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Urban Mass Transportation Administration

Inverter-Controlled ac Induction Motor Propulsion System

Volume II: Final Report

March 1989
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16. Abstract

An inverter-controlled ac induction motor propulsion system for rail transit cars was designed, developed, and tested to verify projected benefits and applicability of ac over conventional dc cars. Two New York City Transit Authority (NYCTA) R-44 dc subway cars were retrofitted with prototype ac propulsion equipment based on mature, low-risk ac propulsion technology. The program showed that propulsion systems using ac motors can provide greatly improved reliability and reduced maintenance, with significant reductions in life-cycle cost. The prototype ac propulsion system conserves energy through regenerative braking, returning energy to the line when the network is receptive. The equipment consists of a control unit incorporating solid-state integrated circuits and two essentially independent truck drives. For each truck, a single inverter unit powers two totally enclosed, self-cooled, squirrel-cage ac induction motors, each motor driving one of the two axles per truck. Each pulse-width-modulated, voltage-fed, thyristor-controlled inverter is forced-air cooled by a blower, which also cools the resistors used to dissipate dynamic braking energy when the line is not receptive. Demonstrated on the NYCTA, the ac propulsion system improved acceleration and braking performance with good electromagnetic interference and acoustic noise control and was fully compatible with the existing trainlines, NYCTA signalling and supervisory equipment, and dc cars. The report explains how the latest technology would be applied in future production equipment to result in even more benefits to the rail transit industry.

Volume I contains the executive summary; Volume II contains final report Sections 1 through 5.

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PREFACE

The subsystem technology application to rail systems (STARS) program was sponsored by the U.S. Department of Transportation (DOT) Urban Mass Transportation Administration (UMTA). The UMTA organizational team was the driving force of the DOT effort to demonstrate the applicability of ac propulsion equipment to the U.S. transit industry. Credit also is due the American Public Transit Association (APTA) and its car equipment liaison board for its support during the entire program.

Work on this STARS program was conducted under DOT/UMTA Contract DTUM60-82-C-71144, initiated on March 31, 1982. Under this contract, the AiResearch Los Angeles Division of Allied-Signal Aerospace Company, teamed with Oy Stromberg Ab of Helsinki, Finland, designed, developed, fabricated, tested, and delivered a prototype inverter-controlled alternating current (ac) induction motor propulsion system for transit vehicle application. The system was demonstrated on two New York City Transit Authority (NYCTA) R-44 subway cars on the NYCTA transit system.

The program was truly a combined effort of administrative ability (DOT, UMTA) and technical initiative and creativity (AiResearch and its team member, Stromberg) resulting in a successful operational demonstration conducted with the support of the NYCTA, without whose help the program would not have been completed. Specifically, AiResearch acknowledges the NYCTA assistance in the areas of engineering support, test vehicle preparation and transport, electromagnetic interference test support and supply of signalling equipment, and the maintenance of the nonpropulsion equipment on the R-44 test/demonstration vehicles. The availability of the NYCTA facilities, test track, and revenue service operation is appreciated. The DOT Transportation Systems Center of Cambridge, Massachusetts, also is recognized as a major contributor to the overall success of this STARS project, especially in the area of EMI and signalling testing. The following individuals are recognized for their specific contributions to the program.

- Ron Kangas, Chief, Technology Division, and Steve Barsony, Director, Office of Systems Engineering, DOT/UMTA, Washington, D.C.

- Ray Wlodyka, UMTA Project Engineer and Program Monitor, DOT, Transportation Systems Center, Cambridge, Massachusetts, and Dr. Ross Holmstrom and Mike West, EMI Support, Transportation Systems Center, Cambridge, Massachusetts
- Chuck Edelson, UMTA contract EMI support
- Richard Goodlatte, Chief Mechanical Officer, NYCTA
- Jack Rogg, New Car Engineering, NYCTA, and his STARS engineering staff, Oscar Rosenes and Arpad Frank; Al Dzingelis, NYCTA Phase I Project Manager
- Steve Shooman, Signal Department, NYCTA

The AiResearch program was under the direction of Charles Weinstein, product line manager of the electrical power and rapid transit systems group. Phase I program manager was Gabor Kalman, and the Phase II program manager was Jim Clemence. The AiResearch technical team was headed by Bob Rudich and Rudy Van Eck, and the NYCTA test program was under the direction of Keith Vasak of AiResearch. Stromberg's technical expertise and on-site support is acknowledged, especially that of Arto Issakainen.

This document summarizes the design, laboratory testing, manufacturing, R-44 car installation, and car test program of the ac propulsion system applicable to a U.S. operating transit system. The program rationale promoted by the UMTA program organization was that the conversion from current dc onboard propulsion to ac will result in improved reliability and reduced maintenance and is compatible with existing transit practices. The introduction of ac induction motors, which have no commutators or brushes to service, is the key to this goal. Improved energy efficiency with elimination of series resistors and the ability to use regenerative braking, reducing electrical energy consumption by up to 37 percent, are additional benefits.

The key to the success of the STARS program as evidenced through the Phase I and Phase II efforts was the initial team decision by AiResearch and Oy Stromberg to use a **proven** ac propulsion concept tailored to the requirements of STARS. The use of this system, already developed and operational in the

European transit market, enabled satisfactory completion of hardware qualification testing, R-44 implementation, and integration of three complete sets of hardware (two installed car sets and one set of spares) and culminated in a lengthy, successful operating program on our nation's most demanding transit system, the NYCTA. The entire program was accomplished within the DOT/UMTA STARS contract budget.

It is acknowledged that the demonstrated system does not represent present-day technology such as the new developments in gate turn-off (GTO) devices that replace thyristors and thus eliminate commutation circuitry, or the latest advancements in microprocessors and software, but to incorporate this technology at the risk of program delays and possible failures was deemed unnecessary because the **system concept** and **application to a real environment** were the main priorities. Continually modifying proven equipment to incorporate the latest technological advances could not have guaranteed the STARS program success and, in fact, would undoubtedly have resulted in program delays and, consequently, financial hardships inconsistent with the STARS goals. Now that ac propulsion has been demonstrated as a viable replacement for outmoded dc equipment, new requirements can be met with the latest-technology systems.

The STARS program success is evident by current "on-the-street" requests for proposals by several U.S. transit authorities, including the NYCTA, for ac propulsion equipment or vehicles operating with ac propulsion. The Southeast Pennsylvania Transit Authority (SEPTA) currently is introducing ac propulsion equipment on its Norristown line. The STARS program was closely monitored by many U.S. transit properties interested in the industry shift from dc equipment to ac, and it has stimulated the widespread acceptance now being shown.

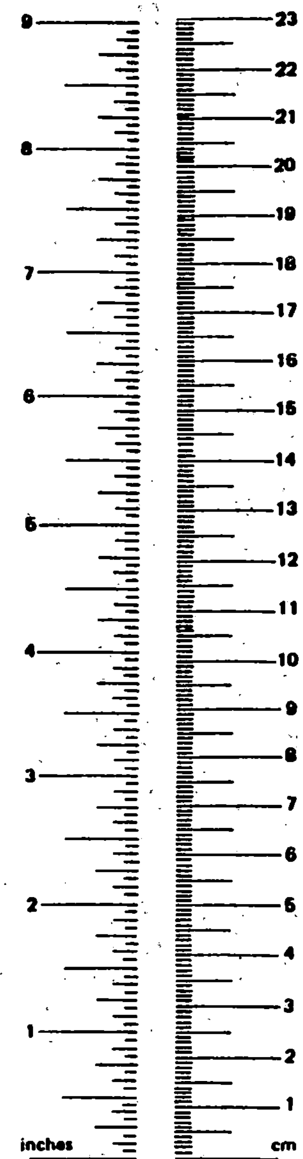
The executive summary, Volume I of this final report, provides an overview of the entire STARS program, including background information on electric rail transit and major program milestones. Volume II presents more detailed information on the activities of each phase of the two-phase program, including representative samples of significant recorded test data and summaries of test results.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

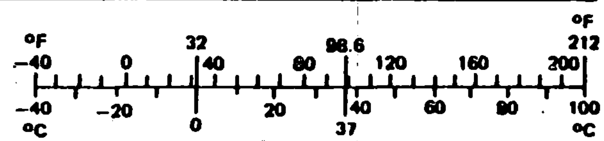
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2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

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



Approximate Conversions from Metric Measures

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



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LIST OF ABBREVIATIONS

"A" Car	R-44 car with cab
AB(ac)	Mated pair, ac two-car consist (one "A" car, one "B" car)
AB(dc)	Mated pair, dc two-car consist (one "A" car, one "B" car)
ABBA	Four-car consist, AB(ac) and AB(dc), joined at "B" cars
APTA	American Public Transit Association
ATO	Automatic train operation
AW0	Empty R-44 car loading condition (87,025 lb for dc; 89,150 lb for ac)
AW2	Fully loaded (crush-loaded) dc R-44 car (AW0 + 43,000 lb = 132,150 lb)
AW3	Fully loaded (crush-loaded) ac-modified R-44 car (AW0 + 43,000 lb = 132,500 lb) (also called "modified AW2 weight")
"B" Car	R-44 car without cab
CDR	Critical design review
CMOS	Complementary metal-oxide semiconductor
DOT	Department of Transportation
EMI	Electromagnetic interference
FSB	Full service brake (controller selection)
GTO	Gate turn-off (thyristor)
HVDC	High-voltage dc (600 vdc nominal)
LCC	Life-cycle cost
LCE	Line control equipment
LED	Light-emitting diode
LVDC	Low-voltage dc (32 vdc nominal)
MDBF	Mean distance between failures
NYCTA	New York City Transit Authority
PAR	Parallel controller selection
PCU	Propulsion control unit
PDR	Preliminary design review
PWA	Printed wiring assembly
PWM	Pulse-width modulation (modulated)
SOW	Statement of Work
STARS	Subsystem technology application to rail systems
TCU	Truck control unit

LIST OF ABBREVIATIONS (Continued)

TTC	Transportation Test Center
UMTA	Urban Mass Transportation Administration
WBS	Work breakdown structure

1. PHASE I DESIGN AND ANALYSIS SUMMARY

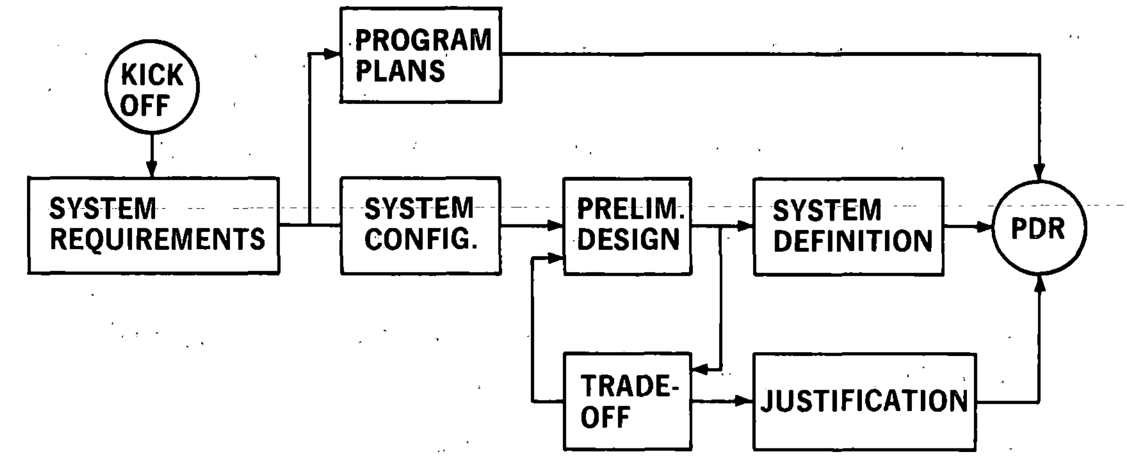
Phase I of the inverter-controlled ac induction motor propulsion system program was a competitive effort involving two different contractors, the AiResearch/Stromberg team and a leading U.S. rail transit equipment manufacturer. During Phase I, both contractors designed and manufactured ac propulsion system equipment for an engineering test model and conducted laboratory tests to show proof of concept and producibility. DOD/UMTA selected the AiResearch/Stromberg team to proceed into Phase II, fabrication, test, and evaluation.

1.1 PHASE I DEFINITION

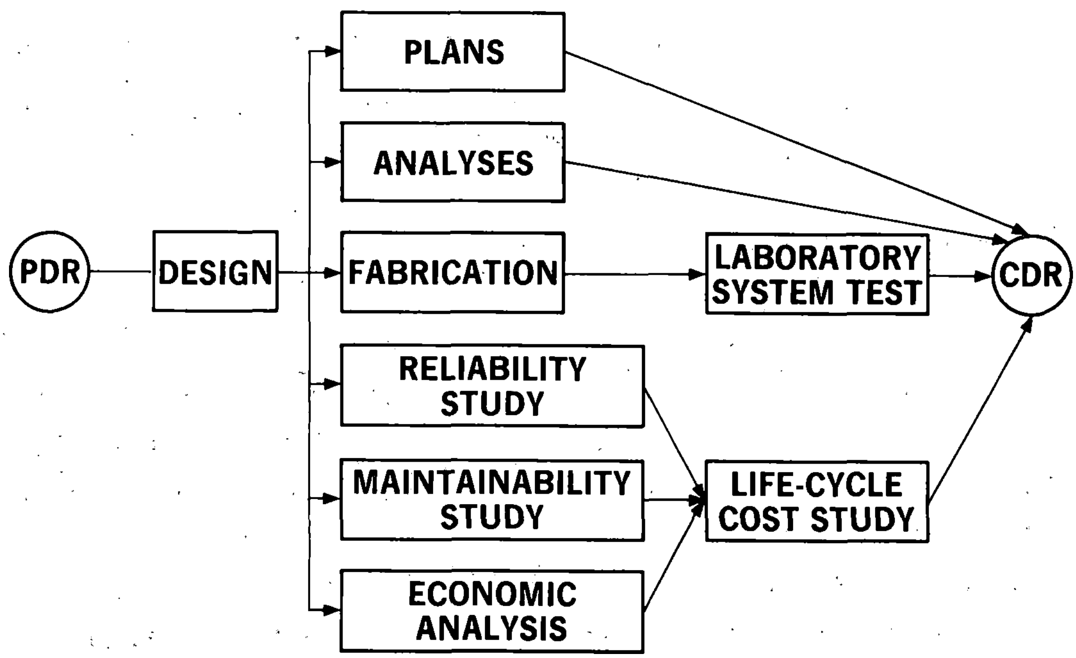
During Phase I, design and analysis, the AiResearch/Stromberg team established the ac propulsion system hardware functional requirements and specifications through extensive design investigations, tradeoffs, and evaluations. The preliminary design review (PDR) and critical design review (CDR) led to the definition of a baseline design for fabrication, test, and evaluation in Phase II.

Phase I of the program was divided into two parts, Phase Ia and Phase Ib. As shown by Figure 1-1, Phase Ia included the events from program kickoff to PDR. Preliminary program plans were generated, system requirements were determined, and the propulsion system preliminary design was defined through tradeoff studies and analysis. Results of Phase Ia included system circuit schematic diagrams; undercar layout drawings; the program schedule and work breakdown structure (WBS); performance estimates; component specifications; preliminary plans for reliability, maintenance, safety, configuration management, and interface management; and a preliminary cost and economic analysis. Details of the Phase Ia activities were published in the PDR report.*

*Inverter-controlled ac Induction Motor Propulsion System Preliminary Design Review (PDR), AiResearch Document 82-19077, June 30, 1982.



a. PHASE Ia FLOWCHART



b. PHASE Ib FLOWCHART

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FIGURE 1-1. FLOWCHART FOR PROGRAM PHASE I

Phase Ib encompassed the engineering test model system final design, fabrication, and test, as well as final plans and studies leading to CDR. Details of the Phase Ib activities were published in the CDR report.*

Major accomplishments during Phase I included:

(a) Defined system and component requirements to meet design specifications and interface requirements.

(b) Defined baseline ac propulsion system design.

(c) Completed system justification study.

(d) Calculated system performance.

(e) Completed component preliminary design.

(f) Outlined technical approach to electromagnetic interference (EMI).

(g) Established reliability, safety, and maintainability methodology.

(h) Performed system verification tests on engineering test model of ac propulsion system.

1.1.1 Design Specifications

The ac propulsion system program was intended to provide a realistic demonstration of ac propulsion equipment that would clearly show the benefits of ac propulsion to members of the rail transit industry and others. The method was to retrofit existing dc rail transit vehicles of known performance with ac propulsion equipment designed to fit with minimal changes in operation and interfaces. The retrofitted vehicles would then be compared to the dc cars in a realistic operating environment to show the merits of ac propulsion.

*Inverter-Controlled ac Induction Motor Propulsion System Final Design Data and Engineering Analysis, Critical Design Review (CDR), AiResearch Document 83-20297, January 10-11, 1984.

1.1.1.1 Equipment Requirements

The initial DOT/UMTA contract called for two car sets of ac propulsion equipment to be installed in place of the dc propulsion equipment in two standard R-44 subway cars donated by the NYCTA. As discussed in Section 2, the contract was modified early in program Phase II to use two upgraded R-44 cars instead. Each car set of equipment was to consist of:

(a) Four squirrel-cage induction motors

(b) One or two static inverters

(c) An electrical braking system

(d) A propulsion system controller including appropriate control circuitry for:

  (1) Common tractive effort control

  (2) Blended friction and electrical braking

  (3) Gap and dead rail detection

  (4) Appropriate safety features

(e) Associated mechanical and electrical equipment including all equipment required for interfacing with the vehicle

The two ac-retrofitted cars were to be capable of operation as a two-car set or with dc cars in trains of four or eight cars. In each case, operation was to be in response to the dc car master controller and other motorman's controls, hostler control system, automatic train operation (ATO) system, and trainlined functions, and with the third-rail power source of 600-vdc nominal line potential.

The system also was required to interface with the existing dc car propulsion system equipment such as:

(a) Trucks

(b) Gear drive units (gearboxes)

(c) Mechanical (friction) braking system

(d) Speed sensors

(e) Variable load sensors

(f) Main switch and auxiliary fuse and main fuse box

(g) Current collection system (third-rail contact shoes)

1.1.1.2 Performance Requirements

To meet the program objectives, the ac propulsion system was required to:

(a) Meet the acceleration and braking requirements of the NYCTA.

(b) Operate in the electromagnetic environment of NYCTA and cause no interference with other vehicle systems or wayside systems.

(c) Be more efficient and cost less to operate than other existing propulsion systems.

(d) Provide data supporting reduced motor and propulsion control maintenance.

Key technical issues that were addressed included:

(a) Impact of NYCTA wheel mismatch standards on system cost, reliability, and maintenance

(b) Signalling compatibility

(c) Mean time between service failures

(d) Availability

(e) Receptivity to regeneration

(f) Life-cycle costs

1.1.2 System Description

As shown by the diagram in Figure 1-2, the inverter-controlled ac induction motor propulsion system consists of two essentially independent truck

ITEM	QUANTITY PER CAR
• LINE CONTROL EQUIPMENT (INCLUDES LINE CONTACTOR UNIT, LINE BREAKER UNIT, PRE-CHARGE RESISTOR)	1
• COOLING BLOWER (COOLS INVERTER, BRAKE RESISTOR)	2
• LINE FILTER UNIT	2
• PROPULSION CONTROL UNIT (INCLUDES ONE CAR CONTROL UNIT, TWO TRUCK CONTROL UNITS)	1
• INVERTER DRIVE UNIT (INCLUDES ONE LINE CHOPPER, ONE INVERTER, ONE BRAKE CHOPPER)	2
• BRAKE RESISTOR	2
• AC TRACTION MOTOR	4

a. STARS AC PROPULSION SYSTEM MAJOR COMPONENTS

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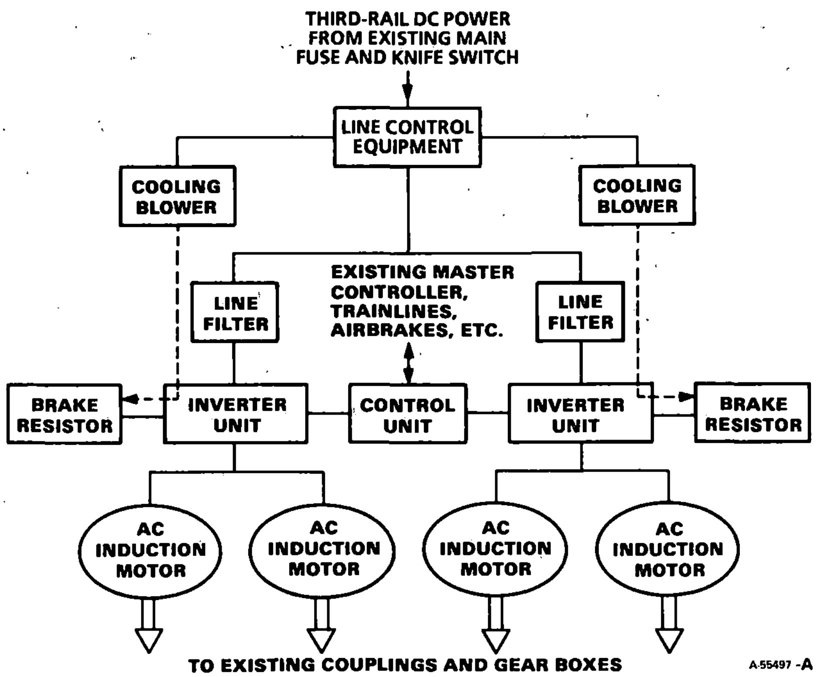


b. AC PROPULSION SYSTEM BLOCK DIAGRAM

F-56544

FIGURE 1-2. AC PROPULSION SYSTEM MAJOR COMPONENTS AND BLOCK DIAGRAM drives, each utilizing two squirrel-cage ac induction motors electrically connected in parallel to drive the two axles per truck. Each pair of ac motors receives power from a single inverter unit that converts the third-rail dc power into variable-frequency, variable-voltage, quasi-sinusoidal ac power suitable for the ac motors.

The ac propulsion system is designed to fit the NYCTA R-44 car retrofit application, using the existing main fuse and switch, master controller, P-signal (braking control) generator, air brakes, couplings, and "clamshell" car-to-truck electrical connectors. The retrofitted R-44 cars were required to operate together with conventional cam-controlled dc R-44 cars for the demonstration program; therefore, the system was designed to be "transparent" to the existing train controls and other vehicle interfaces. The ac propulsion motors were designed to fit the existing R-44 trucks, using the same gearboxes, couplings, and mounting points. The controls were designed to make it easy for operators to use the equipment without having to adapt to procedures that differed greatly from those for normal R-44 dc cars.

The system is capable of full regenerative braking subject to line receptivity.

In line with the decision to use mature, reliable components, the prototype system is a modification of the ac propulsion system used on the Helsinki Metro system, which began service in 1977. The system is designed for compatibility with automatic train control systems and telecommunications systems employed in the U.S. with regard to EMI, harmonics, and supply transients.

Each pair of motors on each truck is driven by a single, solid-state, voltage-fed, pulse-width-modulated static inverter. Both truck drives (four motors and two inverters) are controlled by a single control unit. Other major components are the line control equipment (one per system), line filters (two per system), brake resistors (two per system), and inverter/resistor cooling blower units (two per system).

1.1.2.1 Design and Installation Layout

The prototype ac propulsion system was designed as a retrofit installation on existing upgraded NYCTA R-44 dc subway cars. The ac system uses the existing dc motor mountings, gearboxes, and couplings and operates from the existing dc third-rail power, responding to all interfacing control signals in the same manner as would a conventional cam-controlled dc car.

The system is designed to provide the capability of operating the ac propulsion-equipped cars in-train with existing R-44 dc cars. Trainlining and other vehicle interfaces remain unaltered. The original master controller, pneumatic braking (p-signal) generator, main fuse and knife switch, and the "clamshell" connectors are retained.

This approach affords a practical and realistic demonstration, representing one that could readily be phased into service to replace older dc systems. Some of the features of the ac propulsion system are discussed below.

(a) Variable-voltage, variable-frequency ac traction motor drive

(b) Voltage-fed, pulse-width-modulated, compound-commutated static inverter

(c) Full regenerative braking capability over the entire speed range

(d) Induction traction motors designed to accommodate 3/4-in. wheel diameter differences when supplied from a single inverter

(e) Adaptive spin/slide control circuits

(f) Microprocessor-based inverter controls

(g) Control unit annunciators to aid diagnostics

(h) Tractive effort feedback controls with automatic current limits

(i) Thirty-seven-percent energy savings over specified duty cycle with fully receptive lines

(j) Undercar layout compatible with existing dc equipment arrangement

(k) Utilization of existing dc motor mounting points, flexible couplers, and gearboxes

(l) Fifty-percent higher mean distance between failures (compared to dc chopper motors)

(m) Proven electromagnetic compatibility in existing transit vehicles

(n) Open frame construction for inverter, filter, and control units housed in enclosures designed to facilitate equipment installation and removal

(o) Complete self-protection by built-in and external circuits

(p) Dead-rail protection and incorporation of a ripple detector to satisfy NYCTA specific requirements

The two drives share only those portions of the controls that are, of necessity, car-oriented. Provisions are made for both automatic and manual isolation of a malfunctioning truck drive.

The equipment furnished and its specifications (Table 1-1) were dictated by the intent to retrofit two NYCTA R-44 cars with service-proven ac traction motor propulsion while retaining the capability of operating these cars in-train with existing cam-controlled R-44's.

For each drive, a single inverter unit powers two squirrel-cage induction motors in parallel. Each inverter is cooled by a dedicated blower, the exhaust air being used to cool the brake resistor. The traction motors are of totally enclosed, self-cooled construction.

The ac propulsion equipment was installed in the R-44 cars in place of the dc equipment that was removed.

The ac propulsion system installation in the R-44 car involves:

(a) Control equipment

(b) Undercar equipment

(c) Truck equipment

TABLE 1-1

AC PROPULSION SYSTEM SPECIFICATIONS

Specified Service Conditions		
Line voltage	Nominal Range	600 vdc 425 to 720 vdc
Regeneration voltage limit		600 to 720 vdc, setable
Low voltage supply	Nominal Range	37.5 vdc 28 to 44 vdc
Wheel diameter range		31 to 34 in.
Wheel diameter difference		0.75 in. max. (between axles on same truck)
Ambient temperature		-20° to +110°F (-29° to +43°C)
Performance Requirements		
Initial acceleration		2.5 mphps
Time to 70 mph		90 sec
Service brake rate (linear brake taper)		3.0 mphps below 50 mph to 2.3 mphps at 80 mph
Jerk limit		Setable: 1.0 to 2.5 mphpsps
Maximum speed		80 mph
Maximum normal speed		70 mph (31- to 34-in. wheels)
Control		Match existing R-44 cars
Duty cycle		NYCTA RR line (AW3)

Notes: Unless otherwise indicated, performance is for 32-3/8-in. wheels and unloaded (AWO) to fully loaded (AW3) weight.

AW3 is defined as:

87,025 lb	AWO of car with dc propulsion
-10,491	Dc propulsion equipment (removed)
76,534	
+11,590	Ac propulsion equipment (added)
88,124	
+43,000	Maximum passenger capacity
131,124 lb	AW3 of car with ac propulsion

The control equipment was installed in place of the removed dc automatic train operation (ATO) equipment on the "A" car and includes the propulsion control unit, load weigh unit, and miscellaneous equipment such as the low-voltage supply circuit breaker and blower circuit breakers (plus the associated equipment retained from the R-44 dc installation). On the "B" car, which has no cab, the control equipment was installed on the engineer's panel.

The undercar equipment (Figure 1-3) includes the line control equipment (LCE), line filters, inverters, cooling blowers and plenums, air filters, and brake resistors. The ac equipment is arranged to fit into the undercar space available after removing the dc equipment, which included the lighting inverter, control group, and associated resistors. The original knife switch, converter, brake operating unit, air supply reservoir, and battery box were retained, but relocated in the undercar area.

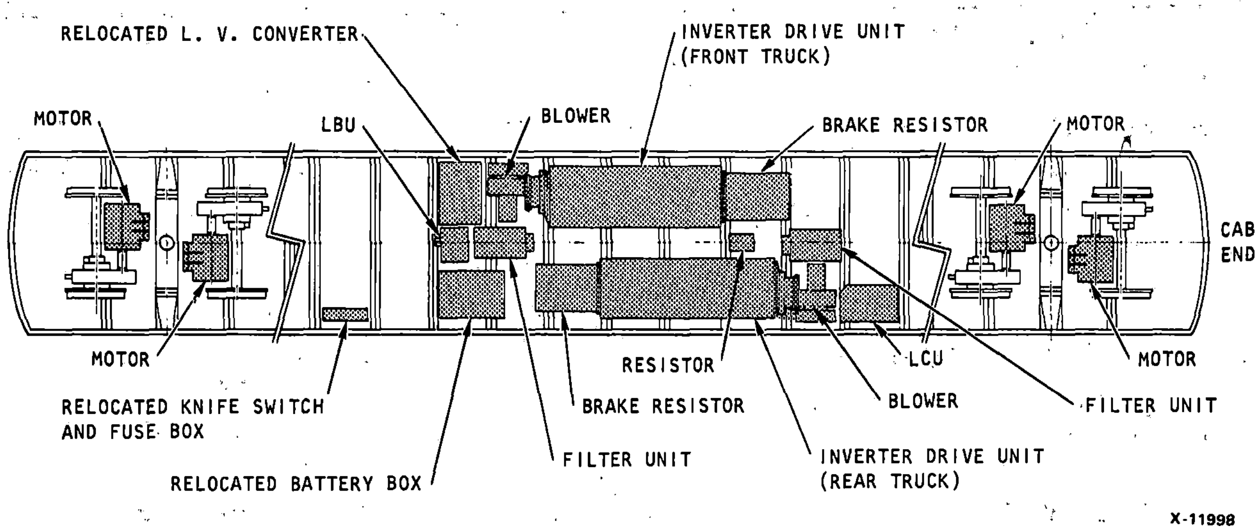


FIGURE 1-3. UNDERCAR EQUIPMENT ARRANGEMENT

The undercar equipment is located essentially in two symmetrical groups about the car centerline, to maintain required balance. All of the equipment fits within the clearance lines, allowing good access and good airflow for all units.

The truck equipment consists of the ac induction traction motors and mounting hardware. The ac motors were designed to use the same mounts as the dc motors they replace, and the same couplings to the original gearboxes.

1.1.2.2 Power Circuit

The power circuit for the ac propulsion system converts third-rail 600-vdc power into variable-frequency, variable-voltage ac suitable for the induction traction motors.

The main elements of the power circuit are:

(a) The knife switch and main fuse (existing R-44 equipment)

(b) The line control equipment

(c) Two identical truck drives, each consisting of:

(1) One line filter

(2) One inverter

(3) Two ac traction motors

As shown by Figure 1-4, current drawn from the third rail flows via the knife switch and main fuse to the line control equipment (LCE). The LCE includes a fast-acting dc circuit breaker (MCB), a differential current relay (KDC), a contactor (KBL) for blower control, contactors (KIS) that switch power to the two drives (also used to isolate a malfunctioning drive), and a contactor (KRS) that switches out the resistor (RSL) used to limit the in-rush current when the line filter capacitors are charging.

Each drive is isolated from the line by a line filter, which provides required inductive source impedance to the inverter input chopper and mitigates EMI. Each inverter consists of a dc-link (capacitor bank) and the following:

(a) A line chopper to provide the desired internal dc-link voltage regardless of line voltage fluctuations and to control the power returned to the line during regenerative braking.

(b) A three-phase inverter to convert the dc power to ac, and, in the regenerative braking mode when the motors function as induction generators, to rectify the generated ac for return to the third rail.

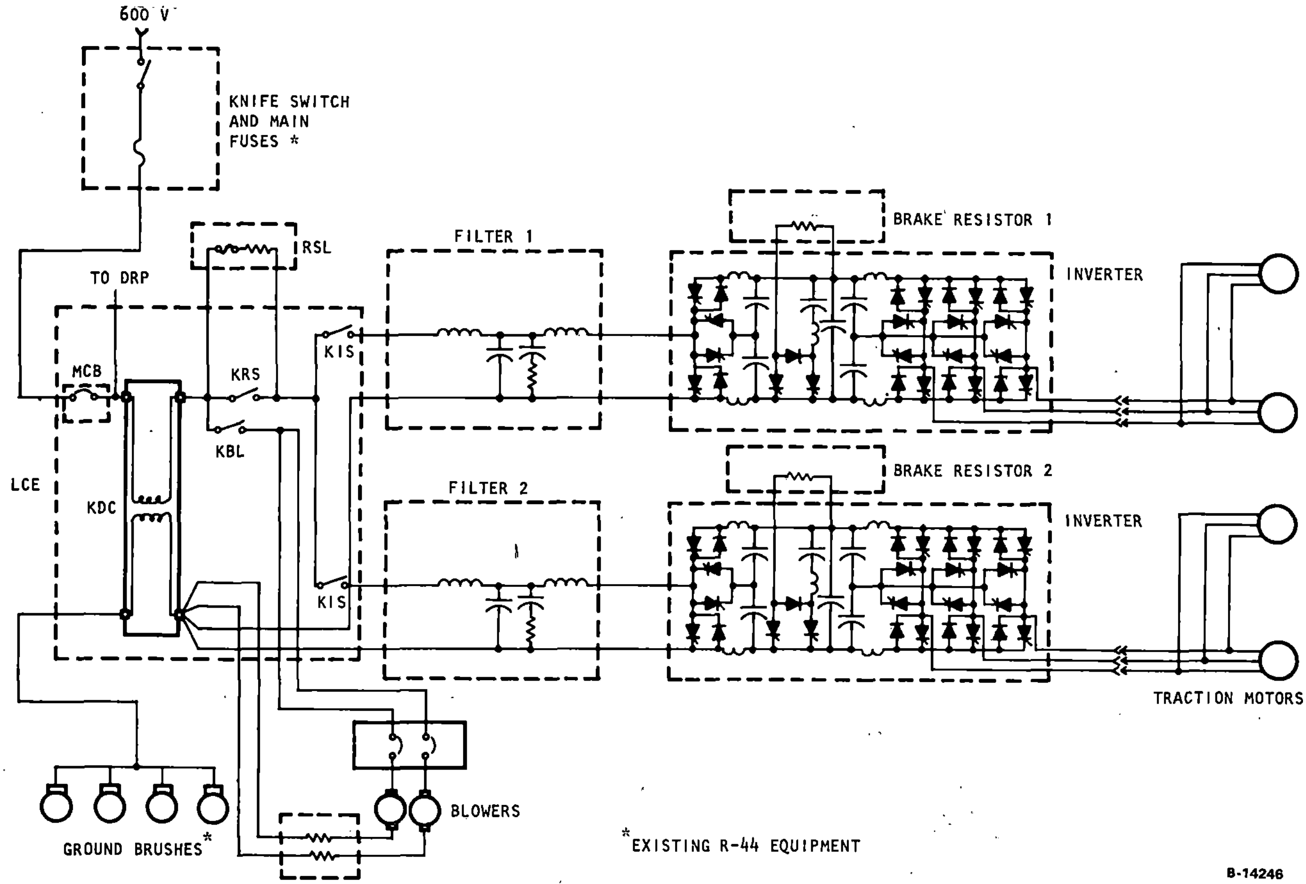


FIGURE 1-4. AC PROPULSION SYSTEM POWER CIRCUIT

(c) A brake chopper to direct power that cannot be regenerated to the brake resistor instead. The resistor is sized to dissipate all of the dynamic braking energy under conditions of no line receptivity.

1.1.2.3 Controls and Operating Modes

The ac propulsion system is designed to operate in a manner that closely matches the R-44 dc cars operation for compatibility with the existing NYCTA rail operations.

The propulsion control unit (located in the cab) interfaces with the trainlines and the line control equipment by means of optical couplers to provide high-voltage isolation. It receives the commands from the master controller (existing R-44 equipment) through the trainlines and provides the signals to the truck drives to obtain the desired propulsion system response.

Functionally, the control unit is divided into three sections, a car control section and two truck control sections. The car control section delivers load-weight-compensated motor torque requests to each of the two truck control sections as a function of trainline signals. The two truck control sections provide inverter frequency and voltage commands to the two truck drive inverters so that the sum of the two traction motor torques corresponds to the requested level.

1.1.2.3.1 Propulsion

Normally, the controls are set to match the R-44 torque/speed performance characteristics and trainline command response. These performance characteristics are considerably less than the capability of the ac propulsion system. Consequently, an alternative full-performance mode is provided, which features continuous tractive control. The capability to respond to a spin-slide system also is provided.

1.1.2.3.2 Braking

In the braking mode, the ac propulsion system provides preferential blended electric brake control in the following order:

(1) Regenerative braking to the extent that the third rail is receptive

(2) Dynamic (resistive) braking when third-rail receptivity limits the amount of regeneration

(3) Smoothly blended friction braking at very low speeds (below 5 mph)

Regeneration can be switched off by a switch located in the cab, and provisions are made for both automatic and manual isolation of a malfunctioning truck drive. When one truck is cut out because of a malfunction, the other truck continues to provide its rated tractive effort in motoring; however, the system reverts to friction braking because friction brake control is not implemented on a per-truck basis in the R-44 car (thus no blending is possible).

1.1.2.3.3 Spin/Slide Detection and Control

The propulsion control system includes provision for detecting and controlling wheel spin and slide conditions.

Wheel spin occurs when the applied tractive force exceeds the frictional force coefficient between the wheels and the track, such as may be caused by the application of too much torque for the existing track conditions. Wheel slide may occur during braking when the applied braking force exceeds the frictional force coefficient between the wheels and the track.

The spin/slide circuits detect these conditions by frequent, repeated measurements and comparison of wheel speeds. Correction is implemented on a per-truck basis as discussed in the following paragraphs.

1.1.2.3.3.1 Spin Prevention

Wheel spin is detected in two ways: (1) by wheel/axle speed increase rate (dv/dt), and (2) by indication of excessive speed differences in tractive mode (Δv).

The dv/dt spin prevention operates within one truck drive because the two axles driven by parallel-connected traction motors always operate at speeds within a few percent of each other. The speed difference, or Δv control of wheel spin, operates in such a way that the speeds of all four axles of a car are compared to each other by the speed sensors mounted in each traction motor. If one axle is detected to have a speed much higher than the others, the torque of that truck is reduced until the speed of all axles is within permissible limits. In operation, the tractive torque is quickly reduced until there is no indication of wheel spin. After this, the torque is increased relatively quickly (in about 1 sec) to a value about 80 percent of the torque at which the spin began, and then slowly (in 5 to 10 sec) to full value. If the spin is detected again while increasing the torque, the same sequence is repeated, but with a lower starting torque, now equal to the one corresponding to the beginning of the second spin. This procedure is continued until the torque actually used does not force the wheels to exceed the friction limit. The spin circuit is therefore an adaptive system.

1.1.2.3.3.2 Slide Prevention

The slide prevention system operates with the same two detection principles as the spin prevention system, dv/dt and Δv detection. The operating principle for electrical braking is the same in slide prevention; however, the mechanical brakes also have to be controlled. If a wheel slide is detected, the electrical braking torque is reduced for the sliding truck. If the sliding state continues, a Δv or dv/dt signal is given to the dump valves of the mechanical brakes, which also reduces the mechanical braking until the slide has ceased.

The electrical braking torque is then restored as described above, and if the friction limit is not exceeded, the mechanical brakes are also restored. If sliding starts again, the entire sequence is repeated until a steady braking effort is obtained.

In emergency braking, there will be no dynamic braking. The slide circuit is deactivated similar to the system presently existing on the R-44 car.

If one truck drive is out of operation, it cannot brake electrically. In that case, electrical braking effort is replaced by mechanical braking effort. The slide protection and detection circuit remains active even for the failed truck drive.

The principle in slide prevention is to affect only one truck. Thus, if only one axle of the car goes to a slide condition, the braking effort is not reduced in the entire car but only in the two axles of that truck.

If mechanical brakes force one axle to slide during blended electrical and mechanical braking, its electrical braking torque tends to reduce, and the torque of the other axle on the same truck tends to increase because of the frequency control characteristics that regulate the sum of electrical braking torques. To prevent an excessive difference in braking torques, the speed of both axles are compared, and if their difference exceeds a certain percentage, the mechanical braking effort is reduced to restore an equal electrical braking torque.

1.1.2.3.4 Dead Rail and Power Gap Detection

During regenerative braking, braking energy is converted to electrical energy and returned to the transit authority third-rail power network (line) to conserve energy. When regenerative braking is incorporated in a transit car propulsion system, therefore, protective measures are appropriate to guard against the possibility of electrifying unenergized or "dead" sections of third rail which exists under certain conditions.

Although safe operating practices dictate that such "dead" sections must be safely isolated and grounded at the site of work to prevent electrical shock during rail maintenance or other work, the protection provided by dead-rail-sensing and regenerative-braking-inhibit circuitry in cars equipped with regenerative braking is an added safeguard required by the NYCTA.

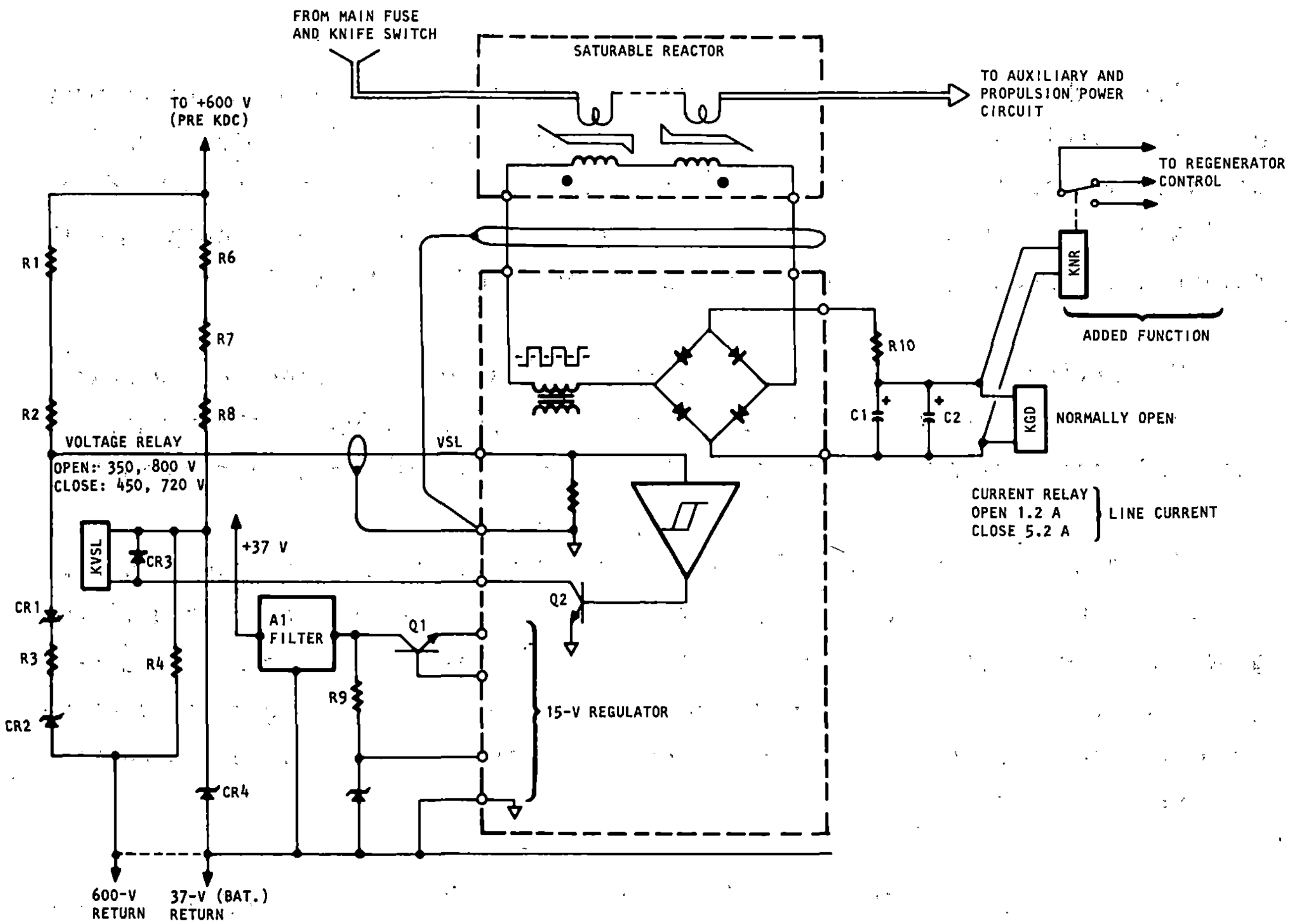
Of particular concern is the possibility that during regenerative braking, the vehicle, after passing an interruption of the supply (third rail gap), can energize a dead section of the third rail when regaining contact.

The ac propulsion system includes circuitry to sense power gaps and shut off the current flow from the system to the line during braking. An antiregeneration relay (KNR) in the line control equipment reacts rapidly to a rail gap or dead rail, preventing regeneration by removing the triggering signals from the regeneration thyristors in the power circuits and initiating resistive braking instead.

Figure 1-5 shows the dead rail detection circuit and its interfaces with the line control equipment and power and control circuits.

As long as line current is flowing through the saturable reactor (a condition that exists whenever the third rail is energized from the power network, because there is always some auxiliary current flow), an oscillator circuit on the secondary side of the saturable reactor provides ac to a rectifier circuit that energizes gap detector relay KGD and antiregeneration relay KNR.

Gap detector relay KGD and line-voltage-sensing relay KVSL have normally open contacts in series with the current supply to the line contactor coils. Both must be activated for current to reach the line contactor actuation coils; if either relay "drops out," reflecting interruption of third-rail supply current (due to rail gap) or out-of-tolerance third rail voltage, the line contactor coil current is stopped, and the line contactors open, disconnecting the propulsion system from the line.



Dead Rail Detection

- The contacts of relays KVSL and KGD are in series with the line contactor actuation coil. Both must be closed for line current to flow.
- If 600 ±150 vdc from third rail is present, line voltage sensing relay KVSL is activated and its normally open contacts remain closed, allowing current to flow in the line contactor coils.
- If current is flowing through the saturable reactor, gap detector relay KGD receives current and its normally open contacts remain closed, permitting line current.
- If current is not flowing through the reactor, anti-regeneration relay KNR is deactivated and its normally closed contacts open, causing the regeneration thyristor to turn off.

FIGURE 1-5. DEAD RAIL DETECTION CIRCUIT

When the vehicle is in the tractive mode and receiving power from the third rail, regenerative braking can be applied, with the current sensing circuitry acting to protect against energizing a dead rail. When the current being supplied to the line ceases (indicating a gap or dead rail), the system switches to resistive braking and the line switch is opened. Regenerative braking cannot be resumed until 600 vdc is sensed on the third rail again, which allows the line switch to close.

1.1.2.4 Built-In Circuit Protection Measures

In addition to the main current limiting fuse and knife switch, the ac propulsion system includes built-in input circuit protection as well as internal circuit protection.

1.1.2.4.1 Input Circuit Protection

Figure 1-6 shows the input circuit and dead rail protection provided in the line control equipment (LCE). In this simplified circuit diagram, the left side shows the 600-vdc supply connection through the LCE to the input of the line filter. The main circuit breaker (MCB) in series with the main fuse is a fast-acting dc circuit breaker that operates to limit total current drawn by the two truck drives during traction and the total regenerative braking current returned to the line. The charging contactor (KRS) opens to insert the resistor (RSL) and associated fuse into the circuit during starting to protect the filter capacitors from in-rush current when they are charging.

1.1.2.4.2 Internal Circuit Protection

Energy-absorbing elements in the ac propulsion system power electronics provide built-in protection against such conditions as line voltage transients. Other condition-monitoring elements and circuitry provide continuous feedback to the control unit, which provides corrective action commands upon detection of overtemperature, overcurrent, etc.

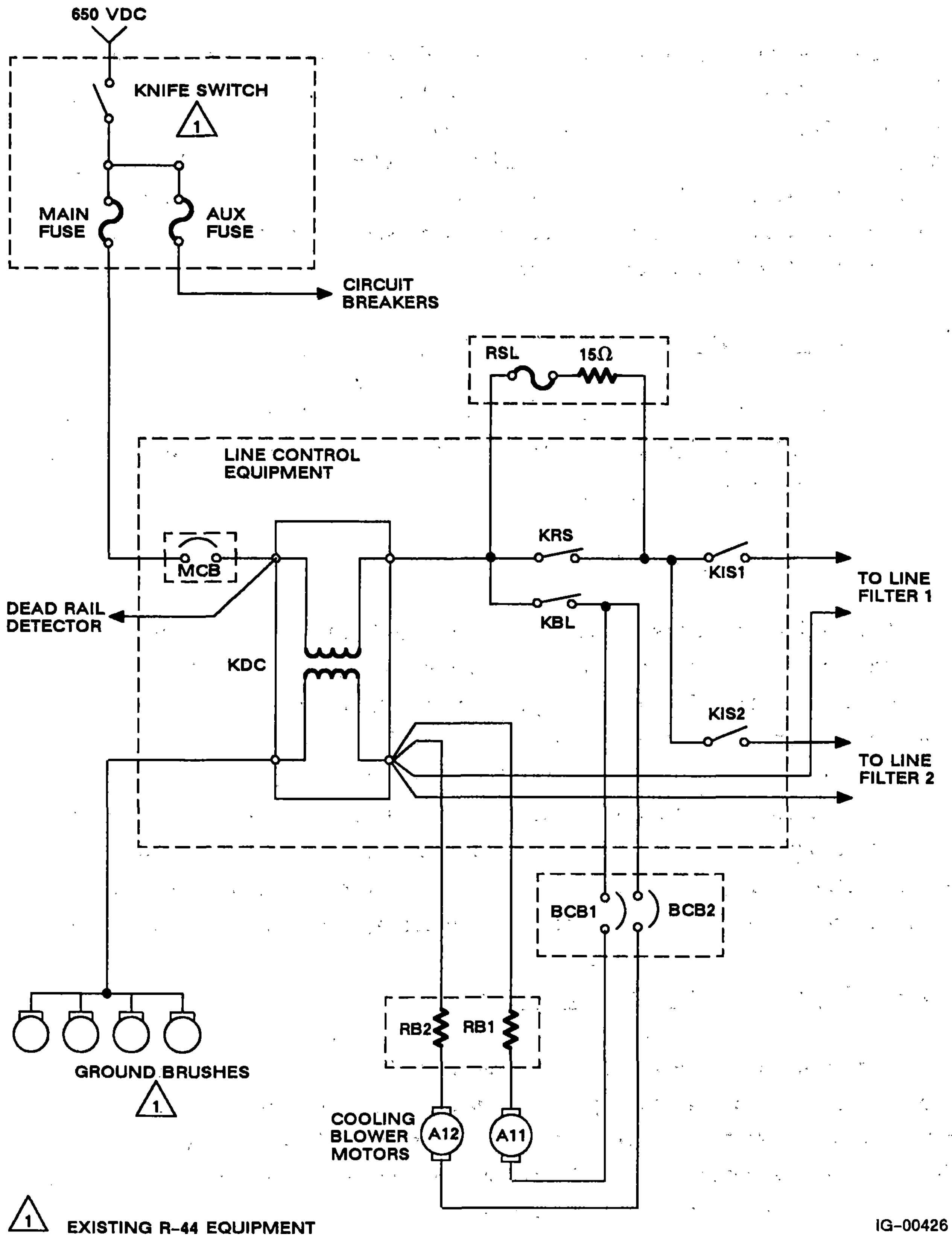


FIGURE 1-6. LINE CONTROL EQUIPMENT CIRCUIT PROTECTION PROVISIONS

Figure 1-7 identifies circuit components that provide protection against line transients. Figure 1-8 summarizes the internal circuit condition monitor/corrective action afforded by the sensing elements and control unit.

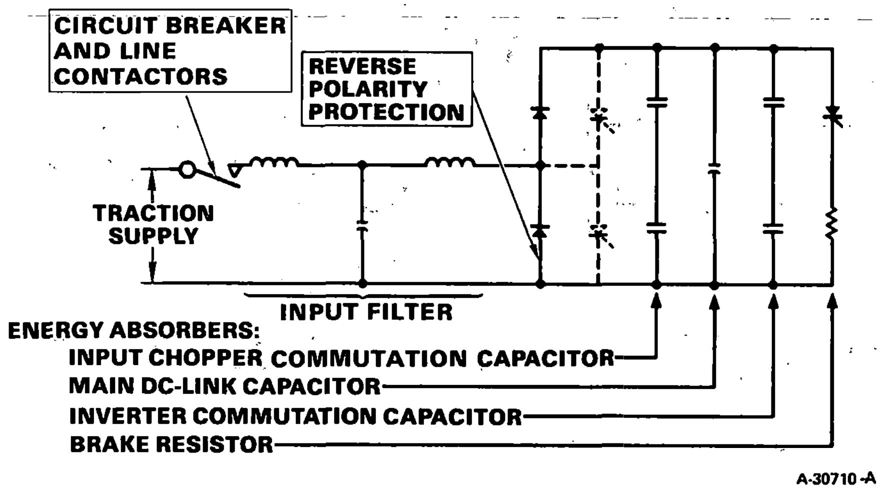
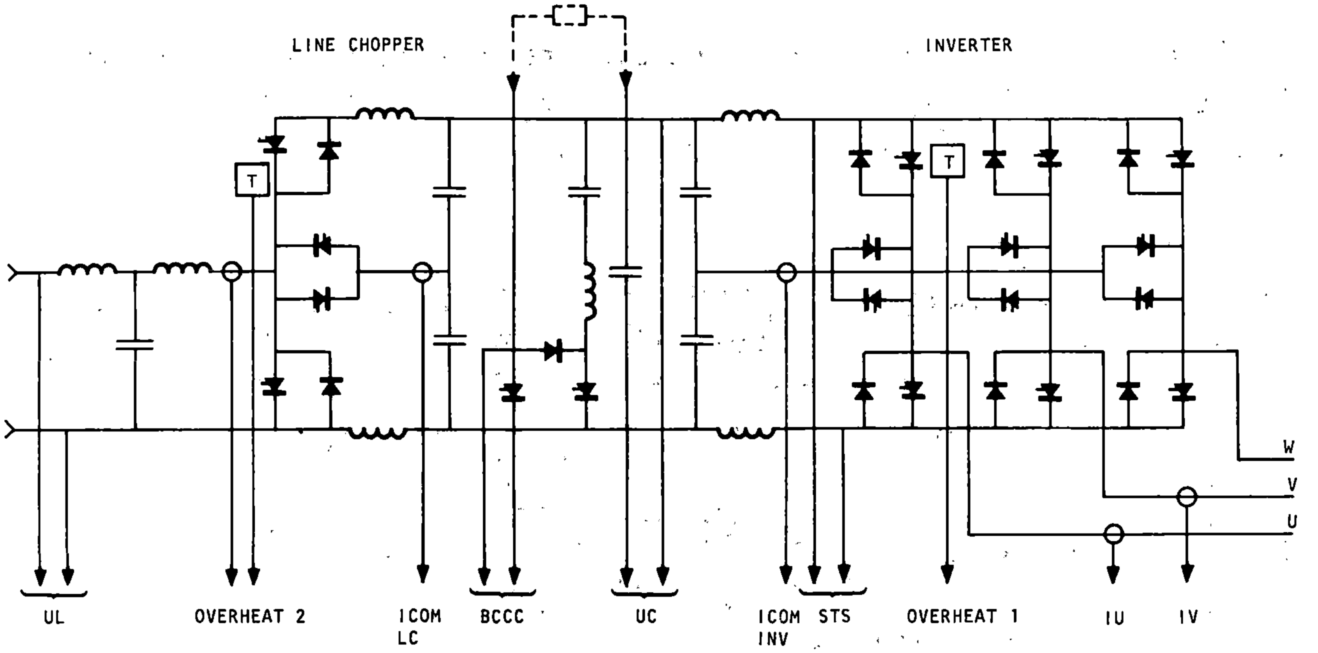


FIGURE 1-7. LINE TRANSIENT AND REVERSE POLARITY PROTECTION

1.1.2.4.2.1 Overcurrent, Overvoltage, and Undervoltage Protection

The overcurrent protection circuit in the inverter control prevents sustained excessive phase currents that might be higher than the commutating capability of the thyristor switches. The current is sensed by a phase current transducer. If the momentary current exceeds the maximum safe current of the inverter, the control logic stops the inverter immediately. A control unit signal light indicates the condition. The electronic overcurrent release is automatically reset to prevent occasional overcurrent spikes or disturbances from interrupting service. The reset is allowed to occur several times before the traction motor drive is finally switched off. If the failure persists, the inverter will shut down, and manual trainlined reset is required. This condition is annunciated through the trainlined indication circuit.

The overvoltage protection operates in the same way as the overcurrent protection. If the internal dc voltage rises significantly above the maximum level, it is sensed by a voltage transducer, and the inverter is switched off



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- UL (line voltage)
  - Match R-44 characteristic in drive
  - Control regeneration voltage limit
  - Provide line gap indication
- IL (line current)
  - Control of line current limit
  - Overcurrent (shutdown/auto restart
- OVERHEAT 2
  - Line chopper overtemperature (shut down chopper)
- ICOM LC, ICOM INV (line chopper and inverter commutation current)
  - Commutation failure (open line breaker, shut down truck drive)
- BCCC (brake chopper continuous conduction)
  - Brake chopper failed on (shut down truck drive)
- STS (inverter shoot-through indication)
  - Initiate shoot-through response (trigger all semiconductors, open line breaker)
- UC (main capacitor voltage and rate of change)
  - Overvoltage sense (shutdown/auto restart)
  - Undervoltage sense (shutdown/auto restart)
  - Transient overvoltage (fire brake chopper)
- OVERHEAT1
  - Inverter overtemperature (shut down truck drive)
- IU, IV (Phase U and V current)
  - Overcurrent sense (shutdown/auto restart)

FIGURE 1-8. AC PROPULSION SYSTEM INTERNAL PROTECTION to protect the semiconductors. After an overvoltage release, the control system resets the inverter automatically a few times to avoid unnecessary shutdowns.

The built-in undervoltage protection operates in such a way that if the supply dc voltage is low, the line chopper increases the internal dc voltage to meet full performance characteristics. When the supply voltage is near the lower limit, the power drawn from the line is limited (to protect against line voltage collapse, since the power is taken in the form of a very high current). The power limit is zero at a selected voltage below the lowest practical voltage, and undervoltage release takes place at that voltage. If the supply voltage increases again, the inverter restarts automatically.

If the line voltage drops below the zero power point, the line switch and charging contactor are opened to recharge the capacitors through the resistor. This prevents the current pulse caused by a rapid and high increase of the supply voltage from causing an overcurrent release of the protection devices.

In addition to the internal overvoltage protection of the inverter described above, the braking chopper acts as another automatic overvoltage protector. If the internal dc voltage increases above the maximum allowable level, the chopper is switched to the on state; it will stay in this state until the voltage has decreased to below maximum.

The control logic of the inverter has built-in protection to ensure the correct sequence of triggering pulses for the thyristors. If the sequence is incorrect and there is a possibility of main circuit malfunction, all main thyristors are triggered to the on state and they short-circuit the dc terminals, which leads to a high current pulse that opens either the protection fuse at the input terminal or the line switches.

The main fuse of each truck drive protects the semiconductors in cases of controlled short circuits as a consequence of a logic failure. The differential current protection, or earth leakage protection, is located in the line switch unit and limits the maximum allowable differential current for the propulsion system to a small value.

1.1.2.4.2.2 Surge Protection

The protection principles of the electronic equipment against surge voltages coming from the supply line are shown in Figure 1-9. The protection can be divided into two categories, which are described below.

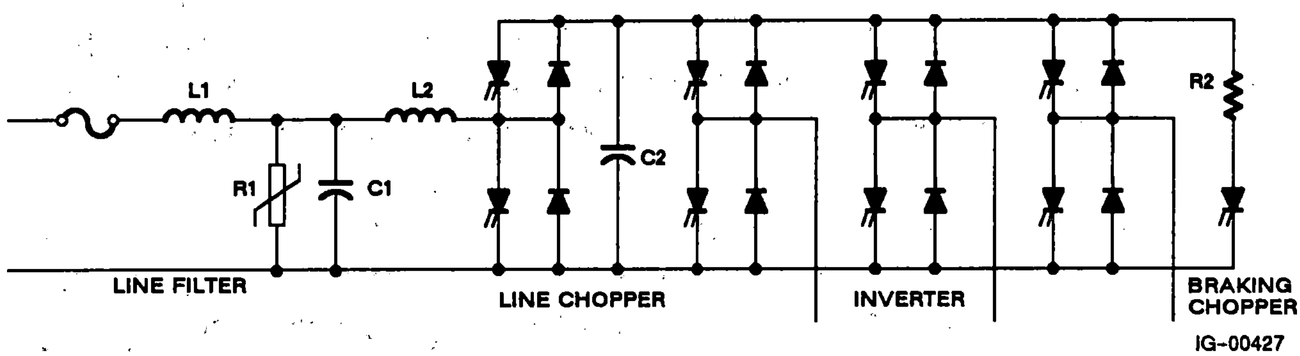


FIGURE 1-9. SURGE PROTECTION OF THE DRIVE UNIT

1.1.2.4.2.2.1 Short-Duration Surges

The sensitive electronic equipment of the drive unit is protected against short high-voltage pulses by line reactor L1. The energy of a voltage surge of the microsecond range is so low that it cannot significantly increase the voltage of line-filtering capacitor C1; thus, practically the entire voltage is between the terminals of L1, and the surge does not affect the capacitors or semiconductors of the drive unit. Line reactor L1 is designed to withstand microsecond-duration surges at 3600 v.

1.1.2.4.2.2.2 Longer Duration Surges

Because voltage transients of the msec range contain such high energy, overvoltage protection is provided for capacitors C1 and C2. If the line chopper is in the low state (i.e., the lower thyristor is conducting,) or the surge voltage is negative, the input circuit is short-circuited by the lower thyristor or diode of the line chopper, and the transient voltage cannot damage the electronic equipment. Line capacitor C1 is protected by a nonlinear resistor, which limits the voltage across the capacitor.

Usually, however, the line chopper must be stopped to ensure its proper commutation, and in that case, the surge current continues flowing through the upper diode of the line chopper to the internal dc circuit of the drive unit. Several protective measures prevent circuit damage. The first protection is the braking chopper, which always switches on braking resistor R2 when the internal dc voltage rises to a certain value, whether due to a nonreceptive line or as a result of an overvoltage in the supply line. Additional protection is provided by the nonlinear resistors of the line filter unit.

Depending on the energy content of the transient, the protecting devices either absorb the transient (and the inverter only stops for a while because of overvoltage release, then restarts) or the transient current increases high enough that it either blows the main fuse of the drive unit or trips the line switch by overcurrent.

1.1.2.4.2.3 Overheat Protection

The main components of the propulsion system are protected against excessive heating by thermal sensors. If the power stage of the drive unit becomes too warm, the line chopper is stopped as a first protective step. After this, the system operates directly at the line voltage, and the system performance is reduced, but the train may operate further. If the temperature still increases, the system is switched off.

The traction motors are equipped with thermal sensors at critical places. If their temperatures become too high, the system is switched off.

1.1.2.5 Major Components

The inverter-controlled ac induction motor propulsion system includes the following major components:

(a) Two line filters, one for each inverter

(b) Two inverters, one for each truck drive

(c) Four ac induction traction motors, two per truck, one driving each axle

(d) A propulsion system control unit

The following paragraphs provide component details.

1.1.2.5.1 Line Filters

The line filters isolate each truck drive from the line and attenuate the line current harmonics generated by the line chopper (in the inverter) to prevent EMI to the signalling or track circuits. They also protect the inverter line choppers from surge voltages coming from the line.

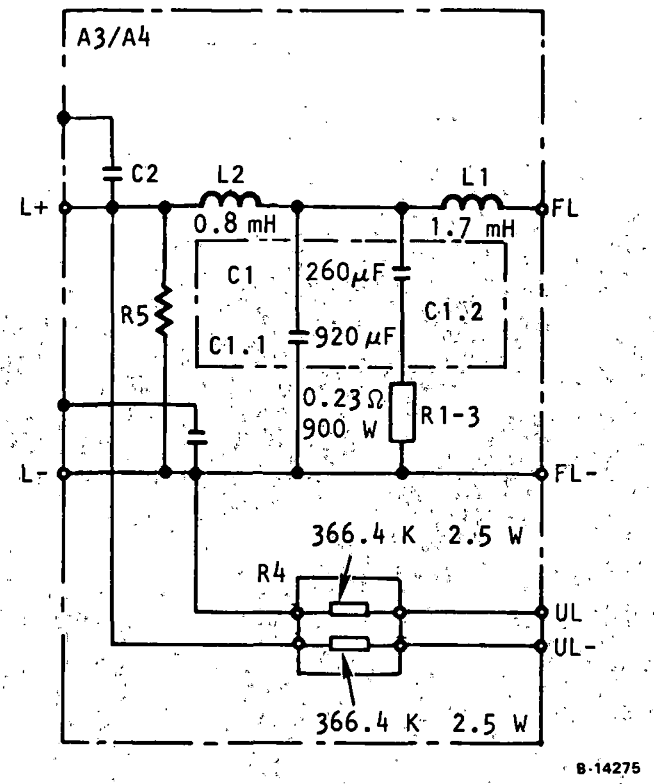
As shown by Figure 1-10, each line filter circuit includes two dc reactors (inductors L1 and L2), a filter capacitor unit (C1), a damping resistor (R1-3), two radio frequency (rf) capacitors (C2, C3), a voltage divider resistor unit (R4), and a discharging resistor (R5), all mounted in a separate aluminum enclosure located under the car.

1.1.2.5.2 Inverters

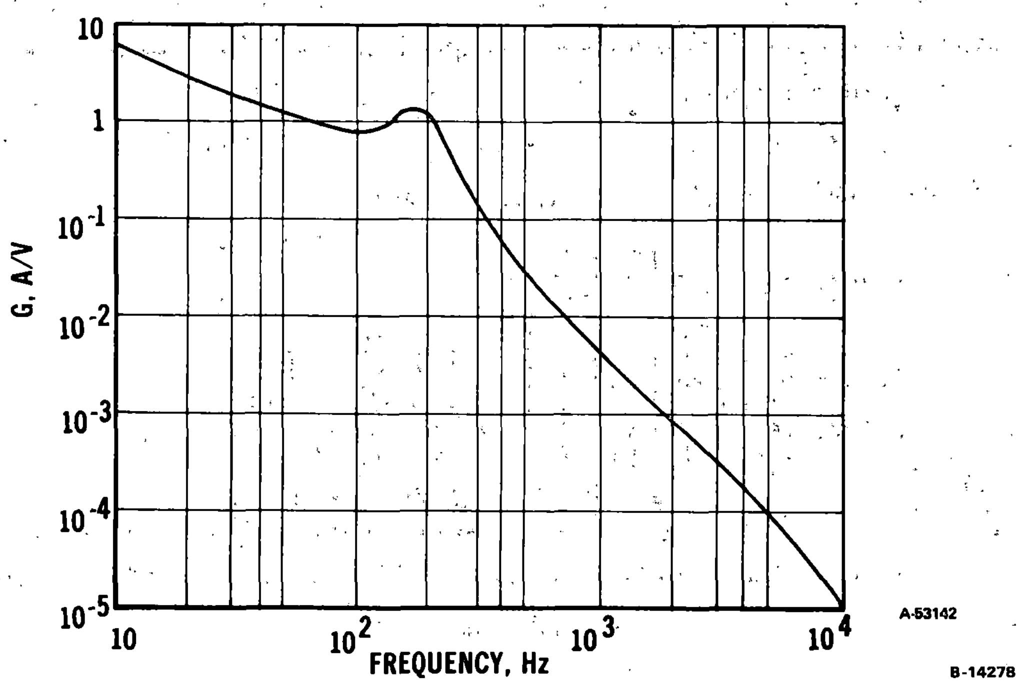
Two voltage-fed, pulse-width-modulated (PWM), compound-commutated solid-state static inverters supply variable-frequency, quasi-sinusoidal, 3-phase ac power to the ac squirrel-cage induction traction motors.

There is one inverter for each truck drive, each of which powers two ac induction traction motors electrically connected in parallel (Figure 1-11).

Located beneath the car, the inverters are forced-air cooled by blowers (one per inverter) that provide clean filtered air to cool the electronics.

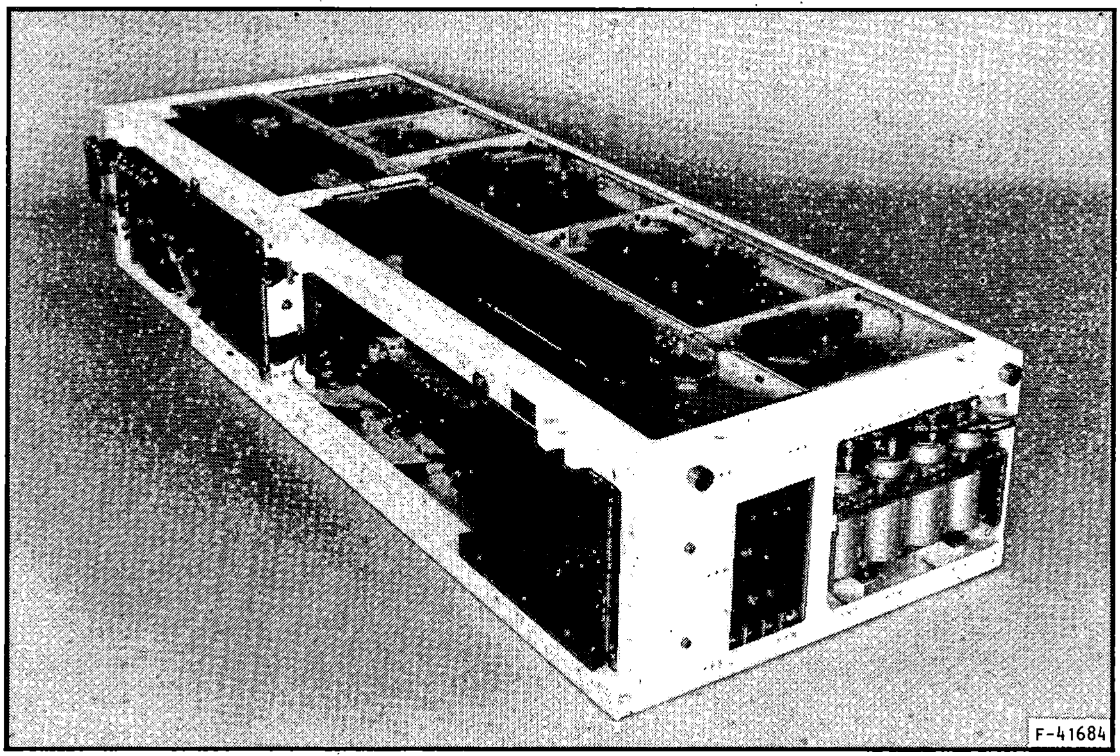


a. CIRCUIT DIAGRAM OF LINE FILTER



b. FILTERING CURVE OF LINE FILTER

FIGURE 1-10. LINE FILTER CIRCUIT AND RESPONSE



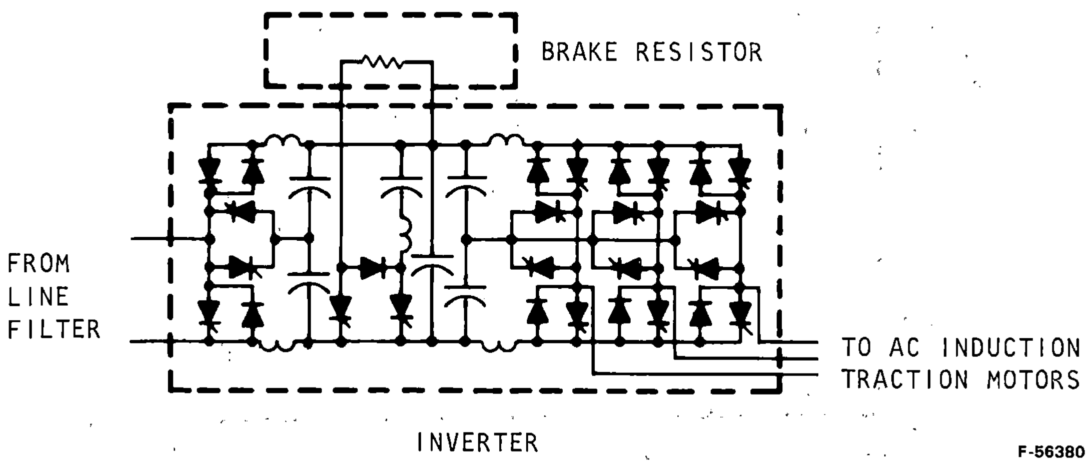


FIGURE 1-11. INVERTER AND SIMPLIFIED CIRCUIT DIAGRAM

Each inverter interfaces with the propulsion system control unit and operates from the low-voltage dc supply. Depending on the operating mode (traction or electrical braking), the inverter (1) converts dc received from the line filter into ac for the traction motors, or (2) receives ac from the motors (operating as generators) and transfers power to the line (regenerative braking) or to braking resistors (dynamic braking).

During traction operation, the inverter operates under control of the control unit to regulate ac frequency and voltage to achieve the desired motor speed and torque. Each inverter includes three subunits:

(a) A line chopper that regulates dc voltage obtained from the line filter so that the dc link voltage supplied to the inverter and brake chopper is independent of line voltage variations

(b) An inverter that converts the dc-link power into variable-frequency, variable-voltage ac suitable for the traction motors

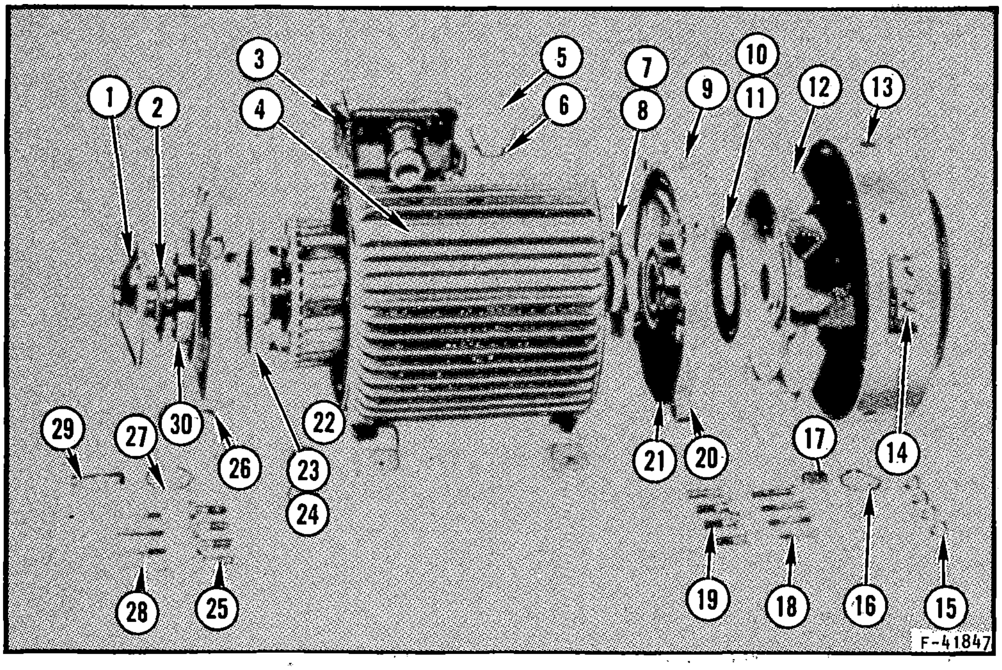
(c) A brake chopper that regulates the dynamic braking power dissipated in the braking resistors during conditions of inadequate line receptivity for full regeneration

Each of these subunits includes thyristor switching circuits based on forced-commutated thyristors with feedback diodes. The thyristors are triggered by signals from the control unit.

1.1.2.5.3 Induction Motors

The STARS ac propulsion system is designed around and achieves many of its benefits from the minimum-maintenance, squirrel-cage ac induction traction motor.

The high reliability and low maintenance benefits of the ac propulsion system are derived primarily from this brushless ac motor (Figure 1-12), which eliminates the inherent weak points of dc propulsion systems--the maintenance-intensive brushes and commutator in the dc motors.



TRACTION MOTOR PARTS LIST

(1) OUTER BEARING COVER, DRIVE END

(2) DISC

(3) TERMINAL BOX, COMPLETE

(4) HOUSING

(5) EYE BOLT

(6) WASHER FOR LIFTING LUG

(7) INNER BEARING COVER, NON-DRIVE END

(8) SEAL FOR INNER BEARING COVER, NON-DRIVE END

(9) GREASE NIPPLE

(10) WAVE SPRING WASHER

(11) OUTER BEARING COVER, NON-DRIVE END

(12) FAN

(13) FAN COVER

(14) NAMEPLATE

(15) SCREW FOR FAN COVER

(16) RETAINING RING FOR FAN

(17) KEY FOR FAN

(18) SCREW FOR BEARING COVER, NON-DRIVE END

(19) SCREW FOR ENDSHIELD, NON-DRIVE END

(20) ENDSHIELD, NON-DRIVE END

(21) BEARING, NON-DRIVE END

(22) ROTOR

(23) INNER BEARING COVER, DRIVE END

(24) SEAL FOR INNER BEARING COVER, DRIVE END

(25) SCREW FOR ENDSHIELD, DRIVE END

(26) ENDSHIELD, DRIVE END

(27) RETAINING RING FOR DISC

(28) SCREW FOR BEARING COVER, DRIVE END

(29) KEY FOR SHAFT END

(30) BEARING, DRIVE END

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FIGURE 1-12. SQUIRREL-CAGE AC INDUCTION MOTOR EXPLODED VIEW

The squirrel-cage ac induction motor has no windings on the rotor (the "squirrel-cage"), which turns in response to interaction of the rotating field created by the 3-phase ac current in the stator and currents resulting in the rotor; thus, brushes and commutator are unnecessary.

For this application, a totally enclosed, fan-cooled motor is used. The ac motor features:

(a) Simple, rugged construction

(b) Lightweight, low-inertia aluminum rotor

(c) Electrical parts not affected by environment

(d) No scheduled maintenance except infrequent bearing relubrication

(e) Mounting provisions and interfaces compatible with existing R-44 truck mounting points, couplings, and gearbox.

The motor has a steel housing with welded, widely separated cooling fins; a 4-pole, 60-slot stator with a single-layer diamond winding of class H insulated copper wire in double-delta 3-phase connection; a cast aluminum rotor cage; and cast aluminum stator bars. The rotor is supported by two single-row deep-groove ball bearings equipped with relubrication pins. Motor specifications are:

Type	HXUR/E 562G2
Power	128 kw
Voltage	470 v
Connection	D2
Rated current	205 amp
Rated frequency	45 Hz
Rated speed	1325 rpm
Power factor	0.83
Protection class	TEFC
Insulation class	H
Weight	1336 lb (606 kg)

With no insulated windings on the rotor, the ac motor is able to operate at higher temperature, reducing the cooling requirements. With no brushes/commutator and no internal cooling air passages required, the motor can be totally enclosed, improving reliability by providing protection from dust, dirt, rain, snow, etc. The motor is self-cooled by a built-in fan that forces cooling air over the outer finned surface of the stator housing. No special cooling air filters with attendant periodic replacement requirements are necessary.

The rotational speed of an ac induction motor depends on the frequency of the ac power supplied to it. The control unit and inverter act together to provide the required motor torque/speed and directional response in traction and during electrical braking modes. Unlike conventional dc traction motors, there is no need to electrically reconnect the motors for different operating modes--thus, no main circuit contactors are needed. There are no switched resistances in the field circuit. No reversing contactors are needed--to reverse motor direction, the ac voltage phase sequence is electronically reversed. The transition from drive to braking mode is made by reducing the synchronous speed of the motor from slightly greater than to slightly less than shaft speed, whereupon the motors act as ac generators.

The combined effects of many of these features of the ac motors result in additional benefits to the ac propulsion system:

(a) <u>No Brushes/Commutator</u>--No costly brush examination/replacement or commutator grinding, no problems at higher voltage from arc-over, no exposed electrically "hot" surfaces

(b) <u>No Rotor Windings</u>--Allows higher operating temperature, higher speed, and less complicated cooling system; simpler construction reduces weight, resulting in less unsuspended mass, less rotating inertia, less wear for wheel rims and flanges, rails

(c) Totally Enclosed, Self-Cooled Design--Eliminates complicated cooling systems, ducting, filters; provides additional protection against contaminants

1.1.2.5.4 Propulsion System Control Unit

The control unit operates in conjunction with the inverters to control the ac frequency and voltage supplied to the ac induction traction motors as shown by the block diagrams in Figure 1-13.

Operating in response to trainline commands and feedback signals, the controller provides the triggering signals to the thyristor switching circuits in the line filters and inverters. It is powered from the R-44 low-voltage supply and interfaces with:

(a) The master controller

(b) The line filters

(c) The line control equipment

(d) The pneumatic friction brakes

(e) The ac traction motors

(f) Sensors and transducers

The control unit performs the calculations necessary for ac motor directional control and torque control, and regenerative and dynamic braking. The control unit uses combined analog and digital circuitry with complementary metal oxide semiconductor (CMOS) and solid-state microprocessor devices. The electronics are contained on printed wiring assemblies (PWA's) installed in removable racks, and have built-in test connections for testing without removing PWA's. Light-emitting diodes (LED's) provide indications of normal/abnormal (failure) PWA conditions.

The circuits are sectionalized according to function to comprise one car control section and two truck control sections, each in a separate PWA rack.

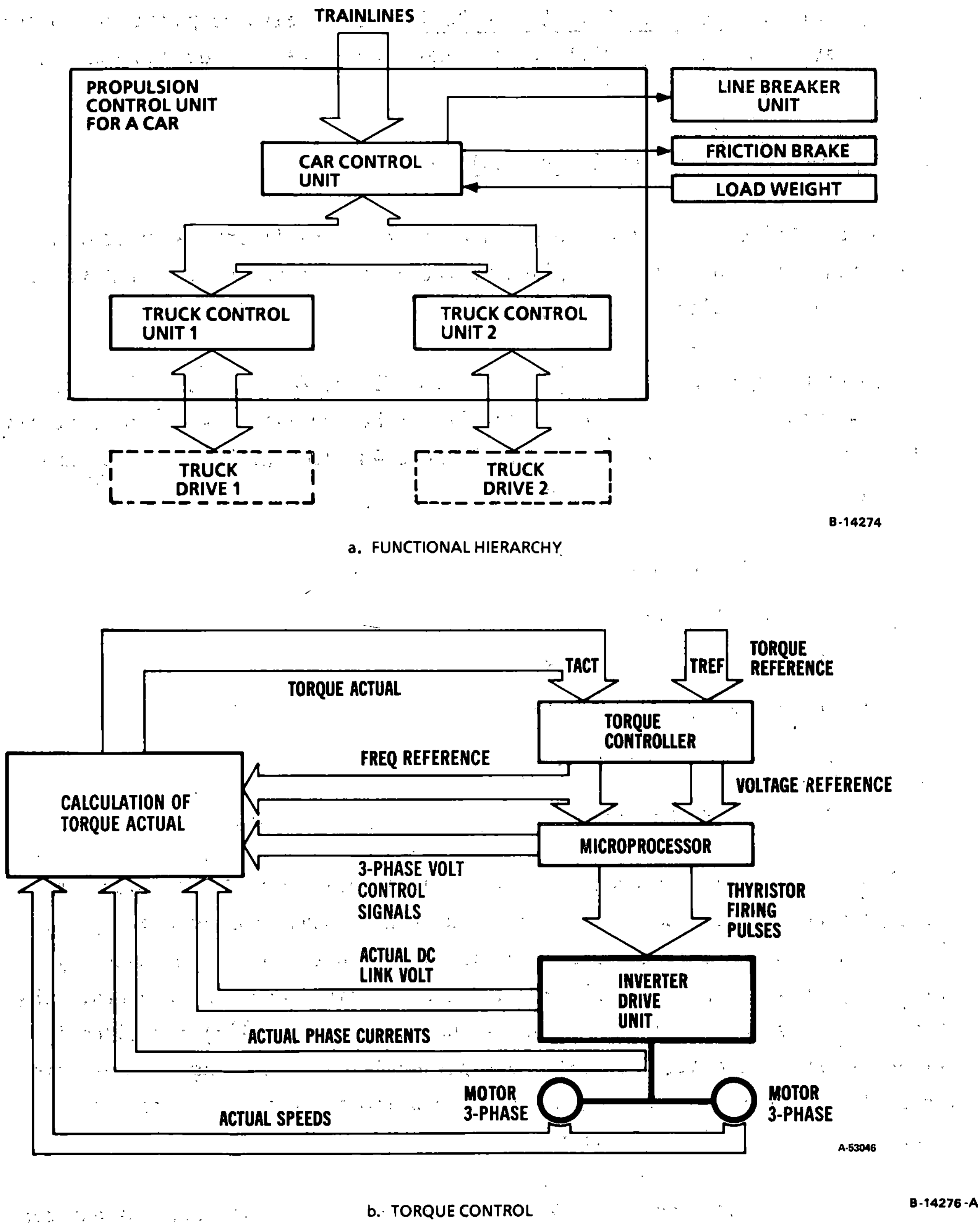


FIGURE 1-13. PROPULSION CONTROL UNIT SIMPLIFIED BLOCK DIAGRAMS

The car control section delivers the load-weight-compensated torque request to each of the truck control sections as a function of trainline signals.

The two identical truck control sections regulate inverter frequency and voltage to each truck so that the sum of the two traction motor torques corresponds to the level commanded by the master controller.

1.1.3 Technical Issues

Some of the key technical issues that were addressed by this program were the control of ac motor speed and torque, the effects of wheel diameter differences on ac propulsion system operation, and the ac propulsion system electromagnetic interference characteristics.

The following paragraphs discuss these topics.

1.1.3.1 Speed/Torque Control

The rotational speed of an induction motor is a function of the motor design and ac supply frequency.

Depending on the motor design, there will be a minimum supply frequency at which the motor will develop sufficient torque for starting. Once started, the motor will operate at a rotational speed (n) that is below the synchronous speed (n_s) by an amount termed the slip (s). The synchronous speed (n_s) is the speed of the rotating magnetic field established in the air gap between stator and rotor by the three-phase ac supplied to the stator windings.

$$n_s = 120f/p \tag{1-1}$$

where

n_s = synchronous speed
f = frequency
p = number of poles (a function of the stator configuration)

(To generate current in the rotor that causes its rotation through the resulting counter-electromotive force, the rotating magnetic field must "lead" the rotor so the lines of magnetic flux are cut by the current-carrying segments in the rotor.) The slip (s) represents the difference between synchronous speed and rotor speed.

$$s = (n_s - n)/n_s \qquad (1\text{-}2)$$

As shown by the equation for rotor speed (n) obtained by combining equations 1-1 and 1-2,

$$n = 120f(1-s)/p \qquad (1\text{-}3)$$

rotor speed depends on the frequency of the ac voltage, the amount of slip, and the number of poles. The number of poles is fixed by the stator configuration, but frequency can be adjusted and slip can also, by changing the synchronous speed through frequency adjustment.

As slip increases, the motor torque increases up to a maximum (the breakdown point), after which torque decreases. The breakdown torque is a function of the square of the voltage.

By controlling ac frequency and voltage, motor speed and torque can be varied.

The direction of rotation of a 3-phase induction motor such as is used in traction motor applications can be easily reversed by interchanging two of the three stator connections. With thristor circuitry this can be done electronically; no mechanical reverser contactor is necessary. Of importance in regenerative and dynamic braking systems, the induction motor operates as an induction generator when driven at a rotor speed above synchronous speed. Thus, simply reducing the frequency of the ac supply to reduce synchronous speed below rotor speed will initiate electrical braking action.

Figure 1-14 shows motor torque/speed curves for three different supply frequencies. At the lowest frequency (Curve 1), torque is available at standstill; as the vehicle accelerates, the supply frequency must be increased to maintain adequate torque. At an intermediate speed (Curve 2), the slip (S_2) is controlled to produce the required torque or tractive effort. At top speed (n_3 on Curve 3), the torque drops off very rapidly if overspeeding occurs.

Figure 1-15 demonstrates drive-to-brake transition without using a reversing contactor. The solid curve is the motor torque/speed curve in drive with the traction motor turning at speed n. The slip is the synchronous speed, n_{S1}, minus the rotating speed, n. The resulting motor torque is positive (drive mode). For the transition to brake mode the inverter output frequency is reduced to the dashed curve. Motor speed has not changed, so it now exceeds the new synchronous speed n_{S2}; the slip is negative, or the motor is now running supersynchronously, and the torque is now negative (brake mode).

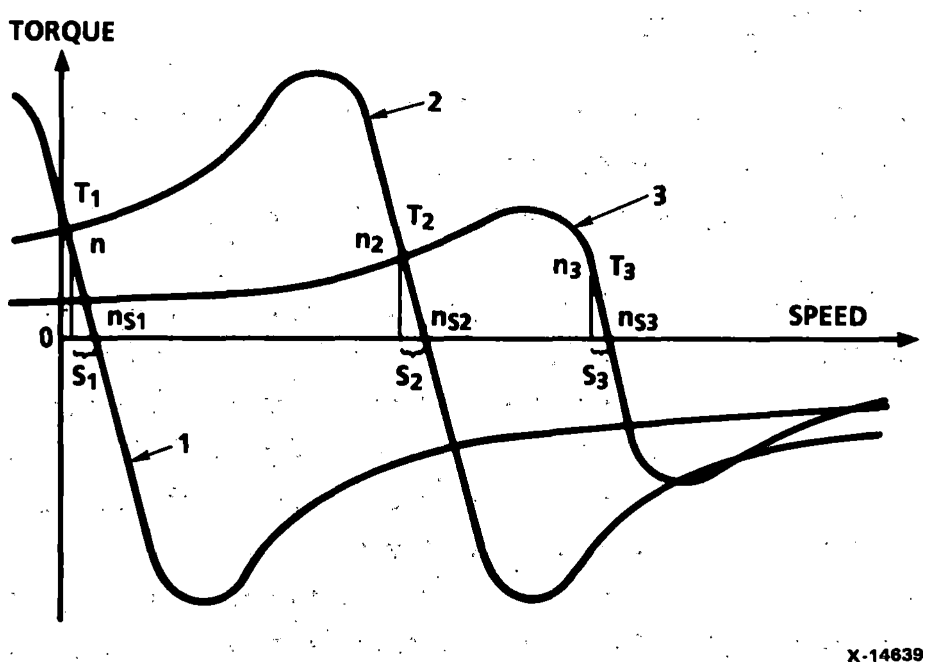


FIGURE 1-14. SQUIRREL-CAGE INDUCTION MOTOR TORQUE/ SPEED CURVES AT THREE FREQUENCIES

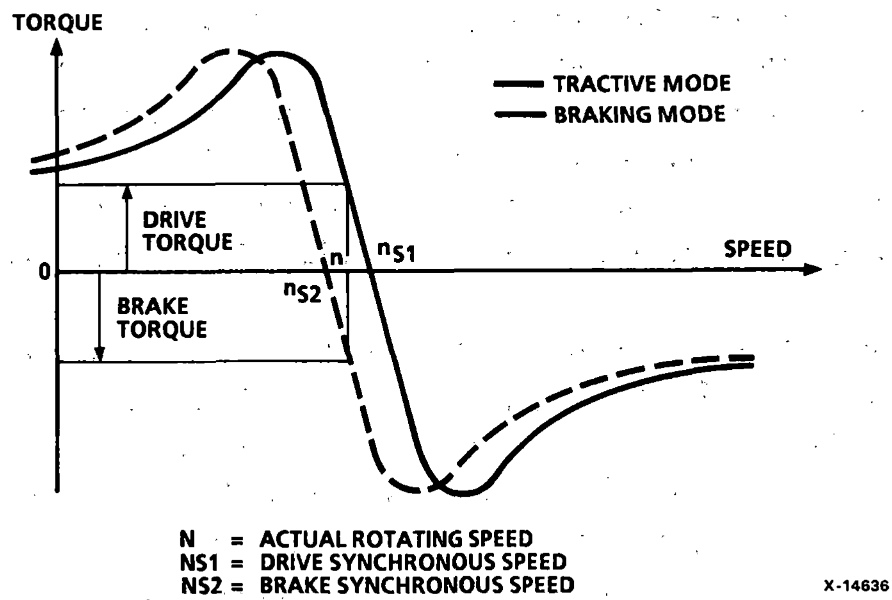


FIGURE 1-15. DRIVE/BRAKE TRANSITION BY FREQUENCY CONTROL

1.1.3.2 Wheel Diameter Variations

When two induction motors driving different axles are electrically connected in parallel and powered from a common inverter, some limits are placed on the allowable wheel diameter difference between axles.

Figure 1-16 shows a typical ac system torque/speed curve at a given inverter frequency. If the inverter powers two parallel motors, which drive two axles having wheels of differing diameters, then the two motor speeds will be different. From the curve, it is clear that the motor driving the axle with the larger diameter (slower) wheels develops the larger torque; the average or effective torque is midway between the two axle torques. The slower motor, producing the greater torque, will demand more current from the inverter than the machine turning faster. In the brake mode, however, the axle with the smaller diameter wheels develops the higher braking torque. Hence, there is a compensating effect which tends to even out motor loading due to wheel diameter differences. For a given wheel diameter difference, the resulting variation in axle torques depends on the motor characteristic as shown in Figure 1-17. The higher the slip characteristic of a motor, the

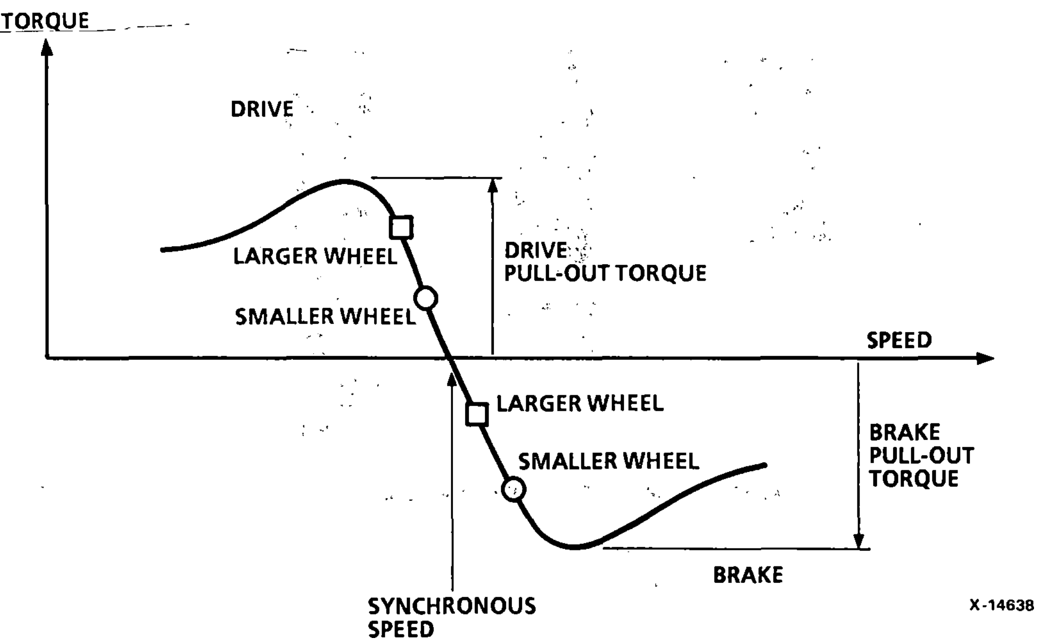
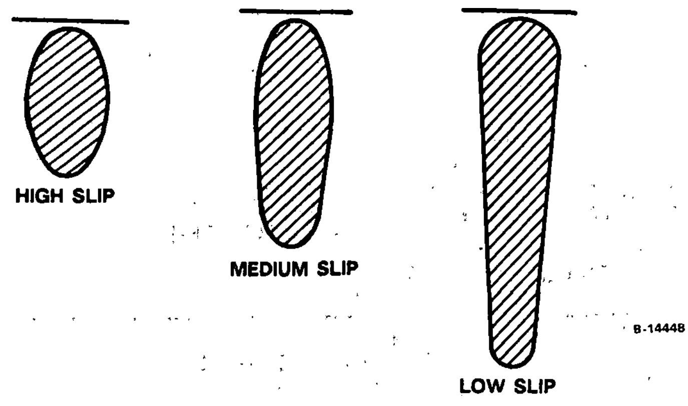


FIGURE 1-16. EFFECT OF DIFFERENT WHEEL DIAMETERS ON PARALLEL-FED MOTORS

lower the variation in axle torque, but the lower the motor efficiency. The motor slip characteristic can be tailored to suit the application by selecting the appropriate rotor bar cross-section, as shown. The NYCTA requirement for the STARS program was to allow a 3/4-in. difference in diameter within a truck and anything up to new/fully worn variation on a car. Hence, separate inverters were selected for each truck with a medium slip motor characteristic to allow the 3/4-in. variation.

1.1.3.3 Electromagnetic Interference (EMI)

Throughout the ac propulsion system program design phase, particular attention was devoted to the subject of ac propulsion system-generated EMI and its possible effects, especially on track circuit signalling systems. The ac propulsion system design incorporates measures to minimize EMI. Extensive analytical studies, laboratory tests, and field tests were performed to establish EMI requirements and verify compatibility with both power frequency and audio frequency signalling circuits.



ROTOR BAR CROSS SECTION DETERMINES SLIP

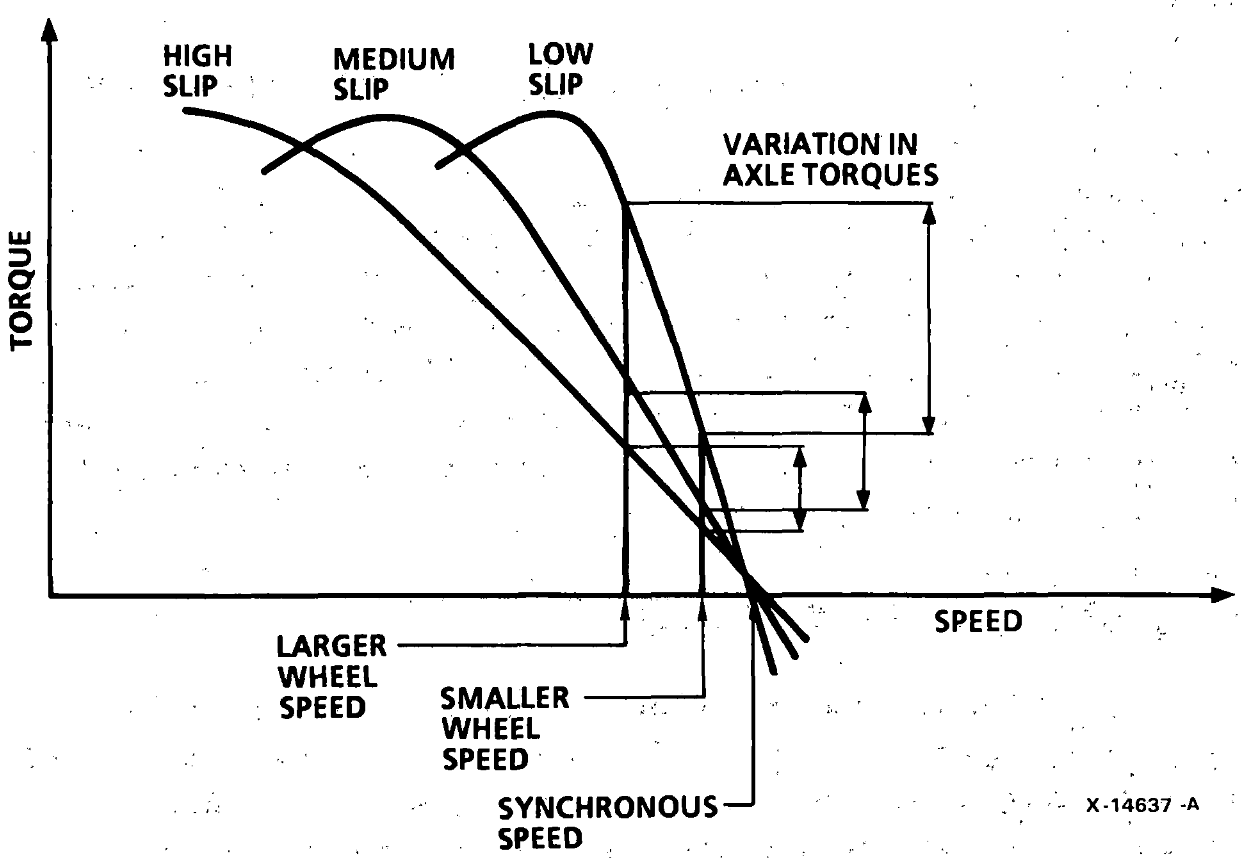


FIGURE 1-17. VARIATION IN AXLE TORQUE FOR DIFFERENT WHEEL DIAMETERS VS MOTOR SLIP CHARACTERISTIC

1.1.3.3.1 Signalling Circuit EMI Susceptibility Considerations

Some U.S. electric rail transit systems, including NYCTA, use ac power-frequency track signalling systems for train car control and switching. The various NYCTA track signalling circuits usually use signals of 60 or 25 Hz to operate electromechanical dual-element vane relays or similar items. Power for the 60-Hz circuits is from 110-vac power lines. The 25-Hz power is from motor-generator sets. In the single-rail system, one running rail is used for traction power return and the other is a signal rail. In the two-rail system, both rails are power return and the signal is impressed between them. Track transformers are used to couple the signal to the vane relays that activate the signals or track switching systems.

As described in DOT/UMTA Report UMTA-MA-06-0153-85-12, a typical dual-element vane relay has two separate magnetic circuits: one energized by a 110-vac "local" winding, and the other by a low-voltage "track" winding (Figure 1-18). One winding produces an ac magnetic field that induces an ac eddy current in a moveable metal vane that pivots up and down about a horizontal axis and carries the two separate moveable contacts. The other winding produces another ac magnetic field that reacts with the established eddy current in the vane. The resulting force lifts the vane, thus opening the "back" contacts and closing the "front" contacts of the relay. When no train is present in the track circuit (between insulated joints of the signal rail), the track winding is energized, and the relay is "picked up"--the back contacts are open and the front contacts are closed. When a train is present in the track circuit, the circuit carrying signal current to the track winding is shorted by the train, causing the relay to be deenergized or "dropped," thus opening the front contacts and closing the back contacts.

The relay is sensitive to the difference in phase of local and track currents. Maximum lifting force is generated on the vane when the induced current in the vane and the magnetic field with which it reacts are exactly in phase. There is an inverse-cosine relationship between the relative phase variation of signals applied to the local and track windings and the amplitude of track signal required to pick up the relay.

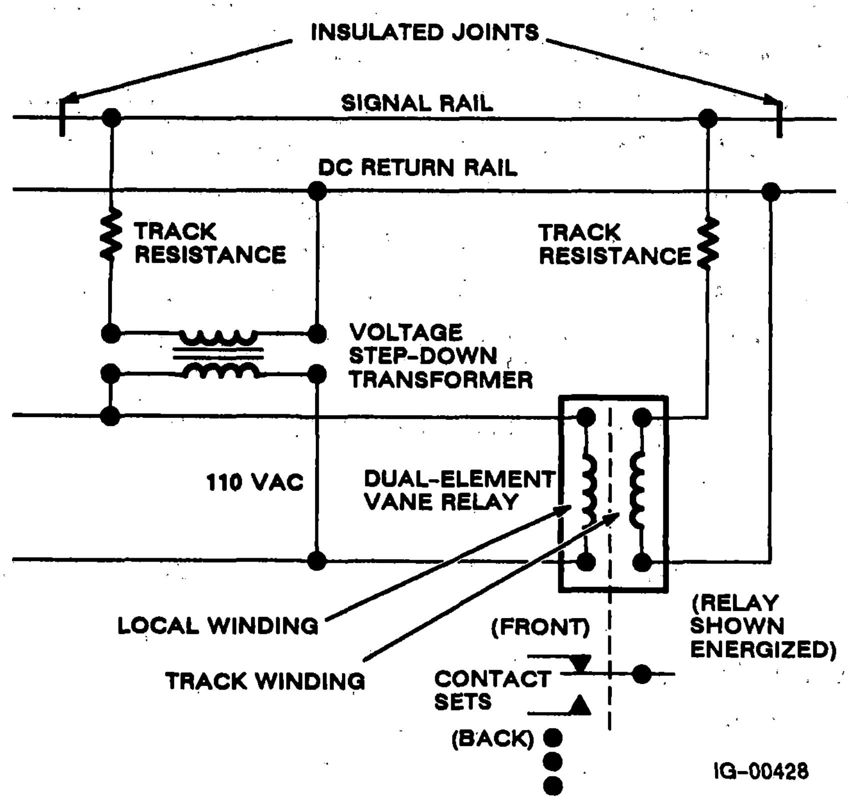


FIGURE 1-18. TYPICAL SINGLE-RAIL POWER-FREQUENCY TRACK CIRCUIT SHOWING VANE RELAY IN ENERGIZED POSITION, WHICH INDICATES NO TRAIN ON THE CORRESPONDING SECTION OF TRACK

The vane relay responds to track circuit current and frequency, as shown by Figure 1-19. Typically, a relay operates in four distinct states that reflect the vane positions during "pickup":

(a) Off back stop

(b) Open back contacts

(c) Close front contacts

(d) Full pickup (on front stop)

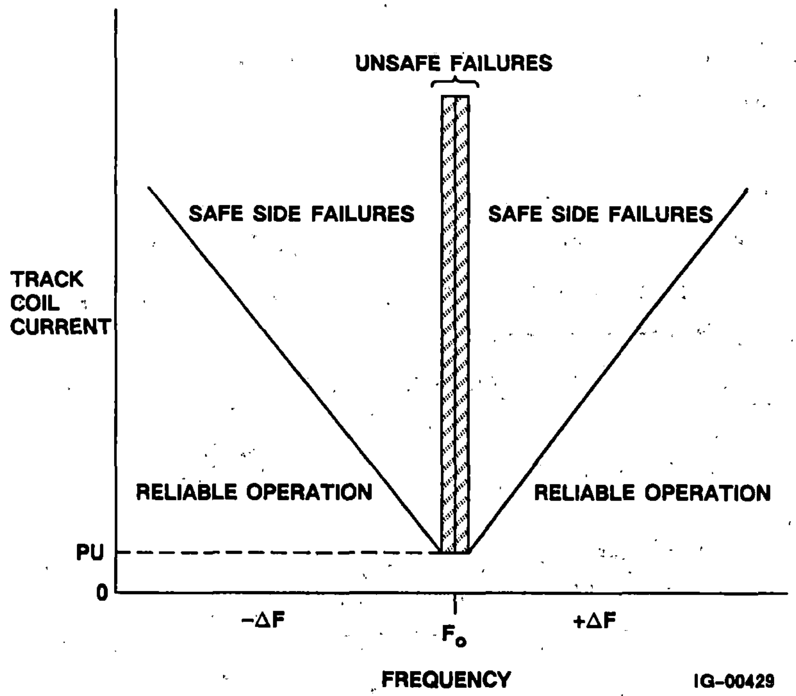


FIGURE 1-19. SUSCEPTIBILITY OF VANE RELAY (FROM DOT/UMTA REPORT UMTA-MA-06-0153-85-12)

and four distinct states that reflect the vane positions during "drop away":

(a) Off front stop

(b) Open front contacts

(c) Close back contacts

(d) On back stop (full drop away)

In either pickup or drop away, the vane deflection that occurs between back or front contacts closure and vane rest against the respective stop maintains circuit continuity through the contacts over a certain signal pass band. Relay motion is possible in response to signal variations without causing contact separation.

1.1.3.3.2 <u>EMI Studies and Testing During Phase I</u>

An extensive preliminary signalling compatibility study was conducted early in Phase I by AiResearch and reported in AiResearch Document 83-20300.

The study included laboratory testing to examine the possible effects of inductively coupled emissions and conducted emissions on track circuits.

These extensive Phase I studies were conducted as part of a cooperative program between AiResearch/Stromberg and the DOT Transportation System Center (TSC). Additional studies were provided by the working group (TWG), a DOT/UMTA-sponsored committee composed of senior engineers from propulsion system suppliers, representatives from the Government and universities, and consultants. The total effort consisted of:

(a) Characterization and cataloging of signalling equipment susceptibility (performed by TSC/TWG)

(b) Characterization of steel rail electrical parameters as a function of dc current (TSC/TWG)

(c) Derivation of train-to-signalling transfer functions (AiResearch/TSC/TWG)

(d) Prediction of drive emissions (AiResearch/Stromberg)

(e) Measurement of drive emissions as part of the Phase I laboratory system test of one prototype truck drive (AiResearch/Stromberg)

(f) Design for compatibility (AiResearch/Stromberg)

The study was further defined in Phase II and emission limits established for continued testing.

1.1.3.3.3 DOT/UMTA Track Circuits

Also, during Phase I, a comprehensive laboratory/field test program was conducted by DOT TSC and directed toward the NYCTA-specific signalling systems. The results of this work are presented in DOT/UMTA Final Report UMTA-MA-06-0153-85-12 (DOT-TSC-UMTA-85-26) by Michael D. West and F. Ross Holmstrom.

As an extension of these efforts, additional tests (discussed in Sections 3 and 4) were performed during Phase II using the actual ac-equipped R-44 cars.

1.1.3.3.4 Design Techniques for Controlling EMI at Audio Frequencies

Both the line chopper and the inverter are potential sources of EMI that can affect signalling systems. The 3-phase inverter is the greater potential source of EMI at power frequencies. It is believed at this time (although on the basis of incomplete analysis) that the line chopper will be the greater source of EMI at audio frequencies. As noted later in this report, electromagnetic compatibility (EMC) with power-frequency signalling systems is largely ensured by the fact that the 3-phase inverter is constantly sweeping in frequency and does not stay at a given power signalling frequency long enough to affect signalling operation.

The following analysis indicates that EMC with audio-frequency signalling systems can be ensured as well, since the inverter-controlled ac propulsion system design can be tailored to suppress EMI within specific frequency bands, thus avoiding interference to known audio frequency signalling system operational frequencies.

Figure 1-20 shows that the current flowing through the input filter is that of the line chopper. (NOTE: At low inverter frequencies, the line chopper current is amplitude-modulated at six times the motor frequency.) At higher inverter frequencies, the line current is harmonically related to the line chopper frequency by a 1/n relationship. Operating the line chopper at a constant frequency of 360 Hz produces a line spectrum as shown in Figure 1-21.

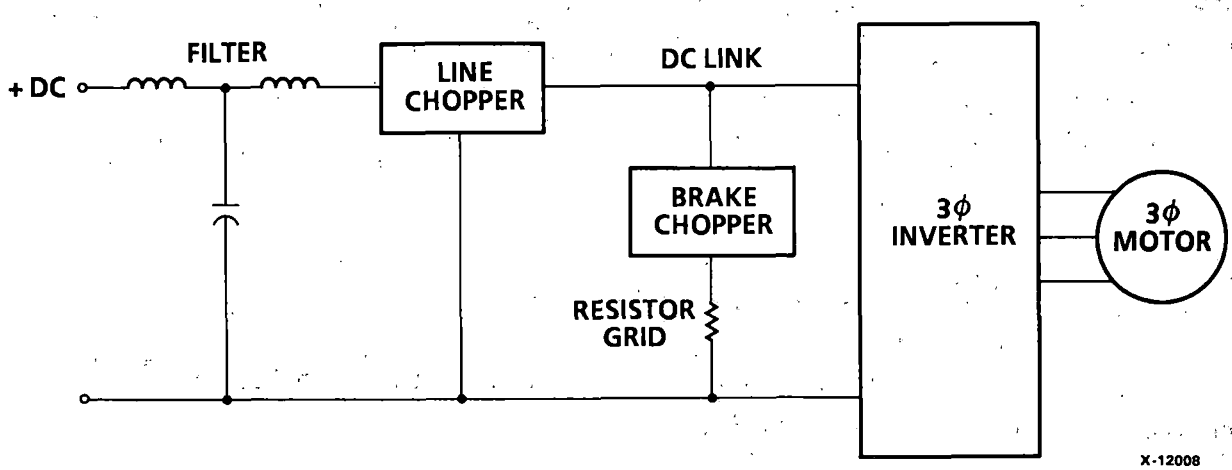


FIGURE 1-20. SYSTEM BLOCK DIAGRAM

- NORMALLY OPERATE AT 360 HZ
- PRODUCES LINE SPECTRA 360 HZ APART
- PROVIDES "WINDOWS" FOR SIGNALLING FREQUENCIES

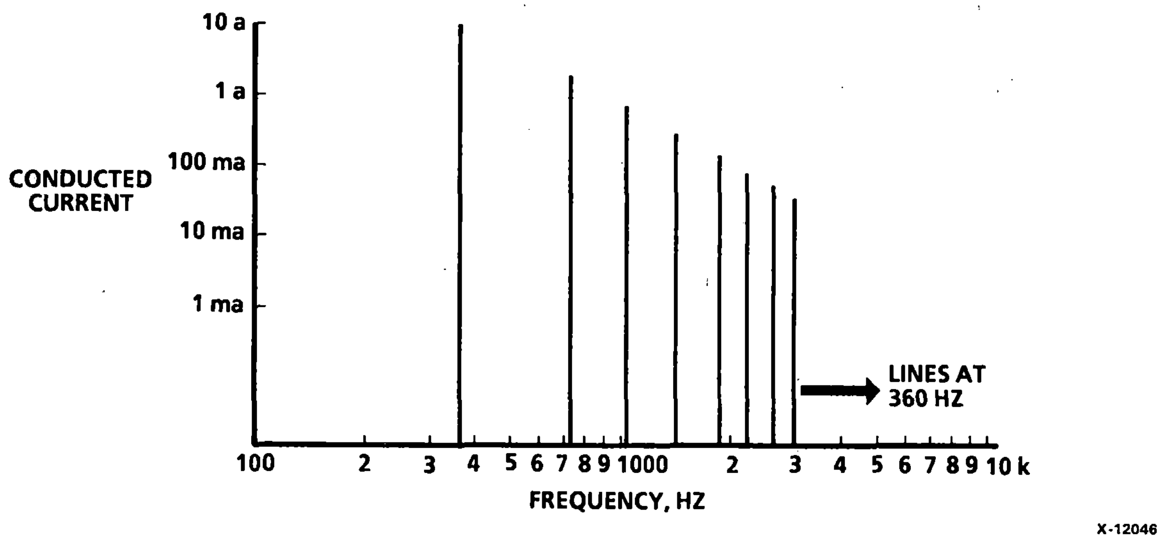


FIGURE 1-21. CONSTANT-FREQUENCY OPERATION OF LINE CHOPPER

The frequency selected is 360 Hz because, being the 6th multiple of 60 Hz, it exists in such magnitude in the substation supply that track circuits must always be designed to have a high immunity at that frequency and its harmonics.

By running the chopper at a constant frequency of 360 Hz, 360-Hz-wide "windows" are available for selection of track circuit frequencies. With two inverters per car it is possible to interleave (fire alternately) the two, producing what appears to be a 720-Hz line chopper.

Figure 1-22 shows harmonic current spectra for different chopper arrangements. A single chopper running at frequency F produces a line spectrum that diminishes as 1/F as shown. If two choppers are synchronized, the resulting line spectra are twice the magnitude of a single chopper. If the two choppers are fired alternately, odd harmonics are eliminated, and even harmonic magnitudes are equal to those of the previous case, i.e., "window" width has been increased to 720 Hz.

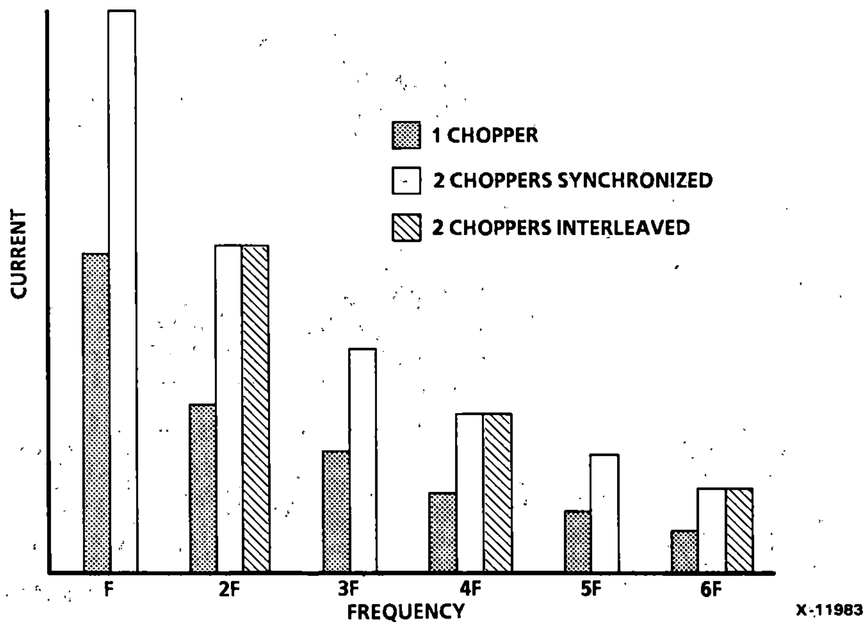


FIGURE 1-22. HARMONIC CURRENT/FREQUENCY (SINGLE, SYNCHRONIZED, AND INTERLEAVED CHOPPERS)

1.1.4 Engineering Model Tests at Helsinki

During the laboratory tests in Phase I, an engineering test model consisting of key system elements was operated and tested under specified environmental and load conditions, in accordance with the laboratory system test procedures, to verify acceptable characteristics in accordance with the DOT/UMTA specifications (Attachment B to Contract DTUM60-82-C-71144).* The tests were performed at Stromberg facilities in Helsinki.

The engineering test model equipment consisted of one complete prototype truck drive excluding gear units and couplings, together with power supply, load equipment for traction motors, and line receptivity simulator (Figure 1-23).

*Kumataka, R., "STARS AC Propulsion System Laboratory System Test Procedure, "AiResearch Document 83-20029, May 31, 1983.

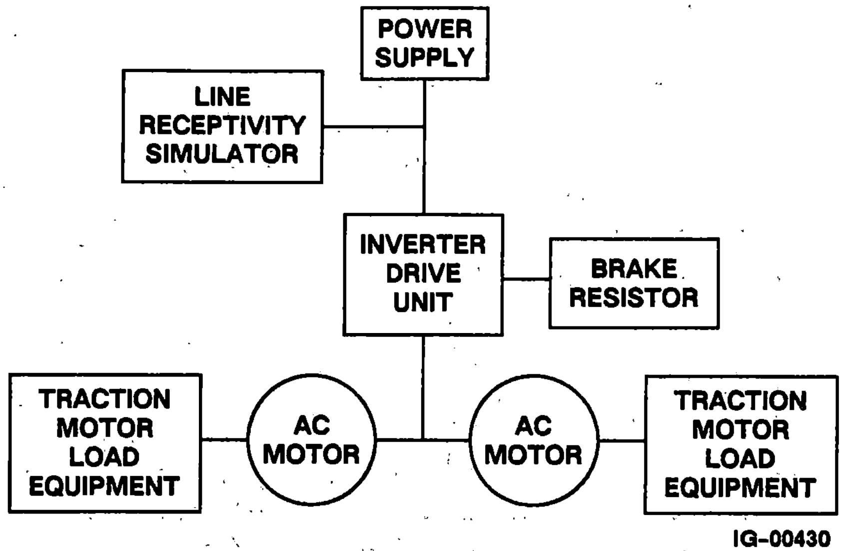


FIGURE 1-23. BLOCK DIAGRAM OF SYSTEM TEST CONFIGURATION FOR ONE TRUCK DRIVE

The tests were conducted to verify that the system would meet the specified performance requirements and to evaluate details of the equipment configuration, thereby providing proof of concept and evidence of producibility of the follow-on prototype hardware. Tables 1-2 and 1-3 list the test equipment. Test results included data on:

(a) Performance characteristics during acceleration and braking

(b) Energy efficiency in all operating modes, including regeneration

(c) Compatibility with transit EMI environments

(d) Tolerance to wheel mismatch between axes

The test duration was approximately two months, and at various times the testing was observed by DOT and APTA personnel. Prototype configuration hardware was used for the motor, inverter unit, line filter, blower motor, and controls. The brake resistor enclosure was not of prototype quality; however, the enclosure and resistor elements were arranged in the final configuration to ensure validity of the thermal and EMI test data. The line control equipment was not of prototype configuration, but the proper switch was used.

TABLE 1-2

SYSTEM TEST AC PROPULSION EQUIPMENT LIST

Equipment	Number of Units	Description
Inverter drive unit	1	Complete dc-to-ac inverter including line chopper and brake chopper (in enclosure)
Line filter	1	Complete unit including line reactor, filter reactor, filter capacitors, and damping resistors
Propulsion control unit	1	Control rack including one truck control unit, one car control unit, and necessary power supplies, relays
Traction motors	2	Two totally enclosed fan-cooled ac traction motors
Brake resistor	1	Forced-air-cooled resistor in enclosure
Plenum	1	Inverter enclosure to brake resistor plenum
Blower	1	650-vdc motor-driven blower for inverter and brake resistor cooling
MCB and contactors	-	Main dc circuit breaker, dc line contactors, dead-rail detector

The system test configuration emulated a correct relationship to the rails to provide EMI data validity.

During the entire test period, the only failure recorded was a nonproduction type of transistor used in the dead-rail detector voltage regulator.

TABLE 1-3

SYSTEM TEST EQUIPMENT

Equipment	Number of Units	Description
Power supply	1	Dc power supply consisting of a network-fed 800-kw squirrel-cage motor, a synchrongenerator, and a rectifier bridge. Adjustable output voltage: 700 vdc (1080 adc max.).
Load equipment	2	Dual load equipment consisting of two squirrel-cage motors (315 kw each) and two frequency converters capable of bidirectional energy flow.
Line receptivity simulator	1	External load consisting of two dc choppers and two resistors in parallel with power capability of 605 adc at 450 vdc line voltage.

The failure caused the detector to revert to a safe mode in which the line contactors opened.

Significant test results are summarized in Tables 1-4 through 1-6. Figures 1-24 through 1-27 are typical of the recorded test data. Complete details of the Phase Ib engineering model tests are contained in the CDR report.

1.2 LIST OF PHASE I REPORTS

Results of the program activities performed during Phase I, design and analysis, have been documented in reports previously transmitted to DOT/UMTA. The information provided in these documents includes details of preliminary design investigations performed to identify hardware functional requirements and specifications, design tradeoffs and evaluation of alternatives on the component and system levels, cost/benefit tradeoff analyses, and engineering model tests performed to establish the baseline ac propulsion system design. Table 1-7 provides a list of documents associated with the design and analysis phase of the program.

TABLE 1-4

PERFORMANCE: ACCELERATION

(Car Loading AW3 for ac Cars)

Specification Requirement	DOT Spec. Para. No.	Test Result	Test No.
Initial acceleration of 2.5 mphps	2.2.2	2.6 mphps*	5.1.5A
Maximum speed of 70 mph in no more than 90 sec**	2.2.3	70 mph in 80 sec	5.1.5A
Maximum speed of 70 mph, 80 mph goal**	2.2.3	80 mph	5.1.5A
Acceleration rate to match existing R-44 cars	2.2.2	Demonstrated comparable calculated and measured torque vs speed curves	5.1.8A 5.1.10A
Torque at zero speed	2.2.2	Demonstrated during locked rotor test	5.8.6

*The initial acceleration rate can be obtained directly from the torque-vs-speed curve.

**Maximum speed requirement of 70 mph was deleted in Specification Modification 7--80 mph remained as goal.

TABLE 1-5

PERFORMANCE: BRAKING

(Car Loading AW3 for ac Cars)

Specification Requirement	DOT Spec. Para. No.	Test Result	Test No.
Maximum deceleration of 3.0 mphps (below 50 mph)	2.2.5	3.0 mphps	5.2.7A
Electrical braking effective from 80 to 0 mph	2.2.5	Demonstrated during system witness test	Demo
Provision of dynamic brake signal for the friction brakes	2.2.5	Demonstrated by DB-signal recordings	All 5.2 tests
Brake blending	2.2.5	Demonstrated full brake performance at 100%, partial, and 0% (regen cut-out) line receptivities	5.2.7A 5.2.4 5.2.10

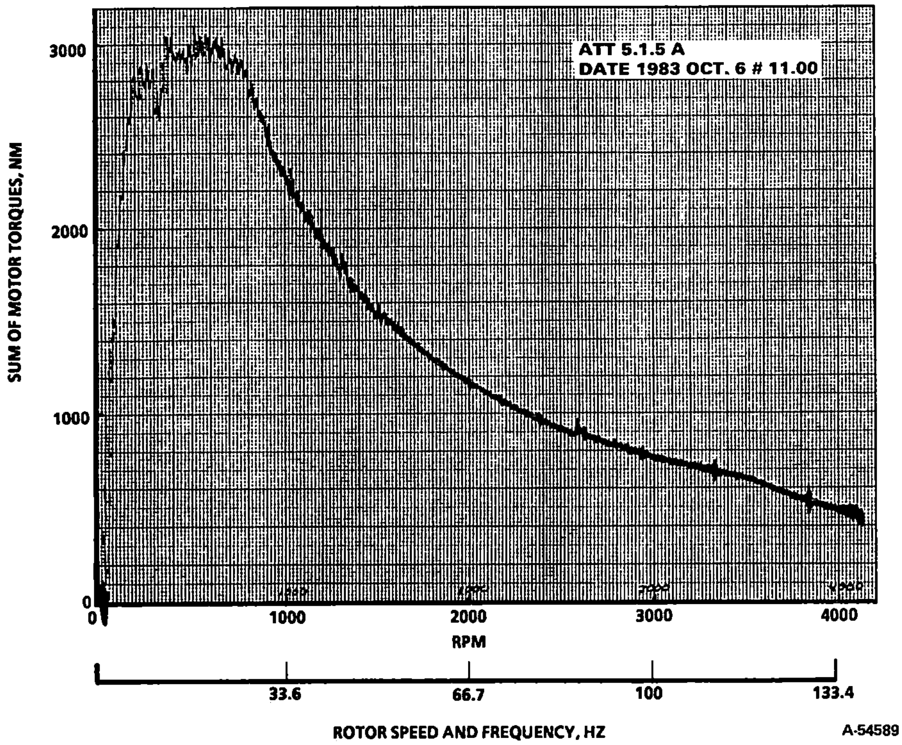
TABLE 1-6

TEMPERATURE RISE AT SYSTEM MEASUREMENT POINTS
FOR DIFFERENT WHEEL DIAMETER DIFFERENCES
AND LINE RECEPTIVITY

Test Condition*	Measurement Point							
	Line Inductor (Hot Spot)	Inverter Outlet Air	Commutation Reactor of the Line Chopper	Inverter Free Wheel Diode V1	Active Snubber Resistor	Brake Resistor (Hot Coil)	TR Motor M1 D-End Stator Winding	TR Motor M2 D-End Stator Winding
Nominal airflow, zero wheel diameter difference, 100% line receptivity (Test 5.3.4)	104°C	8°C	10°C	14°C	40°C	35°C	115°C	114°C
Nominal airflow, 3/4 in. wheel diameter difference, 100% line receptivity (Test 5.5.2)	105°C	7°C	11°C	15°C	39°C	35°C	121°C	122°C
Reduced airflow, zero wheel diameter difference, 0% line receptivity (Test 5.8.12)	**	17°C	15°C	23°C	60°C	270°C	**	**

*All tests at AW3, nominal line.

**Not run to final value. See test 5.3.4.



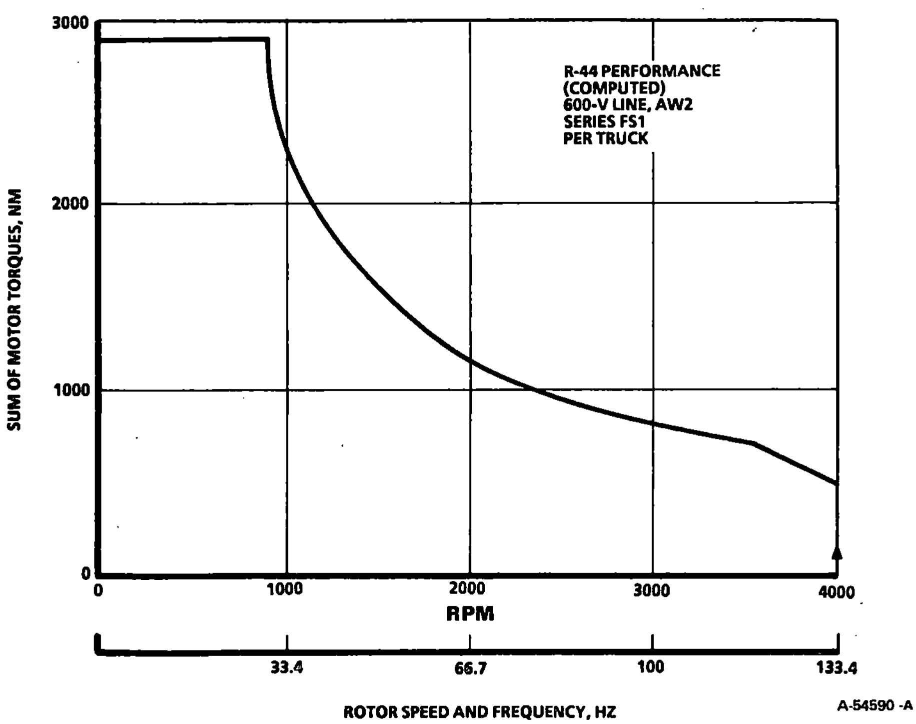


FIGURE 1-24. INITIAL ACCELERATION TO MATCH DC R-44 CARS, SERIES FS1 (TEST 5.1.5A)

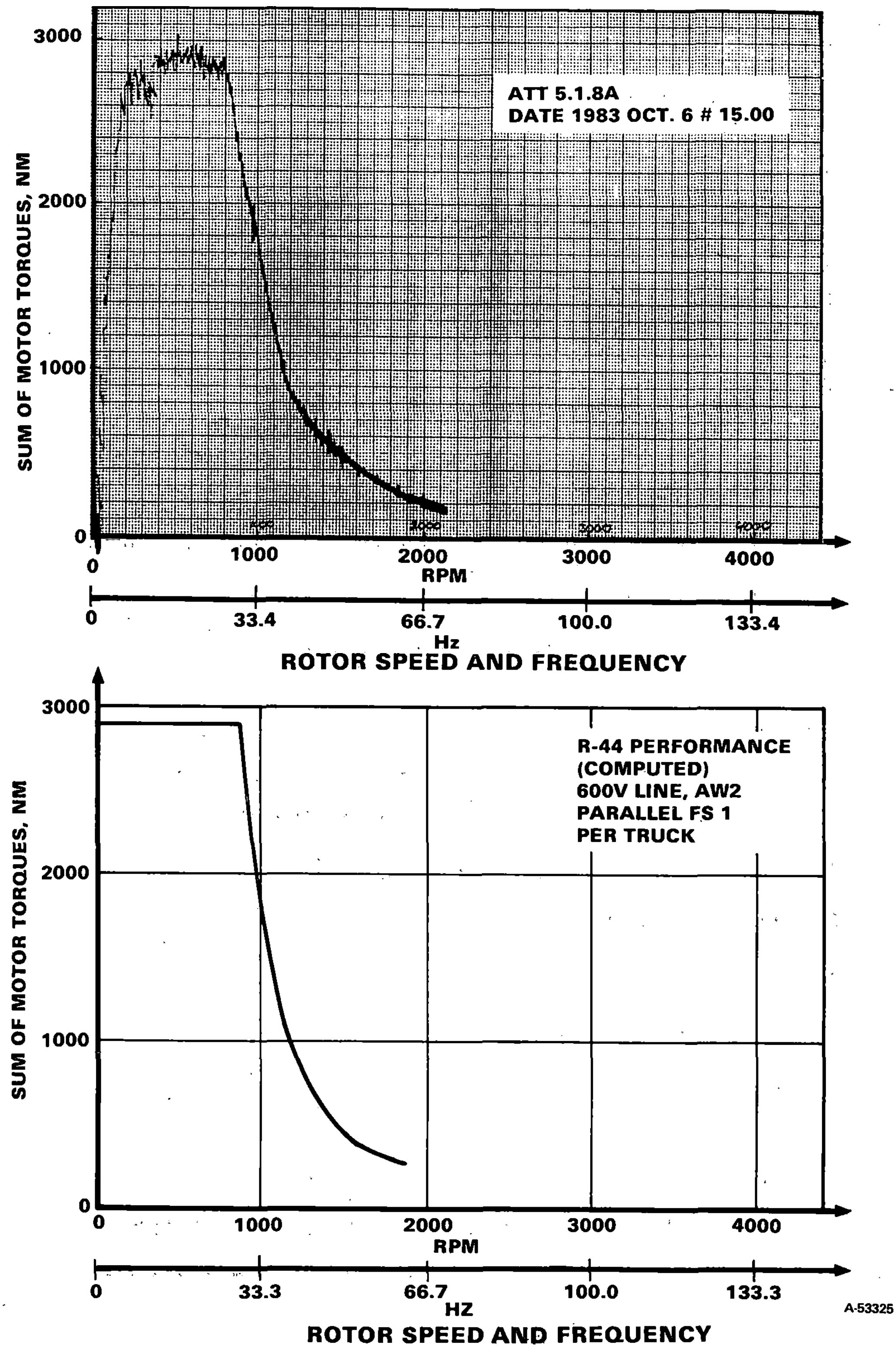


FIGURE 1-25. ACCELERATION RATE TO MATCH DC R-44 CARS, PARALLEL FS1 (TEST 5.1.8A)

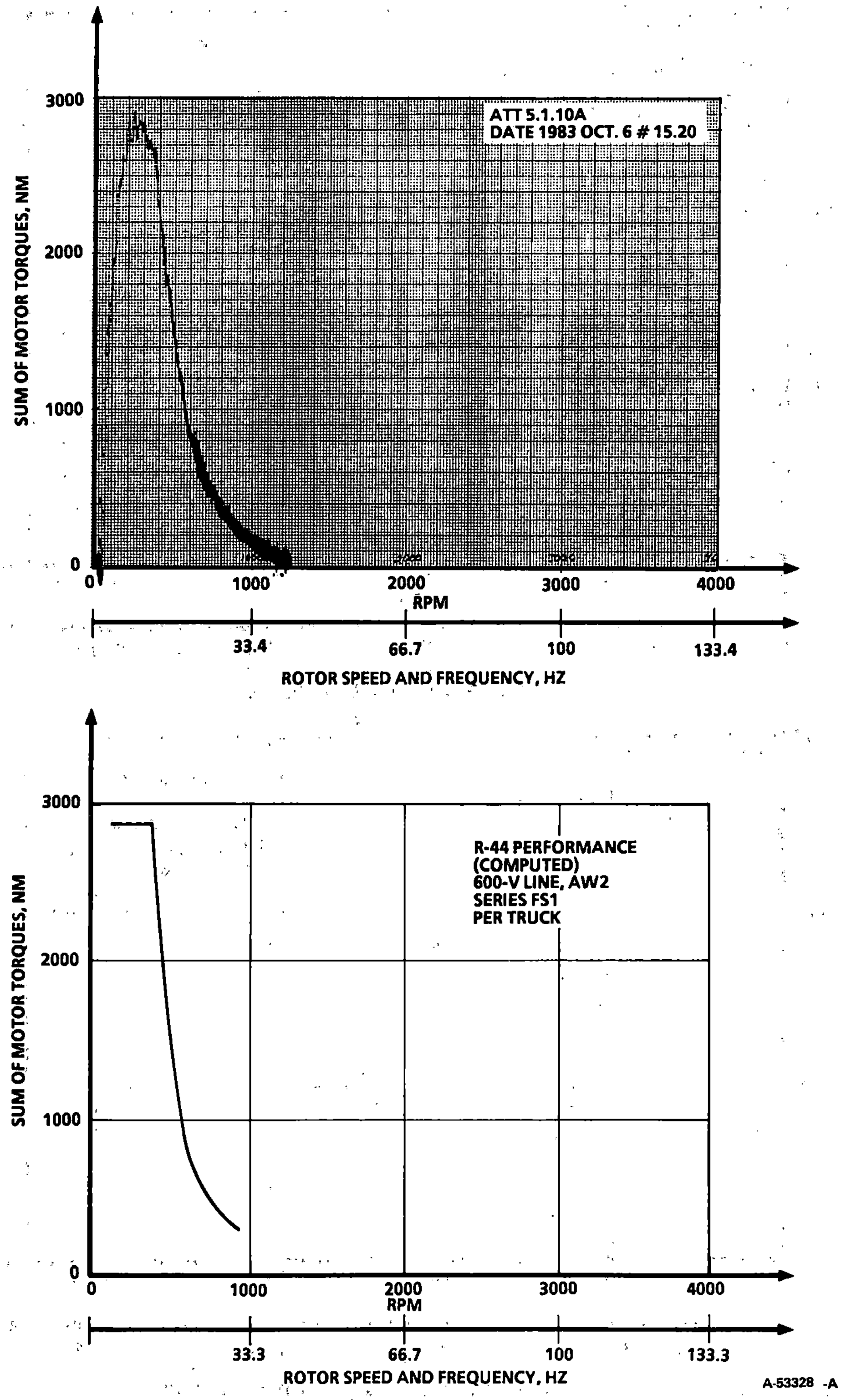


FIGURE 1-26. ACCELERATION RATE TO MATCH DC R-44 CARS, SERIES FS1 (TEST 5.1.10A)

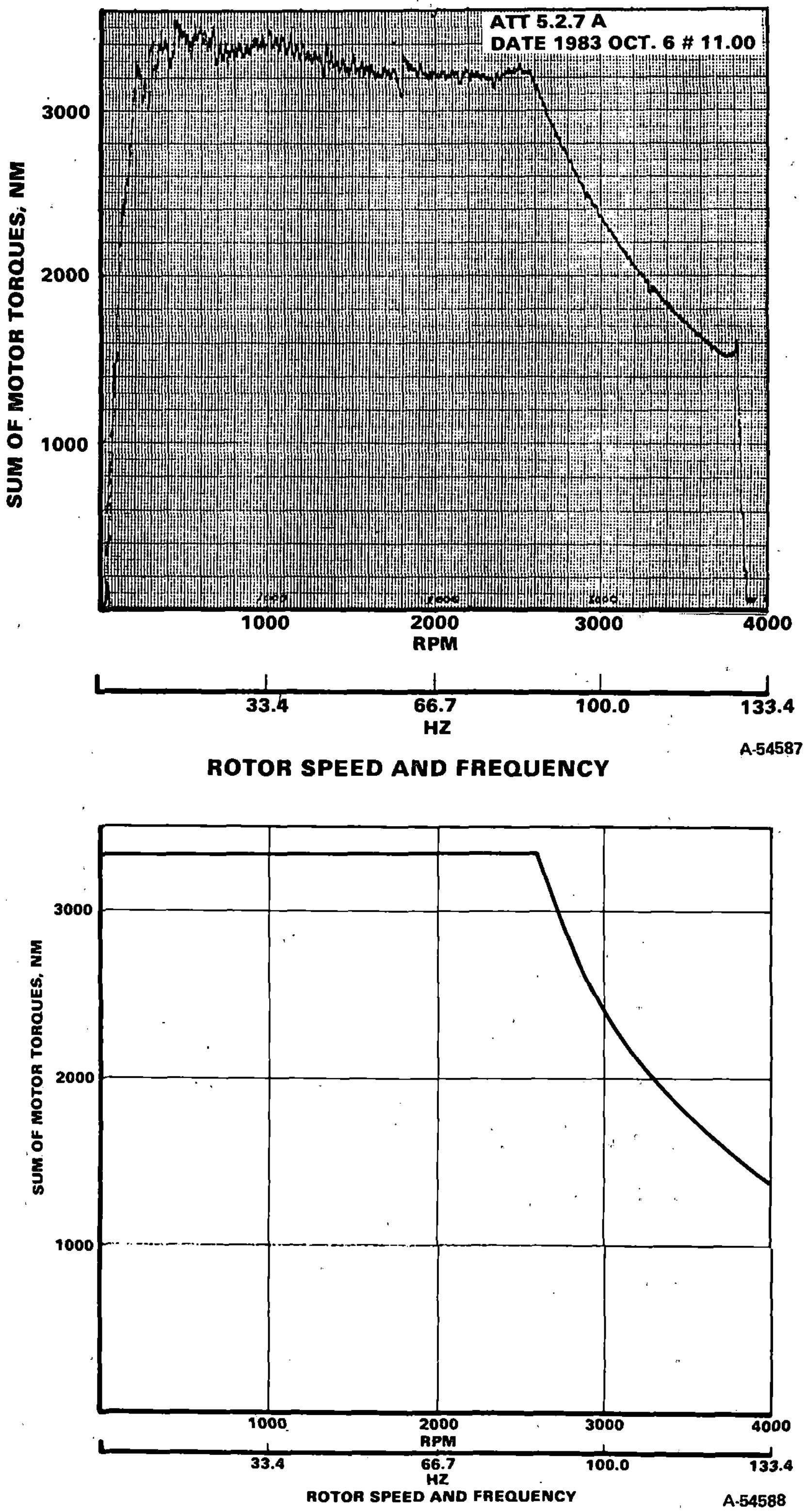


FIGURE 1-27. MAXIMUM DECELERATION TO MATCH DC R-44 CARS (TEST 5.2.7A)

TABLE 1-7

PHASE I PROGRAM DOCUMENTATION

AiResearch Document No.	Item Description	Date
83-20037	Quarterly Program Review	June 7, 1983
82-19066, Rev. A	Configuration Management Plan	Jan. 14, 1983
82-18936, Rev. A	Interface Management Plan	Jan. 14, 1983
83-20296	Manufacturing Plan	Oct. 15, 1983
82-19077	Preliminary Design Data	June 30, 1982
82-18926, Rev. A	Reliability Plan	Jan. 14, 1983
82-19069, Rev. A	Maintenance Plan	Jan. 14, 1983
82-18926, Rev. A	System Safety Plan	Jan. 14, 1983
83-20297, Vol I	Final Design Data (CDR) and Engineering Analysis	Jan. 10, 1984
83-20297, Vol II	Reliability Analysis	Nov. 19, 1983
83-20299	Energy Study	Nov. 15, 1983
83-20300	EMI Study (Preliminary)	Dec. 15, 1983
83-20301	Maintainability Study (Preliminary)	Oct. 15, 1983
83-20302	System Safety Study (Preliminary)	Nov. 15, 1983
83-20229	Overall Vehicle Test Plan	Oct. 15, 1983
83-20303	Recommended Spare Parts List	Oct. 15, 1983
83-20304	Special Test and Support Equipment List	Oct. 15, 1983
83-20230	Quality Assurance Program Plan	Oct. 15, 1983
82-19068, Rev. A	Cost and Economic Analysis Plan	Jan. 14, 1983
83-20305	Life-Cycle Cost Analysis	Nov. 15, 1983
82-18935	Specification for the STARS ac Propulsion System	Apr. 22, 1983
83-20029	Laboratory System Test Procedure	May 31, 1983

2. PHASE II HARDWARE FABRICATION, CAR INSTALLATION, AND PERFORMANCE PROGRAM DEFINITION

The Phase II effort of the STARS ac propulsion system program was awarded to AiResearch following a successful Phase I program consisting of a demonstration of ac propulsion capability coupled with the required design and equipment analysis.

Phase II was defined as an implementation of Phase I ac propulsion equipment in an operational transit car (R-44) and a subsequent comprehensive test program to demonstrate performance characteristics suitable for existing U.S. transit properties. This Phase II effort addressed the following STARS program goals:

(a) Introduction of an ac propulsion system on an operating transit vehicle

(b) Adaptation of ac propulsion to U.S. transit practices

(c) Improved reliability

(d) Reduced maintenance

(e) Superior performance

(f) Energy savings

(g) Low life-cycle costs

The Phase II program was divided into two parts:

(a) Phase IIa, which was to include fabrication of two carsets (plus spares) of ac propulsion equipment, component and system qualification and acceptance tests, equipment installation in the two test vehicles, and system and car operational test verification.

(b) Phase IIb, which was to include a comprehensive vehicle test program and, if successful, a revenue service demonstration.

The original STARS statement of work required submittal of an overall vehicle test plan (OVTP), which was completed in Phase I and submitted to DOT/UMTA.* The tests specified in the OVTP were based on the following documents:

(a) Specification For Inverter Controlled Induction Motor Propulsion System Operational Demonstration Cars, DTUM60-82-C-71144, Attachment B

(b) General Vehicle Test Plan (GVTP) for Urban Rail Transit Cars, Report UMTA-MA-06-0025-75-14

(c) Recommended Practice, Rail Transit Intra-System Electromagnetic Compatibility, Vols. I and II

(d) MIL-STD-461A

The tests listed in the OVTP were categorized according to program phase and test site, with the Phase II tests scheduled to be performed at the DOT Pueblo TTC facility. As discussed subsequently, the loss of the Pueblo facility availability and subsequent agreement among DOT, AiResearch, and the NYCTA resulted in a test program redefinition within the constraints and requirements of the NYCTA and their test facility.

The revised test program plan was presented to all parties, and procedures were created outlining a comprehensive test plan for R-44 ac and dc testing at the NYCTA Sea Beach facility. The change of test site location presented a considerable test program hardship, but also provided the benefit of actual transit property exposure.

2.1 PHASE IIa, COMPONENT FABRICATION AND TEST, EQUIPMENT INSTALLATION, AND INITIAL SYSTEM TESTS

The baseline ac propulsion system design established in Phase I provided the foundation for the fabrication of two carsets of prototype ac propulsion

*Inverter-Controlled ac Induction Motor Propulsion System Overall Vehicle Test Plan, AiResearch Document 83-20229.

equipment and one set of spares in Phase IIa. The system components and subassemblies were tested in the factory to verify suitability for installation before installation and initial system tests. The equipment installation and the initial system tests were performed at the facilities of Morrison-Knudsen Company in Hornell, New York.

2.2 PHASE IIb, PERFORMANCE TESTING AT NYCTA

Phase IIb involved ac propulsion system testing with two carsets ("A" and "B" cars) of prototype ac equipment installed in NYCTA R-44 cars, and comparison testing of an A-B pair of dc cars. Originally to be conducted on the DOT test track in Pueblo, Colorado, the program was redirected to permit testing on the NYCTA railroad in New York.

2.2.1 Program Redirection (Pueblo TTC to NYCTA)

The ac propulsion system program was originally proposed as a 46-month effort to culminate in simulated revenue service testing at the DOT Transportation Test Center (TTC) in Pueblo, Colorado. During the course of the program there were some program modifications that affected both the schedule and scope of work. Having particular significance to the results of this program were the unexpected loss of availability of the TTC Pueblo site and the decision to use upgraded R-44 cars as the demonstration vehicles.

The ac propulsion system originally was to be installed in two standard R-44 cars and subjected to simulated revenue service tests at the TTC controlled test track in Pueblo. Later, during the early part of Phase II, DOT/UMTA accepted an offer from the NYCTA to allow testing on their property in New York using four upgraded R-44 cars to be provided by the NYCTA. Two upgraded R-44 dc cars were retrofitted with the STARS ac equipment and two with upgraded dc equipment at the facilities of the Morrison-Knudsen Company in Hornell, New York. Preliminary car performance and propulsion circuit testing, trainlining, wayside emissions tests, and track circuit tests were conducted on all four cars in Hornell.

2.2.2 NYCTA Test Program

The program redirection resulted in a test program in which two ac cars (A, B pair) were tested together with two dc cars (A, B pair) at the NYCTA Sea Beach facility in Coney Island.

2.2.3 NYCTA Program Impact on Hardware

The change of test vehicles and test site had two important impacts on the program: (1) it provided an opportunity for more realistic testing in actual transit service, and (2) it resulted in a significantly more stringent and comprehensive development test program.

The R-44 upgrade modifications were designed to improve the reliability of the dc cars and therefore minimize nonpropulsion failures during the Sea Beach test program. One of the more significant changes involved the friction brakes.

In the modified test cars, the existing friction brake control system, P-wire control, and the console were replaced by a single-handle controller and SMEE friction brake control. The function of the P-signal was taken over by a variable-pressure straight air line. The SMEE friction brake required three additional train lines for the brake application and release valves. The single-handle controller has three power positions: (1) full resistance, (2) series, and (3) parallel (it has no field-weakening position). In addition, it has a charging position and an emergency braking position. Braking is continuously variable from snow brake through maximum service. The variable brake command is translated through a WABCO actuator into an electrical command for the electrical brakes. An additional electrical circuit holds off the friction brake by supplying voltage to a lockout valve if electrical braking is sufficient. The upgraded cars did not implement blended braking or spin/slide protection.

Other modifications included the addition of a "flash motor" circuit and a "motion-no motion" circuit, the replacement of the Walton electrical coupler by different intercar (A/B) couple electrical connectors, and the replacement of the 1600-Hz lighting inverter by individual inverter ballasts operating from 36.5 vdc.

The flash motor circuit makes it possible to check the propulsion system current drain with the aid of the cab amp meter. Depressing a pushbutton on the controller will allow short-duration application of full resistor and series position current to the motors with the brakes applied. The currents are 150 amp in the first (full resistor) position and 350 to 400 amp in the second (series) position.

All of these modifications had impact on the ac propulsion system program, requiring changes in system interfacing and controls circuitry, as well as revisions to equipment packaging (mounting/wiring) and delaying equipment installation. The anticipated benefit to the STARS program of the R-44 car upgrading was the expected improvement in car reliability (especially brakes) that would reduce the likelihood that nonpropulsion system-related problems would mask the merits of the ac propulsion system during system demonstrations.

Although the TTC tests were planned to simulate revenue service in a typical transit application, the actual testing would have been done in an environment allowing more careful control of test conditions and outside influences than was possible in New York.

Overall, the change in cars and test site had the effect of significantly increasing the scope of work--introducing unanticipated site-specific problems that were not directly related to the equipment performance but still had to be resolved--while, on the other hand, resulting in a more meaningful and convincing demonstration performed under actual revenue service conditions.

Sections 3 and 4 provide details on the program activities of Phase IIa and Phase IIb.

3. PHASE IIa FABRICATION, INSTALLATION, AND TESTING

This phase of the program encompassed the fabrication, qualification, and acceptance tests of ac propulsion system components at the factory; the R-44 car refurbishment and ac system installation; and the initial system verification tests. The Phase IIa system installation and verification activities were performed at the facilities of Morrison-Knudsen Company in Hornell, New York, who provided personnel skilled in rail car repair and overhaul, the essential rail car refurbishment equipment, and suitable test tracks. The initial system checkout tests were performed to ensure that the ac propulsion system installation was correctly done and that the system functioned properly before delivery of the test demonstration vehicles to the NYCTA for the Phase IIb revenue service demonstration testing.

Initial tasks accomplished in program Phase IIa included the preparation of engineering drawings and wiring diagrams depicting the R-44 dc rail cars. These installation drawings, which were coordinated with NYCTA, were essential to adequately define the car configuration and allow the creation of a preliminary statement of work (SOW) for the dc-to-ac car conversion efforts. Potential car refurbishment contractors were contacted to solicit their bids for the work. The responses were evaluated and additional meetings conducted to select the contractor.

Schematic drawings were finalized for ac propulsion system hardware installation and changes integrated into the undercar layout to ensure proper accessibility and mounting arrangement.

A complete stress analysis was prepared, analyzing the structural impact of all car modifications and new bracketry for installation of the ac equipment.

The following major tasks were accomplished at the Hornell site:

(a) Initial inspection of cars

(b) Installation of framework for mounting ac propulsion equipment

(c) Installation and assembly of ac propulsion equipment

(d) Wiring of ac propulsion equipment and complete car rewiring

(e) Checking out trainlining between ac propulsion and upgraded R-44 dc cars with NYCTA/Morrison-Knudsen modifications

(f) Static tests of ac propulsion equipment

(g) Functional track tests (ac and dc cars)

(h) Track circuit interference tests (ac and dc cars)

(i) Radiated EMI tests (ac and dc cars)

(j) Instrumentation checkout

(k) Updating and correction of AiResearch-produced R-44 schematic drawings

(l) Load balance test

3.1 HARDWARE QUALIFICATION AND ACCEPTANCE

Each unit of the ac propulsion system was subjected to routine tests (acceptance tests) that verified proper functioning and configuration prior to installation. Three completed propulsion control unit (PCU) car control units and six truck control units (TCU's) were acceptance tested by Stromberg and delivered. Except for the control units, one unit of each component type was subjected to a type test (qualification test) by Stromberg that demonstrated qualifications for use in the ac propulsion system environment. All control units were subjected to an extensive acceptance test program. The qualification tests included environmental testing to demonstrate that the equipment would withstand the effects of environmental conditions such as ambient temperature extremes, vibration, and acceleration; operate without causing EMI or excessive acoustic noise; and provide the required performance over simulated duty cycles. The acceptance tests included inspections to verify conformance to drawings, correct assembly, quality of workmanship, etc., as well as functional tests to verify acceptable performance. Table 3-1 lists the ac propulsion equipment tested and the tests conducted by the manufacturer. The large volume of test data prevents inclusion in this report of complete test

TABLE 3-1

QUALIFICATION AND ACCEPTANCE TESTING

- Qualification tests (type tests)

  Ac traction motor
  Inverter drive unit
  Line filter unit
  Propulsion control unit
  - Car control unit
  - Truck control unit

- Acceptance tests (routine tests)

  Ac traction motors
  Inverter drive unit
  Line filter unit
  Propulsion control unit
  - Car control unit (same as type test)
  - Truck control unit (same as type test)

details; summaries of the tests conducted are included in the following paragraphs. A complete compilation of the data from these tests has been separately provided to DOT.

3.1.1 Ac Traction Motor Tests

3.1.1.1 Acceptance Tests

Each traction motor was subjected to the following tests or checks before delivery and before qualification testing.

(a) Inspection--intermediate and completed unit

(b) Measurement of winding resistance

(c) No-load test at 500 v/50 Hz, sine wave

(d) Short-circuit test (50 Hz, sine wave)

(e) Dielectric test (3.7 kv, 50 Hz, 1 min)

(f) Insulation test

(g) High-speed test with SAMI frequency converter

(h) Repetition wave test (5000-v pulse to one phase at a time to check windings)

(i) Checkout of temperature sensors

(j) Checkout of speed sensors

3.1.1.2 Qualification Tests

One traction motor was subjected to the following qualification tests:

(a) Continous power determination (1-hr test)

(b) Torque curve at sine-wave supply, 470 v, measuring speed 1500 rpm

(c) Power losses with inverter supply at frequency points and with two different slips

(d) Noise level measurements (these tests were carried out at the end of 1984)

(e) Temperature rises during synthetic duty cycle

3.1.2 Inverter Drive Unit

3.1.2.1 Acceptance Tests

Each inverter was subjected to the following tests or checks before delivery and before qualification testing.

(a) Tests without a motor connected:

  (1) Inspection--intermediate and completed unit

  (2) Insulation and dielectric tests

(3) Auxiliary voltages test (pulse power supply)

(4) Checkout of thyristor gate pulses

(5) Functional test at low-voltage supply (70 v)

(6) Disturbance test at low-voltage supply with Schaffner noise generator (inverter and line chopper functioning during disturbance shots)

(7) Tentative checking of supervision signals

(8) Check of discharging time of dc capacitor

(9) Check of function of inverter and line chopper snubbers at voltages of 100, 750, and 950 v

(10) Checkout of commutation currents, UC = 750 v

(11) Checkout of braking chopper (BC)

- Commutation voltage of BC commutation capacitor
- BC snubbers

(12) Measurement of no-load losses

(b) Tests with motors and line filter connected (test setup is shown in Figure 3-1):

(1) Checkout of feedback and supervision signals

- Voltages UC and UL
- Motor currents IU, IV, and IM
- Line chopper current IL

(2) Checkout of motor currents at rated axle torque (performance check)

(3) Checkout of IL according to an external current measurement

(4) Testing of function of the line filter unit (current waveforms)

(5) Checkout of short-time cycle drive and supervision of cooling

- Inverter and line filter first stressed by 4 cycles of 0 to 70 to 0 mph, then by synthetic duty cycle for 2 hr (1 hr with 100 percent, 1 hr with 0 percent line receptivity)

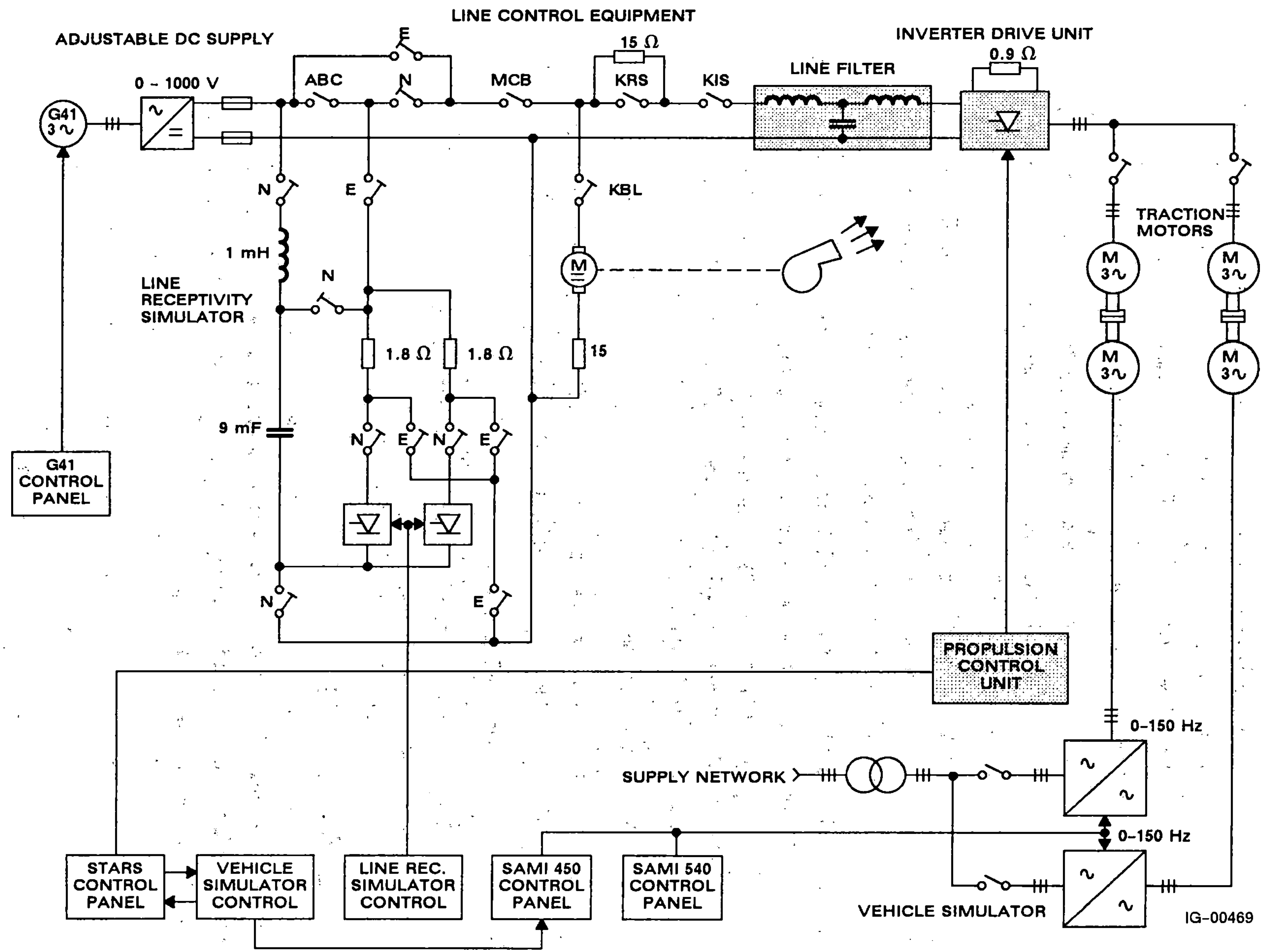


FIGURE 3-1. TEST SETUP FOR INVERTER, LINE FILTER, AND CONTROL UNIT

- After above-mentioned cycles, the blower was switched off while inverter was still running, and cycling continued until the supervision of cooling stopped the inverter

(6) Checkout of the inverter temperature trip

- A special tube was mounted between the air outlet of the inverter and blower so that the same cooling air cycled through the inverter
- The inverter was driven with maximum performance at the maximum commutating frequency (steady frequency point) until thermal tripping occurred

(c) Burn-in tests of inverter electronic components. Burn-in tests were conducted on the inverter electronics in the setup shown in Figure 3-2. Temperature cycling was between -40° and +140°F, with tested cards driven manually between -40° and +158°F. Comparison measurements were taken at:

(1) Room temperature

(2) Limiting temperatures of -40° and 158°F (auxiliary voltages were switched off at these temperatures)

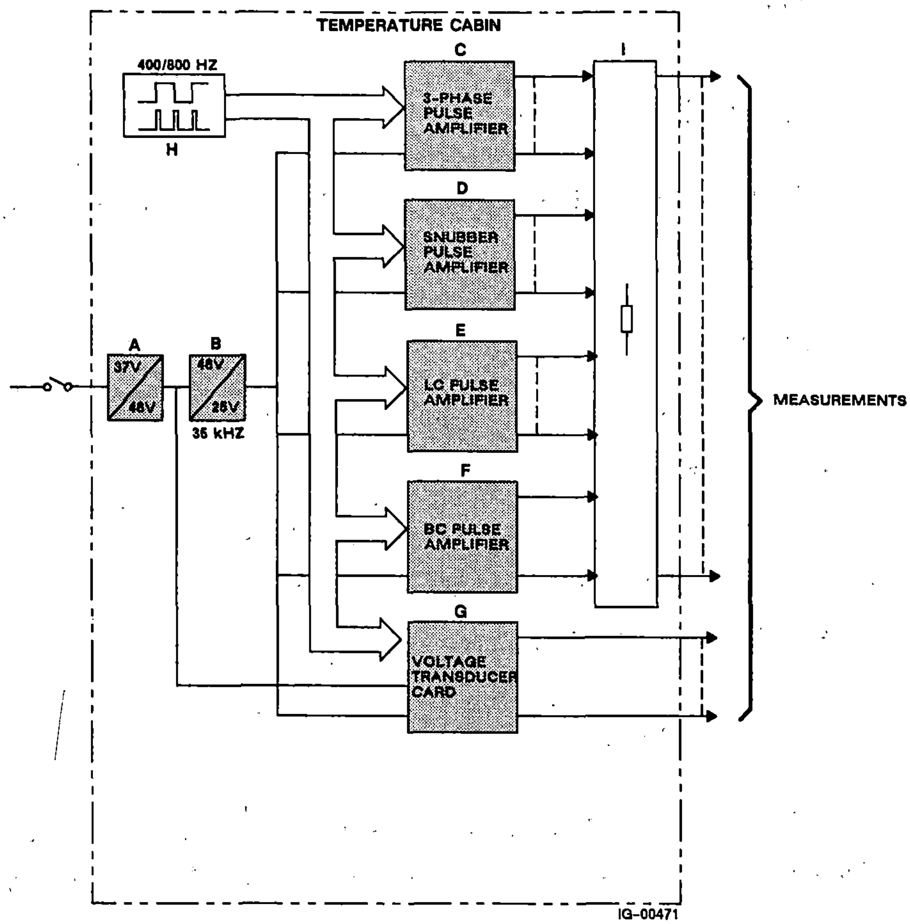
(d) Envelope control wire check:

(1) Check of insulating resistance of each wire

(2) Ohmmeter wiring check

3.1.2.2 Qualification Tests

One inverter was instrumented to record temperatures of selected components during the short-time cycle drive and inverter temperature tripping tests run during acceptance testing.



LEGEND:

A 37/48 v stabilizer, Code 5718629-1

B 48/25 v, 35 kHz pulse power, Code 5718630-5

C 3-phase pulse amplifier, Code 5705941-9

D Snubber-pulse amplifier, Code 5728036-1

E LC-pulse amplifier, Code 5728035-1

F BC-pulse amplifier, Code 5706303-3

G Voltage transducer card, Code 5706385-8

H 400/800-Hz pulses feeding oscillator (400-Hz square wave pulses for main thyristor and supervision controls, 800-Hz/13-μs pulses for auxiliary and snubber thyristor controls)

I Load resistor network (thyristor loads were simulated by 1-ohm resistors)

FIGURE 3-2. BURN-IN TEST SETUP FOR THE INVERTER ELECTRONICS

3.1.3 Line Filter

3.1.3.1 Acceptance Tests

The line filter was subjected to the following tests or checks before delivery:

(a) Inspection

(b) Insulation and dielectric tests

(c) Impedance measurement

(d) Functional test with inverter--the line filter unit was connected with the inverter and functioned with the inverter until motor tests were complete (see Figure 3-1).

3.1.3.2 Qualification Tests

One line filter was then subjected to a temperature rise test while running with the synthetic drive at full regeneration to temperature stability.

3.1.4 Control Unit

3.1.4.1 Acceptance and Qualification

Each control unit was subjected to both component and end-item tests or checks, as listed below, before delivery:

(a) Printed wiring assembly (PWA) tests to check out function of each card

(b) Mechanical inspection and rack wiring tests

(c) Control unit checkout:

(1) Mechanical inspection

(2) Check of insulation resistances to control unit frame

(3) Ohmmeter wiring check

(4) Loading of 37/48-v stabilizers

(5) Check of discharging time of 48 v

(6) Check of functioning of relays

(d) Check of car control unit (CCU) function (Figure 3-3):

(1) Auxiliary and reference voltages

(2) Loading of 37-v battery voltage

(3) Input controls (interface signals)

(4) Output controls (interface signals)

(5) Controls for TCU's (direction request, start permission, drive and brake commands, torque reference in Stromberg mode, etc.)

(6) Functioning of R-44 emulator

(7) Load weigh function

(e) Check of truck control unit (TCU) function (Figure 3-3):

(1) Auxiliary and reference voltages

(2) Reset responses

(3) Function of inverter control with simulated signals (measuring devices: memory oscilloscope, logic analyzer, XY-recorder, and universal meter)

(4) Function of line chopper control

(5) Function of brake chopper control

(6) Offset errors

(7) Torque reference chain

(8) UC-reference in drive and brake mode (XY-recorder plots)

(9) Torque-actual chain (XY-recorder plot)

(10) UC control during line gaps

(11) Relay outputs of truck

(12) Spin/slide prevention

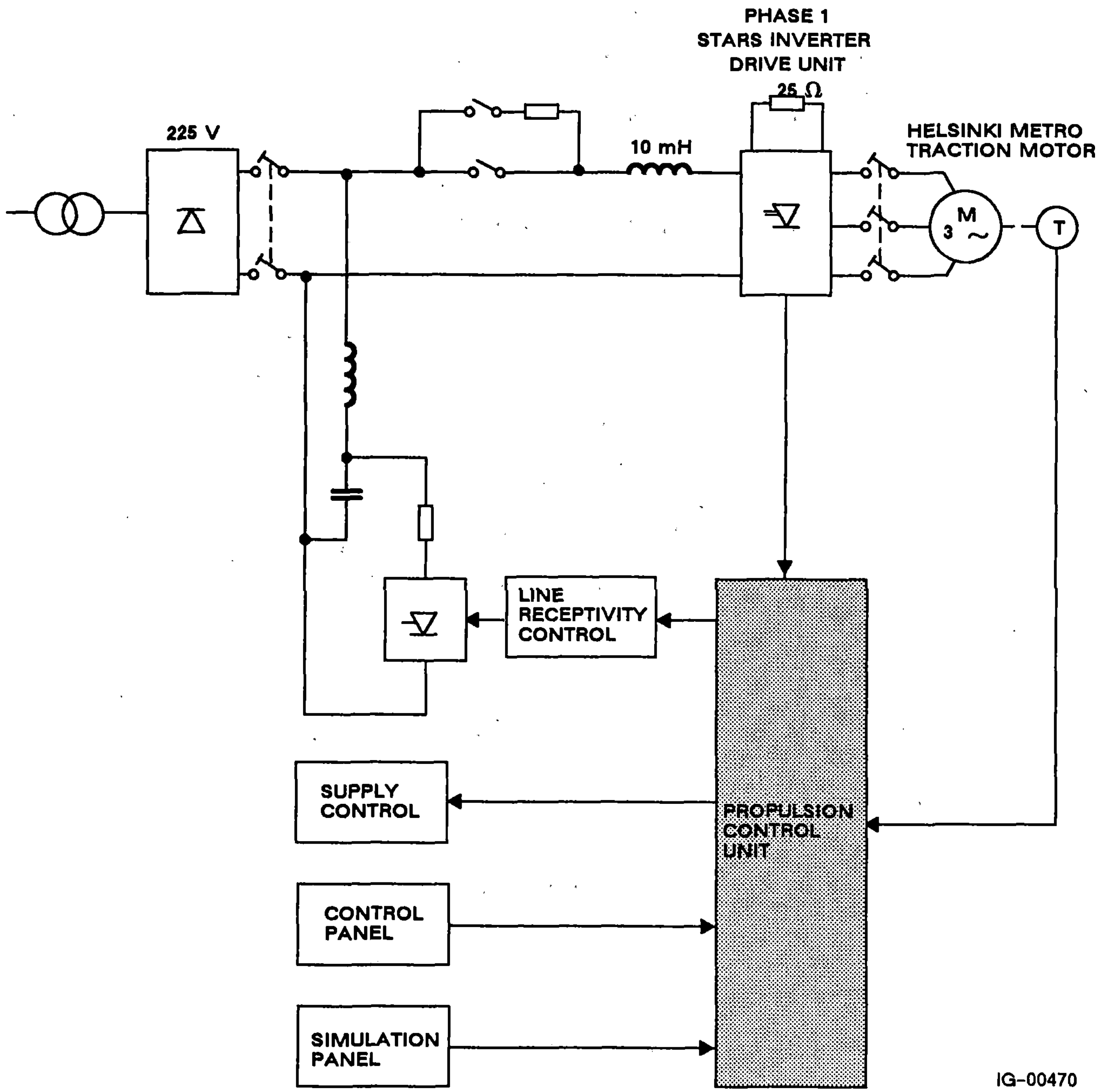


FIGURE 3-3. BURN-IN AND FUNCTIONAL TEST SETUP FOR CONTROL UNIT

(f) Check of function at low voltage supply (70 v) with simulated feedback signals (CCU + TCU)

(g) Check of function at 225-vdc supply without motor

(h) Check of function at 225-vdc supply with a load motor, frequency-controlled

(i) Check of function at 225-vdc supply with a load motor, torque-controlled

(j) Burn-in tests for control unit. In setup of Figure 3-3, the prototype control frame with complete CCU and TCU racks (furnished with PWA's) was stressed in a temperature environment for 15 hr. The control unit was controlling an actual inverter and a load motor in the following circumstances:

  (1) Temperature was cycled between -40° and +131°F

  (2) Line voltage was 225 v in drive mode and 250 v in brake mode (determined by the line receptivity brake chopper); 225 v simulated 600 v

  (3) Drive and brake commands were given by the control panel through the CCU so that the system was accelerating 0 to 70 to 0 Hz with maximum performance request (acceleration and deceleration rates adjusted as in real car)

  (4) Line chopper was functioning in drive mode and in brake mode with blended dynamic braking (brake power into line or resistor)

  (5) Auxiliary voltages were switched off and on periodically at high and low temperatures; train line responses were checked at these temperatures

  (6) Accuracy of torque reference and actual chains as well as UC control were checked at limit temperatures

(k) Tests without motors and main voltages (Figure 3-1 setup) for responses to panel controls (train lines)

(l) Check of function at 600 v with motors (two STARS motors), frequency-controlled, no load (Figure 3-1 setup):

(1) Current signals (IU, IV, IM, IL)

(2) UC and UL

(3) Speed sensor signals

(4) Speed actuals (VACT, VAA, VAB)

(5) Torque actual

(6) Motor temperature measurement

(m) Check of function at 600 v with motors, torque-controlled, no load (Figure 3-1 setup):

(1) Responses to panel controls through CCU

(2) Starting, stopping

(3) Coasting

(4) Speed starts

(5) Phase shifting

(n) Check of functioning at real line voltage (450 to 700 v) with motors, torque-controlled and loaded:

(1) Feedback signals

(2) Static performance points (axle torques measuring), drive and brake mode

(3) Acceleration/deceleration (axle torques plotted by XY-recorder)

(4) System stability

(5) Jerk limiting (measured from axle torque)

(6) Fluttering of commutation pulses

(7) Line gaps in coasting and drive mode

(8) Response to emergency brake command

(9) Line gaps in braking

(10) Effect of line receptivity (0 percent, partial, 100 percent)

(11) Line voltage limitation in brake mode

(12) Spin prevention

(13) Slide prevention

(14) Changeover to mechanical brakes (functioning of friction brake inhibit-relay)

(15) Short-time synthetic cycle drive

(o) Tests of the safety supervising circuits. Tests were done partly simulated and partly with the truck drive unit. Tests were carried out after all the other control tests were completed.

(1) CCU, simulated tests; automatic test and check of every supervision circuit

(2) TCU, simulated tests; automatic test and check of every supervision circuit

(3) Burn-in test; driven with burn-in test simulator for 15 hr

(4) Operation of the CCU and TCU safety circuits with motors connected

3.2 CAR REFURBISHMENT AND EQUIPMENT INSTALLATION

The ac propulsion system equipment was installed in the R-44 test vehicles at the rail car overhaul/refurbishment facilities of Morrison-Knudsen Company in Hornell, New York. Prior to ac equipment installation, the dc propulsion system equipment not common to the ac installation was removed by Morrison-Knudsen under a separate contract to the NYCTA.

Originally, the STARS SOW required two identical sets of ac propulsion equipment for installation in two "A" car (cab) R-44 vehicles. After the Phase II program redirection and work agreement modification, the NYCTA requested that the test vehicles be an A, B car pair (one with cab, one without). This complicated the hardware installation task because the propulsion control unit boxes had to be installed in the "B" car (SN 249) interior. In the "A" car (SN 280), the control unit was designed to fit in the vacant automatic train operation (ATO) box. Other car differences required additional drawing and installation bracket efforts.

The ac propulsion system installation in the R-44 car (Figure 3-1) involves:

(a) Control equipment

(b) Undercar equipment

(c) Truck equipment

The control equipment replaces the removed dc ATO equipment on the "A" car and includes the propulsion control unit, load weigh unit, and miscellaneous equipment such as the low-voltage supply circuit breaker and blower circuit breakers (plus the associated equipment retained from the R-44 dc installation). On the "B" car, which has no cab, the control equipment was installed in the engineer's panel.

The undercar equipment (Figure 3-4) includes the line control equipment (LCE), line filters, inverters, cooling blowers and plenums, air filters, and brake resistors. The ac equipment is arranged to fit into the undercar space available after removing the dc equipment, which included the lighting inverter, control group, and associated resistors. The original knife switch, converter, brake operating unit, air supply reservoir, and battery box were retained, but relocated in the undercar area. The undercar equipment is located essentially in two symmetrical groups about the car centerline to maintain required balance and arranged to fit within the clearance lines, allowing good access and good airflow for all units.

The truck equipment consists of the ac induction traction motors and mounting hardware. The ac motors were designed to use the same mounts as the dc motors they replace, and the same couplings to the original gearboxes.

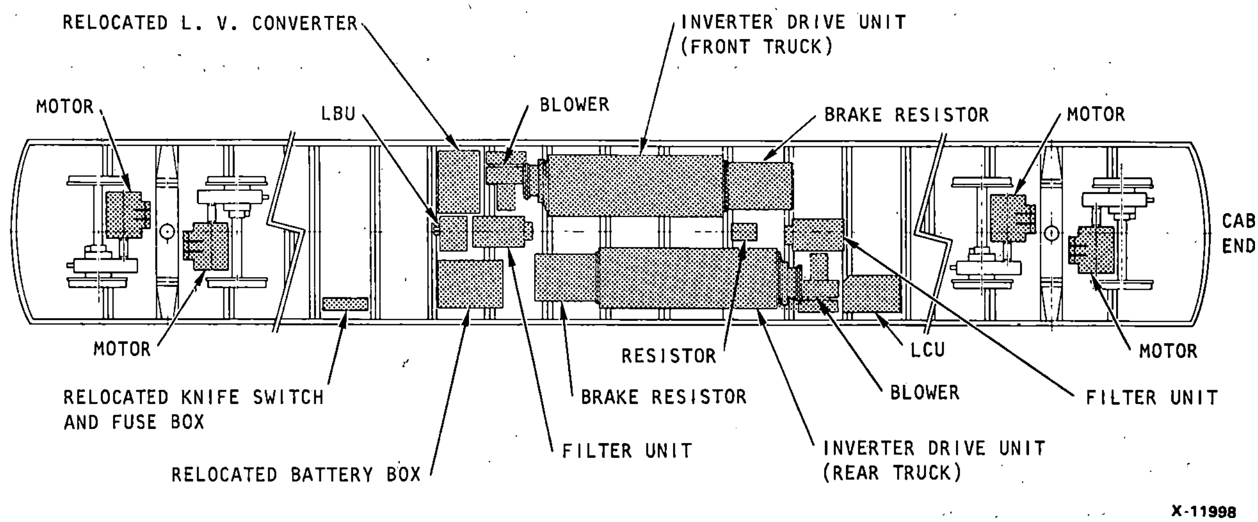


FIGURE 3-4. UNDERCAR EQUIPMENT ARRANGEMENT

3.2.1 Statement of Work

Work involving the ac propulsion system equipment installation and checkout in the R-44 cars was done under subcontract to AiResearch by the Morrison-Knudsen Company of Hornell, New York. The work was defined in the AiResearch statement of work (SOW)*, which was provided to candidate subcontractors for bidding purposes.

*Included as an attachment to the ac propulsion system progress report, AiResearch Document 84-21420(3).

The SOW defined the effort required to install two complete carsets of ac equipment, which included:

(a) Removing existing dc propulsion equipment not required for the program and transferring the removed equipment to a designated NYCTA facility

(b) Relocating equipment installed on the cars and required for the ac propulsion program

(c) Installing and wiring the ac propulsion equipment

(d) Checking out the completed ac installation on both cars, including performance testing on the Morrison-Knudsen test track

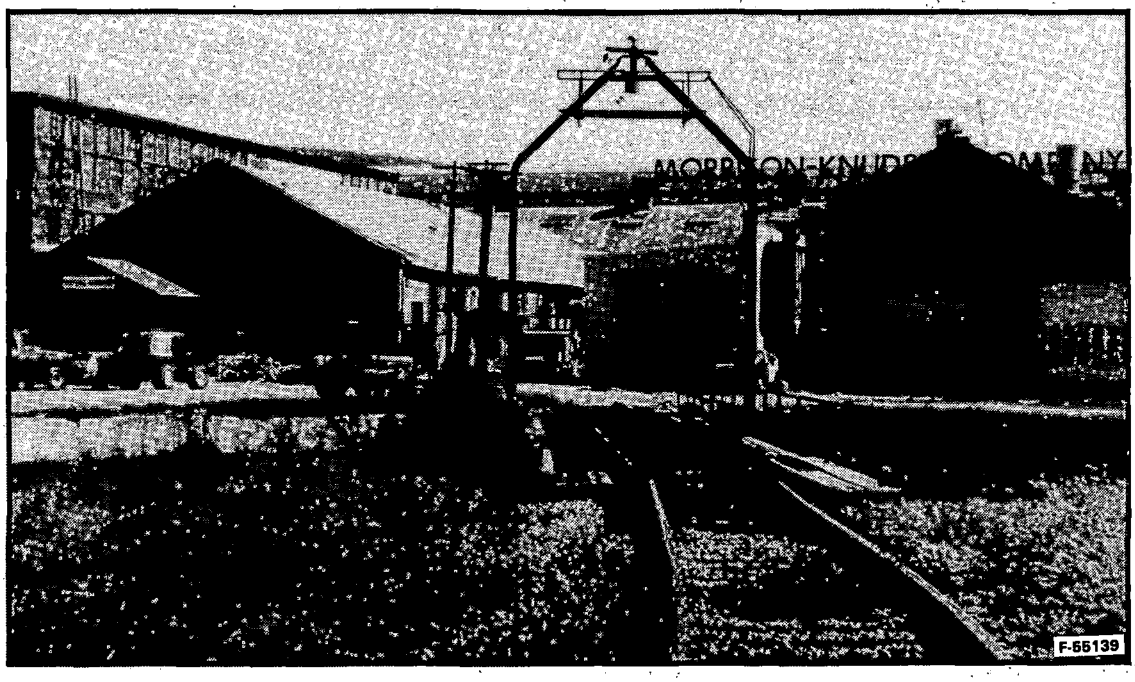
(e) Providing documentation, as-built sketches, and appropriate inspection records required to satisfy the NYCTA, AiResearch, or DOT as to car acceptability for operation on the NYCTA transit system

Some of these efforts, such as Items (a) and (c), were funded separately by the NYCTA.

3.2.2 Selection of Morrison-Knudsen for Car Refurbishment

Evaluation of the responses from candidate rail car overhaul/refurbishment facilities resulted in the selection of Morrison-Knudsen Company of Hornell, New York, to perform the dc-to-ac R-44 car conversion and initial system testing work. The selection was made with the concurrence of DOT/UMTA and the NYCTA, who participated in meetings and discussions that led to the decision.

The Morrison-Knudsen Company Hornell facility (Figure 3-5) is located on a major railway approximately 70 miles south of Rochester, New York. It is the largest industry in Hornell, employing approximately 350 people, and its personnel are experienced in major repairs, maintenance, and refurbishment of rail cars and equipment from Amtrak, the NYCTA, and other properties. The facility includes about 1200 ft of third-rail dc test track for vehicle testing.



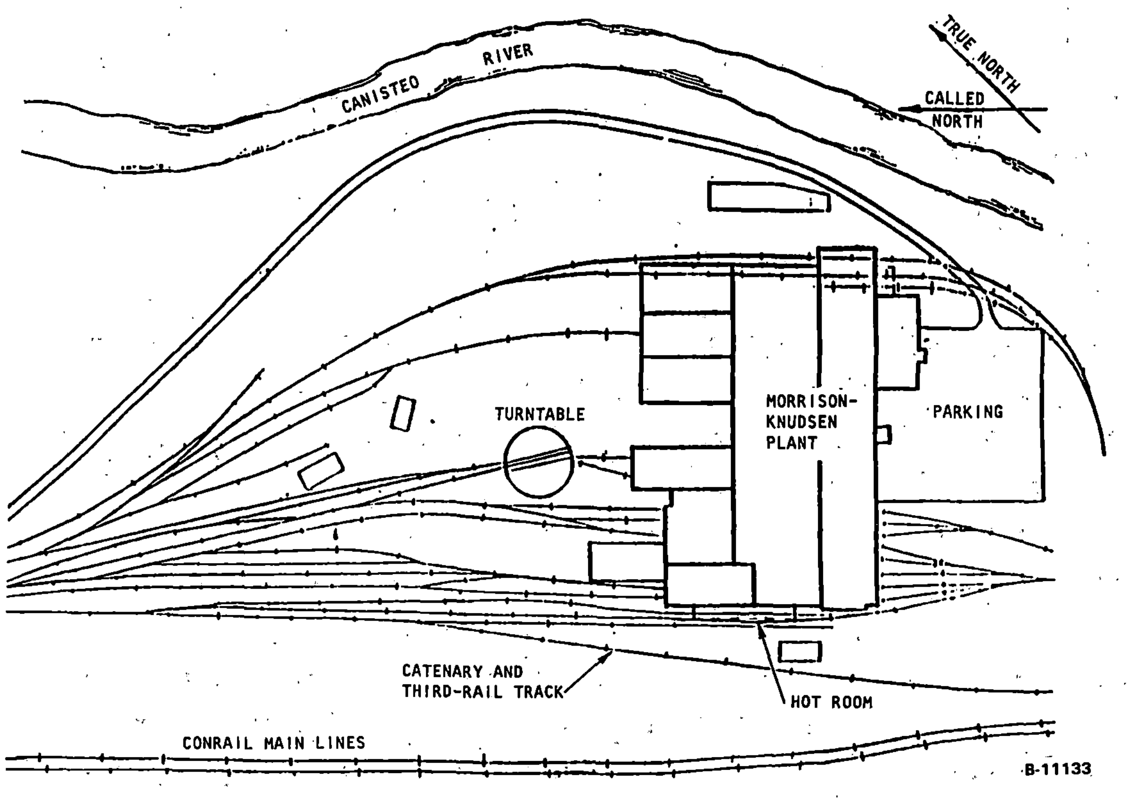


FIGURE 3-5. MORRISON-KNUDSEN HORNELL FACILITY

The test track was utilized for performance (acceleration, braking), regeneration verification and limit setting, car mating, and four-car (ac, dc) trainlining. The track also was upgraded with improved bonding straps and joints were repaired to facilitate the preliminary signalling program.

3.2.3 Car Refurbishment Effort

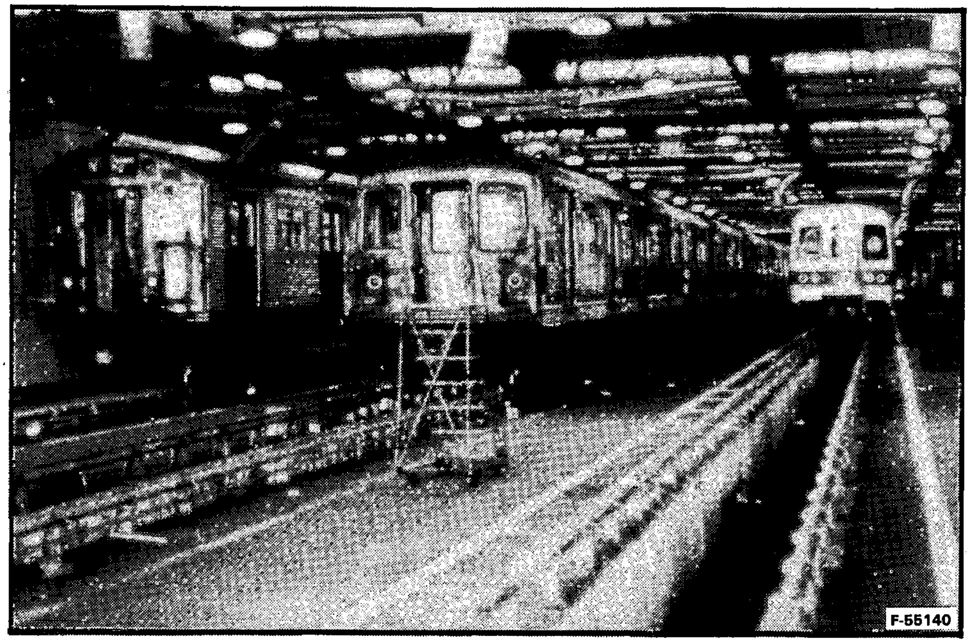
Refurbishment efforts were directed by Morrison-Knudsen with AiResearch and NYCTA engineering on-site participation and monitoring. The upgraded R-44 dc cars were inspected prior to installation of ac equipment, and photographed and measured to assist in equipment layout. AiResearch prepared interface schematics to reflect available component envelopes, mounting means, and car structural design, and wiring diagrams to document the electrical interfaces with the car. Both sets of vehicles (ac and dc) were subjected to extensive equipment upgrading, new wiring, and complete refurbishing in the Morrison-Knudsen shop.

Figure 3-6 through 3-17 show the cars in various stages of the refurbishment and ac equipment installation.

3.2.4 R-44 ac Car Stress Analysis

AiResearch performed a comprehensive stress analysis on the R-44 car structure and the loads induced by installation of the STARS ac propulsion equipment. Design load and stress criteria were taken from the NYCTA Specification for Furnishing and Delivering Passenger Cars for the NYCTS Division B Equipment, Contract R-31468 (R-68). Results were presented in AiResearch Document 86-60222, Stress Analysis for STARS Ac Drive System.

Ample margins of safety were indicated for all system component mounting brackets and the bracket assembly structures. The results of the analysis to determine the reactions on the car floor Z-channel beams induced by the ac drive system were provided to NYCTA.



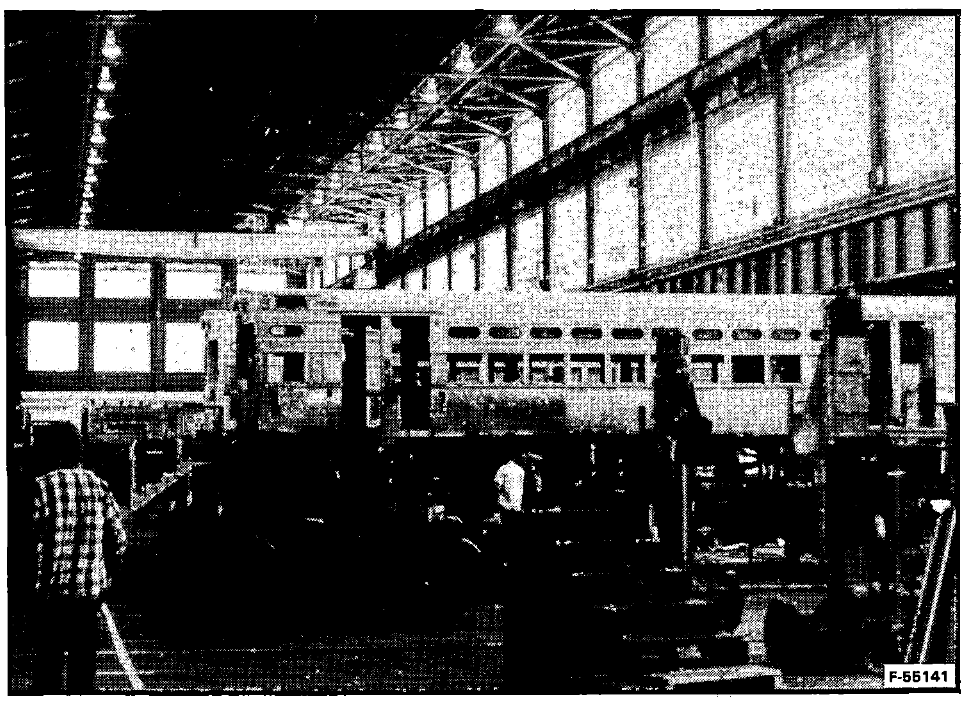


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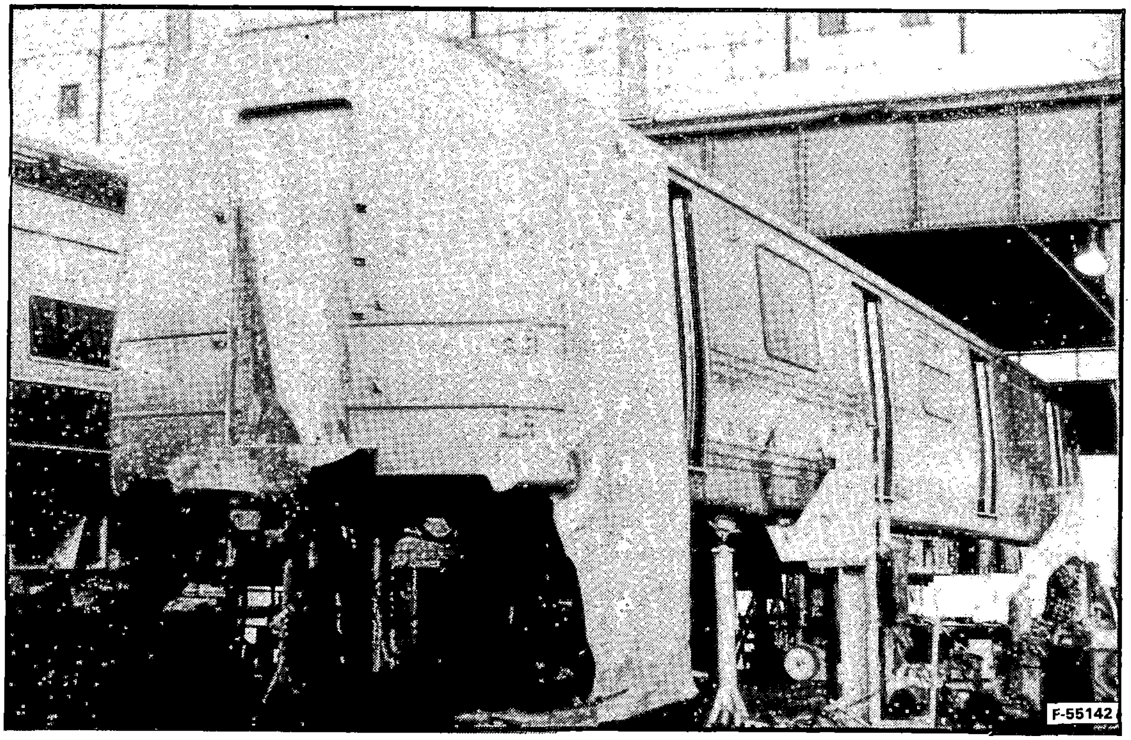
FIGURE 3-6. MORRISON-KNUDSEN SHOP AREAS



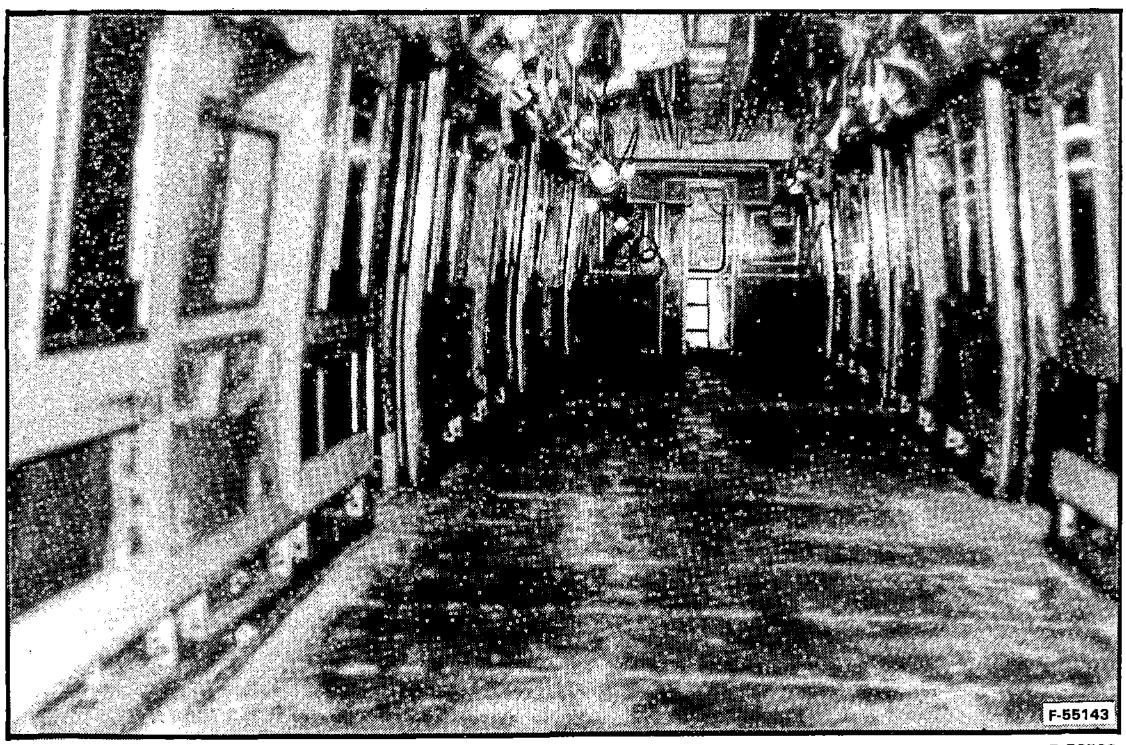


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FIGURE 3-7. R-44 CAR REFURBISHMENT

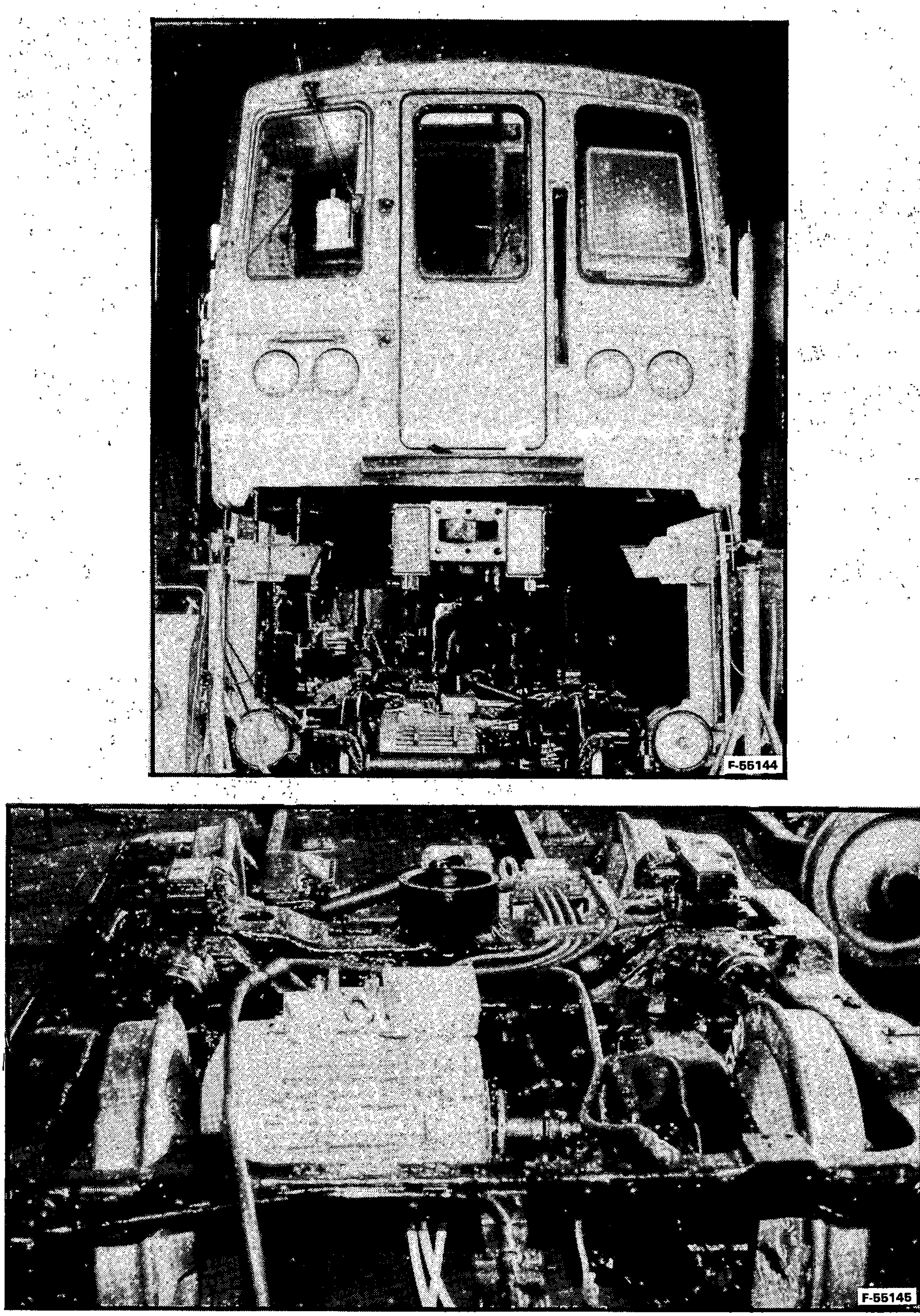

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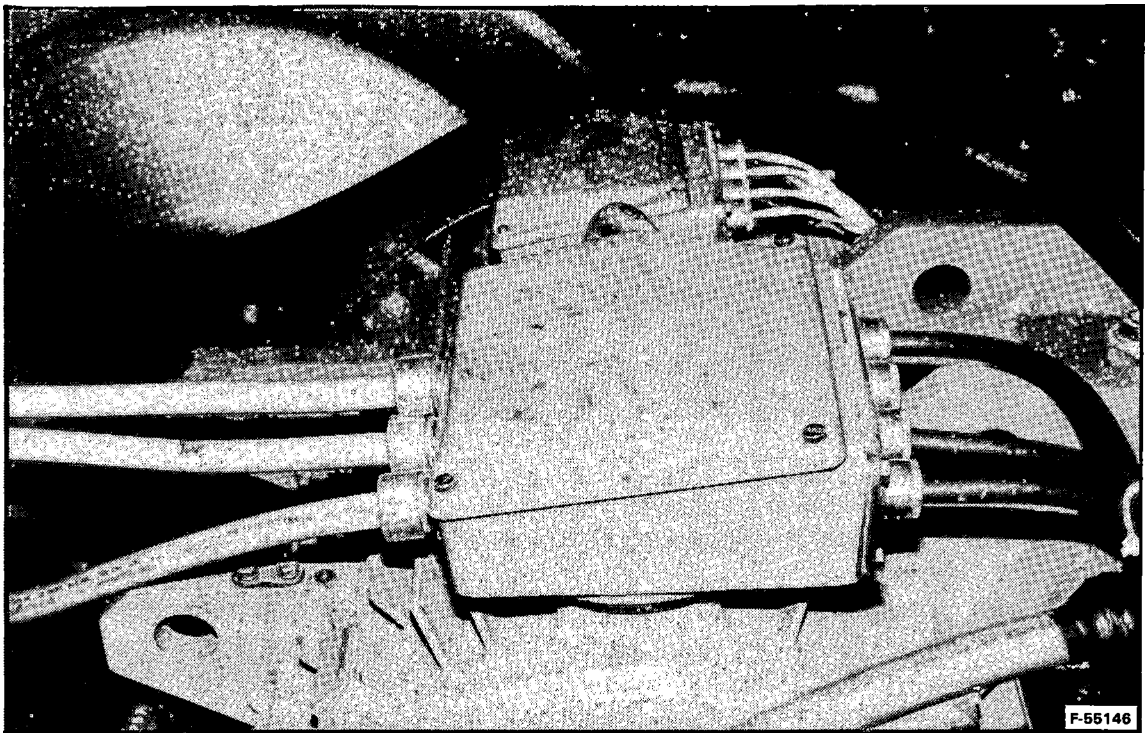
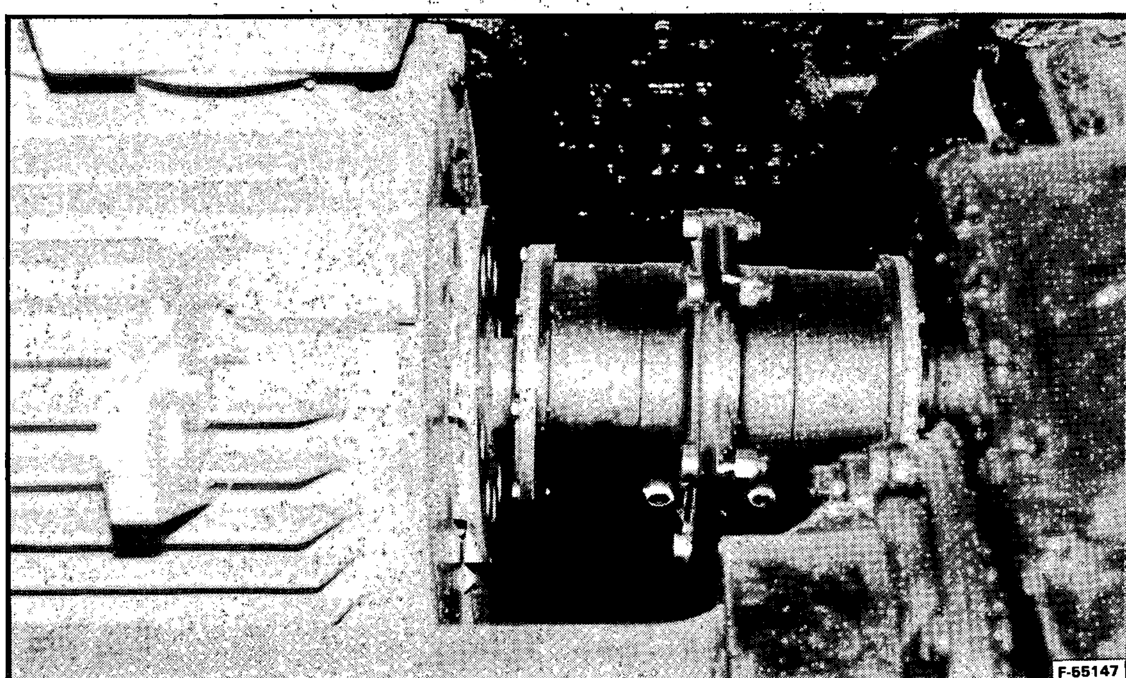
FIGURE 3-8. AC MOTORS INSTALLED ON FRONT TRUCK



a. AC MOTOR POWER CABLES AND DISTRIBUTION BOX



b. MOTOR-TO-GEARBOX FLEXIBLE COUPLING

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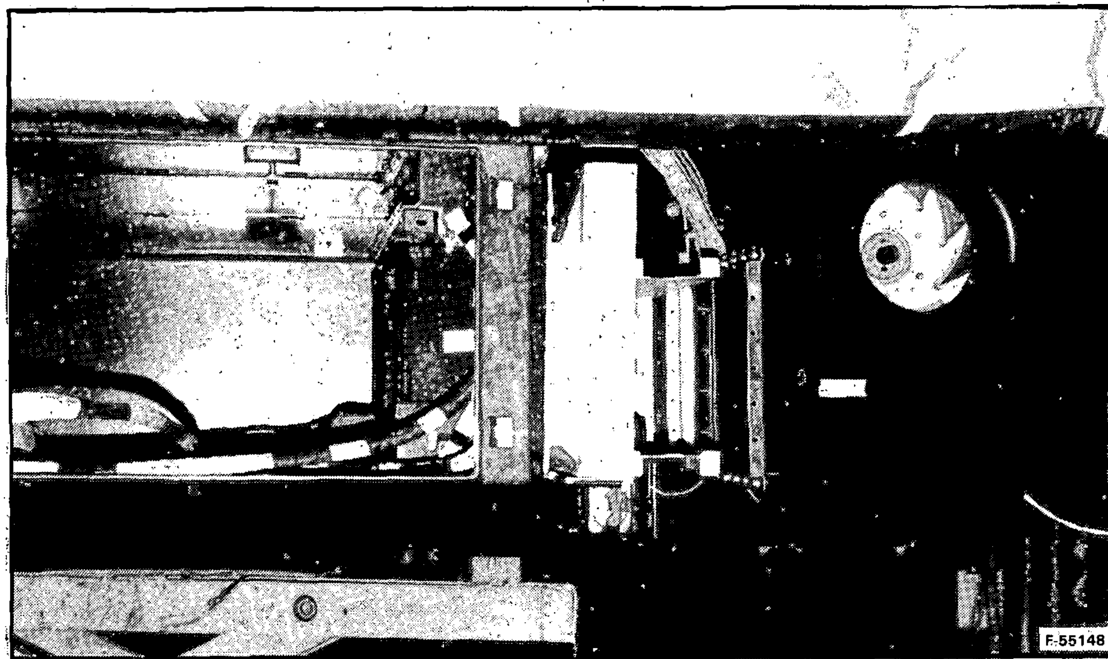
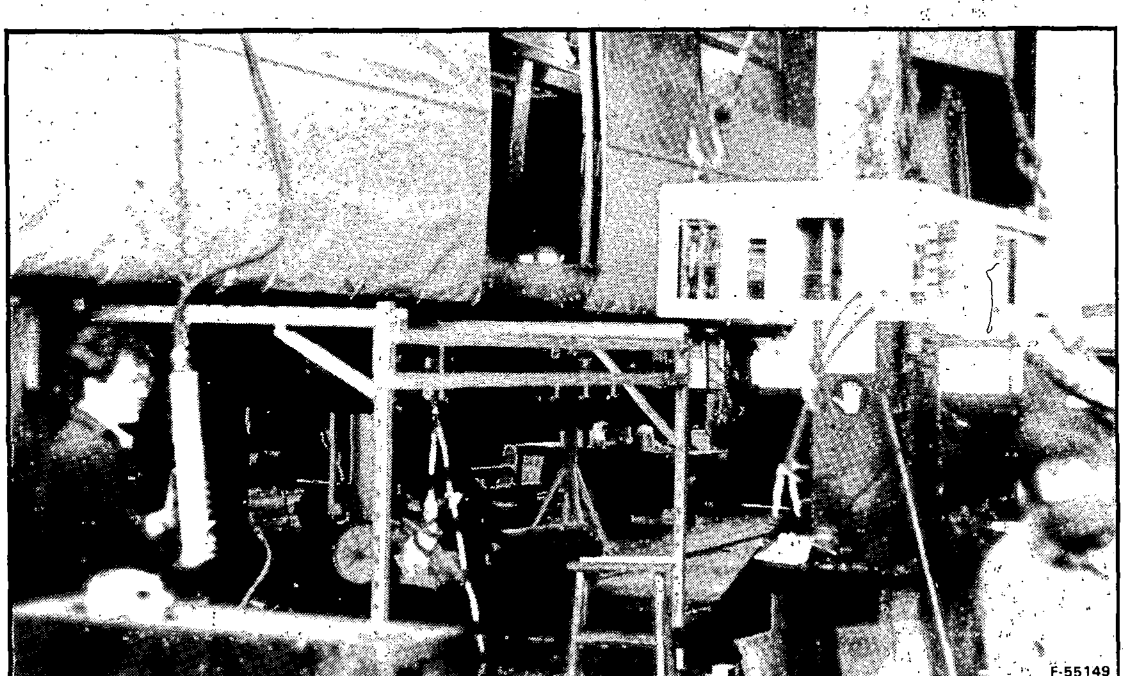
FIGURE 3-9. AC MOTOR INSTALLATION DETAILS



a INVERTER ENCLOSURE AND COOLING AIR BLOWER



b LOWERING INVERTER INTO RACK

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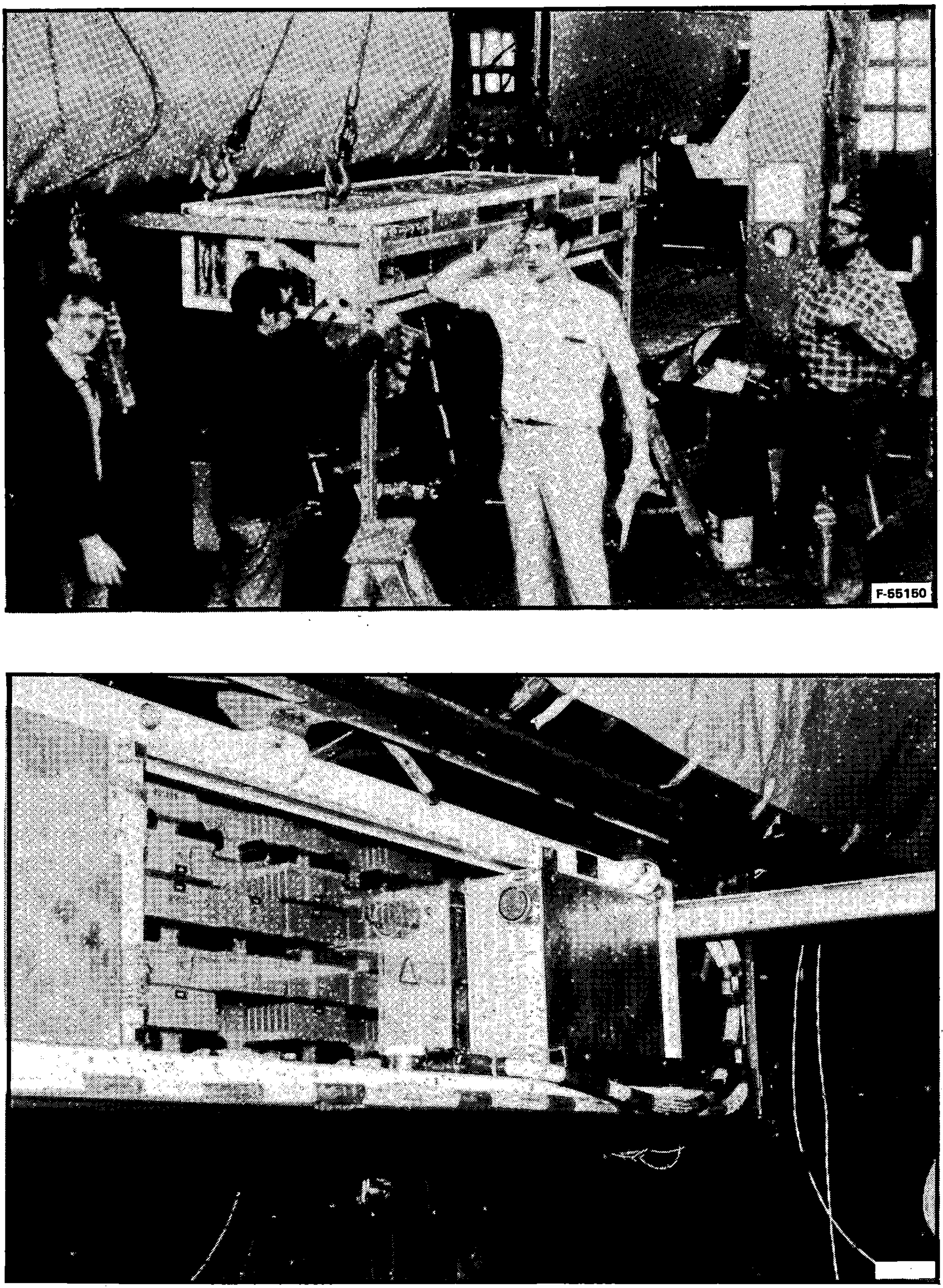
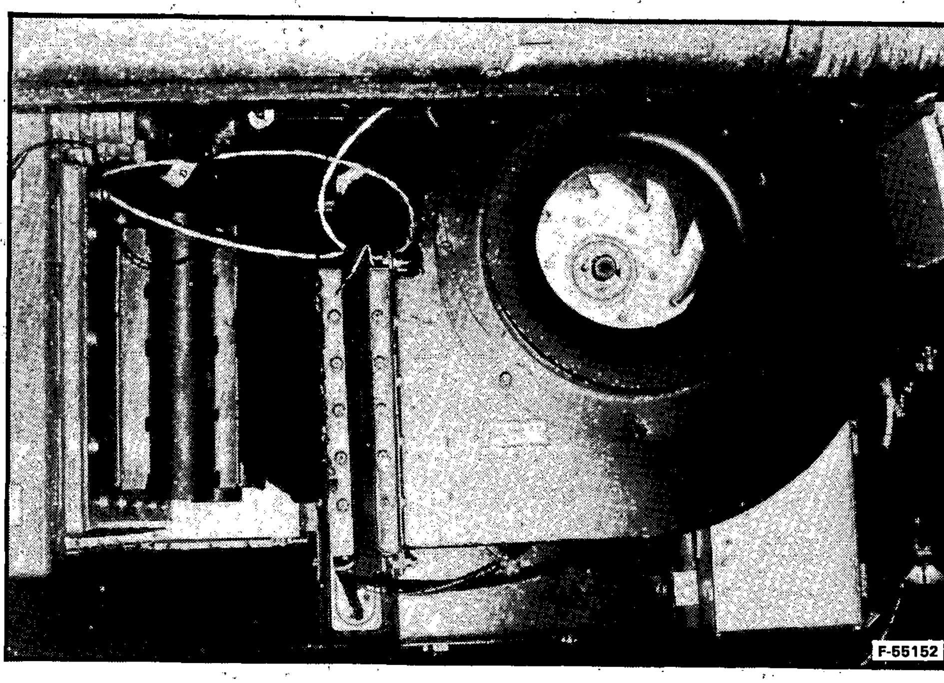
FIGURE 3-10. INVERTER INSTALLATION--LOWERING INVERTER INTO RACK TO SLIDE INTO ENCLOSURE

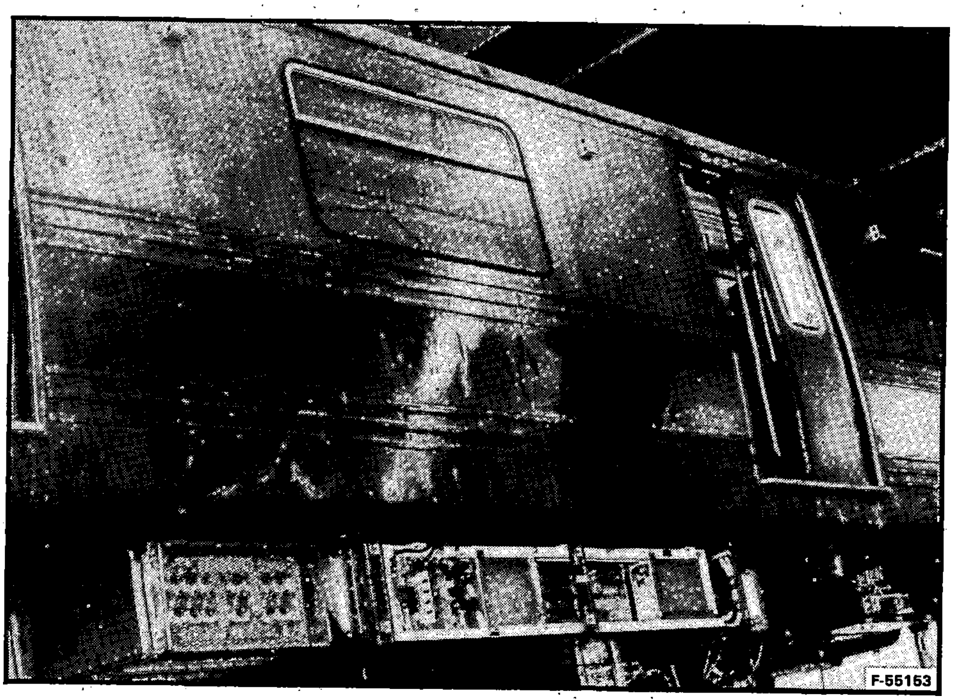


F-56529

FIGURE 3-11. SLIDING INVERTER INTO ENCLOSURE



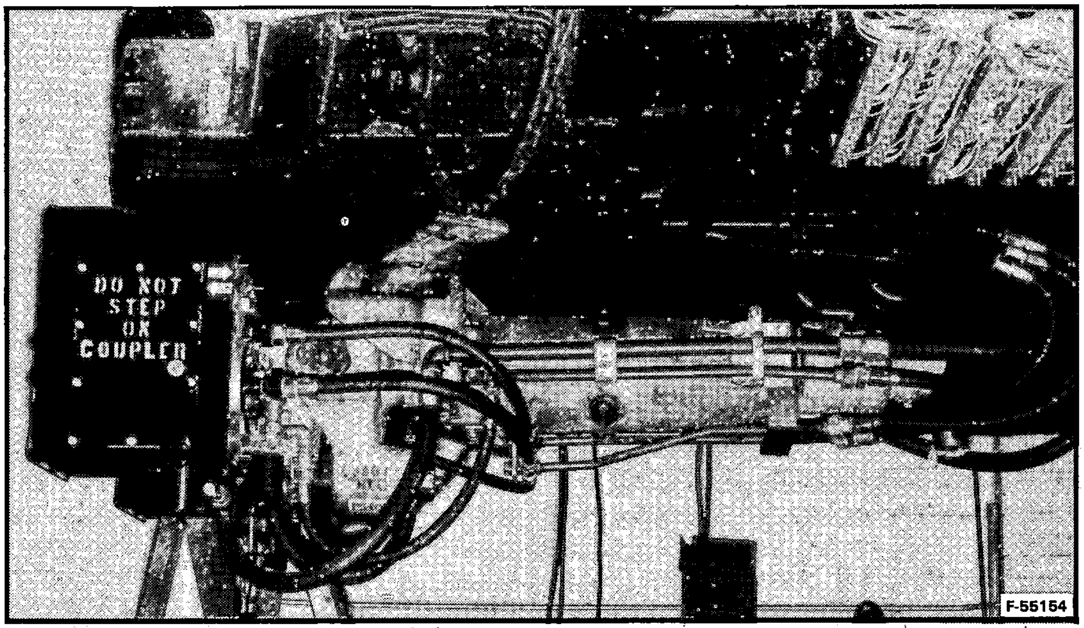
a. COOLING AIR BLOWER



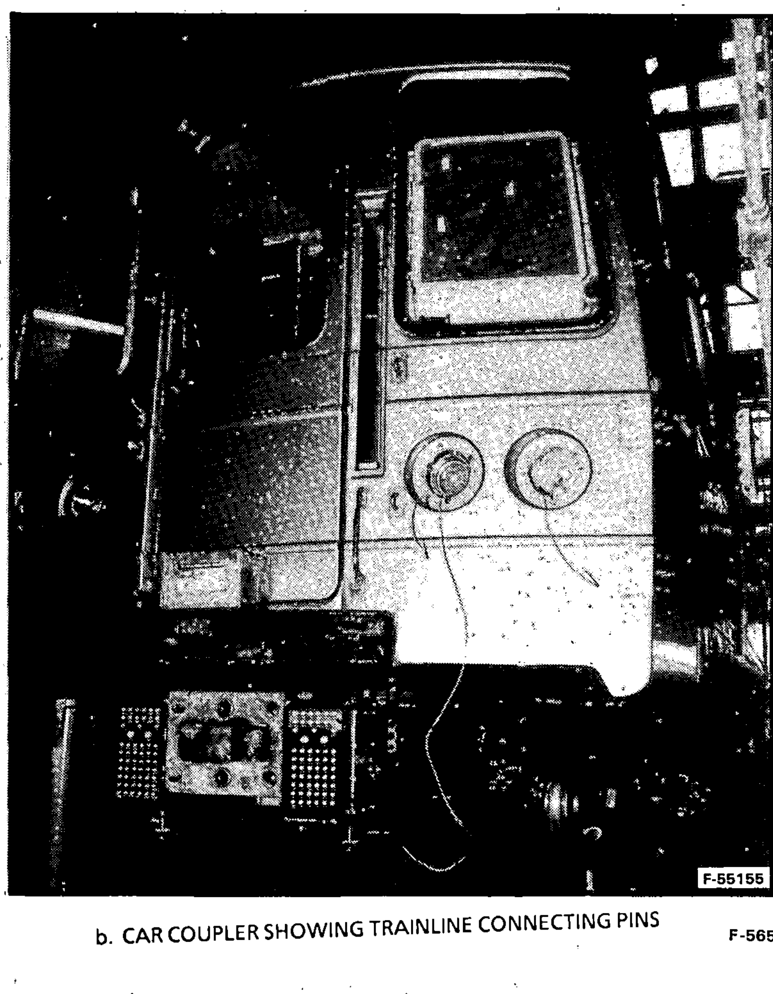
b. BRAKE RESISTOR AND INVERTER

F-56525

FIGURE 3-12. BLOWER, INVERTER, AND BRAKE RESISTOR INSTALLED IN CAR



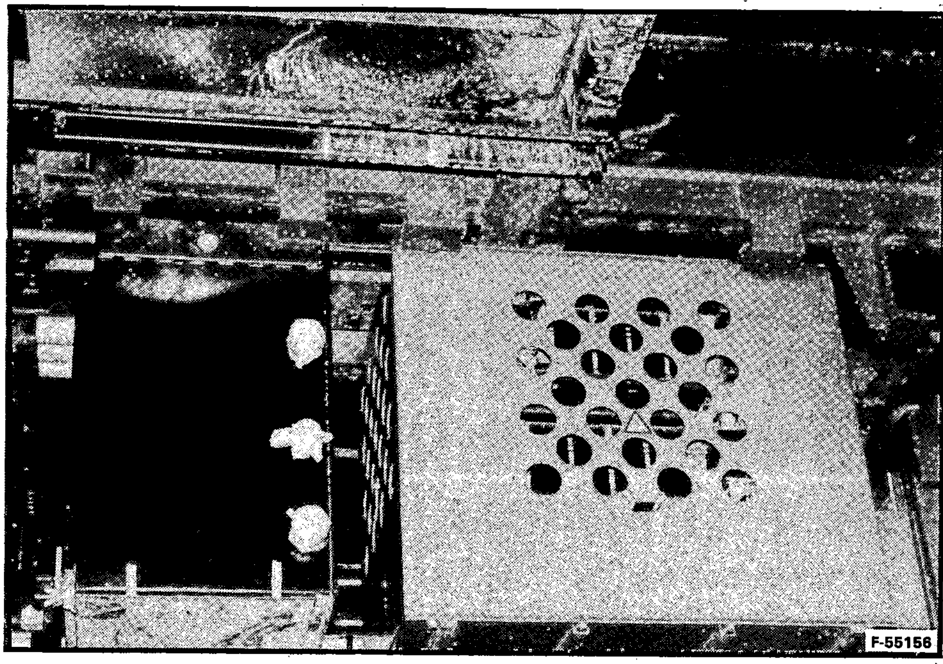
a. UNDERCAR VIEW OF CAR COUPLER

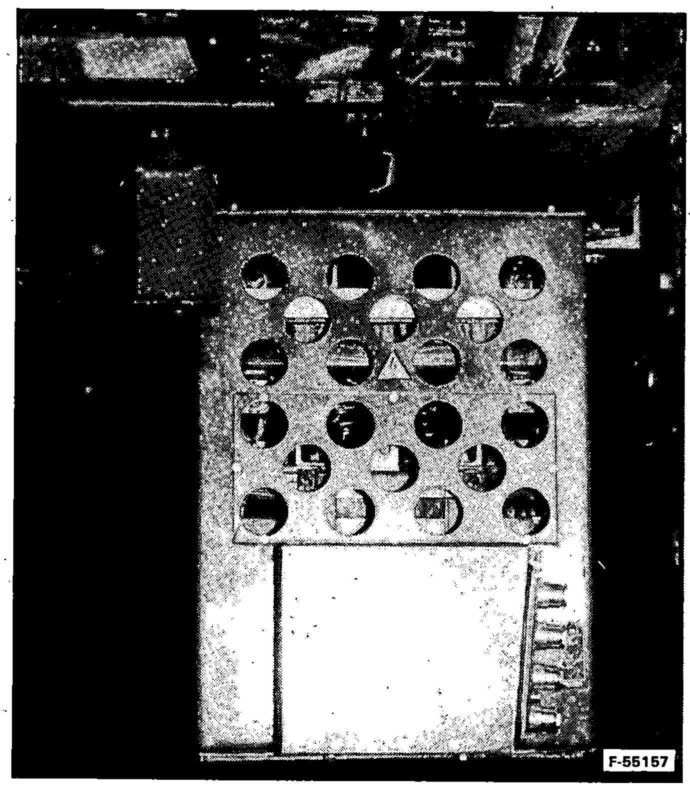


b. CAR COUPLER SHOWING TRAINLINE CONNECTING PINS

F-56526

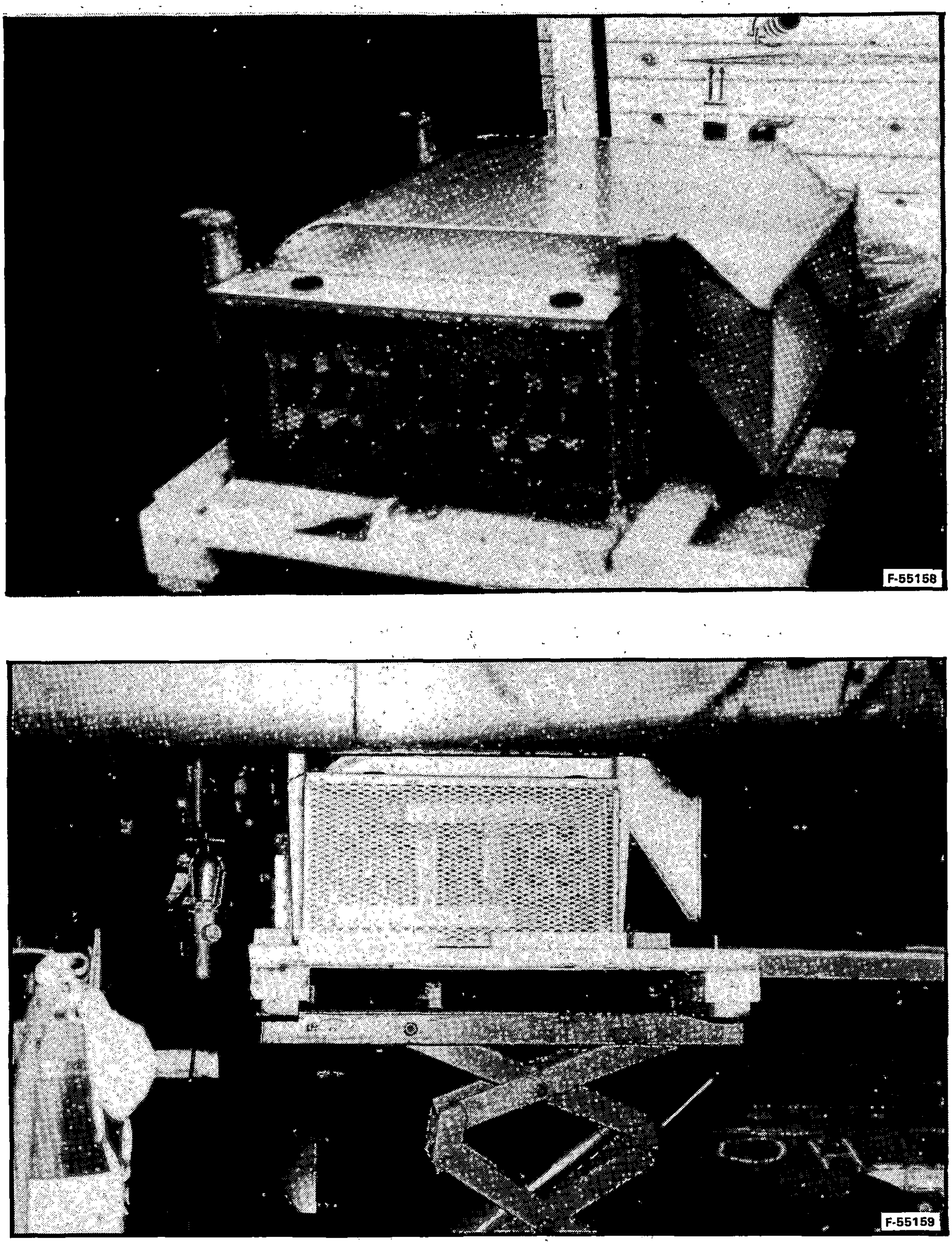
FIGURE 3-13. CAR COUPLER





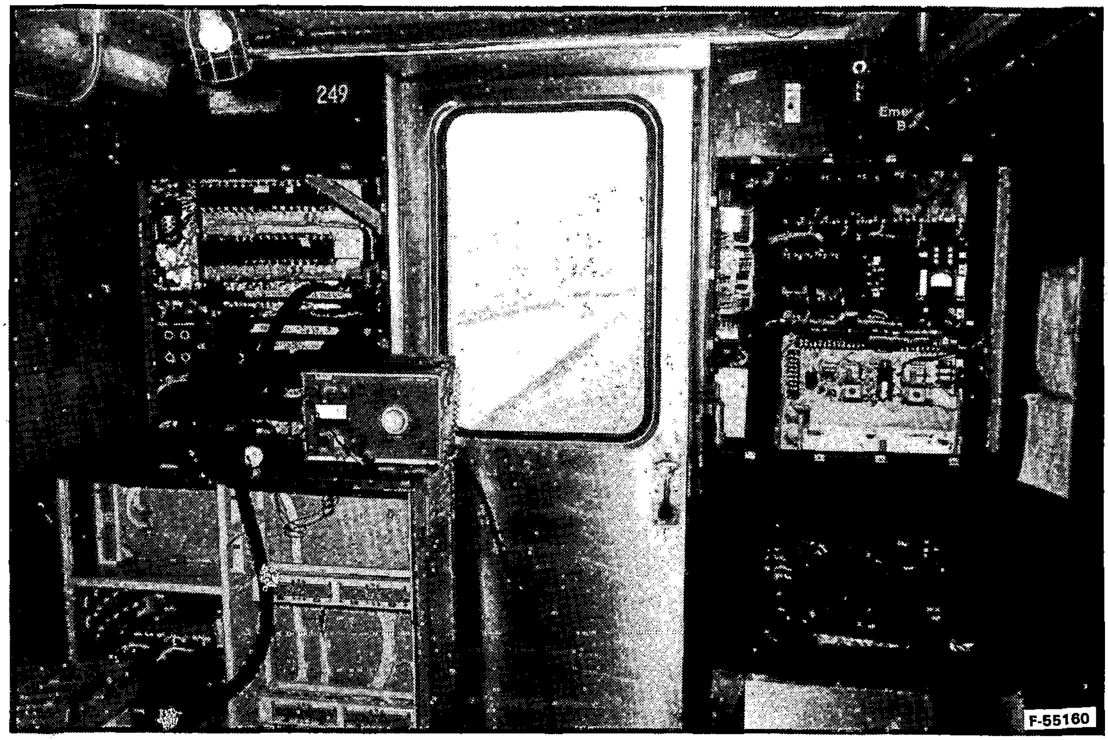
F-56536

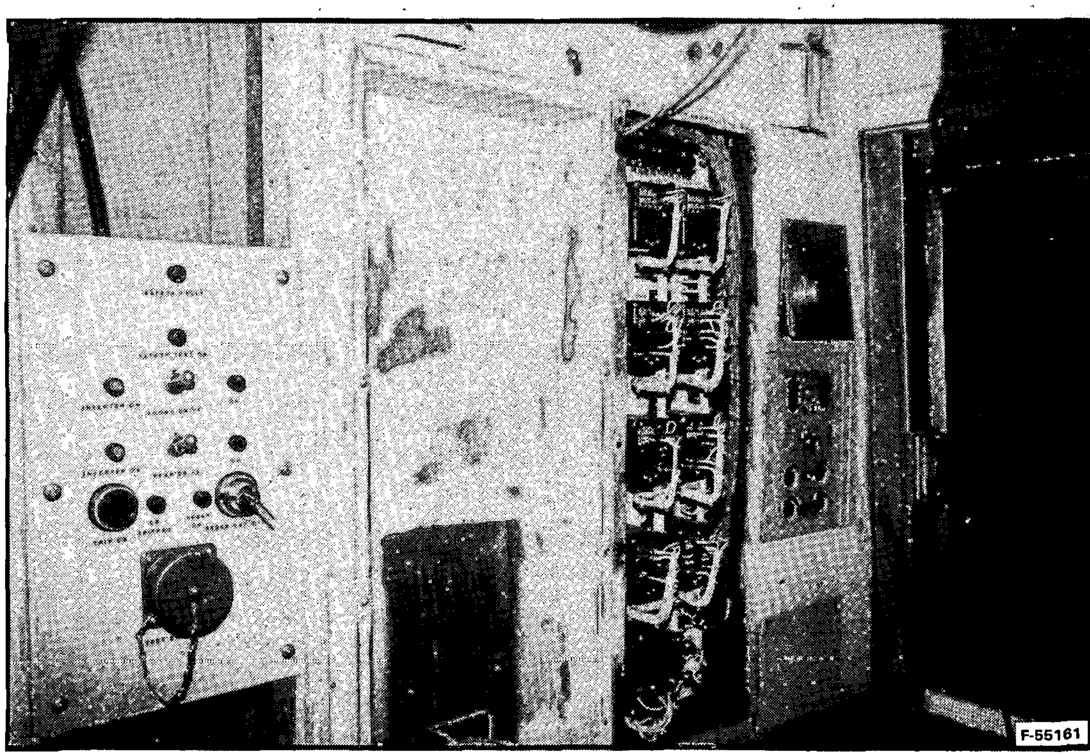
FIGURE 3-14. LINE FILTER UNIT INSTALLATION



F-56530

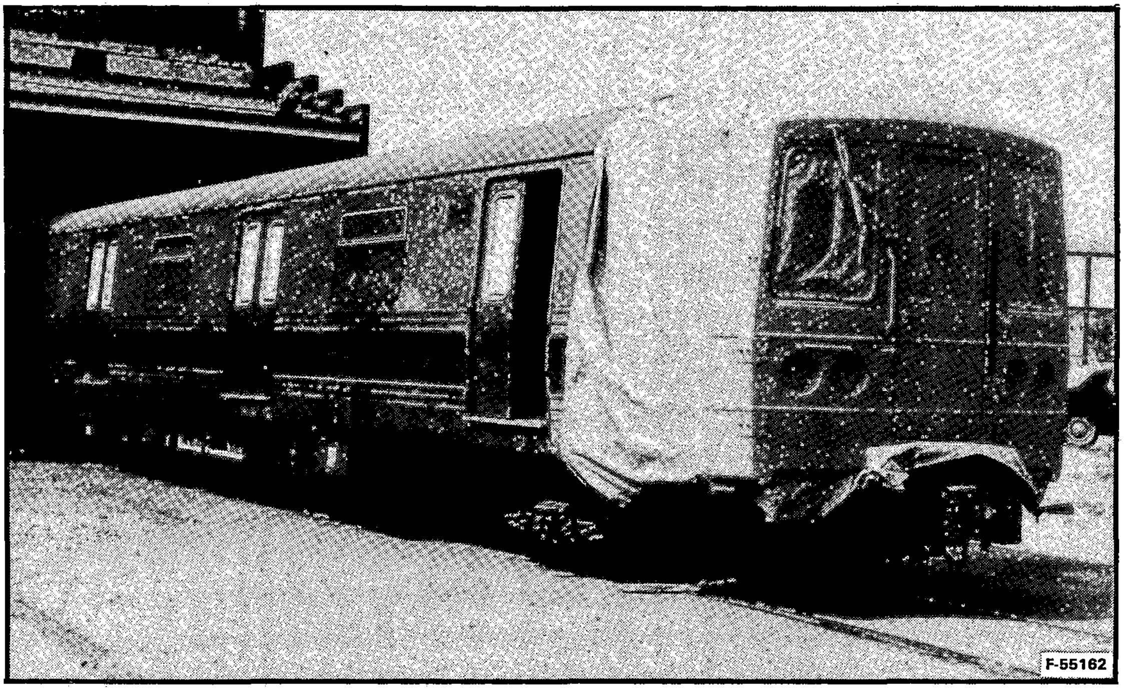
FIGURE 3-15. BRAKE RESISTOR INSTALLATION

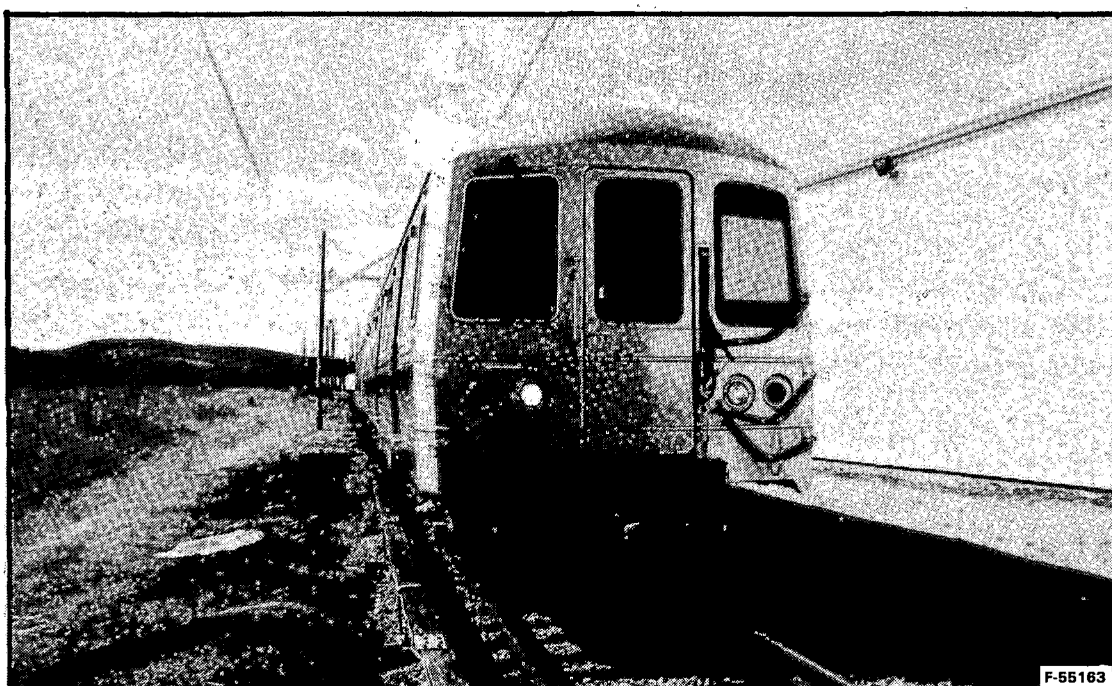




F-56531

FIGURE 3-16. CONTROLS INSTALLATION IN "A" CAR





F-56534

FIGURE 3-17. AC CARS FINAL PREPARATION AND ROLLOUT

Figure 3-18 shows the R-44 undercar frame. The ac equipment layout diagram is shown in Figure 3-19. Figure 3-20 shows the ac equipment stress analysis model used for the finite-element analysis of Figure 3-21. The safety-hung equipment mounting concept is illustrated by Figures 3-22 and 3-23, which show details of the line filter and line control unit mounting arrangements.

3.3 INITIAL SYSTEM TESTS AT HORNELL

System and vehicle "shakedown" checkout and performance tests were conducted on the ac-equipped cars at the Morrison-Knudsen Hornell facilities. The testing was conducted by Stromberg personnel with the assistance of AiResearch and Morrison-Knudsen. Also performed at the Hornell site were tests of radiated and conducted EMI levels and an ac car weight balance analysis.

3.3.1 System Shakedown and Performance Tests

The ac propulsion system and vehicle installation checkout activities included checks of the following areas, all of which were shown to be satisfactory, verifying correct installation and operation.

(a) RC-snubber capacitors replacement

(b) Installation

(c) Wiring--power control unit (PCU) to inverter drive units

(d) Insulation resistance (1000-v megger)

  (1) PCU wiring to ground

  (2) Inverter signal wiring to ground

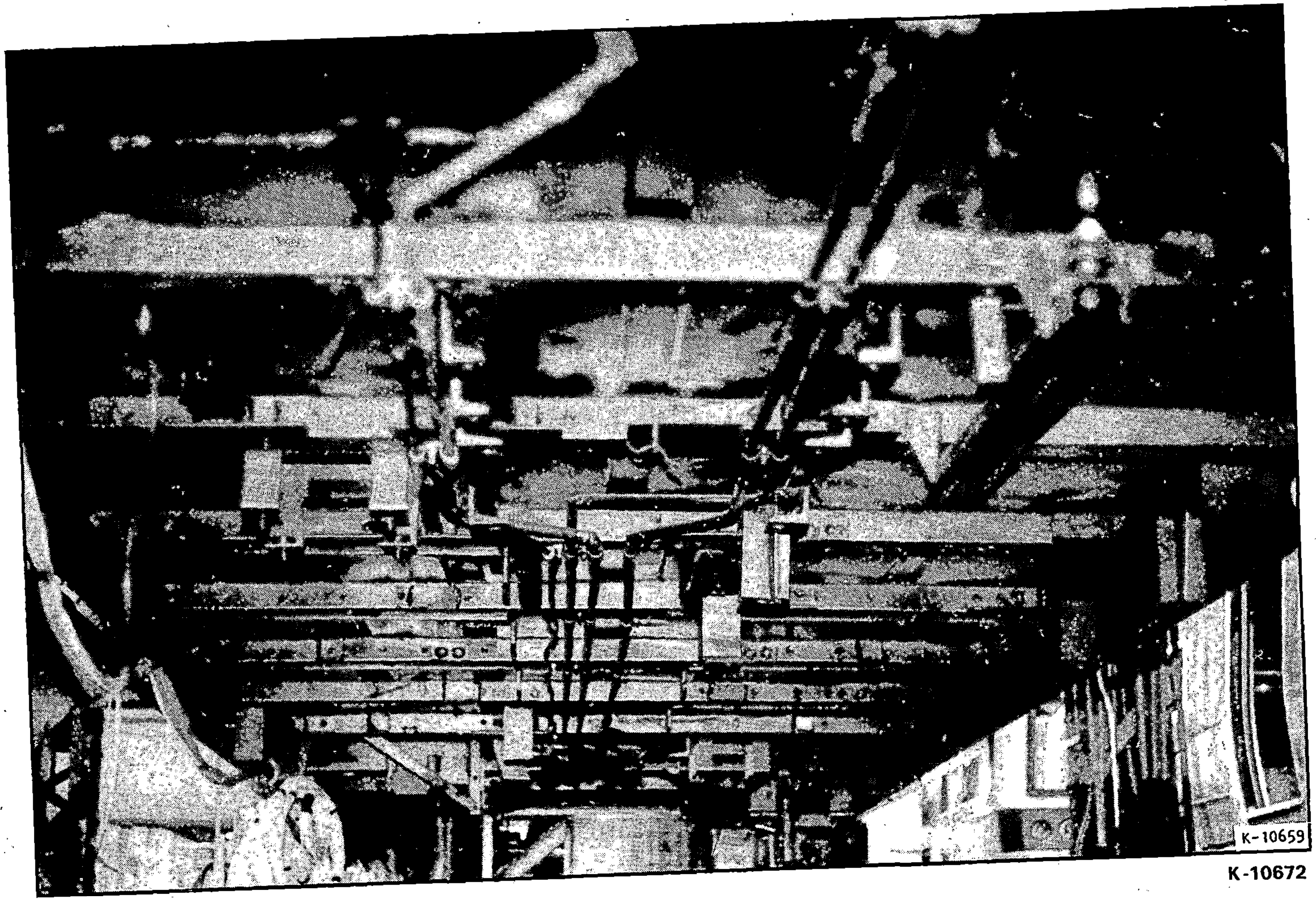
(e) Battery voltage (PCU)

(f) System operation at low voltage (about 100 v)

(g) Input interface

  (1) Car controls to PCU

  (2) Adjustment of P- and load-weigh signals



K-10672

FIGURE 3-18. R-44 CAR UNDERFRAME

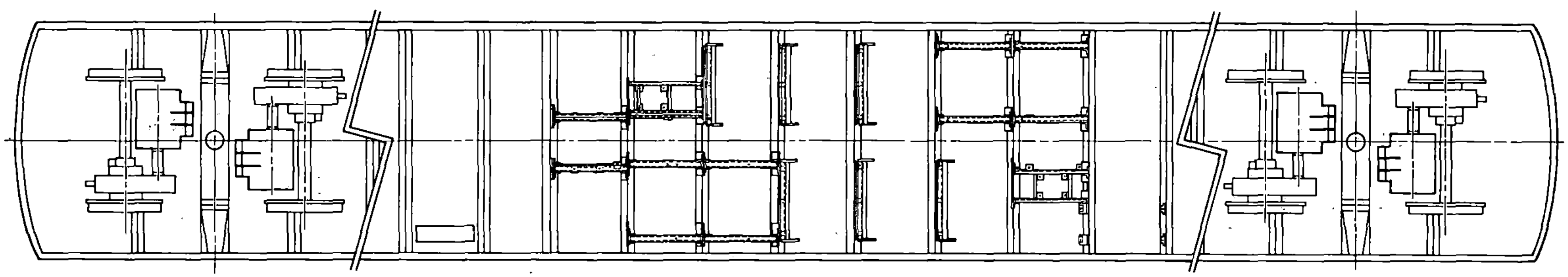
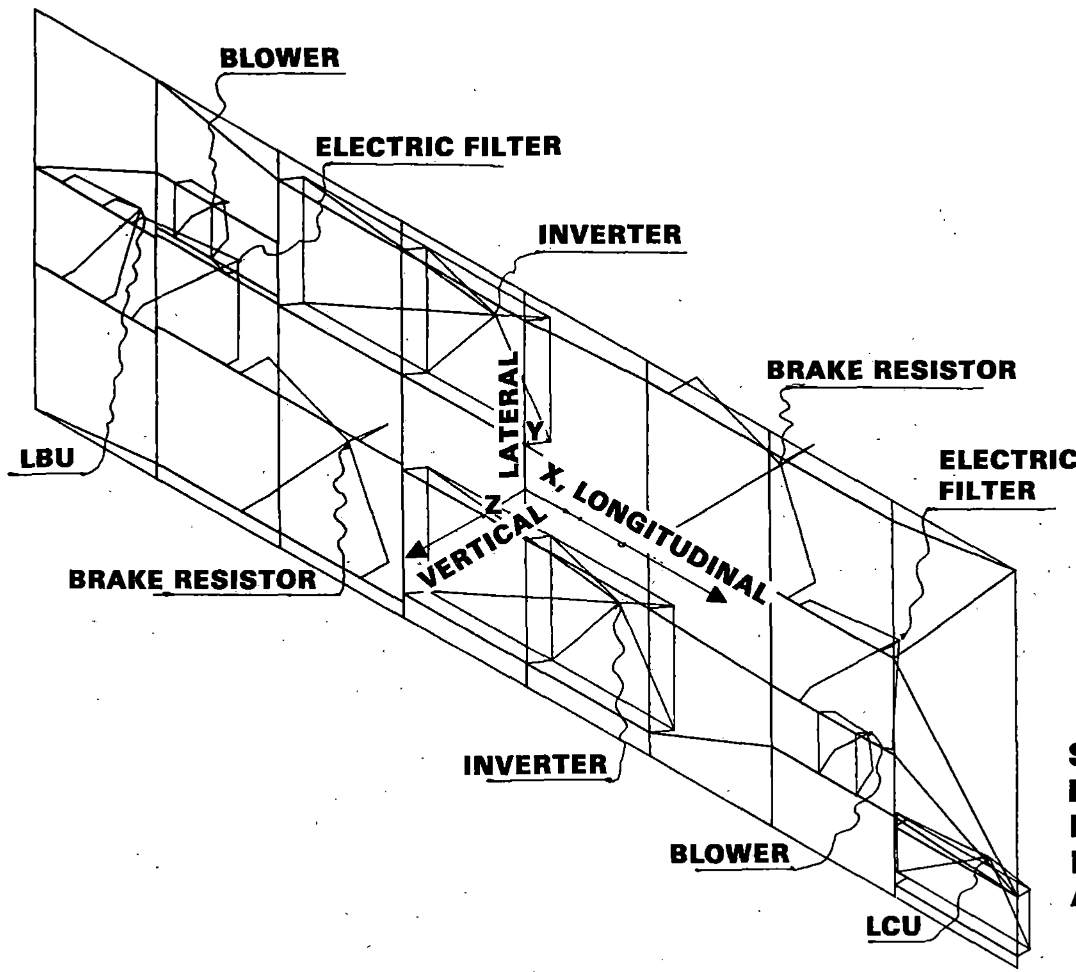


FIGURE 3-19. AC EQUIPMENT FRAMING LAYOUT



- **DESIGN LOADS**

VERTICAL	1.0 ± 0.3g
LATERAL	± 0.5g
LONGITUDINAL	± 1.0g

- **ULTIMATE LOADS**

VERTICAL	1.0 ± 0.3g
LATERAL	± 0.5g
LONGITUDINAL	± 2.0g

- **DESIGN CRITERIA**

AW3 = 279 OCCUPANTS WITH FLOOR PRESSURE OF 100 x 1.3 LB/FT^2

AW0 = NO CREW OR PASSENGERS OR FLOOR LOAD

STARS AC DRIVE DYNAMIC FINITE ELEMENT MODEL ISOMETRIC VIEW LOOKING UP AT EQUIPMENT

X-12032

FIGURE 3-20. R-44 AC EQUIPMENT STRESS ANALYSIS MODEL

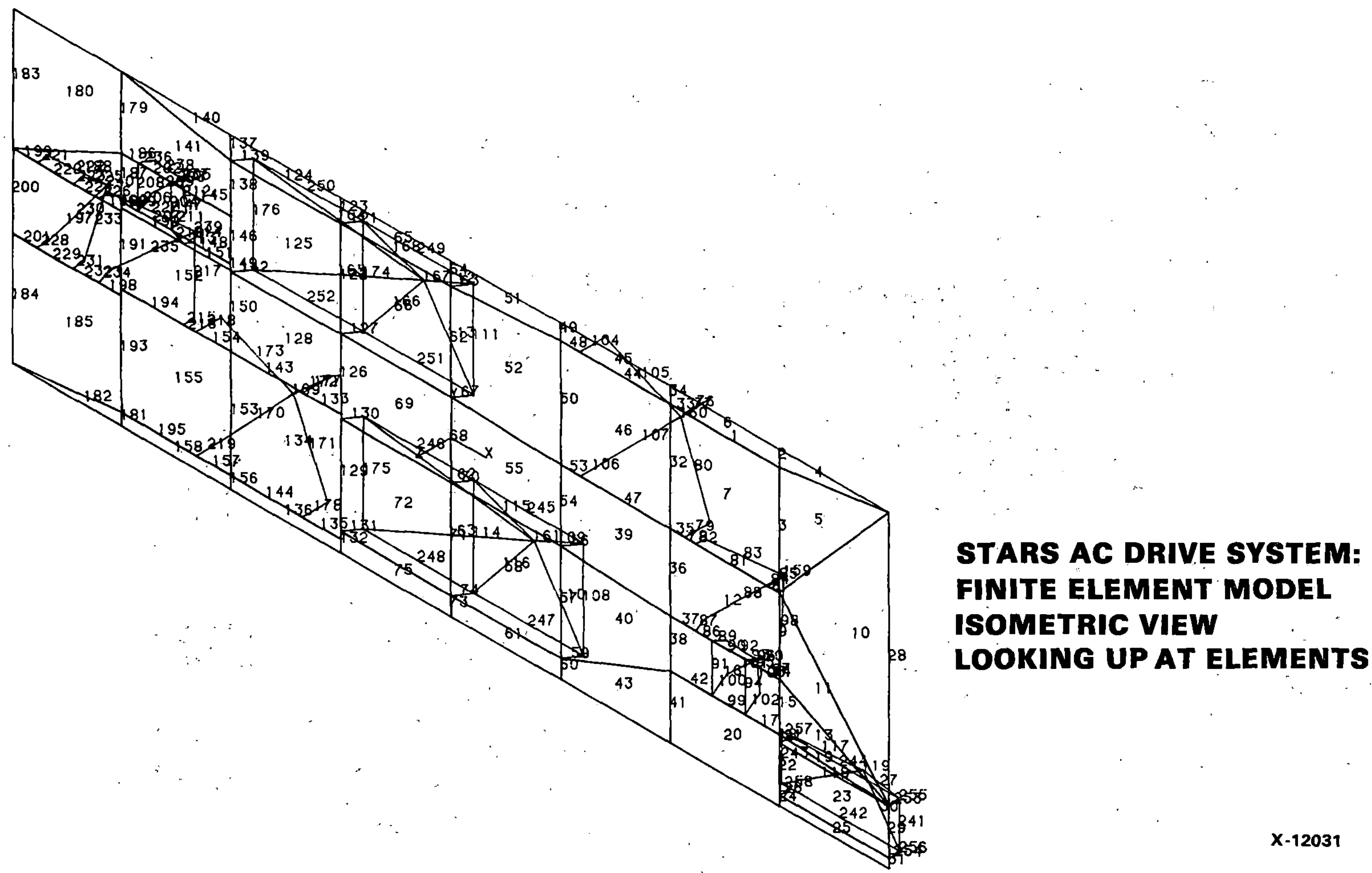
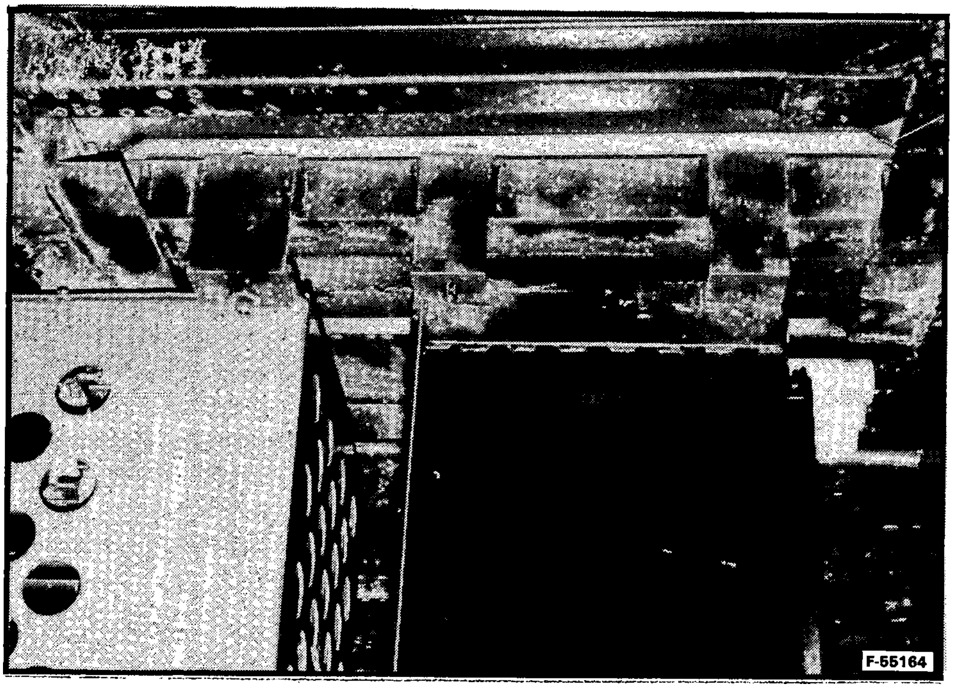
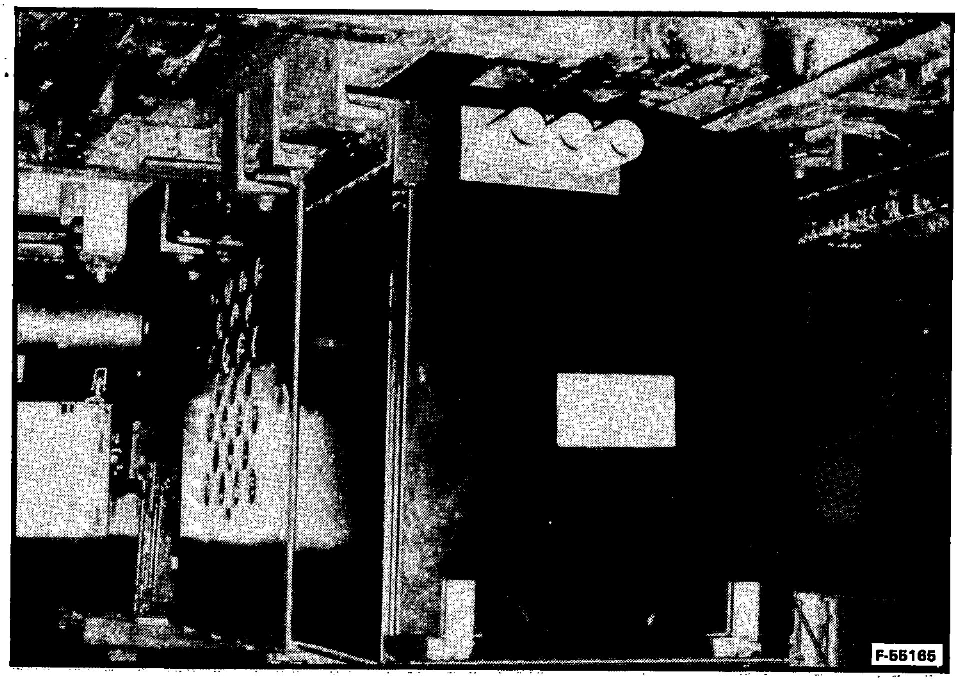


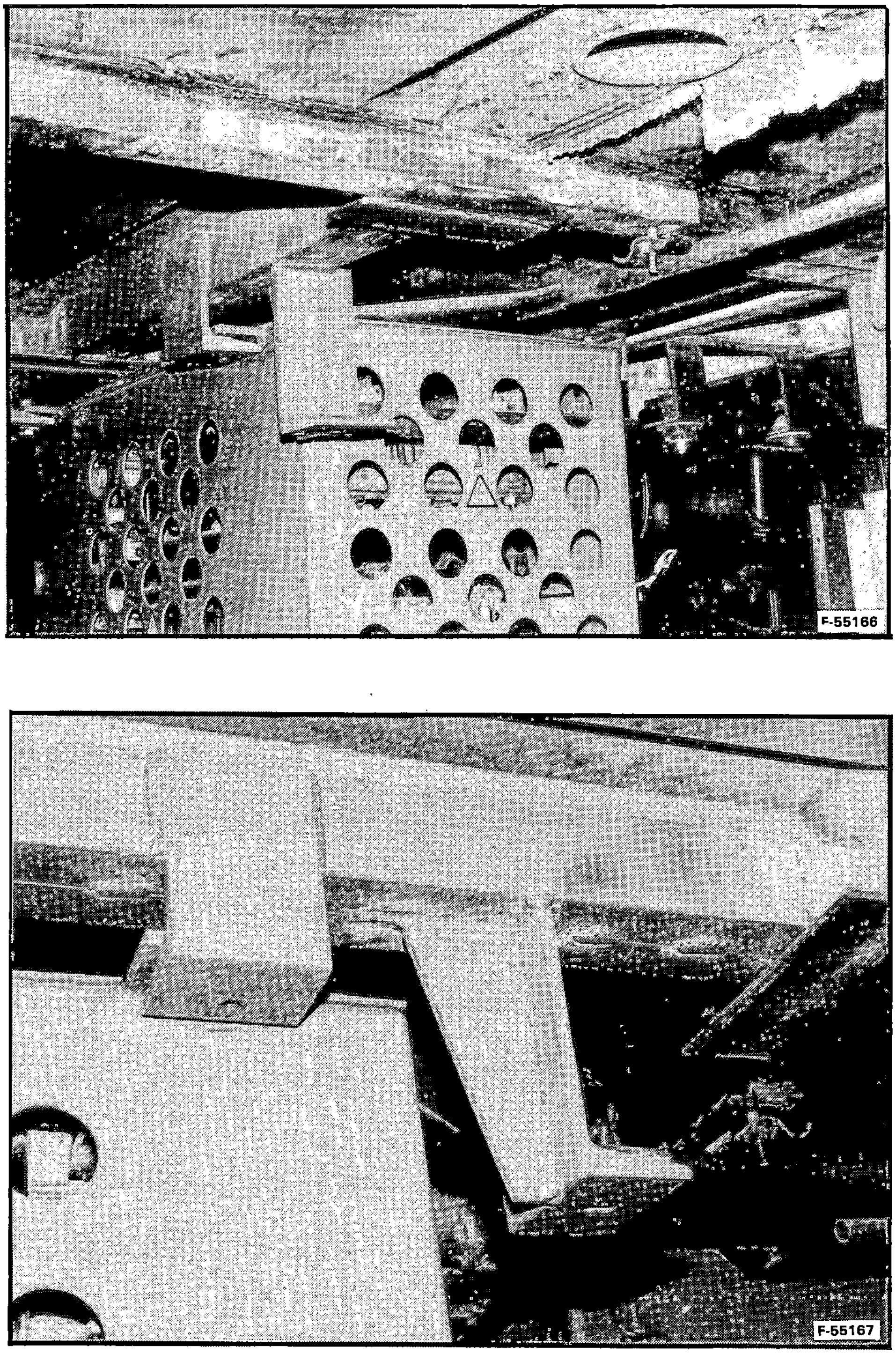
FIGURE 3-21. R-44 FINITE ELEMENT MODEL OF EQUIPMENT LOADING NODES





F-56533

FIGURE 3-22. LINE FILTER UNIT AND LINE CONTROL UNIT BEING SAFETY-HUNG UNDER CAR



F-56532

FIGURE 3-23. SAFETY-HUNG CONCEPT INCORPORATED INTO STARS AC EQUIPMENT

(h) Output interface

    (1) PCU to line control unit

    (2) PCU to friction brakes

    (3) Trippings

(i) System charging (600 v) voltage transducer signals

(j) Driving against parking brakes

    (1) Speed sensor signals

    (2) Direction

    (3) Starting

    (4) Current transducer signals (disturbance levels)

Tests on the Morrison-Knudsen test track included:

(a) Acceleration with various drive notches

    (1) "Stromberg" mode

    (2) Operation with one and both units

    (3) Speed starts

    (4) Jerk limiting

(b) Stability check

    (1) Line current ripple

    (2) UC voltage stability

    (3) Effect of one and both units

    (4) Effect of line chopper

    (5) Effect of line voltage

(c) Electrical braking

    (1) Nonregenerative braking

    (2) Regenerative braking (using the other car as a receptivity simulator)

    (3) Effect of line receptivity

(4) System stability

(5) Speed starts

(6) Braking down to standstill (brake fade)

(7) Checking and adjustment of changeover to friction brake at minimum speed

(8) Jerk limiting

(d) Emergency braking

(1) Electrical brake to emergency brake

(2) Recovery after emergency brake

(e) Changeover to friction brakes in fault situation

(f) Cutout of one of the units

(1) Acceleration with one unit only

(2) Braking with friction brakes only

(g) Safety alarms, braking

(1) Brake supervisions

(2) Changeover to friction brakes

(3) System shutdown

(h) Backwards sliding at starting

(i) Effect of load weighing on car performance

(j) R-44 performance notches

(k) Line gaps

(1) Drive mode

(2) Brake mode

(l) Spin/slide tests

The initial performance tests also demonstrated satisfactory operation of the ac-equipped cars, providing assurance of readiness for the more stringent NYCTA Sea Beach testing that followed.

3.3.2 Radiated and Conducted EMI Testing

The two ac-equipped R-44 cars were tested at Hornell in conjunction with the two R-44 dc cars to establish comparative data on radiated and conducted EMI from the ac propulsion system equipment. The test was limited in scope due to the location and condition of the test track. The Morrison-Knudsen third-rail test track was inspected and repaired prior to the EMI tests to bring it up to NYCTA standards for negative bonding. The track preparation involved negative bond repair and replacement, installation of insulated switch rods, and installation of insulated rail joints (see Figure 3-24). The major accomplishment in the radiated EMI area was to verify that the ac propulsion system-generated EMI levels are not excessive in comparison to dc-propelled cars and would not be expected to affect track signalling circuit operation or the operation of onboard electronics, or to cause high levels of local rf interference to communications. The conducted EMI tests showed that the ac propulsion system built-in filtering reduces conductive EMI to levels well below those that would interfere with normal operation of power frequency track circuit relays.

F-56560

FIGURE 3-24. TYPICAL INSULATED JOINT INSTALLED IN MORRISON-KNUDSEN TEST TRACK FOR EMI, SIGNALLING TESTS

3.3.2.1 Radiated EMI Testing

Tests were performed by DOT/UMTA personnel, with assistance by the NYCTA and AiResearch, using DOT/UMTA equipment to measure radiated EMI levels at the simulated station location while the cars were operated on the Morrison-Knudsen test tracks. The car loading was at empty weight (AWO).

The tests included EMI measurements for five different combinations of receiving antenna configuration and frequency band, covering the frequency range from 115 kHz to 1000 MHz:

(a) Stub antenna, orientation perpendicular to ground: 115 kHz to 30 MHz

(b) Biconical antenna, orientation perpendicular to ground: 20 to 200 MHz

(c) Biconical antenna, orientation parallel to ground: 20 to 200 MHz

(d) Log-periodic antenna, orientation plane perpendicular to ground: 200 to 1000 MHz

(e) Log-periodic antenna, orientation plane parallel to ground: 200 to 1000 MHz

Ambient EMI levels were measured with third-rail power turned off and with third-rail power turned on, and with ac propulsion auxiliaries turned off and turned on, to establish background EMI levels in the ranges of interest. The tests up to 200 MHz included measurements of EMI during the following performance conditions for both ac and dc cars; above 200 MHz, these tests were performed for the ac cars only:

(a) Maximum acceleration towards plant

(b) Full braking away from plant

Complete data for the radiated EMI tests of the ac and dc cars are presented in DOT/UMTA Report UMTA-MA-06-0153-85-10 (DOT-TSC-UMTA-88-1). Salient results are summarized here.

Below 12 MHz, the ac propulsion system generally exhibited lower levels of EMI than the dc propulsion system over the measured frequency bands during both acceleration and braking. Only in the range from 12 to 30 MHz were the ac propulsion EMI levels higher on average than the dc levels (by about 5 to 10 dB). Above 20 MHz, the ac and dc emission measurements were essentially identical, showing no significant radiated EMI above ambient.

Figures 3-25 through 3-27 present representative EMI traces obtained by DOT/UMTA. Similar data were recorded for the remainder of the tests.

The test results show that the ac propulsion system did not create EMI levels that would be expected to adversely affect track circuit signalling circuits, the operation of onboard electronics, or of communications.

3.3.2.2 Conducted EMI Testing

Conducted EMI tests also were performed at Hornell by DOT/UMTA in a cooperative effort with the NYCTA and AiResearch. These tests were reported in a June 1987 paper by F. Ross Holmstrom of the DOT/UMTA Transportation Systems Center, from which the following information is derived. Figure 3-28 shows the layout of the Hornell test track, where tests were made under conditions of maximum acceleration and dynamic braking. Car loading was at empty weight (AWO). Track circuits had worst-case single-rail geometry.

EMI levels produced by the ac propulsion system-equipped cars were observed and recorded, and the response of the power-frequency track circuit relays to the ac cars was observed directly. The results of these initial tests demonstrated that the filtering built into the ac propulsion system reduced EMI to levels well below those that would interfere with normal operation.

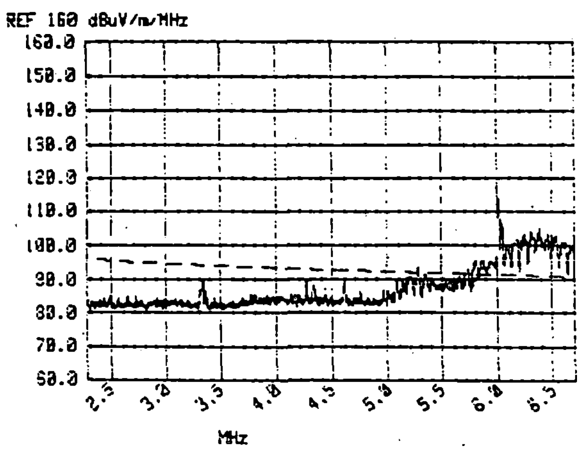
Visual observations during train operation showed that slight motions of the track relay rotor or vane sometimes occurred, but not enough to open the contact set that was closed at the time. A possible cause of such slight

ANTENNA - VERTICAL RVR-25 S/N 565 - BALUN POSITION= 8
Antenna orientation:Perp GROUND.

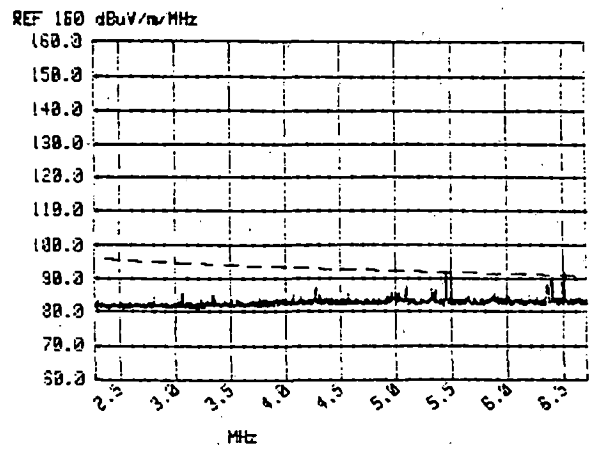
START 2.269 MHz STOP 6.704 MHz
RES BW 10 kHz VBW 10 kHz SWP 100 msec ATTEN 10 dB
NO FILTERS USED

REMARKS: TRACES WERE OBTAINED IN PEAK HOLD FOR 3 SECONDS.

AMBIENT WITH THIRD RAIL POWER OFF



AMBIENT WITH THIRD RAIL POWER ON.



AC TRAIN PROPULSION OFF AUXILIARYS ON.

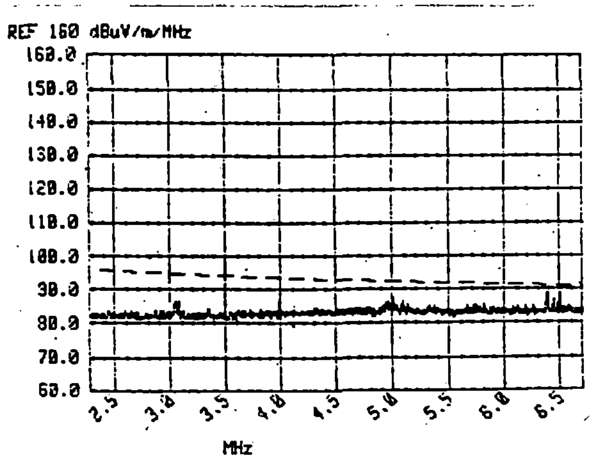


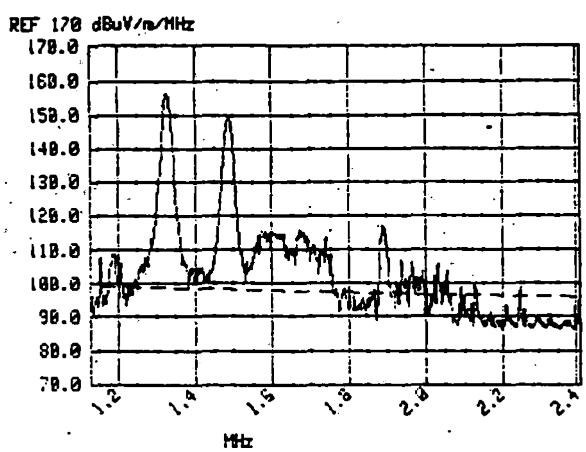
FIGURE 3-25. TYPICAL EMI BACKGROUND LEVEL TRACES (DOT/UMTA DATA)

ANTENNA - VERTICAL RVR-25 S/N 565 - BALUN POSITION= 7
Antenna orientation:Perp GROUND.

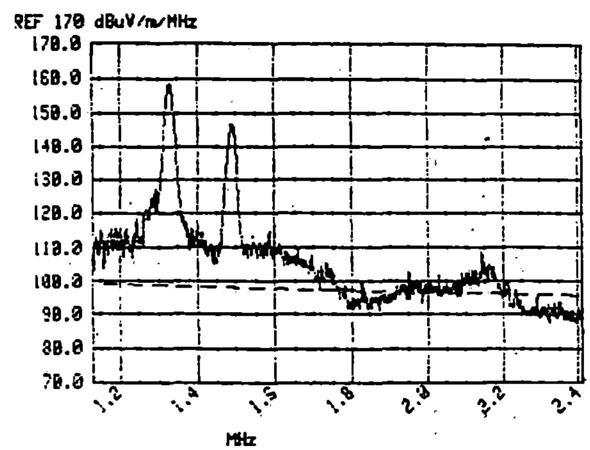
START 1.128 MHz STOP 2.411 MHz
RES BW 10 kHz VBW 10 kHz SWP 30 msec ATTEN 10 dB
NO FILTERS USED

REMARKS: TRACES WERE OBTAINED IN PEAK HOLD FOR 3 SECONDS.

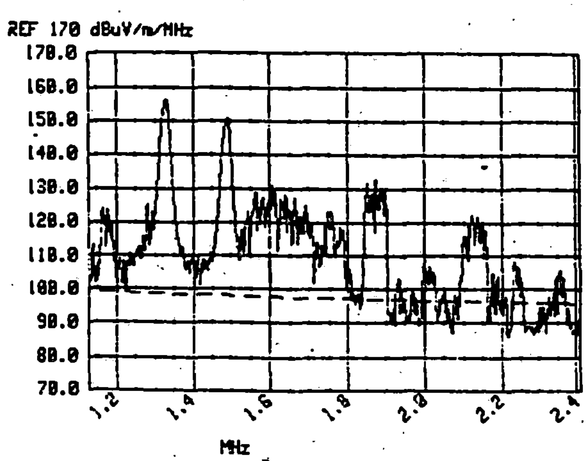
MAX. ACCEL. OF DC CARS TOWARDS PLANT.



MAX. ACCEL. OF AC CARS TOWARDS PLANT.



FULL BRAKING OF DC CARS AWAY FROM PLANT



FULL BRAKING OF AC CARS AWAY FROM PLANT.

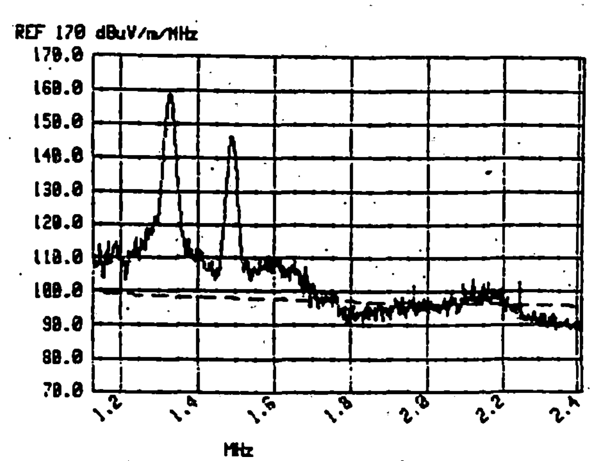


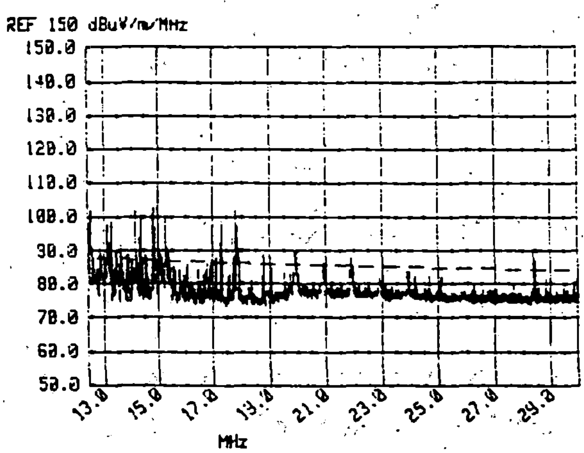
FIGURE 3-26. TYPICAL EMI MEASUREMENTS (IN 1- TO 3-MHZ RANGE) FOR DC AND AC CARS (DOT/UMTA DATA)

ANTENNA - VERTICAL RVR-25 S/N 565 - BALUN POSITION= 10
Antenna orientation:Perp GROUND.

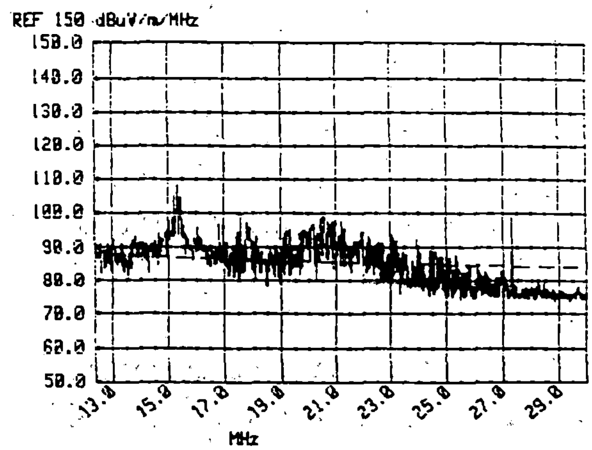
START 12.39 MHz STOP 30.00 MHz
RES BW 10 kHz VBW 10 kHz SWP 500 msec ATTEN 10 dB
NO FILTERS USED

REMARKS: TRACES WERE OBTAINED IN PEAK HOLD FOR 3 SECONDS.

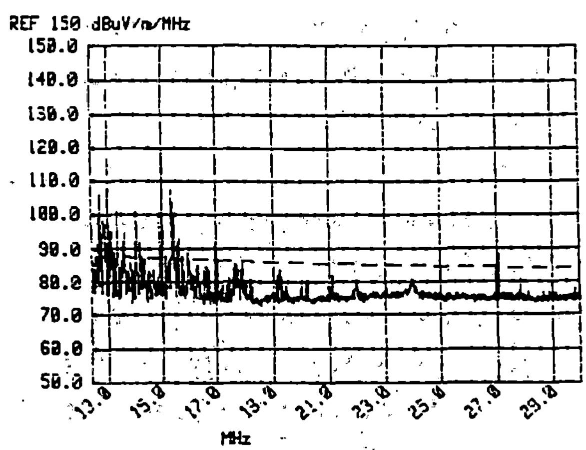
MAX. ACCEL. OF DC CARS TOWARDS PLANT.



MAX. ACCEL. OF AC CARS TOWARDS PLANT.



FULL BRAKING OF DC CARS AWAY FROM PLANT.



FULL BRAKING OF AC CARS AWAY FROM PLANT.

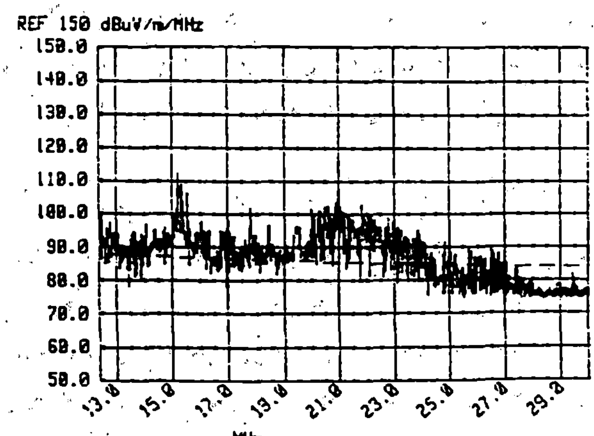


FIGURE 3-27. TYPICAL EMI MEASUREMENTS (IN 12- TO 30-MHZ RANGE) FOR DC AND AC CARS (DOT/UMTA DATA)

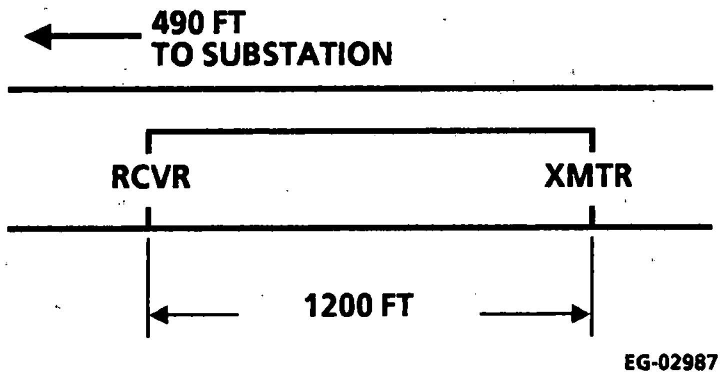


FIGURE 3-28. HORNELL MORRISON-KNUDSEN EMI TEST TRACK SETUP

motion is the dc voltage transient at the track relay that occurs when a train goes from rest into maximum acceleration at the transmitter end of a track circuit. In a track circuit 1200 ft long, an 8-v step was observed across the track terminals at the receiver end, due to the IZ drop in the dc return rail, when the train's main circuit breakers closed. Since similar responses were caused by a cam-controlled dc-propulsion carset and by a 9-v battery whose leads were tapped against the track leads of the track receiver, this problem was not ascribed to the ac propulsion system under test.

During testing, high-quality audio tape recordings were made of the track circuit signals and conductive interference signals present at the track terminals of the track receiver circuit. FM recording was used to ensure record-playback accuracy down to essentially zero frequency. Later, in the laboratory, the signals were played back into an FFT spectrum analyzer, and into a swept-frequency spectrum analyzer operated as a fixed-frequency narrow-band filter-detector. In each case, the spectrum analyzer drove an X-Y plotter that produced hard-copy output.

Figure 3-29 shows the detected signal at the track terminals of a balanced double-rail 60-Hz track circuit receiver, as observed by playing back a tape recording into the fixed-frequency narrow-band filter detector. In this case, the center frequency was 60 Hz, the resolution bandwidth was 10 Hz, and a linear scale for detected signal amplitude was used. The train started from rest inside the signal block at the receive end and accelerated toward the transmit end. A slight "blip" is observed, presumably when the sixth harmonic of the inverter frequency tunes through 60 Hz. However, peak amplitude of this blip is approximately 3 percent of that of the working track signal level, which is observed after the train runs out of the block. Figure 3-30 shows the detected signal from the same run as Figure 3-29, but on a log scale. Figure 3-31 shows a similar plot obtained using a center frequency of 25 Hz during testing of a 25-Hz single-rail track circuit. Absolute worst-case conductive interference levels were obtained in all of these runs by temporarily disconnecting the track receiver circuit.

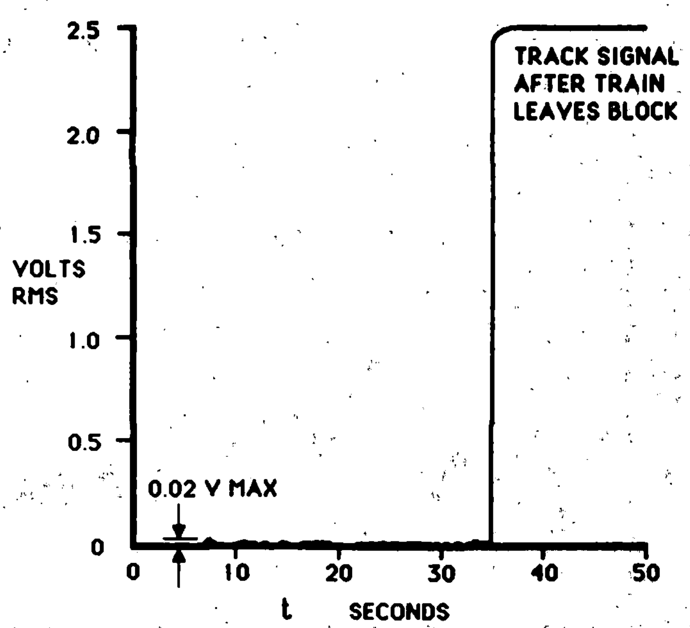


FIGURE 3-29. CONDUCTIVE INTERFERENCE SIGNAL AT 60-HZ CENTER FREQUENCY, 10-HZ RESOLUTION BANDWIDTH, TRAIN STARTED FROM REST IN BLOCK, MAX. ACCELERATION

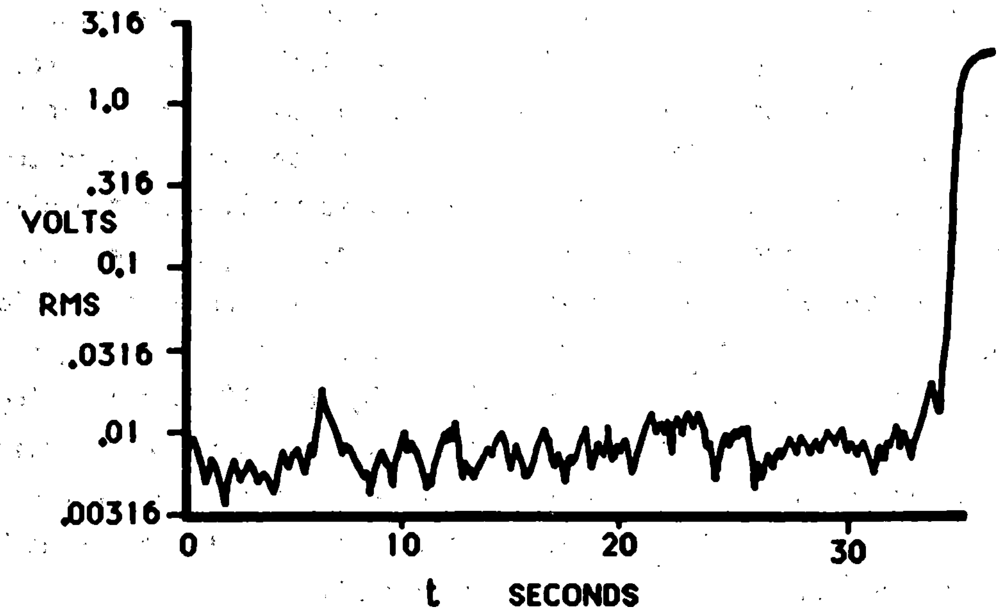


FIGURE 3-30. SAME RUN AS PRECEDING FIGURE, PLOTTED ON LOG SCALE

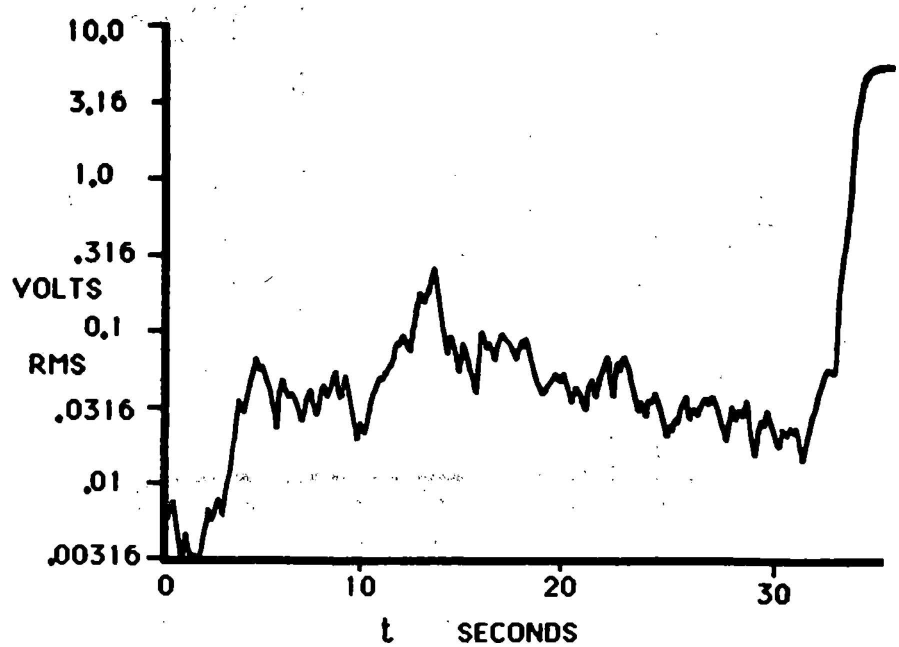


FIGURE 3-31. CONDUCTIVE INTERFERENCE SIGNAL AT 25-HZ CENTER FREQUENCY, 10-HZ RESOLUTION BANDWIDTH, TRAIN STARTED FROM REST IN BLOCK

Results no more dramatic than this were obtained from the analysis of regenerative braking recordings and recordings made while the train cycled repeatedly from acceleration to braking to acceleration to braking. Figure 3-32 shows the signals observed at 60 Hz during a regenerative braking run over the circuit of Figure 3-29, and Figure 3-33 shows the signals observed during a repetitive acceleration-brake, acceleration-brake run over a worst-case single-rail 25-Hz track circuit.

As the ac cars were operated in the test described above, the observed levels of power-frequency conducted interference can be described either as nearly insignificant or barely detectable.

3.3.3 Weight Balance Summary

As a prerequisite to ac car demonstration testing on the NYCTA property, the final activity performed at Hornell was a Transit Authority-required truck weighing test to record wheel weight distribution. The test requirements were outlined in a letter from NYCTA dated March 5, 1986, and the tests were performed by Morrison-Knudsen personnel with AiResearch and NYCTA witnessing the tests. The test objective initially was to show car front/rear truck weight balance within 500 lb.

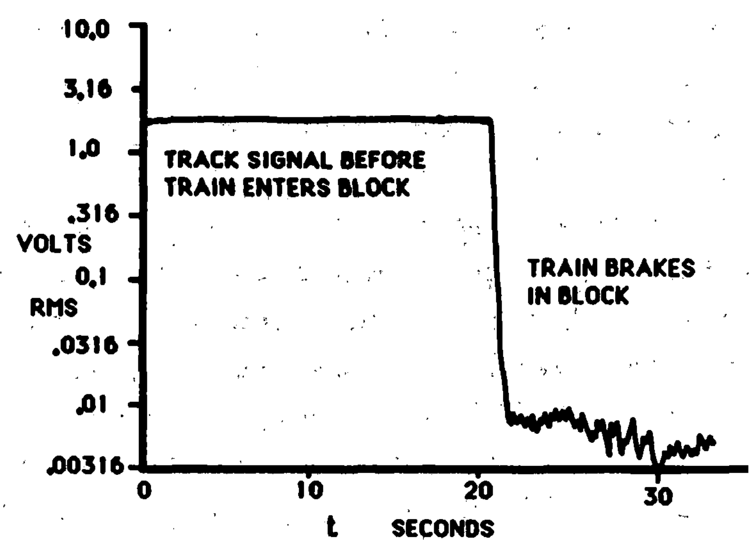


FIGURE 3-32. CONDUCTIVE INTERFERENCE SIGNAL AT 60-HZ CENTER FREQUENCY, 10-HZ RESOLUTION BANDWIDTH, DURING REGENERATIVE BRAKING

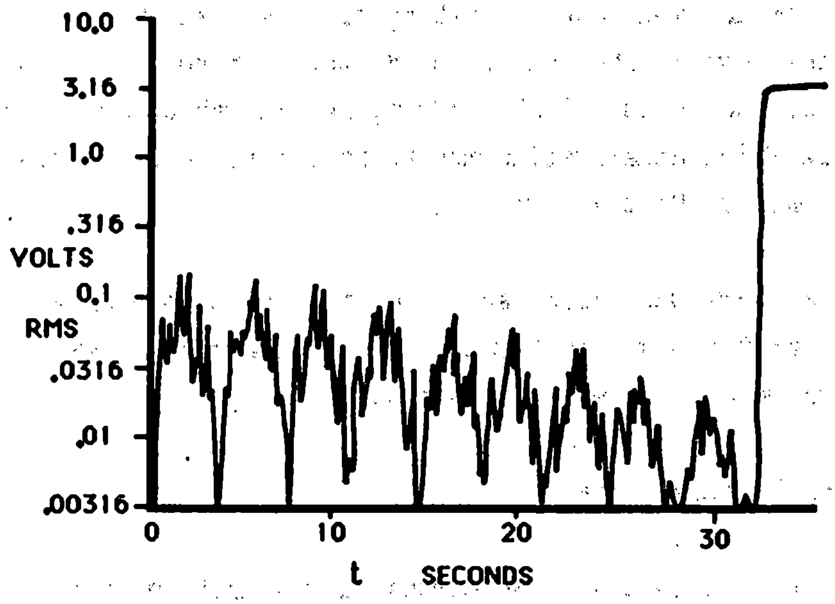


FIGURE 3-33. CONDUCTIVE INTERFERENCE SIGNAL AT 25-HZ CENTER FREQUENCY, 10-HZ RESOLUTION BANDWIDTH, DURING REPEATED MAX. ACCELERATION AND REGENERATIVE BRAKING

The initial weighings showed the "B" car to be within balance requirements; however, the "A" car appeared to be out of balance in excess of the 500-lb limit specified by NYCTA, with the forward (cab) end being heavier. A second weighing using a car-body-only, three-point suspension method (car body isolated from trucks) suggested by NYCTA also showed an "A" car out-of-balance condition front to rear with repeated measurements averaging 1733 lb.

The reason for this degree of imbalance was not immediately evident from review of the AiResearch weight/balance drawings for the ac cars. Upon further investigation, however, it was determined that the original St. Louis Cars R-44 dc cars delivered to NYCTA were out of balance in the same manner by a significant amount (over 2000 lb). Therefore, in agreement with NYCTA, no further attempts were made to adjust ac car balance beyond moving the "A" car 760-lb line filter/brackets from a location forward of the car centerline to a position at the rear of the car compressor (approximately 20 ft to the rear of the car centerline).

4. PHASE IIb NYCTA SEA BEACH TESTING

The ac propulsion system demonstration cars and, for comparison, the dc cars were tested on the NYCTA rail system. The tests were conducted on the Sea Beach section of the NYCTA Coney Island line. The primary purpose of these property tests was to demonstrate the operation, performance, and reliability of the ac propulsion system in the environment of the NYCTA. Some of the objectives of this test program were to:

(a) Investigate interaction and interface with NYCTA wayside and signalling systems.

(b) Determine the interaction of the ac propulsion system cars with the dc propulsion system cars.

(c) Conduct comparison tests between ac propulsion system cars and dc propulsion system cars in accordance with the R-44 car performance specification.

(d) Allow operators of the cars to gain experience.

(e) Obtain experience on maintenance of the ac propulsion system in the car.

(f) Conduct special tests to gain experience on ac propulsion system equipment behavior under simulated abnormal conditions.

(g) Determine public acceptance of ac propulsion system cars.

(h) Evaluate NYCTA upgraded R-44 car modifications.

4.1 SEA BEACH FACILITY DESCRIPTION

All of the Phase IIb demonstration testing, except for the energy consumption testing, was accomplished using the Sea Beach section of Track E3, located between the south end of the New Utrecht Avenue station and 20th Avenue. The energy consumption tests were conducted on the "GG" revenue service line between Continental Avenue/Forest Hills and Smith-9th Street. The dead rail detector performance evaluation with regeneration was conducted on the "A" line, end-to-end.

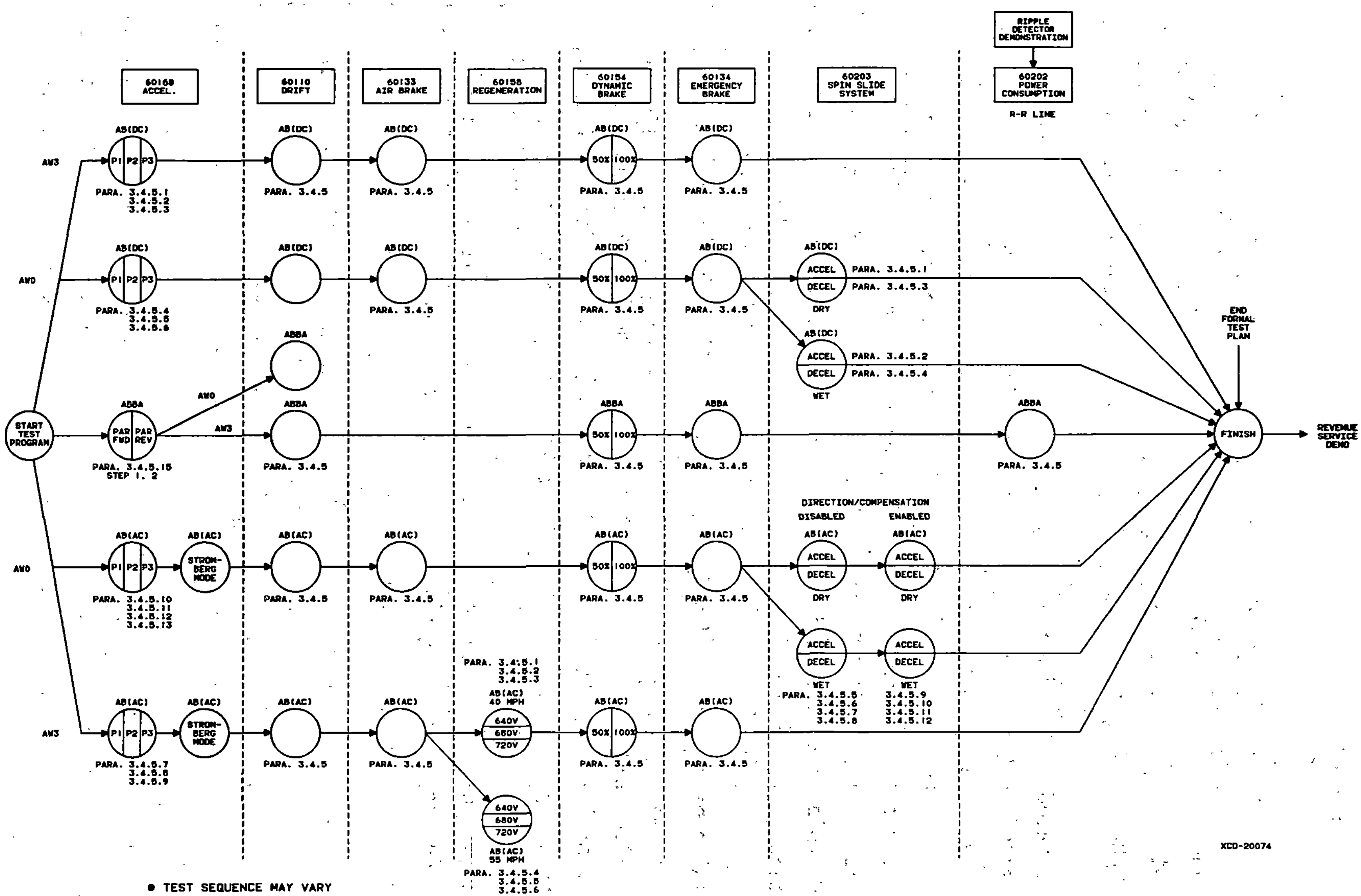
4.2 LIST OF TESTS CONDUCTED

The Phase IIb test program (Figure 4.2-1) included ac and dc car performance testing as well as signalling circuit compatibility tests and dead-rail (ripple) detector and gap detector circuit tests, and culminated in revenue service demonstration tests.

As indicated in the diagram of Figure 4.2-1, tests were performed on both ac and dc mated "AB" car pairs, as well as on a four-car "ABBA" train consist, made up of two ac and two dc cars operated together and with other dc cars to form a revenue service train. An AB car pair, consisting of one "A" car and one "B" car, represents the smallest operating train, with the "A" car having the cab. Tests were performed with ballast in the cars to simulate the fully loaded (AW3 weight) configuration, and with empty cars (AWO weight configuration).

The mated pair of NYCTA Model R-44 "A" and "B" vehicles having ac propulsion systems is a consist represented by "AB(ac)" in this document. The companion mated pair of "A" and "B" vehicles having dc propulsion systems is represented by "AB(dc)." Mating AB(ac) and AB(dc) together forms a four-vehicle consist joined at the "B" vehicles and is represented by ABBA.

The tests conducted provided a direct comparison of the ac- and dc-equipped R-44 cars under essentially identical conditions.



- TEST SEQUENCE MAY VARY
- EMI-SIGNALLING TESTS TO BE ON SEPARATE SCHEDULE

FIGURE 4.2-1. SEA BEACH TEST PROGRAM

4.3 TEST PROCEDURES

The Sea Beach tests were conducted in accordance with test procedures specified in the AiResearch documents and other instructions listed in Table 4.3-1. The paragraph references in Figure 4.2-1 correspond to the applicable paragraph of the listed test procedure for a specific test. Where individual tests were deleted or differed from the procedure requirements, they are explained in the test results summary.

TABLE 4.3-1

TEST PROCEDURES LIST

Test	Test Procedure	
	Doc. No.	Title
Acceleration	86-60168	STARS Acceleration Test Procedure
Drift	86-60110	STARS Ac-Drive Drift Test Procedure
Air brake	86-60133	STARS Ac Drive Deceleration (Air Brake Only) Test Procedure
Regeneration	86-60158	Deceleration Test using Regeneration Dynamic Braking, STARS Ac Drive Test Procedure
Dynamic brake	86-60154	Non-Regenerative Dynamic Deceleration Braking Test, STARS Ac Drive Test Procedure
Emergency brake	86-60134	STARS Ac Drive Deceleration, Emergency Brake Test Procedure
Spin/slide system	86-60203	STARS Ac Drive Test Procedure, Wheel Slip Acceleration/Deceleration Test
Power (energy) consumption	86-60202	STARS ac Drive Test Procedure GG Line Energy Consumption Test
Ripple detector	--	Performed in accordance with NYCTA-specified procedures (see para. 4.4.9)
EMI-signalling	--	DOT/UMTA-specified procedures (see para. 4.4.10)

The Sea Beach performance tests typically were conducted using the instrumentation listed in Table 4.3-2. Data were recorded on magnetic tape as well as strip chart recorders as suited to the test measurements. Specialized equipment used for a specific test is discussed in the applicable test description in the paragraphs that follow.

TABLE 4.3-2

INSTRUMENTATION

Sensor Type	Sensor Location	Parameter	Maximum Value	System Accuracy, percent	Purpose
Monopole	Fwd, rear trucks	Speed	80 mph	±2	(1)
Accelerometer	Inside vehicle	Acceleration	±3 mph/sec	±5	(2)
200:1 voltage divider	Undercar	Line voltage	800 v	±5	(3)
Transfoshunt	Undercar	Line current	±1,500 amp	±5	(3)
Recorders	Inside vehicle	Time	0.1-sec increments	±2	(4)
Track station markers	Trackside	Distance	10-ft increments	±5	(5)
Digital electrical signal	Trainline	Brake command	37 ±5 vdc	±2	(3)
Pressure trans-ducer, 200 psig	Undercar	Brake cylinder pressure	120 psig	±5	(3)
Pressure trans-ducer, 200 psig	Undercar	Straight air-pipe pressure	120 psig	±5	(3)
Kw-hr meter	Undercar	Power	±500 kw	±5	(6)

(1) Required to provide accurate time-speed data (accuracy verified with radar speed calibrator) (also used for distance indication in some cases).

(2) Required for continuous acceleration record.

(3) Required to validate no propulsion or braking.

(4) Required to record responses vs time.

(5) Required for distance measurements--used off-car distance markers. Test zone measured prior to testing.

(6) Required to measure regenerated power (energy).

4.4 TEST PROGRAM SUMMARY

The tests performed at the NYCTA Sea Beach facility are summarized in the following subsections. For each test, the test objectives and procedures are described and the test results discussed. Tabular summaries of reduced test data are provided whenever applicable because of the large volume of recorded data and difficulties associated with reproduction. Typical test data are presented to illustrate significant findings.

The balance of the raw data is retained at AiResearch and is available for on-site review.

4.4.1 Acceleration Tests (Test Procedure 86-60168)

Acceleration tests were conducted to compare the acceleration characteristics of the ac and dc test cars. The tests were conducted on the AB(ac) consist and the AB(dc) consist at each of the master controller settings. Tests were conducted with the cars empty (the AW0 configuration) and with each car fully loaded with 43,000 lb--86,000 lb for each consist (the AW3 configuration). Additional forward and reverse acceleration tests were conducted on the AW3-loaded four-car ac/dc consist ABBA, coupled such that an ac car provided control in the forward direction and a dc car provided control in the reverse direction.

Typical recordings taken during the more critical fully loaded mode (AW3), with the master controller setting in the P1 (PAR) position, are reproduced in Figures 4.4.1-1 through 4.4.1-4.

The results, summarized in Table 4.4.1-1, show that with the cars empty, the acceleration of the ac-driven cars was improved over that of the dc cars by a factor of 1.08 to 1.10. Acceleration tests of the loaded ac cars showed a lower acceleration by a factor of 0.08.

Acceleration of the ABBA consist was improved by a factor of 1.05 with command through the ac master controller.

The tests demonstrated that the ac car consist and the dc car consist accelerations are both slightly below the NYCTA-expected peak acceleration window of 2.5 ±0.25 mph/sec, but ac performance was acceptable, both singly and coupled to the standard NYCTA R-44 dc cars.

To obtain maximum energy conservation, it is recommended that the acceleration and deceleration characteristics of the ac/dc consist be closely matched.

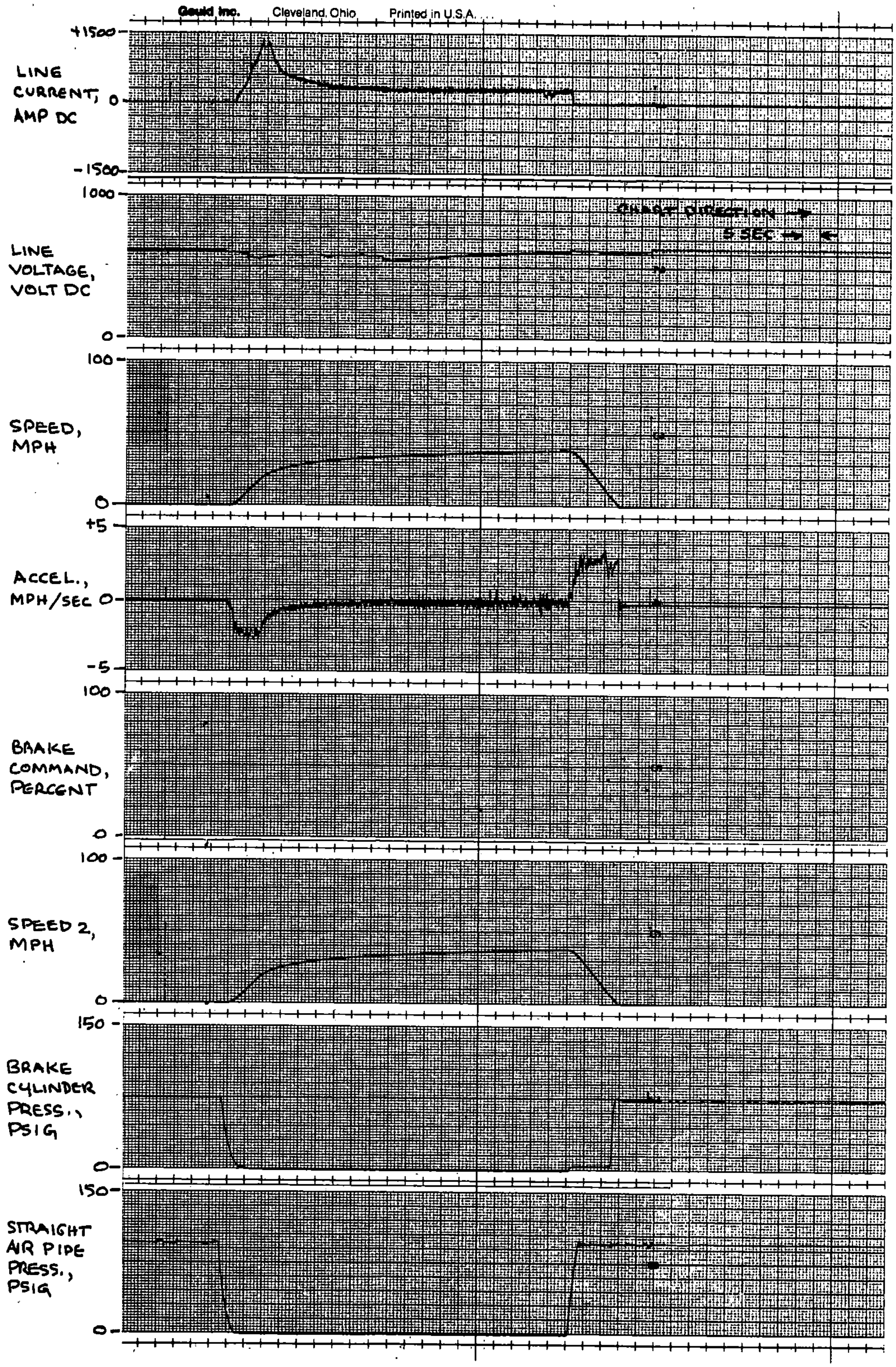


FIGURE 4.4.1-1. AB(AC) CONSIST FORWARD ACCELERATION AWO LOAD, CONTROLLER SET AT PAR (P3)

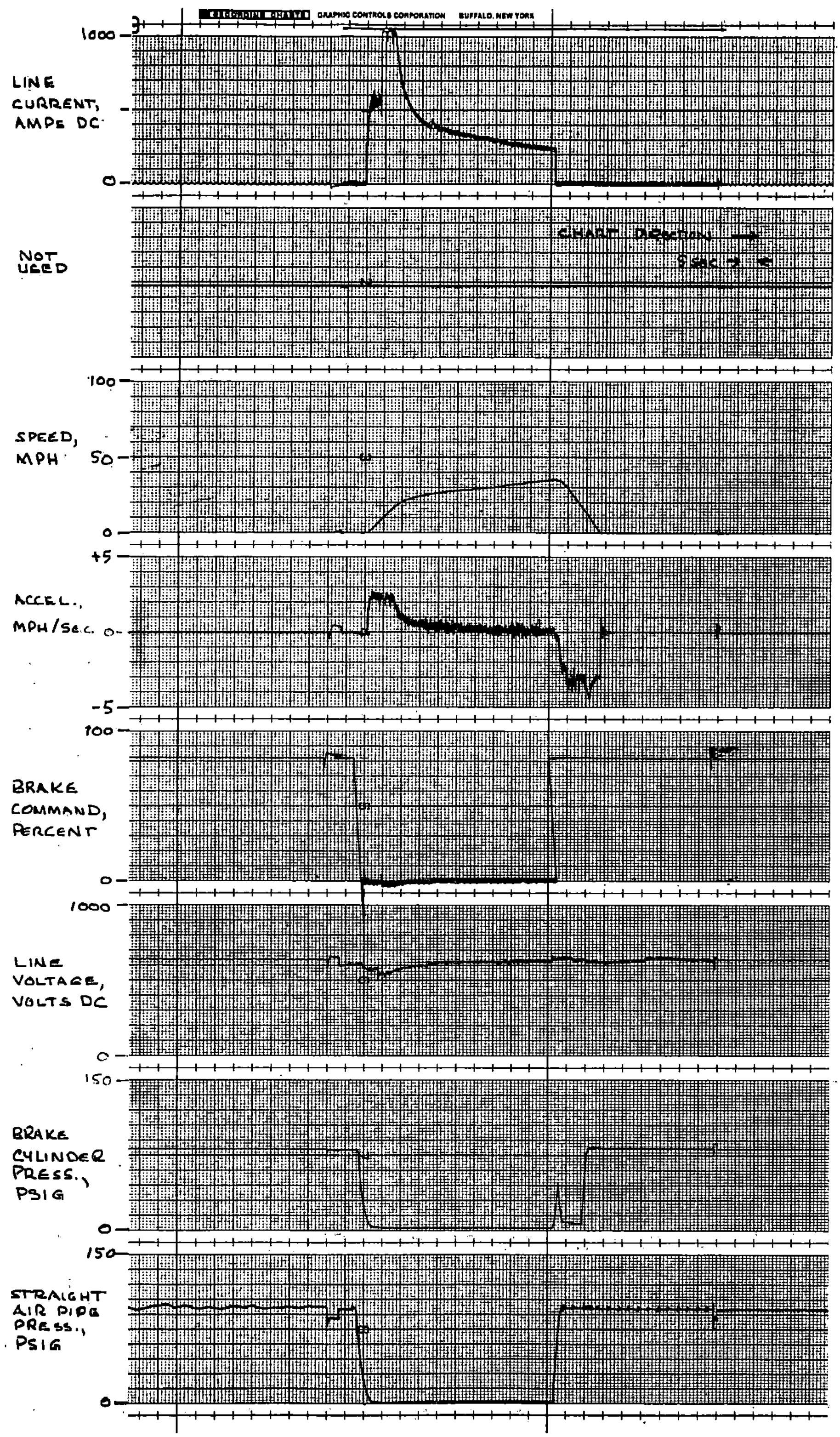


FIGURE 4.4.1-2. AB(DC) CONSIST FORWARD ACCELERATION AWO LOAD, CONTROLLER SET AT PAR (P3)

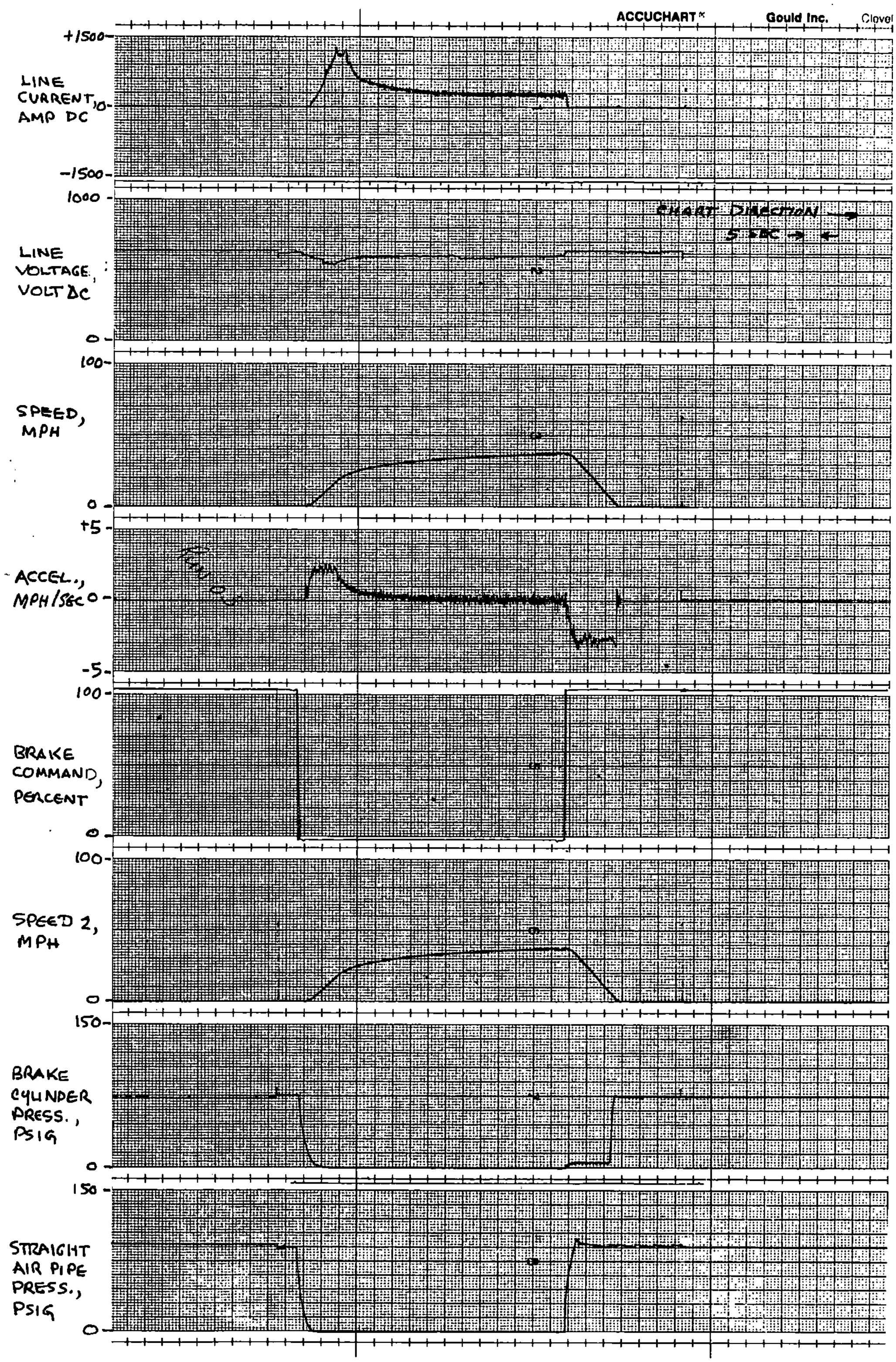


FIGURE 4.4.1-3. ABBA CONSIST FORWARD ACCELERATION AWO LOAD, CONTROLLER SET AT PAR (P3)

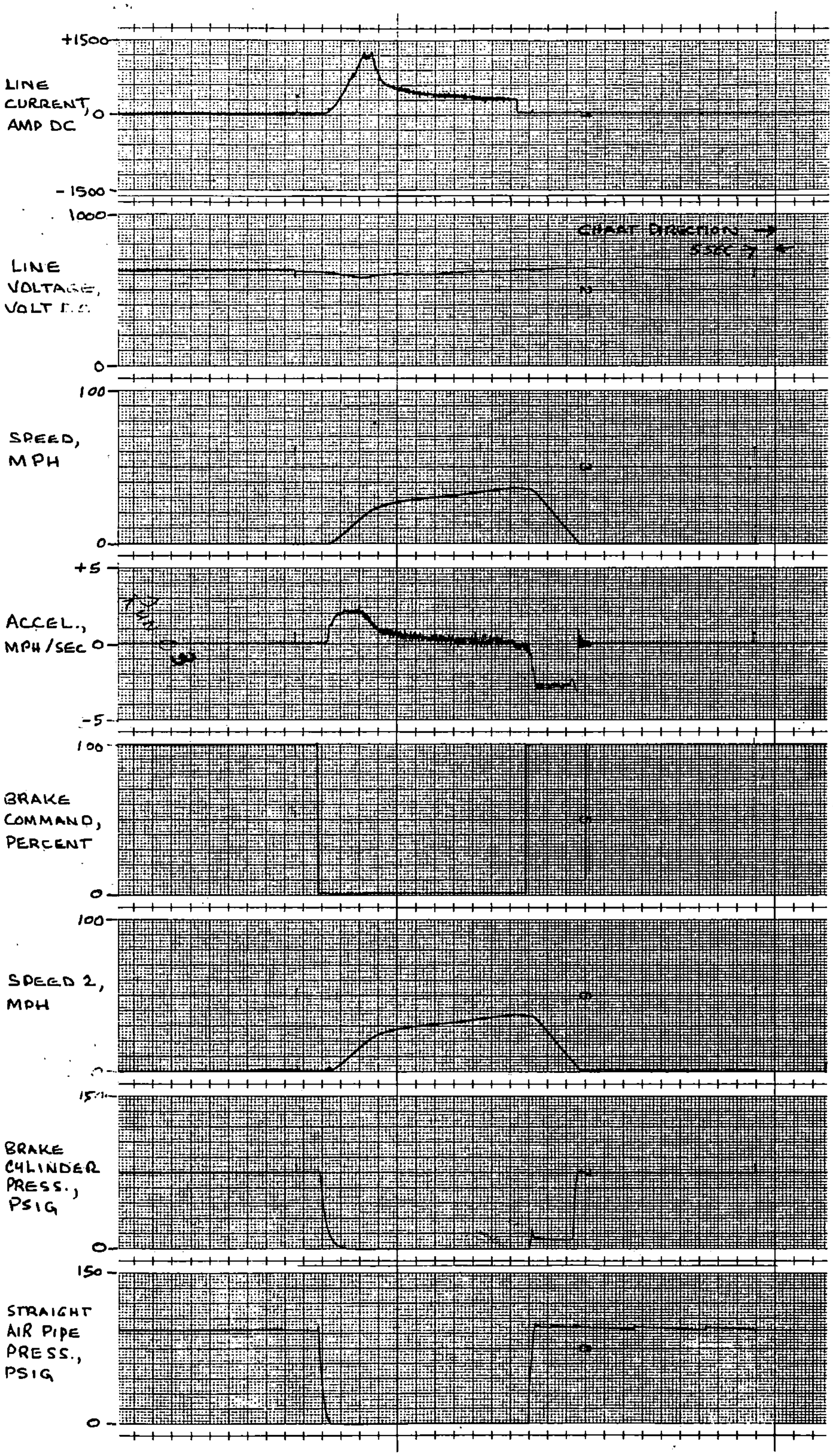


FIGURE 4.4.1-4. ABBA CONSIST REVERSE ACCELERATION AWO LOAD, CONTROLLER SET AT PAR

TABLE 4.4.1-1

ACCELERATION TEST SUMMARY

Cars Empty, AW0			
Consist Test	Acceleration, mph/sec		
	Controller Setting		
	P1 (SW)	P2 (SER)	P3 (PAR)
AB(ac)	1.26	2.15	2.20
AB(dc)	1.15	2.00	2.00
AB(ac) AB(dc)	1.10	1.08	1.10

Difference: AB(ac) - AB(dc) 0.200

Maximum allowable acceleration difference: 0.220
0.06 x AB(dc) + 0.1

Cars Fully Loaded, AW3			
Consist Test	Acceleration, mph/sec		
	Controller Setting		
	P1 (SW)	P2 (SER)	P3 (PAR)
AB(ac)	0.80	2.20	2.20
AB(dc)	0.80	2.40	2.40
AB(ac) AB(dc)	1.00	0.92	0.92
ABBA (forward)	--	--	2.20
ABBA (reverse)	--	--	-2.10
ABBA(ac) ABBA(dc)	--	--	1.05

4.4.2 Drift Tests (Test Procedure 86-60110)

Drift tests were conducted to provide a direct comparison between the coastdown characteristics of the AB(ac), AB(dc), and the ABBA consists. Because both the ac and dc cars were structurally and mechanically similar, any coastdown differences can be expected to have their origin in the propulsion systems and have some impact on energy consumption, acceleration, and deceleration test results.

The drift tests were conducted with the cars empty (AW0) and were not repeated with the cars fully loaded (AW3 condition) as indicated by the test procedure, because the AW0 tests showed insignificant differences in the drift characteristics.

Each of the three car configurations was subjected to three coastdown tests between selected speeds. Coastdown tests were conducted between 40 and 30 mph, between 30 and 20 mph, and between 20 mph and a full stop. Figures 4.4.2-1 through 4.4.2-3 show representative recorder data taken during coastdowns between 20 mph and a full stop. Plots of the deceleration rates taken from all of the coastdown tests are shown in Figures 4.4.2-4 through 4.4.2-6. A summary of the test results (Table 4.4.2-1) shows that the AB(ac) and AB(dc) consists were comparable in deceleration rates, and that the differences were due mainly to the differences in consist test speeds rather than in the propulsion systems. Closer control of the entry speeds, matched within 1 mph for all consists, would have enabled better and more direct correlation of coastdown characteristics. In the first run, AB(dc) and ABBA were within 1 mph of one another in entry speed at 40 and 41 mph, respectively; their deceleration rates were close at 0.171 and 0.172, respectively. The AB(ac) consist was 2.5 mph (minimum) faster at 43.5 mph, resulting in a detectable increase in deceleration to 0.179 mph/sec. This same speed difference in the second run again resulted in a higher deceleration rate for

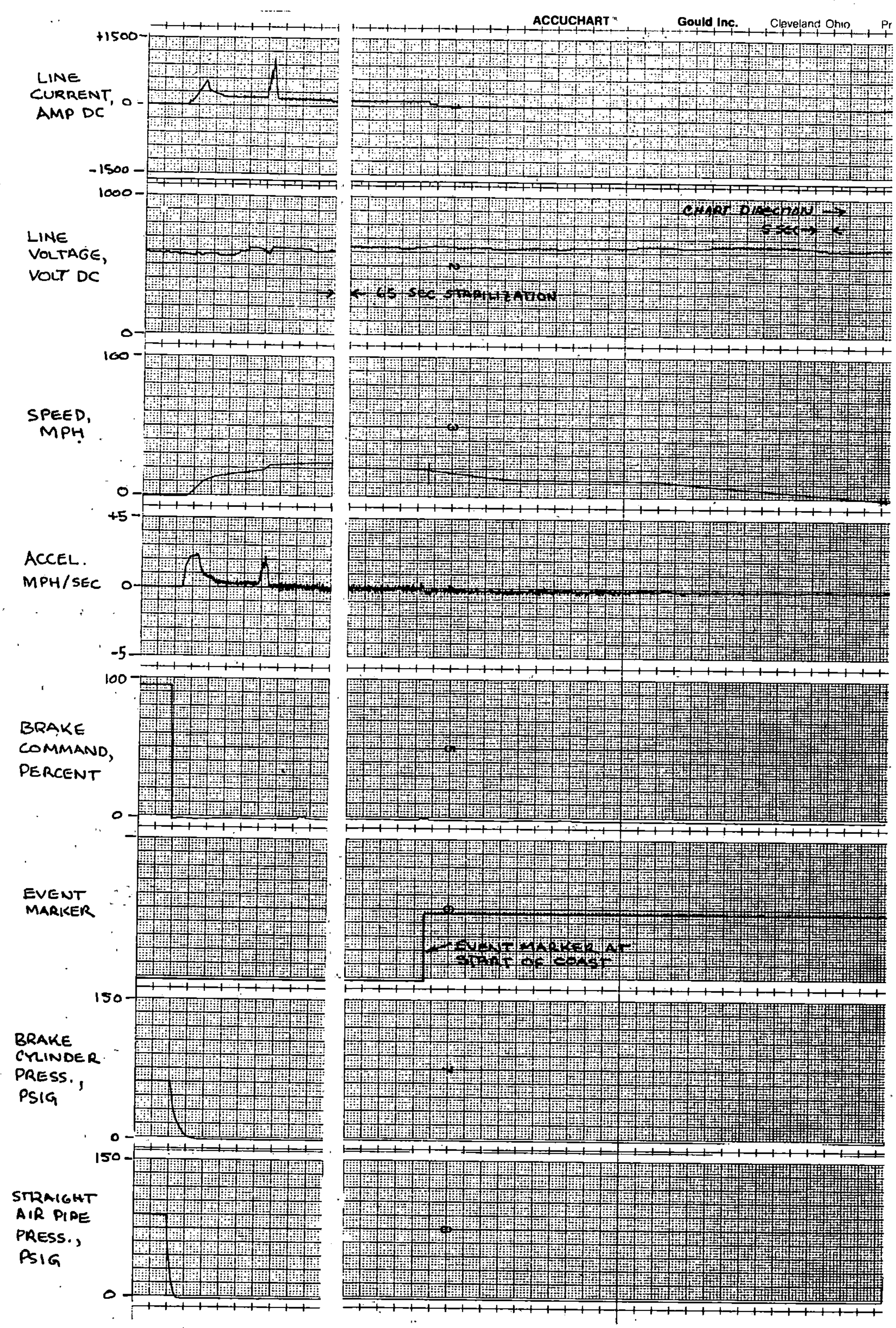


FIGURE 4.4.2-1. AB(AC) CONSIST DRIFT TEST: AWO LOAD, 20 MPH TO FULL STOP

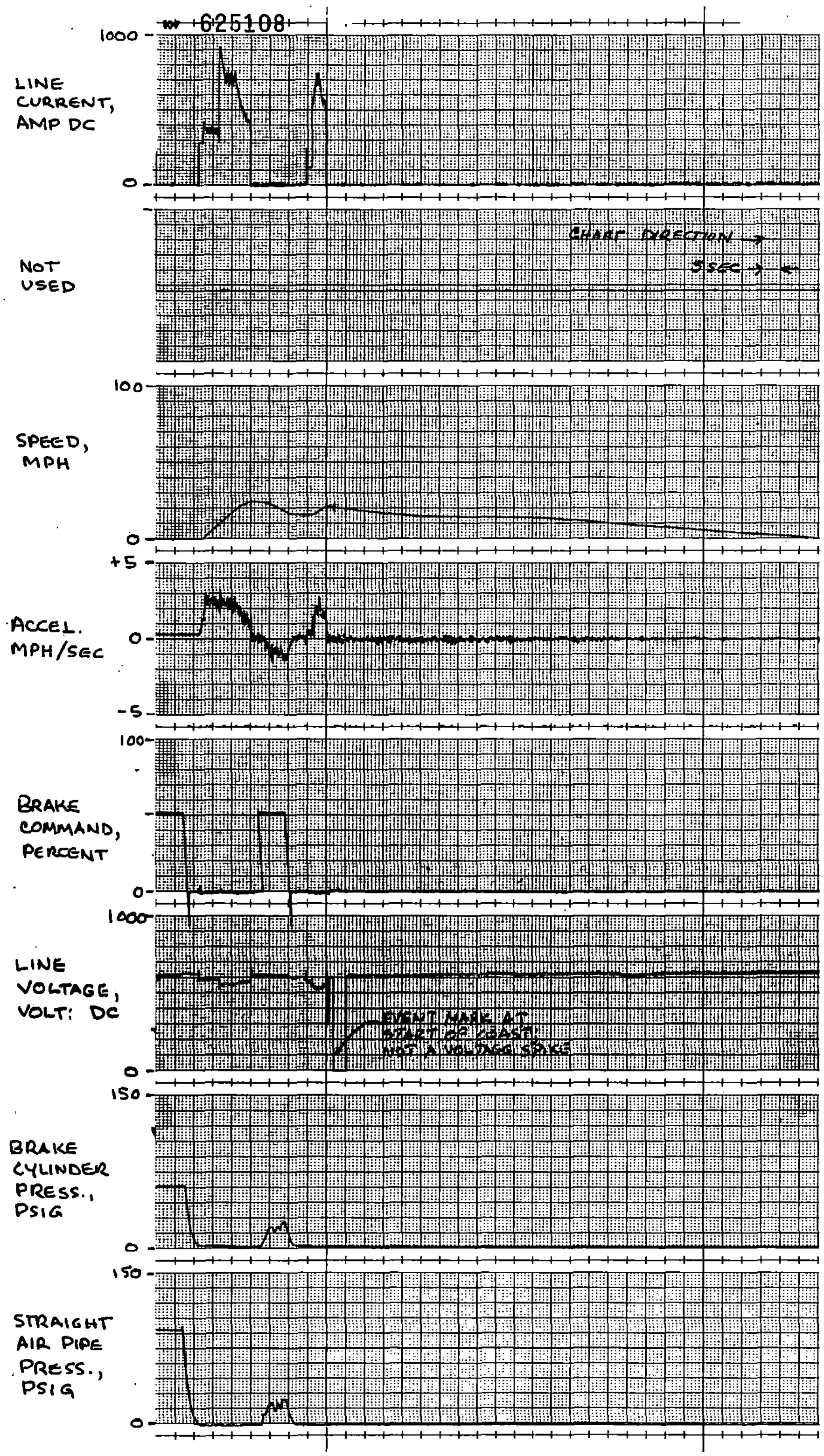


FIGURE 4.4.2-2. AB(DC) CONSIST DRIFT TEST: AWO LOAD, 20 MPH TO FULL STOP

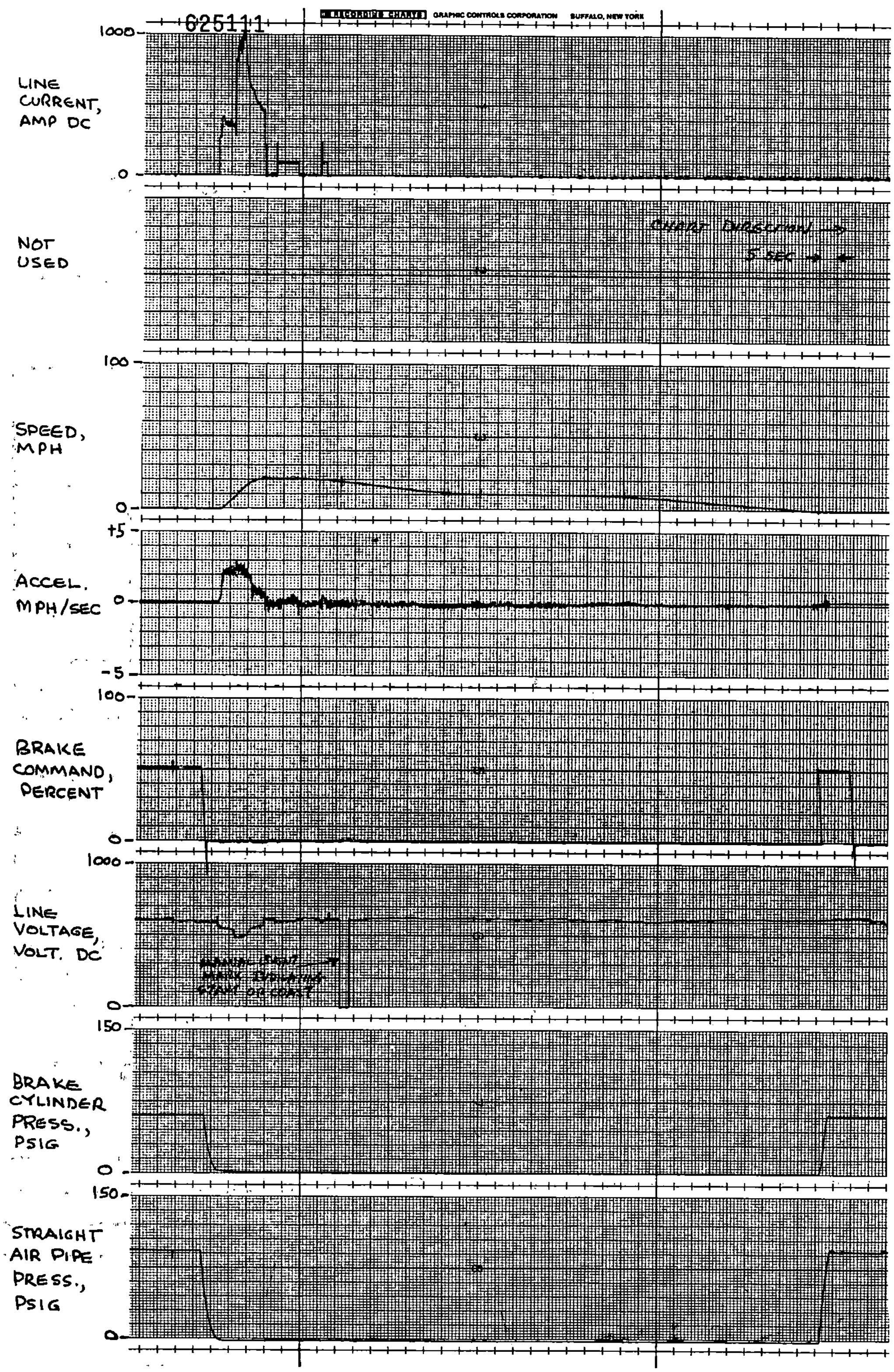


FIGURE 4.4.2-3. ABBA CONSIST DRIFT TEST: AWO LOAD, 20 MPH TO FULL STOP

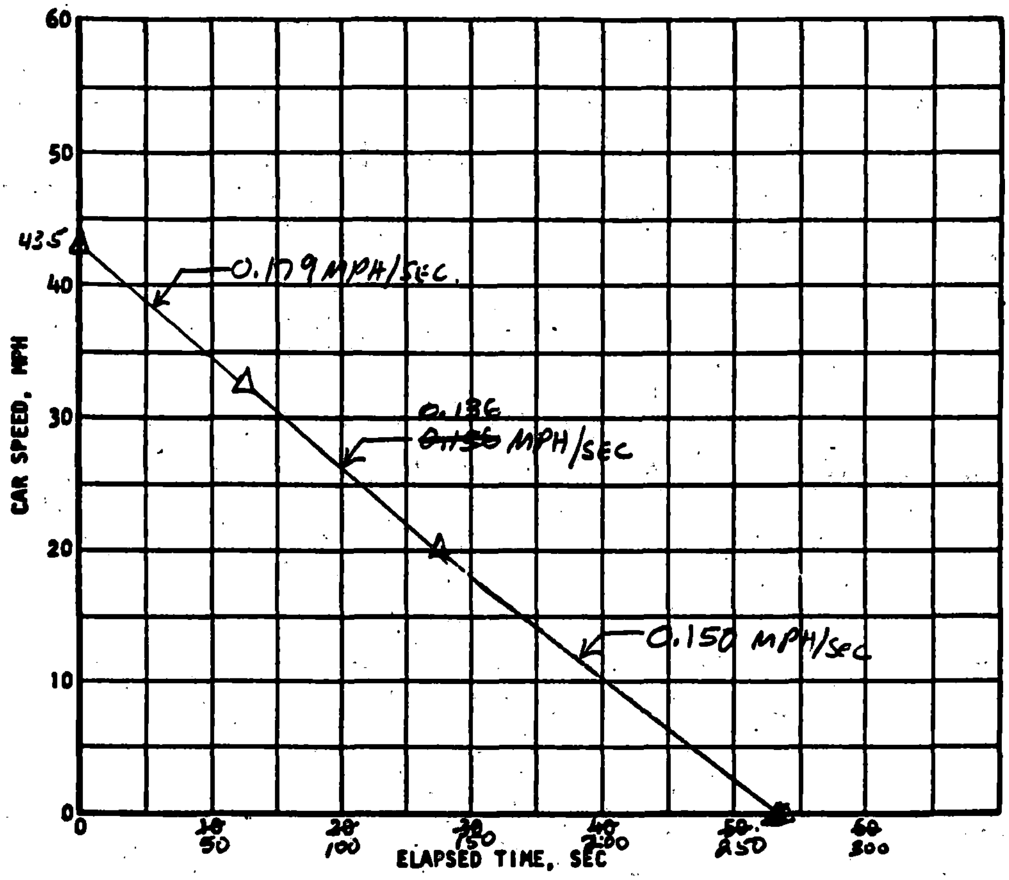
SUMMARY DATA SHEET
DECELERATION TEST DATA
CAR SPEED vs TIME

AC ✓ DC ______ VEHICLE

AW0 ✓ AW3 ______ WEIGHT

△: ENTER FROM SOUTH END OF NEW UTRECHT STATION DIRECTION

O: ENTER FROM 13TH AVENUE DIRECTION



COMMENTS ______

DATE DATA TAKEN ______

RECORD NO. ______

AIRESEARCH TEST ENGINEER: ______

NYCTA WITNESSING ENGINEER: ______

FIGURE 4.4.2-4. AB(AC) CONSIST DECELERATION SUMMARY

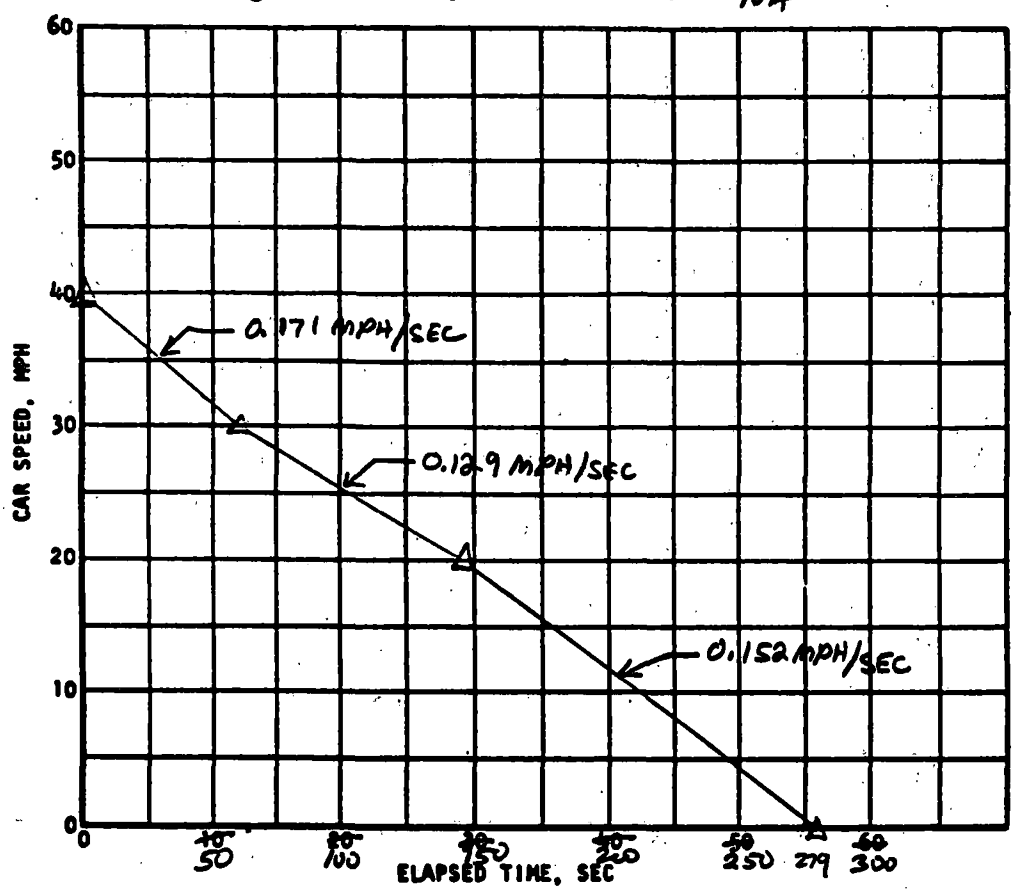
SUMMARY DATA SHEET
DECELERATION TEST DATA
CAR SPEED vs TIME

AC ________ DC ✓ VEHICLE

AWO ✓ AW3 ________ WEIGHT

Δ: ENTER FROM SOUTH END OF NEW UTRECHT STATION DIRECTION

O: ENTER FROM 13TH AVENUE DIRECTION NA



COMMENTS ________

DATE DATA TAKEN 10-4-86

RECORD NO. 10-4-28, 10-4-32, 10-4-33

AIRESEARCH TEST ENGINEER: J. Elam

NYCTA WITNESSING ENGINEER: ________

FIGURE 4.4.2-5. AB(DC) CONSIST DECELERATION SUMMARY

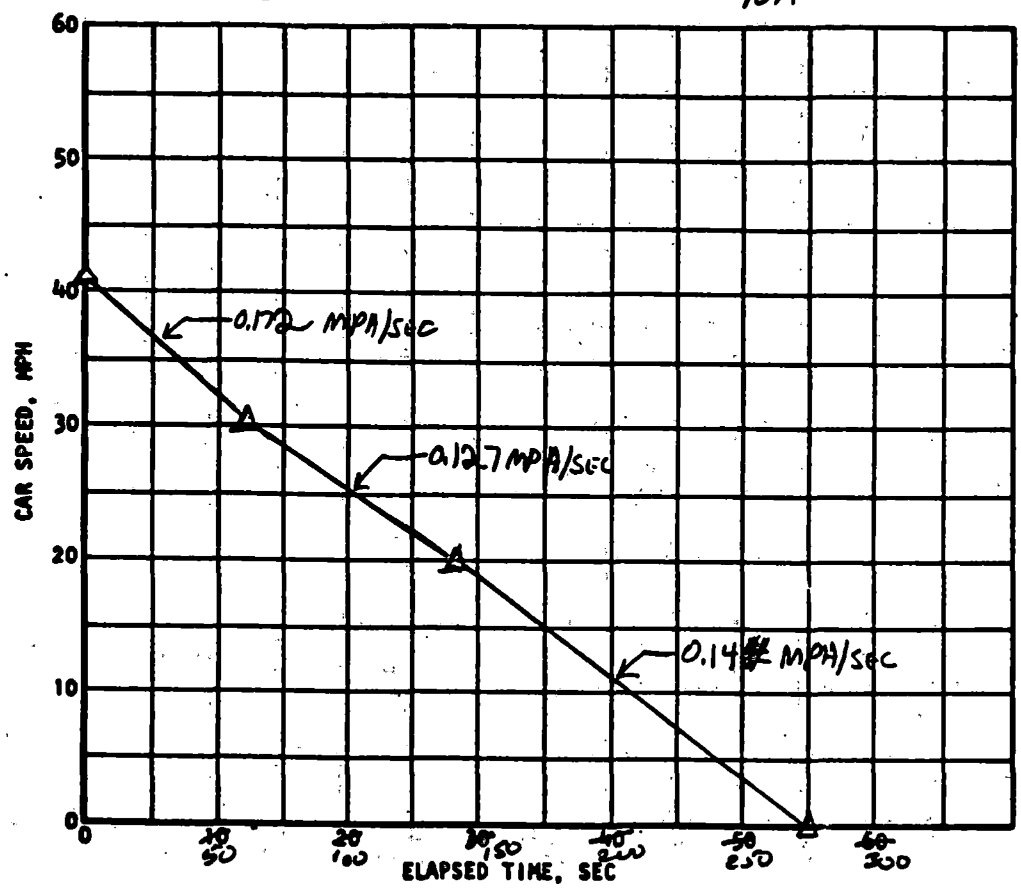
SUMMARY DATA SHEET
DECELERATION TEST DATA
CAR SPEED vs TIME
ABBA

AC ✓ DC ✓ VEHICLE

AW0 ✓ AW3 WEIGHT

△: ENTER FROM SOUTH END OF NEW UTRECHT STATION DIRECTION : NORTH ONLY.

○: ENTER FROM 13TH AVENUE DIRECTION NA



COMMENTS ____________________

DATE DATA TAKEN ____________________

RECORD NO. ____________________

AIRESEARCH TEST ENGINEER: ____________________

NYCTA WITNESSING ENGINEER: ____________________

FIGURE 4.4.2-6. ABBA CONSIST DECELERATION SUMMARY

TABLE 4.4.2-1

AWO DRIFT TEST RESULTS

Consist	Speed Range		Average Speed, mph	Speed Change, mph	Time, sec	Average Decel. ($\Delta V/\Delta T$), mph/sec
	Initial, mph	Final, mph				
Run 1						
AB(ac)	43.5	33.5	38.5	10	56	0.179
AB(dc)	40	30	35	10	58.5	0.171
ABBA	41	31	36	10	58	0.172
Run 2						
AB(ac)	33	22.5	27.8	10.5	77	0.136
AB(dc)	30.5	19	24.75	11.5	89	0.129
ABBA	30.5	20	25.25	10.5	83	0.127
Run 3						
AB(ac)	20	0	10	20	133	0.150
AB(dc)	20	0	10	20	131	0.152
ABBA	19	0	9.5	19	132	0.144

the ac cars over the dc cars and the ABBA consist. The higher deceleration rate of the ac cars is explained by the strong influence of velocity on the vehicle drag, expressed by the equation:

$$F = C_0 + C_1 V + C_2 V^2$$

where C_0, C_1, and C_2 are constants, V is speed, and F is drag force.

Deceleration rates are also quite sensitive to errors in resolving speeds to within 1/2 mph on the strip chart data and in determining times at which the cars stopped. The 20-mph to full-stop traces are very flat near the end of the run, and an error of 4 sec is clearly probable. The ABBA test data (see Figure 4.4.2-3) show a stopping time of between 130 and 134 sec. The deceleration rate at 130 sec would be 0.146 and is in closer agreement with the AB(ac) and AB(dc) consists. At any given speed, the ABBA consist, having almost the same drag rate and greater mass, is expected to have the lower deceleration rates observed.

Based on the results of these tests, any differences between ac and dc cars were not observable and could easily be lost in the track elevation variations and limitations in data resolution of the instrumentation. However, this test conducted at AW0 shows that any undetected differences in the coastdown characteristics attributable to the differences in the propulsion systems were insignificant and have little influence on other propulsion system performance testing. As a result, further drift testing at AW3 was not conducted.

4.4.3 Air Brake (Test Procedure 86-60133)

Air brake tests were conducted to obtain the overall deceleration characteristics, when using air brakes only, for the ac and dc test cars connected as separate two-car consists: AB(ac) and AB(dc). The tests provided not only a comparison between the ac and dc cars, but also a baseline characteristic for evaluation of regenerative braking.

4.4.3.1 Test Description

The vehicle average deceleration rates and stopping distances were determined for both representative cars in the AWO (empty) weight condition.

4.4.3.2 Test Location

This test was conducted on the NYCTA Sea Beach section of Track E3 between the south end of the 20th Avenue station and 13th Avenue.

4.4.3.3 Test Vehicle Makeup

The test was conducted on one AB(ac) consist and one AB(dc) consist. As equipped for this test, the AB(ac) pair weighed 89,460 lb, and the AB(dc) pair weighed 88,600 lb. These weights include the instrumentation and four persons.

4.4.3.4 Test Procedure

The test zone was approached from the south end of the 20th Avenue station at a speed as close to 40 mph as practical. The ac test vehicle speed was exactly 40 mph and the dc vehicle speed was 37 mph. At the beginning of the test zone, full-service braking was selected on the master controller and the vehicle was decelerated to a full stop.

The time to stop the vehicle was determined from the recorder, and the average deceleration was calculated from the equation:

$$\text{Avg. deceleration} = \frac{\text{Initial speed, mph}}{\text{Time to stop, sec}}$$

The approximate stopping distance was determined by a pulse counter (monopole), which counted the wheel revolutions after the start of braking.

Three runs were conducted on each consist to verify the results and ensure consistency. The recorder trace data and the calculated average deceleration rate for a typical run on each consist were entered on the data sheet form provided in the test procedure document.

4.4.3.5 Results

The measured and calculated data are presented in Figure 4.4.3-1 through 4.4.3-4 as listed below:

AB(ac) summary data sheet	Figure 4.4.3-1
AB(ac) typical trace	Figure 4.4.3-2
AB(dc) summary data sheet	Figure 4.4.3-3
AB(dc) typical trace	Figure 4.4.3-4

4.4.3.6 Conclusions

The average decelerations of 3.15 and 3.22 mph/sec for the ac and dc cars agree within 2.5 percent, within the limits of experimental accuracy. The difference in stopping times and distances is attributed to the differences in initial speeds--40 mph for ac and 37 mph for dc. Nearly identical behavior was observed also for the AW3 weight condition.

From these results it is concluded that there is no appreciable difference between the braking characteristics of the ac- and dc-equipped cars.

DATA SHEET

Train Consist AB(AC)

Date Data Taken ____________

Record No. ____________

Responsible Test Engineer ____________

Para. No.	Description	Measured	Required	Acceptance
3.4.4, Step 2	Vehicle weight	lb	AW3	__ Yes __ No
3.4.5, Step 1	Vehicle speed	mph	40 ±2 mph	__ Yes __ No
3.4.5, Step 3	Brake cylinder pressure	psig	105 ref	__ Yes __ No
	Straight pipe pressure	psig	105 ref	__ Yes __ No
3.4.5, Step 6	Time to stop vehicle	sec	13 ref	
	Stopping distance	ft	400 to 450 ft	__ Yes __ No
	Average deceleration rate: V initial (mph) / T: Total stopping time	mph/sec	3.0±0.3 mph/sec	__ Yes __ No
Step 10 (ref. 3.4.4, Step 2)	Vehicle weight	89460 lb	AW0	✓ Yes __ No
Ref. 3.4.5, Step 1	Vehicle speed	40 mph	40 ±2 mph	✓ Yes __ No
Ref. 3.4.5, Step 3	Brake cylinder pressure	63 psig	TBD	✓ Yes __ No
	Straight pipe pressure	96 psig	TBD	✓ Yes __ No
Ref. 3.4.5, Step 6	Time to stop vehicle	12.7 sec	13 ref	✓ Yes __ No
	Stopping distance	397 ft	400 to 450 ft	✓ Yes __ No
9/19/86	Average deceleration rate: V initial (mph) / T: Total stopping time	3.1* mph/sec	3.0±0.3 mph/sec	__ Yes __ No

***RECORDED VALUE. CALCULATED VALUE IS 3.15.**

FIGURE 4.4.3-1. SUMMARY DATA SHEET: AB(AC), AWO, FULL-SERVICE AIR-BRAKE-ONLY DECELERATION TEST

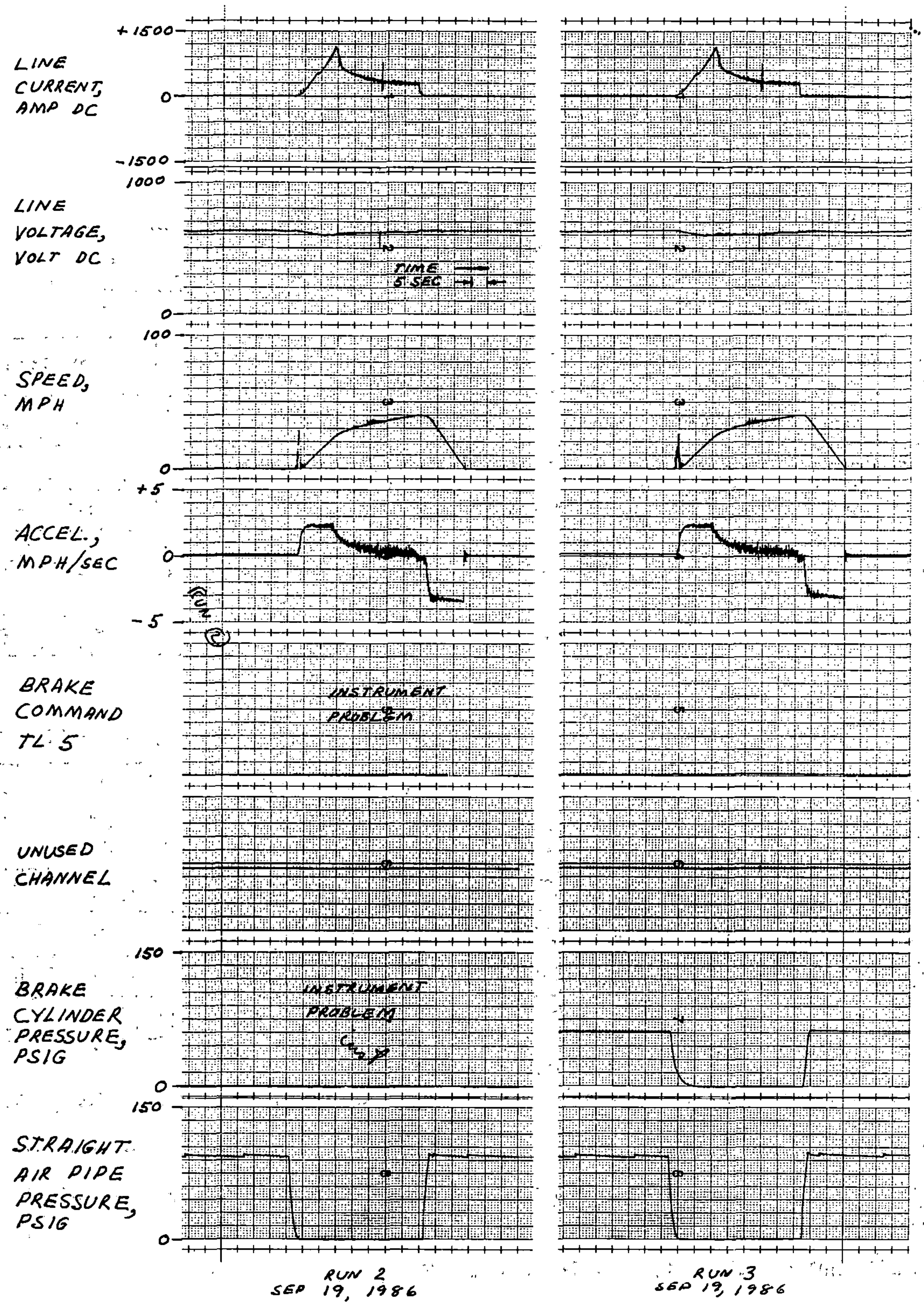


FIGURE 4.4.3-2. AB(AC), AWO, FULL-SERVICE AIR-BRAKE-ONLY DECELERATION TEST

DATA SHEET

Train Consist AB(DC)

Date Data Taken ______________

Record No. ______________

Responsible Test Engineer ______________

Para. No.	Description	Measured	Required	Acceptance
3.4.4, Step 2	Vehicle weight	lb	AW3	__ Yes __ No
3.4.5, Step 1	Vehicle speed	mph	40 $\pm$2 mph	__ Yes __ No
3.4.5, Step 3	Brake cylinder pressure	psig	105 ref	__ Yes __ No
	Straight pipe pressure	psig	105 ref	__ Yes __ No
3.4.5, Step 6	Time to stop vehicle	sec	13 ref	
	Stopping distance	ft	400 to 450 ft	__ Yes __ No
	Average deceleration rate: $\frac{V \text{ initial (mph)}}{T\text{: Total stopping time}}$	mph/sec	3.0$\pm$0.3 mph/sec	__ Yes __ No
Step 10 (ref. 3.4.4, Step 2)	Vehicle weight	88600 lb INSTR. + 4 PEOPLE	AW0	✓ Yes __ No
Ref. 3.4.5, Step 1	Vehicle speed	37* mph	40 $\pm$2 mph	✓ Yes __ No
Ref. 3.4.5, Step 3	Brake cylinder pressure	66 psig	TBD	✓ Yes __ No
	Straight pipe pressure	98 psig	TBD	✓ Yes __ No
Ref. 3.4.5, Step 6	Time to stop vehicle	~~16~~ 11.5 sec	13 ref	✓ Yes __ No
9/26/86 [signatures]	Stopping distance	342.6 ft	400 to 450 ft	✓ Yes __ No
	Average deceleration rate: $\frac{V \text{ initial (mph)}}{T\text{: Total stopping time}}$	RECORDED: 3.2 * ** mph/sec 3.2	3.0$\pm$0.3 mph/sec	✓ Yes __ No

*SPEED AND DECELERATION READINGS ARE CORRECTED FOR ZERO OFFSET OF RECORDER PENS.

**RECORDED VALUE. CALCULATED VALUE IS 3.22.

FIGURE 4.4.3-3. SUMMARY DATA SHEET: AB(DC), AW0, FULL-SERVICE AIR-BRAKE-ONLY DECELERATION TEST

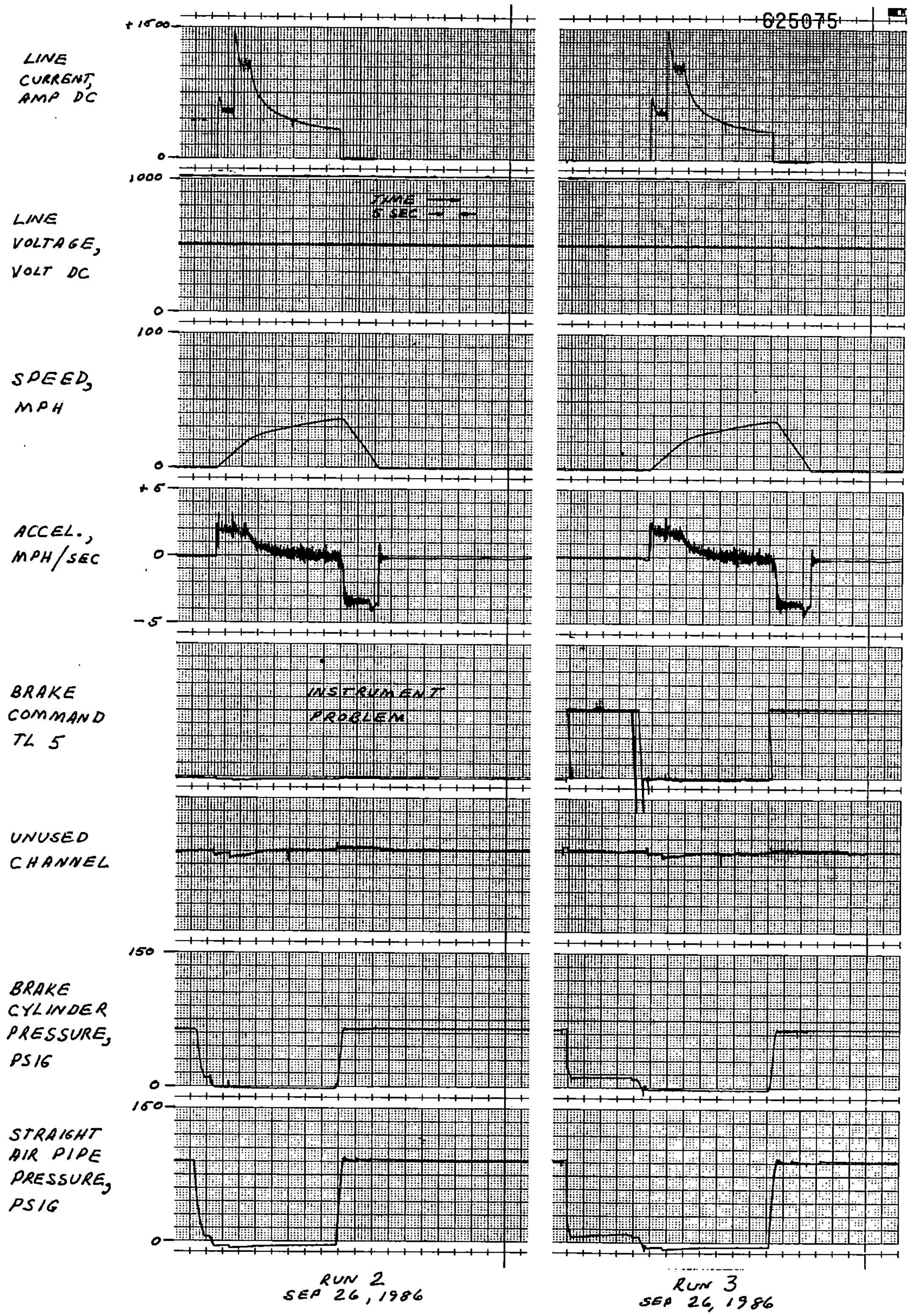


FIGURE 4.4.3-4. AB(DC), AWO, FULL-SERVICE AIR-BRAKE-ONLY DECELERATION TEST

4.4.4 Deceleration Testing with Regenerative Braking (Test Procedure 86-60158)

The comprehensive regenerative braking tests demonstrated results consistent with the STARS ac propulsion system goal of achieving comparative operational performance with existing dc propulsion equipment, plus the added benefits of energy savings. The purpose of the tests was to demonstrate deceleration using regenerative braking and to record:

(a) Braking (deceleration) rates as required on R-44 cars in operation

(b) Energy returned to the line

The ac propulsion cars are capable of regenerative braking during which the ac traction motors operate as generators and return energy to the line, or, if the line is unreceptive, dynamic (rheostatic) braking with energy absorbed by onboard resistance. The ac control system accommodates switching between regenerative and rheostatic braking modes, depending upon receptivity of the line. A switch on the cab panel of the ac "A" car allows manual cutout of regeneration. A light on the panel gives a visual indication when regeneration is present.

Since the Sea Beach track line voltage could not be controlled, receptivity varied during the testing, depending on the ac propulsion preset regeneration levels; at the lower level setting (640 vdc), it was apparent that very little regeneration was available, and therefore no testing was done at 640 vdc. In addition, the regenerated voltage was limited to less than 700 vdc to avoid high-voltage damage to existing line equipment.

The results verify the ability of the ac propulsion cars to decelerate at the required rate (3.0 ±0.5 mph/sec), while using regenerating brakes. Energy savings was from 38.5 to 83.0 percent, depending on line conditions. The braking fade transition from dynamic to friction braking occurred at less than 5 mph in all cases, a major factor in reducing wheel wear. Separate regeneration tests with wheel diameter mismatch of 0.8 in. demonstrated the ac system tolerance to this condition.

4.4.4.1 Primary Regenerative Braking Tests

The regeneration tests were conducted with both the AB(ac) consist and the ABBA consist. Tests with the AB(ac) consist were conducted fully loaded at the AW3 weight, and tests with the ABBA consist were conducted empty at the AW0 weight.

The braking tests were generally conducted from initial speeds of 40 mph, with some tests conducted at initial speeds up to 56 mph. Tests at the higher speeds were limited at the request of the NYCTA because of the operating restrictions of the test track.

Tests were conducted at the prevailing line voltage on the Sea Beach line (normally 650 to 675 vdc) and at regenerated voltage levels of 700 vdc or below. The regenerated voltage was limited to 700 vdc to avoid high-voltage damage to the existing line equipment. Regenerated voltages of 640 vdc, as specified by the test procedure, were not fully tested because little regeneration occurs at that voltage.

NOTE: Regeneration voltage on the STARS ac cars could be set between 640 and 720 vdc.

A schematic of the test track setup is shown in Figure 4.4.4-1. The test train was run on the test line (E3), and regenerated power was absorbed by a 2400-amp load bank installed in a dummy train. Stopping distances were recorded by off-car distance markers located along the test track, and by an on-car pulse recorder.

Recorder traces showing a typical AB(ac) regenerated brake from 40 mph, with full-service braking, are shown in Figure 4.4.4-2. The figure shows that, on brake command, the regenerative braking was initiated. Below 5 mph, transition from regenerative braking to friction brakes occurred to bring the consist to a full stop.

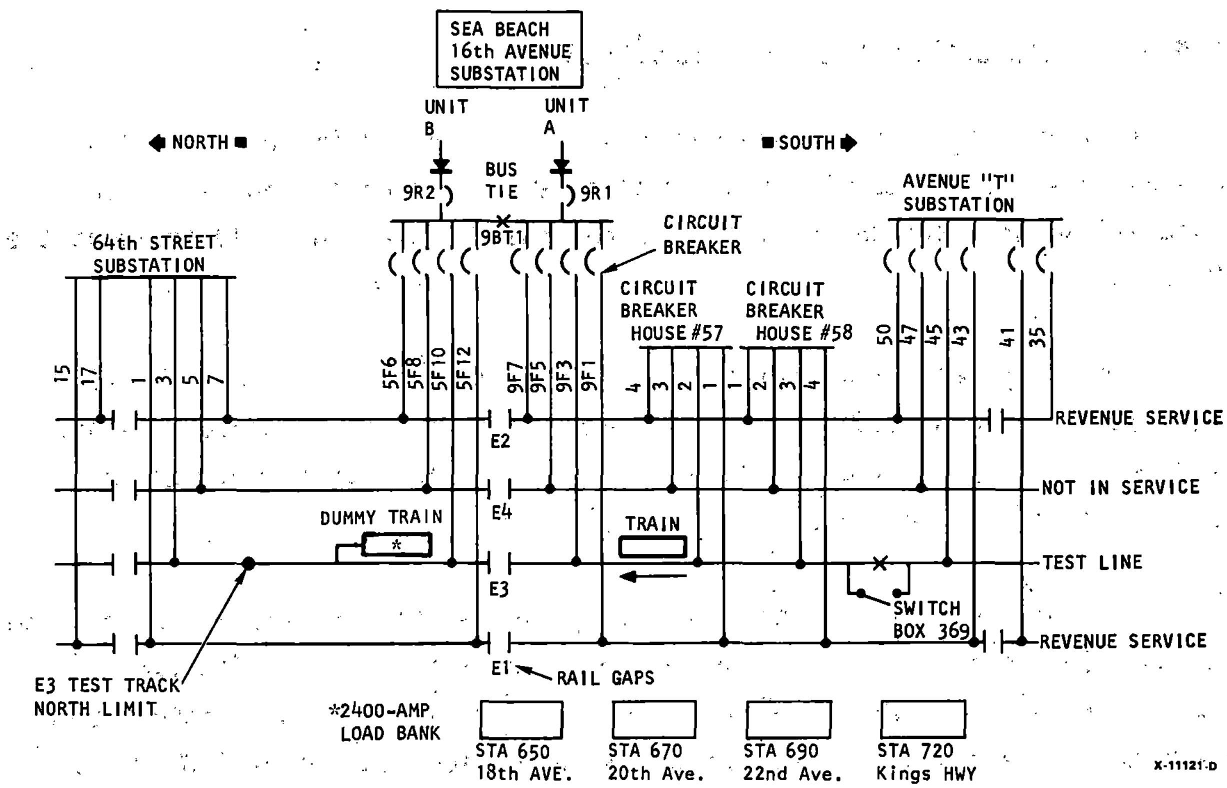


FIGURE 4.4.4-1. TRACK SYSTEM TEST SETUP

A second recorder trace showing a typical AB(ac) brake from 55 mph is shown in Figure 4.4.4-3. These data also verify the required transition from regeneration to friction braking at 5 mph.

A summary of the AB(ac) consist tests with AW3 loads is shown in Table 4.4.4-1. The regeneration capability was demonstrated with regenerated energy recovery variable between 38.5 and 83.0 percent when compared to the theoretically available kinetic energy at the start of braking.

Stopping distances were recorded during the AB(ac) AW3 tests, with first the "A" car regeneration disabled and then with "B" car regeneration disabled, to provide the most adverse stopping conditions. The average stopping distance from the 40-mph initial speed was 427.8 ft. This is within the acceptable limits of between 400 and 450 ft.

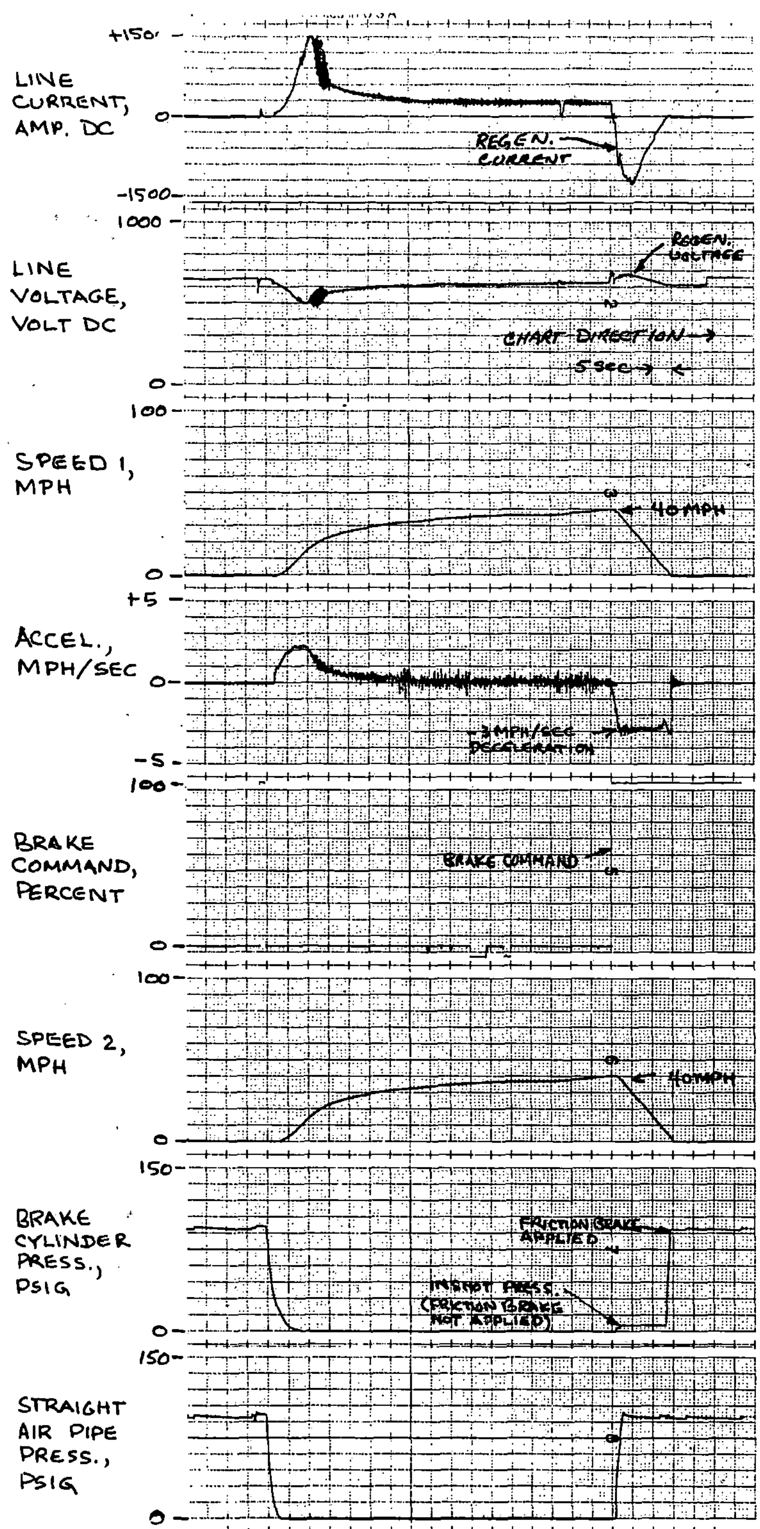


FIGURE 4.4.4-2. TYPICAL REGENERATIVE BRAKING TEST DATA, AB(AC) CONSIST; FULL-SERVICE BRAKING FROM 40 MPH

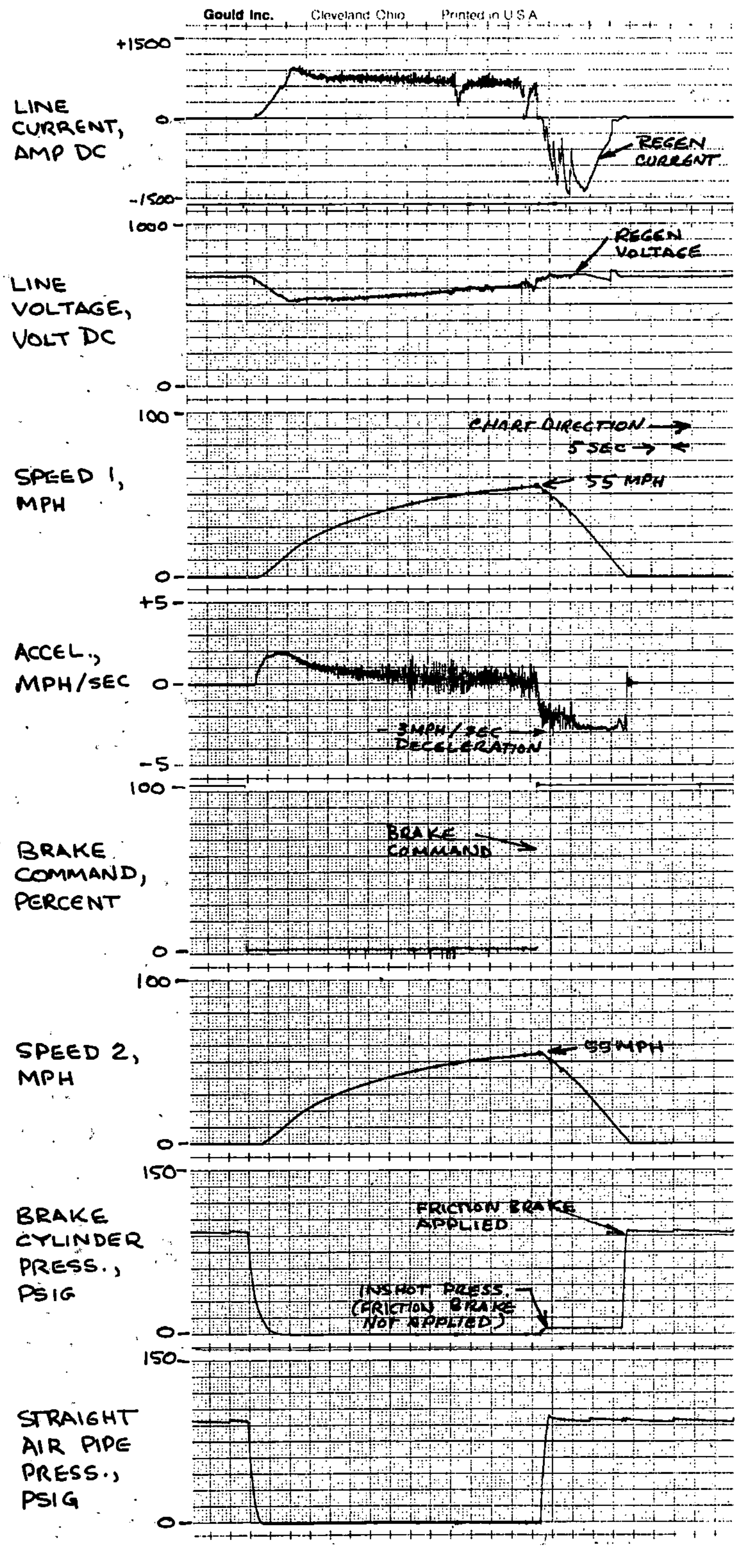


FIGURE 4.4.4-3. REGENERATIVE BRAKING TEST DATA, AB(AC) CONSIST; FULL-SERVICE BRAKING FROM 55 MPH

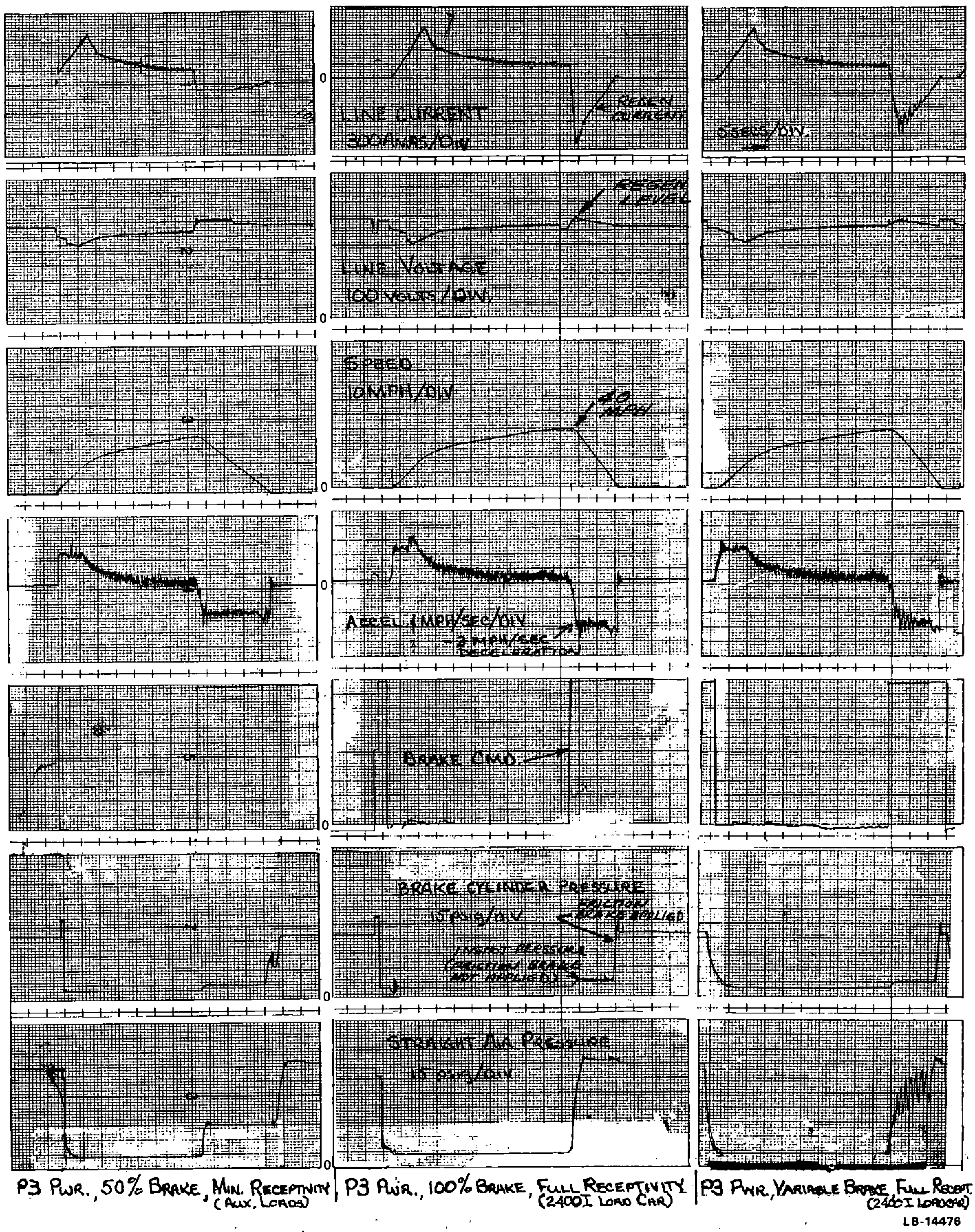
TABLE 4.4.4-1

VEHICLE KINETIC ENERGY TO REGENERATED ELECTRICAL ENERGY CONVERSION SUMMARY

Run No.	Peak Speed, mph	Decel. Rate, mph/sec	Computed Kinetic Energy (E_T), kw-hr	Actual Regenerated Energy (E_R), kw-hr	Energy Conversion Efficiency Ratio (E_R/E_T x 100), percent
720-vdc Regeneration					
1	37	2.5	2.27	1.8	79.3
2	40	2.8	2.65	1.7	64.2
3	40	2.8	2.65	2.2	83.0
4	41	2.8	2.79	0.1	NA
5	55	2.8	5.01	2.9	57.9
6	55	2.8	5.01	3.1	61.9
680-vdc Regeneration					
7	56	2.8	5.20	2.0	38.5

NOTE: Vehicle kinetic energy: $E_T = 1.2578 \times 10^{-8} WV^2$
where W is vehicle weight in lb = 131,800
V is vehicle speed in mph

Tests with the ABBA consist empty (AWO) were conducted with 50 percent, 100 percent, and variable brake settings from speeds of 40 mph. The tests were run with both minimum line receptivity (auxiliary loads) and full receptivity (2400-amp load). Recorder traces from these tests are presented in Figure 4.4.4-4. The results show that in each case, regenerative braking was within acceptable limits, slowing the consist to 5 mph or below before the transition to friction brakes.



NOTE: Data traces partially enhanced from the damaged original data.

FIGURE 4.4.4-4. TYPICAL REGENERATIVE BRAKING TEST DATA, ABBA CONSIST; VARIABLE BRAKE SETTINGS FROM 40 MPH

4.4.4.2 Wheel Mismatch Deceleration Tests

Regenerative braking tests were conducted, in addition to those specified by the test procedure, to demonstrate the ability of the ac cars to meet the regenerative braking requirements with mismatched wheel diameters on a single car. The measured extreme wheel diameters were recorded as 0.8 in. between a wheel on axle 1 and axle 3. The train is required to meet specified performance without overheating or efficiency loss, with wheel diameter differences of up to 0.75 in. The motor was designed with a slip characteristic to accommodate this wheel mismatch..

Data traces showing the acceleration and regenerative braking performance of the test car from 32 mph are presented in Figure 4.4.4-5. The results of this test show acceptable regenerative braking with the existing 0.8-in. wheel mismatch.

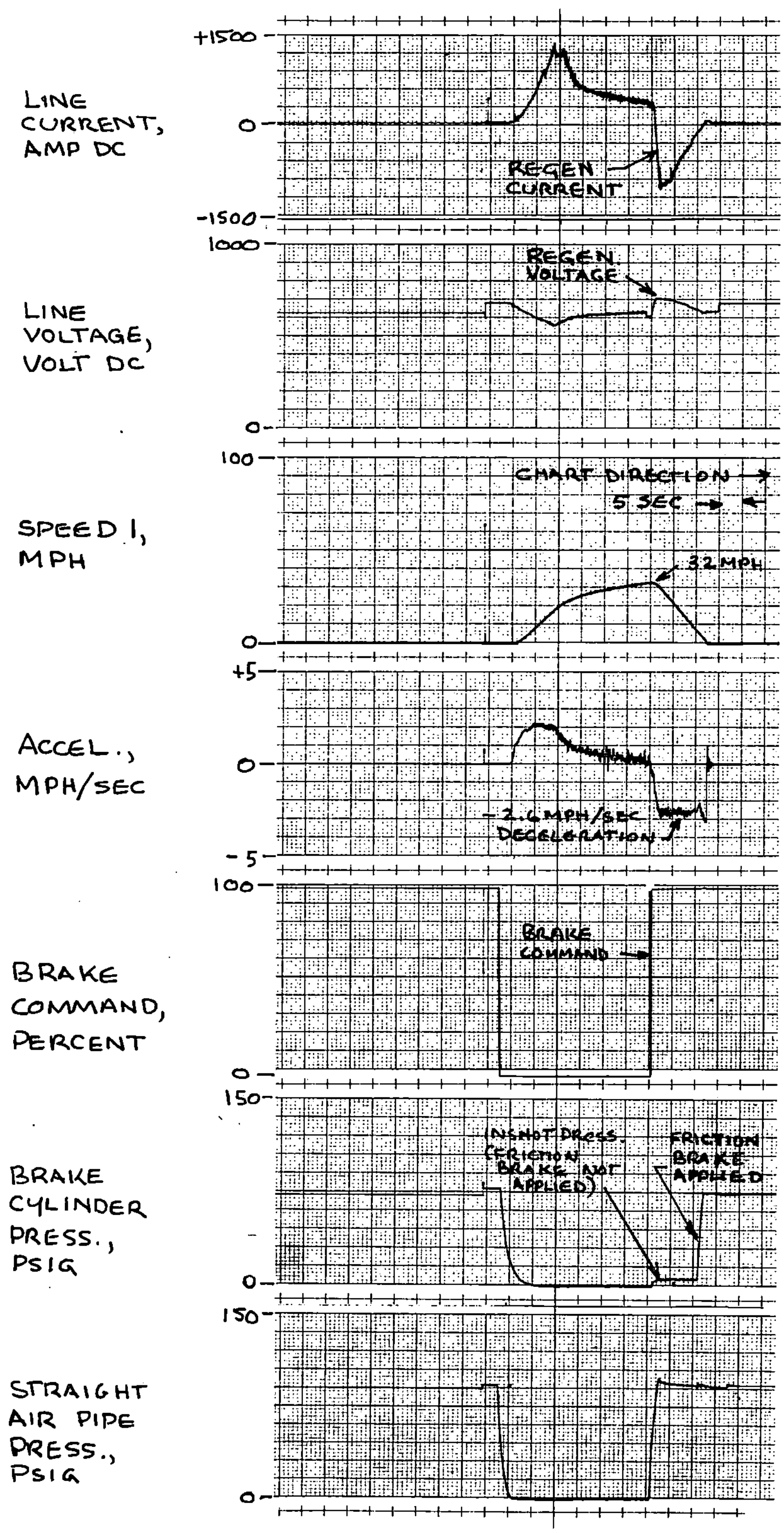


FIGURE 4.4.4-5. REGENERATIVE BRAKING TEST WITH "A" CAR (AC) FROM 34 MPH; WITH 0.8-IN. WHEEL MISMATCH

4.4.5 Nonregenerative Dynamic Deceleration Braking Test (Test Procedure 88-60154)

Nonregenerative dynamic (rheostatic) braking tests were conducted to obtain comparative deceleration performance data on the ac- and dc-equipped R-44 cars connected in AB(ac), AB(dc), and ABBA consists. With 50-percent and full-service braking (FSB) selected on the vehicle master controller, the average vehicle deceleration rates and stopping distances were determined for both empty (AW0) and fully loaded weights (AW3). Only fully loaded vehicles were tested when ac and dc units were coupled together (ABBA consist).

For the ABBA consist configuration, the designations ABBA(ac) and ABBA(dc) indicate the type of propulsion/braking in effect during the test run. Tests in which the propulsive vehicle leads the ABBA consist are designated as being conducted in the forward direction. Testing was performed in the forward direction only for AB(ac) and AB(dc) consists at two different weights, AW0 and AW3 (AW0 + 43,000 lb). ABBA testing was conducted for AW3 only, but in the forward and reverse directions for both ac and dc propulsion/braking.

Tests were performed in accordance with AiResearch Document 86-60154, dated April 29, 1986: STARS ac Drive Test Procedure, Nonregenerative Dynamic Deceleration Braking Test. All tests were conducted at the normal ambient conditions that occurred during the test periods from September 22 to November 14, 1986 and from February 11 to February 19, 1987.

Testing was conducted at the NYCTA Sea Beach test track, on the section of track between the south end of the New Utrecht Avenue station and 13th Avenue. All deceleration braking tests were performed with the vehicles moving toward the north at approximately 40 mph. At the beginning of the test zone, the required braking level (either 50-percent or full-service) was selected on the master controller. Automatic recording (strip chart) of test parameters provided data to derive average deceleration and stopping distance. The parameters recorded include:

(a) Line voltage and current

(b) Speed (measured as wheel rotational velocity)

(c) Instantaneous acceleration

(d) Brake command

(e) Brake cylinder pressure

(f) Straight air pipe pressure

(g) Time

A total of 55 valid test runs was recorded, with a minimum of 3 runs of each individual test for computation of average test values.

A representative example of the strip chart data, with pertinent indications highlighted, is presented in Figure 4.4.5-1. A summary of the tests performed, arranged for comparison of ac and dc braking results, is presented in Table 4.4.5-1. The data reduction technique used to calculate average deceleration and stopping distance is illustrated by the sample worksheet presented in Figure 4.4.5-2. This worksheet also defines terminology and shows the equations used in calculation of results.

A careful review of the test data was conducted to correlate the dynamic braking performance of the ac and dc vehicles. The following observations were considered in the evaluation and, to the extent indicated, were used in support of the conclusions:

(a) The initial speed of the ac cars averaged 1.5 mph faster than the dc cars during the two-car consist testing of procedure paras. 3.4.5.1 through 3.4.5.8. The dc consists were below the required 38- to 42-mph range, while the ac consists were within the low limit. The computed average deceleration rate is unaffected by initial speed; however, dc consist stopping times and distances listed in Table 4.4.5-1 should be increased approximately 4 percent for an equitable comparison with ac consist values.

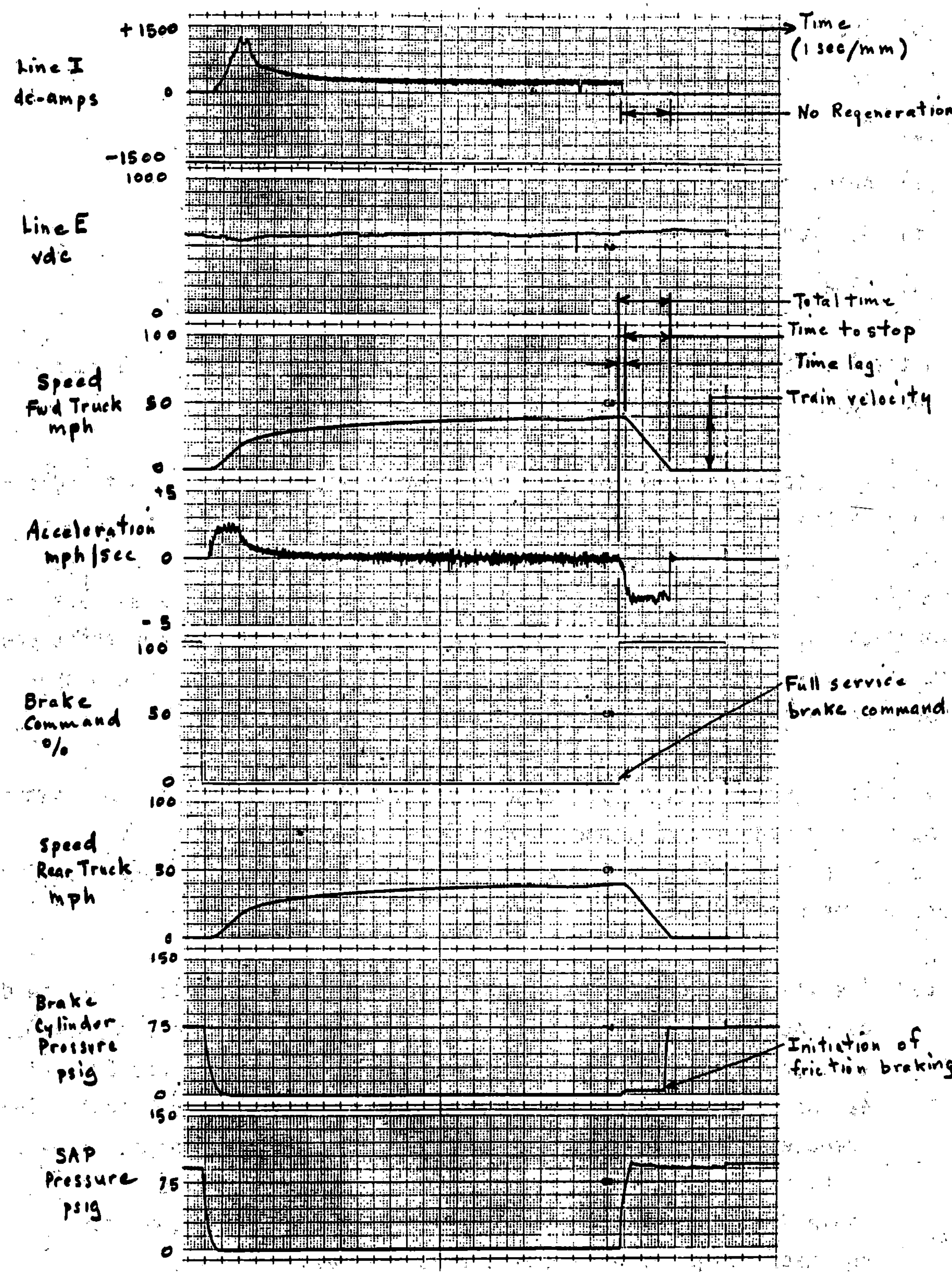


FIGURE 4.4.5-1. SAMPLE CHART RECORDING--DECELERATION TEST

TABLE 4.4.5-1

DYNAMIC BRAKING TEST RESULTS

Test Parameter	Test Requirement	Consist Configuration			
		AB(dc)	AB(ac)	ABBA(dc)	ABBA(ac)
Test direction		Forward	Forward	Forward	Forward
Test procedure para.		3.4.5.1	3.4.5.5	3.4.5.9, Step 1	3.4.5.9, Step 1
Weight		AW3	AW3	AW3	AW3
Braking		50%	50%	50%	50%
Time (total), sec		26.9	23.9	23.7	23.8
Deceleration, mph/sec	1.35 to 1.65	1.45	1.62	1.76	1.75
Distance, ft	800 to 900	760	677	715	724
Friction braking, mph	<5	8.7	4.5	9.5	5.0
Test procedure para.		3.4.5.2	3.4.5.6	3.4.5.10, Step 1	3.4.5.10, Step 1
Braking		FSB	FSB	FSB	FSB
Time (total), sec		14.3	14.8	16.7	15.7
Deceleration, mph/sec	2.7 to 3.3	3.11	2.71	2.69	2.80
Distance, ft	400 to 450	448	435	536	499
Friction braking, mph	<5	14.3	5.1	14.0	5.0
Test direction		Forward	Forward	Reverse	Reverse
Test procedure para.		3.4.5.3	3.4.5.7	3.4.5.9, Step 2	3.4.5.9, Step 2
Weight		AW0	AW0	AW3	AW3
Braking		50%	50%	50%	50%
Time (total), sec		19.0	22.1	25.5	21.8
Deceleration, mph/sec	1.35 to 1.65	2.11	1.75	1.67	1.95
Distance, ft	800 to 900	554	628	791	691
Friction braking, mph	<5	8.2	4.5	10.7	4.3
Test procedure para.		3.4.5.4	3.4.5.8	3.4.5.10, Step 2	3.4.5.10, Step 2
Braking		FSB	FSB	FSB	FSB
Time (total), sec		12.0	13.4	17.2	14.8
Deceleration, mph/sec	2.7 to 3.3	3.52	3.00	2.52	2.92
Distance, ft	400 to 450	365	395	539	470
Friction braking, mph	<5	12.7	4.8	17.0	5.0

Dynamic Braking Summary

Test paragraph: 3.4.5.9 — Date of test: 2-19-87

Car configuration: ABBA(dc)

Weight: AW3

Direction: Forward (DC cars NB)

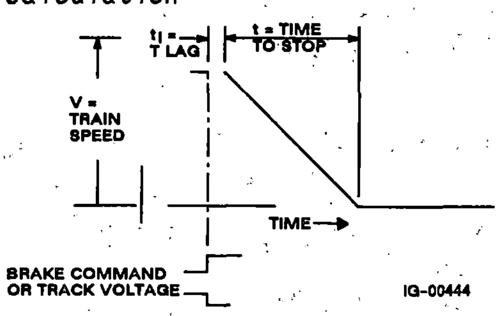
Brake command: 50%

Run number	1	2	3	4	5	Reqd
Train speed, mph	37	38	39	38.5		
Time lag, sec	2.0	2.0	1.75	1.75		
Time to stop, sec	18.75	24.0	23.0	21.5		
Max. decel., mph/sec	1.97	1.58	1.69	1.79		
Distance, feet	617	780	758	705		
x to friction, mph	11	8	10	9		

Average of all runs

- Time: 23.7
- Decel rate: 1.76
- Distance: 715
- x to friction: 9.5

Calculation



$$\text{Time} = t + t_{\ell}$$

$$\text{Decel. peak} = v/t$$

$$\text{Distance} = v\left(t_{\ell} + \frac{t}{2}\right) \times \frac{5280}{3600}$$

FIGURE 4.4.5-2. DATA REDUCTION WORKSHEET

(b) The initial speeds of all tests in the four-car ABBA configuration were within the required 38- to 42-mph range; however, the initial speed of the ac-driven consist averaged nearly 2 mph faster than the dc-driven consist. This is equivalent to a 5-percent correction, which should be applied when comparing stopping times and distances.

(c) The transition from dynamic to friction braking as the test vehicle slowed to a stop occurred at a substantially higher speed on the dc-powered vehicle, and was much greater than the 5-mph maximum value required. In addition, friction braking was initiated at a higher speed during full-service braking than during 50-percent braking. During AB(dc) consist testing, the average values were 13.5 and 8.5 mph, respectively, as measured at the increase of brake cylinder pressure as indicated on Figure 4.4.5-1. The corresponding values during ABBA(dc) tests were 15.5 mph and 10.1 mph. Friction braking consistently occurred at 5 mph or less during all AB(ac) and ABBA(ac) testing, in accordance with requirements. There is no apparent difference between application of 50-percent or full-service braking. The effect of the higher speed initiation of friction braking on the calculated value of average dynamic braking deceleration is difficult to quantify and no attempt will be made to approximate compensation factors. It is also undetermined whether the higher speed onset of friction braking was unique to the dc vehicle under test, possibly due to improperly set controls, or if this routinely occurs throughout the passenger-service vehicle fleet. The consequences of friction braking at higher-than-necessary speed include additional brake lining wear and deterioration of wheel and track surfaces. During ABBA(dc) testing in the reverse direction, very early friction braking occurred, which resulted in wheel lockup during a substantial portion of the stopping period. This is shown clearly in Figure 4.4.5-3, where the wheel rotation speed (used to measure the train speed) becomes zero several seconds before the deceleration (as measured by an accelerometer within the vehicle) reached zero. This evidence of wheel

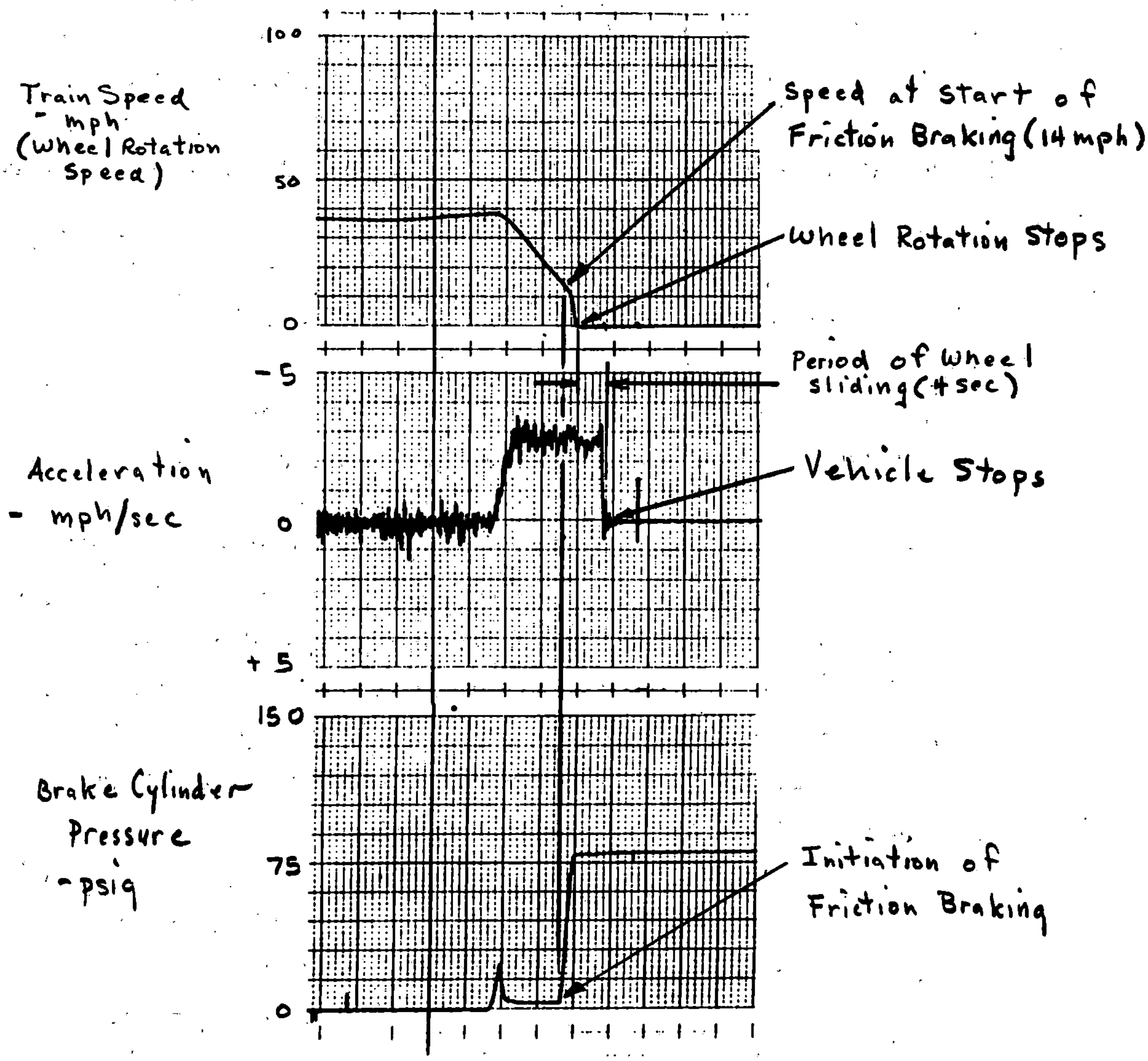


FIGURE 4.4.5-3. WHEEL SLIDING DUE TO EARLY FRICTION BRAKING DURING ABBA(DC) TESTING

sliding was noted to a greater or lesser extent on several runs in the ABBA(dc) configuration in the reverse direction. In the figure, it should be noted that the inverted sense of acceleration is due to the reverse direction of train motion.

(d) The time lag from initiation of the braking command to the beginning of the vehicle speed reduction was greater in the dc vehicles (1.9-sec average) than the ac vehicles (0.7-sec average). Deceleration calculations are not affected by the time lag because deceleration time is considered to start when the vehicle speed decreases, not when the braking command is issued. Distance travelled, however, does include the time lag, and the stand-alone benefit of the faster response of the ac control system is a 70-ft shorter stopping distance.

(e) Deceleration and stopping distance were within or better than (greater deceleration and shorter distance) requirements for AB(dc) and AB(ac) consists for 50-percent and full-service braking at both AW0 and AW3 weights. This was also true for ABBA(dc) and ABBA(ac) AW3 consists at 50-percent braking. With the application of full-service braking, however, the required stopping distance of 400 to 450 ft was exceeded, although the ABBA(ac) configuration performed substantially better (485 ft avg.) than the ABBA(dc) unit (538 ft avg.). Deceleration of the ABBA(dc) vehicle also was slightly less (2.6 mph/sec avg.) than the required 2.7 to 3.3 mph/sec.

(f) During ABBA(ac) testing in the reverse direction, the data show a deceleration component that occurs prior to the increase of brake cylinder pressure. This is due to the occurrence of frictional braking on the dc car. This is considered to be a test anomaly, and the test results do not appear to be appreciably affected by this component as shown by Figure 4.4.5-4.

In conclusion, the overall dynamic braking performance of the ac propulsion system is superior to that of the dc vehicle. The ac propulsion cars consistently demonstrated faster response to the braking command, and, with allowance for the higher initial speed of the ac vehicle, roughly equivalent stopping distance was achieved. The deceleration of the ac vehicle was consistently acceptable during all testing, while the ABBA(dc) consist deceleration was below requirement during full-service braking. The early transition to friction braking undoubtedly shortened the stopping distance of,

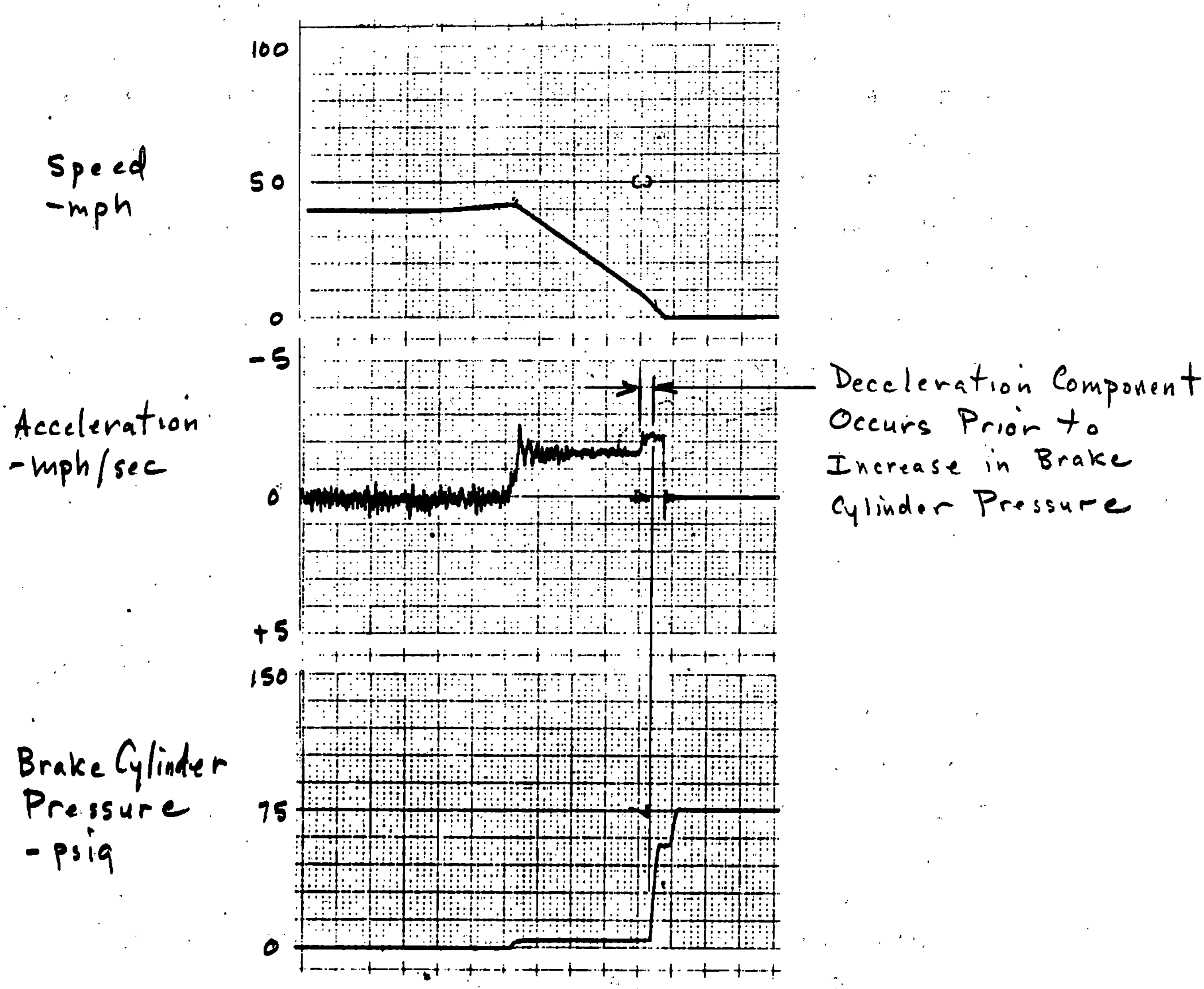


FIGURE 4.4.5-4. EFFECT OF FRICTION BRAKING OF AB(DC) UNIT DURING ABBA(AC) TEST

and to some extent is unfairly advantageous to, the dc vehicle; however, the resultant wheel sliding could be a serious maintenance drawback and possible safety consideration.

4.4.6 Emergency Brake Deceleration Test (Test Procedure 86-60134)

Emergency brake deceleration testing was conducted on the ac and dc test cars connected in the AB(ac) and AB(dc) two-car consists. Testing was performed to determine average deceleration and stopping distance when the emergency brake was commanded while the vehicles were at full forward speed. The vehicles tested were at AWO (empty) weight. Comparable, consistent, and predictable results were obtained, such that testing at maximum weight (AW3) and with vehicles coupled together (ABBA consist) was deemed unnecessary.

Tests were performed at the NYCTA Sea Beach station, on the section of Track E3 between the south end of the New Utrecht Avenue station and 13th Avenue. Testing was conducted in accordance with AiResearch Document 86-60134, dated March 27, 1986: STARS Ac-Drive Deceleration Emergency Brake Test Procedure. All emergency brake deceleration tests were performed with the vehicles moving toward the north at approximately 40 mph. The emergency brake was selected on the master controller as the vehicle entered the test zone. Automatic recording (strip chart) of the test parameters provided the data to derive average deceleration and stopping distance. The parameters recorded as a function of time include: line voltage and current, speed measured as wheel rotational velocity, vehicle acceleration, brake command, brake cylinder pressure, and straight-air-pipe pressure. Detailed descriptions of each recorded parameter may be found in the previously referenced test procedure document.

Normal environmental conditions prevailed throughout the test period. The AB(dc) consist was tested on October 14, 1986, and the AB(ac) consist on October 15, 1986. Four runs were made with the AB(dc) vehicle and three with the AB(ac) vehicle. The strip chart data from the first and last run for each vehicle are reproduced in Figures 4.4.6-1 and 4.4.6-2. Corresponding data sheets are presented in Figure 4.4.6-3.

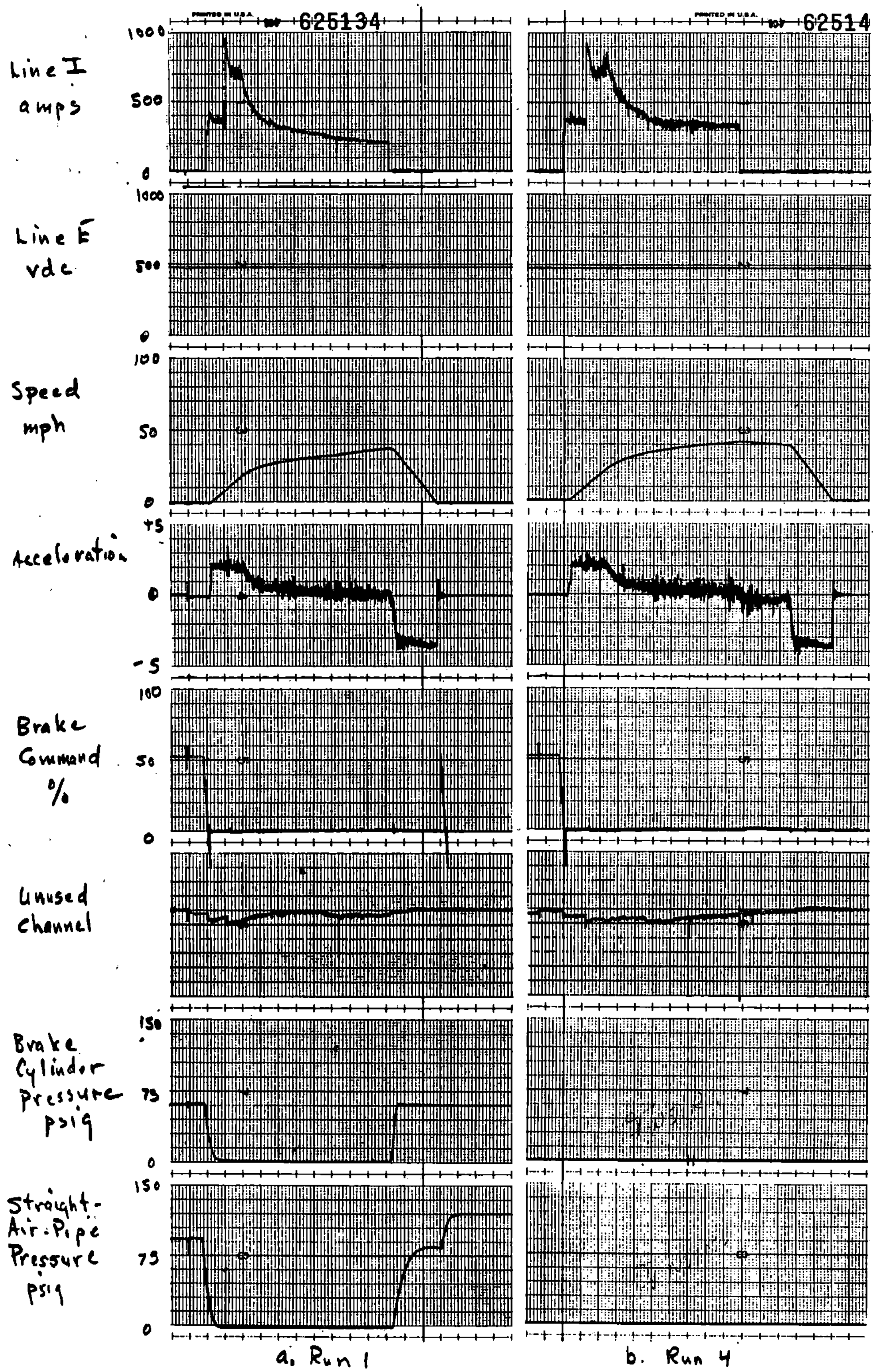


FIGURE 4.4.6-1. AB(DC) EMERGENCY BRAKING TEST RECORDINGS

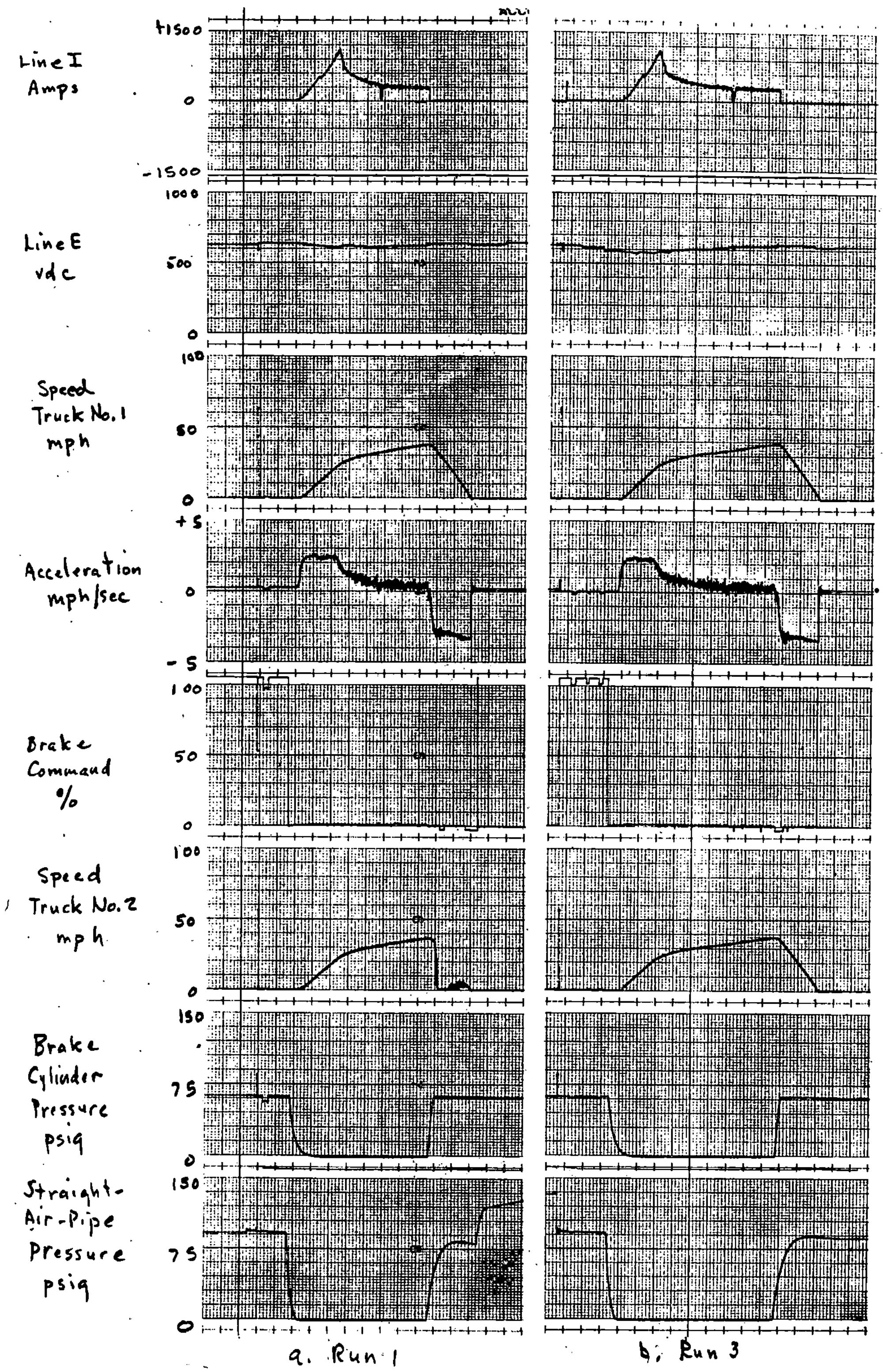


FIGURE 4.4.6-2. AB(AC) EMERGENCY BRAKING TEST RECORDINGS

DATA SHEET

Train Consist AB(AC)
(AB(ac), AB(dc), or ABBA)
NOTE: ABBA tested for AW3 only.

Date Data Taken 10/15/86 (AW0)
Record No. 101579,80 (AW0)
Responsible Test Engineer ______________

Para. No.	Description	Measured	Required	Acceptance
3.4.4, Step 2	Vehicle weight	lb	130,400 lb ref. (AW3)	__ Yes __ No
3.4.5, Step 1	Vehicle speed	mph	40 ±2 mph	__ Yes __ No
3.4.5, Step 3	Brake cylinder pressure	psig	105 ref.	__ Yes __ No
	Straight pipe pressure	psig	105 ref.	__ Yes __ No
3.4.5, Step 6	Time to stop vehicle	sec	12.5 ref.	
	Stopping distance	ft	370 to 425 ft	__ Yes __ No
3.4.5, Step 7	Average deceleration rate: $\frac{\text{V initial (mph)}}{\text{T: Total stopping time}}$	mph/sec	3.2±0.3 mph/sec	__ Yes __ No
Step 8 (Ref. 3.4.4, Step 2)	Vehicle weight INSTR + 4 PEOPLE	88600 lb	87,400 lb ref. (AW0)	✓ Yes __ No
Ref. 3.4.5, Step 1	Vehicle speed	39.5 mph	40 ±2 mph	✓ Yes __ No
Ref. 3.4.5, Step 3	Brake cylinder pressure	63 psig	TBD	__ Yes __ No
	Straight pipe pressure	88.5 psig	TBD	__ Yes __ No
Ref. 3.4.5, Step 6	Time to stop vehicle	12.5 sec	13 ref.	
	Stopping distance	396 ft	370 to 425 ft	✓ Yes __ No
Ref. 3.4.5, Step 7	Average deceleration rate: $\frac{\text{V initial mph}}{\text{T: Total stopping time}}$	3.16 mph/sec	3.2 ±0.3 mph/sec	✓ Yes __ No

FIGURE 4.4.6-3. EMERGENCY BRAKE TEST DATA SHEETS

DATA SHEET

Train Consist AB(DC)
(AB(ac), AB(dc), or ABBA)
NOTE: ABBA tested for AW3 only.

Date Data Taken 10/14/86 (6:00)
Record No. ____
Responsible Test Engineer ____

Para. No.	Description	Measured	Required	Acceptance
3.4.4, Step 2	Vehicle weight	lb	130,400 lb ref. (AW3)	__ Yes __ No
3.4.5, Step 1	Vehicle speed	mph	40 ±2 mph	__ Yes __ No
3.4.5, Step 3	Brake cylinder pressure	psig	105 ref.	__ Yes __ No
	Straight pipe pressure	psig	105 ref.	__ Yes __ No
3.4.5, Step 6	Time to stop vehicle	sec	12.5 ref.	
	Stopping distance	ft	370 to 425 ft	__ Yes __ No
3.4.5, Step 7	Average deceleration rate: $\frac{\text{V initial (mph)}}{\text{T: Total stopping time}}$	mph/sec	3.2±0.3 mph/sec	__ Yes __ No
Step 8 (Ref. 3.4.4, Step 2)	Vehicle weight	88600 lb INSTR + 4 PEOPLE	87,400 lb ref. (AW0)	✓ Yes __ No
Ref. 3.4.5, Step 1	Vehicle speed	39.5 mph	40 ±2 mph	✓ Yes __ No
Ref. 3.4.5, Step 3	Brake cylinder pressure	60 psig	TBD	__ Yes __ No
	Straight pipe pressure	87 psig	TBD	__ Yes __ No
Ref. 3.4.5, Step 6	Time to stop vehicle	12.5 sec	13 ref.	
	Stopping distance	407 ft	370 to 425 ft	✓ Yes __ No
Ref. 3.4.5, Step 7	Average deceleration rate: $\frac{\text{V initial mph}}{\text{T: Total stopping time}}$	3.16 mph/sec	3.2 ±0.3 mph/sec	✓ Yes __ No

FIGURE 4.4.6-3. (CONTINUED)

A review of the test data shows that both the dc and ac cars had deceleration rates of 3.16 mph/sec from an approximate forward speed of 39.5 mph. The stopping distances were 407 and 396 ft for the dc and ac cars, respectively. These stopping distances were within the test requirement, and satisfactory operation of the vehicles during emergency braking is established. Because this is a test of the mechanical braking system, which is the same on both vehicles, the similarity of test results is not unexpected. Brake cylinder pressures were 60 and 63 psig, and straight-air-pipe pressures were 87 and 88.5 psig for the dc and ac cars, respectively. As shown by Figure 4.4.6-2, the rear truck locked up during the first run of the ac vehicle. This did not recur during subsequent runs. No regeneration occurred during emergency braking. During the second and third runs of the dc test vehicle, partial application of braking occurred (evidenced by increase of brake cylinder pressure to 10 to 15 psig for 5 to 8 sec) prior to full emergency brake. For this reason, these runs were disregarded in the evaluation of test results.

In conclusion, the performance of the ac and dc vehicles during emergency braking was similar and within requirements. Deceleration rates and stopping distances are satisfactory and predictable.

4.4.7 Wheel Slip Acceleration/Deceleration Test (Test Procedure 86-60203)

Wheel slip acceleration/deceleration tests were conducted to obtain spin/slide performance data on the ac and dc test cars connected in AB(ac) and AB(dc) two-car consists. The ac vehicle has a feature to minimize wheel spin and slide that is not furnished on the dc vehicle; therefore, to provide a basis of comparison of the propulsion systems and the spin/slide control feature, the ac vehicle was tested with the spin/slide control feature both enabled and disabled. Testing was performed with vehicles at AWO weight (empty) to determine the time, distance, and acceleration (positive and negative) required to reach base speed and to decelerate from the maximum permissible vehicle speed.

Testing was conducted at the NYCTA Sea Beach station Track E3 between the south end of the New Utrecht Avenue station and Kings Highway. Tests were performed in accordance with AiResearch Document 86-60203, dated May 30, 1986: STARS Ac Drive Test Procedure, Wheel Slip Acceleration/Deceleration Test. Normal ambient conditions prevailed throughout the test period, which began September 30, 1986 and concluded October 15, 1986. Dry track testing of consists AB(dc) and AB(ac) had been performed previously in accordance with Test Procedure Documents 86-60168 for acceleration testing and 86-60154 for dynamic brake testing, and data from these tests were referenced instead of repeating essentially identical tests. Test data were reviewed by the NYCTA representative, and the use of previous testing by similarity was approved.

A review of the data revealed that with the ac car spin/slide system disabled, dry track spin/slide performance was the same as when spin/slide was enabled and reasonably comparable to the dc car. On wet track, with spin/slide disabled, the ac cars performed better (did not spin) in acceleration than the dc cars, while the dc cars performed slightly better in deceleration; however, wheel lockup occurred in both ac and dc cars. With the ac cars' spin/slide enabled, the ac cars were better in both acceleration and deceleration, and wheel spin/slide was effectively controlled. Wheel lockup during rapid deceleration also was prevented.

A typical sample of the data recorded for each test is provided in Figure 4.4.7-1. A summary of tests performed and results obtained is presented in Table 4.4.7-1. Selected strip chart records that provide evidence of particular spin/slide occurrences are reproduced in the following figures:

(a) Figure 4.4.7-2--During acceleration of the AB(dc) vehicle on a wet track, an extended wheel spin of nearly 17 sec is exhibited. Wheel slide is also shown during deceleration.

(b) Figure 4.4.7-3--Wet track deceleration produced wheel slide throughout the entire stopping interval (16 sec) during testing of the AB(dc) vehicle. Early initiation of friction braking (wheel speed = 18 mph) resulted in wheel lockup during the final 9 sec before the vehicle stopped.

(c) Figure 4.4.7-4--The AB(ac) vehicle experienced momentary wheel spin of the rear truck at startup. The spin/slide compensation was disabled during this wet track test.

(d) Figure 4.4.7-5--Wheel slide similar to that experienced by the AB(dc) consist during the test shown by Figure 4.4.7-3 was also exhibited by the AB(ac) vehicle during wet track deceleration testing. Spin/slide compensation was disabled and friction braking was initiated at 3 mph wheel speed, substantially slower than the AB(dc) tests.

(e) Figure 4.4.7-6--Spin control is effectively demonstrated in this wet track acceleration test of the AB(ac) vehicle with spin/slide compensation activated. As the wheel contact with the rail changes from rolling to sliding friction, the ac control system rapidly responds to prevent an extended spin occurrence.

(f) Figure 4.4.7-7--During wet track deceleration of the AB(ac) consist, the enabled spin/slide compensation clearly controls wheel slide to short intervals, typically less than 1 sec, which recur as necessary as the vehicle is brought to a stop. Wheel lockup is entirely prevented.

Figure 4.4.7-8 presents the spin/slide test data sheets.

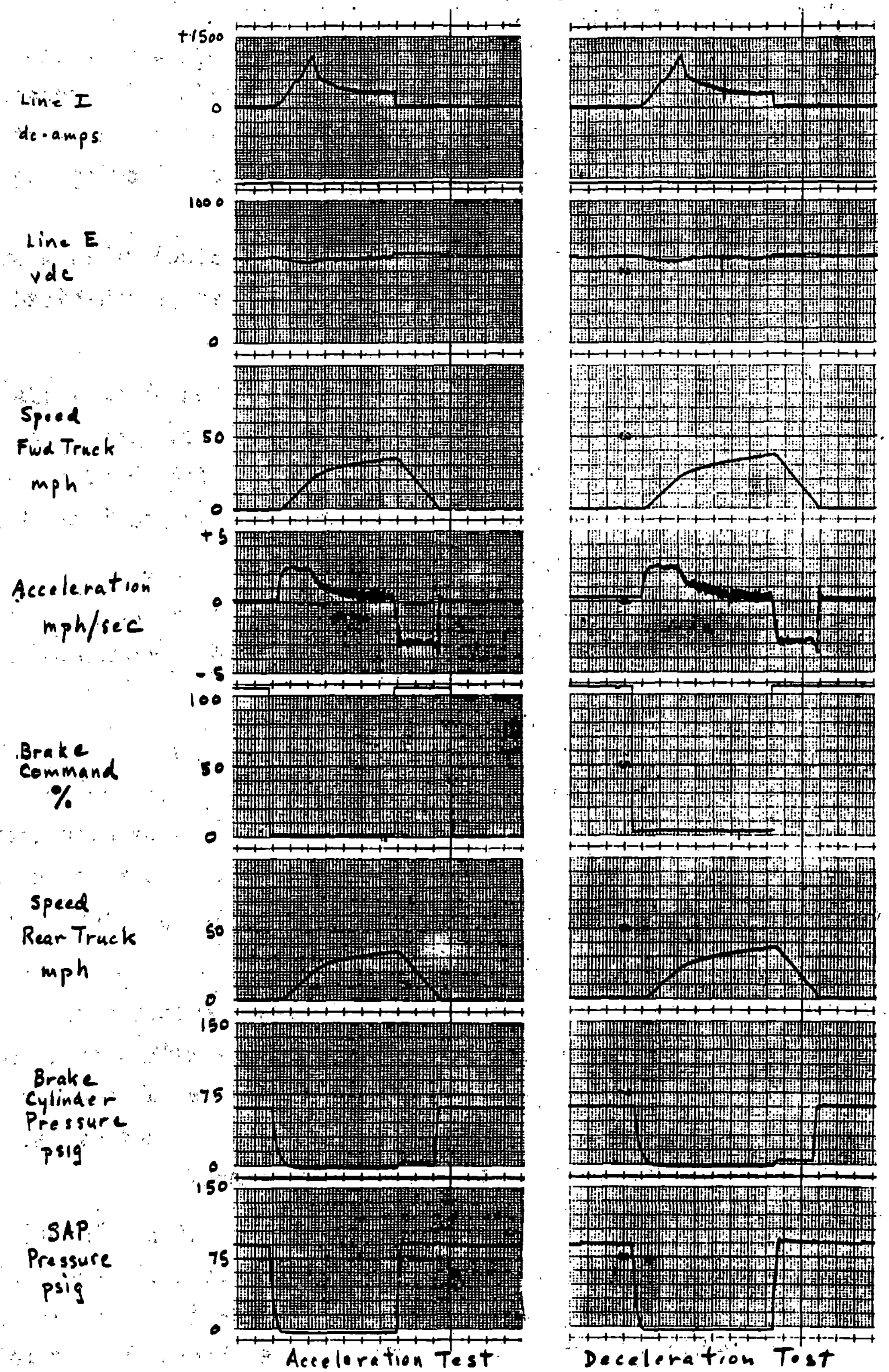


FIGURE 4.4.7-1. REPRESENTATIVE STRIP CHART RECORDING FOR SPIN/SLIDE TESTS

TABLE 4.4.7-1

SPIN/SLIDE ACCELERATION TEST RESULTS

Train Consist	Track Condition	Spin/Slide Compensation	Master Controller*	Procedure Para.	Test Type	Number of Runs	Test Date	Accel./Decel. Wheel (max.), mph/sec	Comments/ Observations
AB(dc)	Dry	N/A	PAR	3.4.5.1	Accel.	Several	9-26-86	2.0	Did not spin
AB(dc)	Dry	N/A	FSB	3.4.5.3	Decel.	Several	9-26-86	3.25	Did not slide
AB(dc)	Wet	N/A	PAR	3.4.5.2	Accel.	4	10-14-86	15.67	Spin occurred
AB(dc)	Wet	N/A	FSB	3.4.5.4	Decel.	3	10-14-86	9.5	Slide occurred
AB(ac)	Dry	Disabled	PAR	3.4.5.5	Accel.	3	10-15-86	<2.75	Did not spin
AB(ac)	Dry	Disabled	FSB	3.4.5.7	Decel.	3	10-15-86	<3.3	Did not slide
AB(ac)	Wet	Disabled	PAR	3.4.5.6	Accel.	3	10-13-86	2.0	Momentary spin
AB(ac)	Wet	Disabled	FSB	3.4.5.8	Decel.	4	10-13-86	17.0	Slide occurred
AB(ac)	Dry	Enabled	PAR	3.4.5.9	Accel.	Several	9-30-86	2.2	Did not spin
AB(ac)	Dry	Enabled	FSB	3.4.5.11	Decel.	Several	9-22-86	2.85	Did not slide
AB(ac)	Wet	Enabled	PAR	3.4.5.10	Accel.	5	10-7-86	1.8	Spin controlled
AB(ac)	Wet	Enabled	FSB	3.4.5.12	Decel.	4	10-7-86	2.0	Slide controlled

*PAR: Maximum Drive
FSB: Full Service Brake

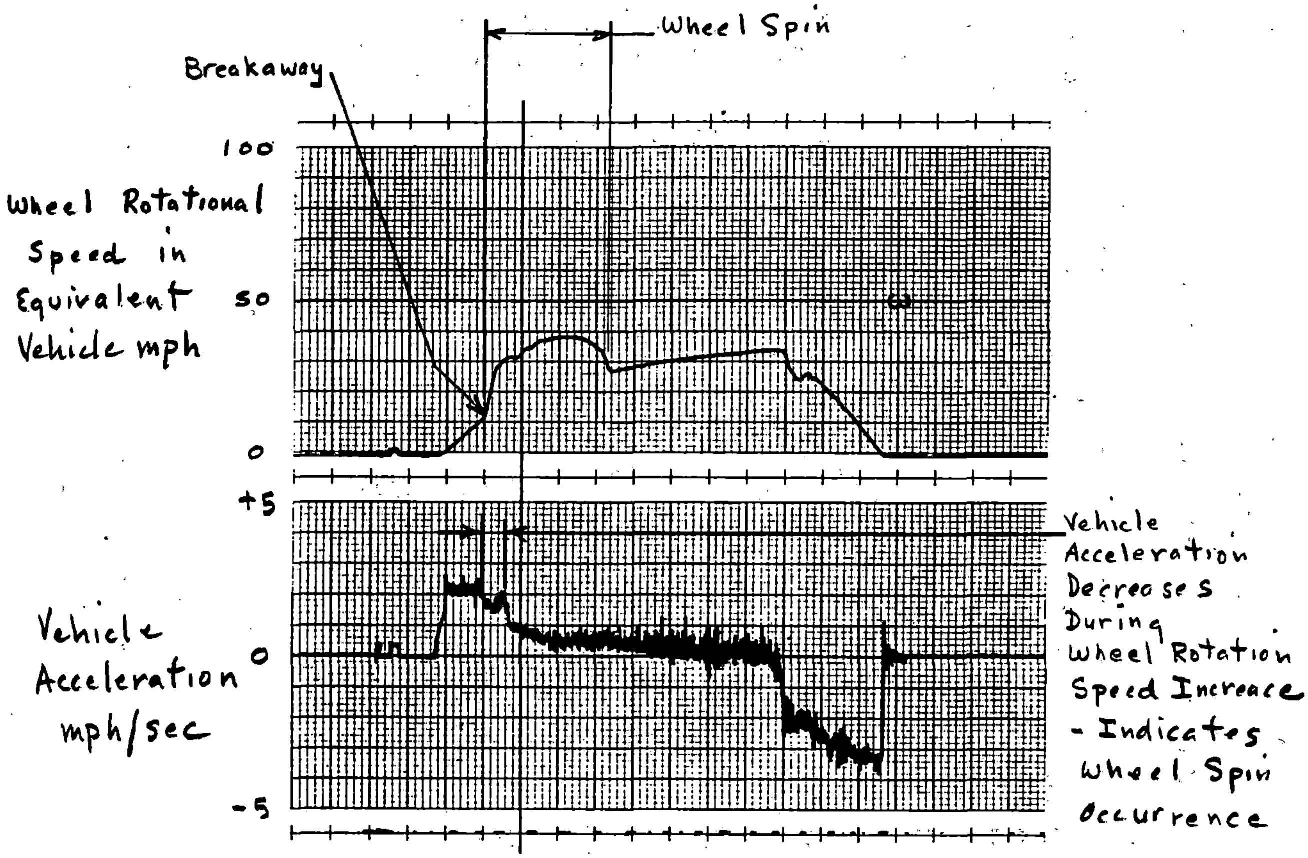


FIGURE 4.4.7-2. AB(DC) WHEEL SPIN DURING ACCELERATION (WET TRACK)

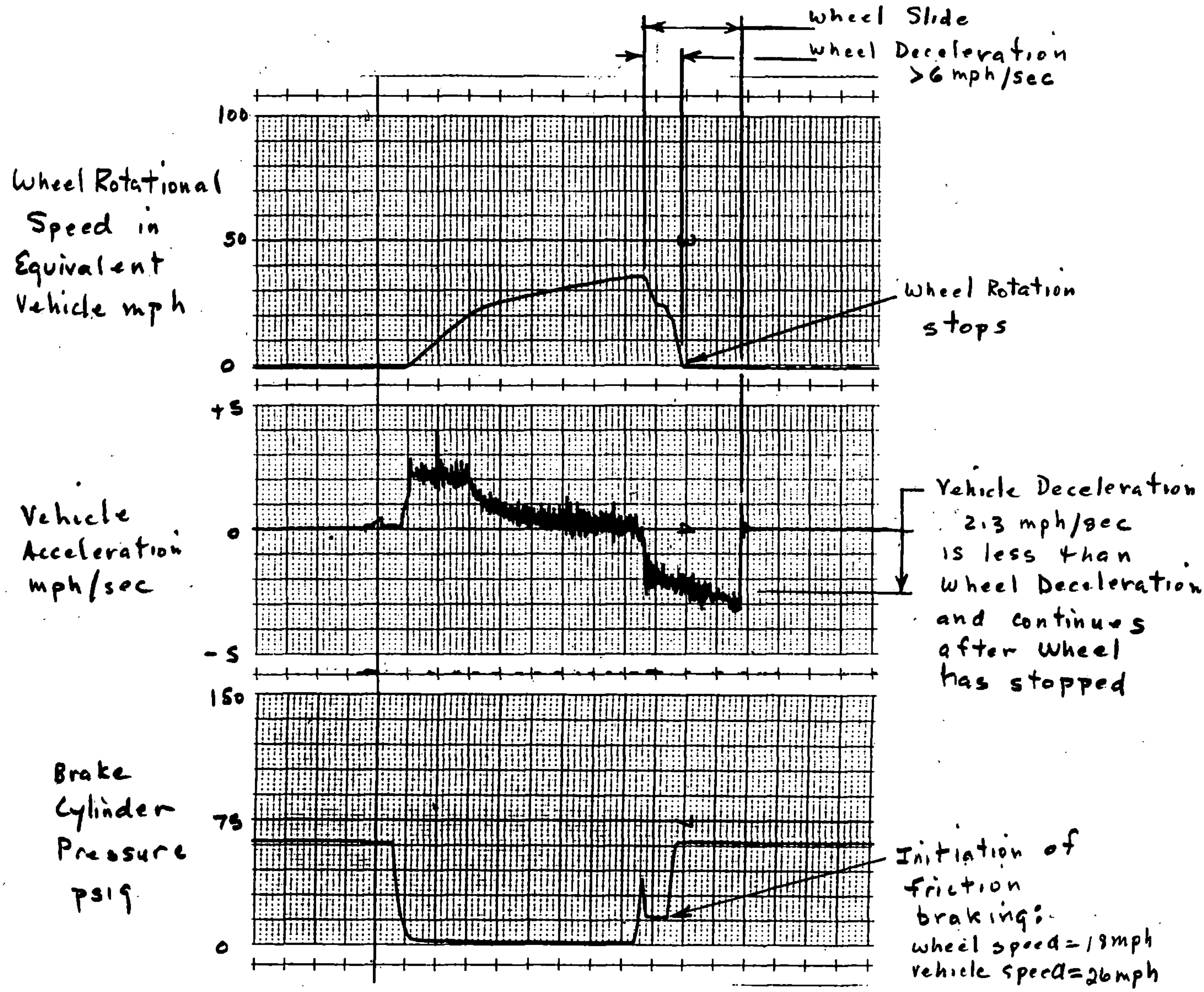


FIGURE 4.4.7-3. AB(DC) WHEEL SLIDE DURING DECELERATION (WET TRACK)

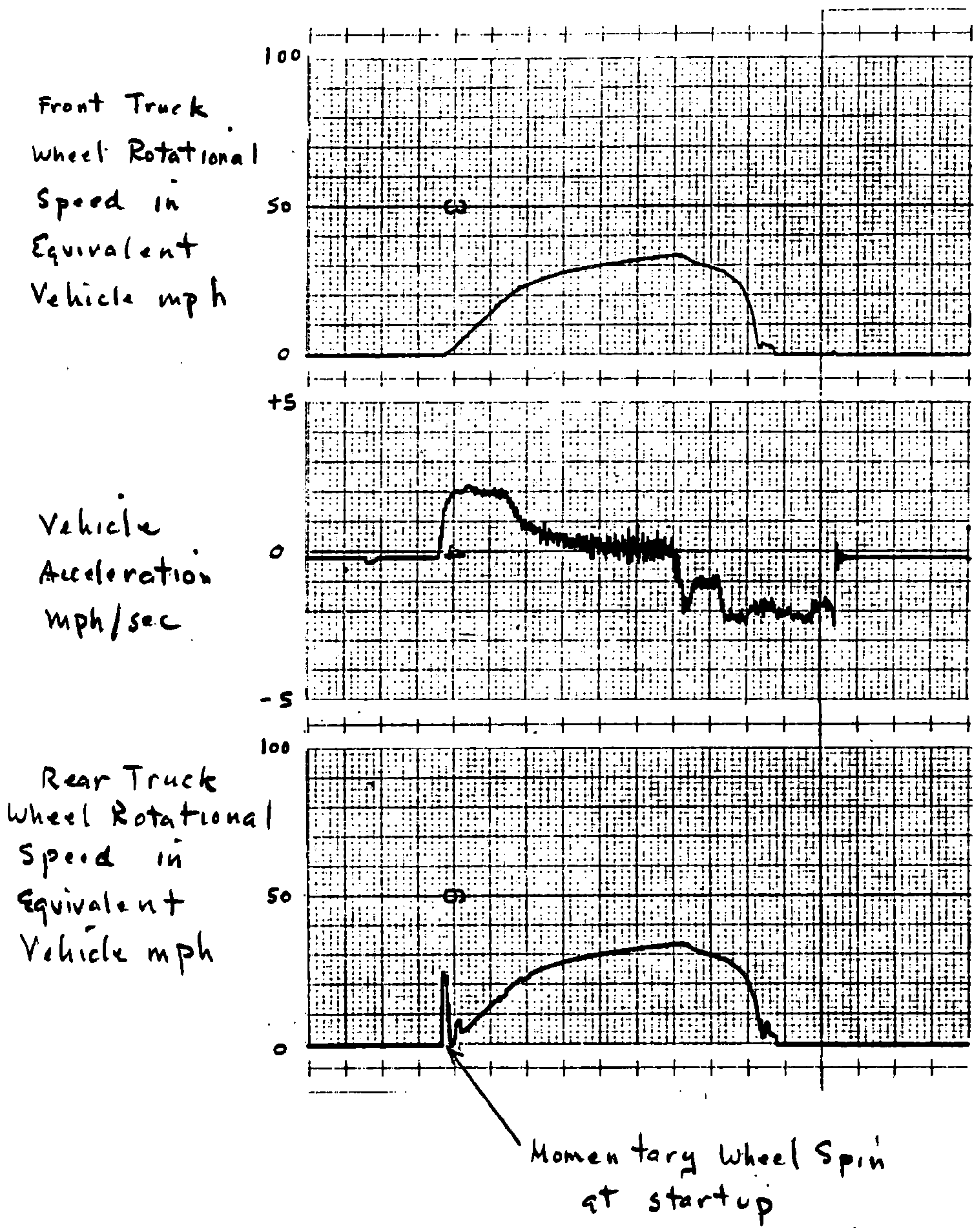


FIGURE 4.4.7-4. AB(AC) WHEEL SPIN ACCELERATION (WET TRACK--SPIN/SLIDE COMPENSATION DISABLED)

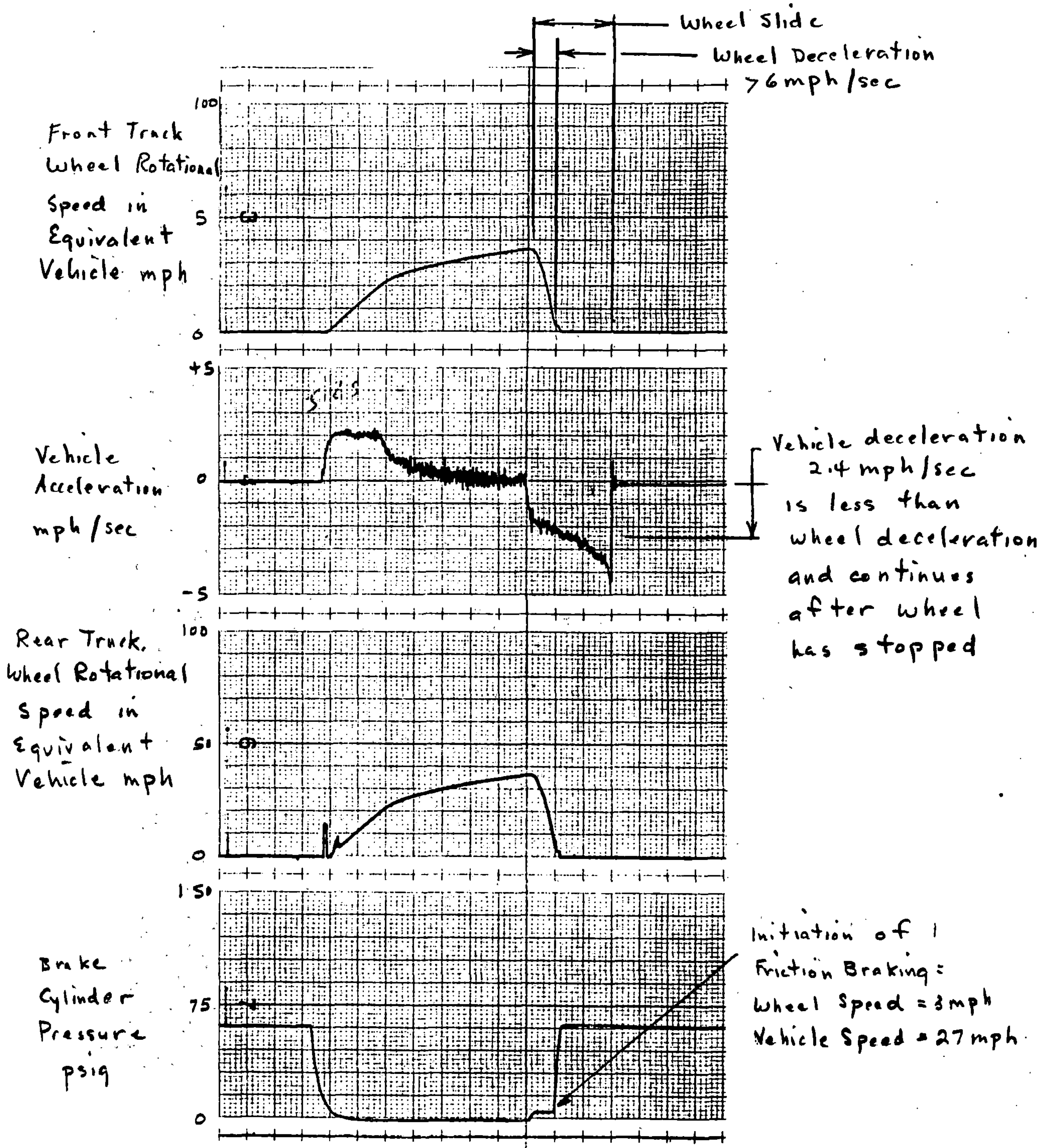


FIGURE 4.4.7-5. AB(AC) WHEEL SLIDE DECELERATION (WET TRACK--SPIN/SLIDE COMPENSATION DISABLED)

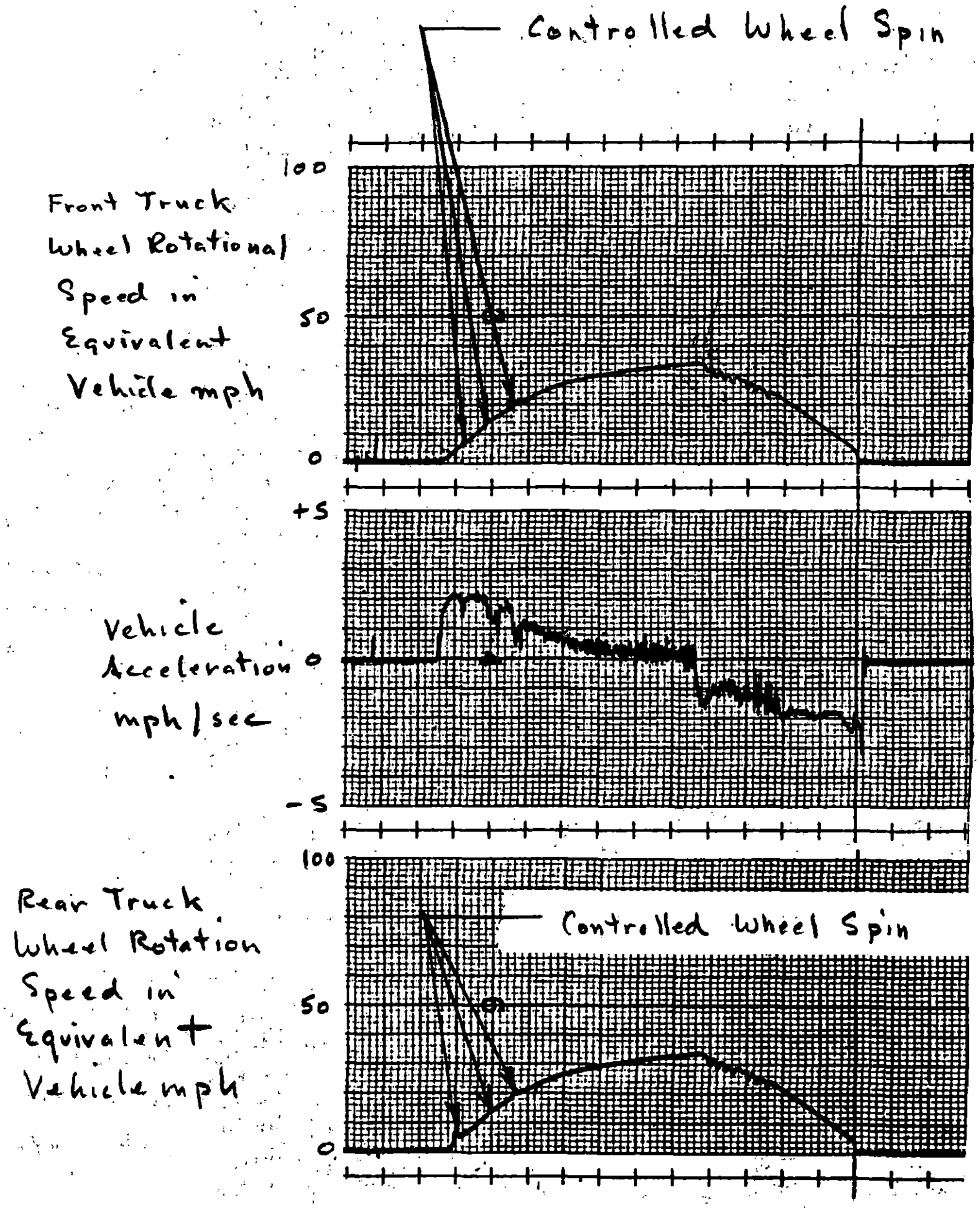


FIGURE 4.4.7-6. AB(AC) WHEEL SPIN CONTROLLED DURING ACCELERATION (WET TRACK--SPIN/SLIDE COMPENSATION ENABLED)

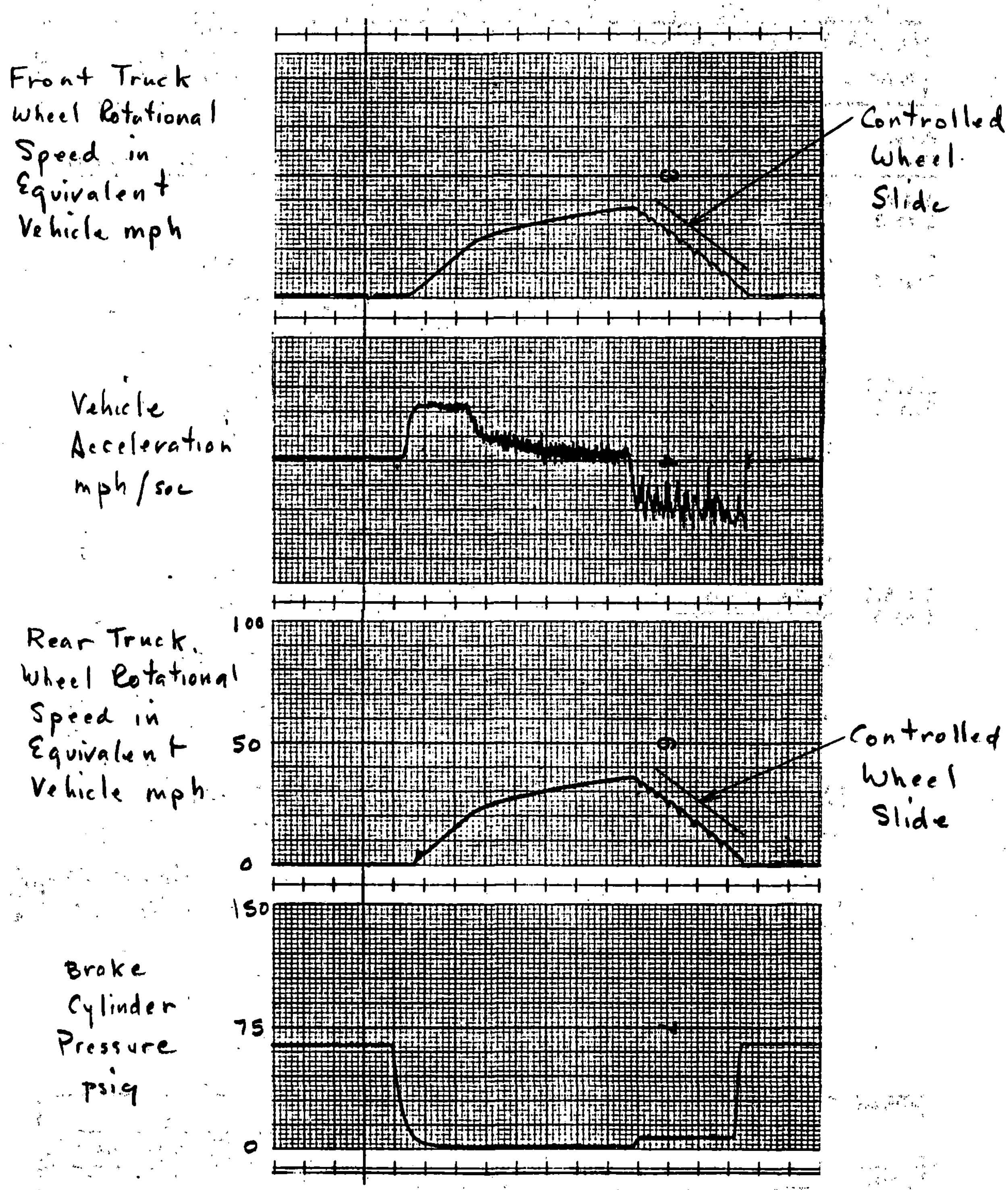


FIGURE 4.4.7-7. AB(AC) WHEEL SLIDE CONTROLLED DURING DECELERATION (WET TRACK--SPIN/SLIDE COMPENSATION ENABLED)

AB(DC) AWO DRY TRACK WHEEL SLIP ACCEL

DATA SHEET	PART NAME	MFG SERIAL NO.
PAGE 1 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.4 Step 2	Vehicle weight	88600 INSTR + 4 PEOPLE	lb	AWO: 87,400 (ref)	lb	
3.4.4 Step 7	Wheel diameter	Recorded in vehicle test log	in.	Nominal: with 0.75 max. difference between wheels	in.	
3.4.5.1 Step 1	Track condition	________	--	Dry	--	
	Train consist	________	--	AB(dc)	--	
	Train direction	________	--	Forward	--	
	Initial train speed, V	________	mph	0	mph	
3.4.5.1 Step 3	Master controller position	________	--	PAR	--	
	Maximum speed reached, V(final)	________	mph	35 to 40*	mph	
	Run time, T	________	sec	20 max.	sec	

DATA TO BE SATISFIED BY SIMILARITY TO TP86-60168 ACCEL. TESTING PER N.Y.C.T.A. 10/14/86

[signature] 10/24/86

*If run time reaches 20 sec max. stop vehicle, minimizing wheel slip. Record maximum speed reached.

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FIGURE 4.4.7-8. TEST DATA SHEETS

DATA SHEET	PART NAME	MFG SERIAL NO.
PAGE 2 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.1 Step 6	Straight-pipe pressure	______	psig	TBD	psig	______
	Distance traveled during run time	______	ft	N/A	--	______
	Wheel slip as evidenced by high acceleration rates? Record maximum.	______	mph/sec	Greater than 2.75	mph/sec	______
	Average acceleration rate, $\frac{V(final)}{T}$	______	mph/sec	N/A	--	______

DATA REQMT. SATISFIED BY SIMILARITY TO TP 86-60168 ACCEL. TESTING PER NYCTA 10/14/86

Garrett test engineer [signature]

New York Transit Authority engineer [signature] 10/24/86

Date 10/14/86

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FIGURE 4.4.7-8. (CONTINUED)

AB(DC) AUTO DRY TRACK WHEEL SLIP ACCEL

DATA SHEET	PART NAME	MFG SERIAL NO.
PAGE 3 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.2	Track condition	DRY	--	Wet	--	
	Train consist	AB(DC)	--	AB(dc)	--	
	Train direction	FORWARD	--	Forward	--	
	Initial train speed, V	0	mph	0	mph	
	Master controller position	PAR	--	PAR	--	
	Maximum speed reached, V(final)	*35	mph	35 to 40*	mph	
	Run time, T TO V_F	*44.83	sec	20 max.	sec	
	Straight-pipe pressure	96 ON DECEL 0 ON ACCEL.	psig	TBD	psig	
	Wheel spin as evidenced by high acceleration rates? Record maximum.	*15.67	mph/sec	Greater than 2.75	mph/sec	
	Average acceleration rate, $\frac{V(final)}{T}$	*.781	mph/sec	N/A	--	
	Distance traveled in run time, T	*1616.67	ft	N/A	--	

* ARITHMETIC MEAN OF LAST 3 RUNS

*If test run time reaches 25 sec max. and the vehicle has not stopped, bring the vehicle to a stop, minimizng wheel slip. Record speed at 25-sec test time.

Garrett test engineer [signature]

New York Transit Authority engineer [signature] 10/24/86

Date 10/14/86

REMARKS	TECHNICIAN		
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FIGURE 4.4.7-8. (CONTINUED)

AB(DC) AWD DRY TRACK WHEEL SLIP DECEL

DATA SHEET	PART NAME	MFG SERIAL NO.
PAGE 4 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.3 Step 1	Track condition	______	--	Dry	--	
	Train consist	______	--	AB(dc)	--	DATA REQMTS SATISFIED BY SIMILARITY TO TP 86-60154 DYNAMIC BRAKE TESTING PER NYCTA 10/14/86
	Initial train speed, V	______	mph	Maximum permissible	mph	
	Brake command	______	--	FULL SERVICE BRAKE	--	
	Speed after deceleration, V(final)	______	mph	N/A	--	
	Run time, T	______	sec	25 max.*	sec	
	Straight-pipe pressure	______	psig	105 ref.	psig	
	Time to stop, TS	______	sec	N/A	--	
	Average deceleration rate, $\frac{V - V(final)}{T}$	______	mph/sec	N/A	--	
	Stopping distance	______	ft	N/A	--	
	Wheel slide as evidenced by high deceleration rates? Record maximum.	______	mph/sec	Greater than 3.3	mph/sec	

*If test run time reaches 25 sec max. and the vehicle has not stopped, bring the vehicle to a stop, minimizing wheel slip. Record speed at 25-sec test time.

Garrett test engineer [signature]

New York Transit Authority engineer [signature] 10/24/86

Date 10/14/86

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FIGURE 4.4.7-8. (CONTINUED)

AB(DC) AND WET TRACK WHEEL SLIP DECEL

DATA SHEET	PART NAME	MFG SERIAL NO.
PAGE 5 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.4	Track condition	WET	--	Wet	--	
	Train consist	AB(DC)	--	AB(dc)	--	
	Initial train speed, V	*36.83	mph	Maximum permissible	mph	
	Brake command	FSB	--	FULL SERVICE BRAKE	--	
	Speed after deceleration, V(final)	0	mph	N/A	--	
	Run time, T	*55s	sec	25 max.*	sec	
	Straight-pipe pressure	96 ON DECEL	psig	105 ref.	psig	
	Time to stop, TS	*17.23	sec	N/A	--	
	Average deceleration rate, $\frac{V - V(final)}{T}$	2.14	mph/sec	N/A	--	
	Stopping distance	*495.25	ft	N/A	--	
	Wheel slide as evidenced by high deceleration rates? Record maximum.	9.5 DUE SOLELY TO PROPULSION SYSTEM	mph/sec	Greater than 3.3	mph/sec	

* ARITHMETIC MEAN OF 3 RUNS.

*If test run time reaches 25 sec max. and the vehicle has not stopped, bring the vehicle to a stop, minimizing wheel slip. Record speed at 25-sec test time.

Garrett test engineer [signature]

New York Transit Authority engineer [signature] 10/24/86

Date 10/14/86

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FIGURE 4.4.7-8. (CONTINUED)

AB(AC) AWO DRY TRACK WHEEL SLIP ACCEL.

DATA SHEET	PART NAME SPIN/SLIDE DISABLED	MFG SERIAL NO.
PAGE 6 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.4	Vehicle weight	88600 INSTR. + 4 PEOPLE	lb	AWO: 87,400	lb	
	Wheel diameter	Recorded in vehicle test log	in.	Nominal: with 0.75 max. difference between wheels	in.	
3.4.5.5	Spin/slide control	DISABLED	--	Disabled	--	
	Track condition	DRY	--	Dry	--	
	Train consist	AB(AC)	--	AB(ac)	--	
	Train direction	FORWARD	--	Forward	--	
	Initial train speed	0	mph	0	mph	
	Master controller position	PAR.	--	PAR	--	
	Maximum speed reached, V(final)	* 35	mph	35 to 40*	mph	
	Run time, T TO BRK.CMD.	* 32.16	sec	20 max.	sec	
	Distance traveled in run time T	* 1201.9	ft	N/A	--	
	Straight-pipe pressure	0 ON ACCEL 94 ON DECEL	psig	105 ref.	psig	

*If run time reaches 20 sec max., stop vehicle, minimizing wheel slip. Record maximum speed achieved.

* ARITHMETIC MEANS OF ALL RUNS

REMARKS	TECHNICIAN		
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FIGURE 4.4.7-8. (CONTINUED)

DATA SHEET	PART NAME	MFG SERIAL NO.
PAGE 7 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.5 (Cont.)	Wheel spin as evidenced by high acceleration rates? Record maximum.	None Recorded	mph/sec	Greater than 2.75	mph/sec	____
	Average acceleration rate, $\frac{V(final)}{T}$	1.09	mph/sec	N/A	--	____

Garrett test engineer [signature]

New York Transit Authority Engineer [signature] 10/24/86

Date 10/ /86

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FIGURE 4.4.7-8. (CONTINUED)

AB(AC) AWD WET TRACK WHEEL SLIP ACCEL

DATA SHEET	PART NAME SPIN/SLIDE DISABLED	MFG SERIAL NO.
PAGE 8 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.6	Spin/slide control	DISABLED	--	Disabled	--	
	Track condition	WET	--	Wet	--	
	Train consist	AB(AC)	--	AB(ac)	--	
	Train direction	FORWARD	--	Forward	--	
	Initial train speed, V	0	mph	0	mph	
	Master controller position	PAR	--	PAR	--	
	Maximum speed reached	34.	mph	35 to 40*	mph	
	Run time, T	32.5	sec	20 max.	sec	
	Distance traveled	1182	ft	N/A	--	
	Straight-pipe pressure	94 ON DECEL 0 ON ACCEL	psig	TBD	psig	
	Wheel spin as evidenced by high acceleration rates? Record maximum.	2 (RUNAWAY)	mph/sec	Greater than 2.75	mph/sec	
	Average acceleration rate: $\frac{V(final)}{T}$	1.05	mph/sec	N/A	--	

*If run time reaches 20 sec max., stop vehicle, minimizing wheel slip. Record maximum speed achieved.

Garrett test engineer [signature]

New York Transit Authority engineer [signature] 10/24/86

Date 10/13/86

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FIGURE 4.4.7-8. (CONTINUED)

AB(AC) AWO DRY TRACK WHEEL SLIP DECEL

DATA SHEET	PART NAME SPIN/SLIDE DISABLED	MFG SERIAL NO.
PAGE 9 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.7	Spin/slide control	DISABLED	--	Disabled	--	
	Track condition	DRY	--	Dry	--	
	Train consist	AB(AC)	--	AB(ac)	--	
	Initial train speed, V	*36.17	mph	Maximum permissible	mph	
	Brake command	FSB	--	FULL SERVICE BRAKE	--	
	Speed after deceleration, V(final)	0	mph	N/A	--	
	Run time, T	*43.3	sec	25 max.*	sec	
	Straight-pipe pressure	94	psig	105 ref.	psig	
	Time to stop, TS	*12.5	sec	N/A	--	
	Average decel-eration rate, $\frac{V - V(final)}{T}$	*2.894	mph/sec	N/A	--	
	Stopping distance	*346	ft	N/A	--	
	Wheel slide as evidenced by high deceleration rates? Record maximum.	NONE RECORDED	mph/sec	Greater than 3.3	mph/sec	

* ARITHMETIC MEAN OF ALL RUNS

*If test run time reaches 25 sec max. and the vehicle has not stopped, bring the vehicle to a stop, minimizing wheel slip. Record speed at 25-sec test time.

Garrett test engineer [signature]

New York Transit Authority Engineer [signature] 10/24/86

Date 10/15/86

REMARKS	TECHNICIAN		
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FIGURE 4.4.7-8. (CONTINUED)

AB(AC) AND WET TRACK WHEEL SLIP DECEL

DATA SHEET	PART NAME SPIN/SLIDE DISABLED	MFG SERIAL NO.
PAGE 10 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.8	Spin/slide control	DISABLED	--	Disabled	--	
	Track condition	WET	--	Wet	--	
	Train consist	AB(AC)	--	AB(ac)	--	
	Initial train speed, V	36	mph	Maximum permissible	mph	
	Brake command	FSB	--	FULL SERVICE BRAKE	--	
	Speed after deceleration, V(final)	0	mph	N/A	--	
	Run time, T	* 52.66	sec	25 max.*	sec	
	Straight-pipe pressure	96 ON DECEL	psig	105 ref.	psig	
	Time to stop, TS	* 16.33	sec	N/A	--	
	Average decel-eration rate, $\frac{V - V(final)}{T}$	* 2.21	mph/sec	N/A	--	
	Stopping distance	* 524.5	ft	N/A	--	
	Wheel slide as evidenced by high deceleration rates? Record maximum.	34MPH / 2SEC = 17 RUN 02	mph/sec	Greater than 3.3	mph/sec	

* ARITHMETIC MEAN OF ALL RUNS

*If test run time reaches 25 sec max. and the vehicle has not stopped, bring the vehicle to a stop, minimizing wheel slip. Record speed at 25-sec test time.

Garrett test engineer [signature]

New York Transit Authority engineer [signature] 10/24/86

Date 10/13/86

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FIGURE 4.4.7-8. (CONTINUED)

AB(AC) AWD DRY TRACK WHEEL SLIP ACCEL

DATA SHEET	PART NAME SPIN/SLIDE ENABLED	MFG SERIAL NO.
PAGE 11 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.9	Spin/slide control		--	Enabled	--	DATA REQMTS
	Track condition		--	Dry	--	SATISFIED BY
	Train consist		--	AB(ac)	--	SIMILARITY TO
	Train direction		--	Forward	--	TP86-60168
	Initial train speed, V		mph	0	mph	ACCEL TESTING
	Master controller position		--	PAR	--	PER NYCTA 10/15
	Maximum speed reached, V(final)		mph	35 to 40*	mph	
	Run time, T		sec	20 max.	sec	
	Distance traveled		ft	N/A	--	
	Straight-pipe pressure		psig	TBD	psig	
	Wheel spin as evidenced by high acceleration rates? Record maximum.		mph/sec	Greater than 2.75	mph/sec	
	Average acceleration rate: $\frac{V(final)}{T}$		mph/sec	N/A	--	

*If run time reaches 20 sec max., stop vehicle, minimizing wheel slip. Record maximum speed achieved.

Garrett test engineer [signature]

New York Transit Authority engineer ______

Date 10/15/86

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FIGURE 4.4.7-8. (CONTINUED)

AB(AC) AWD WET TRACK WHEEL SLIP ACCEL.

DATA SHEET	PART NAME SPIN/SLIDE ENABLED	MFG SERIAL NO.
PAGE 12 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.10	Spin/slide control	ENABLE	--	Enabled	--	
	Track condition	WET	--	Wet	--	
	Train consist	AB(AC)	--	AB(ac)	--	
	Train direction	FORWARD	--	Forward	--	
	Initial train speed, V	0	mph	0	mph	
	Master controller position	PAR.	--	PAR	--	
	Maximum speed reached, V(final)	*34.13	mph	35 to 40*	mph	
	Run time, T	*34.88	sec	20 max.	sec	
	Distance traveled	*1244	ft	N/A	--	
	Straight-pipe pressure	94 ON DECEL 0 ON ACCEL	psig	TBD	psig	
	Wheel spin as evidenced by high acceleration rates? Record maximum.	1.8 (RUN 4)	mph/sec	Greater than 2.75	mph/sec	
	Average acceleration rate, V(final)/T	.98	mph/sec	N/A	--	

* ARITHMETIC MEAN OF ALL RUNS

*If test run time reaches 20 sec max., stop vehicle, minimizing wheel slip. Record maximum speed achieved.

Garrett test engineer [signature]

New York Transit Authority engineer ____________

Date 10/7/86

REMARKS	TECHNICIAN		
	DATE ☐ ACCEPT REJECT ☐		
AIRESEARCH MANUFACTURING COMPANY — FSCM NO. 70210	DOCUMENT NO. 86-60203	REV LTR -	PAGE 20

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FIGURE 4.4.7-8. (CONTINUED)

AB(AC)AWD DRY TRACK WHEEL SLIP DECEL

DATA SHEET	PART NAME SPIN SLIDE ENABLED	MFG SERIAL NO.
PAGE 13 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.11	Spin/slide control	______	--	Enabled	--	DATA REQMTS.
	Track condition	______	--	Dry	--	SATISFIED BY
	Train consist	______	--	AB(ac)	--	SIMILARITY TO
	Initial train speed, V	______	mph	Maximum permissible	mph	TP 86-60154
	Brake command	______	--	FULL SERVICE BRAKE	--	DYN. BRAKE
	Speed after deceleration, V(final)	______	mph	N/A	--	DECEL. TESTING
	Run time, T	______	sec	25 max.*	sec	PER NYCTA
	Straight-pipe pressure	______	psig	105 ref.	psig	______
	Time to stop, TS	______	sec	TBD	sec	______
	Average deceleration rate, $\frac{V - V(final)}{T}$	______	mph/sec	TBD	mph/sec	______
	Stopping distance	______	ft	TBD	ft	______
	Wheel slide as evidenced by high deceleration rates? Record maximum.	______	mph/sec	3.3	mph/sec	______

*If test run time reaches 25 sec max. and the vehicle has not stopped, bring the vehicle to a stop, minimizing wheel slip. Record speed at 25-sec test time.

Garrett test engineer [signature]

New York Transit Authority engineer ______

Date 10/15/86

REMARKS		TECHNICIAN		
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FIGURE 4.4.7-8. (CONTINUED)

AB(AC) AUTO WET TRACK WHEEL SLIP DECEL

DATA SHEET	PART NAME SPIN/SLIDE ENABLED	MFG SERIAL NO.
PAGE 14 OF 15	PART NO.	NAMEPLATE SERIAL NO.

Para. No.	Description	Actual	Units	Required	Units	Comments
3.4.5.12	Spin/slide control	ENABLED	--	Enabled	--	
	Track condition	WET	--	Wet	--	
	Train consist	AB(AC)	--	AB(ac)	--	
	Initial train speed, V	* 36.5	mph	Maximum permissible	mph	
	Brake command	F.S.B.	--	FULL SERVICE BRAKE	--	
	Speed after deceleration, V(final)	0	mph	N/A	--	
	Run time, T	* 57.4	sec	25 max.*	sec	
	Straight-pipe pressure	94 ON DECEL	psig	105 ref.	psig	
	Time to stop, TS	* 21 SEC	sec	TBD	sec	
	Average deceleration rate, $\frac{V - V(final)}{T}$	* 1.793	mph/sec	TBD	mph/sec	
	Stopping distance	* 604.25	ft	TBD	ft	
	Wheel slide as evidenced by high deceleration rates? Record maximum.	2.0 DUE SOLELY TO (PROPULSION) SYSTEM	mph/sec	3.3	mph/sec	

* [illegible] MEAN OF 4 RUNS.

*If test run time reaches 25 sec max. and the vehicle has not stopped, bring the vehicle to a stop, minimizing wheel slip. Record speed at 25-sec test time.

Garrett test engineer [signature]

New York Transit Authority engineer [signature] 10/24/86

Date 10/7/86

REMARKS	TECHNICIAN		
	DATE ☐ ACCEPT REJECT ☐		
AIRESEARCH MANUFACTURING COMPANY — FSCM NO. 70210	DOCUMENT NO. 86-60203	REV LTR -	PAGE 22

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FIGURE 4.4.7-8. (CONTINUED)

DATA SHEET	PART NAME	MFG SERIAL NO.
PAGE 15 OF 15	PART NO.	NAMEPLATE SERIAL NO.

3.4.5.13 AB(dc) and AB(ac) without spin/slide

AB(dc) better than AB(ac) ________ AB(ac) comparable to AB(dc) ________ AB(ac) better than AB(dc) ________

AB(dc) and AB(ac) with spin/slide

AB(dc) better than AB(ac) ________ AB(ac) comparable to AB(dc) ________ AB(ac) better than AB(dc) ________

Garrett test engineer ______________________________

New York Transit Authority engineer ______________________________

Date ______________________

REMARKS		TECHNICIAN		
		DATE ☐ ACCEPT REJECT ☐		
AIRESEARCH MANUFACTURING COMPANY	FSCM NO. 70210	DOCUMENT NO. 86-60203	REV LTR -	PAGE 23

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FIGURE 4.4.7-8. (CONTINUED)

4.4.8 Power Consumption (Test Procedure 86-60202)

Power consumption testing was performed on the ac and dc test cars connected as a four-car ABBA consist to evaluate and compare energy consumption from the two different propulsion systems.

Due to the loss of the Pueblo test facility and the amendment of the ac propulsion test program in conjunction with the redirection to the NYCTA, several test parameters were revised. They were:

(a) The Phase I performance and endurance profile, based on the NYCTA "R" line, could not be performed on the actual facility due to limits on equipment and the line's ability to accept regeneration from the ac cars.

(b) Energy consumption comparison testing was conducted on the Sea Beach test track, and continued testing was planned for the "G" line, which could accept regeneration under a maintained maximum regeneration voltage of 680 v. Test documents were prepared for the "G" line program.

With the success of the Sea Beach test program demonstration of regeneration and the ripple detector, AiResearch/Stromberg decided to perform the "G" line test as a limited revenue service demonstration. The four-car (ABBA) test consist of two ac and two dc cars coupled to four standard R-44 cars was run in off-hours, with onboard instrumentation to record:

(a) Energy consumption, ac cars and dc cars

(b) Ripple detector operation

(c) Regeneration operation (NOTE: Regeneration level was set at 680 vdc.)

After three days of "G" line revenue service, the following results were tabulated:

(a) Power consumption on the ac cars averaged 18 percent less than on the dc cars.

(b) The ripple detector often functionally disabled regeneration over the route due to low ripple signal level.

Because the 18-percent savings in energy was much less than demonstrated on the Sea Beach test track, a careful review of all previous performance data on the ac and dc cars was made, and the following conclusions were reached:

(a) There was substantial mismatch in acceleration rates between the ac and dc cars. As such, the ac cars acted as locomotives for the rest of the consist, thus increasing the energy consumption. Since the "G" line revenue service demonstration consisted of two ac propulsion cars and six dc propulsion cars (typically, eight-car trains make up a consist), any mismatch is exaggerated when comparing energy consumed by the ac propulsion cars with that consumed by typical R-44 dc propulsion cars. An analysis performed by AiResearch and presented to the NYCTA showed:

    (1) At AW0: Difference in drive energy consumed = 11.8 percent

    (2) At AW3: Difference in drive energy consumed = 35.3 percent

    or an overall average of 23.5 percent higher drive consumption by the ac cars due to the mismatch.

    Even with the mismatch, the overall energy savings recorded by the ac cars over the dc cars was 18 percent; if the cars had been matched for acceleration, a much greater savings would have been evident.

(b) Because the cars were operated at off-hours, receptivity of the line was lower than would be expected during rush hours; hence, regeneration was not optimum. Limiting the regeneration voltage to 680 v also restricted regeneration capability. Raising the regeneration level would have substantially increased energy savings.

(c) Operation of the ripple detector is directly in conflict with increased emphasis on energy savings. The loss of a detectable level of ripple was evident along the route and many times disabled regeneration during braking. Lowering the detector sensitivity would result in lower overall reliability. Review of the measured ripple signal showed a nonuniform wave pattern along the route, which varied depending upon several factors (traffic, time of day, distance away from substation, etc.).

In summary, overall energy savings by the ac propulsion cars was documented, with the magnitude of the savings varying from 40 to 18 percent, depending upon the factors in the aforementioned discussions. The charts shown in Figures 4.4.8-1 and 4.4.8-2 are conservative predictions based on the accumulated data.

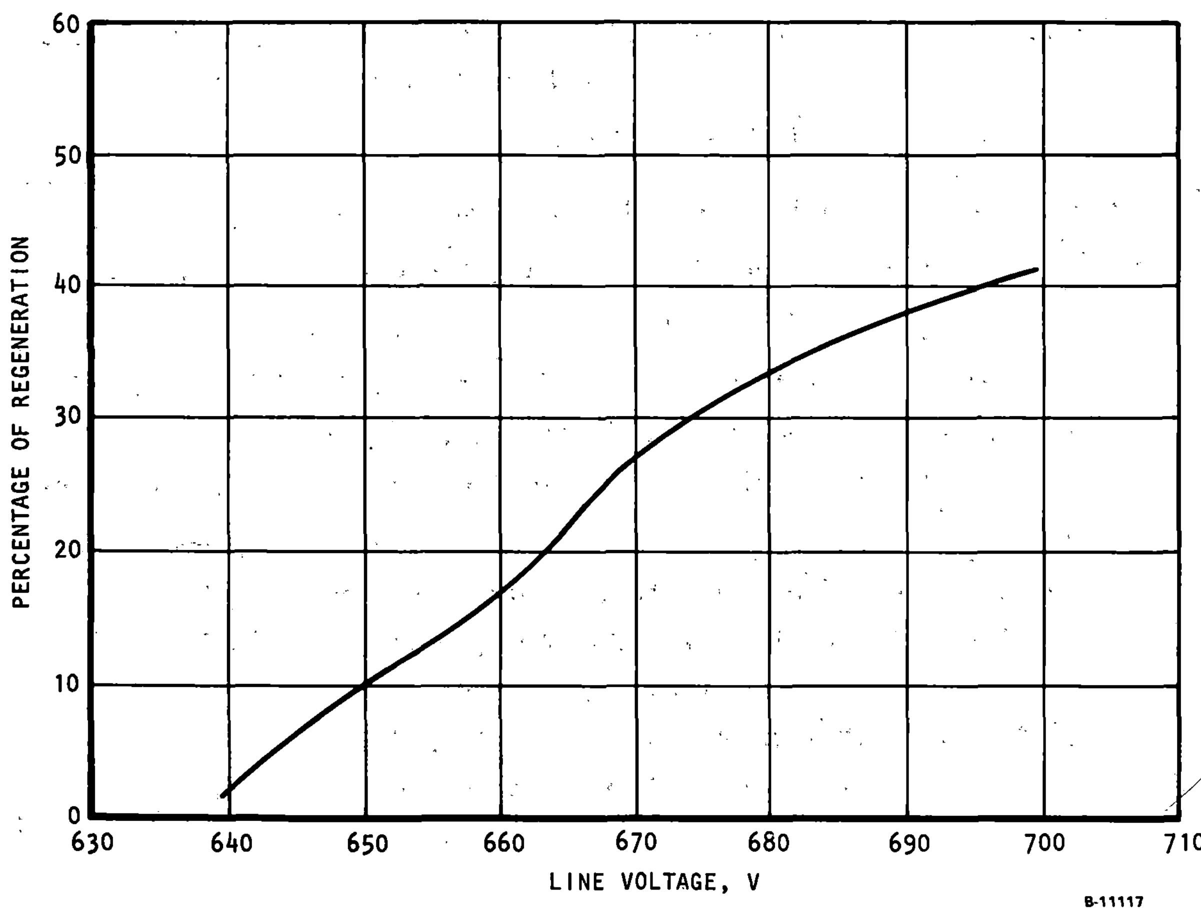


FIGURE 4.4.8-1. PERCENTAGE OF REGENERATION VS MAXIMUM REGENERATION VOLTAGE

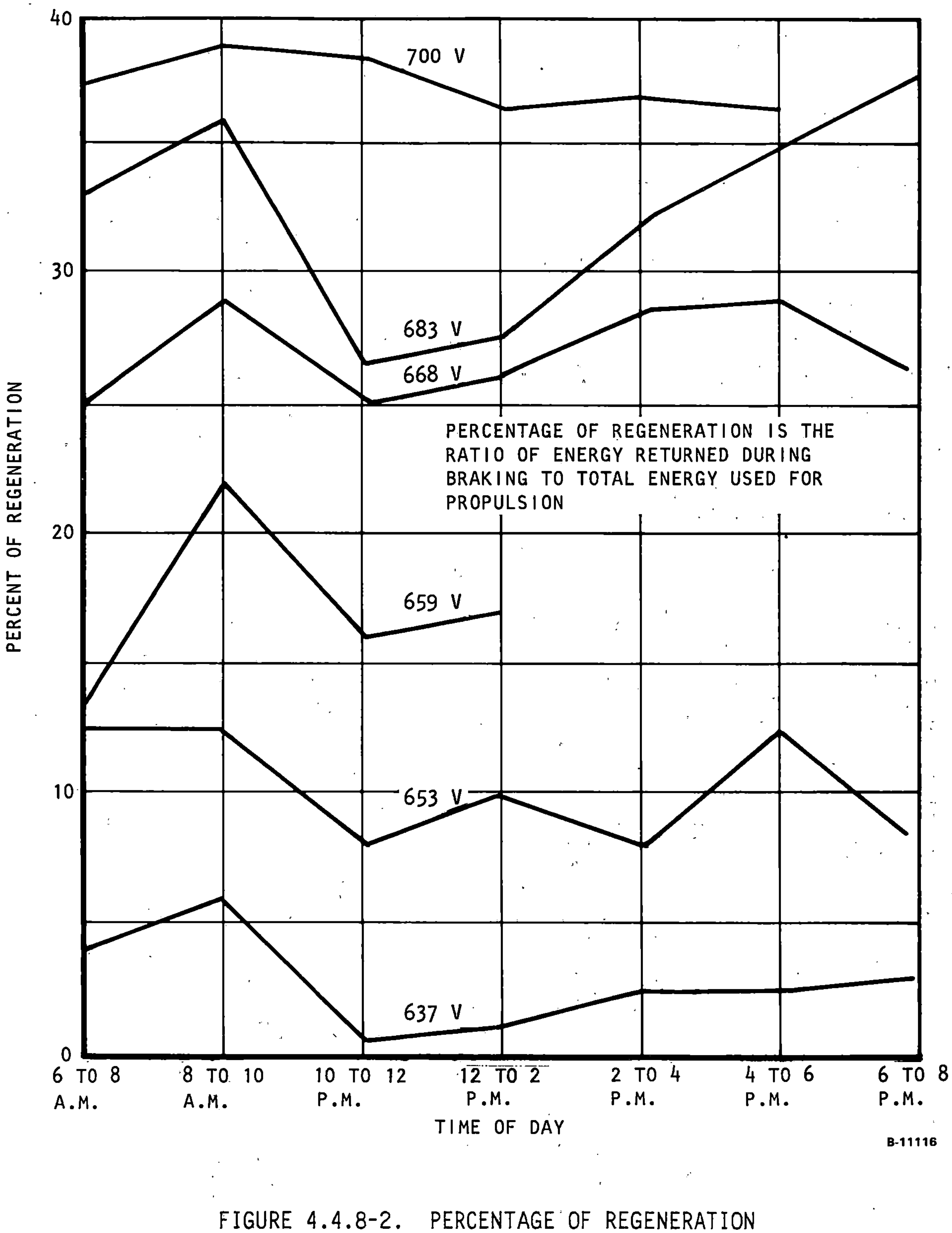


FIGURE 4.4.8-2. PERCENTAGE OF REGENERATION AS A FUNCTION OF TIME OF DAY

4.4.9 Ripple Detector

The ac propulsion system design established in Phase I of this program incorporated a demonstrated dead-rail and rail gap detection equipment design identical to that used successfully for regenerative chopper systems operating in existing transit services in Atlanta and Toronto. The system reacts to the loss of 600-vdc third-rail power, opening the line contactors and inhibiting regenerative braking within 150 msec after detecting a power gap or dead rail condition, to prevent electrification of a dead rail. An additional requirement was imposed when program redirection resulted in the change from the Pueblo TTC test site to the NYCTA test/demonstration site. As discussed in the following paragraphs, before permitting operation on the NYCTA revenue transit system with car regeneration, the NYCTA required the addition of a fast-acting regeneration-inhibit circuit of unique design that would be sensitive to substation-generated 720-Hz ac ripple voltage on the 600-vdc line. System operation based on the presence or absence of the substation-generated 720-Hz ac ripple voltage would enable the system to detect the loss of third-rail power from the power station even during regenerative braking, as well as to discriminate between a third rail electrified by the power substation or a "dead" rail electrified by regenerative braking entry from a car.

4.4.9.1 NYCTA Requirements

During the Phase I program, AiResearch was notified by the NYCTA that a review of the ac propulsion system design analysis and description had brought attention to the rail gap detector operation. The NYCTA considered the time response of the rail gap detector as inadequate to satisfy their Safety and Car Operations Departments for revenue service operation with regeneration. The NYCTA notified DOT and AiResearch in writing of the unacceptability of the rail gap detector if the ac cars were to be introduced into a revenue service demonstration with regeneration on their facility.

This issue was not addressed in Phase I, but with the loss of availability of the Pueblo TTC and subsequent redirection of Phase II to New York, the success of the STARS program depended upon a NYCTA transit environment demonstration, and as such this issue had to be dealt with.

The NYCTA stressed the requirement for an onboard detector to sense the removal of third-rail power and inhibit any regeneration into a "dead" third rail. A train entering a dead section of rail or encountering a sudden substation power chop would be required to eliminate regeneration into the contact rail. The required time limit for regeneration inhibition was determined based on an effective gap of 6 ft at 50 mph. (Current collectors are 54 ft apart on R-44 cars, and third-rail gaps are 60 ft maximum.) This results in a required time response of within 82 msec.

To meet this requirement, the onboard detector would sense the presence of the 720-Hz ripple voltage that accompanies the power substation rectifiers. A decrease or elimination of this ripple signature to a predetermined point would trigger, through the onboard electronic control unit, an immediate elimination of regeneration capability into the contact rails. If the ac car were in regenerative braking into a receptive line and loss of ripple occurred, the ac cars would switch to rheostatic braking into the onboard resistors within the required time.

A Phase II design and development program resulted in incorporation of a ripple detector into both ac cars. It was tested following the Sea Beach performance testing program. The test program demonstrated compliance with the NYCTA criteria and, in fact, showed effective regeneration cutoff times as short as 35 msec, considerably faster than the requirement. The dead rail detector operates independently of the rail gap detector. A major consequence of the dead rail (ripple) detector is that the incorporation of this device results in inability to achieve maximum regeneration and energy savings due to low ripple levels at many places on the revenue lines, and subsequent loss of regeneration as encountered during the revenue test program.

The following paragraphs provide details on the additional ripple-detection circuit that was designed, and the extensive test efforts that were performed to show its capabilities to meet the NYCTA requirements.

4.4.9.2 Dead Rail Detector System Design

4.4.9.2.1 Description

The dead-rail (ripple detector) design to prevent regeneration into the third rail when no 720-Hz ripple voltage is present is shown in Figure 4.4.9-1. The system consists of a dual-channel ripple detector (for redundancy) that operates in conjunction with two regeneration-disabling, series-connected relay contacts (K1, K2) connected to the cab-mounted propulsion control unit equipment. Both relays must be activated to allow regeneration; if either one of the relays is deactivated, there is no regenerative braking power delivered to the third rail. A cab-mounted switch enables manual selection of "REGEN ON OR OFF". A light on the cab monitor is a visual indicator of regeneration status (Figure 4.4.9-2).

4.4.9.2.2 Operation

The third-rail signal is prefiltered to remove dc. The remaining ac is alternately toggled through Q_A and Q_B to either remove or apply the signal to the inputs of the detector channels A and B. When the signal is input to a detector channel, it is further filtered to detect 1-v rms (minimum), 720-Hz ripple voltage. Toggling of the detector input causes cycling of the detector's output response, thereby enabling and disabling regeneration at a rate of 10 times per sec. The detector responses are out of phase with one another, allowing continuous regeneration as long as 720 Hz is present.

In synchronism with this cycling, detector response is sampled and held by two sets of sample and hold (SH) circuits. One set stores detector channel responses to the disabling of its input, and the other set stores channel responses to the enabling of its input.

Stored channel-disabled information is processed through a transformer-rectifier to activate relay K2. Relay K2 remains activated as long as the channels continue to give the proper response. K2 is a fault relay that monitors the detector for proper operation.

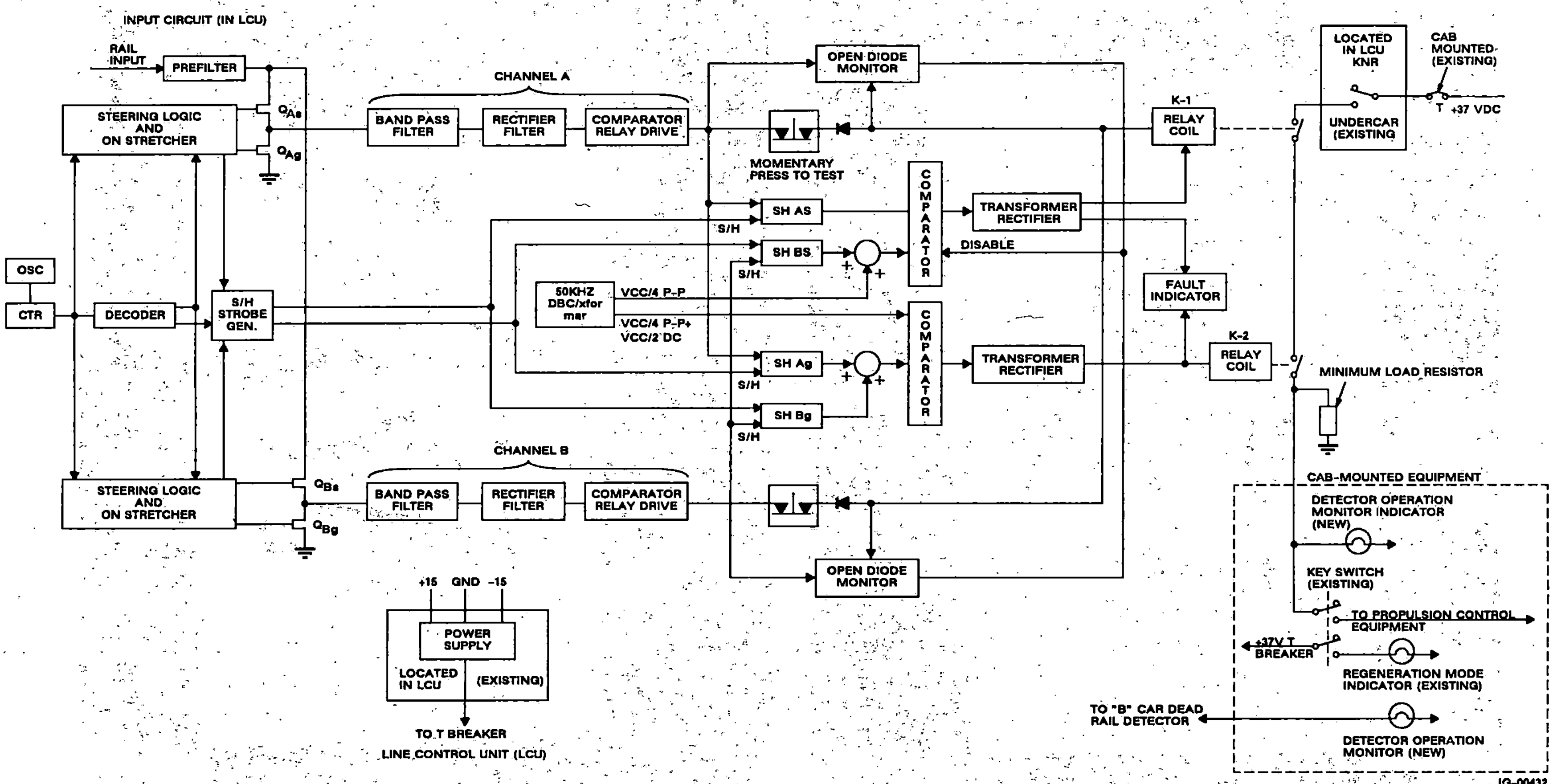
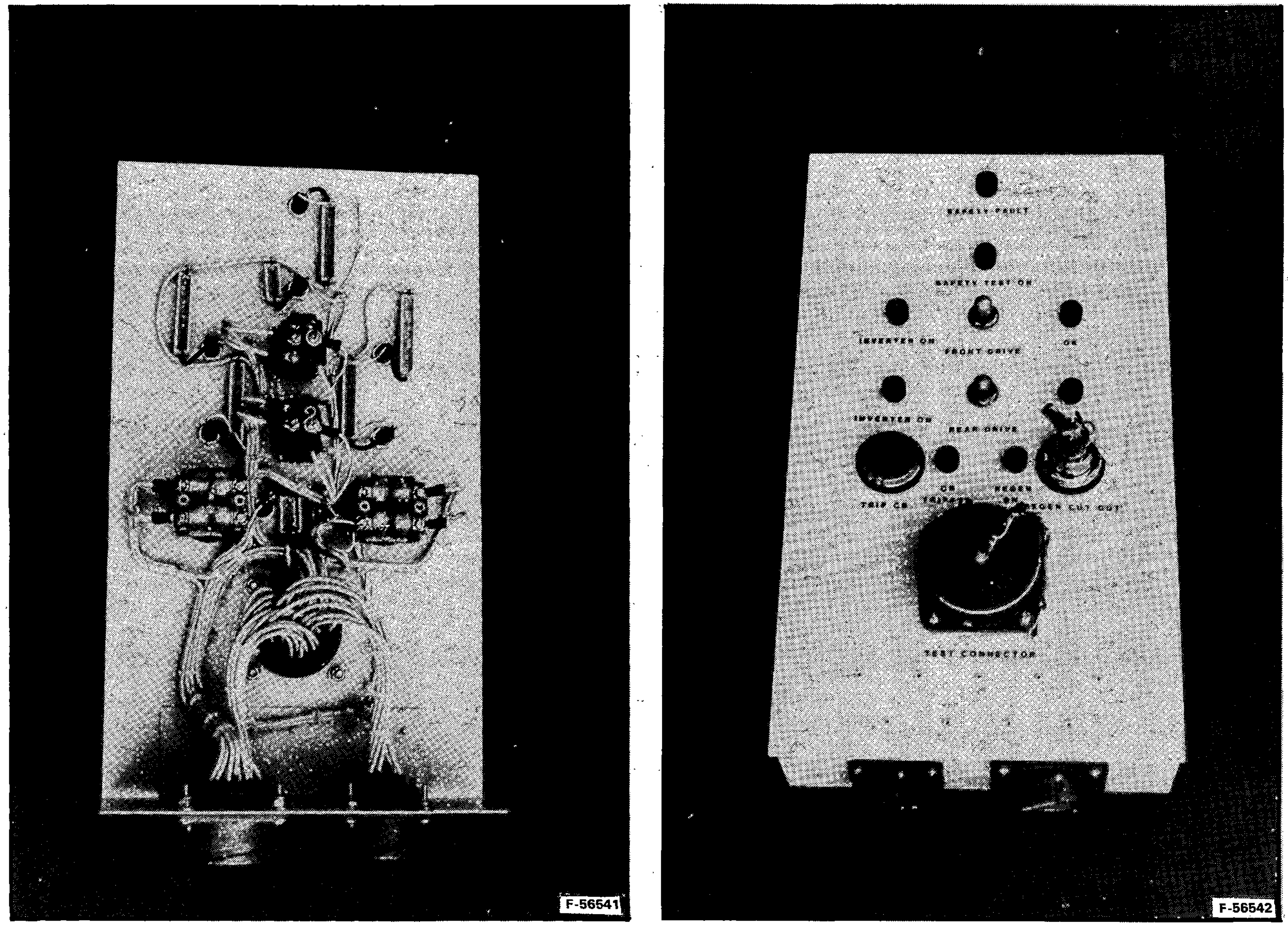


FIGURE 4.4.9-1. DEAD-RAIL (RIPPLE) DETECTION SYSTEM BLOCK DIAGRAM



F-56543

FIGURE 4.4.9-2. CAB MONITOR PANEL SHOWING KEY-ACCESS SWITCH FOR MANUAL SELECTION OF REGENERATION

Stored detector-enabled response information verifies that both channels agree that third-rail ripple is present or not present. When 1-v rms, 720-Hz ripple is present, a comparator supplies ac power to a transformer-rectifier to activate the K1 relay. Differing in operation from K2, K1 activates only in the presence of ripple. Both relays were especially selected for high reliability.

Because the detector channels are dynamically tested at a rate of 10 times per sec, there is a high degree of assurance that the ripple detector is always operating properly.

4.4.9.3 Tests on AB Car Pair

4.4.9.3.1 Introduction

This series of tests was conducted to demonstrate the performance of the dead-rail (ripple) detector. The objectives of the test were:

(a) To demonstrate that the ripple detector is effective in disabling propulsion regeneration for gap and nongap situations within 82 msec of a substation power chop. The requirement of 82 msec (maximum.) was imposed by the NYCTA (traverse time across a 6-ft gap at 50 mph).

(b) To demonstrate that the gap detector is effective during gap traversals.

All the ripple detection tests were conducted in the Rail Section E3 on the Sea Beach line. For rail gap tests, where transition was made from a live rail section across a third-rail gap to a dead-rail section, E3 South (E3-S) was the live-rail section and E3 North (E3-N) was the dead-rail section.

The receptivity or nonreceptivity of the third rail to accept regeneration was simulated by connection or disconnection of a 0.25-ohm resistive load located in the 16th Avenue substation.

The following test cases were investigated:

(a) Nongap Test Data--In Cases 1 and 2, a performance comparison was made between operation with the onboard auxiliary loads on and with those loads off. In both cases, the third rail was nonreceptive.

In cases 3 and 4, regeneration cutoff times are compared when the ripple detector is enabled and disabled (bypassed). In both these cases, the third rail was receptive and the auxiliary loads were on.

(b) Gap Traversal Data--In these cases, the ripple detector performance was measured when the car traversed a third-rail gap from a live-rail section to a dead-rail section with various combinations of receptivity and auxiliary loads as follows:

Case No.	Substation Load		Auxiliary Loads
	E3-S (Live)	E3-N (Dead)	
5	Off	Off	On
6	Off	Off	Off
7	On	Off	On
8	Off	On	On

The gap traversal test cases also yielded performance data on the effectiveness of the gap detection circuitry.

4.4.9.3.2 Conclusion

The case summaries that follow support the conclusion that the performance objectives of the ripple detector have been satisfied.

(a) The ripple detector is effective and reliable in disabling regeneration to a receptive or nonreceptive line within 82 msec of any third-rail power loss.

(b) The gap detector is effective and reliable in cutting propulsion regeneration and the propulsion primary power link during gap traversals.

Among the parameters recorded to evaluate the effectiveness of the ripple detector was the line voltage, termed LINE E on the strip charts presented herein. In a power chop or a gap traverse test, the line voltage was at times seen to decay too slowly, evidencing voltage spikes. This would occur after the ripple detector had isolated the propulsion system regeneration from the line.

Numerous test runs were made to isolate the cause of this undesirable characteristic of the line voltage following regeneration cutoff. It was determined that the undesirable voltage characteristic was not related to the ac propulsion system, but was the result of existing onboard dc auxiliaries discharging into the line. The information was given to the NYCTA and the phenomenon was not addressed further in the program.

The phenomenon does underscore the need for the ripple-detection type of dead-rail protection when using the existing R-44 cars.

4.4.9.3.3 Case Summaries

The following legend is provided to facilitate reading the strip charts presented in the case summaries:

Strip Chart Legend

BRK CMD	Brake command signal
K1/2	Ripple detector relays. The opening of either relay cuts off regeneration.
KGD	Gap detector relay
KIS	Truck isolation relay
KNR	Regeneration circuit relay, in series with K1/2

Strip Chart Legend (continued)

KVSL	Line voltage sensor relay
LINE E	Line voltage, vdc
LINE I	Line current, amp

4.4.9.3.3.1 Case 1

(a) Objective--The specific objective of this test was to determine the response time of the ripple detector after power chop during regenerative braking under the following conditions:

(1) No rail gap

(2) All auxiliary loads on (except brake compressor)

(3) Substation load (0.25 ohm) on (E3 South)

(4) Ripple detector enabled

(5) Regeneration voltage limit: 700 vdc

(b) Test Method--The ac car pair was accelerated to approximately 42 mph, then full-service braking was applied, and then the substation power was chopped. The test took place entirely in the E3 South rail section.

(c) Findings--The recorder traces are shown in Figures 4.4.9-3 and 4.4.9-4. The regeneration was cut off approximately 65 msec after power chop.

(d) Analysis--The regeneration cutoff time was well within the allowable 82 msec.

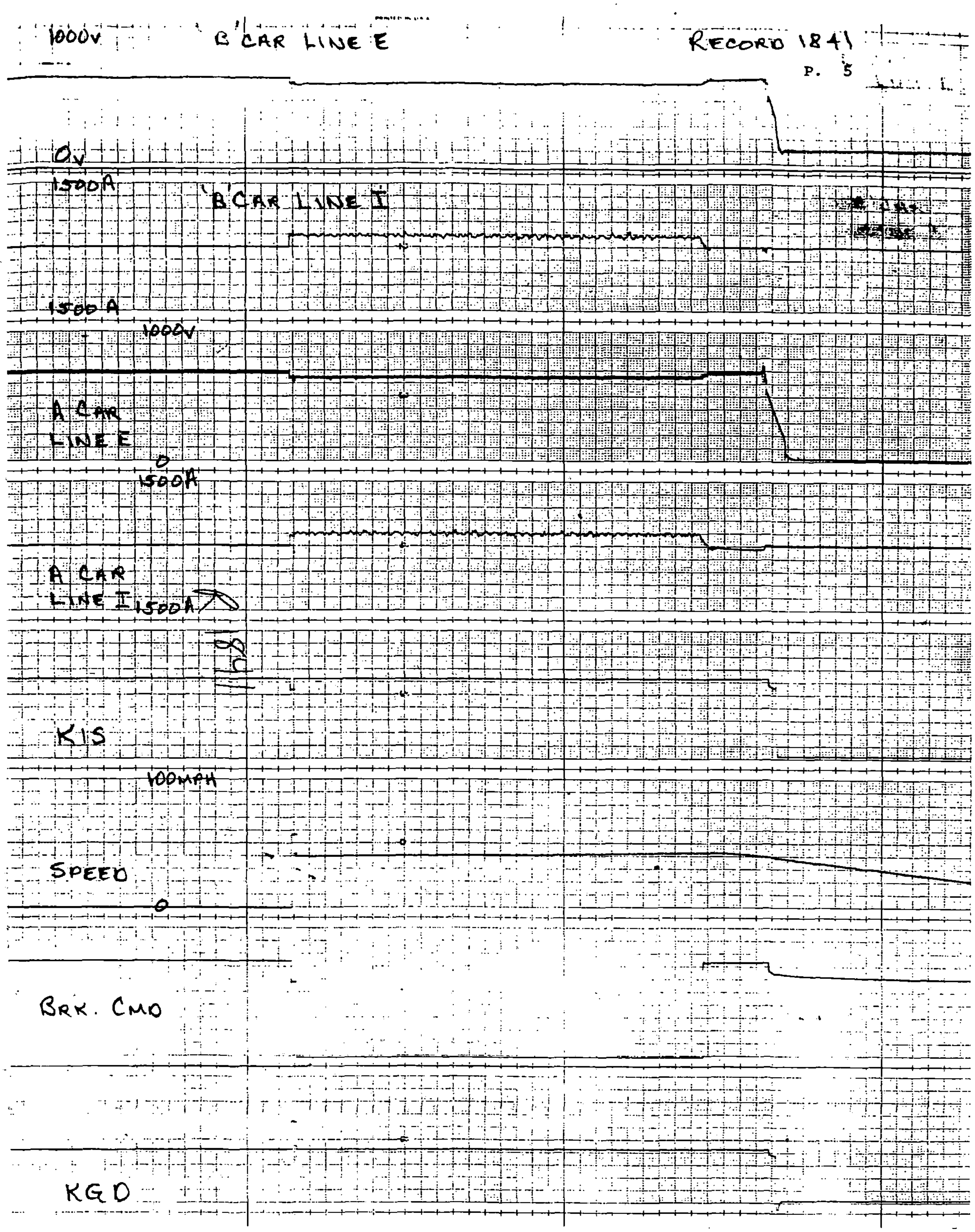
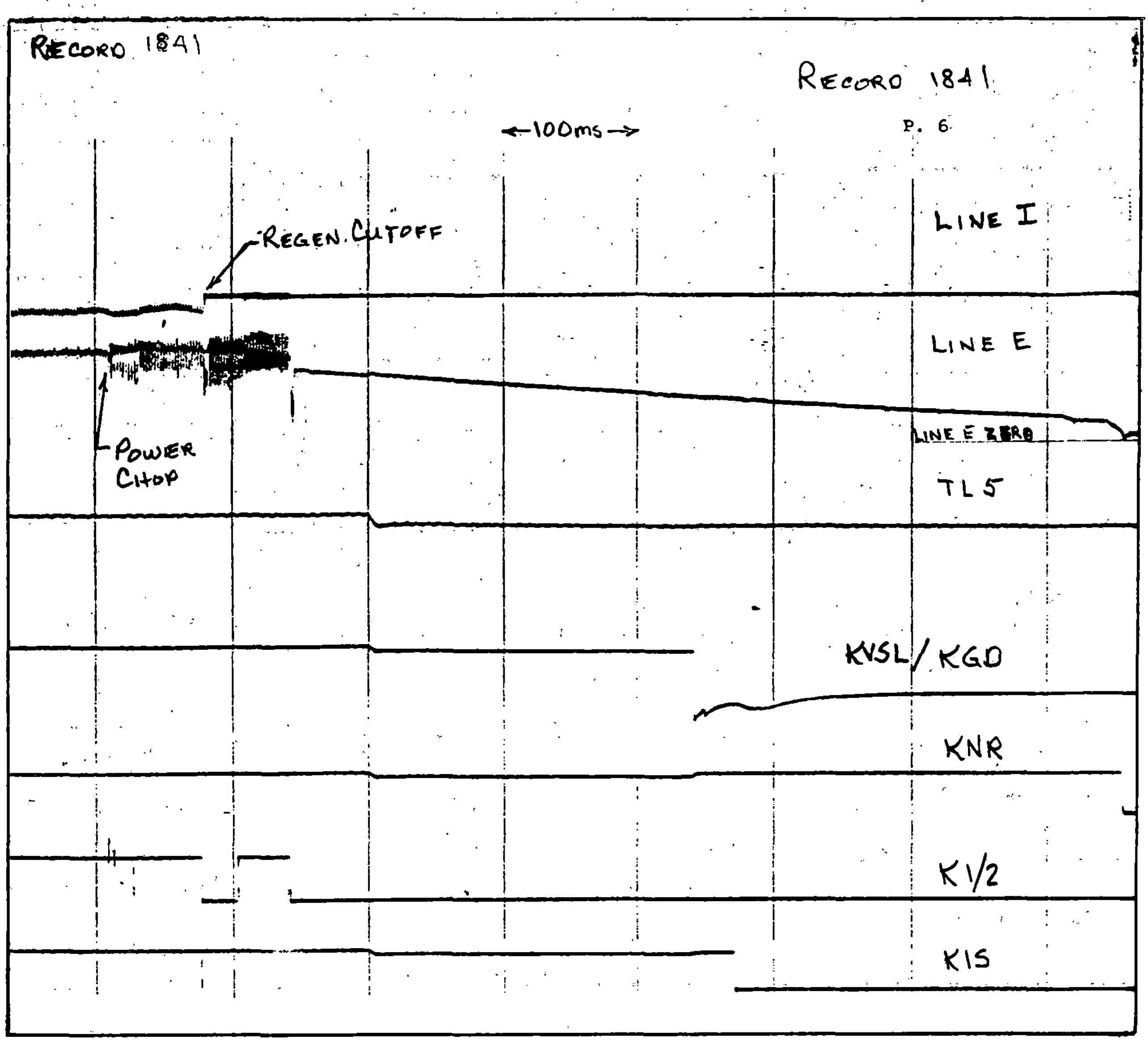


FIGURE 4.4.9-3. CASE 1 RECORDING, 10 MM/SEC



ONBOARD INSTRUMENTATION

FIGURE 4.4.9-4. CASE 1 RECORDING, 10 IN./SEC

4.4.9.3.3.2 Case 2

(a) Objective--The specific objective of this test was to determine the response time of the ripple detector after power chop during regenerative braking under the following conditions:

(1) No rail gap

(2) All auxiliary loads off (except low-voltage (L.V.) converter)

(3) Substation load off

(4) Ripple detector enabled

(5) Regeneration voltage limit: 700 vdc

(b) Test Method--The car pair was accelerated to approximately 40 mph, then full-service braking was applied, and then substation power was chopped. The test took place entirely in the South E3 rail section.

(c) Findings--The recorder traces are shown in Figures 4.4.9-5 and 4.4.9-6. The regeneration was cut off approximately 40 msec after power chop.

(d) Analysis--The regeneration cutoff time was within the allowable 82 msec by a margin greater than 100 percent.

4.4.9.3.3.3 Case 3

(a) Objective--The specific objective of this test was to determine the response time of the ripple detector after power chop during regenerative braking, under the following conditions, as a basis of comparison with Case 4, in which the ripple detector was bypassed.

(1) No rail gap

(2) All auxiliary loads on (except brake compressor)

(3) Substation load (0.25 ohm) on

(4) Ripple detector enabled

(5) Regeneration voltage limit: 700 vdc

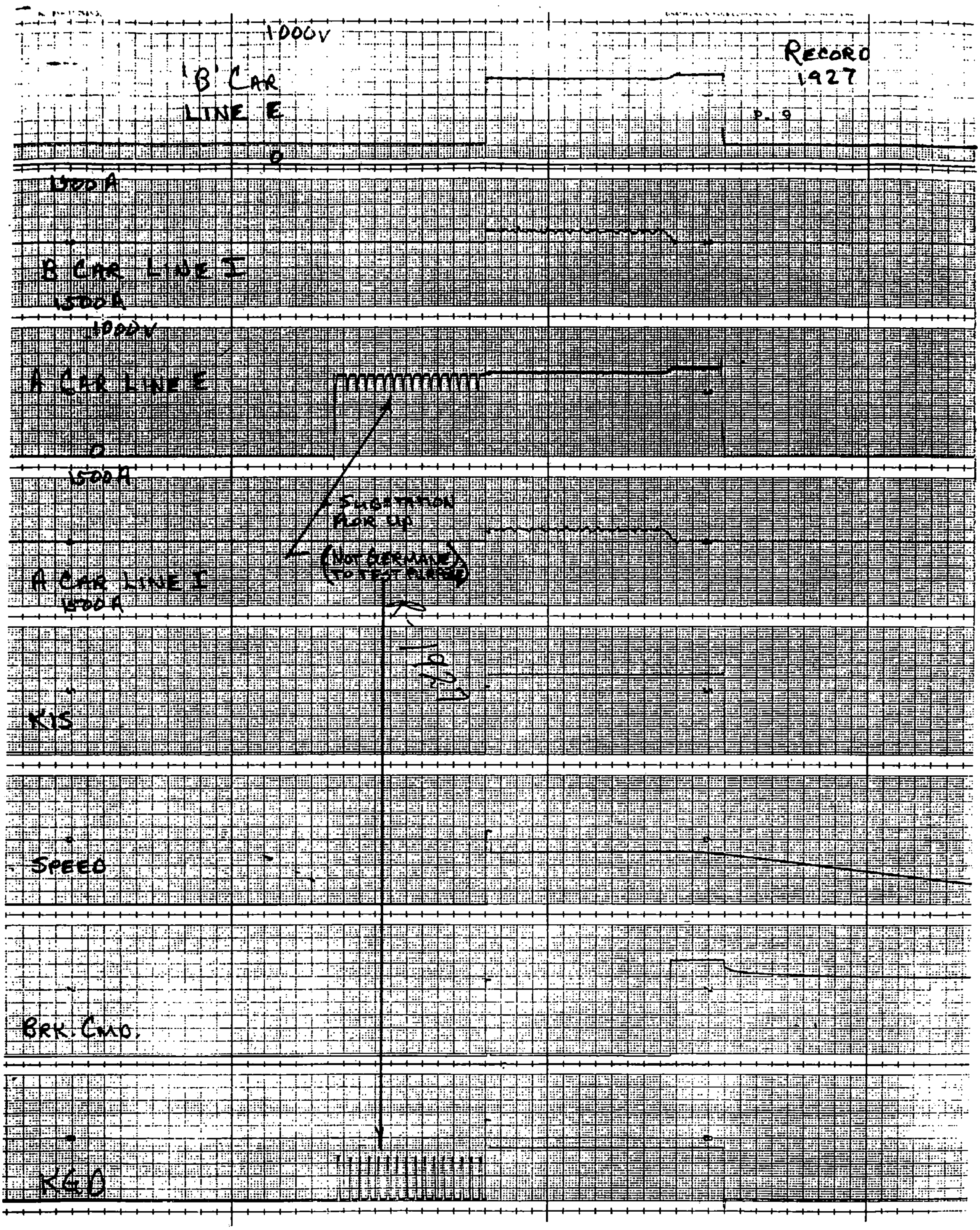


FIGURE 4.4.9-5. CASE 2 RECORDING, 10 MM/SEC

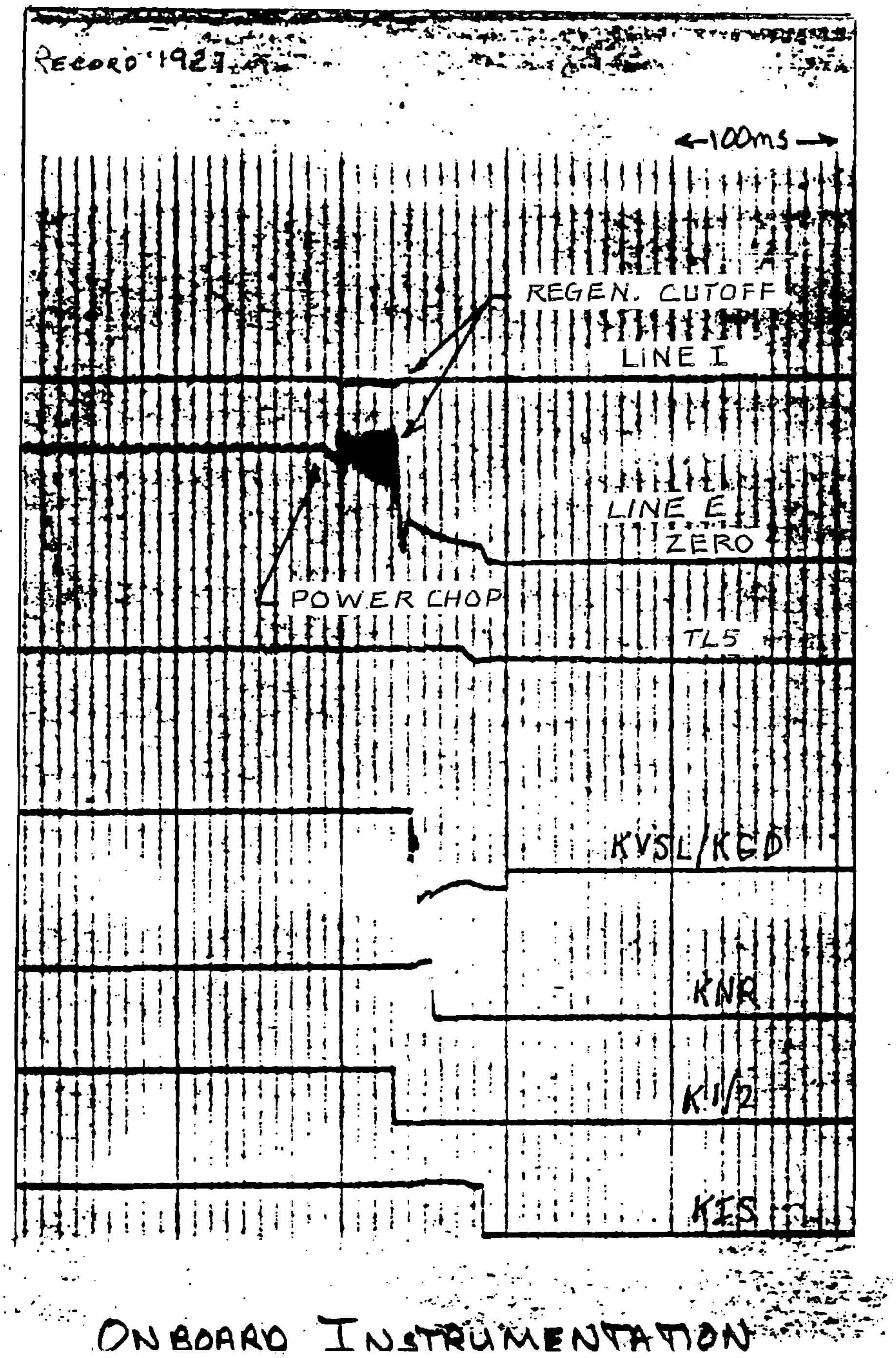


FIGURE 4.4.9-6. CASE 2 RECORDING, 10 IN./SEC

(b) Test Method--The car pair was accelerated to approximately 42 mph, then full-service braking was applied, and then substation power was chopped. The test took place entirely in the South E3 rail section.

(c) Findings--The recorder traces are shown in Figures 4.4.9-7 and 4.4.9-8. The regeneration was cut off approximately 33 msec after power chop.

(d) Analysis--The regeneration cutoff time was within the allowable 82 msec by a margin greater than 100 percent.

This test case is considered representative of the typical power chop operating scenario in that an electrical transmission grid is rarely unloaded.

This case, when contrasted with Test Case 4, demonstrates the ripple detector's singular effectiveness in cutting regeneration in a nongap dead rail situation.

4.4.9.3.3.4 Case 4

(a) Objective--The specific objective of this test was to determine the regeneration cutoff response time after power chop during regenerative braking, when the ripple detector has been disabled. The defining conditions were as follows:

(1) No rail gap

(2) All auxiliary loads on (except brake compressor)

(3) Substation load (0.25 ohm) on

(4) Ripple detector disabled (bypassed)

(5) Regeneration voltage limit: 700 vdc

(b) Test Method--The car pair was accelerated to approximately 34 mph, then full-service braking was applied, and then substation power was chopped. The test took place entirely in the South E3 rail section.

(c) Findings--The recorder traces are shown in Figures 4.4.9-9 and 4.4.9-10. The regeneration was cut off approximately 160 msec after power chop. The line voltage decay time was approximately 175 msec.

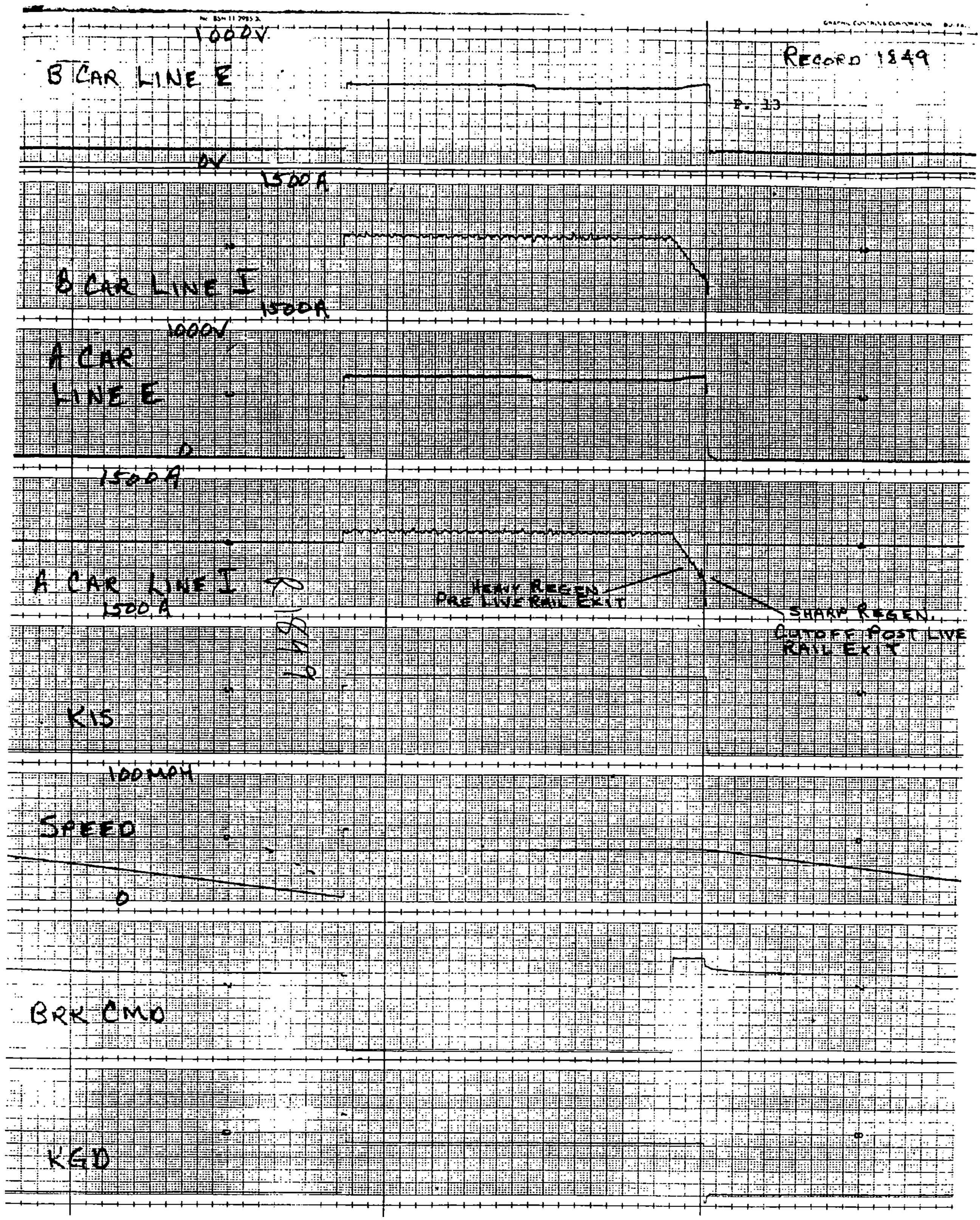
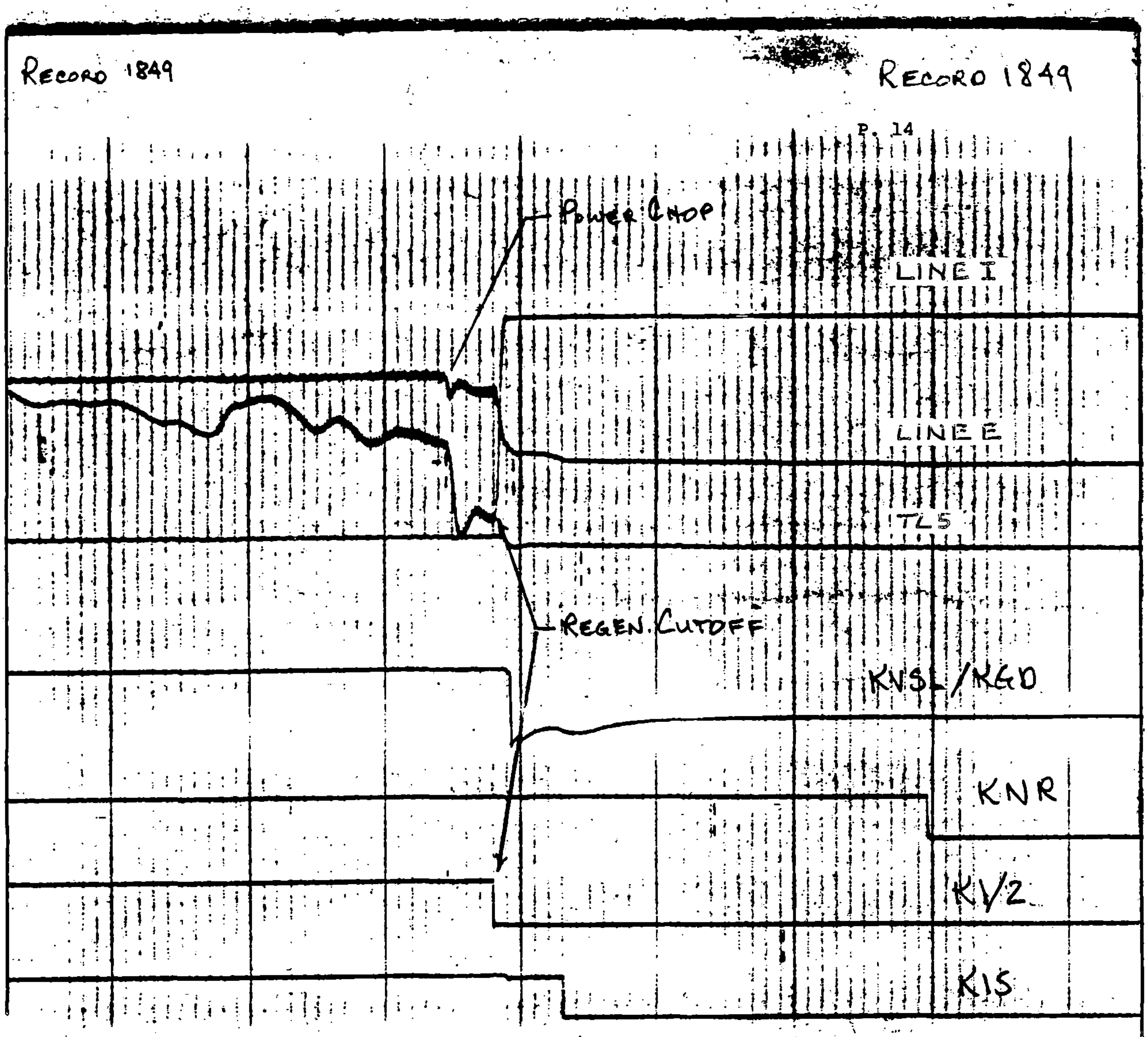


FIGURE 4.4.9-7. CASE 3 RECORDING, 10 MM/SEC



ONBOARD INSTRUMENTATION

FIGURE 4.4.9-8. CASE 3 RECORDING, 10 IN./SEC

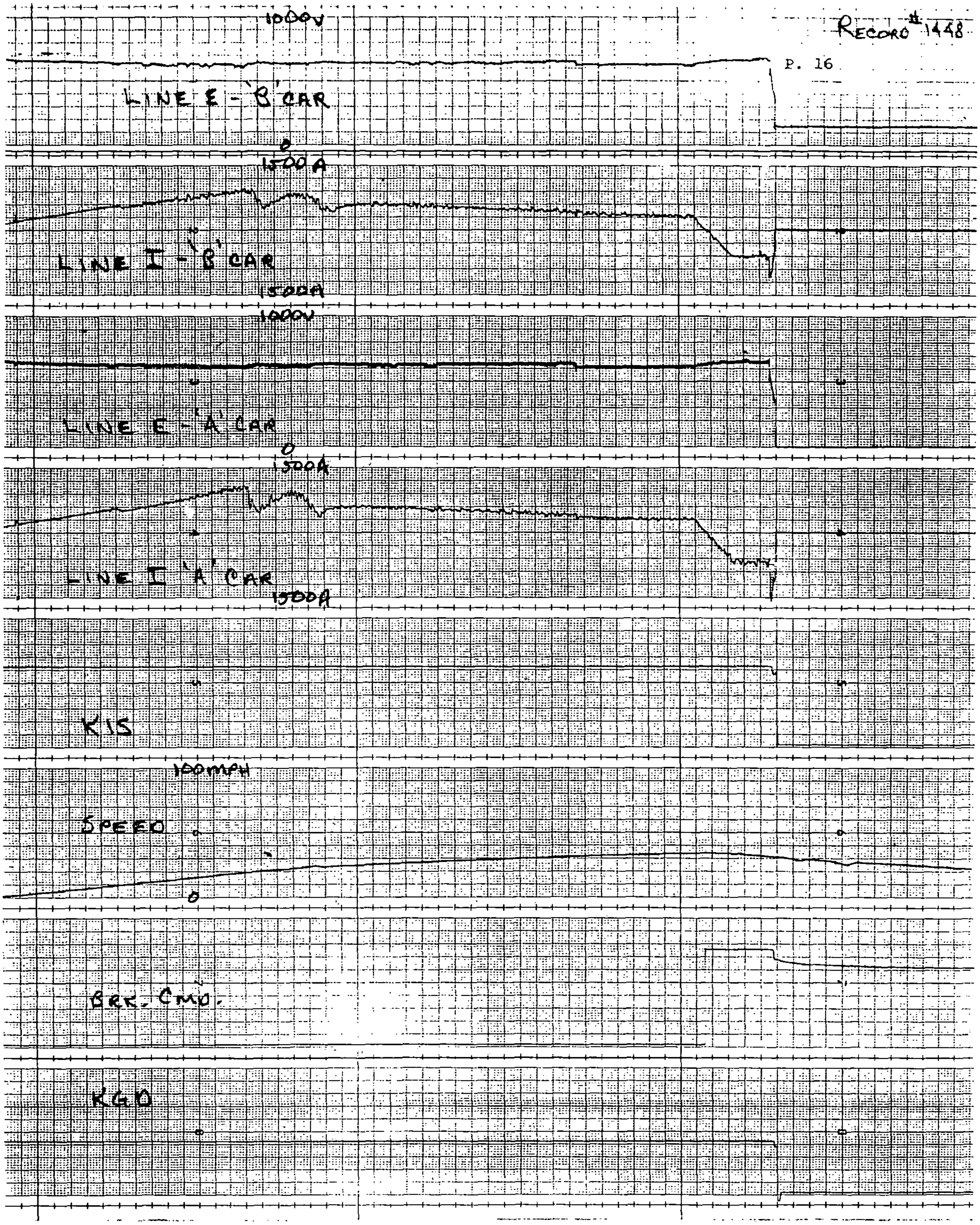


FIGURE 4.4.9-9. CASE 4 RECORDING, 10 MM/SEC

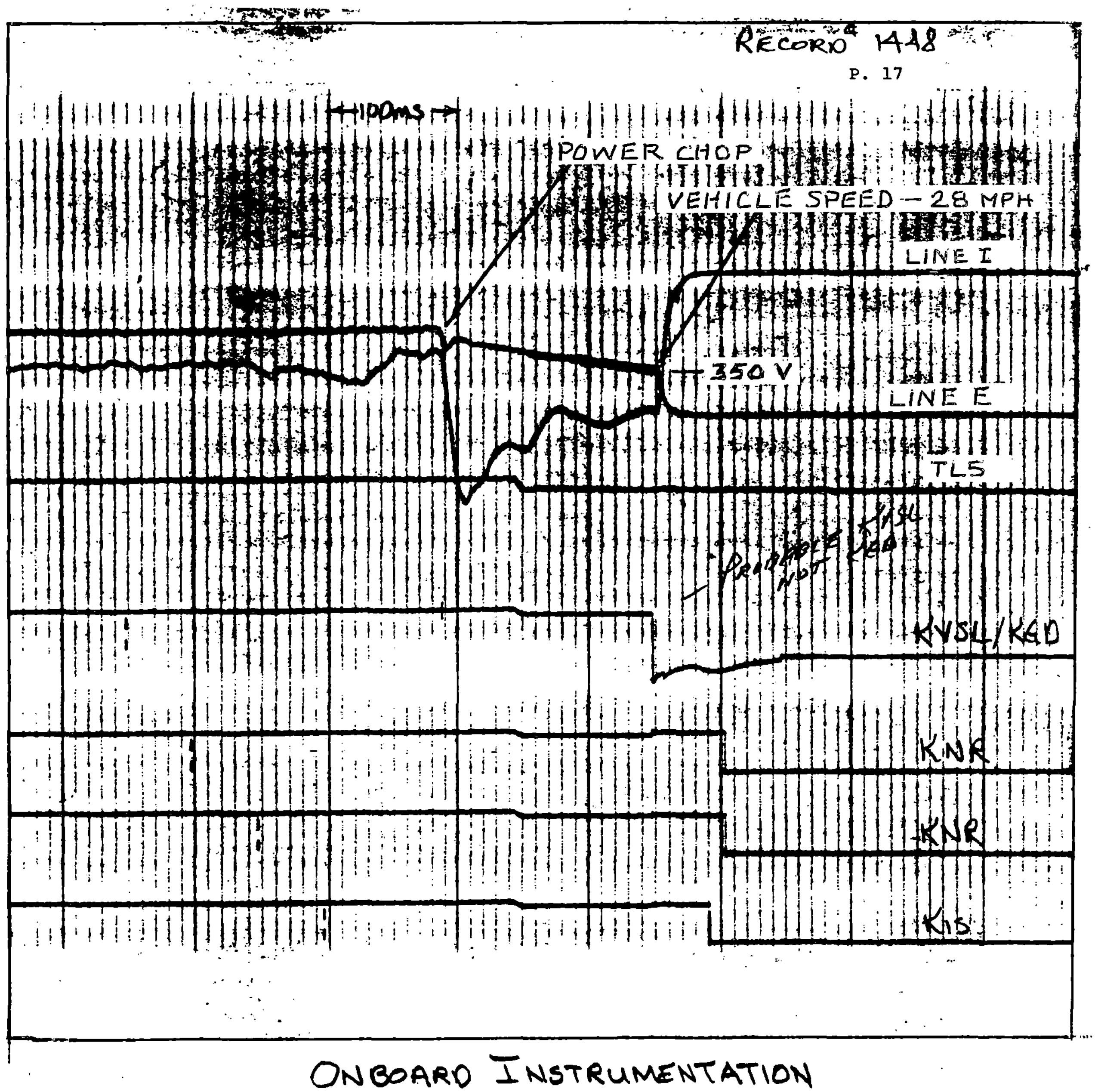


FIGURE 4.4.9-10. CASE 4 RECORDING, 10 IN./SEC

(d) Analysis--With the ripple detector bypassed in this nongap test scenario, regeneration cutoff depends on KNR or KVSL dropout and a number of dependent variables. In this case, KVSL in concert with the power control unit (PCU) internal thresholds have reacted to declining line voltage, caused by the vehicle's declining ability (speedwise) to sustain a heavily loaded, power-chopped third rail. This test case (i.e., ripple detector bypassed), which shows unacceptable cutoff response (160 msec) when contrasted with Case 3 (33 msec), demonstrates the ripple detector's singular effectiveness in cutting regeneration in a nongap dead-rail situation.

4.4.9.3.3.5 Case 5

(a) Objective--The specific objective of this test was to determine the response time of the ripple detector and the gap detector upon exiting an unloaded live rail to a gap during regenerative braking, and subsequently entering an unloaded dead rail. The defining conditions were as follows:

(1) Gap speed: 43 mph

(2) Effective gap time: 95 msec (calculated)

(3) All auxiliary loads on (except brake compressor)

(4) Substation load off, both live- and dead-rail sections

(5) E3 North dead

(6) Ripple detector enabled

(7) Regeneration voltage limit: 700 vdc

The effective gap time is the period when neither of the two shoes is in contact with the third rail.

(b) Test Method--The car pair was accelerated to approximately 43 mph. Regenerative braking was applied when the A-car front third-rail shoe was at or near entry to the 60-ft gap at 16th Avenue. This gap is between the South E3 and North E3 rail sections. Because of a 5-ft ramp at the entry and exit of each third-rail section, the total distance that any one shoe was out of contact was variable but probably more than 60 ft. The variable was dependent on the shoe elevation at the instant of exit and entry.

Data recording spanned the time from brake application before South E3 to a point beyond North E3 entry.

(c) Findings--The recorder tracks are shown in Figures 4.4.9-11 and 4.4.9-12. The regeneration was cut off approximately 35 msec after live-rail exit and remained off during and after dead-rail entry. The gap detector dropout was at 65 msec after live-rail exit.

(d) Analysis--The regeneration cutoff time was within the allowable 82 msec by a margin greater than 100 percent. The nearly 2-to-1 response time ratio in favor of the ripple detector as compared to the conventional gap detector is noted.

4.4.9.3.3.6 Case 6

(a) Objective--The specific objective of this test was to determine the response time of the ripple detector and the gap detector upon exiting a live rail to a gap during regenerative braking, and subsequently entering a dead rail. The defining conditions were as follows:

(1) Gap speed: 43 mph

(2) Effective gap time: 95 msec (calculated)

(3) All auxiliary loads off

(4) Substation load off, both live- and dead-rail sections

(5) E3 North dead

(6) Ripple detector enabled

(7) Regeneration voltage limit: 700 vdc

(b) Test Method--The test method for this case is identical to the test method for Case 5, para. 4.4.9.3.3.5, with the exception that the onboard auxiliary loads, which were on for Case 5, were off for Case 6.

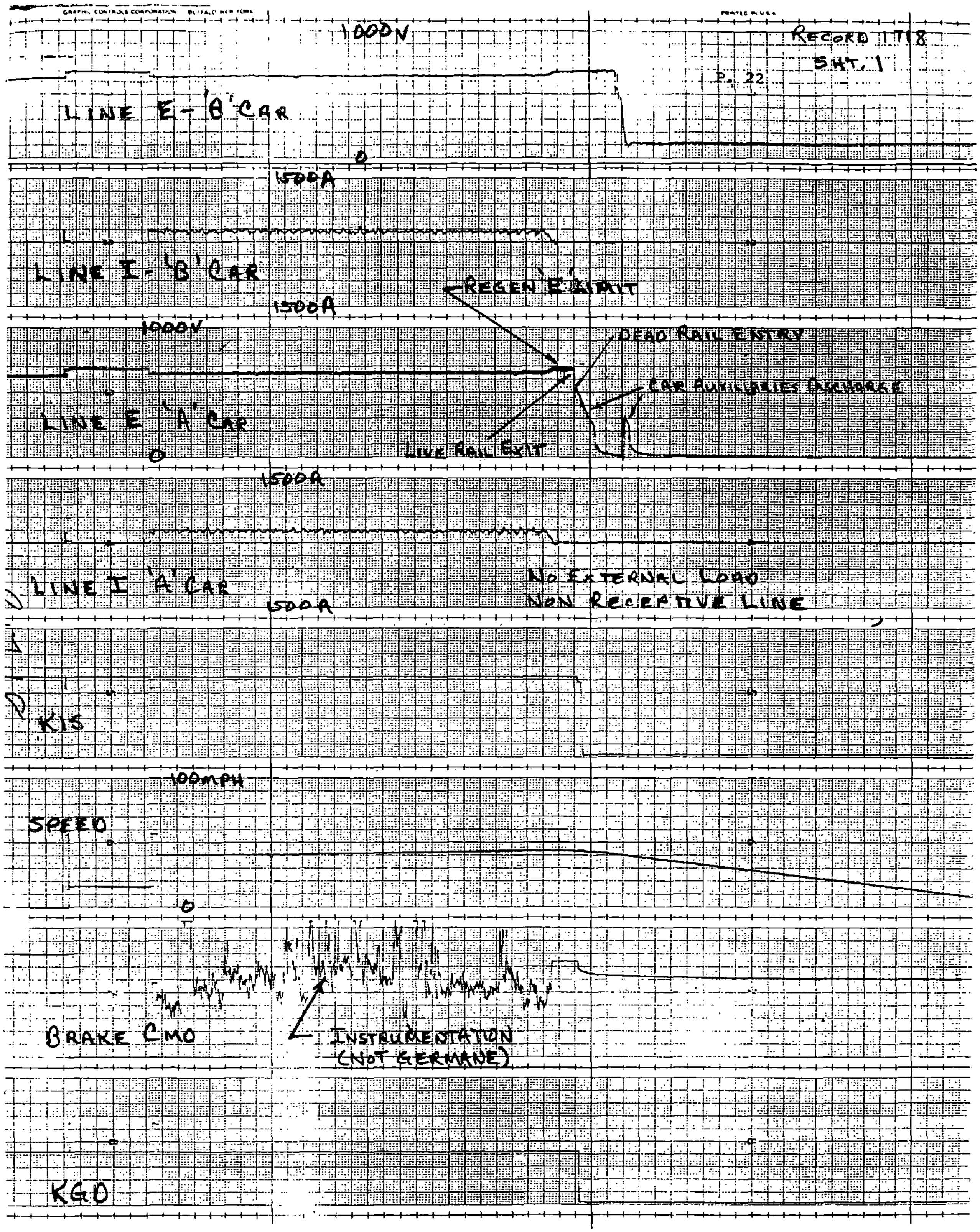


FIGURE 4.4.9-11. CASE 5 RECORDING, 10 MM/SEC

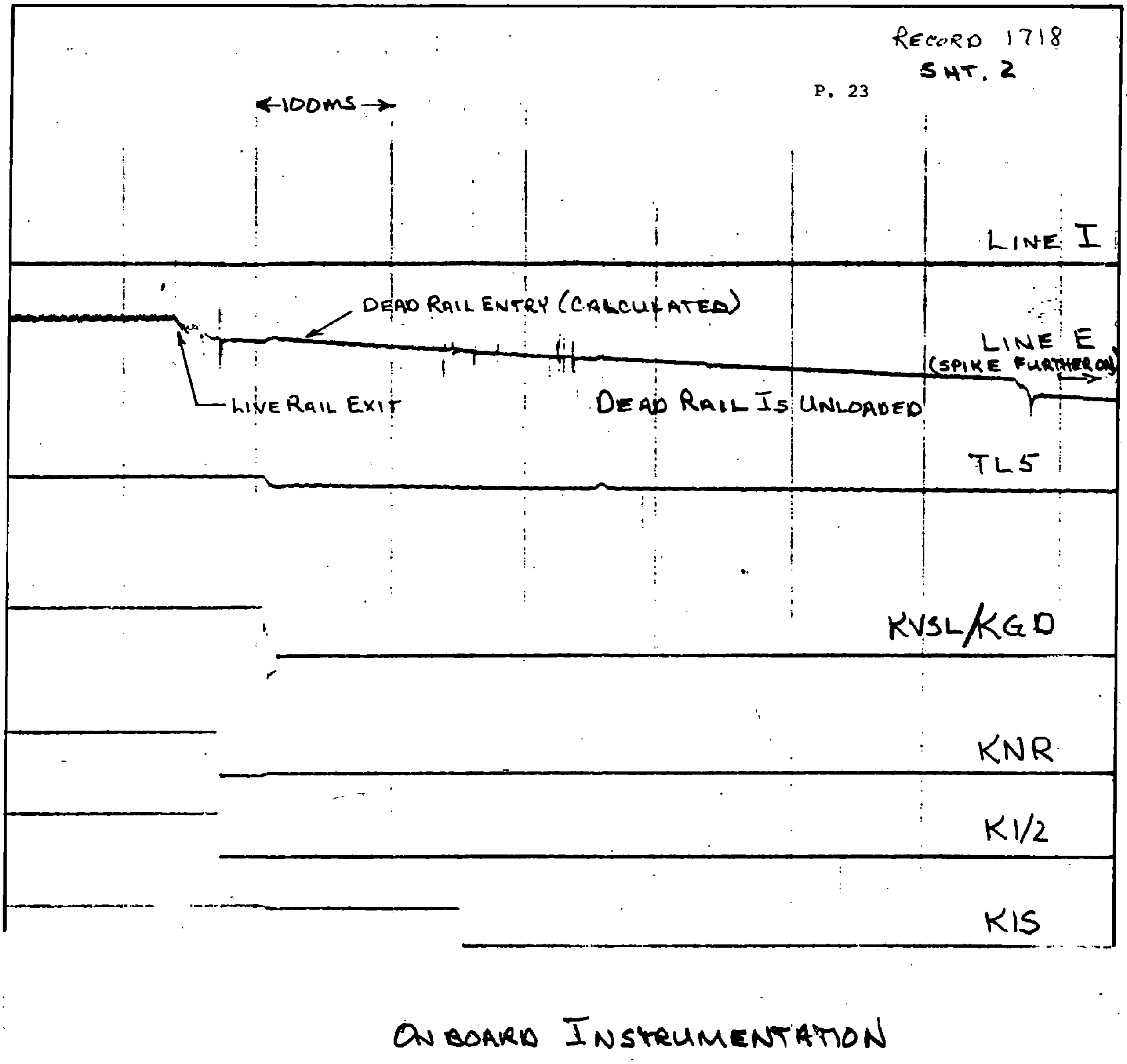


FIGURE 4.4.9-12. CASE 5 RECORDING, 10 IN./SEC

(c) Findings--The recorder traces are shown in Figures 4.4.9-13 and 4.4.9-14. The regeneration was cut off approximately 15 msec after live-rail exit and remained off after dead-rail entry. The gap detector dropout was at 23 msec after live-rail exit.

(d) Analysis--The regeneration cutoff time was excellent at 15 msec, less than one-fifth the allowable 82 msec. The gap detector dropout time was also excellent at 23 msec, but the ripple detector was even faster, functioning in about one-third less time.

4.4.9.3.3.7 Case 7

(a) Objective--The specific objective of the test was to determine the response time of the ripple detector and the gap detector upon exiting a heavily loaded live rail, with the auxiliaries on, during regenerative braking, and subsequently entering an unloaded dead rail. The defining conditions were as follows:

(1) Gap speed: 32 mph

(2) Effective gap time: 128 msec (calculated)

(3) All auxiliary loads on (except brake compressor)

(4) Substation load: live rail on, dead rail off

(5) E3 North dead

(6) Ripple detector enabled

(7) Regeneration voltage limit: 700 vdc

(b) Test Method--The test method for this case is the same as for Case 5, para. 4.4.9.3.3.5, with the exception that the live rail is loaded for Case 7, whereas it was unloaded for Case 5. Also, in Case 7 braking was applied well in advance of the gap, and speed had decayed from about 42 mph to about 32 mph by the time of gap entry.

(c) Findings--The recorder traces are shown in Figures 4.4.9-15 and 4.4.9-16. The regeneration was cut off by the ripple detector approximately 15 msec after live-rail exit and remained off after dead-rail entry. The gap detector dropout was at 50 msec after live rail exit.

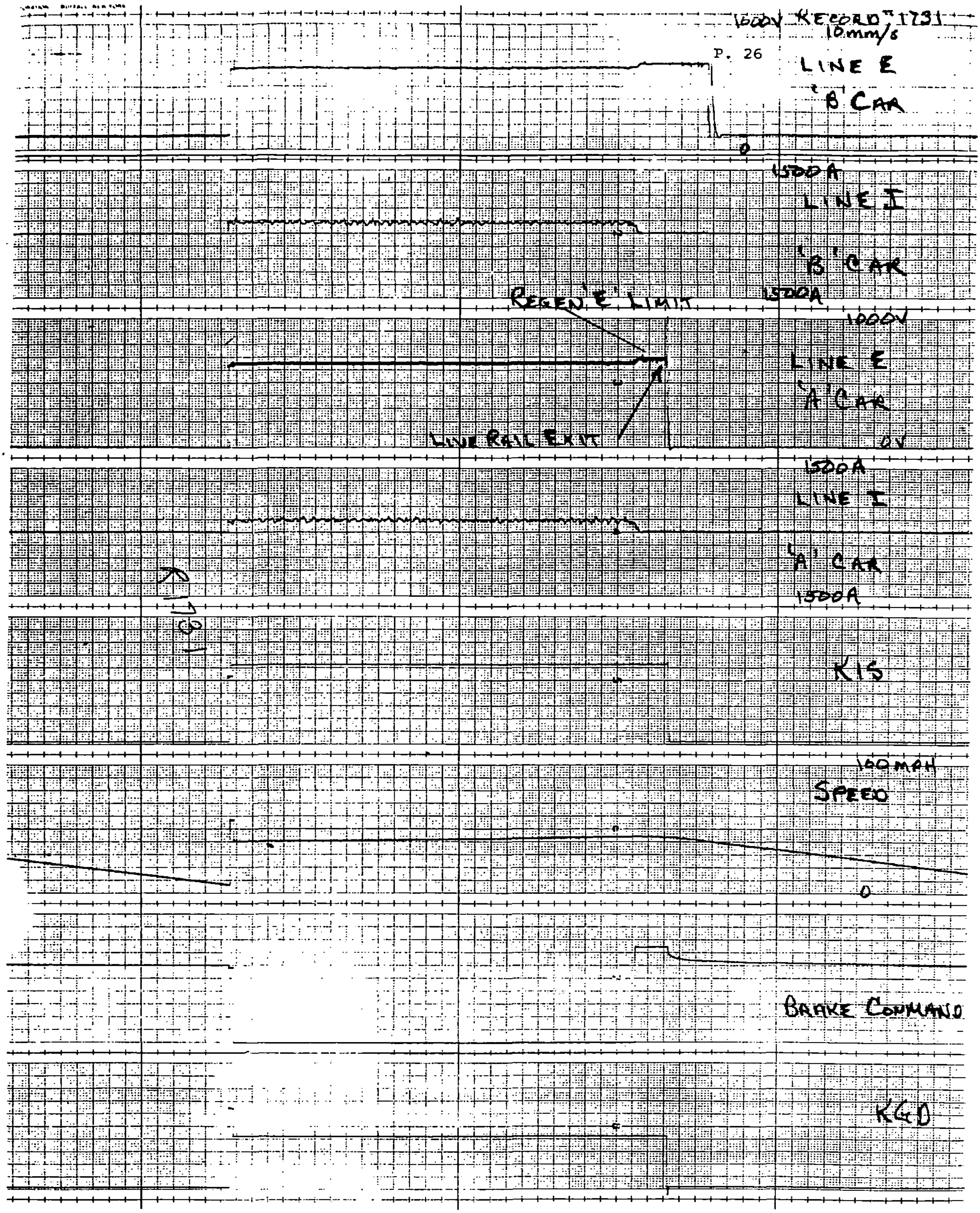


FIGURE 4.4.9-13. CASE 6 RECORDING, 10 MM/SEC

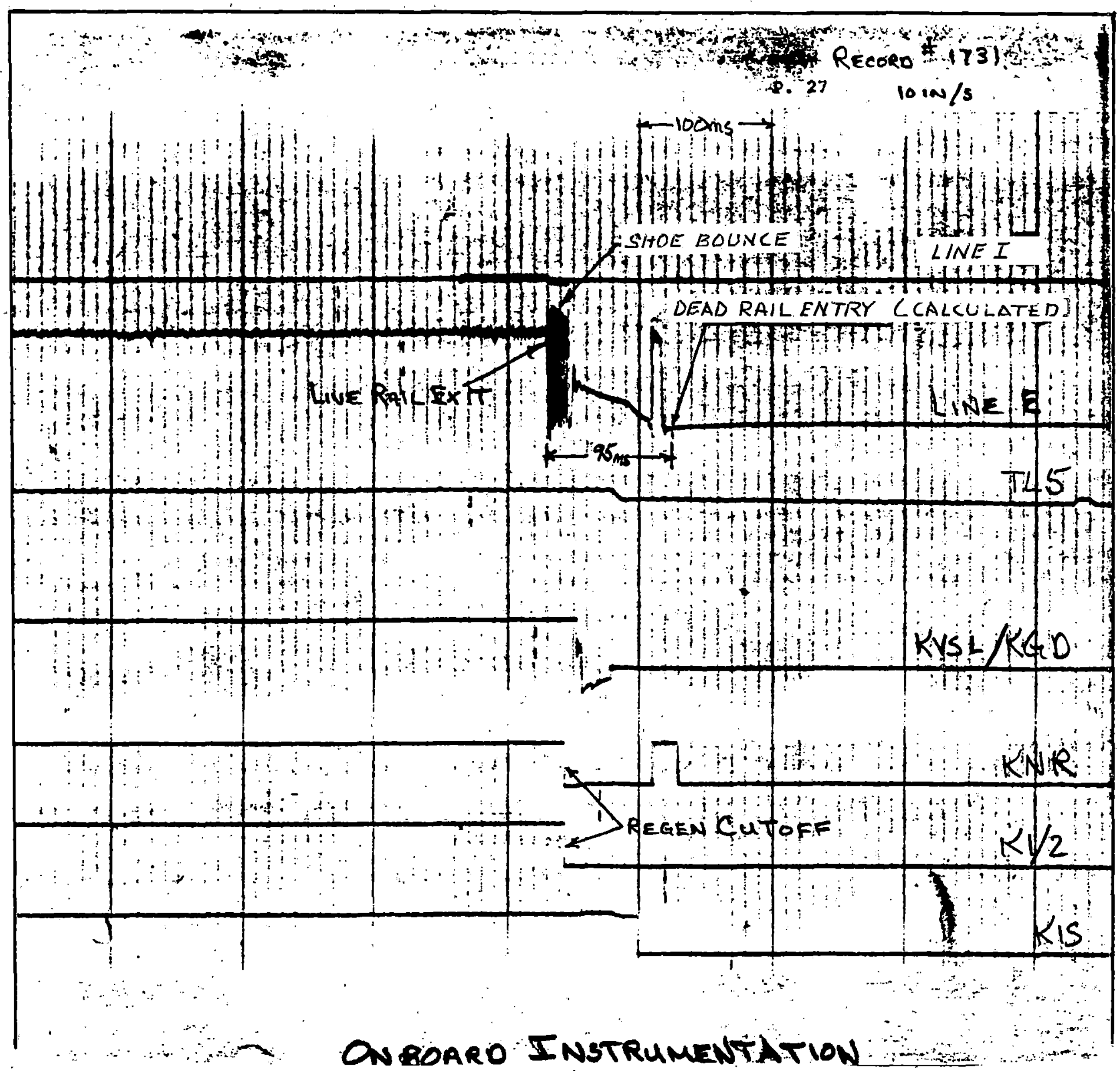


FIGURE 4.4.9-14. CASE 6 RECORDING, 10 IN./SEC

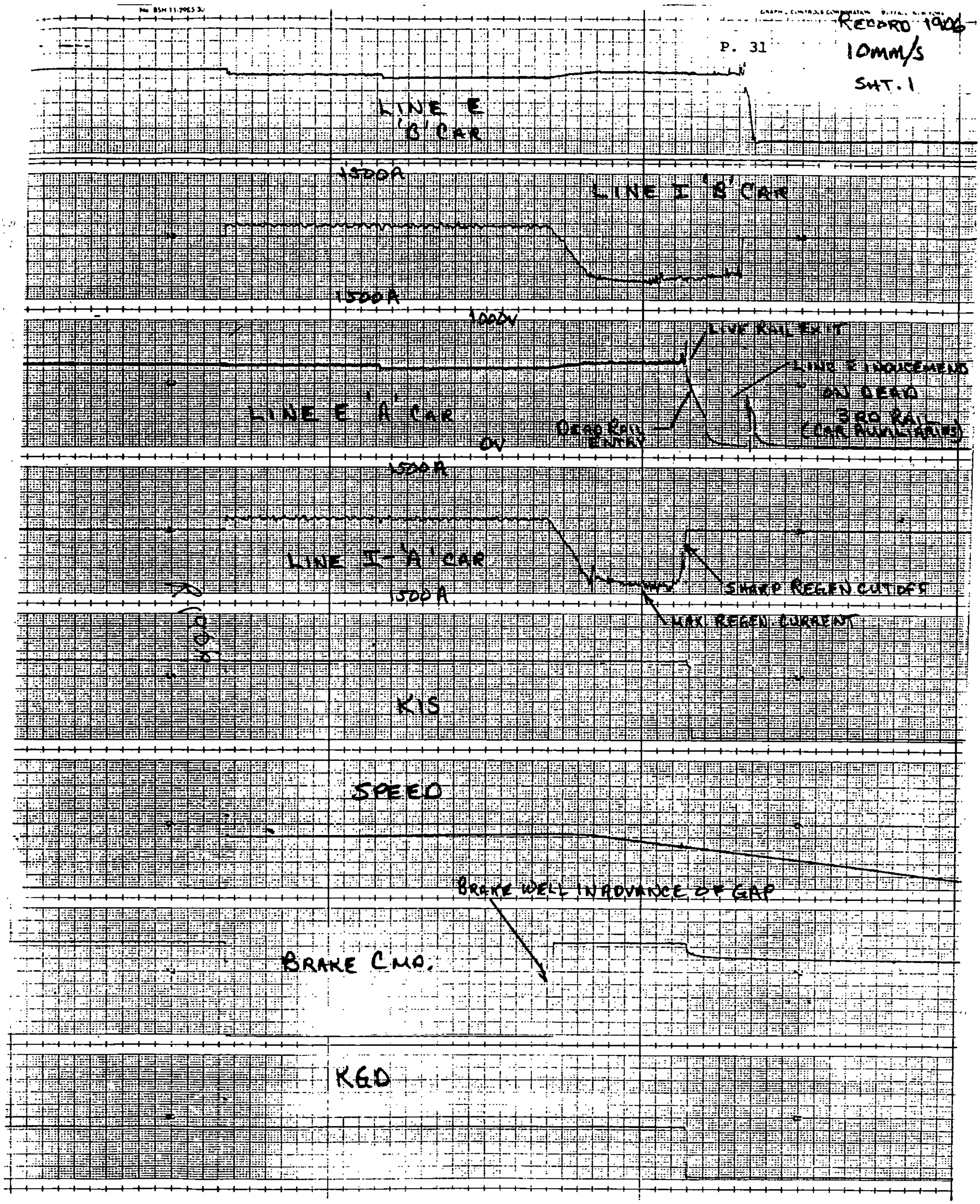


FIGURE 4.4.9-15. CASE 7 RECORDING, 10 MM/SEC

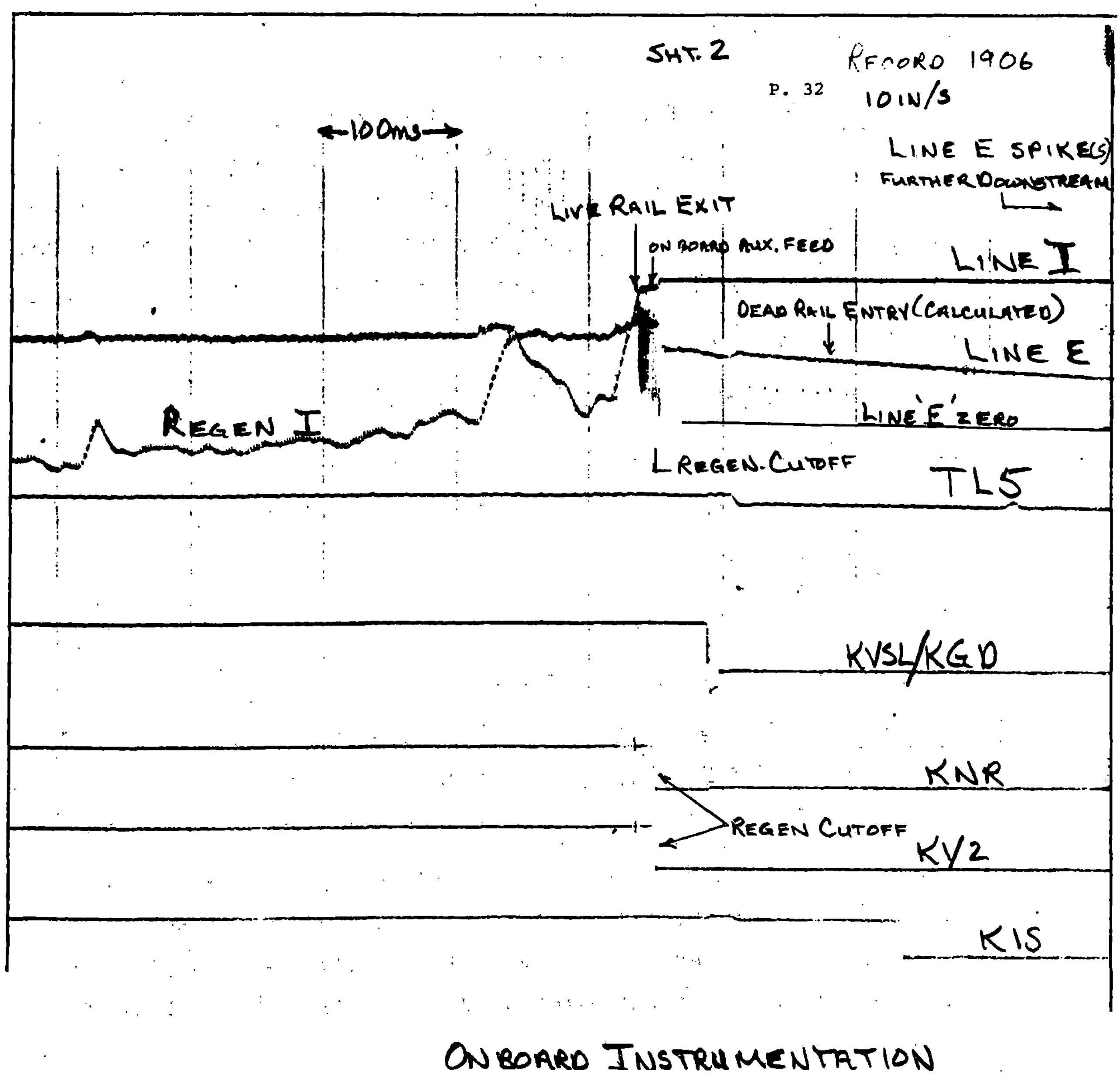


FIGURE 4.4.9-16. CASE 7 RECORDING, 10 IN./SEC

(d) Analysis--The regeneration cutoff time by the ripple detector was excellent at 15 msec, less than one-third the 50 msec required for gap detector dropout.

4.4.9.3.3.8 Case 8

(a) Objective--The specific objective of the test was to determine the response time of the ripple detector and the gap detector upon exiting a lightly loaded (nonreceptive) live rail, with the auxiliaries on, during regenerative braking, and subsequently entering a loaded dead rail. The defining conditions were as follows:

(1) Gap speed: 41 mph

(2) Effective gap time: 100 msec (calculated)

(3) All auxiliary loads on (except brake compressor)

(4) Substation load: live rail off, dead rail on

(5) E3 North dead

(6) Ripple detector enabled

(7) Regeneration voltage limit: 700 vdc

(b) Test Method--The test method for this case is the same as for Case 5, para. 4.4.9.3.3.5, with the exception that the dead-rail substation load is on for this case, whereas it was off in Case 5.

(c) Findings--The recorder traces are shown in Figures 4.4.9-17 and 4.4.9-18. The regeneration was cut off by the ripple detector approximately 15 msec after live-rail exit and remained off after dead-rail entry. The gap detector dropout was at 50 msec after live-rail exit.

The actual gap period was about twice as long as the 100-msec calculated period.

(d) Analysis--The regeneration cutoff time by the ripple detector was excellent at 15 msec, less than one-third the 50 msec required for the gap detector dropout.

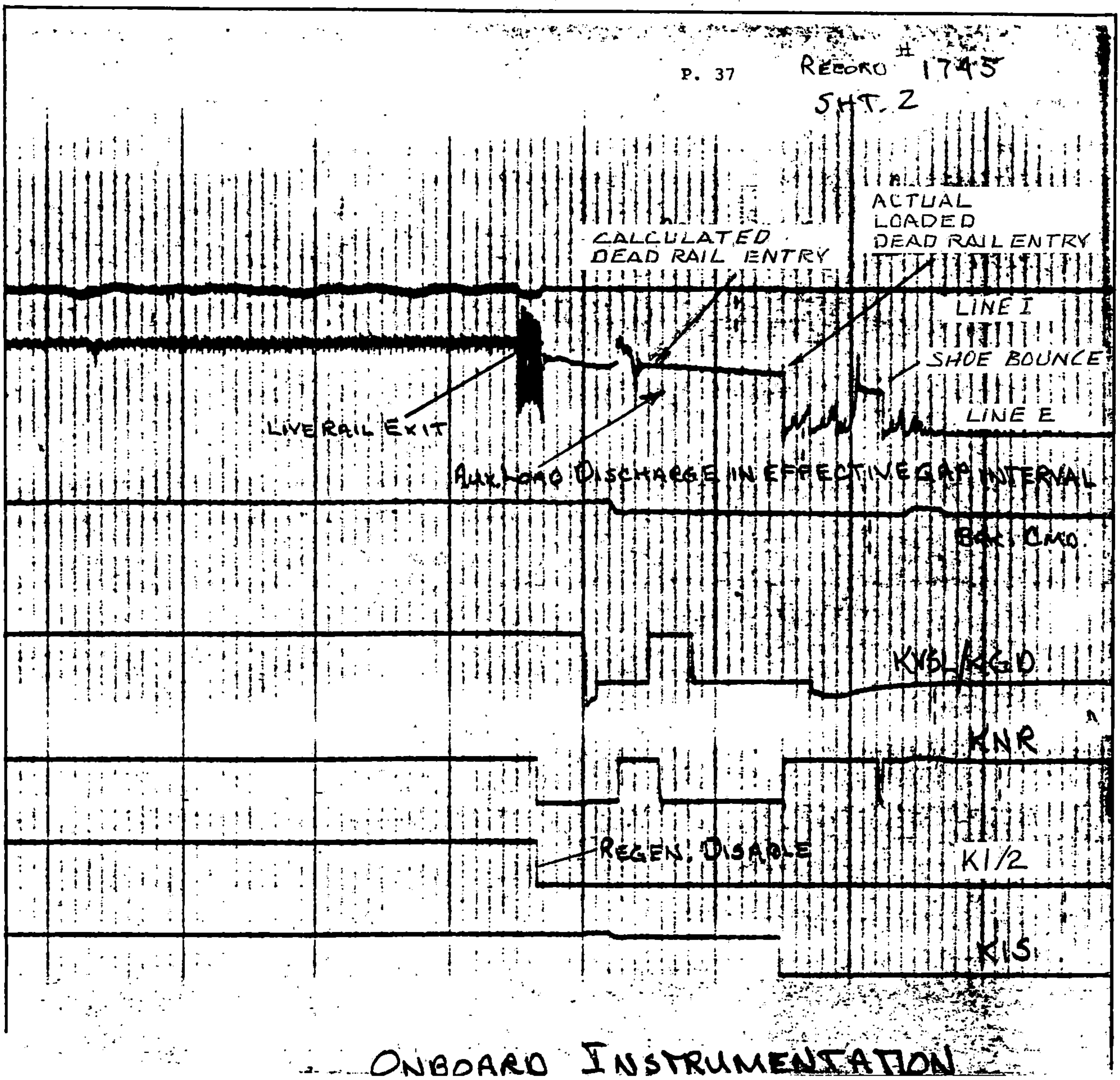


FIGURE 4.4.9-17. CASE 8 RECORDING, 10 MM/SEC

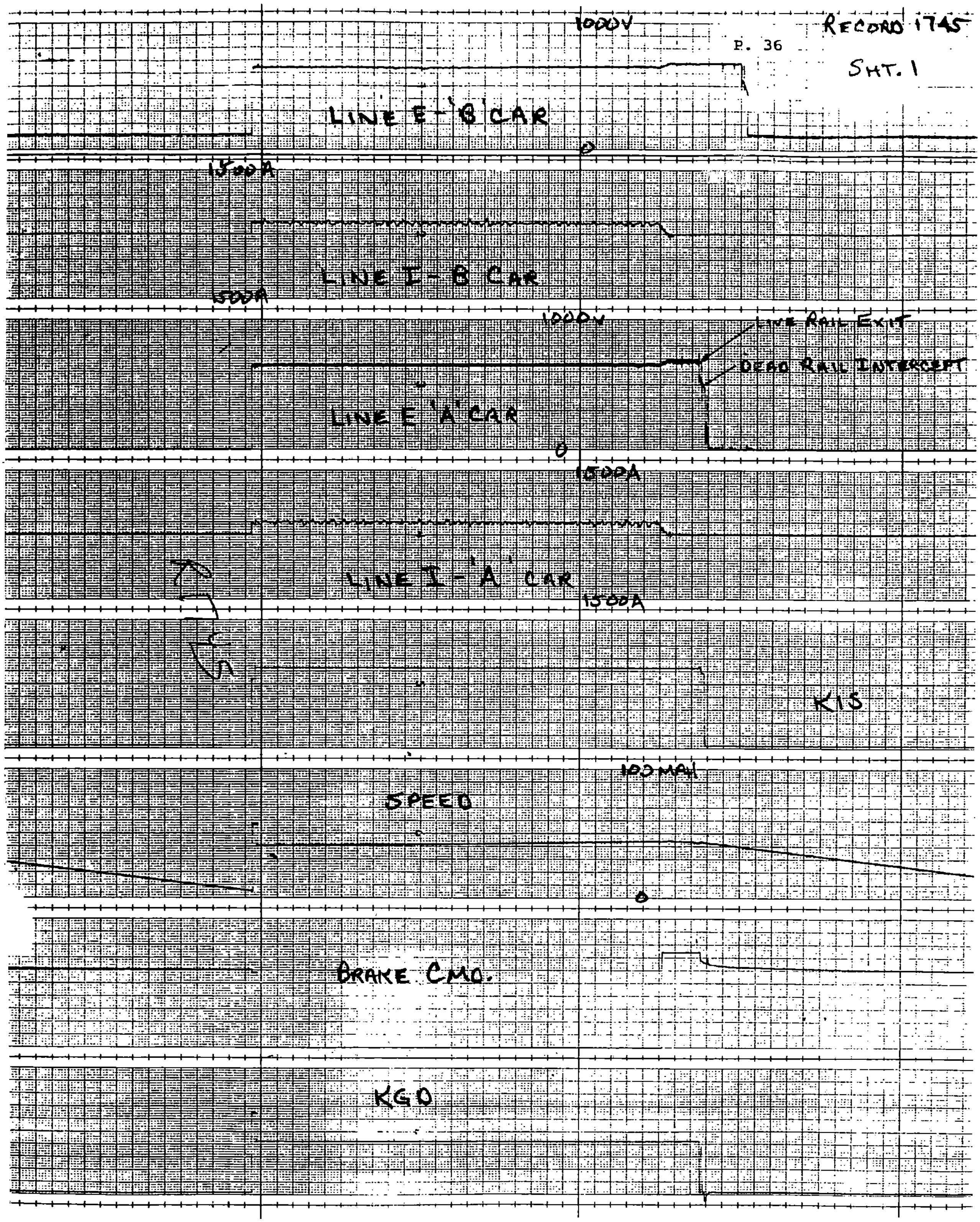


FIGURE 4.4.9-18. CASE 8 RECORDING, 10 IN./SEC

The difference in calculated and recorded gap transit times is apparently caused by the third-rail exit and entry ramps described in Case 5, para. 4.4.9.3.3.5. It is reasonable to expect that an additional 5 to 6 ft of gap could exist, depending on car movement about the roll axis. The additional gap could double the effective gap and the gap transit time at a speed of 6 ft per 100 msec (about 41 mph).

4.4.10 EMI, Signalling Tests

Both inductive and conductive EMI tests were conducted at the NYCTA Sea Beach facility to validate compatibility of the ac propulsion system operation with regard to the NYCTA track circuit signalling and power substation equipment operation as discussed in the following subsections.

4.4.10.1 Track Circuit EMI Signalling Tests

The comprehensive track circuit test program was of primary importance in establishing the validity of the STARS ac propulsion equipment compatibility with existing NYCTA operating facilities.

In previous Phase I test programs, headed by the the Rail Transit EMI/EMC Technical Working Group, track signalling tests were conducted by applying ac signals at 25 and 60 Hz to selected track circuits with the intent of validating previous electrical structure models and laboratory EMI test results. The results of this test program, prepared and presented by the DOT/UMTA Transportation Test Center, showed favorable rail characteristics with no increase in relay activity present with predicted ac signals.

The Phase II ac car performance program required the actual demonstration of an operating ac propulsion transit car(s) under controlled conditions with selected NYCTA track circuits.

The track circuit testing was conducted on the NYCTA Sea Beach track in Coney Island, using Track E3 south of the 20th Avenue substation. Both of the STARS ac cars, SN 280 and 249, as well as the dc-equipped pair of cars, were used in the program.

The specified test procedure and track circuits were furnished by the NYCTA electrical and signal departments. UMTA TSC personnel recorded and coordinated the program, which was conducted by AiResearch and witnessed by the NYCTA. The signalling system tests included a total of 18 track circuits as well as 2 open-circuit configurations, which were provided by the NYCTA as representative of their signalling system. Figure 4.4.10-1 shows the signalling circuit test track. Twelve circuits were tested with the negative return isolated through the substation, which was considered worst-case because all propulsion return current is returned through the track circuit. Seven circuits were tested with nonisolated returns. Of the seven track circuits tested with a nonisolated return, one potentially susceptible track circuit was retested with an isolated return. The tests included single- and double-rail configurations at both 25 and 60 Hz. The worst-case conditions are:

(a) Longest track circuit in the signal system

(b) Highest ballast resistance

(c) Track circuit adjacent to the third rail

(d) High negative-rail and low signal-rail resistance for single-rail track circuits

(e) Unbalanced rail resistance for double-rail track circuits

(f) Fully loaded car operation

Test track conditions included a track circuit 845 ft in length, high ballast resistance of approximately 100 ohms, and the signal rail adjacent to the third rail. The test track had very low negative- and signal-rail resistance.

In all, about 500 test runs of the ac cars were made, during which track circuit relay activity was observed visually and by using recordings. The ac cars were maintained at the most severe AW3 load conditions (fully loaded) for the tests, with all ac equipment and auxiliaries operating.

The results of this comprehensive test program (which took place over a 4-week period) showed that the EMI characteristics of the ac cars were comparable with those of the existing dc cars and resulted in no additional EMI-induced track circuit relay activity. The NYCTA was in concurrence with these results.

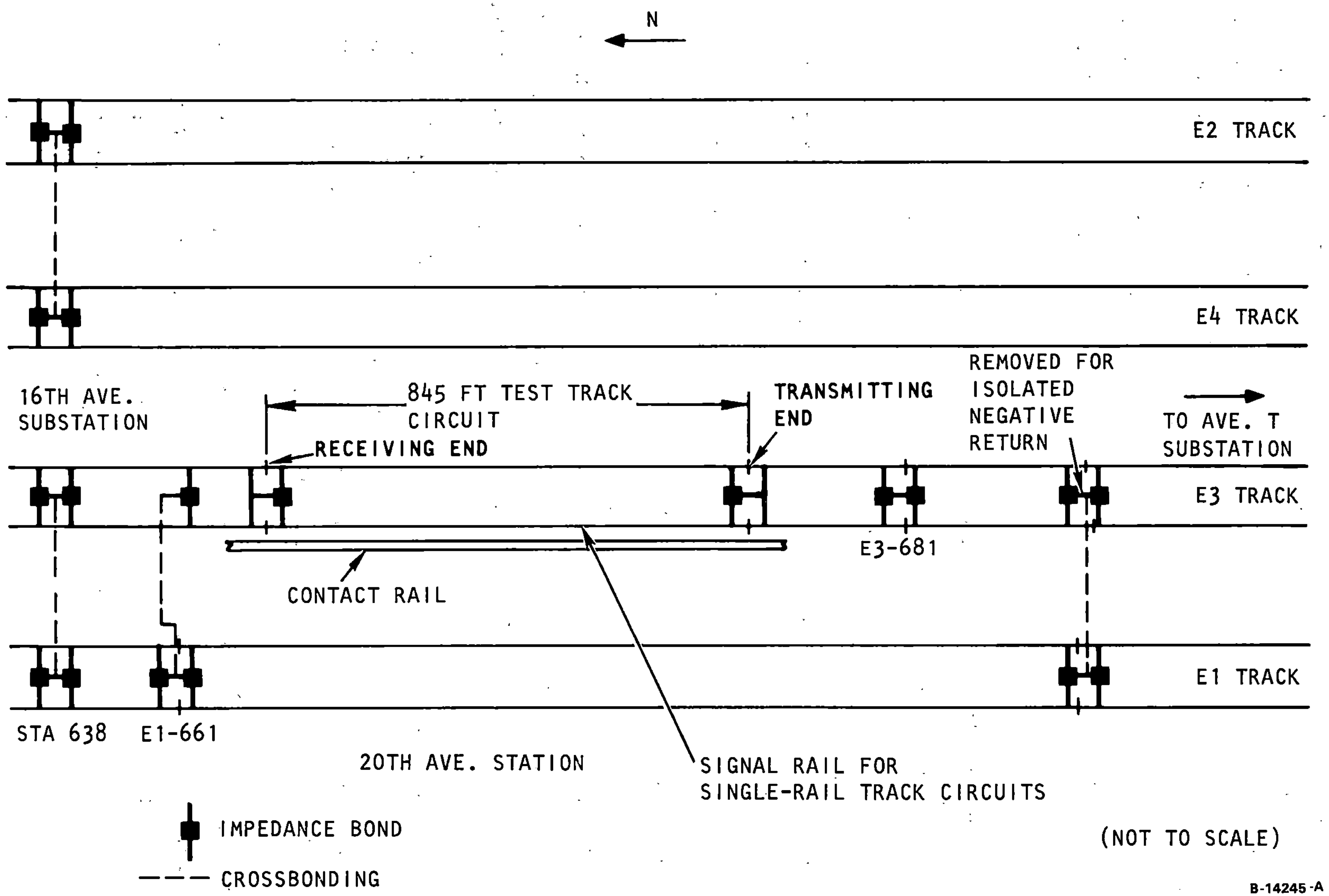


FIGURE 4.4.10-1. SIGNALLING TEST TRACK CIRCUITS AT SEA BEACH

The following paragraphs provide details of the tests.

4.4.10.1.1 Test Description

The testing of NYCTA track circuits began on March 19, 1987 with the retesting of Track Circuit 1, a GRS single-rail balancing reactor type that was previously tested during Fall, 1986. Unlike the Fall test, however, in which the negative return rail of the dc current was isolated, the return rail was cross-bonded with negative return rails from adjacent tracks. Overall, 18 representative track circuits were tested through April 20, 1987, including two open-circuit configurations, as identified in Table 4.4.10-1.

TABLE 4.4.10-1

TRACK CIRCUIT SIGNALLING TESTS

Circuit Description	Circuit No.
GRS balancing reactor single rail--60 Hz	1
US&S capacitor-type single rail--60 Hz	12
GRS balancing reactor single rail--60 Hz	2
GRS capacitor-type single rail--60 Hz	4
GRS capacitor-type single rail--25 Hz	6
US&S shielding reactor single rail--60 Hz	10A
US&S single rail (no shielding reactor)--60 Hz	10
GRS matching transformer single rail--60 Hz	3
US&S balancing reactor single rail--60 Hz	11A
US&S single rail (no balancing reactor)--60 Hz	11
US&S matching transformer single rail (PV250 relay)--60 Hz	14
US&S shielding reactor single rail--25 Hz	17
US&S matching transformer single rail (PTV-42 relay)--60 Hz	13
US&S shielding reactor single rail--25 Hz	18
GRS balancing reactor single rail--25 Hz	5
GRS rotary-type relay double rail--25 Hz	7
GRS vane relay double rail--60 Hz	8

TABLE 4.4.10-1 (Continued)

Circuit Description	Circuit No.
US&S matching transformer double rail--60 Hz	15
Open-circuit single rail	--
Open-circuit double rail	--

All of the vehicle runs were northbound in the direction going from the feed end of the track circuit towards the receive end. The train configuration consisted of the two ac motor-driven vehicles loaded to AW3 conditions, except during the second day of the Circuit 1 retest, when the train consisted of two dc cars with AW3 loading.

The primary signal, which was monitored in real time using a GENRAD 2512 spectrum analyzer, was the voltage across the rails at the receive end of the track circuit. This rail-to-rail voltage was recorded, along with five other measurements, on a Honeywell 101 tape recorder. A vocal description of each run was recorded onto the voice track of the tape recorder. In addition to the measurements, the track circuit relay was closely monitored by a signalling expert from the NYCTA during the vehicle runs. Any vane movement was noted on the data log sheets when observed and called out by the NYCTA expert. No breaking of relay contacts was observed in any of the track circuits tested, although some relay vane motion was observed. The tape-recording channel assignments were as follows:

Channel	Assignment
1	Voice
5	Rail-to-rail voltage
7	Relay track coil voltage
11	Reference voltage (across local voltage of relay)
13	Back contacts
15	Front contacts
19	Track circuit current
21	Relay track coil current (added 4/10/87)

The signal levels were reduced by voltage division in some cases to prevent overloading of the recorder channels. The rail-to-rail voltage was divided by 10 and recorded on Channel 5. The track coil voltage of the relay was divided by 10 and recorded on Channel 7. The relay local coil voltage was stepped down using a small isolation transformer, then reduced by a 10-to-1 voltage divider and recorded on Channel 11. This signal was directly in phase with the actual local coil signal level, but was of greatly reduced amplitude.

The data on Channels 7 through 21 were primarily recorded for analysis in case there were EMC problems between the vehicles and any of the tested track circuits. Such electromagnetic incompatibility would be revealed by the opening of the relay contacts as noted in real time by the NYCTA signalling expert and by the change in dc voltage levels recorded on tape Channels 13 or 15. By playing back the appropriate channels into a voltmeter, phase meter, or spectrum analyzer, the recorded data could be analyzed to determine such information as the voltage levels and phase relationships between the relay track coil voltage and the local (reference) voltage.

4.4.10.1.2 Test Procedures

For each track circuit tested, a complete set of measurements consisted of the following:

(a) Track characterization measurements

(b) Unoccupied calibration of the track circuit before vehicle run measurements

(c) Vehicle run measurements

(d) Unoccupied calibration of the track circuit after vehicle run measurements

In addition to the track circuit tests, a throughput calibration at the receive end of the track circuit was performed at the start of almost every day of testing to verify the accuracy of the rail-to-rail voltages as measured by the test instrumentation inside the test bunker. This calibration procedure consisted of using a Rockland 5100 frequency synthesizer to generate a 1-vrms ac signal (measured to 1-percent accuracy) directly across the rails at both 25 and 60 Hz. The signal was measured directly across the rails at the signal source using a Fluke voltmeter and inside the bunker using the GENRAD 2512 spectrum analyzer. This signal also was stored on tape and a plot was produced from the spectrum analyzer display. In all cases, the 25-Hz and 60-Hz signals displayed on the spectrum analyzer generally correlated very accurately with the Fluke reading after correcting for the 10-to-1 voltage division, adding the Hann correction factor, and converting the dBV readings to volts. The receive end track circuitry was open-circuited for these calibration tests to avoid overloading the frequency synthesizer.

The track circuit measurements listed above are discussed in more detail in the following paragraphs.

4.4.10.1.2.1 Track Characterization Measurements

The purpose of these measurements was to determine the voltages across and currents through various components of the track circuit, both at the normal operating voltage across the secondary winding of the transmit end track transformer and at lesser voltages. The NYCTA signalling expert set up the track circuit to its normal operating conditions based on his judgement as to how solidly the vane of the track circuit relay picked up and struck the front stop when the relay track coil was energized. To obtain the lesser voltage measurements, an autotransformer was inserted into the circuit to vary the primary voltage of the track transformer.

For each of the feed-end voltage levels, a set of transmit-end voltage levels (measured with a Fluke meter) was recorded along with a set of measurements made at the receive end of track circuit from inside the test bunker. At the transmit end, the voltages measured were:

(a) Across the transformer secondary windings

(b) Across the transmit end ballast resistor

(c) Across the rails at the feed end

At the receive end of the track circuit, the measurements recorded were:

(d) The reference voltage

(e) The receive-end rail-to-rail voltage

(f) The track coil voltage of the relay

(g) The track current (current in the rail)

The relay track coil current also was measured and recorded during later track circuit measurements when different from the track current.

At the receive end of the track circuit, the voltages were measured using both a Hewlett Packard HP3403 true rms meter and an HP3582A spectrum analyzer. In addition, phase angle measurements with respect to the local voltage of the relay were taken at some relay positions using the HP3582A. The HP3403 readings and the HP3582A readings were in fairly close agreement. However, the HP3403 measurements were of the entire signal waveform, while the HP3582A readings were taken at the 25- or 60-Hz component only. The HP3403 readings were therefore slightly higher, since a fairly significant 720-Hz component also was present in the signals. During the latter track circuit measurements, the HP3582A became inoperable and an oscilloscope was used in its place for making approximate phase measurements.

By varying the voltage from the feed end of the track circuit, the track coil voltage of the relay could be raised or lowered to change the position of the vane with respect to the front stop and back stop of the relay. The first part of the track characterization consisted of starting with a completely deenergized relay and increasing the transmit-end voltage to change the closure states of the front and back contacts and the vane position with respect to the front and back stops. At each of the following "pick up" positions, the following transmit-end and receive-end measurements were taken:

Off back stop

Open back contacts

Close front contacts

Full pickup

Next, starting from a near full pickup position, the voltage at the feed end was reduced and measurements were taken at the following "drop away" positions:

Off front stop

Open front contacts

Close back contacts

Make back stop

Often, while gradually increasing the voltage to advance from one relay state to the next, mechanical "sticktion" within the relay would cause it to overshoot the next state and come to rest at the following one or two higher states. This condition also was found to exist during the dropaway characterization measurements of some of the track circuits. For such cases, one set of measurements sufficed to represent several relay states.

4.4.10.1.2.2 Unoccupied Calibration Of Track Circuit (Before and After Vehicle Run Measurements)

A measurement of the unoccupied track (vehicle outside of track circuit) was made before and after every set of the vehicle run measurements taken for every track circuit. Usually the measurement was stored on tape and/or a plot was made of the rail-to-rail voltage spectrum on the display of the spectrum analyzer. The frequency of interest was the operating frequency of the track circuit (25 or 60 Hz) that was present when the track circuit was unoccupied. The before and after measurements were compared with each other and, after correction and conversion from dBV, also to the corresponding (receive-end rail-to-rail volts) track characterization measurement. In this way the accuracy and stability of the track signal thoughout an entire set of track circuit measurements could be verified.

4.4.10.1.2.3 Vehicle Run Measurements

For each track circuit tested, nine different types of vehicle runs were performed and each type was performed two or three times in succession. On the data log sheets these runs were labeled 3 through 11. (Runs 1 and 2 are the first unoccupied track circuit and track characterization measurements). Runs 3 through 7 were regarded as the worst-case runs that would be most likely to cause EMI problems if they were to occur. For each of these runs, a spectral plot was produced and the measurements were stored on tape.

Runs 8 through 11 were performed to satisfy the NYCTA that no run modes could cause EMI with the track circuits. They were also recorded on tape but not plotted. Note that in open-circuit tests, the relay was not in the circuit because the receive end of the track circuit was disconnected. Since Runs 8 through 11 were performed in order to monitor any relay movement by the NYCTA, these runs were omitted during open-circuit tests.

Radio communications between the test bunker and the vehicle during the vehicle runs kept the personnel in the test bunker continuously informed as to the instantaneous operating modes of the vehicle (e.g., acceleration, braking, coasting). Likewise, these instantaneous operating modes were recorded immediately onto the voice track of the tape either by repeating the radioed information into the tape recorder microphone or by holding the microphone directly up to the two-way radio.

The following is a description of each run type.

Type 3--Starting from just inside the feed end of the track circuit, the vehicle begins accelerating from a dead stop at the maximum rate possible, P3 acceleration. The run lasts as long as the vehicle is accelerating. This run was performed twice for every circuit.

Type 4--This run starts from the feed end of the track circuit with a P3 acceleration just as in run Type 3. When 20 mph is reached, the vehicle is braked to a full stop by maximum regenerative braking. In this type of braking, the kinetic energy of the train is converted into electrical energy, which is fed back into a bank of resistors set up at the substation powering the third rail. In normal operation, the energy returned to the substation would be reused. The resistor bank is connected just before the vehicle begins to brake.

Type 5--This run starts with the vehicle traveling about 30 mph outside of the track circuit. Just before entering the feed end of the circuit, the vehicle goes into maximum regenerative braking. The measurement begins just after the vehicle enters the track circuit and lasts until the train comes to a complete stop. This run type was performed twice for every circuit tested.

Type 6--This run is almost identical to run Type 5, except that the train begins maximum regenerative braking just after the vehicle enters the track circuit so that the measurement picks up the transition to braking. This run type was performed twice for every circuit tested.

Type 7--This run is similar to run Type 3. Starting from just inside the feed end of the track circuit, the vehicle accelerates in P2 acceleration from a dead stop. P2 is a lesser acceleration than P3, the maximum acceleration. The duration of the measurement is the time it takes for the vehicle to continue accelerating in P2 mode, which it does for almost the whole length of the track circuit. This run type was performed twice for every circuit tested.

Type 8--This run is similar to run Type 4, except that the P3 acceleration followed by regenerative braking is performed with the vehicle entirely outside of the circuit, braking to a stop just before entering the feed end. The purpose of this run type was to determine if any EMI could be generated for the unoccupied case that would cause the "picked" relay to drop, thus falsely indicating a train inside the track circuit. This run type was performed twice for every circuit.

Type 9--In this run type, the train is situated at the receive end of the track circuit with one car situated inside the track circuit and the other car outside the circuit. From this stationary position the train accelerates in P3 mode northbound out of the circuit. The measurement spans the time from the start of acceleration to the time the rear axle of the lagging car leaves the circuit. This run type was performed three consecutive times for every track circuit.

Type 10--This is a regenerative braking run type. The vehicle accelerates to approximately 30 mph inside the track circuit and then begins maximum regenerative braking just as the first car crosses the receive end of the circuit. The measurement spans the time from the beginning of braking until the train comes to a complete stop. This run type was performed three consecutive times on every track circuit.

Type 11--In this run type the train, starting from the feed end of the track circuit, accelerates in P3 mode to 10 mph, coasts, and then brakes to a stop using maximum regenerative braking. This cycle of acceleration, coasting, and braking is repeated as many times as can be performed before the train reaches the receive end. Normally about seven cycles can be performed in a single run down the track. This run type was performed three consecutive times on every track circuit.

4.4.10.1.3 Test Results

Table 4.4.10-2 lists those vehicle runs performed with each track circuit that generated the highest rail-to-rail noise levels in the sensitive frequency band from 25 to 60 Hz. The signal levels as detected by the spectrum analyzer were referenced to the rail-to-rail track circuit voltages in order to obtain margins of safety for both the unoccuppied and occupied track circuits. These margins are shown in the last two columns of the table.

The Table 4.4.10-2 column explanations are as follows:

Sig. Levl (DBV) = Chart Level (dB) + Ref (dBV)
+ Hann (1.8 dB) + Volt Div (20 dB)

TABLE 4.4.10-2

NYCTA TRACK CIRCUIT MEASUREMENT DATA

(Highest Vr-r Levels Detected For Each Track Circuit Tested)

Date	Run #	Run Type	Freq.	Sig. Levl (dBV)	Sig Levl (Volts)	Unocc. Margin (dB)	Occup. Margin (dB)
Circuit #1. GRS Balancing Reactor Single Rail - 60 Hz							
3/19/87	1649	Max Regen	40.00	-18.9	.11	-26.47	-15.42
3/19/87	1655	Max Regen	36.25	-18.2	.12	-25.77	-14.72
3/20/87	1132	P3 Accel	21.25	-14.1	.20	-21.67	-10.62
Circuit #12. US&S Capacitor Type Single Rail - 60 Hz							
3/23/87	1307	Type 4	22.50	-14.1	.20	-23.04	-15.90
3/23/87	1343	Type 6	41.25	-13.2	.22	-22.14	-15.00
3/23/87	1350	Type 6	37.50	-14.3	.19	-23.24	-16.10
Circuit #2. GRS Balancing Reactor Single Rail - 60 Hz							
3/24/87	1115	Type 3	33.75	-17.3	.14	-20.59	-13.56
3/24/87	1203	Type 5	37.50	-10.8	.29	-14.09	-7.06
Circuit #4. GRS Capacitor Type Single Rail - 60 Hz							
3/25/87	1128	Type 5	38.75	-15.9	.16	-22.30	-19.54
3/25/87	1135	Type 6	37.50	-16.3	.15	-22.70	-19.94
3/25/87	1142	Type 6	32.50	-15.4	.17	-21.80	-19.04
3/25/87	1151	Type 6	36.25	-14.6	.19	-21.00	-18.24
Circuit #6. GRS Capacitor Type Single Rail - 25 Hz							
3/26/87	1150	Type 4	27.50	-15.5	.17	-24.13	-22.11
3/26/87	1240	Type 6	37.50	-13.0	.22	-21.63	-19.61
3/26/87	1250	Type 6	38.75	-9.6	.33	-18.23	-16.21
3/26/87	1300	Type 6	23.75	-16.5	.15	-25.13	-23.11
Circuit #10A. US&S Shielding Reactor Single Rail - 60 Hz							
3/26/87	1526	Type 3	33.75	-16.8	.14	-21.04	-14.97
3/26/87	1533	Type 4	18.75	-17.3	.14	-21.54	-15.47
3/26/87	1558	Type 5	33.75	-15.7	.16	-19.94	-13.87
Circuit #10. US&S Single Rail - 60 Hz (Like #10A without Shield. React.)							
3/27/87	1254	Type 4	27.50	-16.4	.15	-23.86	-15.48
3/27/87	1502	Type 5	25.00	-17.6	.13	-25.06	-16.68
3/27/87	1515	Type 6	35.00	-16.0	.16	-23.46	-15.08
Circuit #3. GRS Matching Transformer Single Rail - 60 Hz							
3/30/87	1240	Type 3	33.75	-15.4	.17	-19.64	-14.29
4/6/87	1430	Type 5	47.50	-14.9	.18	-19.14	-13.79
4/6/87	1440	Type 5	56.25	-12.6	.23	-16.84	-11.49
Circuit #11A. US&S Balancing Reactor Single Rail - 60 Hz							
4/7/87	1150	Type 3	35.00	-15.6	.17	-20.51	-17.11
4/7/87	1217	Type 4	27.50	-13.8	.20	-18.71	-15.31
4/7/87	1226	Type 5	28.75	-12.7	.23	-17.61	-14.21

TABLE 4.4.10-2 (Continued)

Date	Run #	Run Type	Freq.	Sig. Levl (dBV)	Sig Levl (Volts)	Unocc. Margin (dB)	Occup. Margin (dB)
Circuit #11. US&S Single Rail - 60 Hz (Like #11A without Bal. React.)							
4/7/87	1510	Type 3	33.75	-14.5	.19	-21.92	-18.02
4/7/87	1530	Type 4	28.75	-15.7	.16	-23.12	-19.22
4/7/87	1536	Type 4	28.75	-16.4	.15	-23.82	-19.92
Circuit #14. US&S Matching Transformer Single Rail - 60 Hz (PV250 Relay)							
4/8/87	1138	Type 3	33.75	-12.6	.23	-17.85	-14.74
4/8/87	1159	Type 4	22.55	-16.2	.15	-21.45	-18.34
4/8/87	1253	Type 6	38.75	-12.4	.24	-17.65	-14.54
Circuit #17. US&S Shielding Reactor Single Rail - 25 Hz							
4/9/87	1158	Type 4	28.75	-14.7	.18	-12.43	-12.08
4/9/87	1225	Type 5	36.25	-14.1	.20	-11.83	-11.48
4/9/87	1240	Type 6	18.75	-13.5	.21	-11.23	-10.88
Circuit #13. US&S Matching Transformer Single Rail - 60 Hz (PTV42 Relay)							
4/9/87	1522	Type 4	27.50	-14.9	.18	-9.05	-20.01
4/9/87	1528	Type 5	32.50	-15.4	.17	-9.55	-20.51
4/9/87	1541	Type 6	35.00	-12.5	.24	-6.65	-17.61
Circuit #18. US&S Shielding Reactor Single Rail - 25 Hz							
4/10/87	1150	Type 3	33.75	-13.6	.21	-17.57	-10.50
4/10/87	1333	Type 5	40.00	-16.1	.16	-20.07	-13.00
4/10/87	1341	Type 4	25.00	-18.5	.12	-22.47	-15.40
4/10/87	1418	Type 7	18.75	-17.2	.14	-21.17	-14.10
Circuit #5. GRS Balancing Reactor Single Rail - 25 Hz (Non-Isolated Rtn)							
3/25/87	1403	Type 4	27.50	-15.0	.18	-18.11	-9.81
3/25/87	1403	Type 4	31.25	-14.7	.18	-17.81	-9.51
3/25/87	1432	Type 5	33.75	-16.1	.16	-19.21	-10.91
3/25/87	1447	Type 6	15.00	-14.5	.19	-17.61	-9.31
Circuit #5. (Isolated Return - Wet Track)							
4/13/87	1236	Type 3	32.50	-16.6	.15	-19.71	-11.41
4/13/87	1402	Type 5	38.75	-16.1	.16	-19.21	-10.91
4/13/87	1450	Type 6	20.00	-15.7	.16	-18.81	-10.51
Circuit #5. (Isolated Return - Dry Track)							
4/14/87	1100	Type 3	35.00	-15.9	.16	-19.01	-10.71
4/14/87	1108	Type 3	35.00	-16.0	.16	-19.11	-10.81
4/14/87	1115	Type 4	28.75	-12.9	.23	-16.01	-7.71
Open Circuit Single Rail (Isolated Return - Wet Track)							
4/13/87	1704	Type 4	27.50	-13.5	.21		
4/13/87	1704	Type 4	38.75	-16.1	.16		
4/13/87	1739	Type 6	41.25	-16.2	.15		

TABLE 4.4.10-2 (Continued)

Date	Run #	Run Type	Freq.	Sig. Levl (dBV)	Sig Levl (Volts)	Unocc. Margin (dB)	Occup. Margin (dB)
Open Circuit Single Rail (Non-Isolated Return)							
4/14/87	1451	Type 4	17.50	-17.3	.14		
4/14/87	1516	Type 6	15.00	-15.7	.16		
4/14/87	1516	Type 6	38.75	-16.5	.15		
4/14/87	1528	Type 6	40.00	-17.0	.14		
Open Circuit Single Rail (Isolated Return - Dry Track)							
4/14/87	1629	Type 3	17.50	-16.1	.16		
4/14/87	1718	Type 5	36.25	-16.5	.15		
4/14/87	1735	Tupe 6	43.75	-14.7	.18		
Circuit #7. GRS Rotary Type Double Rail - 25 Hz							
4/15/87	1529	Type 4	56.25	-37.3	.014	-23.74	-22.88
4/15/87	1538	Type 5	27.50	-34.7	.018	-21.14	-20.28
4/15/87	1603	Type 6	38.75	-33.1	.022	-19.54	-18.68
Circuit #8. GRS Double Rail - 60 Hz							
4/16/87	1128	Type 3	32.50	-36.5	.015	-30.48	-34.45
4/16/87	1128	Type 3	40.00	-35.3	.017	-29.28	-33.25
4/16/87	1155	Type 4	30.00	-36.3	.015	-30.28	-34.25
Circuit #15. US&S Matching Transformer Double							
4/16/87	1448	Type 7	17.50	-35.2	.017	-30.91	-34.19
4/16/87	1557	Type 3	32.50	-31.0	.028	-26.71	-29.99
4/16/87	1605	Type 3	16.25	-30.8	.029	-26.51	-29.79
Open Circuit Double Rail							
4/20/87	1129	Type 3	23.75	-36.9	.014		
4/20/87	1129	Type 3	33.75	-33.1	.022		
4/20/87	1158	Type 5	30.00	-32.3	.024		
4/20/87	1158	Type 5	36.25	-30.5	.030		
4/20/87	1228	Type 6	23.75	-37.4	.013		
4/20/87	1228	Type 6	35.00	-32.7	.023		

where Ref = 10, 20, or 0 for double rail

Sig. Levl (Volts) = 10A [Sig. Levl (dBV)/2.0]

Unocc. Margin = 20 log (Sig. Level (volts)/(V_{RRFP} - V_{RROF}))

Occup. Margin = 20 log (Sig. Level (volts)/V_{RROB})

where V_{RRFP} = Full pickup voltage across rails*

V_{RROF} = Drop away volts off front stop*

V_{RROB} = Pickup volts off back stop*

*From track characterization data sheets

Example: Circuit 12, Run 1307

Sig. Level (volts) = 0.20 at 22.50 Hz

V_{RRFP} = 5.65

V_{RROF} = 2.85

V_{RROB} = 1.23

Unocc. Margin = 20log(0.20/(5.65 - 2.85))
= -23.04 dB

Occup. Margin = 20log(0.20/1.23)
= -15.90 dB

4.4.10.1.4 Conclusions

The comprehensive nature of this test program produced an extensive library of data for reduction and analysis. No attempt to include all of the data is made in this report; only a summary directed at amplifying the signal test conclusions is provided (Table 4.4.10-2). This summary shows that at least 7 dB of safety margin is present between signal relay activity and relay activation under worst-case car operating conditions.

4.4.10.2 Conductive Emissions Tests at 16th Avenue Substation

Following the successful signalling test program, the STARS ac cars were subjected to a conductive emissions interference test program using the 16th Avenue substation, instrumented in accordance with Figure 4.4.10-2. The

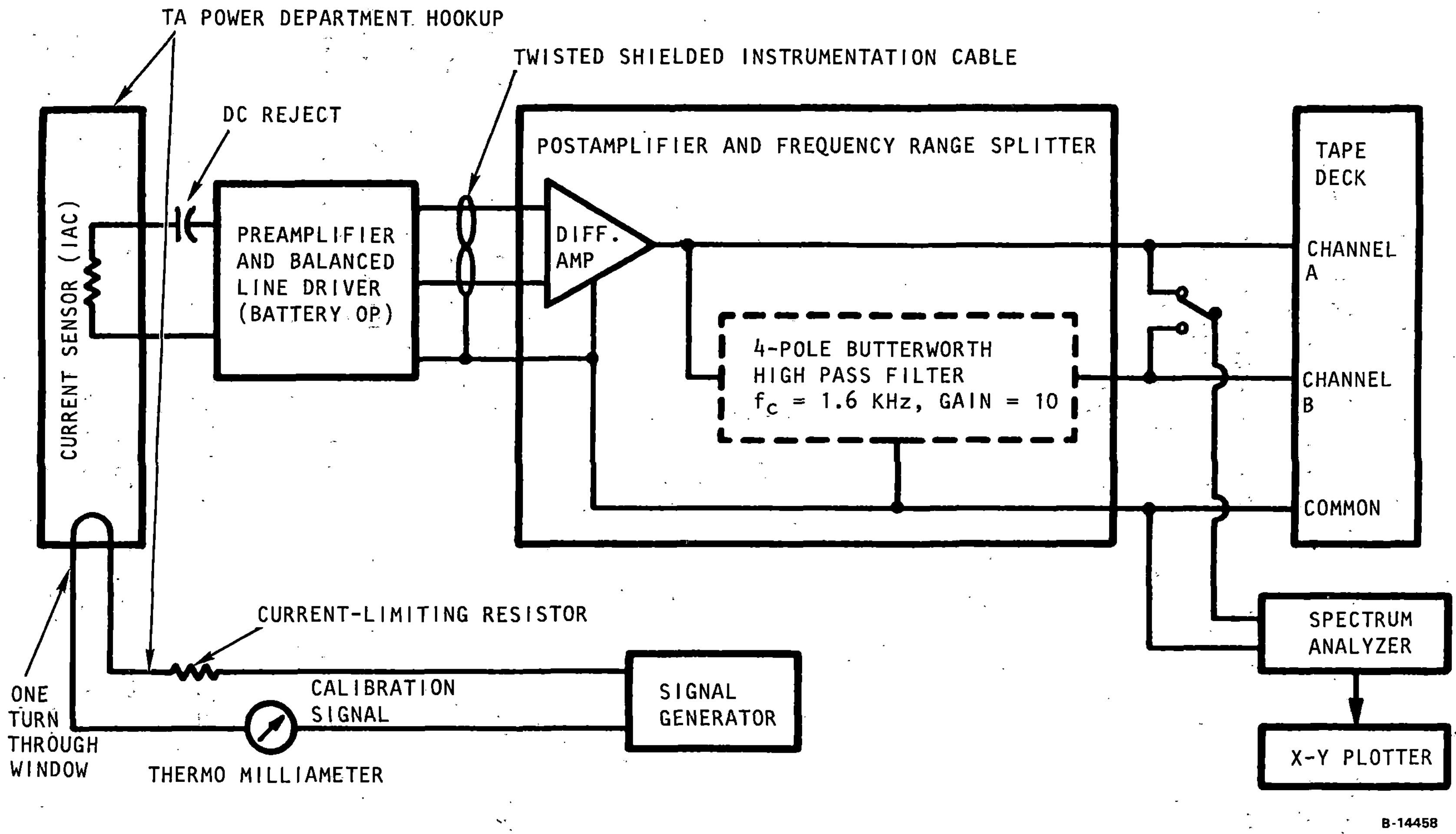


FIGURE 4.4.10-2. SUBSTATION SETUP SHOWING INSTRUMENTATION FOR CONDUCTIVE EMISSIONS TESTS

purpose of this test was to observe and record any ac car emissions affecting substation equipment or operation.

4.4.10.2.1 Test Description

The ac car pair was operated on Track E3, northbound between the Avenue "T" substation and the 16th Avenue gap (Figure 4.4.10-3). Testing was conducted by AiResearch under the direction of the NYCTA power department and operating group. The ac harmonic currents flowing in the third rail between the substation and train were measured using the current sensor indicated in the schematic diagram of Figure 4.4.10-2, installed at the location shown in Figure 4.4.10-3.

4.4.10.2.2 Test Conditions

The conductive emissions tests were performed at a car weight of AW3, the fully loaded condition, using the AB(ac) car pair as well as the ABBA consist with the ac car driving.

Tests were conducted with the cars accelerating towards the substation to approximately 40 mph and then braking.

4.4.10.2.3 Conclusions

Twelve ac car runs were conducted under varying modes of operation (acceleration, deceleration, regeneration, nonregeneration), and the conclusions reached were that no emissions affecting either power substation equipment or operation were observed.

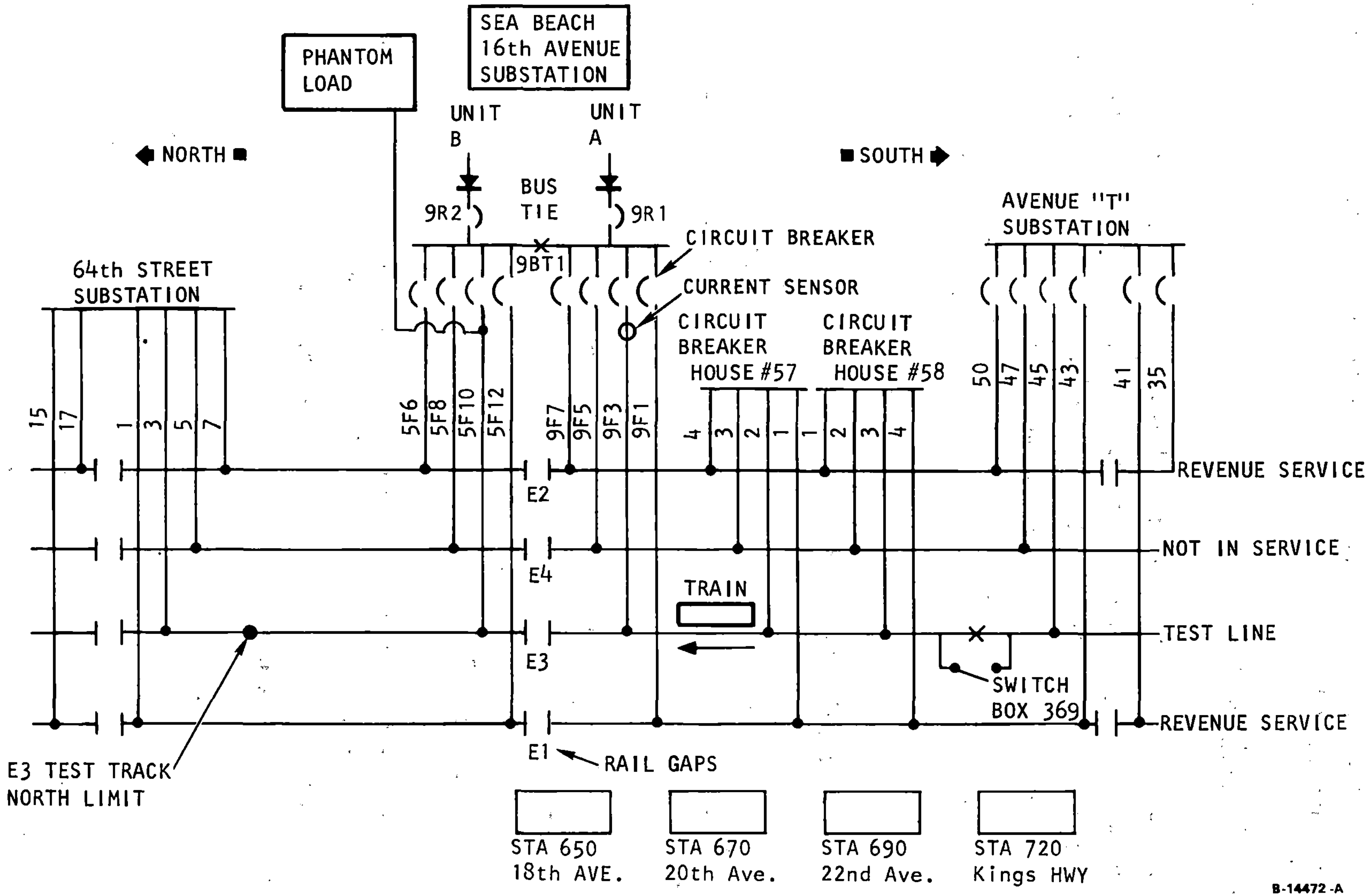


FIGURE 4.4.10-3. CONDUCTIVE EMISSIONS TEST TRACK CONFIGURATION

4.4.11 Revenue Service Demonstration ("A" Line)

The last formal test in the STARS ac propulsion demonstration was a one-week reliability run as part of an eight-car consist (the ac-dc STARS pairs plus four standard R-44 cars) in regular revenue service on the NYCTA "A" line. This display of confidence by the NYCTA in the ac propulsion equipment is considered to be another significant indicator of program success, underscoring the technical commitment to upgrading U.S. rail transit equipment. During the comprehensive 1-1/2-year program, there were no ac traction motor failures, and overall ac propulsion system performance was exceptional.

For the "A" line revenue run, only one significant ac propulsion control modification was made. This was an automatic reset mechanism to prevent "nuisance" propulsion shutdowns due to line power interruptions. Regeneration was also manually cut out.

Universal acceptance of a successful STARS ac propulsion demonstration was expressed by those concerned following this revenue demonstration. The program showed that ac propulsion is a viable replacement for existing ac technology. A logical next step in the application of STARS is a U.S. transit procurement for an ac propulsion train utilizing the latest ac equipment technology.

4.4.12 Test Program Incidents, Trouble Analysis, and Corrective Action

The lengthy and comprehensive test program conducted at the Sea Beach facility was successful in demonstrating its goal of ac propulsion integration into an operating transit system with no impact on existing "in-place" equipment or facilities. The benefits of regeneration and the reduction in car maintenance requirements were evident.

As in any complex test program, some difficulties occurred; however, they did not alter the test program conclusions and only served to provide technical additions to future procurement specifications. Two noteworthy incidents that resulted in lengthy investigations were:

(a) Transfer of Braking Energy from Regenerative or Rheostatic to Friction, and Subsequent Wheel Lockup and Slide--During a demonstration run, the ac cars were placed in "full service brake" for regeneration testing. In the ac control unit, an optical isolator is used to limit braking rate and prevent wheel slide. In this test run, the wheels were locked and the isolator, sensing no relative axle motion, switched from regenerative brake to friction. Since the R-44 car onboard friction brake system was not equipped with a spin-slide circuit, the slide continued. Subsequent lengthy testing of both ac and dc cars showed that slides could be induced on a regular basis when friction brakes were suddenly applied. Considering the track conditions, wheel lockup was substantiated. In future systems, the ac propulsion would be designed for a longer "window" on electrical braking to allow for momentary wheel and axle-to-axle lockup before switching to the friction brake system from regenerative braking. It also is recommended that all friction brake systems be equipped with spin-slide controls. It is noteworthy that the ac car system appropriately functioned as designed to switch from regenerative to friction-only braking as a safety measure in response to any slide indication. It was also conclusively shown that there could be no overlap of electric and friction brakes.

(b) Several Power Device Failures of the Onboard ac Inverters During Regeneration and Power Consumption Testing in Conjunction with the Ripple Detector Tests--These device failures were traced to inadequate component grounding and shielding procedures. The R-44 utilizes the car body as ground. This would be taken into consideration on future designs.

At various times throughout the test program, difficulties were encountered that were, at first, attributed to the ac propulsion system. Further analysis generally showed that the propulsion system was not at fault or provided solutions in the form of system/component readjustments and operating procedure revisions.

Some of the areas of concern related to system performance were the result of a careful and conservative approach toward achieving program success for this critical initial demonstration of modern ac propulsion equipment on a U.S. property. AiResearch, recognizing the importance to overall success of the STARS program of achieving a safe and successful introduction of this new equipment to the U.S. rail transit industry, set the equipment protection to a conservative level as a safeguard for the vehicle tests. This approach proved to be a good one. As the program progressed and the unique characteristics of the NYCTA operating environment and its influence on the ac propulsion system were more fully analyzed and understood, the system could be tuned to more fully demonstrate its potential, while maintaining safe operation.

A number of highly demanding program tasks resulted from NYCTA requirements outside the original scope of the STARS program, such as the prerequisite for a dead rail detector with ripple detection capability. The following topics, of particular concern to the NYCTA (NYCTA letter of November 30, 1987), are typical examples. Results of the AiResearch investigations and the methods of resolution are summarized.

(a) Intermittent Loss of Power--Loss of power was sometimes experienced due to intermittent contact in the train line circuits. The momentary loss of contact created a normal reaction in the ac equipment, which immediately recognized a fault and began to shut down.

An automatic reset system, described in principle to the NYCTA engineering department, is the potential solution. The automatic reset would compensate for these brief interruptions (in the milliseconds range) without compromising system operation.

(b) Intermittent Loss of Dynamic Braking--This occurrence also was associated with intermittent train line contact. The potential solution is the same as for item (a), an automatic reset system.

(c) Main Circuit Breaker (MCB) Trippings--Unwarranted MCB tripping occurred because the trip setting of the MCB was too low. The solution is to reset the MCB trip setting to a higher but safe level.

(d) Low Regeneration Level (and High Drive Energy Consumption)--This was caused by a number of circumstances, including:

(1) Inhibition of the regeneration system by the ripple detector (dead rail detector). The ripple detector was designed to cut out regeneration if the ripple signal drops below a predetermined level.

(2) Line voltage restrictions. Since regeneration is based on line receptivity, the ac car energy savings were not maximized due to limitations placed on regeneration voltage levels. The main concern was back-biasing of substation equipment.

(3) Energy consumption mismatch between the ac-powered and dc-powered cars because of load-weigh system differences. A calculation verified that the measured mismatch would cause higher drive energy consumption of the magnitude measured in revenue service. A true consist of ac-powered cars would have provided actual energy savings as predicted.

Investigation and analysis efforts related to these incidents were extensive and time-consuming, but provided additional assurance of system integrity.

Overall, the ac propulsion system performed with remarkable success. In over 1400 hr of ac car testing (approximately 20,000 mi of testing) there were no ac traction motor failures and only minor propulsion system component problems, which were not attributed to system design deficiencies. The few instances of component-related difficulties were traceable to unforeseen installation error (such as the inadequate grounding afforded through the R-44 car structure) and would be avoidable for future ac propulsion installations.

4.4.13 Life Cycle Cost Analysis Update

The following life cycle cost estimate for the STARS ac propulsion system is presented in the form of an updated summary of the detailed cost analysis originally submitted in AiResearch Report 83-20305, dated November 15, 1983.

The summary presents costs on a present-worth-per-car basis over a 30-year life cycle based on a 100-car fleet as operated by the NYCTA. In addition, the estimated life cycle cost for a dc propulsion system is presented for comparison.

The analysis method is in accordance with the methodology and data base in the Urban Mass Transportation Administration report referenced in para. 4.4.13.1, except that the base year is 1987 rather than 1982. The referenced technical paper by Karl W. Berger, while not employed directly in the analysis, was useful for confirmation.

4.4.13.1 Related Documents

The following documents were used as references:

(a) Inverter-controlled Ac Induction Motor Propulsion System Life Cycle Analysis--AiResearch Report 83-20305, dated November 15, 1983

(b) Costs and Benefits of Ac Propulsion, Final Report--UMTA Report UMTA-IT-06-0273-87-1, dated July 1987

(c) Costs and Benefits of Ac Inverter Propulsion--a technical paper presented by Karl W. Berger, P.E., at the 1987 APTA Rapid Transit Conference, Toronto, Canada, June 16, 1987

4.4.13.2 Updated Cost Summary

The updated cost summary estimate presented in Table 4.4.13-1 shows an overall life cycle cost savings attributable to the STARS ac propulsion

TABLE 4.4.13-1

UPDATED LIFE CYCLE COST SUMMARY

(100-Car Fleet in Operation, 30 Years, Present Worth)

Cost Item	Dc Propulsion, $1000	Ac Propulsion, $1000
Propulsion system price	225	225
Energy Costs		
No regeneration	263	236
100% regeneration	--	166
Maintenance	88	17
Cost of required spare cars	146	46
New technology introduction	--	2
Present worth per car:		
No regeneration	722	526
100% regeneration	--	456

system of about $266,000 per car year, a savings of 37 percent, assuming full use of regenerative braking and 100 percent line receptivity. Of this savings, 37 percent is related to the cost of spare cars, 36 percent to energy costs, and 27 percent to maintenance. For evaluation purposes, if no regenerative braking is used, the energy savings is reduced by $70,000, and the overall savings is reduced from 37 to 27 percent. Actual overall savings realized will be between 27 percent with no regeneration, and 37 percent with complete regeneration. The higher limit can be approached by a fully developed system properly mated to individual transit system characteristics.

The first costs of the dc and ac systems were considered equal, although a penalty was assessed the ac system to account for the introduction of new technology with probable initial adjustments required.

4.4.13.3 Discussion

4.4.13.3.1 Spare Car Costs

The higher reliability of the ac propulsion system is responsible for the largest segment of the total savings. Because of the increased availability of the cars due to the more reliable propulsion system, the number of spare cars required to allow for car removals from the fleet for propulsion-system-related causes is reduced from 16 to 5. The five-car figure is conservative compared to the recommendations in the Berger paper, which hypothesizes that two spare cars is a sufficient number.*

4.4.13.3.2 Maintenance Costs

The savings in maintenance costs results not only from less costly maintenance actions (fewer mean manhours to maintain (MMHTM) and less annual cost per car for replacement parts) but also from less frequently required maintenance, i.e., greater mean distance between maintenance (MDBM). This savings also reflects the higher reliability of the ac system.

A review of the Berger paper suggests that the 81 percent lower maintenance cost shown in Table 4.4.13-1 may be a conservative estimate. Berger claims potential maintenance costs that are 91 percent lower than the dc system costs and purports even this figure to be conservative when compared to the Helsinki Metro experience**.

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*UMTA-IT-06-0273-87-1, p. 19.
**Ibid, p. 11.

4.4.13.3.3 Energy Costs

The energy cost analysis does not assess the significant additional savings to be realized with regenerative braking under an energy rate structure that penalizes power consumption during peak electricity demand periods. Over 40 percent of NYCTA car operation is at the AW3 "crush" load condition**, much of which occurs during peak energy demand periods. The premium-priced, peak-demand energy costs will be substantially reduced by regenerative ac propulsion during rush-hour use, a time when the third rail is fully receptive to regeneration.

4.4.13.4 Derivation of Cost Factors

The estimated dc propulsion system costs are derived from the analysis of the existing NYCTA dc propulsion system contained in Attachment 1 of the referenced UMTA report. Those data are based on 1982 dollars. The only adjustment to those data necessary for this update is to update the labor costs to reflect an increase in loaded labor rate from $22 per hour in 1982 to $26 per hour in 1987. This labor rate is obtained verbally from the NYCTA and is confirmed by the Berger technical paper. The higher labor rate directly affects the cost of maintenance, a cost which then affects to a lesser degree the life cycle cost of spare cars. The propulsion system price and energy rates, however, are considered to have remained unchanged in terms of 1987 dollars.

The estimated ac propulsion system costs are those presented previously in the original life cycle cost analysis, AiResearch Report 83-20305, with the same adjustment for labor cost as described for the dc system in the foregoing paragraph. A small adjustment was made in the ac propulsion system purchase price from $220,000 to $225,000, a price that has been used consistently in more recent cost analyses and comparisons.

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*UMTA-IT-06-0273-87-1, Attachment 1 data base.

4.4.14 List of Phase II Reports

Table 4.4.14-1 provides a partial list of pertinent AiResearch documents associated with the Phase II hardware fabrication, car installation, and performance test activities, that were previously transmitted to DOT/UMTA. As discussed in this final report, additional written/verbal communications from DOT/UMTA, NYCTA, and others also were used for guidance during portions of the STARS program, and are referenced where applicable in the text. AiResearch Drawing 2008984 lists the STARS ac propulsion system drawings previously transmitted to DOT/UMTA.

The Phase II program originally was defined in the Overall Vehicle Performance Test Plan (OVPTP), AiResearch Document 83-20229, dated October 15, 1983, as discussed in Section 2. The OVPTP provided the outline for the system shakedown tests at Hornell and the property tests at Sea Beach, with appropriate adjustments made to the plan and reflected in individual test procedures to accommodate the program redirection from Pueblo TTC to New York.

As indicated in the OVPTP, the requirements for the ac propulsion system tests were derived from the following documents (listed in order of precedence):

(a) Specification for Inverter Controlled Induction Motor Propulsion System Operational Demonstration Cars, DTUM60-82-C-71144, Attachment B.

(b) General Vehicle Test Plan (GVTP) for Urban Rail Transit Cars, Report UMTA-MA-06-0025-75-14.

(c) Recommended Practice, Rail Transit Intra-System Electromagnetic Compatibility, Vols. I and II.

(d) MIL-STD-461, Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference.

TABLE 4.4.14-1

PHASE II PROGRAM DOCUMENTATION

AiResearch Document No.	Description	Date
84-21420	Progress Report, Ac Propulsion System STARS Program, for period of August to September 1984	Oct. 2, 1984
84-21420(2)	Progress Report, Ac Propulsion System STARS Program, for period of November to December 1984	Jan. 23, 1985
84-21420(3)	Progress Report, Ac Propulsion System STARS Program, for period of September to October 1985--including Attachment A, Statement of Work, STARS Program ac Propulsion System Installation and Checkout	Nov. 18, 1985
84-21420(4)	Progress Report, Ac Propulsion System STARS Program, for period of October to November 1986	Dec. 12, 1986
85-21963	STARS Ac Propulsion Program Review	Apr. 2, 1985
2008984	Drawing Tree, STARS Ac (R-44 Car)	Nov. 15, 1985
85-22667	STARS Ac Drive Test Plan at NYCTA	Nov. 19, 1985
86-60168	STARS Acceleration Test Procedure	Apr. 30, 1986
86-60110, Rev. 1	STARS Ac-Drive Drift Test Procedure	July 3, 1986
86-60133, Rev. 1	STARS Ac Drive Deceleration (Air Brake Only) Test Procedure	July 22, 1986
86-60158, Rev. 1	Deceleration Test using Regeneration Dynamic Braking, STARS Ac Drive Test Procedure	July 22, 1986
86-60154	Non-Regenerative Dynamic Deceleration Braking Test, STARS Ac Drive Test Procedure	Apr. 29, 1986
86-60134	STARS Ac Drive Deceleration, Emergency Brake Test Procedure	Mar. 27, 1986
86-60203	STARS Ac Drive Test Procedure, Wheel Slip Acceleration/Deceleration Test	May 30, 1986
86-60202, Rev. 1	STARS ac Drive Test Procedure GG Line Energy Consumption Test	Jan. 29, 1987
86-60222	Stress Analysis for STARS Ac Drive System	June 11, 1986

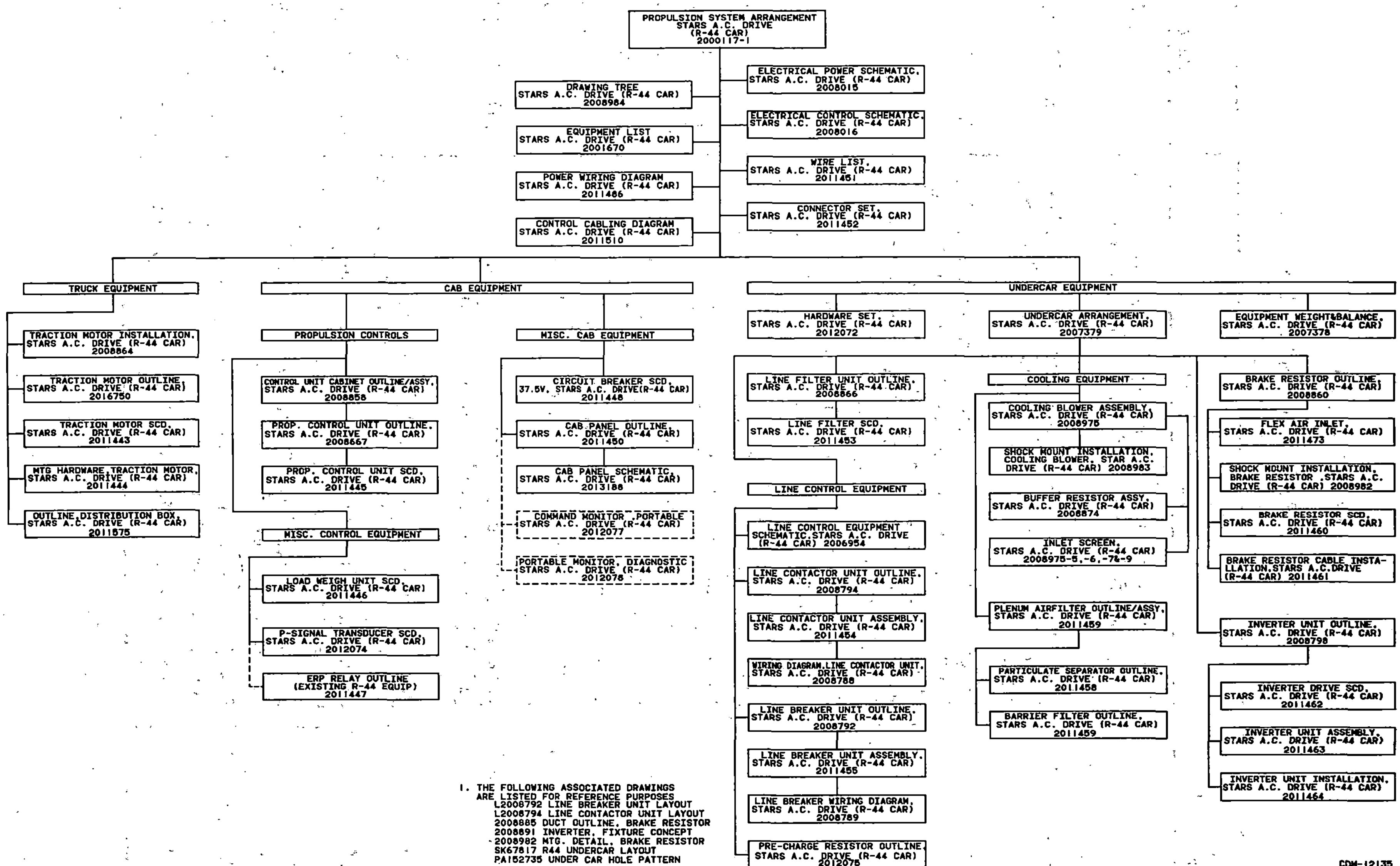

FIGURE 4.4.14-1. DRAWING TREE FOR STARS AC PROPULSION SYSTEM

5. PROGRAM CONCLUSIONS AND RECOMMENDATIONS

The DOT/UMTA-sponsored STARS program to demonstrate ac induction motor propulsion for the rail transit industry was an unqualified success. The major program achievement, the demonstration that existing ac technology could be suitably adapted to an existing U.S. transit system, provides incentive to further expand the implementation of ac propulsion equipment by specifying ac equipment in future transit system procurements. In addition, as the rail transit industry seeks to upgrade its equipment and reduce cost of operation while reducing maintenance costs, retrofit with ac propulsion now offers a valid alternate solution to that of upgrading the existing dc propulsion equipment.

5.1 CONCLUSIONS

The STARS ac propulsion system performance shows that significant improvements are obtainable by ac propulsion retrofitting. Addressing U.S. rail industry concerns about increasing operating and maintenance costs and unsatisfactory experiences with prior introduction of unproven equipment, the AiResearch/Stromberg team provided a system that was based on revenue-service-proven hardware (primarily that of Helsinki Metro) suitably adapted for use in U.S. transit properties. The projected energy consumption and life-cycle costs are significantly lower than for dc, and the reliability record of the ac equipment is better than that of dc propulsion. An ac propulsion system uses the existing 600-vdc third-rail power, is interchangeable with present dc propulsion equipment, requires minimum revision to current operating practices, and would be easily integrated into ongoing vehicle overhaul programs.

Even though the STARS ac propulsion system equipment was not initially intended for operation in the severe New York environment and does not incorporate the most recent technology, it demonstrated a remarkably trouble-free operating record and clear benefits. Most of the problems encountered in the two-year test period were overcome through extensive testing and development effort; those related to hardware would be eliminated with today's technology and increased knowledge of the New York system.

5.2 RECOMMENDATIONS

The prototype ac propulsion system, based on mature, proven technology to minimize development risk when the program was proposed in August of 1980, provided ample proof of the ac propulsion system advantages. Newer technology now can provide even greater benefits.

The inverter-controlled ac induction motor propulsion system program successfully demonstrated the projected performance improvements and operating and maintenance cost reductions that can be realized by changing from dc to ac propulsion, and did so on schedule, in a demanding, real-life environment. The decision to base the prototype system on service-proven hardware rather than attempting to develop all-new, state-of-the-art equipment with more potential for development problems to resolve no doubt contributed to this success.

Since 1980, however, newer, more efficient technology, especially in the area of power electronics and controls, has been developed and proven and is available for new designs. AiResearch recommendations for a future production version of this ac propulsion system would include the following equipment upgrades:

(a) Gate turn-off (GTO) thyristor power control devices

(b) Fully digital microprocessor-based propulsion control with built-in test

(c) Heat pipe cooling for power control equipment

(d) Modularized construction

The use of GTO thyristors rather than the older conventional thyristor circuits and the use of fully digital microprocessor-based controls offer dramatically reduced parts count, and therefore increased reliability. The induction motor reliability is already so high that little improvement is expected with motor improvements. Table 5-1 compares the Helsinki Metro component reliabilities with the predicted improvements possible with these technology improvements.

TABLE 5-1

COMPARISON OF COMPONENT RELIABILITIES

Component	MDBF, miles*	
	Helsinki Metro	Future
Control unit	120,000	150,000
Inverter	410,000	500,000
Motors (4)	5,500,000	5,500,000
Total system	91,000	113,000

5.2.1 GTO Thyristors

Still a new development when the ac propulsion system program began, but now fully proven, the GTO thyristor combines, within a single unit, the current switching capabilities of the more complex multi-component conventional thyristor switching circuit used in the inverter.

The conventional thyristor turns on in response to a triggering signal, but requires an auxiliary commutating thyristor/capacitor circuit (with associated capacitor charging delay) to turn it off. GTO's turn off rapidly in response to a triggering signal, just like they are turned on, with no additional circuitry required. The benefits are:

(a) Reduced cost, volume, and weight

(b) Fewer parts, greater reliability

(c) Reduced switching losses

(d) Faster available switching response

The increase in available switching speed enables faster control loop response and allows the pulse-width modulation mode to more nearly generate a sinusoidal output. Motor losses are reduced and the application of torque is smoother.

5.2.2 Fully Digital Microprocessor Control

Digital microprocessors are now available with greatly increased capabilities and speed.

The new microprocessors can perform the functions that previously required many more components and offer built-in diagnostics and automatic malfunction indication to greatly simplify troubleshooting. At the same time, reliability is improved and cost reduced. Some of the benefits are:

(a) Extensive built-in test is practical, which simplifies troubleshooting, shortens turnaround time, and reduces cost of maintenance.

(b) Parts count is dramatically reduced, thus reducing cost, space requirements, and logistics burden while improving reliability.

(c) Control parameters are easy to modify through software (rather than hardware), which reduces development cost and widens product applicability.

5.2.3 Heat Pipe Cooling

Heat pipe cooling is an efficient method of cooling semiconductors that avoids the necessity for having cooling air (carrying potential contaminants) come into contact with any electrically live components.

Figure 5-1 shows a typical heat pipe. A hollow copper evaporator is joined to a finned copper tube (condenser) by a hollow electrically insulating section. A small amount of liquid Freon is introduced before sealing the heat pipe. The fins on the condenser increase thermal efficiency, and the pipe is slightly inclined to make the evaporator the lowest point. The evaporator is clamped to the device to be cooled. Heat is conducted through the copper evaporator into the liquid Freon, which boils. The gaseous Freon rises up the tube until it condenses and gives up its heat before flowing back to the evaporator as liquid Freon again. Air may be blown over the condenser fins to

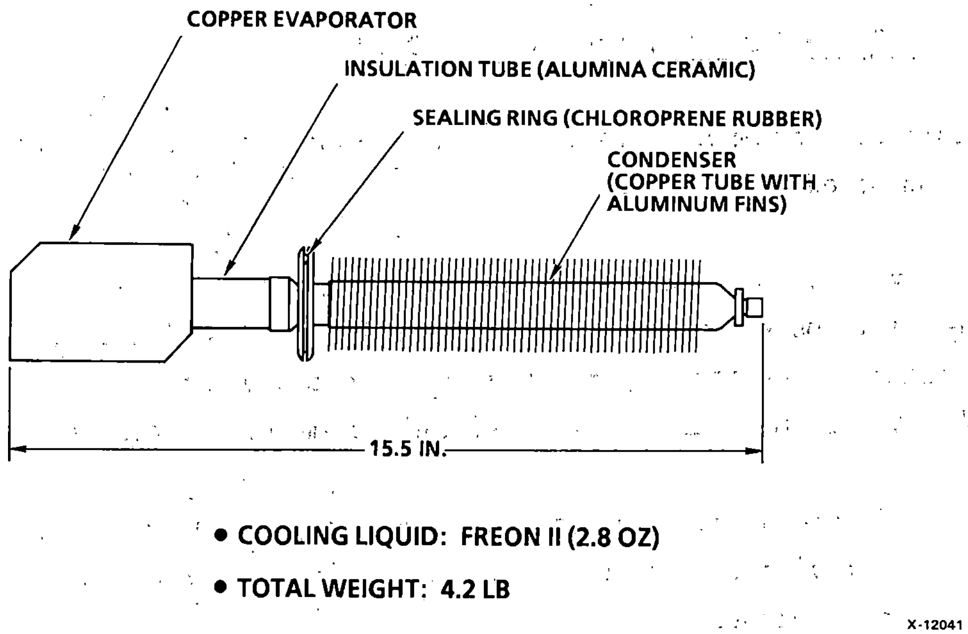

FIGURE 5-1. HEAT PIPE CONSTRUCTION

increase cooling effectiveness without requiring airflow over the electrical device to be cooled.

Figure 5-2 shows a practical heat pipe inverter cooling package. Two semiconductors are double-side cooled using three heat pipes. All three condensers are located in a cooling air channel that runs through the center of the inverter box, isolating them from the electronics. Cooling air is blown down this channel.

All semiconductors and gating components are readily accessible through the front access door, and filter capacitors are located on the opposite side of the air channel. No air is blown over any component other than the heat pipe condensers (which are electrically neutral), so there are no dirt buildup "tracking" problems. Cooling fins can be cleaned by blowing compressed air through the cooling channel with a hose.

5.2.4 Modular Construction

The use of GTO phase modules in the inverter offers the advantage of ease of testing and servicing, which reduces maintenance time.

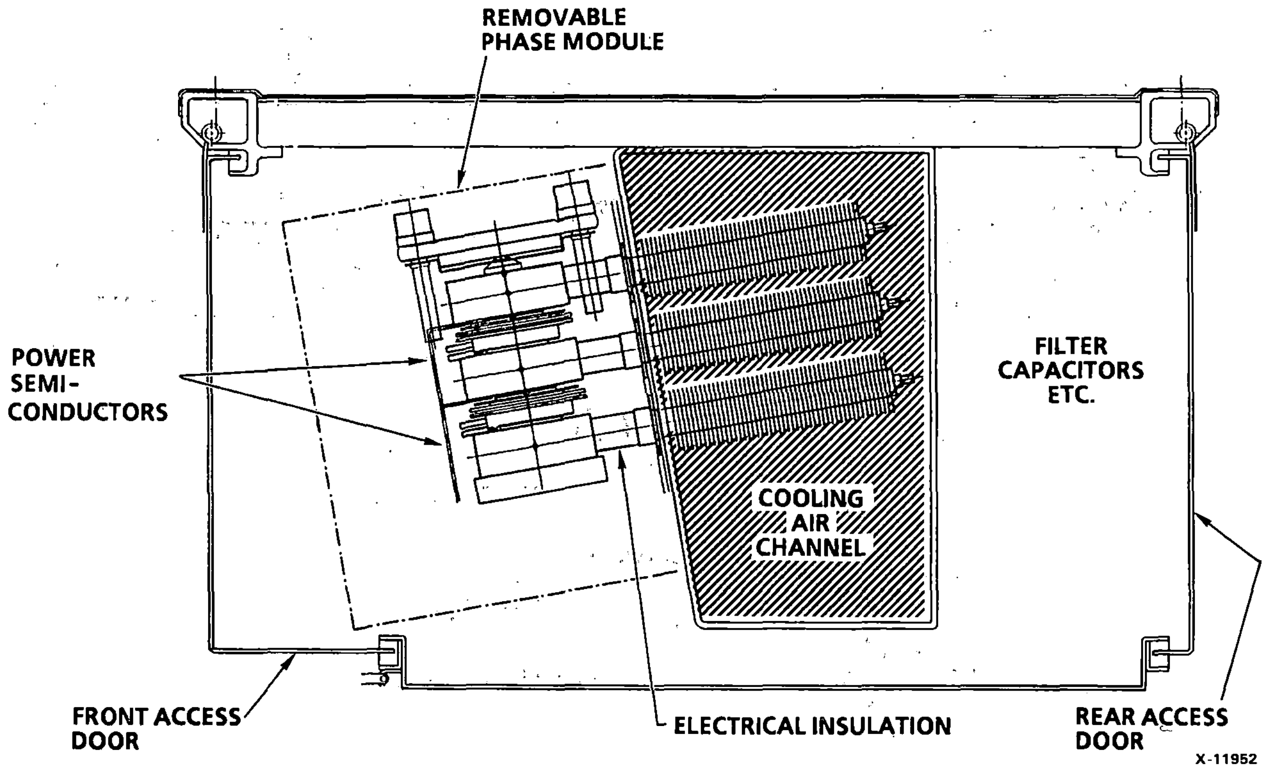

FIGURE 5-2. HEAT PIPE INVERTER PACKAGE

The modularized construction approach is demonstrated in Figure 5-3. By opening the front access door and loosening four bolts, a GTO phase module can be completely removed and replaced in minutes. Control and power connections are by plug and socket. A gasket between the module and cooling channel provides an airtight seal between the cooling air channel and electronics section.

Figure 5-4 shows a production GTO phase module which contains two GTO's for one phase, complete with three heat pipes and all gating components. Three such modules are required for an inverter.

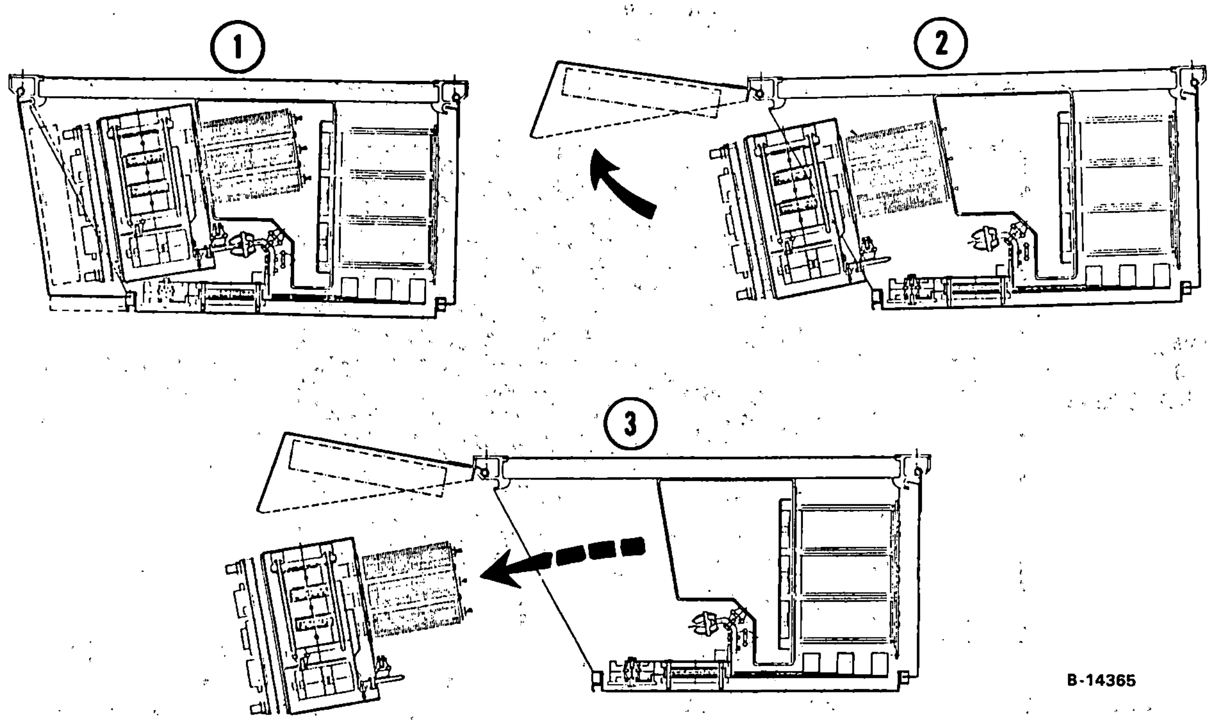

FIGURE 5-3. REMOVAL OF A GTO PHASE MODULE

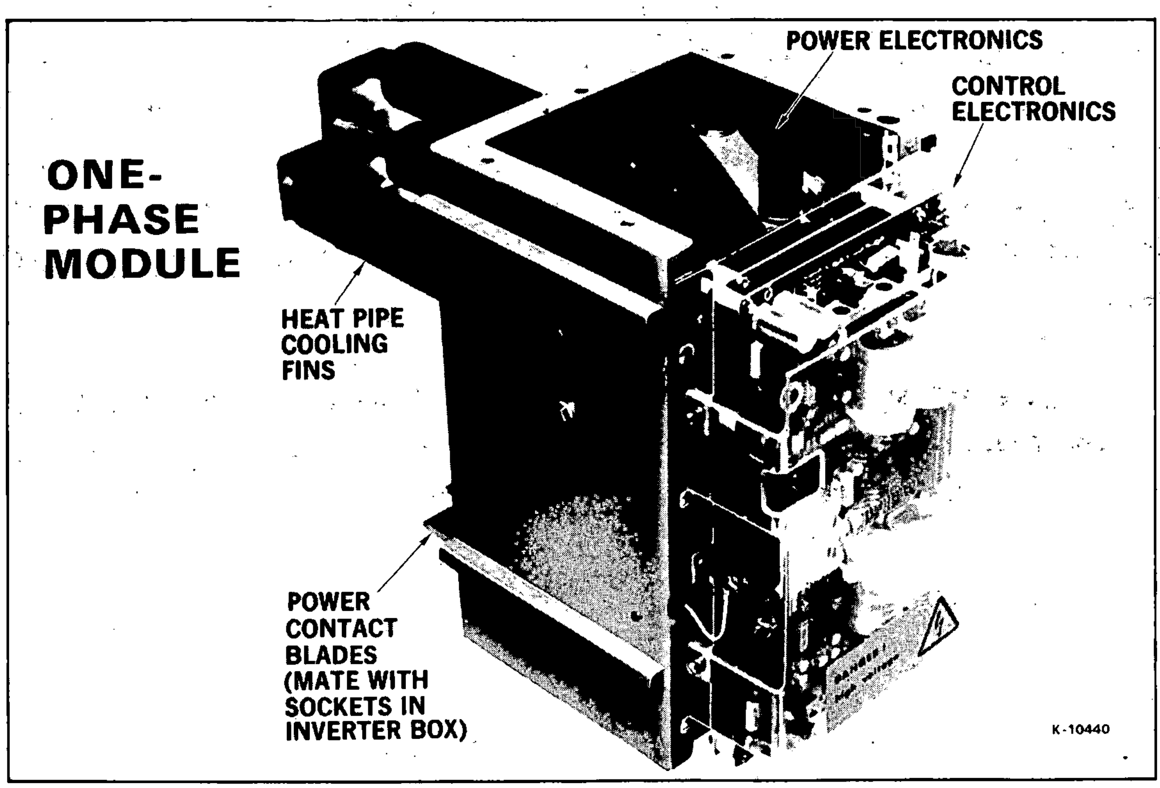

FIGURE 5-4. PRODUCTION GTO PHASE MODULE

F-55162