

It should be noted that the asymmetric input voltages are derived from two unequal main transformer secondary windings.

5.3.3 Traction Motor Field Supply

The traction motor field supply for all four motors is derived from one center-tapped secondary winding of the main transformer. However, each field supply is separately controlled with its own current control and field weakening capability. The field current is fixed at 300 A below base speed, the balance speed for full armature current with no field weakening. Above base speed, field weakening is used for speed control, allowing the armature current to increase while maintaining a constant armature voltage of 900 V.

5.3.4 Traction Motor Armature Supply

Each pair of motors on a truck form a traction motor module (TMM) fed from a pair of main transformer secondary windings. Each motor armature is controlled by a separate pair of thyristor controlled rectifiers and smoothing reactors. The maximum armature voltage is limited to 900 V. The maximum armature current is limited to 2250 A at approximately 80 mi/h. Above 80 mi/h the maximum permissible armature current and power are gradually reduced until at 120 mi/h the armature current maximum is limited to approximately 1350 A.

5.3.5 Dynamic Braking

In normal operation the AEM-7 locomotive is equipped with dynamic braking. In the braking mode the traction motors become separately excited d.c. generators, the power from which is dissipated in individual resistor grids mounted on the locomotive roof. With motors in the generator mode, torque applied to the motors by the wheelset applies a braking force to the wheelset. The maximum total braking force is 15,000 lbs.

The braking load is controlled by the field current. For braking at low speeds (below 30 mi/h) the field current is limited to 300 A. Above 30 mi/h the maximum armature current limits the maximum permissible braking load. The brake resistor grid resistance is 0.64 ohms and the maximum current is 970 A. If any of the traction motors is isolated due to a fault, the dynamic brake system becomes inoperative.

5.4 LOCOMOTIVE CONTROL SYSTEMS

5.4.1 Voltage Changeover System

To accommodate operation on the existing 11 kV 25 Hz and the proposed 12.5 kV and 25 kV 60 Hz supplies on the Northeast Corridor it was necessary to incorporate a voltage changeover capability in the AEM-7 control system. The voltage changeover system, which is used to configure the primary winding connections through the motorized tap changer can be used to select the voltage setting either automatically, by means of track mounted targets, or manually. In either case the roof mounted PT is used to check the measured line voltage against the transformer tap changer position before the ABB is closed.

5.4.2 Rectifier Convertor Control

The principles of operation of each of the thyristor controlled rectifiers is identical. In all cases phase controlled thyristors are used to vary the voltage output of the rectifier against current demand by adjusting the position in the supply current waveform (phase angle) at which the thyristor trigger pulse is fired.

At low current demand levels the power factor of a thyristor controlled rectifier output is low because of the large effective phase difference between voltage and current waveforms resulting from late firing of the thyristors. Where large load fluctuations are imposed on a convertor, two-stage rectifier systems are employed to increase the power factor. Such a system is used in the AEM-7 control system. The mode of operation in such a system is that the lower demands are taken care of by the first stage. Once the first stage is 'full on' (the thyristors are conducting for the full half cycle) the second stage starts to operate.

5.4.3 Propulsion Power Control

The propulsion power control is a closed loop feedback control in which the current demand is set by the throttle as it feeds an output voltage proportional to the throttle position to the traction motor control logic. The armature convertor reacts to output the desired current level provided all safety criteria such as wheelslip, load sharing, and motor temperature are met.

Speed control has been incorporated in the propulsion control system in which the desired speed can be set on a rotary dial. When the locomotive reaches set speed, the propulsion control becomes a closed loop system with the locomotive speed signal as the feedback.

5.5 THE LOCOMOTIVE TRUCKS

5.5.1 General Description

The AEM-7 locomotive trucks consist of the following main parts:

- Wheelsets with journal bearings and gear box
- Rubber chevron type primary springs

- Truck frame
- Bolster with pendulums
- Secondary coil springs
- Yoke with traction rods
- Dampers (lateral and vertical)
- Traction motors
- Disc brakes
- Tread brakes

The two trucks on the AEM-7 locomotive are identical with the exception of the axle box mounted apparatus and hand brake equipment. The trucks are fabricated steel design and construction. Both axles on each truck are separately powered.

The primary suspension consists of rubber chevrons located between the pedestals and the journal boxes. The chevrons are designed to permit the axles to move in the lateral, longitudinal, and vertical directions with respect to the truck frame.

The secondary lateral suspension is provided by the lateral stiffness of the secondary vertical suspension coil springs. In addition, rubber side buffers acting betwen the locomotive body and truck frame supplement the coil springs for over-travel requirements.

The bolster is suspended from the truck frame by four pendulum rods carried at each end by spherical rubber bearings. The pendulums, in conjunction with an internal rubber pivot element, provide the truck rotational stiffness necessary for high speed stability.

The secondary vertical suspension consists of three coil springs on each side of the bolster. The coil springs are attached to the locomotive body by a yoke assembly, Figure 5-3. The yoke assembly is connected to the bolster by two traction rods which transmit the longitudinal forces from the locomotive body to the bolster. The yoke is attached to the body by bolts to the underframe. Two vertical hydraulic dampers are mounted between each yoke assembly and bogie frame to provide the required vertical damping.

5.5.2 Traction Motors

The locomotive is powered by four eight-pole, separately excited, separately ventilated, truck suspended, direct current, traction motors manufactured by ASEA. These motors, type LJH 108-5 are similar to the traction motors used in the RC and RM series locomotives, the main difference being the type of brush holder used.

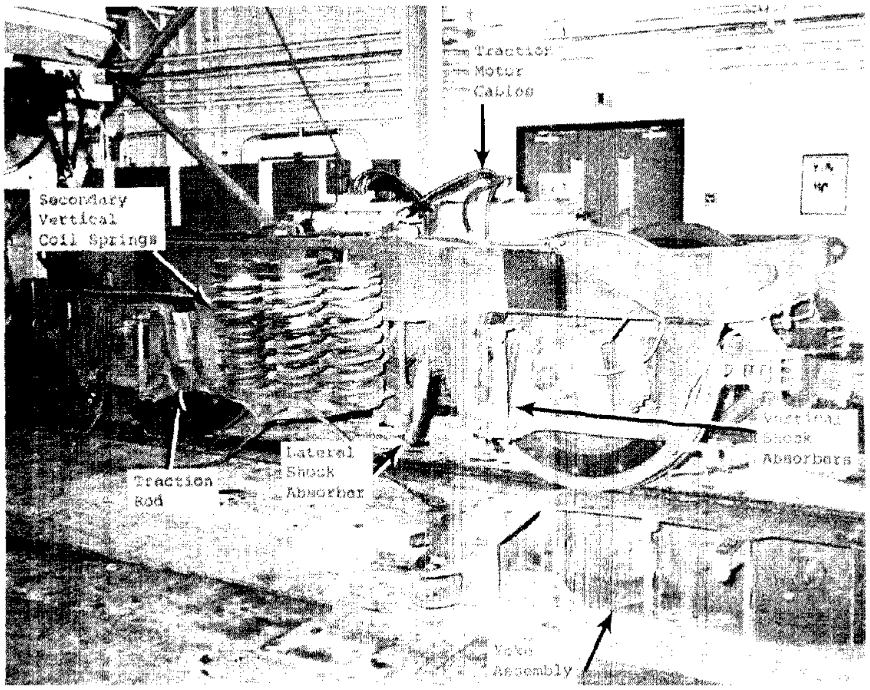


FIGURE 5-3. THE AEM-7 LOCOMOTIVE TRUCK-TO-BODY CONNECTIONS.

The motor ratings for the type LJH 108-5 are as follows:

Motor Specification	Rated	Maximum
Input Power	P = 1080 kW	P = 1370 kW
Armature Voltage	U = 900 V	U max = 900 V
Armature Current	I = 1290 A	I max = 2350 A
Field Current	If = 260 A	If max = 300 A
Armature Speed	N = 1220 RPM	N max = 1985 RPM

Cooling air flow = 1.9 m^3/sec by forced air blowers.

The stator consists of a welded cylindrical shell onto which the field poles and interpoles are directly mounted. The brush holder mounting ring is mounted in the stator at the commutator end with a mechanical arrangement which allows the brush ring to be rotated to permit easy brush inspection and replacement.

The armature commutator and bearings are mounted on a hub. The commutator is made of strips of heat resistant silver-copper alloy separated by strips of mica. The commutator poles are laminated to reduce the requirement for smoothed d.c. and to reduce the power losses.

5.5.3 Traction Motor Supports and Transmission

The traction motors are attached to the truck frames by a three part bolted suspension, two on the center transom and one on the end transom. The motor output torque is transmitted by a quill shaft, installed through the hollow armature, to a rubber coupling and hence to the final drive gear box mounted in the axle.

5.5.4 Wheelsets and Brakes

The wheelsets consist of solid, 51" (new) diameter wheels mounted on a solid axle with conventional outboard bearing boxes. The main bearings are grease lubricated spherical roller bearings manufactured by SKF.

Two systems of air operated brakes are used. Disc brakes provide 80% of the mechanical braking effort. This system consists of full discs bolted to the inside and outside faces of the wheel center. Four brake pads per wheel (eight per axle) provide the brake force. Tread brakes provide the remaining 20% of the mechanical braking effort. These are used mainly to clean the wheel treads in order to maximize the adhesion coefficient.

6.0 THE AEM-7 TEST SCHEDULE

6.1 THE SCOPE OF THE TEST PROGRAM

The test program for which this report was prepared includes not only the tests carried out on the AEM-7 locomotive itself, but many of the earlier tests on the catenary system and substation distribution system. Additional tests authorized during the AEM-7 test program are also included, the majority of which were added as a result of problems encountered with the locomotive. The major objectives of the tests are outlined in section 2.0.

6.2 TEST OUTLINE

A chronological outline of the combined test program is presented in Figure 6-1. The test program was in three major parts spanning a time frame of approximately 2 years, of which the AEM-7 locomotive was onsite for approximately 1 year. For completeness the test outline includes the original 'dead line' pantograph tests which were separately reported[1] and are, therefore, not included in this report.

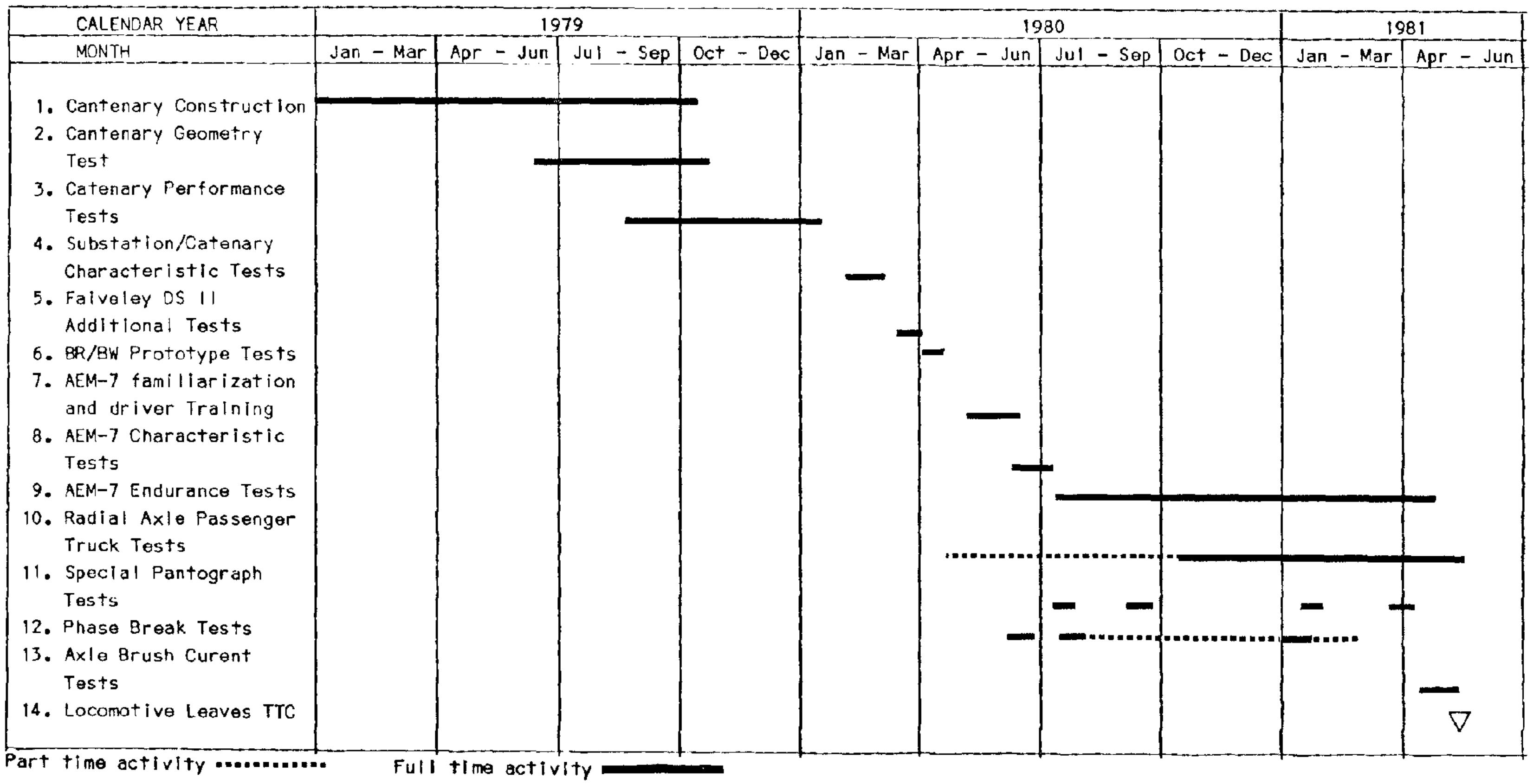


FIGURE 6-1. TEST OUTLINE.

7.0 AEM-7 LOCOMOTIVE CHARACTERISTIC TESTS

7.1 CHARACTERISTIC TEST OBJECTIVES

The fundamental Characteristic Tests to compare the performance of the locomotive with the design specification had been carried out by General Motors and AMTRAK[2] on the NEC prior to delivery of AMTRAK 900 to the TTC. The purpose of the tests at the TTC was to augment the NEC tests, particularly with respect to 60 Hz supply frequency operation. With this overall objective in mind the following test program was initiated:

- Testing of the interaction of the locomotive with the TTC catenary and power distribution system. This was intended as an initial controlled startup on 12.5 kV 60 Hz and 25 kV 60 Hz supply voltages followed by locomotive instrumentation checkout.
- Measurement of critical component temperatures within the locomotive systems. These were to be defined as a result of much more detailed measurements carried out by EMD.
- Measurement of the locomotive energy requirements on the 60 Hz supply voltages. The data included current, power factor, and power (kW) measurements.
- Measurement of the harmonic content of the catenary current waveform under various load conditions.
- Measurement of the transformer inrush current on both 12.5 kV 60 Hz and 25 kV 60 Hz supplies.
- Operation of the locomotive at both the high (+10%) and low (-35%) limits of the nominal catenary voltage.
- Operation over the phase breaks including voltage change phase breaks and operations with an energized locomotive.
- Filming of pantograph arcing on the contact wire.

7.2 INSTRUMENTATION

7.2.1 General Description

The instrumentation required to furnish data consisted of two parts:

- Special transducers and recording devices provided by the TTC.
- Hookups to existing locomotive measuring systems and logic circuits.

For the duration of the Characteristic Tests the DOTX-208 instrumentation car was used to provide the signal conditioning supplies and to house the recording instrumentation.

The following is a list of data channels utilized during the tests.

- Locomotive Primary Current
- Pantograph Voltage
- Train Speed
- Traction Motor Armature Current
- Air Blast Breaker Position
- Transformer Primary Tap Changer Position
- Throttle Position
- Power/Brake Control Logic
- Left and Right Magnet Sensors (automatic phase break system)
- Thermocouple Temperature Measurements
- IRIG B Time
- Power Measurement

7.2.2 Instrumentation

a. DOTX - 208 Car. The DOTX-208 instrumentation car was equipped to provide full instrumentation signal conditioning and data recording facilities. The signal conditioning equipment consisted of integrated transducer power supplies and variable gain amplifiers. In addition, adjustable frequency, 8-pole, low pass filters were available to filter the data when necessary.

Recording devices included a 14-channel analog tape recorder, an 8-channel Brush strip chart recorder and a 20-channel oscillograph. In addition, the car was equipped with a PDP 11/34 digitial acquisition system and data processor. However, this system was not fully operational during the AEM-7 Characteristic Tests and was, therefore, not fully used.

b. Primary Current Measurement. In preparation for the test program two high resolution instrumentation quality current transformers were purchased. These units were selected because of their high frequency response. The specification is as follows:

Manufacturer - Pearson Electronics Inc.
Model # - 1330
Output Sensitivity (nominal) - 0.005 V/A
Current rating (RMS) - 1400 A
Maximum current (peak) - 100,000 A
Maximum permissible d.c. offset - 10 A max (0.7% full scale)
Frequency range - d.c. to 1 MHz
Core hole diameter - 3 1/2 inches

c. Pantograph/Catenary Voltage. The line voltage reference measurements were obtained using a resistive voltage divider. The unit selected for use was designed for limited outdoor use. The outer case is constructed of self-cleaning fiberglass; the inside of the unit containing the resistors is pressurized with Freon to prevent the ingress of moisture. The specifications are as follows:

Manufacturer - Ross Engineering Corp.
Model- VD 120-3.1 B-K-A
Max Voltage Rating (Peak) - 85 kV at 60 Hz
Input Impedence - 238 M
Output Impedence - 313 K
Overall Ratio - 1000:1
Frequency Response - 60 to 1200 Hz

The output of the voltage divider was connected to an operational amplifier by means of short calibrated cables to prevent loading. Long cables for installation at the substation were connected to the amplifier output. The V 60 to 1200 Hz frequency response of the unit (including the operational amplifier) was determined by the TTC and represents the maximum frequency to which the unit was calibrated.

d. Train Speed. For the purposes of the Characteristic Test the train speed was measured by means of a calibrated tachometer mounted on the DOTX-208 car axle. Later testing derived the signal from the locomotive speed recorder input.

e. IRIG B Time. The IRIG B time reference for all the data collected was recorded from a time code translator which in turn derived its input from a site-wide transmitted radio signal. The overall accuracy of this system is ± 1 millisecond.

f. Power Measurement. One of the major requirements for both the Characteristic Tests and later the Endurance Test was the ability to accurately measure the locomotive power consumption parameters. The original substation instrumentation system was designed to monitor the full power rating of the substation output, and proved to be too insensitive for the purposes of the test program. In addition, the utility type current and potential transformers used in the substation did not meet the calibration and frequency response specification for the measurement accuracy required.

A special power consumption processor was designed and built by the TTC Instrumentation Group to provide the necessary data. The processor was designed to accept the outputs from the Ross voltage divider and the Pearson current transformer and provide the following outputs:

RMS current
RMS voltage
RMS kilovolt Amps (kVA)
RMS kilowatts (kW)
Power Factor
Cumulative Power (energy) (kW hr)

The current transformer was fitted to the substation transformer return cables and the voltage divider connected to the substation output bus-bar. The signals were analog processed using precision analog multipliers, dividers, and integrators. A 6-cycle (100 ms) averaging period was used for all RMS values. To provide the cumulative power (energy) output the kilowatts were integrated with respect to time and used to gate a voltage pulse signal calibrated at one pulse per kW hr. Thus the cumulative power output consisted of a chain of voltage pulses each representing one kilowatt hour. A block diagram of the processor is shown in Figure 7-1.

Analog outputs were provided to enable the data to be recorded on analog tape or strip chart. A parallel output was fed to a switch selectable digital display for 'instantaneous' readout of any one of the outputs except cumulative power. A separate resettable digital counter display was provided to indicate cumulative power. The overall accuracy of the digital display outputs was calibrated to better than 1%. However, the accuracy of the power factor output relied heavily on the quality of signal from the current and voltage sources, hence the use of high quality measuring devices corrected for phase angle shift.

7.2.3 Locomotive System Hookups

a. Pantograph Current. The prime measurement of locomotive main transformer primary current was taken from the output of one of the Pearson CT's fitted to the transformer ground connection in the locomotive. However, for the purpose of inrush current measurement in particular, current measurements were also made using the output of the locomotive bushing CT. Since the primary purpose of the bushing CT was to provide overcurrent protection, a separate precision shunt was installed in the CT output to provide the instrumentation signal in order not to interfere with the protective circuits. The bushing CT shunt was calibrated against the Pearson CT at the 60 Hz fundamental frequency. The bushing CT was a nominal utility type unit with limited frequency response but was less prone to d.c. saturation.

b. Pantograph Voltage. After arrival of the AEM-7 a decision was made to the roof mounted potential transformer (PT) for as many of the voltage measurements as possible to avoid the use of the more delicate voltage divider on the locomotive roof. The PT was calibrated for frequency and was found to give a flat response to 1 kHz. The output sensitivity of the roof mounted PT was calibrated using a comparison between it and the instrumentation voltage divider. The overall performance of the PT was found to be totally acceptable in all respects and it was used throughout the remainder of the test program for locomotive voltage measurements.

c. Traction Motor Armature and Field Currents. Calibrated shunts were provided in all four traction motor armature and field circuits for motor control purposes. When necessary, instrumentation supplies were taken from the shunts in parallel with the monitoring circuits. Care was taken to provide high impedance loads using voltage isolation amplifiers on the

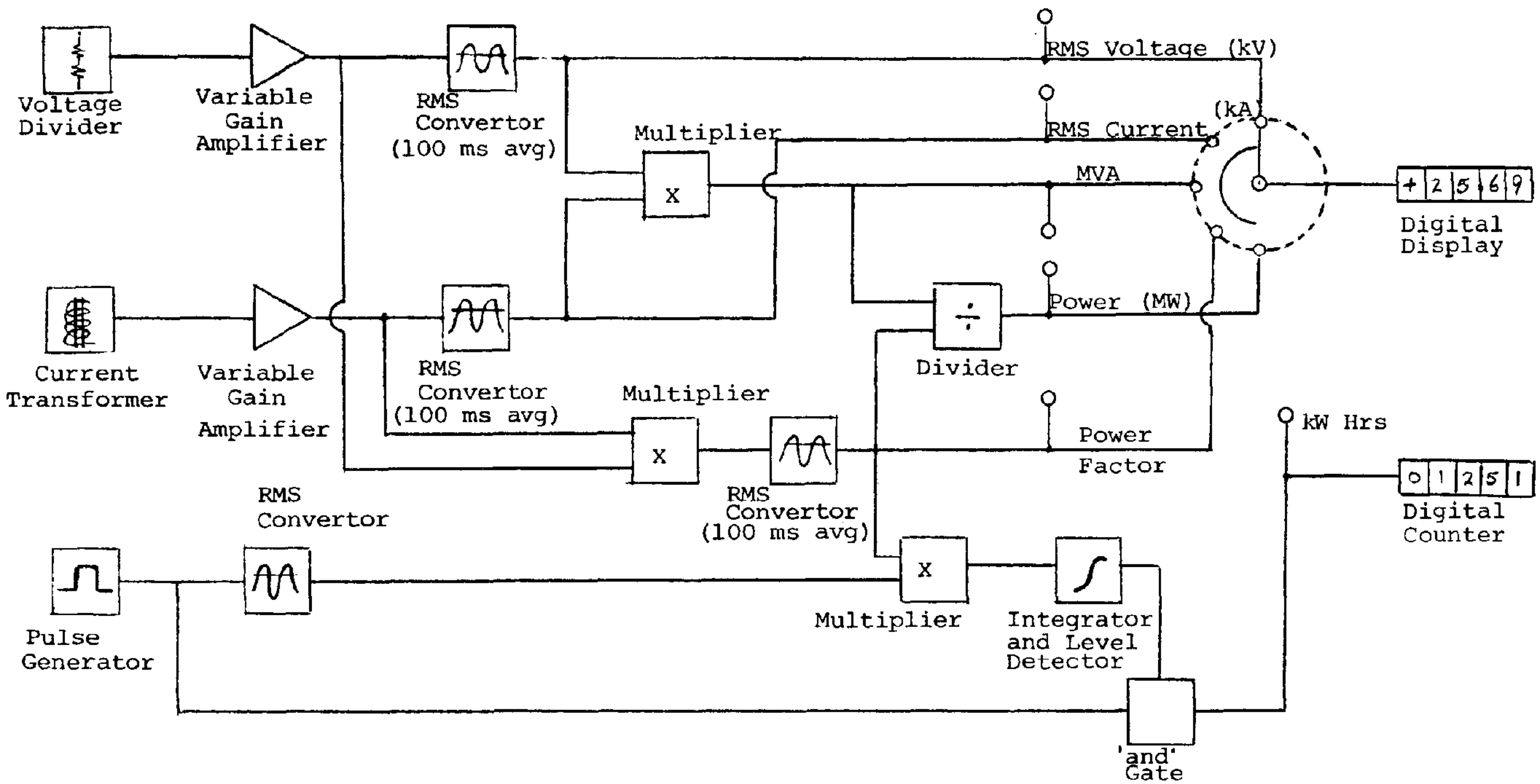


FIGURE 7-1. SCHEMATIC DIAGRAM OF THE POWER CONSUMPTION PROCESSOR.

shunt connections to avoid interference with the normal control functions.

d. Locomotive Logic Signals. When necessary, connections were made into the locomotive control logic to provide instrumentation data. These included such signals as Air Blast Breaker position, transformer primary tap changer position, automatic phase break control magnet sensor signals, and throttle position. Where necessary, buffer amplifiers were used at source to prevent feedback interference from the instrumentation system. To further avoid problems of interference, the use of such connections was kept to a minimum.

7.3 THE INTERACTION BETWEEN THE LOCOMOTIVE, CATENARY AND SUBSTATION

7.3.1 Initial Energization of the AEM-7

Prior to arrival of the AEM-7 locomotive at the TTC no electrical load had been applied to the RTT catenary or substation, although full rated current had been passed through the catenary during the electrical Characteristic Tests (appendix A). Conversely the AEM-7 locomotive had not operated on a 25 kV 60 Hz supply, although it had been powered up at a voltage of 12.5 kV 60 Hz by General Motors at EMD.

The initial startup was carried out by General Motors and AMTRAK personnel as a training exercise for TTC staff. The first training attempt to power the locomotive was at the high line voltage of 25 kV with manual voltage selection in the locomotive cab. Initially a voltage change/phase break (VP/PB) fault indication prevented the locomotive from energizing. The fault indication was cleared and the locomotive was powered up without further problems. A similar exercise at a line voltage of 12.5 kV, again with manual voltage selection, proved equally successful.

7.3.2 Initial Operation

After successful energization of the locomotive the unit was set up for its first operation on the RTT. The DOTX-211 pantograph test car was coupled to the rear of the locomotive so that the locomotive pantograph could be observed from the test car viewing platform. Two significant events took place during the first lap on the track:

- During the first pass over the BICC phase break at station R70 + 800 the manual phase break approach button was not fully depressed. The locomotive Air Blast Breaker remained closed causing an arc to be drawn over the phase break to the grounded center section. The resultant ground fault tripped the substation Oil Circuit Breaker. Several large fragments of carbon were blown out of the pantograph collector strips.

- As the locomotive power demand was increased during the first acceleration the substation OCB was again tripped due to overcurrent and differential current indications. Initially both relay system settings were increased. Subsequent accelerations again tripped the OCB, at which point the substation relaying system was thoroughly checked. Several wiring errors were identified and subsequently remedied.

7.3.3 Locomotive Speed Upgrade and Vehicle Operator Training

During the initial vehicle operator training provided by AMTRAK the opportunity was taken to speed up-grade the locomotive to its full operational speed of 120 mi/h. During this process the pantograph was observed from the DOTX-211 car. Speed increments of 10 mi/h were used from 60 mi/h to 120 mi/h.

Initial observation of the pantograph showed a larger than expected lateral sway mode of the pantograph head (collector shoe) at speeds above 100 mi/h. In addition, the general current collection performance was considered worse than expected from the earlier dead line test results. However, high speed operation over the phase breaks did not appear to be a problem at that stage. After the initial flashover incident the ground connections to both phase break centers were removed. Initial assessment of the locomotive ride on the RTT track was favorable as were the locomotive handling characteristics.

7.4 LOCOMOTIVE TRANSFORMER INRUSH CURRENTS

7.4.1 Background

Inrush current is defined as the initial surge of current which flows into an electrical device when voltage is applied to it. The magnitude and direction of the resultant inrush depends on the equivalent circuit (resistance, capacitance, and inductance) of the device.

In an unloaded transformer (one in which the secondary winding is an open circuit) the applied voltage on the primary winding causes an excitation current to flow. A large transformer, such as the one used on the AEM-7, develops high inrush currents because of its highly inductive characteristics.[5] Since the primary winding is highly inductive the current lags the voltage by almost 90°. Under steady state conditions (after inrush) the magnetization of the transformer core (see Figure 7-2) is forced to follow the core material magnetization curve by the applied voltage at the excitation frequency. Interruption of the supply to the primary winding causes the magnetization process to halt at the equivalent point on the curve and then to fall along a modified magnetization curve to the permanent (or residual) magnetization value.

Upon re-energization a transient current (inrush) flows which attempts to return the core magnetization to the equivalent steady state value for the

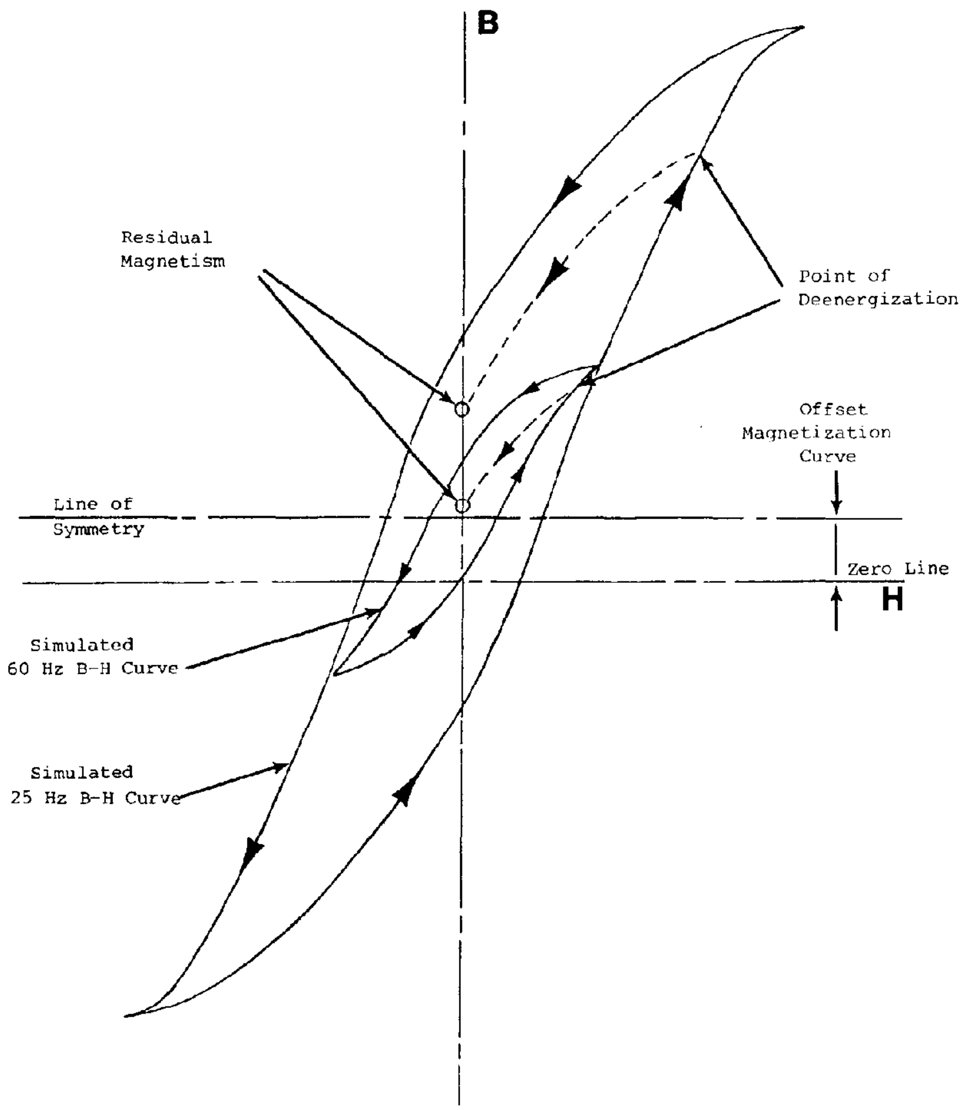


FIGURE 7-2. TYPICAL B-H MAGNETIZATION CURVE FOR A TRACTION TRANSFORMER.

initial applied voltage. The resultant current flowing through the winding consists of a steady state excitation current superimposed on a gradually reducing transient. In some extreme cases it can take as many as 30 to 40 cycles for the transient to decay. The magnitude of the transient depends on the interaction between position of the applied voltage within the waveform at the instant of energization, the internal and external line impedances, and the residual magnetic condition of the core. All of these conditions combine to make inrush currents occur when the transformer is energized at zero volts, that is, when the steady state current would have been maximum.

7.4.2 AEM-7 Inrush Current Data Collection

The initial method used to collect inrush current data consisted of positioning the locomotive near the substation energized at the desired line voltage. Measurements were then made of line voltage and locomotive primary current while the main ABB was opened and closed using the manual phase break control push buttons on the engineer's control panel. In approximately 80 ABB operations only five resulted in measurable inrush currents, and these were of a relatively low magnitude. To avoid unnecessary ABB operation this test method was abandoned.

From the data collected it was possible to compare both the Pearson CT and bushing CT outputs from a current shunt temporarily installed in the transformer ground connection. The bushing CT and the shunt gave good agreement on waveshape and magnitude. However, the Pearson CT output showed a flattened response on the lower half cycle due to saturation, but a full, undistorted, waveform on the the high amplitude side of the characteristic.

An alternative method of collecting inrush current data was devised in which the transformer primary current and voltage were recorded over the phase breaks during normal Endurance Test operations. Examples of typical inrush currents measured at 12.5 kV 60 Hz and 25 kV 60 Hz are presented in Figure 7-3. A survey of the occurrence of inrush currents and their magnitudes for various phase break operating conditions is presented in appendix B.

7.4.3 Discussion of Results

The maximum inrush currents measured during approximately 300 phase break passes were 600 A at 12.5 kV and 400 A at 25 kV. On the average, measurable inrush currents occurred at approximately 25% of the phase break passes monitored.

Inrush currents measured by General Motors on 11 kV 25 Hz[2] reached levels of 2300 A. On a 60 Hz supply the amplitude of the magnetization cycle of the transformer core is smaller than for the 25 Hz case by the the inverse ratio of the frequencies.[5] It therefore follows that the expected inrush currents are less by approximately the same proportion.

Changing the supply voltage from 12.5 kV to 25 kV required the series

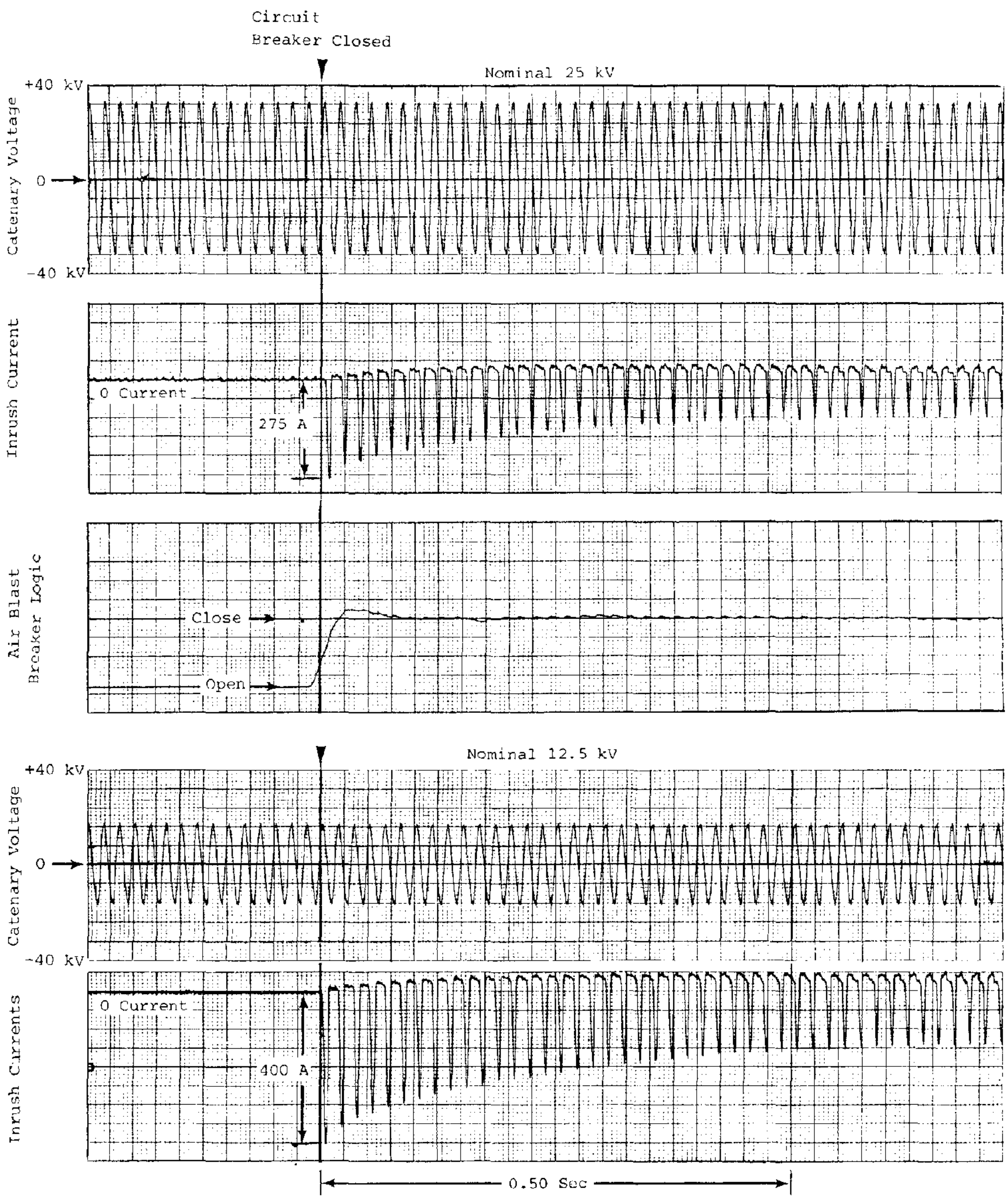


FIGURE 7-3. EXAMPLES OF INRUSH CURRENT DATA.

connection of the two primary windings which resulted in an increase in initial internal impedance. This increase in impedance served to limit the initial transient surge of current.

One aspect of the measured inrush currents remains unexplained. All inrush currents measured on the AEM-7 were of positive polarity, although for a transformer with a magnetically balanced core (a symmetrical B-H curve) an equal number of positive and negative inrush surges would have been expected. Two possible theories are suggested:

- The inclusion of the locomotive smoothing reactors within the same magnetic circuit causes the residual magnetism of the transformer to be biased toward one polarity.

- In general the magnetic cycle of the transformer core is slightly biased toward one polarity. For a transformer built for 25 Hz operation operating at 60 Hz, the reduced amplitude of magnetization would cause the magnetic bias to be exaggerated (see Figure 7-2), and therefore cause the residual magnetism to be biased toward one polarity.

Neither of those theories can be substantiated in any way by the data collected during the testing. Therefore, the exact phenomena so far remains unexplained.

7.5 THE AEM-7 LOCOMOTIVE ENERGY REQUIREMENTS

7.5.1 Background

Important aspects of locomotive performance include the total power (kVA) drawn by the locomotive over its speed range, and at what power factor that power is utilized. Other important data include a measurement of how the locomotive utilizes its available power to haul a load.

These quantities are best analyzed from data collected for an acceleration from standstill to full speed hauling a train of known weight and train resistance.

7.5.2 Presentation of Results

The data is presented in Table 7-1 for an acceleration from 0 to 120 mi/h starting at RTT station R34 in a clockwise direction. All measurements were made at the locomotive, not at the substation. The rail conditions were dry and the weather conditions dry and warm. The catenary voltage was set at 25 kV nominal. Two accelerations were recorded and found to be consistent within approximately 200 ft of cumulative distance or 2 seconds of cumulative time (1% overall repeatability). The data are also presented in Figure 7-4 in graphical form. Graphs are also presented for power (Figure 7-5) and line

TABLE 7-1. SUMMARY OF 0-120 MI/H ACCELERATION - 20 JUNE 1980.

AMTRAK 900 + 6 CARS

(ELAPSED TIME SECS)	SPEED (MI/H)	CUMMULATIVE DISTANCE (FT)	VRMS (kV)	I RMS (AMPS)	AVERAGE POWER (MW)	MVA (RMS)	POWER FACTOR
0	0	0	25.0	25.4	0.17	0.64	0.27
5	2.4	6	24.6	131.1	1.02	3.29	0.30
10	7.5	43	24.5	152.7	1.50	3.73	0.42
15	12.8	117	24.4	163.3	2.14	3.99	0.54
20	18.3	233	24.4	173.3	2.68	4.22	0.63
25	23.7	388	24.3	190.4	3.21	4.63	0.69
30	29.2	585	24.1	232.1	3.80	5.60	0.68
35	32.9	814	23.8	296.7	4.31	7.07	0.61
40	37.2	1,069	23.6	317.1	4.84	7.50	0.65
45	41.9	1,360	23.8	333.4	5.36	7.85	0.68
50	47.0	1,685	23.3	341.0	5.91	8.16	0.72
55	51.6	2,046	23.3	366.4	6.52	8.54	0.76
60	56.4	2,443	23.4	364.8	6.71	8.52	0.79
65	60.2	2,872	24.1	352.2	6.64	8.48	0.78
70	65.1	3,331	24.0	329.0	6.31	7.90	0.80
75	68.7	3,824	23.9	321.1	6.20	7.69	0.81
80	72.7	4,344	23.8	321.1	6.23	7.65	0.81
85	76.1	4,890	23.7	320.4	6.26	7.60	0.82
90	79.5	5,460	23.9	312.8	6.09	7.48	0.81
95	81.7	6,051	24.1	302.2	5.89	7.29	0.81
100	84.5	6,661	24.0	301.5	5.90	7.24	0.81
105	87.3	7,292	23.9	301.2	5.91	7.21	0.82
110	89.2	7,938	24.0	296.5	5.81	7.12	0.82
115	90.6	8,594	24.1	292.7	5.73	7.06	0.81
120	91.8	9,263	24.1	291.1	5.73	7.00	0.82
125	93.1	9,941	24.0	288.4	5.71	6.93	0.82
130	94.8	10,630	24.0	286.0	5.66	6.86	0.83
135	96.1	11,327	24.2	278.0	5.48	6.72	0.81
140	97.1	12,036	24.1	276.6	5.49	6.67	0.82
145	98.8	12,756	24.1	274.4	5.49	6.60	0.83
150	99.7	13,484	24.2	265.9	5.27	6.45	0.82
155	101.1	14,221	24.2	261.1	5.21	6.33	0.82
160	102.9	14,970	24.2	253.5	5.11	6.13	0.83
165	104.3	15,729	24.2	250.9	5.07	6.07	0.84
170	103.9	16,491	24.4	239.7	4.79	5.86	0.82
175	105.0	17,258	24.4	235.6	4.73	5.75	0.82
180	105.3	18,026	24.4	231.6	4.65	5.65	0.82
185	106.0	18,800	24.4	231.4	4.67	5.64	0.83
190	107.3	19,577	24.4	231.1	4.67	5.63	0.83
195	109.1	20,375	24.3	234.7	4.75	5.71	0.83
200	110.6	21,182	24.3	226.3	5.57	5.51	0.83
205	111.5	21,995	24.3	219.1	4.40	5.32	0.83
210	112.3	22,812	24.3	220.5	4.41	5.36	0.82
215	113.3	23,638	24.3	218.4	4.35	5.30	0.82
220	113.8	24,470	24.3	217.8	4.32	5.29	0.82
225	114.6	25,308	24.3	209.5	4.16	5.10	0.82
230	115.4	26,154	24.3	205.9	4.09	5.01	0.82
235	116.2	27,002	24.5	206.1	4.13	5.04	0.82
240	115.8	27,856	24.5	204.4	4.15	5.00	0.83
245	118.8	28,717	24.5	195.1	3.96	4.77	0.83
250	119.7	29,586	24.5	198.7	3.92	4.87	0.80
255	119.9	30,464	24.5	193.4	3.91	4.73	0.83

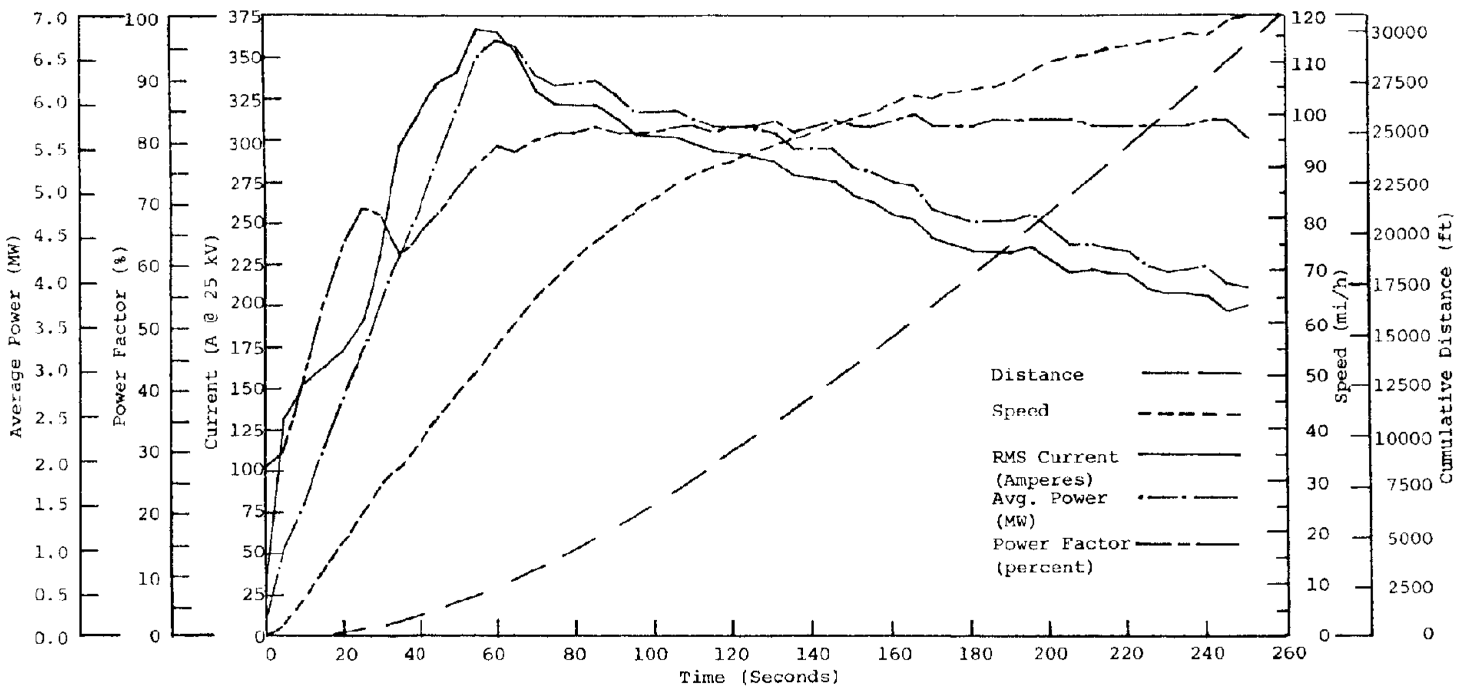


FIGURE 7-4. ACCELERATION TEST DATA FOR THE AEM-7 LOCOMOTIVE ON THE RTT.

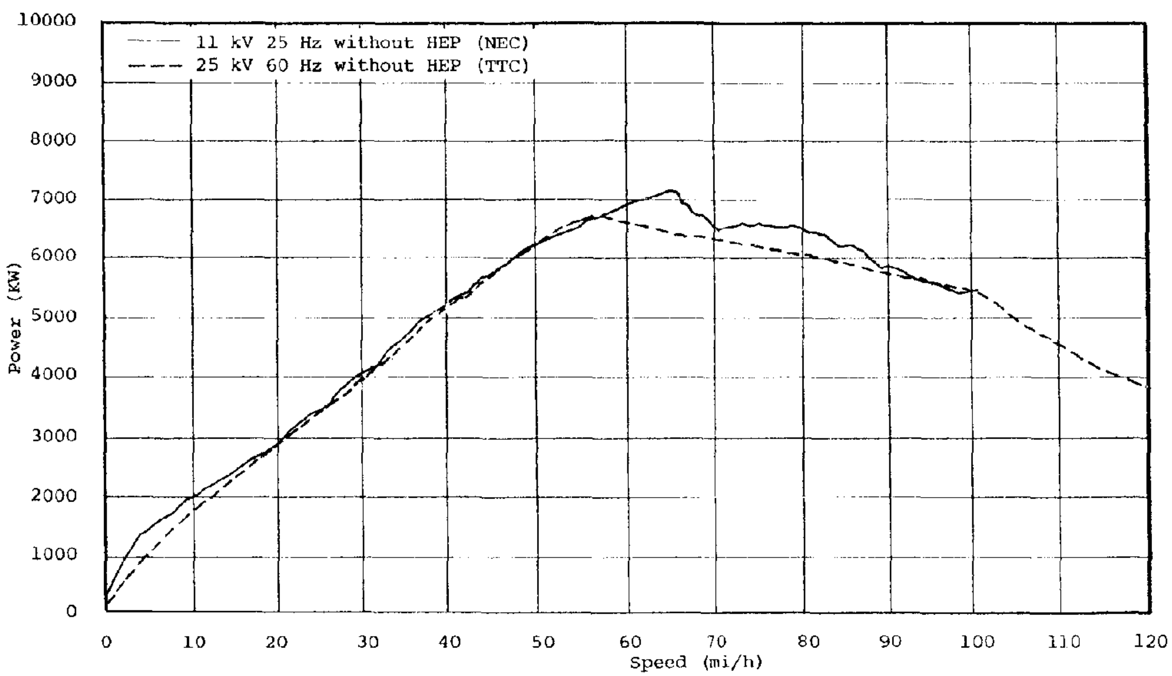


FIGURE 7-5. POWER/SPEED CURVES FOR THE TTC AND NEC TESTS.

current (Figure 7-6) using speed as the independent variable. Both are overlayed onto equivalent test data from the NEC.[2]

7.5.3 Discussion of the RTT Test Results

The maximum power used by the locomotive transformer was 6.71 MW (9007 hp) at a speed of 56 mi/h. From the peak power point the power reduces with increased speed, until at 120 mi/h the power drawn is 3.91 MW (5428 hp).

The line current peak is 366 A at a speed of 52 mi/h. It follows a similar characteristic to the power curve, falling to a value of 193 A at 120 mi/h.

The power factor, which is a measure of the locomotive line current converted to useful power, follows a characteristic typical of a two stage Thyristor controlled locomotives. The power factor rises from less than 0.30 at standstill to a first stage peak of 0.69 at 24 mi/h from where it falls to a second stage low of 0.61 at 33 mi/h. From there, it gradually rises until at a speed of 65 mi/h it reaches a value of 0.80. Above 95 mi/h the power factor stabilizes at a value of 0.83.

The double peak characteristic is caused by the two stage control of the locomotive power output described in section 5.4.2. During the first stage the output is derived from one bank of thyristors. Once these are phased fully on, the output from a second bank is added. During each stage the power factor curve reflects the change in the firing angle of the thyristor bank. At the low speed and low current levels the HEP and auxiliary power system loads are dominant, and the propulsion thyristors are fired late in the cycle resulting in a lower power factor.

The speed and distance against time curves, as presented in Figure 7-4, have not been corrected for curvature and gradient. This data was supplied to J. W. Marchetti of Marchetti and Associates who produced an equivalent tractive effort against speed curve, not presented in this report.

The voltage at the pantograph shown in Table 7-1 only reflects the catenary voltage drop between the substation and locomotive. At the peak power point the voltage drop is 1.7 kV (7.8%). According to the locomotive specifications a voltage drop of less than 10% does not affect the locomotive output.

7.5.4 Comparison with the NEC Data

In general the two sets of data presented in Figures 7-5 and 7-6 are in good agreement considering the differences in conditions under which the data was taken.

The power characteristics (Figure 7-5) show that slightly higher power was drawn during the Northeast Corridor tests. Both sets of data were taken on the locomotive; therefore only the line supplies differed between the tests.

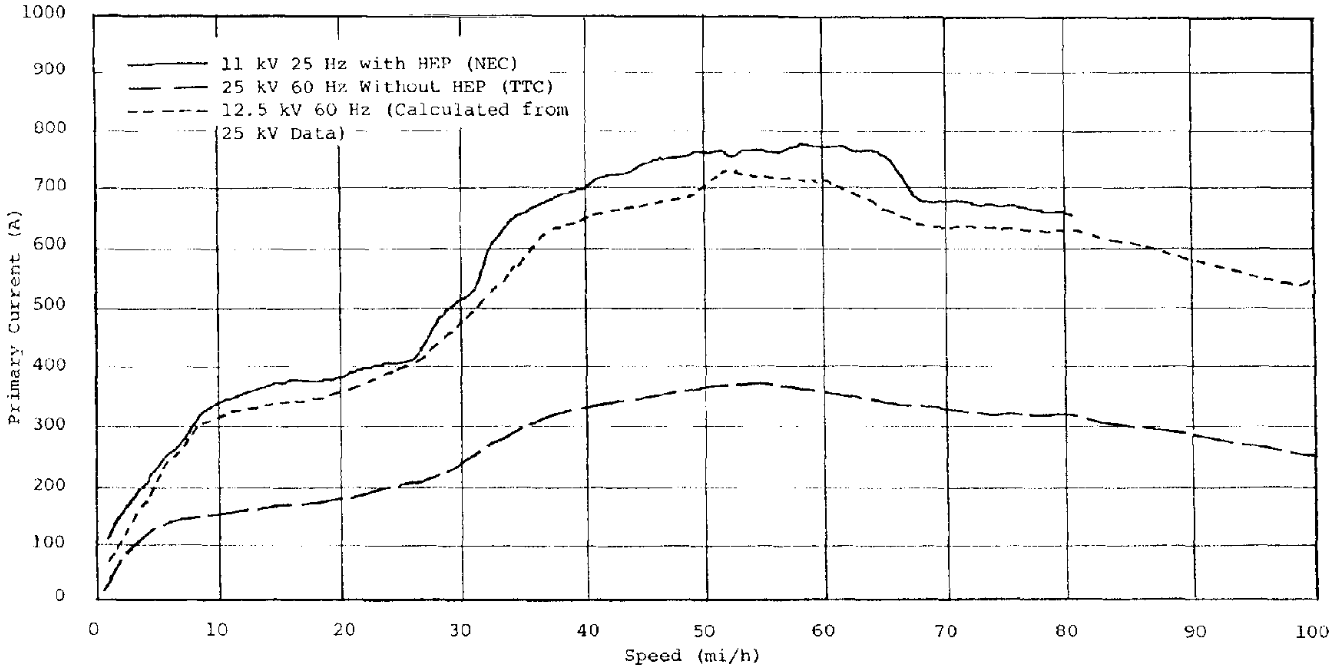


FIGURE 7-6. PANTOGRAPH CURRENT/SPEED CURVES FOR THE TTC AND NEC TESTS.

The line current characteristics cannot be compared directly since the data was collected at different line voltages. However, the RTT data 'corrected' for voltage shows good agreement with the equivalent NEC data.

7.6 CATENARY CURRENT HARMONICS

7.6.1 Background

The theoretical shape of an a.c. waveform is a sinusoid at the fundamental frequency. However, non-linearities within electrical circuits tend to generate harmonics on the fundamental sinusoidal waveform. For example, a transformer[5] tends to generate a large 3rd harmonic, and a thyristor controlled rectifier, which tends to chop the waveform, generates significant odd harmonics up to the 15th and beyond. The adverse effects of harmonics can be far reaching:

- They can cause interference with other sensitive equipment within their immediate electrical vicinity such as signalling systems on the railroad.
- The higher harmonics can cause radiated interference to be transmitted over a wider area and affect low level signals such as telephone lines.
- The harmonics can be transferred back along the utility transmission line and appear on the supplies of other utility company customers.

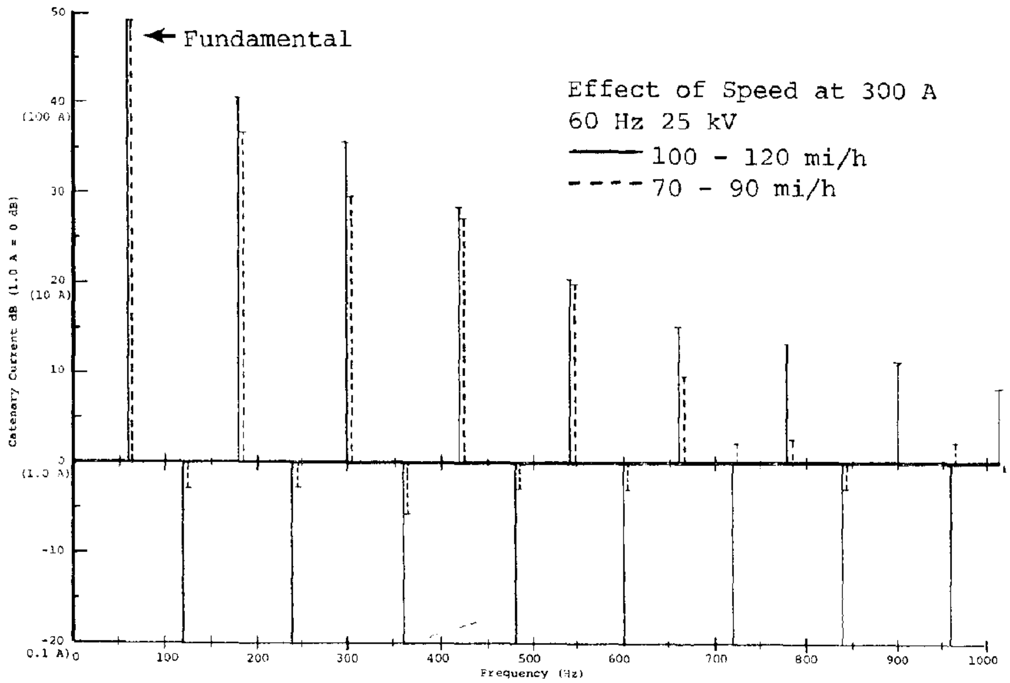
7.6.2 Presentation of Results

Since one objective of the test on the AEM-7 was to check the level of harmonics fed back on the utility supply, the original harmonic content measurements were confined to the substation only. A Pearson CT was installed on the substation transformer connection to ground. It was not possible to install a suitable high frequency CT on the high voltage side of the transformer secondary winding. The Pearson CT output was recorded and analyzed using the substation frequency analyzer over the range of frequencies from 0 to 1200 Hz. The data was taken for a number of train speeds and RMS current levels.

The data is presented in hand plotted form for two representative cases in Figure 7-7. It should be noted that the presentation is in decibels (dB) based on the datum of 0 dB = 1 A (RMS). The conversion factor to absolute current is

$$I_{RMS} = [10]^{x/20} \qquad \text{where } x = \text{current level in dB}$$

The catenary voltage and primary current data collected on board the locomotive during the phase break dual voltage tests (section 11.3) were later analyzed for harmonic content in order to augment the data collected in the



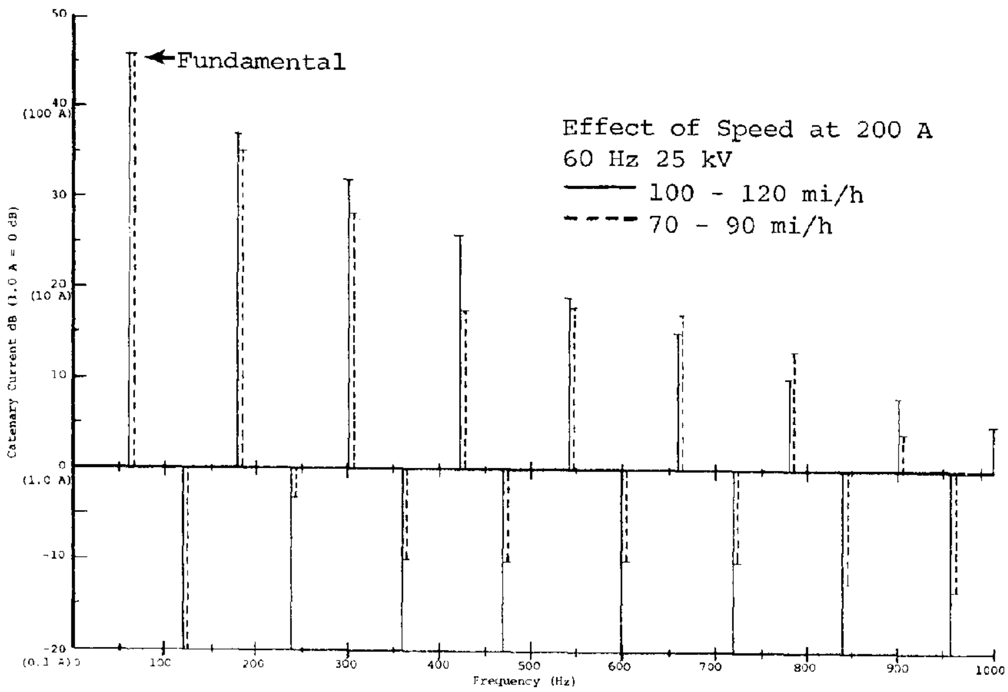
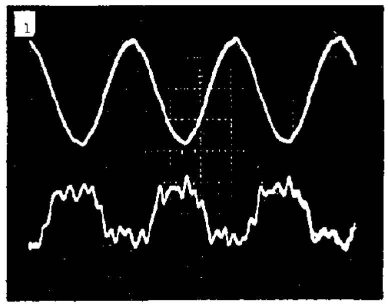


FIGURE 7-7. AEM-7 LOCOMOTIVE HARMONIC ANAYSIS.

substation. Typical examples of the current and voltage waveforms are presented in Figure 7-8, together with the operating conditions under which the data were collected. The examples were chosen to represent the full range of speed and current levels of the locomotive, starting with Head End Power and Auxiliary Power only, up to full speed and 75% full current. The harmonic content analyses for three of the more significant current waveforms and one voltage waveform are presented in Figure 7-9.

Photo Number	Speed (mi/h)	Voltage (kV)	Current (A)	MVA
1	0	12.5	15	0.2
2	20	12.5	200	2.5
3	20	25.0	100	2.5
*4	35	12.5	215	2.7
*5	40	12.5	425	5.3
*6	75	12.5	400	5.0
7	120	12.5	75	0.9

* Examples used for harmonic analysis in Figure 7-9



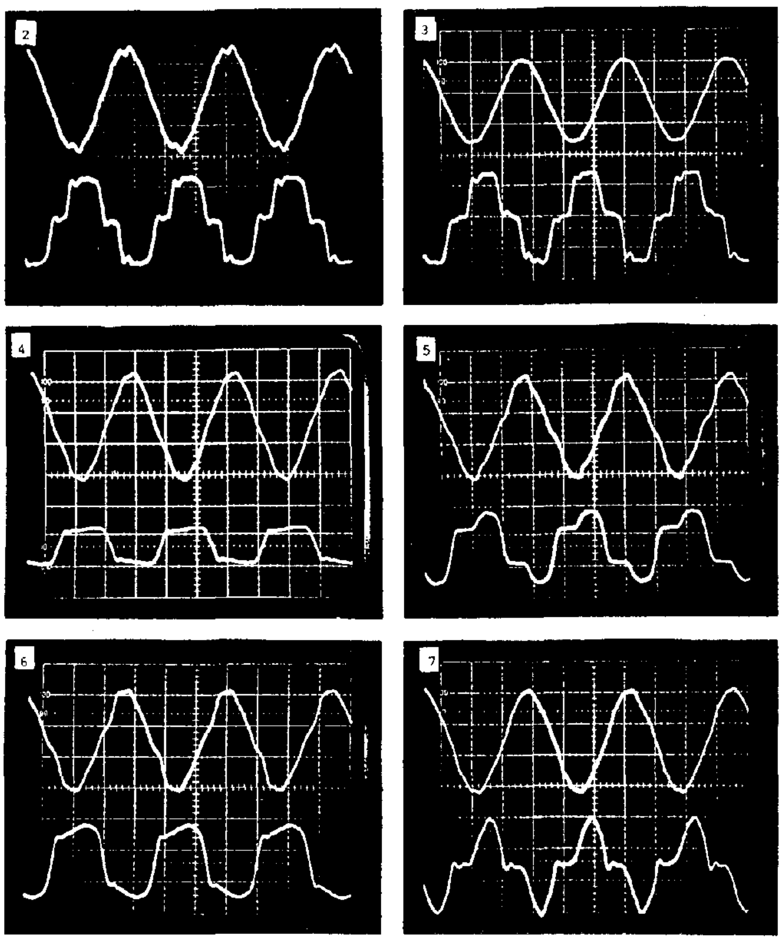


FIGURE 7-8. TYPICAL PRIMARY CURRENT AND CATENARY VOLTAGE WAVEFORMS RECORDED ON BOARD AEM-7 LOCOMOTIVE, AMTRAK 900.

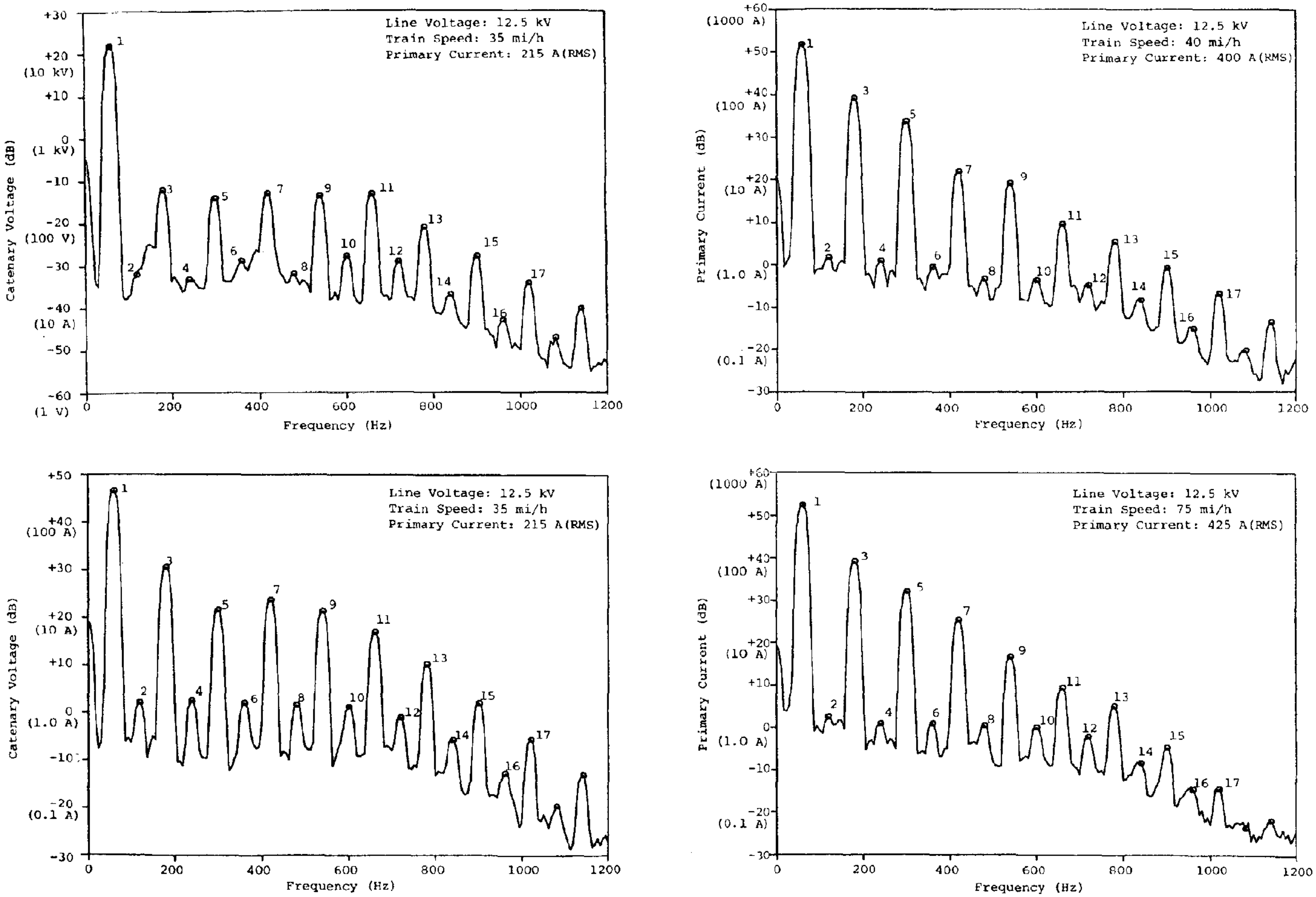


FIGURE 7-9. HARMONIC ANALYSIS OF LOCOMOTIVE PRIMARY CURRENT AND CATENARY VOLTAGE WAVEFORMS COLLECTED.

Measurements were also made on the AEM-7 at the TTC by the Electromagnetic Compatibility Analysis Center (ECAC) as part of a separate test program.[6] A sample result of these tests, together with equivalent data taken on the E60 CP (AMTRAK) and E50 (Muskingham Coal Mine) locomotives[7] are shown in Figure 7-10, together with a sample of the TTC measured data.

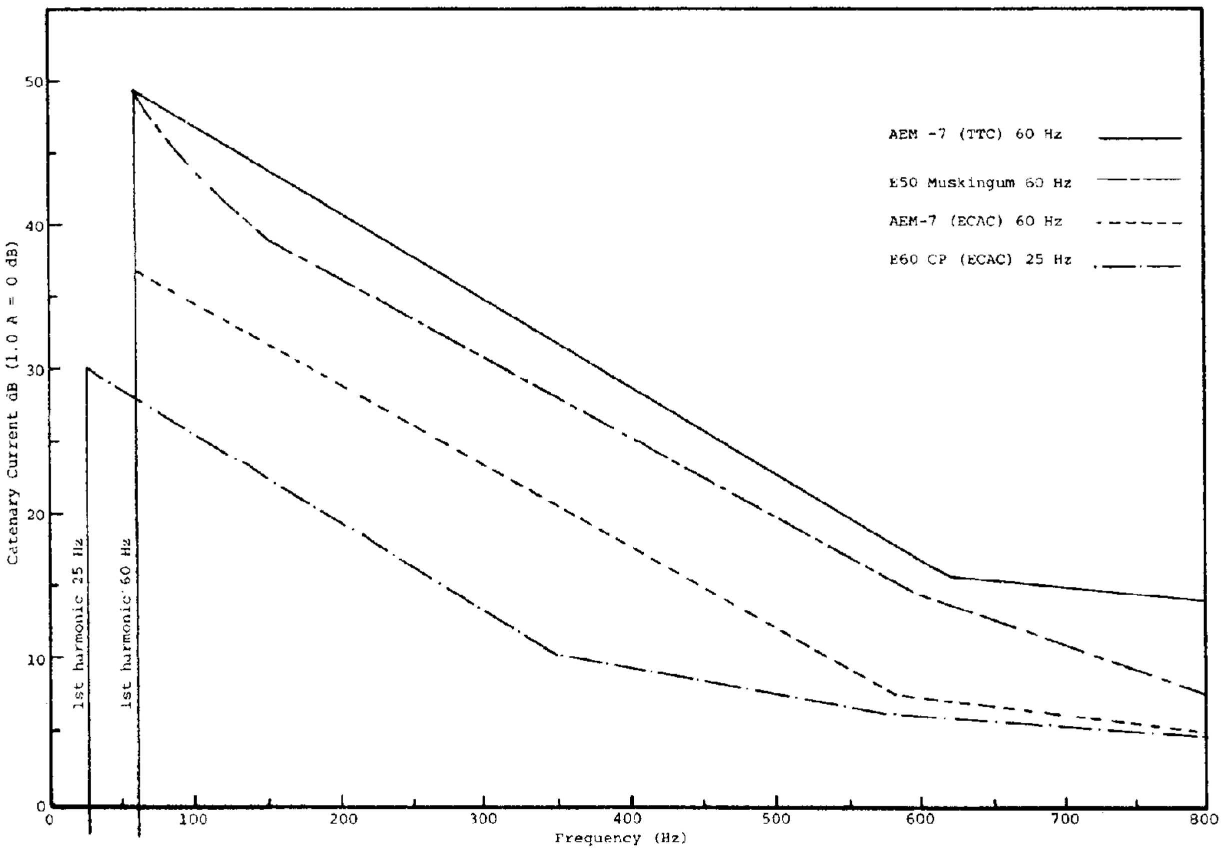


FIGURE 7-10. AEM-7 LOCOMOTIVE HARMONIC ANALYSIS.

7.6.3 DISCUSSION OF RESULTS

From the harmonic content data collected at the substation it was determined that the locomotive speed in the 70 to 120 mi/h range had little effect on the relative magnitude of the fundemental and harmonics of the currrent waveform. The data presented in Figure 7-7 shows a small increase in the relative magnitudes of the higher odd harmonics (11th, 13th, and 15th) with speed, coupled with a corresponding decrease in the even harmonics. The effect of current level over the same speed range was found to have an equally small effect.

The data collected on board the locomotive showed the following.

- The current waveforms are more heavily distorted by harmonics than the voltage waveform. This is apparent from both the waveform pictures in Figure 7-8 and the harmonic analysis in Figure 7-9.

- The effect of adding the second stage of the traction supply can be seen in examples 4 and 5, Figure 7-8. The corresponding harmonic analysis indcates that the relative magnitudes of the even harmonics are higher in the fully phased on convertor, although they still remain 40 dB lower than the fundamental.

- The absolute level of the even harmonics remained substantially constant over the speed and current range evaluated.

Comparison of the TTC measured data with the other measurements showed the following.

- Apart from the difference in RMS current level, as indicated by the change in vertical position, the ECAC measured data was in good agreement with the TTC measurements.

- The data for the E60 CP showed the same characteristic of harmonic content bearing in mind that the E60 CP data was measured on a fundamental frequency of 25 Hz.

- The data for E60 CP locomotive showed a 10 dB reduction in harmonic current levels although no deliberate attempts have been made to reduce the harmonics generated by this locomotive. It was concluded that this data was taken with the locomotive thyristors fully conducting.

Methods of reducing the harmonic output of locomotives are available in the form of tuned filter circuits. These tend to be physically large and heavy, particularly for dual frequency locomotives. However, the investigation of such devices lies outside the scope of this report. The subject of electromagnetic interference is under study in detail by several groups, including ECAC and Bell Laboratories, under contract to the FRA.

7.7 OPERATION OF THE LOCOMOTIVE AT THE HIGH AND LOW LIMITS OF THE CATENARY VOLTAGE

7.7.1 Background

The supply voltage at the pantograph of a locomotive can vary depending on a number of conditions:

- The incoming supply voltage to the substation.

- The voltage drop in the catenary system due to the current flow with the locomotive at the end of the electrical feed section.

- Emergency feed arrangements due to a substation shutdown.

The tolerance of the catenary voltage for normal feed arrangements is +10% to -15% of the nominal line voltage. In emergency feed situations allowance is made for the locomotive to operate under reduced power to a limit of -35% of the nominal voltage. The locomotive is designed to lock out at -45% nominal voltage.

7.7.2 Test Procedures

a. High Voltage Limits. The voltage was set to the high limit using the substation transformer secondary tap changer. The actual voltages used are shown in Table 7-2.

TABLE 7-2. VOLTAGES FOR CATENARY HIGH AND LOW VOLTAGE LIMITS TEST.

VOLTAGE LIMIT (%)	SET VOLTAGE (kV)			
	25 kV NOMINAL		12.5 kV NOMINAL	
	REQUIRED	ACTUAL	REQUIRED	ACTUAL
NOM	25.0	25.6	12.5	12.7
+10	27.5	28.1	13.8	14.0
-20	20.0	20.5	10.0	10.4
-35	16.3	NOT USED	8.2	8.7

NOTE: The actual voltages used were measured on the unloaded substation transformer. These voltages dropped by approximately 2% at the substation due to transformer regulations under load. The voltage at the pantograph was further reduced due to catenary line losses.

The line was energized at the 'set' voltage with the locomotive and two car consist at station R18. The locomotive was powered up and the train accelerated counterclockwise toward the substation. The locomotive operation was checked for malfunctions. Recordings were made of speed, pantograph voltage, and catenary current. These were processed by the digital computer on the DOTX-208 car to produce speed, RMS voltage, and RMS power against time tabulations.

b. Low Catenary Voltage. The voltage was set at the -20%, and -35% levels specified in Table 7-2 using the substation transformer tap changer. The line was energized at the set voltage with the locomotive and two car consist at the substation. The locomotive was powered up and the test train accelerated away from the substation in the counterclockwise direction. The locomotive was checked for operational malfunctions.

The train was stopped at station R18 and then accelerated at full throttle toward the substation up to a speed of 100 mi/h. Again recordings were made of speed, pantograph voltage, and current. These were processed to produce speed, RMS voltage, and RMS power against time tabulations.

7.7.3 Presentation of Results and Observations

The results and observations for this test are in two parts:

- The measured voltage, and power against time.
- The logging of equipment malfunctions or reduced capabilities.

Table 7-3 presents a summary of the Power and Performance data at the catenary voltage limits tested.

Table 7-3. POWER AND PERFORMANCE DATA FOR CATENARY VOLTAGE LIMITS.

Required Catenary Voltage		Actual (Measured) Pantograph Voltage		Power at 70 mi/h (MW)	Average Acceleration from 40-80 mi/h (mi/h/sec)
kV	% Limit	kV	% Limit		
12.5	NOM	10.6	-15	5.8	1.39
13.8	+10	--	---	-	--
10.5	-20	9.6	-23	4.0	1.10
8.2	-35	8.3	-34	1.7	0.24
25.0	NOM	23.4	- 6	*	*
27.5	+10	26.1	+ 4	7.5	1.82
20.0	-20	18.9	-24	4.2	1.09
16.5	-35	--	--	--	--

* Data not included due to manual power reduction during the acceleration characteristic.

Figure 7-11 presents a family of power against speed curves for the catenary voltage limits specified in Table 7-3. The data presented in Table 7-3 are shown in graphic form in Figure 7-12.

There were no operational failures at the +10%, Nominal, or -20% levels, but some traction power reduction was noted at -20%. At -35% severe traction power reduction was noted. In addition, the auxiliary voltage dropped to 375 V from the nominal 440 V, a reduction of 12.5%. This resulted in a slowdown of the blower fan motors for the cooling air systems and lockout of the locomotive battery charger.

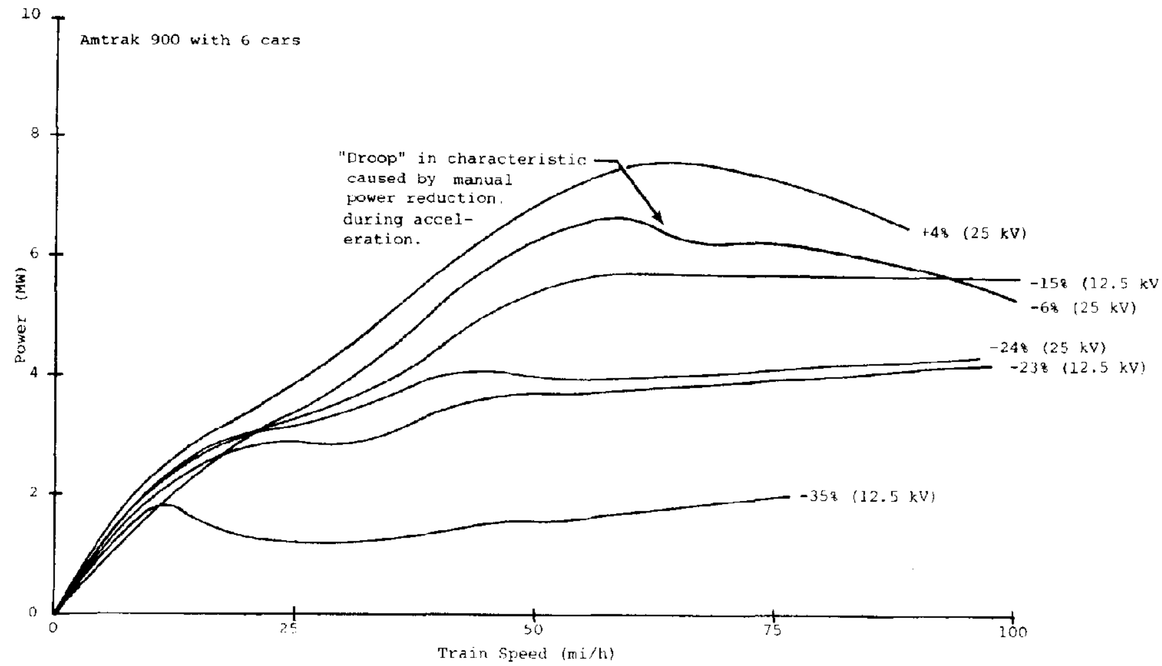


FIGURE 7-11. POWER VS SPEED CURVES FOR THE AEM-7 LOCOMOTIVE AT THE CATENARY VOLTAGE LIMITS.

7.7.4 Discussion of the Results

The locomotive continued to function as a power unit over the full +10% to -35% voltage range. However, between -25% and -35% the available power is greatly reduced. If the locomotive operated at the -35% limit over a long period of time the reduced cooling and battery charger lockout would lead to locomotive shutdown. However, operation at this voltage level would only take place for a short period of time in very extreme emergency feed situations.

The data presented in Figure 7-11 demonstrates the affect of catenary voltage on the available power. The reduction in voltage tends to flatten out the power characteristics in the 10-100 mi/h speed range.

Another effect is demonstrated by two curves in Figure 7-12. The curve of power at 70 mi/h, which is normally at or near the peak power, is a measure of the maximum peak limitation. The curve of average acceleration is an approximate measure of the average tractive effort. This suggests that from +10% to -15% the available power is dependent on the available voltage at the pantograph. Below -15% the power limitation is controlled, not only by the pantograph voltage reduction, but also by enforced current limitation within the locomotive control system. Between -25% and -35% the control system further reduces the power output. It should be noted that the apparently large change in acceleration rate between the -25% and -35% cases is due in

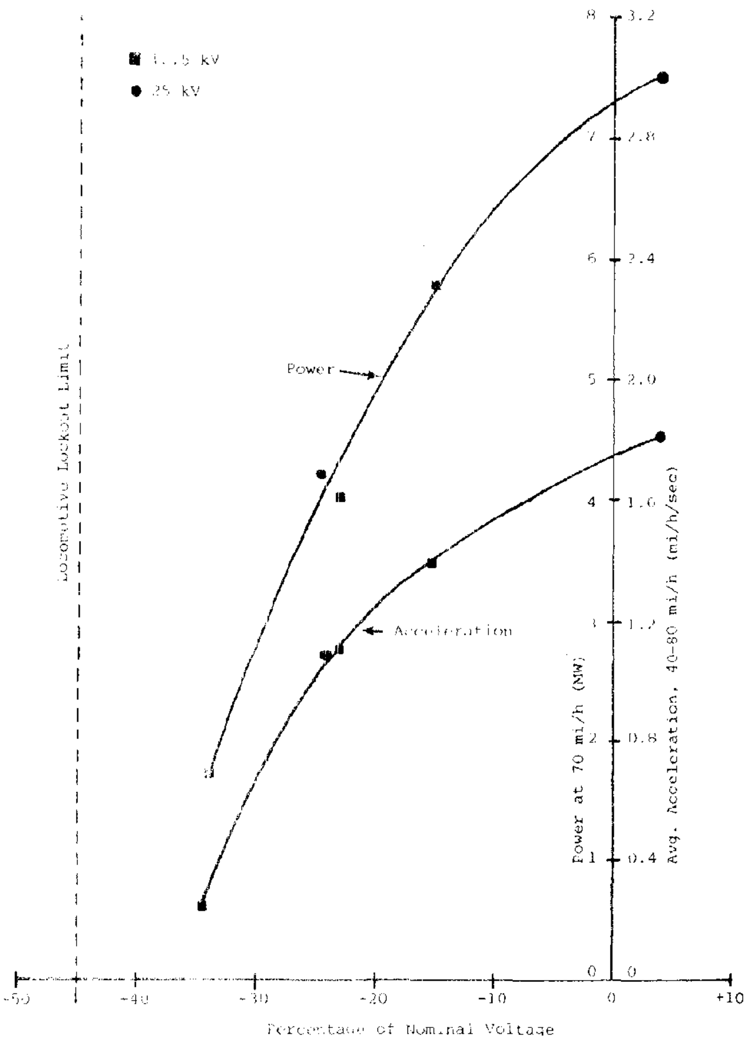


FIGURE 7-12. PERFORMANCE COMPARISON DATA AT THE CATENARY VOLTAGE LIMITS.

part to an increase in track gradient at the upper end of the speed vs time characteristic.

7.8 MEASUREMENT OF CRITICAL TEMPERATURES.

7.8.1 Background

All major components and systems were temperature monitored during the tests on the NEC[2] and no major overheating problems were identified. Therefore temperature measurements during the test program were considered to be a low priority. However, during early operations in ambient temperatures of 90-100°F, it was found that cab and equipment room temperatures rose accordingly, particularly at standstill. It was therefore decided to monitor some of the system temperatures, since some of the early electronic failures were attributed to overheating.

7.8.2 Discussion

The temperature recorder was set up in the locomotive cab recording the output from thermocouples fitted to what were considered to be the critical areas. These included:

- Ambient temperature
- Y2 Electronic cabinet cooling air
- Locomotive equipment room ambient
- Transformer cooling oil
- Thryistor cooling oil
- Traction motor cooling air outlet

However, before meaningful data could be recorded, the temperature recorder failed due to overheating. The temperature specification of the unit was 10°F to 120°F. Originally the temperature recorder was set up on the 'helpers' side desk top and was subject to direct sunlight.

While the recorder was under repair, conventional thermometers were used to spot check the temperatures of the Y2 cabinet interior and the equipment room ambient. In both cases temperatures in excess of 145°F were measured with the locomotive at standstill. Modifications were subsequently made to the ventilation system between the Y2 and S7 cabinets to reduce the running temperatures of the electronic equipment.

Later in the test program temperature probes were installed in all axle boxes to monitor the axle bearing temperatures. This was initiated as the result of the number 4 axle bearing failure.

7.9 PHASE BREAK OPERATION AND PANTOGRAPH FILMING

Since Phase Break operations developed into a major investigation later in the test program, and filming techniques were used to investigate the pantograph failures, both of these topics are fully discussed in sections 10.2 and 11.4

8.0 THE AEM-7 LOCOMOTIVE ENDURANCE TEST

8.1 ENDURANCE TEST OBJECTIVES

The Endurance Test objectives are as follows:

- To demonstrate that under simulated service conditions the AEM-7 locomotive (hauling a consist of eight cars or less) could regularly and consistently meet the accelerated NEC service. The accelerated journey times have been defined by the U.S. Congress as:

Washington, D.C. to New York	2 hours	40 minutes
New York to Boston	3 hours	40 minutes

- To demonstrate the ability of the AEM-7 locomotive design to withstand the electrical and mechanical loads imposed on it by continuous service.

- To demonstrate that the routine maintenance procedures adopted for the AEM-7 locomotive adequately maintain the locomotive for continuous service.

The original plan, based on the assumption that no major failures of the locomotive system would occur, called for accumulation of 250,000 miles under simulated service conditions over a 36 week period. At the outset this was considered to be an extremely optimistic target. Actually, several major failures did occur and the mileage finally accumulated at the TTC was 156,200 miles.

8.2 TEST PLANNING AND COORDINATION

8.2.1 Test Operations

In order to meet the mileage accumulation rates, test operations were planned for 16 hours per day, 6 days per week. The normal 16 hour window for test operations was 1530 to 0730 allowing use of the RTT for track maintenance and other test programs during the remaining eight daylight hours. The day shift was also used for locomotive maintenance, troubleshooting, and special investigations.

The operation test crew consisted of two vehicle operators (engineers) and a test controller on the train, and a track security guard at the trackside. Each crew manned the operation for an eight hour period, with the vehicle operators sharing the locomotive operation on a two hour rotation.

The test controller maintained the operational log, an example of which is shown in appendix C. The operational log was used to record such baseline

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information as test train consist, weather conditions, line voltage, and accumulated mileage, together with locomotive discrepancies. One operational log was produced for each eight hour shift. A full set of operational logs can be made available to interested agencies upon request.

The test crew was responsible for making a walkaround inspection of the train at the end of each trip profile, a period of approximately 2-3 hours. In addition the test controller was required to ride in the cars for at least one section of each profile to detect poor ride in any vehicle.

8.2.2 Maintenance

All routine (preventive) maintenance was carried out by the TTC Rail Vehicle Maintenance group using maintenance schedules provided by EMD or AMTRAK. The short term maintenance schedules based on time were modified to suit the increased mileage accumulation rate. The schedules based on mileage were used as specified. The equivalent schedules are given in Table 7-4. All maintenance was recorded on the appropriate maintenance forms, sample copies of which are included in appendix C.

TABLE 7-4. AEM-7 MAINTENANCE SCHEDULES

AMTRAK/EMD Maintenance Schedule		Equivalent TTC Maintenance Schedule	
Mileage	Time Period	Mileage	Time Period
	Daily		Daily
	30 Day		7 Day
	45 Day		30 Day
	90 Day		45 Day
	1 Year		1 Year
45,000		45,000	
90,000		90,000	
135,000		135,000	

Unscheduled maintenance, normally resulting from system failure, was coordinated by the Program Coordinator. The work was initiated, either by an internal memorandum or by a Configuration Control Form (see appendix C) signed by the Test Manager, Chief Test Engineer and Program Coordinator. Technical approval for all unscheduled maintenance and repairs was sought from AMTRAK or EMD/ASEA by the Chief Test Engineer before the work commenced. Major items were also approved by the Program Manager.

8.2.3 Technical Evaluation and Coordination

The technical coordination of the Endurance Test and the evaluation of the data were the responsibility of the Chief Test Engineer. He or his staff continually monitored the maintenance data, assisted with fault finding where necessary, and initiated special investigations as required. This enabled the detailed objectives of the program to be continually revised and updated without interfering with the major objective of mileage accumulation and with only minor impact on the test operations.

The main purpose of the technical coordination was to incorporate the information supplied by AMTRAK, General Motors, and ASEA, resulting from NEC service experience into the TTC test program, and to relay up-to-date information from the TTC test back to the participating organizations in a timely manner. An informal weekly report (highlighting the major incidents and milestones during the previous week) was prepared by the Chief Test Engineer for distribution to the interested groups. An example of this document is presented in appendix C.

8.3 INSTRUMENTATION

8.3.1 Train-Borne Instrumentation

In order to collect baseline data and to assist in troubleshooting when necessary, an instrumentation system was installed on one of the AMFLEET cars (#21003).

Power was provided from a 12.5 kW 115 V single phase generator temporarily installed in the vestibule of the car. Inside the car at the center of the vehicle two seats were temporarily removed and replaced with a small instrumentation rack containing the signal conditioning and recording systems. Signal conditioning was provided by 16 channels of 'Dynamics' variable output gain amplifier/conditioner modules. The data was recorded on a 14 channel analog tape recorder at a tape speed of 1 7/8 inches per second for tape economy. A time code generator was also provided to insert an IRIG B time reference on one channel of the tape recorder. Variable bandwidth, low pass filters were available to filter the data as necessary. This was normally done at the replay stage. An 8 channel Brush pen recorder or a 10 channel oscillograph recorder was connected to the replay side of the tape recorder. These could be used to read-after-write (downstream) monitor the data during recording to ensure data capture, or to replay the data after testing for post-test analysis.

The data signals were derived from the locomotive logic and control systems, or from the transducers as described for the Characteristic Tests for routine measurements. However, during special tests and investigations other instrumentation signals were installed. These will be fully described within the relevant sections.

To enable the locomotive to be easily removed from the consist, a set of instrumentation cables was installed from an interface junction box in the locomotive machine room to each end of the locomotive. A junction box was provided in the front vestibule of the AMFLEET (# 21003) car into which the instrumentation cable on the locomotive rear end could be connected. The cable at the other (front) end of the locomotive was secured and sealed to prevent damage.

During the early stages of the Endurance Test running, data was collected during all operations. As the program progressed the data was only taken on a weekly basis and during troubleshooting. To avoid the accumulation of a large number of data tapes the data was reviewed soon after recording and any tapes not considered to be of future use were erased and re-used. Tapes containing relevant data were retained for permanent storage at the TTC.

8.3.2 NEC Route Profile Simulator

The Endurance Test was based on operations representing the accelerated NEC schedule between Boston and Washington, D.C. The schedules were supplied in the form of Train Performance Calculation outputs from Bechtel, Inc.

A small programmable micro-processor simulator was designed and built by ENSCO, Colorado Springs under contract to FRA/OR&D. The unit consisted of the pre-programmable memory and operational address panel contained within a cabinet (Figure 8-1). This fed a digital display (Figure 8-2), which was set up on the vehicle operator's desk to act as a prompt system providing the following information:

- The present posted speed
- The present location (mileage)
- Time to next posted speed change
- The next posted speed
- Location of the next posted speed change
- Elapsed time since the profile start.

In addition, a row of lights at the top of the display provided a countdown to the next speed change from the tenth mile to one mile in one mile increments, and then in tenths of a mile for the final mile.

The vehicle operator interpreted the profile simulator display as he would the posted speed limits on operational railroads. For a speed reduction he was required to be at the new posted speed before reaching the specified location, for an increase in speed acceleration commenced on reaching the posted speed location.

A speed signal from the locomotive speed system was supplied to the simulator from which it calculated the elapsed distance to reference the posted speeds and provided the countdown. The unit was calibrated using the surveyed length of the RTT. The unit proved to be highly reliable. Without it, consistently run profiles would have been impossible.

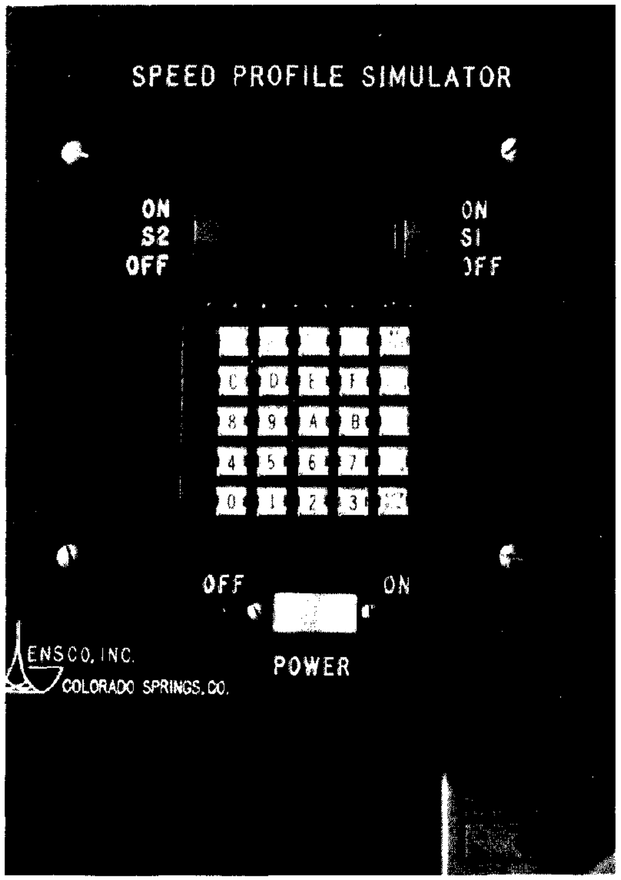

FIGURE 8-1. THE PROFILE SIMULATOR ADDRESS AND MEMORY.

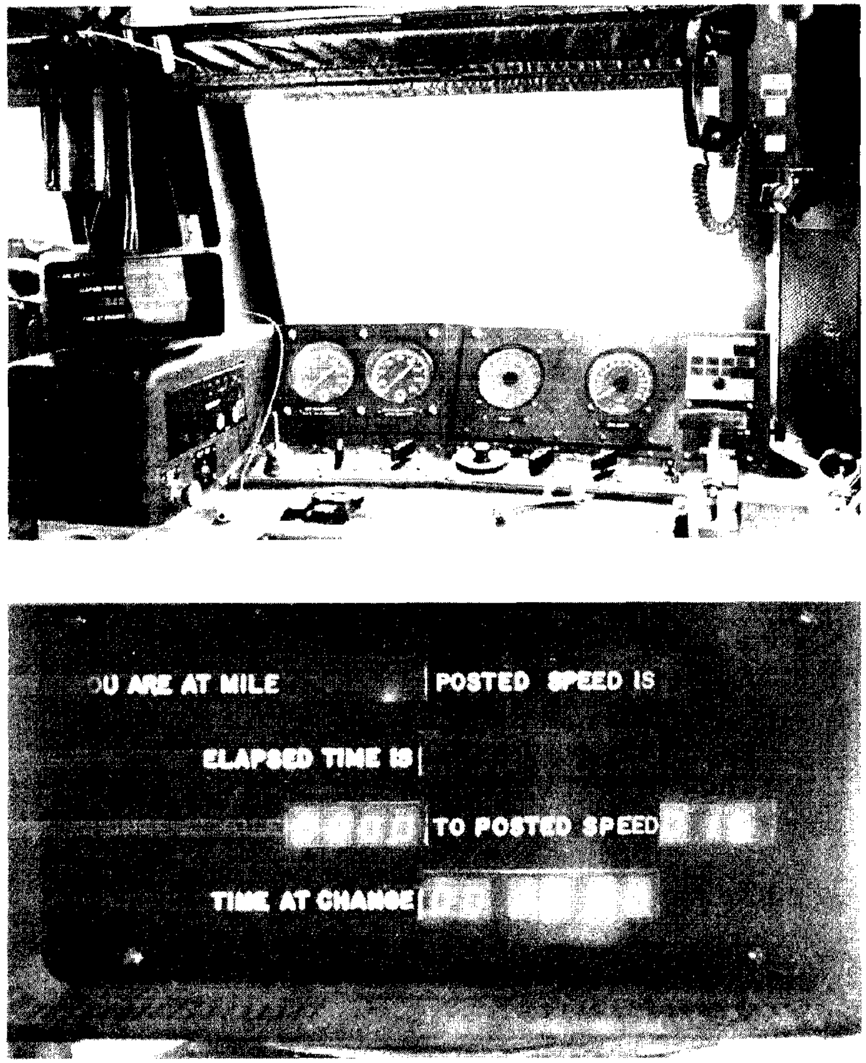

FIGURE 8-2. THE PROFILE SIMULATOR DATA DISPLAY.

The simulator memory was capable of storing up to three profiles at any one time. The three profiles used for the majority of the test period were:

- o Boston to New York (five stop)
- o New York to Washington (two stop)
- o New York to Washington (five stop)

Listings of all three profiles are presented in appendix D.

A modified profile was devised based on constant speed laps of the RTT with limited braking. This was used on the rare occasions when the simulator was not operational or when limited braking was used due to extended periods of traction motor failure. This profile is also presented in appendix D.

8.3.3 Power Consumption Measurements

Power consumption data was provided by the analog power consumption processor set up in the substation. Since a profile did not necessarily begin or end at the substation, the track security officer stationed near the substation was tasked to reset the kilowatt hour display at the start of a profile and take the reading at the end of the profile. This ensured that the power consumption data contained only the profile. A log of the profile performance, including the actual intermediate station stop times and power consumption, was maintained by the test controller for each profile. An example is also contained in appendix C.

8.4 LOCOMOTIVE PERFORMANCE

8.4.1 The Ability to Meet the NEC Schedule

a. Data Constraints. Not all simulated profiles were included in the assessment of the ability of the AEM-7 to meet the NEC accelerated schedules. Before the data can be presented, the acceptable data must be defined.

In the early stages of running, before the track was finally reballasted, a speed restriction of 90 mi/h was imposed on the operation until the rail temperature had fallen to 100°F. Many profiles were started under these conditions, but are not included in the performance data. During the first series of tests with the Radial Axle Passenger Truck (RAPT) test car many of the profiles were run with a maximum speed of 100 mi/h imposed on the consist. These are also not included in the data.

In order to be included in the data the profile must have satisfied all of the following conditions:

- The train must consist of the locomotive and at least three cars.

- The maximum speed restriction on the consist for the whole track was to be greater than 110 mi/h. Local restrictions could, however, be lower than the 110 mi/h limit.

- At least three traction motors were to be operational at the start of the profile.

- All profiles included were to be complete. No partial profiles were included.

In some cases these conditions were more stringent than were normal on a railroad. For example, a 90 mi/h speed restriction imposed on a set of switches on the RTT represented 16 such temporary speed restrictions on the equivalent NEC profile. However, the impact of this varied according to how many of the passes of the RTT temporary restriction called for a higher speed in the profile.

b. Data Presentation. The journey time is presented as scattergraphs in Figure 8-3 (New York-Washington five stop profile), Figure 8-4 (New York-Washington two stop profile), and Figure 8-5 (Boston-New York). This data is then summarized in Table 8-1 as a comparison of the legal time, the calculated time, the mean operational time, and the standard deviation about the mean. Data is also presented in Table 8-1 for a reduced sample of (ideal) six car runs for direct comparison with the Train Performance Calculations.

c. Interpretation of the Data. The wide range data presented in Table 8-1 demonstrates that the locomotive was able to meet all three schedules well within the mandated (legal) time. In addition, the locomotive was able to better the TPC time by approximately 1 minute in the case of the New York-to-Washington, profiles and by approximately 2 1/2 minutes in the Boston to New York profile. Many of the profiles in late August 1980 were run with only three traction motors operational, and many of the profiles run in December 1980 had a maximum train speed restriction of 110 mi/h due to difficulties with the RAPT car. The two profiles were run with eight cars in April 1981 (before traction motor problems terminated the test). Both were within the equivalent TPC time. It should be noted that the TPC was produced for a six car consist, whereas the average TTC consist was five cars. The reduced sample of data for a six car consist shows a much closer agreement with TPC and less scatter than the wide range data.

Some areas of the performance data require further explanation. First, the data presented for July and August show a much wider scatter than later data and were not included in reduced sample analyses for the six car consist (Table 8-1). This was caused initially by vehicle operator misinterpretation of the simulator instructions. Then, in August, the first in the series of traction motor failures was developing and some of the profiles were completed with only two traction motors operational. Later in the test, profiles were abandoned when more than one traction motor became defective to avoid unnecessary damage to the motors.

The standard deviation has no relevance other than a relative measure

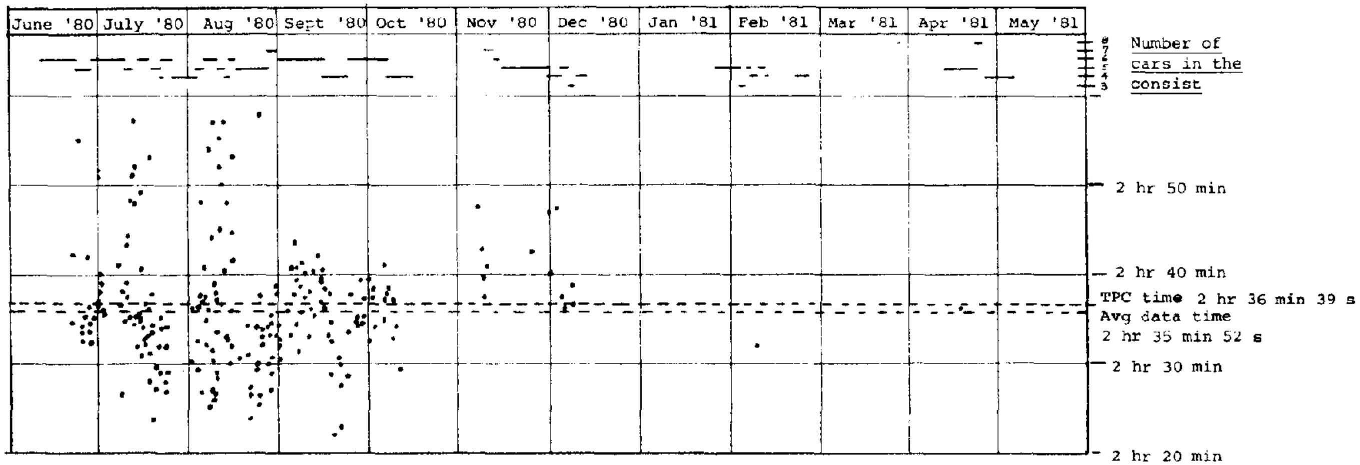

FIGURE 8-3. NEW YORK TO WASHINGTON (FIVE STOP) TRIP TIMES.

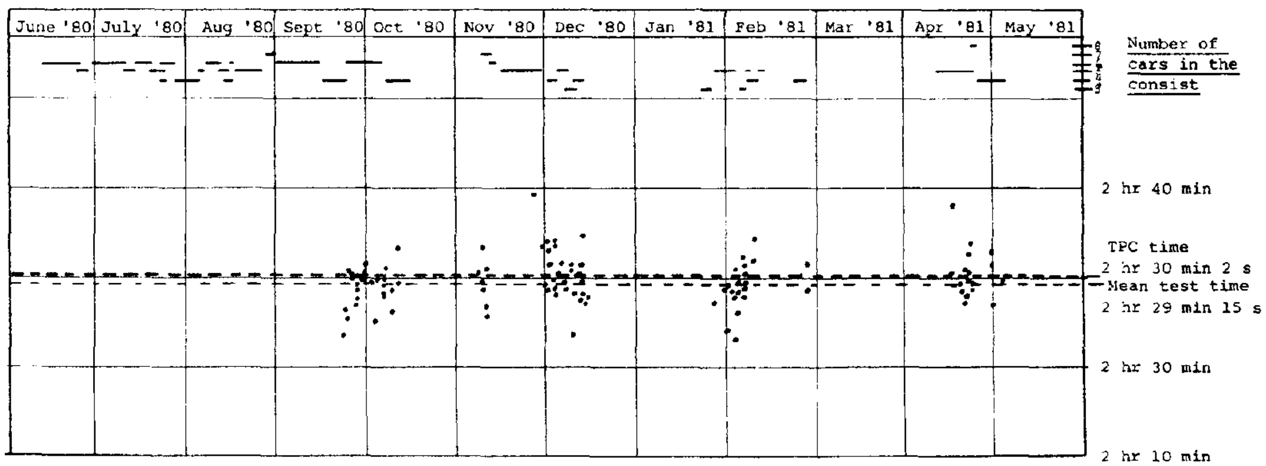

FIGURE 8-4. NEW YORK TO WASHINGTON (TWO STOP) TRIP TIMES.

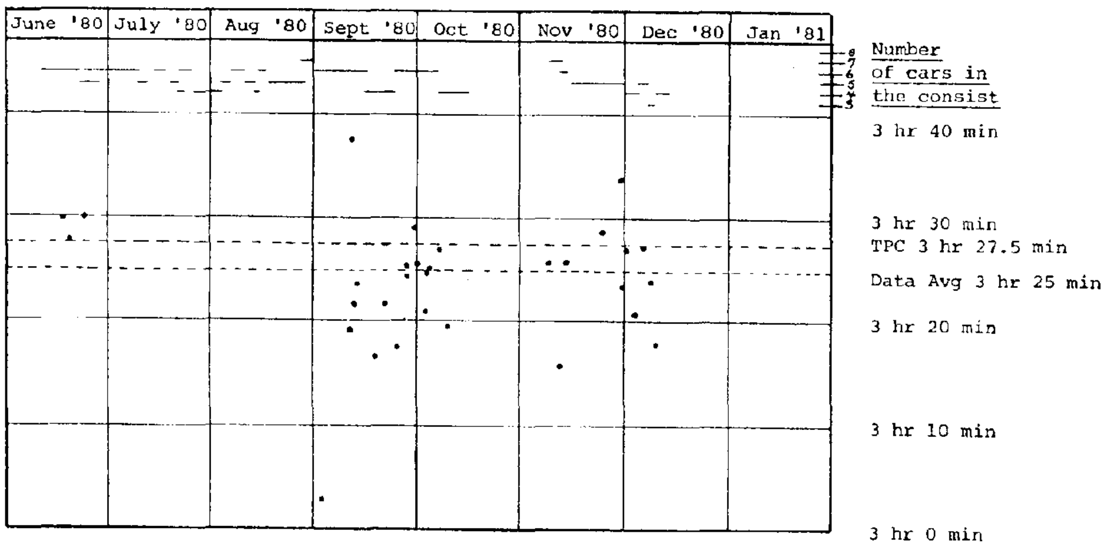

FIGURE 8-5. BOSTON TO NEW YORK TRIP TIMES.

TABLE 8-1. SUMMARY OF THE SIMULATED PROFILE JOURNEY TIME DATA

Profile	Legal Time		TPC Time			Mean Test Time			Standard Deviation	
	Hr	Min	Hr	Min	Sec	Hr	Min	Sec	Min	Sec
NY - Wash (Five Stop)	2	40	2	36	39	2	35	52	7	07*
						2	36	58	3	50**
NY - Wash (Two Stop)	2	40	2	30	02	2	29	15	3	06*
						2	29	31	2	15**
Boston - NY	3	40	3	27	30	3	25	05	7	02*
						3	26	03	2	58**

* Data taken over a wide range of operating conditions and consist sizes.
** A reduced sample of six car consist data.

of data scatter. The Boston-to-New York profile was only used occasionally since it tended to underutilize the locomotive power capabilities in the context of the Endurance Test.

The data indicates that the locomotive was capable of meeting the NEC accelerated schedule with up to eight cars, provided all traction motors were operational, and with up to six cars and three traction motors. However, no attempt was made to run with eight cars and three traction motors.

The weather conditions experienced at the TTC varied from hot (107° maximum) and dry to extreme cold (-22°F minimum). In addition, the locomotive operated under high wind conditions (up to 40 mi/h, gusting to 50 mi/h) and in powder snow. Some difficulty with icing of the air intakes was noted, although icing conditions were much less severe than would normally be experienced on the NEC. Examples of profiles run under most of the extreme weather conditions are included in the data.

8.4.2 Energy Consumption Data

a. Overall Energy Consumption. The average energy consumption data for the wide range of profiles are presented in Figures 8-6 through 8-8. The TPC predicted energy consumption, available for the six car consist case only, are superimposed on the measured data.

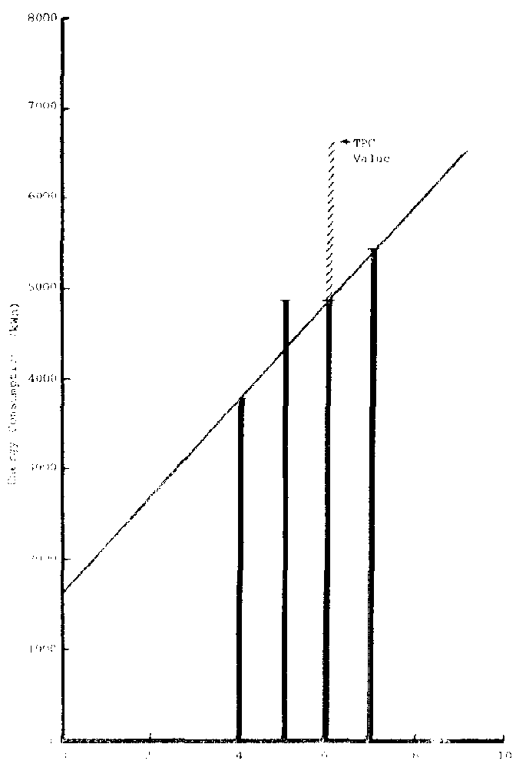

FIGURE 8-6. BOSTON - NEW YORK CITY (5 STOP PROFILE) ENERGY CONSUMPTION.

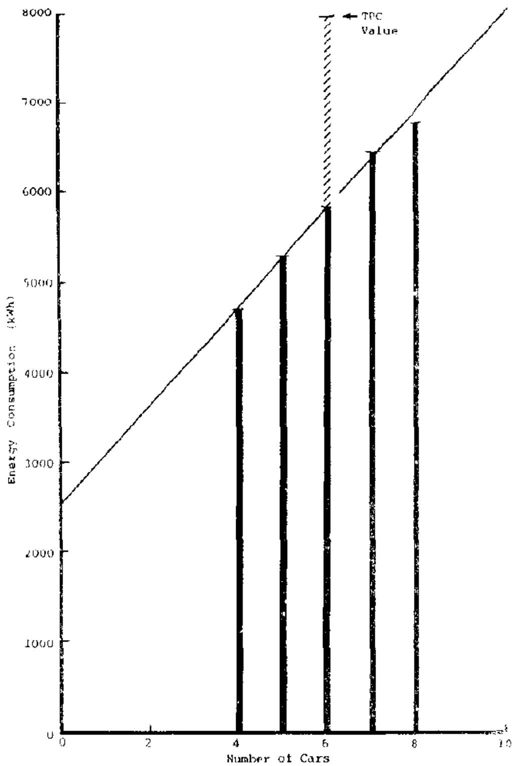

FIGURE 8-7. NEW YORK CITY - WASHINGTON (5 STOP PROFILE) ENERGY CONSUMPTION.

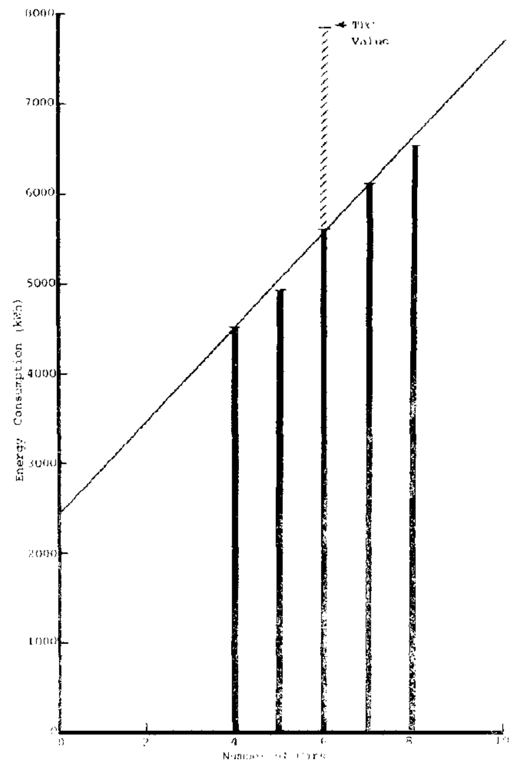

FIGURE 8-8. NEW YORK CITY - WASHINGTON (2 STOP PROFILE) ENERGY CONSUMPTION.

The data for each profile is presented as a histogram of the average power consumption against the number of cars in the consist. The relationship between the energy consumed and the number of cars appears to approximate a linear function. Extrapolation of the line to y axis projects the approximate energy consumed by the locomotive to run the profile. Approximately 43% of the power required to haul a six car fully laden consist (the cars were ballasted to their fully laden condition) is used by the locomotive. Since the locomotive weight and its aerodynamic drag both influence this base-line energy consumption, the use of a lightweight, aerodynamically efficient locomotive is readily apparent.

To provide a more realistic comparison between the measured and predicted power consumption much of the early data was discarded as being unreliable, and the energy consumption data for the reduced sample of six car consist profiles, (section 8.4.1 b) are presented in Table 8-2.

TABLE 8-2. ENERGY CONSUMPTION DATA FOR A SIX CAR CONSIST

Profile	TPC Predicted Energy (kW hrs)	Average measured Energy (kW hrs)	Standard Deviation (kW hrs)	% of TPC
Boston-New York	6609	4994	167	75.6
New York-Washington D.C. (two stops)	7858	5568	381	70.9
New York-Washington D.C. (five stops)	7992	5837	293	73.0

b. Comparisons Between Measured and Predicted Energy Consumption. Comparisons of the measured and predicted energy comsumption data show the AEM-7 consist to be much more energy efficient than the calculations predict. The measured energy consumption averages approximately 73% of the predicted value for a six car consist. As a result of discussions between the authors and J. Harrison of Bechtel, Inc., who were responsible for the TPC predictions, a number of possible causes for the apparent discrepancy were identified.

- The TPC calculates the electrical energy consumption on the basis of converted mechanical energy, assuming a 0.80 efficiency factor.
- The aerodynamic drag coefficient used in the TPC represented sea level conditions. A correction factor of 0.864 is normally applied to the coefficient for the TTC altitude (reference 16).
- The HEP load assumed in the TPC was 300 kW. The actual average HEP load used during the TTC tests was 175 kW.
- The Davis formula for train resistance used in the TPC may not be accurate

at the higher speeds.

- The TPC assumes the worst case train handling techniques. Actual train handling techniques are somewhat better than the worst case.
- Due to the difference in curvature between the TTC and the NEC, the curve resistance component of the TPC may be in error.
- To offset the above the catenary losses were included in the TTC energy consumption measurements but not in the TPC.

An estimation of the effect of the discrepancies on energy consumption is presented in Table 8-3.

TABLE 8-3. ESTIMATED ERRORS DUE TO DIFFERENCES BETWEEN THE TPC AND MEASURED ENERGY CONSUMPTION DATA.

Description	Possible % Error
1. Mechanical to electrical conversion	+5
2. Aerodynamic drag coefficient	+10
3. HEP load factor	+5
4. Davis formula inaccuracy at high speed	not assessed
5. Train handling	+3 to 5
6. Curve resistance difference	+1 to 3
7. Catenary losses	-3
8. Measured accuracy	±2

c. <u>The Effect of Journey Time on Energy Consumption</u>. A section of the data for a series of six-car consist operations was plotted against the difference between measured and predicted profile journey times. This data is shown in Figure 8-9. The sensitivity of the energy consumption to accelerated journey time is smaller than expected, representing approximately 1.25% increase in energy consumed for each minute of journey time saved. However, the scatter on the energy consumption data caused by variations in train handling techniques, weather conditions, Head End Power loads, and direction of travel on the test track is ±5%. It should be noted that, while the data as presented approximates a linear function for the small time segment taken, this does not necessarily represent the relationship between energy and journey time over a much larger time frame.

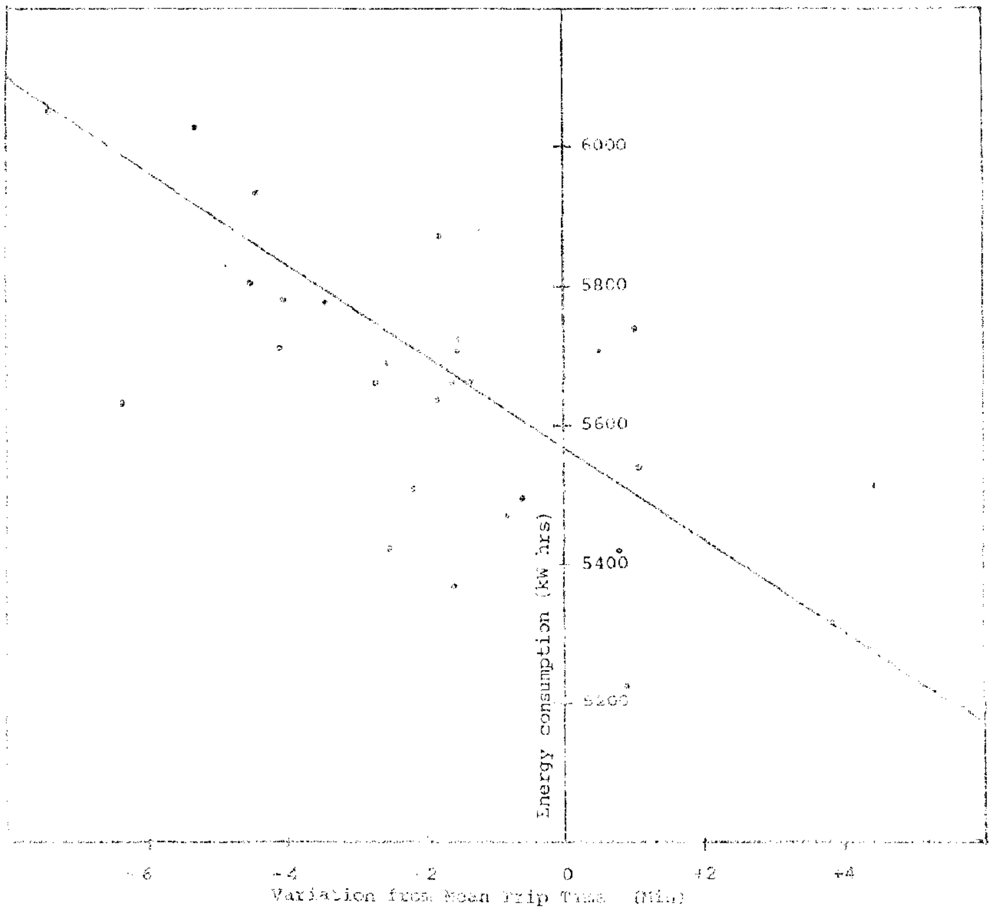

FIGURE 8-9. RELATIONSHIP BETWEEN ENERGY CONSUMPTION AND TRIP TIME

8.4.3 Operational Convenience

In general the vehicle operators found the AEM-7 locomotive to be relatively simple to understand and operate compared with the Diesel Electric locomotives with which they were familiar. However, some comments were made by the operators concerning the convenience of equipment and the comfort levels. For example:

- The position of the pantograph selector switch for the 'F' end pantograph made it difficult to operate for all but the tallest of people. With the lighting levels available it was also difficult to see the switch position without the use of a handlamp.

- The intensity levels of the fault indicator panel lights made them difficult to read. After a time the more common fault indications became identifiable with position on the panel.

- In summer the ambient temperature in the machine room and cab reached unacceptable levels while the locomotive was standing for long periods. Under moving conditions the cab ventilation system was ineffective.

Attempts to run with cabside windows open resulted in unacceptable noise levels at speeds above 100 mi/h.

- In winter the cab heating system was not sufficient to keep the cab warm under high speed operating conditions. Weather sealing of doors and windows was inadequate to prevent drafts.

- Some form of padding should be added to the front of the operating console to prevent abdominal injuries in the event of slow speed derailment or collision.

- An indicator light should be added to cab monitor panel to indicate the presence of catenary/pantograph voltage to enable the operators to distinguish between locomotive lockout and loss of catenary power.

8.4.4 Fault Indication and Alarms

The number and comprehensiveness of both the operator's monitor panel, and the machine room alarms and relay flags were generally adequate. However, the intensity and reliability of the overhead panel fault lights were inadequate. The average life of the light bulbs was approximately 8 weeks. The lights were particularly difficult to identify and even detect in bright sunlight.

A number of instances occurred on initial powering up where the Air Blast Breaker failed to close without a fault indication appearing and where the Phase Break approach and leave push button sequence failed to clear the problem. Usually the fault could only be cleared by removing the battery power and restarting the powering up procedure. No definite explanation was found for this problem which continued even after the YMX 125 K interface cards were replaced, (see section 8.6.5).

8.5 LOCOMOTIVE MAINTENANCE

8.5.1 Description of the TTC Maintenance Facilities

The TTC locomotive and car maintenance facilities are concentrated within the Center Services Building (CSB) in the maintenance core area. The building is equipped with four tracks, two of which have inspection pits. The other two tracks are level with the concrete floor. The two overhead cranes in the CSB have a maximum safe working capacity of 20 tons and can only be used for component lifting.

One of the pit tracks houses a Hegenscheidt wheel turning lathe which is designed to machine the wheels without removing them from the trucks. In addition to machining the AEM-7 and consist wheels, this facility was used to 'bed in' new brushes when installed in the AEM-7 traction motors, and to rotate the traction motors for commutator grinding. In all cases the axles, and therefore the traction motors, were driven by lathe powered rollers applied to the locomotive wheels.

Locomotive and car detrucking is carried out on one of the three plain tracks using four 50-ton capacity electromechanical screw jacks, one at each corner of the vehicle. The jacks are electrically connected to provide simultaneous operation, and are designed to lift on the normal jacking pads supplied with the vehicle. Figure 8-10 shows the AEM-7 during a typical detrucking operation.

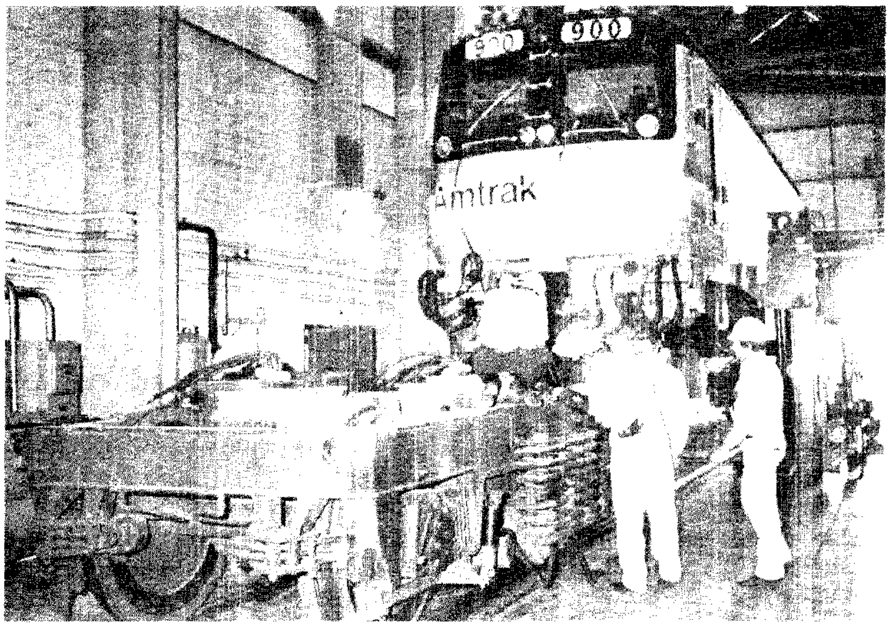

FIGURE 8-10. THE AEM-7 LOCOMOTIVE DETRUCKING OPERATION.

In addition to the direct maintenance facility the TTC provided full weld shop, machine shop, and electric shop services. These facilities were used to support the AEM-7 program for such items as yoke bolt, yoke and shock absorber bracket repairs, and pantograph installations.

8.5.2 Routine Maintenance

Since the access tracks from the electrified RTT to the CSB were not electrified, all routine maintenance requiring catenary power was carried out on the RTT or Balloon Track. All maintenance, whether routine or unscheduled, requiring use of an inspection pit or lifting facilities necessitated a logistics movement involving a diesel electric locomotive.

The maintenance procedures were found to be adequate and easy to follow. The only difficulties arose from the lack of adequate spares and special equipment to fulfill the longer term schedules. For example the Silica Gel dryer package for the transformer tank air breather and the equipment required to dismantle the Air Blast Breaker for the 45,000 mile inspection were not readily available. These latter problems resulted from the logistics of having to maintain a single locomotive, where it was not economical to provide a large number of spare components. Some of the more frequently used spares, such as light bulbs were not made available in sufficient quantities at the start of the program. This situation improved as the program progressed.

8.5.3 Failure Reporting and Analysis System

A separate contract between the FRA and the Transportation Services Center (TSC) involved the development of a Failure Reporting and Analysis System (FRAS). The inputs to this system were supplied by the TTC to TSC for failures occurring during the Endurance Test using the approved documentation supplied by TSC.[9]

Many of the failures reported were genuine failures of the locomotive system. Others were direct results of experimental equipment failures. It is therefore possible that some of the actual data is meaningless with regard to fleet operation. However, the data will be useful to test the FRAS principle.

Since this data forms part of a separate report to be issued by TSC, no discussion of the FRAS will be made in this report. It is sufficient to document that the data was indeed supplied. Separate maintenance records were maintained by the TTC to provide information for this report. It should be noted that the FRAS deals only with failures and not routine, scheduled maintenance activities.

8.6 HEAVY MAINTENANCE AND UNSCHEDULED REPAIRS

8.6.1 Locomotive Detrucking

The heavy maintenance and unscheduled repairs, generally involving locomotive detrucking, accounted for over 50% of the maintenance carried out on AMTRAK 900. This was mainly due to the major failures such as the yoke assembly failures, traction motor failures, and pantograph problems. In all the locomotive was detrucked a total of nine times as detailed in Table 8-4. Each detrucking operation and the associated repairs resulted in considerable program delays. For example, the traction motor rebuild resulted in the locomotive being out of service for almost five weeks.

TABLE 8-4. AMTRAK 900 DETRUCKING OPERATION.

Date	Main Reason
5-21-80	Yoke assembly replacement
7-24-80	Broken yoke bolt
8-29-80	Traction motor #4 change
9-3-80	Broken yoke bolt
9-10-80	Damaged traction motor cable repair (#4)
10-15-80	Truck Inspection (truck noise reported)
10-17-80	Traction motor removal (all motors)
11-14-80	Siezed axle bearing
2-27-81	Wheel bearing repacking and truck general inspections

8.6.2 Yoke Assembly Failures

Much of the early unscheduled repair resulted from the failure of the yoke assembly structure and the yoke-to-body retaining bolts. The yoke assembly (Figure 8-11) forms the main interface between the top of the secondary vertical suspension springs and the locomotive body. It also acts as the body side anchor structure for the longitudinal traction rods and the secondary lateral and vertical shock absorbers. The yoke assembly is located onto the underside of the locomotive underframe by means of two 3 inch diameter (Figure 8-12) dowel pins, which are designed to react the loads between the yoke and body. The yoke is retained on the dowel by means of 7/8" diameter bolts, designed only to support the assembly for lifting the vehicle during a derailment recovery operation.

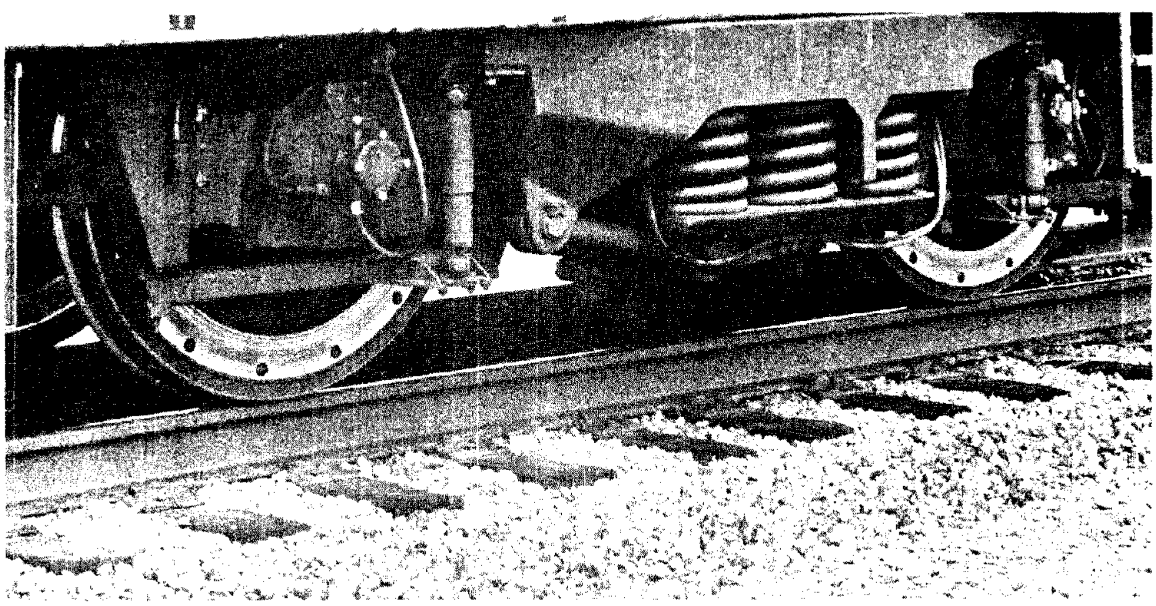

FIGURE 8-11. THE AEM-7 YOKE ASSEMBLY.

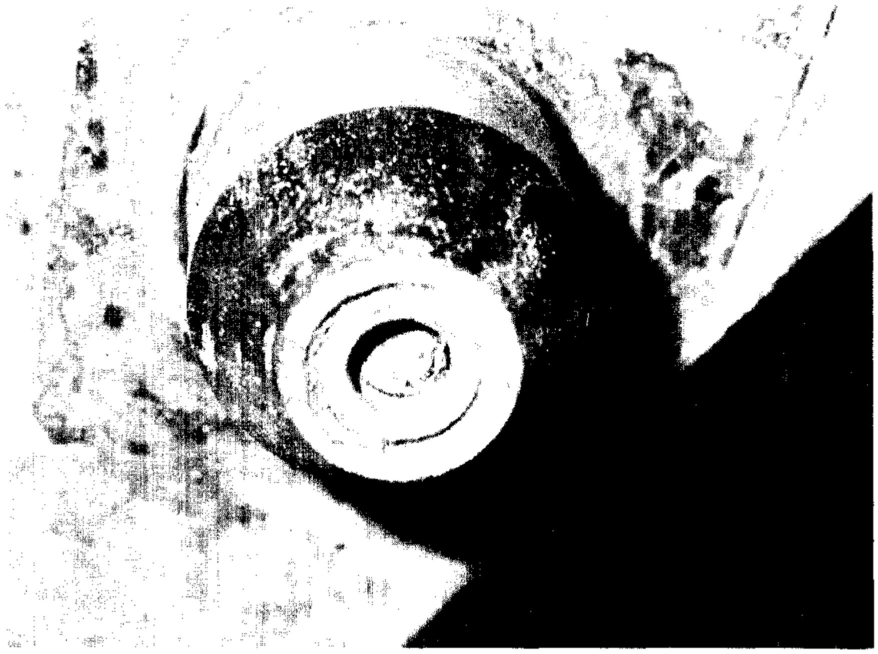

FIGURE 8-12. THE YOKE ASSEMBLY DOWEL PIN.

In May 1980 the four yoke assembly fabrications were replaced at the request of General Motors due to faulty manufacture of the original units.

After approximately 3000 miles of the Endurance Test the yoke retaining bolts were found to be loose. Tightening of the bolts to the recommended 300 lb ft became a daily occurrence. A higher torque value of 400 lb ft was used as recommended by General Motors but after a further 24,000 miles one of the bolts was found to have broken at the thread entry point into the dowel pin. A strengthening modification was supplied by General Motors for the yoke assembly and this was incorporated. Similar problems on the locomotives in service on the NEC had prompted the modification.

After a further 25,000 miles one of the retaining bolts again broke. A chamfer was ground on the top edge of the dowel pin locating hole in the yoke. No further bolt failure occurred during the remainder of the test program, although cracks developed in the yoke assembly webs. These were rewelded as required.

A completely redesigned yoke assembly has since been tested by General Motors and incorporated on the later locomotives. A retrofit program is underway for the earlier locomotives.

8.6.3 Traction Motor Bellows

Cooling air for the traction motors is supplied by forced air fans, one for each motor and associated electronic control equipment, mounted within the locomotive body. The air is taken in through vents in the bodyside at the roof line and forced by the fans through paper element filters to the traction motors. A portion of the filtered cooling air is bled off the traction motor circuit to cool the associated electronic equipment cabinet.

The continuity between the top of the traction motor and the underside of the locomotive body is maintained by a flexible bellows attached to the body to allow for minor truck movements, with a sliding contact surface on the traction motor to allow for major truck movements. The sliding contact surface consists of a phenolic ring riveted to the underside of the bellows (see Figure 8-13).

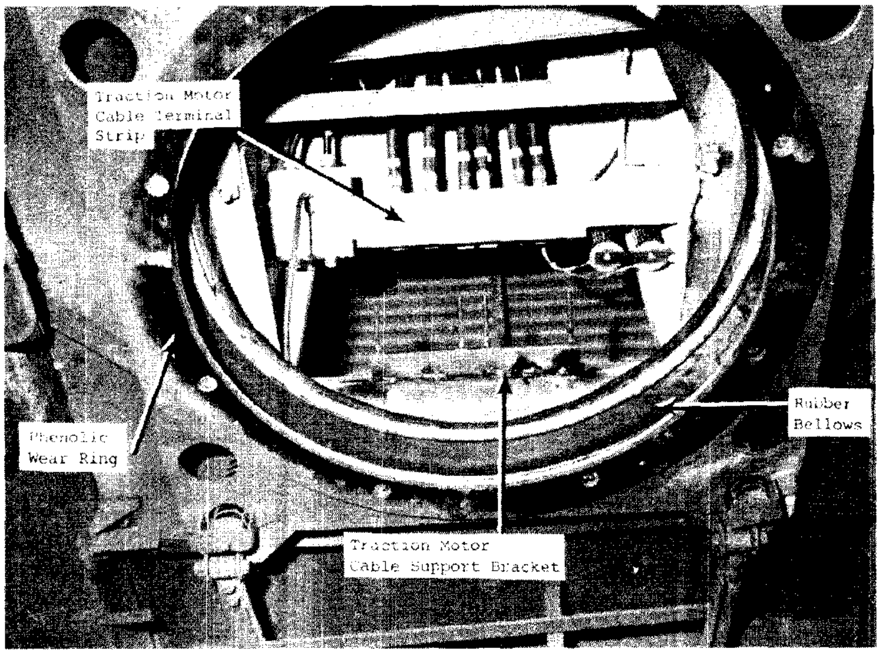

FIGURE 8-13. THE TRACTION MOTOR BELLOWS.

When the locomotive was detrucked for the first time it was discovered that the phenolic ring segments were loose and that a number of the bellows retaining ring bolts had sheared off. The nuts and sheared bolts were found in the traction motor cavities and air screens.

The number of rivets holding the phenolic rings in place was increased from one per segment to three per segment, which eliminated that problem. A redesigned bellows assembly was supplied by General Motors in October 1980 and fitted to all traction motors on AMTRAK 900. However, when the locomotive was detrucked in February 1981 several of the bellows retaining bolts were again found to have sheared. The bellows hangers had also fractured and were repaired. The bellows failure was traced to an interference problem between the bellows and underframe mounted equipment and has since been solved.

8.6.4 Shock Absorbers and Brackets

A number of failures occurred in the shock absorbers and associated brackets. The left side shock absorber on the 'F' truck failed at approximately 25,000 miles into the Endurance Test. This was replaced with a new unit supplied by General Motors. During a component examination by the Aerospace Corporation after the TTC testing, the right side shock absorber was also found to have failed.

A series of failures of the vertical and lateral shock absorber brackets occurred during early testing. The cantilever pin arrangement was considered to be a design weakness and was redesigned by General Motors. Meanwhile the original brackets were rewelded by TTC personnel to provide a temporary repair. It was noted that after rewelding, none of the brackets failed a second time indicating that the original failures were, perhaps, the result of poor quality control.

After approximately 100,000 miles it was noted that severe distortion and cracking of the shock absorber end rubber bushings had developed. Indeed, one of the vertical rubber bushings had to be replaced. The damage seemed to be indicative of excessive deflection due to rotary motion of the shock absorbers. Since testing of AMTRAK 900 at the TTC ended, the lateral and vertical shock absorber application has been completely redesigned by General Motors. The improved design utilizes spherical mounting bushings and new brackets.

8.6.5 Wheel Bearings

One of the major failures, and potentially the most dangerous, was complete breakdown of the left journal bearing on the #4 axle. The resultant overheating caused the bearing and rubber suspension units to catch fire. This incident occurred at approximately 105,000 miles.

Soon after the locomotive's arrival it had been noted that grease was leaking from the #2 and #4 axle box seals. It was concluded that this resulted from overfilling of the bearings which had been repacked at Wilmington shops before departure. After a few laps on the RTT the leakage ceased.

At the 90,000 mile inspection the maintenance staff had noted that the lubrication film on the bearings appeared to be inadequate. After consultation with General Motors Service Department the decision had been made to continue running without adding grease.

After the bearing failure the old wheelset was replaced with a new unit from the Wilmington Shops. The remaining axle boxes were dismantled, cleaned, inspected, and repacked with new lubricant. During this operation it was discovered that a difference existed between the lubricants specified by SKF Bearing Co., Sweden, and those used by General Motors. This was due to an inconsistency in specification and manufacture between Mobil Oil, Europe and Mobile Oil, U.S.A. Eventually the situation was resolved and the AMTRAK 900 bearings were repacked with Mobilux EP2 grease. Some slight pitting, possibly due to electrical erosion, was found on one of the #3 axle bearings.

A similar bearing failure occurred on the locomotive AMTRAK 901 on the NEC approximately one week after the TTC incident. Although the cause of this failure was also lubrication breakdown, there was allegedly some evidence of electrical damage in this case. A full investigation of the AEM-7 bearing and ground brush designs was initiated, including a series of tests on a specially prepared rig at General Motors, EMD. In the meantime, as a safety requirement, a set of thermocouples was installed to monitor all axle boxes on AMTRAK 900 to give advanced warning of potential failure during the remainder of the Endurance Test.

After 145,000 miles the bearings were once again cleaned and repacked with ESSO Beacon EP2 grease.

No further problems were experienced with the bearings during the remainder of the program. The bearing design and lubrication for the AEM-7 locomotive is presently under review by AMTRAK and General Motors.

8.6.6 Electronic Cards

In general the electronic components on AMTRAK 900 proved to be very reliable. The only major failures occurred on the six interface circuit boards. These boards, part number YMX 125K, are designed to provide electrical isolation between the logic error detection and interlock circuits on one hand, and the required alarm and protection circuits on the other. The card uses the logic signal inputs to operate reed relays. The resultant contact operations are used to switch circuits based on the 74 volt battery supply. Each card can handle up to eleven interface functions. There are four cards used in the general control circuits, one in the Head End Power convertor control, and one in the auxiliary convertor control.

At first the faults were intermittent. Often these could be cleared by simply reseating the boards in the rack. Later, certain circuits on the cards developed permanent faults. These were temporarily circumvented by changing the position of the boards so that the faulty circuit was moved to an unused location or operated a fault light only. Detailed investigation showed that the contacts on many of the reed relays were welded or stuck. Eventually all of the original YMX 125K boards were replaced with new boards by ASEA personnel. The problem was investigated by ASEA. Since the reed relay contacts were rated for 12 VA and a maximum of 200 V a.c./V d.c., the failures have been attributed to closing into capacitive loads. Inductors have been added in series with the power supply inputs to the YMX125, which has solved the problem.

Circuits affected by these faults include:

- Wheel slip indicator light
- Sand application and light
- Electronic overload
- 12/24 volt fault indication and lockout

- Armature current greater than 200 A (this resulted in the motor contactors opening under load)
- 12.5 kV 60 Hz line voltage interlock

Modifications were carried out on the YMX 125K by ASEA personnel including the removal of some of the input surge capacitors. However these modifications were not considered to be responsible for the card fault.

Some concern was expressed by TTC maintenance personnel at the occurrence of apparent overheating on the pulse driven resistor boards, part number YXX 145-B. Although the lacquer on the resistors was discolored, no incidents of component overheating were noted. It was therefore concluded that the boards were acceptable.

At 140,000 miles a modification was made by ASEA personnel to the Auxiliary Power Load Convertor (APL) control circuits. Immediately afterwards, a fault developed in the APL. The auxiliary loads were switched to the Head End Power convertor until an ASEA engineer could return to investigate the problem. The locomotive was returned to the NEC before the fault could be investigated.

At 162,000 miles, intermittent shutdown of the locomotive developed, the indication being transformer/thyristor low oil pressure. The transformer oil level was checked, and the circulating oil pumps inspected for locked rotor indicative of pump or motor failure. Both aspects of the system were found to be normal.

Systematic checkout of the electrical circuits showed the wiring to be in good condition. The fault was finally cleared by sharply tapping the thyristor cooling oil pressure switch. Thereafter no further problems occurred with the system, although the solution used was somewhat unsatisfactory.

8.6.7 Electrical Failures

Three failures of the high voltage equipment on the locomotive occurred during the AEM-7 test.

- Failure of the LAH2 surge arrestor on the #2 winding for the HEP supply. This fault was diagnosed as a random failure. The unit was replaced by a new one supplied by General Motors.

- Two pantograph base insulators flashed over at a line voltage of 25 kV. Again the fault was diagnosed as a random fault, but insulator cleaning procedures were modified to require the use of high voltage cleaning fluid instead of soap and water.

- Under normal start-up on a line voltage of 25 kV the 12.5 kV surge arrestor failed. Inspection of the motor driven switch showed that it was closed when it should have been opened for 25 kV energization. Rigorous checks were made of the logic circuits by injecting the relevant voltage signals into the potential transformer circuits, but the fault could not be repeated. No further incidents of this nature occurred. It was later discovered that one of the faults on the YMX 125 K interface cards could have been responsible for this incident.

The only other major failures of electrical equipment to occur during the AEM-7 testing were the pantograph and traction motor problems. These will be discussed separately in section 9.0 (Traction Motors) and section 10.0 (Pantographs).

8.7 RELIABILITY AND MILEAGE ACCUMULATION

8.7.1 The Impact of Major Breakdowns

To base the reliability of AMTRAK 900 on its availability would be totally unrealistic, since much of the time the locomotive was unavailable resulted from waiting for the delivery of spares. In the normal railroad environment spares are readily available from stock. Even in the case of traction motor repairs a spare set of trucks from a damaged unit would probably have been made available to keep the locomotive running. However, motor failures at the rate experienced would certainly have impacted fleet operation.

Another factor involved in arriving at a measure of reliability based on the test program is the downtime due to test requirements. For example the time required for installation of instrumentation cannot be included in the reliability measure, neither can some of the early operational failures caused by instrumentation interaction. Traction motor brush changes were made for evaluation purposes which also required downtime. It must therefore be left to fleet operation by AMTRAK to provide basic reliability data.

By dividing the locomotive into two systems, namely electronic and mechanical/electrical a much clearer picture emerges. Electronically, the locomotive was highly reliable, particularly once the interface card problem was resolved. Only two shifts of operation were completely lost as a result of electronic failure, both associated with the interface card problems. Had spare cards been available, the downtime would probably have been further reduced. The locomotive was, however, dispatched for service with electronic faults when it would not normally have been dispatched on the NEC; for example with the locomotive auxiliary load supplied by the HEP convertor.

The mechanical/electrical equipment on AMTRAK 900 tended to be much less reliable. The four major items, namely, the traction motors, the pantographs, the truck yokes, and the wheel bearings were responsible for the loss of 57 days of testing. This does not include the additional test runs to investigate these problems or the days when testing was terminated early because of initial fault indications. It should again be stressed that much of the lost test time was due to awaiting spares and repairs. Taking the waiting time into account, the total equivalent downtime could be reduced to less than 20 days excluding the early termination days.

8.7.2 The Mileage Accumulation Rates

A time history of the mileage accumulation rate is presented in Figure 8-14. Superimposed is the original target of 250,000 miles in 36 weeks.

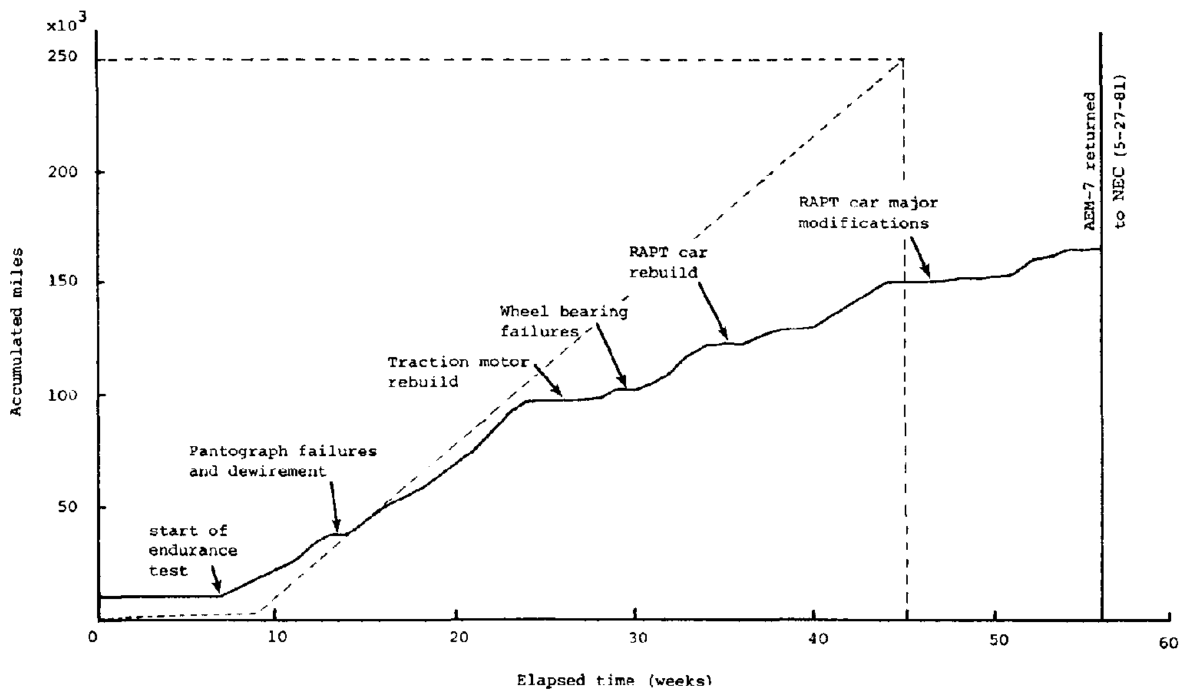

FIGURE 8-14. MILEAGE ACCUMULATION RATE FOR AMTRAK 900 AT THE TTC.

For the first 90,000 miles the original, very optimistic target was being achieved, although seven days per week operations were necessary at this time to accomplish this. However, toward the end of September 1980, during a period when very few failures occurred, even when operations had been reduced to six per week, the target rate was exceeded. This success was short lived, due to the failures of the traction motors and the wheel bearing.

The remainder of the test program was involved with the RAPT test during which large periods of downtime resulted from problems with the RAPT vehicle. However, traction motor problems periodically appeared during the remaining 66,000 miles and the emphasis of the AEM-7 test portion of the now combined AEM-7/RAPT program was shifted toward the phase break evaluation, pantograph testing, and traction motor brush evaluation.

The final mileage accumulation during the AEM-7 program at the TTC was 156,200 miles excluding the nominal 10,000 miles accumulated on the NEC.

9.0 TRACTION MOTOR FAILURES

9.1 BACKGROUND

9.1.1 Failure History

Problems with the traction motors and associated equipment started to occur within the first week of operation. A milestone diagram of the major traction motor incidents is shown in Figure 9-1. At first the problems were minor in nature, starting with the failure of the traction motor cable lugs and the cooling air pressure detection system. There then followed the first of a series of loose brush holder incidents. These continued periodically throughout the test program, and were responsible for at least two of the motor flashover incidents.

In early August 1980, the first of the major traction motor flashovers occurred resulting in the changing of traction motor #4 in late August (50,000 miles), and the repairing of all four traction motors in October 1980. In order to alleviate the commutation problems, a number of different brush grades were tried at two brush pressures. However, the commutation quality, as judged by the commutator and brush appearance, proved to be unstable. At the end of the test no satisfactory explanation for the motor commutator problems had been found, although an extensive brush material and brush pressure test is continuing on the NEC.

9.1.2 Factors Affecting the Quality of D.C. Motor Commutation

The most critical factors in determining the quality of motor commutation are the roundness and surface finish of the commutator, and the seating of the brushes on the commutator. Under ideal conditions the current passing through the interface between the brushes and commutator forms a thin, lubricating, protective film on the commutator surface. This film, which is dark golden in color with some gray, is a complex combination of copper oxide and copper hydroxyl salts. These salts are somewhat unstable and will readily deteriorate. Their formation is greatly affected by the relative humidity and oxygen content of the cooling air.

Another important aspect of commutation is the grade and pressure of the brushes. If the brushes are too hard or the brush pressure too high, a phenomenon known as copper drag occurs. In this case the commutator takes on a roughened, bright copper appearance. Copper particles can also become embedded in the brushes and the commutator grooves. Too low a brush pressure can result in brush bounce, particularly if the commutator is uneven. Finally the commutation quality is affected by the motor speed, the armature current, the presence of a.c. ripple on the armature current, and the magnetic balance provided by the interpoles. It is evident, therefore, that d.c. motor commutation is a finely balanced process.

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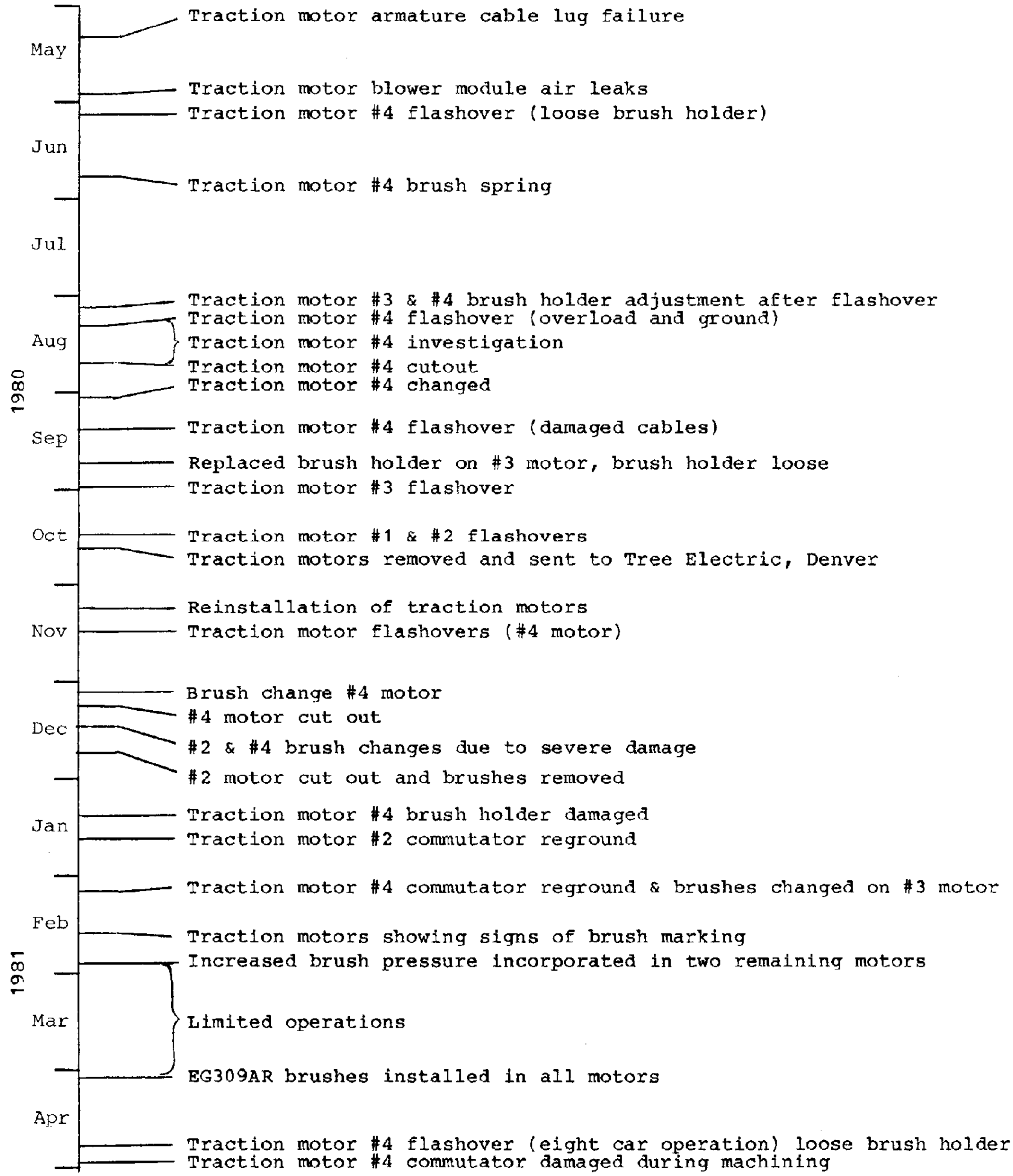

FIGURE 9-1. TRACTION MOTOR FAILURE MILESTONES.

9.2 TRACTION MOTOR MECHANICAL FAULTS

9.2.1 Traction Motor Cables

Within a few days after arrival of AMTRAK 900 a ground fault indication on the #4 motor was found to be caused by a broken traction motor armature cable. The cable lug had fatigued at the terminal bolt in the S4 cabinet. Subsequent inspection of the other traction motor cables showed varying degrees of fatigue damage.

A modification was initiated by General Motors to shorten the traction motor cables, which were too long, and to incorporate a cable support bracket shown in (Figure 8-13) to remove the weight of the cables from the terminal lugs. A heavier terminal lug for the cables was also supplied by General Motors.

When the original #4 motor was replaced by the spare unit, a similar modification was incorporated in the replacement motor cables. However, the cables were not cut short enough and after six days of operation the motor developed an armature ground fault. This time the cables were found to have been rubbing on the traction motor screen (see Figure 9-2) which wore through the insulation, causing a ground fault. The cables were repaired with shrink tubing and shortened to match those on the other motors. This incident demonstrated that both the cable mounting and the cable length are critical.

9.2.2 Blower Module Pressure Switches

To protect the traction motors from damage due to overheating caused by cooling air supply failure, a pneumatic differential pressure switch is incorporated in the blower module. Upon detection of a low pressure differential between the upper and lower levels of respective motor cabinets (S1 through S4) the pressure switch signal is used to block the motor control logic and prevent application of power to that motor.

At the beginning of operations, the traction motors on AMTRAK 900 failed to load, and the fault was eventually traced to the pressure switch system. The pressure switch system was temporarily disconnected until the fault could be rectified.

At first the problem was thought to be air leakage at the base of the cabinets due to broken seals caused by the welding of the traction motor cable support brackets. Caulking compound was used to reseal the cabinet bases, but did not solve the problem.

It was later found that due to a design oversight the upper cabinet was also sealed and was consequently pressured by the traction motor cooling supply. A vent to atmosphere was provided in the upper cabinet and the pressure switch system functioned normally.

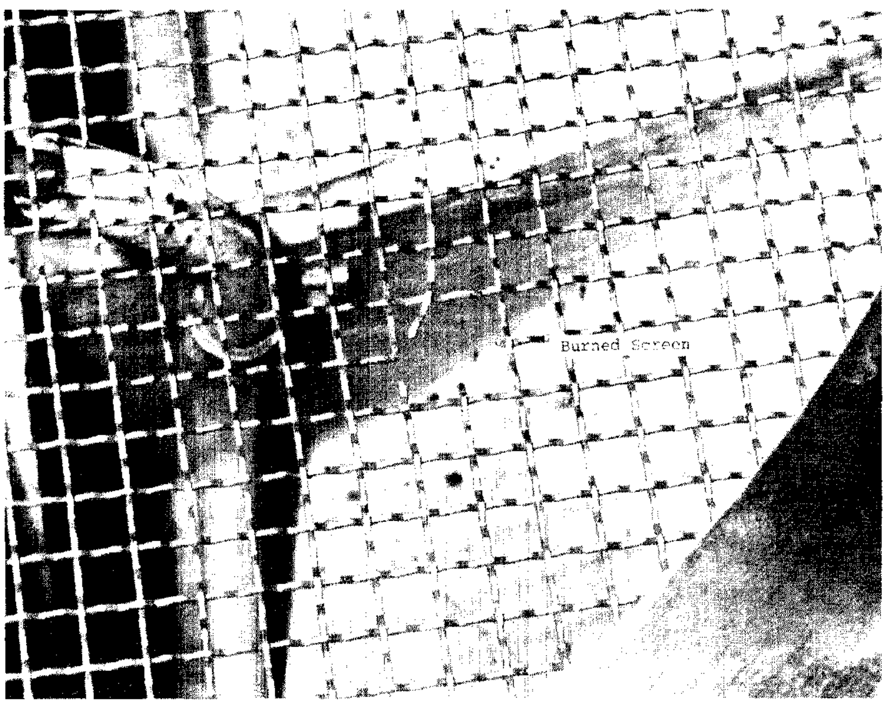

FIGURE 9-2. TRACTION MOTOR #4 CABLE DAMAGE.

9.2.3 Brush Holders

In early June 1980 the first of four loose brush holder incidents occurred. The first case caused traction motor #4 to flash over. It was found that the brush holder had come loose and reduced its clearance with the commutator and flashed over. No apparent damage was suffered by the commutator but two of the brush holders were severly damaged and were replaced. All other brush holders were checked and found to be tight.

In early August 1980, the brush holders on the #3 and #4 motors again were found to be loose after both motors had flashed over. This time two holders on the #4 motor were found to be contacting the commutator. The brush holders were cleaned up, the commutators hand stoned and hand undercut, and the brush clearances adjusted.

In early September 1980 during routine inspection, brushes were found to be partly dislodged from their brush holders in the #3 motor. One brush holder was loose but had not moved.

Finally in late April 1981, during the eight car tests, traction motor #4 flashed over. During the motor inspection a loose brush holder was found in contact with the commutator. This had worn grooves approximately 0.002" deep around the circumference of the commutator. There were also burn marks on the brush holder, leaving little doubt that the loose brush holder had triggered the flashovers.

The number of incidents of loose brush holders suggests that some improvement is necessary in the brush holder locating mechanism. It became regular practice during all traction motor inspections to carefully check for loose brush holders.

9.3 TRACTION MOTOR FLASHOVERS

9.3.1 Fault Indications

A traction motor flashover is indicated on the overhead fault panel by a traction motor overload light, a traction motor fault light and a main circuit breaker open light. If the motor flashed to ground a traction motor armature ground fault light would also appear. In addition, the overload and ground fault relays in the S7 cabinet would be flagged. For example, a flashover to ground in the #4 motor would give a traction motor overload, a traction motor armature ground and a traction motor #4 fault indication. Also the MO4-1, and the MAG34-1 relays would be flagged. The locomotive could be re-energized by pressing the overhead fault reset button. If the motor fault recurred within a short time the motor had to be cut out (isolated) before operations could continue.

During the motor flashover problems in August 1980 and again in October 1980, the motor currents and voltages were measured in an attempt to determine the cause of the motor failures. A typical example of the data is presented in Figure 9-3. The relevant section of the same incident is shown at a faster replay speed in Figure 9-4. These records show that the disturbance first appeared in the field current signal, followed by a rapid rise in armature current and a corresponding fall in armature voltage. The main breaker then opens on overcurrent. The significance of this sequence of events will be discussed later.

9.3.2 Traction Motor #4 Flashover

On August 10, 1980 the first in a series of flashovers of the #4 motor occurred. At first it was assumed that another brush holder had come loose and the motor was isolated. Inspection of the motor on the following day showed the brush holders to be tight but there was evidence of flashover. Over the next three days further flashovers occurred in motor #4. The special test points on the motor electronics were monitored on the instrumentation to give records similar to those presented in Figures 9-3 and 9-4.

An EMD electronics engineer was sent by General Motors to investigate the problem. A number of tests were carried out, including the powering of the #3 motor by the #4 electronics, and the #4 motor by the #3 electronics, for which a special set of cables was manufactured. Since the fault followed the motor, it was concluded that the motor was faulty. The #4 motor was isolated until a replacement was sent from the AMTRAK Wilmington Shops. The original was returned to Wilmington. From the data recorded during the early tests it was concluded that the fault was probably in the field windings. Events were to prove this to be an erroneous conclusion.

9.3.3 Traction Motor #1 and #2 Flashovers

In early October 1980 an increase in the pattern of traction motor overloads began to emerge. The symptoms were similar to those experienced with traction motor #4 in August but were now shared between traction motors 1, 2 and 3. The distribution was approximately 45% in TM #1, 45% in TM #2, and 10% in TM #3.

Again instrumentation was used to monitor the faults. An identical sequence of events to the #4 incidents was repeated. General Motors recommended the interchange of the trucks in order to demonstrate the problem was associated with the motors; this was done with the expected result that the faults would be found to be associated with the motors.

Inspection of the motors showed that all four commutators were damaged. However, the #1 and #2 motors showed signs of excessive damage. At the request of ASEA the four motors were removed and sent to the local ASEA repair agency, Tree Electric Company, Denver, Colorado.

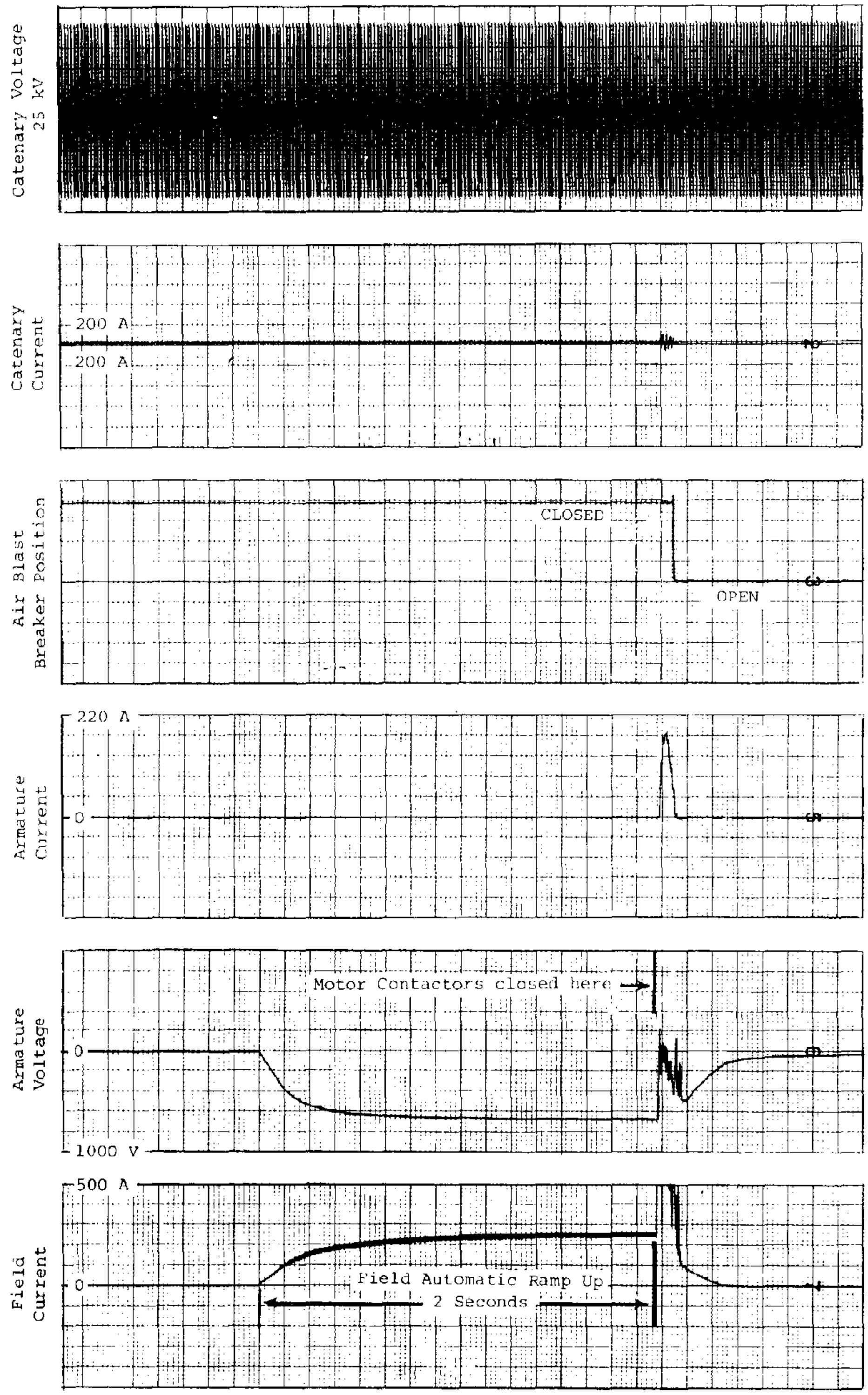

FIGURE 9-3. TRACTION MOTOR FLASHOVER (CURRENT AND VOLTAGE DATA).

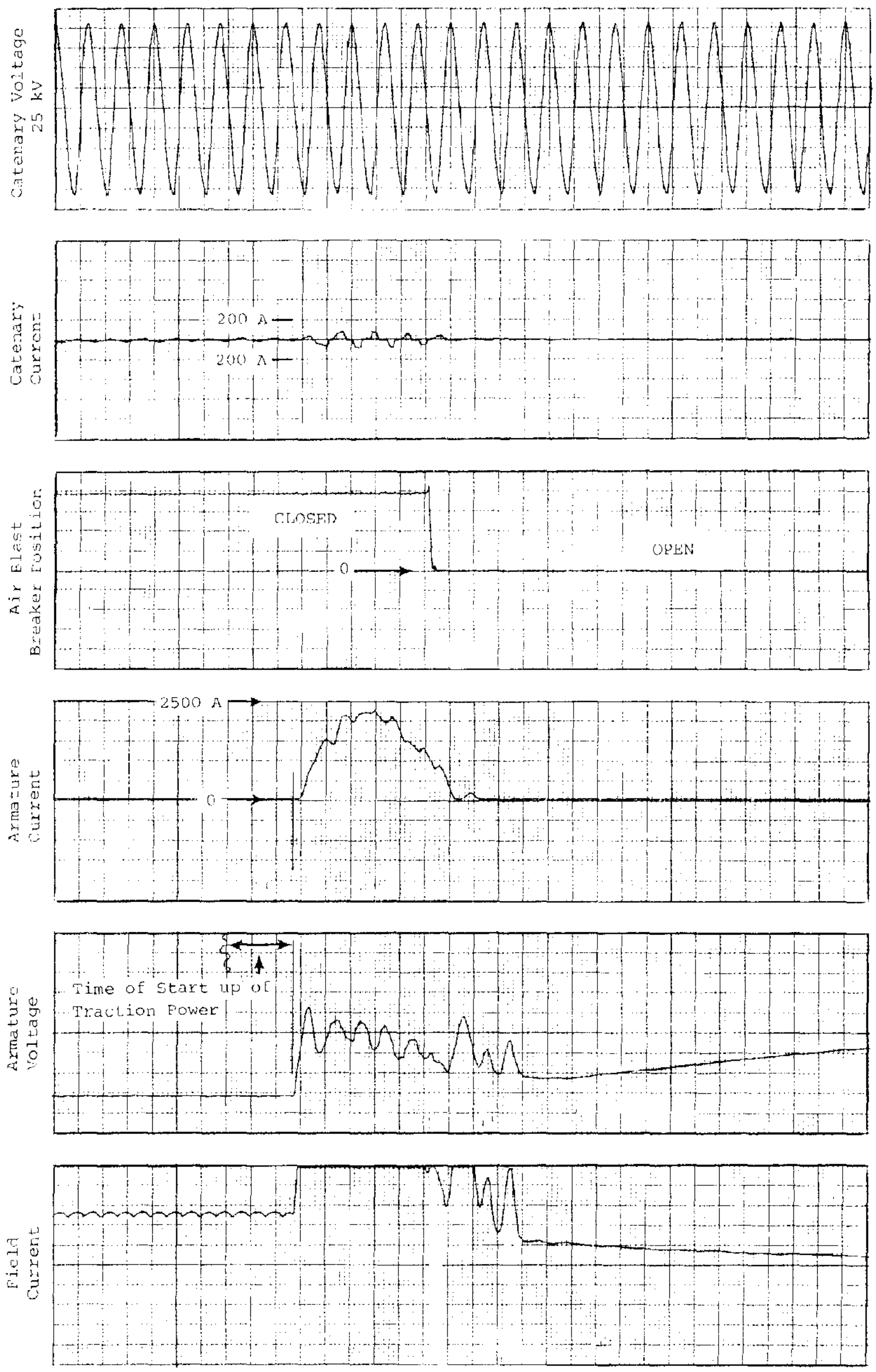

FIGURE 9-4. EXPANDED SCALE FLASHOVER DATA.

9.4 TRACTION MOTOR REPAIR

9.4.1 The Motor Inspection at Tree Electric

Although a full inspection report was prepared by Tree Electric for ASEA, General Motors, and AMTRAK, this was not made available to the TTC. However, TTC representatives were at Tree Electric for the dismantling of the #1 motor and for part of the inspection. A copy of the inspection report compiled by TTC personnel is included in appendix E.

The main feature of the damage was the appearance of four flat spots at 90° intervals around the circumference of the commutator. Each flat spot was approximately 0.003 inches deep on five successive commutation bars. For approximately twenty bars in the direction of rotation the surface was pitted and rough, indicating that the brushes were lifting over that section. At first, the flat spots were thought to be due to stall burning of the commutator; this was later shown to be unlikely for the following reasons.

- The flat spots were over the full length of the commutator bars and not confined to the brush tracks.
- The marks were associated with one polarity of brush although the motor is equipped with eight brush sets at 45°.

The #2, #3, and #4 motors, which had been fitted with EG309 brushes, showed signs of copper drag. In addition, the #2 motor showed signs of heavy flashover including pitting of the commutator bars. The brushes showed signs of arcing on the trailing edges. The #1 motor had been fitted with DE7 brushes.

The #1 and #2 motors were dismantled, the commutators were machined and undercut, and the motors reassembled. As a precautionary measure the main bearings were replaced. The #3 and #4 motors were not dismantled. The commutators were ground and undercut in situ.

At the suggestion of the TTC, the brush holders on the #1 and #2 motors were modified to accept stiffer springs to increase the brush pressure from 3.0 psi to 4.2 psi. The object of this modification was to permit the evaluation of higher brush tensions on commutation.

9.4.2 Reinstallation Configuration

After the repairs at Tree Electric Company were complete the motors were returned. The motors were reconfigured within the trucks so that one high brush pressure and one low brush pressure motor was allocated to each truck. The details are shown in Table 9-1. A brief description of the brush material, together with other options used, will be given in section 9.5.1.

TABLE 9-1. TRACTION MOTOR POSITION SCHEDULE.

New Position	Old Position	Serial #	Brush Type	Brush Pressure
TM 1	TM 1	7141917	DE 7	4.2 psi
TM 2	TM 3	7141922	EG 309	3.0 psi
TM 3	TM 2	7141925	DE 7	4.2 psi
TM 4	TM 4	7141866	EG 309	3.0 psi

After installation of the motors and retrucking, the locomotive was road tested under the guidance of an ASEA engineer. Almost immediately the #2 and #4 motors flashed. Upon inspection the motors did not show signs of heavy flashover. In the opinion of the ASEA engineer, the initial flashovers were due to copper dust residue from the grinding process. The locomotive was returned to service, after which two further flashovers occurred in the #2 motor before the motors settled down.

9.5 BRUSH MATERIAL AND PRESSURE EVALUATION

9.5.1 Description of the Brush Material

The brush types are classified by their relative hardness in Table 9.2.

TABLE 9-2. AEM-7 BRUSH TYPES.

Material	Manufacturer	Remarks
DE 7	National Carbide	Soft material*
TB 596	--	Hard material
EG 309	Carbone Corp	Hard material
EG 309 AR	Carbone Corp	Medium Hard w/lub**

* The original DE 7 brushes were later exchanged for an improved DE 7.

** The original EG 309 AR prototype brushes were hand manufactured. During the process the binding pad glue spilled between the two brush segments preventing relative motion between the segments.

9.5.2 Brush Change Schedule

The brush change schedule following the traction motor rebuild is presented in Table 9-3. The main reason for each change is also given.

9.5.3 Commutator Stoning Process

The stoning (or grinding) of General Motors traction motor commutators in situ is standard practice. Stoning attachments, designed for General Motors standard traction motors, are supplied by the General Motors Service Department. The fixture is designed to bolt in the place of a row of brush holders It is equipped with the means of holding a pair of carborundum grinding stones which can be adjusted to press on the commutator circumference. Provision is also made to traverse the stones backwards and forwards across the commutator (parallel to the bars) so that an even grinding cut is taken.

The axle associated with the motor to be ground is set up on the wheel lathe. The brushes are all removed, together with one set of brush holders. Depending on the severity of the cut required, a suitable grade of grinding stone is fitted in the attachment which is then bolted in place. The wheel lathe is then started to rotate the wheel and motor while the stones are lightly applied to commutator and traversed backward and forward across the commutator surface. Repeated cuts are taken until the required surface is achieved. In all cases the final cuts are taken with a fine grinding stone to provide a good surface finish.

After stoning the commutator grooves are cleaned with a hand held tool, and the whole cavity cleaned with a heavy duty vacuum cleaner.

For the AEM-7 traction motors a standard General Motors stoning attachment was used with an adapter plate manufactured at the TTC to fit the motor brush holder mounting arrangement. Since the commutator was much wider, extra width grinding stones were also used.

During the grinding of the #4 motor in April 1981, the commutator was accidentally gouged. It should be stressed that this incident occurred, not as a direct result of the stoning attachment or grinding process, but as the result of a brush pigtail set screw, which had not been secured, coming loose and becoming trapped between the stoning attachment and commutator. The lesson to be learned from this incident is that all potentially loose objects must be removed from the motor brush cavity before stoning commences.

This process was found to be extremely useful in repairing motors which had suffered slight to moderate commutator damage. This could be accomplished without locomotive detrucking and motor removal. With experience, it was found that a typical motor could be ground, cleaned, and rebrushed in three to four hours.

TABLE 9-3. AMTRAK 900 BRUSH CHANGE SCHEDULE.

Date	TM #1		TM #2		TM #3		TM #4		Mileage	Reason for Change
	Type	Psi	Type	Psi	Type	Psi	Type	Psi	(miles)	
11/06/80	DE 7	4.2	EG 309	3.0	DE 7	4.2	EG 309	3.0	98,000	Rebuild configuration
12/01/80	DE 7	4.2	TB 596	3.0	DE 7	4.2	TB 596	3.0	108,000	Assessment of TB 596 brushes
12/12/80	EG 309	4.2	EG309AR	3.0	EG 309	4.2	EG309AR	3.0	117,000	Incompatibility of TB 596 brushes with the commutators.
12/16/80	EG 309	4.2	EG 309	3.0	EG309AR	4.2	EG 309	3.0	119,000	Both #2 and #4 motors severly damaged by prototype EG 309AR brushes. The #2 commutator was $^{+0.002''}_{-0.001''}$ out of round, the stoning fixture was used to grind the commutator (see section 9.5.3)
2/23/81	EG 309	4.2	EG 309	4.2	EG 309	4.2	EG 309	4.2	147,000	Brush pressure increased on the #2 and #4 motors to make all four motors identical
4/03/81	EG309AR	4.2	EG309AR	4.2	EG309AR	4.2	EG309AR	4.2	152,000	New commercial type EG 309AR brushes installed in all motors for evaluation. All commutators lightly stoned to remove oxide film before brush replacement.
5/31/81	EG309AR	4.2	EG309AR	4.2	EG309AR	4.2	---	---	166,000	TM #4 commutator gouging. Testing completed at the TTC.

9.6 ANALYSIS OF THE TRACTION MOTOR PERFORMANCE

9.6.1 The Traction Motor Flashovers

Analysis of the early traction motor incidents was influenced by the occurrence of loose brush holders. It was assumed that reduced brush holder clearance was the trigger mechanism for the initial flashover, which then became self-perpetuating.

The analysis of the original traction motor #4 and subsequently the #1 and #2 recorded data was carried out by TTC personnel with limited experience in this area. The conclusions that the original disturbance, being in the field supply (Figure 9-4), was indicative of a field winding failure was subsequently proven incorrect. It was not until traction motor experts from General Motors and ASEA were made available that the investigation progressed.

Once the disturbance in the field current was understood as being the result of transformer action between field and armature, and that the armature supply disturbance was caused by interference of the armature current by the start of the flashover process, attention was concentrated on the brush and commutator interface. With this in mind, the second phase of testing, in which the brush material and pressures were changed, was initiated. During the second phase of testing the frequency of traction motor inspection was increased.

9.6.2 The Effect of Brush Material and Brush Pressures

A great deal of discussion during the investigation of the commutator problems centered on the conditions of climate and altitude at the TTC. The low relative humidity at the TTC was considered to be particularly significant to commutator performance because of the part moisture plays in formation of commutator surface film discussed in section 9.1.2. The TTC staff carried out a survey of the relative humidities at Pueblo and at Philadelphia from April through October 1980. Since the TTC AEM-7 operations were almost exclusively at night, the relative humidity there, averaged on a daily basis over the operation period, was generally in the 30 to 60% range. On the NEC (Philadelphia) the general daily average was in the 45-75% for the same period.

Experience with other vehicles has shown that high performance traction motors may suffer increased commutator damage due to TTC climatic conditions. This was particularly true of the State-of-the-Art Cars (SOAC) and the Advanced Concept Train (ACT 1).[13] However, the conventional traction motors used on diesel electric locomotives and conventional transit cars, do not appear to suffer ill effects from the TTC climate. This suggests that where commutator performance is at the design limit under normal climatic conditions, the altitude and low humidity at the TTC are sufficient to push the performance over the limit, causing commutator damage. Further data on low humidity commutator operation can best be sought from ASEA, Sweden, who have operated extensively in Tundra regions of Northern Europe.

The brush pressure changes demonstrated that the increased brush pressures had a beneficial effect. This was recognized early in the evaluation and all motors were modified accordingly.

The conclusions from the brush material changes were less clear. The main period of stability with the EG 309 brushes coincided with a maximum operating speed of 100-110 mi/h due to the RAPT car problems. Periodically the EG 309 brushes would give the appearance of slight copper drag which would disappear almost as readily. The installation of the EG 309AR commercial brushes, unlike the poorly manufactured prototypes, had the immediate effect of cleaning up the commutators. Throughout the majority of the 14,000 miles for which the brushes were used, the commutator appearance was stable. The maximum speed of operation had once more been increased to 115-120 mi/h but the consist size was only four cars. At the end of this period a series of eight car consist tests was initiated. After two NEC simulated profiles two flashovers of the #4 motor occurred and testing was terminated.

The motors were inspected the following day. It was found that the #4 motor commutator was 0.002" out of round with eight of the now, characteristic burn marks spaced at 45°. Heavy stoning was required to renovate the motor. It was during this process on the final fine stone polishing cut, that the commutator was gouged (see section 9.5.3).

The #2 and #3 motors were also found to be lightly damaged. The #2 motor had burn marks which were not as deep as those in the #4 motor. Both motors were lightly ground before rebrushing. The locomotive was operated on three traction motors with a three car consist for another 2,000 miles before testing was terminated.

One aspect of TTC operations, so far not addressed during the commutation discussion, is the almost exclusive use of the automatic speed control system during profile running. This system, which is not generally used extensively by engineers on the NEC, controls the train speed by applying the required average armature current to the motors continously. This results in extended operation of the motors at high speed with low armature currents, rather than a series of on/off currents derived from manual control. The implications of this mode of operations should be discussed with the locomotive manufacturers.

9.6.3 Summary of Findings

The traction motor problems resulted in one probable positive finding, together with several unanswered questions, probably the most unsatisfactory aspect of the AEM-7 test program.

The only positive finding was that increased brush pressure improved the commutation performance of the motor. Based on the apparent lack of motor commutation problems in service on the NEC compared with the extensive TTC problems, the following questions are raised.

- What is the significance of increasing the maximum operating speed to 120 mi/h?

- What is the effect of increasing the RMS power output of the motors as demonstrated by the eight car test?

- How significant are climatic effects in the overall commutation picture, and what impact might these have on future locomotive traction motor design?

- Did the use of the speed control feature on the locomotive during the TTC profile operations contribute to the commutation problems?

Since the present train size and schedules on the NEC do not appear to result in traction motor commutation problems the answers to these questions are not urgent. However, as train size and schedule requirements increase, service history may provide some of the answers.

10.0 PANTOGRAPH INVESTIGATIONS

10.1 BACKGROUND

The standard pantograph used on the AEM-7 is the Faiveley DS 11 (dual stage) unit, which is an extended (stretched) version of the DS 12 pantograph used by SNCF on their TGV trains. The AEM-7 came to the TTC equipped with DS 11 units on both ends.

A prototype DS 12 pantograph was also tested at TTC mounted on the pantograph test car DOTX-211 as part of the Dead Line Test Program.[1] A much fuller test program (section 18.2) was carried out to evaluate the pantograph on the catenary design styles at the TTC (and on the DOTX-211 car) under varying temperature conditions. It was found that the current collection performance was acceptable, and that no significant lateral flexibility motion of the pantograph existed.

During the initial TTC tests of AMTRAK 900 the pantograph test car observation facility was used to view the DS 11 pantograph during the speed upgrade process. The excessive lateral deflection of the pantograph head, particularly on the curved sections of the RTT caused concern. It was also noted that the quality of current collection was worse than would have been expected from the dead line test results. After consultation with AMTRAK and EMD personnel the decision was made to continue operations up to 120 mi/h with the same unit.

On July 16, 1980 the first of two failures of the DS 11 pantograph was discovered. During routine inspection it was found that the main knuckle casting on the 'B' end pantograph had fractured. While this failure was being investigated, operations continued with the 'F' end pantograph, and on July 26, 1980 the second unit failed resulting in a serious dewirement. This failure was diagnosed as a fracture of the lower arm of the upper stage.

In order to continue test operations with AMTRAK 900 the prototype British Rail/Brecknell Willis pantograph was fitted on the locomotive. This unit had already been dead line tested on the DOTX-211 car at speeds up to 120 mi/h not as part of the NECPO series of tests, but in preparation for a lightweight catenary proposal to be submitted by the TTC to FRA/OR&D.

Between July and December the locomotive continued to operate with the prototype BR/BW pantograph while various modifications were made to the DS 11 pantograph in order to improve its performance on the catenary. None of the modifications was successful, although no significant problems with the DS 11 pantograph were reported from the NEC. In January 1981 a prototype 'stretched' BR/BW High Speed pantograph was received at the TTC. This unit, which was designed to fit on the AEM-7 and conform to NEC wire heights, was installed on AMTRAK 900. The pantograph was tested and evaluated for current collection quality and lateral flexibility. It was found that the unit performed satisfactorily on both counts.

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In April 1981 a modified pantograph head was provided by Faiveley, S.A., for the DS 11 pantograph. The two pantographs on the NEC Locomotive AMTRAK 902 were fitted with the modification, and, after aerodynamic testing, were placed in service on the NEC. The one remaining DS 11 pantograph at the TTC was also modified and reinstalled on AMTRAK 900. A special series of tests then carried out to measure the aerodynamic characteristics of the pantograph and the current collection performance. The current collection performance was found to be satisfactory. However, the aerodynamic force data showed there to be a substantial differential force distribution between the leading and trailing collector strips. The pantograph was placed in service at the TTC. After approximately 2500 miles the leading collector strip of the pantograph head failed and testing with the DS 11 pantograph was terminated.

10.2 FILMING TECHNIQUES FOR MEASURING LATERAL FLEXIBILITY

10.2.1 Camera Mounting

The use of film to make remote displacement measurements is well established. All that is required is a rigid camera mount and a known reference measurement on the subject to be measured. An identical technique was used for each of the pantographs installed during the AEM-7 test program. The camera was mounted on a rigid bracket (Figure 10-1) attached to the hand rails on the locomotive roof. A platform was provided on the bracket to enable the camera to be lined up with the pantograph head at normal wire height. Since the camera was rigidly attached to the locomotive roof, any lateral displacement of the pantograph head within the picture frame was relative to the locomotive roof.

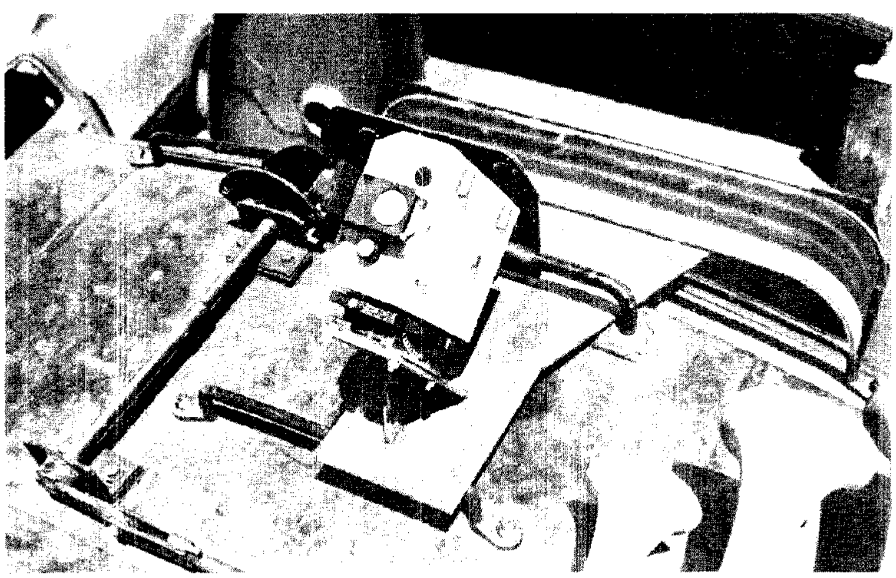


FIGURE 10-1. MOVIE CAMERA MOUNTING BRACKET ON AMTRAK 900.

10.2.2 Measurement Procedure

For all pantograph assessment a frame rate of 100 frames/second was selected as the best compromise between data resolution and film economy. The camera was set up accordingly. The frame rate was checked periodically and found to be within 1%.

Observation of the pantograph on the initial speed upgrade of the AEM-7 indicated that the major current collection problem occurred between RTT stations R18 clockwise to R32 at speeds between 115 and 120 mi/h.

The camera was equipped with a remote control switch which could be used to start and stop the film as required. At a speed of 115 mi/h enough film was available to monitor the pantograph for approximately 25,000 feet.

The measurement procedure consisted of accelerating the train up to 115 mi/h. The speed was then held constant over the track length between R15 clockwise to R45. The camera was switched on at R15 and off again at R45. One complete roll of film was used per data run. After removal of the film from the camera the film was processed and printed for analysis.

10.2.3 Film Motion Analyzer Measuring System

A special film reader, called a film motion analyzer, can be used to provide measurement data from the film frame. The frame is projected onto a sensitized screen which is equipped with calibrated cross wires which can be used to reference any point on the screen to an X-Y coordinate system. An electrical readout of the coordinates is provided which drives a digital display, but can also be used to interface with a microcomputer.

The film feed can be controlled in both the forward and reverse direction either in a frame by frame step mode or in a finely controlled slow speed mode. In either case a frame count readout is provided, referenced to a selected frame in the sequence. The frame count readout can be reset by the operator at any desired frame.

10.2.4 Film Measurement Technique

Two pieces of information were extracted from the film data. These were:

- lateral displacement peak-to-peak amplitude
- lateral flexibility resonant frequency

Before the amplitude could be determined, a dimensional scale factor for the film frame had to be determined. This was done by measuring the coordinates of each extreme of a reference dimension in the picture and relating the coordinates to the known physical dimension. Thereafter any coordinate dimension could be translated into a displacement measurement.

To determine the maximum amplitude of lateral displacement the film was run slowly through the reader so that areas of lateral activity could be identified. Each time one was found it was referenced by the start and end frame numbers. The amplitude of the lateral motion was then measured by using the cross wires to establish the coordinates of a point on the pantograph collector shoe at the left and right extremes of the motion. The frame step control was used to fix the motion extremities. The difference in coordinates was turned into a displacement measurement by applying the scale factor. A number of cases were measured in order to establish a representative case.

The frequency of the lateral oscillation was determined by counting the number of frames it took to oscillate through 5 to 10 complete cycles. By relating the number of frames and the number of cycles to the frame speed it was possible to determine the resonant frequency to an accuracy of $\pm 2\%$. The data for all pantographs tested is summarized in Table 10-1.

TABLE 10-1. SUMMARY OF LATERAL FLEXIBILITY RESULTS.

Pantograph Type	Date Mo/Day/Yr)	Speed (mi/h)	P-P Amplitude (in)	Frequency (Hz)
DS 11 (RTT)	7/16/80	115	9.75	2.46
DS 11 (RTT)	9/21/80	115	9.80	2.48
DS 11 (NEC)*	11/1/80	110-120	4.75	2.63
BR/BW (Proto)	9/21/80	115	0.5	4.36
BR/BW(Stretched)	1/29/81	120	1.0	3.98
DS 11 (Mod)	4/6/81	120	5.25	2.66

* Measurements derived from film taken by TTC personnel during AMTRAK tests on Unit 903.

10.3 THE FAIVELEY DS 11 PANTOGRAPH

10.3.1 Description

The Faiveley DS 11 pantograph, (Figure 10-2), like the DS 12, is a single arm design. The unit consists of the conventional lower (or main) stage (GEP) which is designed to accommodate the long wavelength, large amplitude changes in wire height. A second stage (LEP) is mounted on top of the lower stage. The LEP is designed to respond to the shorter wavelength, medium amplitude (typical span length) variations in contact wire height. A third stage of suspension is provide between the LEP and the collector shoe by means of spring plunger assemblies.

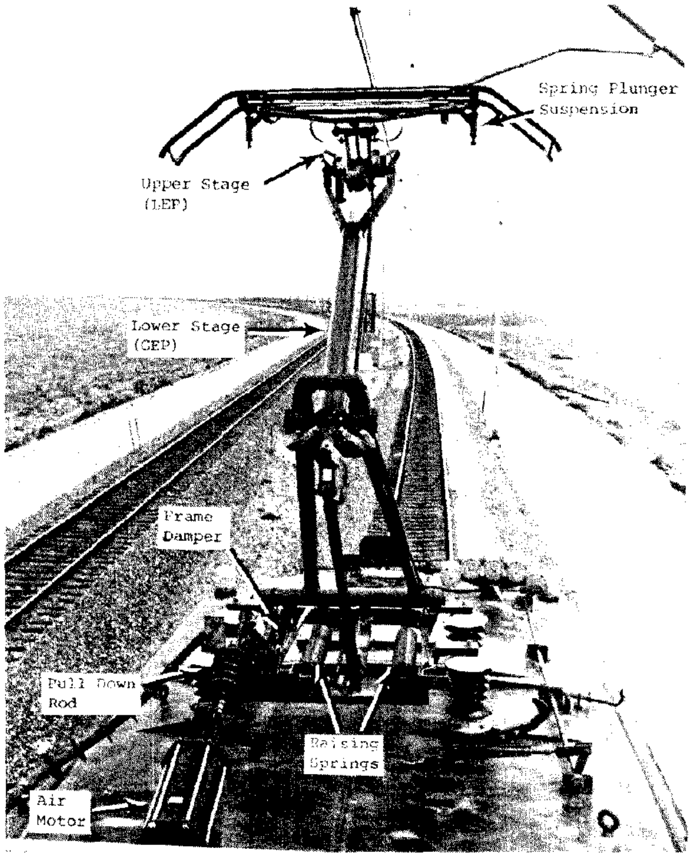


FIGURE 10-2. GENERAL VIEW OF THE FAIVELEY DS 11 PANTOGRAPH.

The pantograph is spring/air raised and spring lowered. A set of main frame springs provides the force necessary to raise the pantograph and generate the static uplift pressure to the GEP through a mechanism designed to maintain a constant upward force regardless of pantograph operating height. The pantograph is raised and lowered by means of an operating cylinder mounted on the roof structure through an insulated pull rod. The operating cylinder contains a spring of sufficient strength to overcome the raising springs and provide the necessary lockdown force. To raise the pantograph, air pressure is applied to the cylinder to overcome the lowering spring and allow the raising springs to become effective. The motion of the GEP is controlled by a high rate damper (shock absorber).

The mean position of the LEP is controlled by the stiffness of its suspension. The LEP has a total travel of 40 cm (16") and an effective stiffness of approximately 1.5 lbs/in. The LEP is adjusted to mid travel with the static uplift force applied to the collector shoe by changing the pretension of the LEP suspension coil springs.

The construction of the GEP is tubular steel. The lower half of the GEP is a twin tube construction forming the base frame bearing assembly to the main articulation joint (knuckle). At the knuckle end the two tubes are joined by a casting which also forms the housings for the knuckle bearings. The upper arm of the GEP is a single tube forked at the upper end to provide bearing supports for the LEP.

The LEP itself is of lightweight construction. The lower arm is an aluminum casting, the upper arm is fabricated of thin walled steel tubing.

The pantograph head is a two strip head designed to conform to the NEC collector head profile. The center section of each strip is fitted with carbon segments to provide a total carbon length of 35 inches.

10.3.2 Comparisions between the DS 11 and DS 12 Pantographs

Two major differences exist between the DS 12 and DS 11 pantographs. The DS 12 pantograph head was based on the SNCF head. It was constructed basically of sheet steel bent to form an inverted U channel 3/4" wide by 3/4" deep. The carbon segments were bolted through the base of the U section to form a carbon wear strip width of 40 inches. Two collector strip assemblies were used spaced 19 inches apart. The head had been aerodynamically trimmed by means of tabs fixed to the center of each collector strip. The total head assembly weight was 30 pounds.

The DS 11 pantograph head was constructed of rectangular steel bar stock 2" by 3/4" (cross section). The standard AMTRAK carbon segments were used to form a total carbon collector width of 35". Again, two strips were used, spaced 14" apart. The total head weight was 38 pounds.

The DS 12 unit had a total vertical reach of 2.6 m (8',6") of which 2.2 m (7',2") resulted from the mainstage extension and 0.4 m (1',4") from the second or upper stage. To accomplish this reach, the lower members of the main stage were designed 72" long and the upper member was 63" long.

To accommodate the NEC contact wire height specification, the DS 11 pantograph reach was increased to 3.2 m (10',6"). To accomplish this, the lower members were increased in length to 88" and the upper member to 76". The upper stage design remained the same.

10.3.3 The Failure of the 'B' End Pantograph Knuckle Joint

During a routine inspection of the 'B' end pantograph (Type DS 11) it was found that the main joint casting was completely cracked through, (see Figure 10-3). The structural integrity of the knuckle was retained only by the bearing shaft, which was held in place by the retaining nuts. Fortunately the fault was discovered before more serious damage was sustained.

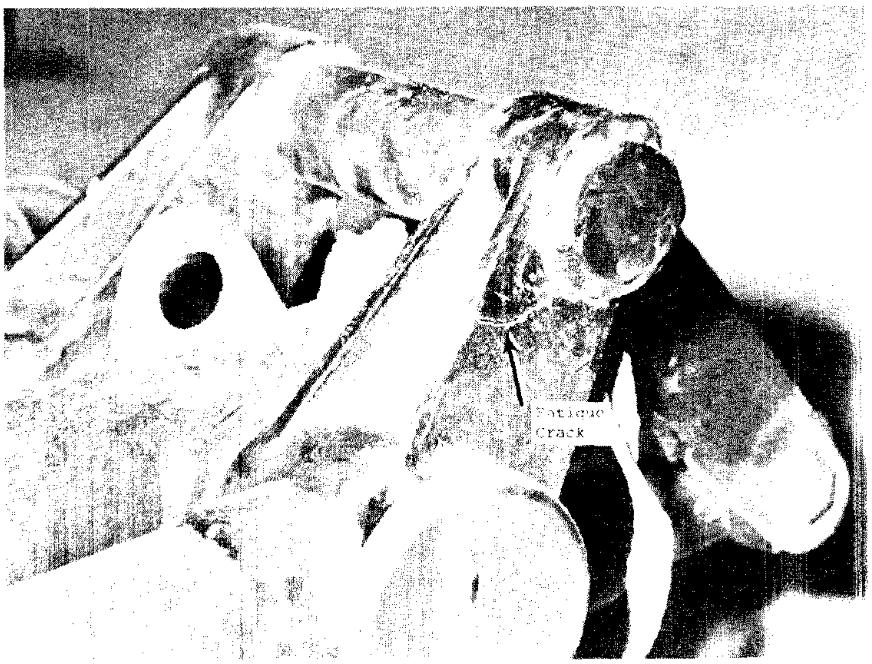


FIGURE 10-3. FAIVELEY DS 11 PANTOGRAPH FAILED KNUCKLE ASSEMBLY.

Before the reasons for the failure could be understood, analysis of the knuckle load cases was necessary. Lateral deflection of the pantograph head placed the upper member of the lower stage in bending which in turn applies a moment to the knuckle assembly. The moment at the knuckle was reacted by vertical bending of the lower tubular members. Tying together the ends of the lower members greatly increased the stiffness of the system by limiting the relative displacement of the member ends but resulted in high stresses in the cross member (knuckle casting). It was concluded that the knuckle casting failed due to fatigue caused by the excessive lateral flexibility in the pantograph frame.

A similar failure had occurred on an identical unit during structural testing by Faiveley, S.A., in France. As a result of this earlier failure the knuckle casting had been redesigned. Only the pantographs on AMTRAK 900 and one unit on AMTRAK 901 retained the original knuckle casting design. Arrangements were made to supply a new lower frame for each of the AMTRAK 900 pantographs. Meanwhile operations were to be continued with the second DS 11 pantograph. Daily crack detection tests were made on the knuckle casting as a safety precaution.

10.3.4 Failure of the 'F' End Pantograph

The failure of the 'F' end DS 11 pantograph occurred approximately 5,500 miles after the failure of the first unit. A speed upgrading test was being carried out on the newly installed Balfour Beatty phase break. A complete lap of the RTT had been completed in a clockwise direction at 110 mph at the end of which the pantograph had successfully negotiated the new phase break. During the acceleration to 120 mph for the next and final phase break pass, power loss to the locomotive was reported at station R23 and the substation Oil Circuit Breaker tripped. The train finally braked to a stop at R32.

The pantograph was inspected, and it was found that the upper stage (LEP) and collector shoe were missing and that the upper member of the main stage (GEP) was entangled in the catenary. The pantograph could not be lowered by means of the pantograph controls and had to be manually disentangled from the catenary and tied down into the lowered position.

Inspection of the catenary showed there to be extensive damage between stations R21 clockwise to R32. Inspection of the pantograph showed that the collector shoe and upper member of the LEP were still attached to the GEP by means of the control rod (Figure 10-4), and that both members of the GEP were severely distorted (see Figure 10-5). Very little remained of the aluminum casting forming the lower member of the LEP (Figure 10-5) or the LEP suspension (Figure 10-4). This was later found at the trackside.

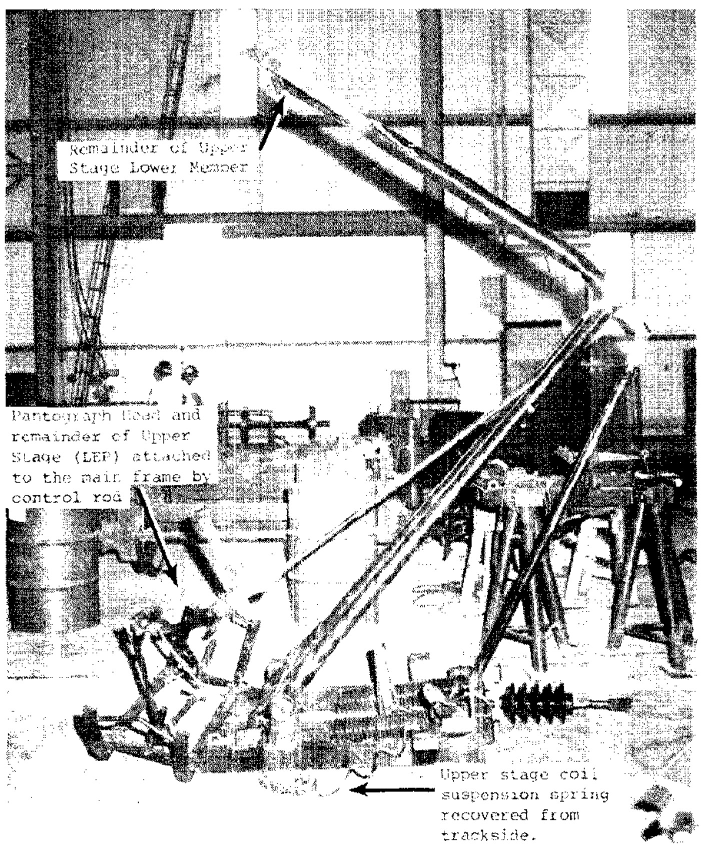


FIGURE 10-4. FAIVELEY DS 11 PANTOGRAPH AFTER THE DEWIREMENT.

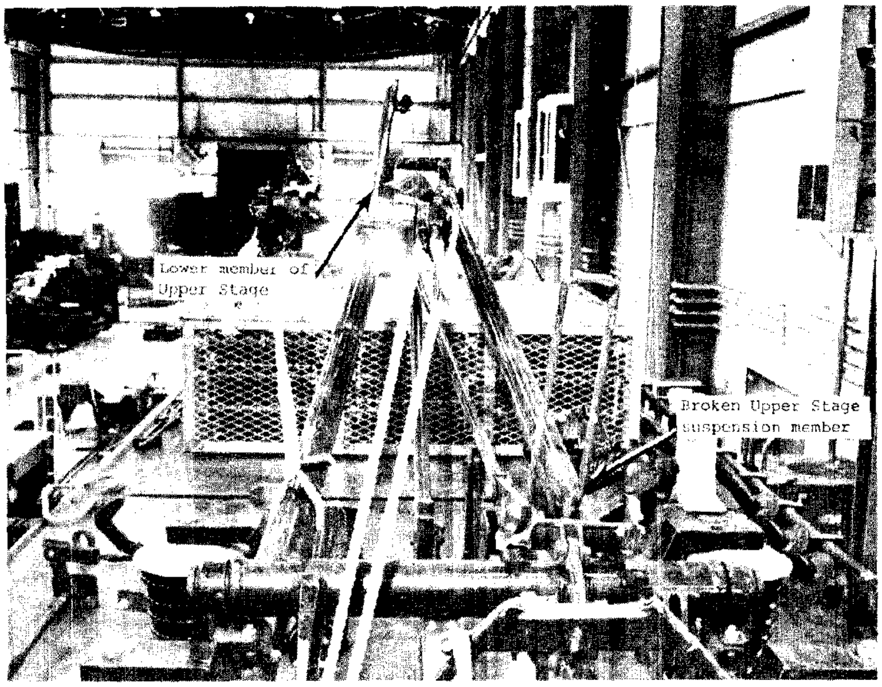


FIGURE 10-5. THE DAMAGED MAIN FRAME (GEP).

Further investigation of the pantograph raising and lowering mechanism showed that the full extension of the pantograph during the dewirement had allowed the pull-down bell crank to go over-center thus locking the pantograph lowering mechanism in the raised position. This design error has since been corrected. However, in the case of the RTT incident, damage was caused to an extra 1 1/2 miles of catenary because the pantograph would not lower when commanded to do so.

In order to determine the cause of the failure of the second pantograph a detailed inspection of the catenary was initiated to discover the first visible signs of catenary damage. Two pieces of information were already established:

- The pantograph was known to be in good condition at the last pass over the Balfour Beatty phase break as witnessed by trackside observers.
- The only sign of damage to the collector shoe was a single impact (Figure 10-6) at the leading right hand corner looking in the direction of travel. This indicated that the wire did not come off the end of the horn due to track or catenary misalignment.

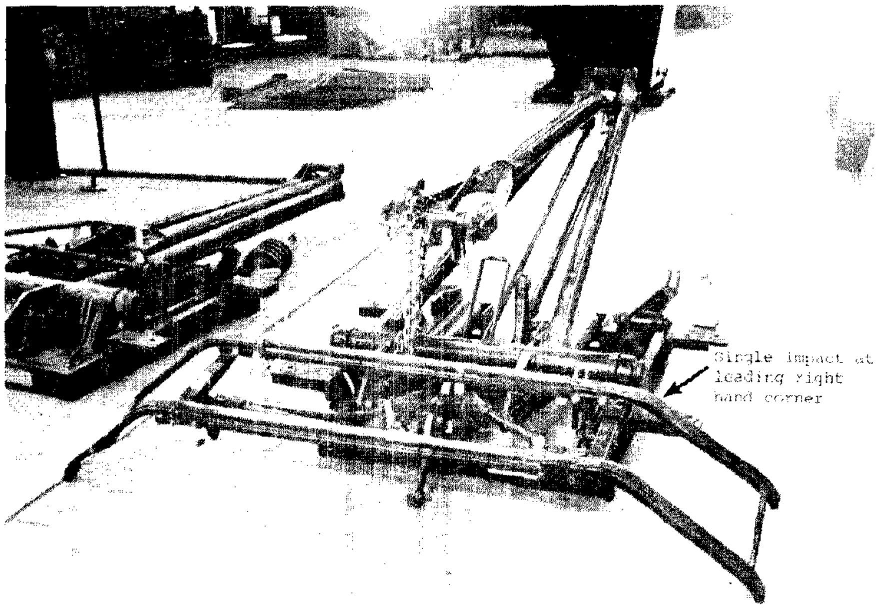


FIGURE 10-6. IMPACT DAMAGE ON THE PANTOGRAPH HEAD.

In an incident such as this on an operational railroad, it is often difficult to establish the exact cause. However, since the RTT catenary was a new facility, it proved relatively easy to determine the exact sequence of events.

The section of catenary from station R71 clockwise to R21 was inspected in detail by representatives of Faiveley, S.A., AMTRAK, and the TTC. The inspection concentrated on obstructions on the catenary such as displaced registration arms, loosened equalizing jumpers or out-of-running contact wire support brackets. The results of the inspection are summarized in Table 10-2.

TABLE 10-2. FINDINGS OF THE RTT CATENARY INSPECTION AFTER THE DEWIREMENT.

STRUCTURE	LOCATION	COMMENTS
Balfour Beatty phase break to 12/17	R70+800 R18+681	no visible signs of damage
12/17 to 12/22	R18+681 to R19+731	Faint scratches on the contact wire indicating abrasive rubbing possibly caused by a tilted pantograph head.
12/22	R 19+731	An impact mark on the registration arm (Figure 10-7) exactly matching the indention on the pantograph collector shoe. The position of the mark indicated that the pantograph head must have been inclined at an angle of 45° to the projected track center line indicating that the upper stage had already failed.
2/22 to 12/30	R19+731 to R21+201	Deeper score marks on the contact wire and hanger bolt heads resulting from contact with parts of the pantograph mechanism other than the head.
12/31	R21+381	Bent registration arm (Figure 10-8) the first sign of heavy catenary damage. The double indentation in the registration arm matched the spacing of the forked end on the upper member of the GEP.

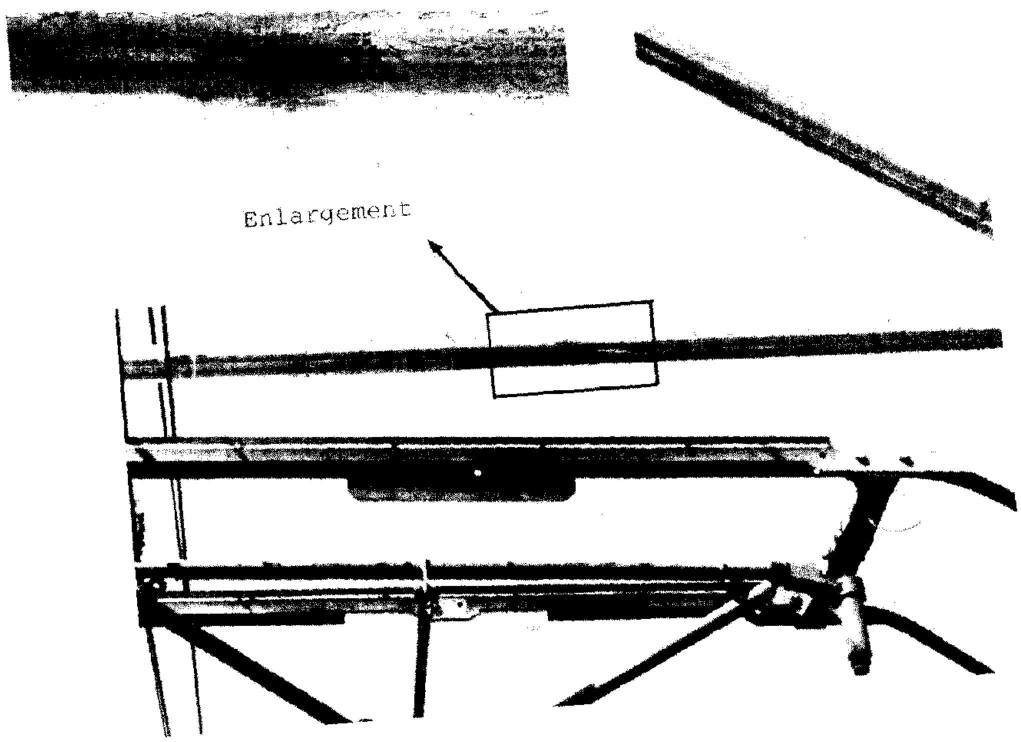


FIGURE 10-7. THE INDENTATIONS ON THE REGISTRATION ARM AT STRUCTURE 12/22.

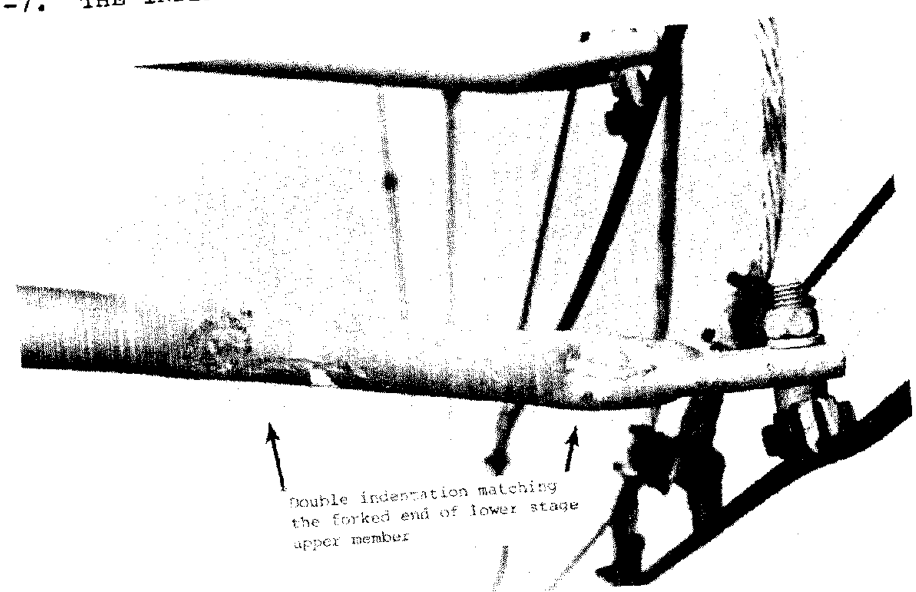


FIGURE 10-8. DOUBLE INDENTATIONS ON THE REGISTRATION ARM AT STRUCTURE 12/31.

It was concluded that structural failure of the lower member of the LEP occurred somewhere in the vicinity of structure 12/15 (R18 + 531) which allowed the head to tilt laterally at an angle of approximately 45°. The head continued to run on the side of the contact wire until impact with the registration tube at 12/22 occurred. Thereafter structure failure became more rapid.

Subsequent metallurgical analysis of the available pieces of the LEP showed no evidence of structural fatigue. To date no reasonable explanation for this failure has been found. In addition no apparently identical failures have occurred on the NEC.

10.3.5 Aerodynamic Tuning of the DS 11 Pantograph

In September 1980 aerodynamic testing of the DS 11 pantograph was carried out on the NEC. A set of airfoils designed to give the best aerodynamic performance were selected from these tests. One of the DS 11 pantographs on AMTRAK 900 was fitted with the new airfoils and tested at the TTC. No significant improvement in either the current collection performance or the lateral flexibility resulted from this modification. Operations with the DS 11 pantograph on the RTT catenary were restricted to speeds below 100 mi/h until further modifications were available.

10.3.6 The Faiveley Lightweight Head Design

a. Background. Following the unsuccessful attempt at improving the current collection performance of the DS 11 with the original head, Faiveley, S.A., designed and built a lightweight collector shoe.

In March 1981, two of the modified collector shoes were fitted to the DS 11 pantographs on the AMTRAK 902 locomotive. A series of tests was then conducted by AMTRAK to evaluate the aerodynamic and current collection performance of the modified units. From these tests, it was concluded that the overall aerodynamic lift of the pantograph was acceptable and that the current collection performance was much improved. AMTRAK 902 was then put into service on the NEC with the modified pantographs for long-term evaluation.

In April 1981, the Faiveley DS 11 pantograph remaining at the TTC was equipped with the modified collector shoe and set up by a Faiveley engineer. This unit was then installed on AMTRAK 900 for evaluation on the lightweight catenary. A series of performance tests conducted on this unit included an aerodynamic evaluation. The unit then embarked on an accelerated service evaluation as part of the TTC AEM-7 endurance test program. After approximately 2,500 miles, a major failure of the modified collector shoe occurred. As a result of this incident the pantographs on AMTRAK 902 were inspected. Excessive wear of the lead collector strip carbons were found and the modified heads were removed from that unit.

b. Preliminary Tests. In preparation for the long-term endurance test of the modified DS 11 pantograph, a series of preliminary performance tests was carried out. These had the following main objectives:

- To determine the lateral flexibility displacement amplitude of the modified pantograph.

- To measure the current collection performance of the pantograph based on percentage loss of contact measurements.

- To measure the aerodynamic lift forces generated by the forward motion of the pantograph through the air.

c. Aerodynamic Test Procedure. The technique used for aerodynamic testing at the TTC differed from that used on the NEC. It was designed to provide more complete information on the aerodynamic behavior of the pantograph. The pantograph collection shoe was restrained to two load cells mounted on the locomotive roof by means of nylon cord, (Figure 10-9).

One load cell was used to measure the aerodynamic force generated in each collector strip in order that two pieces of information might be extracted from the data:

1. The overall lift force.
2. The leading and trailing collector strip differential load.

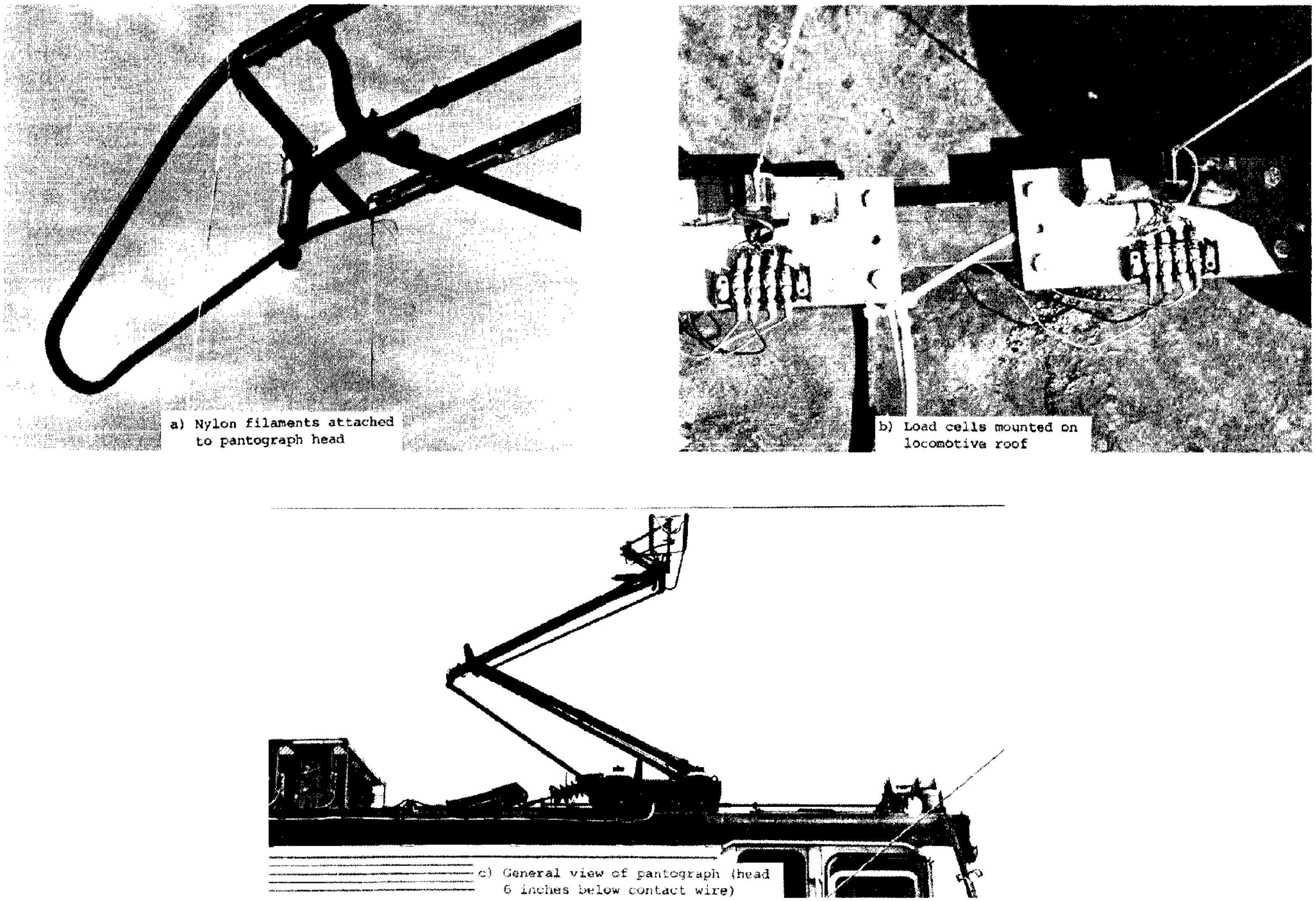
The load cell outputs were zero balanced with the pantograph raised. This eliminated the static uplift from the measurement, allowing the aerodynamic force to be measured directly.

The aerodynamic forces were measured over a length of tangent track at speeds of 100, 110, and 120 mi/h. The second pantograph was used to power the locomotive. Four configurations were evaluated.

• Lead pantograph	22 ft above rail
• Lead pantograph	19 ft 6 in above rail
• Trailing pantograph	19 ft 6 in above rail
• Trailing pantograph	22 ft above rail

d. Summary of Results. Examples of the 'raw' data are presented in Figure 10-10. It should be noted that some zero drift was experienced and was allowed for in the data reduction. The drift was caused mainly by friction in the pantograph mechanism due to the high rate frame damper and slight stretching of the nylon cords. Disconnecting the frame damper for this test was considered, but the risk of excessive frame vibrations was too great to allow this. For each of the test runs, the data were reduced to give:

1. The total aerodynamic lift (given by the arithmetic sum of the two components).



a) Nylon filaments attached to pantograph head

b) Load cells mounted on locomotive roof

c) General view of pantograph (head 6 inches below contact wire)

FIGURE 10-9. FAIVELEY DS 11 PANTOGRAPH AERODYNAMIC TEST ARRANGEMENT.

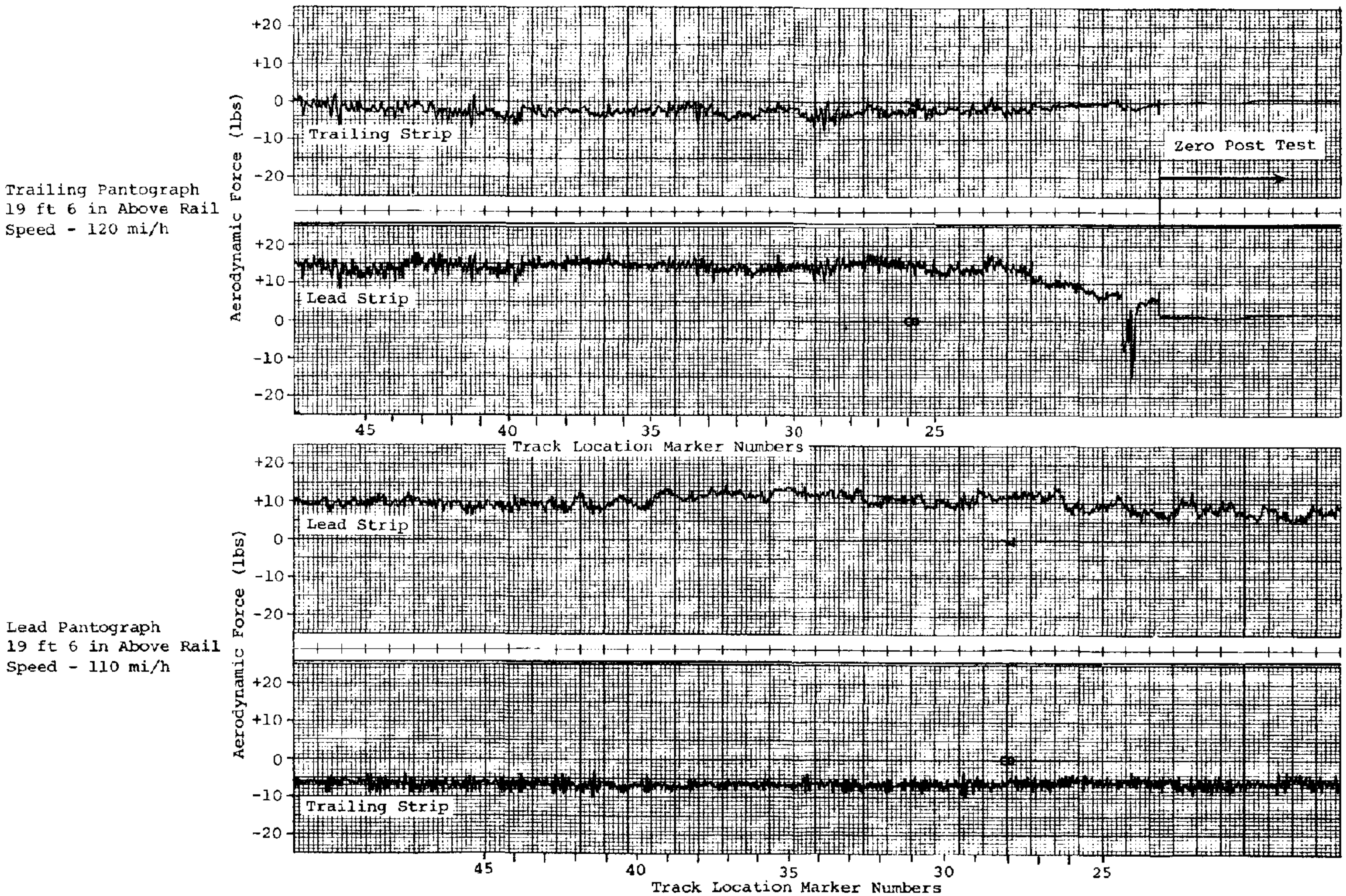


FIGURE 10-10. AERODYNAMIC TEST 'RAW' DATA.

2. The magnitude and direction of the leading and trailing collector strip differential load (given by half the arithmetic difference of the two components).

The summary plots of total aerodynamic lift against the square of the train speed are presented in Figure 10-11 (lead pantograph) and Figure 10-12 (trailing pantograph). A velocity squared law was assumed, and the best fit straight line was constructed through the data to the origin. Based on the test conditions (wind, speed, and airflow variations) and the reduction of the data from strip charts, an accuracy tolerance of ±1 lb is placed on the data. The total aerodynamic lift results are summarized as follows:

- Lead pantograph (120 mph)

22 ft above rail	12.0 ± 1 lb
19 ft 6 in above rail	6.0 ± 1 lb

- Trailing pantograph (120 mph)

22 ft above rail	6.0 ± 1 lb
19 ft 6 in above rail	13.0 ± 1 lb

Analysis of the results yielded a higher than expected differential force distribution between the leading and trailing collector strips. In all cases, the lead strip developed a large positive force and the trailing strip a negative force. The results for the individual cases are presented in Figure 10-13. Two conclusions are immediately obvious:

- The individual collector strip forces do not closely obey a speed squared law.

- A large difference exists among the cases tested. The aerodynamic forces generated in the pantograph are derived from a combination of drag on the frame and collector shoe members and lift developed on the collector shoe. To complicate matters further, the air flow around any component of the pantograph is affected by the pantograph structured members in the immediate vicinity and by the locomotive roof equipment. For example, the trailing collector strip is in the wake of the leading strip. In the trailing pantograph position, the trailing strip is further affected by the air flow already disturbed by the upper stage mechanism. To fully understand the aerodynamic behavior of the DS 11 pantograph, a much fuller test in a wind tunnel would be necessary. However, enough information is already available to help determine the cause of the pantograph head failure at the TTC.

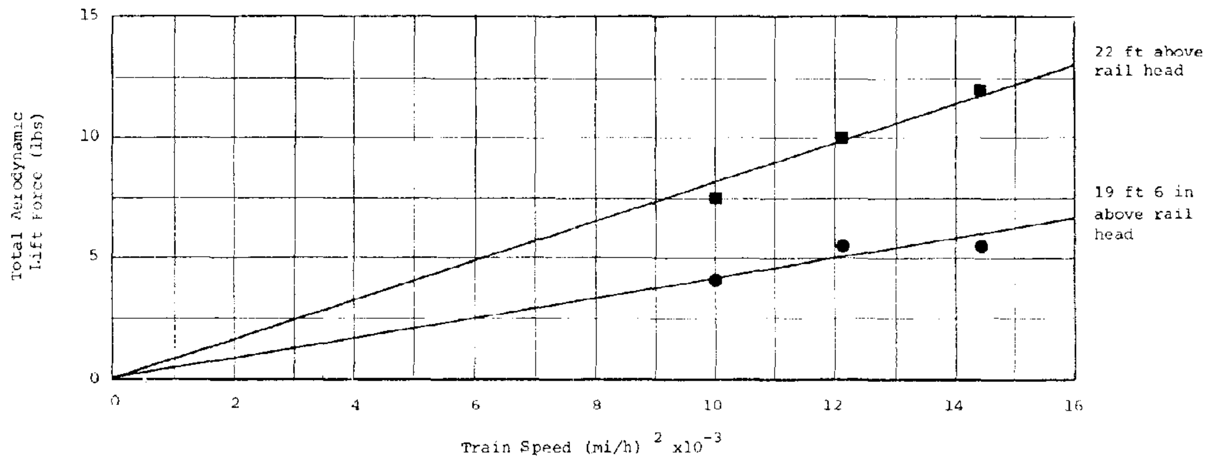


FIGURE 10-11. AERODYNAMIC LIFT FORCE/SPEED CURVES (LEADING PANTOGRAPH).

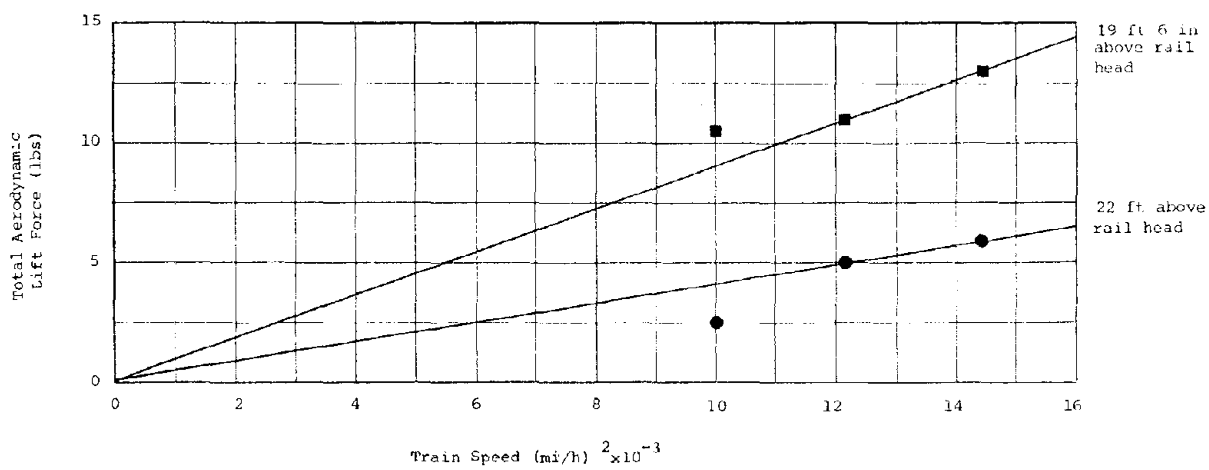


FIGURE 10-12. AERODYNAMIC LIFT FORCE/SPEED CURVES (TRAILING PANTOGRAPH.

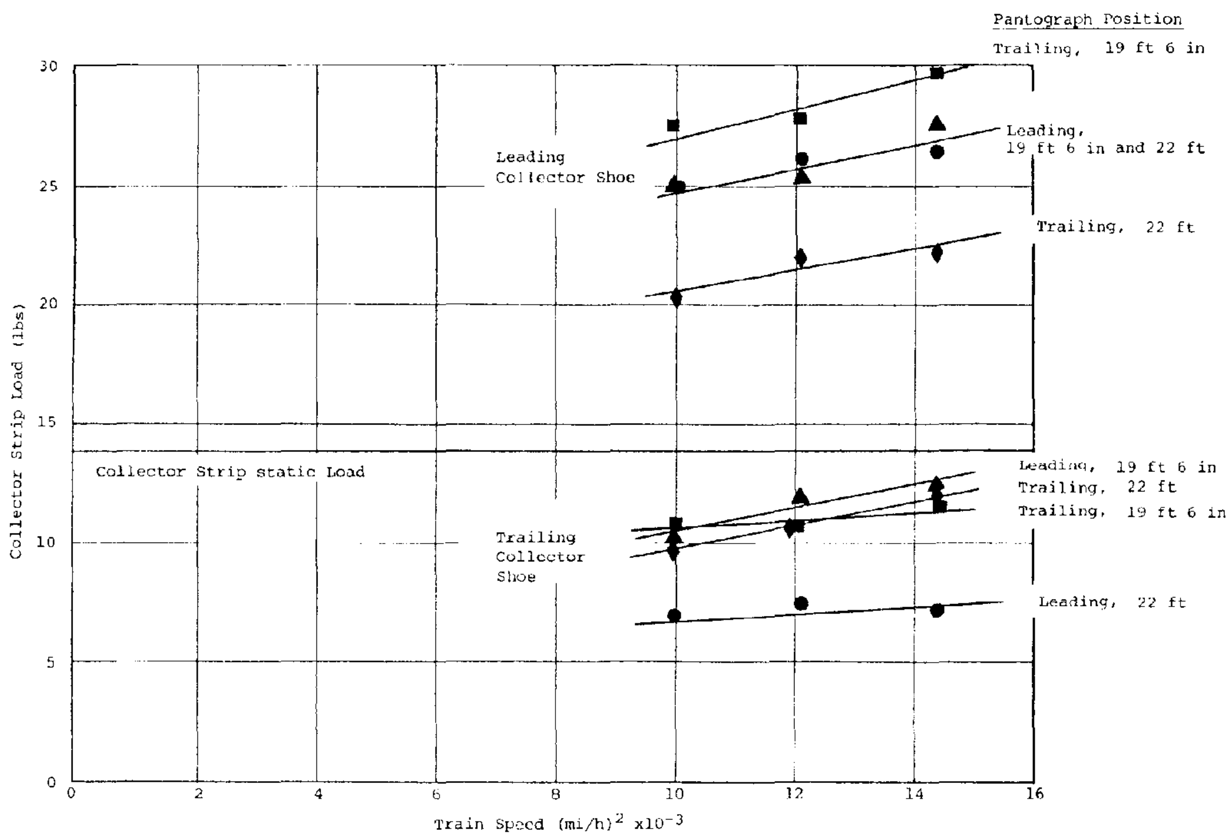


FIGURE 10-13. PANTOGRAPH COLLECTOR STRIP DIFFENTIAL LOAD/SPEED CURVES.

e. Pantograph Head Failure. It is almost certain that the pantograph head failure started with the loss of a carbon segment from the lead collector strip. The resultant gap was rapidly widened due to removal of the remaining carbons in the lead strip by the contact wire and phase breaks. Once the carbons were removed, the support structure became an open channel section with little resistance to longitudinal forces generated by motion along the contact wire and phase breaks. After a short time, the damaged lead collector strip collapsed in the vertical direction, whereupon the pantograph rode on the trailing collector strip only. Before final collapse and probable dewirement, the damaged unit was discovered. Figure 10-14 shows the damaged head before it was removed from the pantograph.

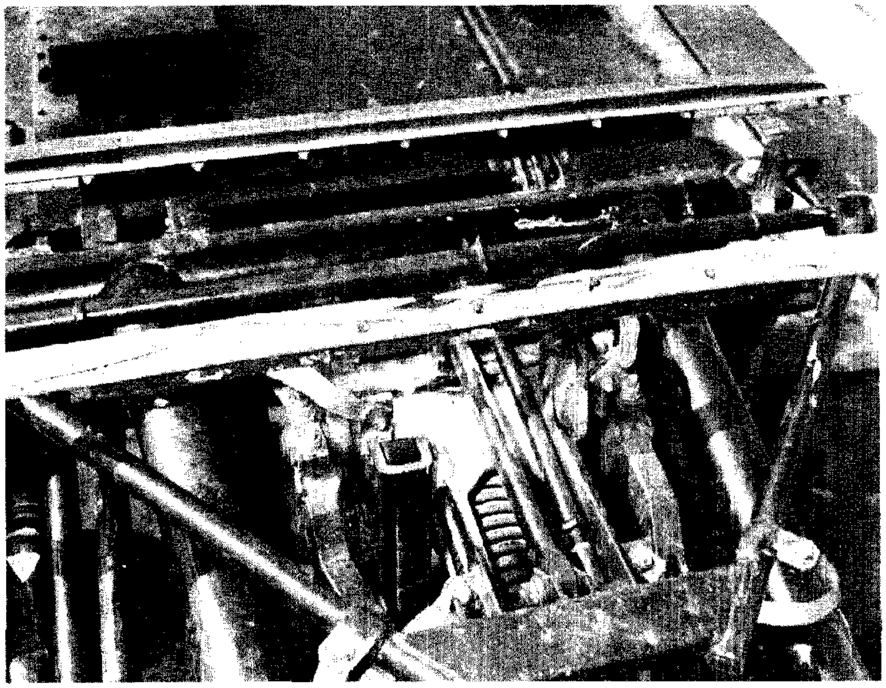


FIGURE 10-14, GENERAL VIEW OF THE FAIVELEY 'LIGHTWEIGHT' HEAD DAMAGE.

f. Possible Corrective Measures. The aerodynamic force distribution between collector strips may be equalized by the use of drag foils on the tips of the collector shoe horns. Designed not to affect the overall lift of the pantograph, the drag foils would transfer load from the leading to the trailing collector strip.

The open channel section used in the 'lightweight' shoe design relies on the carbon segments to form the fourth side of the structure and provide the basic box structure strength. Once the carbon segments are removed, the structure becomes an open channel section with very much reduced strength in both the vertical and longitudinal directions. To overcome this problem, a separate "fourth" side should be included in the the structure which would add little weight but would necessitate a revised clipping arrangement for the carbons. One added advantage would be improved electrical conductivity between carbon and structure, particularly if conducting grease were used at the interface.

g. Lateral Flexibility. While the lightweight modification was not a deliberate attempt by Faiveley to correct the lateral flexibility problem, some benefit resulted. Film measurement of the unit showed that the maximum peak-to-peak amplitude was decreased from 9.75" to 5.25", and the frequency was raised from 2.46 Hz to 2.66 Hz. The significance of these changes will be discussed under section 12.4.2.

h. <u>Current Collection Performance</u>. Visual assessment of the pantograph indicated that the current collection performance was greatly improved by the use of a lightweight head. This was confirmed by dead line and arc detector live line measurements made on the unit. The results of these tests will be described and discussed in section 18.0.

10.4 THE BRITISH RAIL/BRECKNELL WILLIS HIGH SPEED PANTOGRAPH

10.4.1 Description

Two versions of the BR/BW high speed pantograph were used during the AEM-7 test program. The first was the European Reach unit (Figure 10-15). The second was the 'stretched' version (Figure 10-16) designed to conform to NEC wire height requirements.

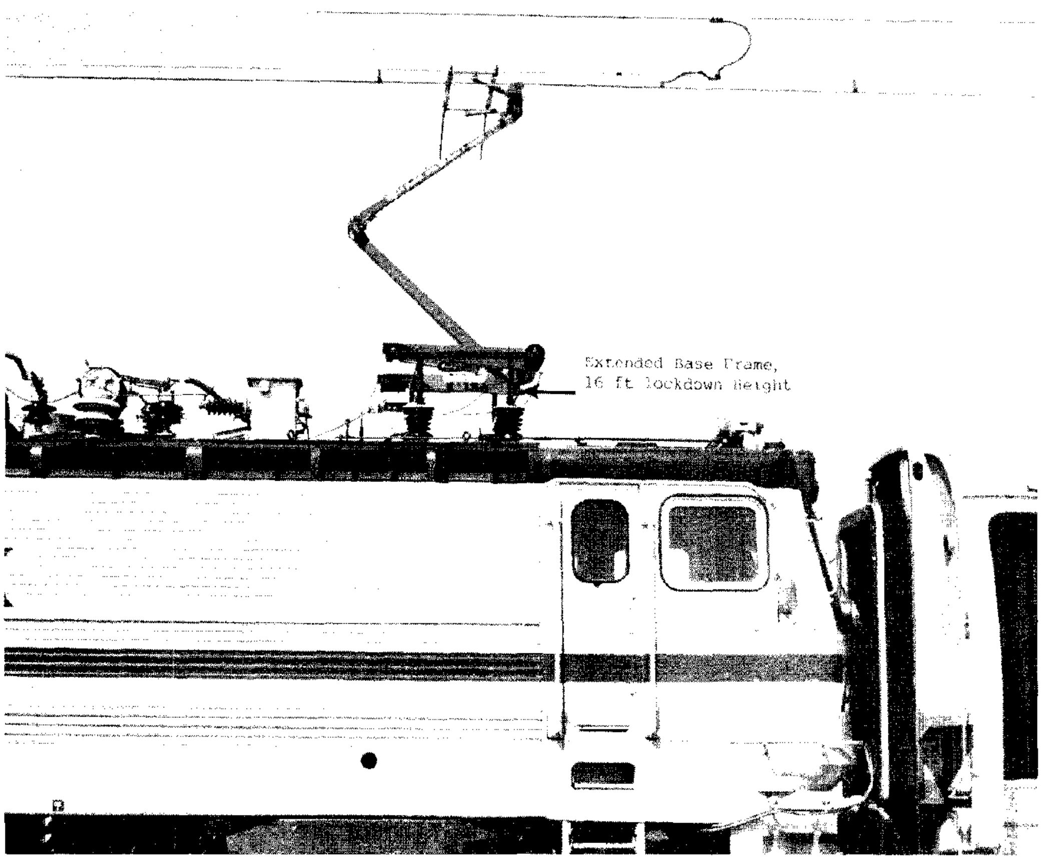


FIGURE 10-15. THE 'PROTOTYPE' BR/BW PANTOGRAPH ON AMTRAK 900.

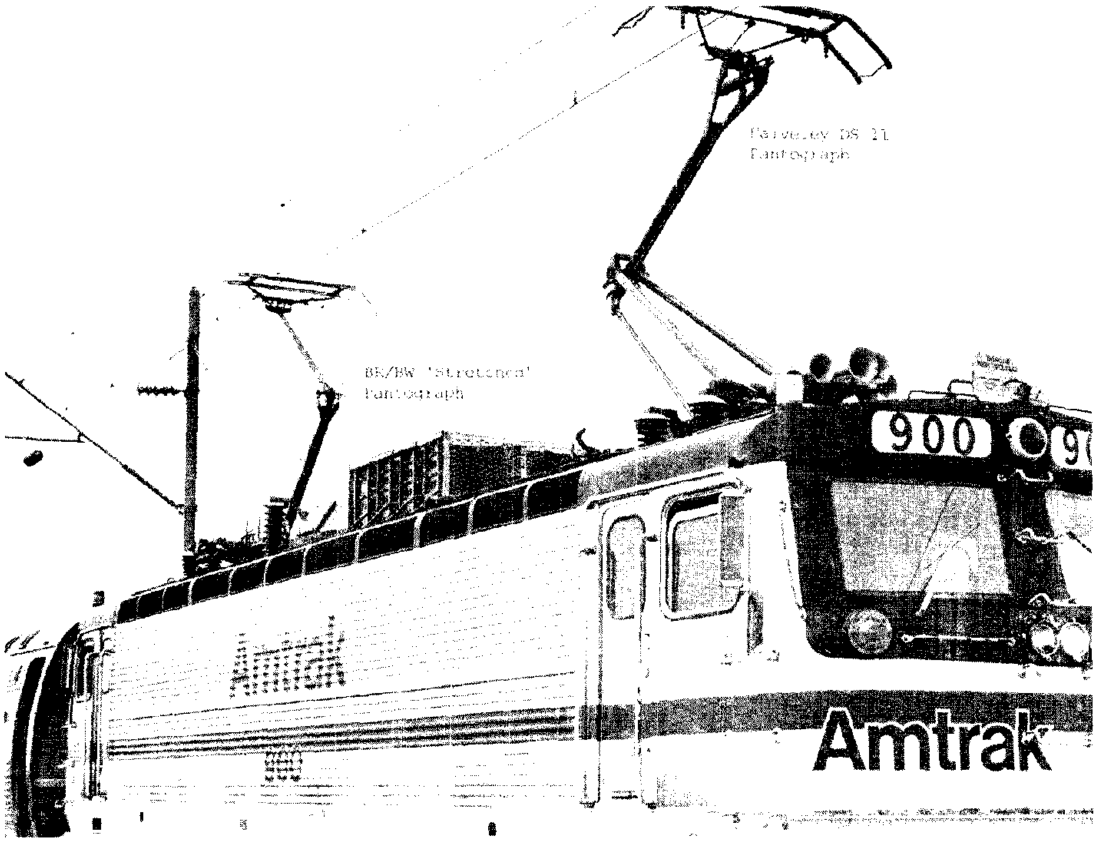


FIGURE 10-16. THE 'STRETCHED' BR/BW PANTOGRAPH.

The BR/BW high speed pantograph is of the single articulated arm design similar to the Faiveley range of pantographs. The lower arm is constructed of a tapered square section tube with the control rod for the upper articulated arm enclosed within the lower arm. The upper arm is also of tapered tubular construction enclosing the control rod for the head assembly. The original European Reach unit used a square section for the upper arm. However, this was changed to a circular section for the 'stretched' unit to give better over-all aerodynamic performance based on tests carried out in South Africa. The main frame design is intended to produce an efficient weight-to-strength structure which is aerodynamically streamlined.

The head suspension consists of a leading/trailing arm arrangement (Figure 10-17) pivoted on the end of the upper arm and connected to the control rod through a torsion spring. A total head travel of 100 mm (4") is permitted by this arrangement.

The head or collector shoe for the European Reach model (Figure 10-18) was constructed of extruded aluminum carbon carriers and hot sprayed stainless steel coated aluminum tubular horns. To expedite testing standard British Rail carbon carriers were used and the horn assemblies were suitably

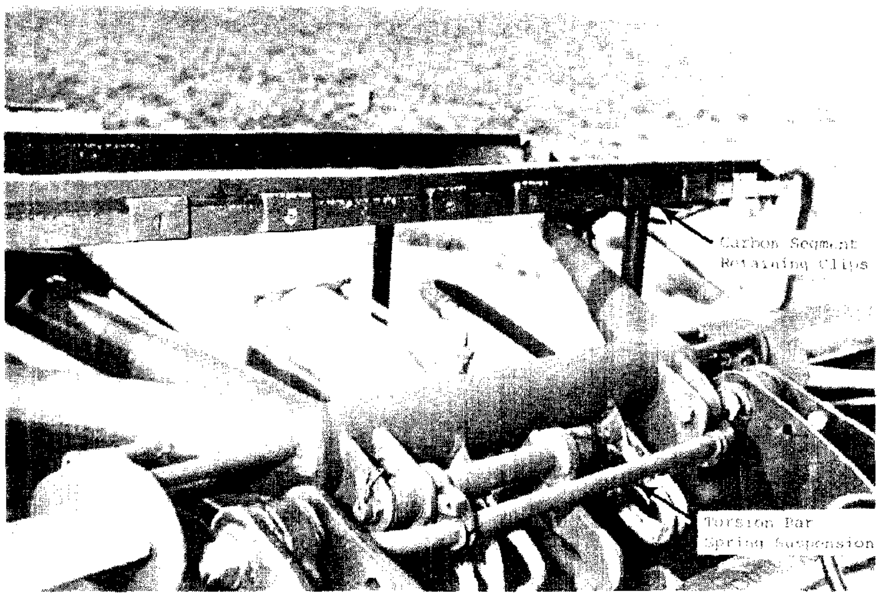


FIGURE 10-17. THE BR/BW UPPER ARM ASSEMBLY.

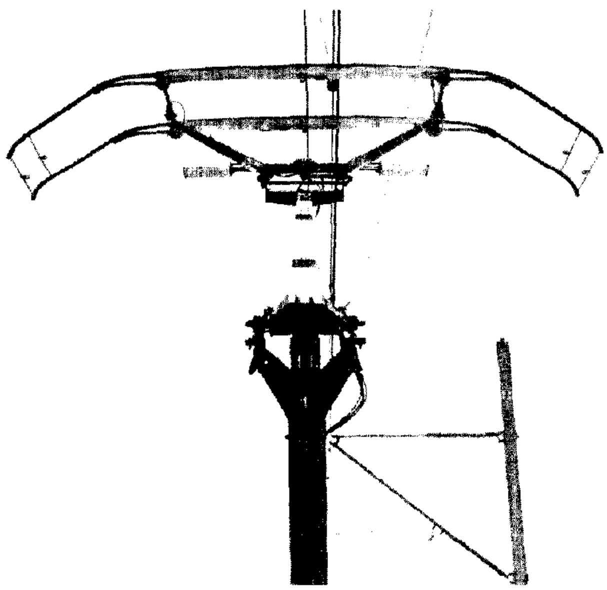


FIGURE 10-18. THE 'PROTOTYPE' HEAD ASSEMBLY.

lengthened to conform to the AMTRAK collector shoe profile. A total carbon length of 39 inches was provided by this arrangement. The total head weight was 15 lbs.

The head for the 'stretched' pantograph is constructed of extruded aluminum carbon carriers with tubular stainless steel horns. The same section extrusion is used as for the European Reach unit, but it has been lengthened to provide 48" of 1" square section carbon. The total head weight is 16.5 lbs. The current rating of the shoe is:

- RMS service 500 A
- standstill continuous 200 A
- short term (accelerating) 800 A

The pantograph is direct air raised by an air cylinder which also provides the static uplift force. Adjustment of the uplift force is by means of a pressure regulator. This, together with the remainder of the pneumatic control system, is mounted on the base frame.

Pantograph lowering is achieved by exhausting the air from the raising air cylinder to the atmosphere. The pantograph is lowered by its own weight and automatically locked down against an acceleration level of 1 g.

The European Reach pantograph was designed for a total reach from lockdown of 8' 2" (or 22' 10" above rail level if mounted 14' 8" lockdown height). The 'stretched' model is designed for 120 mi/h operation up to a wire height of 24' 6" and for 40 mi/h up 25' 6" wire height.

Provision is made for aerodynamic force correction by adjustable airfoils mounted on either side of the top of the upper arm (Figure 10-19), and by drag trim tabs on the ends of the horns (Figure 10-20).

10.4.2 Installation of the BR/BW Pantographs

To provide the necessary reach a special base frame extension (Figure 10-15) was constructed to raise the lockdown for this unit on the AEM-7 to 16'. No aerodynamic adjustments were made on the pantograph while mounted on the AEM-7 because of the urgent requirement to make the locomotive operational. However, aerodynamic adjustments had been made during the earlier dead line tests on the DOTX-211 car in the knuckle leading direction of travel. After mounting on the locomotive the unit was speed upgraded in 10 mi/h increments to 120 mi/h. The pantograph was visually assessed for lateral flexibility and current collection quality. The unit was also filmed in order to measure the lateral flexibility displacement amplitude and frequency. A maximum peak-to-peak amplitude of 0.5" was measured at a frequency of 4.36 Hz. The current collection quality was observed to be good.

Since the 'stretched' pantograph was designed specifically for the AEM-7, no modification to the support insulators or the high voltage connection were required. However, slight modifications were necessary to the grounding

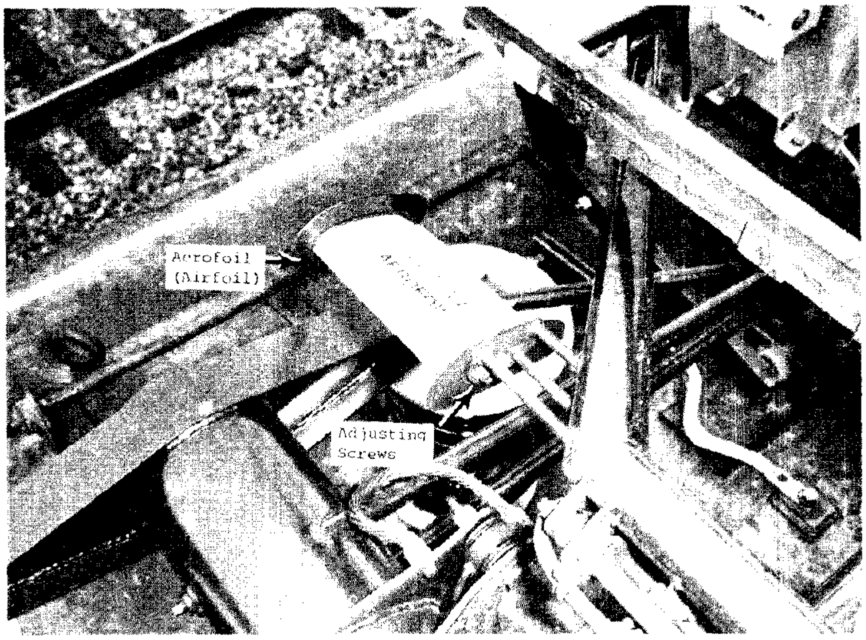


FIGURE 10-19. THE AERODYNAMIC LIFT CORRECTION AIRFOILS.

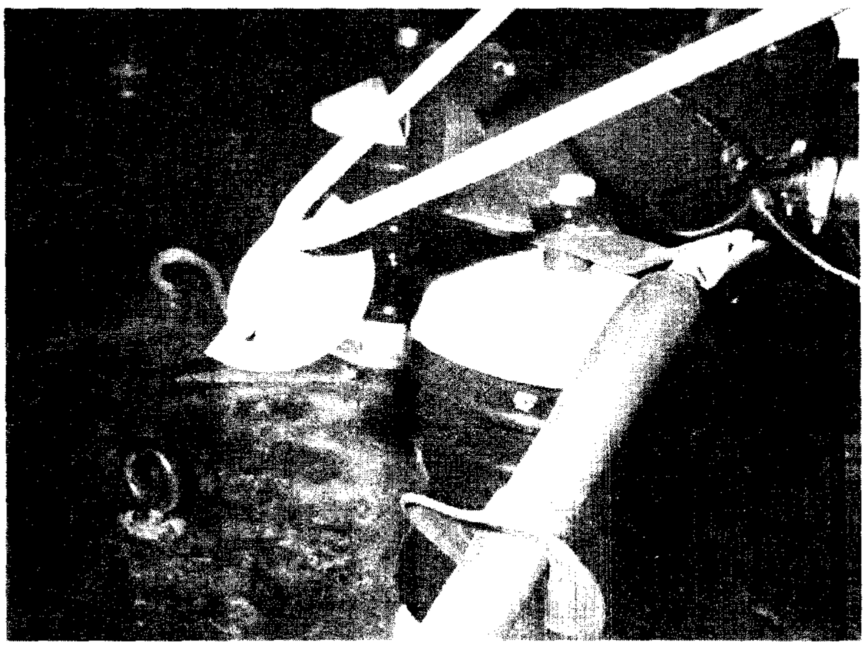


FIGURE 10-20. THE COLLECTOR STRIP DIFFENTIAL LOAD CORRECTION TRIM TABS.

switch assembly and frame lockdown hook shown in (Figure 10-21). The head lockdown hook was not required for this design.

Since the pantograph was direct-air raised, an air connection was required between the pantograph control block mounted on the base frame and the pantograph air supply outlet on the roof. A length of nylon hose approximately 5 ft long was used for this purpose (Figure 10-21), a sample of which had been 'hipot' tested to 110 kV without breakdown. A similar arrangement was used on the European Reach unit.

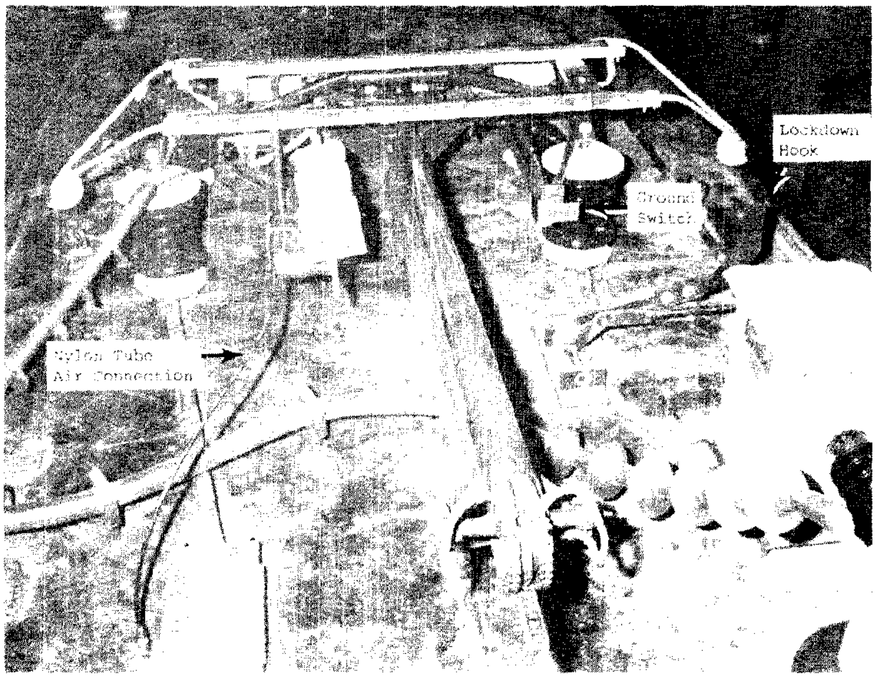


FIGURE 10-21. MODIFIED LOCKDOWN HOOK, GROUNDING SWITCH, AND AIR LINE CONNECTION.

10.4.3 Checkout of the 'Stretched' BR/BW Pantograph

Since the pantograph was shipped with the air cylinder separately packed, it had to be installed and the length adjusted to provide the full reach. This adjustment was successfully made to attain a reach of 10' 9" (25' 6" above rail). The uplift pressure was set to 20 lbs ±1 lb using a dead weight.

A series of aerodynamic tests was carried out to 'tune' the unit to the AEM-7. To provide aerodynamic adjustment, two different collector strip cross sections (T-shape and 5°crimp) were provided, a range of head pitch drag trim tabs for the horns was supplied, and the adjustable lift airfoils were mounted on the top of the lower frame.

The test pantograph was set up with two load cells attached to the locomotive roof restraining the pantograph head through insulated cables similar to the method used for the DS 11 pantograph. The two load cell support arrangement was used in order to correct both for overall lift and for head overturning moment. Again the locomotive was powered by means of the second pantograph. Six test runs were made at a speed of 100 mph as follows:

Run #	Collector X Section	Airfoil Angle	Head Height above Lockdown	Pantograph Position
1	T -	0	7' 6"	Trailing
2	5° -	0°	7' 6"	Trailing
3	5° -	15°	7' 6"	Trailing
4	5° -	15°	4' 0"	Trailing
5	5° -	15°	4' 0"	Leading
6	5° -	15°	7' 6"	Leading

After aerodynamic testing was complete, the pantograph was speed upgraded to 120 mi/h while drawing current. The pantograph was visually observed during this process and film taken of the unit at a speed of 120 mi/h. The film was analyzed for lateral flexibility amplitude and frequency and for current collection performance.

10.4.4 Preliminary Analysis of the 'Stretched'BR/BW Pantograph Performance

a. Aerodynamic Testing. The output from the two load cells was recorded for each of the runs and visually analyzed for total uplift and head overturning movement. Samples of the data are presented in Figure 10-22. On the basis of these tests, the following settings were selected.

- Head collector cross section - 5° crimp, wide base
- Airfoil angle of attack - 12°
- Drag trim tab (semicircular) - radius 2.5"

This resulted in a pantograph aerodynamically tuned to an uplift tolerance of 20^{+4}_{-2} lbs and a collector strip differential of 0 to 2 lbs higher on the trailing collector, over the speed range 0 to 120 mi/h, and in both the leading and trailing stations on the locomotive.

b. Lateral Flexibility. Analysis of the film for lateral flexibility yielded a maximum peak to peak displacement amplitude of 1.0 inch at 3.98 Hz. While this amplitude was double that measured on the European Reach model, it was considered acceptable by the pantograph manufacturer from a fatigue life standpoint.

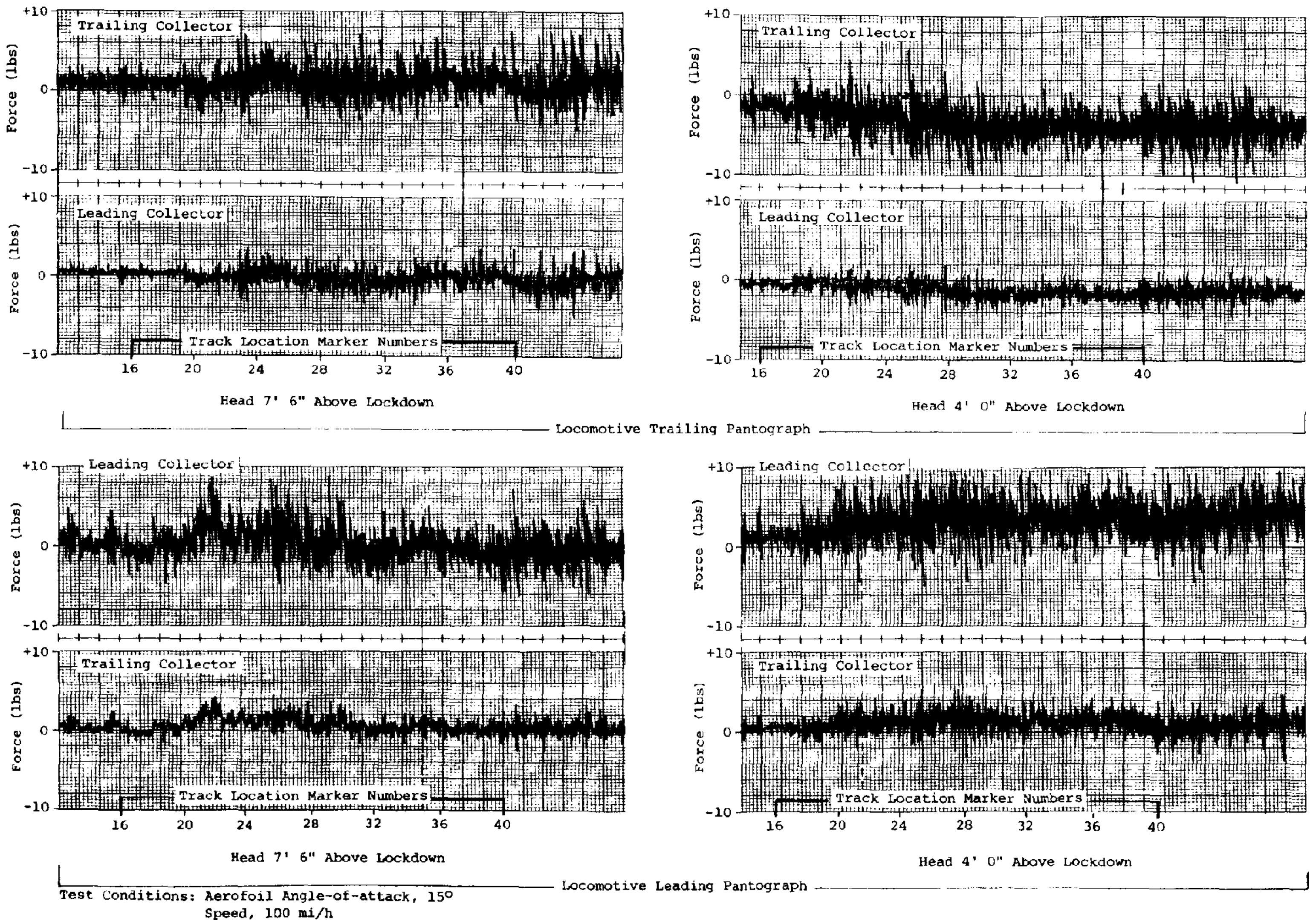


FIGURE 10-22. AERODYNAMIC DATA FOR THE "STRETCHED" BR/BW PANTOGRAPH.

c. Current Collection Performance. Visual assessment of the current collection performance during the speed upgrade tests indicated that the performance of the 'stretched' unit is only marginally inferior to the 'European' unit. It was therefore decided to commence longer term evaluation of the unit as part of the locomotive endurance test.

Current collection performance measurements were made on this pantograph by both dead line and live line methods later in the program. These are presented and analyzed under the title "Additional Pantograph Tests", section 18.7.

10.4.5 Operational Experience With the BR/BW Pantographs

Operation with the European Reach BR/BW pantograph was not without problems, although these were mainly derived from the temporary nature of the installation. These included:

- Main cylinder air leak caused by a seal damage resulting from a damaged piston rod sustained during shipment to the TTC for the dead line test. The air leak at times was severe enough for the locomotive auxiliary compressor not to be able to maintain pressure to close the air blast breaker. This problem was overcome by a replacement piston rod and seal.

- Erratic uplift pressure caused by a faulty pressure regulator. The system used on this unit was designed primarily for use on an exhibition stand and not for long term use on a locomotive. The 'stretched' pantograph uses a more suitable regulator.

- Loose carbon sections caused by the use of an unsuccessful crimping arrangement for holding the carbons. The resulting poor electrical contact between the carbon sections and aluminum extrusion caused electrical erosion of the aluminum, see Figure 10-23. This problem was overcome by adopting the conventional clipping arrangement similar to that shown in Figure 10-17 and by using conducting graphite grease under the carbons.

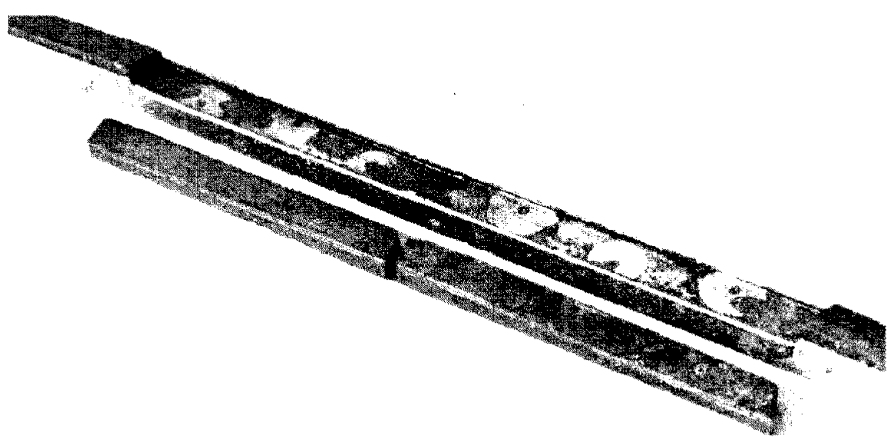


FIGURE 10-23. ELECTRICAL EROSION UNDER THE CRIMPED CARBON SEGMENTS.

- Smashed carbons and carbon chipping caused by badly adjusted phase break runners. This was particularly true during early operations over the newly installed Kupler phase break. On that occasion all carbon sections in one collector strip (Figure 10-24) were removed and the pantograph ran on the aluminum extrusion for approximately four hundred miles. However, because of the inherent strength of the box section extrusion and the 'soft' aluminum material no significant damage was done to the catenary system or the pantograph.

- Fatigue failure of the airfoil brackets caused by aerodynamically induced vibrations. The brackets on the 'stretched' pantograph were partially strengthened to eliminate the problem.

These problems had a relatively small impact on the AEM-7 operation. In all, this pantograph collected current for 101,00 miles and was used for the phase break arcing test. The last set of carbons lasted for approximately 35,000 miles before being destroyed by the phase break.

No significant operational problems were experienced with the 'stretched' BR/BW pantograph in 34,000 miles of operation. The only problems associated with pantograph design were:

- Frayed head-to-upper frame continuity braids due to aerodynamic excitation oscillation.

- Excessive gaps between carbon sections caused by lateral movement of the carbon sections. A modification to overcome this problem has since been incorporated.

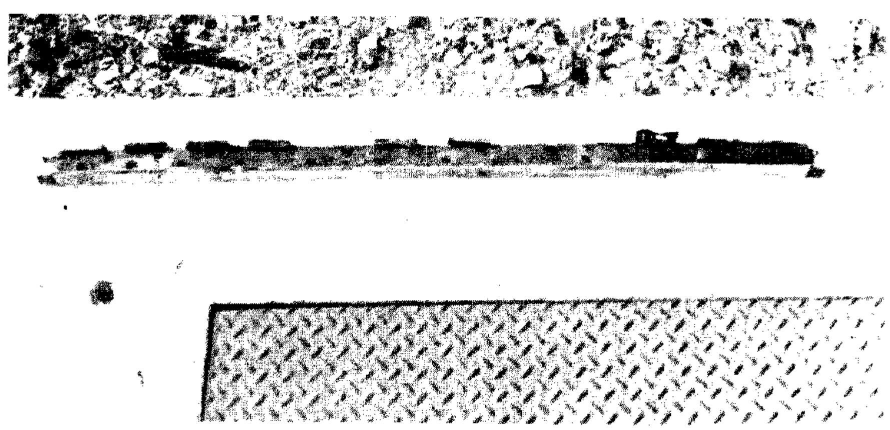


FIGURE 10-24. CARBON SEGMENT REMOVAL DUE TO PHASE BREAK DAMAGE.

The first set of carbons was changed after 29,000 miles, and then only because of excessive wear and chipping caused by running over the damaged phase break after the Faiveley DS 11 lightweight head failure. The 'stretched' BR/BW pantograph was returned to the NEC with AMTRAK 900 for further evaluation.

11.0 PHASE BREAK OPERATIONS

11.1 BACKGROUND

11.1.1 Purpose

As explained in section 4.2.4, section insulator type phase breaks are incorporated in a catenary system to provide electrical isolation between feed sections, while maintaining the mechanical integrity of the contact wire for smooth passage of the pantograph. In Europe, where phase breaks are extensively used in commercial frequency railroad electrification systems, the power unit (locomotive or power car) is de-energized at all phase breaks to allow unpowered operation across the phase break. This results in complete shutdown of the train auxiliary and service power systems. A typical interruption of power lasts 5 to 10 seconds.

Electrical isolation is provided in the catenary for one of the following reasons.

- A change of line voltage (for example, 25 kV to 12.5 kV).
- A change of electrical phase, either within the same utility supply or to provide isolation between the supplies from different utility companies.
- A section insulator which is normally at the same voltage and phase but becomes a phase or voltage change in an emergency supply arrangement.

11.1.2 NEC Phase Breaks

The existing 25 Hz system on the NEC employs a slightly different design of phase break, called an air gap insulator, in which the catenary at the ends of the electrical section is graded up out of reach of the pantograph and terminated on electrical insulators. The pantograph follows the initial upgraded catenary until the pantograph mechanism reaches its up stop. It then traverses the air gap on the up stop before regaining contact on the down graded catenary. This type of installation requires substantial headroom to accomplish the required wire heights and gradients, and can only be negotiated at relatively slow speeds.

Since the existing 25 Hz system is a dedicated distribution system, air gap insulators are required at relatively infrequent intervals, and can therefore be positioned to suit the space requirements. On the commercial frequency sections of the upgraded NEC the length of electrical sections will be governed by the utility company distribution area. The projected average phase break spacing between New York and New Haven is approximately seven miles which will leave little scope for repositioning of air gap phase breaks for space reasons. The decision was adopted to use the section insulator type phase break in all future NEC electrification and replacement electrification.

11.1.3 NEC Operations With Insulated Rod Phase Breaks

The problematical effect of the seven mile phase break spacing on NEC operations is great if the conventional de-energization of the locomotive at phase breaks is adopted. The main effects are summarized as follows:

- The interruption of the Head End Power supply to the cars would cause frequent shutdown of the air conditioning systems and loss of car lights (light flicker).
- The frequent de-energization of the locomotive would cause heavy duty cycling of the locomotive rotating machinery and switch gear with consequential interruption of vital cooling functions such as transformer oil, traction motors, and rectifiers.

Various suggestions have been made to overcome the light flicker problem including the provision of larger car battery packs to power the lights through inverters. However, none of these addressed the fundamental problem of the rotating machinery adverse duty cycle.

11.1.4 Alternative Operating Procedures

An investigation was proposed by AMTRAK to examine the possibility of negotiating all phase breaks, except voltage change phase breaks, without locomotive de-energization. This has already been successfully accomplished by Japanese National Railways.[4] Pilot tests were conducted on the original Kupler phase break at RTT station R33 + 033 and the BICC ceramic bead and Balfour Beatty phase break at station R70 + 800. Approximately 6,000 passes were made over each phase break location without de-energizing the locomotive, although traction power was removed. No electrical or mechanical deterioration was noted. For these tests the phase break center sections were ungrounded and the same supply voltage and phase were applied to either side of the phase breaks. In addition, powered negotiation was only permitted at speeds above 60 mi/h, below which the main breaker was opened manually.

Based on the pilot test results, a new improved design of phase break, which had already been selected for NEC application, was installed at station R70 + 800. This unit was used for all subsequent phase break negotiation evaluation testing.

11.2 THE IMPROVED KUPLER PHASE BREAK

The improved phase break was installed at the substation feed point, replacing the Balfour Beatty unit. Since the Kupler unit was slightly longer than the Balfour Beatty unit, a direct substitution method of installation was used. New insulated runners were placed over the existing units and the end fittings clamped in place. The Balfour Beatty insulators were then removed. Once this was accomplished, the remainder of the installation was straightforward.

The setup procedures were made more difficult due to the location of the phase break on a curve spiral, and because of the requirement for high speed running in both directions of travel. However, the along-track profile and lateral cross level were set up to the satisfaction of the Pfisterer engineers.

The setup was followed by a checkout procedure in which a pantograph was passed over the phase break at speeds of 5, 10, and 30 mi/h with the catenary deenergized. This was followed by a speed upgrading to 120 mi/h with the AEM-7 under load. At the end of this process the pantograph collector shoe was inspected for damage, and apart from some minor carbon chipping, the collector shoe was found to be undamaged.

A limited electrical evaluation was then carried out in the speed range 30 to 60 mi/h. Two test conditions with the center grounded were of particular interest:

- At a train speed of 30 mi/h, a pantograph current of 35 A, and the phase break center directly grounded, the resulting arc bridged the first insulator causing a phase-to-ground fault and tripping the substation OCB.

- At a train speed of 30 mi/h, a pantograph current of 25 A, and the phase break center grounded through the fuse, the arc again bridged the first insulator causing ground fault. This time the fuse blew before the OCB opened. At a pantograph current of 15 A the arc did not bridge the insulator.

As a result of the preliminary tests, an operating condition was set as follows:

- At 40 mi/h and above, coasting over the phase break with up to 20 A pantograph current would be permitted; below 40 mi/h the Air Blast Breaker on the locomotive would be opened manually.

A new fuse unit was installed for a trial period. After two weeks of trouble free operation, this unit was blown when traction power was accidentally drawn into the phase break. Again the substation OCB did not trip.

After two days of operations, damage to pantograph carbons began to appear. Inspection of the phase break showed there to be severe damage to the approach skids (Figure 11.1), uneven wear on the teflon rods, and evidence of wear on the rod end skids. The contact wire height of the two spans on either side of the phase break was carefully checked. It was found that the phase break center was four inches higher than the contact wire at the adjacent support structures. This represented a wire gradient of 1:300 (0.33%) which is 2.5 times the Task 16 recommended maximum.

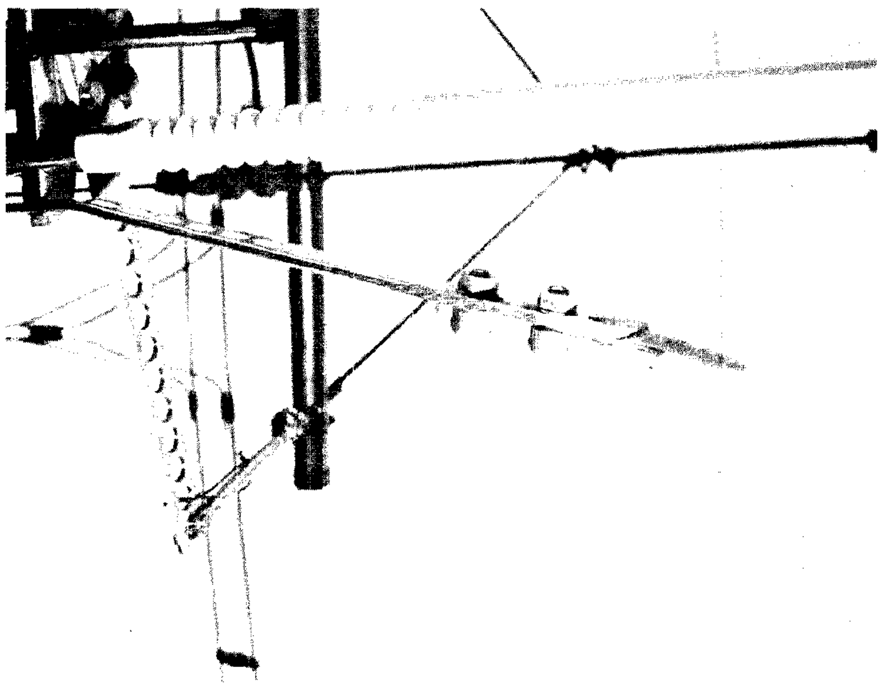


Figure 11-1. DAMAGED SKIDS ON THE KUPLER PHASE BREAK.

Corrective action included the reprofiling of the approach spans to a tolerance of ± 0.75". Yellow marker paint was used to set the skid cross level to give uniform wear. However, before the unit could be set up finally, one pantograph collector strip sustained serious damage from repeated passes over the low skid resulting in total removal of all four carbon segments.

11.3 DUAL VOLTAGE OPERATION

The locomotive was fully equipped to handle a voltage change in either a manual mode or a fully automatic mode. The locomotive main transformer primary winding is in two halves. These are connected in series to accommodate 25 kV 60 Hz line voltage and in parallel from both 11.0 kV 25 Hz and 12.5 kV 60 Hz. The series/parallel switching is accomplished with a motorized tap changer. The locomotive Air Blast Breaker logic is interlocked with the VC/PB system to prevent breaker closure on the wrong voltage setting.

The manual voltage change system is built into the locomotive control system. The Power Source Selector on the engineer's control console has four positions, namely 25 kV, 12.5 kV, 11 kV, and AUTO. The first three, in conjunction with the phase break approach/leave push button, are used for manual operation. The engineer initiates the voltage change by selecting the next voltage on the Power Source Selector before reaching the phase break. Operation of the phase break approach push button at the phase break opens the Air Blast Breaker and sets the transformer primary tap and surge arrestor switch to the configuration for the next voltage. After the phase break has been negotiated, operation of the phase break leave push button causes the Air Blast Breaker to close provided the measured line voltage and frequency agree with the tap changer setting.

The automatic phase break control system was installed on AMTRAK 900 by AMTRAK and General Motors before the locomotive was shipped to the TTC. The system was originally designed by General Electric for application to South Eastern Pennsylvania Transportation Authority (SEPTA) dual voltage equipped transit cars. The same system was also used by General Electric on the Metroliner improvement project.

The automatic system is designed to interface with the locomotive standard voltage changeover system by using the locomotive potential transformer to detect the line voltage. The automatic system configures the main transformer primary windings accordingly, checks the configuration, and closes the Air Blast Breaker. The system is controlled by a pattern of track mounted magnetic targets and corresponding magnetic reed switch sensors mounted on the locomotive. Any error in either the magnetic sensor detection sequence, or the logic check procedures causes the locomotive to lock out with the ABB open.

The voltage change sequence was controlled by a four magnet, two sensor, arrangement as specified in Table 11-1. A separate two magnet, one sensor system was used for the phase change sequence as described in section 11.4.1.

The magnetic targets used were manufactured at the TTC to a specification supplied by General Electric Co. The magnetic field strength was specified as 8.5 Gauss at 9 inches above the target. In addition, the targets were to be installed with the magnet south pole at the top since the sensors are south pole sensitive. In fact, the TTC magnets had a field strength of 9.3 Gauss at 9 inches at the time of manufacture.

TABLE 11-1. FOUR MAGNET, TWO SENSOR VOLTAGE CHANGE SEQUENCE.

Magnet	Sensor	Action
#1	Right	Open ABB (after 300 ms delay)
#2	Left	Check that ABB is OPEN. If not, open ABB immediately and lock system out.
		PHASE BREAK
#3	Right	Close ABB and power up locomotive
#4	Left	Reset VC/PB logic to look for the next phase break

The magnetic target spacing was originally specified in the report of a study conducted by Louis T. Klauder and Associates.[15] Slight modifications to the along-track spacings were found necessary for AEM-7 operation, and the final arrangement is shown in Figure 11-2.

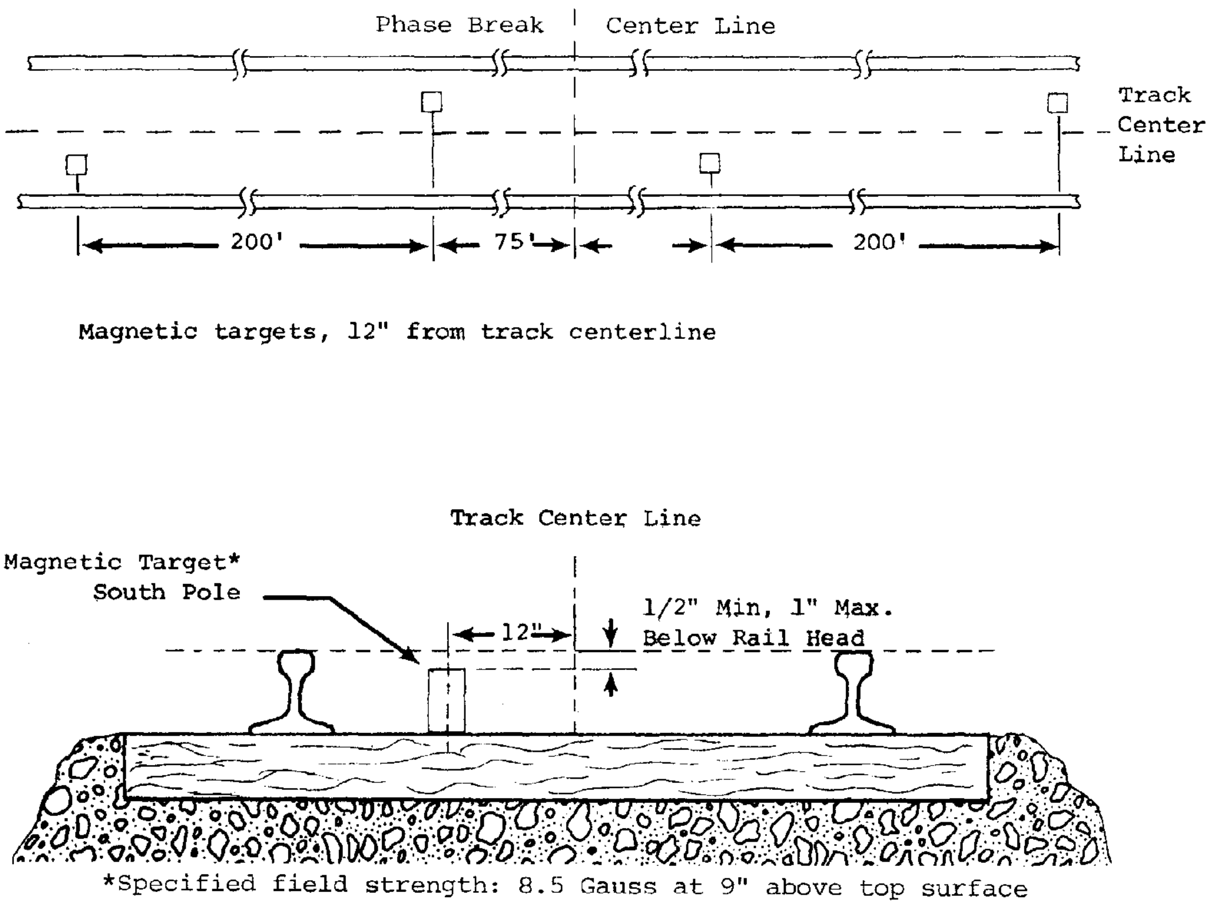


FIGURE 11-2. FOUR MAGNET AUTOMATIC PHASE BREAK CONTROL SYSTEM - TTC TARGET LAYOUT.

11.3.1 Dual Voltage Tests

Before voltage change operations were initiated, it was necessary to completely evaluate the voltage change logic on the locomotive including the four magnet automatic changeover system. Initial operations with the four magnet system were carried out over the phase breaks with the same voltage and phase on either side to avoid the possibility of a malfunction causing a catenary fault. These operations involved the evaluation of the correct magnet spacing for speeds up to 120 mi/h, and the reliability of the system for repeated cycles. The system was used to operate the Air Blast Breaker at each phase break for a period of approximately 3 weeks (20,000 miles, 2500 cycles) trouble-free duty before the system was accepted for actual dual voltage operation.

After successful completion of this test phase, dual voltage operation was to be initiated. However, during the week prior to start of the second phase of testing, the locomotive was powered up on 25 kV in the manual mode; the tap changer remained in the 12.5 kV position, and the Air Blast Breaker CLOSED. This resulted in the 12.5 kV lightning arrestor blowing and tripping the catenary breaker. Extensive checkout of the logic by an ASEA engineer did not reveal the cause of the malfunction although a possible cause was found several weeks later in the YMX 125 K interface cards. The dual voltage tests were delayed for three weeks until confidence in the system was restored.

After the resumption of dual voltage testing two modes of voltage change operations were tested. First, manual negotiations were tried over the speed range 30 to 120 mi/h. This included the deliberate selection of the wrong voltage. Automatic negotiations were then tested over the same speed range without a malfunction. Finally, three weeks of intensive dual voltage operations were carried out in which the locomotive negotiated a voltage change at each half lap of the RTT. In all, a total of 1000 voltage changes were accumulated.

11.3.2 Analysis of Test Results

The original magnet spacing provided by Louis T. Klauder was found to be inadequate for AEM-7 operation at 120 mi/h due to the time delay in the Air Blast Breaker logic. Figure 11-3 shows the sequence at 120 mi/h. Two factors determine the magnet spacing. First, the distance between the phase break and the left side magnet is determined by the time taken for the breaker to open before the lead pantograph reaches the phase break. The distance between left and right side magnets is fixed by the requirement that the rightside breaker must be OPEN before the left magnet is detected. Allowing for slight variations in logic sequence times, spacings of 75' and 200' were selected.

During the voltage change operations, a power resistor failed in the automatic system causing an error in the voltage detection system. The locomotive logic detected an error in the automatic system and failed to close the Air Blast Breaker. The failed component was replaced and the system suffered no more failures or malfunctions.

Manual phase break negotiations were successfully accomplished in all cases, both as part of the special test and as repeated operations when the automatic system failed. The concentration required of the engineers at speeds above 100 mi/h was such that the risk of error was greatly increased, although no errors were in fact made during the course of the test. It was concluded that operator error would result only in a phase-to-ground fault on the catenary if the Air Blast Breaker were not opened in time.

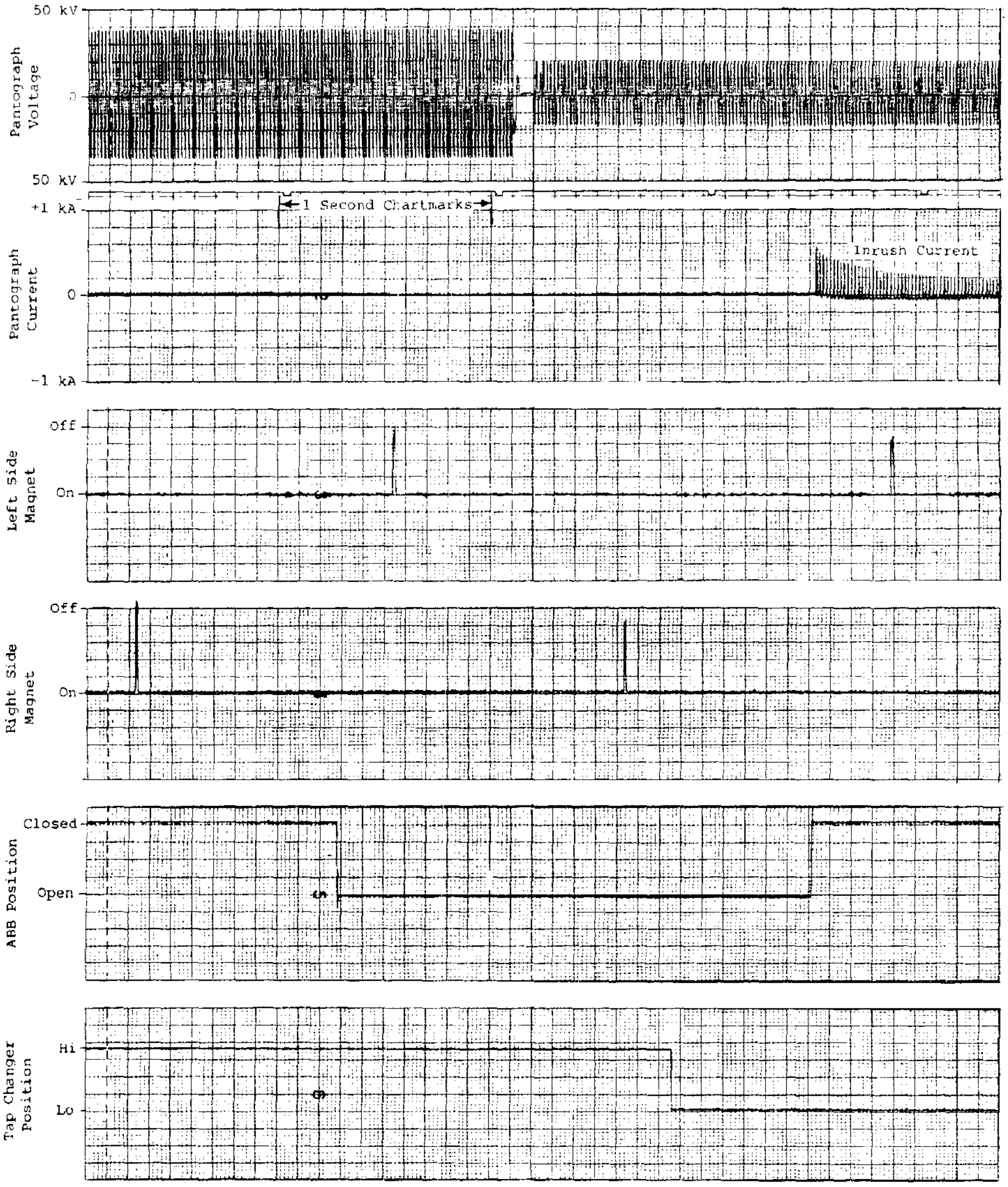


FIGURE 11-3. FOUR MAGNET CONTROL SEQUENCE AT A SPEED OF 120 MI/H.

On the plus side, all attempts to fool the system failed to close the Air Blast Breaker on the wrong voltage setting. However, the one incident of wrong voltage energization before the test began still cast the system's integrity in doubt.

11.4 DUAL PHASE OPERATIONS

11.4.1 System Descriptions

The dual phase power supply for the RTT Catenary was obtained from the RTT substation transformer. The temporary arrangement to accomplish this is described in section 4.2.4 h.

To enable coasting through the phase breaks without opening the locomotive Air Blast Breaker, a second magnet pickup system was added to the locomotive logic. Designed to ramp down propulsion power only, the system used a magnet sensor mounted on the locomotive's longitudinal centerline with corresponding magnetic targets on the track centerline. Two magnetic targets per phase break were used. These were spaced 600' before and after the phase break, the distance required to allow for a 3 sec propulsion ramp down at 120 mi/h. Since the two magnetic sensor systems were independent of each other, both systems could be active at the same time. For example, it was possible to open the Air Blast Breaker at one phase break and ramp down propulsion power at the other.

Instrumentation was provided to monitor the locomotive reaction to the phase break negotiation. In particular, the Auxiliary and Head End Power supplies were monitored to look for current surge and voltage stability. The primary current was also monitored for inrush currents. In addition, one of the AMFLEET cars was instrumented to measure light flicker. The following data channels were used for the analysis:

- Pantograph voltage
- Locomotive transformer primary current
- Head End Power Current (one phase)
- Head End Power Voltage (phase-to-phase)
- Auxiliary current (one phase)
- Auxiliary voltage (phase-to-phase)
- Traction Motor #1 armature current
- AMFLEET car light flicker

A voltage divider was used at the phase break to monitor the center section voltage. The purpose of this was two-fold. First, with the center section ungrounded, the voltage divider could be used to detect any gross changes in insulator impedance by monitoring the standing voltage. Second, it could be used to detect bridging of the first insulator by looking for the full line voltage.

A movie camera was set up to record the passage of the pantograph across the phase break under the different test conditions. An exposure rate of 250 frames/sec was selected as being the most economical rate that would provide the necessary information.

11.4.2 Test Operations

a. Preparatory Work. The dual phase operations in January 1981 were the final stage of a test which had started in June 1980. As described in section 11.1.4, Auxiliary and Head End Power negotiations of the phase breaks with the same voltage and phase on either side had become standard practice at the TTC. From the success of this limited operation it was felt that partial power negotiation from phase to phase at the same voltage was also possible above a minimum speed yet to be determined. The experiences of Japanese National Railways in Japan, and Balfour Beatty in South Africa, supported this view.

A revised phase break specification was drawn up requiring the installation to be capable of handling a current of 50 A at a speed of 30 mi/h with the center grounded. It was this requirement which led to the installation of the 'improved' Kupler phase break.

b. Electrical Evaluation of the New Phase Break. Once mechanical evaluation of the new Kupler phase break was complete, a revised test plan was drawn up to electrically evaluate the unit. This plan was based partly on a Test Request submitted by AMTRAK and partly on operational experience at the TTC.

Preliminary evaluation of the unit immediately after installation had shown that it would not meet the revised specification with the center grounded. However, formal tests were still necessary to establish the operational limits of the unit. A three-part test was aimed at this.

c. Preparatory Tests. These tests were carried out with the phase break center ungrounded and the same voltage and phase on either side. Two line voltages used were 25 kV 60 Hz and 12.5 kV 60 Hz. The test runs tabulated below were made at each of the voltages with the locomotive Air Blast Breaker closed.

Each pass was filmed, on-board data was taken, and a standing voltage measurement of the phase break center was noted.

The pantograph current levels were maintained by a combination of HEP, Auxiliary power, and partial traction power. A suitable load bank installation could not be provided in the time available.

Run Number	Speed (mi/h)	Pantograph Current (A)
1	100	40 - 60
2	80	40 - 60
3	60	40 - 60
4	40	40 - 60
5	30	40 - 60
6	25	40 - 60
7	20	40 - 60
8	15	40 - 60
9	10	40 - 60
10	80	15 Dynamic Brake
11	35	150 (25 kV) 200 (12.5 kV)
12	35	300 (25 kV) 410 (12.5 kV)

d. Phase-to-Phase Initial Tests. A series of controlled passes was made over the phase break setup with opposing phases at 25 kV, the center grounded through the fuse, and with the locomotive Air Blast Breaker closed. The number of passes was curtailed by over-cautious setting of the substation protective relay system, which resulted in substation lockout when full power was drawn by the locomotive. After the necessary relay setting corrections were made the following tests were run.

Run Number	Speed (mi/h)	Pantograph Current (A)
1	80	18 - 20
2	60	18 - 20
3	40	18 - 20

None of the test runs resulted in insulator flashover.

e. Phase-to-Phase Extended Operations. Based on observations and preliminary analysis of the recorded data, extended phase-to-phase operations were initiated on the following schedule.

- West phase break (original Kupler):
  center section grounded, ABB open at all speeds.
- East phase break (new Kupler):
  center section grounded through the fuse.

On the East phase break routine phase-to-phase operations were cautiously initiated on the following schedule:

Day	ABB Open (mi/h)	ABB Closed* (mi/h)
1	0 - 60	60 - 120
2	0 - 50	50 - 120
3 - 10	0 - 40	40 - 120

*Pantograph current 18-20 A.

11.4.3 Analysis of Test Results

a. Arcing Conditions. A summary of the arc length (severity) for each of the test conditions is contained in Table 11-2. Three observations are immediately clear.

1. The severity of the arcing condition increases with decreasing speed.
2. The arc severity increases with current.
3. The arc severity increases with voltage.

The interpretation of these observations requires a basic understanding of arc initation propagation. An arc is formed in the air gap between two electrodes (called the anode and the cathode) by the conduction of electrical current through an ionized gas path. While the current flows the ionized gas is self-replenishing, and, under ideal conditions with a direct current high voltage source, arcs several feet long may be drawn. Alternating current is complicated by the instantaneous zero current at each half cycle. Momentarily, at each half cycle, ionized gas production ceases, and the arc tends to extinguish. However, it takes a finite time for the ionized gas to dissipate under still air conditions, and the arc reforms when the voltage gradient between the electrodes across the ionized gas path exceeds the critical value. Any air disturbance in the intervening period causes the ionized gas to dissipate and permanently extinguish the arc.

As a pantograph head runs over a phase break insulator, the trailing collector strip becomes a moving electrode. This motion helps to extinguish the arc in two ways. First, the forward motion tends to create an air gap between the collector edge and the ionized gas for the small period when the current is at, or near, zero. Second, turbulence in the wake of the pantograph head tends to dissipate the ionized gas.

TABLE 11-2. SUMMARY OF ARCING CONDITIONS OVER THE KUPLER 'IMPROVED' PHASE BREAK.

Day 1 (1/21/81) Line voltage 25 kV

Run #	Speed (mi/h)	Pantograph Current (A)	First Insulator % Bridged	First Insulator Comments	Second Insulator % Bridged	Second Insulator Comments
1	95	100	60	pantograph	0	
2	78	80	45	head to arc	0	
3	56	40	46	horn	0	
4	40	40	55	knuckle to horn	0	
5	30	20	30	pantograph head	0	
6	30	45	100	to arc horn	0	
7	26	25	88		0	
8	22	42	100	pan knuckle to	80	pan knuckle
9	18	43	100	support wires	0	to horn
10	12	36	100		0	
11	37	142	100	pan knuckle to	0	
12	40	302	100	horn and support wires	100	pan head to horn

Day 2 (1/22/81) Line voltage 12.5 kV

Run #	Speed (mi/h)	Pantograph Current (A)	First Insulator % Bridged	First Insulator Comments	Second Insulator % Bridged	Second Insulator Comments
1	80	35	0	pantograph head	0	
2	60	60	38	to contact wire	0	
3	40	29	32	clamp and arcing horns	0	
4	30	38	32		0	
5	26	68	37		0	
6	20	66	100		0	
7	15	56	100	support	0	
8	10	49	100	wires	0	
9	120	12	0		0	
*10	65	20	34		0	
11	35	202	100		0	
12	411	100	100	support wires	100	

*Dynamic brake applied

Note: This analysis is from high speed movie data.

Thus, it becomes clear why speed, current, and voltage affect the severity (length) of arc. The higher the speed the greater the turbulence and separation rate at the zero current point. The higher the current the greater the amount of ionized gas in the arc length. Finally, the higher the peak voltage, the more rapidly the critical voltage gradient is reached.

Two other factors, not evaluated at the TTC, affect the ability of the arc to sustain itself, namely, power factor and frequency, both of which affect the rate at which the critical voltage gradient is reached. The lower the power factor, the greater the lead of voltage over current and the more rapidly the initial voltage gradient is reached after the zero current point. On the other hand, the lower the frequency, the slower the rate of voltage rise and the less rapidly the critical voltage gradient is reached. It is possible, therefore, that on 11 kV 25 Hz, the arc may be more easily extinguished than on 12.5 kV 60 Hz, although the longer dwell time in an arcing condition may offset this.

To summarize, more severe arcing arises from:

- Lower speed
- Higher current
- Higher voltage
- Lower power factor*
- Higher frequency*

*not evaluated at the TTC.

b. Hardware Considerations. Each conductor termination at the phase break is equipped with arcing horns (wands) designed to act as one of the arc electrodes and protect the phase break hardware from electrical erosion damage. Analysis of the films showed a tendency for the arc to be reluctant to transfer from the contact wire clamp to the arcing horns. Once there, the arc tended to drift to the support cables. Evidence of burning damage was found during the post-test inspection. However, considering the intensity of the high current arcs, the visual damage must be described as minimal.

Analysis of the films also showed there to be a tendency for the arc to transfer to the trailing knuckle joint on the BR/BW pantograph frame. This was confirmed by the post-test inspection of the pantograph. As in the case of the phase break the damage was rated as slight.

c. Locomotive Systems. The locomotive systems are in two main parts:

- Propulsion and Braking System
- Auxiliary and HEP System

The propulsion system response to the phase break negotiation with the Air Blast Breaker closed is straightforward. The system will continue to function as long as the voltage remains above the -35% nominal level at which point the system switches off. The normal automatic power reduction system also functions to ramp the traction power off with decreasing voltage as can be seen in Figure 11-4.

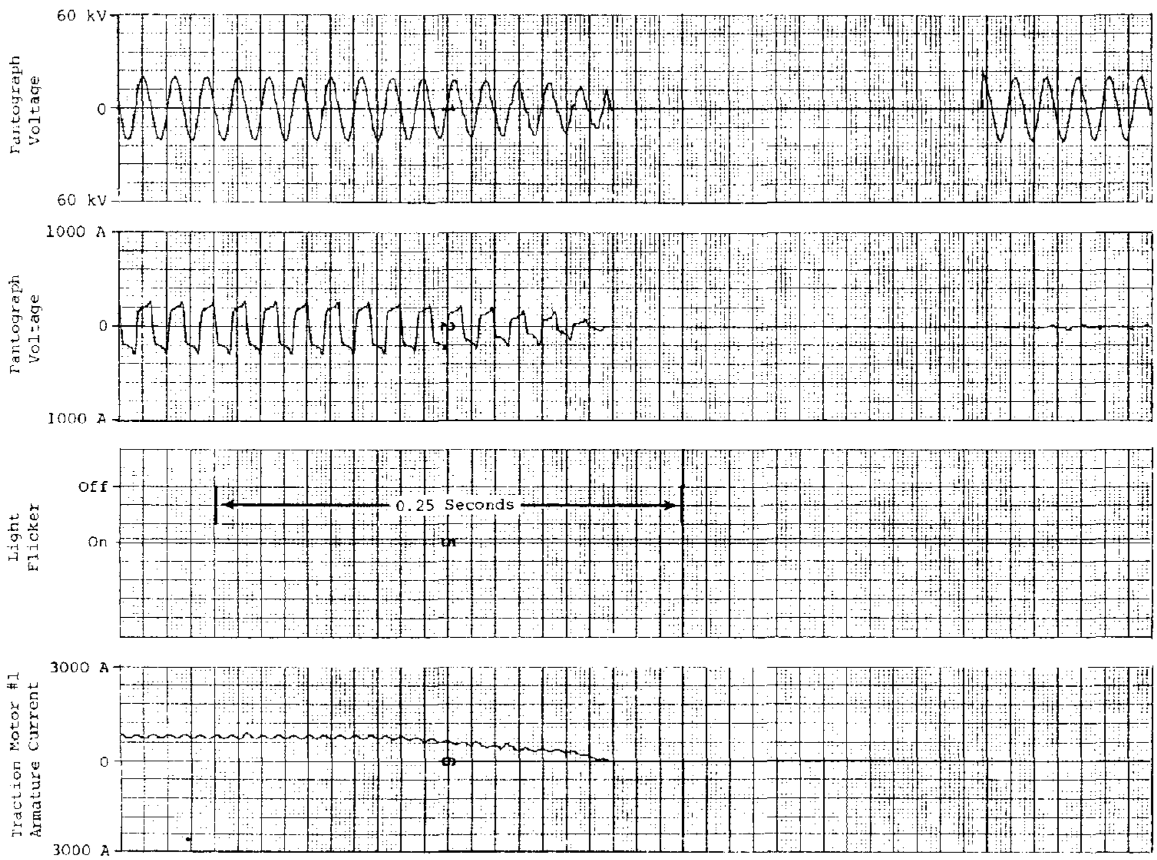


FIGURE 11-4. TRACTION MOTOR CLOSE DOWN AT THE PHASE BREAK.

The dynamic braking system continues to function through the phase break, although some reduction in braking effort is noted, (Figure 11-5). This is not surprising since the dynamic braking armature current is independent of the pantograph. The dynamic braking field current is dependent on the pantograph supply, but is sustained by the field convertor.

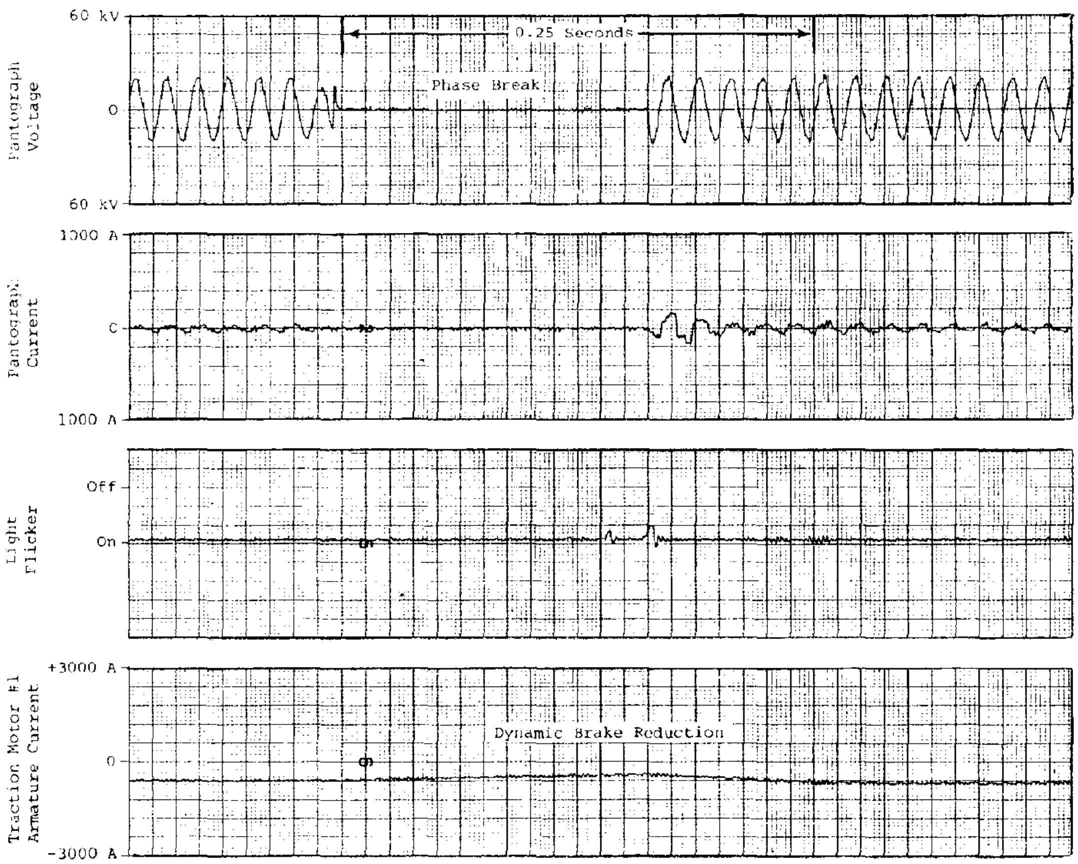


FIGURE 11-5. DYNAMIC BRAKE REACTION TO THE PHASE BREAK.

The auxiliary supply was maintained through the phase break down to a speed of 15 mi/h due to the ability of the system to continue to draw power through the arc over the first insulator. Some supply instability was noted on voltage, current, and frequency which was corrected within the first second of full power restoration. One pass at 10 mi/h resulted in the one-second automatic lockout of the auxiliary supply when the total loss of voltage to the pantograph was 0.650 seconds in duration.

The HEP supply was only loaded to 25% capacity since only five AMFLEET cars were available. As expected, therefore, the voltage and frequency stability was much better than the auxiliary supply. Since the winter heating load is almost all resistive, the stability of the HEP under coasting conditions would rapidly drop off with load. However, six or eight AMFLEET cars should not greatly affect the system.

d. AMFLEET Car Light Flicker. The car light flicker problem was almost totally removed by coasting the phase break. All instances but one resulted in only minor disturbance of the light intensity, and some passes over phase breaks created no disturbance at all. Two examples of flicker data are presented in Figure 11-6. The 60 mi/h example shows only minor disturbance, while the one at 10 mi/h resulted in total light removal for 0.200 sec after a disturbance lasting 0.300 sec. For comparison, the total light interruption time for a four magnet breaker open negotiation of the phase break at 120 mi/h was recorded as 3.9 seconds.

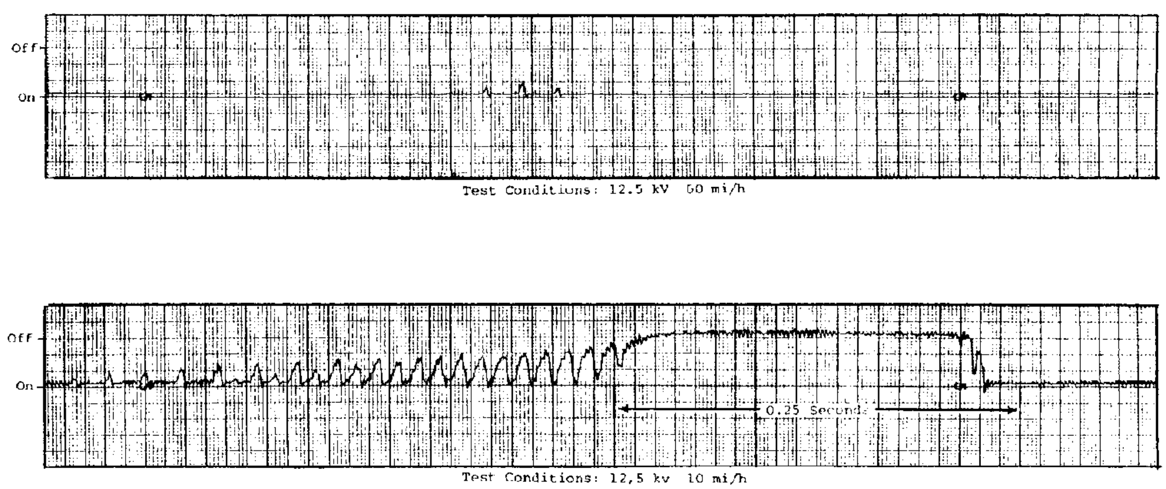


FIGURE 11-6. LIGHT FLICKER IN THE AMFLEET CARS.

e. Operational Limitations. A period of ten days was set aside for phase change operations over both phase breaks. The locomotive Air Blast Breaker remained closed at the new Kupler unit at speeds above 40 mi/h; the pantograph current was approximately 20 A at 25 kV. The center of this phase break was grounded through the fuse. The original Kupler phase break was set up with the center directly grounded; the four magnet system was used to open the Air Blast Breaker throughout the speed range. No fuse link failures occurred at the new Kupler unit during the test, indicating that the arc did not bridge the insulator.

f. Inrush Currents. One aspect of phase break operations considered throughout the program was the effect of the various operational options on locomotive transformer inrush current. Three basic options were tested.

1. Voltage change with ABB open
2. Same voltage and phase with ABB closed
3. Opposing phases at the same voltage with ABB closed

Between January 9 and January 26, 1981, all three operations were tried. For a sample number of profiles the occurrence of inrush currents and their approximate magnitudes were tabulated (see appendix B). This subject has been fully discussed in section 7.4.

11.4.4 Options for the Northeast Corridor

a. Air Blast Breaker Open. The opening of the Air Blast Breaker will be required for all voltage change phase break negotiations since time is required for the locomotive transformer primary tap changer to operate. Either manual or four magnet automatic control may be used for this. At speeds below some limit, probably 40 mi/h, the Air Blast Breaker should be opened for all other phase breaks types. Again this operation may be manually controlled. If the two magnet system is retained for propulsion power ramp down, addition of a speed input signal to the logic may then be used to open the breaker below a fixed speed threshold (40 mi/h for example), with a manual reset after the phase break.

b. Air Blast Breaker Closed. At all phase breaks other than voltage change locations, the Air Blast Breaker can remain closed at speeds in excess of 40 mi/h and a pantograph current of 30 A at 25 kV 60 Hz, and 60 A at 12.5 kV 60 Hz or 11 kV 25 Hz. Steps will have to be taken to remove all propulsion power. These may be the provision of reflective trackside coasting boards to prompt the engineer to manually ramp down the power or of the two magnet automatic control systems described in paragraph 11.4.1 b. The limiting speed may be further reduced by the provision of arc interruption devices or by the extension of the phase break insulators. However, the latter may require extensive modification to gain 10 mi/h and will probably result in locomotive lockout anyway. Since the majority of the proposed phase break locations are in the posted speed range of 60 - 90 mi/h, further modifications to reduce the permissible coasting speed are probably not justified. Modifications to improve the arc control almost certainly are justified in order to reduce phase break maintenance.

c. Phase Breaks With or Without a Center Section. The provision of a phase break center conductor is based on the requirement to provide a grounded section to give protection against a phase-to-phase fault. Traditionally, phase-to-ground faults are preferred by utility companies. It should be noted that a phase-to-phase catenary fault is not transmitted directly to the utility as a phase-to-phase fault. Figure 11-7 shows a typical feed arrangement in which two Railroad Traction transformers are fed from different phase combinations, either from one utility or from separate utilities. A phase-to-phase fault is isolated from the utility by the Railroad Traction transformer at worst. In most cases, additional fault current limitation is provided by the catenary impedances between fault point and supply points. Enhanced protective relaying may also be available to provide the necessary fault protection.

Two center section configuration designs are now worthy of consideration.

1. The fused center section may be used to provide a first-line of protection against a phase-to-phase fault from an accidental arc or a failed insulator. The first fault would be indicated by fuse failure; thereafter the center section would become a floating section until a new fuse unit is fitted. Two alternatives are now possible.

- Continue to coast through with the increased risk of a phase-to-phase fault, particularly if a broken insulator was the cause of the original fault.

- Revert to an Air Blast Breaker open negotiation of the phase break. This may be initiated manually as a result of an Engineer's Special Instruction. Alternatively, a simple voltage divider connected to the phase break center section may, by detecting an increase in voltage level, be used to post an alarm on the substation monitor system and switch electro-magnets on the track to operate the four magnet control system. By extending the voltage divider option to a two-level detection system, a failed insulator may be identified by full-line voltage on the center section. Experience at the TTC shows that approximately one-third of phase-to-phase voltage appears on the floating center section with good insulators.

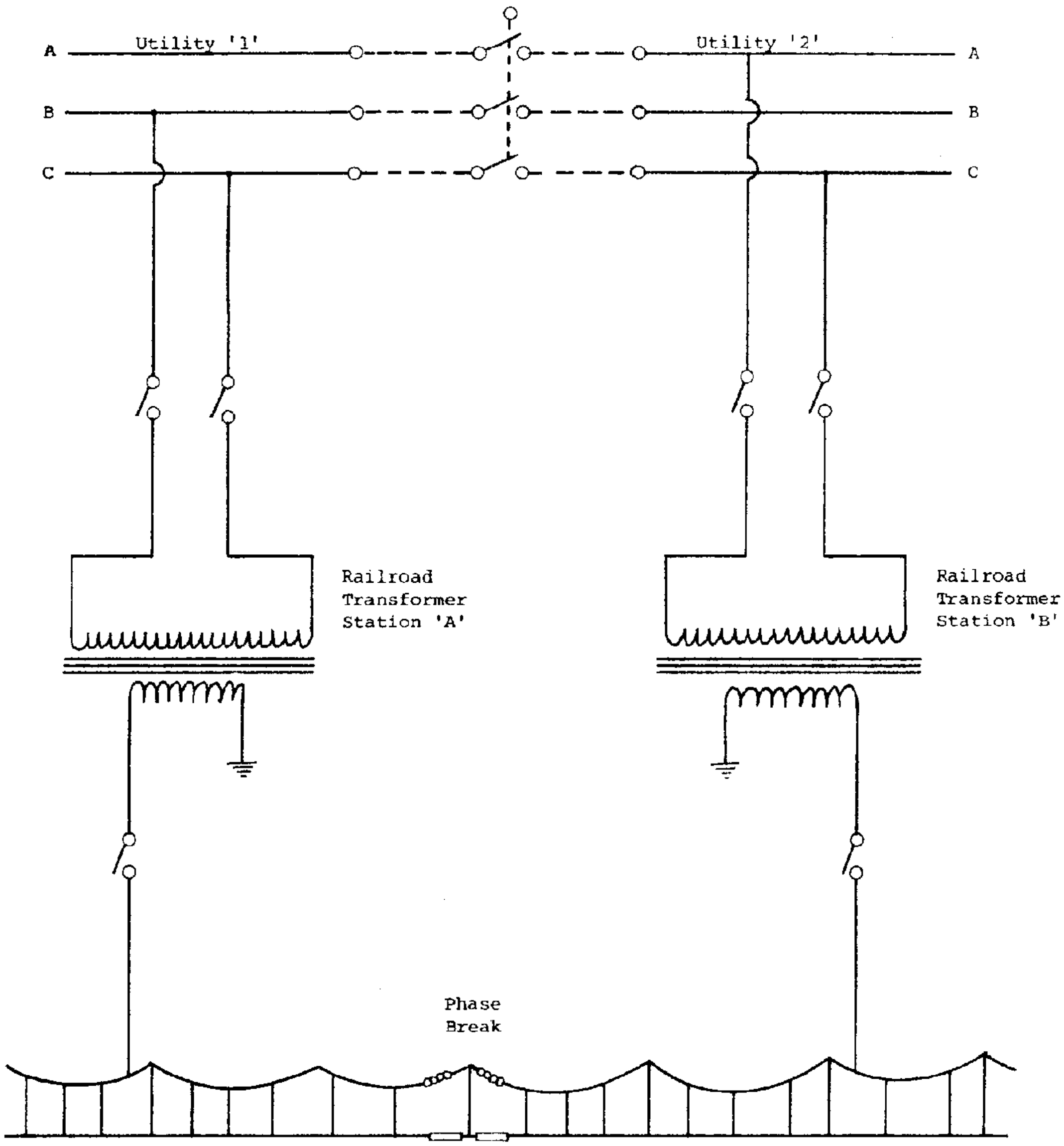
2. The 'Improved' Kupler phase break installation is 21 ft long which is very close to the Japanese National Railways single insulator design length of 26 ft. The single insulator design has the following advantages:

- It reduces the number of discontinuities in the mechanical arrangement; hence it is easier to install.

- It makes fuller use of the installation length. The present design provides only 12 ft of effective insulation in two 6 ft lengths.

- It provides a much greater tolerance to insulation contamination.

However, these advantages are somewhat offset by the absence of the first line protection provided by the center section. Enhanced substation protection would certainly be necessary with this option.



Note: Stations 'A' and 'B' may be transformers within the same substation fed from the same utility but across different phases.

FIGURE 11-7. TYPICAL RAILROAD FEED ARRANGEMENT.

12.0 RIDE QUALITY AND WHEEL WEAR INVESTIGATIONS

12.1 AEM-7 RIDE QUALITY DATA ACQUISITION

12.1.1 Ride Box Description

The ride quality measurements on the AEM-7 were made using a portable, self-contained unit equipped with two Kistler Instrumentation Corporation d.c. servo accelerometers. The two accelerometers are supplied electrically by two series-connected 12-volt rechargeable batteries. The two accelerometers are set up to measure independently the vertical and lateral accelerations of the locomotive with a full scale value of 1 g. Vertical accelerations corresponded to the motion of the locomotive car body perpendicular to the cab floor. All lateral accelerations corresponded to the motion of the locomotive car body parallel to the cab floor, in the across-track direction. Table 12-1 gives the ride box specifications.

The electrical output of the ride box can either be two voltages proportional to vertical and lateral accelerations or two multiplexed frequencies that are frequency modulated by the accelerometers. The voltage outputs are compatible with analog strip chart recorders or FM tape recorders. The multiplexed signal is designed to allow recording on a single channel direct tape recorder but requires a demultiplexer for playback.

TABLE 12-1. RIDE BOX SPECIFICATIONS

Frequency Response:	100 Hz
Overall Dimensions:	8.0 x 6.0 x 5.5 Inches
Weight:	8.0 lbs.
Accel. Axis:	Vertical and Lateral
Output Voltage Signal:	1 Volt/g both channels

12.1.2 Recording and Playback.

When used on the locomotive the ride box was turned on and connected directly to a tape recorder by means of BNC connector leads (Figure 12-1). During the test program two different tape recorders were used to record and play back test data. Initially a Nagra IV-SU two channel direct 2.5 Hz to 35 kHz (3 dB level) open reel recorder was used. This was later replaced by a TEAC R-61 four channel FM, d.c. to 625 Hz cassette recorder (shown in Figure 12-1). On the Nagra recorder both vertical and lateral ride box signals were multiplexed onto one channel. On the TEAC recorder two separate FM channels were used to record the vertical and lateral accelerometers individually.

For quick look visual analysis of the data the signals were low pass filtered at 30 Hz and replayed onto a Brush strip chart recorder, both at a sensitivity of 0.5 g full scale. The strip chart was run at a paper speed of 10 mm/sec.

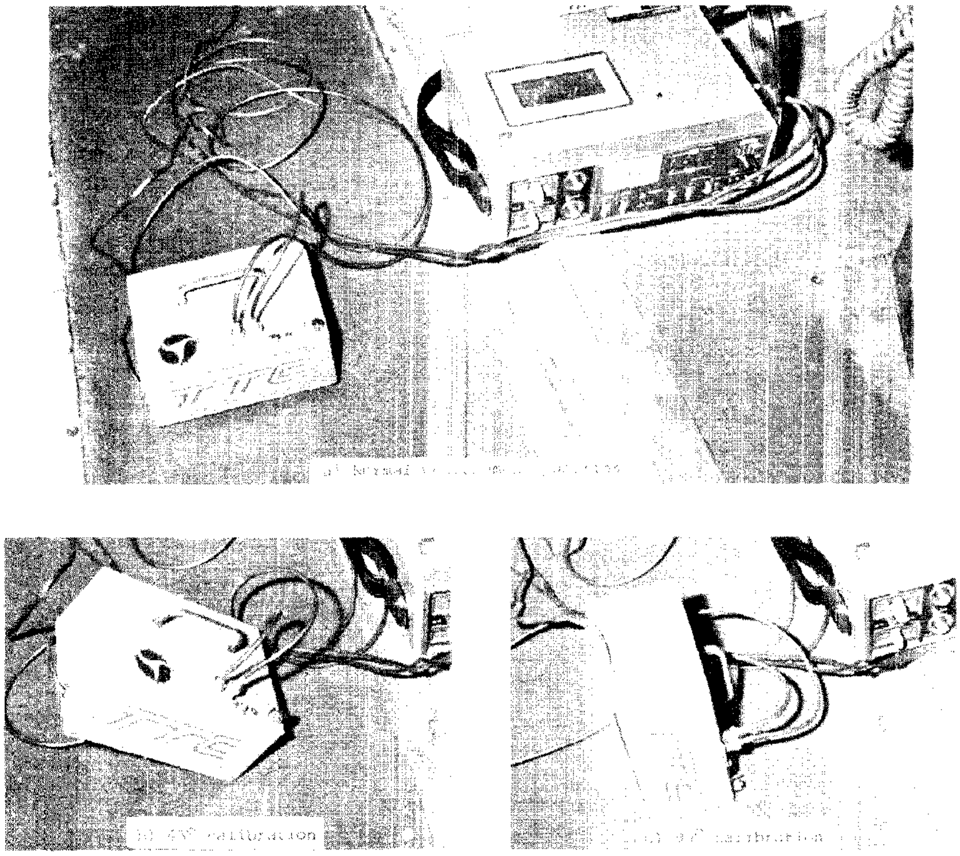


FIGURE 12-1. RIDE BOX AND TAPE RECORDER.

For more detailed analysis the signals were replayed into a Hewlett Packard model 5420A spectrum analyzer. The spectrum analyzer outputs included power spectral density (PSD) and root mean square (RMS) acceleration levels.

12.1.3 Calibration Procedures

Immediately before or after ride data collection a calibration test was done to assure accurate replay of the data recorded. Since in its normal mode the vertical accelerometer will experience a 1 g force due to gravity, an electrical signal equivalent to -1 g is used within the accelerometer circuits to null the vertical accelerometer output. The lateral accelerometer requires no correction since its axis of sensitivity is positioned 90° with respect to the acceleration due to gravity. With the ride box level on the locomotive cab floor the vertical and lateral voltage signals are proportional to zero g calibration.

With the ride box set at an angle of 45° relative to the locomotive cab floor the vertical voltage signal is proportional to 0.707 - 1.0 = - 0.293 g. The lateral voltage signal is proportional to 0.707 g. At an angle of 90° the lateral signal is equivalent to +1 g and the vertical signal is proportional to -1 g, both of which represent the full scale output of the two channels. The calibration procedure consisted of recording the output from the accelerometers for a period of at least 30 seconds in each of the 0, 45° and 90° positions. Ride data was then recorded without changing any of the preset sensitivities.

12.1.4 Data Acquisition

No special provision was made to mount the box in the cab of the locomotive since the box was designed to sit on three feet attached to the bottom of the unit. The bottoms of the feet were pointed to provide a firm location in the cab floor material. Data was normally recorded during simulated profile running without special provision for set test speeds. However, track location and train speed were annotated onto the tape recorder voice channel at 1000 ft intervals for data referencing. Ride data acquisition was initiated either by reports of bad vehicle ride or at 17,000 to 22,000 mile increments to coincide with wheel profile measurements.

One particular set of data was taken to measure the lateral acceleration levels at the lead pantograph base. For the purpose of those measurements the ride box was positively mounted on the roof under the pantograph which was locked down and grounded. The output from the ride box was cabled to the tape recorder situated in the lead cab of the locomotives. A schedule of ride quality data acquisition is presented in Table 12-2.

TABLE 12-2. RIDE QUALITY DATA ACQUISITION TEST MATRIX

Date	Mileage	Direction	Remarks
07-01-80	20,851	CCW	Routine
07-08-80	23,030	CCW	Rough track investigation
08-06-80	41,380	CCW	Routine
08-27-80	57,493	CW	Routine
09-16-80	73,963	CW	Rough switch investigation
09-17-80	75,050	CCW	Rough switch investigation
09-19-80	87,055	CW	Pantograph base measurements
11-09-80	100,120	CCW	Routine
02-09-81	137,416	CW	Routine
05-07-81	165,500	CW	Routine

12.2 AEM-7 WHEEL PROFILE MEASUREMENT METHODOLOGY

12.2.1 General Description

Three different wheel profilometers were utilized to provide wheel profile data during the AEM-7 endurance test. A Yoshida wheel profilometer was used to monitor progressive wheel wear through the first 82,000 miles of the program. A Canadian National profilometer and a British Rail profilometer were employed during the remainder of the program. Wheel profile data was taken at approximately 20,000 mile intervals.

12.2.2 The Yoshida Profilometer

The Yoshida wheel profilometer consists of a machined reference frame which clamps to the wheel and, by means of a shaft mounted stylus and a helical gear turned by a small handle, produces a tracing of the wheel profile (Figure 12-2).

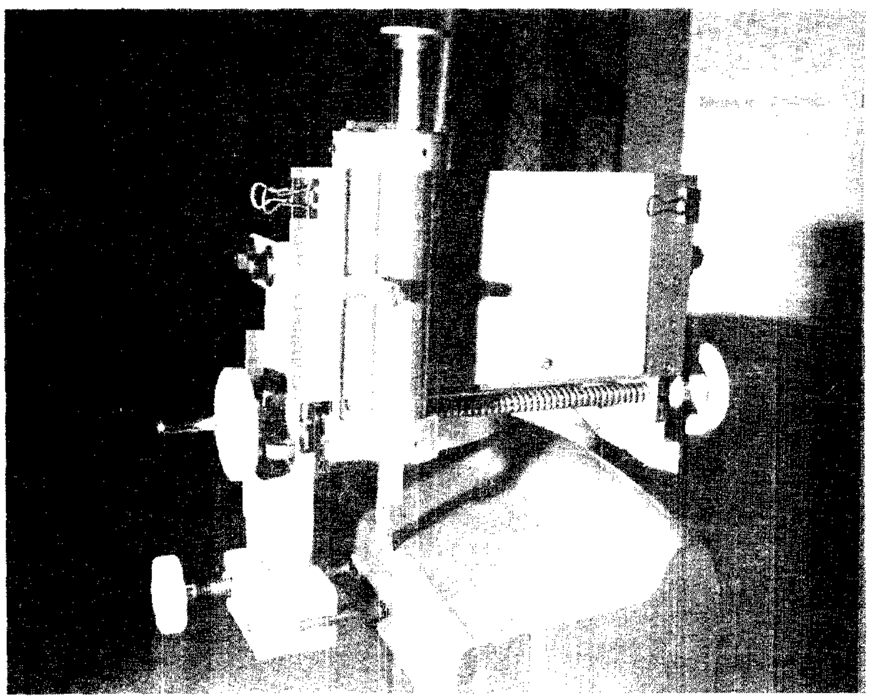


FIGURE 12-2. YOSHIDA PROFILOMETER.

12.2.3 The Canadian National Profilometer.

A Canadian National wheel profilometer similar to the one shown in Figure 12-3 was utilized to collect data in support of a separate study conducted by the Aerospace Corporation, Washington, D.C.

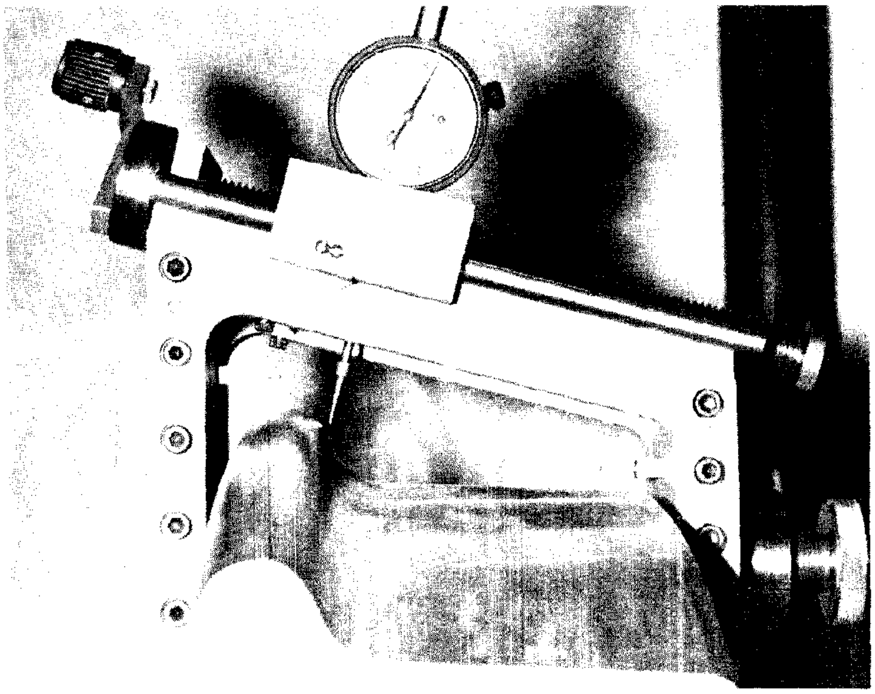


FIGURE 12-3. CANADIAN NATIONAL (CN) PROFILOMETER.

The CN profilometer consists of a cast and machined reference frame equipped with a dial gage mounted in a machined block. The block is drilled and tapped to accommodate two steel guide rods and a threaded shaft rotated by a small handle. Lateral movement of the dial gage across the flange and tread of the wheel is referenced to a 6 inch machinist scale mounted on the frame of the profilometer. The motion is indexed by a click stop mechanism attached to the handle assembly. A small indentation is made in the face of the wheel below the tread by means of a jig equipped with a drill bit (Figure 12-4), and the profilometer is then clamped to the wheel and positioned by means of a threaded pin locator.

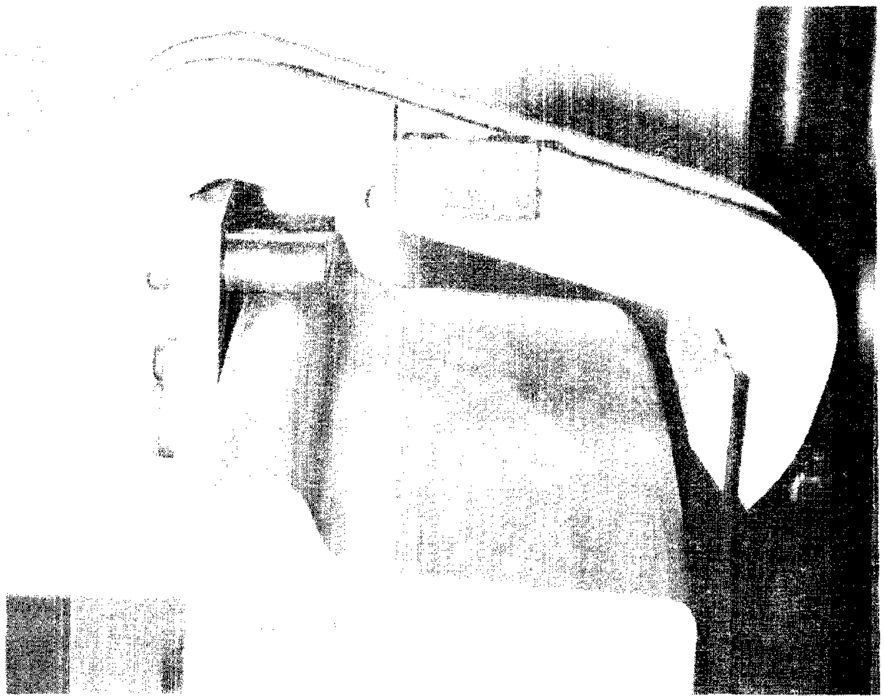


FIGURE 12-4. CANADIAN NATIONAL PROFILOMETER LOCATION ARRANGEMENT.

12.2.4 The British Rail Wheel Profilometer

The British Rail wheel profilometer consists of a rectangular reference frame with a measuring head mounted at each end (Figure 12-5). The profilometer is located on the flange tips of the wheelset to be measured and then is is positioned between the two flange backs so that the measuring heads are equidistant from the wheelset centerline. A dial gage on each measuring head is rotated about a fixed pivot and measurements from 40 positions across the wheel flange and tread are taken. The wheel profile is defined as a set of R, ϕ coordinates, the angles being defined by a series of equally spaced notches around an indexing track located above the fixed pivot (Figure 12-6). Two dial gages mounted parallel to the reference frame are utilized to measure the flange back dimensions of the wheelset. The BR wheel profilometer provides profile data which is referenced to the wheelset flange back spacing.

12.2.5 The British Rail Rail Profilometer

The British Rail rail profilometer consists of a similar reference frame with one profile measuring head and one gage measuring head (Figure 12-7). Knife edges on the reference frame locate the profilometer across the crowns

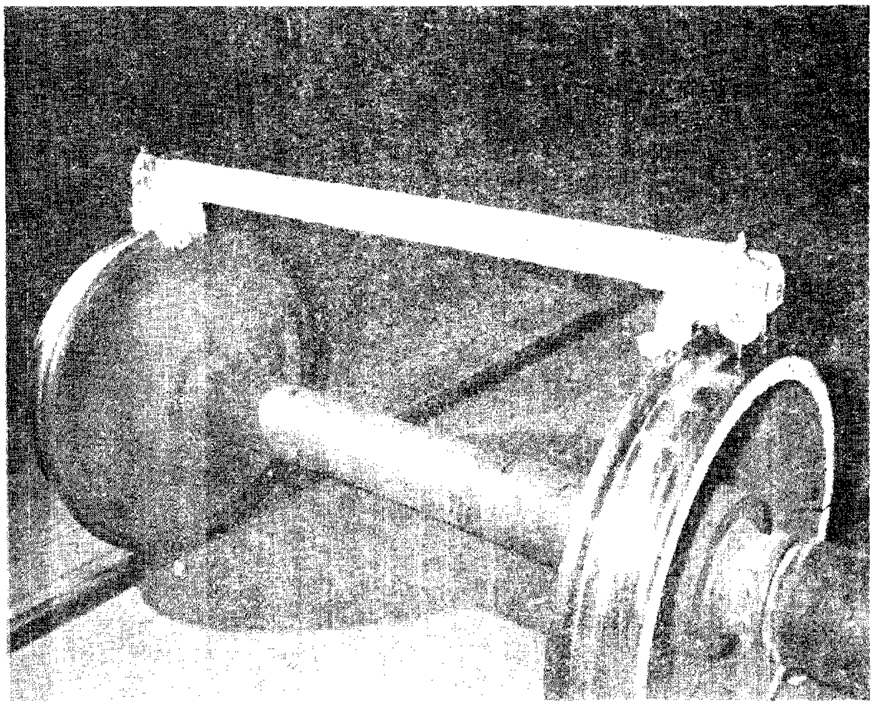


FIGURE 12-5. BRITISH RAIL WHEEL PROFILOMETER.

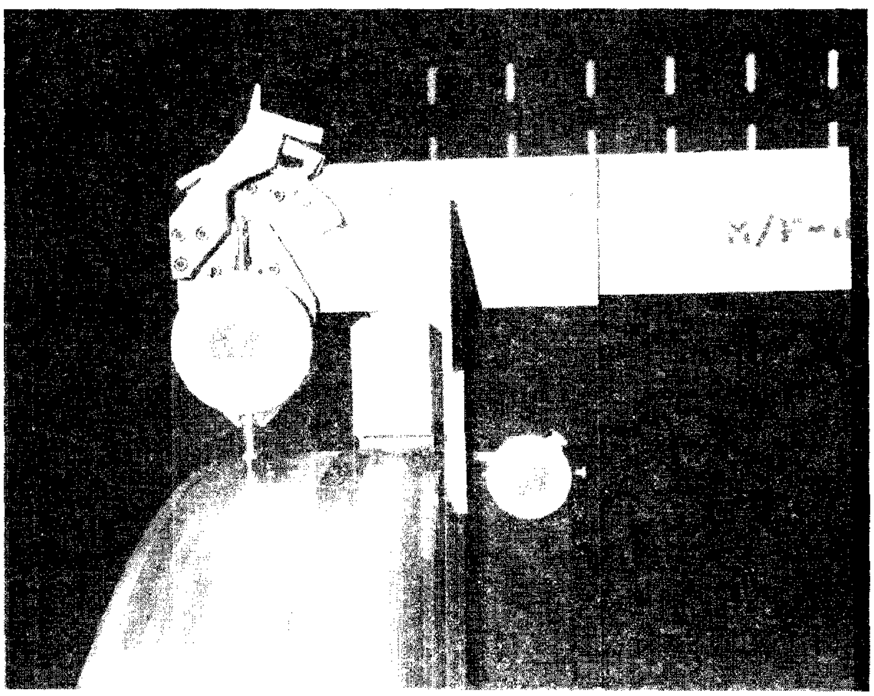


FIGURE 12-6. BRITISH RAIL WHEEL PROFILOMETER INDEXING HEAD.

of the two rails, and a gage measuring head is held against the gage corner of the rail by a light spring. The profile measuring gage is mounted on a notched track and rotated about a virtual center rather than a fixed pivot as does the wheel profilometer. Again the R, ϕ coordinates are produced. The track separation is measured by a dial gage mounted parallel to the reference frame and located 19 mm beneath the rail head crown. The profilometer is then turned end-for-end and the opposite rail is measured.

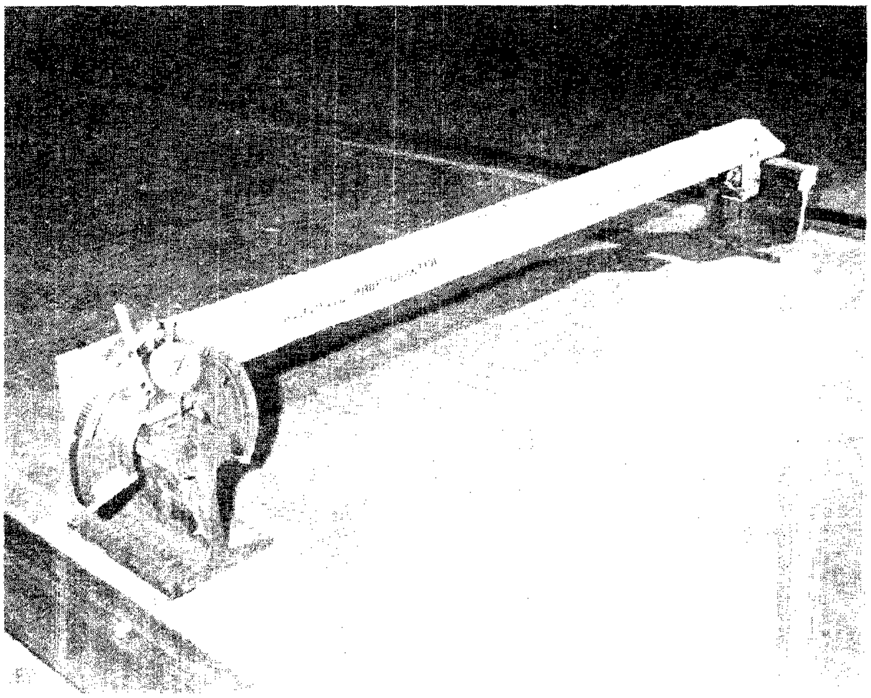


FIGURE 12-7. BRITISH RAIL RAIL PROFILOMETER.

12.2.6 British Rail Profilometer Data Reduction

Computer analysis converts the R, ϕ measurements into y, z coordinates relative to the wheelset or track centerline. By combining the profiles of a particular wheel and rail pair, the mutual contact geometry can be studied. For a series of lateral shifts of the wheelsets relative to the track, various parameters can be calculated including rolling radius difference (effective conicity), contact angles, wheelset roll angles, and contact patch size and shape. This will be described further in section 12.3.6.

12.3 REDUCTION AND ANALYSIS OF THE RIDE QUALITY DATA

12.3.1 Methodology

The ride data (vertical and lateral cab floor accelerations) were reduced in three parts:

- The data was replayed onto a strip chart so that peak accelerations could be identified with the safety criteria supplied by Japanese National Railways.[8]
- Selected test lengths of data were analyzed for root-mean-square (RMS) acceleration levels. Comparisons were then made of RMS acceleration against track location at a constant speed, and against speed for two locations.
- For the same test lengths measurements were made of Power Spectral Density (PSD) to determine the relative powers contained within frequency bandwidths of interest.

Both PSD and RMS were produced using a Hewlett-Packard Model 5420A frequency response analyzer.

12.3.2 Peak Acceleration Levels

Originally the ride quality measurements were made as a periodic check to determine the track and vehicle ride deterioration with time. Threshold criteria were supplied by Takeshi Kawazoe, Japanese National Railways[8] as follows:

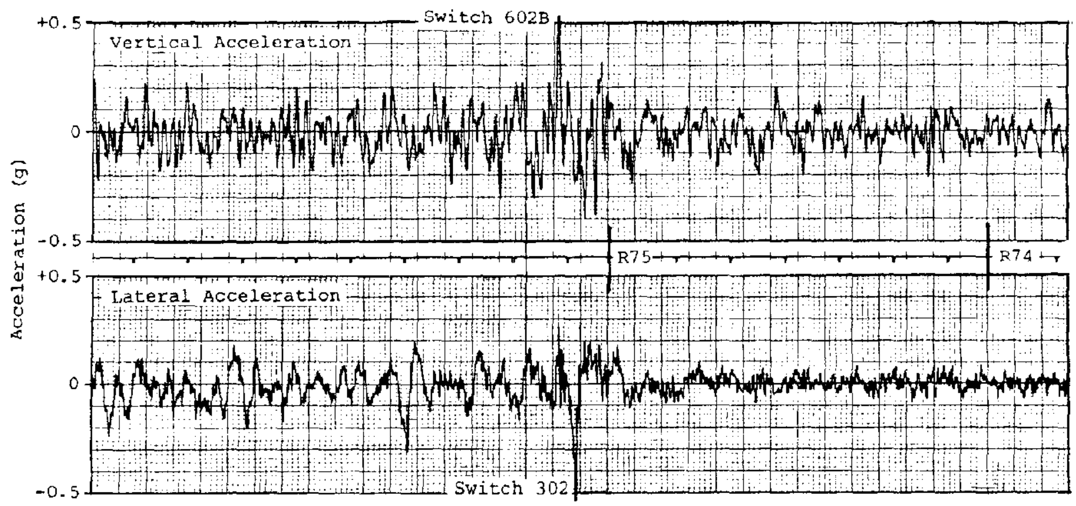
- Maximum Cab Floor Lateral Acceleration (0 to peak) $\pm$ 0.4 g
- Maximum Cab Floor Vertical Acceleration (0 to peak) $\pm$ 0.5 g

After each ride quality measurement the data were replayed onto a strip chart for visual analysis and comparison with the criteria above. Whenever serious exceedences of the criteria were encountered the site locations were reported to the Track Maintenance Supervisor for corrective action.

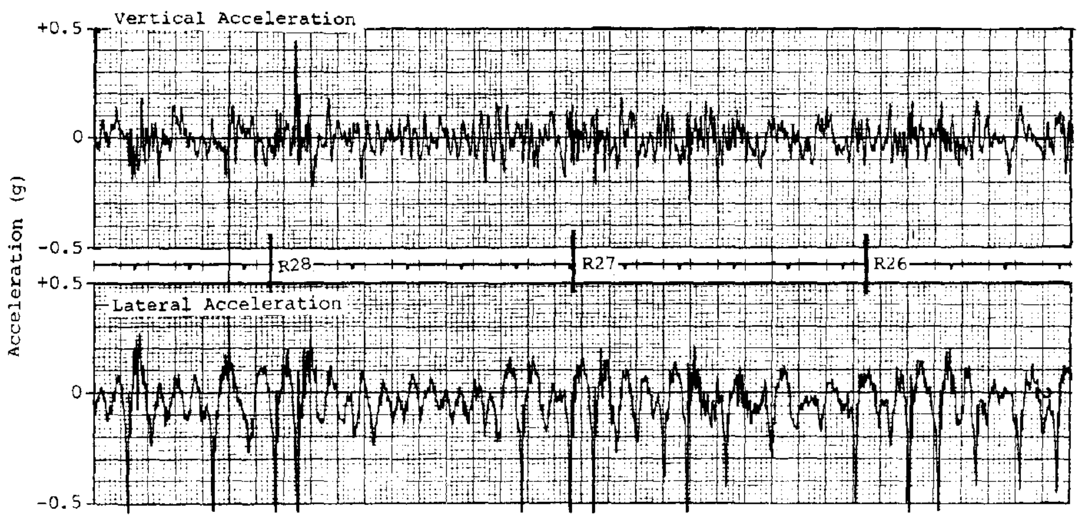
As experience developed, a number of known 'trouble spots' were identified. The main one, a badly aligned switch (#305B), was removed in July 1980. This switch, originally used as a second access to the FAST facility, was situated on the RTT FAST curve spiral, making its alignment difficult.

Other trouble spots included the Balloon Track/Transit Track access switches (#301 & #602B) and a series of misalignments in the South Curve near station R27. All these spots were identified by peak level acceleration exceedence. Examples of the acceleration time histories are presented in Figure 12-8.

Early in the program ride quality measurements were often initiated by reports of a rough ride from the vehicle operators. In general these reports were substantiated by the data. As the program progressed it was possible to rely on the vehicle operators to report 'bad track' and to use the ride quality measurements as a periodic quantitative measure of track performance.



a) Track Switch Location Acceleration Exceedence, 117 mi/h



b) Curved Track Location, Exceedences Caused by Bad Track Alignment, 120 mi/h

NOTE: RTT Turnout Details are given in Table 4.4

FIGURE 12-8. PEAK ACCELERATION LEVEL EXCEEDENCES.

12.3.3 Presentation of the RMS and PSD Ride Data

a. Root-Mean-Square Accelerations. The RMS vertical and lateral acceleration levels were extracted for the RTT test sections specified in Table 12-3. These sections were chosen as representing the worst sections of a given track type as identified from the strip chart data.

TABLE 12-3. RTT RIDE QUALITY TEST SITES.

Location (clockwise)		Track Features	
Start	Finish	Curved/Tangent	Jointed Rail/CWR
R75	R5	Tangent, switches	Jointed
R15	R17	Tangent	CWR
R26	R28	Curved	CWR
R35	R37	Tangent	Jointed
R57	R59	Curved	CWR
R71+200	R73+200	Tangent	Jointed

The results for a nominal 120 mi/h lap of the RTT in counterclockwise and clockwise directions for selected test sections are presented in Table 12-4.

TABLE 12-4. RMS ACCELERATION LEVELS FOR RTT TEST SECTIONS (SPEED 120 mi/h).

i. Counterclockwise

Section	Vertical (g)	Lateral (g)
R5 - R75	0.091	0.060
R55 - R57	0.057	0.031
R37 - R35	0.057	0.040
R28 - R26	0.056	0.081
R17 - R15	0.046	0.027

Data taken with newly turned wheels.

ii. clockwise

Section	Vertical (g)	Lateral (g)
R75 - R5	0.089	0.054
R15 - R17	0.042	0.019
R26 - R28	0.059	0.073
R35 - R37	0.055	0.033
R57 - R59	0.058	0.039
R71+200-R73+200	0.054	0.030

Data taken with worn wheels.

Since the acceleration ride quality measurements were made during the normal endurance test profile runs, the speed range over which data could be obtained was limited. Table 12-5 presents data for a section of tangent track and a section of curved track over a limited speed range. The data is presented in graphic form in Figure 12-9.

TABLE 12-5. RMS ACCELERATION CHANGES WITH SPEED.

i. Counterclockwise

Test Section	Speed (mi/h)	Vertical (g)	Lateral (g)
R37 - R35	95	0.022	0.030
R37 - R35	107	0.047	0.036
R37 - R35	117	0.057	0.040
R28 - R26	100	0.050	0.034
R28 - R26	119	0.056	0.081
R28 - R26	121	0.058	0.092

Data taken with newly turned wheels.

ii. Clockwise

Test Section	Speed mi/h	Vertical (g)	Lateral (g)
R26 - R28	68	0.036	0.030
R26 - R28	93	0.048	0.032
R26 - R28	100	0.050	0.037
R26 - R28	110	0.055	0.049
R26 - R20	118	0.059	0.073
R35 - R37	71	0.028	0.019
R35 - R37	110	0.055	0.032
R35 - R37	120	0.055	0.033

The 2000 ft test sections specified in Table 12-5 highlight the worst sections of track but are not representative of the overall ride quality. To give a more realistic assessment of the overall ride quality, longer sections of track (of the order of a mile) were selected for analysis. These sections, which contained most of the sections in Table 12-3, are specified in Table 12-6.

TABLE 12-6. OVERALL RIDE QUALITY TEST SECTIONS.

Location (clockwise)		Track Features	
Start	Finish	Curved/Tangent	Jointed Rail/CWR
R12	R18	Tangent	CWR with switches
R22	R32	Curved	CWR
R33	R39	Tangent	Jointed
R55	R68	Curved	CWR

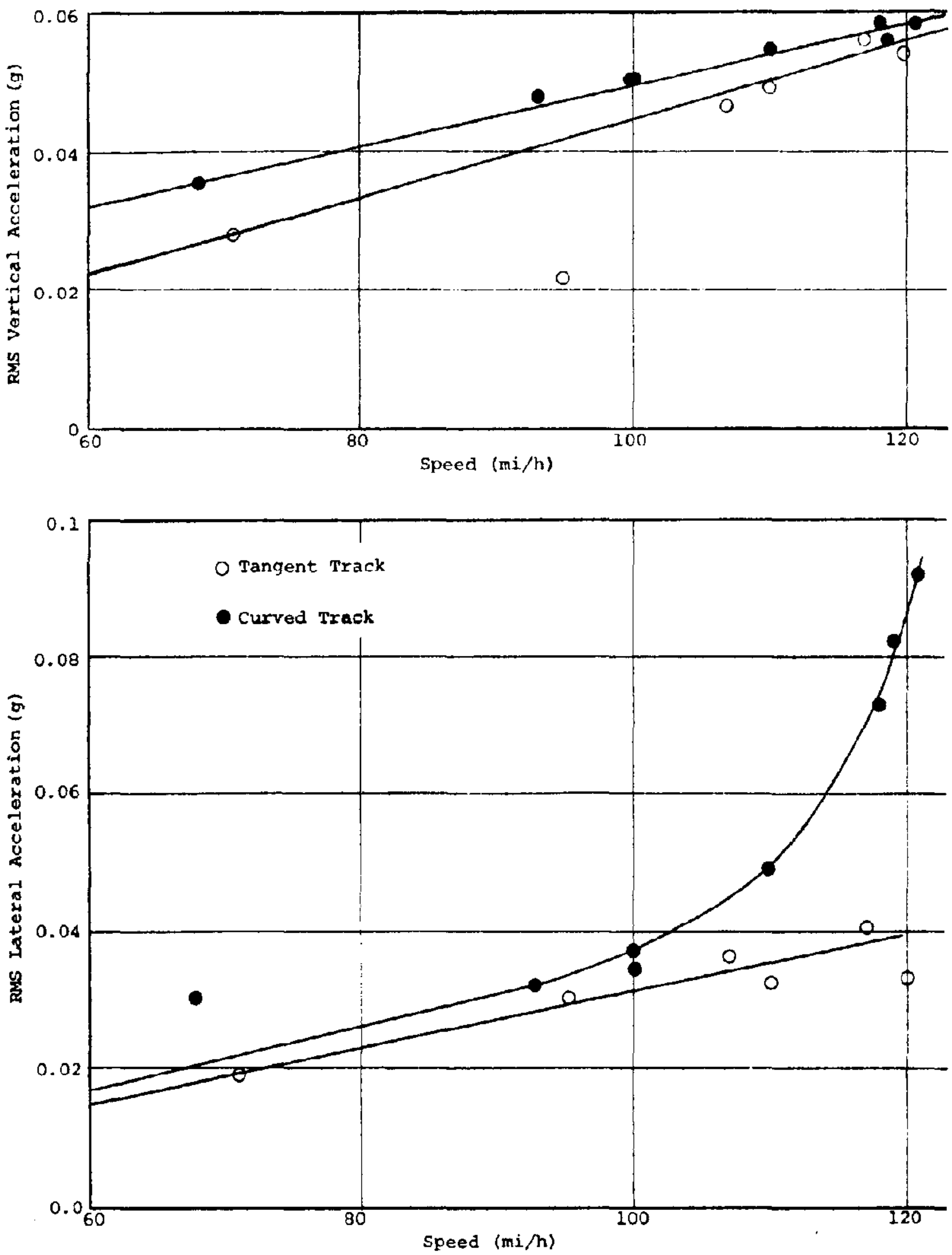


FIGURE 12-9. THE EFFECT OF SPEED ON VERTICAL AND LATERAL ACCELERATIONS.

Two sets of data are presented in Table 12-7. One is for a speed of 110 mi/h the other for 120 mi/h. It should be noted that the data were not taken on the same day.

TABLE 12-7. RMS ACCELERATION LEVELS ON AMTRAK 900 LEAD CAB FLOOR

Location	Speed 110 mi/h		Speed 120 mi/h	
	Vertical	Lateral	Vertical	Lateral
R12 - R18	0.047	0.025	0.048	0.026
R22 - R32	0.051	0.040	0.061	0.052
R33 - R39	0.052	0.031	0.057	0.030
R55 - R68	0.047	0.031	0.054	0.042

b. Power Spectral Density (PSD) Results. The RMS data presented in the previous paragraph (12.3.3 a) gives a measure of the overall ride quality in the locomotive cab floor over the bandwidth of interest, namely 0-25 Hz. However, it is also important to identify the major frequency components within that bandwidth. One method to accomplish this is to plot the Power Spectral Density of the accelerometer signal over the frequency range of interest.

Examples of the PSD's are presented in Figures 12-10 through 12-12. These will be used to support the discussion of results.

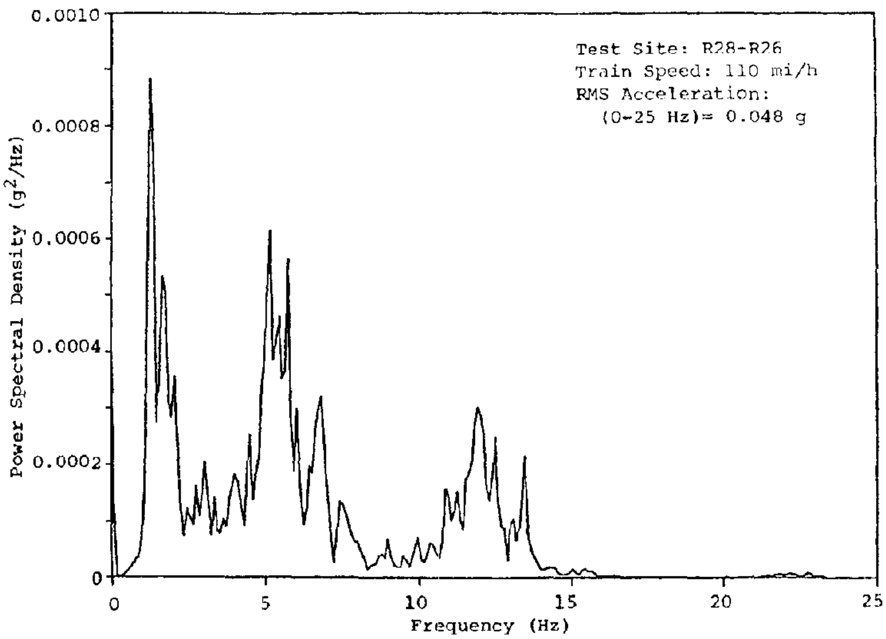


FIGURE 12-10. TYPICAL VERTICAL ACCELERATION POWER SPECTRAL DENSITY.

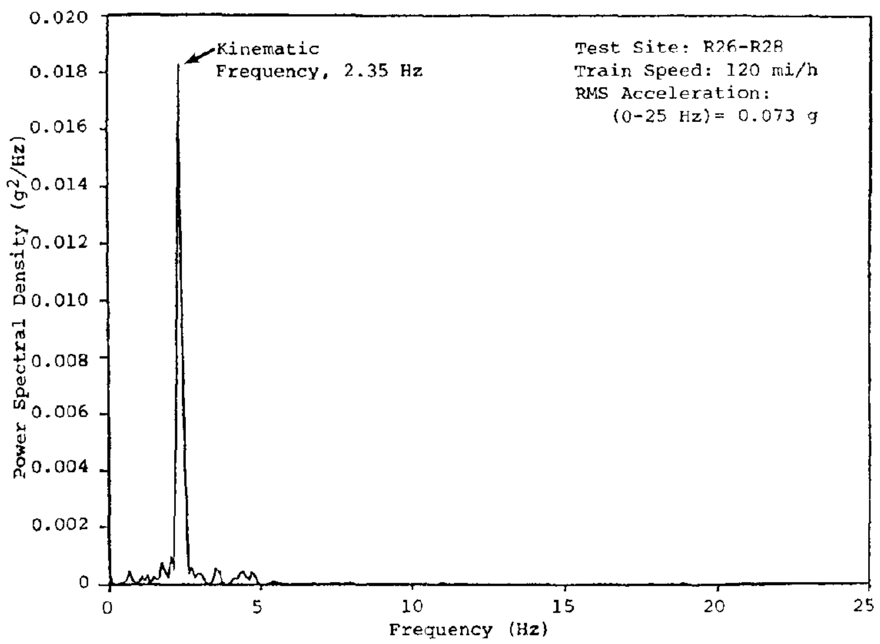
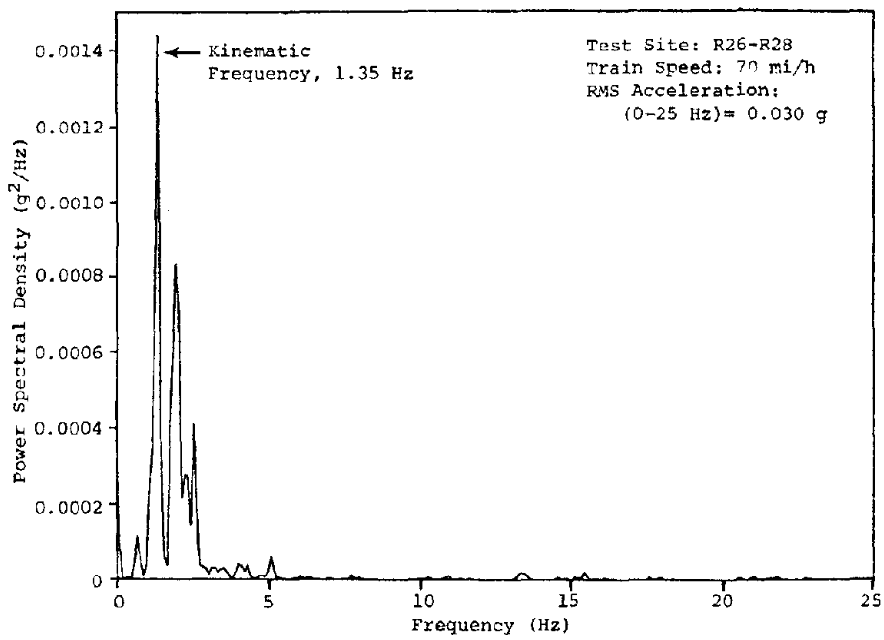


FIGURE 12-11. LATERAL ACCELERATION PSD AT 120 MI/H.



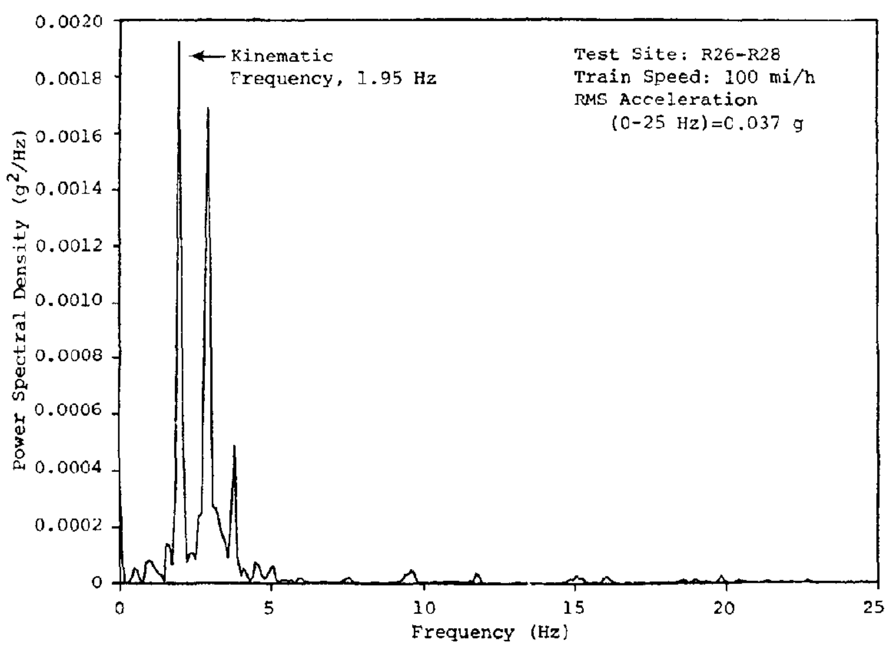


FIGURE 12-12. LATERAL ACCELERATION PSD'S AT SPEEDS OF 70 MI/H AND 100 MI/H.

12.3.4 Discussion of Ride Quality Results

a. Vertical Data. The vertical ride of AMTRAK 900 on the RTT obeyed a near linear relationship with speed (Figure 12-9) and showed very little dependance on the type of track. Reference to Table 12-7 will, however, show that a slightly better overall vertical ride was measured on the tangent CWR section of track between R12 and R18. No evidence of vertical ride deterioration with wheel wear was found. The variations in measured quality seemed to be within the tolerances expected due to track maintenance. The measured values are approximately two times the values typical of a high speed passenger car. This represents a good ride quality for a locomotive.

Examination of the representative vertical acceleration PSD's presented in Figure 12-10 shows a broad band excitation in the 0-15 Hz range. These effects are immediately noticeable.

- The rigid body modes (pitch, heave, and roll) in the 1-2 Hz region.
- The truck resonant frequencies in 6-7 Hz bandwidth coupled with the truck center and truck wheelbase filtering effect.[9]
- Excitation of a resonant mode at 12 Hz at some of the locations only. The source of this excitation could not be determined from the data available but is probably a truck mode or vertical bending of the locomotive body.

As expected from the overall RMS vertical acceleration levels the four sections chosen for analysis (representing 50% of the RTT) show substantially uniform frequency content patterns.

b. Lateral Data. Unlike the vertical data the lateral data exhibit a large variation in RMS acceleration level with track location as can be seen in column 5 of Table 12-7. The two curved track test sections show a significant increase in overall accelerations level, particularly the South Curve section (R22 - R32). This is further emphasized by the data presented in Table 12-4. As previously explained, the test sections contained in Table 12-4 represented the worst section of each major test length. The section between R26 and R28 on the South Curve exhibits a rapid deterioration in lateral ride quality over the speed range 100-120 mi/h. At a speed of 120 mi/h an overall RMS lateral acceleration level of 0.092 g was measured.

To examine the cause of this sharp increase reference should be made to the PSD plots presented in Figures 12-11 and 12-12. At 120 mi/h (Figure 12-11) the lateral acceleration PSD is dominated by one peak at approximately 2.4 Hz. Comparison with the slower speed runs (Figure 12-12) shows the same tendency for the frequency response to be dominated by one peak, but at a lower frequency. The dominant frequency was extracted for the lateral accelerations over test length R26 to R28 in Table 12-5 (clockwise portion) and the results are plotted against speed in Figure 12-13. The results show a linear relationship with speed. This frequency, called the truck kinematic frequency, will be discussed further in section 12.3.5.

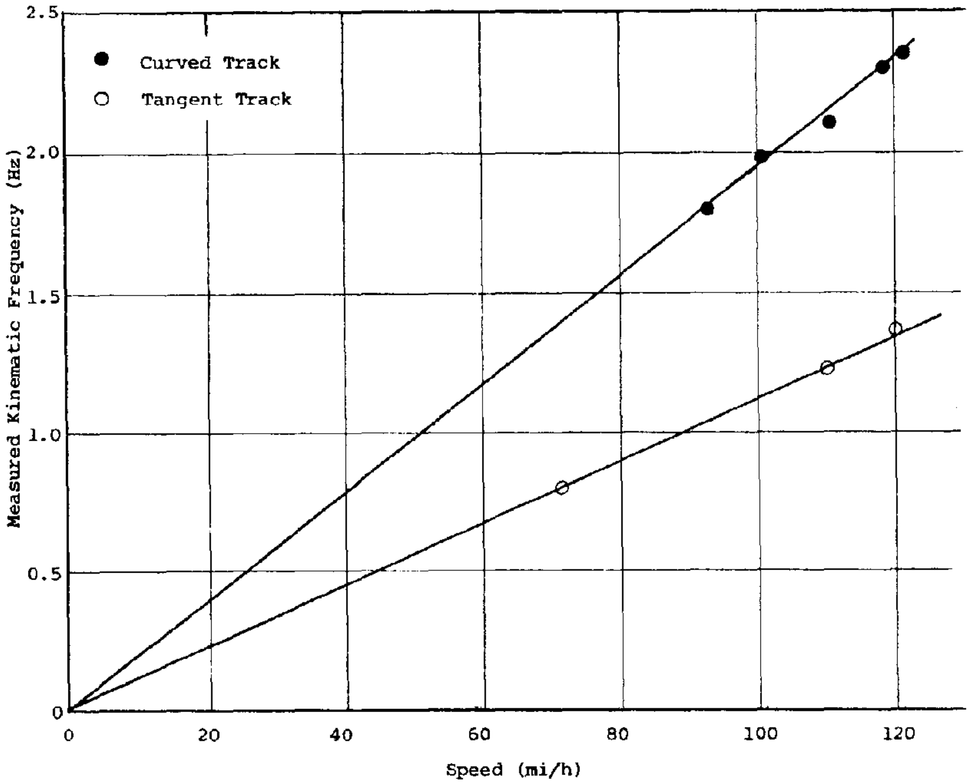


FIGURE 12-13. THE EFFECTS OF SPEED ON KINEMATIC FREQUENCY.

On the tangent track (R35 - R37) two frequency peaks appear on the PSD plots. The upper frequency, which is also linearly proportional to speed, is the 39 ft spaced rail joint passing frequency. This strong coupling of this effect in the lateral plane is due to the vehicle tendency to roll toward the rail joint in an oscillatory fashion. The staggered joint pattern approximates a sinusiodal input with a 39 ft spatial wavelength. The tangent track kinematic frequency (the lower peak) was also plotted against speed in Figure 12-13.

12.3.5 The Kinematic Frequency of a Rail Vehicle Truck

Truck kinematic motion is fully discussed by Cooperrider and Law,[10] however, a short description of the phemonenon is necessary here in order to better understand the measured ride quality data.

A coned wheelset moving along a tangent track has a natural tendency to oscillate laterally. These oscillations occur at a fixed spatial wavelength dependent upon track gauge, wheel diameter, and conicity (the effective cone angle between the wheels and rails), but independent of speed.

Wheelsets confined within a truck frame also exhibit the same tendency, but in this case the spatial wavelength is additionally dependent on the truck wheelbase. Typical spatial wavelengths are in the 50 to 100 ft range.

The kinematic temporal frequency (Hz) is speed dependent, being derived from the kinematic wavelength by dividing the truck forward speed, v, by the spatial wavelength.

$$f_k = \frac{v}{\Omega}$$

where f_k = kinematic frequency (Hz)
v = Forward speed (ft/sec)
Ω = Kinematic wavelength (ft)

For a truck with a kinematic wavelength of 75 ft travelling at a speed of 120 mi/h (187 ft/sec) the corresponding kinematic motion frequency is 2.5 Hz. A speed of 100 mi/h (146 ft/sec) the frequency is 2.07 Hz.

The calculation of the spatial wavelength for a complete vehicle is complex. Simplifying assumptions can make the calculations easier but less reliable. Vehicle dynamics calculations are outside the scope of this report, but to ensure that the ride analysis was sound, the relevant dimensions of the AEM-7 trucks were applied to the 'free truck' equation[10] and it was found that a wheelset effective conicity of 0.133 would be required to give a kinematic frequency of 2.33 Hz at 120 mi/h on tangent track.

In any natural frequency the motion amplitude is controlled by the modal damping; with too little damping the motion becomes unstable. In the case of the truck kinematic mode this instability produces a phenomenon known as truck hunting. However the kinematic motion can be detected in the lateral ride of the vehicle long before hunting occurs.

12.3.6 The Curving Behavior of the AEM-7

Although kinematic motion was discussed in the previous section in the context of tangent track, kinematic motion is also present on curved track. This is also fully discussed in reference 10 by Cooperrider and Law, who state that "on gentle curves at or a little above balance speed, kinematic motion can be induced on the entry spiral and cause the wheelsets to oscillate on and off the flange throughout the curve". Evidence of this was apparent from subjective assessment of the AEM-7 ride over the South Curve (R19 to R33) on the RTT. In addition the ride quality measurements discussed in section 12.3.4, strongly supported this assessment.

12.3.7 The Wheel/Rail Profile Conicity Predictions

Since the AEM-7 wheel profile and RTT rail profile measurements were taken with the BR profilometers it was possible to utilize the measurements to predict the range of wheelset effective conicities over the section of track of interest. This was accomplished using the Asymmetric Wheel/Rail Contact Characterization Program, WHRAILA, developed by Heller and Cooperrider.[11]

The required inputs to the program consist of the x, y coordinates specifying the wheel and rail profiles (both left and right) together with the track gauge and wheelset flange back dimension. The outputs include a plot of the difference in rolling radius against wheelset lateral displacement, the slope of which is the effective conicity of the wheelset/rail combination.

Two examples of the output are presented in Figures 12-14 and 12-15. The first, Figure 12-14, is derived from the rail profiles taken at station R26 on 02-12-81 and the AEM-7 #2 wheelset wheel profiles taken on 10-14-80, 250 miles after wheel reprofiling. The second example, Figure 12-15, is derived from the same rail profiles, but using the AEM-7 #2 wheelset wheel profiles taken on 02-17-81, 45,000 miles after wheel reprofiling.

Within the computer program the y-axis of the conicity plot has been nondimensionalized by dividing the difference in wheel rolling radii by the track gauge. To extract the effective conicity from the graph, the slope of the constructed line must first be multiplied by the track gauge.

The output from the newly turned wheels, Figure 12-14, gives uniform effective conicity, of 0.023 over the full width of the lateral displacement of the wheelset relative to the rail. This value compares favorably with the theoretical 1 in 40 taper effective conicity of 0.025.

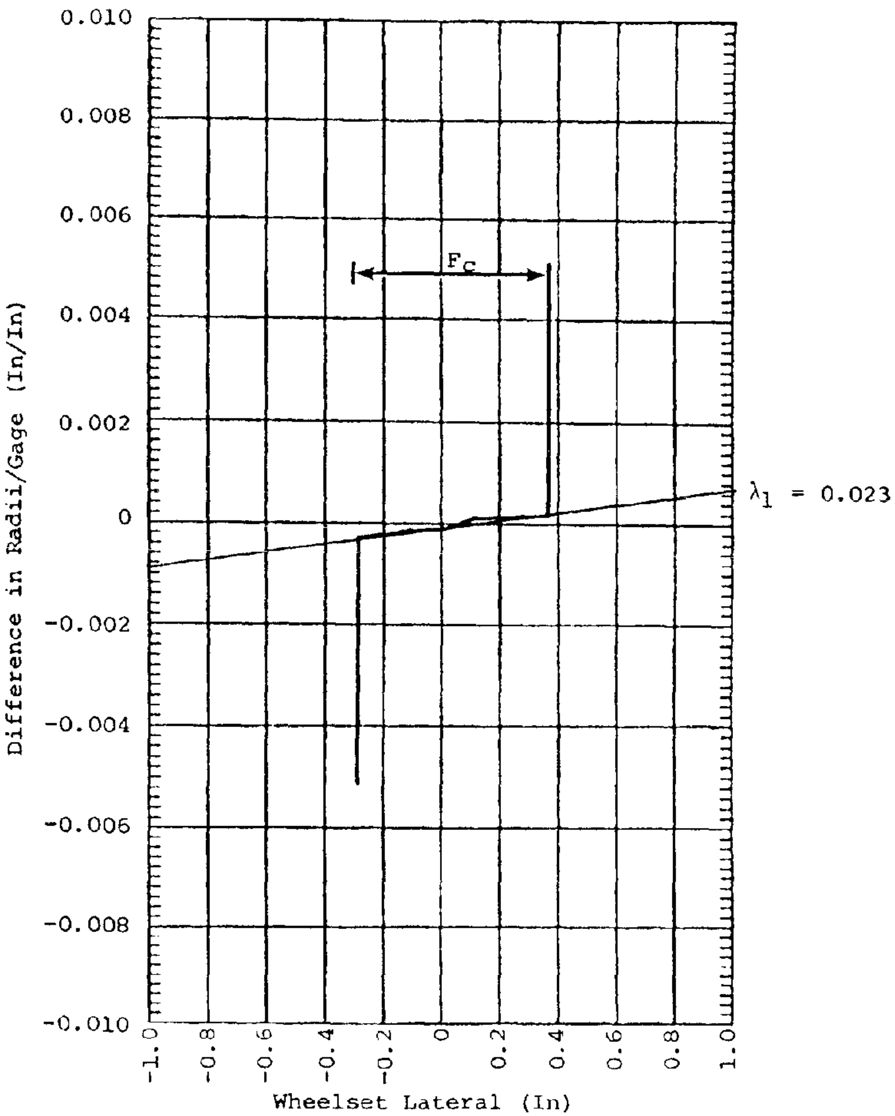
The output from the second wheel/rail combination, Figure 12-15, is a little more difficult to interpret. The center section of the wheelset lateral displacement yields an effective conicity value of 0.033. The center section is then bounded, on either side, by a 'false flange' before the main flange contact occurs. Constructing the effective conicity line through the flange-to-flange contact points yields an effective conicity, λ, of 0.136. A summary of the results for all four wheelsets is given in Table 12-8.

TABLE 12-8. SUMMARY OF AEM-7 WHEELSET MEASURED CONICITY VALUES.

Wheelset #	Central Band Conicity λ_1	Flange-to-Flange Conicity λ_2	Flangeway Clearance (in)
1	0.028	0.144	1.12
2	0.033	0.136	1.01
3	0.031	0.120	0.98
4	0.043	0.135	--
Average	0.034	0.135	1.04

Accumulated miles since reprofiling - 45,000

The fourth column in Table 12-8 presents the measured flangeway clearances (the total permissible lateral displacement between full flange contact) for



<u>Data Input</u>

Wheel Profiles - Wheelset #2 (10-14-80)
Rail Profiles - R26 (2-12-81)
Mileage Since Wheel Profiling - 250

<u>Calculation of Effective Conicity</u>

$$\lambda = \frac{\left(\frac{\Delta R}{G}\right) \times G}{2 \times L}$$

Where: $\frac{\Delta R}{G} = \frac{\text{Difference in Radii}}{\text{Gage}}$

G = Track Gage

L = Wheelset Lateral Displacement

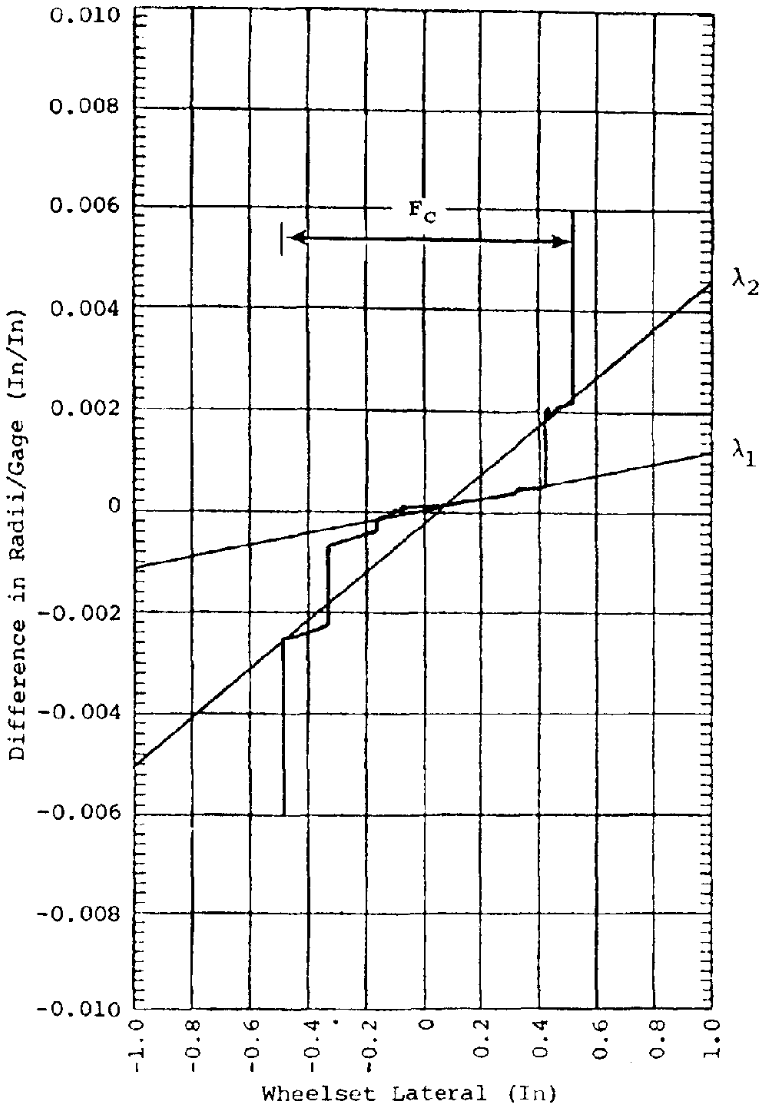
$$\lambda_1 = \frac{1.6 \times 10^{-3} \times 56.5}{2 \times 2} = 0.023$$

(Theoretical conicity of a 1 in 40 profile = 0.025)

<u>Flangeway Clearance</u>

F_c = 0.66 inches

FIGURE 12-14. THE EFFECTIVE CONICITY OF A NEW WHEEL.



<u>Data Input</u>

Wheel Profiles - Wheelset #2 (2-17-81)
Rail Profiles - R26 (2-12-81)
Mileage since wheel reprofiling - 45,000

<u>Calculation of Effective Conicities</u>

$$\lambda = \frac{\left(\frac{\Delta R}{G}\right) \times G}{2 \times L}$$

$$\lambda_1 = \frac{2.32 \times 10^{-3} \times 56.5}{2 \times 2} = 0.033$$

$$\lambda_2 = \frac{9.6 \times 10^{-3} \times 56.5}{2 \times 2} = 0.136$$

<u>Flangeway Clearance</u>

F_c = 1.01 inches

FIGURE 12-15. THE EFFECTIVE CONICITY OF A WORN WHEEL.

wheelsets #1 through #3. The average clearance of 1.04 inches compares with a value of 0.66 inches for a newly profiled wheelset on the same rail section. This will be further discussed in section 12.6.2.

12.3.8 Correlation Between Wheel/Rail Effective Conicity and Measured Kinematic Frequencies

Three pieces of data are now available for correlation:

- The effective conicity value of 0.133 calculated by using the curved track measured kinematic frequency and the AEM-7 truck dimensions in the Cooperrider and Law free truck equation, (section 12.3.5),

- The predicted conicity values from the wheel and rail profiles and the WHRAILA presented in Table 12-8, and

- The tangent and curved track measured kinematic frequencies presented in Figure 12-13.

For the purposes of the following argument it is assumed that, on tangent track, the wheelsets tend to run over the center band of the flangeway clearance, but on curved track the wheelsets tend to run against the flange. There is strong evidence to support the latter assumption from the rapid initial wheel wear experienced and the measured lateral acceleration levels on curves.

The 'free truck' equation applied to the tangent track measured kinematic frequency would predict an effective conicity of 0.045. It has already been stated that the curved track measured kinematic frequency yields an effective conicity of 0.133. Comparison of these values with the WHRAILA values of 0.034 and 0.134 respectively shows remarkable agreement.

Before too much emphasis is placed on the good agreement between the separate derivations of the effective concity values, the following should be noted.

The use of the 'free truck' equation in the context of the AEM-7 violated the derivation of that equation in three ways:

- The equation was applied to trucks having suspensions between the wheelsets and the truck frames, although the lateral and longitudinal stiffnesses were very high.

- The trucks were constrained within a vehicle suspension system and were therefore not free.

- The equation was applied to the truck on large radius curves when the derivation was based on tangent track.

The conicity values extracted from the WHRAILA program resulted from the 'best fit' straight line through highly non-linear data. Without a comparable full modeling exercise the extent of the exact validity of this analysis is unknown.

12.4 PANTOGRAPH LATERAL FLEXIBILITY AND THE KINEMATIC FREQUENCY

12.4.1 Definition

The lateral flexibility of a pantograph is defined as motion of the pantograph head in the lateral (cross - track) direction caused by the natural vibration of the pantograph structure. Vibration of the structures can be induced by aerodynamic effects, catenary excitation, but more usually by the locomotive truck suspension dynamics.

Since a pantograph must track the vertical variations in the catenary contact wire, it is a light structure. In general pantograph structures tend to be weakest in the lateral direction. The fundamental natural frequency of lateral bending is correspondingly low, tending to be in the 3.5 to 5.0 Hz bandwidth. Normally this bandwidth is clear of any significant lateral excitation from truck dynamics.

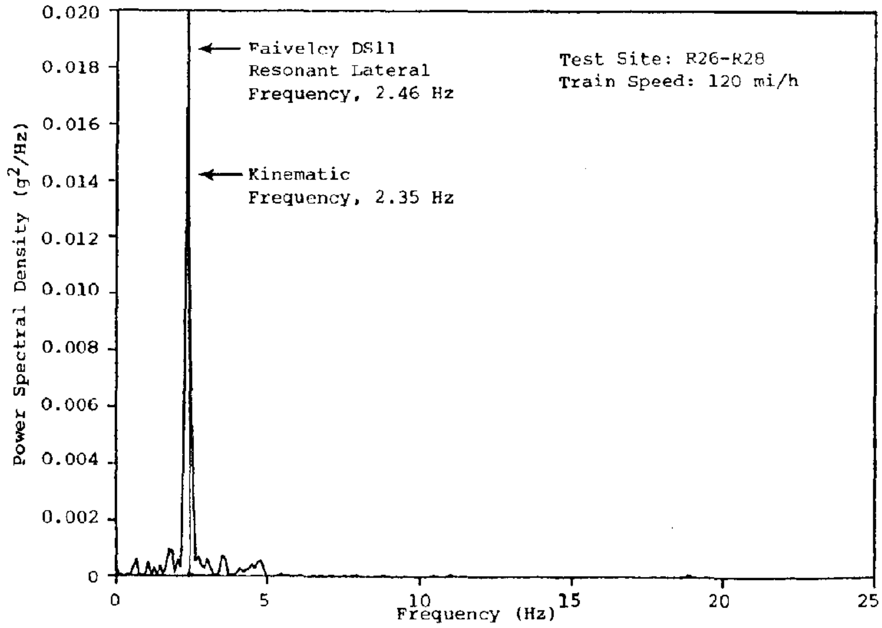
12.4.2 The AEM-7 Pantographs

In the case of the Faiveley DS 11 pantograph the lateral frequency was much lower than normal, ranging from 2.4 Hz to 2.7 Hz depending on the pantograph extension.

On the RTT the pantograph extension was such that the pantograph lateral flexibility frequency was measured as 2.46 Hz. On the south curve in particular, near stations R23 and R26, excessive lateral displacements of the pantograph head were noted. Movie film measurements of the displacement indicated a peak-to-peak amplitude of 9.75 inches at the two critical locations. As reported in section 10.1 two pantograph structural failures resulted.

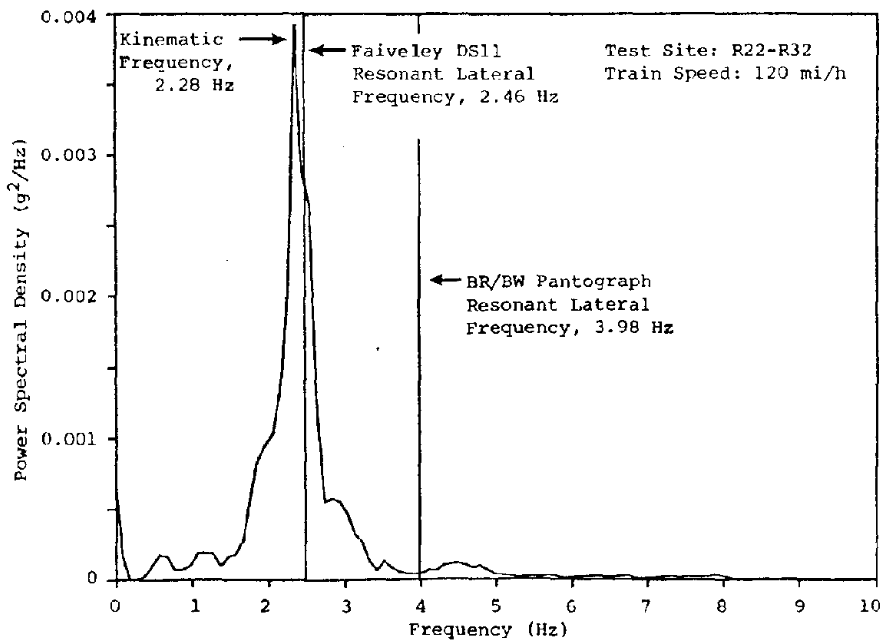
The pantograph lateral resonant frequency superimposed on the expanded PSD frequency response curve for the AEM-7 on the R26 to R28 test section is shown in Figure 12-16. The kinematic frequency input represents an acceleration input to the pantograph base of 0.085 g at 2.33 Hz. However the excitation range is from 2.15 Hz to 2.60 Hz bandwidth. The pantograph lateral frequency is strongly coupled into this bandwidth.

With the lightweight head modification, the lateral frequency rose to 2.63 Hz which lies outside the excitation bandwidth at the particular test site analyzed. However, peak-to-peak amplitudes of 5.25 inches were measured at other locations. Because of the variations in effective conicities and other effects the kinematic frequency bandwidth is variable. Figure 12-17 shows the expanded kinematic frequency bandwidth over the test section R22 to R32. The lateral frequencies for the Faiveley DS 11 pantograph and the BR/BW 'Stretched'



NOTE: This figure demonstrates the strong dynamic coupling between the kinematic frequency of the locomotive trucks and the pantograph structure. The test section selected for these data contained the maximum lateral amplitudes of the pantograph measured by the movie film technique.

FIGURE 12-16. THE FAIVELEY DS 11 PANTOGRAPH LATERAL RESONANT FREQUENCY.



NOTE: An expanded test section was used for this PSD to demonstrate the effect of a more representative length of track. The results are lower average power and a wider kinematic response. The resonant frequencies of both pantographs are superimposed.

FIGURE 12-17. THE FAIVELEY DS 11 AND BR/BW 'STRETCHED' PANTOGRAPH RESONANT FREQUENCIES IN RELATION TO THE KINEMATIC FREQUENCY RESPONSE.

unit are superimposed. The results show that the DS 11 unit is very strongly coupled and the BR/BW unit is not. Measurement of a lateral flexibility peak-to-peak amplitude of 1.0 inch for the BR/BW unit confirmed this.

12.5 YAW DAMPERS

Yaw dampers are devices which are designed to provide damping in the truck kinematic mode. Provision is made for the installation of these units on the AEM-7 but during the testing at the TTC none were actually fitted to AMTRAK 900. Therefore, any conclusion regarding the effects of these devices is purely speculative.

From the PSD plot, Figure 12-11, it can be assumed from the ratio of amplitude to bandwidth that the kinematic mode is lightly damped. Increased damping from the yaw dampers could be assumed to reduce the overall amplitude of the mode and would therefore be beneficial. However the effect of yaw dampers on the rate of wheel wear, particularly at curve entry and exit, cannot be speculated upon. Therefore, the decision not to utilize yaw dampers on AMTRAK 900 at the TTC leaves some gaps in the test data.

12.6 AEM-7 WHEEL WEAR DATA

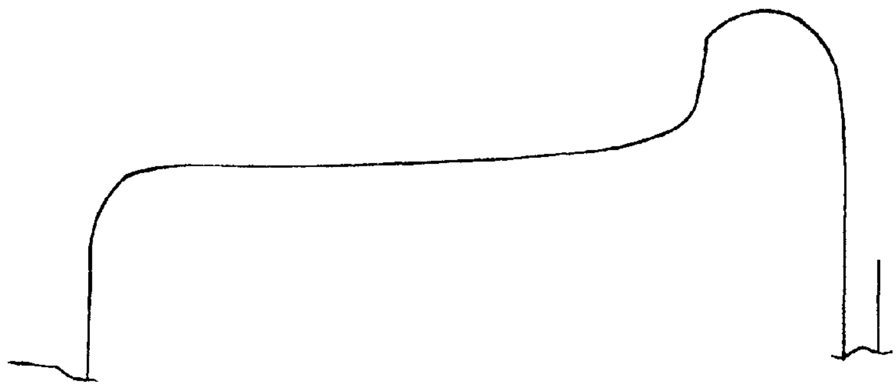
12.6.1 Presentation of Results

As described in section 12.2 three methods were used to measure the wheel profiles of AMTRAK 900 during the test program. The original measurements made with the Yoshida wheel profilometer proved to be inconsistent due to the use of different machines to make measurements during the cycle. These were, therefore, of limited value in the context of a detailed wheel wear and geometry study. The wheel measurements made with the CN profilometer for the Aerospace Corporation, and those measured with BR profilometer for TTC use provided the most reliable information, particularly for the wheel rail geometry studies later undertaken.

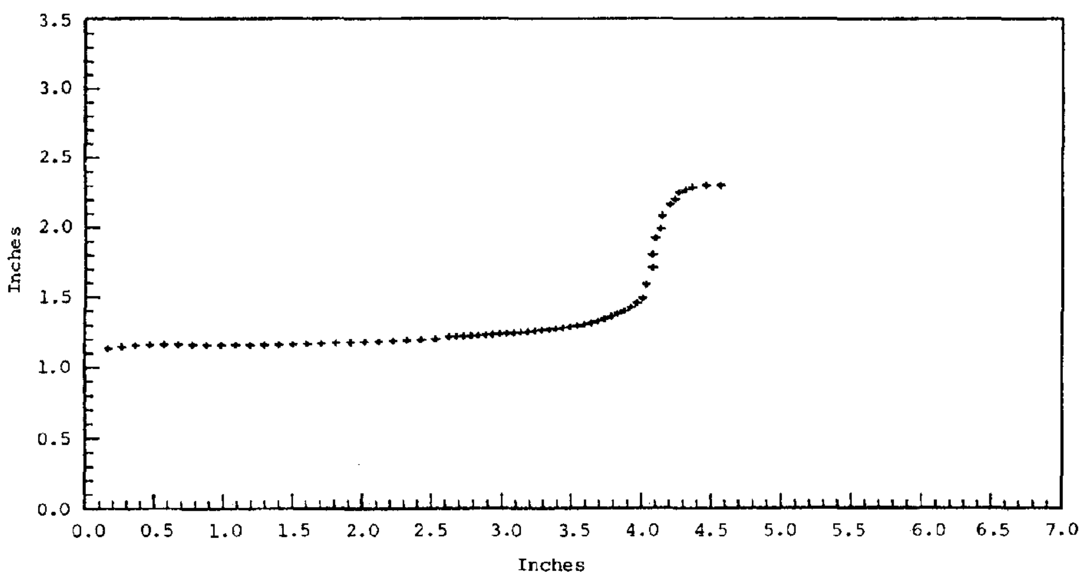
An example of the raw output of the Yoshida profilometer is presented in Figure 12-18, together with the plotted output from the CN profilometer. A typical plotted output from the BR profilometer is presented in Figure 12-19.

Two wheel reprofiling operations were carried out. The first was at 97,734 miles, the second at 166,200 miles. The first reprofiling resulted from exceedence of the thin flange condemnable limit, the second because of termination of the test program. However, it was estimated that less than 10,000 miles of wheel life were left before the second reprofiling.

Since the BR and CN profilometers first became available just prior to the 97,734 mile reprofiling, the only accurate wheel wear data available is for the 98,000 to 166,200 mileage band.



Typical Yoshida Wheel Profile



Typical CN Wheel Profile

FIGURE 12-18. TYPICAL YOSHIDA AND CN WHEEL PROFILES.

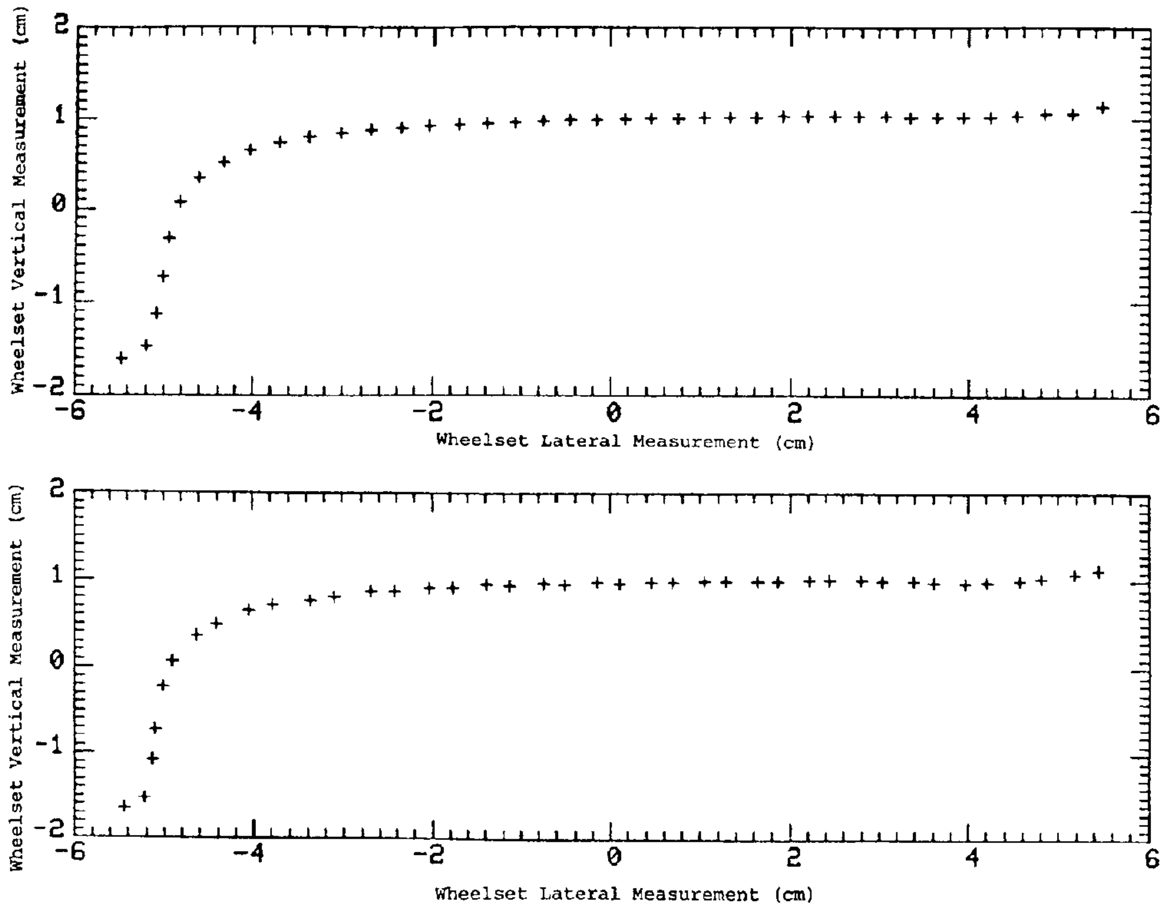


FIGURE 12-19. A TYPICAL PRESENTATION OF A BR WHEEL PROFILE MEASUREMENT.

A sequence of BR wheel profiles is presented in Figure 12-20 for two of the AEM-7 wheels. Data was, of course, taken for all wheels. The flange wear was measured along a line forming the horizontal reference of the BR profilometer coordinate system from the origin (0,0 point) of that system. The tread wear was measured along the vertical reference line from the origin. The first and last points on the plot were used as reference points for the plotted profile with respect to the top of the flange or at the extreme outside of the tread, and, where necessary, a correction factor based on the two chosen reference points on the profile was applied to the data. The combined flange and tread wear data for all wheels at the prescribed mileage intervals are presented in Table 12-9.

12.6.2 Discussion of the Data

The flange wear shows a large variation in magnitude among the individual wheels. In particular the #1 axle right wheel shows much more wear than the

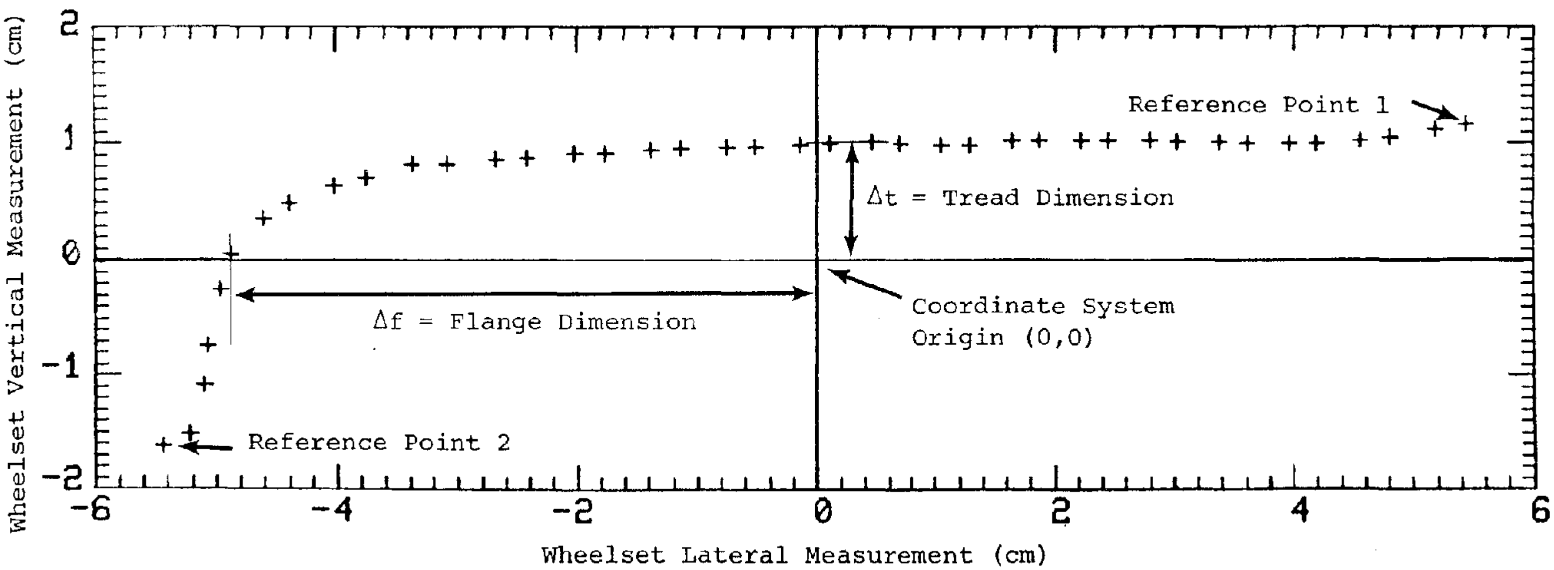


FIGURE 12-20. WHEEL WEAR MEASUREMENT AXES.

TABLE 12-9. AEM-7 LOCOMOTIVE CUMULATIVE WHEEL WEAR ON THE RTT.

Mileage	97,984				121,233				142,832				166,143			
Wheel No	Flange Tread Dim x(in)	Flange Tread Dim y(in)	Cumulative Wear Flange	Cumulative Wear Tread	Flange Tread Dim x(in)	Flange Tread Dim y(in)	Cumulative Wear Flange	Cumulative Wear Tread	Flange Tread Dim x(in)	Flange Tread Dim y(in)	Cumulative Wear Flange	Cumulative Wear Tread	Flange Tread Dim x(in)	Flange Tread Dim y(in)	Cumulative Wear Flange	Cumulative Wear Tread
1L	1.717	0.343	0	0	1.890	0.362	0.173	0.019	1.886	0.382	0.169	0.039	1.898	0.382	0.181	0.039
1R	1.693	0.350	0	0	1.909	0.378	0.216	0.028	1.937	0.386	0.244	0.036	1.953	0.398	0.260	0.048
2L	1.740	0.358	0	0	1.862	0.366	0.122	0.006	1.870	0.390	0.130	0.032	1.882	0.400	0.142	0.042
2R	1.720	0.358	0	0	1.815	0.362	0.095	0.004	1.858	0.388	0.138	0.030	1.866	0.394	0.146	0.036
3L	1.744	0.382	0	0	1.886	0.390	0.142	0.008	1.906	0.394	0.162	0.012	1.890	0.420	0.156	0.038
3R	1.717	0.346	0	0	1.839	0.350	0.122	0.004	1.819	0.374	0.102	0.028	1.937	0.378	0.220	0.032
*4L	1.740	0.382	0	0	1.768	0.390	0.028	0.008	1.811	0.394	0.061	0.012	1.815	0.394	0.075	0.012
*4R	1.728	0.378	0	0	1.740	0.378	0.012	0.000	1.740	0.386	0.012	0.008	1.783	0.386	0.055	0.008

NOTE:

* Wheelset #4 changed at 102,917 due to axle bearing failure. Wear data corrected for difference in measured flange back spacing of the old and new wheelset.

#2 right wheel. One the other hand, the tread wear is much more uniform among the wheels within the realms of accuracy of measurement.

From the wheel profile data alone it appears that the rate of wear is rapid within the first 20,000 miles. Thereafter the rate of wear is much slower. Visual observation and periodic flange thickness measurements confirmed this finding.

From the ride quality data there is evidence to support the theory that the initial rapid wheel wear takes place within the first 2000 to 3000 miles. The initial wheel profiles taken after 250 miles show very little wear, which is not suprising since the first 100 miles were run at 60 mi/h in order to 'roll' the new profiles in. By the time the ride quality was taken at 2500 miles the lateral ride, dominated by the kinematic mode, had already settled into what was to become a substantially consistent ride quality over the remainder of the wheel life. It can therefore be assumed that the wheelsets had already developed their high conicity curving characteristics at the 2500 mile point.

A sequence of expanded wheel and rail profile overlays are presented in Figure 12-21 (new wheel profile) and Figure 12-22 (worn wheel profile). The new wheel profile in flange contact shows a substantial gap at the flange root. Evidence of this was photographed (Figure 12-23) during early wheel profile life.

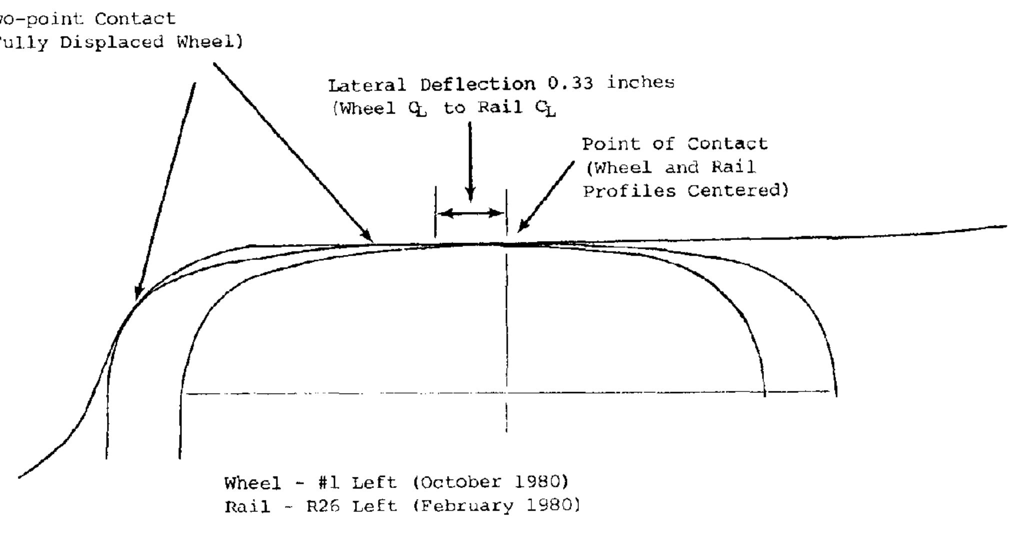
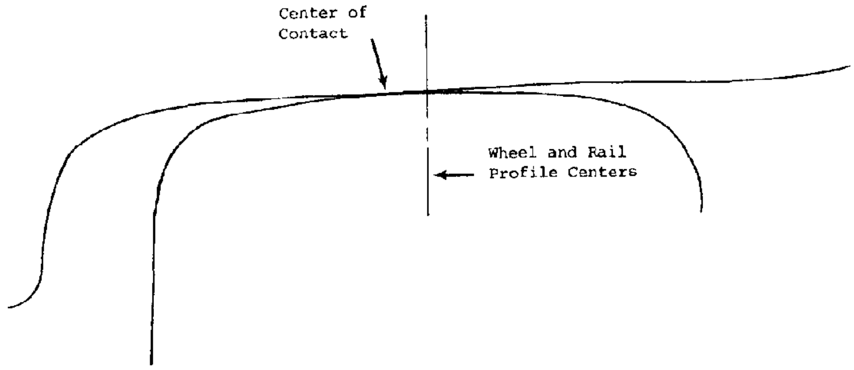
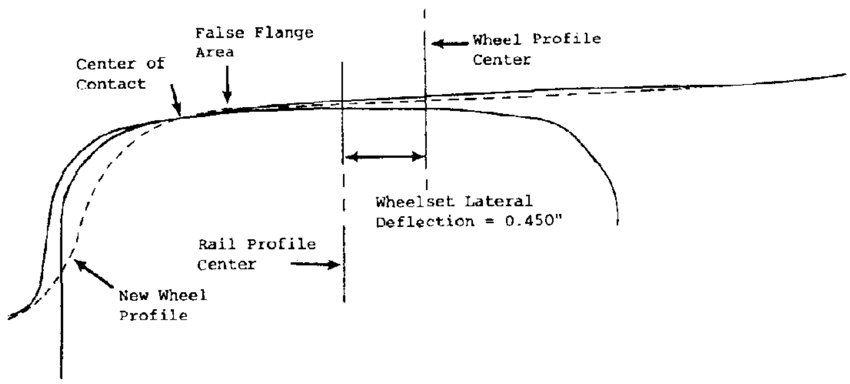


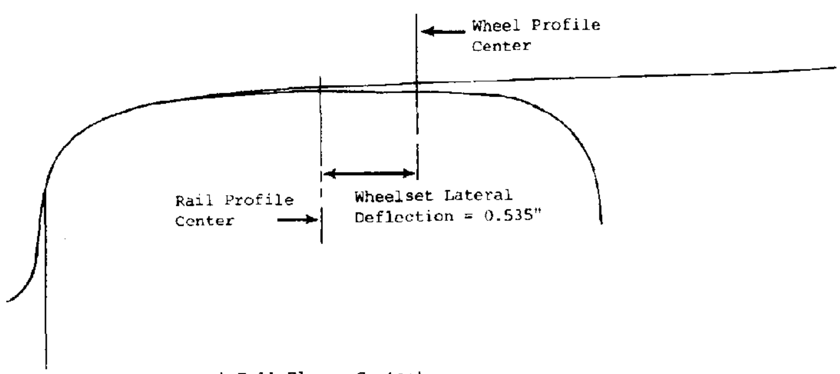
FIGURE 12-21. WHEEL/RAIL OVERLAY (NEW WHEEL).



a) Centered Wheelset



b) False Flange Contact



c) Full Flange Contact

Wheel Profile - #1 Left (February 1980)
Rail Profile - R26 (February 1980)

FIGURE 12-22. WHEEL/RAIL OVERLAY (WORN WHEEL).

FIGURE 12-23. VIEW OF THE INITIAL RAPID FLANGE WEAR PATTERN.

On the other hand the worn wheel shows a large area of contact between wheel and rail at flange contact. Also the gap at the flange root has disappeared. A false flange has also formed at approximately 0.100 to 0.200 inches before full flange contact. This was probably formed by plastic flow of the wheel material into the original flange root gap coupled with grinding of flange face due to the profile mismatch.

One aspect of wheel wear which caused concern during the early stages of the test were gouges at the top of the flange (Figure 12-24). After approximately 40,000 miles of the endurance test these disappeared, although a brief recurrence was noted at approximately 120,000 miles. No definite explanation of these marks was found, the most likely causes were considered to be either a badly aligned rail joint or switch frog.

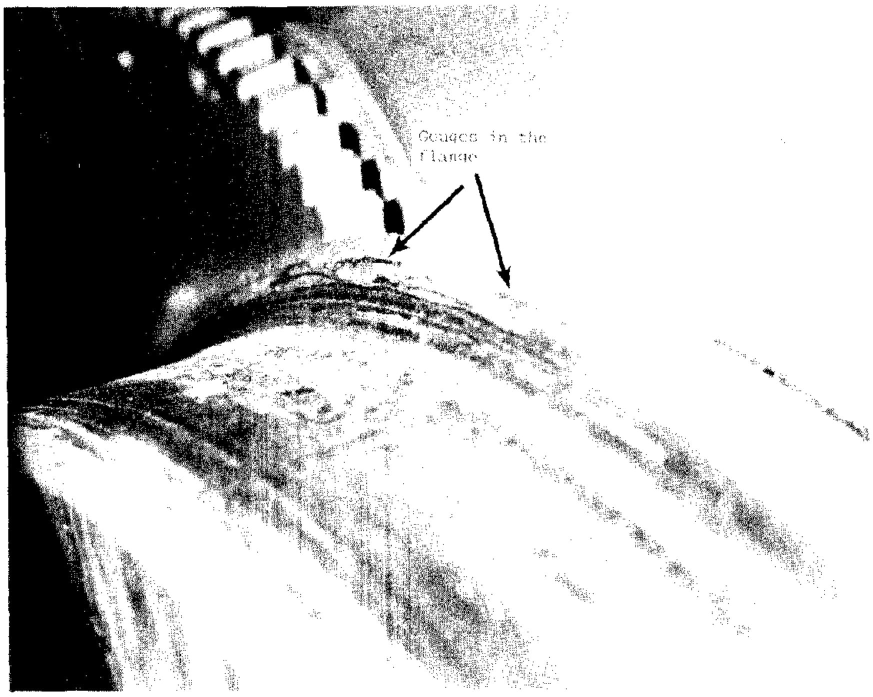


FIGURE 12-24. AEM-7 LOCOMOTIVE WHEEL GOUGES.

The main contributory factor in the rate and pattern of wheel wear of AMTRAK 900 was undoubtedly the relatively high proportion of curved track with a uniform railhead profile. However, the RTT curves were much less severe than the majority of curves on the NEC. Two aspects of the wheel wear suggest that the truck curving performance can be improved.

- The unequal wear of the left and right wheels on the individual wheelsets was probably caused by wheelset misalignment within the truck frames. The direction of rotation of the consist on the RTT was alternated on a daily basis to ensure that each wheel saw equal operation as the high and low rail wheel. With perfectly aligned wheelsets equal wheel wear on each wheelset would therefore have been expected. Due to the pantograph problems it was not possible to alternate the lead end of the locomotive on a weekly basis as planned, therefore the #1 and #3 wheelsets were the lead wheelsets for 80% of the operations. Therefore, unequal wear of the wheelsets would have been expected.

- The flangeway clearance provided by the existing new wheel profiles may not be adequate to allow generation of the necessary steering forces to avoid hard flange contact on large radius curves.

Wheel wear data collected during the fleet operation on the NEC will provide a better base for judging the long term performance of the AEM-7 trucks.

13.0 GROUND BRUSH RETURN CURRENTS

13.1 DESCRIPTION

As described in section 5.2.6, the locomotive primary current returns to the running rails, and hence to the substation, through a grounding transformer and ground brush assemblies on the axle ends (Figure 13-1). The grounding transformer is designed to force the total current in the transformer primary winding to flow through the ground brush leads. Since the locomotive underframe is the common connection on the grounding transformer no net current flow is permitted into the locomotive underframe. Excluded from this arrangement are capacitive leakage currents from the transformer and associated connections, and the overvoltage potential transformer current. However, these are considered to be negligible.

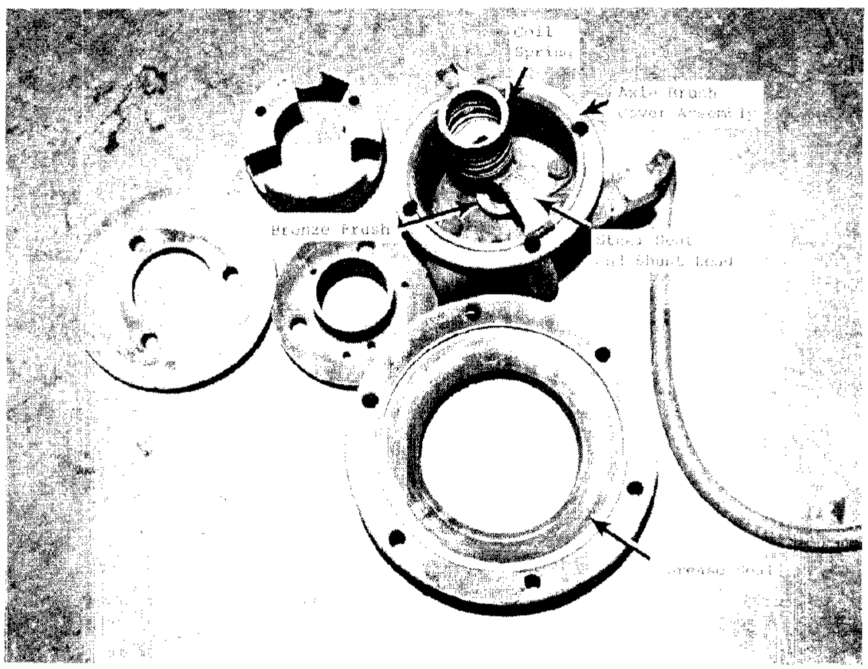


FIGURE 13-1. AXLE BRUSH ASSEMBLY (GENERAL VIEW).

The grounding brush assemblies consist of a spring loaded steel seat (Figure 13-2) mounted on the axle and pressing against a bronze ring located in the axle brush cover assembly (Figure 13-3). Electrical continuity is provided by means of braided copper straps between the seat and axle, and by direct connection of the ground transformer output cable to the cover assembly. A rotating seal is provided to exclude axle bearing grease from the axle brush assembly.

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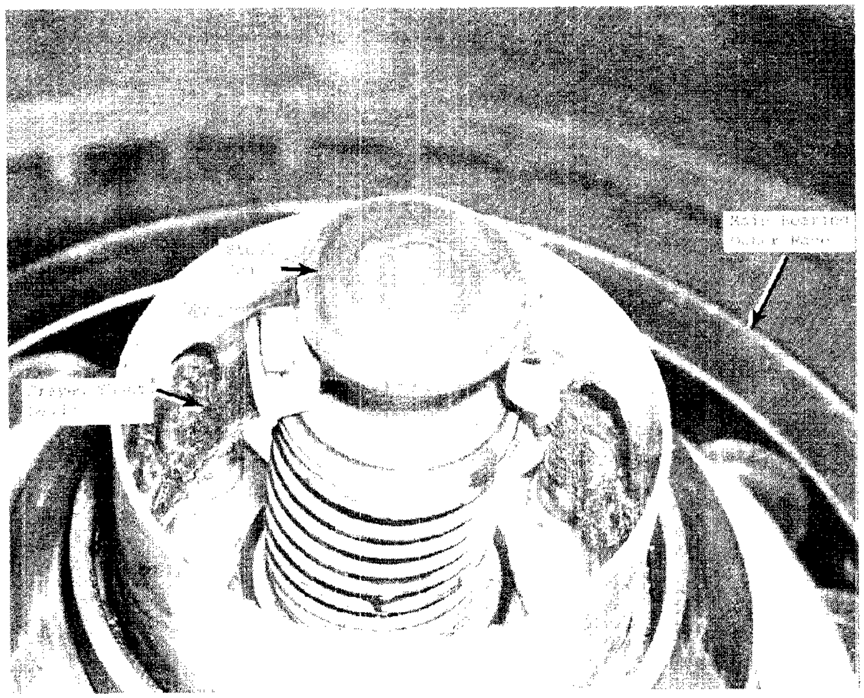

FIGURE 13-2. AXLE BRUSH ASSEMBLY (STEEL SEAT).

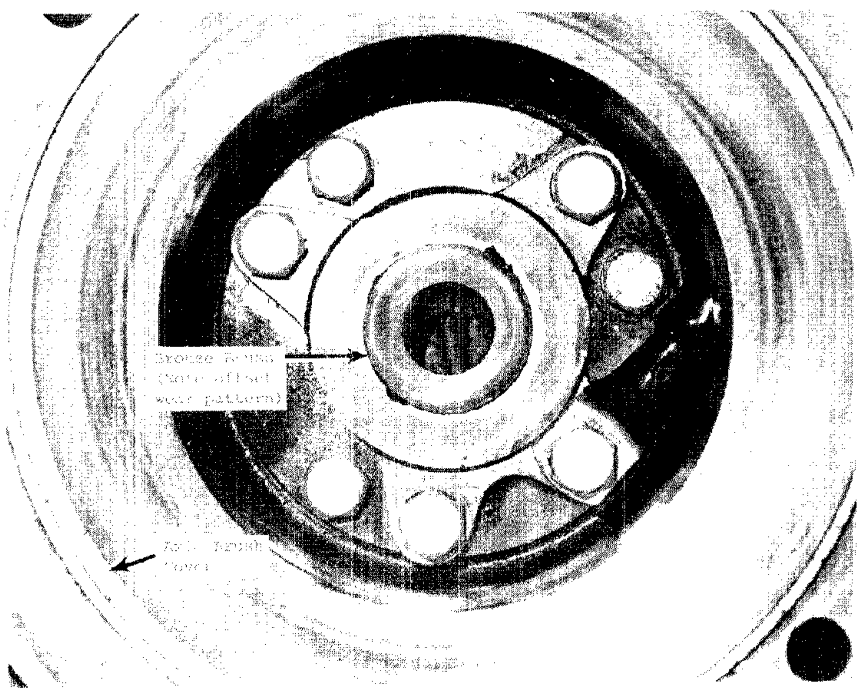

FIGURE 13-3. AXLE BRUSH ASSEMBLY (BRONZE BRUSH).

13.2 MECHANICAL PERFORMANCE

Periodic inspection of the axle brush assembly showed there to be uneven and eccentric wear of the bronze brush ring. The results of this can be seen in Figure 13-3. Comparisons of the four axles showed that the #1 axle brush had fully worn by 140,000 mi, whereas the #2 and #3 axles were less than half worn. The #4 axle brush was replaced at 110,000 miles because of fire damage.

Severe fraying of the axle seat continuity braids was also noted as can be seen in Figure 13-2. The probable cause was thought to be an 'egg beater' effect caused by incursion of grease past the seal into the axle brush chamber. This leakage was noted on a number of occasions, particularly after bearing repacking. The axle brush housings were found to contain varying quantities of grease. This implies that the seal arrangement is a borderline design case under certain conditions.

13.3 ELECTRICAL PERFORMANCE

13.3.1 Current Distribution Tests at Standstill

After the main axle bearing failure in November 1980, and the subsequent discovery of possible electrical erosion of the bearing rollers on AMTRAK 901 on the NEC, the adequacy of the axle brush arrangement became suspect. Currents measurements were made on each axle brush cable using a clip-on ammeter while the locomotive was stationary. The results showed that two axles, #2 and #4, each carried 40% of the total current, #1 carried 20% of the total, and #3 carried a negligible component. On the basis of these results provision was made to measure the axle brush current distribution under mobile conditions and with full current flowing through the ground brushes.

For the full scale current measurements a 250 A current transformer was fitted to each of the axle brush leads. The output signals were cabled to the on-board instrumentation system where they were recorded on analog tape for subsequent replay onto a strip chart.

13.3.2 Axle #3 Cable Connections

During the instrumentation checkout for the traction power current distribution measurements it was again noted that the #3 axle brush was not carrying current. During the subsequent investigation it was discovered that no continuity existed through the ground brush cable between the grounding transformer and the axle brush assembly. The reason for this was found to be in the axle brush cabling arrangement.

To avoid difficulty during the locomotive detrucking operation the cable from the grounding transformer is terminated on the locomotive underframe on a standoff insulator. A separate cable then provides the connection to the axle box. On the #3 axle the mechanical arrangement at the standoff insulator logically called for the connection to be made with one cable on either side of the insulator on the terminal bolts provided. However, it was discovered that no electrical continuity existed between the bolts. The cable connections were both remounted to one terminal bolt and the fault cleared. The connection had been made incorrectly before arrival at the TTC and was perpetuated during each of the detrucking operations.

13.3.3 Current Distribution Measurements with Traction Power

After the #3 axle brush connection was corrected, a number of measurements were made of the following major parameters.

- Axle #1 ground current
- Axle #2 ground current
- Axle #3 ground current
- Axle #4 ground current
- Main transformer primary current
- Pantograph Voltage
- Train Speed

Measurements were made under various load, speed, and line voltage conditions. A representative sample of the data is presented in appendix F.

13.4 DISCUSSION OF RESULTS

13.4.1 Ground Brush Leakage

No evidence was found of leakage of the return current from the ground brush system. Based on the data presented in appendix F the total current through the transformer primary winding is shared among the four axle brushes to within the instrumentation accuracy of $\pm$ 5%.

13.4.2 Ground Current Distribution

The ground current distribution among the axles is erratic. At slow speeds the 3-4 axle pair shows a slightly less stable performance than the 1-2 pair. However at the higher speeds (between 70 and 115 mi/h) all four ground brush currents become unstable.

The wheel rotational periodic time has been superimposed on a number of the data examples. It can be seen that the wheel rotation has a significant effect on the pattern of distortion. At 115 mi/h the pattern is more broken in nature, indicating possible breakdown in efficient current transfer.

At low current levels and slower speeds some of the ground brushes cease to conduct current completely. However, the brush combination conducting current under these conditions is not consistent. All these factors seem to indicate that the brush current distribution is a finely balanced system.

When looking for the causes for the ground brush behavior, two aspects of the mechanical inspection are relevant:

- The presence of grease in the ground brush housing.
- The eccentric and uneven wear of the ground brush.

The inconsistent performance of the individual brush assemblies over a period of time could be explained by the presence of grease on the conducting surface interfaces. The wheel interference with the brush current could be due to eccentricity in the ground brush and axle alignment, which at high speeds would probably result in intermittent contact. This demonstrates the critical nature of the axle brush alignment.

One positive finding of this test was that the grounding transformer was functioning correctly by forcing the total current through the ground brush assemblies, choosing the instantaneous path of least impedance to ground through the individual brushes.

14.0 CONSIST VEHICLE DESCRIPTIONS

14.1 AMFLEET CARS

14.1.1 Standard cars

A total of four standard AMFLEET cars were available for all or part of the AEM-7 endurance test. Three were allocated directly for the AEM-7 test program, and one was allocated as a reference car for the Radial Axle Passenger Truck program.

The cars were equipped with the standard trucks and braking systems, no special provisions were made for high speed running since the cars were designed for 120 mi/h operation. In order to maintain a Head End Power load for the locomotive, all air conditioning, lights, and heating systems were made operational.

14.1.2 RAPT car

The RAPT test vehicle consisted of a standard AMFLEET carbody mounted on experimental trucks which were designed for 120 mi/h operation. Since these trucks were part of a separate test program a description of them is not within the scope of this report. Whenever the RAPT vehicle was in the AEM-7 consist its performance was monitored by the test crew as part of its test program. From the equipment standpoint it was fully compatible with the four standard AMFLEET cars.

14.2 TTC VEHICLES

14.2.1 DOTX-211 Pantograph Test Car

The pantograph test car is fully described in reference 1. It is a converted AMTRAK passenger car built in 1953. The trucks, which were manufactured by American Steel Foundries for 90 mi/h operation, are of the conventional coil spring primary vertical and secondary vertical suspension, swinging bolster lateral suspension design. The main axle bearings are taper roller bearings. The braking system consists of air actuated composition brake shoes applied to the wheel treads. Since the car was originally steam heated and battery lighted, no HEP load could be utilized by this car.

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14.2.2 DOTX-208 Instrumentation Car

The instrumentation car was equipped complete with electrical services. This car was originally built as a hospital car with a maximum speed of 65 mi/h. This car had been speed upgraded to 120 mi/h for short duration high speed testing. However, the main axle bearings are of the oil bath lubricated, plain journal type, which are not designed for continuous high speed running. The braking system, as with the DOTX-211 car, is a conventional tread brake system.

14.2.3 DOTX-210 Car

This car is similar to the DOTX-211 except that no conversion work has been carried out on the car for test purposes. Slight differences exist in the truck and braking systems. The main bearings are parallel roller bearings with thrust faces manufactured by Hyatt Bearing Company. A disc brake system is used on the DOTX-210 car instead of tread brakes.

14.3 AMTRAK SLEEPER CARS

Two redundant sleeper cars were provided by AMTRAK to augment the AEM-7 consist. These cars had recently been removed from revenue service and were in storage. The trucks and braking systems on these cars were identical to the DOTX-210 car, except that the wheel bearings were taper roller bearings. The maximum service speed of these vehicles was 100 mi/h, but they were successfully speed upgraded to 120 mi/h for AEM-7 test purposes.

15.0 CAR MAINTENANCE

15.1 GENERAL

The assessment of the car performance was not originally part of the AEM-7 test plan. In addition the plan did not call for the assessment of the car maintenance schedules. It is sufficient to say that the maintenance was carried out using the approved AMTRAK and AAR procedures. The main highlights of the car failures and problems are outlined in sections below.

15.2 AMFLEET CARS

In general the AMFLEET cars proved to be reliable mechanically. Apart from a small number of loosened components, traction arms for example, the trucks performed well throughout the endurance test.

The braking systems withstood the high speed braking loads without major failures of the brake discs. The brake shoe life averaged approximately 9,000 mi during normal operations with locomotive blended brake, and less than 8,000 mi without blended brake when the locomotive operated for extended periods with traction motors cut out.

The average period between wheel machining for the AMFLEET cars was approximately 60,000 mi. This did not include cases where the wheels were machined because of flat spots. It was also noted that the wheel wear was uneven. This applied in some cases to a pair of wheels on a wheelset and in other cases to wheelsets on a vehicle. It should be noted that the cars in the consist were regularly turned both with regards to lead end of the cars and to the direction of travel on the RTT.

The only major problem associated with the AMFLEET car maintenance was the electrical control equipment such as automatic door openers and the air conditioning switch gear. These were found to be susceptible to the ingress of sand and dust.

15.3 OTHER VEHICLES

The major share of the consist maintenance effort was applied to the fleet of conventional type vehicles. The only exception to this generalization was the DOTX-211 car. It ran for approximately 100,000 mi before removal from service for wheel truing. It was subsequently found that two of the wheelsets had insufficient rim thickness for further machining. Consequently the DOTX-211 car was unavailable for service until replacement wheels could be procured. During the period it was operational the DOTX-211 car suffered no major failures and was the most reliable car in the consist.

For the other conventional cars in the consist performance is summarized below:

- DOTX-208. This car ran for 10,000 mi before the journal bearing overheated and seized. This car did not run in the AEM-7 consist thereafter.

- DOTX-210. Major problems included numerous broken and loose truck components, a cracked brake disc rotor, a broken suspension coil spring, and a condemnable wheelset. In general the maintenance requirement for this vehicle was high for the 50,000 mi it formed part of the consist.

- AMTRAK 2151 and 2153 (Sleeper Cars). The AMTRAK sleeper cars required the heaviest maintenance of all. The 2151 car accumulated less than 10,000 miles; the 2153 car accumulated approximately 30,000 mi. Both cars suffered cracked brake disc rotors, broken and loose shock absorber brackets and traction rods. Additionally, the 2151 car suffered brake gear failure.

The maintenance costs for the conventional type vehicles were not justified by the technical benefits of continuous use of these cars in the consist. Consequently, toward the end of the endurance test program, the conventional cars were only used when special purpose tests called for a large consist.

16.0 TRACK MAINTENANCE

16.1 TRACK BALLAST STRENGTHENING

A detailed inspection of the RTT structure was carried out before the AEM-7 program commenced. It was determined that at a number of locations on the track, the ballast shoulders and ballast cribs did not meet the FRA Class 6 track specifications. A reballasting operation was initiated which required a total of 47 100-ton cars of ballast to complete. Meanwhile, a maximum speed restriction of 90 mi/h was imposed on the AEM-7 locomotive and consist when the rail temperature exceeded 95°F until the track reballasting was complete.

16.2 ROUTINE TRACK MAINTENANCE

16.2.1 Track Car

Before the start of each test operation the RTT was inspected using the special purpose track car. The track car, which consists of a platform rigidly attached to two short wheelbase wheelsets, is designed to react to all track irregularities. When operated by an experienced track inspector, this unit provides a qualitative assessment of the track alignment.

The purpose of this inspection during the AEM-7 program was to look for gross distortions in the track resulting from such phenomena as sun kinks, broken rails, or track shift. In addition, all switches were manually inspected by the track car operator for any irregularities. In general the full inspection for the 13.5 mi track took 2 hours to complete.

16.2.2 Plasser EM80C and Railflaw Measurements

At approximately two week intervals the RTT was inspected using the Plasser EM80C (track geometry) and Railflaw detection vehicles. The EM80C data was useful in documenting the RTT general track standards at regular intervals.

The purposes of this twofold inspection were as follows:

- To provide a quantitative measure of the track geometry based on exceedences of the Class 6 track standard.
- To detect the initiation of metallurgical flaws within the rail structure which might lead to possible rail break situations.

16.2.3 Vehicle Operator "Rough Track" Reports

Reports of bad or rough track entered in the test controller's daily logs were transmitted to the Track Maintenance Supervisor. On the basis of the report, together with recent track car inspection reports and EM80C data, the Track Maintenance Supervisor initiated remedial action. After an initial familiarization period, certain trouble spots became predictable. One of these, switch 305B, was removed in July 1980 because of its heavy maintenance.

17.0 CATENARY MAINTENANCE, REPAIRS, ALTERATIONS, AND SPECIAL MEASUREMENTS

17.1 MAINTENANCE FACILITIES AND SCHEDULES

17.1.1 Overhead Catenary Maintenance Vehicle

As part of the RTT catenary construction and commissioning program the TTC was provided with a road/rail vehicle (Figure 17-1) designed specifically for catenary maintenance. This vehicle, which was one of eighteen procured by NECPO for NEC catenary maintenance, has proved to be extremely useful for TTC catenary maintenance purposes.

FIGURE 17-1. OVERHEAD CATENARY MAINTENANCE VEHICLE.

The maintenance vehicle converts from a standard four wheel road vehicle to a rail vehicle by means of hydraulically applied rail trucks at the front and rear. In the rail mode the front road wheels are lifted clear of the rails, but the rear road wheels are maintained in contact with the rails for traction purposes.

Access to the catenary is provided by means of a variable height, hydraulically operated lifting platform with a capacity of 2,000 lbs. For safety reasons the platform is completely surrounded by handrails with a gate for access.

17.1.2 Catenary Maintenance Periods

The maintenance periods for the catenary were based on the requirement to assess the long term reliability of the lightweight Style 5 catenary as part of the experimental investigation. These do not necessarily reflect the maintenance requirements of the equivalent catenary system on the operational railroad.

Two maintenance periods were chosen for the catenary during the program:

- A monthly inspection was carried out to look for major problems such as excessive contact wire wear or erosion, bent or loose hangers, and loose brackets.

- An annual inspection was made before the AEM-7 program commenced in which the catenary components and fittings were individually checked for wear, tightness, and distortion. The thoroughness of this inspection was abnormal for an annual catenary maintenance inspection, but was deemed necessary because the system had not been inspected since construction.

17.1.3 Inspection Procedures

The RTT catenary was inspected from the platform of the overhead maintenance vehicle with the catenary isolated and grounded. The platform was raised to approximately 6 ft below contact wire height. Two maintenance personnel were positioned on the platform, one on each side of the catenary. The vehicle was driven by an operator at speeds between 5 and 10 mi/h around the RTT while the inspectors on the platform observed the catenary for damaged or loose components. For detailed inspection or repair the operator was signalled to stop the vehicle and back up. Major items not requiring immediate attention were noted for future remedial action.

17.2 ROUTINE MAINTENANCE FINDINGS

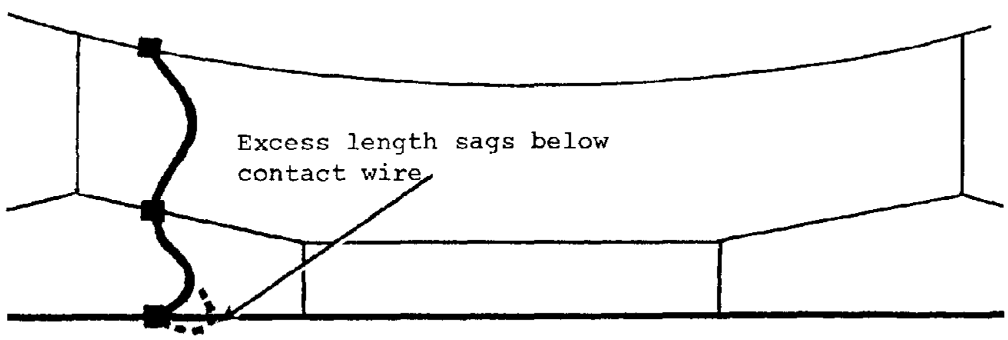
17.2.1 General

During the annual inspection, a large number of loose components was found, mainly hanger clips. In addition, three cantilever assemblies were found to be misapplied and were changed out.

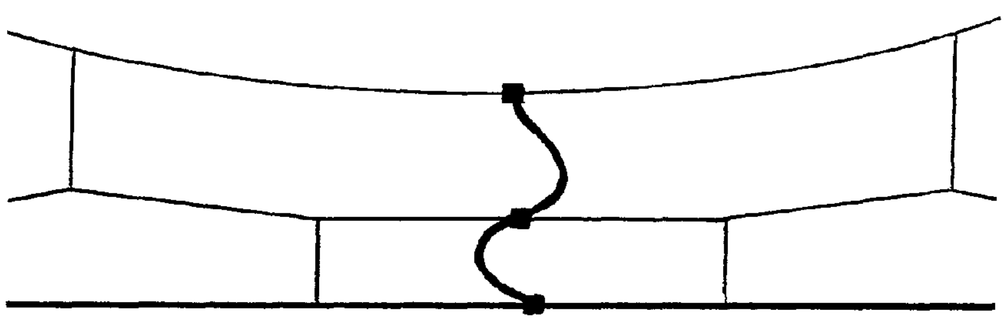
17.2.2 Equalizing Jumpers

The in-span equalizing jumpers showed signs of fraying of the strands of copper. As a result a design change has been recommended. In the original design[12] the equalizing jumper is routed from the main messenger to the auxiliary messenger and then to the contact wire. The equalizing jumper is held at right angles to the auxiliary messenger by the wire clamp. Thus the jumper has a natural tendency to sag toward the contact wire, and because of the small separation between contact wire and auxiliary messenger, the jumper is bent through a small radius to avoid sagging below the contact wire.

A more convenient routing for the equalizing jumper is proposed (Figure 17-2) in which its attachment to the auxiliary messenger is rotated through 90° so that the jumper lies parallel to auxiliary messenger. This forms a more natural "s" shape for the equalizing jumper and removes the neccessity for the tight bends and the tendency of the jumper to sag below the contact wire.



a) Original Jumper Configuration



b) Proposed Alternative

FIGURE 17-2. CATENARY EQUALIZING JUMPER (ALTERNATIVES).

17.2.3 Contact Wire Kinks and Splices

During the construction of the catenary some irregularities were built into the system. These included a number of contact wire kinks and a contact wire splice. Other irregularities were added as a result of the dewirement. Although contact wire irregularities are normally undesirable in high speed catenary, these particular features in the system provided the opportunity to study the effect of irregularities on contact wire wear.

Particular attention was focused on a contact wire kink at station R37+600 in the Style 3 catenary. This had been identified as a large loss of contact during the dead line tests. The kink (Figure 17-3) was approximately 0.25 inches deep with an along-track wavelength of approximately 6 inches. There were also smaller kinks on either side of the one described above.

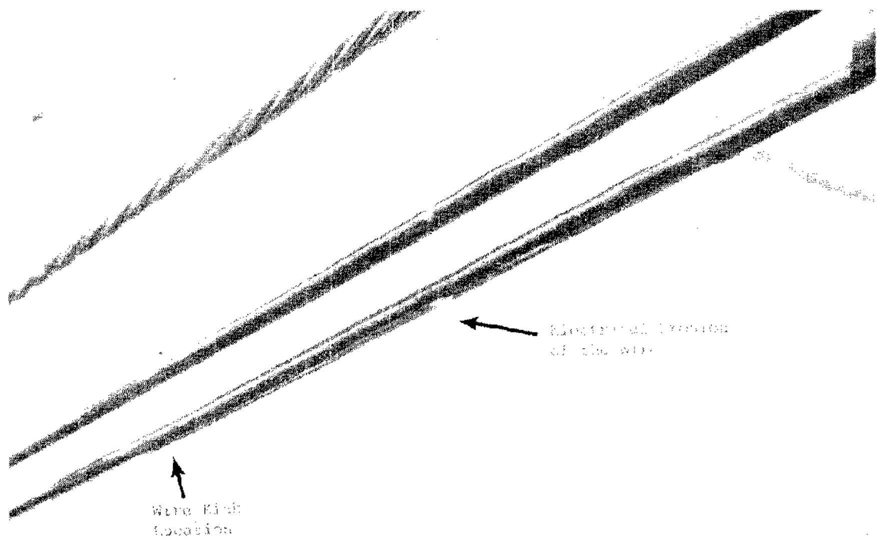
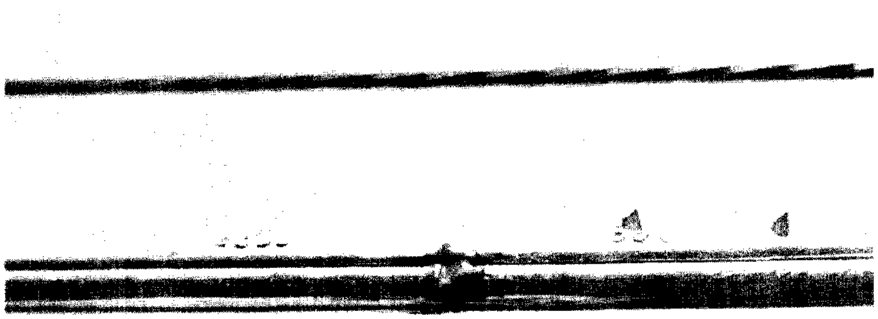


FIGURE 17-3. CONTACT WIRE KINKS.

During the September 1980 catenary inspection it was noted that the contact wire had become worn at the kink location, and that heavy copper spatter was present for a distance of 12 ft on either side of the kink. Measurement of the wire depth with a micrometer showed a decrease in diameter of 0.029 inches representing a 2.7% reduction in cross sectional area. Elsewhere in the system the general wire wear was measured as 0.003 inches decrease in diameter (0.1% reduction in cross-sectional area). These measurements compare with a maximum permissible wire wear of 20% reduction in cross-sectional area.

After the measurements were taken the wire kink was straightened. The straightening process is time consuming, requiring the use of a soft mallet and soft supports. The use of an Alloy 80 contact wire further complicated the process, since the material is non-ductile. The contact wire straightening process was designed to prevent further localized wear. Measurements taken at the end of the test program showed that the wire had worn a further 0.002 inches, representing a decrease in diameter of 0.031 inches from new or a reduction in cross-sectional area of 3.2%.

Other irregular contact wire features studied included two splices, one example of which is shown in Figure 17-4. These demonstrate the irregular wear resulting from such devices, and how they can shorten the wire life by accelerating the local wire wear. Both splices remained in the contact wire until the end of the AEM-7 program without further problems.



Mechanical and
Electrical Wire
Damage

FIGURE 17-4. CONTACT WIRE SPLICE.

17.2.4 Lightning Damage

During the AEM-7 test program the RTT catenary was struck by lightning at least four times. On each occasion the substation breaker opened to protect the substation transformer. On each occasion the cantilever (crossarm) insulators were damaged, but not sufficiently to require immediate replacement. A typical example of lightning damage is shown in Figure 17-5. It was clear from these incidents that the ground wire on the top of the masts was not 100% effective in protecting the catenary from lightning strikes, although it is not known how many lightning strikes the ground wire did receive.

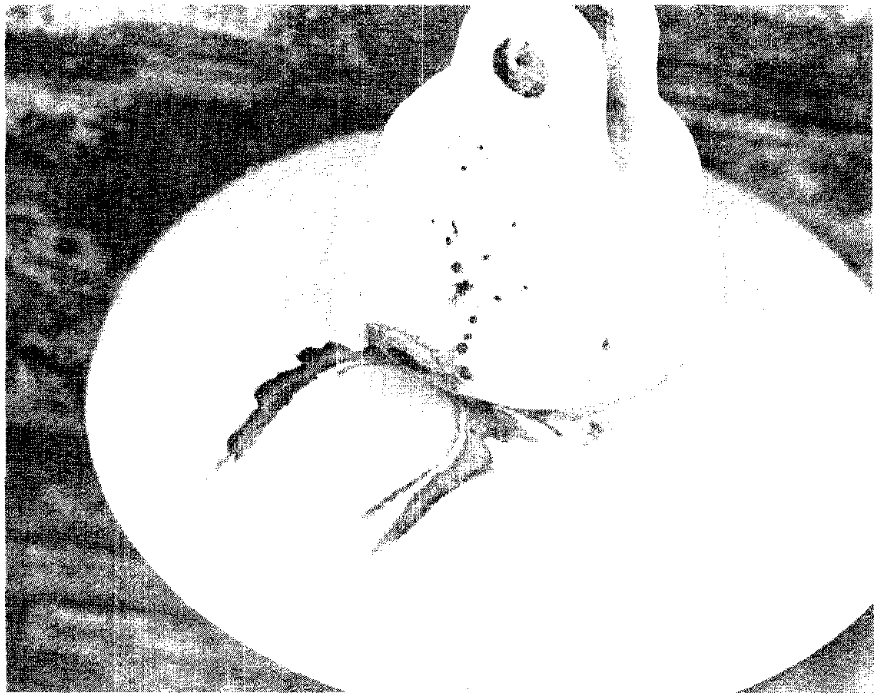


FIGURE 17-5. CATENARY INSULATOR - LIGHTNING DAMAGE.

17.3 THE DEWIREMENT

17.3.1 Description

On July 26, 1980, the upper stage of the DS11 pantograph on the 'F' end of AMTRAK 900 fractured causing the pantograph to dewire. Damage was caused to the catenary system between RTT stations R20 and R32, a distance of 12,000 ft. Half of one tension section of catenary was brought down (Figure 17-6) necessitating the replacement of 3,000 ft of auxiliary messenger, the whole section of contact wire (5,200 ft), and several cross arm assemblies and registration arms. Two further tension sections received lesser damage, mainly to registration arms (Figure 17-7) and lower hanger assemblies. The total damage was not severe considering that the incident occurred when the consist was travelling at 120 mi/h. However, the extent of the damage was compounded by a design fault in the pantograph lowering mechanism which

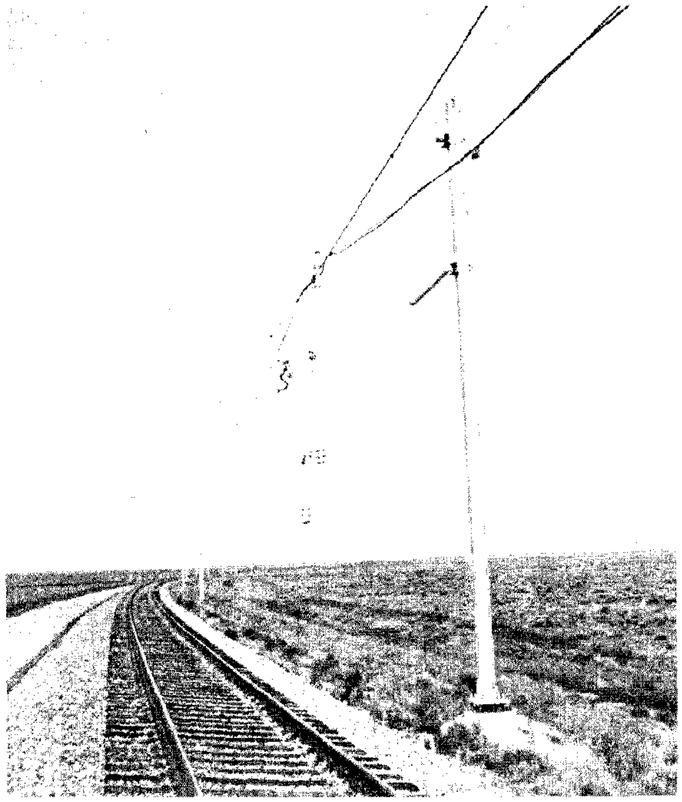


FIGURE 17-6. GENERAL VIEW OF THE DEWIREMENT DAMAGE IN TENSION SECTION #3.

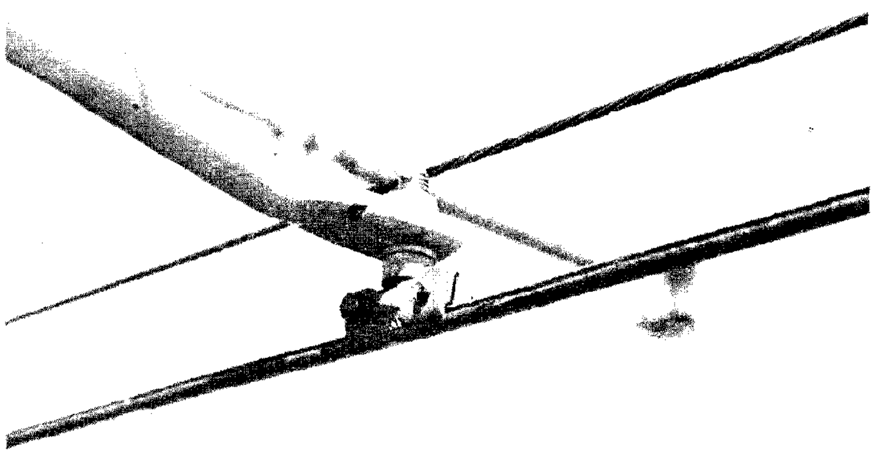


FIGURE 17-7. DAMAGED REGISTRATION ARM IN THE 'LIGHTLY' DAMAGED SECTIONS.

allowed the lower stage to lock itself up in the fully extended position so that the pulldown rod was unable to lower the pantograph. Lowering had to be accomplished by hand once the locomotive had come to a standstill. Much of the damage in the second and third tension sections would have been avoided had the pantograph lowered when commanded to do so.

17.3.2 Catenary Repair

Major repairs were required in the first damaged tension section (#13) in which the first 2,500 ft of contact wire and auxiliary messenger were pulled down leaving the main messenger intact. To help matters, the mid-point anchor held, which kept the second half section in place, although the contact wire was subsequently replaced because of severe scoring and kink damage.

To expedite the restringing of the catenary, the Southern Colorado Power Company repair crew was hired to assist, together with a local contractor. No heavy equipment existed at the TTC to string the contact wire by the traditional railroad method so the contact wire was hauled through using power line stringing methods. Since no rotational restraint was imposed on the wire during stringing, it tended to twist as it ran. As a result, 36 twists had to be taken out of the wire during the clipping in process. A further delay was caused by the bolt type hangers used in the RTT design, which proved to to be time consuming to install, and these should be avoided where possible in future designs.

The spare contact wire provided under the original construction contract was in three 3,000 ft lengths. Two lengths had to be used with a mid-section splice. As a result, the wire was unavoidably kinked where grips were used in mid span to secure the splice. To avoid this in the future, a 6,000 ft drum of wire has been procured.

In tension sections #14 and #15, damage was limited to displaced and bent registration arms and ripped out hanger clips. Each time the registration arm was hit by the pantograph frame, the arm was forced along the contact wire causing a kink and a gouge in the retaining groove. Kinks formed in this way cannot be fully removed, thus numerous small kinks still exist, mainly at structures. The gouges in the contact wire caused by the registration arm and hanger clips effectively reduce the cross sectional area of the wire and hence the wear allowance. One such gouge has reduced the local cross-sectional area by an estimated 10%, or one half of the wear allowance. Since this is in close proximity to a kink, careful maintenance will be required to avoid heavy wear at that location in the future.

17.4 CATENARY BLOWOFF MEASUREMENTS

17.4.1 Background

One of the most critical aspects of catenary design which affects the maximum span length or pantograph head width is the allowance to be made for blowoff (crosstrack deflection) of the catenary under high crosswind conditions. Since the catenary is fixed laterally at the structures the maximum blowoff occurs at mid span. The blowoff allowance used in catenary design has to take account of lateral motion under iced wire conditions, since the layer of ice on the wires effectively increases the diameter of the wire and hence the wind resistance. While it was not possible to measure the blowoff of the catenary at the TTC with ice on the wires, a method was derived to measure the blowoff under dry wire conditions. This method is described below.

17.4.2 Blowoff Measurement Methodology

The method used to measure contact wire blowoff was similar to that used to measure pantograph lateral flexibility. A movie camera was mounted on a rigid frame, Figure 17-8, attached to the track at mid-catenary span vertically below the catenary wires. The camera was set up to look vertically upward with the contact wire in the center of the frame under still air conditions. A suitable lens was fitted to the camera to give a field of view of 10 inches on either side of the contact wire mean position.

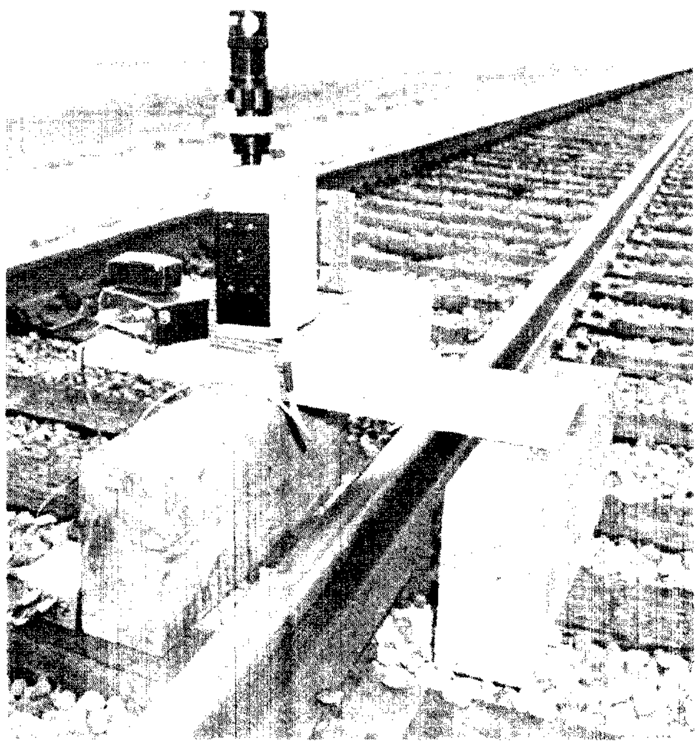


FIGURE 17-8. BLOWOFF MEASUREMENTS - CAMERA MOUNTING.

An anemometer to measure the wind speed was set up on the roof of a data van (Figure 17-9) which also contained the recording instrumentation and camera remote control. The data van also provided the house power required to run the instrumentation and camera. A time code generator was provided to synchronize the wind speed measurements and film frame by inserting a time code signal simultaneously on the recorder and on the film frame edge.

FIGURE 17-9. BLOWOFF MEASUREMENTS - DATA VAN.

The test equipment was assembled in the data van awaiting the first weather report of potentially high wind conditions. Once the report was received the equipment was dispatched to an RTT location which was predicted to receive a cross wind. The equipment was set up as described above and made ready for operation.

Data were taken when the wind gusts reached 20 mi/h. A typical data run consisted of a burst of film and wind speed recording of approximately 10 seconds duration. The anemometer output was monitored to detect high wind gusts, and with experience, it became possible to recognize the patterns of wind rise and fall. Data was collected over a range of wind speeds from 10 mi/h to 35 mi/h during the particular storm front selected for the test. To provide a zero reference, the contact wire was filmed the following day under still air conditions, after which the equipment was dismantled.

The film was processed and set up on the Film Motion Analyzer described in section 10.2.3. The center of the frame was used as the zero reference, and the contact wire diameter used to determine the frame scale factor.

Due to an incompatability between the time signal from the generator and the camera system decoder, the time reference was not superimposed on the film frame. An alternative analysis method was used to extract the data in which the maximum displacement in each 10 second burst of film was matched to the maximum air speed measured in the corresponding 10 second length. This method required a large number of data points to compensate for the data scatter. The results are presented in Figure 17-10 as a graph of blowoff displacement against the square of the wind speed.

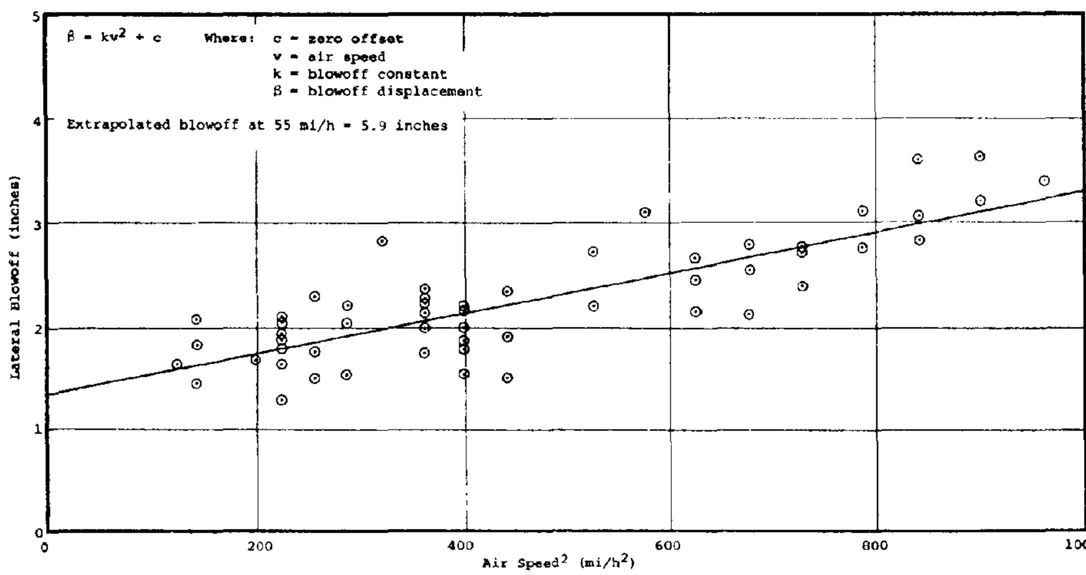


FIGURE 17-10. LATERAL BLOWOFF DATA.

17.4.3 Discussion of Blowoff Test Results

The data presented in Figure 17-10 exhibit a large scatter about the mean line, and a zero offset. The zero offset was caused by the camera not being set up with the contact wire exactly in mid frame, and has no relevance to the measurements. The data scatter resulted from a combination of the method used to reduce the data and the film rate chosen to record the wire motion.

The predicted blowoff of the contact wire for a cross wind of 55 mi/h was 6.4" using the Suberkrub method.[14] Extrapolation of the measured data to an equivalent wind speed of 55 mi/h gives a blowoff value of 5.9 inches, a difference of 8%. Considering the method by which the data were reduced, and the extrapolation of data, this agreement is as good as can be expected. If a time reference signal had been successfully applied to the film frame it is anticipated that the measurement accuracy could have been improved to better than 4%. Steps must be taken in any further blowoff measurements to provide the time reference and to provide data up to 50-60 mi/h.

17.5 GRADED CATENARY

In March 1981 authorization was given to install a length of graded catenary in the RTT system. The tension section between R12 and R17 (#11) was selected for this installation, mainly because it was on tangent track.

It was decided to install different gradients on either side of a low point so that, by making use of both directions of travel, pantographs could be assessed on two gradients.

The first gradient of 1:600 (or 0.167%) represented the maximum recommended gradient for 120 mi/h. The second gradient of 1:400 (or 0.25%) represented a typical gradient which presently exists on high speed sections of the NEC. The height change between the low point and the normal wire height was determined by a requirement not to adjust the overlaps. Consequently the gradients started at the first support structure beyond the overlap span support structure.

A layout diagram of the actual graded catenary section is presented in Figure 17-11. As shown in the diagram the transition from level wire to the 0.167% gradient was immediate at both ends of the shallower gradient. A half gradient span was provided at either end of the 0.25% gradient section for blending purposes. One span of level catenary was retained at the low point between the graded sections, although the normal "hard spot" associated with bridge supports was not simulated.

17.6 STRUCTURE TO TRACK BONDS

During the initial phase of the AEM-7 program the structure-to-track bonds and the track-to-substation return connections were ripped out by the track maintenance machines. Examples of the damaged components are shown in Figure 17-12.

At first the bonds were simply replaced, but were again damaged at the next track maintenance operation. The original routing of the bonds along the top of the ties was analyzed and found to conflict with the maintenance machinery requirements. The bonds were replaced once more, but this time were rerouted along the face of the tie and vertically downwards to below the ballast layer. No further problems were experienced thereafter with the bonds that had been rerouted. The remaining bonds are to be rerouted in the course of normal maintenance.

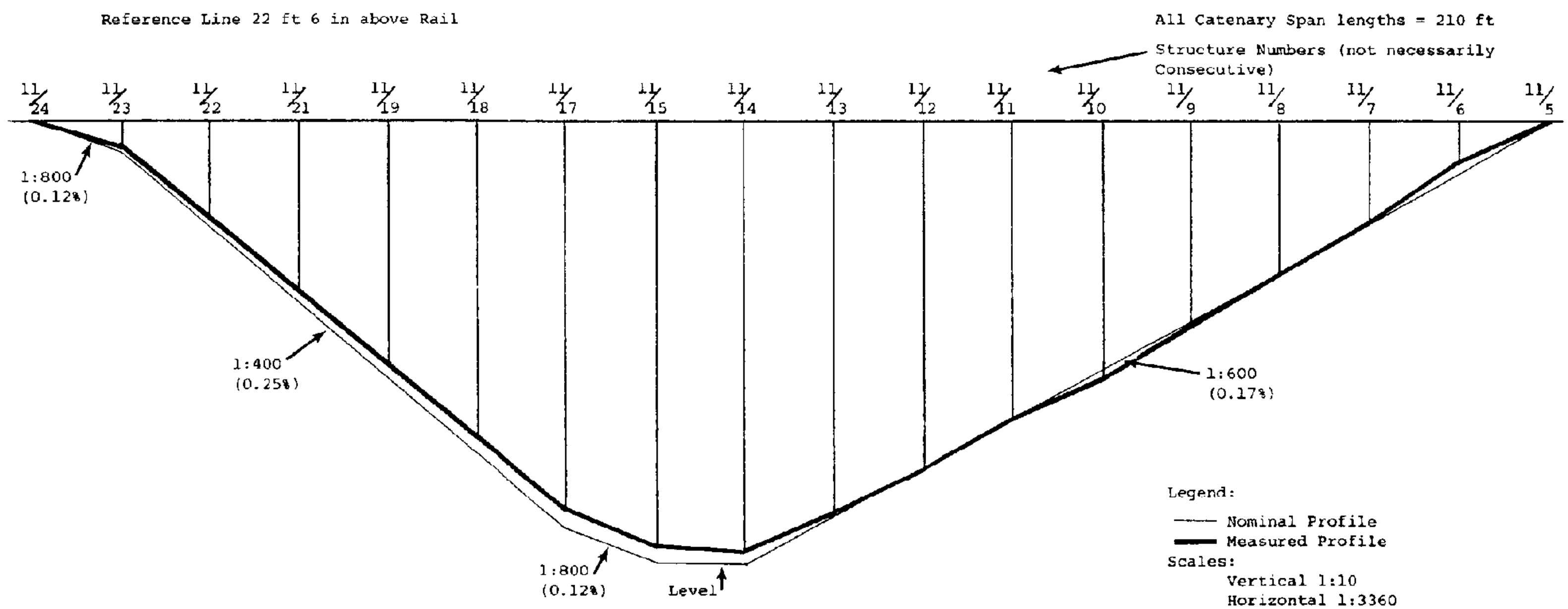


FIGURE 17-11. GRADED CATENARY PROFILE.

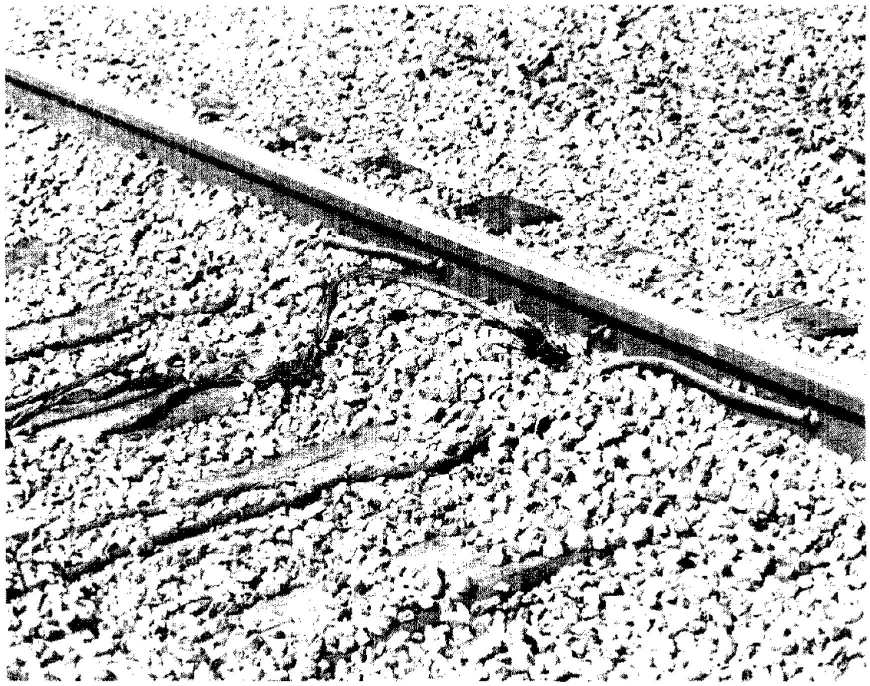


FIGURE 17-12. DAMAGED TRACK AND SUBSTATION BONDS.

18.0 ADDITIONAL PANTOGRAPH TESTS

18.1 SUMMARY OF THE EARLIER DEAD LINE TEST RESULTS

Since the early dead line tests are fully described in reference 1, only a brief summary of the test results and conclusions will be included in this document.

Dead line pantograph tests are carried out on an isolated and grounded catenary system to enable the necessary transducers to operate at ground potential. Measurement parameters include mechanical loss of contact, and computed contact force between pantograph head and contact wire. Based on an acceptability criterion of not greater than 1% loss of contact, it was concluded that the single stage Faiveley pantograph should be limited to a maximum speed of 100 mi/h on the RTT catenary, but the Faiveley DS 12 (two stage) pantograph was acceptable for 120 mi/h on all but the Style 3 catenary. However, it was recommended that the Style 3 catenary be retained in the RTT system for the duration of the AEM-7 test to provide data on wire wear.

18.2 ADDITIONAL TESTS ON THE FAIVELEY DS 12 PANTOGRAPH

18.2.1 Test Objectives

The purpose of the additional tests on the Faiveley DS 12 pantograph was to investigate the effect of ambient temperature change, and hence the conductor tension changes of the Style 1 and 3 catenary systems, on the pantograph current collection performance.

18.2.2 Test Method

The Style 1 and 3 catenary systems were set up to simulate four ambient temperatures, namely 0°F, 30°F, 60°F, 90°F. This was accomplished by changing one end of the two half tension sections from a fixed termination to a balance weight tensioned system. The correct number of weights were then applied to the balance weights to provide the total tension equivalent to the desired temperature.

The test train consisted of the DOT-001 locomotive, the Instrumentation car DOTX-208, and the pantograph test car DOTX-211. Test runs were made in a counterclockwise direction of travel round the RTT with pantograph performance data being recorded from station R46 to R22. Test speeds were 60, 70, 80, 90, 100, 105, 110, 115, and 120 mi/h. The data channels recorded were:

- Loss of contact
- Contact Force
- Pantograph Head Trajectory

- Structure Location
- Train Speed
- Automatic Location Detector
- IRIG B time code

18.2.3 Data Reduction and Presentation of Results

For an initial 'quick look' assessment the data was reduced to produce percentage loss of contact against train speed at each of the representative temperatures for the three test sites defined in Table 18-1.

TABLE 18-1. CATENARY TEST SITES FOR DEAD LINE PANTOGRAPH TESTS.

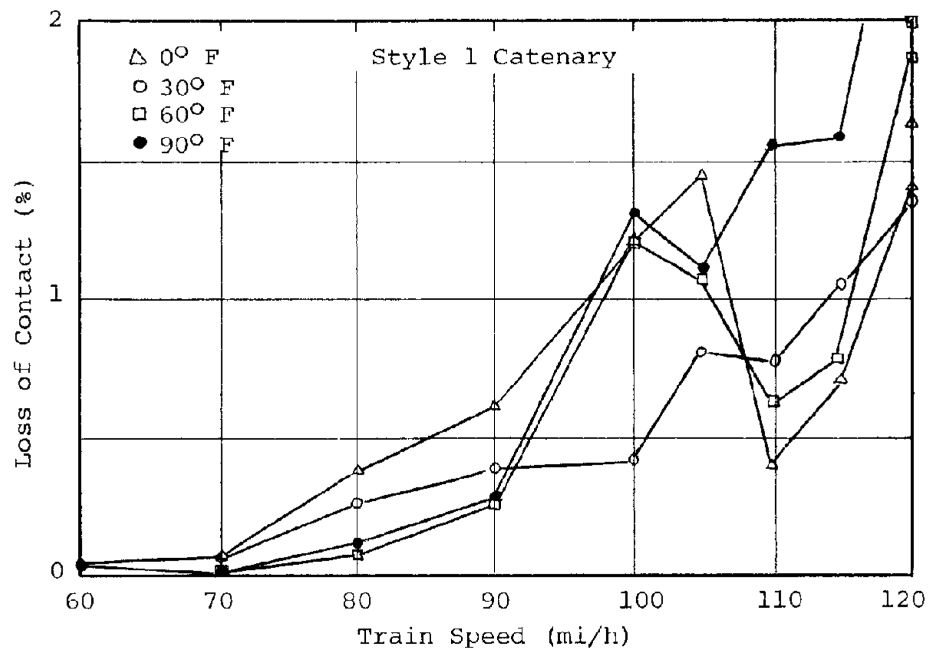
CATENARY DESIGN	TEST SITE (COUNTERCLOCKWISE)
Style 5	R46 + 150 to R39 + 450
Style 3	R38 + 700 to R36 + 700
Style 1	R36 + 200 to R33 + 900

The results for the Style 1 and 3 catenaries are presented in Figure 18-1, the data for the style 5 test length are presented in Figure 18-2.

18.2.4 Discussion of Test Results

The results for the Style 1 and 3 catenary designs (Figure 18-1) indicate that the current collection performance is dependent on temperature. However, in the case of the Style 1 catenary the relationship is not clearly defined by the data available. Two of the temperatures (0°F and 60°F) give a performance curve with an apparent improvement in performance in the 110 mi/h region while the other two temperatures do not. The most likely reason for the indicated change in performance characteristics is considered to be the errors associated with the selection of data blocks for analysis coupled with the short overall length of the test zone. Data block lengths could only be defined to the nearest whole second in a test zone time length of 12 to 18 seconds. If a large loss of contact was situated near the end of the test zone it is conceivable that it could be included in some time slices and not in others. Since the overall test zone is so short, one large loss of contact would make a large difference in the measured percentage loss of contact.

The Style 3 catenary shows a much clearer relationship with temperature, indicating that the optimum performance occurs at an equivalent temperature of 30°F. The consistency in indicated performance of the Style 3 catenary



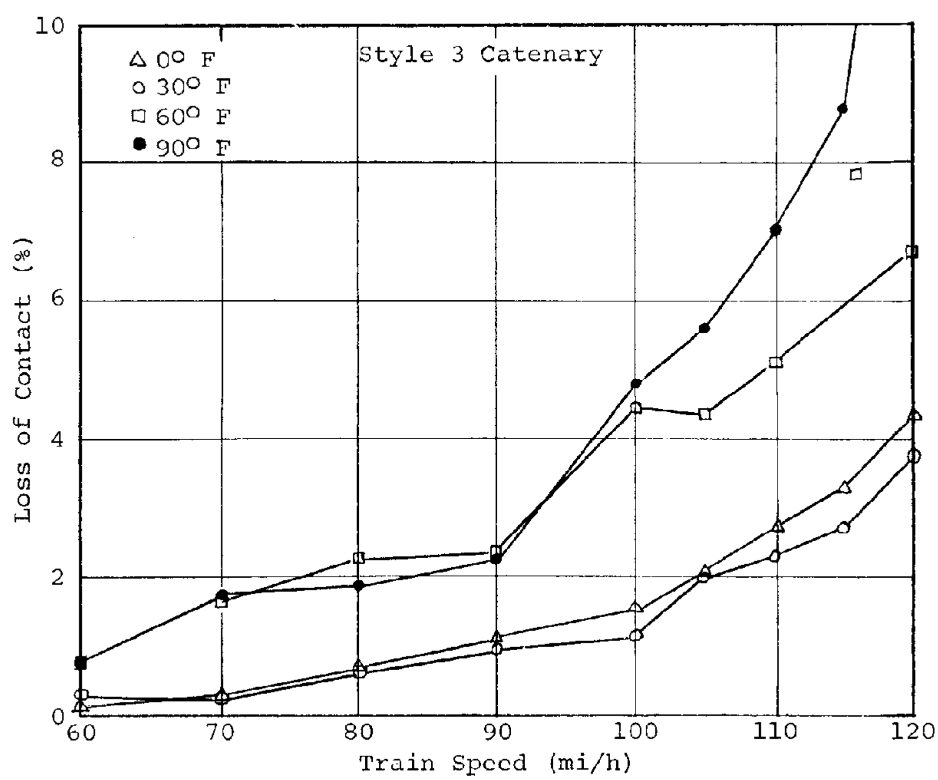


FIGURE 18-1. LOSS OF CONTACT DATA FOR THE FAIVELEY DS 12 PANTOGRAPH ON THE STYLE 1 AND 3 CATENARIES AT DIFFERENT SIMULATED TEMPERATURES.

results from the fact that the known large losses of contact were near the center of the test zone.

The data for the Style 5 catenary presented in Figure 18-2 is a measure of the repeatability in performance, since no attempt was made to modify the tensions of this equipment. Therefore, all four test runs represent the same nominal operating conditions. The results indicate a large scatter in equivalent data points for the four test runs considered. A single test data set for a lower pantograph uplift force is also presented.

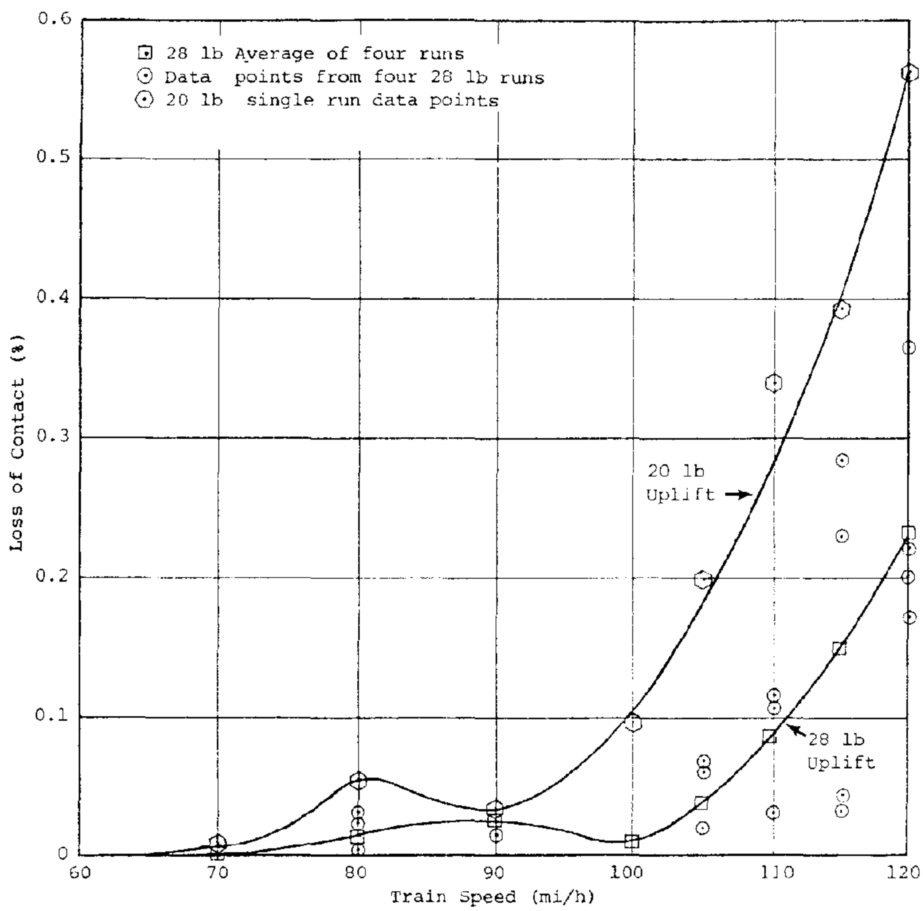


FIGURE 18-2. LOSS OF CONTACT DATA FOR THE FAIVELEY DS 12 PANTOGRAPH ON THE STYLE 5 CATENARY.

The reasons for the data scatter are not clear but could result from a combination of the following:

- Variations in uplift force due to slight differences in set up procedures.
- Variations in uplift force due to changes in aerodynamic forces.
- Variations in conductor tensions due to friction in the system causing stick-slip action of the catenary tension balance weights.
- Variations in speed over the test length.

An indication of the effect of uplift force change is given by the two curves presented in Figure 18-2.

The factors affecting the style 5 catenary performance also affect the Style 1 ad 3 catenary performances. These systems were also further complicated by the fact that tensions were being modified as part of the test, but the individual conductor tensions were not measured since a proposal to incorporate load cells to do this was rejected. In the case of the Style 3 catenary no provision was made to adjust the tension of the support wire. It must be concluded that the conditions were not adequately controlled to provide an accurate measure of system performance at a set temperature, but were adequate to indicate trends.

The catenary system was set up for the AEM-7 test program on the basis of these tests to give the best overall performance, particularly the overlap between the style 1 and 3 catenaries. Accordingly, the tensions of the Style 1 and 3 catenaries were set at the following values.

Catenary Style	Total Tension (lbs)	Equivalent Temperature (°F)
1	10,800	60
3	12,700	30

18.3 CURRENT COLLECTION PERFORMANCE EVALUATION OF THE PROTOTYPE BRITISH RAIL/BRECKNELL WILLIS PANTOGRAPH

18.3.1 Background

While the BR/BW pantograph was not tested as part of the NECPO funded program, the results of the test are considered relevant to the later pantograph testing carried out on the AEM-7 locomotive. The test results are therefore presented in summary form.

18.3.2 Test Method

The pantograph was mounted on the DOTX-211 car at a lockdown height of 16 ft. Test runs were made at the same speeds and direction of travel over the test lengths (specified in Table 18-1) as were used for the DS 12 tests. The dead line instrumentation system was used to measure loss of contact and contact force. A percentage loss of contact against train speed graph was produced for each of the styles of catenary. These tests were carried out at uplift forces of 20 and 28 lbs.

18.3.3 Presentation of the Data

The data is presented in Figure 18-3 (20 lb uplift) and Figure 18-4 (28 lb uplift) shown superimposed on the equivalent data for the Faiveley single stage and dual stage (DS 12) pantographs.

18.3.4 Discussion of Results

The BR/BW pantograph gives a significantly improved performance on all styles of catenary at both uplift forces. On the basis of this comparison the pantograph was considered acceptable for 120 mi/h operation on the TTC catenary system. The decision to use this unit on the AEM-7 after the July 1980 dewirement was based partly on the findings of the performance evaluation test, and partly on the convenience of substitution of this unit for the DS 11 pantograph.

18.4 DEAD LINE TESTING OF THE FAIVELEY DS 11 AND BR/BW 'STRETCHED' PANTOGRAPH ON THE AEM-7 LOCOMOTIVE

18.4.1 Background

Soon after the start of operations with the AEM-7 it became clear that the current collection performance of the Faiveley DS 11 pantograph was not as good as would have been expected from the dead line testing of the DS12 'prototype' unit. At first visual qualitative assessment in the form of direct observation and movie film was used to document the DS 11 pantograph performance in its various stages of modification. This relied on the subjective opinion of observers with varying degrees of experience in assessing pantograph arcing.

When the BR/BW 'stretched' pantograph was made available for evaluation and later when the lightweight pantograph head modification was carried out on the DS 11 pantograph it became important to assess quantitatively the pantograph performances. It was recommended that a simple dead line test should be made on both the BR/BW 'stretched' pantograph and the modified Faiveley

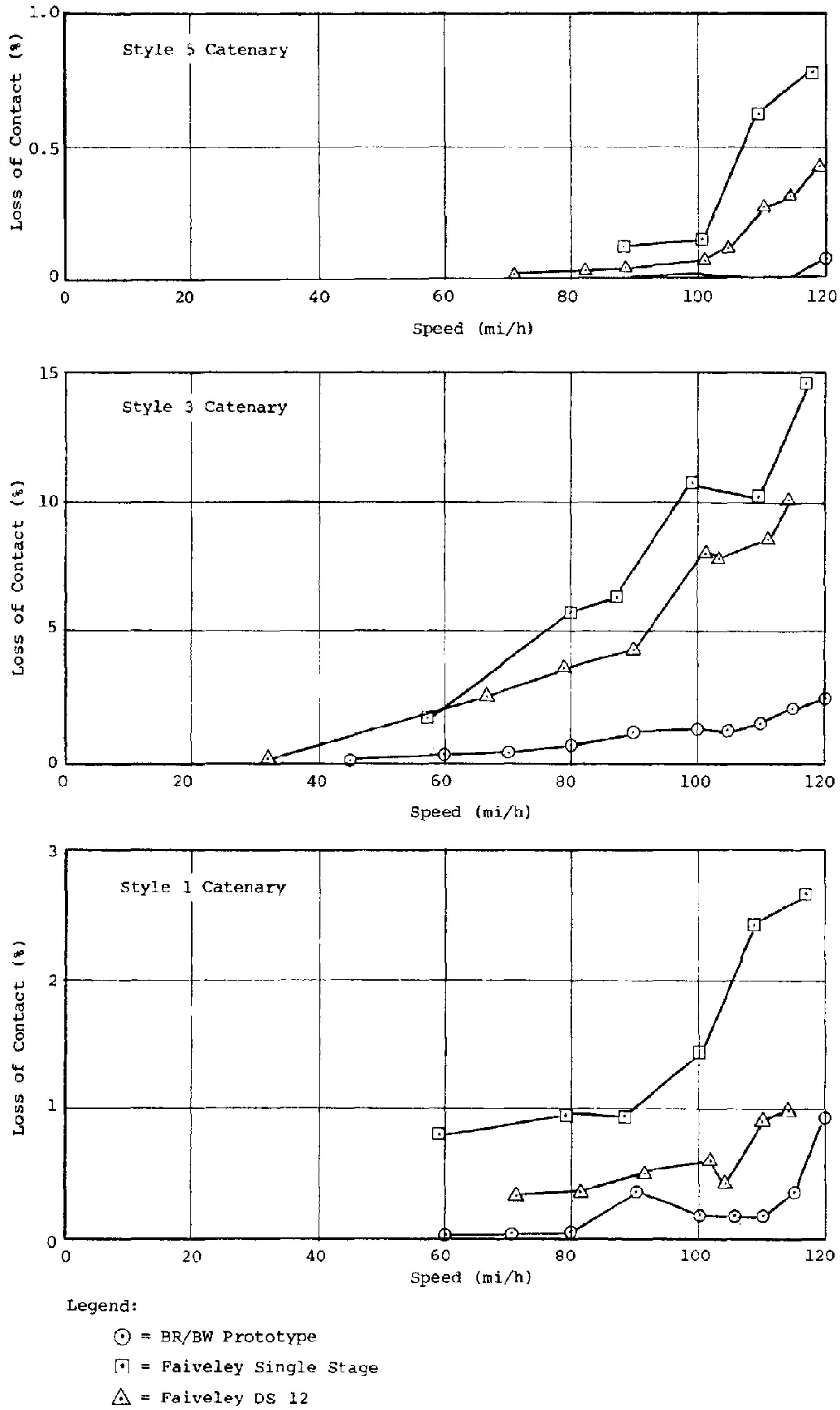


FIGURE 18-3. LOSS OF CONTACT DATA FOR THE BR/BW PROTOTYPE PANTOGRAPH (20 LB UPLIFT).

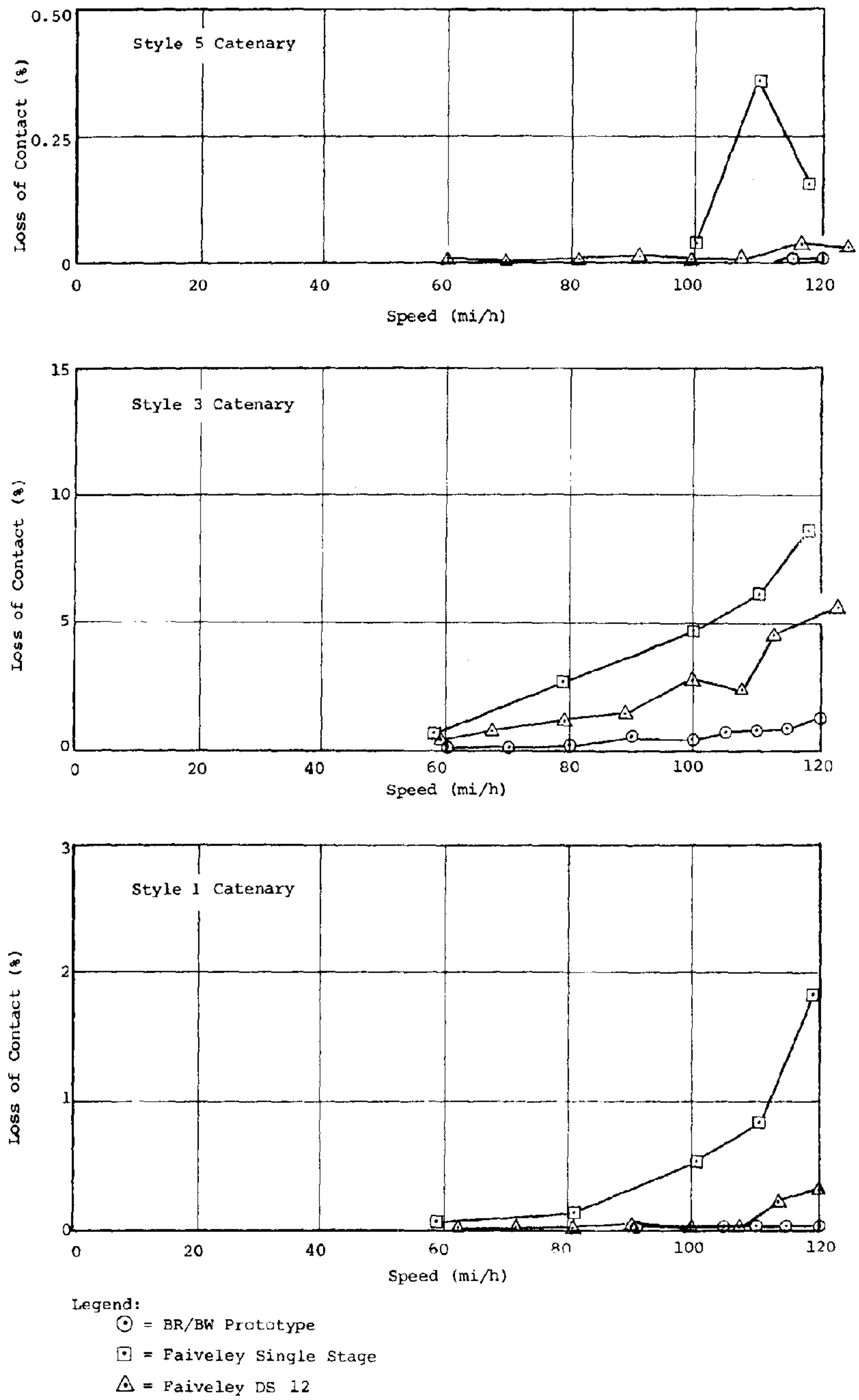


FIGURE 18-4. LOSS OF CONTACT DATA FOR THE BR/BW PROTOTYPE PANTOGRAPH (28 LB UPLIFT).

DS 11 pantograph mounted on the AEM-7 locomotive. Since the graded catenary had been installed by the time these tests were initiated, the dead line measurements were also used to evaluate the pantograph performances over this feature.

18.4.2 Test Objectives

The main objectives of the AEM-7 dead line pantograph test were as follows:

- To measure the current collection performance of the BR/BW 'stretched pantograph and the Faiveley modified DS 11 pantograph on the RTT catenary system using dead line loss of contact data.
- To assess the performance of both pantographs on the graded catenary.
- To correlate the measured pantograph performance with the previous pantograph tests on the DOTX-211 car.

18.4.3 Test Method

a. Train Consist. The test train consisted of the following vehicles:

- AEM-7 Locomotive (AMTRAK 900)
- AMFLEET car (2103)
- Diesel Electric Locomotive (DOT-001)

Concern was expressed by the TTC operational personnel regarding the propelling of the test train by a locomotive at the rear. However, the use of push - pull trains at speeds up to 125 mi/h is a well established procedure, even with the lead power unit 'dead'. The technical requirement that the aerodynamic flow around the AEM-7 pantograph should be identical to that experienced during powered operation justified that unusual operational mode. However, certain safety requirements were placed on the operation.

- The lead cab of the AEM-7 was manned by the test controller, a technical engineer experienced in ride assessment, and a vehicle operator. The AEM-7 control stand was made operational to allow the vehicle operator to make brake applications as required.
- The test speeds were increased in 10 mi/h increments from 60 mi/h to 120 mi/h.
- Uninterrupted radio communication was maintained between the operating cabs of the two locomotives.

b. Instrumentation. The pantograph was instrumented to measure loss of contact by the dead line technique described in reference 1. A low voltage supply was connected to the test pantograph base, the pantograph selector switch was placed in the open position. The loss of contact signal was fed to the appropriate channel of the dead line instrumentation system which was temporarily located in the AMFLEET Instrumentation car (#21003). The processed loss of contact signal was recorded onto one channel of a 14 channel analog tape recorder.

A manually operated positional event button was located in the AEM-7 lead cab. The manual event signal was recorded onto a second channel of the analog tape recorder. The RTT location and train speed were annotated onto the tape recorder voice channel by the Technical Engineer in the AEM-7 cab, who also operated the manual event button.

c. Locomotive and Catenary Configuration. The catenary was isolated from the substation transformer and grounded by the catenary feeder switches #314-1 and #314-3 at the substation. The pantograph selector switch interlock was temporarily immobilized to permit the trailing pantograph to be raised with the switch open. During test runs the AEM-7 battery system was switched on to power the pantograph controls and also the locomotive speed and wheelslip systems.

d. Test Operations. The test operations for each pantograph were identical. The test pantograph was raised and lowered a few times to ensure that a reliable loss of contact signal was received at the tape recorder. The consist was propelled around the RTT in a clockwise direction at a speed of 30 mi/h for the normal track conditioning run with the test pantograph raised. The pantograph was raised and lowered while the train was in motion to check for reliable loss of contact information.

The data test runs were made at speeds of 80, 90, 100, 110, and 120 mi/h. Data were collected between R8 and R42 with event signals, together with the corresponding track location and current train speed, being provided at the 1000 ft locations. During each operation the personnel in the lead cab were responsible for assessing the AEM-7 ride to permit the next speed increase.

18.4.4 Presentation of Results

The recorded signals from each pantograph were processed using the dead line instrumentation system to produce percentage loss of contact data at each test speed for the three selected test sites shown in Table 18-2.

TABLE 18-2. CATENARY TEST SITES FOR AEM-7 PANTOGRAPH TESTING.

TEST SITE		CATENARY
START	FINISH	STYLE
R12	R32	5
R34	R36	1
R37	R39	3

The data were processed at contact loss rejection levels of 0 and 2 milliseconds (corresponding to the earlier dead line test data) for all speeds, and at 1, 5 and 10 millisecond levels for a reduced number of speeds.

A summary of the data is presented in graphical form in Figures 18-5 through 18-7. Figure 18-5 shows the relationship between the loss of contact duration rejection level and the measured percentage loss of contact over the test speed range 80-120 mi/h for each pantograph on the Style 5 catenary. Figure 18-6 presents similar data for the Style 3 catenary. In Figure 18-7 the percentage loss of contact at the conventional rejection level of 2 ms is plotted against speed for both pantographs on each of the styles of catenary.

18.4.5 Discussion of Results

a. Contact Loss Duration. The effect of loss of contact duration was discussed in detail in reference 1. The data for both the pantograph configurations tested (Figure 18-5 and 18-6) shows a loss of contact duration distribution similar to that presented in reference 1 for the Faiveley single stage pantograph. The data from the AEM-7 Dead Line Test were extracted for the zero time duration rejection level in order to determine whether approximately half the percentage contact loss lay on either side of the 2 millisecond duration limit. The approximation was demonstrated, although it should be noted that the accuracy of loss of contact measurements in the 0-2 millisecond range by the low voltage d.c. method is suspect. The 2 millisecond rejection level was used for performance comparison throughout the remainder of the dead line test data analysis. The longer time duration losses of contact do not, in general, exceed the 10 millisecond level. Comparison with the equivalent data in reference 1 indicates that the long duration loss of contact in the Style 3 catenary had been removed between the two series of tests. This, of course, resulted from the straightening of the contact wire kink at R37 + 600 described in section 17.2.3. The combination of the observed relatively light contact wire damage and the measurement of few contact loss durations greater than 10 milliseconds tends to support the hypothesis in reference 1 concerning the probable effect of the various bands of contact loss duration.

b. Performance of the Faiveley DS 11 modified and the BR/BW 'stretched' Pantographs. The relative performance of the two pantographs shows that both units gave acceptable performance on both the Style 1 and Style 5 catenaries at speed up to 120 mi/h. On the Style 3 catenary the BR/BW unit gave an acceptable performance up to 120 mi/h, but the DS 11 exceeded the 1% acceptability level at speeds above 110 mi/h. In all cases the BR/BW pantograph gave a slightly better performance level. However, the comparison became irrelevant after the structural failure of the DS 11 modified head.

c. The Graded Catenary Performance. The performance of both pantographs on both of the catenary gradients was acceptable. No excessive contact loss was measured at any of the gradient transitions or on the 0.25% up gradient.

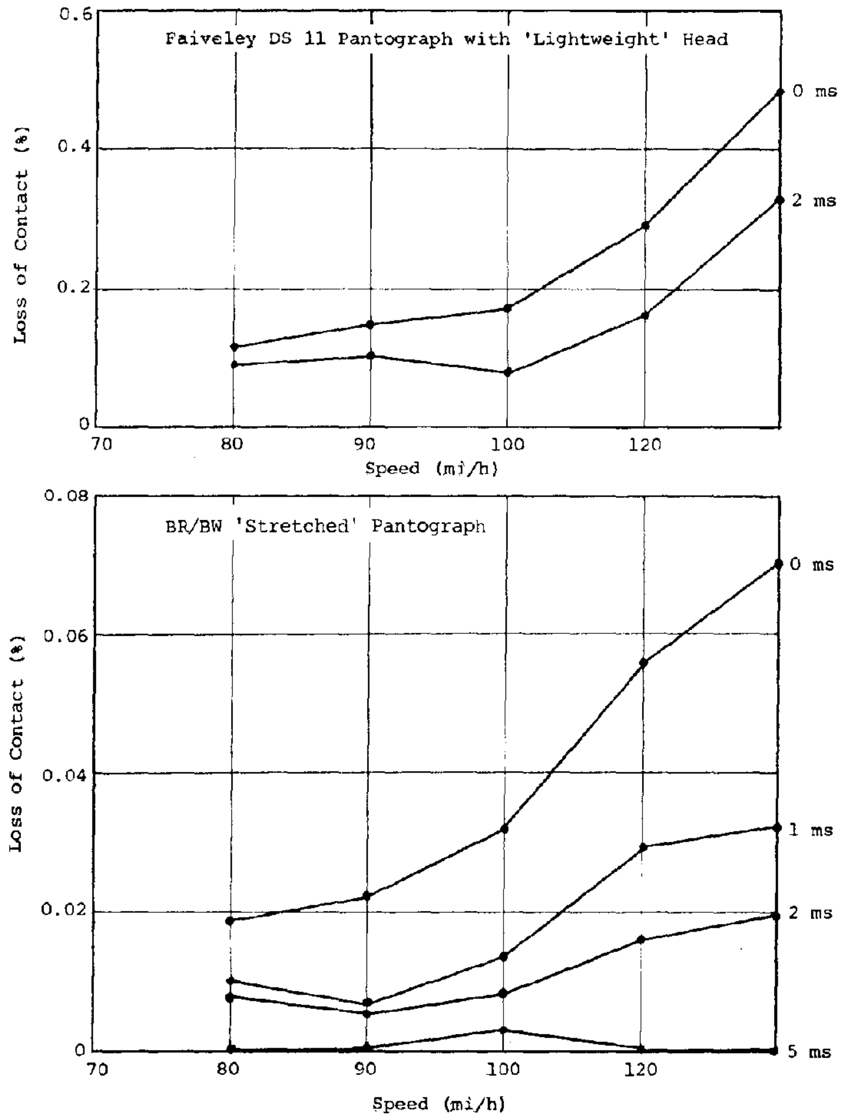


FIGURE 18-5. THE EFFECT OF LOSS OF CONTACT DURATION (STYLE 5 CATENARY).

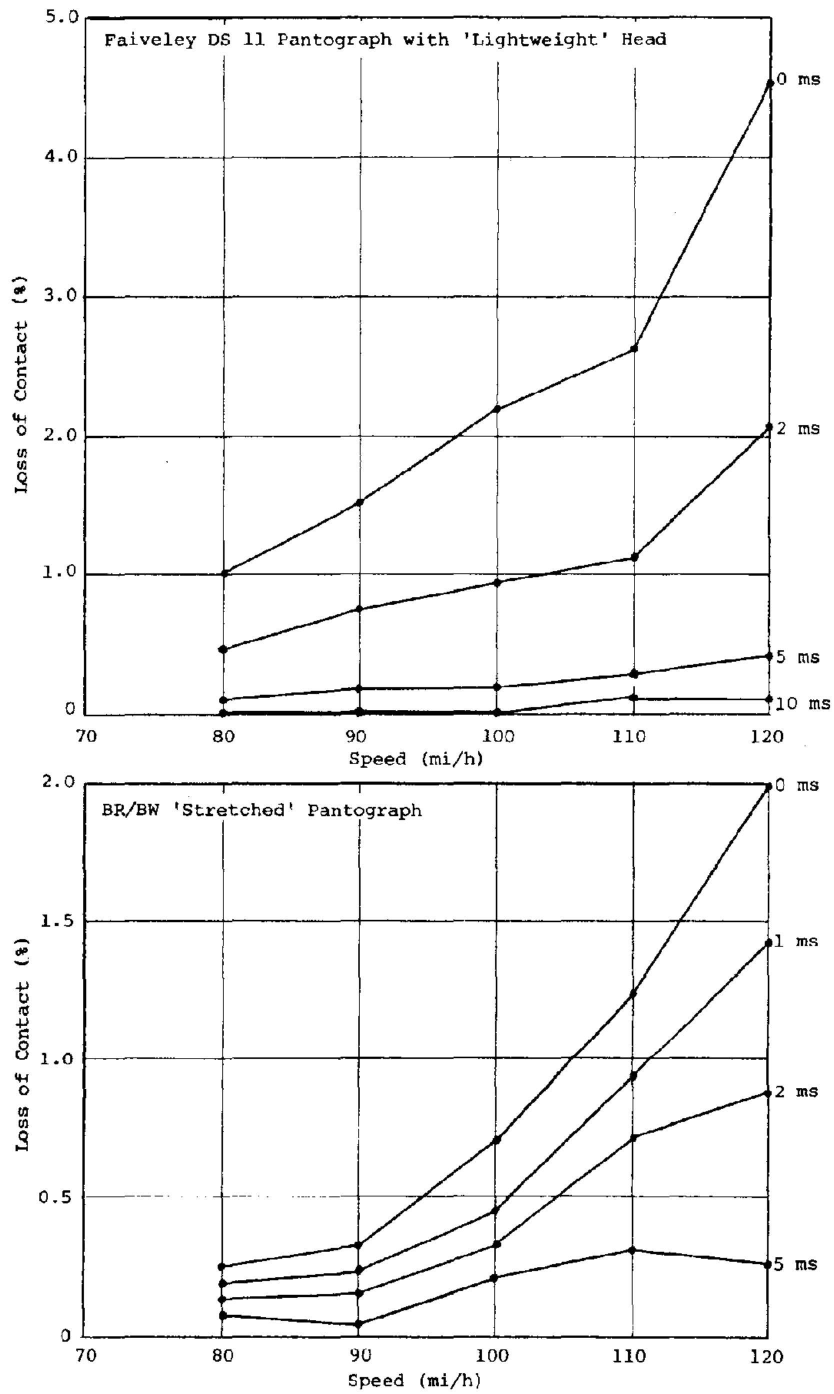
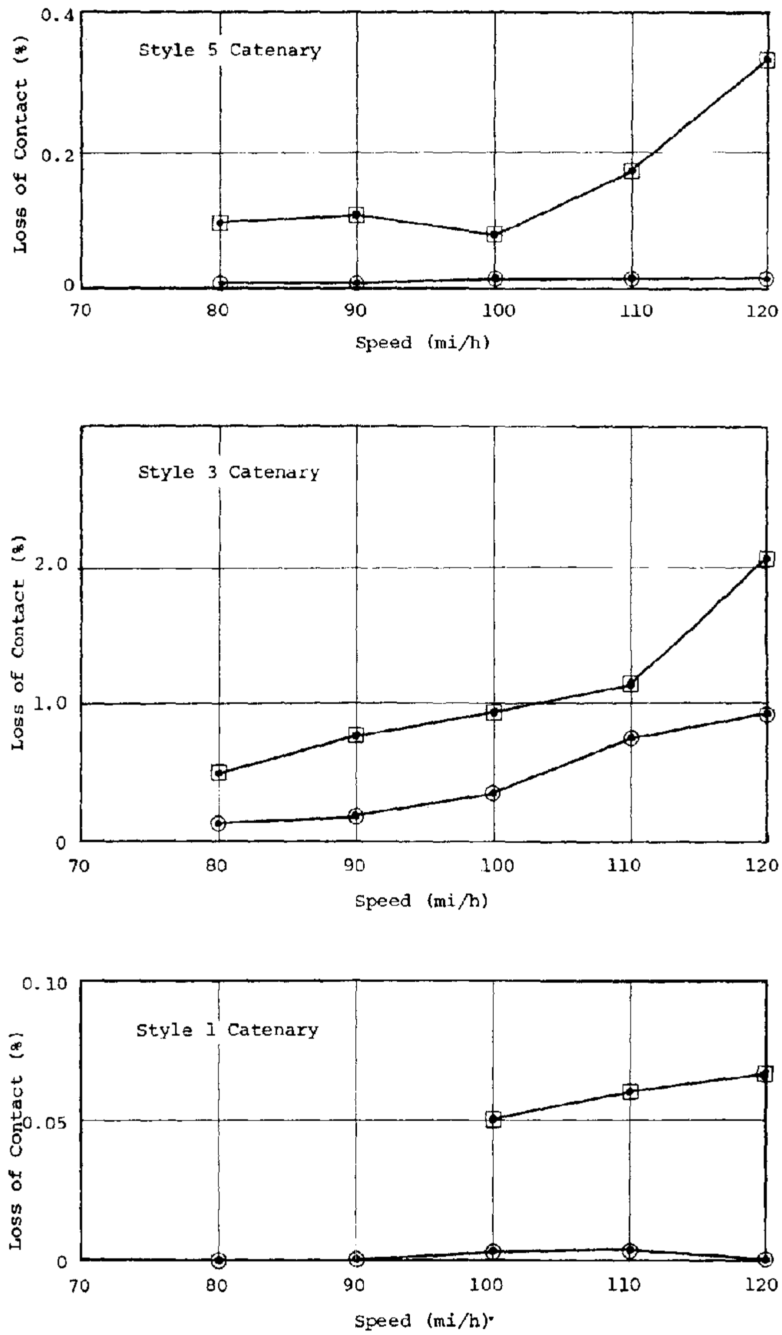


FIGURE 18-6. THE EFFECT OF LOSS OF CONTACT DURATION (STYLE 3 CATENARY).



Note: 2 ms Rejection Level Used Throughout

Legend:

⊙ = BR/BW 'Stretched' Pantograph

⊡ = Faiveley DS 11 Pantograph with 'Lightweight' Head

FIGURE 18-7. LOSS OF CONTACT DATA FOR THE PANTOGRAPH DEADLINE TESTS ON THE AEM-7 LOCOMOTIVE.

Analysis of the movie films showed that the Faiveley DS 11 unit tended to lift the catenary in mid span on the down slope, indicating an excessive uplift force. On the upward slope the pantograph head trajectory was much flatter. The BR/BW pantograph head gave a smoother response on the down grade but showed evidence of slight offloading on the steep upgrade. In order to adequately evaluate the pantographs on the graded catenary the contact force measurements would have to have been better employed. However, the added depth of investigation was outside the scope of this test.

18.5 LIVE LINE TESTS ON THE FAIVELEY DS 11 AND THE BR/BW 'STRETCHED' PANTOGRAPH ON THE AEM-7 LOCOMOTIVE

18.5.1 Background

While the dead line loss of contact measurements quantify the mechanical separations between the pantograph head and contact wire, the direct measurement of pantograph arcing gives a more accurate measure of the electrical separations. Several methods are available to measure the occurrence of electrical arcs including ultra violet (UV) arc detectors and carbon line light detectors. In general straight optical measurements of electrical arcs are not employed because of the interference caused by daylight during daytime operations, and extraneous overhead light sources at night.

The TTC did not own or have access to any of the conventional arc detector systems and was therefore unable to directly measure pantograph arcing. As an interim measure an optical system was developed from the dead line instrumentation structure marker. The operational restriction was imposed on the system that it could only be used at night during complete darkness. Because of the remote location of the TTC this was not an unrealistic requirement. If successful this unit was to provide an economical method of measuring pantograph arcing.

18.5.2 Test Objectives

The major objectives of this test were to detect and measure the pantograph arcs in order to provide the following information:

- To measure the percentage occurrence of pantograph arcs.
- To correlate the arc measurements with the equivalent dead line loss of contact requirements.

18.5.3 Test Method

The test train consisted of the AEM-7 locomotive (AMTRAK 900) and AMFLEET car (21003).

A description of the optical arc detector is given in appendix G. Since the arc detector was designed to provide an identical output signal to the dead line loss of contact system, a direct substitution of the arc detector for the dead line system was made into the recording instrumentation. All other aspects of the instrumentation remained the same as for the dead line tests described in section 18.4.3 b.

The locomotive was configured onto the consist with the test pantograph trailing. The optical arc detector was mounted on the film camera bracket previously used for pantograph filming. The lens of the arc detector was aligned to view the trailing edges of the pantograph head collector strip over the full vertical travel of the pantograph, and focused at the pantograph/catenary interface. The locomotive was set up to draw power through the test pantograph.

The arc detector itself was used to determine when the background sky was dark enough to permit testing. Once the ambient light conditions were suitable, the arc detector was checked for a signal output by flashing the light from a hand lamp across the lens. After satisfactory checkout test operations commenced.

The test data runs were identical to those used for the dead line tests (section 18.4.3 d), namely, speeds of 80, 90, 100, 110, and 120 mi/h with data collected between R8 and R42. Again voice annotation was used to record train speed and track location. A catenary voltage of 12.5 kV was used for this test in order to maximize the pantograph current level.

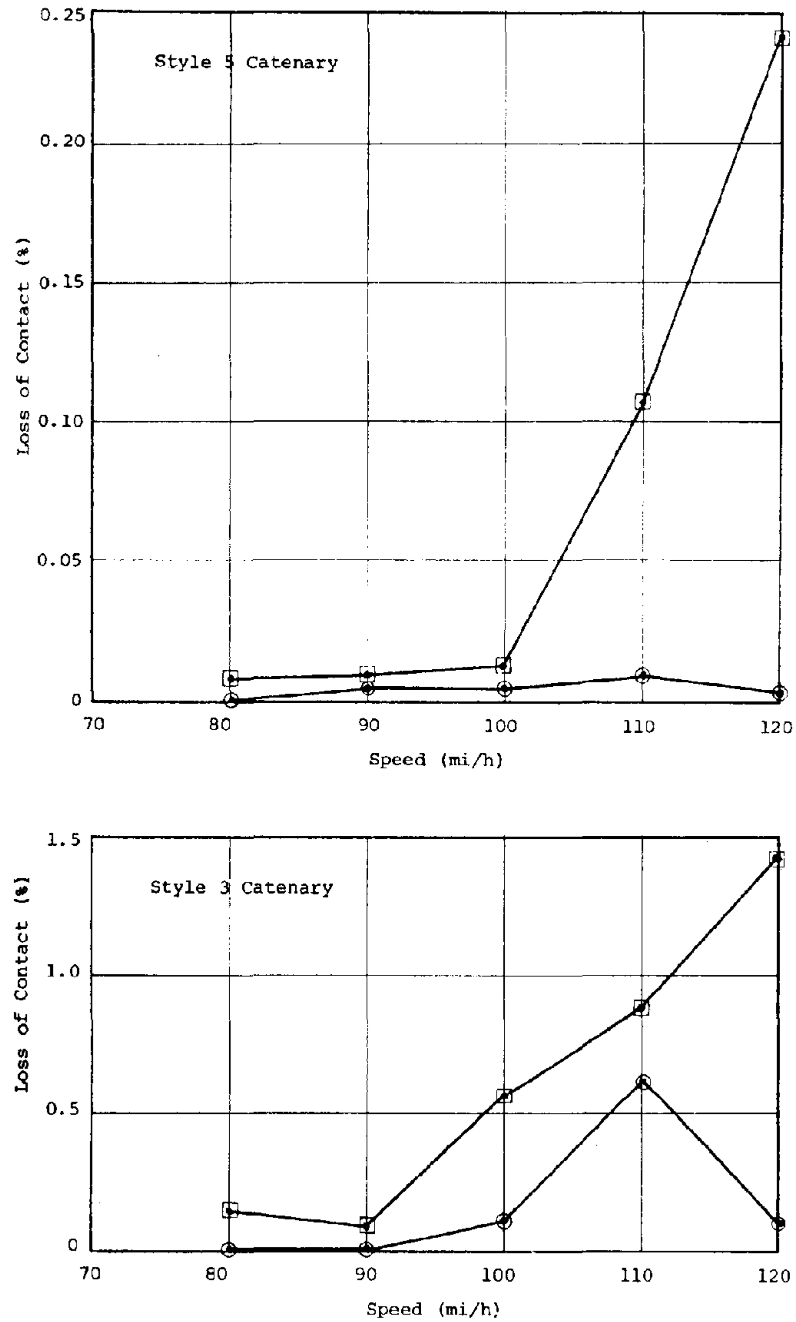
18.5.4 Presentation of Results

The recorded loss of contact data were processed using the dead line loss of contact processor to compute percentage loss of contact. The test sites specified in Table 18-2 were used to make the live line and dead line data compatible. The loss of contact processor was set up at zero duration rejection level for the live line data processing.

The percentage loss of contact computed from the live line data for each pantograph is shown plotted against train speed in Figure 18-8 for the Style 5 and Style 3 catenaries. No arcing was detected on the Style 1 catenary because of lack of pantograph current.

18.5.5 Discussion of Results

Comparison of the dead line data in Figure 18-7 and live line data in Figure 18-8 shows that the live line data apparently indicates a better pantograph



Legend:

⊙ = BR/BW 'Stretched' Pantograph

⊡ = Faiveley DS 11 Pantograph with 'Lightweight' Head

FIGURE 18-8. ARC DETECTOR DATA FROM THE AEM-7 LOCOMOTIVE LIVE LINE PANTOGRAPH TESTS.

performance than the equivalent dead line data. However, it should be noted that the live measurement methods were not exactly equivalent as explained below. The dead line technique detected the duration of the mechanical separation between pantograph head and contact wire. The live line techniques, on the other hand, detected the presence of the electrical arc. Since the arcing condition is heavily dependent on current, it is possible for mechanical separation to occur without a detectable electrical arc, or for the duration of the arc to be less than the duration of the mechanical separation. All arc detector systems, whether UV, carbon line, or light sensitive, are threshhold devices which must exceed a given level to register a signal. Therefore under low current conditions, whether because of locomotive idling, waveform position, or arc blowout, no arc will be detected.

In the data collected the low current phenomenon was demonstrated in two ways. First, no arcing was detected on the style 1 catenary because the locomotive did not draw traction current over that section following the phase break negotiation and subsequent startup sequence. Second, at the 120 mi/h speed increment on the style 3 catenary with the BR/BW pantograph, the traction current was removed prematurely, again resulting in reduced arcing conditions.

In conclusion it must be emphasized that neither measurement technique is incorrect, they simply interpret the information differently. The dead line technique provides data which can best be used to evaluate the dynamic behavior of the pantograph and catenary system, and to quantify pantographs against a loss of contact acceptance level criteria, for example the 1% at 2 millisecond rejection level used in the program. The live line technique, being current dependent, provides an actual measure of arcing and therefore the effect of loss of contact. Taken over a sufficiently long length of catenary, live line arc detector data can be made equivalent to dead line data, provided the power duty cycle is known or measured.

It should further be noted that the optical measuring system used was only intended as an assessment of arc detector type measurements and their relationship to dead line measurements. The actual reliability of the optical method used compared with the other sensing methods was not assessed. It is probable for a 'production' arc detector that either the UV or carbon line systems would be better employed, if only to eliminate the operational restrictions on the system.

19.0 CONCLUSIONS

19.1 THE AEM-7 LOCOMOTIVE

19.1.1 The Locomotive Characteristics

- Transformer inrush currents should not be a problem on 60 Hz frequency operation since the inrush current peak level does not exceed the normal full load current values.

- The AEM-7 locomotive energy requirements data taken at the TTC are in good agreement with the equivalent data taken on the NEC.

- The TTC peak power factor value of 0.83 on the 60 Hz supply is a slight improvement on the 0.81 value measured on the NEC at 25 Hz.

- The relative levels of the locomotive primary current harmonic content are substantially independent of both RMS current and speed, although at the lower speeds the relative levels of the even harmonics are slightly increased.

- The AEM-7 locomotive current harmonic levels compare favorably with data taken on the E60CP and E50 locomotives.

- The locomotive operated satisfactorily over the +10% to -25% supply voltage range. At -35% of the nominal supply voltage the propulsion power was severely limited and the battery charger ceased to function; therefore, the locomotive cannot be satisfactorily operated at this level for extensive periods.

- The operating temperatures in both the cab and equipment room were excessive during high ambient temperatures. A level of 145°F was measured in the Y2 electronic cabinet interior.

19.1.2 The Endurance Test

- Based on TTC profile simulations it is concluded that the locomotive is capable of meeting the Washington-to-New York and New York-to-Boston mandated schedules hauling a consist of six AMFLEET cars, provided at least three traction motors are operational. With four motors operational the locomotive was able to meet the mandated schedule between Washington and New York hauling a consist of eight cars.

- The measured energy consumption data for the simulated profiles was approximately 73% of that predicted by the Train Performance Calculations. The differences were probably caused by a combination of the method used to calculate energy in the TPC and differences between the assumed and actual resistance coefficients.

- The electronic control systems on the AEM-7 locomotive were found to be reliable except for the YMX 125 K interface cards.

- The traction motor flashovers resulted from poor commutation. The exact cause of the commutation problems was not identified by the TTC tests.

- The mechanical reliability of the locomotive should be improved by the redesign of such items as the truck yokes, shock absorber end bushings and brackets, and traction motor blower bellows. Many of these redesigned items have already been incorporated.

- The operational convenience of the locomotive should be improved by redesign of the pantograph selector switches and assorted microswitch adjustments.

- The wheel bearing failure on AMTRAK 900 resulted from lubrication film breakdown due to the use of inferior quality grease. No firm evidence of electrical damage was apparent from the inspection of the other wheel bearings.

- While the electrical behavior of the individual ground brush assemblies was erratic, there was no evidence of system malfunction of the ground brush arrangement as determined by the measurements made on AMTRAK 900.

- The standard Faiveley DS 11 pantograph was found to be unacceptable for operation on the RTT catenary system at speeds above 100 mi/h. The current collection performance was judged to be inadequate and the lateral flexibility displacements excessive.

- The British Rail/Brecknell Willis high speed pantograph gave acceptable performance on the RTT catenary at speeds up to 120 mi/h.

19.2 PHASE BREAK OPERATIONS

- The locomotive automatic Voltage Change/Phase Break negotiation equipment functioned satisfactorily. The traction power ramp down system was also successful.

- Head End and Auxiliary power could be maintained across the Kupler 'modified' phase break at speeds above 40 mi/h for all electrical configurations except voltage changes. Below 40 mi/h either manual or automatic breaker open negotiations must be made.

- The AMFLEET car light flicker problems are almost totally eliminated by powered operation over the phase breaks.

- Special care is required in setting up and maintaining the Kupler 'modified' phase break due to its increased length.

19.3 AEM-7 RIDE QUALITY AND WHEEL WEAR

- The AEM-7 wheel profiles were subject to rapid initial wear on the RTT due to the high proportion of curved track. Once the worn wheel and rail profiles became compatible, the rate of wheel wear decreased.

- The wheel wear produced an effective high conicity (effective cone angle) area near the wheel flange which resulted in increased kinematic motion of the locomotive on curved track.

- The kinematic frequency of the AEM-7 locomotive trucks on the RTT curves coupled closely with the lateral natural frequency of the Faiveley DS 11 pantograph, resulting in large lateral deflections of the pantograph head; this contributed to the pantograph structural failures.

19.4 ADDITIONAL PANTOGRAPH AND CATENARY TESTS

- The catenary blowoff measurements agreed to within 10% of the values predicted by IECO. However, measurements accuracy can be further improved for any future measurements to provide more reliable information.

- The use of balance weight assemblies on the Style 1 and 3 catenaries could not be used with sufficient accuracy to simulate equivalent ambient temperature tensions. However pantograph performance trends showed that the optimum performance of the Faiveley DS 12 pantograph on both styles of catenary was at an approximate equivalent ambient temperature of 30°F.

- The Faiveley DS 11 pantograph with the lightweight head and the British Rail/Brecknell Willis both performed acceptably on the RTT catenary at speeds up to 120 mi/h when assessed by dead line loss of contact measurements.

- The use of live line arc detectors to measure loss of contact does not provide identical data to that produced by the dead line method. It provides a measure of the actual arcing condition which is current dependent.

19.5 GENERAL

- The test program conducted at the TTC on the AEM-7 locomotive, coupled with the testing and service experience on the NEC combined to provide one of the most extensive tests carried out on any newly introduced service locomotive.

20.0 RECOMMENDATIONS

20.1 LOCOMOTIVE

- Further evaluation of the traction motor commutator life should be carried out during early service life of the locomotives on the NEC.
- All mechanical design changes initiated during the combined test at the TTC and the NEC early service should be incorporated in all locomotives including AMTRAK 900.
- The BR/BW pantograph should be subjected to NEC service evaluation before consideration as an alternative to the DS 11 unit.
- Faiveley, S.A., should be encouraged to continue with their efforts to improve the performance of the DS 11 by providing a mechanically reliable lightweight head.

20.2 PHASE BREAKS

- Coasting of phase breaks with partial power at speeds above 40 mi/h should be adopted where possible for NEC operation to reduce the instances of car light flicker and auxiliary equipment cycling.
- The long single insulator type phase break used by Japanese National Railways should be investigated as a possible alternative to the double insulator type presently proposed for use on the NEC.
- Careful installation procedures should be adopted for all high speed phase breaks on the NEC.
- A double structure support should be used to stabilize the long insulator type breaks on the NEC.

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APPENDIX A

EVALUATION OF THE ELECTRIC SUPPLY SYSTEM FOR THE RAILROAD TEST TRACK

1.0 SUBSTATION MODIFICATION

Power for the RTT catenary is supplied from the RTT substation located at R70 + 800. This substation is of standard configuration for railroad use and has a 16/21.3 MVA OA/FA rating. Input power is supplied at 115 kV single phase and a switchrack on the secondary provides 12.5 kV, 25.0 kV and 50.0 kV to the catenary through standard protective equipment.

The first use of the substation was as a power source to test the catenary to determine its electrical characteristics. When the substation was first energized and connected to the catenary, built-in metering did not indicate any loads. Clamp-on ammeters indicated load current correctly. Investigation of the instrumentation wiring revealed that all current measurements were shunted out so no indication of current was available on the control panels. Wiring errors were corrected and relays checked to ensure relay protection was intact. Wiring errors were found in the RTT substation in 45% of the cables and are detailed in section A-5.0.

When the AEM-7 locomotive was first tested the transformer differential relay repeatedly tripped the oil circuit breaker. Wiring errors on both the primary and secondary sides were found and corrected. These wiring errors explained why some faults during testing were not correctly detected by the substation relays. Correction of this wiring resulted in correct relay action for a number of faulting conditions that occurred during testing. Included were a number of lightning strikes to the vicinity of the catenary, a flash-over of wiring to a test voltage divider, and the failure of a lightning arrestor. Additional relay work included the removal of installed relays for the PTACV transmission line and their replacement with fast CO-2 type relays. This change provided relay coordination of the RTT substation (fed by a spur line to the PTACV line) to the TTC site circuit breaker relays. Recalibration of RTT relays was performed to remove a condition called creep.

Additional metering of the transformer secondary was added to panel #5 of the substation and a precision power and energy instrumentation system was added to obtain energy consumed for each profile. This precision package was later removed from the substation and installed on the consist to measure locomotive conditions instead of substation conditions.

Midway in the endurance testing the substation was modified by adding switches and buswork to provide dual voltage of 12.5 kV on the north half of the catenary and 25.0 kV on the south catenary. After three weeks of dual voltage operation the substation configuration was temporarily changed to two 25 kV voltages that were 180° out of phase. Upon satisfactory completion of the phase break tests the substation returned to straight 25 kV operation.

2.0 TEST RESULTS

Besides debugging the substation and ensuring that the station could supply a variety of power options to the locomotive, the tests performed prior to locomotive testing produced the following results.

2.1 SAFETY AND COMMUNICATION INTERFERENCE

Prior to energization of the substation there was concern at TTC that the catenary voltage could produce situations that would be dangerous to site personnel, especially track personnel. Tests indicated typical induced voltages of wayside structures were only 10 to 20 volts with one insulated rail joint having 30 volts across the joint. All masts and poles were at ground potential. It was therefore concluded that no electrical hazard was presented to wayside crews. In addition no telephone, radio, or TV interference problems were caused by electrification.

2.2 MEASUREMENT OF IMPEDANCE

Tests were planned to measure the impedance of the loop consisting of the outgoing catenary and its return to the substation ground mat. During the planning stages it was determined that the testing configuration of the RTT track and catenary would constitute a three winding transformer with the two secondary windings shorted. The testing used the impedance of the catenary to limit the current of a special transformer connection up to full rated catenary current (640 A). Current was sent out to one half the catenary, through the bypass switch at R33 and returned to the substation ground mat via the other catenary, thus forming a primary loop. The continuous rails formed one shorted secondary loop and the continuous return wire on top of the masts formed the second shorted loop. Thus the impedance of the test configuration is different than in the normal railway configuration, so duplication of IECO's computer calculation results were not anticipated. Test results yielded an overall impedance of $0.226 + j0.668$ ohms/mile compared to the design value $0.344 + j0.787$ ohms/mile of straight track. The transformer theory calculations are presented in section A-7.0 and produced 19.5 ohms at $-77.5°$ phase angle compared to test results of 9.5 ohms at $-71.3°$ phase angle.

2.3 RAIL SATURATION

A nonlinearity of impedance with catenary current was found and explained as changes in impedance of the rail iron due to partial saturation. The following table shows the test impedance change:

TABLE A-1. MEASURED IMPEDANCE CHANGE WITH CURRENT.

Catenary Current (A)	Impedance (ohms)
5	10.38
10	10.15
20	9.87
over 30	9.75

The apparent discrepancy of 9.75 ohms compared with 19.5 ohms in section A-2.2 is due to the impedance within the switch yard ground mat being included in the table above.

2.4 CURRENT DISTRIBUTION

While impedance testing was being conducted the current distribution within the catenary was measured. Good agreement with design data was obtained as indicated in the following table:

TABLE A-2. ACTUAL VS DESIGN CATENARY CURRENT DISTRIBUTION.

Catenary Type	TTC Measured			IECO Design		
	Messenger (%)	Auxiliary (%)	Contact (%)	Messenger (%)	Auxiliary (%)	Contact (%)
Style 5	40.25	15.10	44.65	39.58	17.09	43.33
Style 1	41.53	25.96	32.51	39.95	32.09	27.96
Style 3	13.46	44.50	42.04	9.93	51.47	38.60

2.4.1 Total Ground Current

During testing of the catenary the return current flowing in the ground was measured. It was found that 110 A or 21.8% of the outgoing current returned to the transformer via the substation ground mat. Another 65 A left the ground near the substation and joined the current flowing from the rails and return wire and returned to the transformer via the three cables from the track bonds. Thus 175 A or 35% of the outgoing current returned to the substation via ground current. IECO calculated that 36% should return through ground, again a very close agreement between test and design.

2.5 CURRENT DISTRIBUTION WITH GROUND AT R33 + 625

The paths of the ground current in this test case were approximated from a series of measurements of return wire, rail currents, and ground currents at the substation. Figure A-1 illustrates the complex paths, mostly due to the stored catenary in the test section of the RTT. Only 40 A of the 505 A in the catenary entered the ground near the shorting point. Another 135 A entered the ground at the end of the stored catenary to flow directly across the RTT loop to the substation. Near the track bonds at the substation, a complex grounding pattern was found due to the use of uninsulated cables from the track which were in contact with the earth from the track to a manhole. Since more current came from the three cables than left the track, ground currents took a lower impedance path to the transformer by leaving the ground and entering the bare cables.

2.5.1 Catenary Auxiliary Wire Burnout

During catenary testing at 620 A the auxiliary wire burned out near R12 + 435. The wire had burned a mark on the cross arm in mast #11/4 and scratch marks indicated that considerable rubbing of the wire on the mast arm had occurred with a de-energized catenary. Calculations of voltage drop in the in-running catenary span and the induced voltage of the outgoing span confirmed the theory that a shorted loop had overheated the wire and caused extensive pitting prior to actual separation of the auxiliary wire. Figure A-3 (presented on page A-31) shows the physical and electrically equivalent circuit.

After pulling in a replacement section of auxiliary wire, adjustments were made to the catenary suspension so that design clearance was obtained between the auxiliary wire and its crossarm. Several other crossarms were in contact or so close that they required adjustments.

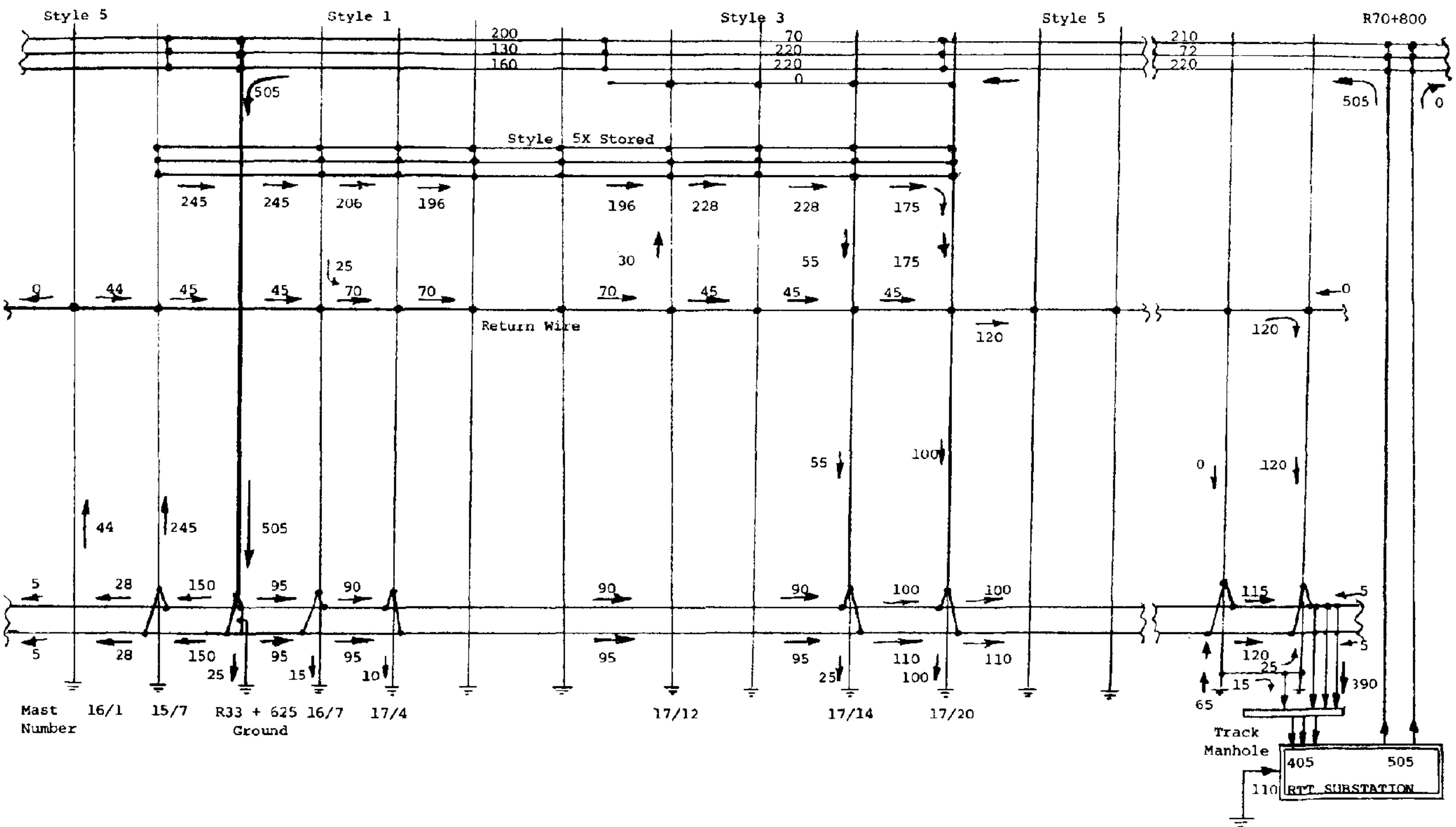

FIGURE A-1. CURRENT DISTRIBUTION AT STATION R33+625 FOR 505 A.

3.0 SCHEDULE OF ELECTRICAL TESTING PERFORMED ON CATENARY AND SUBSTATION WITH A SUMMARY OF THE RESULTS

The RTT substation and catenary were energized on the following days to perform these tests.

Tests Performed	Results
01-26-80	
1. Impedance of loop circuits at low and high currents.	1. Impedance decreased slightly from 10.38 to 9.75 ohms.
2. Checkout of catenary with current.	2. Increased current in steps from 5.8 A to 627.8 A.
3. Checkout of RTT substation.	3a. Found no current measurement. 3b. Transformer relay tripped above 440 A.
4. Verify induced currents.	4. The induced currents measured for 628 A from the transformer were: west rail current, 117 A; east rail current, 118 A; return wire at R708, 120 A. These three currents are flowing around the periphery due to transformer action of transformer current flowing through the catenary and back to the transformer.
02-01-80	
1. RTT energizing for CT check.	1. Ground tripped site breaker.
02-02-80	
1. Check 87-T relay new settings of current taps.	1. Relay currents balanced to 620 A and verified operational.
2. Check removal of shorts on primary and secondary CT's.	2. Ammeters indicated; primary very low deflection.
3. Interference with FAST.	3. Large induced 60 Hz signal on 3 FAST sensors.

Tests Performed	Results
4,5. Shorting device placed at midcatenary for ground current measurements.	4. Obtained ground currents. 5. Burned up auxiliary wire at R12 + 400.
02-02-80 thru 02-09-80	
1. Calculation of PTACV line relaying for isolation.	1. Calculation reveals site breaker will almost always trip before switcher #301.
02-09-80	
1. Verification of shorting current at R12 + 400.	1. Found 45 A in the jumper with 248 A in the catenary.
2. Measurement of FAST interference.	2. Results duplicated 02-02-80 data. Ungrounded dummy gage received no interference.
3. Measurement of voltages at FAST and Wayside for safety.	3. Less than 10 V to ground of fences and rails. Some bonds, 30 A.
4. Start of ground current measurements.	4. Ground currents measured.
02-12-80	
1. Distribution of current in catenary.	1. Measured distribution and found agreement with design parameters.
2. Rail and ground current measurements.	2. A catenary to rails jumper at R33 + 625 had 556 A flowing to rails, of which 123 A went to earth and 273 A flowed in the return wire.
3. Measurement of temperature rise of catenary wires.	3. Found wires only warm with 554 A total.
03-07-80	
1. Change of CT ratio on transformer primary from 600:5 to 100:5.	1. Indicated current, watts and kW hr now readable.

Tests Performed	Results
2. Verification of currents in all relays.	2. Overcurrent relay currents correct, therefore protecting. Differential relay currents too low to check.
3. Check on ammeters.	3. AMR-2 catenary output current is to be read on 0-1200 A scale without using multipliers for voltage listed on nameplate.

4.0 CATENARY DESIGN DATA SHEETS

The following tables (Tables A-3, A-5 and A-6) are the catenary design data sheets for styles 5, 3, and 1 catenaries.

TABLE A-3. CATENARY STYLE 5 (RTT), CONDUCTOR CHARACTERISTICS.

Item	Messenger	Auxiliary	Contact	Return
Type and size	19/0.0833	7/0.0833	4/0 Grooved	2/0 Stranded
Material	ASTM Alloy 80	ASTM Alloy 80	ASTM Alloy 80	ACSR Quail
Diameter (in)	0.417	0.250	0.482	0.447
Area (in^2)	0.1036	0.0386	0.1665	0.1219
Weight (lb/ft)	0.4071	0.150	0.6417	0.1831
Modulus of elasticity (lb/in^2)	15×10^6	15×10^6	16×10^6	11.4×10^6
Linear coefficient of thermal expansion (per °F)	9.4×10^{-6}	9.4×10^{-6}	9.4×10^{-6}	10.6×10^{-6}
Minimum breaking strength (lb)	7,885	2,905	10,820	5,345
Normal tension at 60° F (lb)	3,000	1,200	3,500	522
Maximum tension (lb)				
At -10° F (NEC)	3,386	1,228	4,080	-
At -30° F (Pueblo)	4,220	1,410	4,070	2,420
d.c. resistance at 20° C (68° F) (ohms/1,000 ft)	0.1010	0.2741	0.0612	0.1248
Minimum conductivity (% IACS*)	80	80	80	62
Strands	19	7	Solid	7 (6 aluminum, 1 steel)
Geometric mean radius (in)	0.1572	0.0900	0.1626	0.1741
Current distribution at maximum continuous current of 660 A, ambient temperature of 125° F, and wind velocity of 2 ft/s, with contact wire at a height of 22.5 ft (A)	264(39.58%)	114(17.09%)	289(43.33%) 667A	189
Conductor temperature at maximum continuous current of 660 A, ambient temperature of 125° F, and wind velocity of 2 ft/s, with contact wire at a height of 22.5 ft (°F)	181	163	179	168
Loop impedance at above conductor temperatures (ohms/mi)	<------------------ 0.349 + j0.756--------------------------->			
Short-time current rating	200% of baseload for 15 minutes after 30 minutes of no load*			

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* With the following restrictions: when wind velocity is 2 ft/s, ambient temperature must be at least 101.3° F; when ambient temperature is 125° F, wind velocity must be at least 6 ft/s.

TABLE A-4. CATENARY STYLE 5 STRETCHED (TEST SECTION), CONDUCTOR CHARACTERISTICS.

Item	Messenger	Auxiliary	Contact	Return
Type and size	19/0.0833	7/0.0833	4/0 Grooved	2/0 Stranded
Material	ASTM Alloy 80	ASTM Alloy 80	ASTM Alloy 80	ACSR Quail
Diameter (in)	0.417	0.250	0.482	0.447
Area (in^2)	0.1036	0.0386	0.1665	0.1219
Weight (lb/ft)	0.4071	0.150	0.6417	0.1831
Modulus of elasticity (lb/in^2)	15×10^6	15×10^6	16×10^6	11.4×10^6
Linear coefficient of thermal expansion (per ^oF)	9.4×10^{-6}	9.4×10^{-6}	9.4×10^{-6}	10.6×10^{-6}
Minimum breaking strength (lb)	7,885	2,905	10,820	5,345
Normal tension at 60° F (lb)	3,000	1,200	3,500	522
Maximum tension at -30° F (lb)	4,400	1,410	4,070	2,420
d.c. resistance at 20° C (68° F) (ohms/1000 ft)	0.1010	0.2741	0.0612	0.1248
Minimum conductivity (% IACS)	80	80	80	62
Strands	19	7	Solid	7 (6 aluminum, 1 steel)
Geometric mean radius (in)	0.1572	0.0900	0.1626	0.1741
Current distribution at maximum continuous current of 660 A, ambient temperature of 125° F, and wind velocity of 2 ft/s, with contact wire at a height of 22.5 ft (A)	264	114	289	189
Conductor temperature at maximum continuous current of 660 A, ambient temperature of 125° F, and wind velocity of 2 ft/s, with contact wire at a height of 22.5 ft (°F)	181	163	179	168
Loop impedance at above conductor temperatures (ohms/mi)	<------------------------0.349 + j0.756-------------------------->			
Short-time current rating	200% of baseload for 15 minutes after 30 minutes of no load*			

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* With the following restrictions: when wind velocity is 2 ft/s, ambient temperature must be at least 101.3° F; when ambient temperature is 125° F, wind velocity must be at least 6 ft/s.

TABLE A-5. CATENARY STYLE 3 (RTT), CONDUCTOR CHARACTERISTICS.

Item	Messenger	Auxiliary	Contact	Return	Support
Type and size	5/8" Stranded	4/0 Grooved	4/0 Grooved	2/0 Stranded	7/8" Stranded
Material	Steel	Copper	ASTM Alloy 80	ACSR Quail	Steel
Diameter (in)	0.625	0.482	0.482	0.447	0.875
Area (in^2)	0.2356	0.1665	0.1665	0.1219	0.4675
Weight (lb/ft)	0.813	0.6417	0.6417	0.1831	1.5810
Modulus of elasticity (lb/in^2)	27.5×10^6	16×10^6	16×10^6	11.4×10^6	27.5×10^6
Linear coefficient of thermal expansion (per ^oF)	6.4×10^{-6}	9.4×10^{-6}	9.4×10^{-6}	10.6×10^{-6}	6.4×10^{-6}
Minimum breaking strength (lb)	42,400	7,759	10,820	5,345	35,900
Normal tension at 60° F (lb)	5,250	2,000	5,000	522	7,500
Maximum tension (lb)					
At -10° F (NEC)	7,495	3,720	4,970	-	8,374
At -30° F (Pueblo)	9,060[(c)]	4,250	5,250	2,420	12.120
d.c. resistance at 20° C (68° F) (ohms/1000 ft)	0.4200	0.0504	0.0612	0.1248	-
Minimum conductivity (% IACS)	-	97.16	80	62	
Strands	7	Solid	Solid	7 (6 aluminum, 1 steel)	19
Geometric mean radius (in)	0.2225	0.1877	0.1877	0.1741	-
Current distribution at maximum continuous current of 660 A, ambient temperature of 125° F, and wind velocity of 2 ft/s, with contact wire at a height of 22.5 ft (A)	81	420	315	220	-
Conductor temperature at maximum continuous current of 660 A, ambient temperature of 125° F, and wind velocity of 2 ft/s, with contact wire at a height of 22.5 ft (°F)	147	172	171	182	-
Loop impedance at above conductor temperatures (ohms/mi)	<---------------------------0.258 + j0.933-------------------->				

TABLE A-6. CATENARY STYLES 1 (RTT), CONDUCTOR CHARACTERISTICS.

Item	Messenger	Auxiliary	Contact	Return
Type and size	5/8" Type E Copperweld	4/0 Grooved	336.6 Grooved deep section	2/0 stranded
Material	7 Strands Copperweld, 12 strands copper	Copper	ASTM Alloy 80	ACSR Quail
Diameter (in)	0.613	0.482	0.680 x 0.482	0.447
Area (in^2)	0.2239	0.1665	0.2642	0.1219
Weight (lb/ft)	0.8483	0.6417	1.020	0.1831
Modulus of elasticity (lb/in^2)	19.5×10^6	16×10^6	16×10^6	11.4×10^6
Linear coefficient of thermal expansion (per °F)	8.4×10^{-6}	9.4×10^{-6}	9.4×10^{-6}	10.6×10^{-6}
Minimum breaking strength (lb)	20,730	7,759	15,010	5,345
Normal tension at 60° F (lb)	4,640	1,200	5,000	522
Maximum tension (lb)				
At -10° F (NEC)	6,440	3,030	7,850	-
At -30° F (Pueblo)	8,000	3,240	8,580	2,420
d.c. resistance at 20° C (68° F) (ohms/1000 ft)	0.0520	0.0504	0.0385	0.1248
Minimum conductivity (% IACS)	-	97.16	80	62
Strands	19	Solid	Solid	7 (6 aluminum, 1 steel)
Geometric mean radius (in)	0.2053	0.1877	0.2544	0.1741
Current distribution at maximum continuous current of 660 A, ambient temperature of 125° F, and wind velocity of 2 ft/s, with contact wire at a height of 22.5 ft (°F)	310	249	217	217
Conductor temperature at maximum continuous current of 660 A, ambient temperature of 125° F, and wind velocity of 2 ft/s, with contact wire at a height of 22.5 ft (°F)	159	145	145	181
Loop impedance at above conductor temperatures (ohms/mi)	<----- 0.199 + j0.798 ----->			

5.0 CABLING OF RTT SUBSTATION

5.1 SUMMARY OF CABLING FAULTS

Table A-7 lists the cables in the substation and the troubles found.

TABLE A-7. METERING AND RELAY CONTROL CABLES.

Cable No.	Trouble Found	Description of Cable Use
333b	None	Station service 115/0/115 V
103a(1)	None	115 kV W, V
103b(1)	None	115 kV W, V
103a(2)	None	115 kV VARS
103b(2)	None	115 kV VARS
315g	None	13.2 kV PT secondary
315h	None	Secondary V-55.2 kV PT*
313c	One CT secondary reversed	Primary differential current
315b	Interchanged with 315a cable	Secondary differential current
315a	Interchanged with 315b cable	Secondary relaying current
103e(1)	Leads interchanged - short	H1 transformer for 115 kV meters - current
103e(2)	Leads interchanged - short	Secondary total current to ammeter AMR-2
103e(3)	Leads interchanged - short	Secondary total current to ammeter AMR-2
103e(4)	Leads interchanged - short	Secondary total current to ammeter AMR-2
103e(5)	Leads interchanged - short	Secondary total current to ammeter AMR-2
103d	None	Total current ammeter current
103c	None	Return plus rail ammeter current
315d	None	North feeder relay current
315f	None	South feeder relay current

*PT = potential transformer

5.2 ANALYSIS

There are a total of 19 cables for relaying and instrumentation. Eight were found to be incorrectly wired, a 42% error. In addition, PT secondaries were fused with 20 A fuses, whereas 6 A are specified. Two CT's had been installed with their shorting bars intact.

The IECO drawings were correct in each case. The fault was in the construction contractor's wiring.

6.0 RELAY COORDINATION

6.1 GENERAL

This section details the setting of the station and feeder relays according to IECO recommendations. Testing was performed on 12-13-79, by a team from IECO, Fischbach and Moore, and TTC personnel.

6.2 RELAY SETTINGS

Relays were adjusted and their final settings were:

a. Feeder Relay - Type 50/51 Relay, IECO Part 247

- Westinghouse Style CO-9 Inverse Relay with instantaneous trip, supplied from CT 325-1, North Feeder.

  CT ratio = 1600:5 (Parallel Primary Winding)

- IECO Relay settings:

  Current winding = Tap 2.0 A
  Time dial set for #11 curve
  Instantaneous trip = 2 to 7 A; set to 4.0 A

- Adjust so relay trips with 1.5 times tap coil (1.5 x 2.0 = 3.0) after 39 seconds.

- Left with adjustment of 39.36 seconds to trip.

b. Feeder Relay - Type 50/51, IECO Part 247

- Westinghouse Style CO-9 Inverse with instantaneous trip supplied from CT 325-2, South feeder.

  CT ratio = 1600:5

- IECO Relay settings:

  Current winding = Tap 2.0 A
  Time dial set for #11 curve.
  Instantaneous trip = 2 to 7 A; set to 4.0 A

- Left with adjustment of 39.15 seconds to trip.

Note: Relay had to be sent to factory for repairs before calibration.

c. Differential Transformer Relay - Type 87-T, IECO Part 244

- Westinghouse Style HU-1
  Supplied by three sets of CT's:

  Primary to Restraint #1: CT part #324, each line has a CT ratio 300:5 into substation. Connected in parallel adding; overall 30:1 ratio.

  Secondary to Restraint #2: CT in #315 OCB bushing that leads to catenary. Overall ratio 2000:5, but many taps changed via switch 43-1 to 320:1, 160:1, and 80:1.

  Secondary of Dual Voltage to Restraint #3. CT is in #316 OCB load side bushing. Overall ratio 1200:5; used X1 to X5 taps on secondary.

- Coil taps as left: Restraint #1 = 5.0
  Restraint #2 = 4.2
  Restraint #3 = 5.0

d. Catenary Overcurrent Relay - Type 51, IECO Part 243

- Westinghouse Style CO-8 Inverse Relay supplied from CT in #315 bushing.

  Ratio = 2000:5, tap selected by switch 43-3 to 320:1, 160:1, or 80:1

- IECO Relay Settings:

  Current winding = tap 7.0 A
  Time dial set for #1.6 curve.

- Adjusted so relay trips with 3 times tap (3 x 7.0 = 21 A) in 1.3 seconds.

- Reset to time curve #0.7 with trip time of 1.1 seconds and twice tap current on 04-22-80.

e. Reverse Power Relay Type - 32, IECO Part 248

No application at TTC (no regenerative locomotives). Left at 120 W tap and time dial of 10. This effectively negates operation.

f. Mho Distance Relay - Type 21 and 21 x timer, IECO Part 245

- General Electric Model 12GCY51FIA. This device detects which of two track zones has faulted. Not tested at RTT.

g. Angle Impedance Relay - Type 21-2, IECO Part 246

- General Electric Model 12CEX57DIA. This device measures the phase angle between the current and voltage and if set properly, will detect a fault from a normal load. Not tested at RTT.

h. PTACV Line Switcher #301 - Type 50/51

- Westinghouse Style CO-8 Inverse Relay
- Supplied from CT #303 in line to switcher

  CT ratio 600:5; no taps

- IECO Relay Settings:

  Current winding = 2.5 A
  Time dial set for #1.7 curve.
  Instantaneous set for 22 A with 20-40 setting.

- Adjusted so relay trips at 6 times tap setting (6 x 2.5) in 0.55 seconds. Replaced relays with type CO-2's set at 2.0 A coil and #2 time curve on 04-22-80. Instantaneous set at 10 A (lowest). This change was made to greatly accelerate tripping so that the PTACV relay would trip before the site breaker.

- Tripping times as adjusted: #1 relay = 34 cycles at 3 A
  #2 relay = 33 cycles at 3 A
  #3 relay = 34 cycles
  9.95 to 10.1 A instantaneous for all three relays.

i. PTACV Line Switcher #301 - Type 50N/51N

- Westinghouse Ground Detector Relay supplied from the three overcurrent relays detailed in Section 8 (above) to ground.

- IECO Relay settings:

  Current winding = 0.5 A
  Time dial set for #3.0 curve.
  Instantaneous 10-20 A tap, set at 17.0 A.

- Adjusted so relay trips at 6 times tap value (6 x 0.5) A in 1.0 second.

- Left relay adjusted at 0.99 second.

- This relay was left in ground circuit "as is" when the CO-2 relays were installed, as no CO-2 ground relays were available.

- See Figure A-2 for system relay characteristics and Table A-8 for the line relay study.

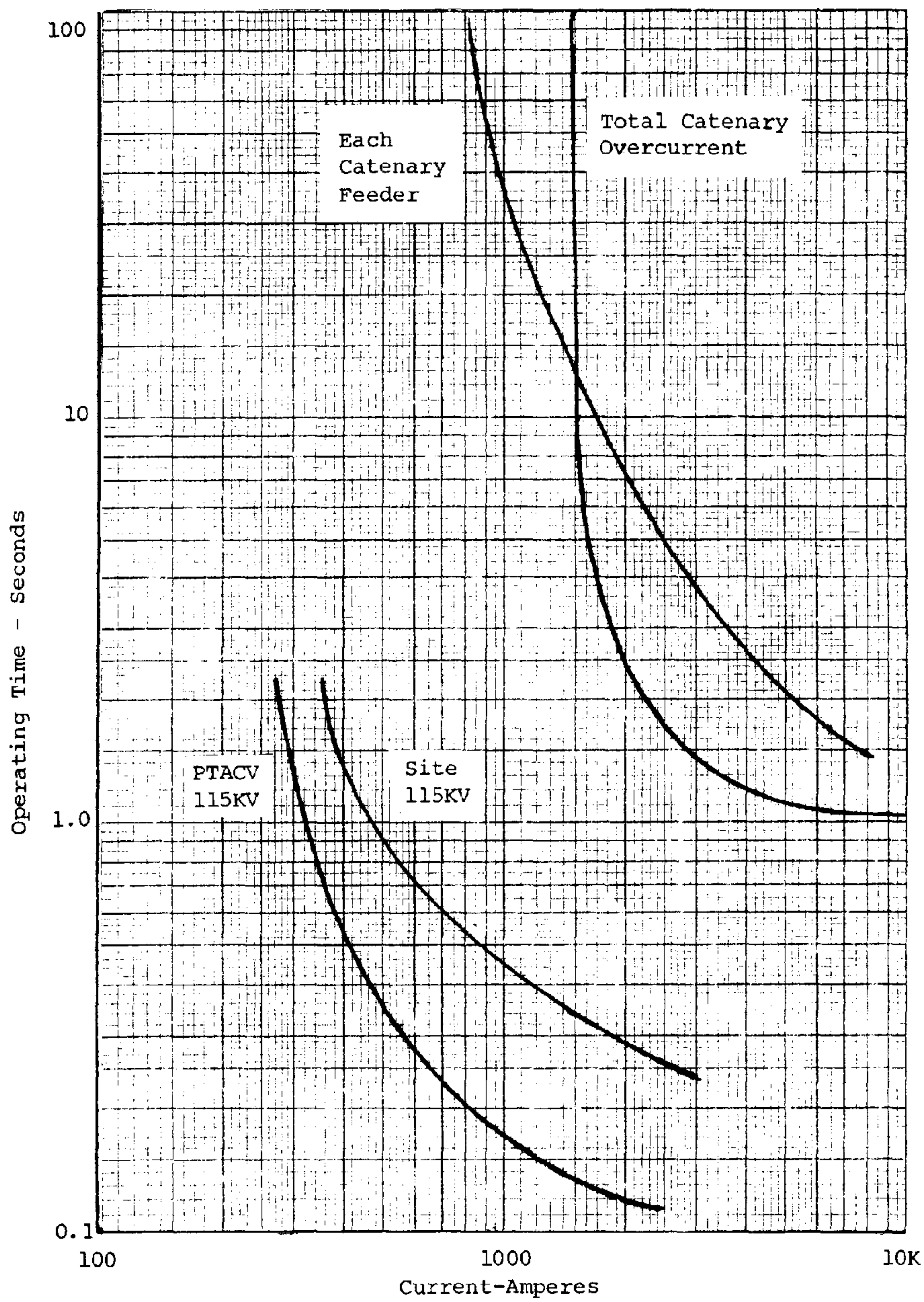


FIGURE A-2. SYSTEM RELAY CHARACTERISTICS.

TABLE A-8. LINE RELAY STUDY.

Description	Feeder Track	Transformer Secondary	Transformer Differential		PTAC Switcher #301		DOT Site Main Breaker	
Calculation by	IECO	IECO	IECO	RPW*	IECO	RPW*	Original	RPW*
Station Data								
CT Values	1600/5	800:5	P=300:5/2 S=800:5	P=300:5/2 S1=800:5 S2=1200:5	600:5	600:5	200:5	200:5
CT Ratio	320:1	160:1	P=30:1 S=160:1	P=30:1 S1=160:1 S2=240:1	120:1	120:1	40:1	40:1
Relay Data								
Type	C09	C08	HU-1	HU-1	C08	C02	C02	C02
Coil Tap Amps	2.0	7.0	P=5.0 S=4.2	P=4.2 S1=3.5 S2=4.2	2.5	2.0	4.0	6.0
Time Curve	#11	0.7	-	-	#1.7	#2	#5	#5
Instantaneous	4.0 A	none	-	-	22A	10A	none	none
AEM-7 Full Load = In	215	215	P=45 A S=215 A	P=45 A S1=215 A S2=655.4 A	45 A	45 A	RTT45 A Site 25 A	70 A
Relay for In = IRN	0.67	1.34	P=1.5 A S=1.34 A	P=1.5 A S1=1.34 A S2=2.73 A	0.37 A	0.37 A	2.72 A	2.72 A
Load for Relay Tap I_T	640 A	1120 A			300 A	240 A	160 A	240
Trip time for multiples								
of Relay Tap $I_T \times 1.5$	39 s	2.4 s**	instantaneous		5.9 s	33 c	-	-
$I_T \times 2$	17 s	1.1 s**	upon fault		3.0 s**	21 c	-	-
$I_T \times 3$	5 s**	0.5 s**	within zone		1.4 s**	13 c	276=70 c**	-
$I_T \times 4$	3.5 s**	0.3 s**			1.0 s**	10 c**	360=42 c**	360=120 c**
$I_T \times 5$	3.0 s**	0.15 s**			0.8 s**	8.6 c**	444=33 c**	444=60 c**
$I_T \times 10$	1.7 s**	0.06 s**			0.4 s**	6.5 c**	863=19 c**	863=24 c**
Instantaneous Trip Load	1280 A	none	overload of 10X tap amps		2640 A	1200 A	none	none

Assumed data: 7000 hp AEM-7 Locomotive at rated output
at 25 kV = 4.5 MW @ 215 A
at 115 kV = 5.3 MW @ 45 A

c = cycles
s = seconds

*Revised for dual voltage operation and increased site loads.
**Catenary load is tripped by C09 instantaneous trip on feeder relays.

j. Current Line Feeder Relay - Type 50/51

- Westinghouse Type CO-9

  Coil = 2.0 A
  Curve = #11
  Inst = 4.0 A

  These two relays protect the halves of the catenary.

- AEM-7 Locomotive Ratings at full load (continuous)

  @ 25 kV = 4.5 MW; 215 A
  @ 12.5 kV = 4.5 MW; 430 A
  @ 115 kV = 5.3 MW; 45 A (at substation primary)

- CT ratio @ feeder line (each line)

  A = 1600:5 = 320:1 ratio

- Relay currents

  Loco @ 25.0 kV = 215/320 = 0.67 A for full load AEM-7
  Loco @ 12.5 kV = 430/320 = 1.34 A for full load AEM-7

- Load for coil A of relay setting = 2.0 A coil

  Loco @ 25.0 kV = 2.0/0.67 = 2.98 full load

  Loco @ 12.5 kV = 2.0/1.34 = 1.49 full load

  Thus, on 12.5 kV full AEM-7 load = 430/640 = 0.67 of the catenary rating

- Overload Testing Margin - Instantaneous 4.0 Relay A

  @ 25.0 kV 4 x 320 = 1280 A to trip, 1280/215 = 6 times full AEM-7 load

  @ 12.5 kV 4 x 320 = 1280 A to trip, 1280/430 = 3 times full AEM-7 load

- See Tables A-9 and A-10 for AEM-7 load vs relay trip times and OCS overcurrent relay, respectively.

TABLE A-9. AEM-7 LOAD VS RELAY TRIP TIMES, CO-9 FEEDER RELAY.

(Feeder Current Transformer Fixed Ratio 1600/5)

AEM-7	Substation A		Relay A		Seconds at 2 A Coil		Seconds at 3 A Coil	
Full Load	25.0 kV	12.5 kV	25.0 kV	12.5 kV	25.0 kV	12.5 kV	25.0 kV	12.5 kV
	215	430	0.67	1.34	-	-	-	-
1.5X	322	645	1.00	2.00	-	-	-	-
2.0X	430	860	1.34	2.68	-	75	-	-
3.0X	645	1290	2.00	4.00*	-	18	-	-
4.0X	860	1720	2.68	5.36*	75	9	-	33
5.0X	1075	2150	3.35	6.70*	37	5	-	17
10.0X	2150	4300	6.70*	13.4*	5	2.3	17	3

* Indicates instantaneous coil operated at 4.0 A.

Note: Above assumes AEM-7 is drawing all power through only one feeder, as in Dual Voltage.

TABLE A-10. OCS OVERCURRENT RELAY, CO-8 TYPE 51.

(Variable CT Ratio 50 kV = 80:1,
25 kV = 160:1, 12.5 kV = 320:1)

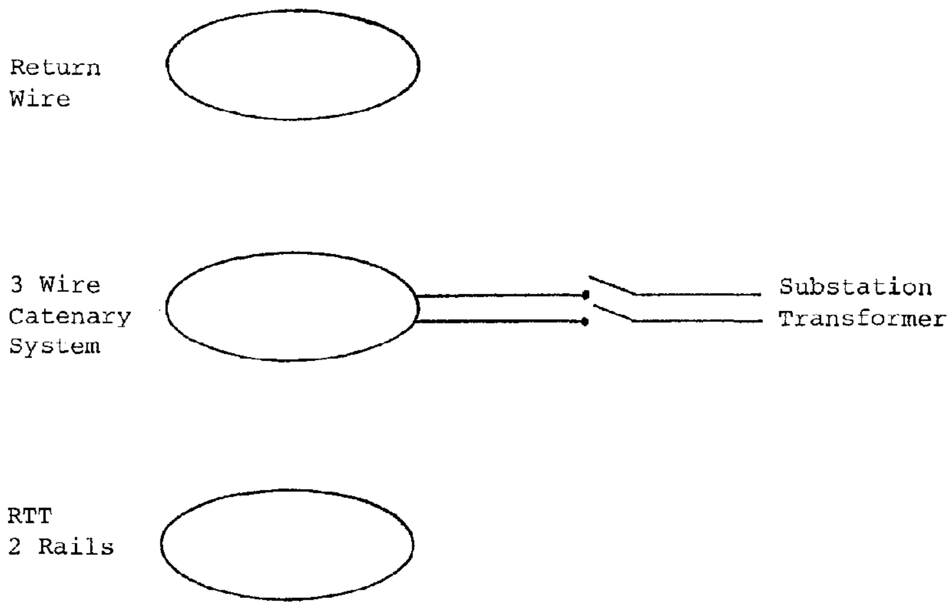
Time Curve Number 0.7

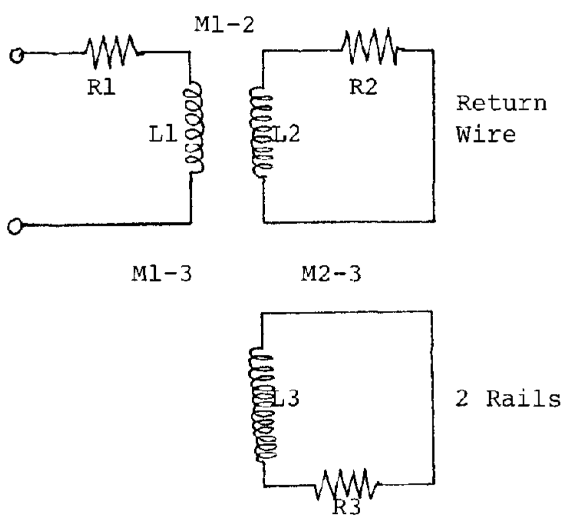
	Relay Current	Seconds at 7.0 A-Coil	
AEM-7	at 25 kV	25 kV	12.5 kV
Full Load	1.34 A	--	--
1.5X	2.00 A	--	--
2.0X	2.68 A	--	--
3.0X	4.00 A	--	10.0 s
4.0X	5.36 A	--	2.2 s
5.0X	6.70 A	--	1.3 s
10.0X	13.40 A	1.3 s	0.4 s

7.0 CALCULATION OF RTT CATENARY IMPEDANCE

7.1 RTT EQUIVALENT CIRCUIT

A very simplified electrical equivalent circuit diagram of the RTT catenary is shown below:





R1, R2, R3 = Resistance Component

L1, L2, L3 = Self-inductance Component

M1-2 = Mutual Inductance of Catenary to Return

M1-3 = Mutual Inductance of Catenary to Track

M2-3 = Mutual Inductance of Return Wire to track

7.2 DATA FROM DESIGN SHEETS

Return Wire: #2/0 ACSR "Quail"
0.447" diameter
0.1219 in^2 area
0.1248 ohm/1000 ft d.c. resistance
0.6589 ohm/mi resistance
GMR* = 0.1741"; X_L = 0.514 ohm/mi, 1 ft

Messenger Wire: 19/0.08333 ASTM Alloy 80
0.417" diameter
0.1036 in^2 area
0.1010 ohm/1000 ft d.c. resistance
0.533 ohm/mi resistance
GMR = 0.1572"; X_L = 0.526 ohm/mi, 1 ft

Auxiliary Wire: 7/0.0833 ASTM Alloy 80
0.250" diameter
0.0386 in^2 area
0.2741 ohm/1000 ft d.c. resistance
1.447 ohms/mi resistance
GMR = 0.0900"; X_L = 0.594 ohm/mi, 1 ft

Contact Wire: 4/0 Grooved Trolley Wire ASTM 80 Alloy
0.482" diameter
0.1665 in^2 area
0.0612 ohm/100 ft
0.3231 ohm/mi resistance
GMR = 0.1626"; X_L = 0.522 ohm/mi, 1 ft

Note: Reactance at 1 ft distance = 0.2794 $\log_{10}$ 1/(GMR/12) ohm/mi.

7.3 INDUCTANCE CALCULATION

Inductance of a large loop of wire by itself:

$$L = \mu \, \ln \left(\frac{8r}{a} - 2 \right) + \frac{\mu 0 \mu 2'}{8 \pi} (2\pi)$$

where:

L = Loop inductance,
μ = Self-inductance of wire,

-----
* GMR = geometrical mean radius

μ_0 = permeability of free air = $4 \;\; \times 10^{-7}$,
μ_1 = permeability of conductor = 1,
r = radius of RTT loop in meters, and
a = radius of conductor in meters

if:

r = 3,586 m, and
a = equivalent radius of all catenary wires (m) assume to be 0.5",

then:

$$L = 4\pi \times 10^{-7} \; (3586) \; (\ell n \frac{8 \times 3586}{0.5/12} - 2) + .0011 \text{ Henry self-inductance}$$

where:

$L = (0.00451) \; (11.44)$,
$L = 0.0516$ Henry loop inductance,

if:

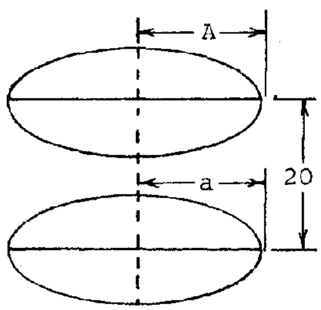
$a = 0.03"$, $L = 0.0494$
$a = 0.8"$, $L = 0.0515$, or only a slight change.

Therefore, inductance of loop = 0.0526 Henry, and
impedance = 377 L = 19.87 ohms at 60 Hz.

This inductance pertains to each of the three RTT elements: the catenary, the return wire, and the rails.

Mutual inductance of two coaxial loops:

Return



Catenary

radius = 3,586 m = 141,177"

distance - vertical = 10 ft = 120"

$$M = f\sqrt{Aa} \times 10^{-6} \text{ Henry (if in cm)*}$$

$$M = f\sqrt{Aa} \; (2.54) \; (10^{-6}) \text{ Henry (if in inches)*}$$

-----

* From Frederich W. Grover's Inductance Calculations: Working Formulas and Tables. Dover, c. 1950.

where $f = 0.014466 \quad \log \left(\frac{1}{K^2}\right) - 0.53307$

a = 141,177" catenary
A = 141,303" return wire (out 10.5 ft)
d = 120" approximate elevation distance

$$K^2 = \frac{\left[1 - \frac{a}{A}\right]^2 + \frac{d^2}{A^2}}{\left[1 + \frac{a}{A}\right]^2 + \frac{d^2}{A^2}}$$

for RTT case:

a/A = 1.00; d/A = 120/141,303 = 0.000849

$$f = 0.014466 \log \frac{1}{0.1803 \times 10^{-6}} - 0.53307$$

$f = 0.0899$

Catenary to return = M = 0.0899 (a) (2.54) (10^{-6}) = 0.0329 Henry or 12.4 ohms

Catenary to rails mutual inductance for RTT:

a/A = 1.00

$$d/A = \frac{22.6 \times 12}{141,303} = 0.00192$$

$$f = 0.0145 \log \frac{1}{0.921 \times 10^{-6}} - 0.533$$

$f = 0.0798$

Catenary to rails:

M = 0.0798 (141,303) (2.54) (10^{-6}) = 0.0286 Henry or 10.78 ohms

Rails to return:

a/A = 1.08

$$d/a = \frac{34.6 \times 12}{141,303} = 0.00294$$

$$d = \sqrt{(22.5 + 10.5)^2} + 10.5^2$$

d = 34.6 ft

$$f = 0.0145 \log \frac{1}{2.16 \times 10^{-6}} - 0.533$$

$$f = 0.744$$

$$M = 0.744\ (141{,}303)\ (2.54)\ (10^{-6}) = 0.0267 \text{ Henry or } 10.07 \text{ ohms}$$

Calculation of resistance in RTT:

Catenary, 3 wires:

Messenger = 0.533 ohm/mi
Auxiliary = 1.447 ohm/mi
Contact = 0.323 ohm/mi

Combined resistance of catenary = 0.1766 ohms/mi

length = 13.506 mi
R cat = 2.447 ohms

Return wire = 0.6589 x 13.506 = 9.13 ohms resistance

Track = parallel of 2 rails resistance

Rails are magnetic, therefore saturable effect

RTT uses 136 lb/yd rails

d.c. resistance assumed = 0.02 ohm/1,000 bolted
0.015 ohm/1,000 welded

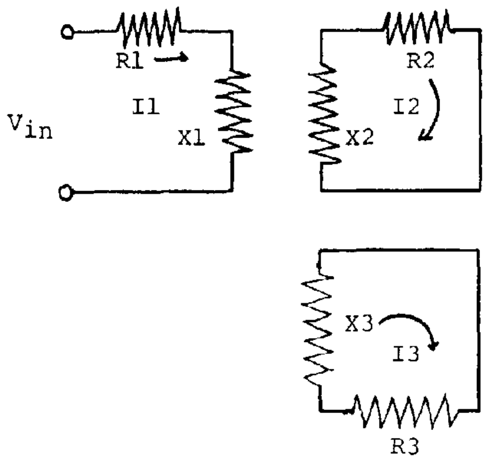
d.c. of track = 0.61 ohm total loop

a.c. 100 A/rail = 9 times d.c. per Woodruff "Electric Power Transmission"

60 Hz resistance = 5.49 ohms loop track

7.4 CALCULATION OF CATENARY CURRENTS

The original transformer circuit can now be calculated:



R_1 = catenary = 2.45 ohms

R_2 = return = 9.13 ohms

R_3 = rails = 5.49 ohms

Assume X1 = X2 = X3 = 19.87 ohm

X12 = 12.40 ohms

X13 = 10.78 ohms

X23 = 10.07 ohms

Writing three equations and solving:

$$Vin = +(R1+jX1)I_1 - (jX12)I_2 - (jX13)I_3$$

$$0 = -(jX12)I_1 + (R2+jX2)I_2 - (jX23)I_3$$

$$0 = -(+jX13)I_1 - (+jX23)I_2 + (R3+jX3)I_3$$

Using Cramer's Rule to solve:

$$\begin{aligned} & [(R1+jX1)][(R2+jX2)\ (R3+jX3) - (jX23)\ (jX23)] \\ = (-) & [(-jX12)][-(jX12)\ (R3+jX3) - (jX23)\ (jX13)] \\ & [(-jX13)][(jX12)\ (jX23) + (R2+jX2)\ (jX13)] \end{aligned}$$

$$I_1 = \frac{V}{\Delta} [(R2+jX2)\ (R3+jX3) - (jX23)\ (jX23)]$$

$$I_2 = \frac{V}{\Delta} [(-jX12)\ (R3+jX3) - (jX13)\ (jX23)]$$

$$I_3 = \frac{V}{\Delta} [(+jX12)\ (jX23) + (jX13)\ (R2+jX2)]$$

Solving these equations for the currents and summarizing the calculated results yields:

Conditions V	= 6149 catenary supply		
Catenary I_1	= 253 $\underline{/-77.5°}$	vs	639.6 $\underline{/-71.3°}$ measured
Return Wire I_2	= 428.5 $\underline{/-26°}$	vs	120 Amperes RMS measured
2 Rails I_3	= 294.5 $\underline{/-43.6°}$	vs	240 Amperes RMS measured

7.5 ANALYSIS

Obviously the constants are in error in magnitude to calculate the catenary current at 40% of its measured value; however, the phase angle is correct. The return wire bonds to the rails on the track allow the higher induced current of the return wire to flow to the rails.

Of primary concern is that the RTT track system has been confirmed to be a large shorted turn transformer with considerable return wire and rail currents. From this analysis, the RTT catenary should be operated as dual feeders whenever possible to prevent transformer action.

It should be noted that when a shorting device was used at midpoint during testing, the return currents flowed under the outgoing currents of the catenary and no transformer action was observed in the unenergized half section of catenary.

7.6 SUMMARY AND COMPARISONS

Method	RTT Loop Catenary Impedance
Design value	0.344+j0.787 ohm/mile = 11.68 ohms at -66.3°
Test value	0.226+j0.668 ohm/mile = 9.5 ohms at -71.3°
Calculated value	0.31+j1.40 ohm/mile = 19.5 ohms at -77.5°

8.0 CALCULATION OF SHORTING CURRENT AT R12+400

8.1 TEST RESULTS AND CALCULATED VALUES

On January 29, 1980, the following loop characteristics were measured:

Length	13.504 mi
Voltage	6,149 V
Current	628 A at 71.3° phase angle

Tests on February 12, 1980, determined style 5 catenary distribution as:

Messenger	40.25%	(IECO design, 39.58%)
Auxiliary	15.10%	(IECO, 17.09%)
Contact	44.65%	(IECO, 43.33%)
Return	19.8%	(IECO, 30.2%)

Length of shorted span = 155 ft (R12+435 to R12+280 + 5)

IZ drop in shorted span of current carrying catenary:

$$IZ = \frac{6,149}{13.504 \times 5,280} \times 155 = 13.37 \text{ V}$$

Auxiliary wire is 7/.0833 stranded cable of 80% conductivity.

Stranding = 7 strands of #14 Birmingham wire gage = #4 AWG
Resistance = 0.2741 ohm per 1,000 ft @ 68° F (IECO spec.)
Reactance of #4 = X_d = 0.595 ohm per conductor per mi at 1 ft

Loop resistance of wire = 0.0002741 x 155 x 2 = 0.085 ohm loop

$$\text{Loop reactance approximates} = \frac{2 \times 0.595}{5,280} \times 155 = j0.035 \text{ ohm loop}$$

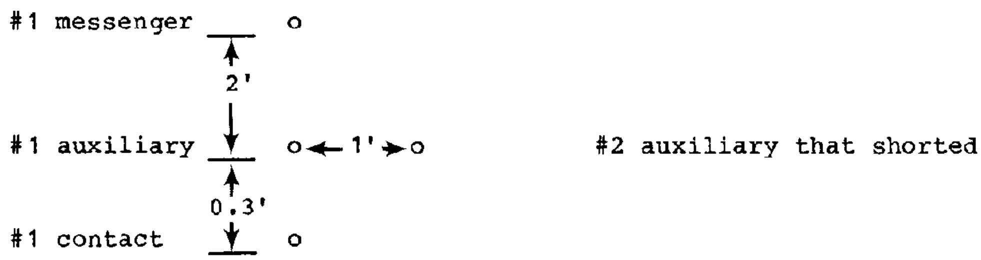
Contact resistance wire to steel crossarm estimated at 0.01 ohm.

Impedance of loop = Z = 0.095 + j0.035 = 0.10 ohm

Catenary current distribution at 628 A.

628 x 0.4025 = 252.8 A messenger
628 x 0.1510 = 94.8 A auxiliary
628 x 0.4465 = 280.4 A contact
628 x 0.198 = 124.3 return (503.6 rail + ground)

Catenary spacing configuration at R12+400 (see Figure A-3):



Rails are on ground, 22.5 ft below; return wire is 15 ft to side.

Distances:

#1 messenger to #2 auxiliary = 5 ft
#1 auxiliary to #2 auxiliary = 1 ft
#1 contact to #2 auxiliary = 0.3 ft

Voltage induced in #2 auxiliary from three catenary wires and the return wire, two rails and earth current:

$$V = j0.2794 \ [I_m \log 5 + I_a \log 1 + 1_c \log 0.3 - I_r \log 15$$
$$- I_{r+r} \log 22.5] \text{ V/mi}$$

$$V = j0.2794 \ [252.8 \times 0.349 + 94.8 \times 0 + 280.4 \ (-.523)$$
$$- 124.3 \times 1.18 - 503.6 \times 1.35] \text{ V/mi}$$

$$V = j0.2794 \ [-884.9] = -247.3 \text{ V/mi}$$

$$V = \frac{247.3}{5{,}280} \times 155$$

$$V = 7.26 \text{ volts}$$

Sum of two driving voltages:

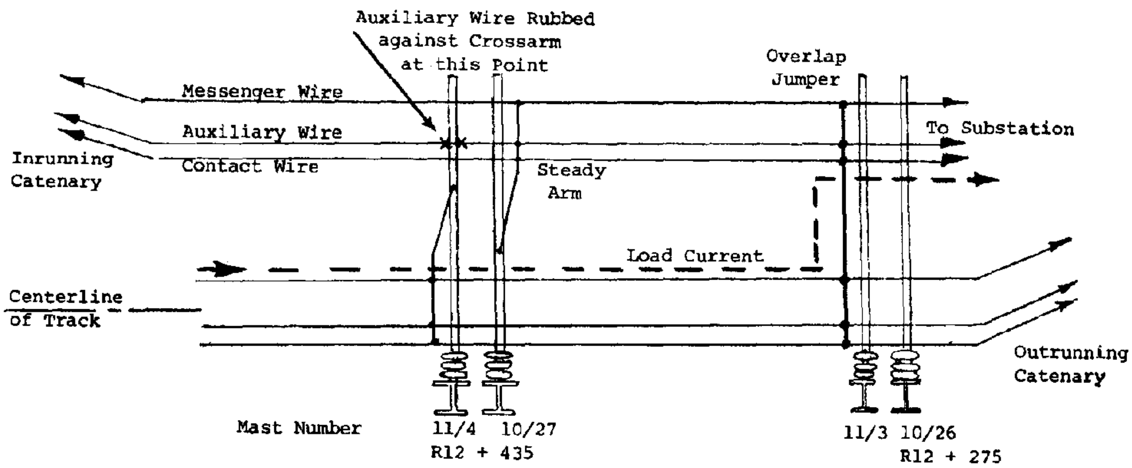
IZ drop is assumed to be north to south.
Induced current opposes driving current, so polarity is south to north.
Jumper cables are on overlap at north end and the short is at the south end.

IZ = 13.37 V

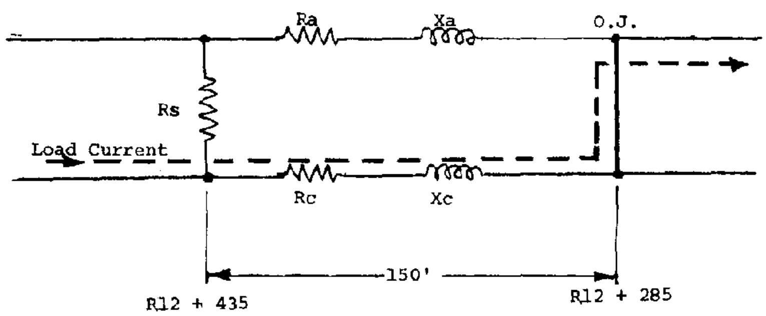
V_{aux} = 7.26 V

Loop = 20.63 V

Loop current = 20.63/0.10 = 206.3 A (calculated)



Overhead View of Shorted Section



Rc & Xc = Impedance of Three Wire Catenary
Ra & Xa = Impedance of Auxiliary Wire
Rs = Resistance of Contact of Auxiliary Wire to Crossarm
O.J. = Overlap Jumper

Electrical Equivalent Circuit

FIGURE A-3. AUXILIARY WIRE GROUNDING TO CROSSARM.

On February 12, 1980, 45 A were measured in the shorting jumper using a clamp-on ammeter when 248.2 A flowed in the catenary. The clamp-on ammeter conversion factor = 0.91. If a full load current of 628 A flowed in the catenary, the equivalent shorting jumper current would be equal to:

$$\frac{45}{0.91} \times 628/248.2 = 125.1 \text{ A (test)}.$$

Auxiliary wire current carrying rating for #4 pure copper wire in open air is 180 A; for 80% conductivity and some heating, current capacity is 144 A.

8.2 CONCLUSION

Theory is substantiated by calculation and test. The variance may be caused by higher contact resistance than 0.01 ohm; 0.016 ohm would produce 125 A of test.

APPENDIX B

AEM-7 INRUSH CURRENT TABULATIONS

The purpose of the inrush current tabulations is to demonstrate that under varying operating conditions a consistent pattern of inrush currents occurs. Measureable inrush currents occur at approximately 20% of transformer energization. The tabulations represent successive energizations at the phase breaks during AEM-7 profile running. This information is intended to provide assistance in the design of substation relaying systems which must allow for locomotive inrush currents without compromising fault protection.

NOTE: INRUSH CURRENT LEVELS BELOW 20 AMPS ARE BELOW THE RESOLUTION OF THE MEASUREMENTS AND ARE THEREFORE LISTED AS ZERO LEVEL.

AEM-7 INRUSH TABULATIONS
(Dual Voltage)

DATE: 09 JAN 81 PROFILE NO: 1

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV
0	Open		X	
300		X		
0			X	
0		X		
100			X	
0		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
200			X	
0		X		
150			X	
0		X		
0			X	
0		X		
100			X	
0		X		
100			X	
250		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0	Open	X		

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AEM-7 INRUSH TABULATIONS
(Dual Voltage)

DATE: 09 JAN 81 PROFILE NO: 2

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV
0	Open	X		
0			X	
400		X		
0			X	
0		X		
0			X	
200		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
0			X	
200 +		X		
200 +			X	
0		X		
0		X		
0			X	
0		X		
0		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
0			X	
400		X		
200 +			X	
200	Open	X		

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AEM-7 INRUSH TABULATIONS
(Same Voltage and Phase)

DATE: 12 JAN 81 PROFILE NO: 1

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV
0	Closed			X
250				
300				
0				
0				
0				
200	Closed			
0	Open			
0	Closed			
0				
0				
0				
0				
0				
0				
0				
0				
50				
400				
0				
0				
0				
225				
0	Closed			
0	Open			
0				
0	Open			
0	Closed			
0	Open			
0	Closed			
0				
0	Closed			X

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AEM-7 INRUSH TABULATIONS
(Same Voltage and Phase)

DATE: 12 JAN 81 PROFILE NO: 2

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV
0	Closed			X
75				
0				
50				
0				
125				
0				
0				
0				
0				
0				
0				
0				
0				
0				
0				
200				
0				
0				
100				
175 +				
50				
0				
50				
0				
200	Closed			X

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AEM-7 INRUSH TABULATIONS
(Dual Voltage)

DATE: 13 JAN 81 PROFILE NO: 1

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV
0	Open		X	
0		X		
0			X	
375 +		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
0			X	
375 +		X		
200			X	
400		X		
0			X	
0		X		
0			X	
0		X		
0			X	
200		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
200 +			X	
0		X		
0			X	
0		X		
200			X	
0		X		

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AEM-7 INRUSH TABULATIONS
(Dual Voltage)

DATE: 14 JAN 81 PROFILE NO: 1

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV
0	Open		X	
0		X		
200			X	
0		X		
100			X	
450 +		X		
0			X	
200 +		X		
100			X	
400 +		X		
0			X	
550 +		X		
0			X	
500 +		X		
0			X	
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
100 +			X	
0		X		
0			X	
0		X		
0			X	
0		X		
100			X	
0		X		
0			X	
0	Open	X		

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AEM-7 INRUSH TABULATIONS
(Dual Voltage)

DATE: 15 JAN 81 PROFILE NO: 1

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV
0	Open		X	
0		X		
0			X	
200		X		
0			X	
0			X	
0		X		
0			X	
0		X		
0			X	
400		X		
0			X	
0			X	
250		X		
0			X	
350		X		
0			X	
400		X		
100			X	
0		X		
0		X		
0		X		
0			X	
0		X		
0			X	
0		X		
100			X	
0		X		
300	↓		X	
0	Open	X		

SIGNATURE: D. Allen PAGE 1 of 2

AEM-7 INRUSH TABULATIONS
(Dual Voltage)

DATE: 15 JAN 81 PROFILE NO: 2

INRUSH CURRENT (AMP)	ABB	25 kV TO 12.5 kV	12.5 kV TO 25 kV	25 kV TO 25 kV
0	Open		X	
0		X		
200			X	
0		X		
0			X	
400 +		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
0			X	
0		X		
200			X	
0		X		
100			X	
300		X		
0			X	
0		X		
0		X		
0			X	
0			X	
400		X		
100			X	
LAPS OF 1/15/81				
0		X		
0	↓		X	
0	Open	X		

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AEM-7 INRUSH TABULATIONS
(Dual Voltage)

DATE: 16 JAN 81 PROFILE NO: 1

INRUSH CURRENT (AMP)	ABB	25 kV TO 12.5 kV	12.5 kV TO 25 kV	25 kV TO 25 kV
0	Open		X	
400 +		X		
0			X	
0		X		
0			X	
0		X		
100 +			X	
0		X		
100			X	
0		X		
100			X	
300		X		
200 +			X	
100		X		
0			X	
0		X		
0			X	
0		X		
300			X	
300		X		
0			X	
400 +		X		
100			X	
300 +		X		
0		X		
0			X	
300 +		X		
0			X	
0	Open	X		

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AEM-7 INRUSH TABULATIONS
(Dual Voltage)

DATE: 16 JAN 81 PROFILE NO: 2

INRUSH CURRENT (AMP)	ABB	25 kV TO 12.5 kV	12.5 kV TO 25 kV	25 kV TO 25 kV
50	Open		X	
0		X		
0			X	
0		X		
0			X	
200		X		
0			X	
500 +		X		
0			X	
0		X		
0			X	
600		X		
0			X	
0		X		
0			X	
0		X		
100			X	
0		X		
0			X	
0		X		
100			X	
0		X		
0			X	
200 +		X		
200 +			X	
0		X		
0			X	
0		X		
0			X	
0	Open	X		

SIGNATURE: D. Allen PAGE 2 of 2

AEM-7 INRUSH TABULATIONS
(Dual Phase)

DATE: 1/26/81 PROFILE NO: #1

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV *
0	OPEN			X
0	OPEN			
0	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			
200	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			X

*Dual Phase

NOTE: CURRENT LEVELS OF 20 AMPS OR LESS ARE BELOW THE RESOLUTION OF THE MEASUREMENT.

SIGNATURE: D.M. JOHNS PAGE 2 of 2

AEM-7 INRUSH TABULATIONS
(Dual Phase)

DATE: 1/26/81 PROFILE NO: #1

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV *
0	OPEN			X
0	CLOSED			
0	OPEN			
0	CLOSED			
100+	OPEN			
0	CLOSED			
300	OPEN			
0	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			X

*DUAL PHASE

SIGNATURE: D.M. JOHNS PAGE 1 of 2

AEM-7 INRUSH TABULATIONS
(Dual Phase)

DATE: 01/26/81 PROFILE NO: #2

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV*
0	OPEN			X
0	CLOSED			
0	OPEN			
300+	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			
0	OPEN			X

*DUAL PHASE

SIGNATURE: D.M. JOHNS PAGE 1 of 2

AEM-7 INRUSH TABULATIONS
(Dual Phase)

DATE: 01/26/81 PROFILE NO: #2

INRUSH CURRENT (AMP)	ABB	25kV TO 12.5kV	12.5kV TO 25kV	25kV TO 25kV*
0	OPEN			X
400	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			
0	OPEN			
0	OPEN			
0	CLOSED			
200	OPEN			
0	CLOSED			
0	OPEN			
300	CLOSED			
0	OPEN			
200	CLOSED			
0	OPEN			
0	CLOSED			
0	OPEN			
300	CLOSED			
0	OPEN			
0	CLOSED			X

*DUAL PHASE

SIGNATURE: D.M. JOHNS PAGE 2 of 2

APPENDIX C

ENDURANCE TEST DOCUMENTATION

This appendix contains examples of the documentation used during the AEM-7 Test Program. A full set of maintenance and test logs will be made available to interested parties upon request.

AEM-7 PROFILE SCHEDULE TRIP FORM

DATE: 9-22-80 p.2
SHIFT: 0100-1000 (hrs.)

	TIME	MILEAGE
Leave BOSTON	01 48 05	
Arrive Station #1	02 00 30	11.8
Leave Station #1	02 01 50	
Arrive Station #2	02 22 50	43.8
Leave Station #2	02 24 15	
Arrive Station #3	03 11 43	106
Leave Station #3	03 13 05	
Arrive Station #4	03 58 10	156.8
Leave Station #4	03 59 26	
Arrive Station #5	04 33 38	196
Leave Station #5	04 34 55	
Arrive NY	05 10 15	231.8
TRIP TIME & MILEAGE	3:22:10	
KW HRS.		4092 KW HRS.

	TIME	MILEAGE
Leave WASH	05 22 30	
Arrive Station #1	06 20 17	90.5
Leave Station #1	06 21 30	
Arrive Station #2	07 17 45	184.7
Leave Station #2	07 19 00	
Arrive Station #3	07 45 55	225
Leave Station #3		
Arrive Station #4		
Leave Station #4		
Arrive Station #5		
Leave Station #5		
Arrive NY		
TRIP TIME & MILEAGE	2:23:25	
KW HRS.		4882 KW HRS.

AEM-7 TEST OPERATIONS

DATE: 10-10-80
SHIFT: 2300-0800

CONSIST LIST: AEM-7, 900, 21246, 21003, 21035, 211

TEST DIRECTION: CCW

CATENARY VOLTAGE: 25KV

TRACK CONDITIONS: Dry

WEATHER CONDITIONS:	TEMPERATURE (Degrees F.)	WIND (mph, Direction)	RELATIVE HUMIDITY (%)	MILITARY TIME
Start Test	57	10 NE	39	2323
Mid-Test	49	4 NNW	44	0315
End Test	44	Calm	52	0600

AEM-7 DISCREPANCIES:

1. Flange on front left wheel of rear truck continues to wear unevenly.
2. TM armature ground and TM overload with TM 3 & 4 fault at 0454.
3. TM armature ground with TM 3 & 4 fault at 0500.
4. Squeak on roof of rear cab is loud enough to possibly do ear damage.
5. Rattle under left side of front cab.
6. TM #2 overload with Aux. converter fault at 0745.
7. TM armature ground with TM 1 & 2 fault at 0746.

CONSIST DISCREPANCIES:

NONE NOTED

TRACK DISCREPANCIES:

1. Speed restriction of 115 mph on AEM-7 for entire track.

GENERAL COMMENTS:

1. Consist inspections: 0312
   0602

Pg. 3.
1. VO said that locomotive felt as if it was trying to fishtail.
   No cause found.

DISTRIBUTION: C. Perry W. McCutchon D. Waldo T. Bomar G. Woy C3

CONFIGURATION CHANGE REQUEST

1. Initiator/Date	2. Type	3. Vehicle	4. Engineering Drawings Required
~~D. K. Waldo 11/25/80~~	Permanent [ ] Temporary [ ]	Program ~~AEM-7~~ Car No. 900	Yes [ ] No [ ]

5. REASON FOR CHANGE:

During energization of the AEM-7 on 11/24/80 the main circuit breaker closed with the 11.5 KV surge arrestor still connected, causing a flash over through the surge arrestor.

6. DESCRIPTION OF WORK (Use continuation pages if required):

1. Remove surge arrestor from the roof.
2. Motorize the transformer tap changer and the 11.5KV surge arrestor to the 25 KV position.
3. Disconnect the power to both motors.

PART B: APPROVALS

Test Support Engineer	Chief Test Engineer	FRA/Date	Vehicle Representative
[signature]	[signature]	[signature]	

PART C: Completed by Rail Vehicle Maintenance

7. Date complete	8. Vehicle Status	9. Labor Hours	10. Materials
11/25/80	Out of Service [ ] Reduced Capability [x] No Effect [ ]	2	N/A

11. REMARKS: New surge arrestor ordered from EMD on 11/25/80 for further evaluation of this problem. Operation of the AEM-7 is restricted to 25 KV until a replacement of the 11.5 KV surge arrestor is installed and an evaluation has been completed.

PART D: Complete if temporary Change

12. Date Restored	13. Signature (TSE)	Control Number
		AEM-7-007

CONFIGURATION CHANGE REQUEST

1. Initiator/Date	2. Type	3. Vehicle	4. Engineering Drawings Required
D. K. Waldo	Permanent [x] Temporary [ ]	Program AEM-7 Car No. 900	Yes [ ] No [x]

5. REASON FOR CHANGE:

Repack all journal bearings with improved bearing lubricant.

6. DESCRIPTION OF WORK (Use continuation pages if required):

1. Detruck locomotive.
2. Remove existing Mobilux 2 EP grease from bearings.
3. Inspect bearings.
4. Repack all journal bearings with. ESSO-BEACON EP2
5. Replace the pressductor cable on TM
6. Retruck locomotive.

All bearing work to be done under the guidence of the EMD representative - H. Schmidt.

PART B: APPROVALS

Test Support Engineer	Chief Test Engineer	FRA/Date	Vehicle Representative
D.K. Waldo	A. J. Peters	W. McCall 3/3/[illegible]	[illegible signature]

PART C: Completed by Rail Vehicle Maintenance

7. Date complete	8. Vehicle Status	9. Labor Hours	10. Materials
3-6-87	Out of Service [X] Reduced Capability [ ] No Effect [ ]	201.0 Straight 45.5 Over Time	

11. REMARKS:

Feb 23 [illegible] new [illegible] board [illegible] commutators [illegible] on high [illegible]

April 3 [illegible] cell TM 309 AR

PART D: Complete if temporary Change		Control Number
12. Date Restored	13. Signature (TSE)	AEM-7-008

CONFIGURATION CHANGE REQUEST

1. Initiator/Date	2. Type	3. Vehicle	4. Engineering Drawings Required
D. K. Waldo	Permanent ☒ Temporary ☐	Program AEM-7 Car No. 900	Yes ☐ No ☒

5. REASON FOR CHANGE:

Modify air blast Circuit Breaker

6. DESCRIPTION OF WORK (Use continuation pages if required):

1. Remove Air Blast Breaker.
2. Clean, inspect and replace metal washer on the shaft of the movable contact.
3. Disassemble, clean and inspect the air control valve. Replaced with Mod. Unit
4. Install two new postion indicating switches on the pantograph positioning switches for the front and rear pantographs.
5. Cycle the air blast breaker through with 150 # of air pressure and wit 74 VDC applied to check for proper operation.
6. Reinstall the AB breaker in the locomotive.

PART B: APPROVALS

Test Support Engineer	Chief Test Engineer	FRA/Date	Vehicle Representative
D. K. Waldo	a. g. Peters	[signature] 3/17/81	[signature] BVW

PART C: Completed by Rail Vehicle Maintenance.

7. Date Complete	8. Vehicle Status			9. Labor Hours	10. Materials
March 20, 1981	Out of Service ☒	Reduced Capability ☐	No Effect ☐	68.0	---

REMARKS:

PART D: Complete If Temporary Change		Control Number
12. Date Restored	13. Signature (TSE)	AEM-7 009

TTC FORM NO 4430.1-1 (7.80)

AEM-7 LOCOMOTIVE TEST

Chief Test Engineer's Weekly Report

Two Weeks Ending 2 August 1980

PART 1: SUMMARY REPORT

Daily Activities

7/20/80	New York - Washington profiles.
7/21/80	New York - Washington profiles.
7/22/80	New York - Washington profiles.
7/23/80	New York - Washington profiles.
7/24/80 – 7/26/80	Locomotive de-trucking and Balfour Beatty Phase Break Installation.
7/27/80	Locomotive and phase break speed upgrade.
7/28/80	Catenary dewirement (pantograph failure).
7/29/80	AMTRAK Board of Directors Visit.
7/30/80 – 8/02/80	Catenary repairs and Locomotive Maintenance.

Major Achievements

1. Accumulation of 2854 miles.

2. Installation of BR/BW lightweight pantograph.

3. Repair of RTT catenary after the high speed dewirement.

4. Modification to locomotive yoke assembly bolts to new standard.

5. Protective screen fitted to the Transformer coding oil radiator outlet.

6. Balfour Beatty Phase Break installed at the RTT substation and successfully speed upgraded to 115 mph

Major Problems

1. One of the yoke assembly to body bolts (Bend left side) fractured during operations on 7/23/80. Upon advice from EMD and AMTRAK, the locomotive was taken out of service and de-trucked.

2. While the locomotive was de-trucked, the wheels were inspected in detail. Two major findings ensued:

   a) Several large bruises were found in the upper flanges of #4 wheelset. A detailed inspection of the RTT switches and frogs yielded no apparent cause. These defects were attributed to damage sustained in shipping the locomotive from Chicago to the TTC. The damage had previously been logged as wheelflats sustained in transit, since they give a similar effect when running.

b) A wavy wear pattern appeared on some of the wheel flange roots. This effect had been previously noted on FAST vehicles which were on the verge of deterioration hunting. This was related to a noticeable deterioration in lateral ride quality between 115 mph and 120 mph. It was later learned that EMD would be fitting yaw dampers to the locomotive in due course. A maximum speed of 115 mph has been subsequently imposed on the locomotive.

3. Severe damage has been sustained by the lateral bump stops.

4. During the speed upgrade of the locomotive and the newly installed Balfour Beatty Phase Break, the #2 Faiveley two-stage pantograph failed. Approximately 12000 feet of catenary was either pulled down or damaged, resulting in suspension of operations.

5. To expedite repair of the catenary, the local Power Company and a firm of local Electric Contractors were called in to assist the TTC Power Systems group. The method used to string the contact wire proved to be unsatisfactory. Thirty-four twists had to be worked out of the wire before clipping in was complete. For future cases, the conventional method of 'laying in' the wire must be used, and a rig for applying this method using the DOTX-211 car is to be designed. This is dealt with more fully in Part 2.

6. The BR/Brecknell Willis high speed pantograph was fitted to the locomotive and speed upgraded to 115 mph. This was used for the AMTRAK Board of Director's visit to the TTC. That pantograph is now the only unit on the locomotive. However, another two stage Faiveley is expected from EMD early in the next week.

PART 2: DISCUSSION

The Dewirement Incident

1900 Retrucking operation complete.

1930 Locomotive energized at 25 kv and initial checkout complete. Some problems existed with field currents on TM #3 & 4 on initial startup but problem disappeared.

2130 Start of track conditioning run at 30 mph followed by successive runs at speeds of 45, 60, 75, 90, 100 and 110 mph over the Balfour Beatty Phase Break. A final run at 120 mph was called for.

2250 OCB at substation opened under a fault condition. Subsequent radio message indicated that a dewirement had occurred and that the train had come to a stand at station R33. Catenary feeder switches opened and grounds were applied.

2310 A fire truck with floodlights arrived at the scene (no emergency had been declared). Initial inspection showed that severe pantograph damage had been sustained. The pantograph lowering system had not functioned and the pantograph had to be lowered forcibly by hand and tied down.

0015 An inspection of the catenary system was started under artificial lighting. Damage was modest for the last 7000 feet ranging from displaced hangers to dented registration arms. The damage from RTT station R21 to R26 was severe with the section between R22 and R24 sustaining the most damage. A much fuller inspection was planned for early morning.

Daylight Inspections

a) Locomotive - The pantograph was found to be extensively damaged. The upper stage and head were still attached to the main stage by the tension rod.

Inspection of the pantograph head showed only one item of damage, namely, a large impact of the front right hand horn near the interface with the carbon carrier.

The pantograph main or lower stage was extensively damaged, in particular, the upper member which was severely bent.

The failure of the pantograph to lower was traced to a fault in the lowering linkage design which allowed the mechanism to lock itself over center when the pantograph reached full extension.

No further damage was sustained by the locomotive roof equipment.

b) Consist - Only two items of damage were apparent on the consist. The DOTX 211 car roof ventilators received impact damage, also the body side and one window was scratched. More serious damage was sustained by AMFLEET car 21035. A large impact on the body side distorted one window frame breaking the window.

c) Catenary - Damage to the catenary was confined to the area R20 to R33, a track length of 13,000 feet. Altogether, four tension sections of catenary were involved, namely #12, 13, 14, 15.

Damage to tension section #12 was confined to a bent registration arm, kinked contact wire and a broken insulator all at structure 12/31.

The most severe damage was to tension section #13 where both auxiliary messenger and contact wires were broken. However, the messenger wire was intact. The mid-point anchor also held which meant that the system beyond the mid-point retained much of its geometry. However, a number of registration arms were badly bent in along track direction.

Tension sections #14 and 15 damage was confined to pulled out hangers and wire kinks due to displaced registration arms. At one of these, approximately 10% of the cross sectional area had been removed due to scoring of the wire.

It was generally concluded that, considering the speed at which the incident occurred, the damage was remarkably light. Before any clean up operations commenced, all damage was photographed as a permanent record.

Restoration of the Catenary System

The major task was to secure the re-useable material in #13 before further damage occurred. To this end, the balance weights were lifted to relieve the tension on the messenger wire. The good lengths of auxiliary was temporarily terminated to stop it running, also the contact wire until it could be inspected. All loose equipment was removed and broken cantilevers replaced.

It was subsequently decided to replace complete tension section of contact wire and approximately 2000 feet of auxiliary wire. Although the west half tension section contact wire was not broken, a great deal of damage was apparent in the form of kinks and severe scoring.

To expedite the repairs, a drum tensioner rated at 4000 lbs, together with operators, was hired from Southern Colorado Power Company. Also a local contractor, Gardener Zimke, was hired to augment TTC personnel to string the wires. Using conventional power line techniques of winching the wires through stringing pulleys, the new wires were in place within 24 hours. This method was used because no equipment was available at the Test Center for laying up the wires by the conventional railroad method using rail mounted vehicles.

The spare contact wire provided by the original installer was in 3000 feet lengths. A splice in the contact wire was necessary to complete the length, an undesirable feature for high speed operation.

The method used to string the wire, far from expediting the process, probably delayed completion. Since no rotary restraint was provided in the stringing process operation the wire followed its natural tendancy to twist. At the end of the process, 34 twists had to be removed from the wire before hanger clipping could be completed. This is very time consuming since no more than three twists can be removed at any one time, also they have to be worked towards one end. The clipping operation which should have been completed in one day finally ran to three days. In addition to the twists, a number of kinks were made in the new contact wire by use of wire grips while making the splice.

In the remaining tension sections repairs were effected as necessary to replace hangers and straighter registration arms. Wire kinks were left for future attention. Upon completion of repairs, a dead line pantograph was run through the section first at 5 mph then at 30 mph to check the geometry. The catenary was restored to service at 1730 on 8/02/80 with a temporary speed restriction of 90 mph until all wire kinks are removed.

Observations

1. The bolted type hanger clips should be replaced by a simpler arrangement, since these hangers were difficult and time consuming to install.

2. At least one 6000 foot length of continuous contact wire should be purchased for future use.

3. The TTC should augment its equipment to enable a similar incident to be handled in-house. This will include a wire roller assembly for the DOTX 211 car.

4. Contact wire should never again be winched through stringing blocks.

Analysis of the Dewirement

In an incident such as this on an operational railroad, it is often difficult to establish the exact cause of such an occurrance. However, since the RTT is a new and dedicated facility, it proved easy to determine the exact sequence of events.

Initial inspection of the pantograph established that the main frame was severely damaged yet the head was comparatively undamaged, having sustained only the one impact. Therefore, it was concluded that this was not the classic dewirement where the horns on the pantograph head sway clear of the contact wire and subsequently become entangled in the hangers. It was further concluded that the pantograph upper stage failed either due to mechanical impact or structural fatigue.

The first damage on the catenary was a bent registration arm in which there were two indentations matching the forked end of the lower stage upper tube. It was therefore concluded that the upper stage had already failed by that time.

A detailed inspection was made of the catenary leading up to initial damaged section with the following results.

STRUCTURE #	
12/17 to 12/21	Faint scratches on the contact wire indicating slight abrasive rubbing, possibly a tilted pantograph head.
12/22	An impact mark on the registration tube (not the registration arm) exactly matching the indentation on the pantograph head. The position of mark indicated that the pantograph head must have been inclined laterally on angle of 45 degrees to the projected track center line, thus the upper stage must have already have been broken at this point.

STRUCTURE#

12/22 to 12/30 Deeper score marks on the contact wire, also damage to the hanger bolt heads.

12/31 Bent registration arm, the first visible signs of heavy damage.

Inspection of the catenary between the Balfour Beatty phase break, the last known point at which the pantograph was observed to be normal, and the impacted registration tube yielded no signs of further impact damage. It was therefore concluded that the incident was the result of structural failure of the pantograph. For the record, the inspection was conducted by:

A. J. Peters (TTC)
K. M. Watkins (AMTRAK) O. Simons (Faiveley S. A.)

Possible Causes of Structural Failure

1. A flaw in the cast aluminum upper stage members.

2. Fatigue failure. This pantograph had spent the majority of its life in the locked down position. During the roof equipment inspection prior to energization on the day of the dewirement it was drawn to the attention of Ken Watkins (AMTRAK) and Bob Consbrook (EMD) that a vibration problem existed with the pantograph in the locked down position.

   After the failure this problem was further considered and concern was expressed about the magnitude of the loads imposed on the lockdown mechanism, and therefore the lower casting of the upper stage, due to vibration. Faiveley had not conducted any tests in this position.

3. Initial metalurgical inspections of the failed components yielded no evidence of fatigue failure or casting flaws so the search for the cause of the failure continues.

Footnote

Initial observations of the BR/BW pantograph indicate a much improved performance over the Faiveley DS 11 pantographs.

a. J. Peters

A. J. Peters
Chief Test Engineer/RTT Electrification

OPERATIONAL DATA SHEET

Each locomotive unit shall be inspected in accordance with Rule 203 of the Laws, Rules and Instructions for Inspection and Testi[ng] of Locomotives Other Than Steam.

LOCOMOTIVE NO.	WORK ORDER NO.		INITIALS
AMT 900	7113C		AEM-7
INSPECTED AT RTT		TIME-START/STOP 1600	A.M. / P.M. DATE 1/14/81

REPAIRS NEEDED	REPAIRS MADE BY
WHEEL SLIP LIGHT STAYS ON CONSTANTLY – WHEN MOVING OR STOPPED.	Speed Pick up out of adj. Fixed & Gen W[illegible]
FRONT RIGHT SIDE OF LOCO BENT IN – MODERATE DAMAGE – FROM HITTING ANTELOPE	Straightened Gen W[illegible]
CHECK LOCO UNDERSIDE FROM ANTELOPE STRIKE. FOR POSSIBLE DAMAGE	
FRONT + RIGHT HAND SIDE OF LOCO NEEDS WASHED DOWN, ESPECIALLY AIR HOSE COUPLINGS ON FRONT.	Gen W[illegible]

PRESSURE	CONDITION
MAIN RESERVOIR 130 - 140 LBS.	BRAKE AND BRAKE RIGGING OK
BRAKE PIPE 112 LBS.	

SIGNATURE OF EMPLOYEE MAKING INSPECTION	OCCUPATION
R.B. Holcomb	Locomotive Engineer

The above work has been performed, except as noted, and the report is approved.

SIGNATURE	OCCUPATION
Gen W[illegible]	Supervisor

TTC FORM 6330.1-1

AEM-7 DAILY INSPECTION

INSTRUCTIONS: Each locomotive unit in use must be inspected in accordance with rule 203 of the laws, rules and instructions for inspecting and testing locomotives.

DATE: 1-30-8/ TIME: 1300 LOCATION: B-Lhen Trk. LOCO NUMBER: 0900

ITEM	ACTION REQUIRED:	MI	INITIALS
Inspection of Unit:	Running Gear, Journal Boxes		
	Draft Gear		
	Transformer Cooler Fins		
	Machine Room		
	Cab Seats for Secure		
	Brake Discs for Blocked Cooling Fins		
	Bell		
	Horn		
	Wipers		
Check Dump Valves Air Dryer & test operation of:	Air Brake Equipment		
	Main Reservoir Safety Valve		
	Compressor Unloader		
Check oil levels Add as necessary:	Transformer cooler; if low check for leaks		
Record amounts added.	Rectifier cooler; if low check for leaks		
	Air compressor		
Check Battery charger voltage 70-72 volts with auxiliary compressor operating			
Test operation of all lights			
Check covers on electrical cabinets are closed			
Check for abnormal noises, rotating equipment			
Check fire extinguisher for seal & proper position			
Check & replenish locomotive supplies			
Check operation of sanders			
Replace worn brake shoes 3/8" min.			
Replace worn brake pads 3/8" min. (3/8" + 1/16, -0)		Changed 3 sets	Cw
Clean cab interior & windows			
Sign TTC 6330.1-2 daily inspection card			
Check cleanliness of toilet			
Check pantograph for damage			
Check S-7 cabinet for tripped relays. (Reset and note.)		DBR1	Cw
Finger Test Decellostat System on Amcoach Cars	2100's		Cw
	21246		Cw
	21035		Cw
	21018		Cw
	21091		Cw

11/80 Attach. 1

AEM-7
WEEKLY INSPECTION REPORT
(In Addition to Dailies)

1. Check air differential, traction motor filters, record level. NA
2. Apply dry lube to the pantograph plungers. DH
3. Measure traction motor brush length. Record position 1. Look for flashing. DH
   #1 45 #2 removed #3 32 #4 45
4. Check gear case oil level & add as needed. Record amount added. DH
5. Inspect and measure pantograph carbon brush - 1/8" over metal base +1/16-0 DH
6. Clean insulators on roof. Use water and soft soap. Rinse with clear water and dry with rag. DH
7. Measure wheels and record on wheel sheet. DH
8. Wash exterior of locomotive and trucks. No time available
9. Clean F & R Cab and service toilet.
10. Check axle box measurements. Mx. differential per axle 5/32. DH

MAX 1-3/4	MIN 1-3/16	A (top) Right	A (top) Left	B (bottom) Right	B (bottom) Left	JOURNAL BOX CLEAN/DIRTY
	Axle 1	1 1/8	1 0/0	1 1/2	1 3/4	OK
	Axle 2	1 1/64	1 0/8	1 1/2	1 5/8	
	Axle 3	1 1/8	1 1/64	1 1/2	1 5/8	
	Axle 4	1 3/8	1 1/8	1 1/4	1 3/8	

Main Reservoir Pressure 140 lbs. Brake Pipe Pressure 110 lbs.

Condition of Brakes OK Condition of Brake Rigging OK

Defects reported have been repaired, except as noted, and report is approved.

Hyndman
Signature

Available for Service ✓ Yes ______ No Harry [illegible]
RVM Supervisor

1-14-81
Date

11/80 Attach. 2

AEM-7
MONTHLY INSPECTION

This inspection to be completed in addition to Daily and Weekly Inspections.

UNIT #, Amtrack 900 DATE 1-14-81

ITEM	ACTION REQUIRED	INITIALS
Battery	Check battery electrolyte level and specific gravity.	DH
	Wash out battery boxes.	DH
Traction Motor	Check traction motor gear case for leakage.	DH
	Check traction motor gear case magnetic plugs and check oil level.	DH
Indicating Lights	Test indicating lights on head-end power plant control panel.	DH
	Test indicating lights on the indicating light panel and the fault and indicator light panel in both cabs.	DH
	Same light out as have been for monthes	
Miscellaneous	Check dynamic brake grids for damage or foreign material.	DH
	Check oil temperature of main air compressor.	DH
	Clean air compressor oil cooler inlet.	DH

Supervisor's Signature

30 DAY LOCOMOTIVE INSPECTION WHEEL REPORT

Location TTC	Date 2-2-81	Unit No. Amtrak 900

POSITION			FLANGE CONDITION HEIGHT	FLANGE CONDITION VERTICAL WEAR	FLANGE CONDITION THICKNESS	RIM THICKNESS	SIDE BEARING CLEARANCE	SPRING CONDITION LEAF	SPRING CONDITION COIL	BRAKE RIGGI[NG]
RIGHT SIDE	Truck # 1		1 1/8 2		1 3/64 3	2 1/2				
			1 1/8 2		1 7/64 4	2 1/2				
	Truck # 2		1 1/8 2		1 7/64 4	2 1/2				
			1 3/16 3		1 5/32 3	2 1/2				
LEFT SIDE	Truck # 1		1 1/8 2		1 3/64 3	2 1/2				
			1 1/8 2		1 3/64 1	2 1/2				
	Truck # 2		1 3/16 3		1 3/64 3	2 1/2				
			1 3/16 3		1 5/32 3	2 1/2				
WEAR LIMITS			Max. TTC 1-7/16 FRA 1-1/2	Max. TTC 7/8 FRA 1	Min. TTC 15/16 FRA	Min. TTC Road 1 FRA Yard 3/4	TTC 1/8"Min FRA Contact .... TTC 1/2"Max FRA	Condition Code: Acceptable Marginal Condemnable	CONDEMNING NUMBER O[F] BROKEN SPRINGS Coil = Any Leaf = Top or in top half - any three.	

	FRONT	REAR	CLEARANCE LIMINTS
Drawbar Height (Above Rail)	33 1/2	33	All locos. TTC/FRA 34 1/2 Max All locos except pass. TTC/FRA 31 1/2 Min Passenger only. TTC 32 1/2 Min
Footboard/Snowplow Height (Above Rail)	4 11/16 Right side, Left side 2 7/8	4 3/8 11/16 Right side, Left 3 7/8	Footboard TTC/FRA 12" Max. 9" Min. Plow/Pilot TTC/FRA 6" Max. 3" Min. Rail Clearance TTC/FRA 2 1/2 Min.
Coupler Slack			1/2" Maximum

Speed Indicator	Type	Condition

Inspector [signature] Supervisor Gene Wo[signature]

APPENDIX D

NEC PROFILE LISTINGS

This appendix contains listings of the profile used during the AEM-7 Endurance Tests. These include the modified profile used when the simulator was inoperative.

TRIP PROFILE SIMULATION

BOSTON - NEW YORK - FIVE STOPS

BECHTEL, INC. 943P-3

DISTANCE MILES	SPEED MPH PER/HR.	ELAPSED TIME H:M:S

LV. Boston, next stop route 128, in 11.6 miles, 12 minutes.

.00	10	0:00:00
.05	35	0:03:05
1.08	100	0:05:24
11.04	50	0:11:46
11.62	0	0:12:18

Stop #1: Ar. route 128 stop Dwell 60 sec. next stop providence RI in 32 mi. 21.5 min.

11.06	50	0:13:18
11.08	95	0:14:55
16.00	105	0:15:55
23.00	120	0:21:31
34.05	90	0:26:50
35.03	110	0:28:26
38.04	55	0:30:22
40.00	50	0:32:03
40.00	70	0:32:29
42.02	65	0:34:06
42.07	55	0:34:34
43.06	20	0:35:42
43.72	0	0:35:56

Stop #2: Ar. Providence RI Dwell 1 min. 15 sec. next stop New London in 62 mi, 48 min.

43.72	20	0:37:11
44.02	55	0:38:51
47.00	50	0:41:58
47.04	58	0:42:29
48.05	95	0:43:26
49.00	120	0:43:44
54.05	90	0:46:47
57.05	95	0:48:45
58.06	120	0:49:25
68.05	110	0:54:39
69.04	120	0:55:08
74.07	80	0:57:53
76.04	75	0:59:12
77.02	85	0:59:51
81.01	80	1:02:36
83.05	70	1:04:27
84.00	80	1:04:50
86.08	75	1:06:58

DISTANCE MILES	SPEED MPH PER/HR.	DISTANCE H:M:S
90.06	85	1:09:59
92.03	55	1:11:16
93.01	65	1:12:11
95.00	60	1:13:54
96.03	55	1:15:16
97.00	70	1:15:59
99.02	60	1:17:53
99.08	75	1:18:30
100.01	80	1:18:49
102.03	60	1:20:29
104.02	50	1:22:25
105.02	40	1:23:32
105.08	30	1:24:34
106.02	00	1:25:01

Stop #3: Ar. New London Conn. Dwell 01:15 next stop New Haven Conn. in 50 mi, 44 min.

106.02	30	1:26:16
106.04	45	1:27:17
108.04	60	1:25:04
112.00	75	1:33:39
113.03	80	1:34:43
115.00	75	1:36:00
116.01	60	1:36:52
117.00	75	1:37:44
119.04	90	1:39:47
121.05	75	1:41:13
122.04	50	1:41:55
122.08	85	1:42:30
125.00	80	1:44:09
126.07	70	1:45:25
127.01	75	1:45:45
129.04	85	1:47:36
132.04	80	1:49:44
134.01	70	1:51:01
134.07	80	1:51:34
136.01	100	1:52:38
137.08	115	1:53:43
140.06	90	1:55:15
141.04	70	1:55:15
141.09	75	1:56:16
143.05	90	1:57:31
146.06	80	1:59:38
147.02	50	1:60:09
148.00	60	2:01:11
155.03	45	2:08:32

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
156.73	0	2:09:34

Stop #4: Ar. New Haven Conn. Dwell 1' 30"
next stop Stanford Conn. in 39 mi, 35 min.

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
156.73	50	2:12:04
157.00	70	2:12:49
159.00	60	2:14:35
159.06	80	2:15:04
165.03	70	2:19:28
166.00	75	2:20:03
172.05	45	2:25:19
173.07	30	2:27:02
174.04	70	2:28:21
176.05	75	2:30:20
179.03	70	2:32:34
179.08	80	2:33:03
187.02	75	2:38:36
187.05	45	2:38:55
188.00	75	2:39:31
194.05	60	2:44:51
194.09	45	2:45:16
195.04	30	2:45:57
195.06	00	2:47:14

Stop #5: Ar. Stanford Conn. Dwell 1'15"
next stop New York in 36 mi, 39 min.

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
195.06	30	2:48:29
195.09	60	2:49:23
196.03	75	2:49:51
198.04	70	2:51:33
202.05	40	2:55:09
203.1	65	2:56:00
204.09	70	2:57:46
206.05	75	2:59:07
207.00	80	2:59:35
211.01	30	3:02:51
212.02	20	3:04:59
212.07	70	3:06:32
213.05	95	3:07:32
215.05	55	3:08:60
215.08	50	3:09:21
216.02	65	3:09:49
217.06	60	3:11:09
218.02	70	3:11:46
219.09	55	3:13:15
220.04	60	3:13:44
221.00	65	3:14:23
221.03	70	3:14:37
222.06	45	3:15:46
222.09	50	3:16:11
224.03	55	3:17:56
225.09	50	3:19:36
226.04	45	3:20:13
227.01	50	3:21:15
227.04	60	3:21:31
228.06	50	3:23:29
221.00	15	3:26:15
231.73	0	3:27:30

Arrive New York

TRIP PROFILE SIMULATION

NEW YORK-WASHINGTON

FIVE STOP PROFILE

BECHTEL INC, 943 P-1 and 943-P-2

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
0.0	15	0:00:00
0.4	30	0: 1:36
0.5	60	0: 1:55
3.7	100	0: 5:03
9.0	55	0: 8:27
9.7	50	0: 9:17
9.9	40	0: 9:31
10.0	0	0: 9:49

STOP #1: Newark, N.J., Dwell 60 Sec,
Next stop Trenton, in 48 miles, 28 min.

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
10.0	40	0:10:49
10.2	60	0:11:31
10.6	90	0:11:55
2.0	120	0:12:57
15.3	70	0:14:46
16.1	120	0:15:38
24.1	110	0:20:04
24.9	90	0:20:31
26.0	95	0:21:15
27.6	75	0:21:19
28.1	90	0:22:42
28.7	110	0:23:08
29.1	120	0:23:24
57.0	45	0:37:04
58.0	0	0:38:45

STOP #2: Trenton, N.J., Dwell 60 Sec,
Next stop, Philadelphia, in 32.5 mi.-23 min.

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
58.0	45	0:40:45
58.3	95	0:41:28
58.5	105	0:41:45
64.5	120	0:43:07
71.0	100	0:48:32
71.8	120	0:49:00
75.0	90	0:50:48
66.4	110	0:51:38
78.4	120	0:52:50
80.2	115	0:53:47
31.9	60	0:54:49
82.4	55	0:55:19
83.1	85	0:56:05
84.5	70	0:57:14
88.6	35	1:00:55
89.4	60	1:02:20
90.1	40	1:03:09
90.6	0	1:03:59

STOP #3: Phil, PA, Dwell 1 min. 45 sec.
Next stop, Wilmington. Del, 25.7 mi 19.5min.

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
90.6	40	1:05:44
91.2	50	1:06:56
92.6	80	1:08:35
92.7	120	1:08:44
94.9	70	1:10:19
96.9	90	1:12:04
97.5	120	1:12:32
98.8	110	1:13:24
101.3	100	1:14:45
103.6	115	1:16:08
104.6	120	1:15:44
107.4	110	1:18:10
112.3	90	1:20:51
113.3	95	1:21:53
115.6	45	1:23:05
115.9	40	1:23:30
116.3	0	1:24:14

STOP #4: Wilmington, Del, Dwell 60 sec.
Next Stop, Baltimore, MD. 68.5mi, 42.5 min.

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
116.3	35	1:25:[illegible]
116.6	45	1:26:01
117.1	105	1:26:44
120.0	120	1:28:45
122.0	105	1:29:50
135.9	115	1:36:59
136.7	120	1:37:24
137.8	110	1:37:59
139.0	90	1:38:39
140.0	120	1:39:18
142.3	105	1:40:40
143.0	115	1:41:03
143.5	120	1:41:19
145.8	95	1:42:32
146.4	110	1:42:56
147.2	120	1:43:24

NEW YORK-WASHINGTON FIVE STOP

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S	DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
49.5	90	1:44:41			
150.6	120	1:45:23			
153.6	110	1:47:07			
154.6	120	1:47:39			
161.1	105	1:50:57			
161.3	120	1:51:04			
166.9	100	1:53:59			
167.6	120	1:54:27			
174.8	110	1:58:09			
177.4	120	1:59:36			
179.2	115	2:00:31			
180.9	75	2:01:31			
181.9	60	2:01:38			
181.6	65	2:02:15			
182.9	50	2:03:25			
184.3	30	2:05:09			
184.8	0	2:06:14			

STOP #5: Baltimore, MD, Dwell 1 min. 30 sec.
Next stop Washington D. C. 40.2 mi, 29 mi.

184.8	30	2:07:44
186.6	40	2:11:34
187.3	45	2:12:38
187.8	80	2:14:16
191.3	110	2:15:51
192.4	95	2:16:30
192.8	110	2:16:47
194.3	105	2:17:39
195.1	100	2:18:04
196.1	120	2:18.44
214.3	110	2:28:11
215.7	105	2:28:58
216.2	110	2:28:58
217.6	100	2:30:01
218.2	120	2:30:24
222.4	100	2:32:24
223.8	45	2:33:42
224.4	30	2:34:27
224.5	15	2:34:42
225.0	0	2:36:39

Arrive Washington D. C.

TRIP PROFILE SIMULATION

NEW YORK TO WASHINGTON

TWO STOPS

BECHTEL INC. 943P-4 & 943P-2

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
LV. New York, next stop Pheladelphia, PA in 90.05 miles, 1 hr.		
.00	15	0:00:00
.04	30	0:01:36
.05	60	0:01:55
3.00	65	0:04:31
3.01	80	0:04:36
3.06	100	0:05:03
9.00	55	0:80:27
9.07	50	0:09:17
9.09	40	0:09:30
10:02	60	0:09:57
10.05	70	0:10:19
10.06	90	0:10:23
12.00	120	0:11:23
15.03	70	0:13:22
16.01	120	0:14:04
24.01	110	0:18:30
24.09	90	0:18:58
26.00	95	0:19:42
27.06	75	0:20:46
28.01	90	0:21:08
28.07	110	0:21:34
29.01	120	0:21:50
57.09	95	0:36:25
58.05	105	0:36:49
60.05	120	0:37:58
71.00	100	0:43:21
71.08	120	0:43:49
75.01	90	0:45:37
76.03	110	0:46:27
78.04	120	0:47:40
80.02	115	0:48:36
81.09	60	0:49:39
82.04	55	0:50:08
83.00	85	0:50:54
84.00	70	0:52:03
88.03	45	0:55:21
88.06	35	0:55:45
89.04	60	0:57:09
90.01	40	0:57:58
90.54	0	0:58:48

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S
Stop #1: Ar. Philadephia, Dwell 1 min 45 sec., next stop Balt. in 94.1 mi, 1 hr 1mi.		
90.54	40	1:00:33
91.01	50	1:01:33
92.05	80	1:03:45
92.06	120	1:03:24
94.08	70	1:05:08
97.00	90	1:07:06
97.05	120	1:07:21
98.08	110	1:08:13
103.05	115	1:10:57
104.06	120	1:11:33
107.03	110	1:12:54
112.02	90	1:15:40
113.03	95	1:16:22
115.05	45	1:17:54
115.08	40	1:18:19
Passes Wilminton Del without stopping at, 116.2 mi, 1:18:57.		
116.05	45	1:19:24
117.00	105	1:20:07
119.09	120	1:22:08
121.09	105	1:23:13
122.05	120	1:23:36
135.08	115	1:30:22
136.06	120	1:30:47
137.08	110	1:31:22
138.09	90	1:22:02
139.09	120	1:32:41
142.03	105	1:34:03
143.00	115	1:34:26
143.04	120	1:34:42
145.07	95	1:35:55
146.03	110	1:36:19
147.01	120	1:36:47
149.04	90	1:38:04
150.05	120	1:38:46
153.05	110	1:40:30
154.05	120	1:41:02
160.02	120	1:44:27

DISTANCE MILES	SPEED MILES PER/HR.	ELAPSED TIME H:M:S	DISTANCE MILES	SPEED MILES PER/HR	ELAPSED TIME H:M:S
166.08	100	1:47:22			
167.06	120	1:47:50			
174.07	110	1:51:32			
177.03	120	1:52:59			
179.01	115	1:53:54			
180.08	75	1:54:54			
180.09	60	1:55:01			
181.05	65	1:55:38			
182.08	50	1:56:48			
184.02	30	1:58:32			
184.68	0	1:59:37			

Stop#2: Ar. Balt. MD. Dwell 1:30 next stop Washington D. C., in 40.2 mi, 30 min.

184.07	30	2:01:07
186.05	40	2:04:57
187.02	45	2:06:01
187.07	80	2:06:39
190.03	100	2:08:43
191.02	110	2:09:14
192.03	95	2:09:53
192.08	110	2:10:10
194.03	105	2:11:02
195.00	100	2:11:27
195.03	90	2:11:40
196.00	120	2:12:07
214.02	110	2:21:34
215.06	105	2:22:21
216.01	110	2:22:37
217.05	100	2:23:24
218.01	120	2:23:47
222.03	100	2:25:59
223.08	45	2:27:05
224.03	30	2:27:50
224.05	15	2:28:05
224.87	0	2:30:02

Arrive Washington D. C.

AEM-7 Operations During Off Nominal Conditions

JUN 25 1980

Test Manager, RTC-41

RTC-41

Cliff Gannett, RRD-21

The purpose of this memo is to clarify the operational requirements in the case of failure of the route simulator and/or the instrumentation.

Condition	Response
1. Route simulator fails - instrumentation working.	
a. Distance still available.	Run simulation by hand with actual profile.
b. Distance not available.	Run attached modified profile based on laps.
2. Instrumentation fails* - route simulator working. *partial or total	Continue running route without instrumentation. Upon 2nd trip of any one locomotive system, notify Chief Test Engineer. If he is not available, notify Test Manager.
3. Instrumentation fails - route simulator fails.	Same as 2, except run the attached modified profile.

During the time limited test period caused by the track re-hab work, we will run the New York to Washington portion of NEC route. The sequence will be the following:

New York to Washington
10 minute station stop (check wheel bearings)
New York to Washington
30 minute station stop (check wheel bearings +)
New York to Washington
10 minute station stop (check wheel bearings)
New York to Washington
10 minute station stop (check wheel bearings)

If time permits, begin another New York to Washington profile and run until shift ends.

CONCURRENCES

RTG. SYMBOL	INITIALS/SIG.	DATE
RTC-41	WPM/[signature]	6/25/80
RTC-40	HLB/[signature]	6/25/80

Form DOT F 1320.65 (4-67) OFFICIAL FILE COPY

Subject: AEM-7 Operations During Off Nominal Conditions

In the event of a single traction motor problem similar to the events of Sunday night (June 22), the profile should be continued on the remaining three motors. If there is a problem with a second traction motor, then the route can be continued, but the Chief Test Engineer must be notified.

If anything else happens and the solution is not obvious, then the Chief Test Engineer must be notified. If he is not available, then the Test Manager is to be notified.

Note: All anomilies must be logged in sufficient detail to allow analysis the next day.

WILLIAM P. McCUTCHON

Attachment
Modified Trip Profile

cc: E. Mathews, RTC-1
T. Tanko, RTC-5
M. Haven, DYN

RTC-41:WPMcCutchon:ad:6/25/80
Reader's file
Official file--7151.1

AEM-7 MODIFIED TRIP PROFILE

Trip will be 17 laps of RTT.

Lap 1	Accelerate to 100 mph. Maintain 100 mph.
Lap 2	Brake to 35 mph, then accelerate to 120 mph. Maintain 120 mph.
Lap 3	Brake to 65 mph, then accelerate to 120 mph. Maintain 120 mph.
Lap 4	120 mph.
Lap 5	Slow to stop (Trenton). 0:1:15 station stop
Lap 6	Accelerate to 120 mph
Lap 7	120 mph.
Lap 8	Brake to 50 mph. Maintain 50 mph until end of lap and then stop. 0:1:15 station stop (Philadelphia).
Lap 9	Accelerate to 120 mph.
Lap 10	Slow to stop at end of lap. 0:1:15 station stop (Wilmington)
Lap 11	Accelerate to 120 mph.
Lap 12	120 mph.
Lap 13	Slow to 100 mph.
Lap 14	Slow to 50 mph. Stop at end of lap. 0:1:15 station stop (Baltimore).
Lap 15	Accelerate to 120 mph.
Lap 16	Slow to stop at end of lap. 0:1:15 station stop (New Carrollton)
Lap 17	Accelerate to 120 mph and brake to stop at end of lap (Washington).

APPENDIX E

TRIP REPORT OF VISIT TO TREE ELECTRIC CO, DENVER

This appendix contains the trip report compiled by TTC personnel after visiting Tree Electric Company, Denver, Colorado, following the inspection of the traction motors during October, 1980.

Report of visit to Tree Electric Company - Denver

Purpose of visit

1. To inspect the dismantled traction motors from AMTRAK 900

2. To draw up a preliminary plan to return AMTRAK 900 to full operation as quickly as possible.

Principle attendees

Lars Wedin	ASEA
Larry Tree	Tree Electric
Gordon Peterson	GM (EMD)
John Peters	TTC
Ray Washburn	TTC

Preliminary Discussion

The discussion commenced with a description of the locomotive test operations at the TTC. This was followed by a detailed comparison of the instrumentation recordings of the traction motor failures presented by TTC personnel and the inspection report on the motors by ASEA and Tree Electric personnel. It was clear from the outset that conflicts exist between the motor inspections and the instrument recordings.

a) Preliminary inspection report

Lars Wedin indicated that preliminary inspection of the motors yielded the following:

1. There was no evidence of a fault in the field circuit either in the field windings or the electrical connections leading to the windings.

2. Some loose material was found in the bottom of the traction motor casing. However this was unlikely to have caused any problems. This material was later recovered and identified as a mixture of welding slag, a pop rivet, and a large aluminum chip. There was no sign of traction motor bellows bolts.

3. Commutator damage ranged from severe in #2 motor to slight in #3 motor. Detailed inspection of the #1 motor, which was the only one to have been dismantled, showed that four flat spots (approximately five commutator segments wide) were located at 90^{0} intervals around the commutator. The questions was raised whether this could have been caused by applying heavy armature current in a stalled condition. This was later proven to be unlikely.

4. For a distance of twenty segments in the direction of rotation of the motor there is evidence that the brushes had been lifting causing pitting damage. This condition would have a tendency to cause ideal flashover conditions, particularly at high speeds.

5. There was some evidence that the commutator had been stoned along the segments and not circumferentially. TTC personnel will investigate this. (It was later established that only the original #4 motor commutator had been stoned at the TTC. This was done using the wheel lathe to rotate the traction motor. No cleaning or stoning of the commutators on #'s 1, 2, 3, and the replacement #4 motors have been carried out at the TTC.)

b) Correlation of Test Data and Motor Damage

The main discrepancy centered around the sequence of events as portrayed by the recorded data. It had been assumed that, since the field current showed signs of disturbance first, the whole incident was caused by some form of field fault bypassing the current from the field windings and causing a high current in the armature. However, no evidence of a field fault was found when the motor was dismantled. Gordon Peterson (EMD) stated that during flashover tests conducted by EMD some years previously field current disturbance usually accompanied armature flashover. This phenomenon is caused by the transformer effect between armature and field such that when the armature current is interrupted by commutator flashover the field is disturbed in sympathy. The reason for the apparent disturbance in the field current 4 milliseconds before the armature current rise is not so clear. The most likely explanation is that the apparent delay is the time it takes for the first armature current disturbance to develop into a full flashover condition. As a guide it takes approximately 3 milliseconds at a road speed of 120 mph for one commutor bar to travel from one brush holder to another. This last observation was supplied by Gordon Peterson.

It was concluded that it was possible for the TTC recorded data to result from a simple commutator flashover condition.

Motor Inspection

Motor #1

Motor #1 was the only motor to have been dismantled on the first day.

This motor was fitted with a full set of DE7 brushes. As stated previously, four flat spots were found on the commutator spaced 90^{0} apart. For approximately 25 commutator bars on the lag side of the flat spots the commutator was roughened and pitted indicative of brush lift and sparking. The negative brush trailing waifers were pitted and the wear uneven. The wear on the positive brushes was normal. As yet no satisfactory explanation for the flat spots can be found. However detailed measurement of the commutator showed that flat was uniform along the commutator bar. This, together with the lack of a corresponding flat spot under the positive brushes would seem to rule out stall current burn. The motor showed definite signs of flashover, both brush holder to brush holder and armature to ground.

Motors #2, #3, #4

Motor #2 was dismantled after the initial inspection. It showed signs of heavy flashover including commutator pitting. All three motors were fitted with EG 309 brushes and all three showed signs of copper drag on the commutator. In particular the #4 motor, which had only accumulated 50,000 miles, showed severe copper drag. The #3 and #4 motors both showed slight evidence of flashover.

Brush Wear

The EG 309 brushes were approximately 60% worn indicating a brush life of 150,000 miles. However, the commutator damage suffered as a result of using these brushes is unacceptable. Since these brushes are used exclusively on the 901 through 906 locomotives, a careful inspection of these traction motors is planned.

The DE7 brushes were less than 30% worn giving a projected brush life of 350,000 miles. This indicates a hard brush material or low brush pressure.

Proposed Rebuild of Motors

Motors #1 and #2

The #1 and #2 motors will have the commutators skimmed and undercut before being rebuilt.

Motors #3 and #4

The #3 and #4 motors will have the commutators dressed and undercut without being stripped down.

Brushes

In order to return the motors to service as quickly as possible, all motors will be fitted with DE7 brushes. One or perhaps two of the motors will have the brush pressure increased from 3 lbs. to 5 lbs.-- the remaining motors will retain the original spring pressure.

After approximately three weeks, all brushes will be replaced as follows:

1. A modified DE7 with standard pressure

2. A modified DE7 with higher pressure

3. A EG 309 AR brush with standard pressure

4. A EG 309 AR brush with standard pressure.

Backup measures

A third type of brush may be introduced if either of the above fail to operate satisfactorily. This brush, a S + E E55L, is manufactured in Austria and used successfully in Norway and Sweden in dry conditions. A three waifer type brush may also be tried.

Operations at the TTC

In spite of the pantograph difficulty the locomotive will be run in alternate directions at weekly intervals. This will be an attempt to wear the brushes and commutators more evenly.

Conclusion

The traction motor problems appear to derive from unsuitable brush material leading to bad commutation and traction motor flashover. There is no evidence of a field fault. The commutation problems are aggravated by the low humidity and altitude in Pueblo. However, it is dangerous to assume that the problems are totally due to the Pueblo climate. The duty cycle in Pueblo, both in terms of speed and power, is more severe. Also, the EG 309 material may be giving trouble on the NEC.

Recommendations

1. The brushes and commutators be inspected at daily intervals for the first two weeks of operation after the rebuild.

2. Accelerometer measurements be made on at least one traction motor to determine whether brush lift due to vibration is possible.

3. Continuous traction motor field and armature current measurements be made for the first few days of operation.

4. The locomotive running direction be changed at weekly intervals.

Footnote

The present plan is to do as many of the outstanding modifications to the AMTRAK 900 as possible during the "down" time. These modifications include:

1. Traction motor bellows

2. Traction rods

3. Lateral bump stops

All of these items are urgent. The present traction rods are causing damage to the bolster assembly.

A. J. Peters

a. J. Peters

Chief Test Engineer
RTT/Electrification

Concurrence

Ray

Ray P. Washburn
Senior Engineer

APPENDIX F

GROUND BRUSH CURRENTS DATA

The data contained in this appendix are intended to demonstate the erratic behavior of the ground brush system. The data presented cover a range of current levels and speeds. One of the major influences on the ground brush performance appeared to be wheel rotation wavelength, which has been superimposed on the data. However, from the data presented no evidence of current leakage through the wheel bearings could be found.

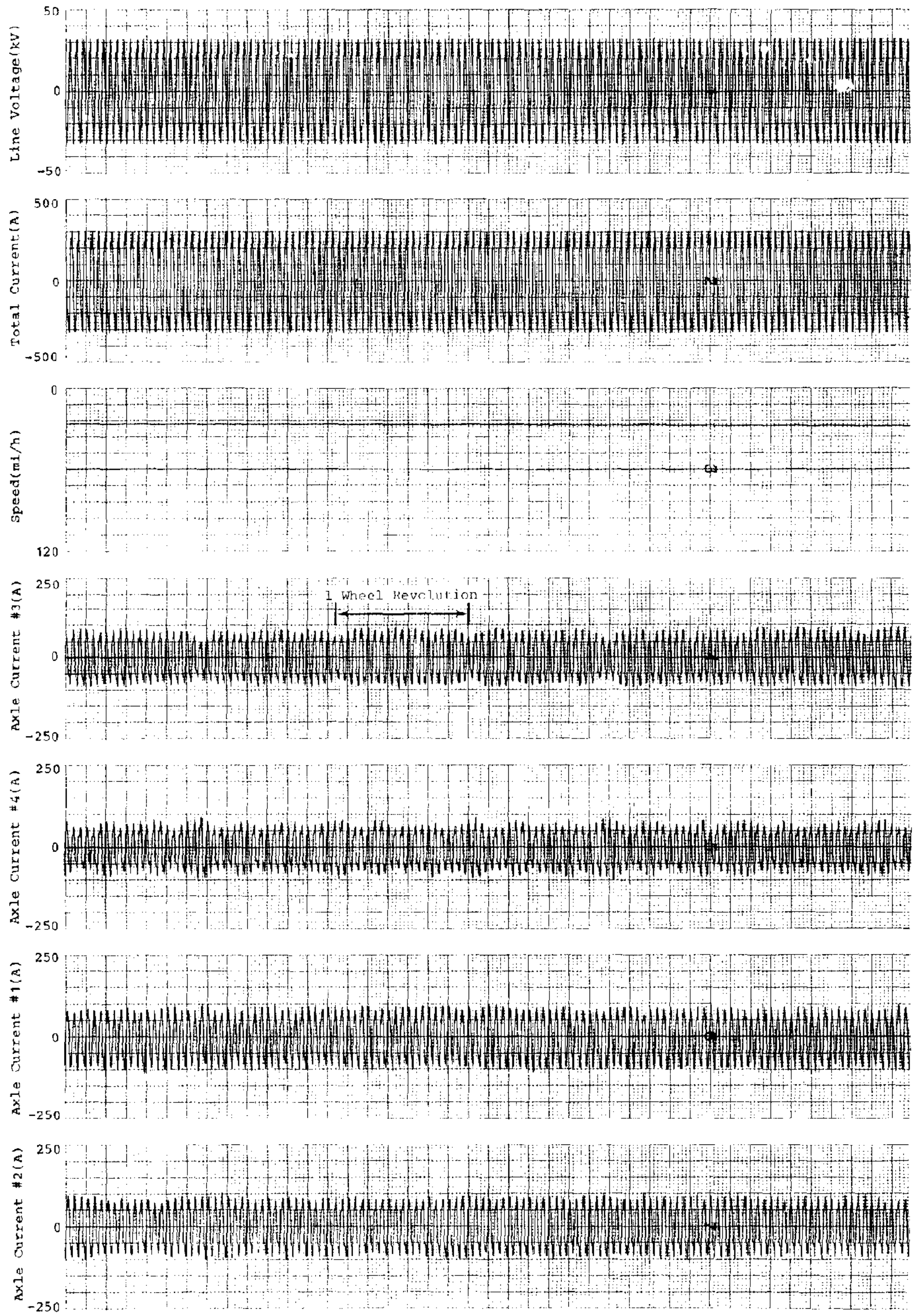


FIGURE F-1. AXLE BRUSH CURRENT DISTRIBUTION
(HIGH CURRENT, LOW SPEED, 25 kV LINE VOLTAGE)

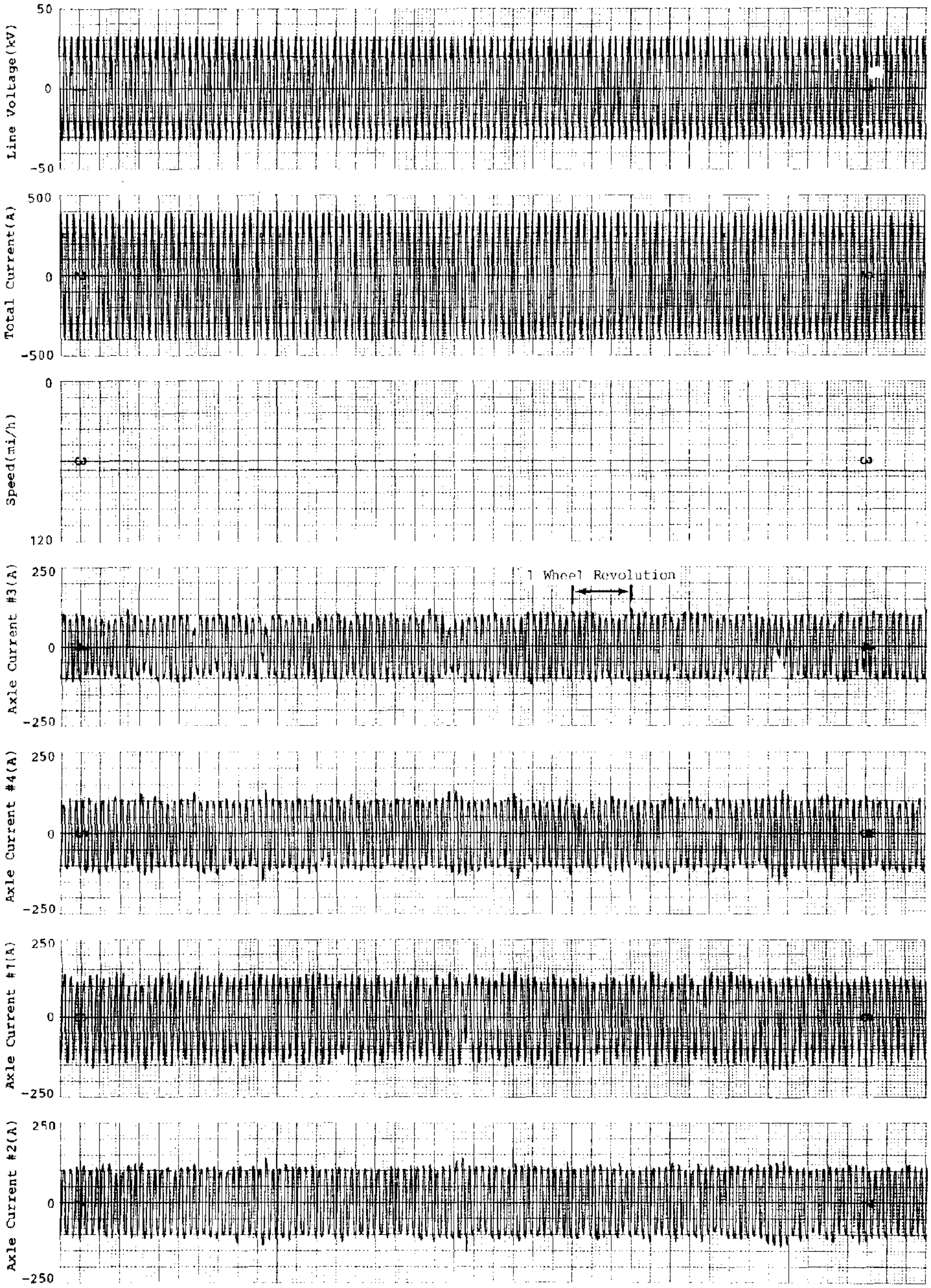


FIGURE F-2. AXLE BRUSH CURRENT DISTRIBUTION
(HIGH CURRENT, MEDIUM SPEED, 25 kV LINE VOLTAGE)

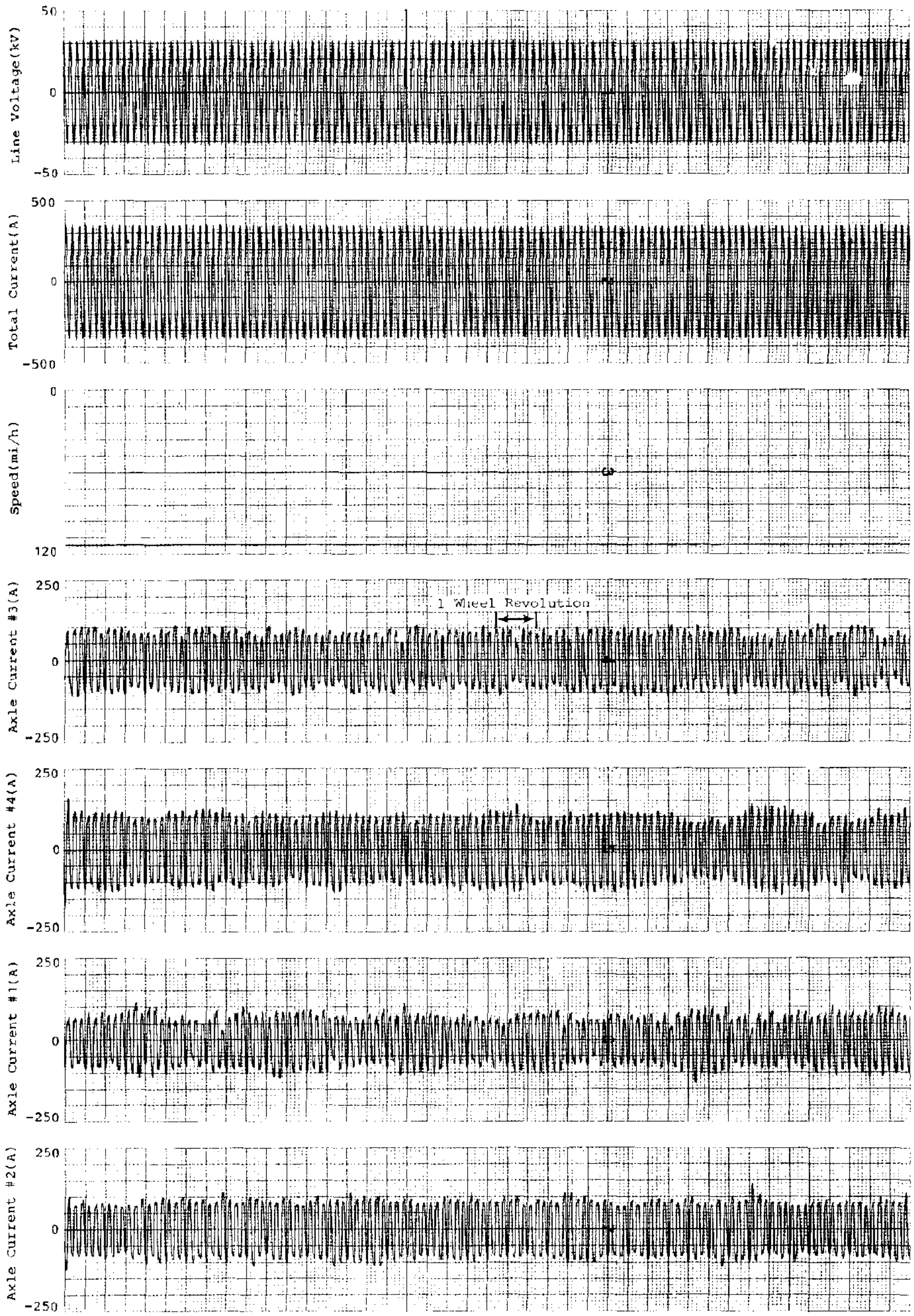


FIGURE F-3. AXLE BRUSH CURRENT DISTRIBUTION
(HIGH CURRENT, HIGH SPEED, 25 kV LINE VOLTAGE)

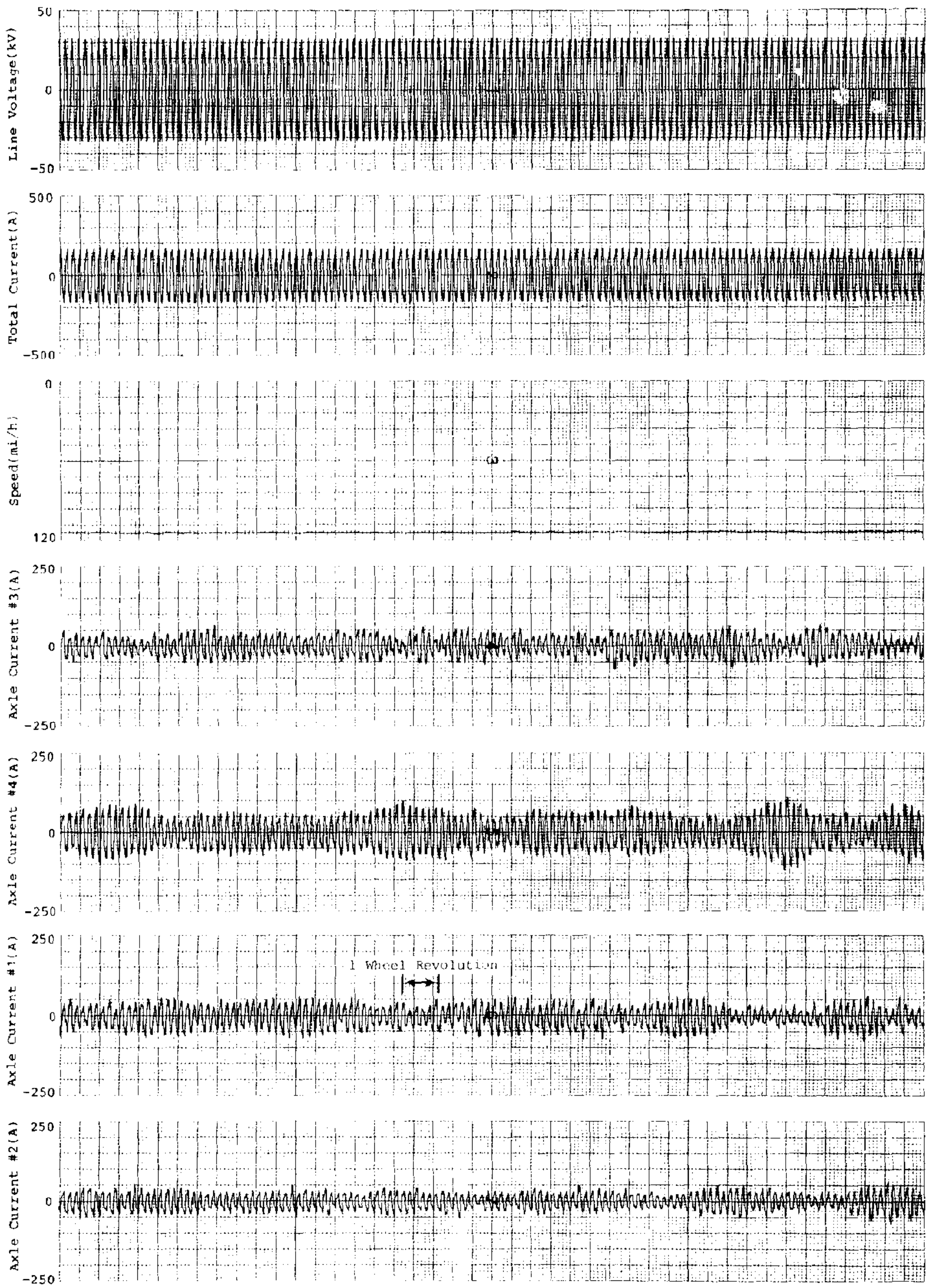


FIGURE F-4. AXLE BRUSH CURRENT DISTRIBUTION (HIGH SPEED, LOW CURRENT, 25 kV LINE VOLTAGE)

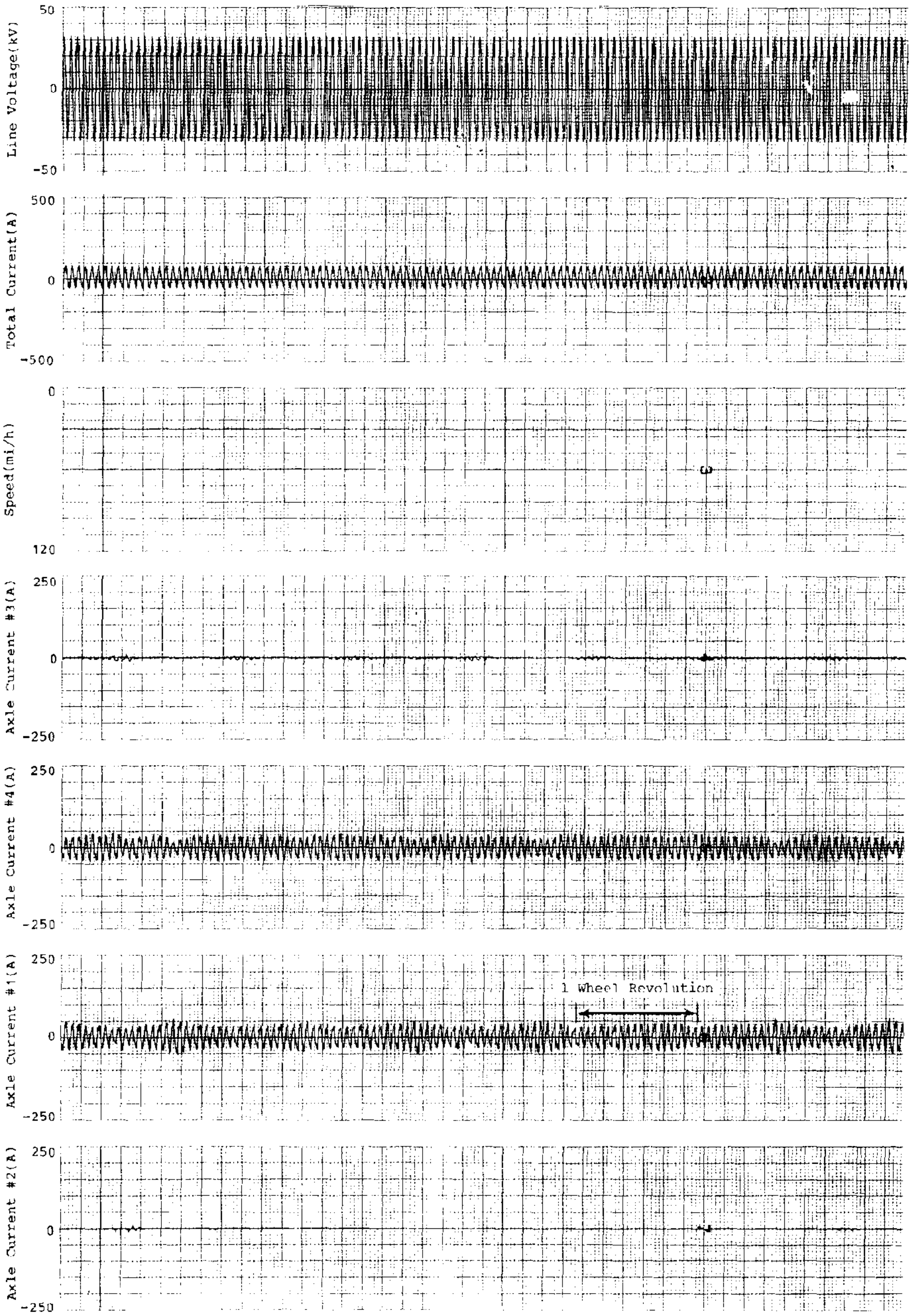


FIGURE F-5. AXLE BRUSH CURRENT DISTRIBUTION
(LOW SPEED, LOW CURRENT, 25 kV LINE VOLTAGE)

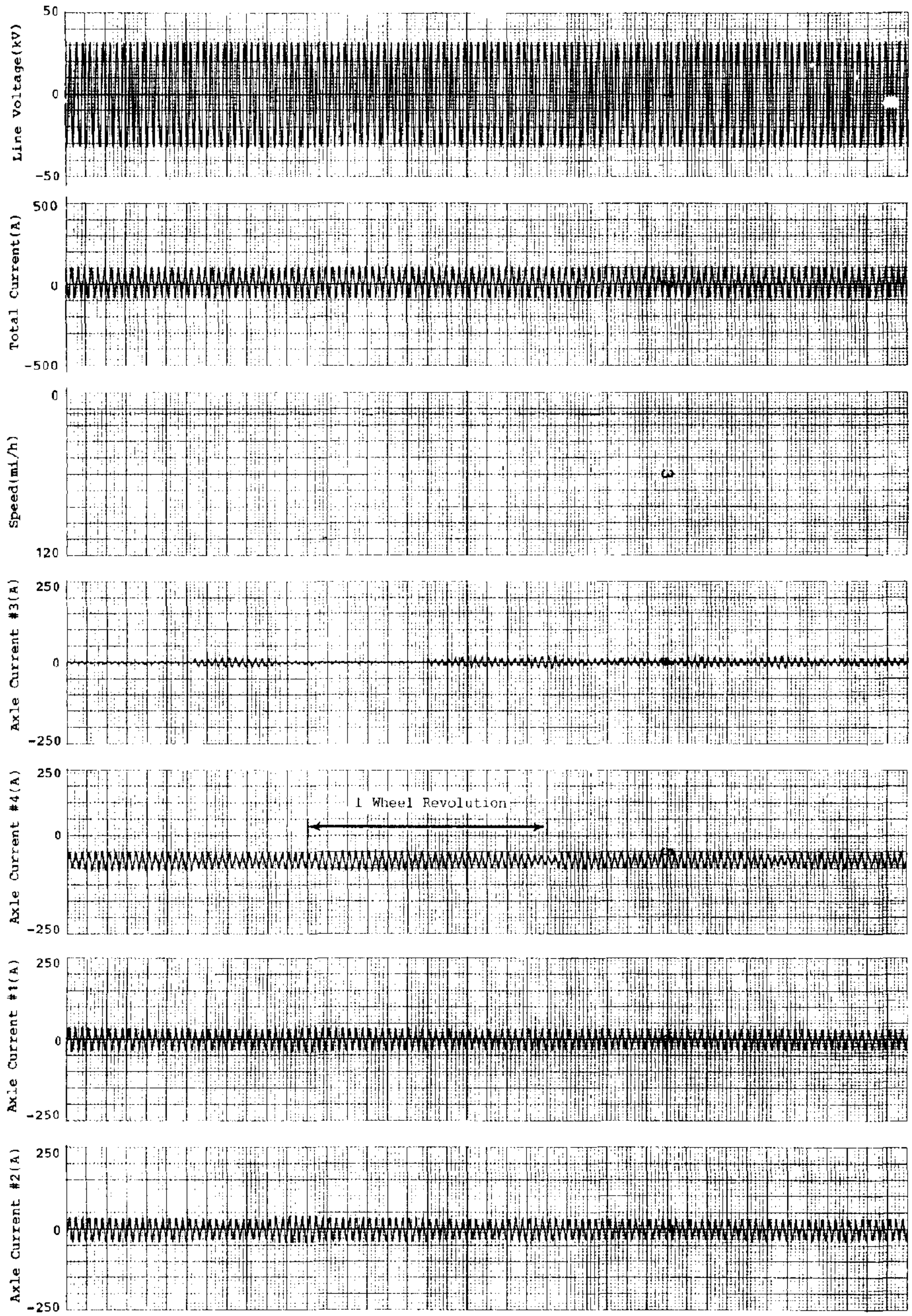


FIGURE F-6. AXLE BRUSH CURRENT DISTRIBUTION (LOW SPEED, LOW CURRENT, 25 kV LINE VOLTAGE)

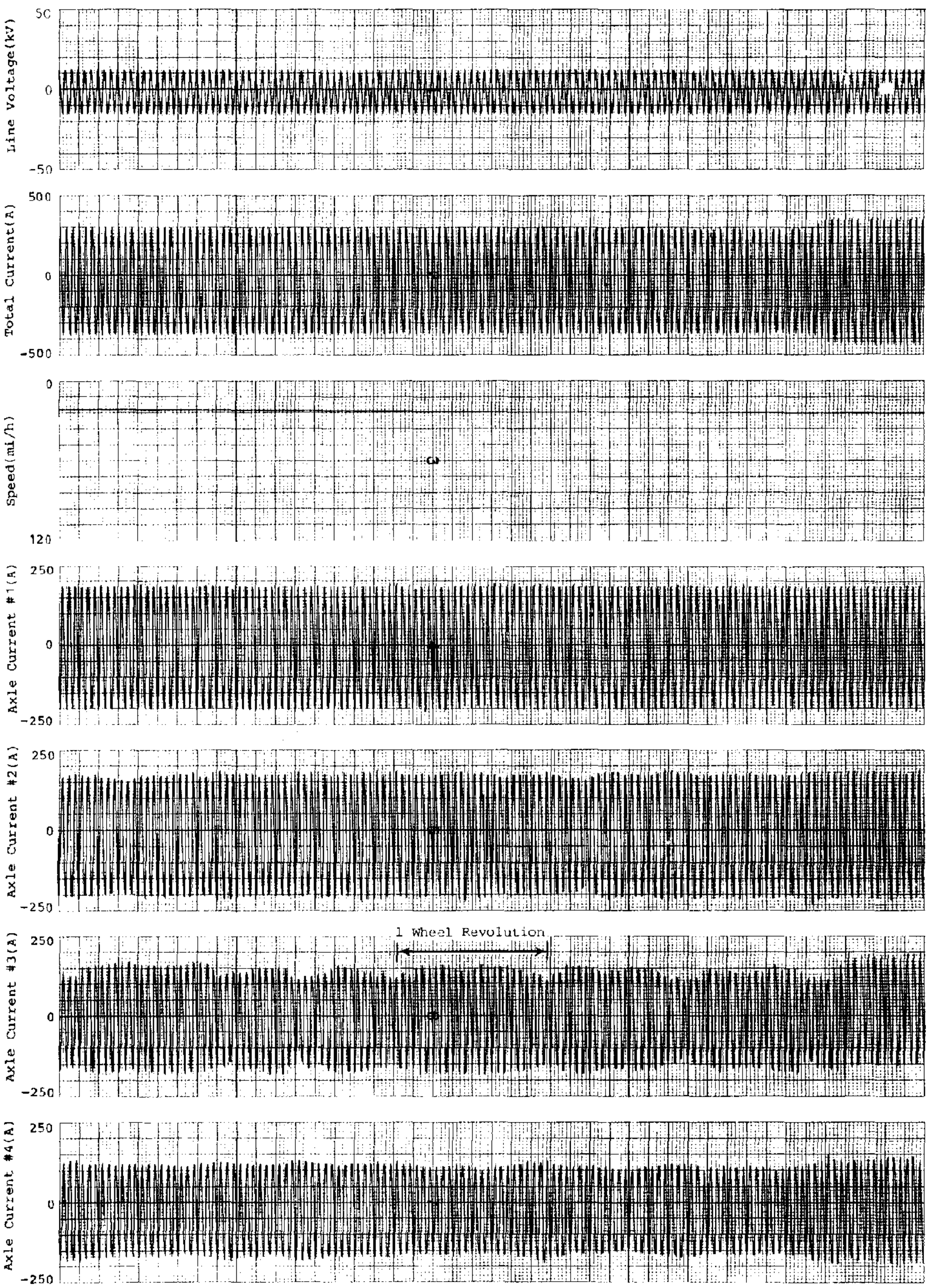


FIGURE F-7. AXLE BRUSH CURRENT DISTRIBUTION (LOW SPEED, HIGH CURRENT, 12.5 kV LINE VOLTAGE)

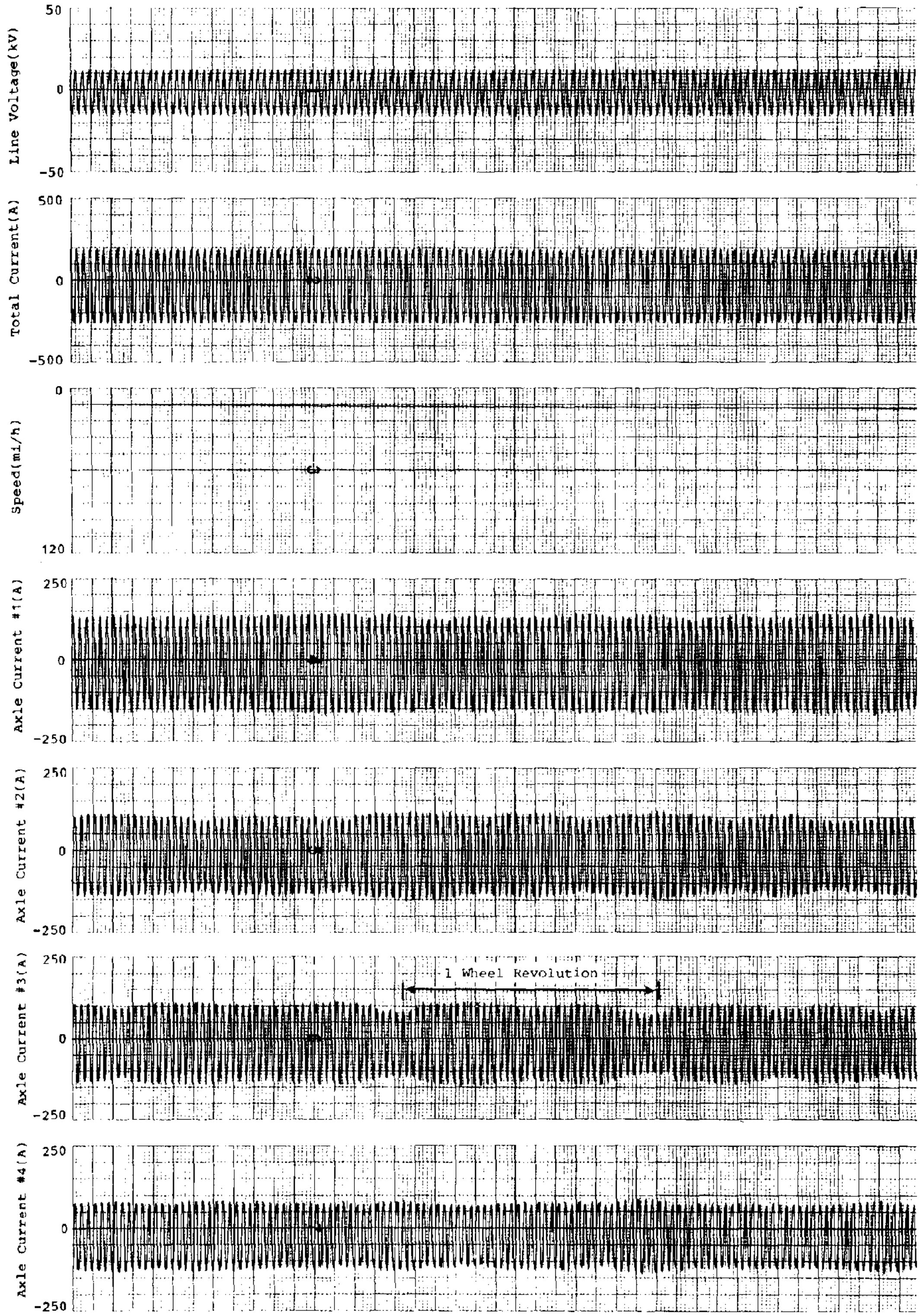


FIGURE F-8. AXLE BRUSH CURRENT DISTRIBUTION
(LOW SPEED, MEDIUM CURRENT, 12.5 kV LINE VOLTAGE)

APPENDIX G

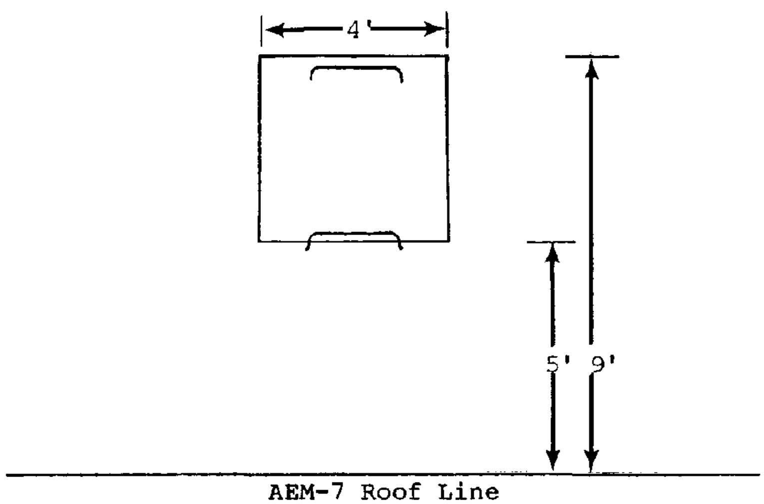
OPTICAL ARC DETECTOR DESCRIPTION

BACKGROUND

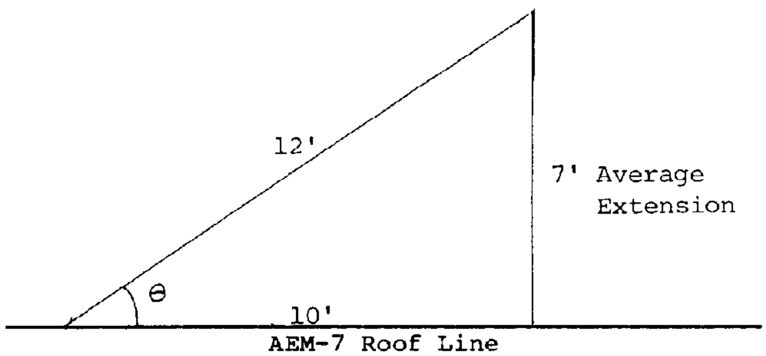
Arc Detector Description. The 'arc detector' is based upon the Deadline Instrumentation Structure Marker Deadline Testing of Pantographs on the RTT Cantenary System, NTIS 123738) which has been demonstrated working in darkness, by detecting the reflections on a structure from a spotlight. Dark conditions are again required to maintain adequate signal/noise rates. For these particular tests the arc between pantograph head and the contact wire when loss-of-contact occurs is the source of radiation for the photo-detector.

Mechanical Arrangement. Some minor modifications to the electronics were necessary to ensure saturation, thus producing an on/off signal which can be compared to dead line measurements. Also the pantograph trajectory (simulated bridge) and lateral motion of the contact wire across the pantograph head necessitated a wide angle lens.

The 10 mm lens used gives a 4' by 4' field of view at 12 ft away from the pantograph.



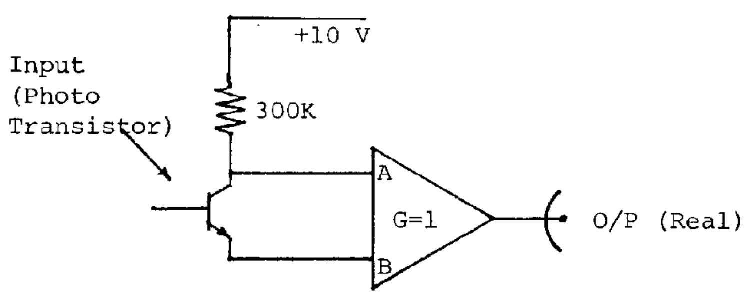
ARC DETECTOR FIELD OF VIEW



ARC DECTECTOR FIELD OF VIEW

The 12' dimension came from the photo section's computer program for the 10 mm lens using an effective photo-detector area of 0.125 inches diameter.

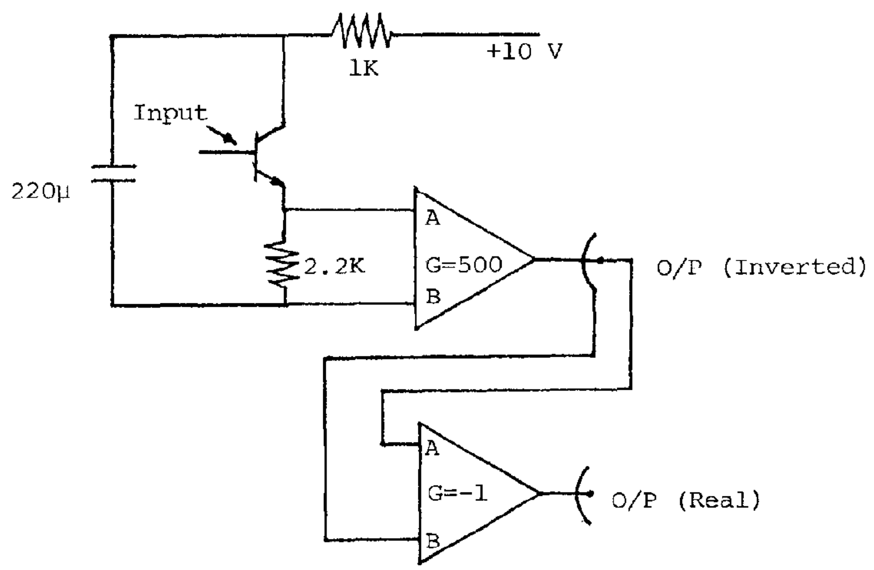
<u>Electrical Circuit Modifications.</u> Testing on 24 and 27 March used a collector load of 300 K (old circuit shown below), and there was some doubt about the response time of this circuit.



G=1, Wide Band
Rise Time = 1 ms
Fall time = 7 ms

OLD ARC DETECTOR CIRCUIT

For Subsequent Testing an improvement was implemented by using an emitter follower circuit with a much lower load resistance of 2.2 K . This has the advantage that the signal goes from zero volts - positive for increasing light. Therefore it was possible to use a dynamics amplifier to provide the gain without loss of response due to the low impendance source, i.e., 2.2 K x 500 gain 3 x 300 K, i.e., we increased the gain by 3 but response was ideal.



Rise Time < 1 ms for an gain >10.
Fall time < 1½ ms for any gain from 1 to 2000.

Recommend gain ≏ 500 on dynamics. Then rise and fall times will be <<, 1 ms. Output swing 0V to 12½ V.

NEW ARC DETECTOR CIRCUIT

One small disadvantage was that the signal was inverted compared to that required by the loss of contact processing unit. Therefore, an inverting stage was built using another dynamics amplifier. The rise and fall times were negligible (5) sec).

Loss of contact results using the old circuit gave loc patterns similar to dead line LOC (neglecting 5 ms occurrences), but the percentage results were much lower. Assuming that the response time was adequate, there were two possible explanations for the lower percentages:

- Limited view due to trailing knuckle which would necessitate measurements from more than one angle. (The outputs are logically 'ORED').
- Insufficient sensitivity to pick up arcing when current waveform was crossing zero (arc intensity decreased).

Increasing the gain and response times using the new circuit should have helped. Also we should measure the actual outputs (arc detector) in millisecs to determine the effect of drawing only 20 amps (total power) compared to dead line results. For the above reasons it may be prudent to increase the arc detector gain to 1000 (response is still < 1 ms).

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