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STARS AC Propulsion Project

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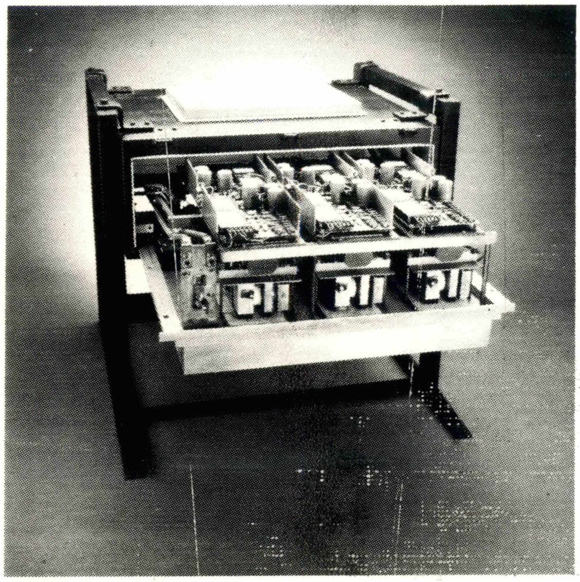
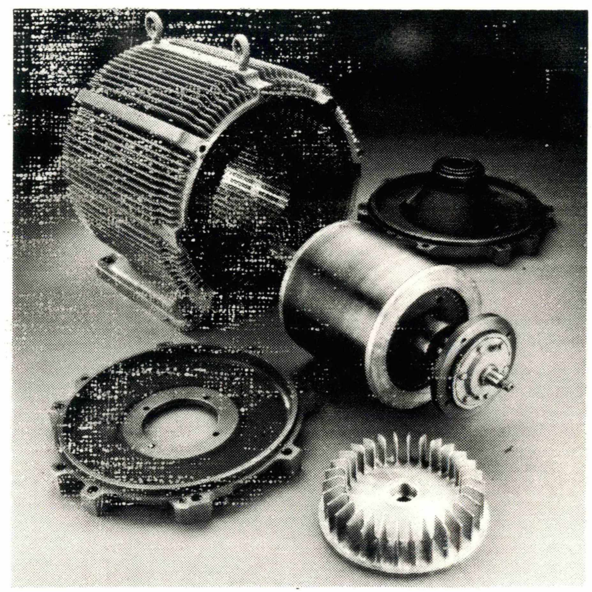
August 1985





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16. Abstract

This report describes the design, manufacture and testing of a propulsion system for passenger rail application utilizing a variable-voltage, variable-frequency (VVVF) inverter and a squirrel cage induction motor, along with associated microprocessor control circuitry. Novel developments in this propulsion system include the use of gate turn-off thyristors (GTO's); advanced semiconductor cooling methods; and, multiple microprocessor, direct digital control.

The rationale behind this development includes several factors: reduced maintenance and improved reliability associated with brushless AC motors and solid state electronics; improved energy efficiency due to elimination of series resistors; and high regeneration capability, further reducing energy usage. A net reduction in life cycle cost is predicted due to these factors when compared with conventional cam-controlled, series resistance DC propulsion systems.

The report describes the six candidate systems studied, and explains the selection and design of the chosen system. Test data from a full scale laboratory model is included, along with studies of reliability, maintainability, safety, energy usage and life cycle cost.

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PREFACE

The Subsystem Technology Applications to Rail Systems (STARS) Program, sponsored by the United States Department of Transportation-Urban Mass Transportation Administration, is fulfilling technical needs of rail transit systems. These various needs, described to a U.S. DOT-UMTA and American Public Transit Association (APTA) team several years ago, were prioritized and became projects within UMTA's STARS Program. APTA advisors identified the AC Propulsion Project as the highest priority project within the STARS Program.

This report describes the design, manufacture and testing of a propulsion system for passenger rail application utilizing a variable-voltage, variable-frequency (VVVF) inverter and a squirrel cage induction motor, along with associated microprocessor control circuitry. The rationale behind this development includes several factors: reduced maintenance and improved reliability associated with brushless AC motors and solid state electronics; improved energy efficiency due to elimination of series resistors; and high regeneration capability, further reducing energy usage. A net reduction in life cycle cost is predicted due to these factors, as compared to conventional, cam-controlled, series resistance DC propulsion systems.

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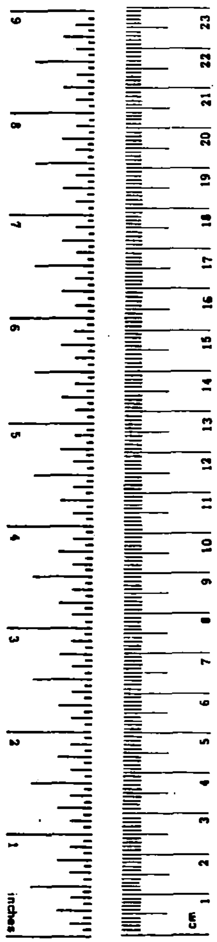
METRIC CONVERSION FACTORS

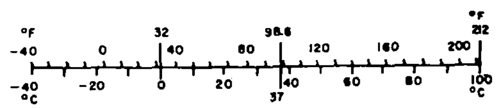
Approximate Conversions to Metric Measures

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



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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EXECUTIVE SUMMARY

The advantages of rugged, simple induction motors have long been known in industry. However, these motors require a more complex drive than their direct current counterparts, in that the propulsion system must precisely control the frequency of the alternating current (measured in hertz) in addition to controlling current (amperes) or voltage (volts).

Recent developments in technology have made it possible to develop a variable voltage, variable frequency (VVVF) inverter drive that is compact and rugged enough to be applied in transit applications. Specifically, two recent developments have made this AC propulsion concept possible. These are the GTO, or gate turn-off thyristor, and the second generation, 16 bit microprocessor.

Just as the development of high powered conventional thyristors years ago made solid state chopper propulsion possible, the GTO makes possible a compact, lightweight VVVF inverter. It does this by virtue of being able to switch large currents much more quickly and efficiently, and without the heavy, costly commutation circuitry required by a conventional thyristor.

The second generation of microprocessors has been on the market for several years, and the 16 bit single chip computers that comprise this new generation offer a quantum leap in the computing power that can now fit on a single printed circuit board. These microprocessors offer computing speed and powerful instruction sets that allow the propulsion logic to solve thousands of complex equations every second. In the midst of performing the calculations necessary to maintain proper torque, the microprocessor control can also monitor the status of events throughout the vehicle, while continuing to fire the GTO's in the precise patterns needed to generate the VVVF waveform to the traction motor.

SYSTEM DESIGN REQUIREMENTS

The following system requirements were established jointly by UMTA and Westinghouse prior to the start of the design process:

- DEMONSTRATE THAT AC INDUCTION MOTORS CAN BE SUCCESSFULLY APPLIED IN TRANSIT SERVICE.
- DEMONSTRATE LIFE CYCLE COST BENEFITS vs. EXISTING PROPULSION SYSTEMS.
- DESIGN WITH FLEXIBILITY FOR A WIDE RANGE OF APPLICATIONS.
- DEVELOP COMPATIBILITY TO TRAINLINE WITH CAM CONTROLLED VEHICLES.
- DEMONSTRATE EMI COMPATIBILITY WITH SIGNALING SYSTEMS.
- ADDRESS PAST CONCERNS OF WHEEL MISMATCH AND COGGING.
- DEVELOP TO BE PRICE COMPETITIVE WITH CONVENTIONAL PROPULSION SYSTEMS.
- SOLID STATE CONSTRUCTION FOR ALL CIRCUITS BETWEEN LINE SWITCH AND TRACTION MOTOR.
- MAJOR REDUCTION IN CONTROL LOGIC HARDWARE COUNT AND MINIMAL ANALOG CIRCUITS FOR IMPROVED RELIABILITY.
- TOTALLY ENCLOSED MOTOR FOR IMPROVED RELIABILITY.
- NO SEPARATE BLOWERS FOR MOTORS OR PROPULSION.
- REDUCE WEIGHT vs. CHOPPER AND CAM PROPULSION SYSTEMS.
- MODULAR DESIGN WITH FLEXIBLE OPTIONS.

AC PROPULSION SYSTEM DESIGN DESCRIPTION

The system developed by Westinghouse is shown in block form in Figure ES-1. Components designed specifically for this project are:

- o A totally enclosed, non-ventilated traction motor which exceeds acceleration, deceleration and duty cycle requirements of the New York City Transit Authority (NYCTA) R-44 DC traction motor

- o A pulse width modulated (PWM) inverter based on gate turnoff thryristor (GTO) technology

- o A multi-microprocessor inverter control/car control logic package

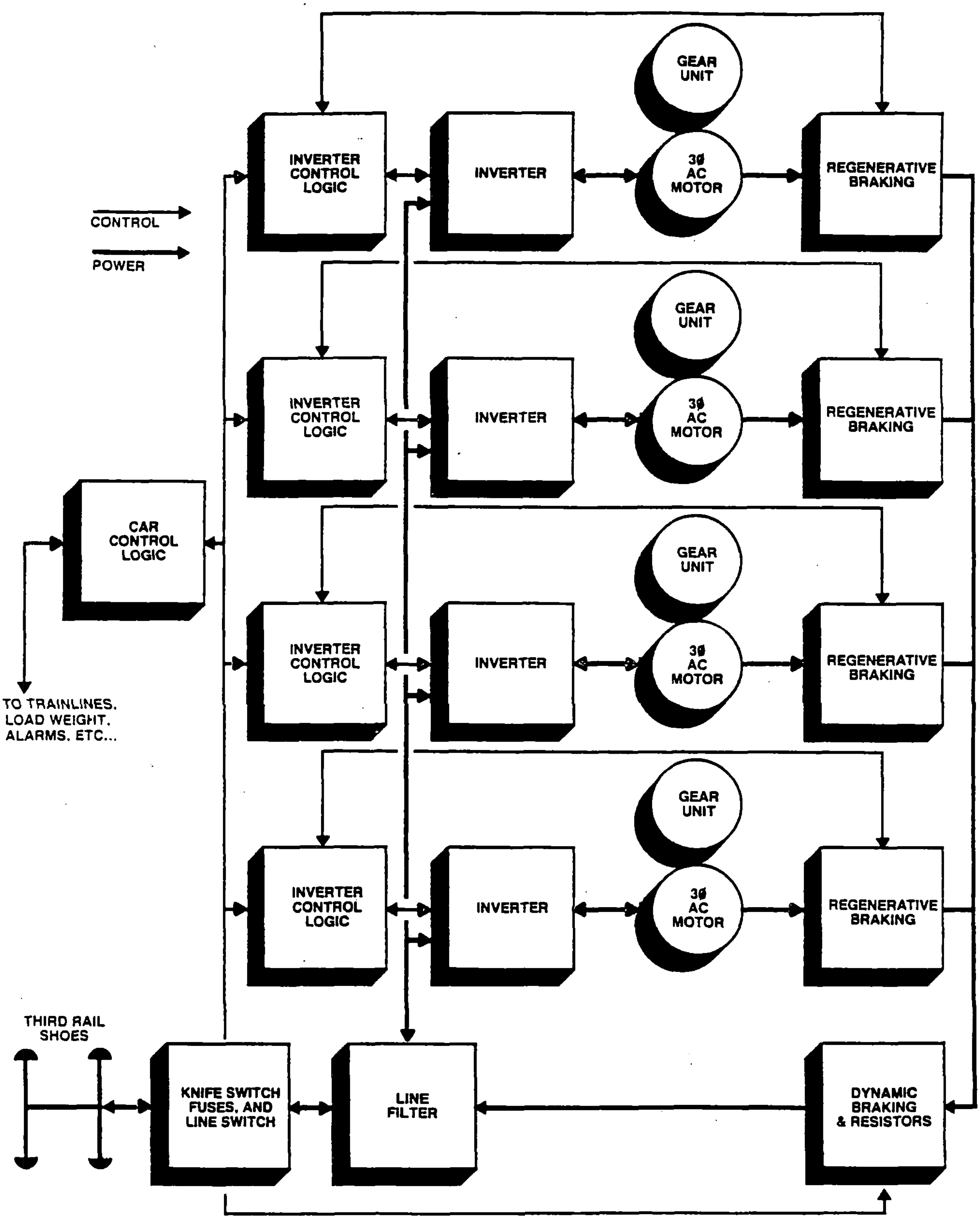
- o An input line filter to reduce EMI and smooth the input line current

- o A GTO-based dynamic brake control package

- o An optional GTO-based regenerative brake control package which supplements the regenerative current produced by the inverter

Many components, such as the line switch, line reactor and master controller, are similar or identical to conventional equipment.

The system configuration tested was based on a design in which one carset consisted of four AC traction motors, four inverters, dynamic brake capability, full regeneration capability, and microprocessor control logic. The actual laboratory test configuration was a half carset that consisted of two AC traction motors and two inverters, with dynamic and regenerative brake control circuits and microprocessor control logic. Line filter, line switch, operator's



System Block Diagram

FIGURE ES-1

controls, and other peripheral equipment were also included in the laboratory test, as were DC motors coupled to the AC traction motors to serve as a load during acceleration and provide power during braking. These DC motors were connected to a computer controlled simulator to allow them to emulate the actual torque of an NYCTA R-44 car under various conditions of service.

PROJECT RESULTS

Approximately 18 months of full-scale system testing was completed in the Transportation Division's power laboratory and in an older facility in the Westinghouse East Pittsburgh Works.

Both the traction motors and the power circuits were extensively outfitted with thermocouples to verify operation within allowable temperatures, and the system was connected to a state-of-the-art computer-controlled load simulator. The system was exercised over a profile equivalent to duty on the NYCTA RR Line. Actual energy usage was computed by the car control logic during these runs, based on varying line receptivity assumptions, and this data was an input to the Cost and Economic Analysis (Section 11).

In addition, the system was exercised over a more severe profile which incorporates high speed operation not seen in RR Line duty. System performance complied with or exceeded all AC Propulsion Project requirements.

Extensive measures were also taken to verify control system operation and stability, including the construction and testing of a large flywheel which was used to simulate the actual inertia of a vehicle. All of these tests demonstrated satisfactory operation of the AC propulsion system.

RELIABILITY, MAINTAINABILITY AND SAFETY STUDIES

Reliability, maintainability and safety of the AC propulsion system were analyzed in depth as a part of the design process. System reliability projections (Section 8) are an input to the Cost and Economic Analysis (Section 11). In addition, the reliability efforts indicated the potential advantage of a two inverter per car system. Maintainability studies (Section 9) confirmed the advantages of the modular design approach with associated ease of replacement of failed assemblies. Safety studies (Section 10) revealed no major hazards, as individual components of the AC system are similar to those now in use in conventional DC chopper propulsion systems.

The elimination of as many electro-mechanical devices as possible was in keeping with the overall program goals of reduced maintenance and improved reliability. The system developed allows for true four quadrant control; that is, transition between all four modes of operation (forward propulsion, forward braking, reverse propulsion and reverse braking) is possible without the need to transfer any mechanical contacts. Contactors for field shunting, reversing, and power/brake are all eliminated along with all of the series resistor contacts required by cam control. The only electro-mechanical devices in the AC propulsion system are the line switches (LS1 & LS2, shown in Figure 3-2). For comparison, in the NYCTA R-44 cam propulsion equipment there are 14 contacts on the power cam controller (PCC), 10 contacts on the brake cam controller (BKCC), 4 contacts on the series-parallel contactor (SPC), 6 contacts on the power/brake contactor (PBC), an S1 contactor, an S2 contactor, a J contactor, 6 field shunt contactors (F1 through F6) and a reverser with 4 contacts for a total of 47 contacts.

DC motors for traction applications have an open, or drip proof, frame so that cooling air passes over the internal parts. This is mainly due to temperature rise restrictions on the commutator and brush gear. The AC induction motor, which has neither brushes nor commutator, does not have this problem, so an environmentally-superior totally enclosed motor was developed, with the internal parts and insulation isolated from the traction environment.

LIFE CYCLE COSTS

Life cycle cost investigations were performed on the entire system, with the cam-controlled NYCTA R-44 car as the vehicle for comparison. As expected, savings in the areas of maintenance and energy are substantial, and help to offset the somewhat higher initial cost of the AC propulsion system. The 30 year life cycle cost analysis estimates that the savings in energy and maintenance will result in a 30 year life cycle cost per propulsion system as shown below (see Section 11, Figure 11-11 for details):

o Present R-44 cam control propulsion	$561,872
o AC propulsion system with four inverters/car	491,524
o AC propulsion system with two inverters/car	475,019

Projected savings in energy and maintenance would pay back the added initial capital cost of the AC propulsion system in approximately four to five years.

This analysis is based on a comparison of equal fleet sizes. In reality, the improved reliability and availability of AC propulsion could justify the purchase of a smaller fleet to support the same peak hour demands. In this case, the savings are immediate, because of the lesser capital cost of a smaller fleet.

SYSTEM CONTROLS

Conventional approaches to controlling VVVF inverters involve substantial amounts of analog circuitry (operational amplifiers, etc.), which are more sensitive to electrical noise and temperature variations than digital circuitry and require calibration on occasion. Additionally, analog circuits must be "hard wired"; that is, a number of integrated circuits and discrete components are permanently wired into a circuit that performs a single function. Since a large number of functions must be implemented in the control, literally hundreds of analog IC's and discrete components are needed. The flexibility of digital circuitry allows the same small number of IC chips to perform dozens of different functions, all under the control of software. The result is a very substantial savings in the total number of control logic components.

Since an inverter does not feed the AC motor with a pure sine wave, low frequency harmonics are present in the output waveform, and cogging (torque pulsations) can be a problem. This is a particular problem with a current source type of inverter. The PWM type of inverter (described later in this summary) permits synthesis of voltage waveforms with suppression of the low frequency harmonics which are the cause of the undesired torque pulsations, or cogging.

Past efforts in AC propulsion development have encountered problems wherein the asynchronous nature of AC motors caused uneven load sharing among the various axles unless extremely tight tolerances were maintained on wheel diameter. The single motor per inverter approach used by Westinghouse eliminates all wheel mismatch problems.

APPLICABILITY TO OTHER SYSTEMS

The basic system design meets the varied needs of a number of transit properties. Requirements such as 80 mph operation and high regeneration capability were included in the design. The modular approach employed is ideally suited to application on many different systems. Options for level of regenerative braking capability, type of motor frame (totally enclosed or drip proof), and other choices make the system easily adaptable to heavy rail, light rail or trolley bus systems.

ELECTRO-MAGNETIC INTERFERENCE (EMI)

Electro-magnetic interference (EMI) is of concern in the development of an AC propulsion system, since an inverter sweeps through a broad range of frequencies. DC chopper propulsion, which can operate at a single frequency, can be designed to avoid critical track signalling frequencies. For this reason, the design efforts included a detailed EMI study, including extensive laboratory testing and measurements. These efforts were run in conjunction with the EMI Technical Working Group, an industry working group sponsored by UMTA and managed by the Transportation Systems Center in Cambridge, MA.

Based on data obtained on the susceptability of existing power frequency track circuits, audio frequency track circuits and extensive design iterations performed by computer simulation, the electro-magnetic emissions from the propulsion system were minimized. Specifically, EMI compatibility was assured by design of the input filters and by appropriate selection of pulse width modulation strategies and frequencies in the proprietary inverter control software. The results of this EMI compatibility design effort were verified by full scale laboratory testing using recommended test procedures developed by the EMI Technical Working Group.

Results of the testing indicate a safe margin for EMI on the power frequency track circuits in use at NYCTA, the primary subject of the investigation. All track circuits in use at NYCTA were catalogued and tested for sensitivity to interference at the signalling frequency. The worst-case track circuits were then connected to the AC propulsion laboratory setup, and the spectral output of the AC propulsion system was fed into the track circuits with a variable gain amplifier so that the actual level at which interference occurs could be recorded. For the most sensitive track circuit tested (a 25 Hz, double rail direct relay receiver), the unoccupied margin was 5.2 dB and the occupied margin was 6.0 dB. Compatibility with audio frequency track circuits is assured through redesign of the line filter based on the specific audio frequencies of interest. This approach has been verified through computer simulation and actual laboratory measurements.

SYSTEM WEIGHT

The system is light in weight when compared with other systems on an equal performance basis. The system weights, on a per car basis, are as follows:

o Existing NYCTA R-44 cam propulsion	13,614 lbs.
o AC propulsion with drip proof motors and inverter-only configuration (includes basic regeneration capability)	12,524 lbs.
o AC propulsion with drip proof motors and partial regeneration configuration (regeneration capability of inverter-only configuration, plus additional electric braking via dynamic brake)	13,139 lbs.
o AC propulsion with drip proof motors and full regeneration circuits (regenerative braking can provide full service brake requirements)	16,549 lbs.

Note that the inverter-only configuration still provides regeneration, which is not available with the cam-controlled propulsion, yet it is 1,090 lbs. lighter than the cam-controlled R-44 car propulsion system.

Totally enclosed motors add 1,400 lbs. per car. This figure was not included in the above chart for comparison, since the present R-44 propulsion system uses drip proof motors.

DESIGN OF SYSTEM COMPONENTS

The individual components that comprise the AC propulsion system are described in more detail in the following sections. Only those components designed specifically for the AC propulsion system, as summarized earlier, are discussed.

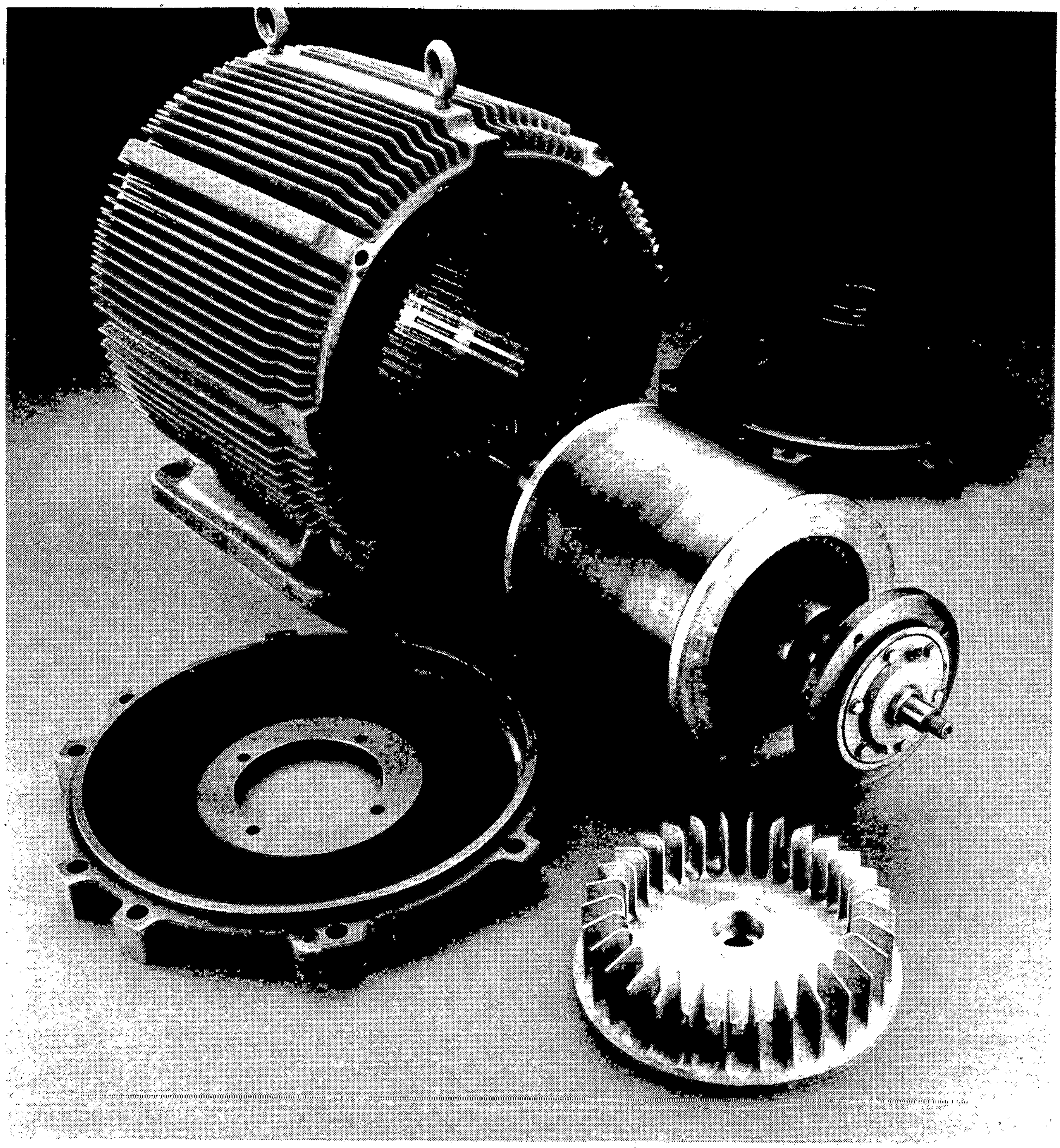
Traction Motor

There are several differences between the Westinghouse AC traction motor, shown in Figure ES-2, and a conventional three phase squirrel cage induction motor. Mechanical construction is in keeping with Westinghouse standards for DC traction motors. Class H insulation, rated for 190°C rise, form wound stator coils, and a speed range of 0 to 6,000 rpm are also superior to industrial motors. The rotor is cast aluminum. The motor is rated 125 HP continuous at 45 Hz base speed (1350 rpm) and 1.5 Hz slip.

A quiet shaft-mounted fan was designed for the traction motor. The fan is designed to circulate air over external fins on the motor frame, requiring no filters. A shroud and screen assembly protects the fan blades from debris.

A parallel design was completed for a drip proof version of the same motor. This option is available in applications where its reduced cost and weight plus cooler running may be seen as an advantage. The laboratory development and testing efforts have been based solely upon the totally enclosed design, however, since this represents the more challenging design from a thermal perspective, and also due to the strong APTA interest in this type of motor noted earlier.

Laboratory testing of the AC traction motors involved exercising them over NYCTA RR Line simulated duty and other, more demanding high speed profiles. The test motors were outfitted with numerous thermocouples throughout in order to verify operation at allowable temperatures. A precision on-line torque meter was used to measure the motor output and verify performance of the motor.



AC TRACTION MOTOR DISASSEMBLED

FIGURE ES-2

When exercised over the relatively low speed NYCTA RR Line profile, maximum temperature rise did not exceed 99.3°C. When run at its continuous rating of 125 HP, the maximum temperature rise did not exceed 159°C, still well within Class H insulation rating.

Inverter

The inverter functions as a variable voltage, variable frequency DC to AC conversion circuit, converting conventional DC power from catenary or third rail into AC power at the voltage and frequency necessary to drive the AC traction motor at the speed and torque selected.

A. Candidate Approaches Studied:

Six candidate approaches to inverter design were studied. Conventional two stage inverters, both current- and voltage-fed, involve a chopper in front of the inverter to regulate either current or voltage and to protect the inverter from line voltage disturbances. In these two approaches, the inverter regulates only frequency. Pulse width modulation, or PWM, is a technique by which both voltage and frequency are controlled in a single stage inverter. This is the third basic approach studied. Each of these three approaches was evaluated using both conventional thyristors and gate turn-off thyristors (GTO's).

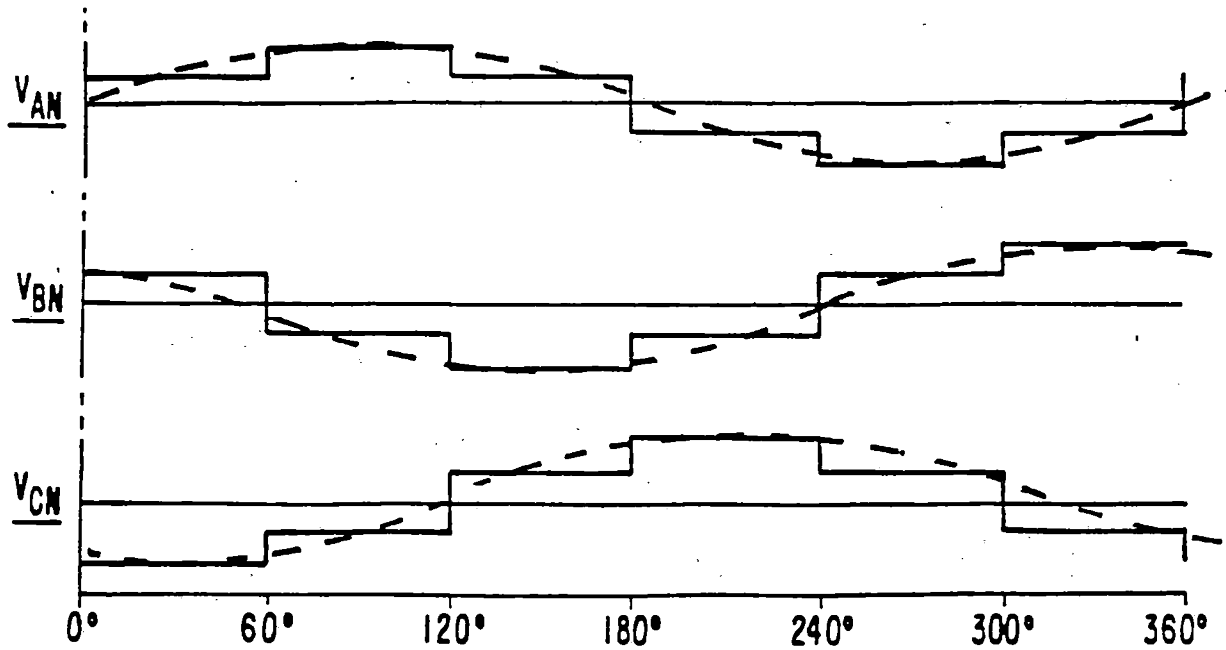
GTO's resemble conventional thyristors in that they are a solid state switch capable of rapidly turning large currents on and off. However, a GTO is turned off by a control pulse, just as it is turned on. A conventional thyristor requires a second thyristor, a capacitor, and several other components to turn off, or commutate. These added components, called the commutation circuit, are not required with a GTO.

Comparing a complete GTO circuit with a complete conventional thyristor circuit (including commutation circuitry), the GTO circuit is smaller, lighter, more reliable and less costly than the equivalent conventional thyristor circuit. Additionally, it does not have to wait for a large commutation capacitor to recharge before a new turn-off command can be given. This makes it ideal for the PWM approach, which requires rapid switching capability to control voltage and protect against faults due to line disturbances.

B. Selection of PWM Inverter Using GTO Thyristors:

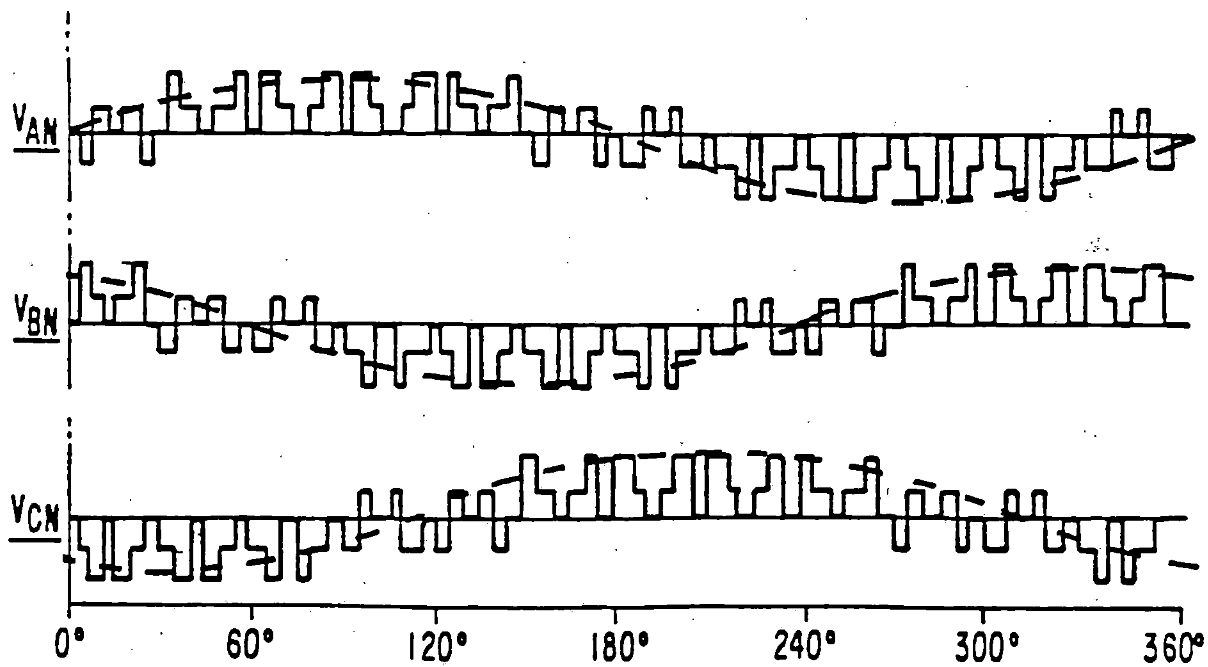
After substantial investigation and a preliminary design of all six candidate approaches, the PWM inverter using GTO thyristors was selected. An analysis was made based on the cost, size, weight and reliability of each approach. The GTO-based PWM inverter was determined to be superior in all of these criteria to the other five approaches. The elimination of the need for a front-end chopper and all thyristor commutating circuitry are the major reasons for this. This circuit is also the most electrically efficient of the six for the same reasons.

As noted above, a PWM inverter does not require a chopper on its input to control current or voltage. The PWM method instead controls voltage in the same stage as frequency. Essentially, the voltage waveform generated by a conventional inverter is a squared-off "six step" approximation of a sine wave to the induction motor (Figure ES-3, top). With the PWM technique, the inverter actually turns rapidly on and off during each half-cycle, producing a waveform with a reduced effective voltage (Figure ES-3, bottom). Note that the "effective" sinusoidal waveform is shown superimposed in dotted lines. This is how a PWM inverter regulates voltage at the same time as it controls the frequency - by switching a GTO "switch" on and off very rapidly and precisely, the "effective" voltage to the motor windings is controlled by the ratio of GTO on-time to GTO off-time. Note that this on/off controlling is done within each half-cycle of the AC waveform. It is here that the high speed and ease of control offered by a GTO makes the PWM inverter easier to implement.



I. 3 PHASE SIX-STEP WAVEFORM (EFFECTIVE SINE WAVE SHOWN SUPERIMPOSED)

V_{AN} = Voltage from 'A' phase to neutral, V_{BN} = 'B' phase - neutral, etc.



II. 3 PHASE PWM WAVEFORM (EFFECTIVE SINE WAVE SHOWN SUPERIMPOSED)

V_{AN} = Voltage from 'A' phase to neutral, V_{BN} = 'B' phase - neutral, etc.

FIGURE ES-3 SIX-STEP vs. PWM WAVEFORM

The PWM inverter has the added advantage of being able to control the harmonic content of its output waveform. This reduces motor heating and torque pulsations ("cogging") which are both due to undesired harmonics in the motor current. Smooth application of motor torque is possible at any motor speed.

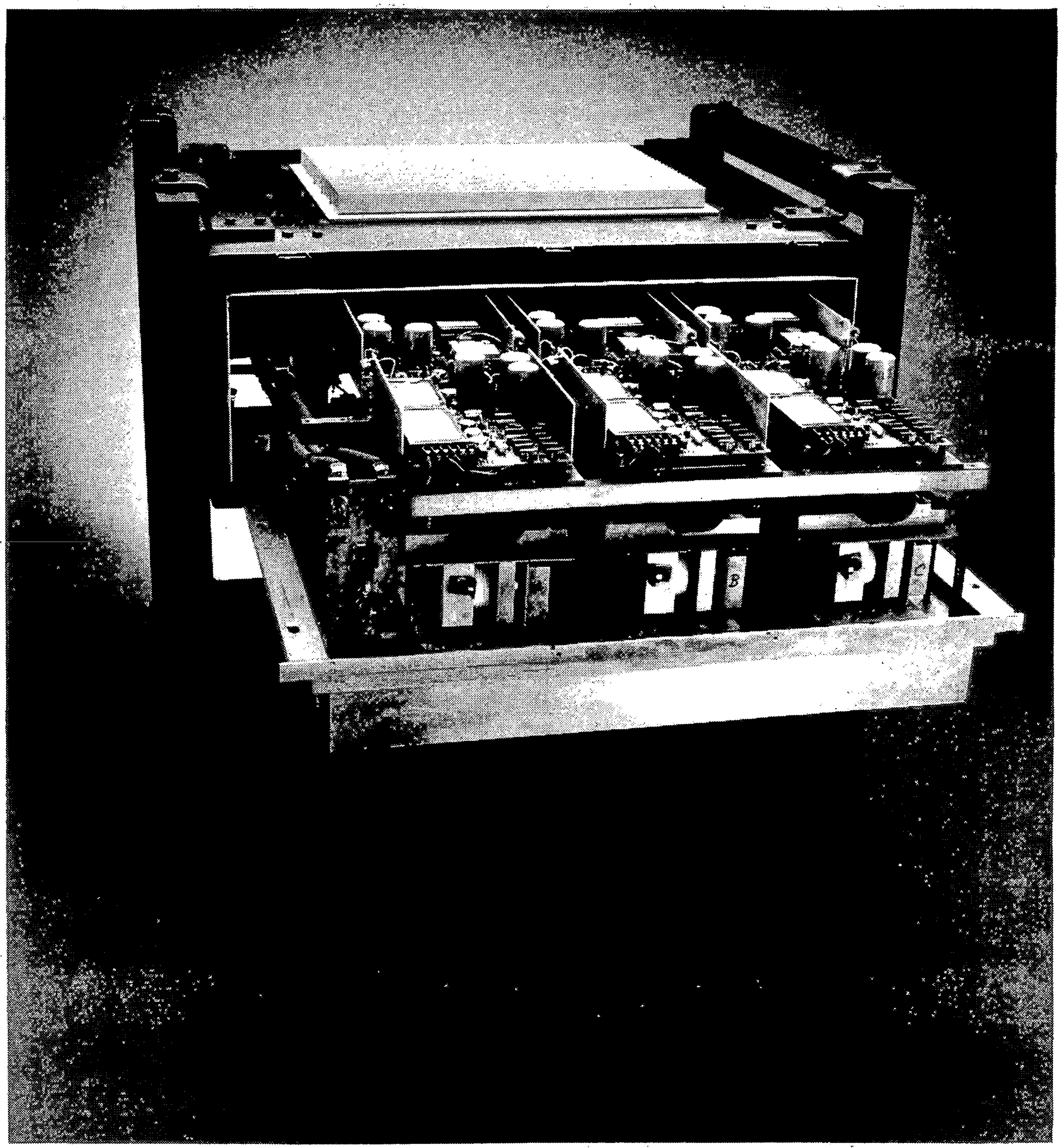
The inverter, shown in Figure ES-4, is designed for superior thermal performance and ease of maintenance. All components are mounted on a slide-out heat sink, and the entire assembly can be easily replaced as a unit. Power-dissipating devices (GTO's and associated snubber diodes) are mounted in a thermal module developed to eliminate the requirement for forced ventilation. The entire assembly is sealed and impervious to moisture and contamination. Teflon bearing surfaces for the slide-out heat sink are also excellent seals, particularly due to the fact that they do not lose their resiliency with age.

The inverter was instrumented with thermocouples during laboratory testing, and during worst-case conditions, all devices ran well within allowable temperature ratings.

Regenerative Braking Circuits

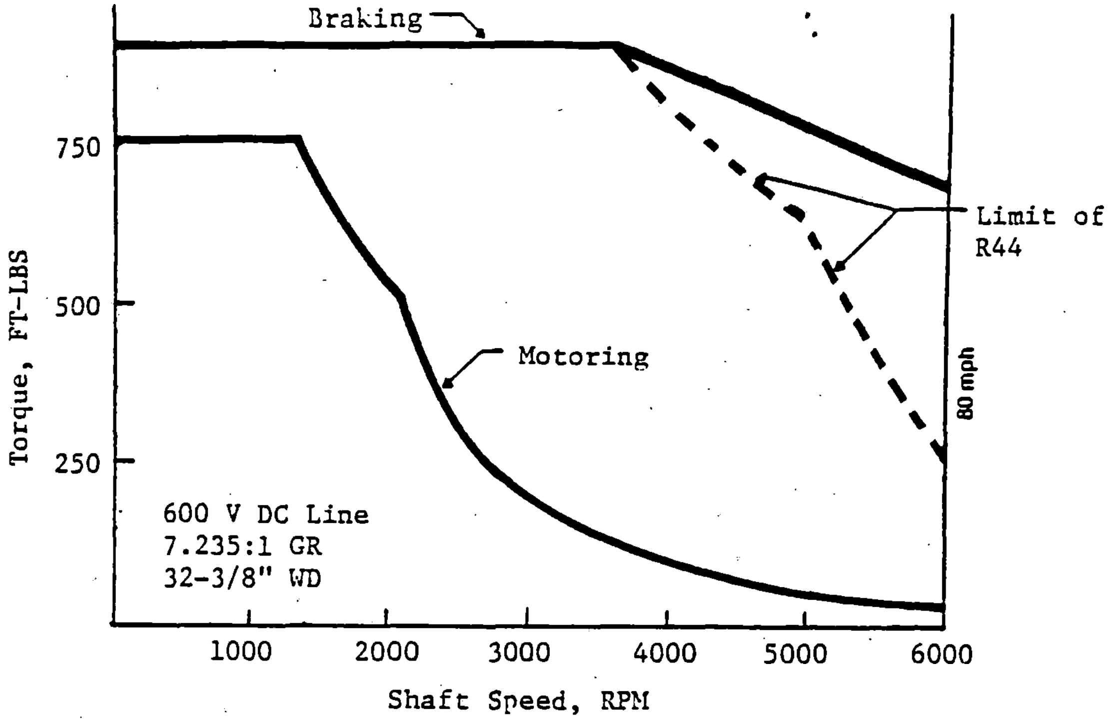
One of the design goals of the AC Propulsion Project was to supply rated R-44 service brake rate from 80 mph using no friction brake. This requires circuitry that can handle nearly four times as much power in braking as it consumes in acceleration, as shown graphically in Figure ES-5. The reason is that power is equal to torque times speed. In motoring, full torque is not available at higher speeds; in braking, however, full torque (deceleration) must be available at speeds up to 50 mph, and 77% of full torque is still required at the top speed of 80 mph. Since braking requires high torque at high speed, substantially more power is needed - in terms of both mechanical braking horsepower at the rail and kilowatts in the inverter circuit.

Rather than oversize the inverter to handle this intermittent requirement, Westinghouse designed separate circuits to handle the additional effort required in braking. This is in keeping with the goal of modular design, as

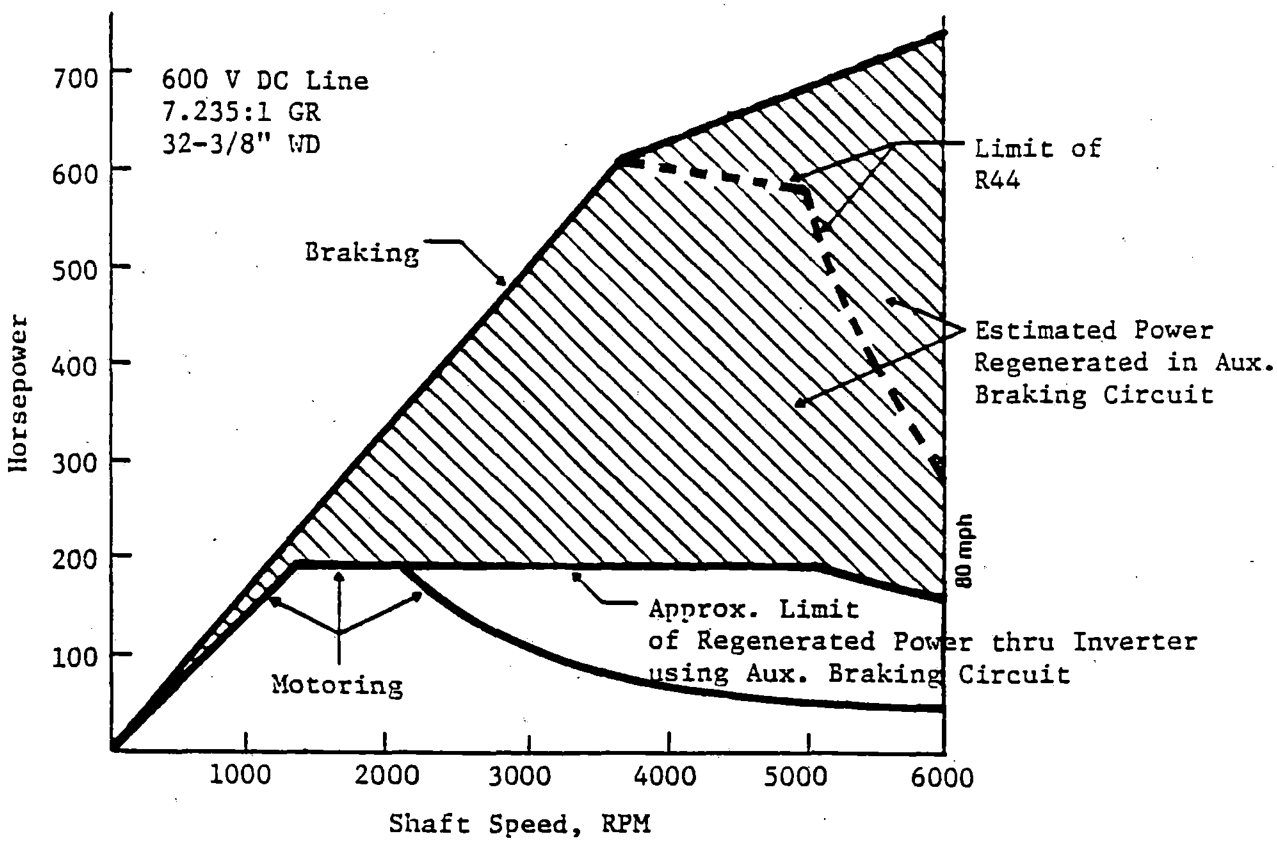


INVERTER WITH HEAT SINK ASSEMBLY IN SLIDE OUT POSITION

FIGURE ES-4



(a) Torque Per Motor Versus Speed



(b) Horsepower Per Motor Versus Speed

FIGURE ES-5 POWER REQUIREMENTS - MOTORING vs. BRAKING these separate circuits are in physically separate packages and can be easily eliminated for applications where they are not required.

Three different configurations are available with this concept, as described below. Packaging for all of these circuits follows guidelines established for the inverter - sealed construction, simple, modular removal and repair, and no requirement for forced cooling.

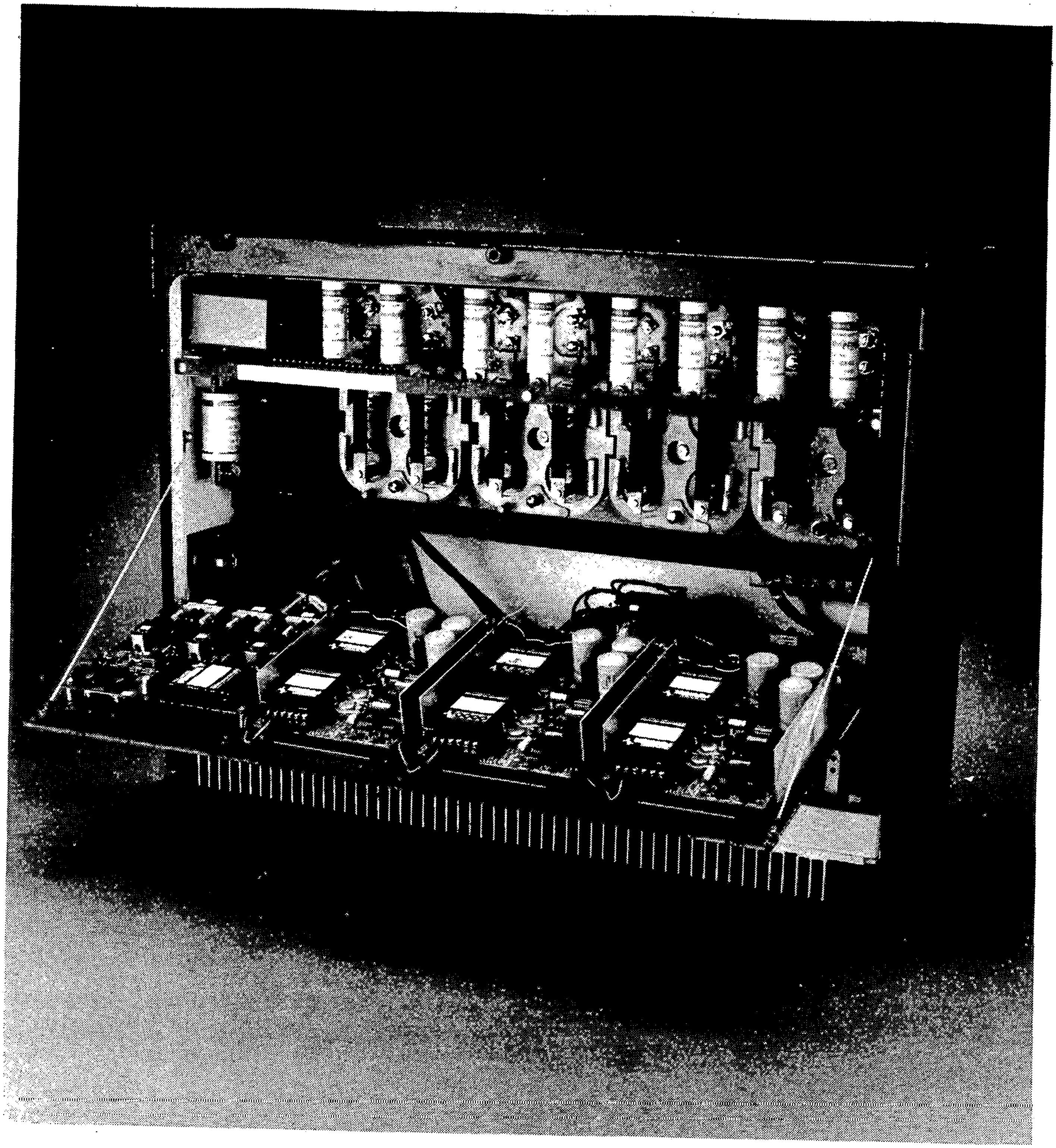
A. Basic Configuration - Inverter Only:

The inverter and AC traction motor can regenerate power with no added circuitry. However, for reasons noted above, the inverter alone cannot apply sufficient voltage to the motor to provide the needed torque at high speeds. This system is appropriate where high electrical braking rates at high speeds are not involved. This approach is sufficient for the speeds and duty seen on the NYCTA RR Line, and thus this is the configuration that is the basis for the Cost and Economic Analysis in Section 11.

B. Full Regeneration Configuration:

Because it is not limited by commutation voltage (which can cause flashover in a DC motor), an AC traction motor can be used for all service braking, eliminating friction brake use almost entirely. This creates the need for extra circuitry to handle the excess power and high voltage which result. The "full" regeneration scheme involves a previous Westinghouse patent to match the high voltage generated in braking to line voltage.† The power that the inverter cannot handle in regeneration is fed directly to the line through this separate circuit (see Figure ES-6), which employs a special transformer to reduce the high motor voltage that is developed.

† - Registered under US Patent No's. 3815002 (6/4/74) & 3991352 (11/9/76)



REGENERATIVE BRAKE UNIT WITH PC BOARDS IN FOLD OUT POSITION
FIGURE ES-6

This circuit provides capabilities beyond those required on the NYCTA RR Line duty cycle, and is not addressed in the Cost and Economic Analysis for this reason. This optional module was, however, built and tested along with the inverter/motor system in the Westinghouse power laboratory. In a sufficiently receptive system with high speed, high rate braking, a fleet of vehicles so equipped would provide substantial energy savings.

C. Partial Regeneration Configuration:

Concepts for a third option have been developed, but have not been tested in the Westinghouse power laboratory to date. This provides an intermediate solution to the first two configurations discussed. By means of resistors, the "excess" braking energy (i.e. that energy which is beyond the capability of the inverter-alone approach) is dissipated as heat.

This approach still provides for the regeneration of a large portion of available braking energy, and in fact can recover most of the energy available in low speed, high station density routes. At higher speeds, the system provides a blend of regenerative and dynamic braking. The service braking is still all-electric, and friction brake usage is nearly eliminated. This option is both lighter and lower in cost than the fully-regenerative system described above.

Dynamic Brake Circuit

In the case of all three of the previously-described configurations for regeneration capability, a dynamic brake circuit is also provided. This is needed when the line is non-receptive or partially receptive, and it functions to dissipate excess braking energy in resistors when necessary.

This circuit is basically a DC chopper, as it is located on the DC input side of the inverters, and it works simply by regulating line filter voltage and dumping excess energy into a conventional grid of braking resistors. However, the circuit is GTO-based, all solid-state, and utilizes sealed construction just as with the other power handling circuits.

Control Logic

Conventional approaches to control of an AC inverter involve substantial amounts of hardware, mostly analog circuitry such as operational amplifiers. Control approaches which do use a microprocessor typically employ the microprocessor only for simple supervisory functions. The actual generation of the complex AC waveform, and from this the commands to fire thyristors, are generally implemented in analog circuitry. Analog circuitry is highly susceptible to electrical noise and its output can vary significantly with variations in temperature; additionally, its components require calibration and occasional adjustment.

Second generation 16 bit microprocessors have arrived over the past few years which are an order of magnitude ahead of their 8 bit counterparts in computational power. As an example, a 16 bit microprocessor can perform multiplication with a single instruction, where the older 8 bit microprocessor performs the same operation via a lengthy series of repetitive additions. This power permits the microprocessor to simply synthesize the required AC waveforms, eliminating large amounts of hard-wired analog circuitry formerly dedicated to this purpose. Microprocessor control also allows for system modifications (acceleration, jerk limit, etc.) via software revision, as opposed to hardware changes.

The control system configuration consists of a single supervisory microcomputer per car, called the car control logic, which in turn directs four slave microcomputers called the inverter control logics.

A. Car Control Logic:

The car control logic interfaces with trainlines, operator's controls, alarms and indicators. The car control logic controls dynamic braking, friction brake blending, dead rail detection/reaction and line switch operation. It is also responsible for self test diagnostics and cam emulation -- in short, the car control logic controls everything except the operation of the individual inverters and full regeneration brake circuits.

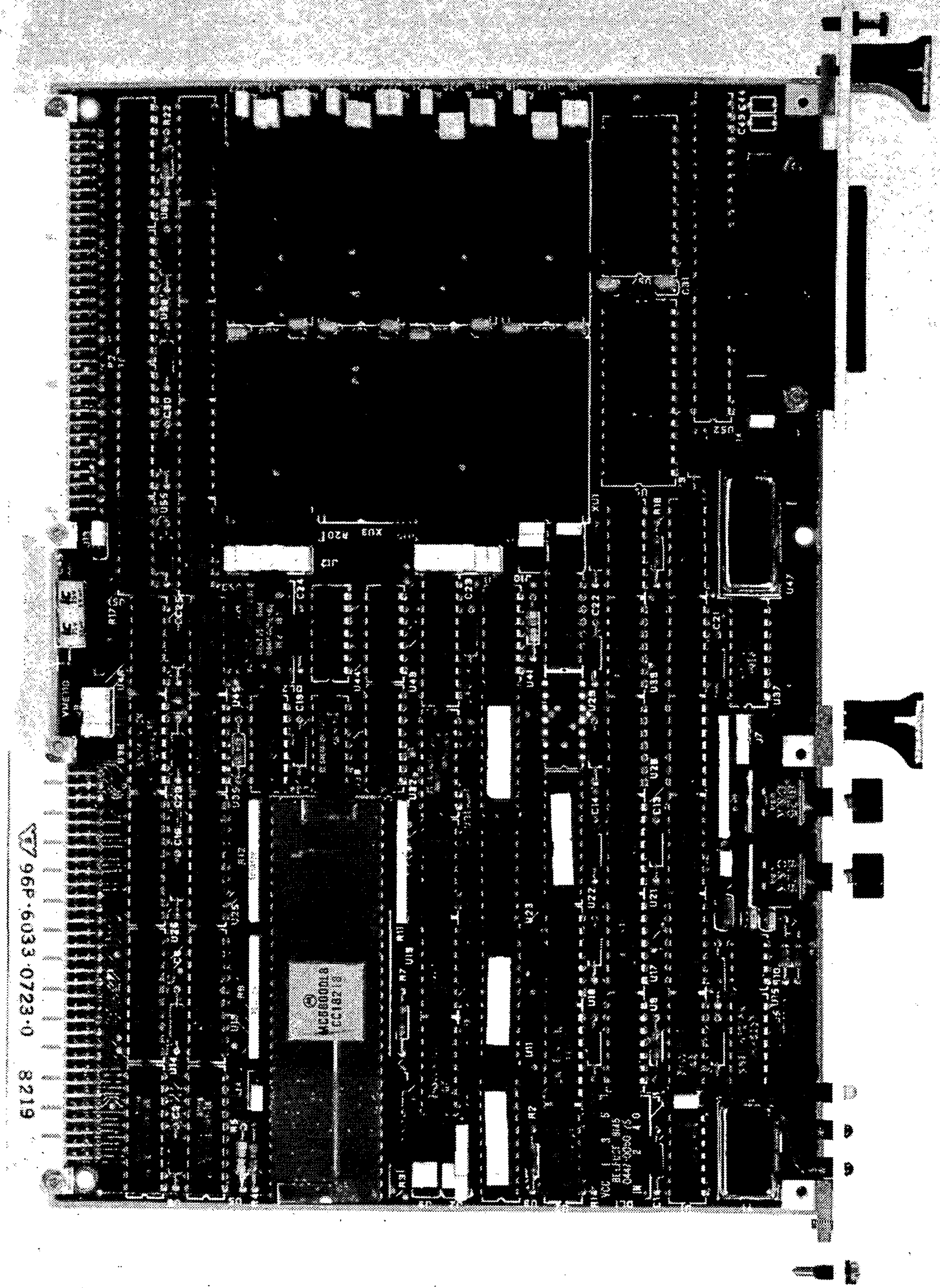
B. Inverter Control Logic:

The car control logic in turn directs four slave microcomputers, called inverter control logics. Each of these is responsible solely for the operation of a single inverter/traction motor (and full regenerative brake circuit, if applicable). The car control logic simply sends a torque request to each inverter control logic, and in turn receives feedback from the inverter control logic on inverter and motor performance. The inverter control logic is dedicated to solving the complex equations necessary to calculating correct GTO firing times, then firing the GTO's and monitoring motor performance.

C. Control Logic Packaging:

Due to this increase in computational power, the selected approach to AC propulsion control utilizes a minimum amount of hardware. Laboratory testing and development has been carried out with off-the-shelf single board computers which use the Motorola MC68000 microprocessor, along with breadboarded peripheral hardware.

Layouts have been developed for the final, minimal configuration boards, and Westinghouse has determined that each inverter can be controlled by a single printed circuit board in the small (6.3" x 9.2") double-width Euro-card format (see Figure ES-7). The supervisory car control computer in final form will occupy four of the same size circuit boards, so that the total logic package



DOUBLE-WIDTH EURO-CARD MC68000 PC BOARD
FIGURE ES-7

consists of eight of these cards, and can fit in a single cradle such as the one shown in Figure ES-8. The major reductions in hardware for the inverter control are accomplished through unique digital methods of PWM waveform synthesis and control loop feedback, which have resulted in several Westinghouse patent applications.

D. Modular Features and Diagnostic Capabilities of Control Logic:

Each inverter control logic, like the inverters, is fully independent for improved availability. Modular design is preserved by minimizing the amount of interconnections to the inverter itself. The inverter control logic accepts a torque request from the supervising car control logic and in return informs the car control logic of its status (motor speed, overcurrent trips, etc.). It sends to the inverter only the commands required to fire the GTO's, and monitors the inverter's performance.

The supervising car control logic, also based on the MC68000 microprocessor, serves to interpret trainlines and allows the vehicle to train with cam-controlled vehicles by "emulating" the tractive effort profile typical of the cam-controlled propulsion. It controls dynamic brake and also serves to monitor axle speeds and react to a wheel slip or slide. Wheel slip and slide are under better inherent control with an AC motor, which tends to lose all torque in response to a rapid change in axle speed.

The final function of the car control logic is to aid in diagnostics and maintenance. The sophistication of the MC68000 allows the car control logic to self-test the majority of circuits in the inverter control logics, inverters and brake circuits without the need for a separate suitcase-type test unit. A troubleshooting concept has been developed which is based on a simple handheld terminal which connects to the car's logic cradle. Software built into the car control logic can self-test most of the major components of the propulsion system, and report test results to the operator on the terminal. This terminal can also be used for monitoring purposes to further enhance maintainability.

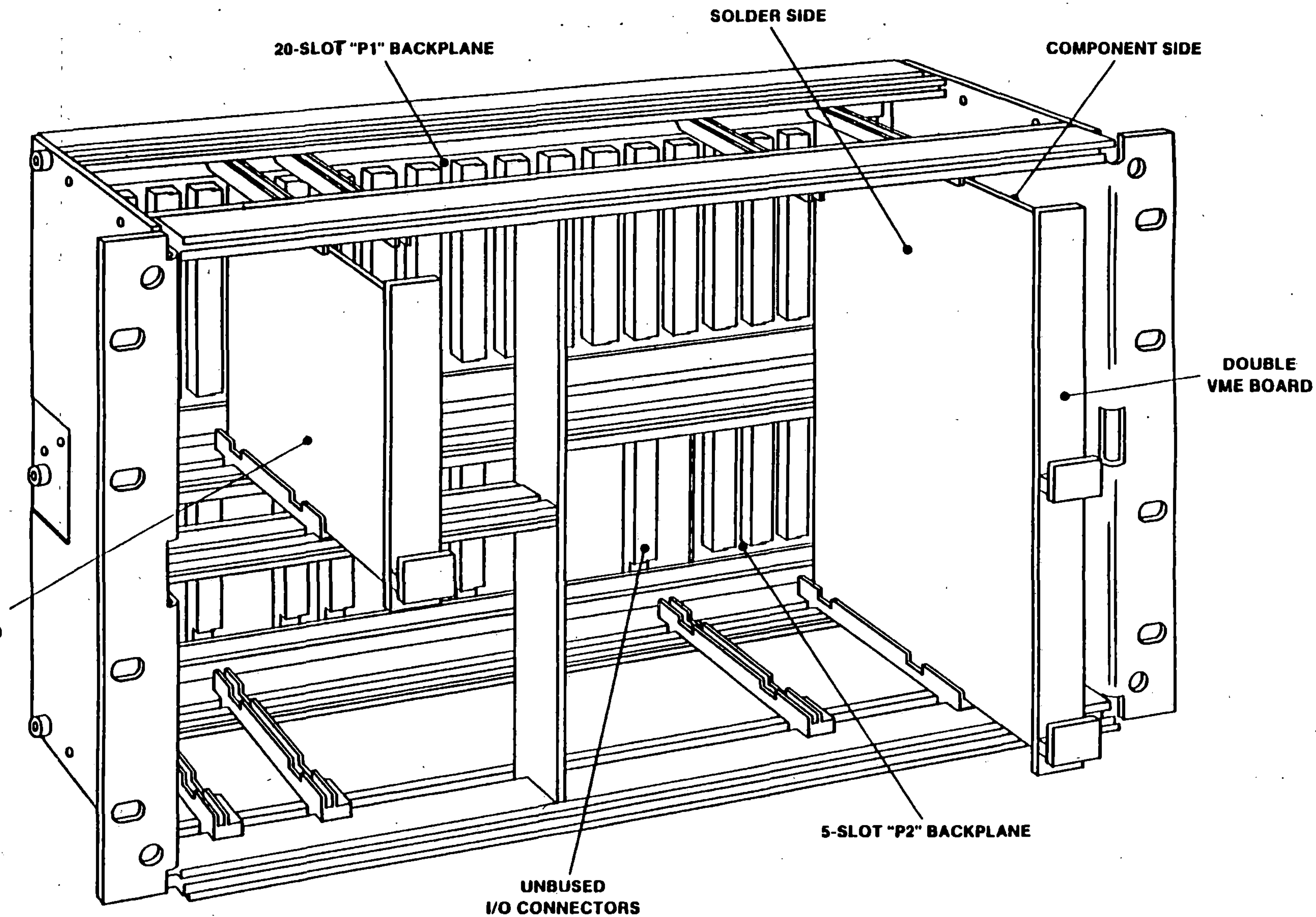


FIGURE ES-8 PROPULSION LOGIC CRADLE

This modular design concept allows for ease in adapting to other configurations. A two inverter per car configuration, or a single inverter trolley bus system, can be implemented with the same basic components. The inverter control logic becomes a standard component, and only the car control logic's inputs and outputs must be tailored to the specific application.

MODULAR DESIGN AND DIAGNOSTICS

The modular design coupled with available options makes the system readily adaptable to other applications, including light rail and trolley bus. Minimal redesign is required to the majority of the hardware, and options for motor frame and regeneration capability allow the system to be tailored to the application.

The maintenance of the system is made simpler by the easily replaceable modular components, and routine preventive maintenance requirements for the system are minimal and simple. Preventive maintenance is essentially reduced to visual inspection and traction motor bearing lubrication. Sophisticated diagnostics allow rapid fault isolation, and all undercar components are easily replaceable.

FUTURE PLANS FOR AC PROPULSION DEVELOPMENT

The efforts summarized in this report reflect the status of the AC propulsion system development as of the Critical Design Review held in March, 1985. In future applications of this system, Westinghouse plans to incorporate several product enhancements which are detailed in this section.

As of this writing, Westinghouse efforts are directed toward the development of standard packaging for the inverter and control logic. In the case of the inverter, recent developments in solid state device packaging are being incorporated. A thermal assembly called a Pow-R-Brick™, developed jointly by Westinghouse Transportation Division and Westinghouse Semiconductor Division, will replace the double side cooled assembly which presently contains the GTO/diode devices. This module is already used in the present packaging for several diodes in the inverter and for several conventional thyristors employed in the full regeneration brake circuit. At the time construction began on the present inverter, this packaging was not available with a GTO, but a GTO/diode Pow-R-Brick™ is now available for testing. The Pow-R-Brick™ simplifies device replacement, since it is replaced as a module and no special clamping procedures are required. The package also permits more effective heat transfer, and provides electrical isolation.

Initial thermal analysis indicates that a two motor inverter using 2,000 ampere GTO's can fit in a package not much larger that the current single motor inverter with its 1,000 ampere GTO's. This standard package will be applied to a range of applications from rail propulsion to trolley bus propulsion to a static inverter for solid state auxiliary AC power generation.

The design of the control logic has been standardized in order to permit the use of a single board inverter controller in a variety of systems. The inverter controller is a standard module, with one per car required on a trolley bus system, and two or four per car on a railcar propulsion system. Standard CPU and I/O boards are used for the car control logic so that, in most instances, only one printed circuit board will require modifications for a specific application.

CONCLUSIONS AND TRADEOFFS

The system as designed and tested successfully met all of the design and performance requirements established. The application of novel approaches to a number of design issues has led to a propulsion system that is lightweight, reliable and cost effective while at the same time providing performance unparalleled in conventional propulsion systems.

The modular design of the AC propulsion system is adaptable to a wide range of vehicle systems and transit applications. For any specific application, a number of tradeoffs must be considered in order to select the optimum configuration. Several of the key tradeoffs are discussed below.

One of the primary tradeoffs studied during the propulsion system design process was the relative advantages and disadvantages of open frame, or drip proof, versus totally enclosed AC traction motors. Strong input from APTA representatives at the preliminary design review led to the selection of a totally enclosed AC traction motor for fabrication and testing in the full scale laboratory setup. The primary advantage of this motor is its completely sealed construction, making it essentially impervious to such environmental factors as snow, moisture, salt, and foreign matter in general. In addition, the thermal design of the totally enclosed motor represented a greater challenge in order to effectively conduct waste heat away from the motor without the use of internally-circulated cooling air. Given a successful totally enclosed motor design, a similar design for a drip proof motor was viewed as a relatively straightforward engineering task.

There are, however, advantages to be gained by employing a drip proof AC traction motor. The weight advantage noted earlier of an estimated 350 lbs. per traction motor, or 1,400 lbs. per rail car, is certainly a viable consideration, especially since the weight saved is in the critical area of the truck. The weight savings is due to more efficiency in heat transfer by the use of internally-circulated cooling air, allowing the use of a smaller motor for the same duty requirements. The smaller motor also costs somewhat less to manufacture.

In addition, the added environmental protection of a totally enclosed motor may be of marginal benefit in all but the most severe of applications, since studies of DC traction motors have generally shown that a large number of problems encountered are related to the commutator and brush gear. Given the lack of commutator and brush gear in an AC traction motor, an open, drip proof frame motor may be a more cost-effective choice in such applications.

For these reasons, a parallel design was completed for a drip proof AC traction motor. However, as noted earlier, only the totally enclosed design was built and tested as a part of the AC Propulsion Project.

A second tradeoff studied during the design process was the number of inverters to be used per car for the AC propulsion system. The selection of a four inverter/four motor configuration was driven by a number of factors. Among these factors were wheel mismatch problems associated with two motors driven from the same inverter; reliability versus availability; and, ease of maintenance. The fact that GTO's were not available in a large enough size (at the start of the design phase) to allow for a two inverter per car configuration was a major factor. Smaller GTO's could be paralleled, but GTO's are inherently difficult to apply in parallel as they are difficult to balance; this approach was seen as inherently too risky. For these reasons, a four inverter/four motor configuration was selected.

Wheel mismatch concerns have been totally eliminated due to the four inverter approach, since each motor is separately controlled, so no special maintenance practices are required. This has the added benefit of providing equal traction to all four axles, providing superior performance on grades and in inclement weather.

The four inverter concept is also very beneficial to availability. Unlike a DC motor, an AC motor can be allowed to spin freely if the inverter driving it fails, without the need to stop the train and electrically disconnect the failed axle or truck. Simulations indicate that a ten car train on the NYCTA RR Line can complete a run without substantial loss of headway with up to ten of its forty inverters failed. The probability of this occuring is negligible, and this means that propulsion failures are unlikely to cause substantial losses in schedule time. Maintenance can be scheduled at the end of the shift, without service interruptions.

A two inverter per car configuration does, however, offer some advantages. Its lesser parts count will improve reliability (with some loss of availability) and reduce cost somewhat. Since the initial selection by Westinghouse of a four inverter per car system, several firms have developed larger GTO's, large enough to make a two inverter per car configuration feasible. This option is also addressed in the Cost and Economic Analysis in Section 11.

1. INTRODUCTION

The advantages of rugged, simple induction motors have long been known in industry. However, these motors require a more complex drive than their direct current counterparts, because a propulsion system must precisely control the frequency of the alternating current (measured in hertz) in addition to controlling current (amperes) or voltage (volts).

This report describes the design, manufacture and testing of a propulsion system for passenger rail application utilizing a variable-voltage, variable-frequency (VVVF) inverter and a squirrel cage induction motor, along with associated microprocessor control circuitry. The rationale behind this development includes several factors: reduced maintenance and improved reliability associated with brushless AC motors and solid state electronics; improved energy efficiency due to elimination of series resistors; and high regeneration capability, further reducing energy usage. A net reduction in life cycle cost is predicted due to these factors when compared with conventional cam-controlled, series resistance DC propulsion systems.

2. AC TRACTION MOTOR

Direct current motors have been the main stay of the traction equipment industry for many years primarily because it is relatively easy to achieve speed control with these machines, and they exhibit very desirable speed torque characteristics. The equipment has been in a constant state of development during these many years which has resulted in the achievement of high reliability and high power density in the traction drives. The advent of high power solid state device technology has impacted the industry as these new technologies have been exploited in an effort to further improve system performance. The entry of power semiconductor equipment to the industry has been staged as electromechanical system components, such as rheostat controls, have been replaced by more efficient electronic controls such as choppers. The power device and control technologies have continued to advance and have achieved a level where replacement of the traditional DC machine with an AC machine and adjustable speed electronic drive is technically feasible and economically attractive.

During the initial stages of the design effort a number of motor design options (listed in Figure 2-1) were considered. Each configuration has its own strengths and advantages which ultimately will be judged in the market place against its initial costs, operating efficiency and maintenance requirements. The choice of the appropriate design configuration is made difficult because all of the listed options can be made to give satisfactory performance in virtually any traction application and, with the elimination of the commutator and brushes, one can expect significantly improved reliability from any one of the listed design options. Ultimately a design course was chosen which would result in the development of a machine which would provide the maximum performance, efficiency and reliability that could be achieved. This also proved to be the most difficult machine concept to design which is an appropriate approach for any development program. Achievement of the program goals with a design which offers options of environmental protection, high efficiency and maximum reliability will conclusively prove that the AC machine is a viable, attractive alternative to traditional DC drives.

Motor Component	Option	Characteristics
Enclosure	Open, Dripproof, Splashproof	Best thermal performance, lightest weight, most affected by environment
	Totally Enclosed	Heaviest, best environmental protection, quiet
	Total Enclosed Fan Cooled	Heavy, good environmental protection, noise may present a problem.
Stator Winding	Form Wound	Sealed insulation system, best environmental protection mechanically most rugged, highest dielectric strength, most expensive
	End Wrapped Mush Wound	Insulation system not sealed, end turns wrapped for additional rigidity and environmental protection, medium cost
	Mush Wound	Insulation not sealed, most economical winding, good thermal performance, mechanically flexible.
Rotor Cage	Copper Bar w/Brazed End Rings	Highest efficiency, highest cost, best transient load performance
	Cast Aluminum	Medium efficiency, lower cost, mechanically rugged.

FIGURE 2-1 MOTOR DESIGN OPTIONS

With these goals in mind the design chosen to develop was a totally enclosed fan cooled enclosure (TEFC) using form wound stator coils and a brazed copper rotor cage. Subsequent operational tests showed that the extremely low slip inherent with a high efficiency copper cage winding caused instability problems when the motor was operated with the developed control system. In addition, the inadvertent use of an incorrect end ring material caused a mechanical failure of the end ring at the highest operational speed. The need to solve the control problem and to rapidly replace the motor rotors was satisfied with the decision to utilize a cast aluminum rotor with higher slip and hence modestly reduced efficiency.

The following sections will report on the design of the motor as initially conceived and the motor modifications and test results.

2.1 MOTOR DESIGN

During the initial stages of the engineering effort a number of decisions were required to define the design approach for the motors. Several design options were investigated and many perfectly suitable choices for enclosures, winding and rotor construction were identified. Initial design choices were made consistent with the philosophy of developing a "top of the line" product. The totally enclosed fan cooled enclosure was chosen because it offers the maximum environmental protection for the motor, the copper rotor cage because it provides the highest achievable efficiency and form wound stator coils to provide the best combination of mechanical rigidity, high voltage capability and environmental protection. In short, it was decided to pursue what was believed to be the highest reliability and performance options available even though these machines would be penalized by modestly increased weight and cost. In addition, we believed the achievement of acceptable power density in a TEFC enclosure to be the most formidable engineering challenge faced. Since the use of open enclosures would provide improved cooling and a relaxation of design constraints, it was felt the more difficult TEFC enclosure should be pursued during this effort.

2.2 ELECTRICAL DESIGN

The initial design goal for the motor was set at 190 HP which we believed was the highest rating which could be achieved in a TEFC enclosure within the available space. Analysis of the chosen car undercarriage showed that a NEMA 445T frame machine would nest within the allowed envelope provided the frame length could be kept less than 31 inches and appropriate end bells were provided to allow the coupling to enter the motor box dimensions.

More detailed analysis of the electrical characteristics and mechanical calculations of the traction system finally resulted in the choice to provide a 445T frame machine with an active core length of 10.75 in. The significant dimensions of the commercially-available stator and rotor slot geometry that were chosen are detailed in Figure 2-2.

Many alternative designs were investigated to determine the most optimum winding configuration for achievement of the design goals. Additionally, alternative operating voltage levels were analyzed to provide the most appropriate system characteristics to achieve the maximum power density and machine performance. It was quickly determined that the machine should be wound with four poles and an investigation of gear ratios resulted in a motor specification which is summarized in Figure 2-3. Figures 2-4 and 2-5 depict the load curves which were chosen to further define the rating requirements of the motor.

Several alternative detailed machine designs were developed as the definition of the system solidified. Five final candidate designs emerged and are summarized in Figure 2-6. Design 4 was chosen after a detailed analysis of its losses, expected temperature rise and electrical performance. This design exhibited the highest efficiency and lowest predicted temperature rise of the candidate designs and met all performance requirements. A summary of the design is shown in Figure 2-7.

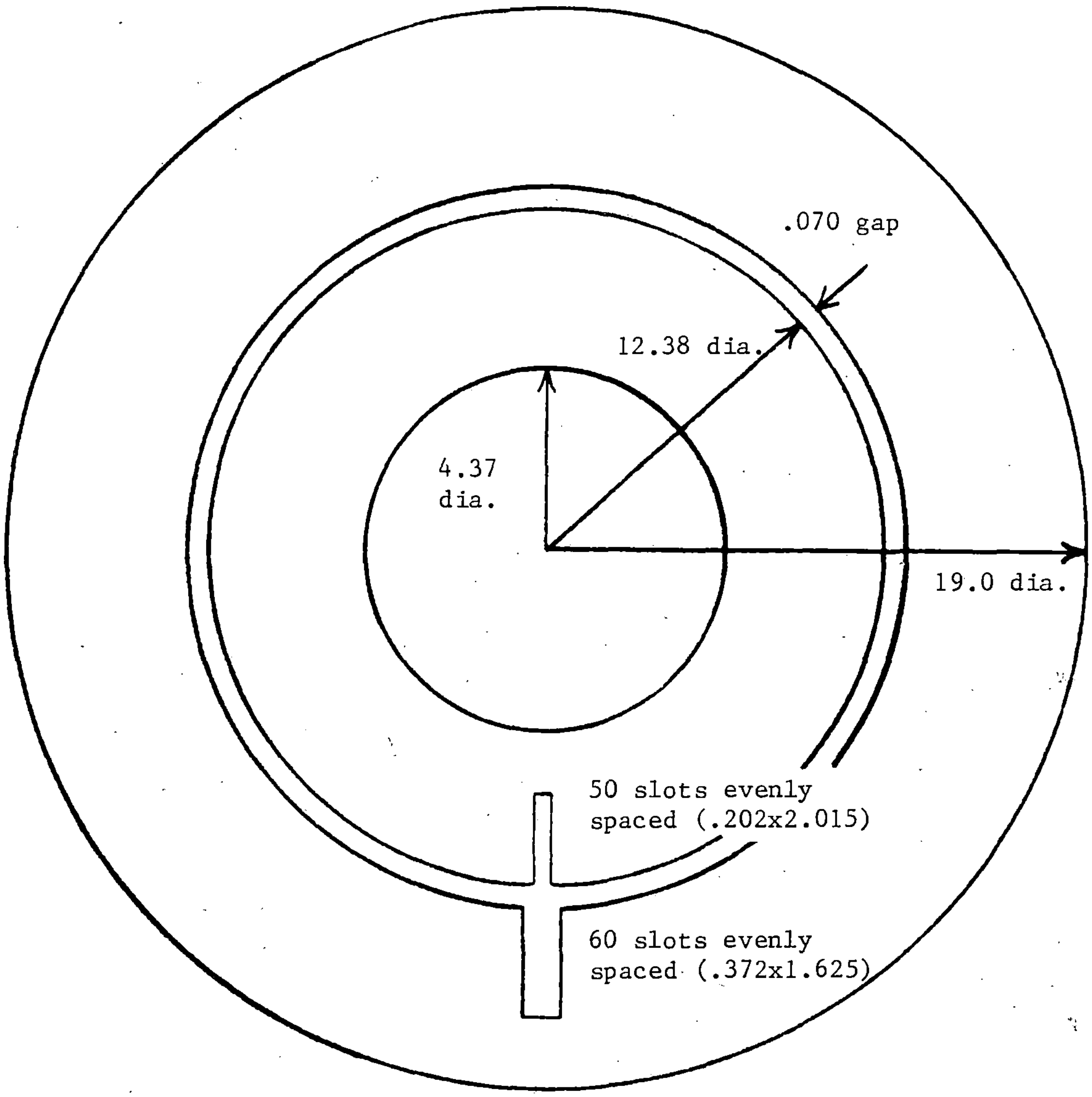


Figure 2-2

Motor Lamination Major Dimensions

Base Rating	190 HP
Base Speed	1334 RPM
Maximum Speed	6000 RPM
Base Frequency	45 Hz
Frame	445 T
Enclosure	TEFC
Frame Length	31.55 inches
Maximum Poles	4

MOTOR SPECIFICATION SUMMARY

FIGURE 2-3

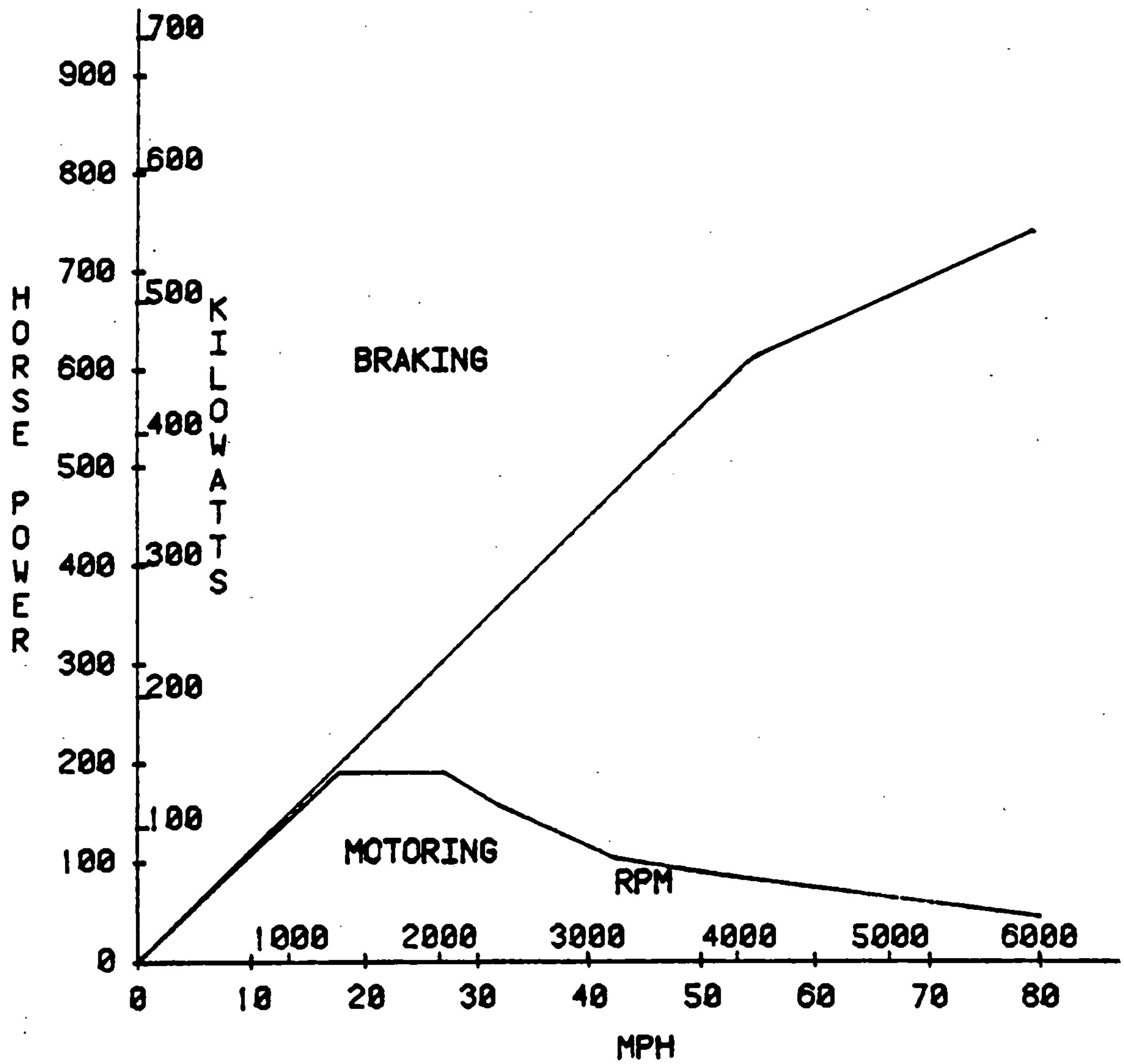


Figure 2-4

Motor Power Requirements

Note: This figure represents the 77th to 86th Street Run of the NYCTA RR Line and is typical of duty over the entire line.

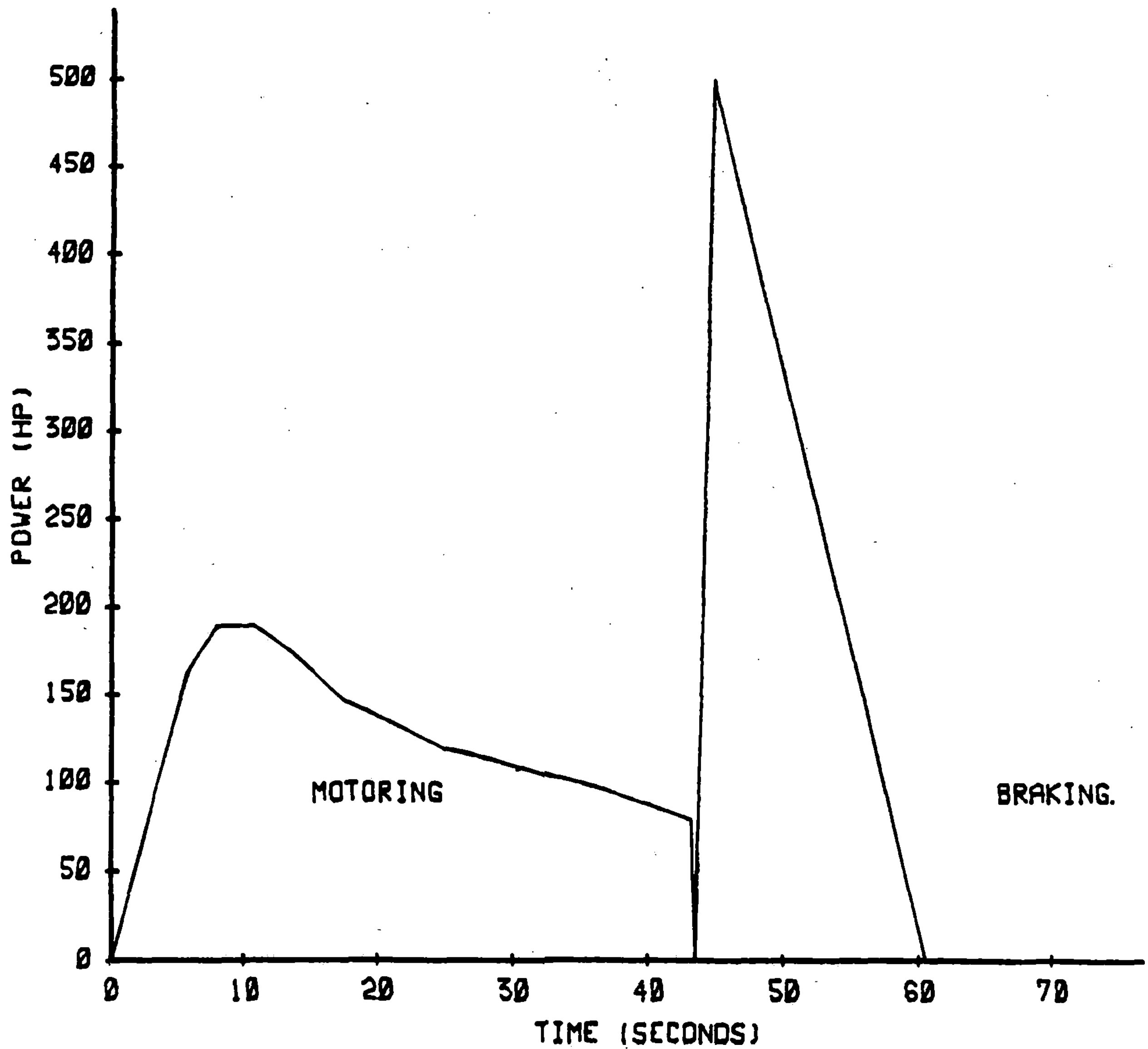


Figure 2-5

Motor Duty Cycle

WINDING	STATOR CORE LOSS (WATTS)	STATOR I^2R LOSS (WATTS)	TOTAL LOSSES (WATTS)	LINE CURRENT (AMPS)	HOT SPOT RISE (^oC) 1700/900CFM	EFFICIENCY (%)	POWER FACT-OR
1. 450V 9 TURNS/COIL 4 PARALLEL .064" X .114"	1,573	6,770	12,146	238	$189^o/217^o$	92.2	83
2. 450V 4 TURNS/COIL 2 PARALLEL .144" X .289"	2,355	7,234	10,920	258	$167^o/197^o$	93.1	75
3. 450V 8 TURNS/COIL 4 PARALLEL .072" X .289"	2,355	4,802	10,456	258	$156^o/186^o$	93.2	75
4. 420V 8 TURNS/COIL 4 PARALLEL .075" X .274"	1,864	4,980	10,366	258	$154^o/183^o$	93.3	80
5. 400V 8 TURNS/COIL 4 PARALLEL .072" X .289"	1,573	5,132	10,479	267	$159^o/189^o$	93.2	82

FIGURE 2-6
FINAL ELECTRICAL DESIGN CANDIDATES

Enclosure	TEFC
Total Length	31.55 in.
Housing Outer Diameter	22.125
Gear Ratio	7.235 (32.375 inch wheels)
Base Speed	1334 RPM
Speed at 80 mph	6009 RPM
Speed at 50 mph	3756 RPM
Frame	445T
Stator Slots	60- .372 1.625
Stator Winding	4 parallel, 8 turns/coil
Conductor	.075 x .274
Rotor Slots	50- .202 x 2.015
Rotor Winding	Brazed Copper Cage
Single Air Gap	.070 in.
Active Core Length	10.75 in.
Coil Throw	1 - 12
Base Voltage	420 V
Base Rating	190 HP
Total Losses, Base Load	10.4 KW
Base Efficiency	93.3%
Power Factor	80%
Current	258 A
R_1 per unit	.0199
R_2 per unit	.0094
X_1 per unit	.0737
X_2 per unit	.1354
XM	1.74

MOTOR DESIGN SUMMARY

FIGURE 2-7

The electrical insulation system chosen for these prototypes is a class H system consisting of a Kapton strand insulation, a Kapton coil insulation and a Kapton-Nomex laminate ground wrapper. Figure 2-8 provides details on the insulating materials while figures 2-9 and 2-10 illustrate the application of these materials in the insulation system. All components are class H and testing of the combined system has confirmed that it also meets class H requirements. IEEE standard 11-1980 entitled "IEEE Standard for Rotating Electric Machinery for Rail and Road Vehicles" allows a temperature rise of 170 C by resistance and 190 C by embedded detector for a totally enclosed class H machine.

2.3 THERMAL DESIGN

The thermal design and analysis of the traction machine consisted of two separate but related tasks. The first task was the analysis of heat flow to the ambient air as a function of air flow velocity and the second task was the development of a fan which would provide the required air flow throughout the motor speed range.

2.3.1 Motor Heat Flow Analysis

IEEE Standard 11-1980 allows a maximum temperature rise for totally enclosed machines with class H insulation of 170°C by resistance and 190°C by embedded detector for transit applications. The goal we set for the machine design was to achieve 190 HP in the TEFC enclosure within these temperature limits.

The prediction of machine temperature rise was made using a finite element model which closely approximates the thermal resistance and loss distribution in the machine. Figure 2-11 illustrates the geometry of the model that was employed to complete the thermal analysis of the motor. A half slot model of the stator was constructed which consists of a one half slot pitch representation of the conductor, ground wall insulation and stator back iron, motor frame, frame fins and a heat transfer layer which represents the thermal

Item	Description	Function
1	.075" x .274" Kapton Insulated Copper Wire	Conductors
2	.001" x 1.00" Kapton Tape	Primary/Seal Tape
3	.006" Kapton-Nomex Laminate	Ground Wrapper
4	.005" x .75" Glass Tape	Finish Tape
5	.0025" x .5" Kapton Adhesive Tape	Spot Tape
6	(1) of .025" Nomex Paper	Filler Between Coils
	(1) of .015" Nomex Paper	Filler Under Wedge
	(1) of .007" Nomex Paper	Slot Liner
7	Class H Solventless Polyester Resin	Impregnating Resin

AC TRACTION MOTOR

STATOR COIL INSULATION SYSTEM

FIGURE 2-8

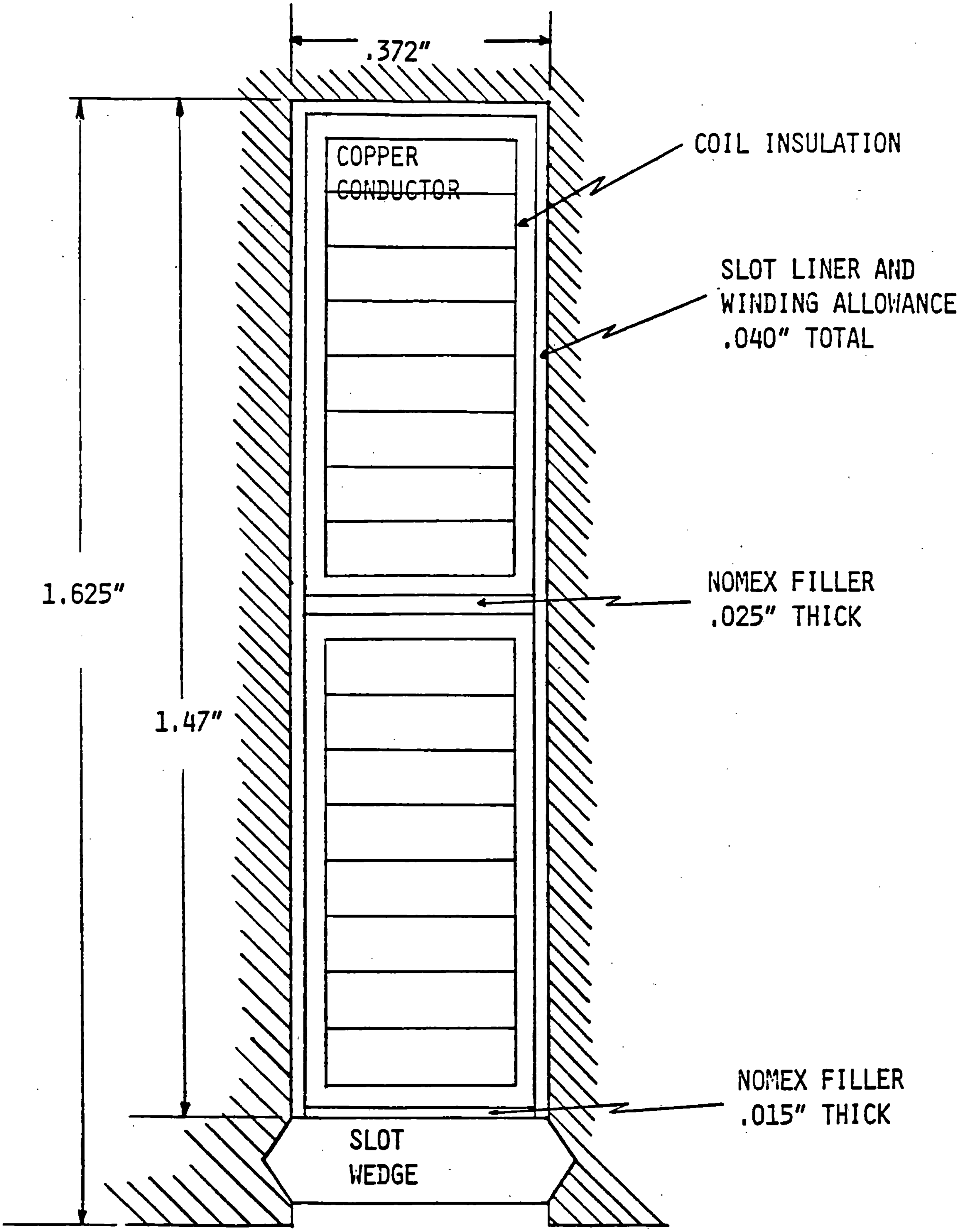


Figure 2-9

Coil Insulation Arrangement

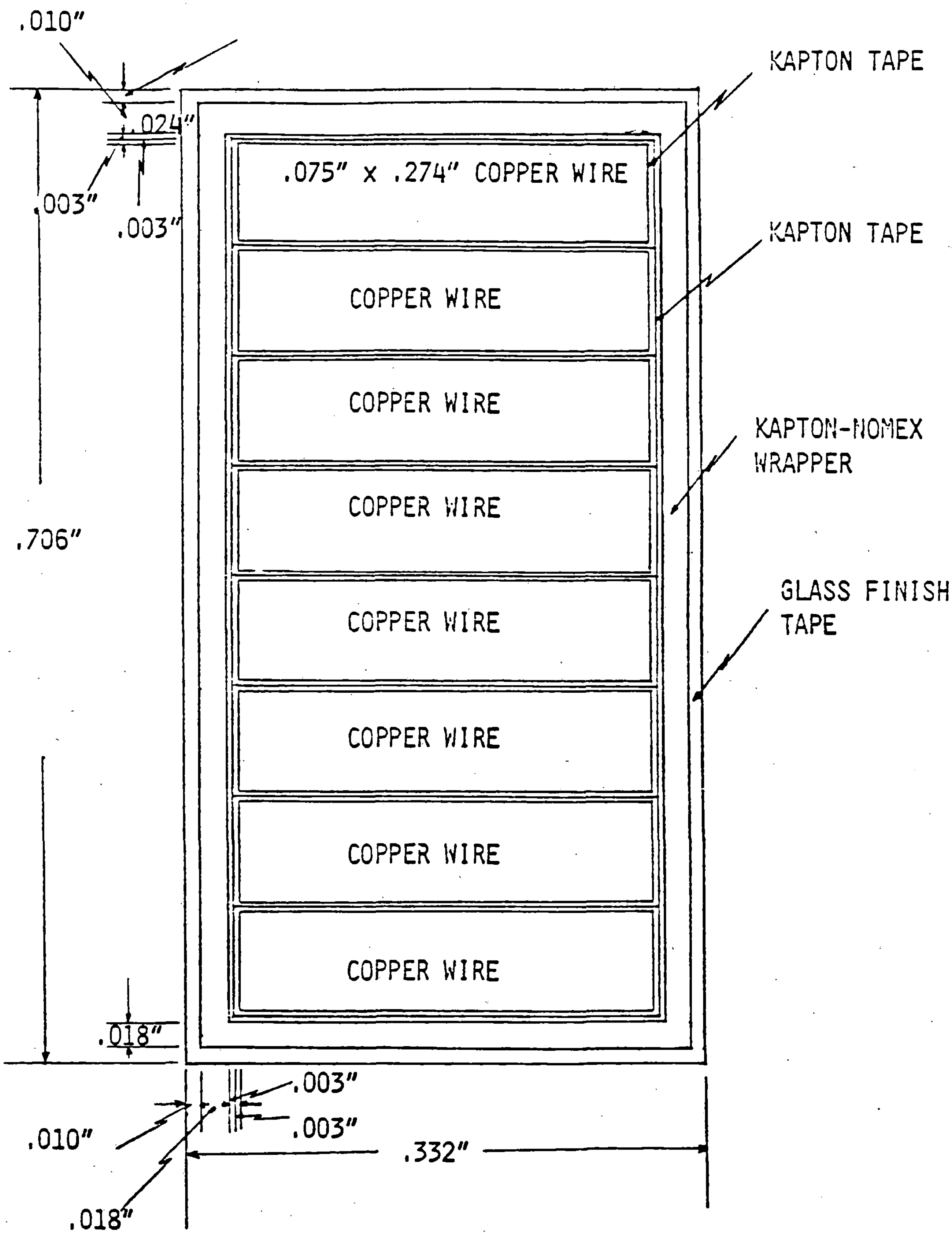
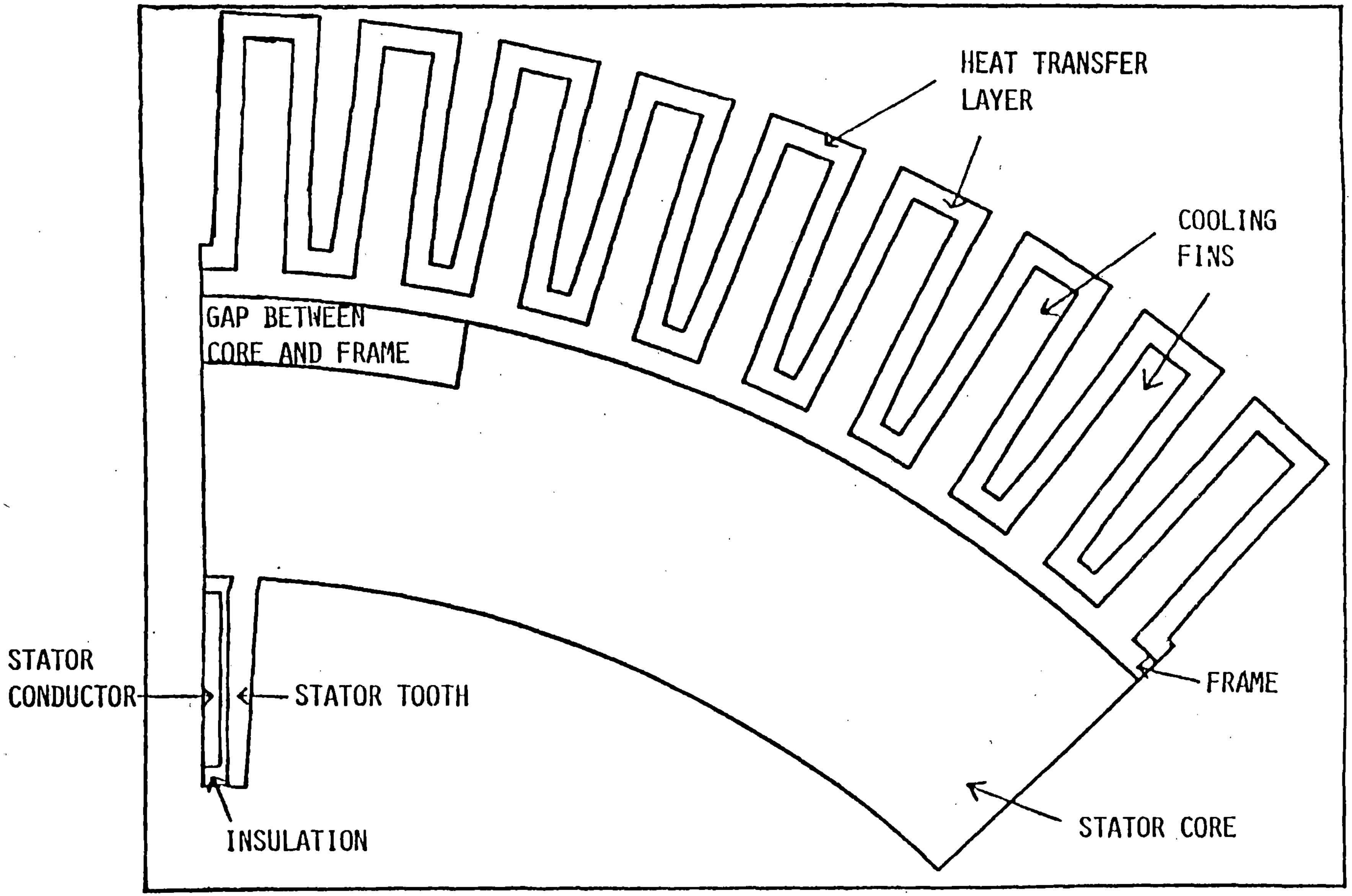


Figure 2-10

Coil Arrangement in Slot



THERMAL MODEL OF MOTOR STATOR

Figure 2-11

drop between the fin and ambient air. The heat transfer coefficient between the fin and ambient air was adjusted to analyze the effects of different air flows over the motor frame fins. The developed finite grid is shown in Figure 2-12 and a representative iso-thermal plot is shown in Figure 2-13.

Figure 2-6 shows the estimated temperature rise of the alternate designs for total fan air flows of 1700 CFM and 900 CFM.

2.3.2 Fan Design

The decision to proceed with a TEFC motor required that a fan be designed which will provide the necessary air flow throughout the speed range without producing unacceptably high noise levels. Therefore it was deciced to design and build a quiet prototypical traction motor blower and shroud which would provide 1000 cfm airflow at 1700 rpm while producing a total noise of less than 90 dBA at 6000 rpm and 84 dBA at 4500 rpm. The design of the blower is consistent with future manufacture of the blower for extended duty on actual truck mounted motors available. Space for the fan and shroud was limited to an axial length of 4.12 inches and a maximum unrestricted outer diameter of 22.125".

The pre-prototype design configuration of the fan consisted of 30 blades with an 11 inch OD, 8 inch ID and an axial blade length of 2.5 inches (at the main radius) as shown in Figure 2-14. The design is based on the required air flow and physical size limitations using the results of earlier work on TEFC motors and traction motor flow rates and noise levels.

Using estimates for flow path resistance derived from the motor geometry, approximate values for flow rates and noise levels were calculated and are summarized in Figure 2-15. Plotted on the Y-axis is noise (SPL, dBA average at 15 ft. from the motor at 6000 rpm). Also shown is the required fan diameter (inches, with 21.5 inches as the upper limit in size) as a function of the flowrate of air. Figure 2-15 shows that 1800 ft^3/min represents the upper limit for flow at 1700 rpm, and that fan noise will fall in the range of 110 dBA or higher. At the other end of the scale, with a fan diameter of 8 inches, the flow rate would be reduced to about 1000 ft^3/min with noise in the 90 dBA range.

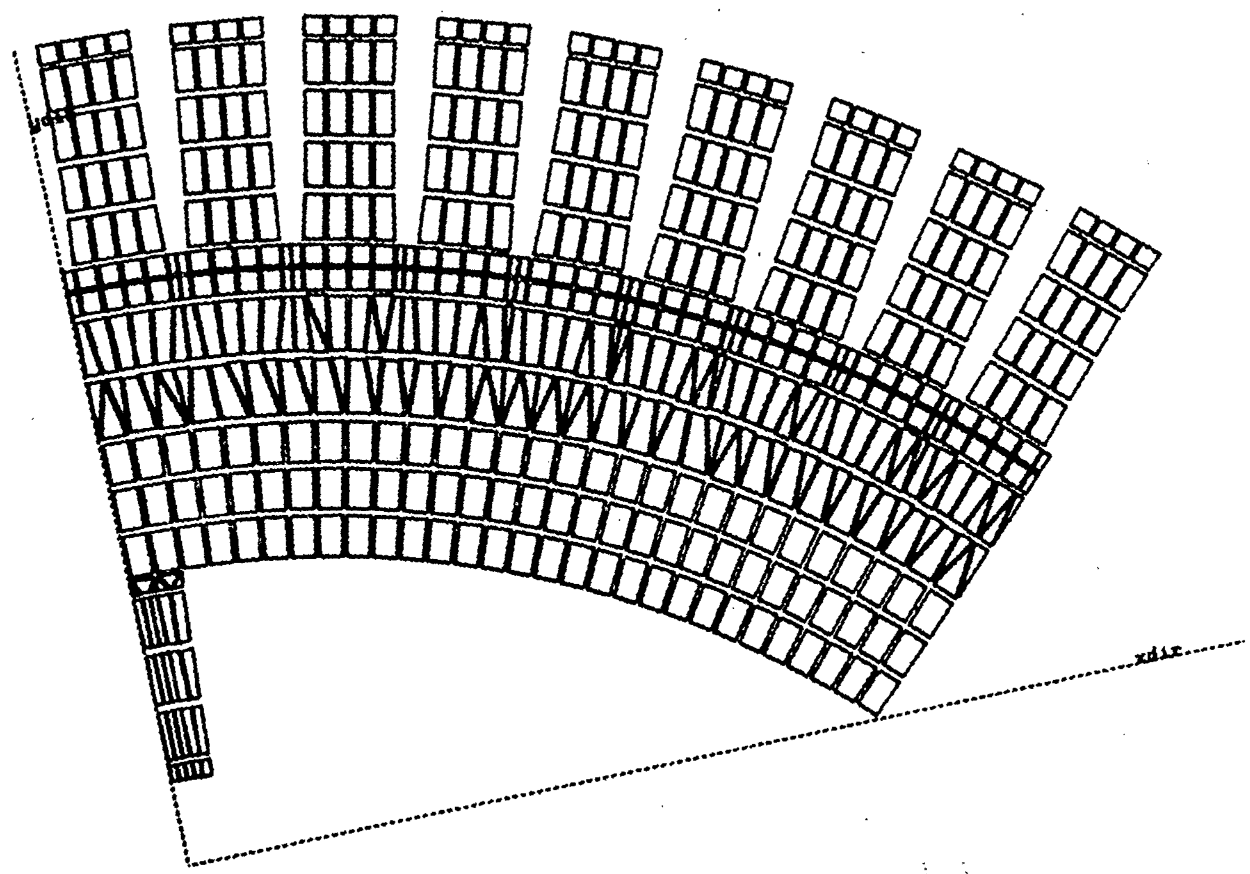


Figure 2-12
Finite Element Thermal Grid

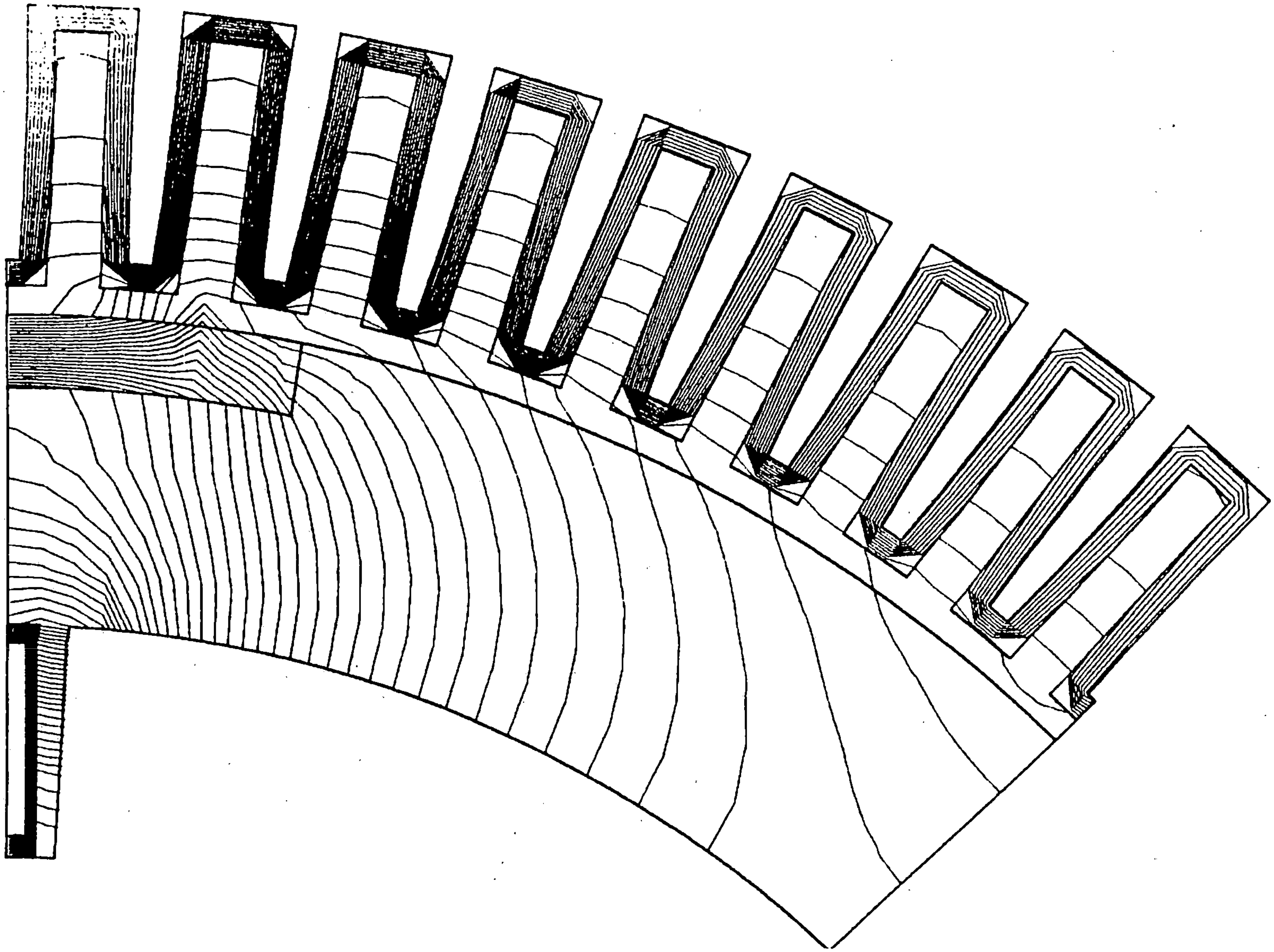


Figure 2-13

Isothermal Plot for 900 CFM Air Flow at the Base Rating

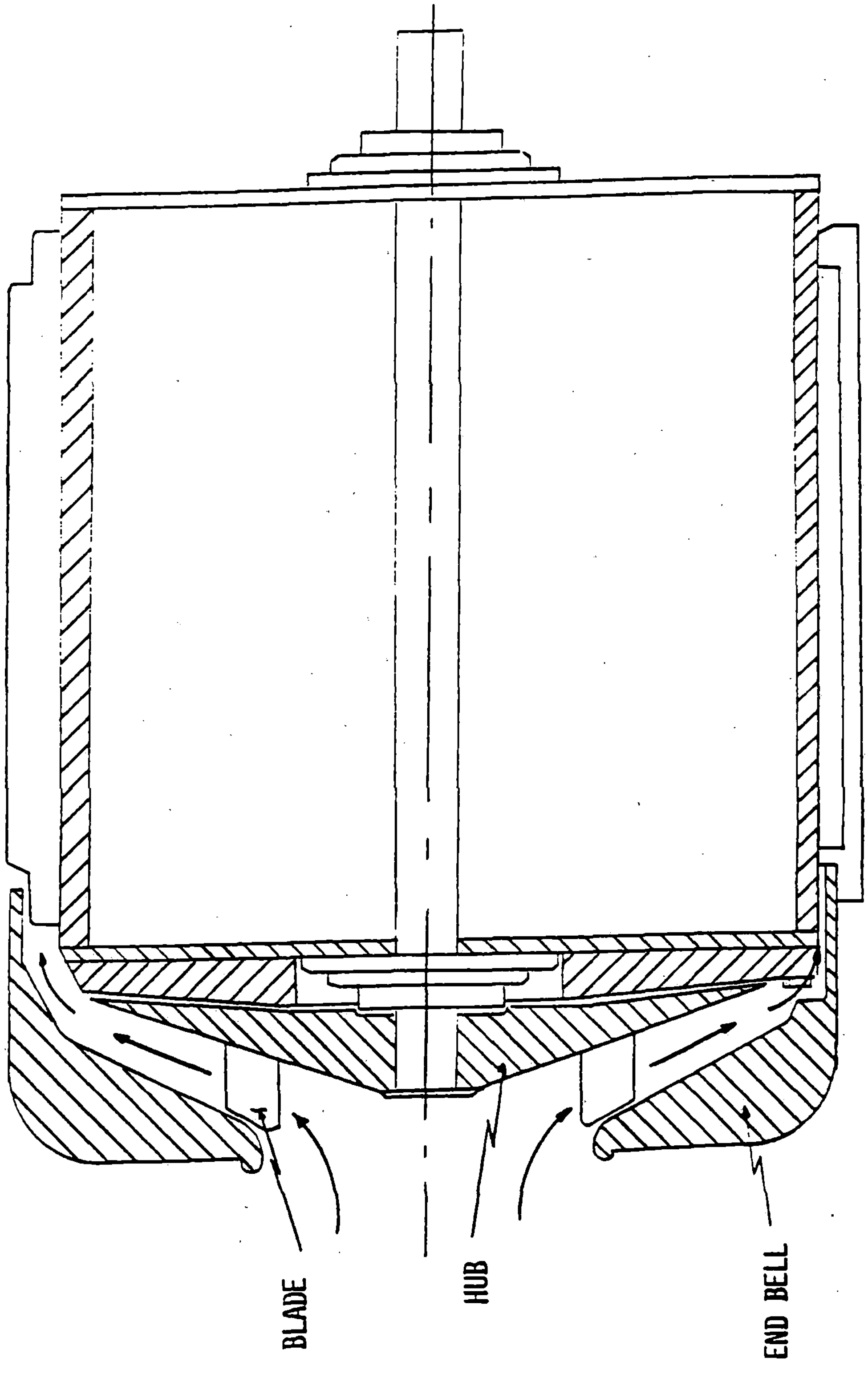
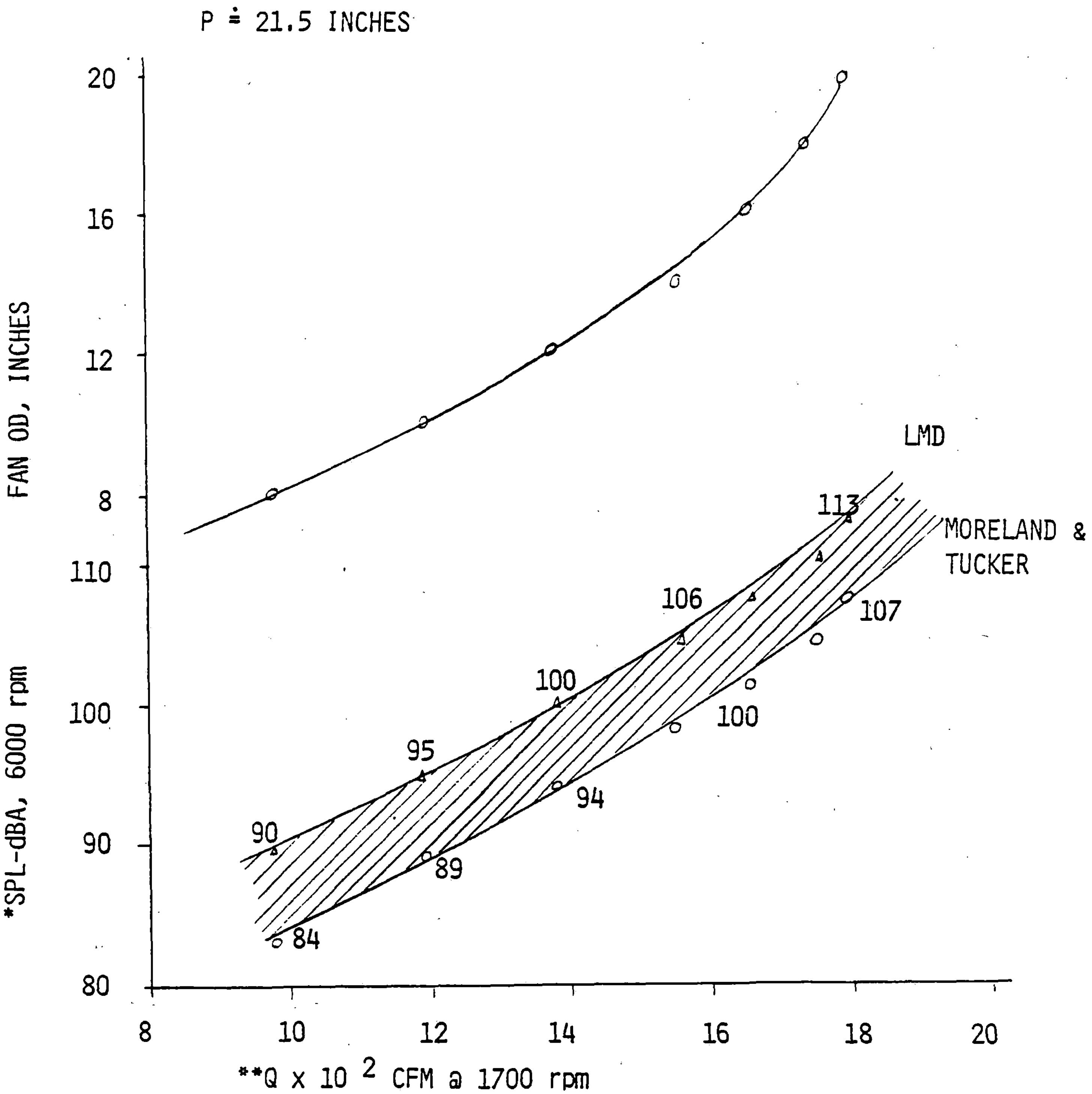


Figure 2-14

Traction Motor Blower with End Bell

ESTIMATES FOR NOISE AND FLOW FOR THE AC TRACTION MOTOR



*NOISE IS ESTIMATED, WITH POSSIBLE ERROR OF 5 TO 10 dBA.
**FLOW RATE IS ESTIMATED, WITH POSSIBLE ERROR OF 100 FT^3/MIN.

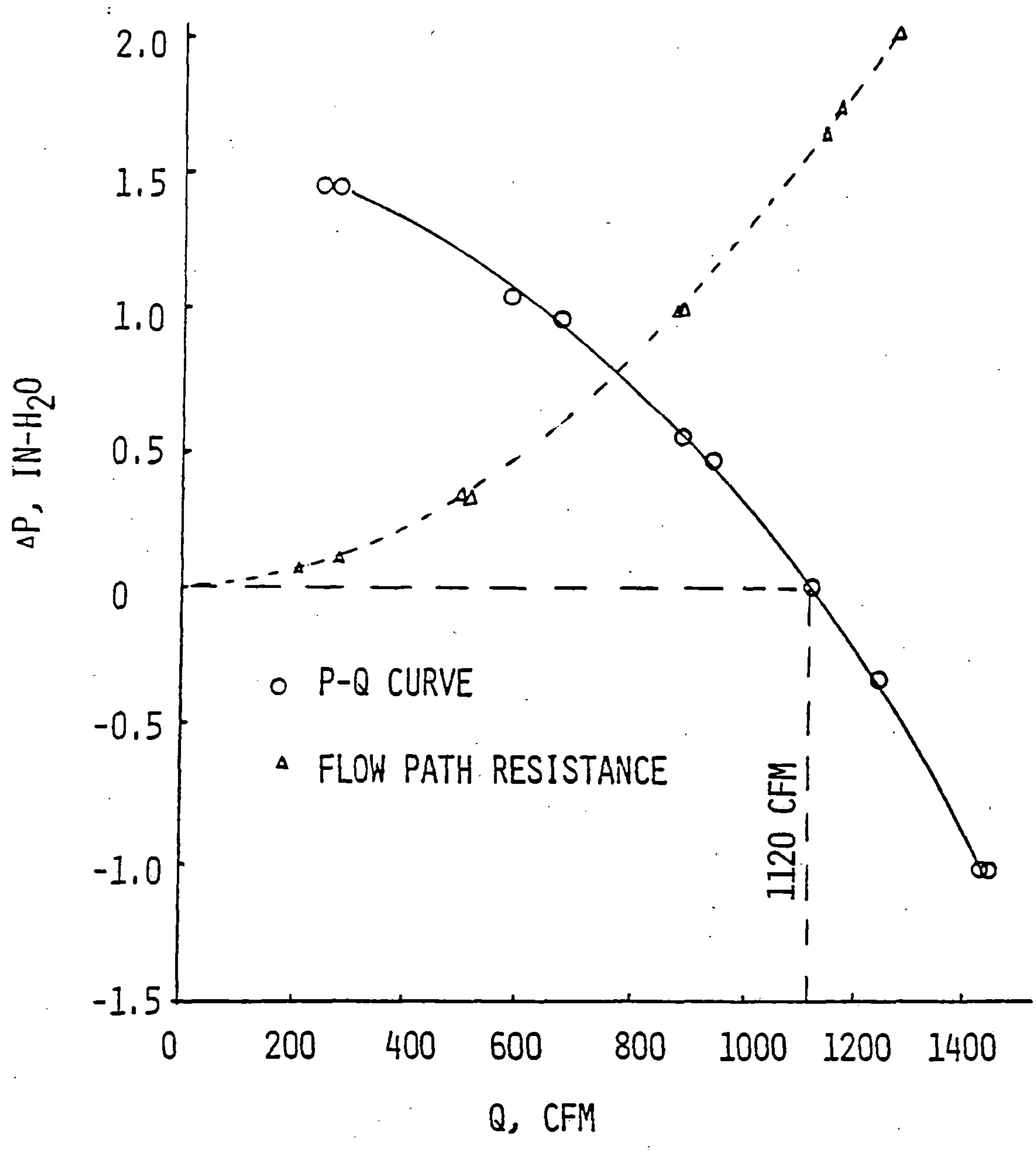
Figure 2-15

Results of tests on the pre-prototype fan are shown in Figure 2-16 which shows a flow delivery of 1120 cfm at 1792 rpm without a suction grill which is equivalent to 1060 cfm at 1700 rpm. Figure 2-17 shows test results obtained using a wooden mockup in front of the fan inlet to simulate the proximity of the wheel to the fan. A volume flow rate of 1032 cfm at 1792 rpm was measured which equates to a flow rate of 980 cfm (versus the requirement of 1000 cfm) at 1700 rpm. The diameter of the prototype fan was set at 11.5 inches outer diameter to regain the 2 percent loss below the specified flow that was observed with the "wheel" in place.

Laboratory measurements of noise (SPL in dBA [re 2 x 10^{-4} microbar]) at 5 feet from the machine yielded an average of 70 - 72 dBA at 1700 rpm. Entering the SPL-vs.-diameter curve shown in Figure 2-15 provides an estimate of 95 dBA for free-field noise level at 15 feet running at 6000 rpm. It appears that the 90 dBA specification on noise will be difficult to meet with a reasonable fan design. The decision was made to proceed with the prototype fan and accept the slightly increased noise levels. The final design configuration of the fan was modified from the pre-prototype design to ease manufacture and improve expected performance. The long (radial) skirt shown in Figure 2-14, which extends beyond the fan blades, was not included in the metal prototype blower since it was only a device to allow diameter changes on the pre-prototype blade row. This skirt was designed to become part of the motor end bracket or a separate piece mounted to the end bracket. The final design configuration of the blower is shown in Figure 2-18. The blower consists of a machined aluminum fan mounted to the shaft of the motor with a slotted key, lock washer and nut for ease in assembly and removal; a directional foam core/fiberglass hub for directing air flow; and a blower shroud of foam core/fiberglass enclosure.

2.3.3 Fan Test Results

Fan testing for flow requirements was performed with the experimental arrangement shown in Figure 2-19. These flow tests indicated that the fan would produce the desired 1000 cfm at 1700 rpm with an approximate noise level of 68 dBA measured 15 feet from the machine based on readings of 70 - 72 dBA at 5 feet.



TRACTION MOTOR COOLING SYSTEM CHARACTERISTICS OF
1792 CFM WITHOUT SUCTION GRILLE OR SIMULATED WHEEL BLOCKAGE

Figure 2-16

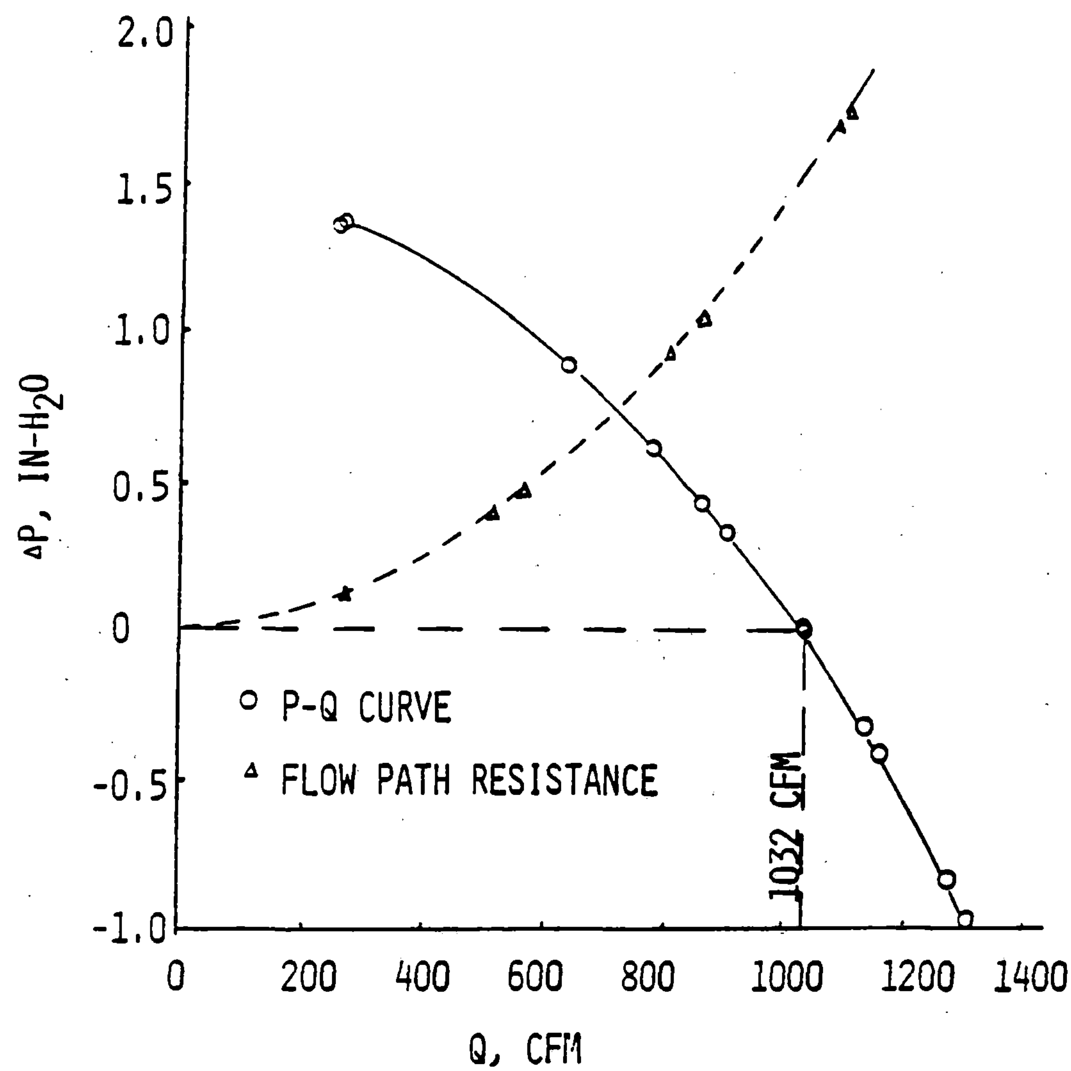


Figure 2-17

Traction Motor Cooling System Characteristics at 1792 RPM with Suction Grille and Simulated Wheel Blockage

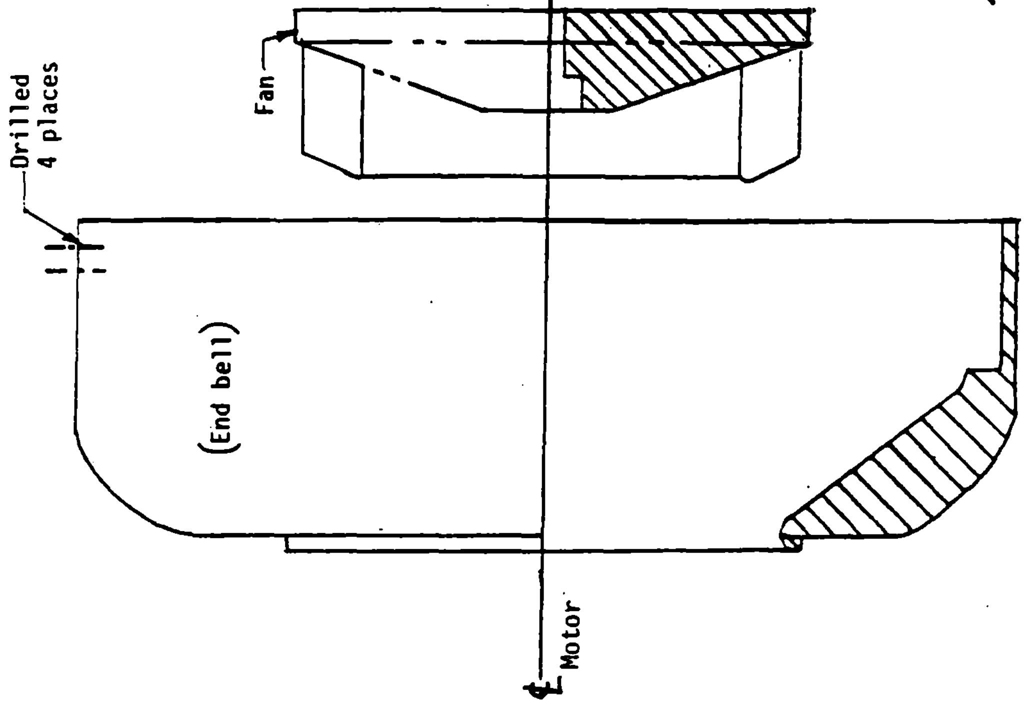
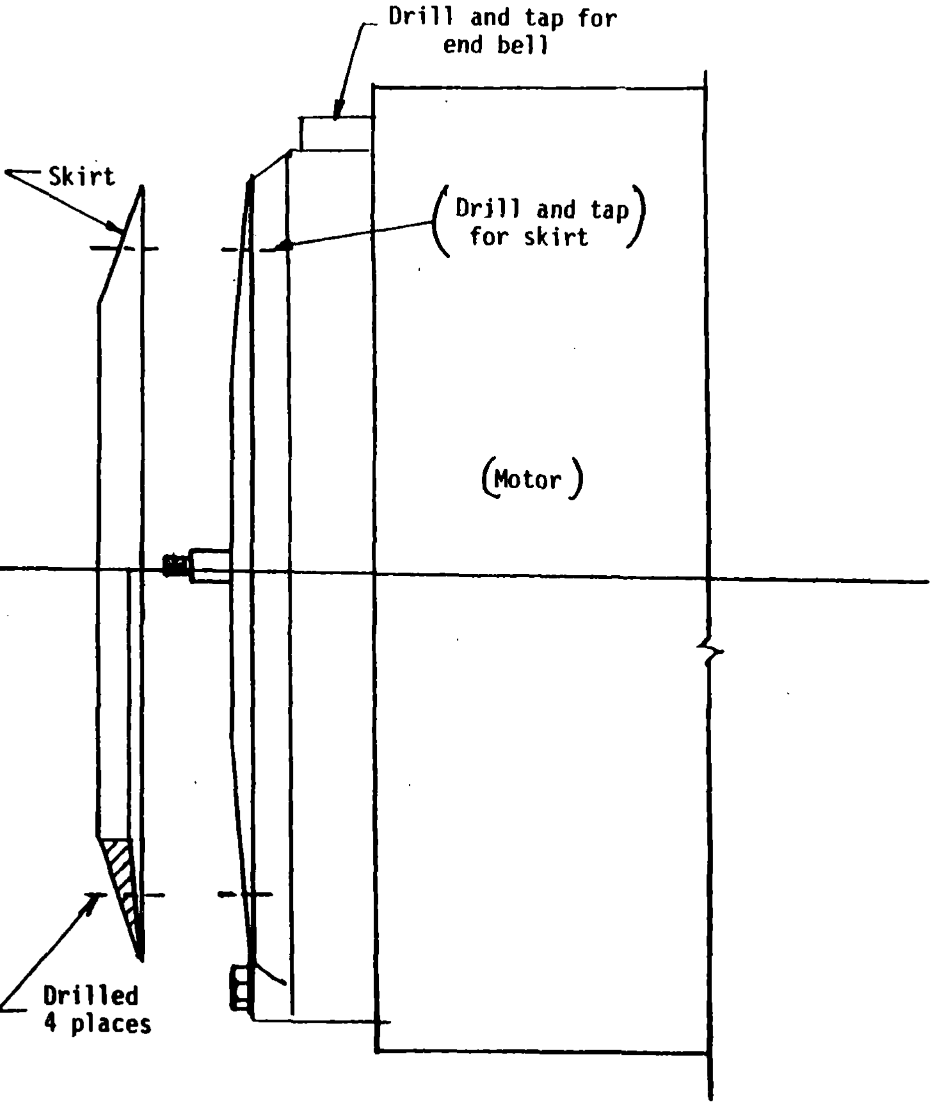
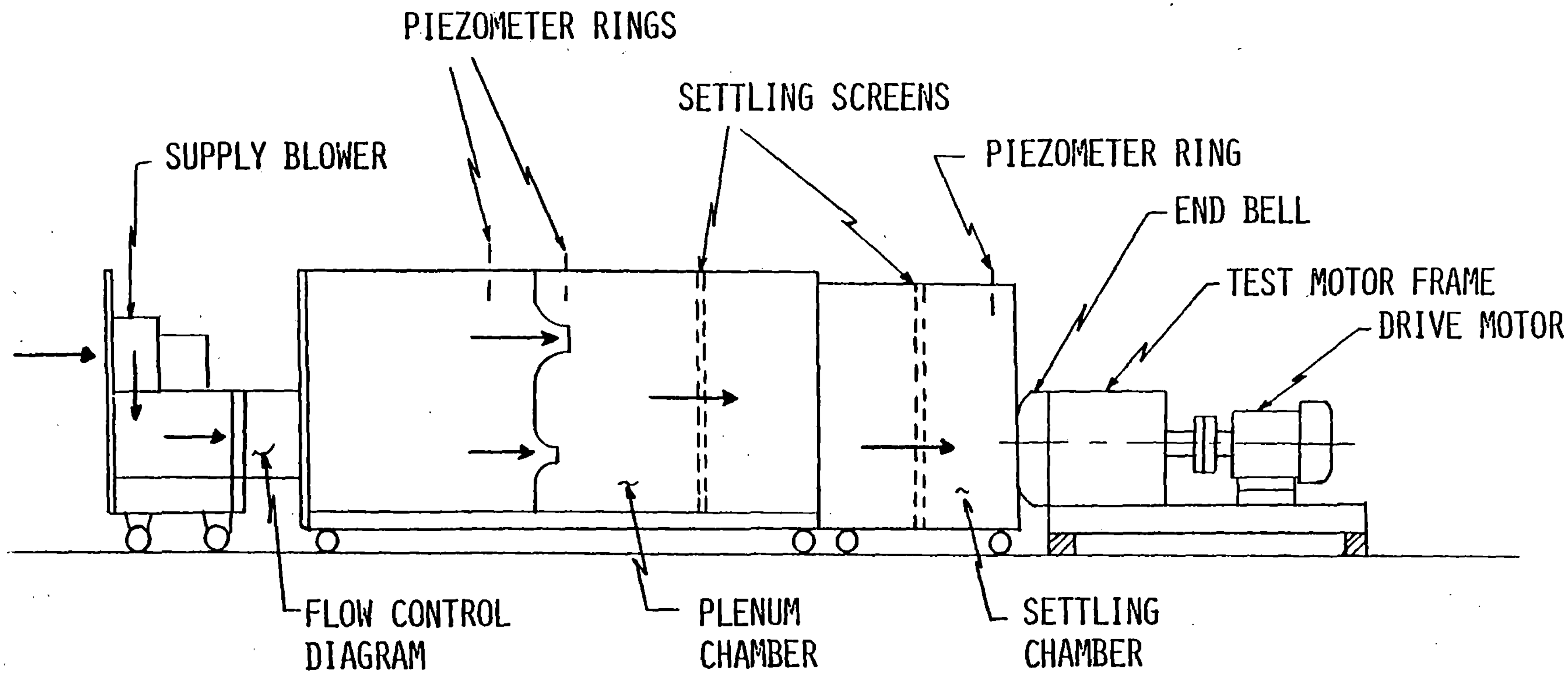


Figure 2-18

Final Fan Design


Drill and tap for end bell
Skirt
Drill and tap for skirt
(Motor)
Drilled 4 places



TRACTION MOTOR BLOWER TEST STAND

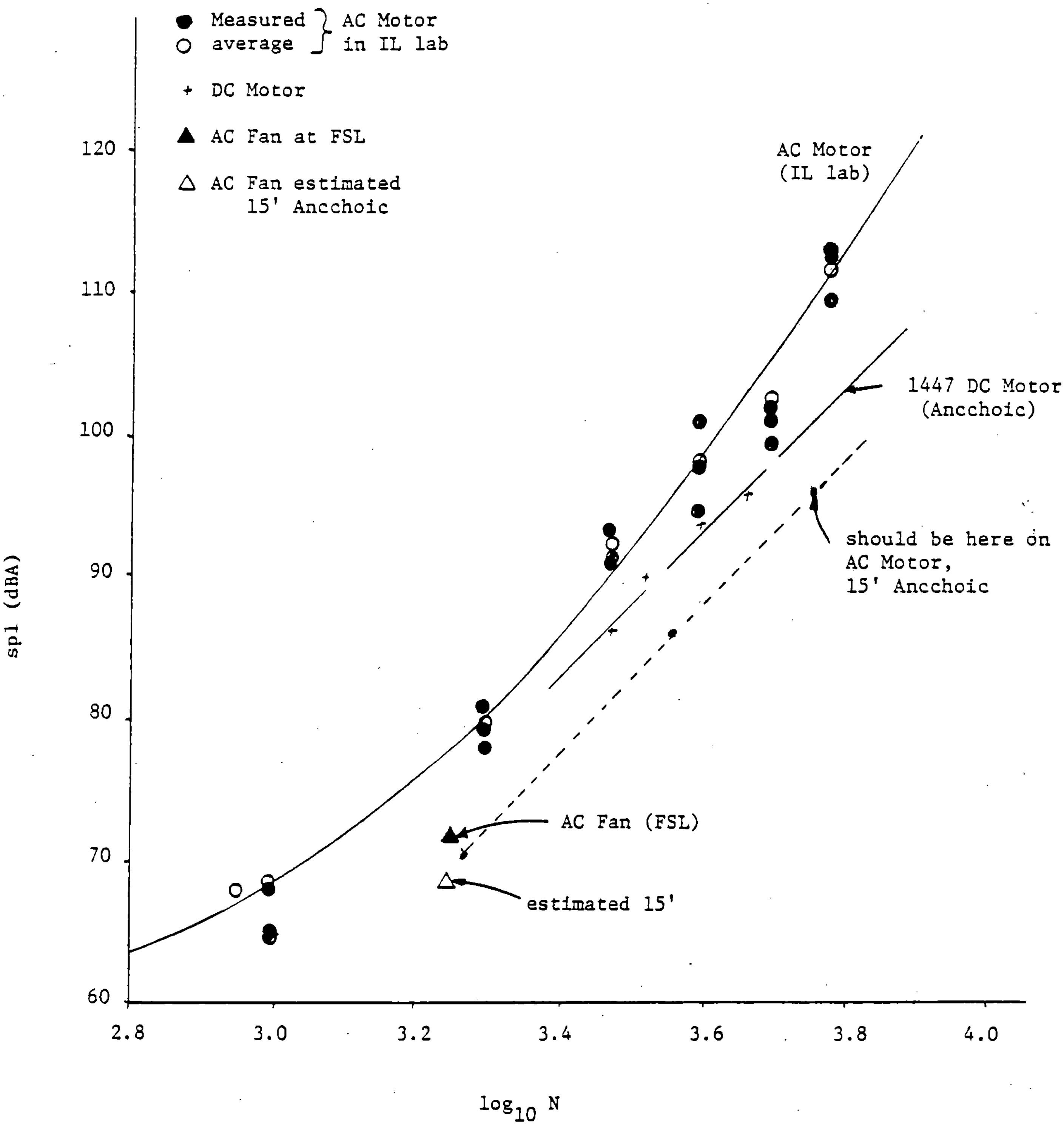
Figure 2-19

After installation of the fan and shroud on the prototype motors it was not possible to determine fan air flow, but motor temperature was obtainable. Initial temperature rise data was obtained. Temperature rises of 130°C for operation at 120 HP and 1343 rpm were obtained which were slightly higher than expected. Inspection of the fan assembly indicated that the fan shroud was not properly fitted and reduced air flow was therefore expected. The shroud was modified to obtain the proper clearance (about 0.12 inches between fan and shoud) and the motor temperature rise decreased to 123°C for 120 hp and 1343 rpm or a reduction of 7°C in rise temperature. This value fit the expected motor temperature for this operating condition. The effect of placing covers over the external fins of the motor frame was investigated to determine if trapping the air within the fins would reduce motor operation temperature. Covers were fabricated and mounted on the motor frame and tested without appreciable improvement in cooling effectiveness.

Noise readings were taken on the combined motor fan assembly at speeds up to 6000 rpm in the 1L test laboratory at the Westinghouse East Pittsburgh site. Results of these tests are plotted in Figure 2-20 and show that the recorded noise levels were quite high in comparison to the expected values due primarily to reflected noise. The data reported in Figure 2-20 compares the AC motor fan to the 1447 DC motor, and the overall level at the two fans, which are similar.

There is no reason to expect one to be much noisier than the other at a given speed if they are the same size (diameter). However, the 1447 motor fan has an outer diameter of about 16 inches, while the AC motor fan has an outer diameter of 11.25 inches. At a given speed, the 1447 fan should be 5 or 6 dBs louder (based on SPL = 10 log $(ND)^5$). The point is that, for a given fan type, higher tip speed should yield higher noise levels.

The noise data was plotted as a function of log N to look for the expected linearity and to estimate the slope of dB-vs-log N. For the 1447 DC fan, the slope is about 5.1 which is reasonable compared to values reported in the literature and shown in Figure 2-20. In the same figure the AC motor fan noise readings taken in the 1L laboratory are shown, and as can be seen it is basically non-linear. The contention that errors due to reverberance and very complicated reflection patterns will increase with power (or speed) seems to



Noise Comparison, AC & DC Motor Noise

Figure 2-20

be borne out by the rapidly increasing slope of the curve. At the low end, the slope is similar to the data for the 1447 DC motor; at 6000 rpm, a slope of 7 or more is indicated, which is much higher than reported data on similar fans.

Also shown in Figure 2-20 is the single point measurement from the Westinghouse Fluid Systems Lab at a speed of 1793 rpm with a raw dBA reading of about 72. It is estimated that a free field measurement at 15 feet should be about 68 dBA. Following a slope parallel to the 1447 DC motor data would give an estimate of 96 dBA at 6000 rpm. This is in agreement with the 5 or 6 dB estimated difference between the DC and AC fans based on diameters. This analysis indicates that for accurate test results the noise test should be repeated in more appropriate surroundings such as an anechoic chamber or a laboratory which approaches free field conditions. Therefore noise levels are expected to be in the range of 96 dBA at 6000 rpm (80 mph) and 90 dBA at 4500 rpm (60 mph).

2.4 MECHANICAL DESIGN

A brazed copper rotor design was initially chosen for the prototype motors. Fifty copper bars are inserted into slots in the rotor punchings and anchored in place by mechanically upsetting the rotor bars and rotor teeth in the center of the rotor. Copper and rings are brazed to the ends of the rotor bars to form the cage circuit. The rotor punchings are keyed and pressed onto the shaft which has a tapered drive extension for mounting to the gear box and a threaded and keyed fan extension to drive the blower.

The effect of skewing the rotor bars of a motor is known to reduce noise effect generated by the interaction of the stator coil and rotor bars. In a standard rotor (no skewing) the entire length of the rotor bar is being acted on by the flux field of the opposing stator slot. As the rotor rotates by attraction to the stator slots the possibility of increased noise can occur by the rotor bar to stator slot magnetic field orientation changes. This effect can be minimized by the design of slot configuration and number of stator slots, rotor bars and air gap. These effects were factored into the design of the original three brazed copper rotor motor designs to minimize noise effects.

Of the original three motors one of the rotors was constructed with a skewed rotor. The effect of a skewed rotor is that the rotor bar is being influenced by more than one stator slot at any particular time. The interaction of more than one stator slot tends to reduce the noise associated with the magnetic field orientation changes. Another advantage of the skewed rotor is that the motor torque pulsations due to the magnetic field change as rotor bar pass by stator slot is reduced. A standard rotor (straight bars) would have a small pulse torque imposed on the steady state torque condition. This condition of torque pulsing and noise are related and can therefore be reduced by the design conditions of slot configuration, number of slots and air gap.

When testing was performed on the three original motors no noticeable effect was found between the straight rotors and skewed rotor. However, no direct measurements were taken to determine noise variations or torque pulsations. In order to accurately determine these effects, noise level reading in an anechoic chamber would be required as well as highly sophisticated torque measurements. Since no noticable effect was found on the system tests, it is felt that no real advantage is obtained by the added operation of skewing the rotor for the system under consideration.

The stator of the machine consists of a stacked, laminated core which is pressed into a cast nodular iron frame. The 445T frame which was used is a commercially available frame which will require only slight mounting modifications for actual traction application. The form wound coils are wound into the core, arch bound with impregnated dacron pads and wedged into the slots to form a solid, mechanically rigid winding.

The end brackets of the motor are attached to the motor frame with 9 mounting bolts and are supported with a machined fit.

Bearings that are presently in use on the Westinghouse DC traction motor line were found to be suitable for this application as well. A 65 mm roller bearing was chosen for the drive end and a 45 mm ball bearing for the non-drive end. The maximum rated speed for the bearings with our anticipated loads is 9000 RPM. The bearings that were chosen have an excellent service record in transit applications.

Figure 2-21 shows an outline of the AC traction motor with shroud installed. A photograph was shown in Figure ES-2.

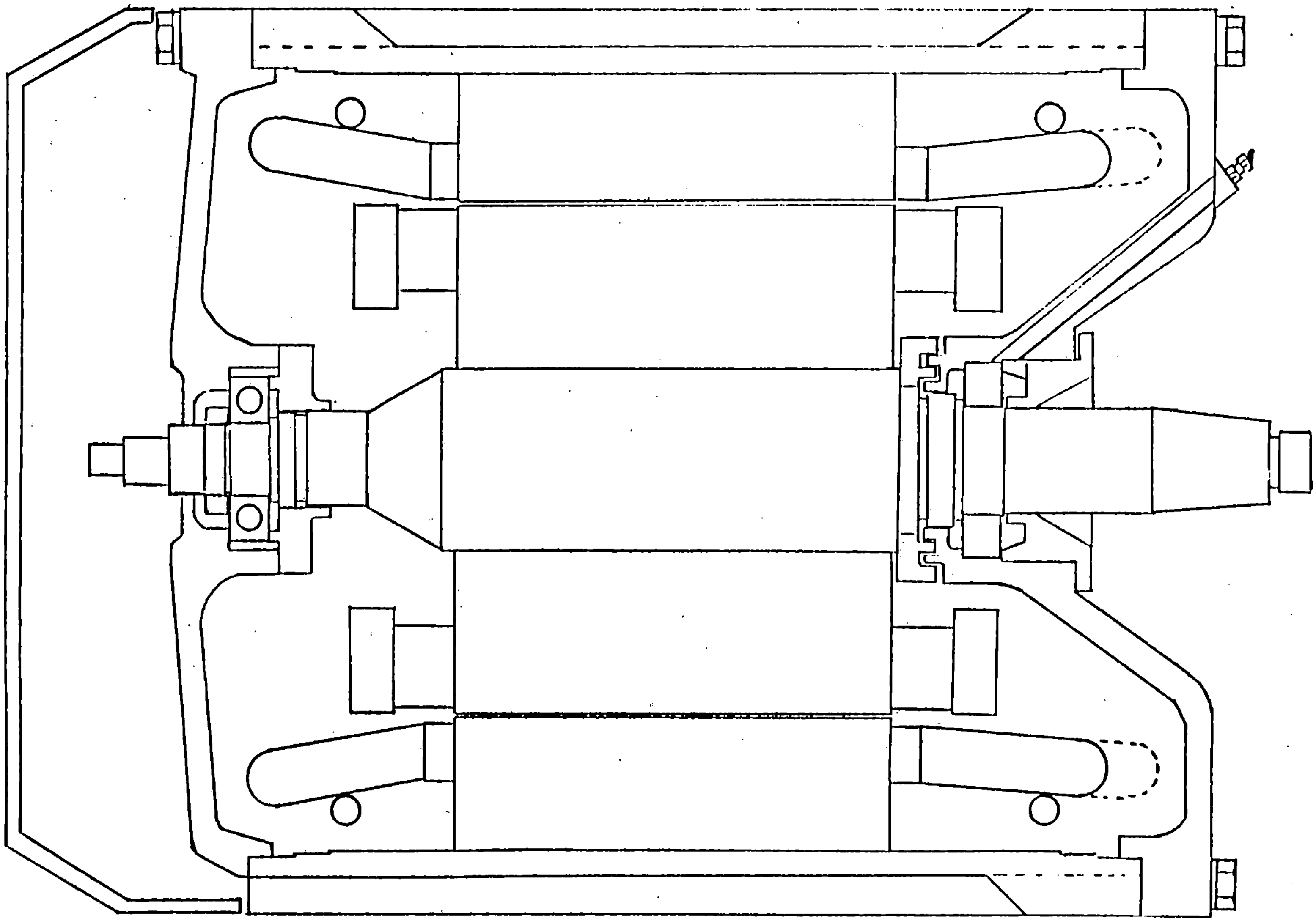


Figure 2-21

AC Motor Outline

During equipment testing, the motor end rings expanded at 6000 RPM and rubbed the stator windings causing a failure. Investigation showed that an incorrect end ring alloy had been provided which did not possess adequate strength. Initially, we planned to rebuild the rotors using the specified copper bars and a brass end ring in place of the originally supplied copper end ring. However, the low slip of the motor made control difficult so the decision was made to replace the copper rotor with a higher slip, cast aluminum rotor. The increased losses present with the aluminum rotor required that the motor rating be reduced as well.

2.5 TEST RESULTS

2.5.1 Temperature Tests

One of the prototype motors was extensively instrumented with thermocouples to provide detailed temperature rise data throughout the machine. Figure 2-22 provides a general location map for the thermocouples while Figures 2-23 and 2-24 show the actual thermocouples in place in a punching stack before pressing into the frame.

Temperature tests were completed on the instrumented prototype at a load of 120 HP at 1343 rpm. Figure 2-25 shows the temperature distribution in the motor at this load. Analysis of the data indicates that operation of this machine at 190 HP without modification would result in a temperature rise of approximately 194°C which exceeds the allowable rise of 170°C rise (by resistance measurement) by 24°C. However, the stator punchings that were employed contained flat spots to increase the material yield during punching. These flat spots effectively eliminate 50% of the backiron to frame contact and thereby double the temperature rise between the frame and stator iron compared to a round punching. This effect is clearly seen in Figure 2-25 when one compares temperatures on the 45° angle which are over the round portion of the punching to the temperature rises on the vertical and horizontal axes which are over the punching flats. Use of round punchings should result in a temperature rise of 169°C at 190 HP, 1343 RPM with the rest of the motor unchanged which is within the allowable 170°C rise.

During motor testing, as noted earlier, the decision was made to replace the copper cage rotor with a cast aluminum rotor to improve stability and speed

General location for thermocouples on instrumented motor.

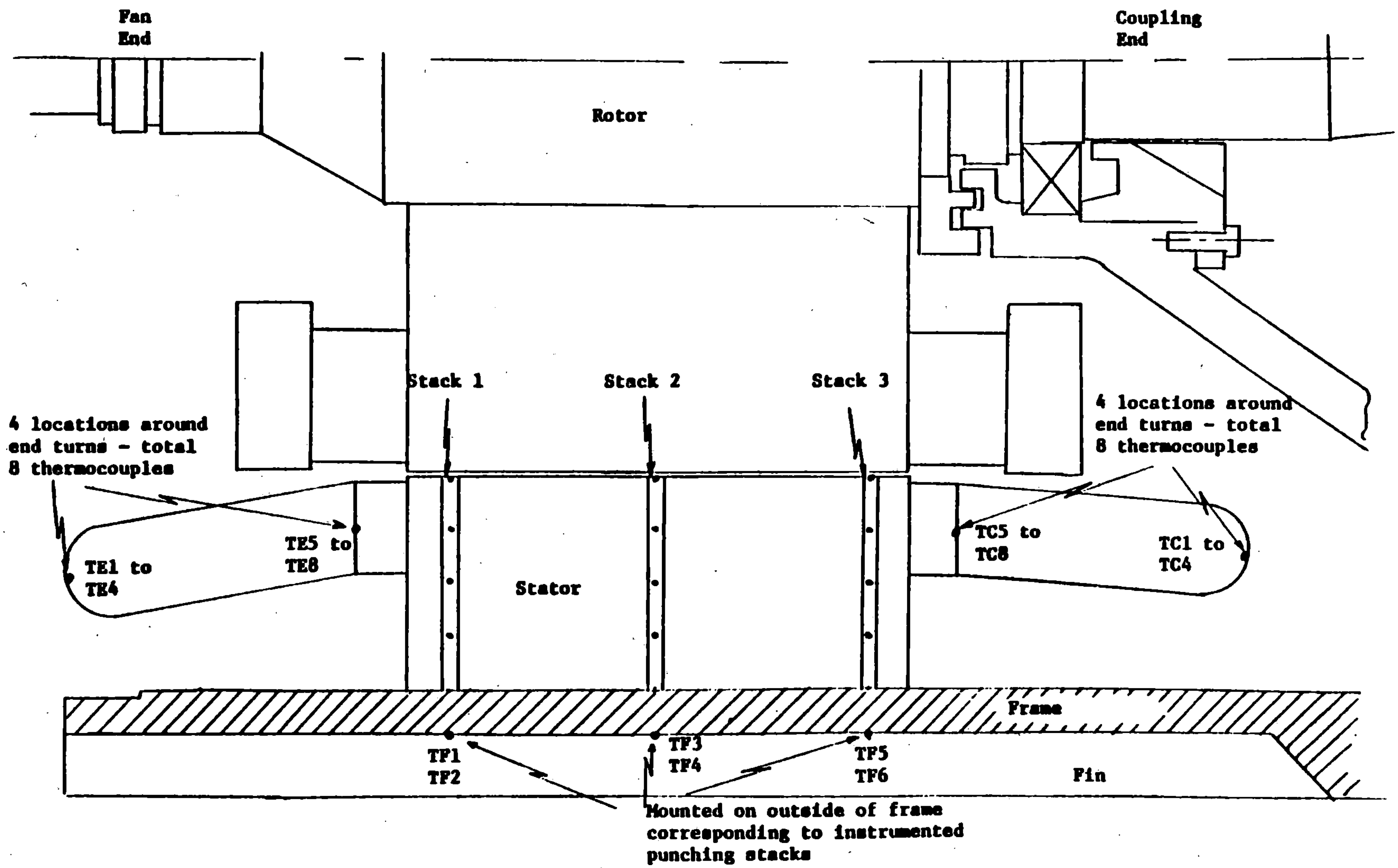


Figure 2-22
Thermocouple Locations on Instrumented Motor

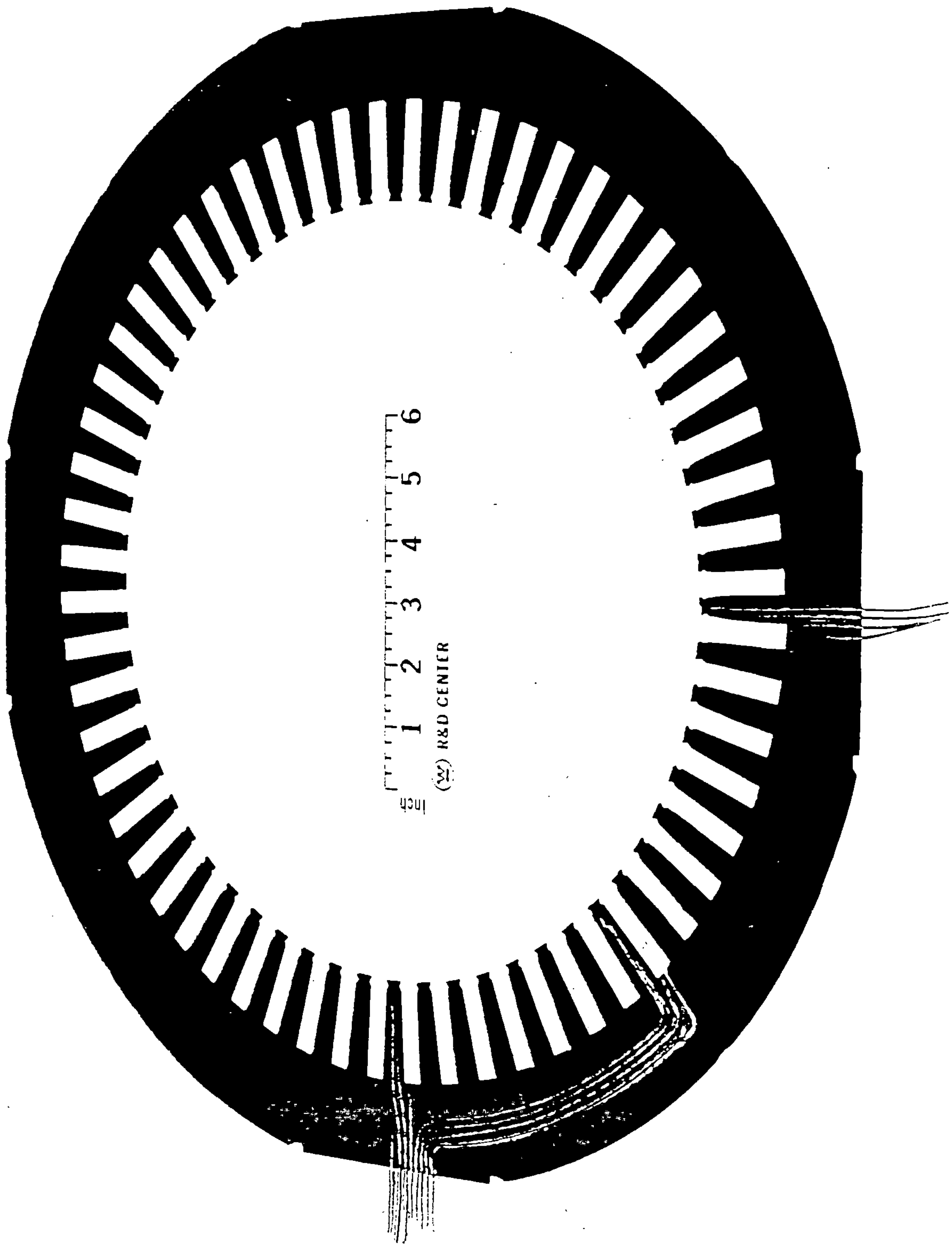


Figure 2-23

Stator Punching with Thermocouples in Place

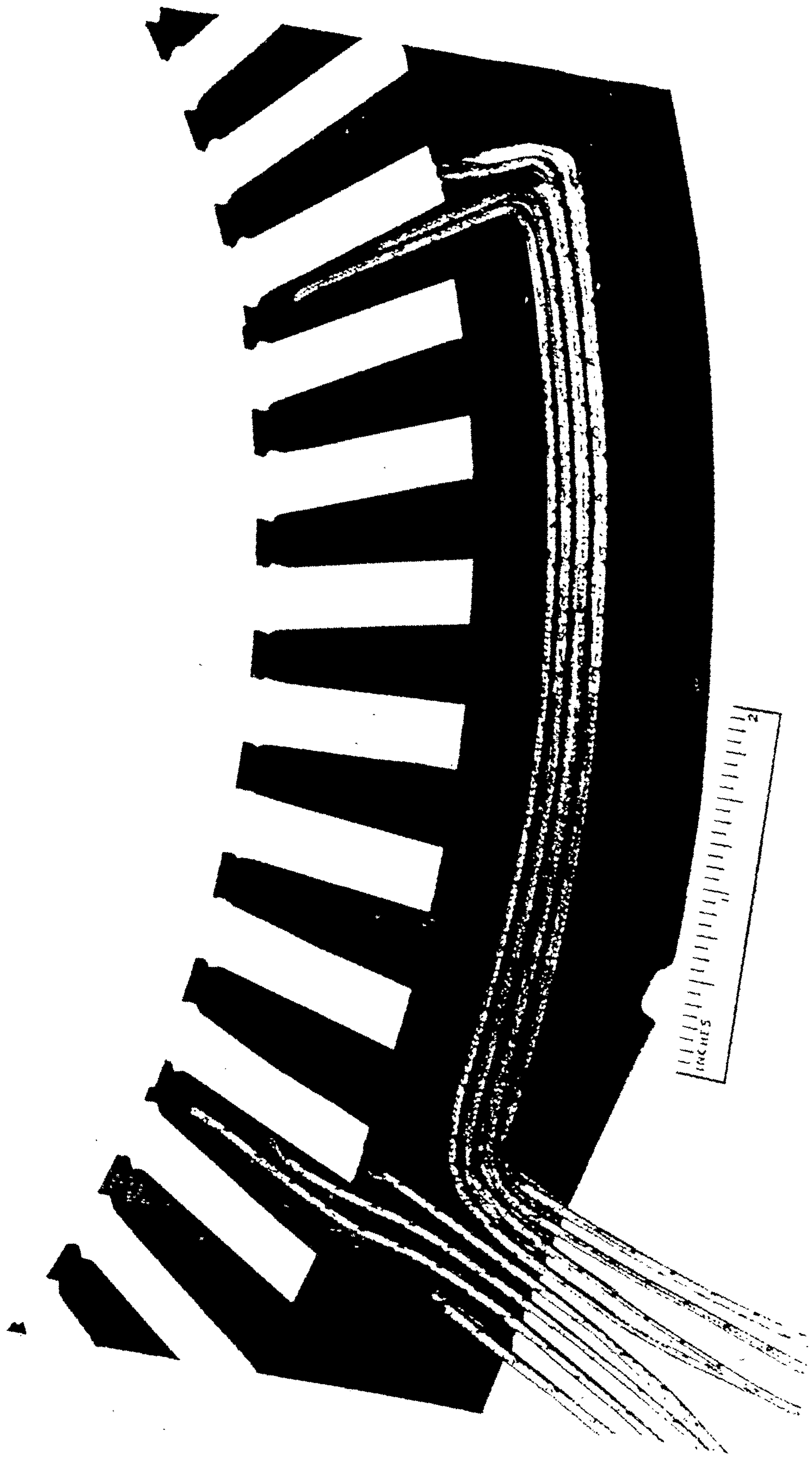


Figure 2-24
Close-Up of Thermocouples in Stator Iron

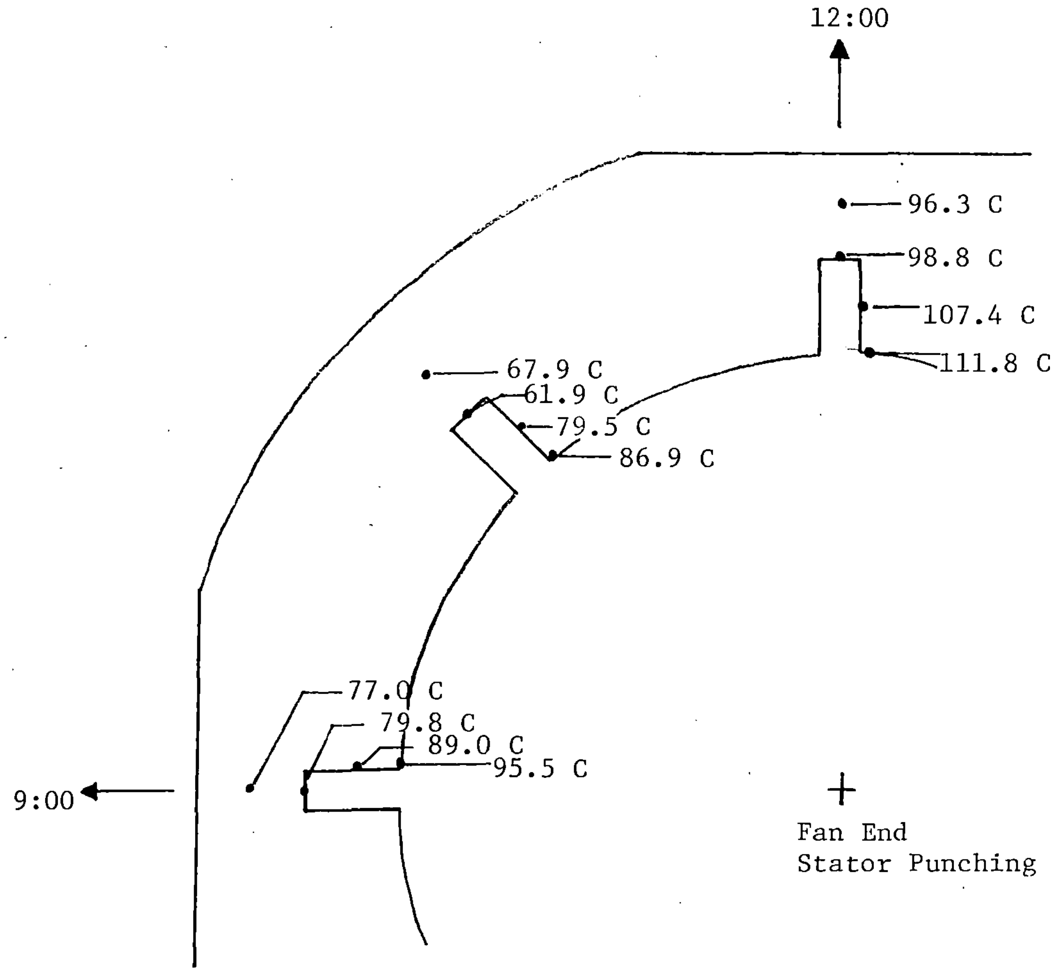


Figure 2-25

Temperature Rise Distribution at 120 HP, 1343 RPM with Copper Rotor replacement of the damaged rotors. The control system engineers requested that the rotor be redesigned as follows:

1. Increase slip from 0.7% to 3.5% at 125 HP.
2. Modify design to prevent end ring growth due to high speed operation.

After detailed study, it was found that the best way to achieve these goals was to use a cast aluminum rotor. The material selected has 30% conductivity and is a high strength alloy.

To save time, the motor manufacturer used an existing mold to cast the aluminum rotor. This mold included fins which were machined off in order to get the right end ring resistance.

The lower conductivity rotor required that the motor be derated from 190 HP to 125 HP, which is still more than adequate for the application.

The manufacturer ran a temperature test at 125 HP with the new medium loss, medium slip rotor. The temperature rise by resistance was 159°C which represents a 36°C increase in temperature over the copper rotor. However, this is well within the thermal limits for Class H insulation. Grease was observed to be leaking out of the bearing during this test. This is due to the higher rotor temperatures. The grease grade was changed to correct this problem.

Temperature tests were also run simulating operating on the RR Line of NYCTA. Under these operating conditions the motor end turn temperature rise was 99.3°C. This is quite cool and shows that the motor is designed for heavier duty than the RR Line requires.

2.5.2 Noise Tests

Due to equipment limitations, it was not possible to test this motor and fan at 6,000 RPM in an anechoic chamber. Hence, an analytical study was undertaken as detailed earlier to predict noise level based on test data on hand. The noise level predicted by this study is 96 dBA at 6,000 rpm and 15 feet in an anechoic chamber. This, unfortunately, exceeds the design goal of 90 dBA, but compares favorably with current DC traction motor fan designs. Also note that a noise level in excess of the design goal only occurs at speeds in excess of 60 mph, which are not seen in NYCTA RR Line duty.

2.6 CONCLUSIONS

Testing has demonstrated that the TEFC motor presented here is satisfactory for use in NYCTA service, and in fact has thermal margin remaining for this application.

The motor was built as a TEFC which has the advantage of environmental protection. However, a drip-proof motor design would have the following advantages:

1. Lower weight (aproximately 350 lbs. less, or about a 20% reduction)
2. Smaller size
3. Cooler operation
4. Lower cost

All of the present DC motors in NYCTA service are drip proof and a drip proof induction motor can be expected to perform better than the DC machine since it has no commutator or brushes.

Figure 2-26 summarizes the characteristics of the final motor configuration which was tested during DOT witness tests in September 1984. This motor meets or exceeds all requirements of the DOT contract with the possible exception of fan noise.

In concluding, it is apparent that more work is needed to address the concern of fan noise. The high airflow requirement of a totally-enclosed motor is the key reason, along with the fact that a shaft fan must supply sufficient cooling airflow at less than maximum speed, and must therefore deliver an even higher airflow at maximum speed. It is at or near maximum speed that the fan noise becomes of concern.

With a drip-proof motor frame, fan noise would not be as significant a problem, since lower airflow is required.

	Final
Stator:	
Diameter	19.0 in.
Length	10.75 in.
Slots	60 rectangular
Winding	Form wound, Y connected
Rotor:	
Diameter	12.36 in.
Length	10.75 in.
Slots	50 rectangular
Bars and Rings	Cast aluminum
Single Air Gap	.070 in.
Base Speed Design Parameters (45Hz, 2.5 mph/s tractive effort):	
Power Out	125 hp***
Speed	1303 rpm
Losses	10.52
Efficiency	89.9%
Power Factor	74.6%
Line Voltage	420 V rms
Line Current	190 A rms
Torque	502 ft. lb.

* Design goal - not a requirement for NYCTA application.

** Based on tests.

FINAL MOTOR CONFIGURATION

FIGURE 2-26

3. GTO-BASED PWM INVERTER

Until recently, the thyristor was the only device available for use in either high power DC or AC motor drives. Approximately four years ago, high power GTOs became available and are now being incorporated in drive systems. The thyristor's dominant position is being challenged by the cost, efficiency and reliability advantages offered by the GTO. The GTO device itself is more costly and has slightly higher losses than a thryistor, however, when the cost and losses of auxiliary components required to obtain proper switching operation are considered, the GTO displays an advantage. The additional complexity of the thyristor circuit compared to that of the GTO not only effects cost and losses, but also reduces the reliability of the thyristor approach.

Although GTOs were initially introduced by Westinghouse approximately 17 years ago, the device at that time did not have sufficiently superior characteristics to attract widespread application. It was not until Japanese manufacturers undertook GTO development that a commercially attractive device was produced and marketed. Within the last four years, the available GTO ratings have increased significantly and device costs are continually falling. Compared to the thyristor, which is now a mature product offering only marginal future improvements and a fixed price structure, the full potential of GTOs is yet to be realized and further significant improvements in ratings, characteristics and costs are expected. For these reasons, the GTO is the preferred device for fulfilling the requirements of advanced AC propulsion systems.

An objective analysis of a wide variety of alternative AC drive system approaches indicated that when all things were considered, a direct fed GTO PWM voltage source inverter driving a single AC motor resulted in a system with the lowest size, weight, and cost, and the highest efficiency. Other considerations which favor the use of one motor per inverter are:

- Use of a single inverter per motor eliminates all problems and penalties associated with wheel mismatch.

- A lower rating, smaller inverter which will be built in larger numbers is more amendable to lower cost and more standardization in fabrication.

- Maintenance, service, and repair will likely be less costly on smaller inverter packages.

- Overall improvement in car availability since a failure of the inverter/motor will result in loss of only one-fourth of propulsion capability.

- More universal applicability to various system properties with less custom design and modification.

Based on the preceding considerations, the inverter approach selected to meet the requirements for an AC propulsion system is a GTO inverter operated directly from the DC supply voltage. This approach meets all performance requirements and offers significant advantages over other alternative systems which were considered.

A simplified block diagram of the selected system for demonstration of AC propulsion, which includes a direct fed GTO-PWM inverter is shown in Figure 3-1. In the selected approach, the inverter sizing is largely determined by motoring rather than braking requirements, since the braking circuit handles the additional power generated when up to full rate braking is provided above base speed. A schematic diagram of the main power circuit for one motor is shown in Figure 3-2.

3.1 DESIGN OBJECTIVES

The general requirements and objectives described here also apply for the regenerative and dynamic brake circuits covered in Section 4.

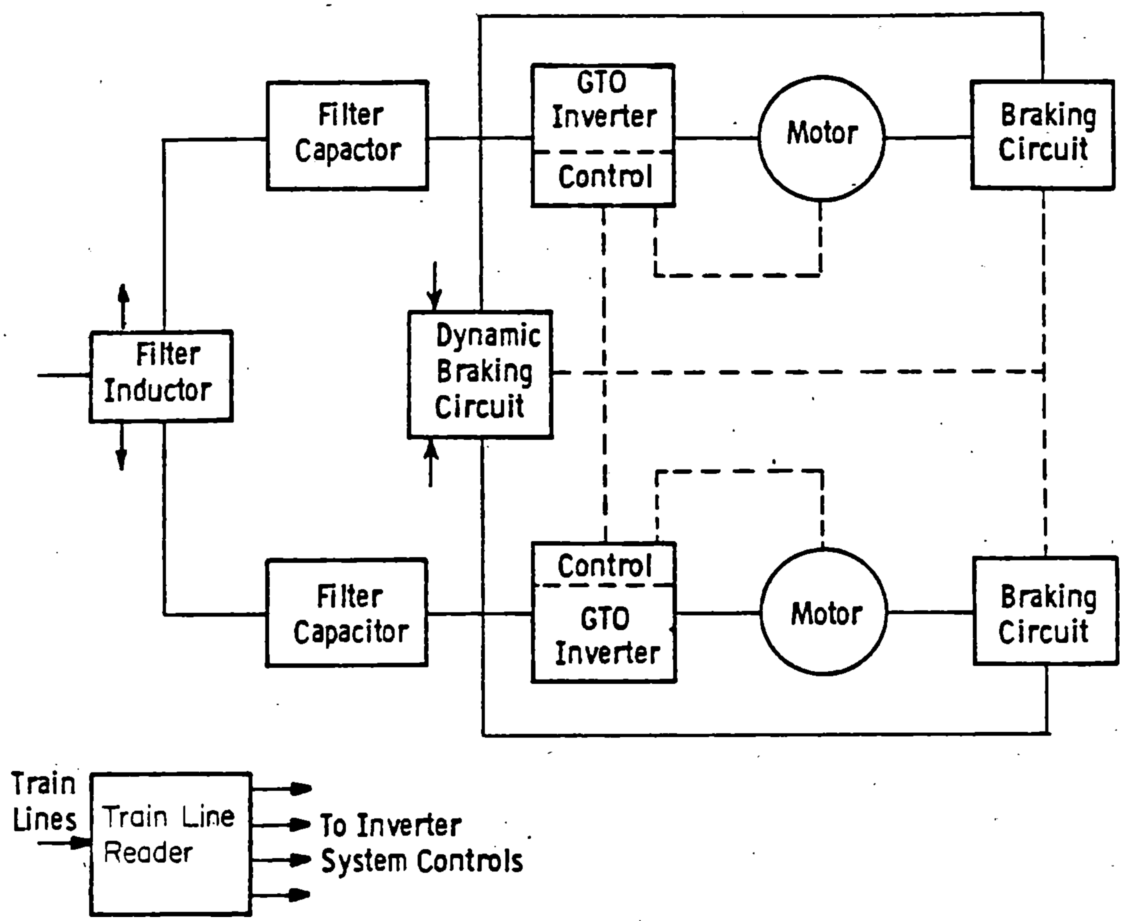


Figure 3-1

Selected System for Demonstration of AC Propulsion
(Shown for one truck)

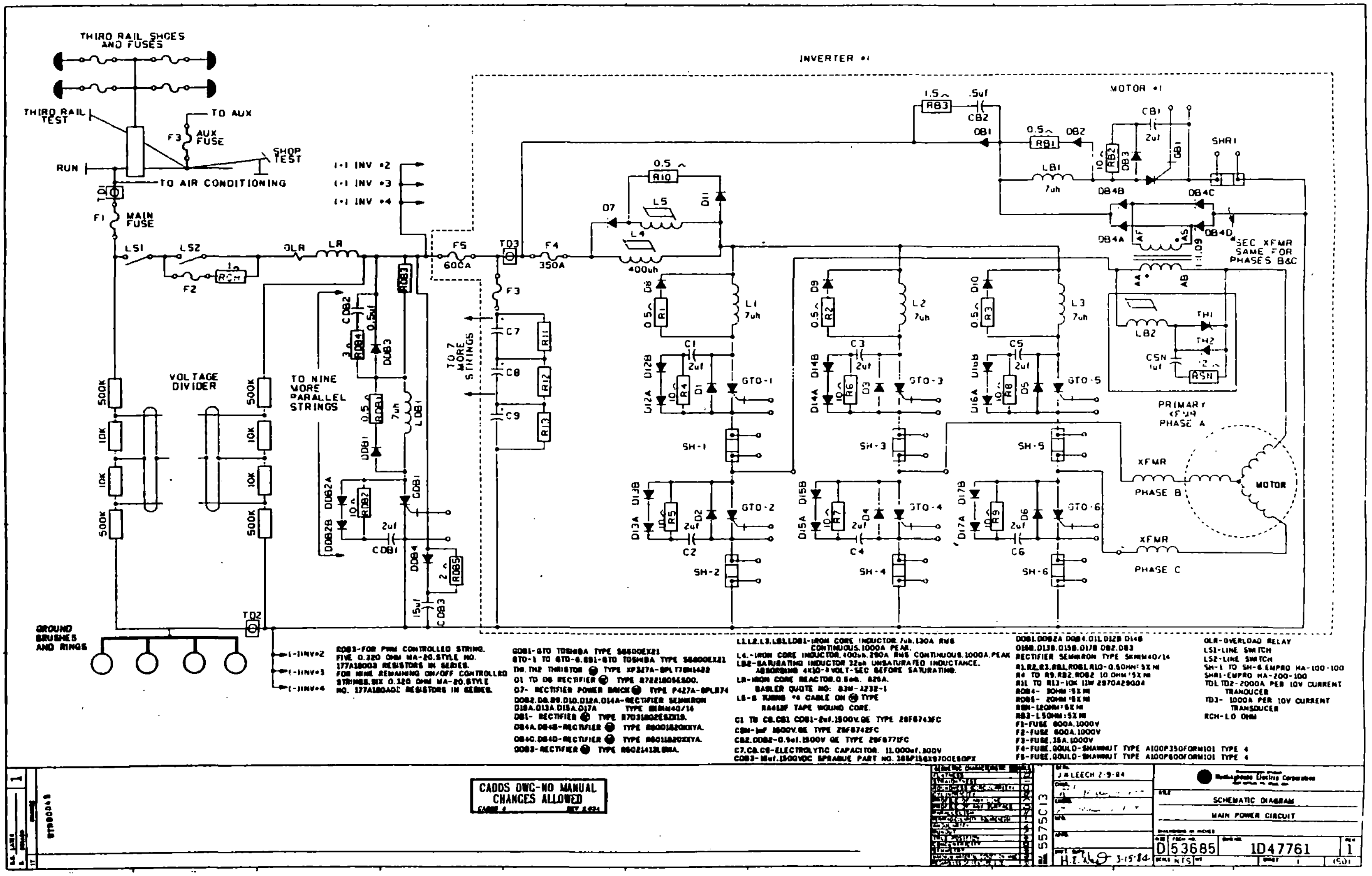


Figure 3-2

Main Power Schematic

3.1.1 Primary Electrical Power

The designed inverter operating input voltage range is 425 VDC to 750 VDC. Nominal operating voltage at which car performance is specified is 600 VDC. The inverter controller protects the inverter from excursions outside this range by shutting off the inverter. Transient voltages on the order of 3000 volts can appear on the third rail. The propulsion system input filter is sized so that in the event of a large transient voltage on the third rail, the transient voltage at the output of the input filter (filter capacitor voltage) is limited to 1350 volts by the zener like breakdown characteristic of the aluminum electrolytic input filter capacitors. The minimum value of DC link filter capacitance and in turn the minimum number of input filter capacitor cans is defined by limits imposed on induced harmonic currents in the third rail at train signaling frequencies. The minimum number of cans required to ensure non-interference with train signaling is more than enough to absorb the energy contained in a worst case line transient and to handle the inverter ripple current. The inverter device voltage ratings are selected to safely withstand at least a 1400 volt inverter input voltage transient with the inverter shut off.

3.1.2 Duty Cycle

The typical duty cycle for the propulsion system is required to conform to the NYCTA "RR" line loading. The average duty of the 77th to 86th street run on the "RR" line is virtually equivalent to the average of the entire "RR" line loading. In addition to handling the typical duty cycle, the equipment should be capable of handling a braking cycle from 80 mph, which begins with a maximum braking rate of 2.3 mphps at 80 mph, linearly increases to 3 mphps at 50 mph, and holds at 3 mphps below 50 mph. A linearized speed vs. time characteristic of the 77th to 86th street typical run is given in Figure 3-3. Repeating 77th to 86th street runs and an 80 mph braking run were used to evaluate inverter component current, switching frequency, and power dissipation versus time for the purpose of sizing power system components and for determining cooling and packaging requirements.

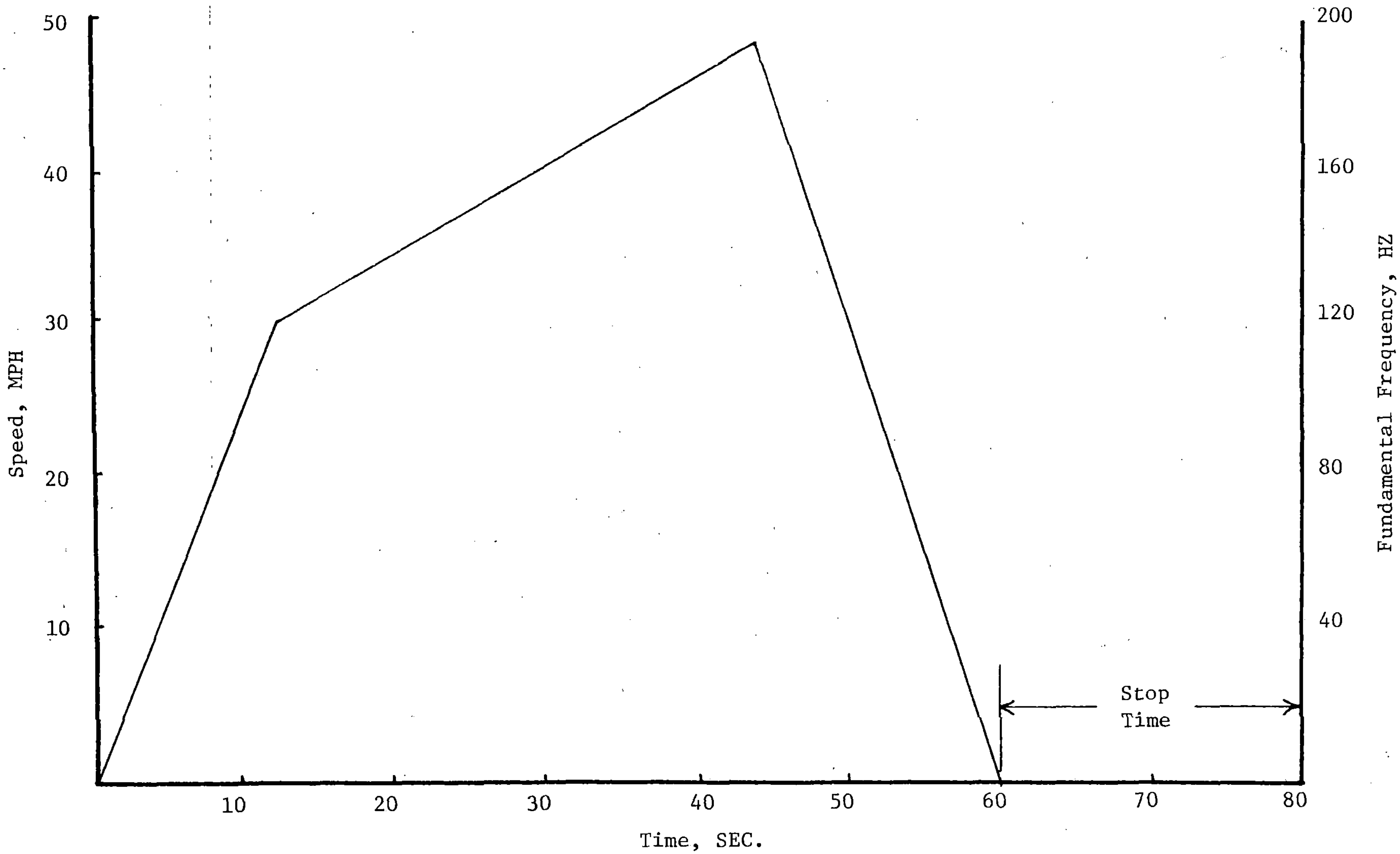


Figure 3-3

Linearized Speed vs Time
(Typical NYCTA 77th to 86th Street Run)

3.1.3 Power Semiconductor Design Safety Factors

1. Under normal operating conditions, power semiconductors in general are to have approximately a 50% safety factor on breakdown voltage.

2. The choice of power semiconductor current rating and cooling requirements is based on obtaining both at least a 10°C margin on maximum allowed operating junction temperature and a cycling junction temperature variation (ΔT) of 40°C maximum.

3.2 PACKAGING OBJECTIVE

The packaging approach chosen for the propulsion system power circuitry does not employ forced air cooling. The undercar mounted power equipment boxes contain finned heatsinks on the bottom which are cooled by the natural air flow available due to the propulsion of the car. The equipment boxes are dustproof and splashproof to protect the equipment from harsh environments.

3.2.1 Minimum Disruption of Existing Undercar Equipment

An effort was made to mount all AC drive equipment in the space available by removing the motor control box and a set of dynamic brake resistors. The area thus available is approximately 144 inches long by 73 inches wide with a height constraint varying from 17 inches at the side of the car to 39.5 inches towards the middle of the car, as shown in Figure 3-4.

3.2.2 Cooling

- The boxes do not require air flowing through them.
- The system does not require blowers.
- Effort was made to make use of ram air for cooling purposes.
- All heat producing components are mounted on the heat sink to minimize box ambient temperature.

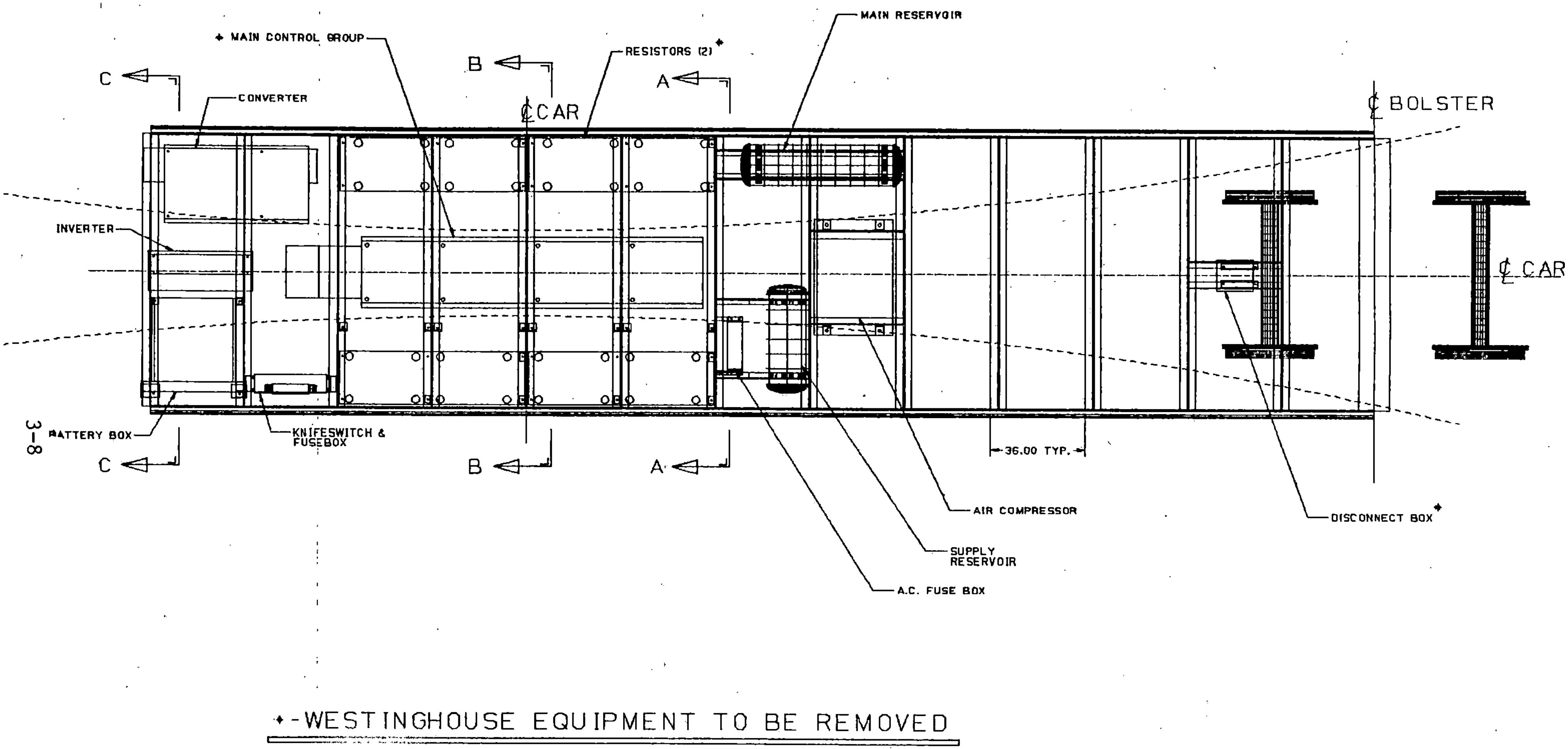


Figure 3-4(a)

Layout of Existing Undercar Equipment

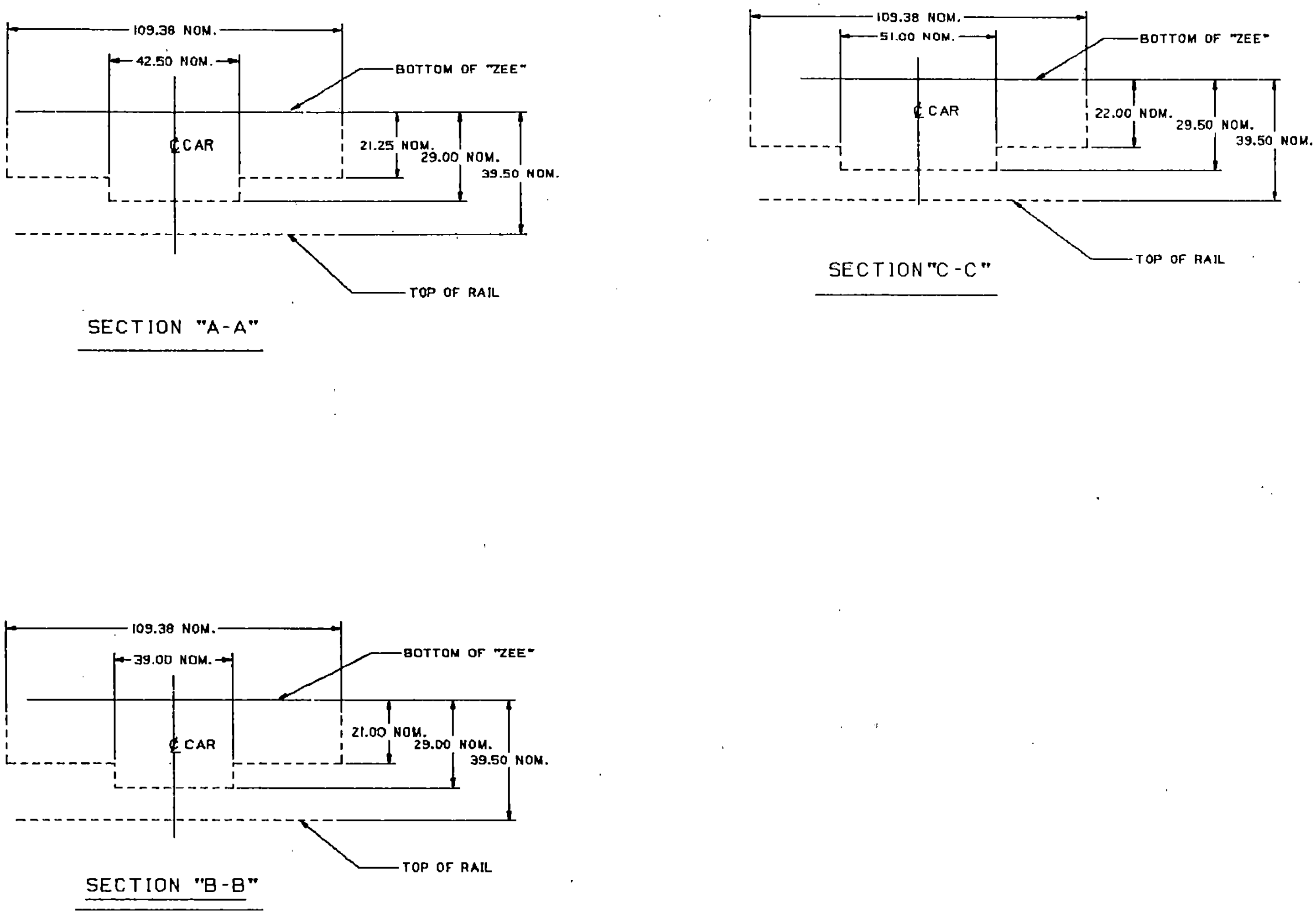


Figure 3-4(b)

Layout of Existing Undercar Equipment

3.2.3 Equipment

Each motor has an independent:

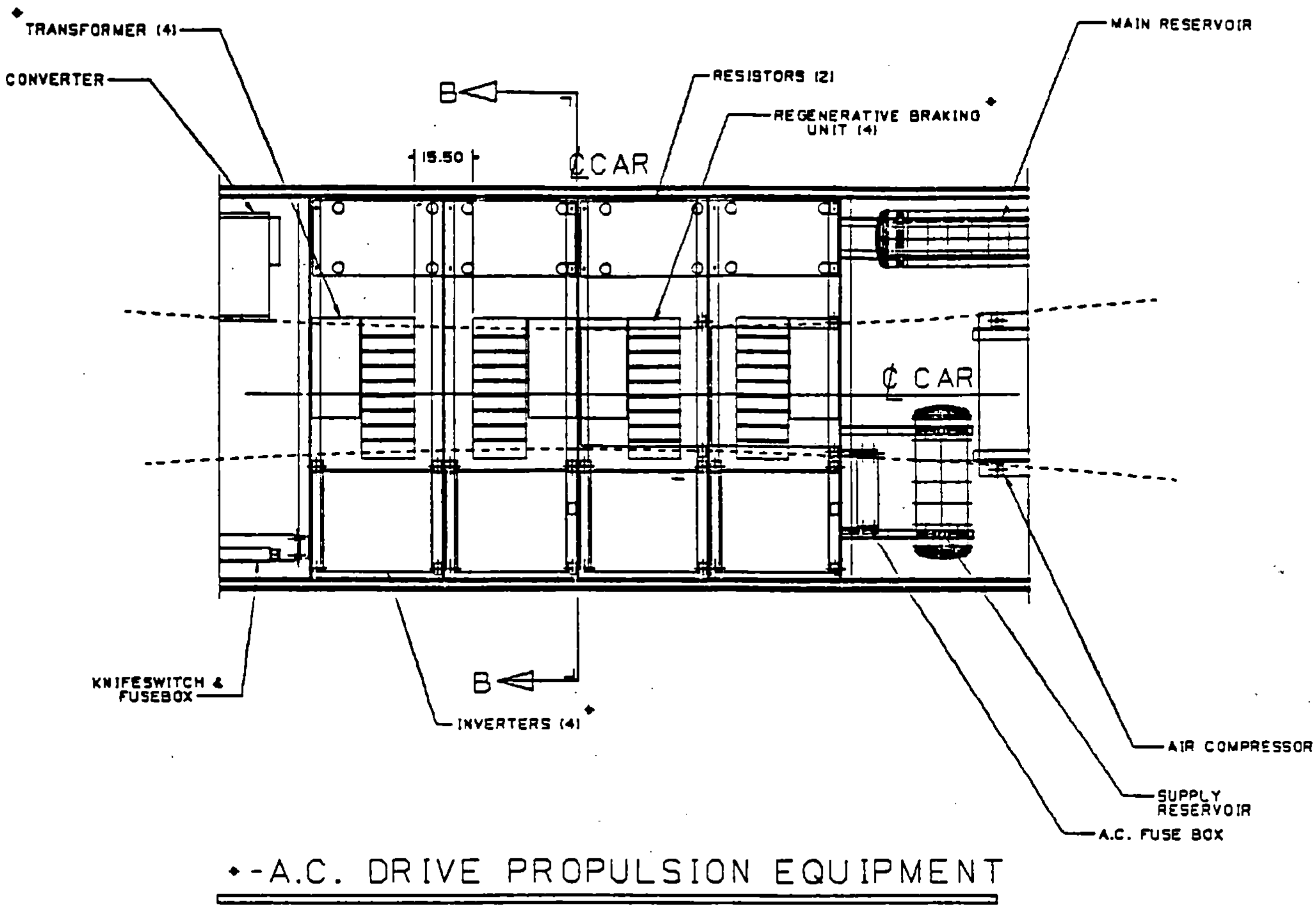
- Inverter Box
- Inverter Reactor
- Regenerative Brake Box
- Braking Transformer

Thus in all there are four inverter boxes, four inverter reactors, four regenerative brake boxes, four braking transformers and one dynamic brake box per car. This equipment is in addition to a line switch, line reactor and dynamic brake resistors which are common for AC and DC systems. The under-car location of this equipment is shown in Figure 3-5.

A half-car set of AC drive equipment was designed, built and tested in the development program. A block diagram of the main power components of this equipment is shown in Figure 3-6. The dynamic braking circuit has been designed to handle requirements for a full car, but at present is fitted to handle a half-car (one truck) set-up.

3.2.4 Service Considerations

The inverter was considered as the component most likely to require maintenance in the system. Therefore, it was decided the inverter should be placed in a location convenient for maintenance, preferably accessible from outside the car. It was also desired to make the inverter a replaceable module to reduce car downtime due to maintenance. Other equipment such as the regenerative unit is considered to be more reliable compared to the inverter. Thus it was decided to locate it in an area not quite as accessible as the inverter.



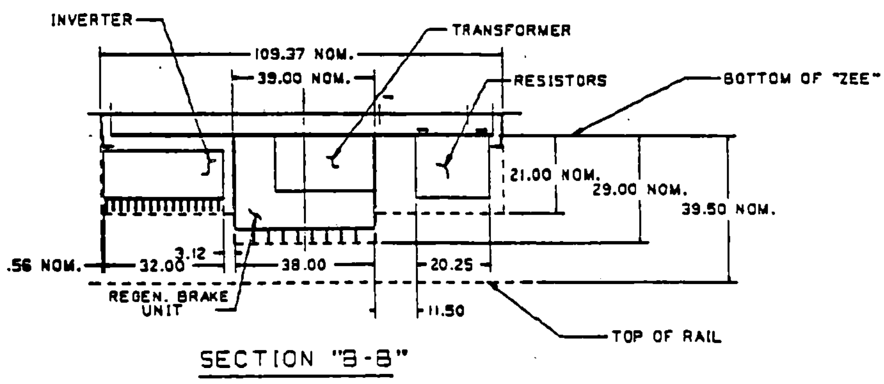


Figure 3-5

AC Drive Equipment Undercar Layout

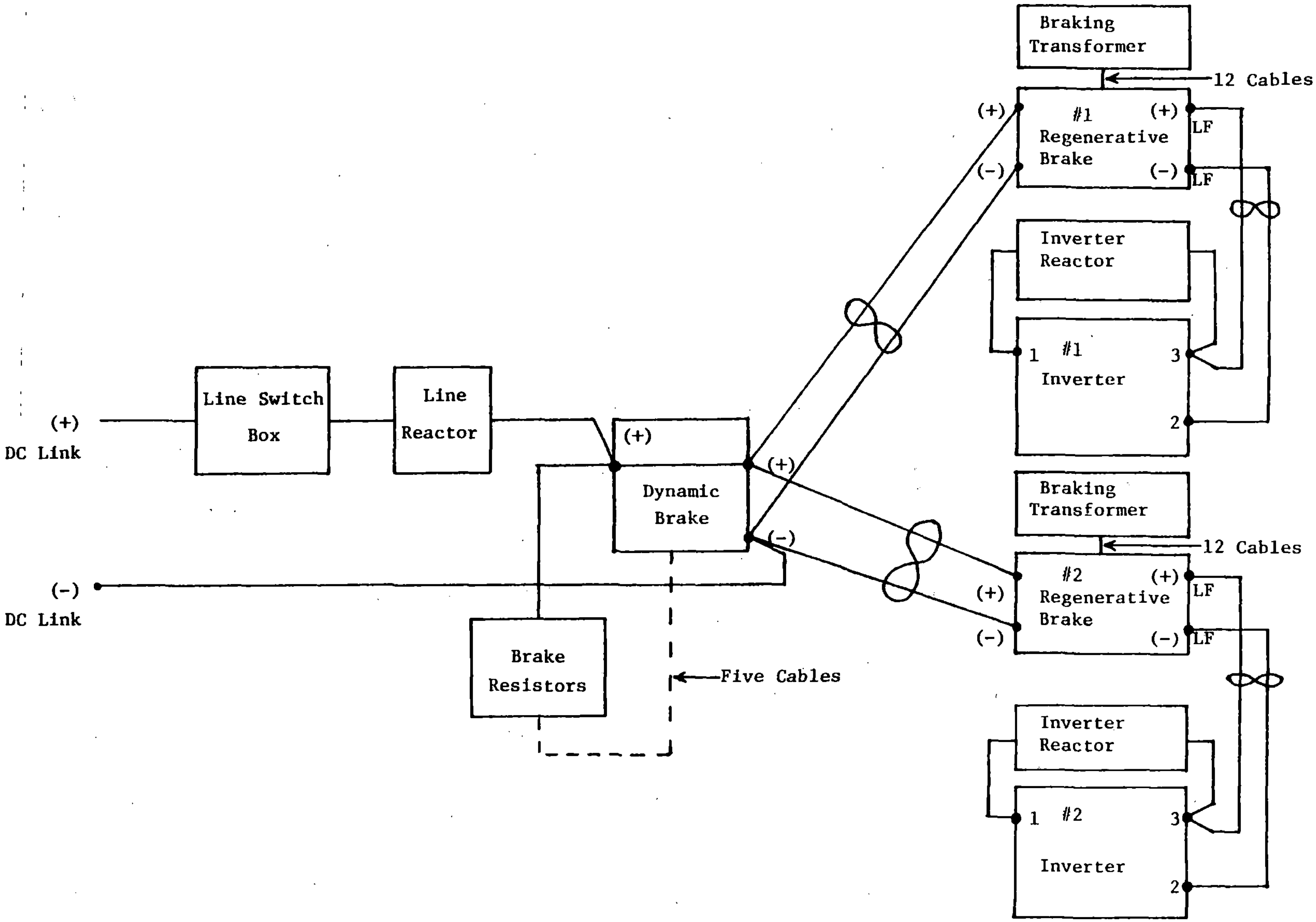


Figure 3-6
Main Power Components for Prototype AC Drive

3.3 POWER CIRCUIT REQUIREMENTS

Power circuit requirements are defined by the DC link voltage and car performance specifications. The motor, described in Section 2, is designed to meet car performance specifications for a 130,000 lb. car at 600 VDC link voltage with a 7.235:1 gear ratio, and 32-3/8 inch diameter wheels.

The required inverter line-to-line fundamental output voltage component versus fundamental output frequency characteristic at 600 VDC link is shown in Figure 3-7(a). Compensation of the inverter output voltage, as a function of motoring or braking load, at low frequencies for voltage drop in the motor stator resistance and leakage reactance to provide constant air gap flux is not shown here for simplicity.

The maximum voltage available from the inverter occurs when the inverter goes into six-step operation (base speed), and is virtually independant of motoring or braking. However the voltage applied to the motor must be increased when operating above inverter base speed to permit full rate braking well above base speed. This increase in voltage is accomplished by a fully regenerative braking circuit, which is described in Section 4. By using a braking circuit it is possible to achieve full-rate braking above inverter base speed with no operating voltage penalty on the inverter and with just a moderate inverter current penalty.

Figure 3-7(b) shows the maximum fundamental inverter line current component versus fundamental frequency requirement in motoring and braking. The higher current in braking than in motoring up to inverter base speed is due to the fact that the required braking rate is 3 mphps while the required motoring rate is 2.5 mphps. Above 125 Hz (50 mph) the maximum braking rate linearly tapers to 2.3 mphps at 200 Hz (80 mph).

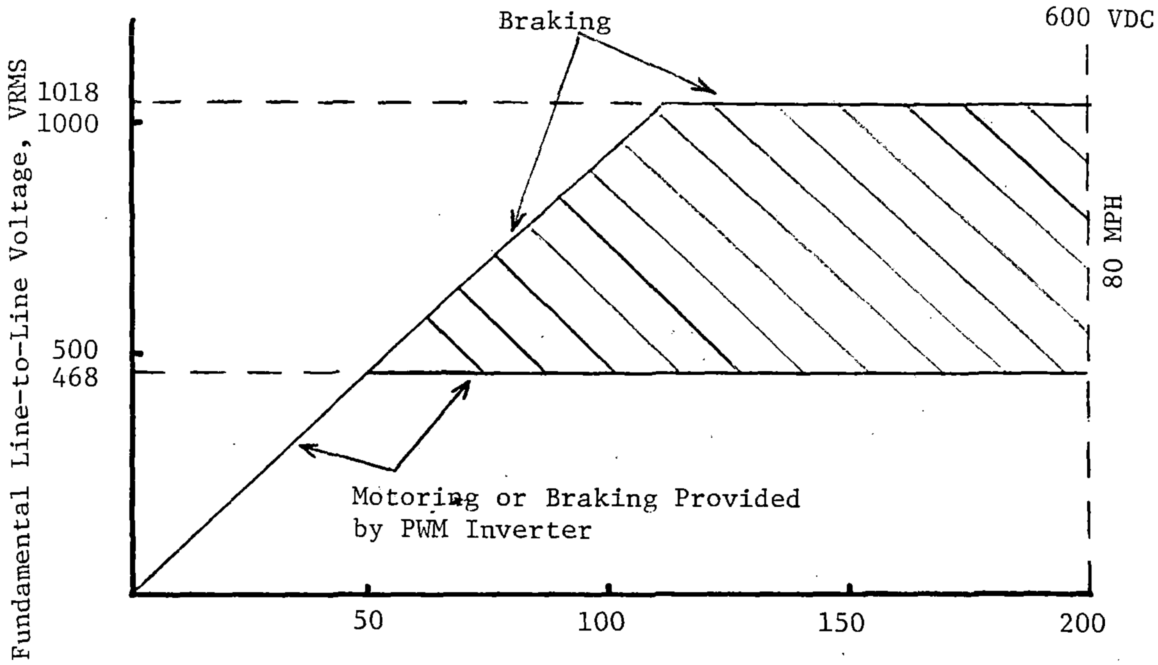


Figure 3-7(a)

Inverter Line Voltage versus Fundamental Frequency

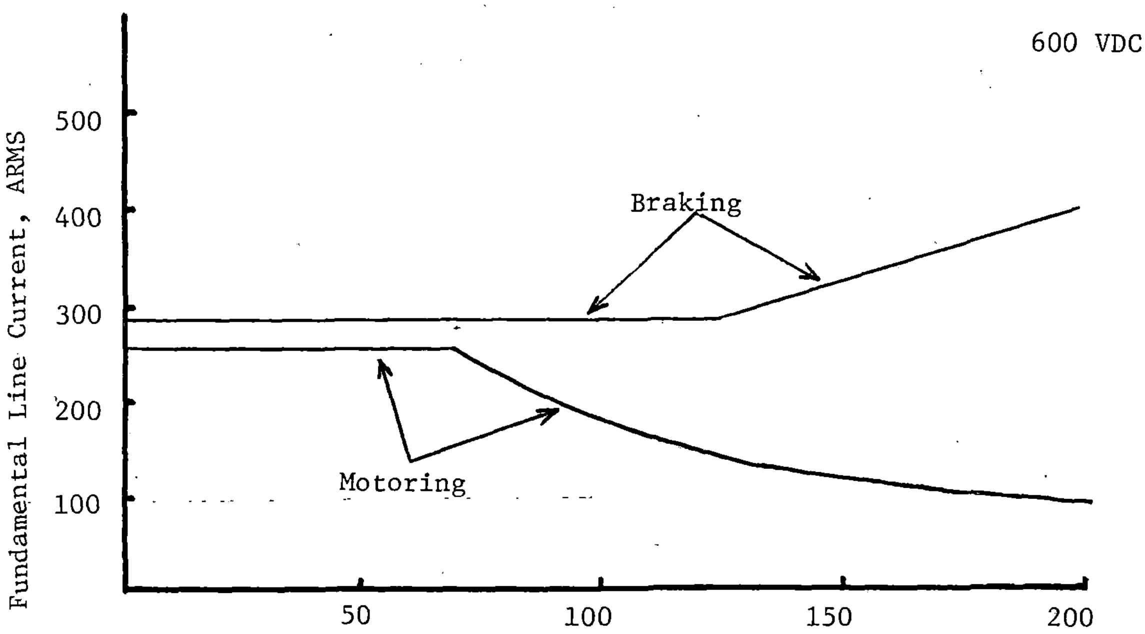


Figure 3-7(b)

Maximum Inverter Line Current versus Fundamental Frequency

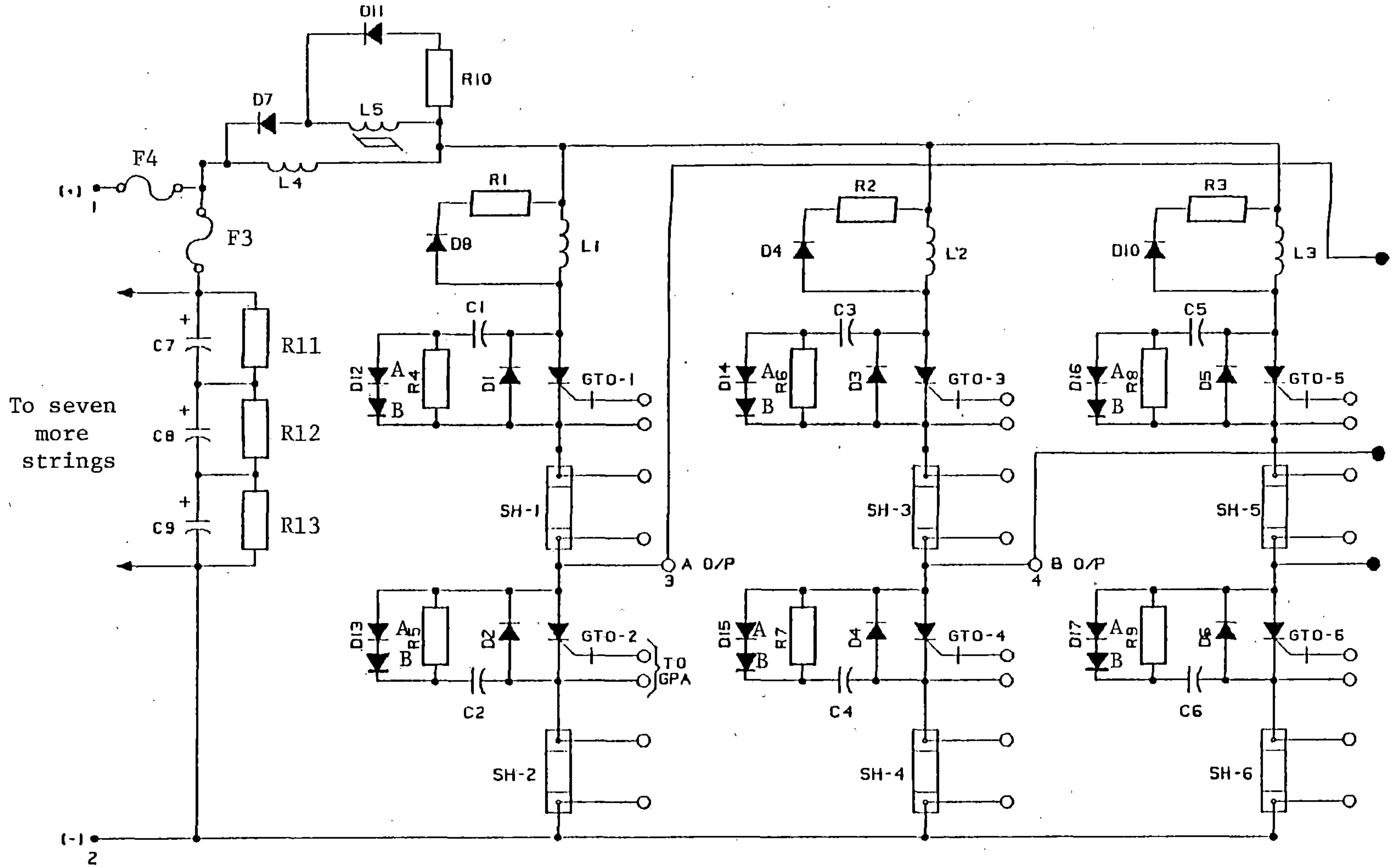
The higher current in braking above braking circuit base speed (43.5 mph or 109 Hz) is due to the fact that the motor operates under-excited, and operates at higher than typical rotor slip frequency to obtain the required braking rate when operating up to 200 Hz (80 mph). The braking circuit base speed is related to the turns ratio selected for the braking circuit transformer and the magnitude of dc link voltage. The terms inverter base speed/frequency or braking circuit base speed/frequency are used here to define the speed/frequency at which the inverter output voltage or the braking circuit output voltage reach their maximum value. This speed/frequency, of course, changes as dc link voltage changes.

In braking, a large portion of the inverter line current and the inverter line current peak flow in the inverter free-wheeling diodes rather than the GTO main switches. In practice, because of harmonics contained in the motor line current, the peak worst case instantaneous motor line current handled by the inverter GTOs under normal operating conditions is about 580A. To handle this current and also have sufficient margin to protect GTOs by shutting them off in the event of a shoot-through fault or an overload, at least 800A turn-off inverter GTOs are required.

3.4 CIRCUIT DESCRIPTION

A schematic diagram of the PWM inverter is shown in Figure 3-8. The inverter consists of an input filter capacitor bank, a fault current limiting circuit and three identical inverter pole circuits. The description of the inverter pole circuit will be made with reference to inverter pole A.

Di/dt protection for upper and lower inverter pole GTOs (GTO-1 and GTO-2) is provided by L1. L1 is 7uH and at a maximum operating voltage of 750 VDC it limits GTO di/dt to 107A/us. The series diode and resistor around L1 serve to limit the voltage on L1 when a GTO is turned-off, and serve to dissipate energy trapped in L1.



Note: Filter capacitors and F4 located in Regenerative Brake Box.
L4 is located outside Regenerative Brake Box.

Figure 3-8

PWM Inverter

A conventional type snubber consisting of a capacitor (C1 and C2), charging diode (D12 and D13) and discharging resistor (R4 and R5) is used to limit GTO dv/dt. When a GTO is turned-off, the GTO current is diverted into the series connected snubber capacitor and diode. The rate of rise of capacitor voltage is i/C, and with a 2uf capacitor and a worst-case turn-off current of 800A, dv/dt is 400 V/us. When the GTO is turned back on, the snubber capacitor is discharged through a snubber resistor (R4 and R5) of 10 ohms and the GTO. The time constant of this snubber capacitor discharge is 20us. For reliable inverter operation, it is required that the snubber capacitor be virtually discharged before its GTO is turned off. If this is not done, the GTO will be subjected to excessive dv/dt when it turns off, which can result in GTO failure. For reliable operation, a GTO should be on at least 2.5 snubber time constants. We have chosen a minimum GTO on time of 3.5 snubber discharge time constants or 70us for the inverter.

One of the worst situations for an inverter is a shoot-through fault. To minimize the possibility of this occurring, the inverter is controlled to provide a 35us minimum "dead time" between an off command to an off-going inverter pole GTO and the on command to the opposite inverter pole GTO. This is more than enough time for the GTO anode current to go to zero and for the GTO to assume full blocking capability before the opposite inverter pole GTO is turned on.

If however, a shoot-through fault should occur, the inverter is protected. Shoot-through fault current rate of rise is limited by the circuitry consisting of L4, L5, D7, D11, and R10. In normal operation, the current in L4 builds up to the peak current drawn by the inverter. As the inverter current fluctuates below this peak level, the difference current free-wheels through D7 and L5. The purpose of L5 is to soften the reverse recovery of D7, and D11 and R10 serve to discharge the energy trapped in L5.

In the event of a shoot-through fault, the initial rate of rise of fault current is limited by the 7uH di/dt reactor (L1) until the current in D7 goes to zero, and subsequent rate of rise of fault current is limited by L4. L4 is 400 uH and at a maximum DC link voltage of 750 VDC, the worst case shoot-through fault di/dt is 1.88 A/us. The shunts in the cathode of each GTO monitor its current, and in the event that a preset over-current trip level is exceeded, the gate driver turns off the corresponding GTO and an SOS signal is generated and delivered to the inverter controller which initiates turn-off of all inverter GTOs. The control and GTO driver are designed to guarantee a minimum GTO on time of 70us, which guarantees that once a GTO is turned on, it is on long enough to discharge its snubber capacitor. A shoot-through fault can therefore exist for up to 70us, and at 750 VDC link voltage and with L4 equal to 400uH, the fault current can increase by 132A over the trip level in 70us. With 800A turn-off GTOs in the inverter, a 650A over-current trip level is selected for safe GTO protection.

3.5 CIRCUIT PACKAGING

Based on the guidelines mentioned in Section 3.1 it was decided to:

- Locate the inverter such that it is accessible from the side of the car.
- Mount a cold plate at the bottom of the box and mount all heat producing components to this plate.
- Make the heat sink a modular removable assembly.

3.5.1 Component Layout Objectives

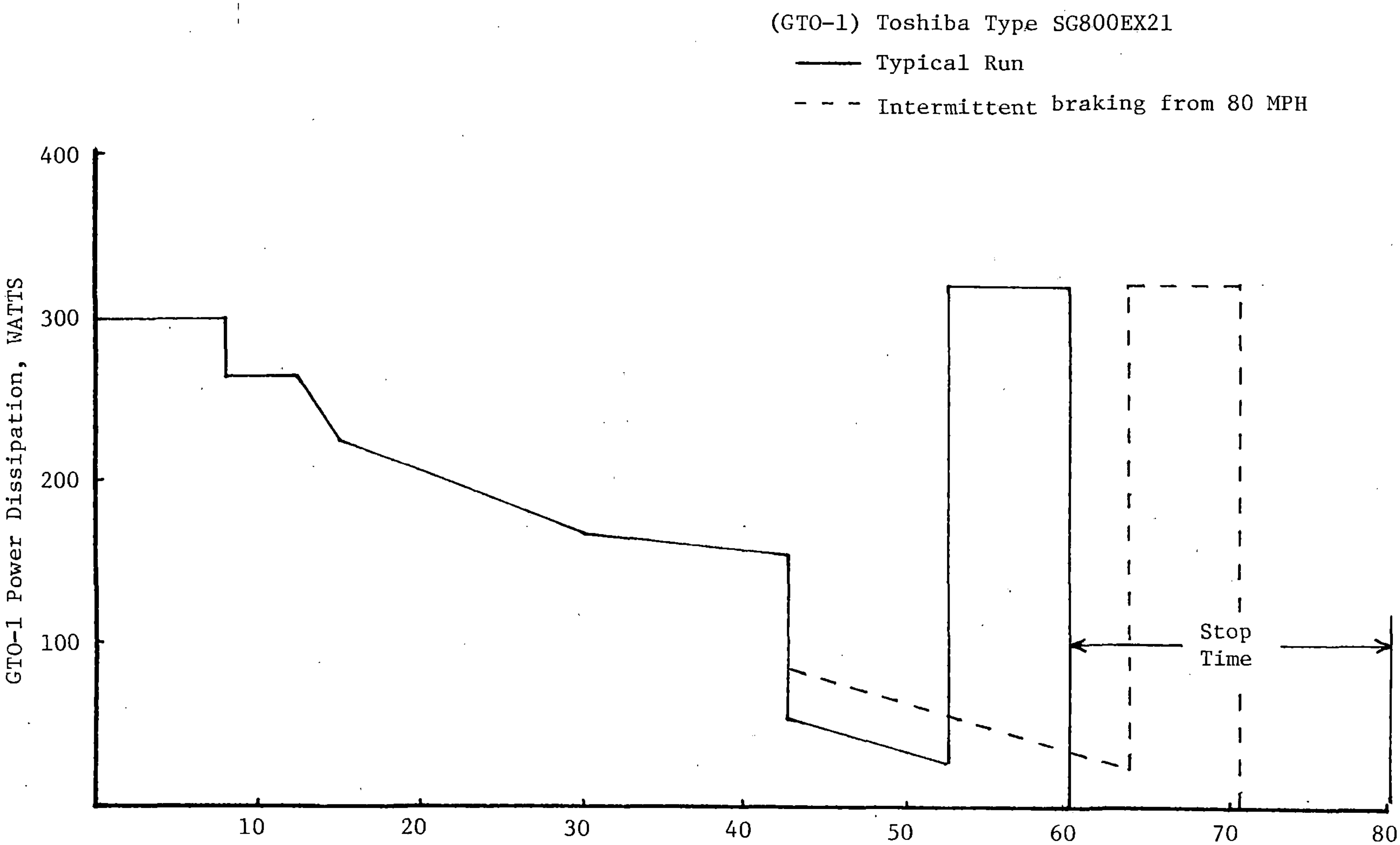
1. Reduce stray inductance in the snubber circuits to a minimum.
2. Limit stray inductance in the circuit as a whole to a minimum.
3. Keep wire lengths from the GTOs to the gate drivers as short as possible.

Approximate estimates of losses in key inverter components are shown in Figures 3-9 through 3-12. These estimates are based on the "typical" run and an intermittent 80 mph braking run described in Section 3.1. The loss estimates were simplified by assuming that the basic inverter pole switching frequency is fixed at 400 Hz at fundamental inverter output frequencies from 0 Hz to 50 Hz, and equal to the fundamental inverter output frequency for frequencies greater than 50 Hz. The average power loss in key components for a "typical" run (defined as Miller Run per Test S-1A with 20 second station stops) is listed below:

	Component	Qty.	Avg. Power Loss Each (Watts)	Total Loss (Watts)
1	GTO	6	150	900
2	Diode-D1	6	55	330
3	Snubber-R4	6	60	360
4	Snubber-R1	3	80	240
5	Diode-D7	1	160	160
6	Inductor	1	(Outside the box)	
7	Capacitors	24	(In Regen. Brake box)	
			Total	1990

Mounting the inverter at the side of the car imposed a constraint of 16.50 inches on the height of the box. Four identical inverters, to be located similarly, restricted maximum width to 36.00 inches. Location of the regenerative brake boxes, mounted behind the inverters, restricted accessibility of the inverter to the front side. The restricted height and one side accessibility prompted an inverter design with a sliding heat sink arrangement, which resulted in ease of manufacturability and serviceability.

During initial design stages, there was some concern with creepage due to the mounting of power devices to the bottom surface of the box, however, the concept of raising the insulating surface 3/8 inch above the main surface resolved these concerns.



Time, SEC.

Figure 3-9

Inverter GTO Power Dissipation vs Time (Typical NYCTA 77th to 86th Street Run)

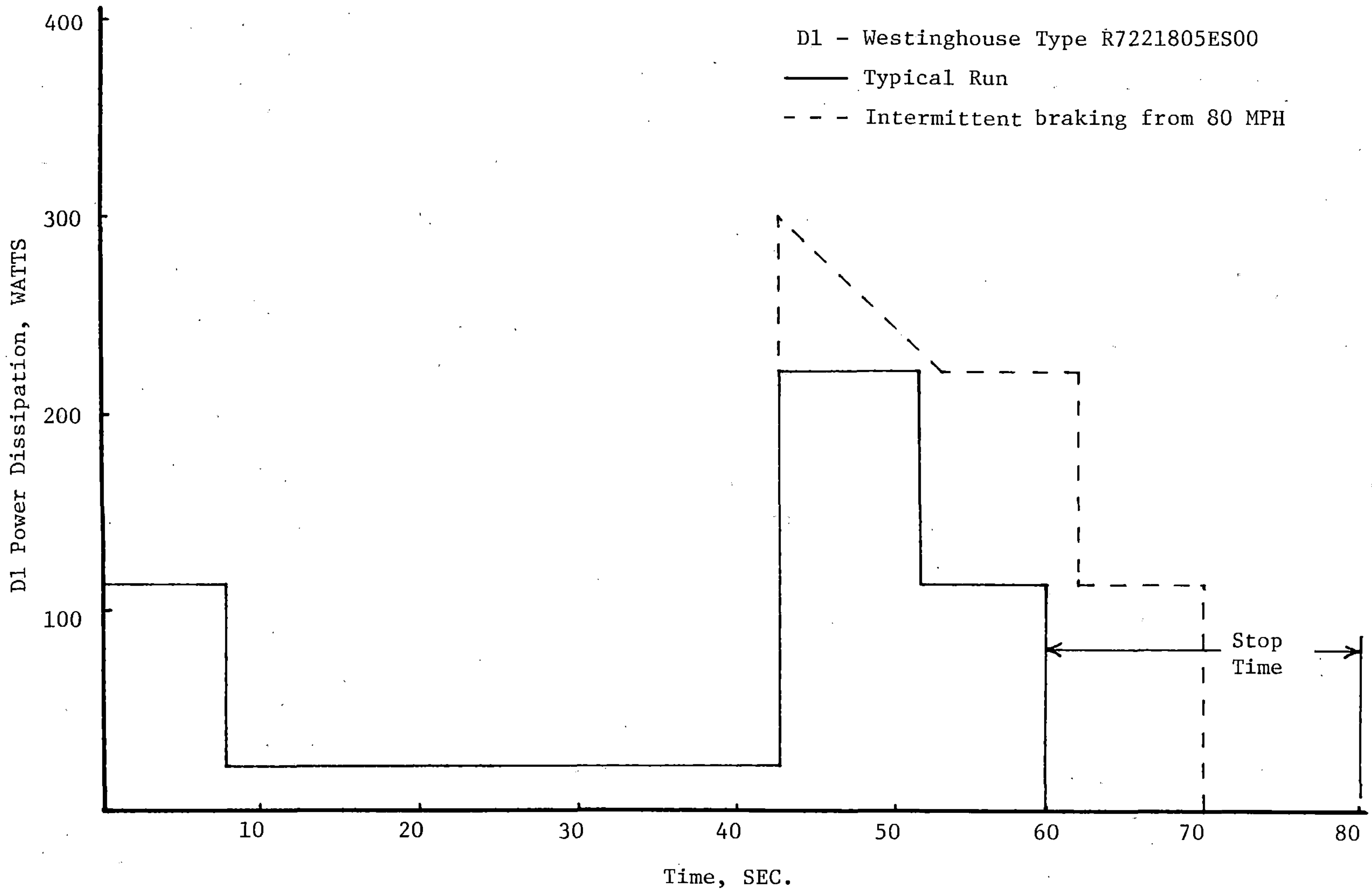


Figure 3-10

Inverter Anti-Parallel Diode Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

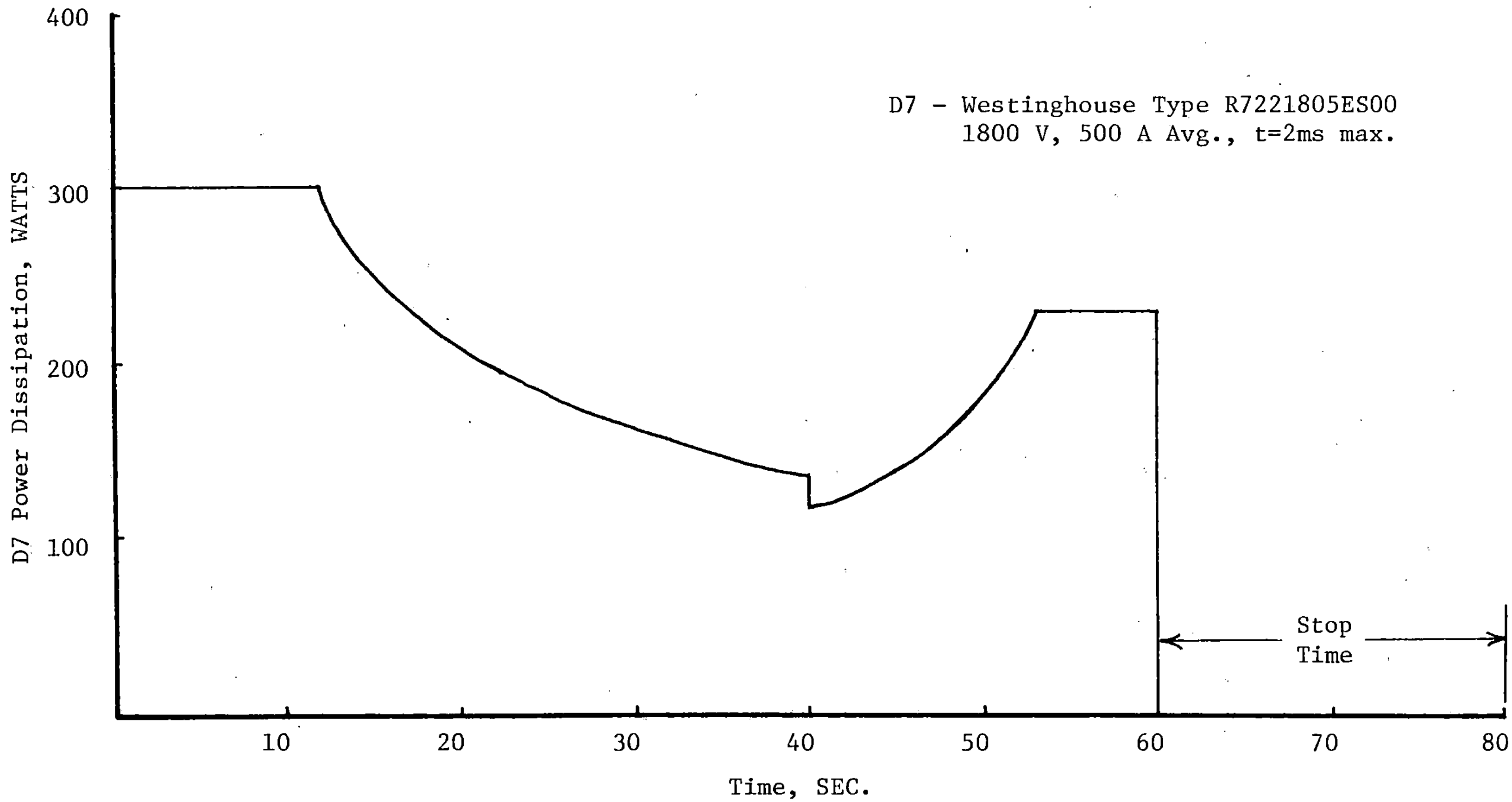


Figure 3-11

D7 Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

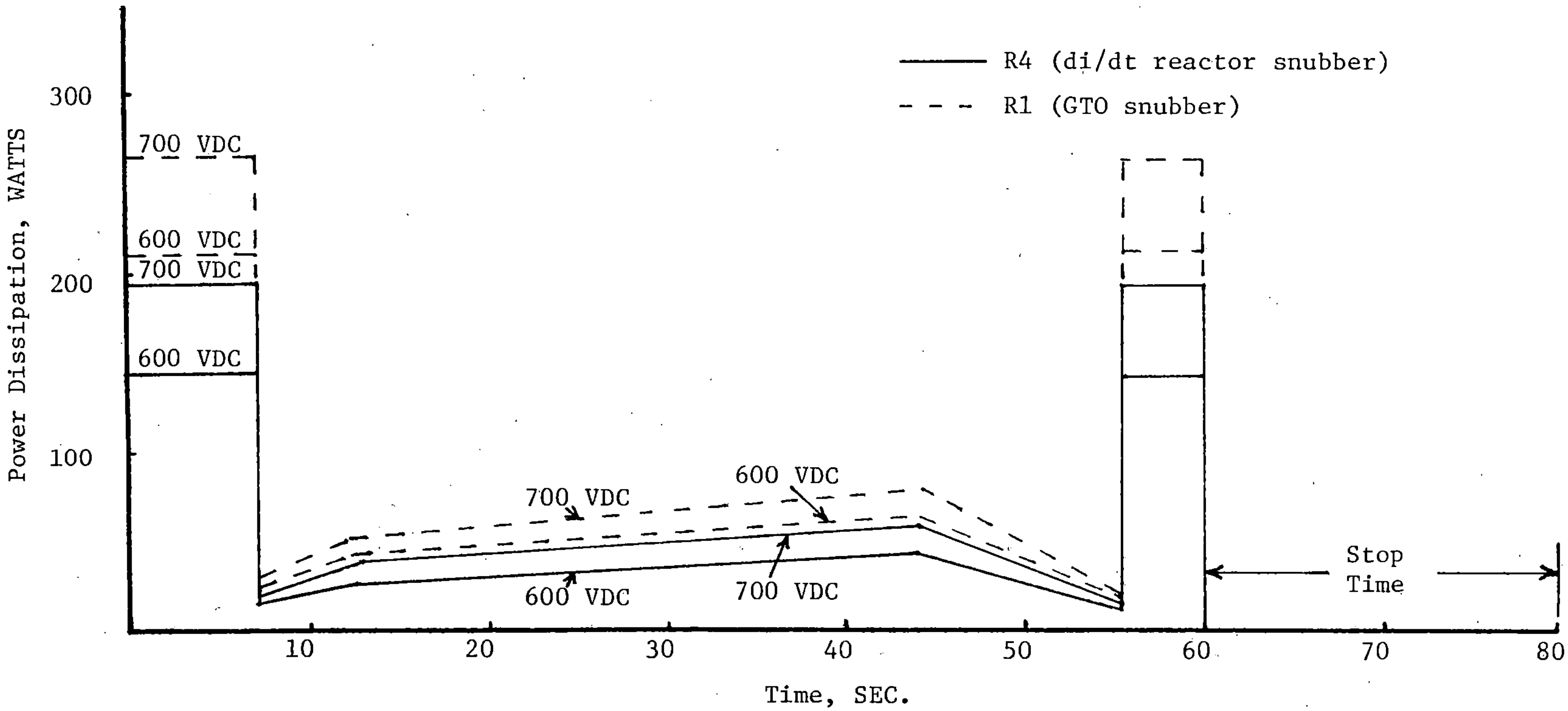


Figure 3-12

Snubber Resistor Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

A GTO/Diode stack per Figure 3-13 was developed for double-side cooling on an insulated sink. The arrangement allows:

- Pre-assembly of devices.
- Double-side cooling, transferring heat from both pole faces to a common sink.
- Mounting of the snubber diode and capacitor close to the GTO.

Note that the base portion of the stack aluminum blocks has a 2 mil electrophoretic deposited polyamide-imide film which increases the creep distance and isolation between the stack and the baseplate. The stack is placed on Chomeric 1671 insulation and fastened to the sink with four bolts. The insulation provides isolation between the device and the heat sink. This arrangement allows use of a common sink for all devices used in the inverter. The snubber diode is mounted on the GTO block and the capacitor is clamped to the mounting bar within a distance of one inch from the GTO block, thus providing low stray inductance in the R-C snubber circuit.

A mathematical model was created to analyze the stack. Nodal and spice programs were developed to analyze the stack for transient and steady state impedence. Per this analysis, the transient impedence is shown in Figure 3-14 and the steady state impedence with 1000 LFM of air flow through the heatsink fins is:

GTO - .278 °C/W

Diode - .345 °C/W

All the inverter resistors are plaqohm type having a flat ceramic base. These resistors are non-inductive and have excellent isolation between the resistance wire and the ceramic base. All resistors are fastened to aluminum blocks with silicone adhesive, and the aluminum blocks are bolted to the common sink. This is done to transfer as much of the heat generated in the resistors as possible into the common sink. Free-wheel diode D7 is a power brick packaged device. The diode is isolated from the package, and so the power brick can be bolted to the common sink. GTO gate drivers are mounted on polyglass panels located directly above the GTO/Diode stacks.

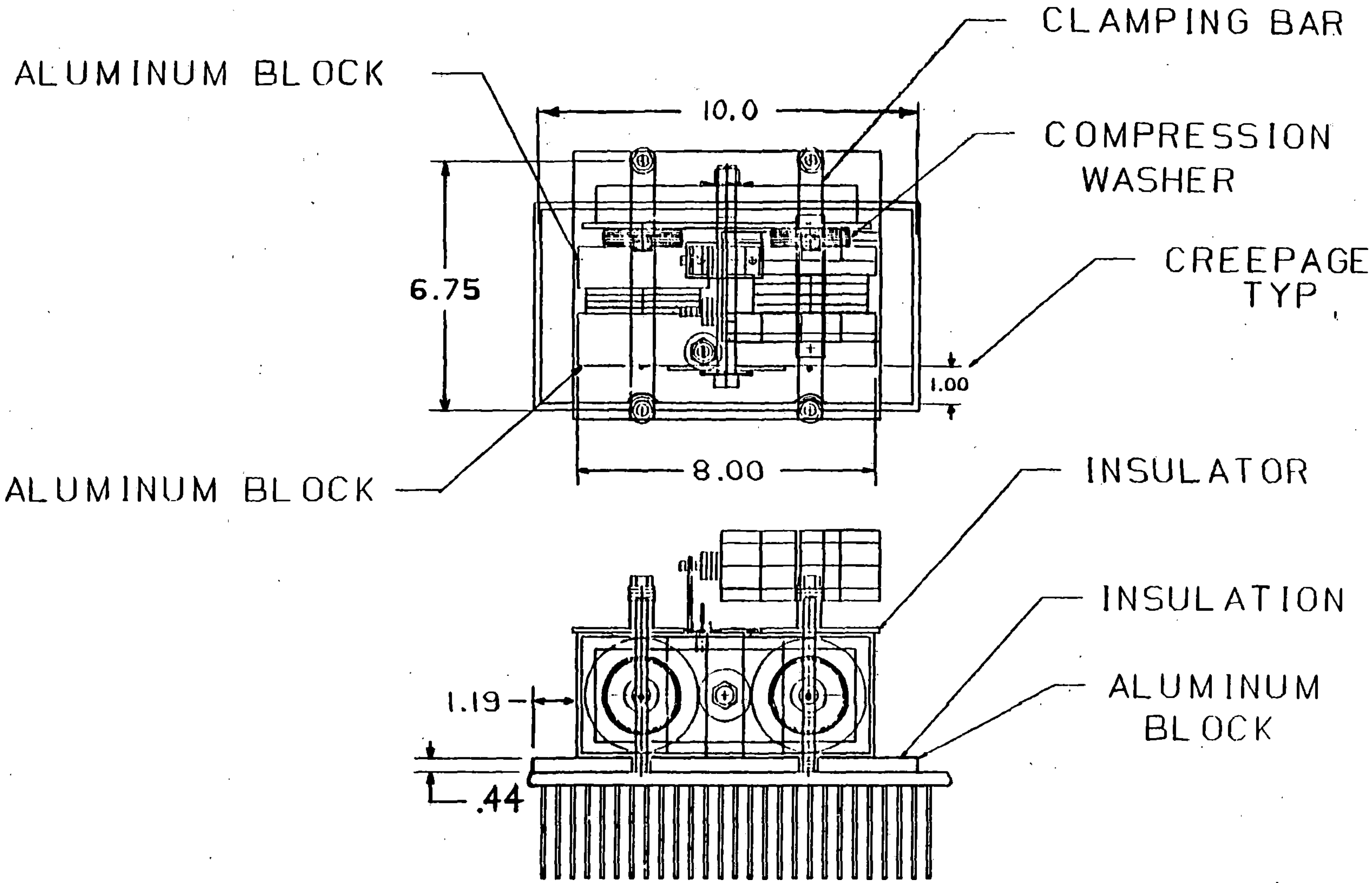


Figure 3-13

GTO/Diode Modular Assembly
(Double Sided Cooled)

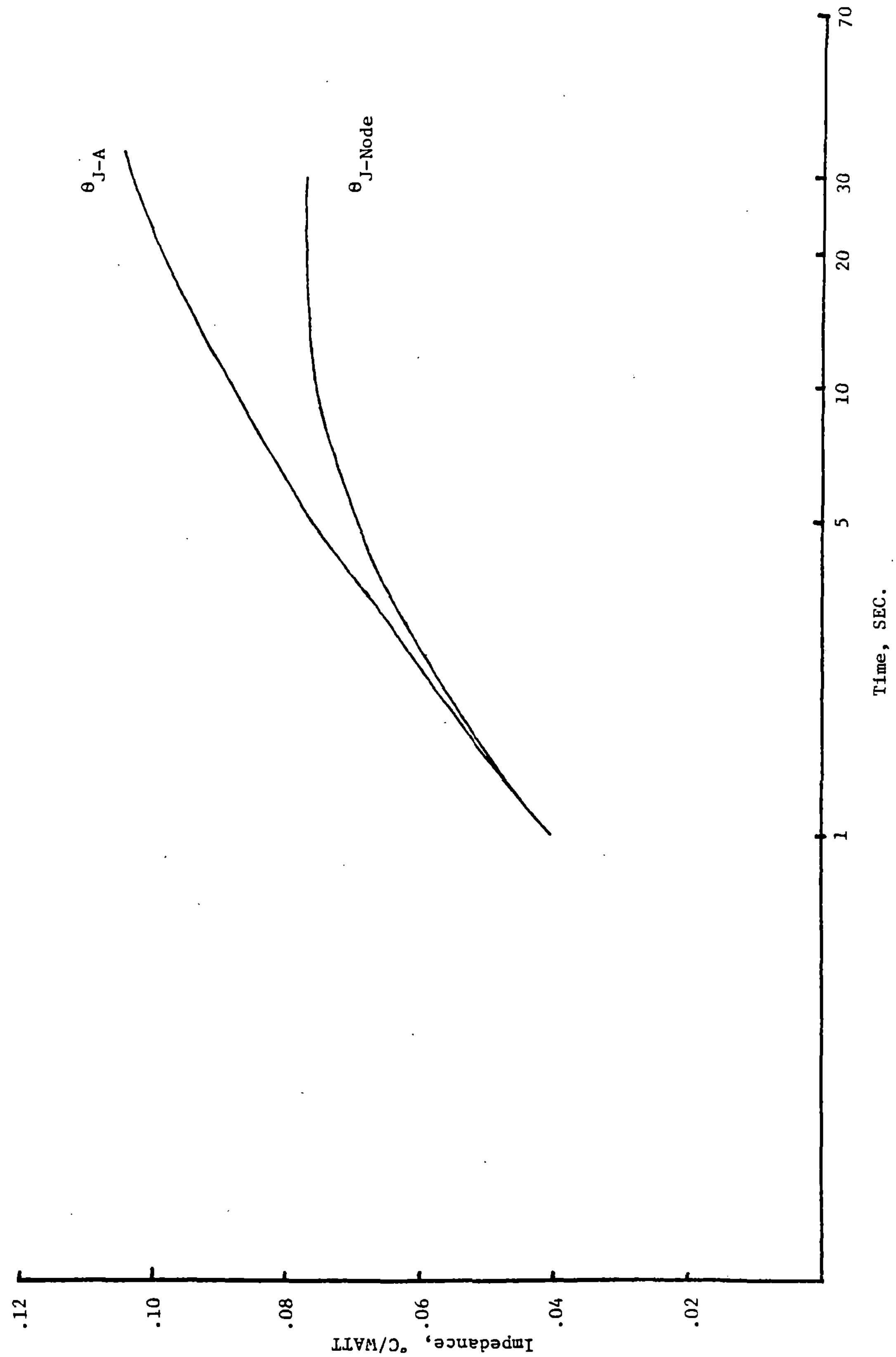


Figure 3-14

Transient Impedance Curve for Toshiba GTO

The overall inverter size is 34.91 inches wide by 31.84 inches deep by 16.09 inches high, excluding mounting brackets but including fins. The heat sink can easily be slid in and out on teflon slides after disconnecting only three motor leads and three power connections. The heatsink itself is a self contained unit and can be easily replaced with another heatsink assembly to reduce car downtime. An outline drawing of the inverter box is shown in Figure 3-15. The inverter heatsink layout is shown in Figure 3-16.

3.6 SELECTED TEST RESULTS

The measured performance of the motor/inverter under steady state operating conditions and the inverter voltage and current waveforms are of particular interest and are given respectively in Figure 3-17 through 3-20, and in the test report titled "Inverter Voltage and Current Waveforms" included as Appendix A. Temperature rises in the inverter package, when operating at a typical load/duty cycle are also of particular interest. Temperature rises in the packaged inverter versus time for a typical load/duty cycle (Figure 3-3) and for the Garrett Synthetic Profile* (Figure 3-22) are listed in Figure 3-21. It is apparent from these results that the Garrett Synthetic Profile represents a significantly less severe duty on the inverter than the assumed typical load/duty cycle since the temperature rises are significantly lower with the Garrett Synthetic Profile. As indicated in other sections of this document, this is also true for the AC motor and regenerative brake and dynamic brake boxes.

It is impossible to measure device junction temperatures directly. One approach that can be used to predict device junction temperature is to measure the temperature rise of the device heatsink block and compare this temperature rise with the calculated temperature rise obtained from a computer model of

* - The "Garrett Synthetic Profile" was provided by Garrett Airesearch Corporation as a common basis for evaluation. It is essentially a simplified equivalent of the NYCTA RR Line.

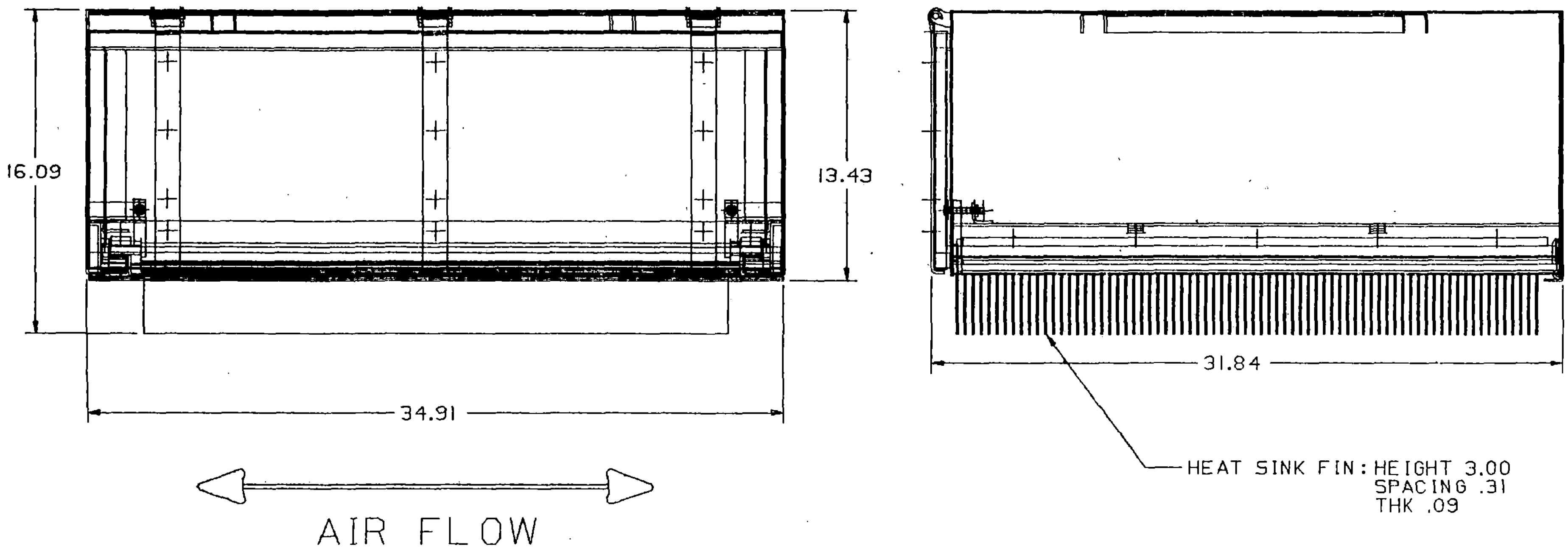


Figure 3-15

Inverter Box Outline

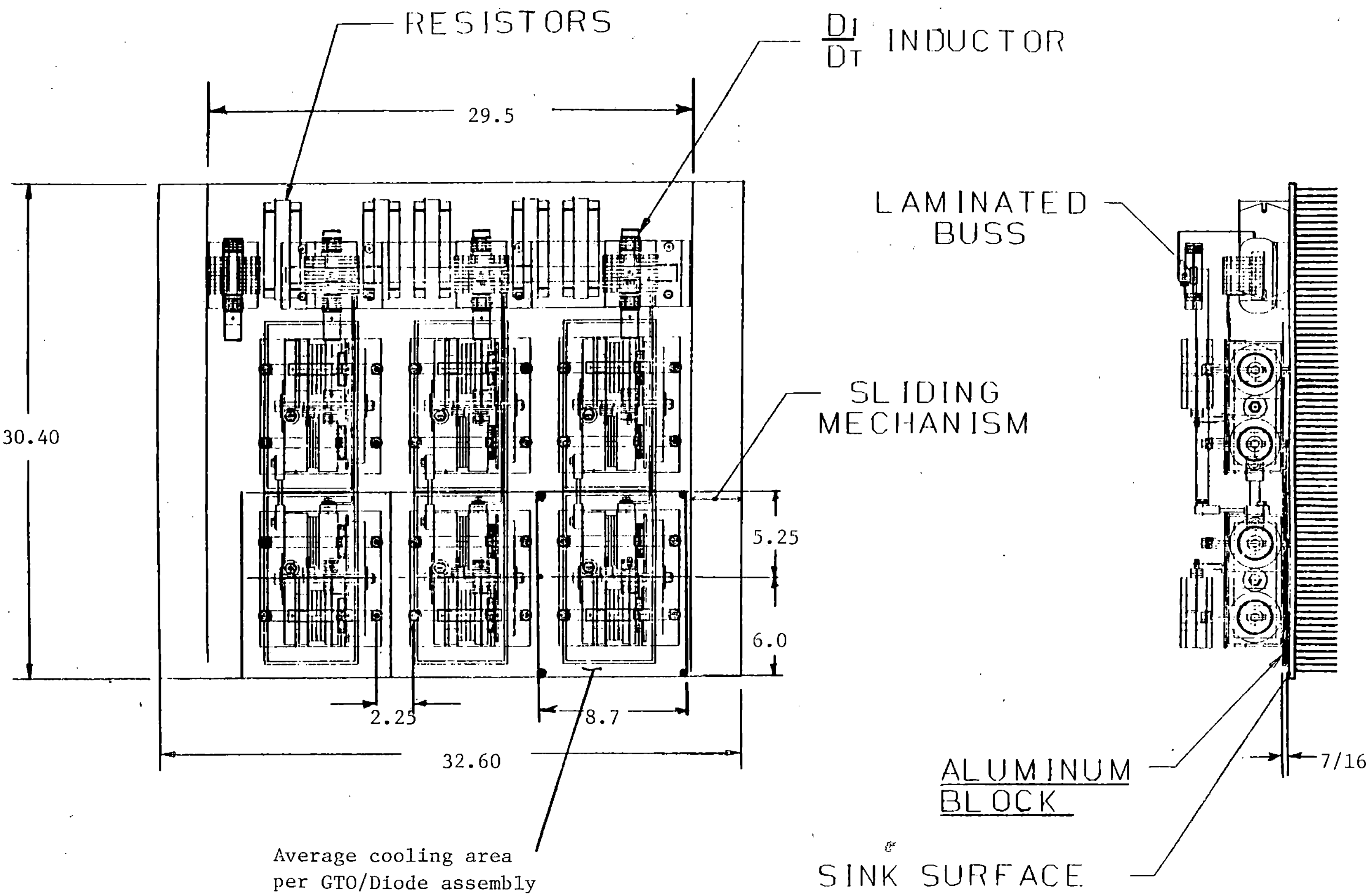


Figure 3-16

Inverter Sink Surface Layout

f_1, Hz	5	5	5	15	15	15	30	30	30
Speed, RPM	183.6	149.7	116.4	488.4	449.4	416.4	933.6	899.1	856.8
f_R, Hz	-1.12	0.01	1.12	-1.28	0.02	1.12	-1.12	0.03	1.44
f_2, Hz	6.12	4.99	3.88	16.28	14.98	13.88	31.12	29.97	28.56
$V_{DC\ LINK}$, Volts	609	609	609	609.5	609	608.5	610	609	608
$I_{DC\ LINK}$, Amps	-10	7	46	-54	11	104	-121	16	185
$P_{DC\ LINK}$, KW	-6.09	4.263	28.014	-32.913	6.699	63.284	-73.81	9.744	112.48
Torque, Ft-Lb.	-720	3	740	-730	7	740	-730	10	740
Shaft Power, KW	-18.764	0.064	12.227	-50.608	0.447	43.738	-96.739	1.276	89.997
Efficiency, %	32.5	-	43.6	65.0	-	69.1	76.3	-	80.0
V_{L-L} Fund., V_{RMS}	24.4	28	31.6	75.6	82.8	89	166	162	158
I_L Fund., I_{RMS}	221	106.5	240	228	105	242	230	104	248
Total Loss, KW	12.674	4.199	15.787	17.695	6.252	19.546	22.929	8.468	22.483

Figure 3-17

Motor/Inverter Test Data

f_1, Hz	30	30	30	45	45	45	65	65
Speed, RPM	936	899.1	856.8	1386.6	1348.8	1309.2	1947.6	1830
f_R, Hz	-1.2	0.03	1.44	-1.22	0.04	1.36	0.08	4.0
f_2, Hz	31.2	29.97	28.56	46.22	44.96	43.64	64.92	61.0
$V_{DC\ LINK}$, Volts	610	609	608	610.5	609	607	609	607
$I_{DC\ LINK}$, Amps	-121	17	190	-198	18	260	17	389
$P_{DC\ LINK}$, KW	-73.81	10.353	115.52	-120.879	10.962	157.82	10.353	236.123
Torque, Ft-Lb.	-730	10	740	-740	11	740	14	720
Shaft Power, KW	-96.987	1.276	89.997	-145.647	2.106	137.517	3.87	187.026
Efficiency, %	76.3	-	77.9	83.0	-	87.1	-	79.2
V_{L-L} Fund., V_{RMS}	166	163	160	248	248	246	270	248
I_L Fund., I_{RMS}	228	104	252	231	107	247	61.5	377
Total Loss, KW	23.177	9.077	25.523	24.768	8.856	20.303	6.483	49.097

Figure 3-18

Motor/Inverter Test Data (Cont'd)

f_1, Hz	65	65	65	75	75	75	100	100	100
Speed, RPM	2019	1947.6	1842	2358	2246.4	2140.2	3090	3006	2910
f_R, Hz	-2.3	0.08	3.6	-3.6	0.12	3.66	-3.0	0.2	3.0
f_2, Hz	67.3	64.92	61.4	78.6	74.88	71.34	103	100.2	97
$V_{DC\ LINK}$, Volts	611	609	607	611	609	607	611	609	607.5
$I_{DC\ LINK}$, Amps	-295	17	383	-333	18	363	-221	24	220
$P_{DC\ LINK}$, KW	-180.245	10.353	232.481	-203.463	10.962	220.341	-135.031	14.616	133.65
Torque, Ft-Lb.	-740	14	720	-740	16	600	-360	21	280
Shaft Power, KW	-212.073	3.87	188.252	-247.682	5.101	182.273	-157.899	8.96	115.656
Efficiency, %	85.0	-	81.0	82.1	-	82.7	85.5	-	86.5
V_{L-L} Fund., V_{RMS}	278	270	260	278	270	262	276	270	264
I_L Fund., I_{RMS}	273	61.5	352	322	53.5	338	210	40	200
Total Loss, KW	31.828	6.483	44.229	44.219	5.861	38.068	22.868	5.656	17.994

Figure 3-19

Motor/Inverter Test Data (Cont'd)

f_1, Hz	125	125	125	150	150	150	175	175	175	200
Speed, RPM	3846	3738	3630	4575	4482	4422	5310	5220	5154	5904
f_R, Hz	-3.2	0.4	4.0	-2.5	0.6	2.6	-2.0	1.0	3.2	3.2
f_2, Hz	128.2	124.6	121	152.5	149.4	147.4	177	174	171.8	196.8
$V_{DC\ LINK}$, Volts	610	609	608	609.5	609	608	610	608.5	607.5	609
$I_{DC\ LINK}$, Amps	-200	30	146	-145	48	146	-105	60	137	100
$P_{DC\ LINK}$, KW	-122	18.27	88.768	-88.378	29.232	88.768	-64.05	36.510	83.227	60.9
Torque, Ft-Lb.	-270	22	200	-170	24	110	-112	23	80	31
Shaft Power, KW	-147.398	11.673	103.05	-110.4	15.269	69.045	-84.417	17.041	58.526	25.979
Efficiency, %	82.8	-	86.1	80.1	-	77.8	75.9	-	70.3	-
V_{L-L} Fund., V_{RMS}	274	268	260	276	270	266	272	264	262	268
I_L Fund., I_{RMS}	203	40	215	140	51	135	90	40	130	100
Total Loss, KW	25.398	6.597	14.282	22.022	13.963	19.723	20.367	19.469	24.701	34.921

Figure 3-20

Motor/Inverter Test Data (Cont'd)

Component		Temperature @ 40°C Ambient Measured (°C)	Calculated (°C)	T_j(Max.)* (°C)	Calculated Cycle ΔT_j (°C)
GTO Block	Typical Run	66.3	62.2	90.3	24.0
	Garrett Run	55.8	52.0	86.9	30.1
Free-Wheel Diode Block	Typical Run	62.8	55.1	81.9	19.1
	Garrett Run	54.9	48.5	70.3	-
Power Brick, D_7	Typical Run	67.0	-	67.0	-
	Garrett Run	61.7	-	61.7	-
Snubber, R=10 ohms	Typical Run	76	-	-	-
	Garrett Run	67	-	-	-
Snubber, R=0.5 ohms	Typical Run	73	-	-	-
	Garrett Run	63	-	-	-
Box Ambient	Typical Run	66	-	-	-
	Garrett Run	55.4	-	-	-

* - T_j (Max.) is based on measured temperature.

Note 1: See Figure 3-3 for profile of "Typical Run" (run with 30 seconds stop time instead of 20 seconds). See Figure 3-22 for profile of "Garrett Run".

Note 2: Air flow over car simulated by blower providing approximately 1000 LFM of air flow through the inverter heatsink fins. The blower was turned off during profile stop intervals. The inverter was shutdown during coast intervals on the Garrett Run.

Note 3: The measured temperature is the highest of all measured temperatures for similar locations.

Figure 3-21

Measured and Calculated Inverter Component Temperatures

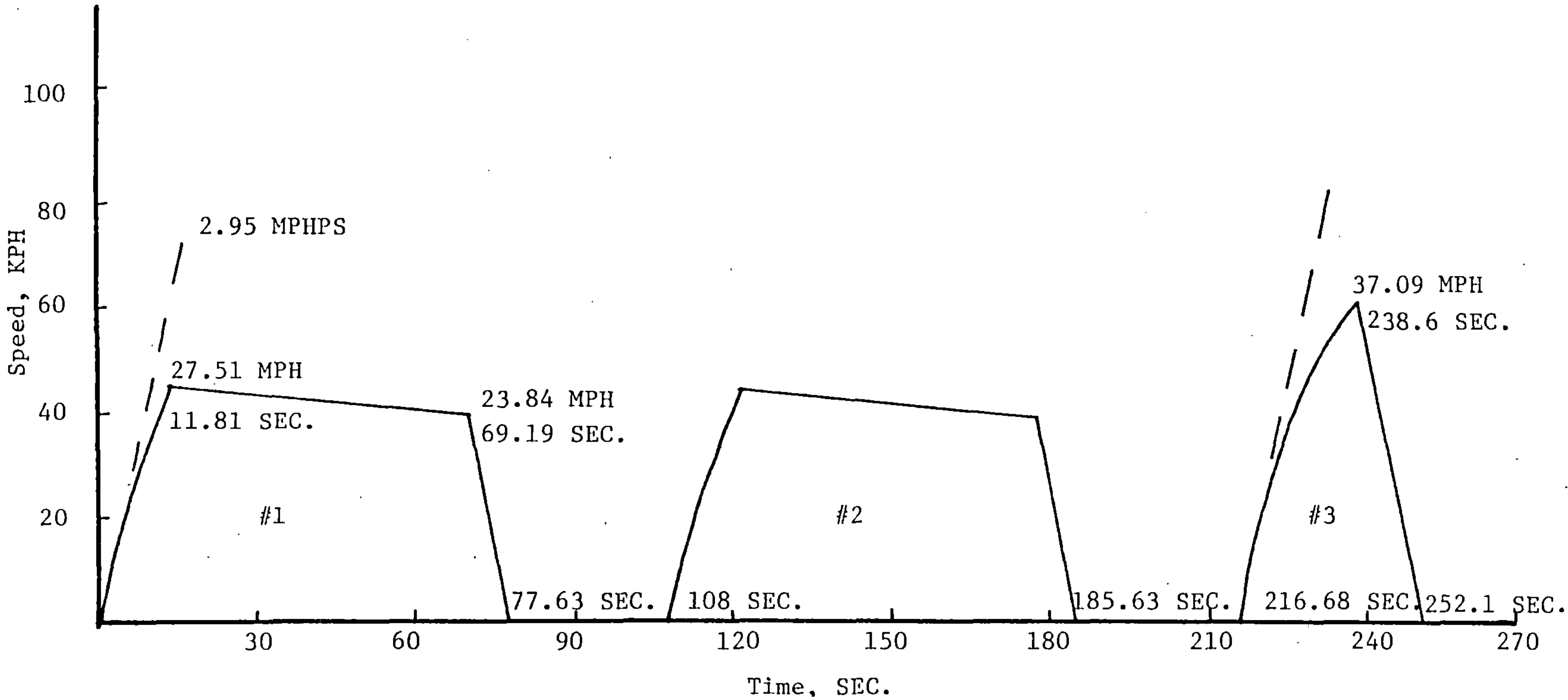


Figure 3-22
Garrett Synthetic Profile

the thermal system. This is done to verify the computer model. Once this is verified, the device junction temperature versus time can be calculated using the computer model and an estimate of device loss versus time for the load-duty-cycle being run. This was done to obtain the calculated results in Figure 3-21.

These selected test results and results of other performed tests verify that the basic design and performance objectives of the GTO-based PWM inverter have been met.

In particular, the concept of a small, sealed convection-cooled circuit has been successfully demonstrated, eliminating the need for blowers and reducing maintenance concerns. During testing, all semiconductor devices ran at or below the manufacturer's rated temperature.

4. BRAKING CIRCUITS

The regenerative and dynamic brake power circuits developed for the AC traction drive and a proposed partial regenerative brake power circuit will be covered in this section. The partially regenerative braking circuit is of interest, because, as will be explained later, it has significantly lower size, weight, and cost than a full regenerative braking circuit, and assuming it can be successfully developed, it would be preferred on systems having low line receptivity.

As will be explained further below, the braking requirements, particularly at high speeds, dictate that the system must regenerate nearly four times the power in braking that it uses in propulsion. A modular approach was chosen in addressing braking requirements. Three basic configurations are available:

1. The inverter and AC traction motor can regenerate power with no added circuitry. However, insufficient braking torque is developed by the inverter alone, and thus electric braking must be supplemented at higher speeds with friction braking. This simple configuration is sufficient for the speeds encountered on the NYCTA RR Line, and is the basis for the Cost and Economic Analysis in Section 11.

2. Because it is not limited by commutation voltage (which can cause DC motor flashover), an AC motor can be used for all service braking, eliminating friction brake use almost entirely. This creates the need for extra circuitry to handle the excess power and high voltage which result. The transformer-based module which provides this capacity is described in this section, and was tested in the lab setup. This circuit provides capabilities beyond those required by NYCTA RR Line duty, and is not treated in the Cost and Economic Analysis for this reason.

3. A third option is discussed in this section which provides an intermediate solution. By means of resistors, the "excess" braking energy (i.e., that beyond inverter regeneration capability) is dissipated as heat. This option still provides inverter regeneration of a large portion of the available energy. In addition, service braking is still all-electric, reducing friction brake usage, but it is now a combination of regenerative and dynamic braking at higher speeds. This option is both lighter and lower in cost than the fully-regenerative system tested in the Westinghouse power lab.

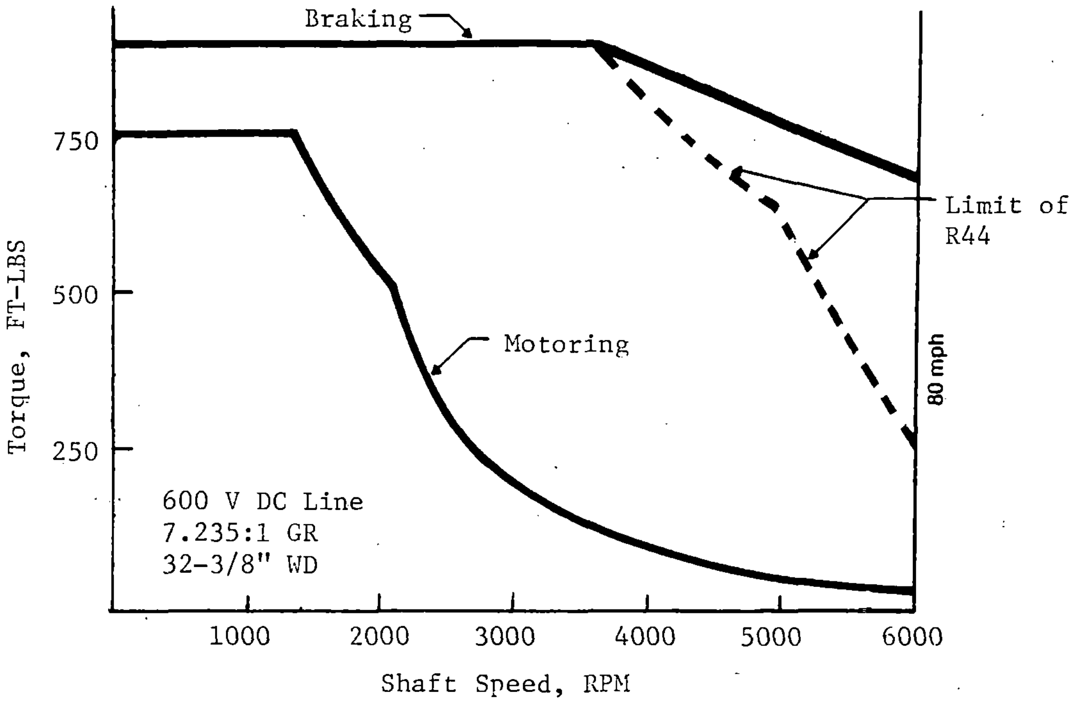
In the case of all three of the above configurations, a separate dynamic brake circuit is also provided. This circuit is needed to handle regenerated power when the line is non-receptive, and is a conventional chopper combined with resistor tubes. This circuit also utilizes GTO thyristors for size and weight benefits.

4.1 REGENERATIVE BRAKE CIRCUIT

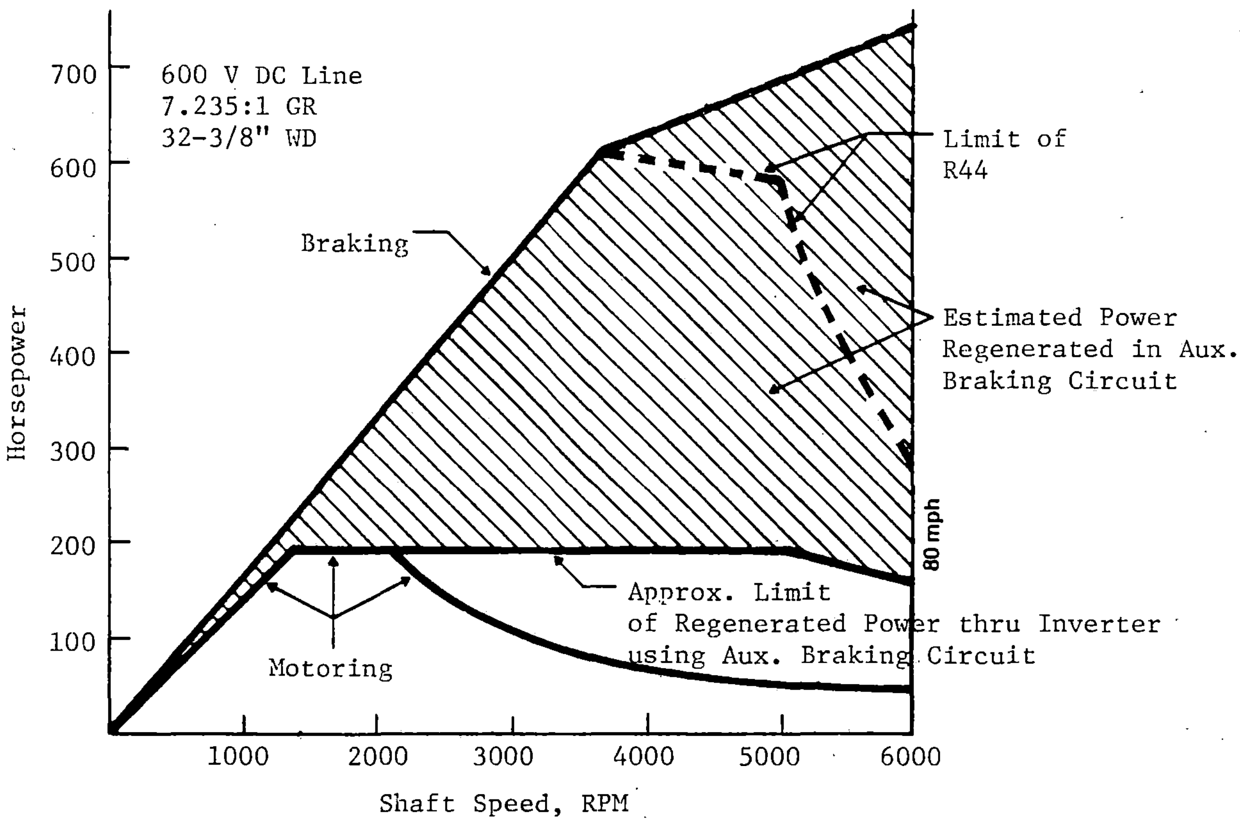
4.1.1 Circuit Design Objective

The performance objectives of the AC traction drive in motoring and braking on a per motor basis are illustrated in the torque and horsepower versus shaft speed characteristics in Figure 4-1. Note that the maximum horsepower in braking (740 HP) is almost four times that required in motoring (190 HP). The power circuit must handle the peak braking power in a drive designed for full regenerating capability.

The maximum RMS fundamental line-to-line voltage available from the inverter (six-step operating mode) in motoring or braking is 0.78 times VDC link or 468 V RMS at 600 volts link. If the inverter is controlled to go into six-step operation at the peak horsepower frequency in motoring, the motor line and inverter current required to obtain 190 HP is about 258 A RMS, however full-rate braking cannot be maintained up to the required high



(a) Torque Per Motor Versus Speed



(b) Horsepower Per Motor Versus Speed

Figure 4-1

Performance Objectives of AC Drive

speed since the inverter is not capable of increasing the motor voltage once it reaches six-step operation. To handle full braking with the inverter alone, it is necessary to control the inverter to go into the six-step operating mode at a much higher frequency than the peak horsepower frequency in motoring. This means that a lower voltage - higher current motor is required, and the inverter is severely penalized because the maximum current for full rate braking or motoring is about 1200 A RMS instead of 258 A RMS. An inverter designed to handle full regenerative braking is prohibitively large and expensive.

The solution adopted to minimize inverter and total power circuit size is to design the inverter to reach full voltage (six-step operation) at the peak horsepower point in motoring and to add a braking circuit which provides an increase in motor voltage when operating at frequencies in the inverter six-step operating range. This approach permits obtaining full rate braking at high operating speeds without a voltage penalty, and depending on braking circuit design parameters, little or no current penalty to the inverter.

A simplified single-phase illustration of the fully regenerative braking approach is shown in Figure 4-2. In this approach the braking circuit voltage Vs adds to the inverter voltage V1 to increase the voltage on the motor, and the braking circuit inherently regenerates all braking energy in excess of approximately the peak motoring horsepower rating. Transformer T1 provides isolation to allow the motor windings to float, and also its turns ratio sets the maximum achievable motor voltage.

In motoring, thyristors TH1 and TH2 are gated on. This disables the braking circuit and provides a "direct" connection between the inverter and motor. To activate the braking circuit when braking, gating signals are removed from TH1 and TH2. The non-conducting thyristor stays off and the conducting thyristor goes off on the next current zero crossing. Gate

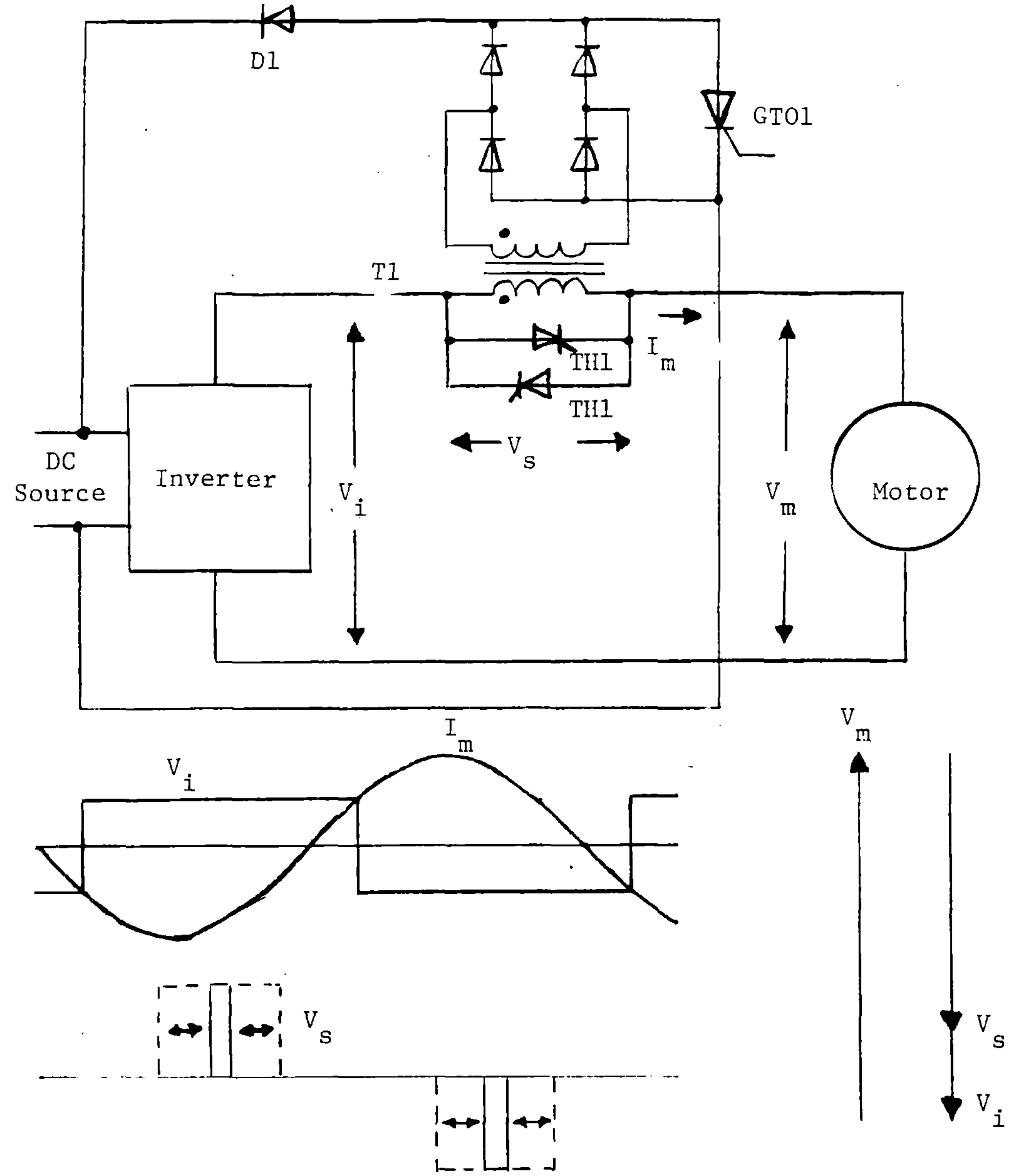


Figure 4-2
Simplified Illustration of Regenerative Braking Circuit Operation (Single Phase)

drive is also applied to GTO1 and controlled so that GTO1 is turned off for a controlled period which is centered at the 90° and 270° positions on the inverter voltage. By controlling in this manner, the fundamental components of V1 and Vs are in phase, and they add directly to increase the motor voltage Vm.

During the interval that GTO1 is off, the current in the secondary of T1 is forced to flow into the DC source through the diode-bridge and D1. This clamps the transformer secondary voltage to the DC source providing transformed braking voltage Vs on the transformer primary. D1 provides isolation from the DC source when GTO1 is on.

The maximum width of each half cycle of Vs is constrained to be sufficiently low to guarantee that the polarity of motor current Im does not reverse polarity during the off interval of GTO1. If Im reverses during the GTO1 off interval, the instantaneous polarity of Vs will reverse near the end of each half cycle, and the average braking voltage will decrease. In practice, the duration of each half cycle of Vs (duration of GTO1 off time) can safely be 80° maximum.

GTO1 could conceivably be removed and TH1 and TH2 replaced by GTOs to obtain equivalent braking circuit operation, however in practice the leakage inductance of T1 renders this arrangement impractical due to the large and highly dissipative snubber circuit that is required and because the edge transitions of braking voltage, Vs, are too slow.

4.1.2 Circuit Description

A schematic diagram of the regenerative brake circuit is shown in Figure 4-3. The major components and the basic circuit operation have been covered in Section 4.1. The minor components are snubber and protection circuits for the main devices. Saturating inductor LS2, resistor RSN, and capacitor CSN form a dv/dt protection network for thyristor TH1. Resistor RB3 and capacitor CB2 soften the reverse recovery transient of DB1. Inductor LB1 limits the turn-on di/dt of GB1 and the turn-off di/dt of DB1 to 100A/ms maximum at 700 VDC line voltage. Resistor RB1 and diode DB2 serve to dissipate energy trapped in LB1, and to limit the voltage transient on GB1 when it turns off. Capacitor CB1, resistor RB2, and diode DB3 limit the dv/dt on GB1 when it turns off. Shunt SHR1 is used in conjunction with the GTO gate drive to monitor GTO current, and in the event a pre-set trip level is exceeded, the GTO is turned off and an SOS signal is generated which shuts down the individual motor drive.

The braking transformer can consist of three separate transformers, one for each phase, or it can be a single three-phase unit with extra shunt legs which serve to decouple the phases from one another. The latter approach has been chosen for the AC drive system since it has a size, weight and cost advantage. An outline of the braking transformer is shown in Figure 4-4.

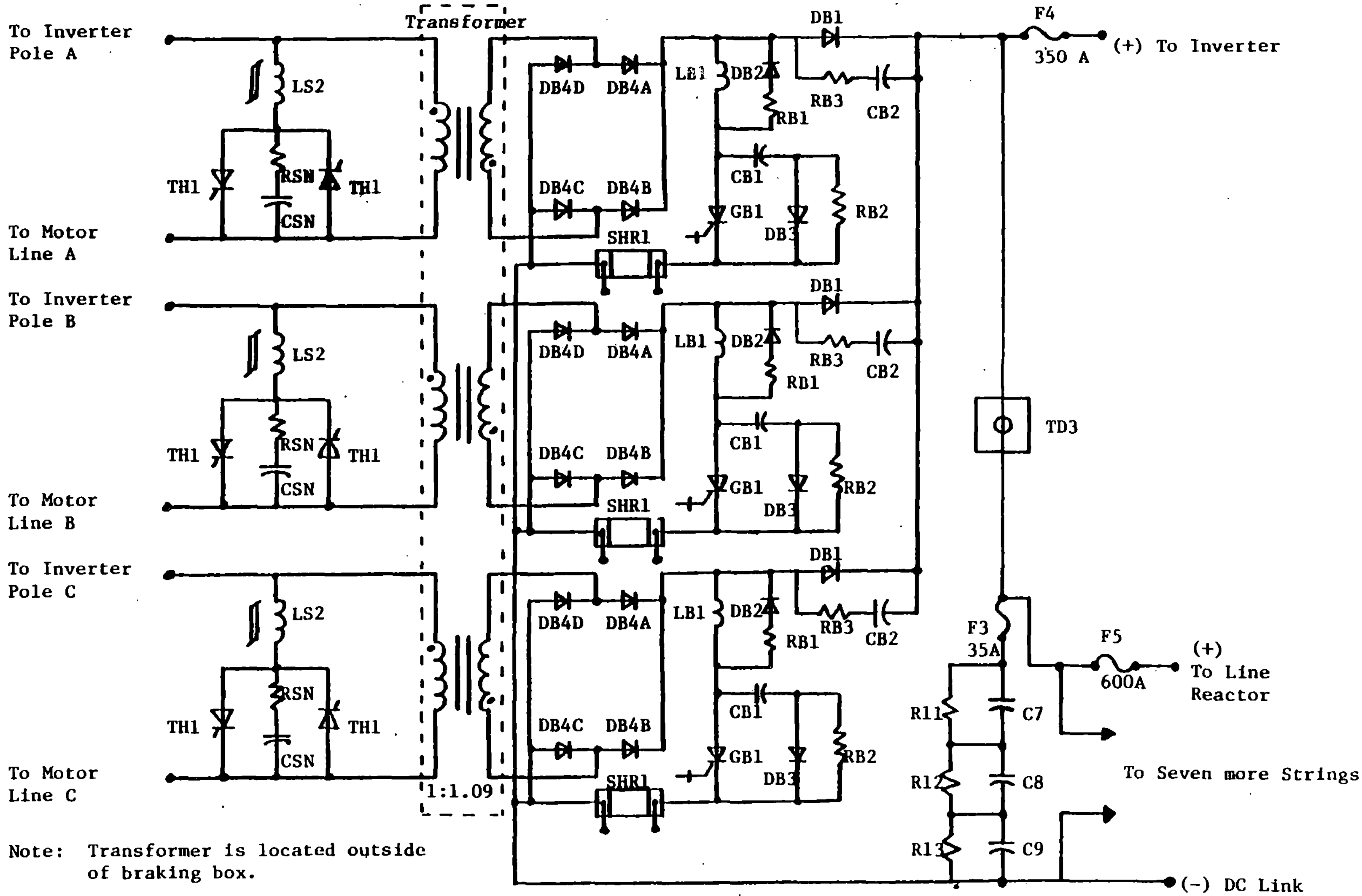


Figure 4-3
Regenerative Braking Circuit

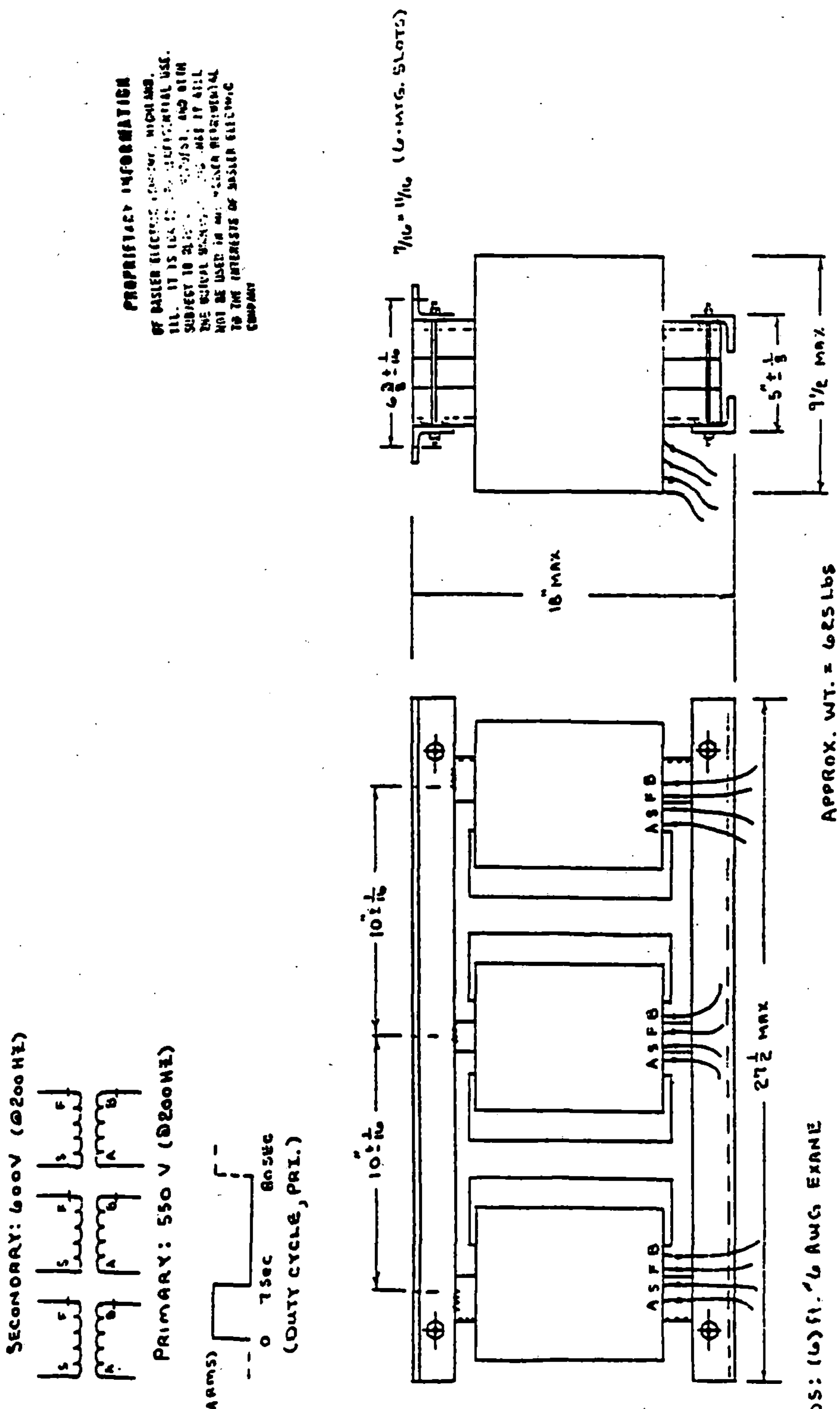


Figure 4-4

Braking Transformer Outline

4.1.3 Packaging Objective

Based on the guidelines mentioned in Section 3.1 and considering that components located in the regenerative brake box are less likely to fail compared to the inverter, it was decided that we would:

- o Locate the regenerative brake box and braking transformer behind the inverter box. (See Figure 3-5.)

- o Mount a cold plate at the bottom of the box and mount all heat producing components to this plate.

- o Mount line filter capacitors in the regenerative brake box.

- o Mount 350A inverter fuse in the regenerative brake box since a convenient location is not available in the inverter.

The space available for:

- o 4 - Regenerative Brake Boxes

- o 4 - Braking Transformers and

- o 4 - Inverter Fault Current di/dt Limiting Inductors

as explained in Section 3.1 is confined to the space shown in Figure 3-4. This space is approximately 144 inches long by 38 inches wide. The undercar equipment layout in Figure 3-5 permits fitting all the equipment in the limited available space under the car, and still allows access to the regenerative brake box from one side.

The overall regenerative brake box is 38.0 inches long by 16.55 inches deep (including cover) by 28.19 inches high, excluding mounting brackets but including fins. An outline of the box is shown in Figure 4-5 and a circuit schematic in Figure 4-3. The length available for a box of such height along the width of car was only 39.0 inches, thus the 38.0 inch limit on box length. The heatsink can be slid in and out of the box on teflon slides and enough slack in cables has been provided for this purpose. The heatsink is a self-contained unit and can be replaced with another heatsink assembly to reduce car downtime.

4.1.4 Packaging Description

In addition to brake circuit components, the regenerative brake box contains 24 cans of line filter capacitors consisting of eight parallel strings with three series cans in each string. This box also contains one 600 amp and one 350 amp fuse.

The braking transformer is a part of the braking circuit; however, it is not packed in the box but separately hung under the car behind each regenerative brake box. An outline of the braking transformer is shown in Figure 4-4. The undercar placement of the regenerative brake box and braking transformer is shown in Figure 3-5. The following is a description of the most significant features of the regenerative brake package:

- Capacitors are mounted on the back wall with long bolts and are supported at the front to restrict vibration. The capacitor bank can be removed without disturbing any other component.

- Thyristors packed in power brick packages are mounted on the sink which is the bottom of the box.

- GTO's are single side cooled by mounting on a copper block which is electrically isolated from the heatsink with Chomeric 1671. The cathode side also has a copper bus bar which is used for electrical connection. The bus bar has been made heavy enough to provide thermal mass for short transient loads.

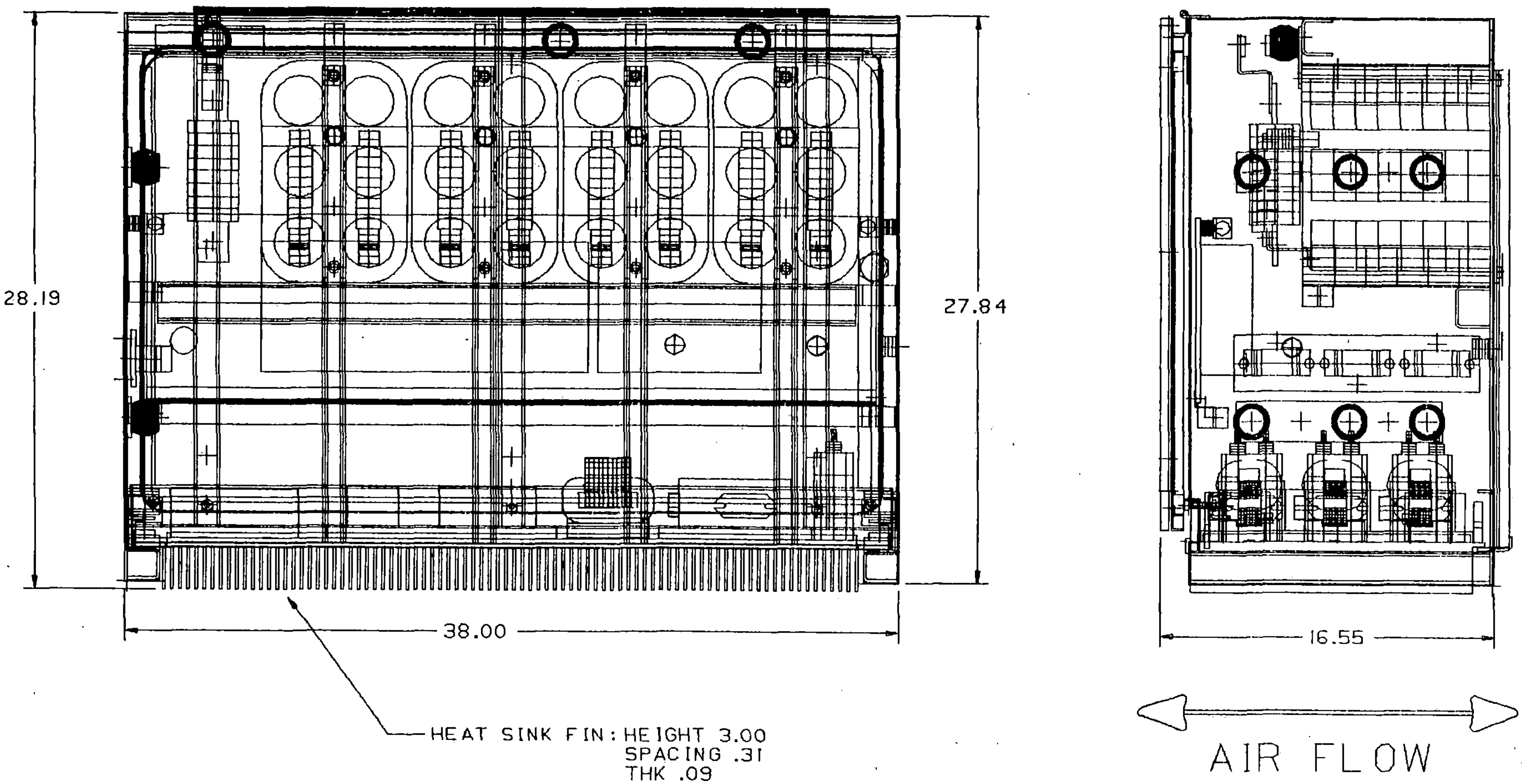


Figure 4-5

Regenerative Braking Unit Outline

- All stud diodes (DB4) are mounted on aluminum blocks which are electrically isolated from the heatsink with Chomeric 1671. The isolated blocks are mounted on pads which are about 3/8" above the surface of the heat sink.

- The gate driver boards for GTO's and thyristors are mounted on a hinged polyglass panel so that gate drivers are easily accessible for maintenance purposes.

- The heatsink and gate driver panel can be removed as one modular assembly.

4.1.5 GTO Assembly

A double side cooled assembly similar to the inverter GTO/Diode assembly could not be used due to limited available space. The conventional WTD single side assembly also could not be used because clamps for mounting the block to the heat sink need more space on the sink than was available. The conventional block to sink clamp also obstructs considerable block surface which could be used for mounting the snubber resistor and diode. Mounting of snubber components close to the main device is necessary to reduce stray inductance in the snubber circuit.

For the above reasons, the arrangement of mounting the block to the heat sink was modified. The modified arrangement makes the assembly compact and also reduces chances of a problem due to uneven torqueing of clamp bolts. The modified arrangement is shown in Figure 4-6.

Due to restricted space, snubber resistors RB2 are mounted on the sides of the copper block on which the GTO is mounted. All the devices are mounted on a common sink. It is estimated that each GTO block dissipates heat on a 14.50" by 4.75" sink surface. The thermal resistance from this sink to air is estimated to be 0.072°C/W.

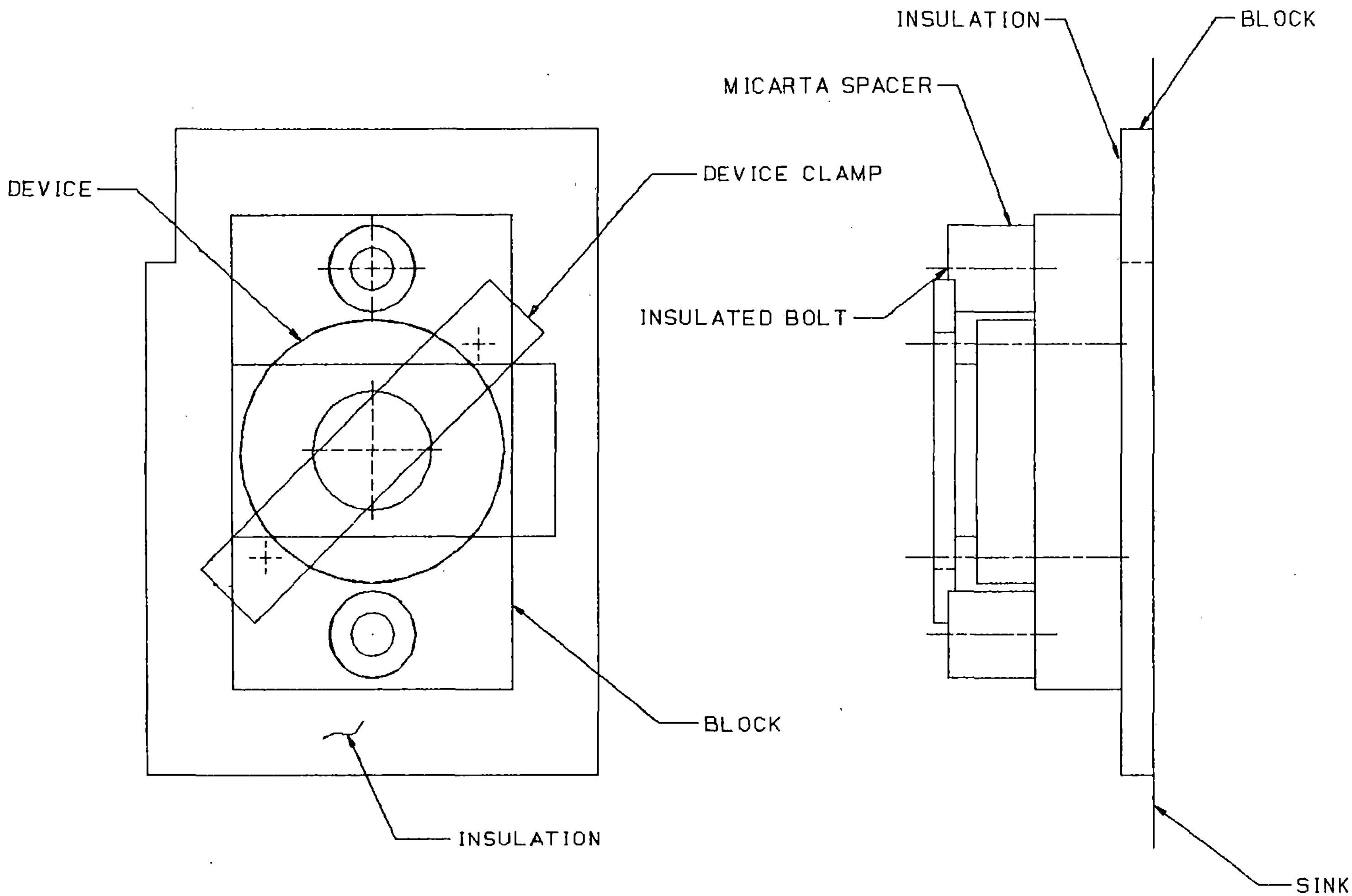


Figure 4-6

Regenerative Brake Circuit GTO Assembly

Estimated power losses in key regenerative brake box components for the typical run of Figure 3-3 and an intermittent 80 mph braking run are given in Figures 4-7 to 4-14. A listing of average component losses and total losses assuming the typical run (defined as Miller Run per test S-1A with 20 second station stops) is given below:

Component	Quantity	Avg Loss (watts)	Total Loss Watts
GTO, GB1	3	75	225
Diodes DB4	12	26	312
Diodes DB1	3	18	54
Thyristors, TH1	6	75	450
Snubber-RB1	3	17	51
Snubber-RB2	3	9	27
Snubber-RB3	3	5	15
Snubber-RSN	3	7	21
		TOTAL	1,155

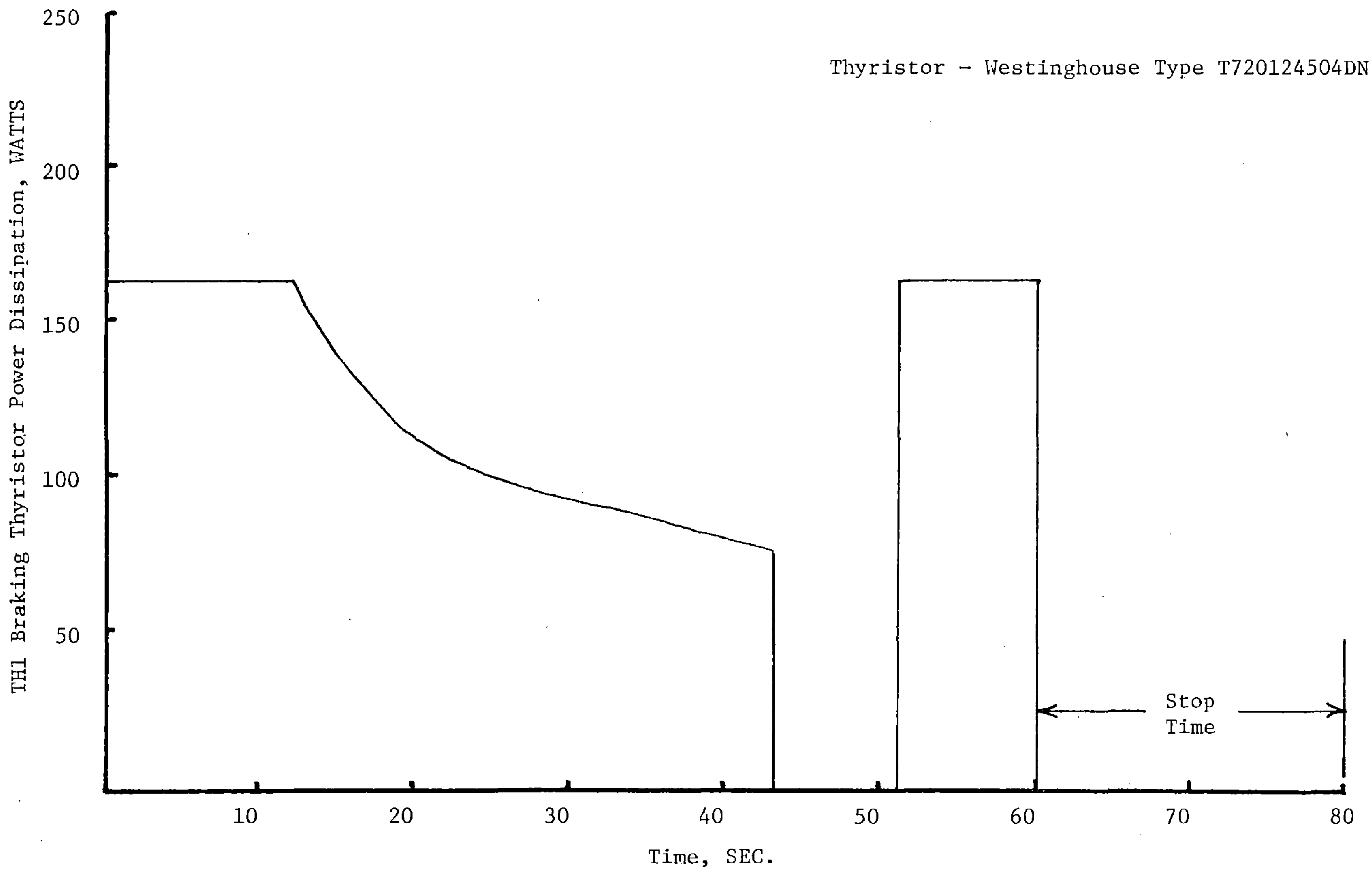


Figure 4-7

THl Braking Thyristor Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

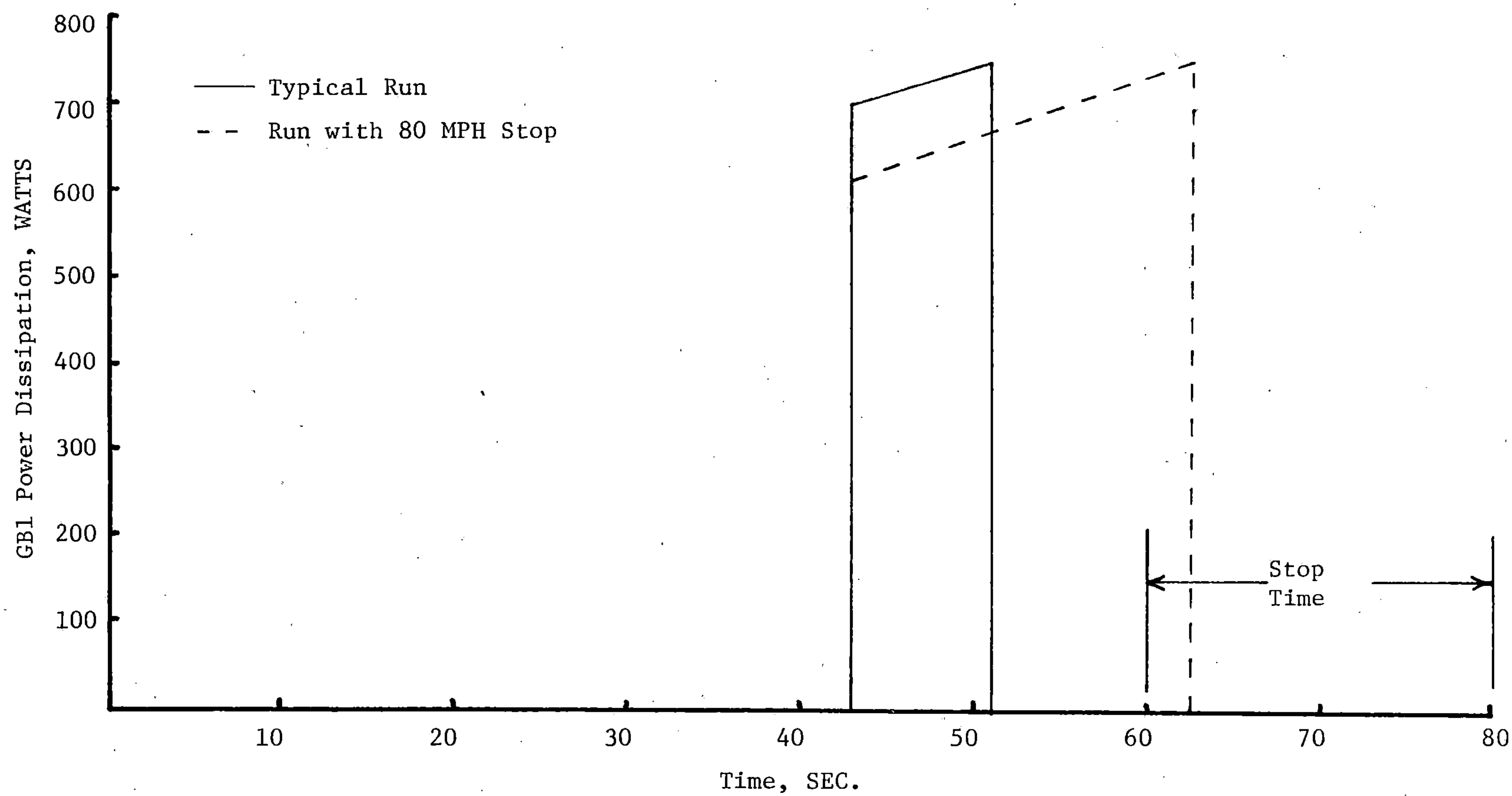


Figure 4-8

GB1 Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

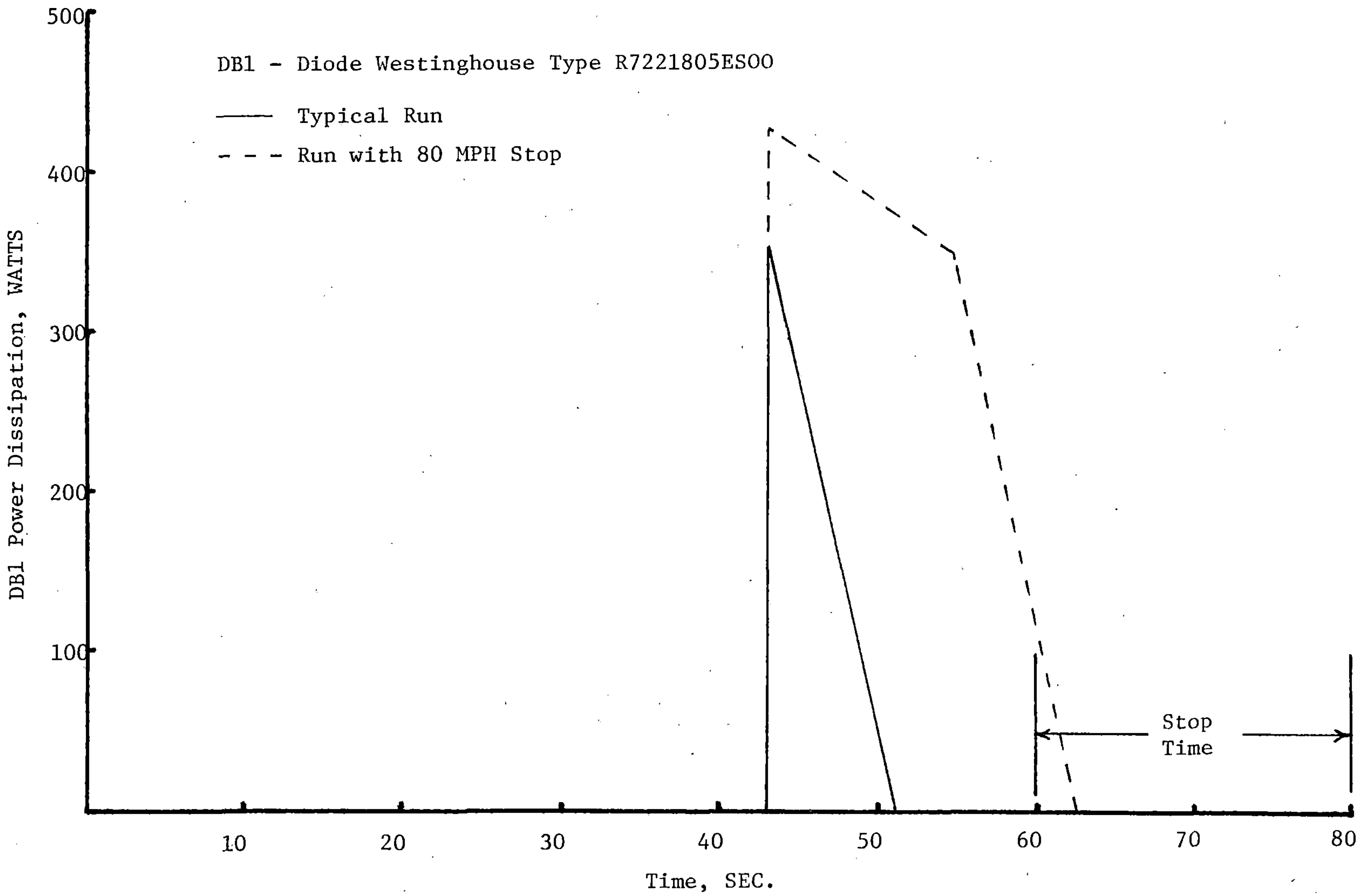


Figure 4-9

DB1 Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street [illegible])

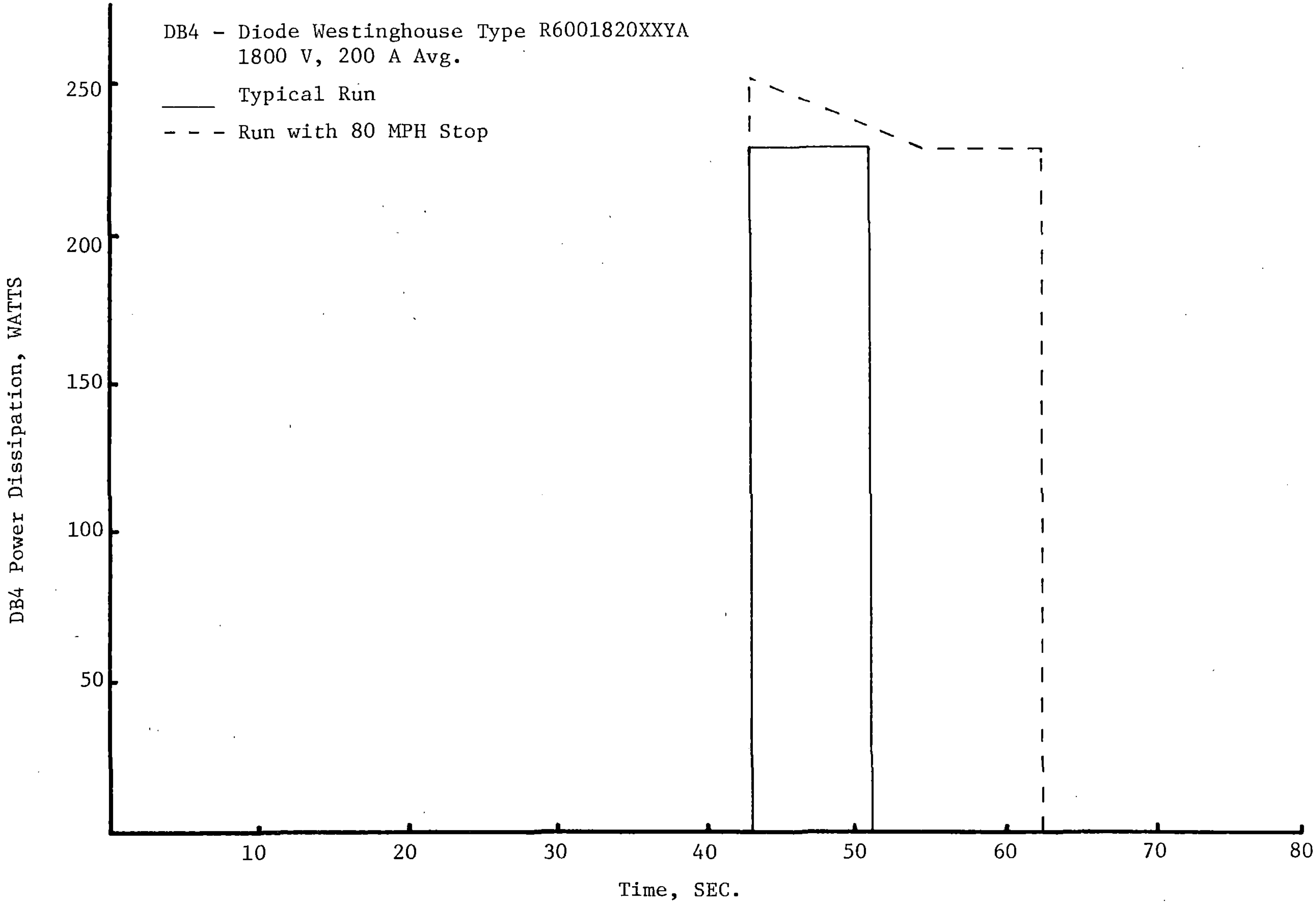


Figure 4-10

DB4 Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

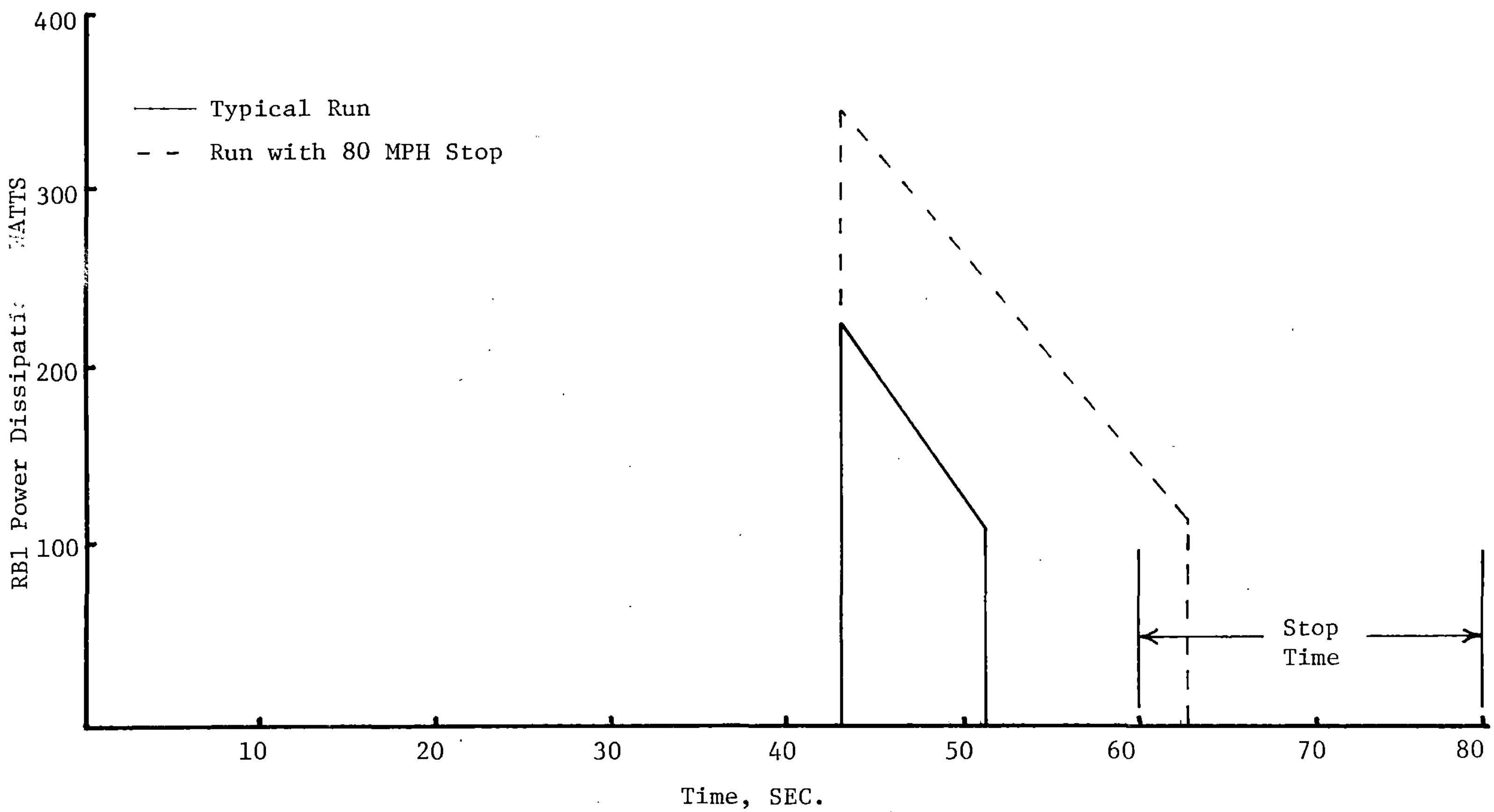


Figure 4-11

RB1 Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

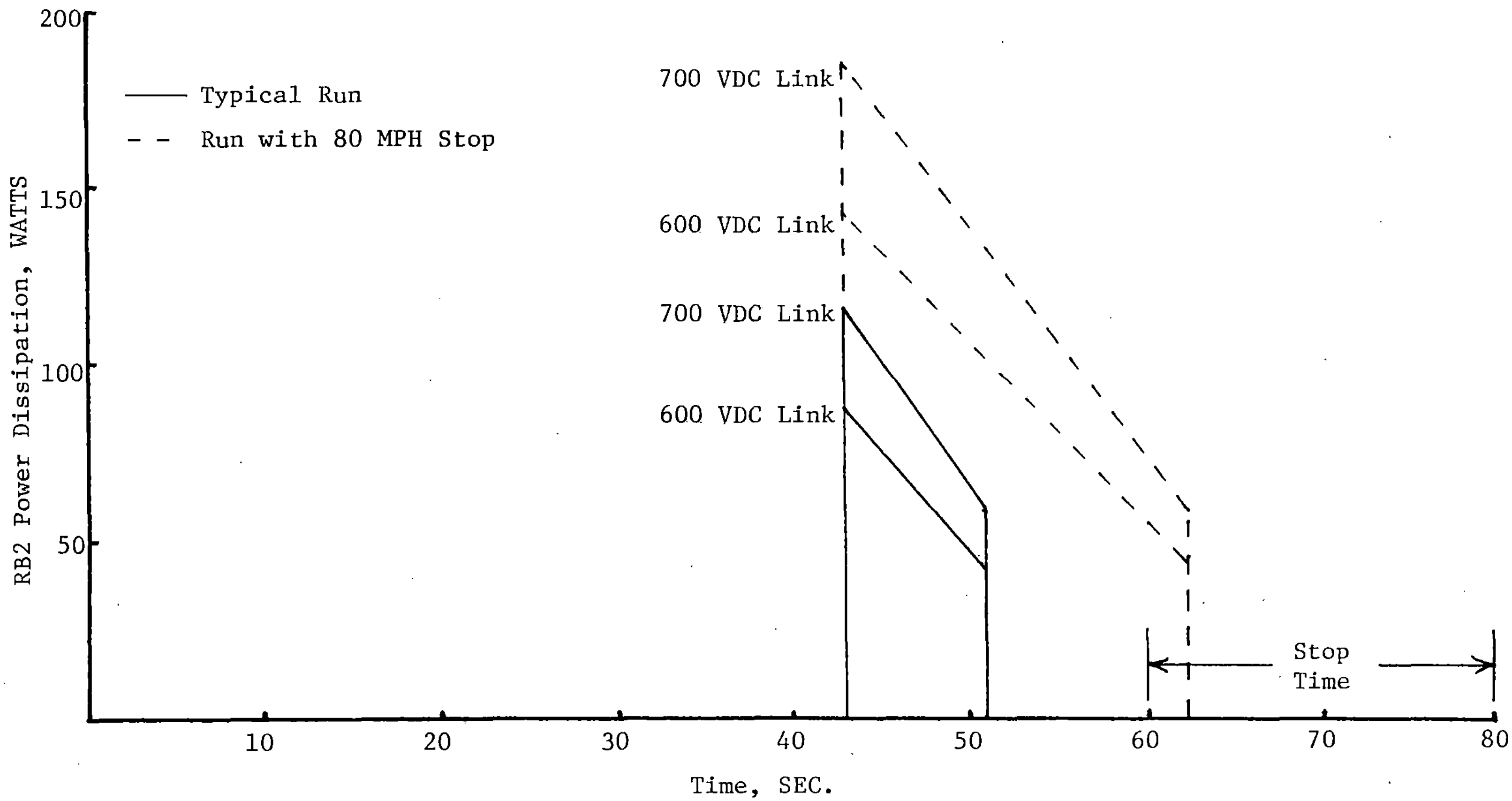


Figure 4-12

RB2 Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

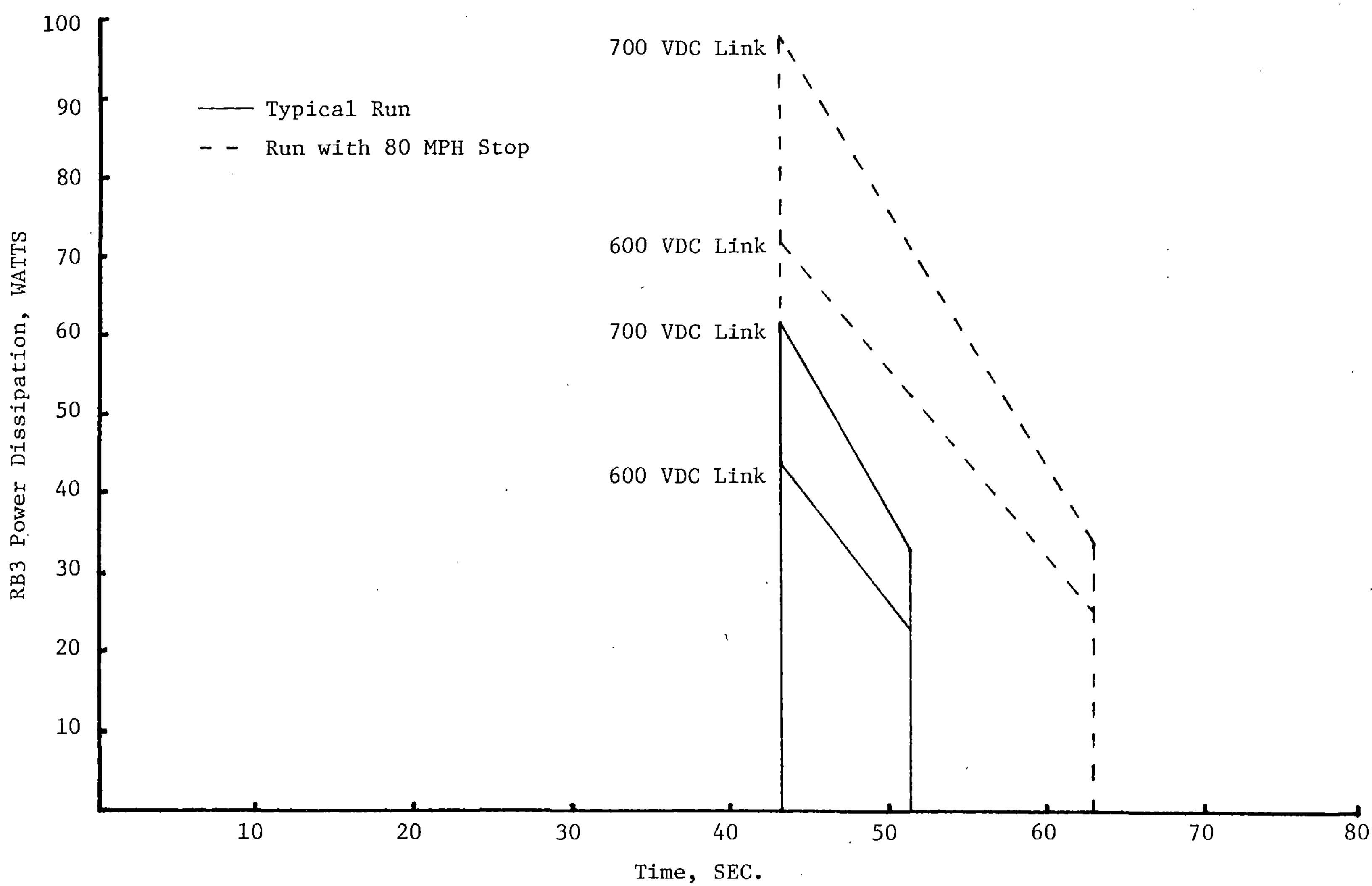


Figure 4-13

RB3 Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

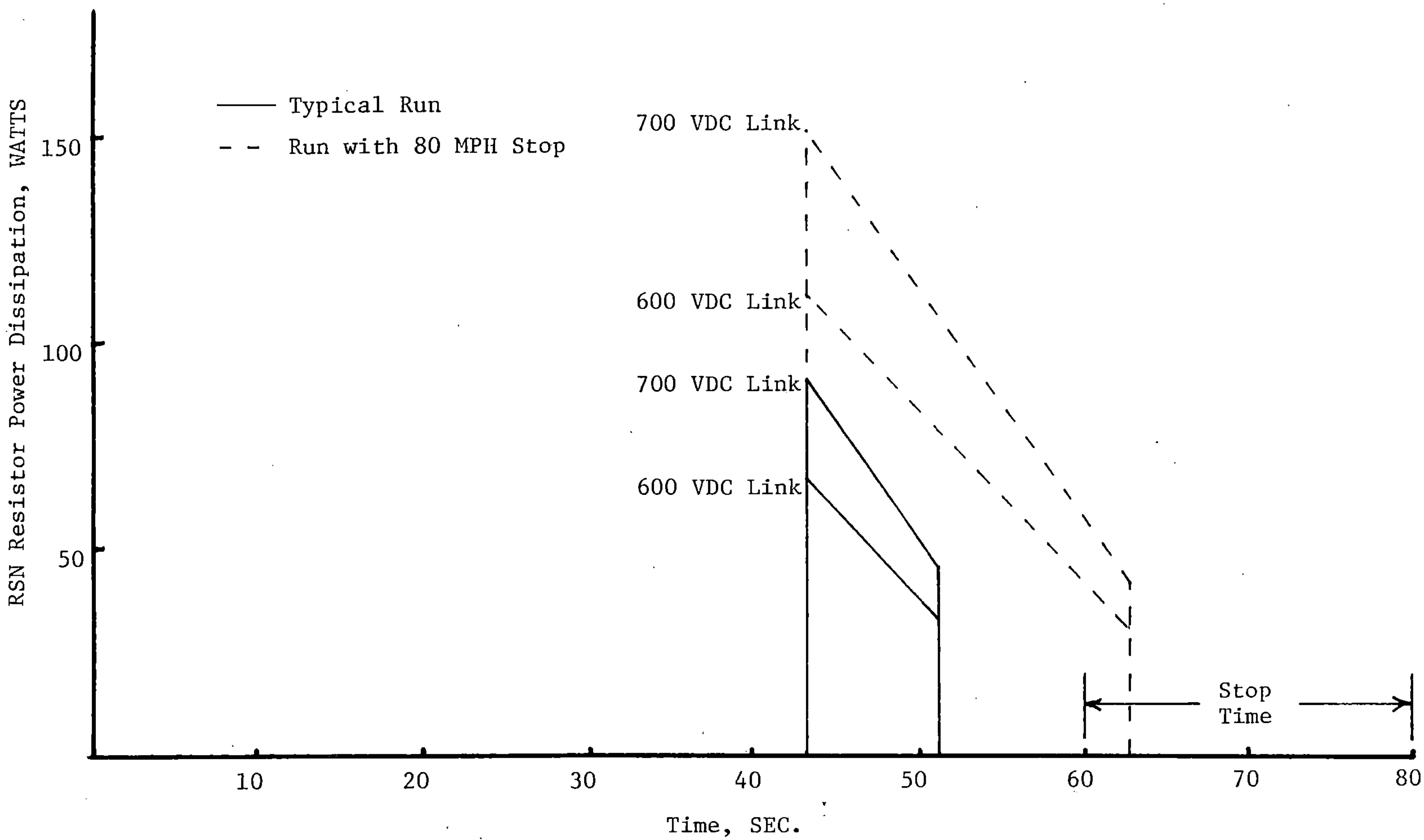


Figure 4-14

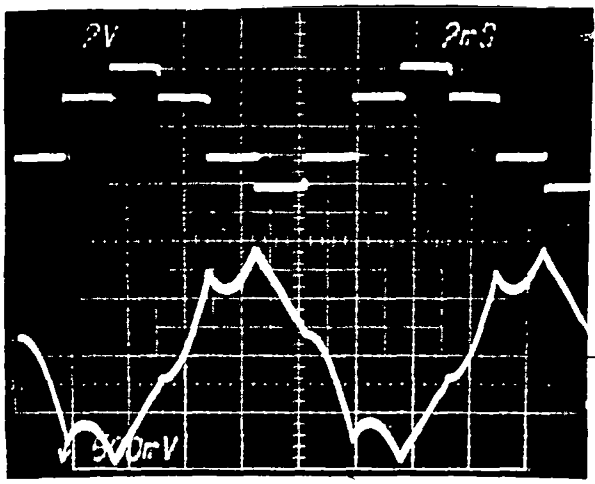
RSN Resistor Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

4.1.6 Selected Test Results

Strip chart recordings of AC drive performance with the regenerative brake circuit in operation are provided in Section 5. Figures 4-15 and 4-16 show the motor line-to-neutral voltage and motor line current waveforms with the regenerative brake circuit operating. The motor voltage is determined solely by the six-step inverter output when the braking transformer is shorted out, i.e., zero degree braking transformer pulse width. As the braking transformer output pulse width is increased to 70°, the increasing braking transformer voltage combines with the fixed inverter output voltage to produce the photographed motor line-to-neutral voltages and line currents shown in Figures 4-15 and 4-16. A comparison of measured and calculated regenerative brake component temperature rises for the assumed typical run of Figure 3-3 and for the Garrett Synthetic profile of Figure 3-22 is given in Figure 4-17. During testing, all semiconductor devices ran at or below the manufacturer's rated temperature.

The results of these and other tests performed on the AC drive system verify that the basic design and performance objectives of the regenerative brake circuit have been met.

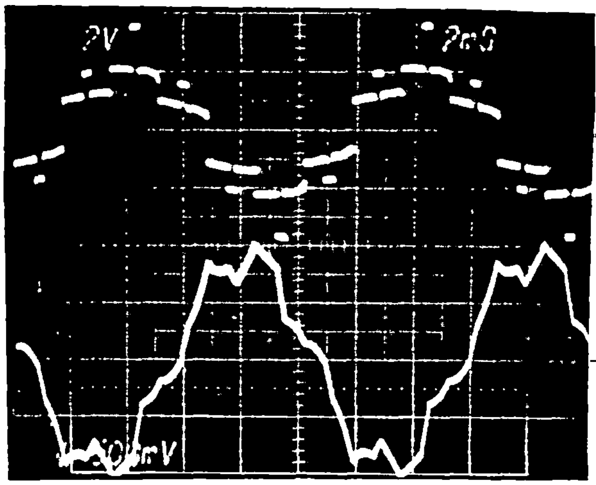
f_{out} = 100 Hz V_{DC} = 600V



— 0 V_{LN} 400V/cm

— 0 I_L 250A/cm

BRAKING TRANSFORMER
SHORTED-OUT
TE = 635 Nm



— 0 V_{LN} 400V/cm

— 0 I_L 250A/cm

BRAKING TRANSFORMER
PULSE-WIDTH = 10°
TE = 705 Nm

— 0 V_{LN} 400V/cm

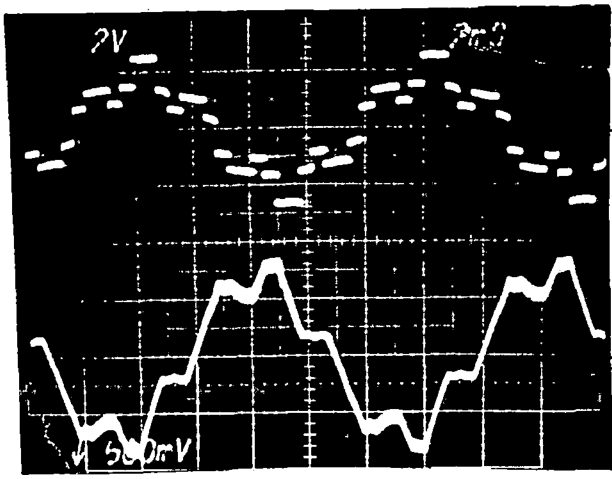
— 0 I_L 250A/cm

BRAKING TRANSFORMER
PULSE-WIDTH = 30°
TE = 1153 Nm

Figure 4-15

Motor Voltage and Current Waveforms with
Regenerative Brake Circuit Operating

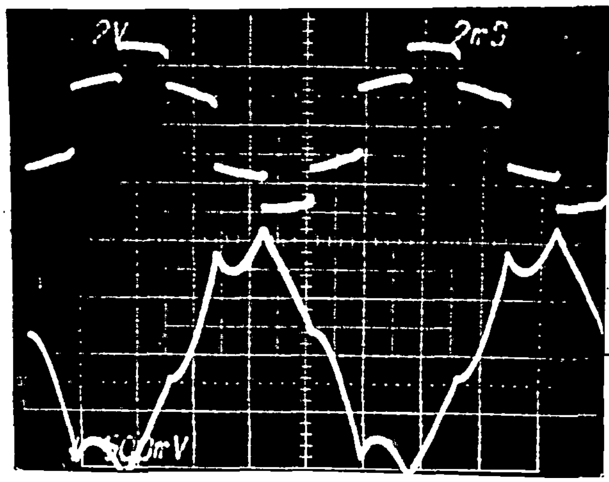
f_{out} = 100 Hz V_{DC} = 400V



0 V_{LN} 400V/cm

0 I_L 250A/cm

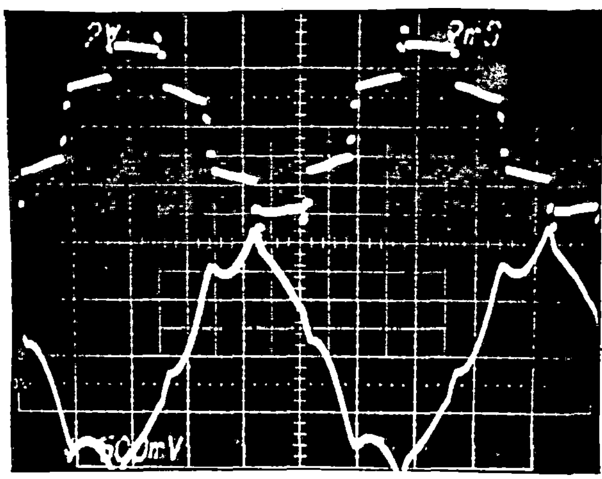
BRAKING TRANSFORMER
PULSE-WIDTH = 30°
TE = 521 Nm



0 V_{LN} 400V/cm

0 I_L 250A/cm

BRAKING TRANSFORMER
PULSE-WIDTH = 60°
TE = 965 Nm



0 V_{LN} 400V/cm

0 I_L 250A/cm

BREAKING TRANSFORMER
PULSE-WIDTH = 70°
TE = 1067 Nm

Figure 4-16

Motor Voltage and Current Waveforms with Regenerative Brake Circuit Operating

Component		Temperature @ 40°C Ambient			
		Measured (°C)	Calculated (°C)	T_j (Max.)* (°C)	Calculated Cycle ΔT_j (°C)
GTO Block	Typical Run	48.1	54.7	105.0	56.7
	Garrett Run	43.6	50.8	94.0	50.8
Power Brick Thyristor	Typical Run	72.0	–	72.0	–
	Garrett Run	62.5	–	62.5	–
DB1 Diode	Typical Run	52.1	51.6	89.0	36.6
	Garrett Run	44.2	–	+	+
DB4 Diode	Typical Run	54.8	52.5	140.0	84.8
	Garrett Run	44.0	+	+	+
Box Ambient	Typical Run	69.0	–	–	–
	Garrett Run	59.0	–	–	–

* – T_j (Max.) is based on measured temperature.

\+ – Data not available.

Note 1: See Figure 3-3 for profile of "Typical Run" (run with 30 seconds stop time instead of 20 seconds). See Figure 3-22 for profile of "Garrett Run".

Note 2: Air flow over car simulated by blower providing approximately 1000 LFM of air flow through the inverter heatsink fins. The blower was turned off during profile stop intervals. The inverter was shutdown during coast intervals on the Garrett Run.

Note 3: The measured temperature is the highest of all measured temperatures for similar locations.

Figure 4-17

Measured and Calculated Regenerative Brake Component Temperatures

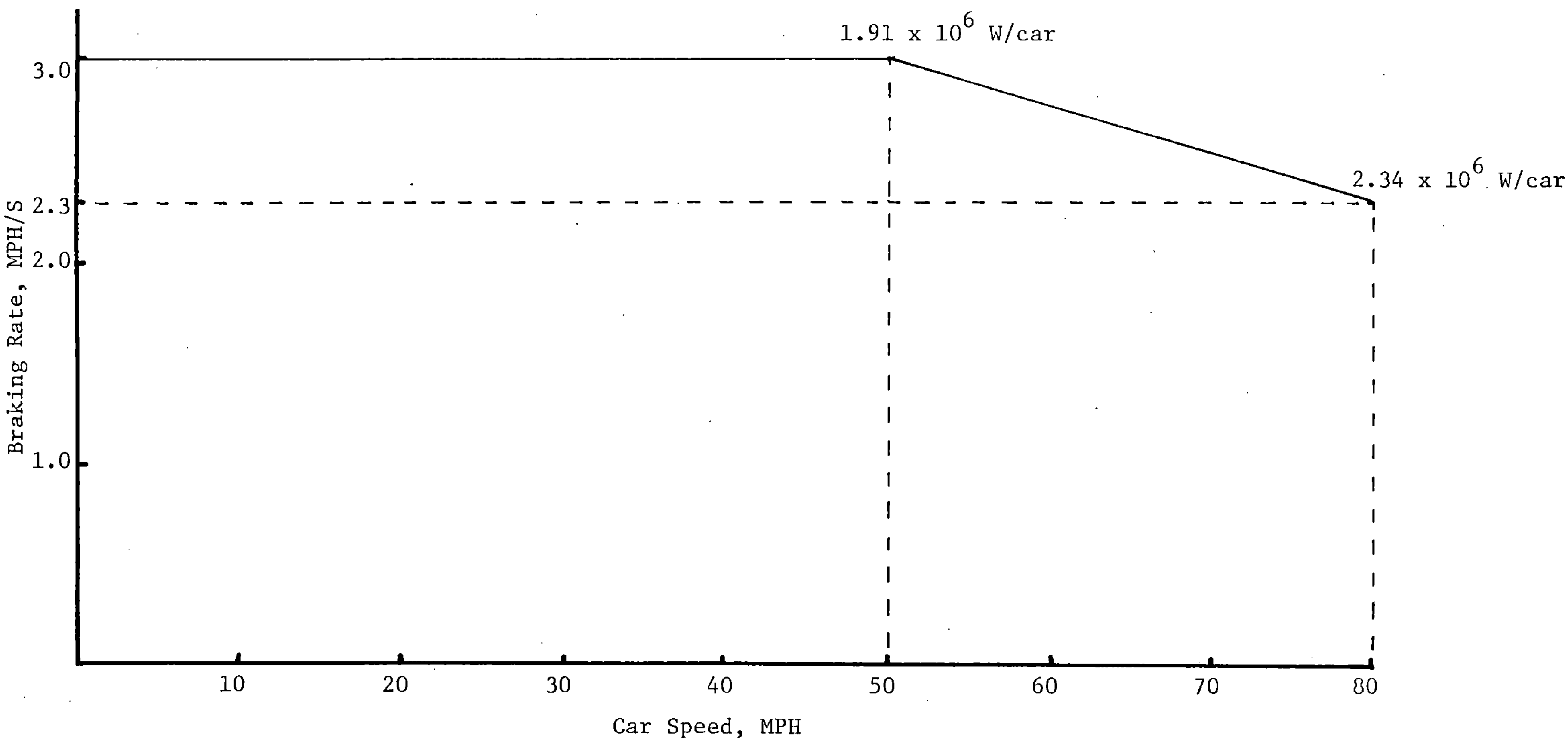
4.2 DYNAMIC BRAKE CIRCUIT

4.2.1 Circuit Design Objective

The AC traction drive contains a GTO based dynamic brake circuit to absorb braking energy and to hold the input filter capacitor voltage at a regulated pre-set maximum level when braking with a non-receptive or partially receptive line. Unlike the inverter and regenerative brake circuits, there is one dynamic braking circuit per four motors, or one per car. This circuit must be capable of absorbing all the energy that can be regenerated for both the typical duty-cycle and the intermittent braking cycle described in Section 3.1 and Figure 3-3.

The worst case energy handling requirement of the dynamic brake circuit is defined by the maximum car weight and the maximum braking rate versus speed requirement. These requirements are illustrated in Figure 4-18. A maximum car weight of 130,000 lbs. is assumed and a 10,490 lb equivalent weight is allowed for energy stored in rotating parts for a total of 140,490 lb maximum equivalent car weight. With this equivalent car weight, a 3 mphps braking rate at 50 mph corresponds to an instantaneous power of 1.91×10^6 W/car and a 2.3 mphps braking rate at 80 mph corresponds to an instantaneous power of 2.343×10^6 W/car.

An estimate of system losses is required to determine the maximum power that must ultimately be dissipated in the dynamic braking circuit. This loss estimate is illustrated in Figure 4-19. This estimate indicates that approximately 83% of the maximum instantaneous car power must be dissipated in the dynamic braking circuit. Figure 4-20 illustrates maximum per car dynamic brake circuit power versus time for a typical NYCTA run (Figure 3-3). This typical run is approximately thermally equivalent to the average of an NYCTA overall system run. Dynamic brake circuit power versus time for a "once a day" 80 mph stop is also shown. Average typical run dynamic brake circuit power is about 163 KW. This is the average power rating required for the dynamic braking resistors assuming 100% dynamic braking.



130,000 lb	car
10,490 lb	equivalent weight to allow for energy stored in rotating parts
140,490 lb	Total maximum car weight

Figure 4-18

Maximum Braking Rate vs Speed Requirement

Maximum Power Available from Car: 2.34×10^3 KW

Estimated Losses Per Car at 80 MPH and 2.3 MPH/S Rate:

Train Resistance		186.3 KW
Gear Losses		9.33 KW
Motor Losses		183.2 KW
Braking Transformer Losses		11.6 KW
Braking Circuit Semiconductor Losses		9.27 KW
Inverters		9.46 KW
Total Losses Per Car	=	409.16 KW

Maximum Net Power Dissipated in Dynamic Braking: 1.94×10^3 KW

Figure 4-19

Dynamic Brake Circuit Peak Power Estimate

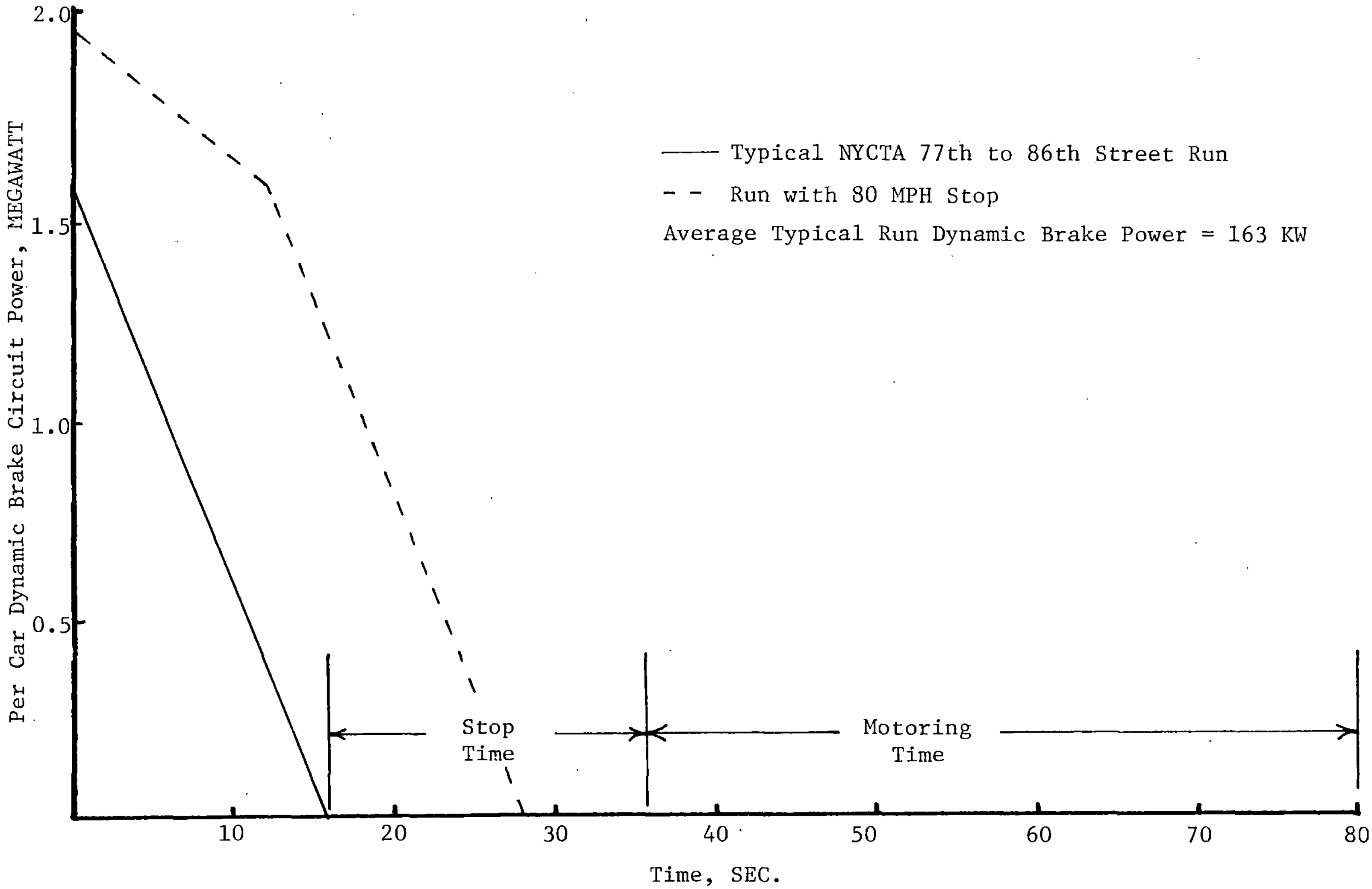


Figure 4-20

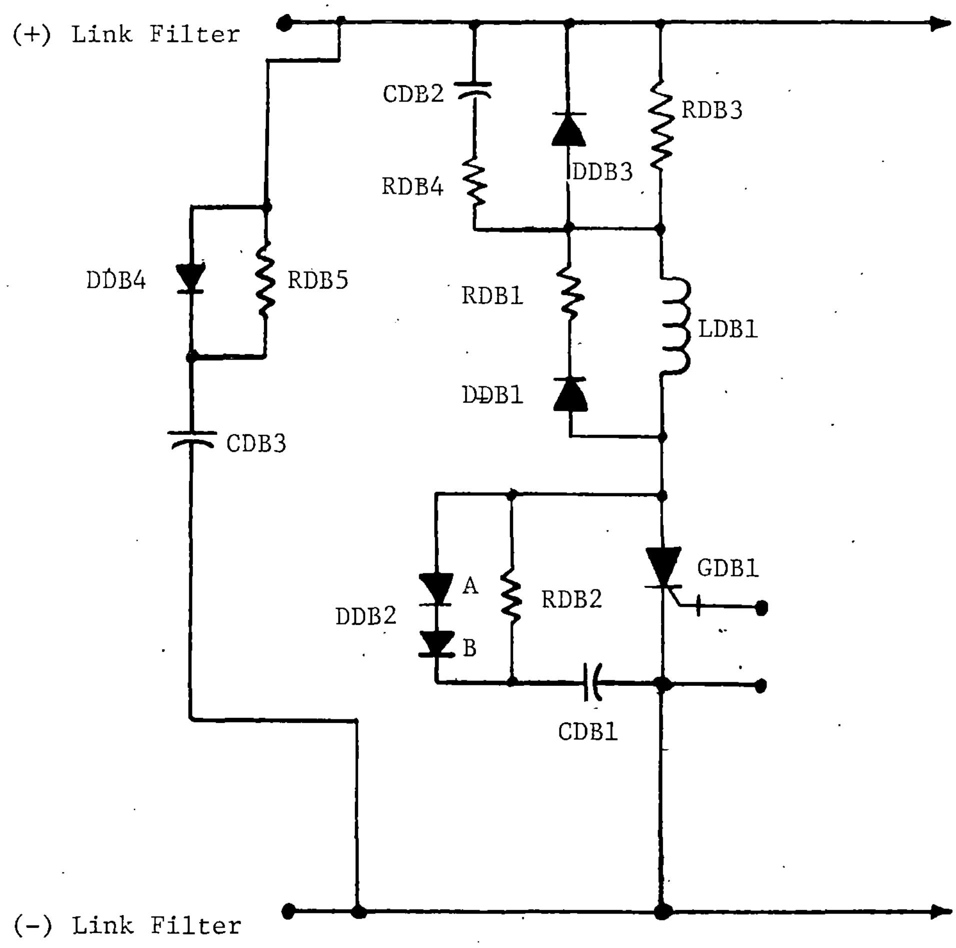
Dynamic Braking Power vs Time

Assuming a 600 VDC minimum dynamic braking voltage and a 1.96 X 10^6 Watt peak instantaneous braking power, the peak dynamic braking circuit current is 3267 amps. The GTO based dynamic braking circuit requires a number of parallel paths to handle this peak current. Among presently available GTOs, the 600A turn-off, 400A RMS, 2500 volt, Toshiba GTO has the highest KW rating per dollar and was chosen for the dynamic brake circuit. The circuit has ten parallel GTO-braking resistor paths requiring a total of ten GTOs per car. Only one of the ten parallel paths is chopper controlled. The chopping frequency is 218 Hz. The other nine parallel paths are switched on/off in sequence as necessary, and the sequence is rotated every 0.5 second to fully utilize all nine on/off controlled parallel paths. Since a half-car set of equipment was built and tested in the development program, operation of the dynamic brake circuit has been limited to five parallel paths or five GTOs.

4.2.2 Circuit Description

A schematic diagram of one of ten virtually identical dynamic brake GTO-braking resistor strings is shown in Figure 4-21. The braking resistor RDB3 consists of five MA-20, 2.5 KW, 0.32 ohm resistors connected in series for the PWM controlled string and six of the same resistors connected in series for the on/off controlled strings. The PWM controlled braking resistor string has less resistance because the maximum chopper on time is always sufficiently less than 100% of the chopping period to allow a very conservative recovery period for the GTO. Since the braking resistors are inductive, diode DDB3 is required to free-wheel braking resistor current when GTO GDB1 is turned off. If the GTO is turned on while current is free-wheeling in DDB3 (this is possible when operating at the maximum chopping duty-cycle), the GTO and diode DDB3 would be subject to excessive di/dt if reactor LDB1 were not present. LDB1 (7uH) limits worst case GTO di/dt to 100 A/us at a 700 volt maximum dynamic braking voltage. Resistor RDB1 and diode DDB1 serve to dissipate energy trapped in LDB1, and to limit the voltage transient on GDB1 when it turns off. Capacitor CDB2 and resistor RDB4 serve to soften the reverse recovery transient of DDB3. The snubber consisting of capacitor CDB1, resistor RDB2, and diode DDB2 protects the GTO from excessive dv/dt when it turns off.

The line filter capacitors are located in each of the four regenerative brake boxes on a car to keep them close to the inverter and regenerative braking circuit for each motor, which places them comparatively far away from the dynamic braking circuit. The connection between the dynamic braking circuit and the line filter capacitors contained in each regenerative brake box is accomplished by tightly bundled pairs of cables. Even so, several of the runs are long enough to insert significant inductance between the line filter capacitors and the dynamic brake circuit. The snubber consisting of diode DDB4, resistor RDB5, and capacitor CDB3 reduces the voltage transient



Note: Design based on 218 Hz chopping frequency

Figure 4-21

Dynamic Braking Circuit

appearing across the dynamic brake circuit terminals due to this inductance when dynamic brake GTOs are turned off, and in turn, reduces the voltage transient appearing on a dynamic brake GTO when it turns off.

4.2.3 Packaging Objective

The undercar space made available by removing equipment such as the motor control box and a bank of braking resistors has been fully utilized to mount:

- Four Inverters
- Four Regenerative Brake Boxes
- Four Transformers
- Four Inverter Fault Current di/dt Limiting Inductors.

Since there was insufficient space available to mount the dynamic brake box in the area made available for the AC equipment, the space where the lighting inverter on R44 cars had been hung was selected for the dynamic brake box. This space was available since the lighting inverter is no longer used.

Based upon basic guidelines established in Section 3.1, it was decided to:

- Mount a cold plate at the bottom of the box and mount all heat producing components to this plate.

- Utilize the rear wall of the box to mount free-wheeling diodes and snubber circuits associated with them.

- Mount GTO gate drivers on a panel which is easily accessible.

The dynamic brake box is 50.5 inches long by 13.34 inches wide (without cover) by 24.50 inches high, including fins but excluding mounting brackets. The bottom heatsink itself is a self contained unit and can be replaced with another heatsink assembly to reduce car down time. An outline of the dynamic brake box is shown in Figure 4-22.

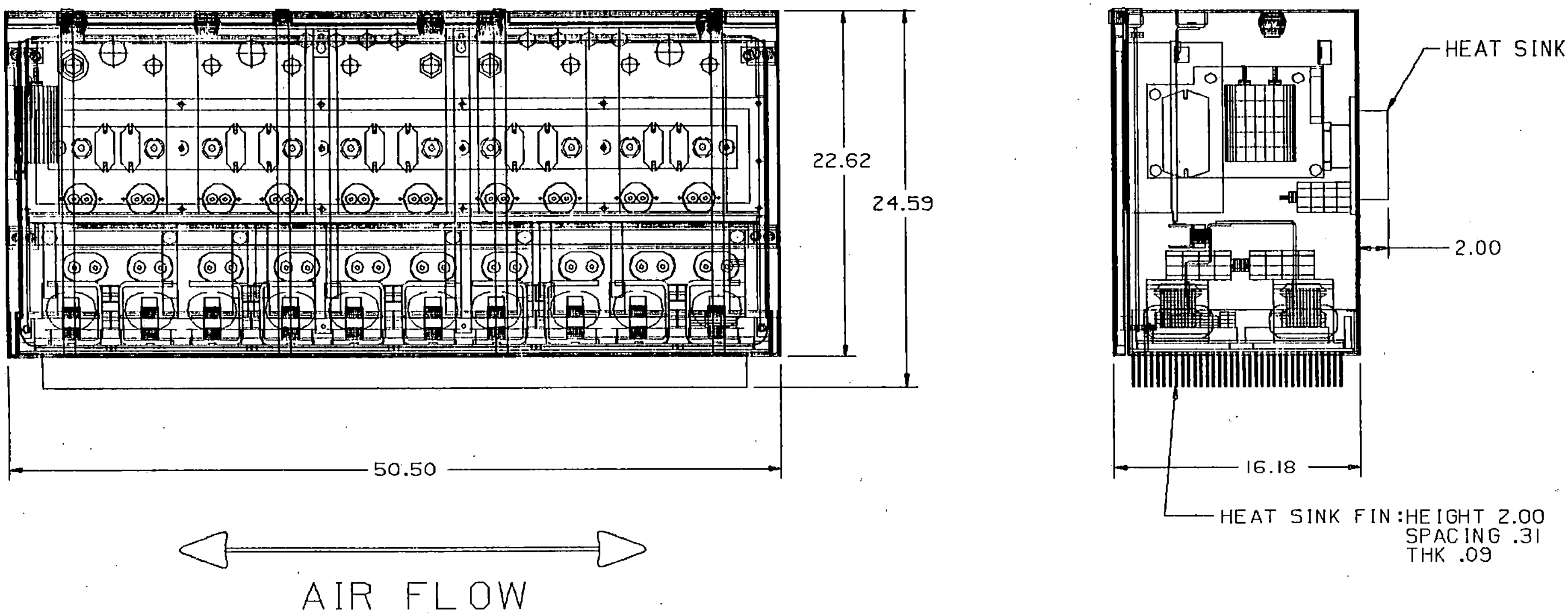


Figure 4-22

Dynamic Brake Unit Outline

4.2.4 Packaging Description

The dynamic brake box includes 10 GTOs and their RC snubber networks, all of which are mounted on the bottom heatsink. Gate drivers for the GTOs are mounted on a hinged panel. Half of the gate drivers are accessible with the hinged panel in a vertical locked position, and the other half by moving the panel to a horizontal position. The remaining components of the dynamic brake circuit, such as diodes and their RC snubber networks are mounted on a heatsink which is 48.67 inches long by 7.66 inches wide and having 2 inch high fins. A component layout of the heatsink showing assembly of GTOs and components associated with the GTO circuit is shown in Figure 4-23.

Estimated power losses in key dynamic brake box components for the typical run of Figure 3-3 and an intermittent 80 mph braking run are given in Figures 4-24 to 4-30. A listing of average component losses assuming the typical run is given below. Snubber resistor and DDB3 losses are significant only for the PWM controlled GTO string since the average switching frequency of the on/off controlled GTO strings is comparatively quite low. The loss estimate in Figure 4-25 for an on/off controlled braking GTO assumes the GTO is on the entire braking cycle. Since the on/off controlled braking GTO conduction times are cycled every one-half second to balance the duty of all on/off controlled GTOs, the average power loss in the on/off controlled GTOs is about one-half the average calculated from Figure 4-25.

Component	Quantity	Avg. Power Loss Each (Watts)	Total Loss (Watts)
PWM GTO	1	77	77
On/Off GTOs	9	26	234
Diode, DDB3 (PWM)	1	17	17
Resistor, RDB1	1	45	45
Resistor, RDB2	1	25	25
Resistor, RDB4	1	11.5	11.5
Resistor, RDB5	1	65	65
		TOTAL	474.5

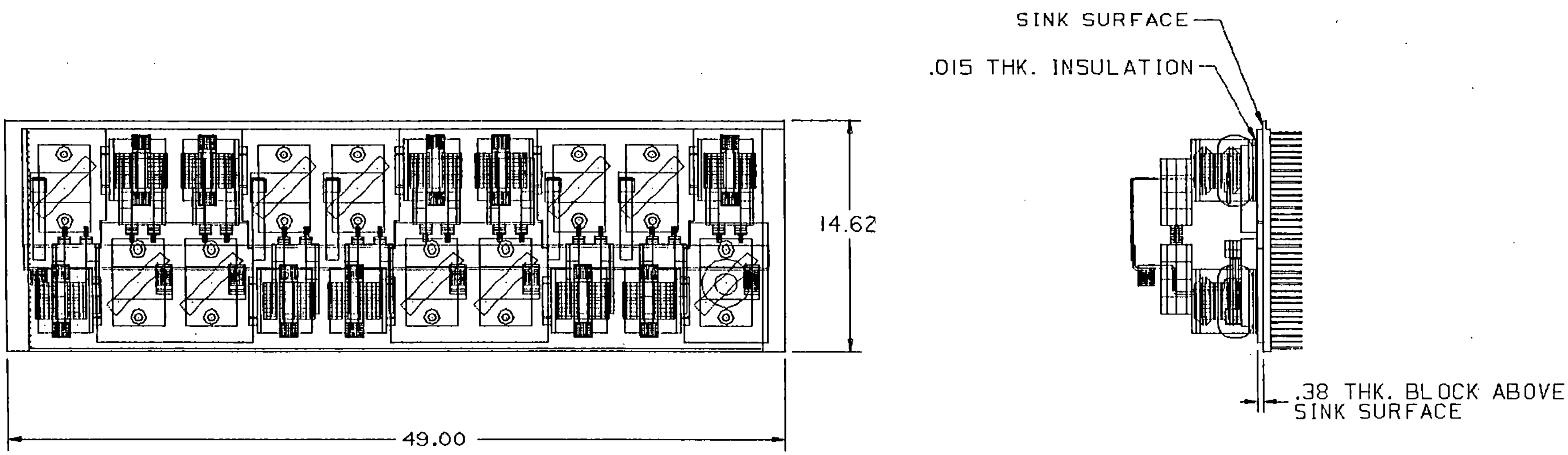


Figure 4-23

Dynamic Brake Heatsink Layout

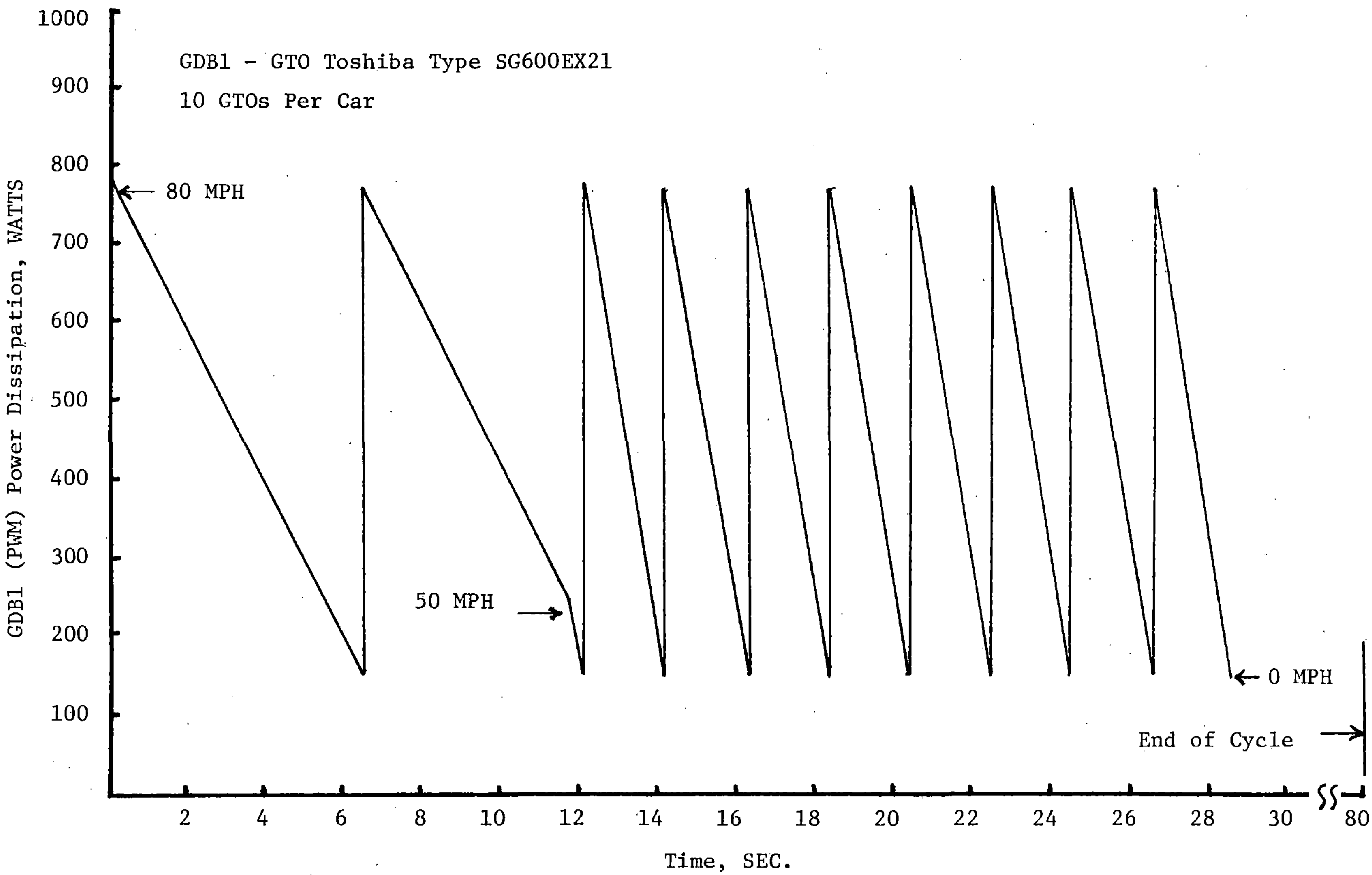


Figure 4-24

GDB1 (PWM) Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

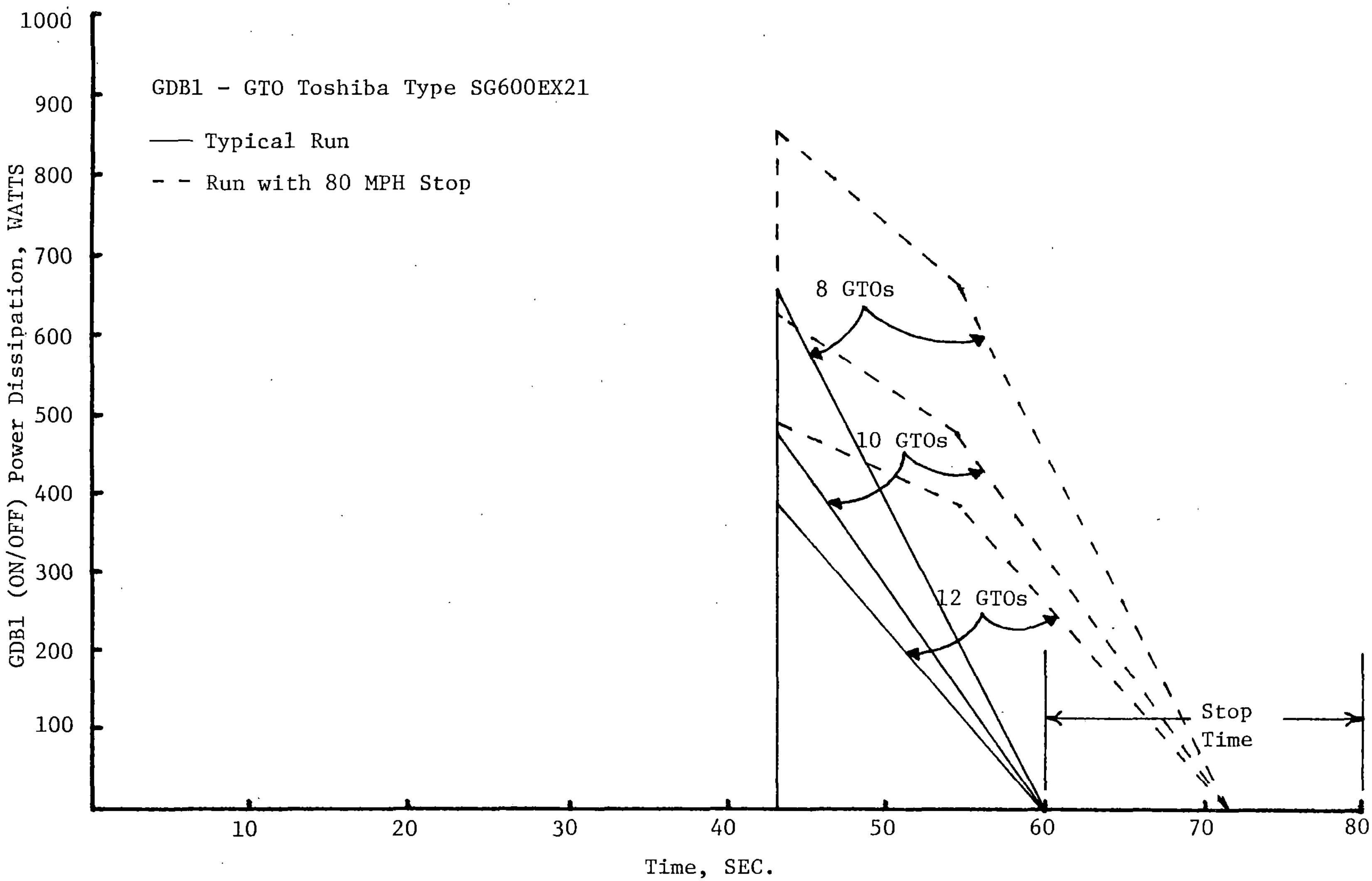


Figure 4-25

GDB1 (ON/OFF) Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

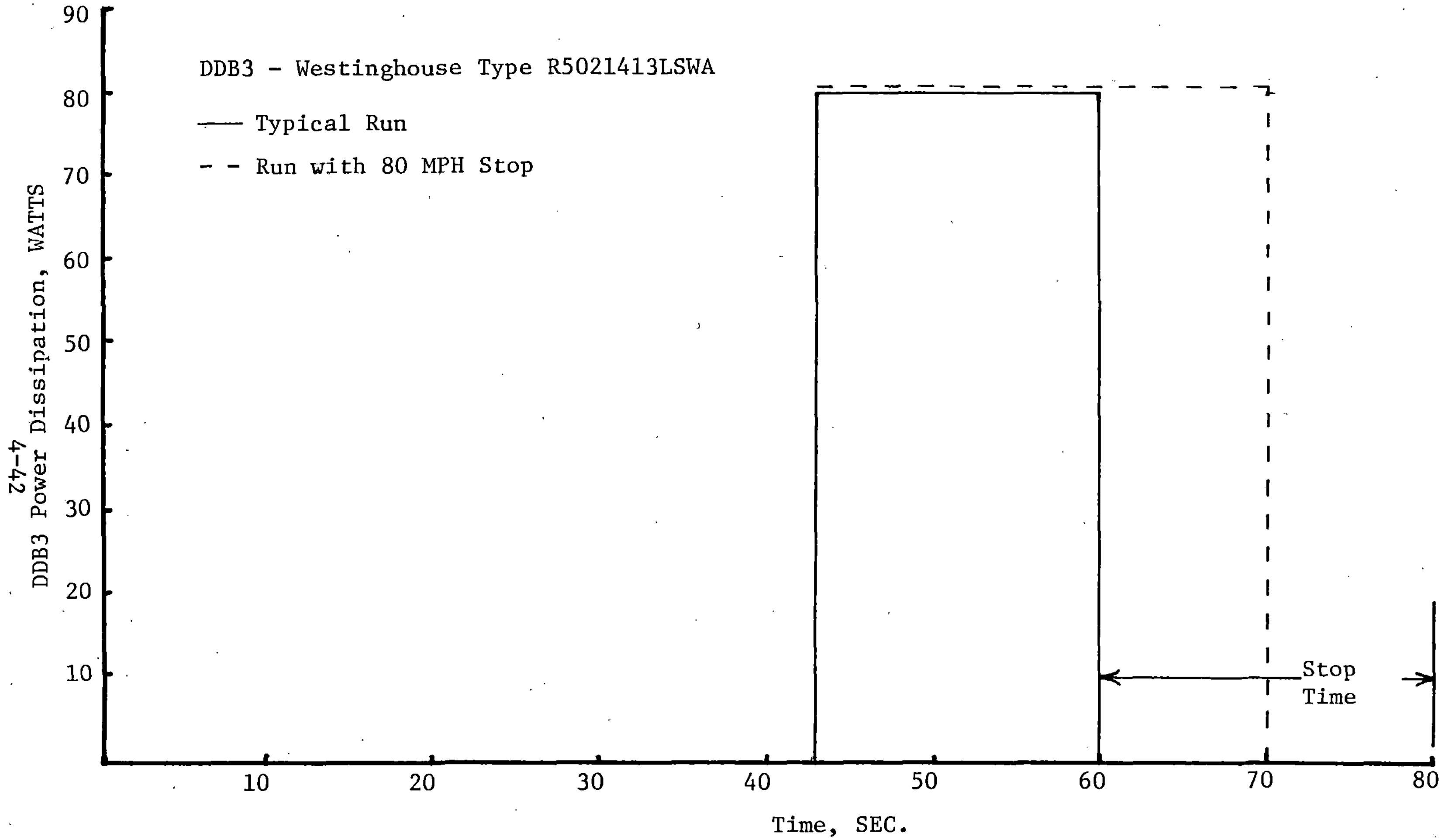


Figure 4-26

DDB3 Power Dissipation vs Time - PWM String
(Typical NYCTA 77th to 86th Street Run)

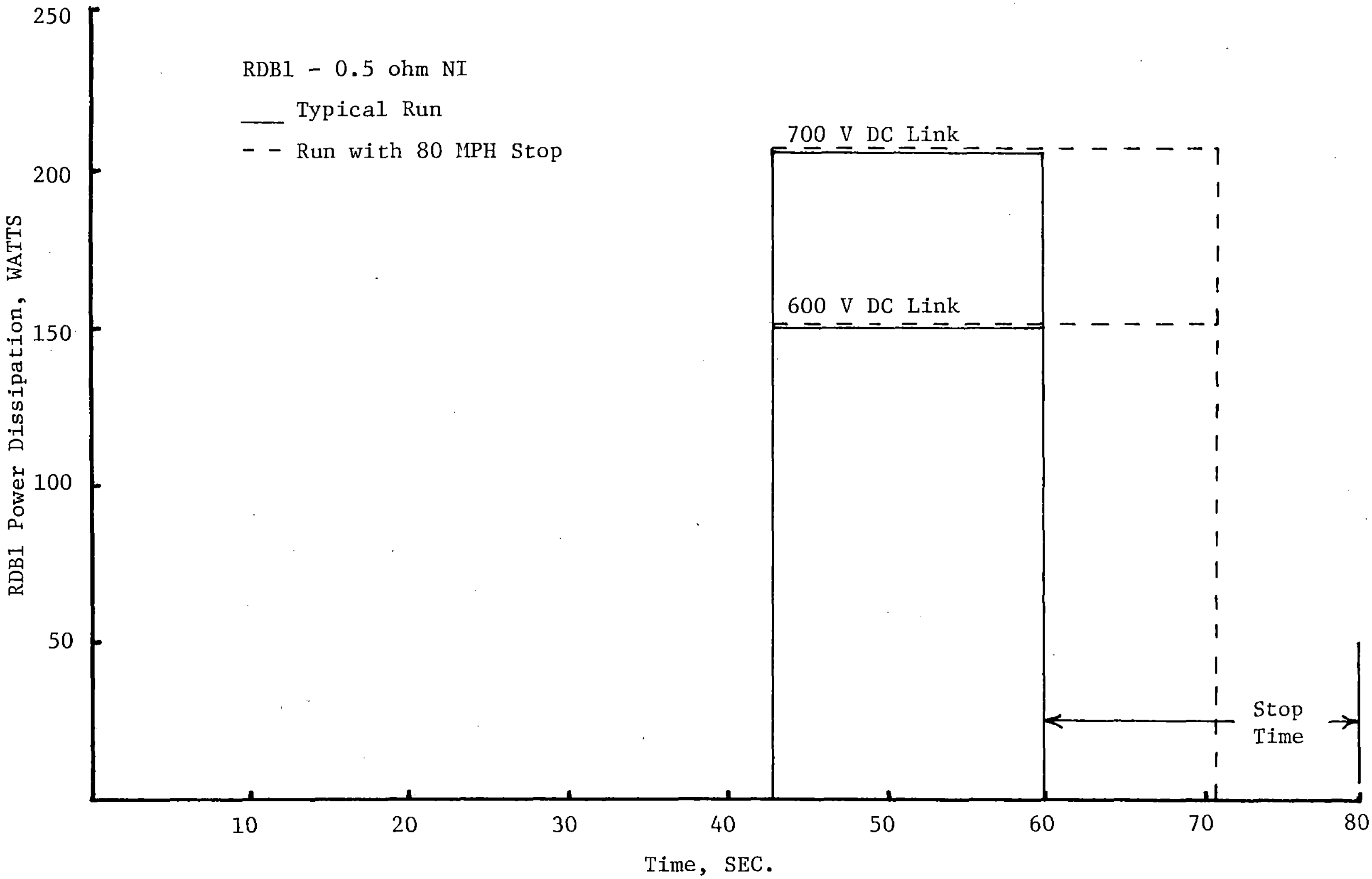


Figure 4-27

RDB1 Power Dissipation vs Time - PWM String
(Typical NYCTA 77th to 86th Street Run)

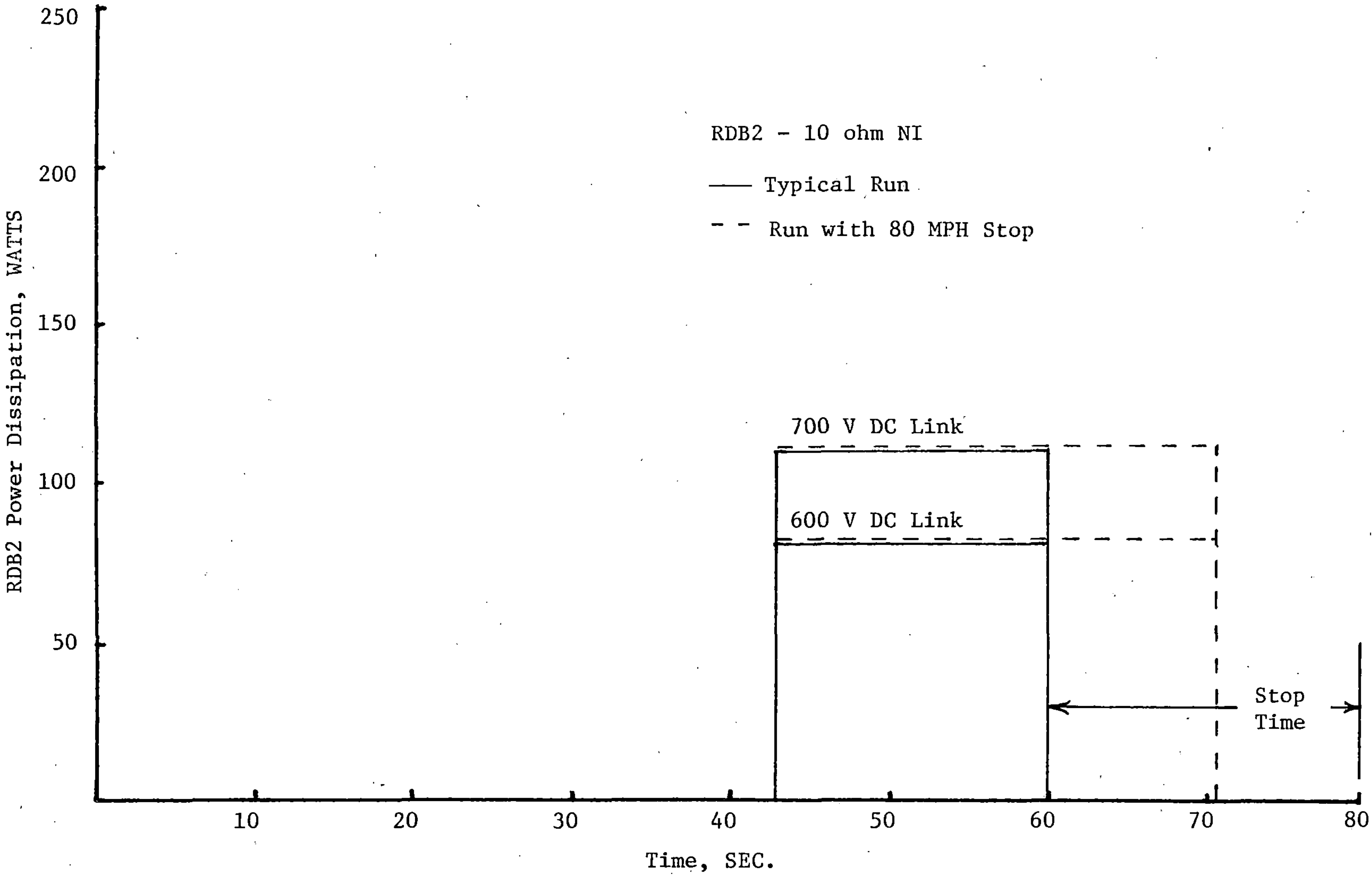


Figure 4-28

RDB2 Power Dissipation vs Time - PWM String
(Typical NYCTA 77th to 86th Street Run)

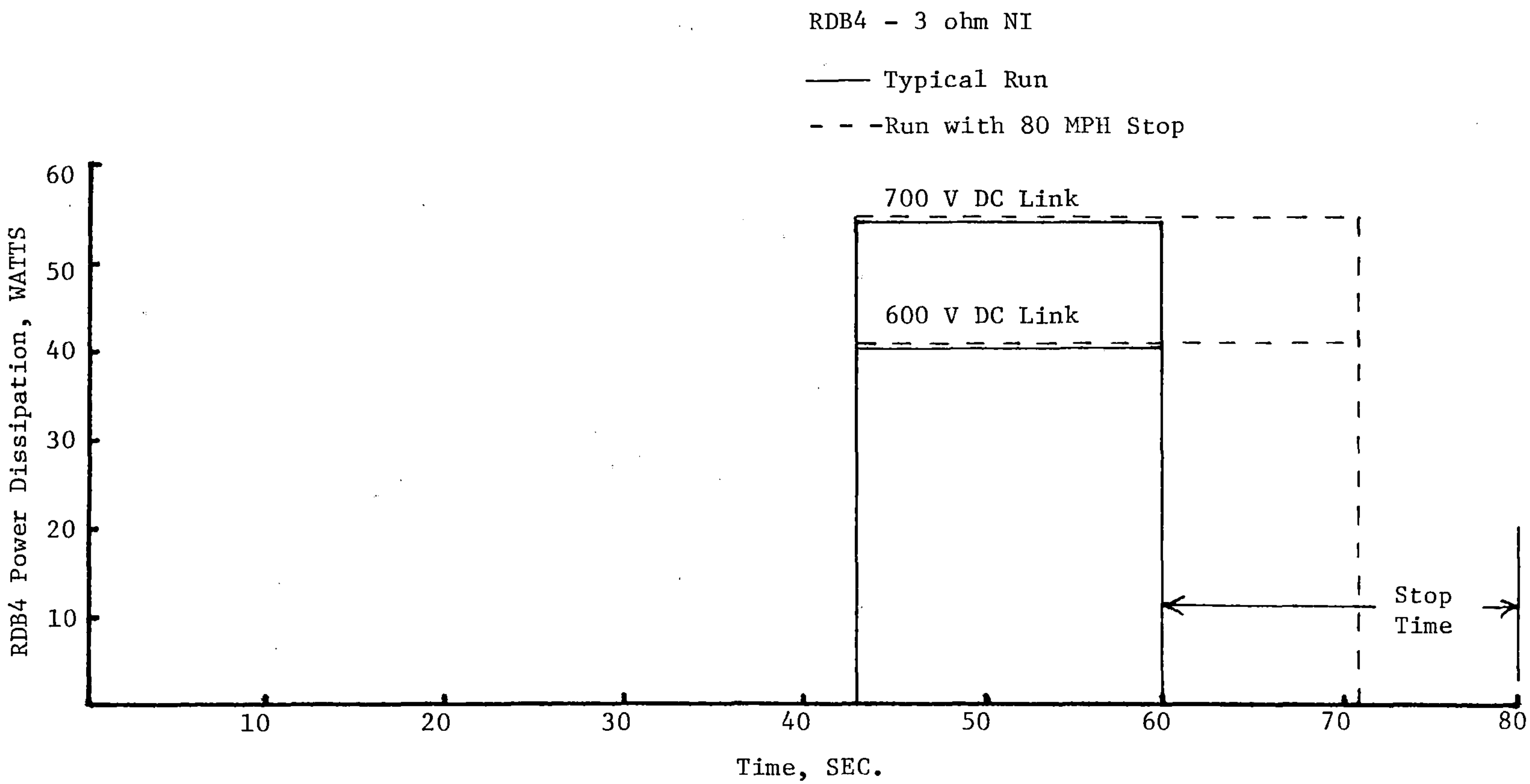


Figure 4-29

RDB4 Power Dissipation vs Time - PWM String
(Typical NYCTA 77th to 86th Street Run)

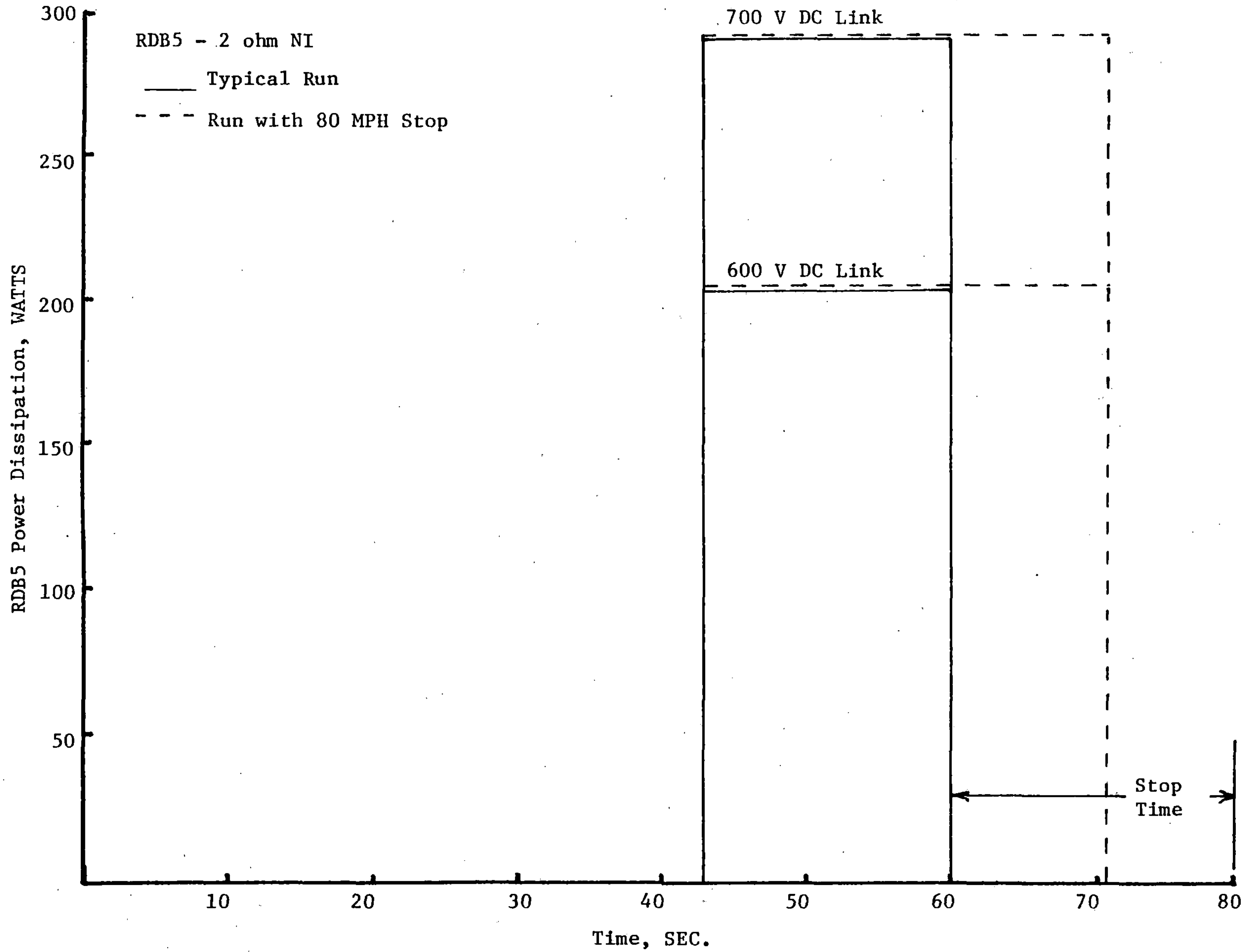


Figure 4-30

RDB5 Power Dissipation vs Time
(Typical NYCTA 77th to 86th Street Run)

All heat producing components listed above are directly or indirectly mounted on the heatsink in order to keep box ambient within reasonable limits. Gate driver board components are the only components which directly dissipate heat within the box.

4.2.5 Selected Test Results

Strip chart recordings of dynamic brake circuit performance are provided in Section 5. A comparison of stabilized dynamic brake box temperature rises for the assumed typical run of Figure 3-3 and for the Garrett Synthetic Profile of Figure 3-22 are listed in Figure 4-31. During testing, all semiconductor devices ran at or below the manufacturer's rated temperature.

The results of these and other tests performed on the AC drive system verify that the basic design and performance objectives of the dynamic brake circuit have been met.

Component		Temperature @ 40°C Ambient			
		Measured (°C)	Calculated (°C)	Calculated T_j (Max.)	Calculated Cycle ΔT_j (°C)
PWM GTO Block	Typical Run	52.8	53.3	88.8	36.0
	Garrett Run	49.1	+	+	+
Box Ambient	Typical Run	50.8	-	-	-
	Garrett Run	47.2	-	-	-

+ - Data not available.

Note 1: See Figure 3-3 for profile of "Typical Run" (run with 30 seconds stop time instead of 20 seconds). See Figure 3-22 for profile of "Garrett Run".

Note 2: Air flow over car simulated by blower providing approximately 1000 LFM of air flow through the inverter heatsink fins. The blower was turned off during profile stop intervals. The inverter was shutdown during coast intervals on the Garrett Run.

Figure 4-31

Measured and Calculated Dynamic Brake Component Temperatures

4.3 PARTIAL REGENERATIVE BRAKE CIRCUIT

On systems having insufficient line receptivity to justify the size, weight, and cost of a fully regenerative brake circuit, a partially regenerative brake circuit with equivalent braking capability is preferred. The size, weight, and cost of a partially regenerative brake circuit is less than a fully regenerative brake circuit primarily due to the fact that in the partially regenerative brake circuit resistors instead of a braking transformer are used to increase the motor voltage at operating frequencies above the normal base frequency and because the braking resistors which replace the braking transformer are available at no added size, weight, or cost. Dynamic braking resistors with a defined energy capacity per car are required regardless of the type of braking circuit used. Also, since a large portion of the braking energy is dissipated in the braking resistors in the auxiliary partially regenerative braking circuit (see Figure 4-32), the regular dynamic brake circuit can be smaller because it handles a reduced amount of braking energy.

Figure 4-32 shows a simplified schematic diagram of this circuit. The effective resistance in each motor line is controlled by phase angle control of thyristors TH1. The C1 capacitors provide compensation for the inductive effect of the motor and thyristor modulation. Resistors R1 limit the discharge current from the C2 capacitors. TH2 permits a single step change in the resistance on the output of the diode rectifier bridge, and enables a significant reduction in the value of C1 (approximately 33%).

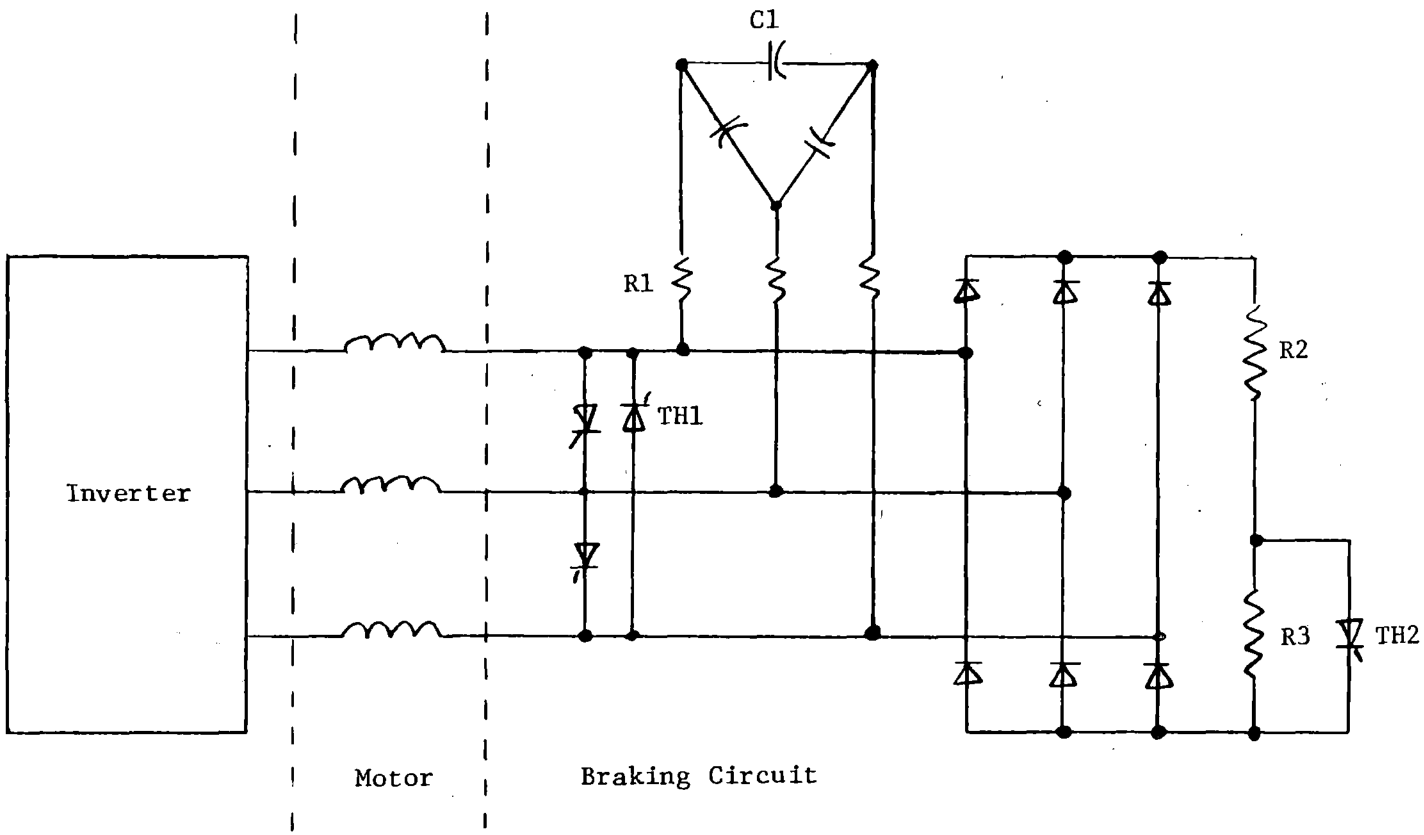


Figure 4-32

Simplified Schematic Diagram of Partially Regenerative Brake Circuit

Disadvantages of the partially regenerative brake circuit of Figure 4-32 are that the size, weight, and cost of C1 are considerable, and that the control characteristic of the braking circuit is quite non-linear making it very difficult to stabilize a closed loop control. Another disadvantage of the circuit is that all six motor winding connections must be brought out from the motor.

4.4 PROPOSED PARTIAL REGENERATIVE BRAKE CIRCUIT

A relatively straightforward partial regenerative alternative to extend the maximum speed for full rate braking above normal base speed is to insert a controlled resistance at the input to the inverter in braking, which raises the inverter and thus the motor voltage in braking. This, of course, increases the voltage stress on inverter components in braking. The amount of voltage stress increase is roughly proportional to the ratio of maximum speed for full rate braking to normal braking base speed. This approach would be preferred if full rate braking can be extended to the desired speed without having to series inverter semiconductor devices. In the event that it is not possible to obtain the desired braking characteristic without resorting to series inverter devices, an alternative approach is needed to obtain partially regenerative extended full rate braking.

A partially regenerative extended full rate brake circuit using GTOs that does not increase the voltage stress on inverter devices in braking, which is patterned after the fully regenerative brake circuit described in Section 4.1, appears on cursory examination to be a better circuit choice than the circuit of Figure 4-32. A simplified diagram of this circuit is shown in Figure 4-33. This choice, of course, would have to be verified by a detailed analysis of size, weight, cost, and performance to verify that it, in fact, is the best circuit configuration when all factors are considered.

In motoring, thyristors TH1 are on, GTO1 is off, and the braking circuit is disabled. To enable the braking circuit, drive is removed from thyristors TH1. The non-conducting thyristor stays off, and the conducting thyristor goes off on the next current zero crossing. GTO1 is then controlled on/off so as to control the resistance and in turn the voltage inserted between motor and inverter. This provides for a controlled increase in motor voltage and extends braking capability beyond normal base speed. The PWM control is also arranged to control the phase of the fundamental component of braking resistor voltage so that the braking circuit operates at an acceptable power factor without the need for compensation capacitors. Obviously, the braking

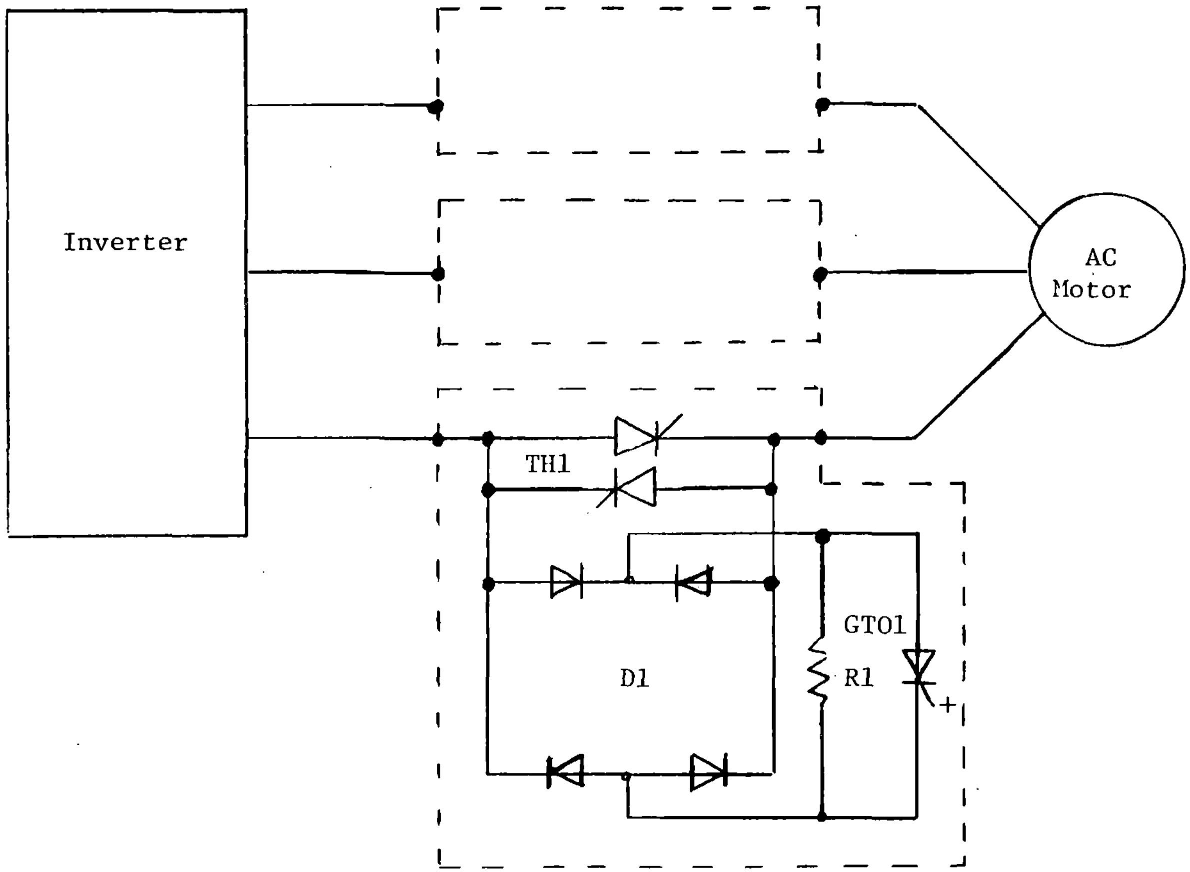


Figure 4-33

Simplified Diagram of Proposed Partial Regenerative Brake Circuit (Single Phase) thyristors could be removed and the braking circuit disabled by gating GTO1 _on_ continuously in motoring. This, however, is unattractive because of the higher cumulative voltage drops and conduction losses in D1 and GTO1 that would always be present in motoring, compared to the lower voltage drop and conduction loss in thyristors TH1.

5. PROPULSION CONTROL LOGIC

The function of the propulsion control logic is to interpret commands received from trainlines (regardless of the source of commands; either train operator or ATO). It is then the job of the propulsion control logic to control the propulsion power equipment so as to provide the vehicle acceleration or deceleration rate requested via the trainlines.

5.1 DESIGN GOALS

In order to establish the standards for evaluation of the design, it is essential to identify the design goals prior to the start of the design phase of the project. This will ensure uniformity of design as well as viability of the resulting product.

The present design has been developed in accordance to the following goals:

1. High reliability.
2. Maintainability and ease of fault identification.
3. Manufacturability.
4. Repeatable performance.
5. Environmental considerations (vibration, temperature, size, etc.).
6. Flexibility and ease of adaptation to various types of transit systems (Heavy rail, Light rail, Trolley bus, etc.).
7. Cost effectivity.
8. Functional modularity and expandability.
9. System energy efficiency.
10. Elimination of the need for "select on test" components.
11. Operational considerations (harmonic generation, etc.).

5.2 FUNCTIONAL DESCRIPTION

In order to accommodate various types of transit systems, it is desirable to separate the motor control functions from the car interface and performance characteristic functions. Paying special attention to grouping of functions on printed circuit boards as well as using a small board form factor results in a highly modular system where functions can be tailored to meet the needs of the customer without the heavy cost associated with a redesign of the hardware. This philosophy has been adapted throughout the design of the AC drive system.

The propulsion control logic consists of two major subsystems, the car control and the motor control logics. Functions such as interfacing with trainline signals, interpretating commands received via the trainlines, and regulating line voltage during non-receptive braking periods fall under the car control logic. Functions associated with each motor/inverter such as output torque calculation and control, inverter waveform synthesis, and auxiliary brake circuit voltage control fall under the realm of the motor control logic. In a typical scenario, the car control logic interprets the commands received via the trainlines, and instructs the motor control logic as to what torque output is desired from the logic based on those commands. The motor control logic returns certain status information to the car control logic as to it's ability to perform the requested task.

On each car, there resides only one car control logic but as many motor control logics as there are inverters. In order to facilitate transfer of information between car control logic and the motor control logics and in order to minimize the amount of redundant functions, the car control and motor control logics reside in the same card cage. Communication path between the logics is over the backplane of the card cage. The use of a microprocessor in the motor control logic allows the packaging of all motor control functions on a single printed circuit board. Each motor controller acts as an intelligent peripheral to the car control logic and will not have direct access to the backplane bus. This priviledge is reserved for the car control logic. To further reduce the hardware in the propulsion control system, the car control logic reads all external circuit parameters (voltages, currents, etc.) needed by all control logics and passes the information needed by the motor control logics over the backplane bus.

Microprocessor based systems were chosen for both the car control and the motor control logics as opposed to conventional analog circuitry. The microprocessor based systems were found to be far superior to the analog circuits of the past. In comparing the two alternatives, the microprocessor based systems were found to cost less, to be far more reliable, to be more flexible, to have much more diagnostic capability, and to be more powerful than any analog equivalent.

The propulsion control logic package uses double height Eurocard printed circuit boards (9.2" x 6.3" size) housed in a card cage having the approximate dimensions 19" x 11" x 8". This board form factor allows the utilization of high power microprocessors and is consistant with the functional modularity principles adapted in this design. This printed circuit board form factor also provides excellent shock and vibration characteristics needed for applications in land mobile environments. Figures 5-1 and 5-2 show a typical card cage to be used as a propulsion control logic and Figure 5-3 shows the dimensions of the double height Eurocard board form factor. As can be seen in Figure 5-1, in addition to the double height standard boards, the card cage has the ability to accommodate small single height boards should that form factor be desired for additional functions. The propulsion control logic has the ability to interface with any common trainline interface and is capable of controlling from 1 to 4 inverters/motors with or without auxiliary braking circuits.

In view of the complex control algorithms that both the car control and motor control logics must perform, a powerful microprocessors, the Motorola MC68000 16/32 bit microprocessor, was chosen to perform both types of control. The microprocessor backplane bus is based on the standard Motorola VME architecture.

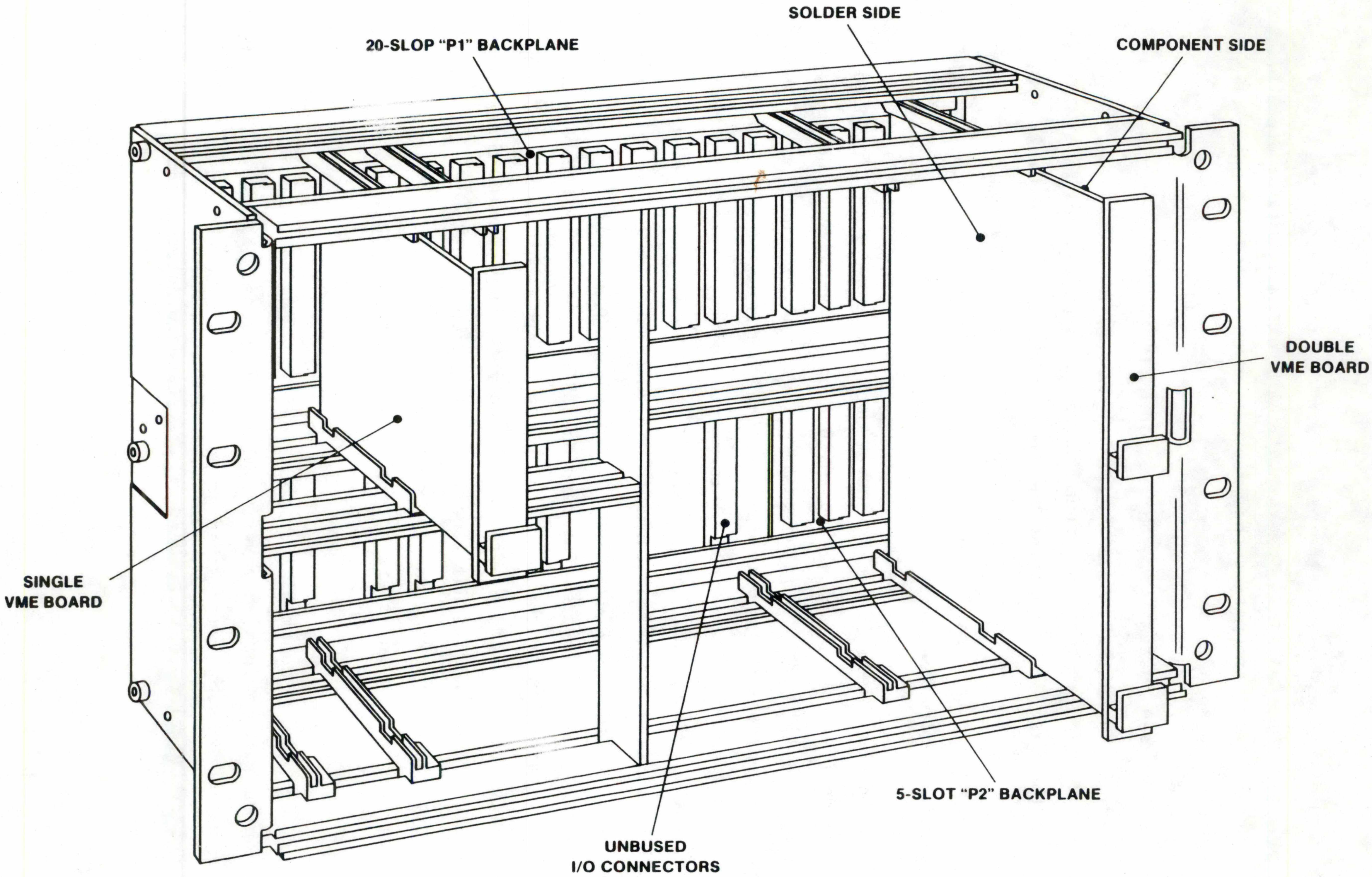
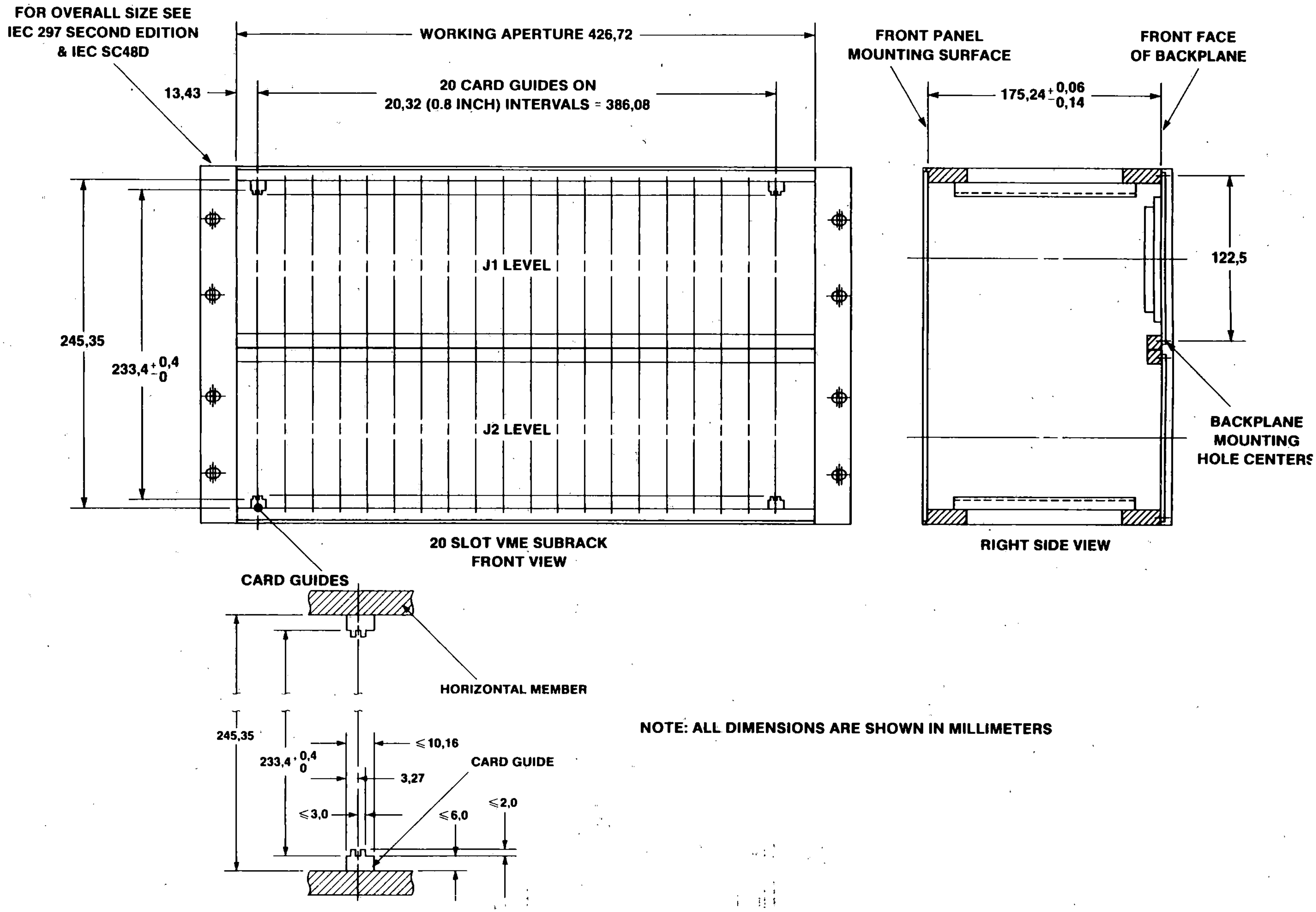


Figure 5-1

Card Cage, Typical Configuration



NOTE: ALL DIMENSIONS ARE SHOWN IN MILLIMETERS

Figure 5-2

Double High Subrack

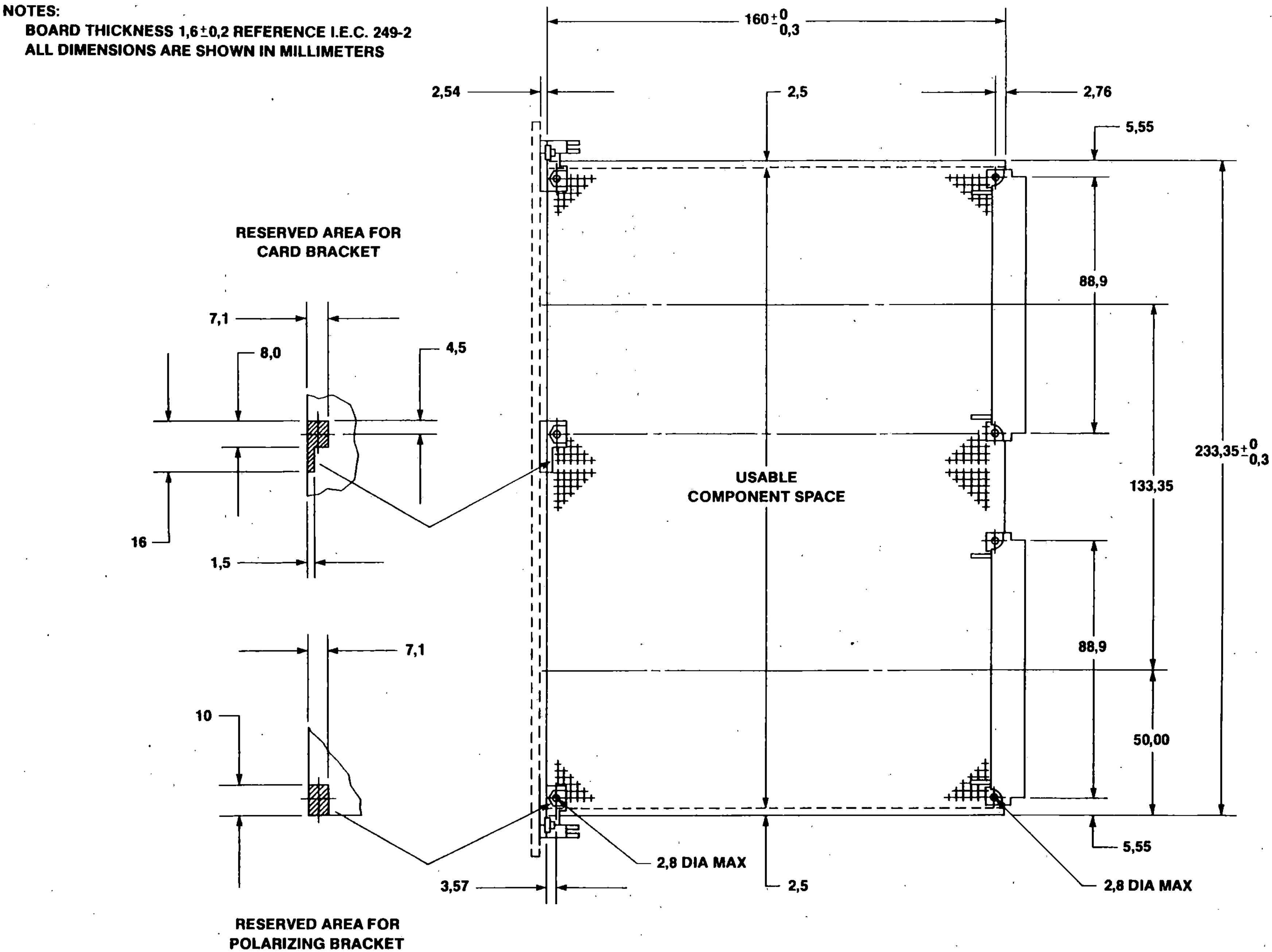


Figure 5-3

Double Height Eurocard Board

The car control logic portion of the propulsion control system consists of three printed circuit boards. The backbone of the car control logic is an MC68000-based computer board. The composition of the other two boards depends on the type of system being controlled but will generally consist of a board capable of reading analog inputs and tachometer signals and a board capable of reading digital inputs and energizing line switches and dynamic brake GTOs. Four slots of the card cage are reserved for the use of up to four motor control boards. Only half of the twenty double height slots shown in the card cage in Figure 5-1 are occupied by a system consisting of a car controller, four motor controllers, and a power supply, thereby leaving ten additional slots available to facilitate the implementation of special functions that may be required for specific applications (ie. line current monitoring at track signal frequencies, etc.). Due to the number of unused slots available in the card cage, a smaller card cage than the standard 19 inch rack-mountable card cage selected could be used to decrease the volume of the propulsion logic card cage. Figure 5-4 shows a propulsion control logic configuration with 4 inverter/motor controllers.

To minimize the need for periodic recalibration of the equipment and improve manufacturability, the function implementations are completly digital. The only exceptions are the input filters on DC line voltage and line current. However, the characteristics of these filters are not critical, thus requiringno maintenance. The digital implementation also assures repeatable and consistant system performance regardless of changes in environmental parameters such as temperature. It should also be mentioned that the Westinghouse AC drive system does not use any "select on test" components.

To facilitate fast development of both the car control and motor control logics, off the shelf hardware was used where possible. Also some duplication of functions was necessary in order to carry out independent development efforts on both controllers. These duplicated functions are eliminated in the final design. In order to take full advantage of off the shelf hardware and in order to carry out independent development, it was necessary to house the car control logic and motor control logic in separate card cages. This separation necessitated the use of serial communication links instead of the more

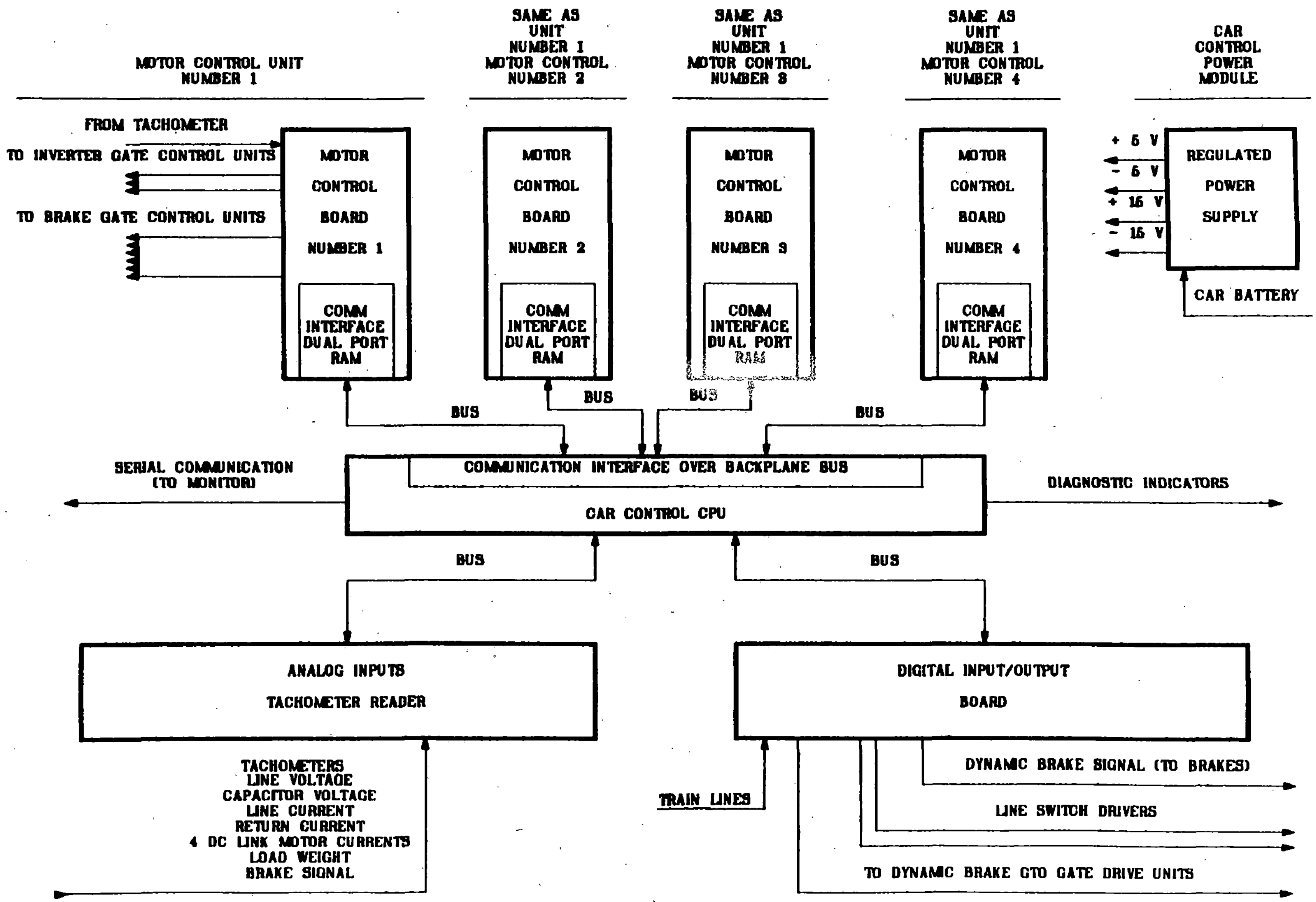


Figure 5-4
Propulsion Control Logic Configuration

desirable backplane communication network that will be used in the final design. Also, at the time that development started on the two logics, the VME bus did not have the support that it does today. It was therefore necessary to use the more popular but less capable Intel multibus in the prototype card cages. Since the prototype design has many extra unused functions, many duplicate functions, and many non-optimised functions, it is not as compact as the final design. The prototype car control logic consists of five printed circuit boards instead of three and the prototype motor control logic consists of three printed circuit boards instead of only one (see Figure 5-5 for the prototype configuration for a system consisting of a car controller and two inverter/motor controllers).

The car control functions and motor control functions are described in greater detail in the sections that follow.

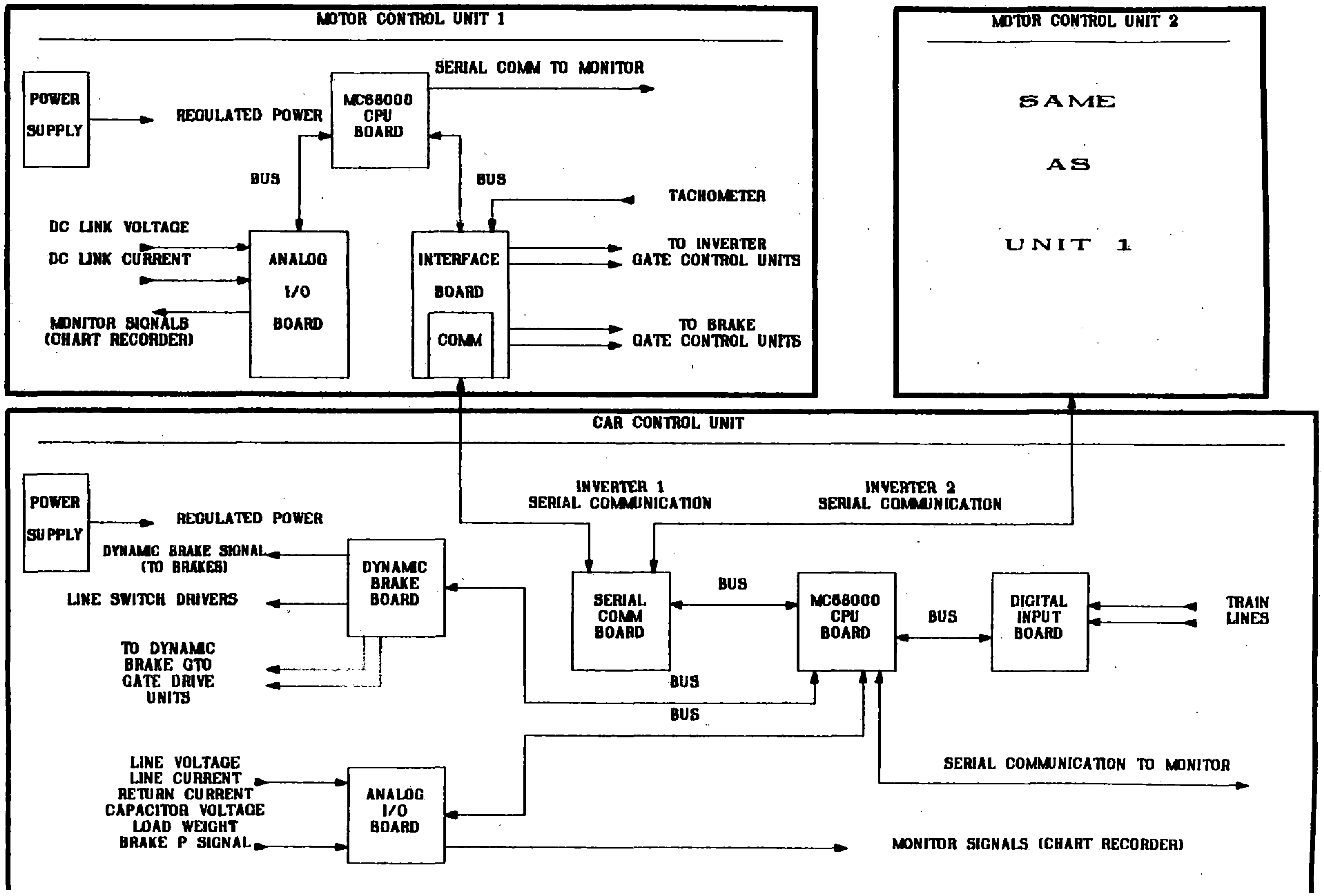


Figure 5-5
Prototype Propulsion Control Logic Configuration

5.3 CAR CONTROL COMPUTER

5.3.1 INTRODUCTION

The Westinghouse AC drive car control computer unit is the supervisory propulsion logic responsible for the control and interpretation of car oriented parameters. These parameters include trainlines, load weight, axle speed, third rail voltage, line current, third rail receptivity, filter capacitor voltage, and tractive effort request. The car control computer is also responsible for the coordination of the individual motor control logic units. This is accomplished through a data communication link established between the car controller and each of the motor controllers.

5.3.2 DESIGN GOALS

Fundamental to all designs is the goal of high reliability and low cost. In keeping with these desirable attributes, a microprocessor based control logic package, similar to that used for the motor control logic units, was selected for the car control computer design as well.

The following is a list of functional design goals for the car control computer:

1. R44 cam control emulation.
2. Dynamic brake control and supervision.
3. Slip/Slide detection and reaction.
4. Motor control logic coordination and communication.
5. P-signal type operation.
6. Line switch control.
7. Dynamic brake feedback.
8. Dead rail detection.

5.3.3 DESIGN DESCRIPTION

The prototype car control logic package and its functions were realized as follows. Several components were bought "off the shelf". These include the multibus card cage, the power supply, the CPU board, the digital input card and the quad serial communications card. The components prototyped by Westinghouse Transportation Division include the analog input/output card and the dynamic brake/digital output card. All car control computer software was designed and developed using Westinghouse Transportation's Vax computer. A functional breakdown of the hardware is as follows (Figure 5.6):

1) CPU card - The CPU card houses the MC68000 16 bit microprocessor responsible for executing the control software stored in on board EPROMs. This card also includes hardware to allow the CPU to access the functions of the other cards in the car controller cradle.

2) Digital input card - The digital input card is used by the CPU to read the status of the R44 system trainlines. The trainlines being either energized (+ battery volts) representing a logic 'one', or de-energized (0 volts) representing a logic 'zero'.

3) Quad serial communications card - The serial communications card provides the CPU the ability to communicate data serially (RS232 protocol) between the motor control logics and the car controller.

4) Analog input/output card - The analog I/O card provides analog to digital conversion of system analog parameters such as line current and line voltage for use by the CPU. The analog I/O card also provides six digital to analog converters for use in driving a six channel chart recorder for system monitoring purposes.

CAR CONTROL HARDWARE (PROTOTYPE VERSION)

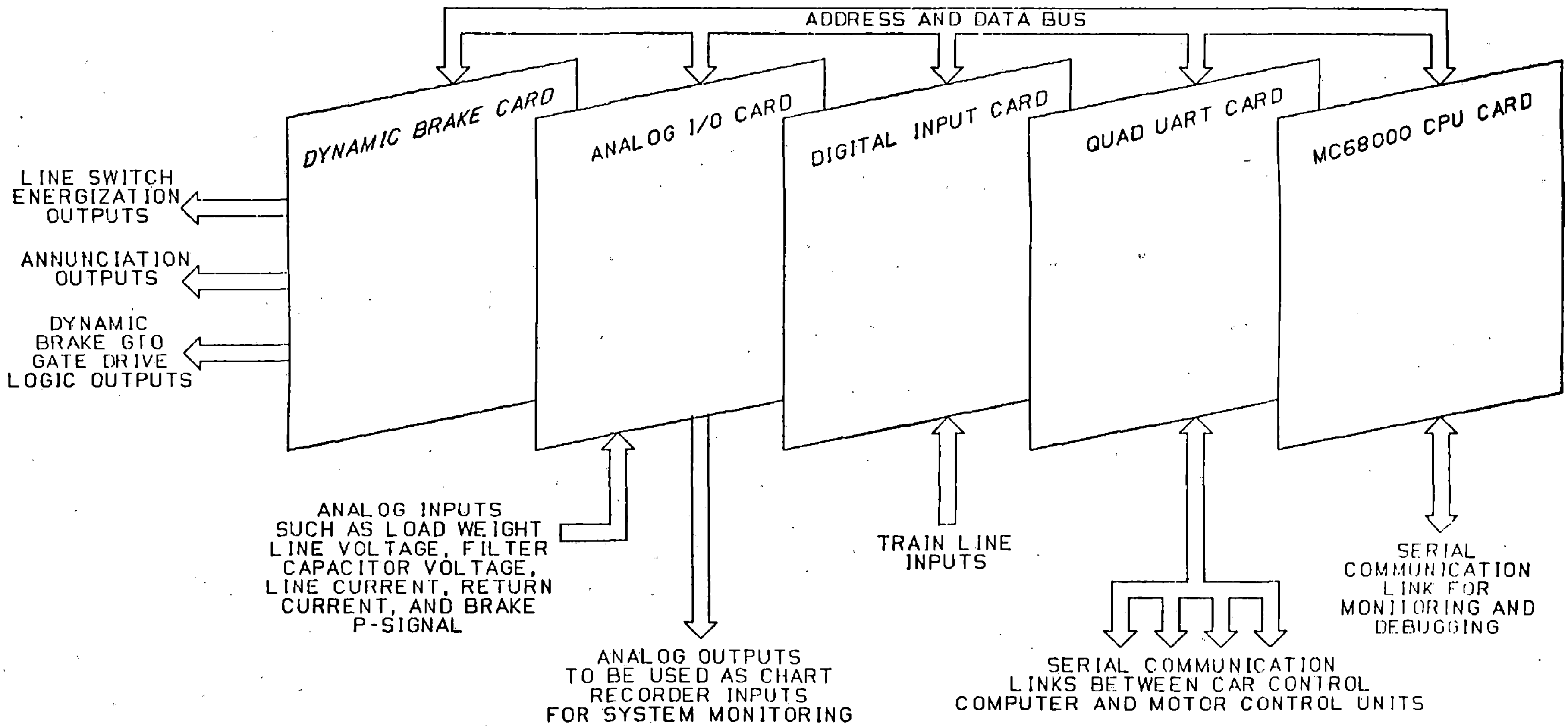


Figure 5-6

Functional Breakdown of Car Control Hardware

5) Dynamic brake/digital output card - This card includes circuitry to allow the CPU to turn on/off the GTOs of the dynamic brake circuit. These GTO preliminary gate drive circuits provide the current to the actual gate drive boards that indicate the desire to turn on a selected GTO. Also present on this card are the solid state relays used by the CPU to energize the line switches.

6) Multibus card cage/power supply - The card cage provides the communication path between the above mentioned cards via the multibus type computer bus. The power supply provides the +5V, +15V, and -15V required by the circuitry.

The car control computer software was written in MC68000 assembly language. A monitor routine on the CPU card permitted software to be written and assembled on the VAX and then "downloaded" into RAM (memory) on the CPU card. The "downloaded" software was then executed out of RAM which permitted gains, thresholds, and other control parameters to be adjusted "on the fly" for optimum debugging efficiency. Software organization consists of three major entities. These include the start-up sequence, the main program, and the interrupt program. A functional description is as follows:

1) Start-up sequence - This software executes upon power-up/reset and is responsible for initializing and configuring the hardware for the required functions. Also, the software variables which require it are set to their initial values to prepare for control software execution. The final function of the start-up sequence is to start-up and enable real time clock interrupts.

2) Main program - The main program in the Car Controller is executed between the completion of the execution of the interrupt routine and the next interrupts arrival. During these execution windows, the main program handles the car control/motor control communications requirements. Also, a background monitor for diagnostic purposes is executed.

3) Interrupt routine - The interrupt routine executes upon arrival of the real time clock interrupt which occurs once every 573 microseconds. The interrupt routine is actually a scheduler which counts interrupts and based on the count selects a list of subroutines to be executed during that interrupt. These subroutine lists contain the software to perform all the major functions such as dynamic brake control/supervision and R44 cam emulation. Upon completion of subroutine execution, the scheduler surrenders execution to the main program.

Due to the wealth of system information available to the car controller and the processing power of the 16 bit CPU, the car control computer is well suited to the performance of detailed diagnostics. At this time, only rudimentary diagnostic functions are performed. However, a more sophisticated scheme is possible where "on the fly" flight recording could be maintained. This would include a continuous comparison of inverter operational parameters in order to detect a discrepancy which could mean a mulfunction. The malfunctioning unit could then be shutdown and annunciated as such via a cab LED. Also, operational parameters such as line voltage, line current, and each inverter's DC link current, RPM, torque estimate, and status could be stored in a continuous fashion in non-volatile RAM for examination at a later time by maintenance personal using a hand held terminal or line printer. The important point is that the computational power and pertinent information is available for use in performing useful diagnostics.

The following provides a description of the realization of the functional design goals listed above:

1. R44 cam control emulation.

The purpose of the cam control emulation is to allow a vehicle equipped with an AC drive propulsion system to operate within a train made up of cam controlled vehicles. The goal is to have the AC car react to the system trainlines such that the tractive effort of the AC car closely matches that of the cam controlled cars. The emulation algorithm estimates, based on trainlines, line voltage, load weight, and car speed, the tractive effort being provided by an R44 cam controlled vehicle. The estimated tractive effort is then transformed into a torque request to be sent to each of the four motor control logic units. The emulation, using trainlines and load weight, will estimate the DC motor current level that the R44 cars will be regulating with cam controlled resistance removal. Then, using a copy of the R44 DC motor curves stored in memory, the emulation algorithm will determine the R44 tractive effort by indexing the full field strength current vs. tractive effort table. This value then becomes the requested AC propulsion tractive effort. In the interim, the emulation is keeping track of line voltage and speed. The speed and line voltage are used to determine when the R44 cars have reached their motor curves and will either ride down the full field speed vs. current curve or field shunt to a different curve. This is dictated by the trainline pattern present. In either case, the emulation will select the proper speed vs. current curve, "field shunting" if necessary, and ride it down as speed increases. Of course, if field shunting is simulated, the appropriate current vs. tractive effort curve based on the new field strength is used to come up with a tractive effort request for the AC motor control logics. The emulation function in brake consists of estimating an R44 current request based on load weight and brake P-signal. Then, using the R44 current vs. braking effort curve, a tractive effort is selected and sent to the AC motor control logic units. Since brake taper is present in the R44 system above 50 mph, a copy of the brake taper maximum brake current request vs. speed curve is stored and used to clamp the R44 current request estimate at speeds above 50 mph. Figure 5-7 and 5-8 are the above mentioned R44 motor curves which were digitized and stored in memory for use in this emulation function. Figure 5-9 provides a flow chart type of summary of the emulation algorithm. The charts in Figure 5-10 depict the torque request profile created by the emulation function for the four modes indicated. Note that the emulation will cause the AC propulsion system to imitate a DC vehicle's characteristic of reaching and riding down its motor curve.

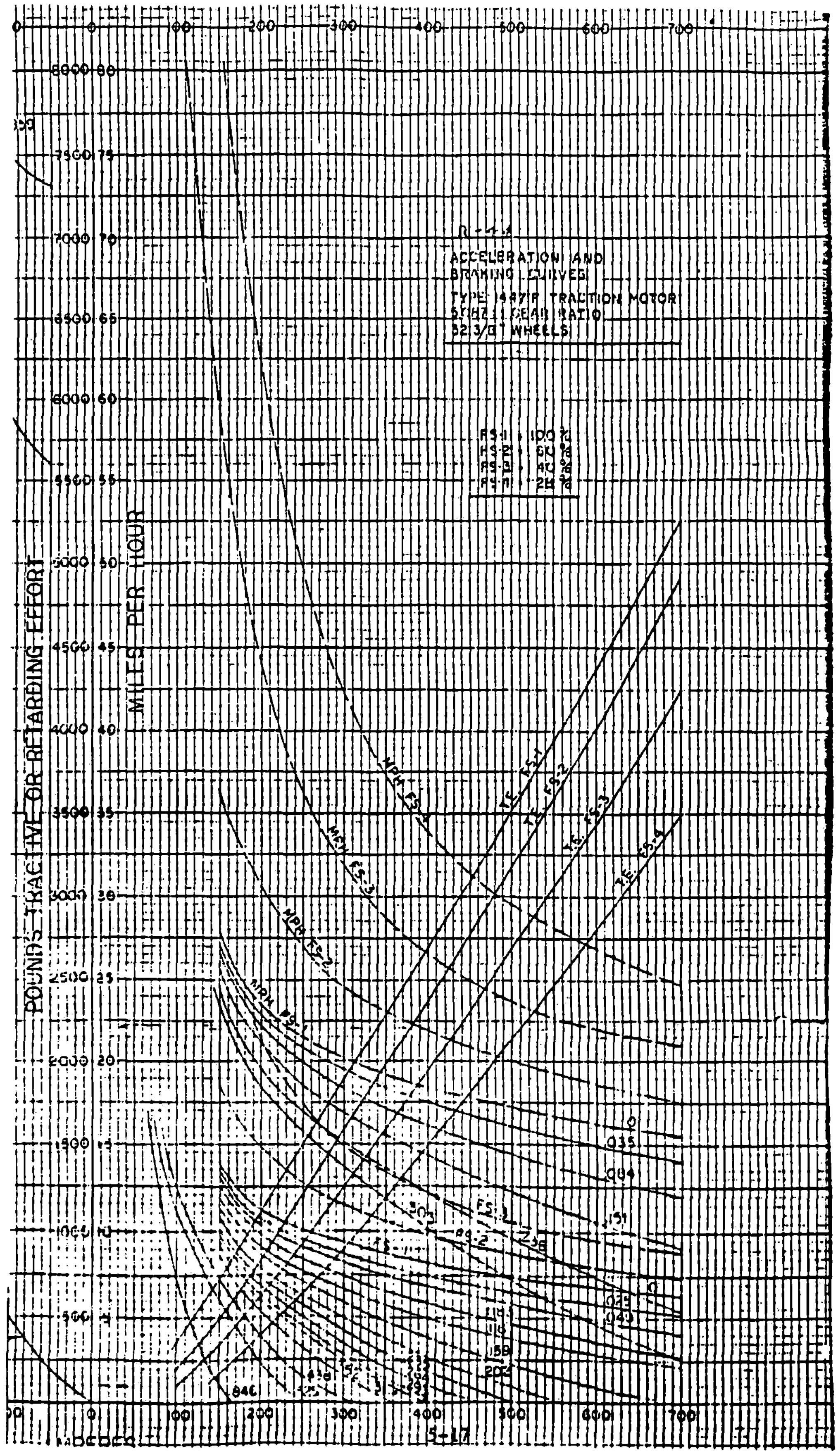


Figure 5-7

R44 Motor Curves - Power

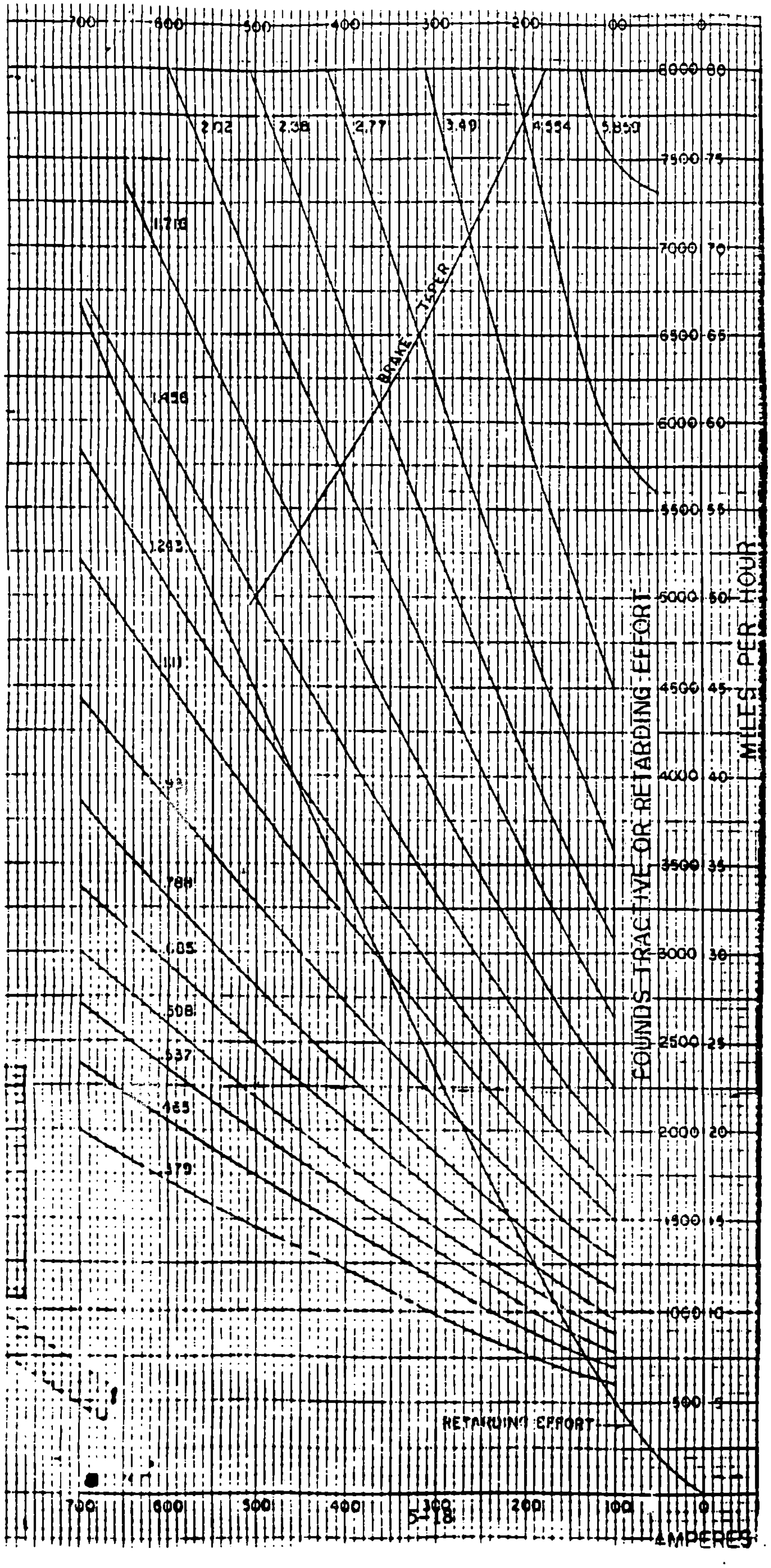


Figure 5-8

R44 Motor Curves - Brake

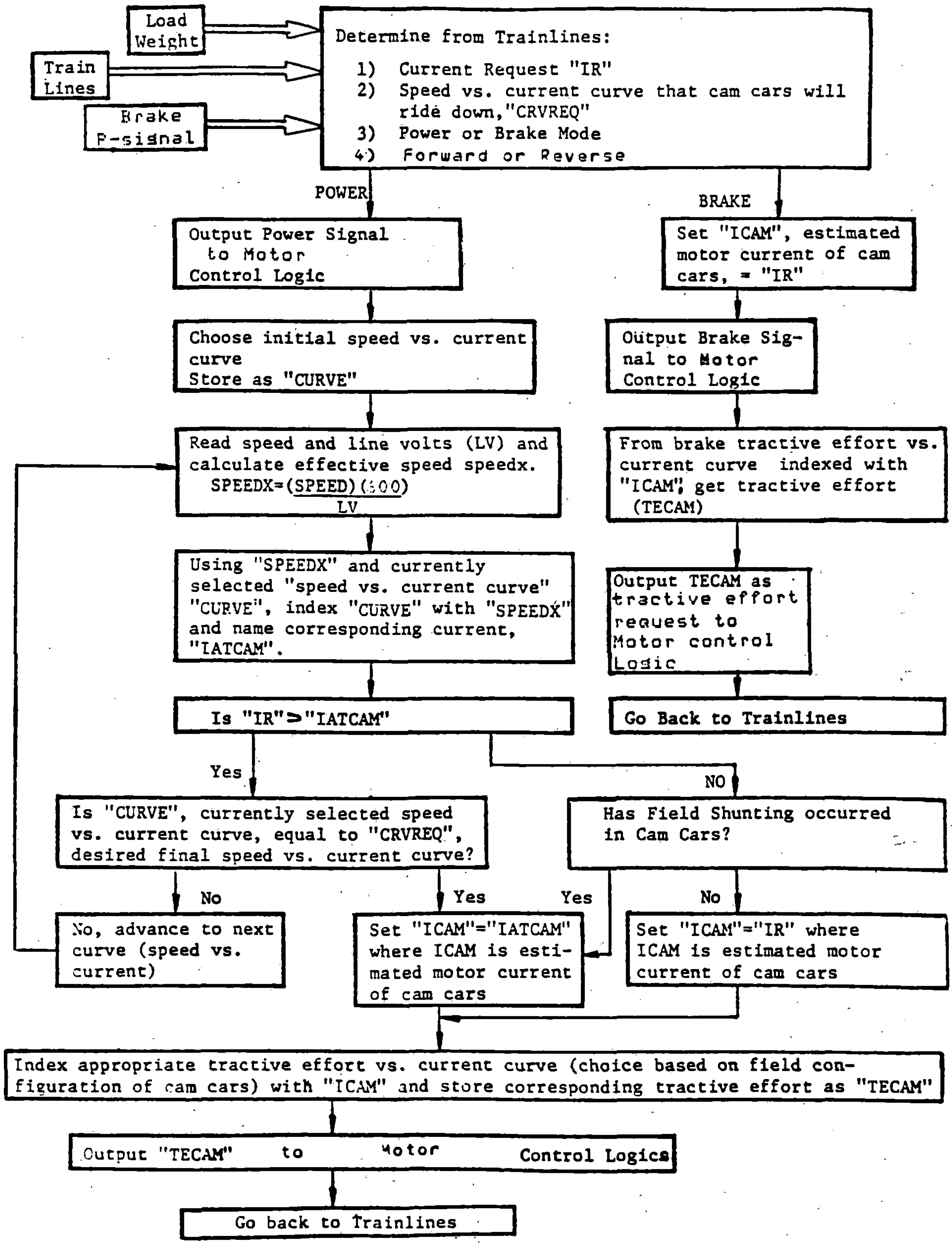
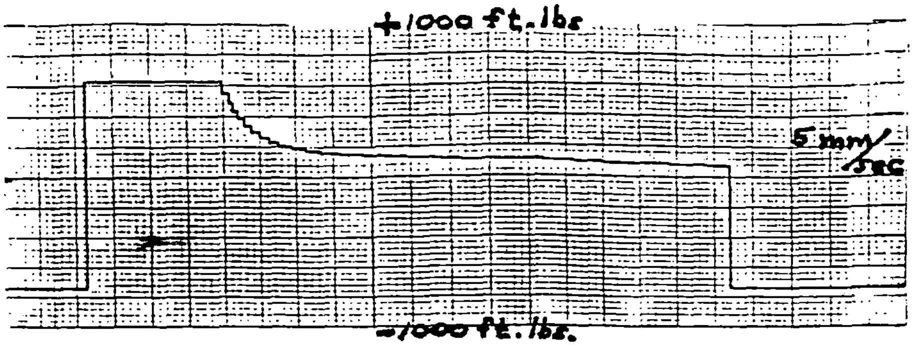
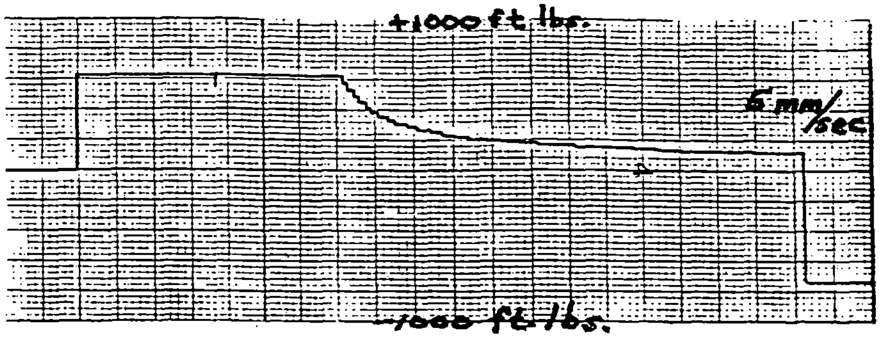


Figure 5-9

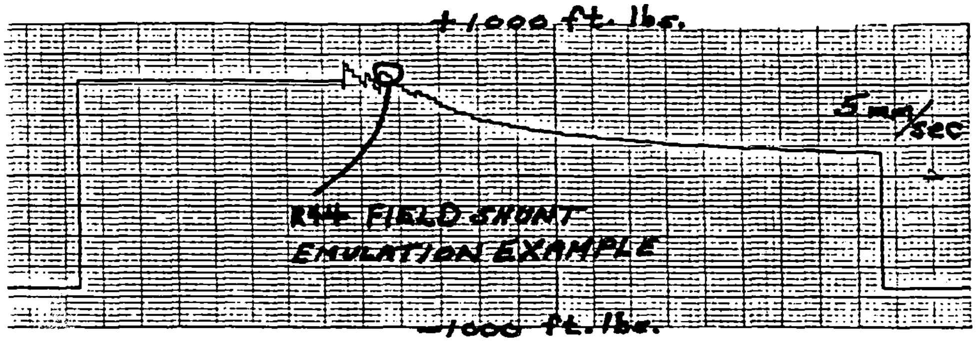
Flow Chart of Emulation Algorithm



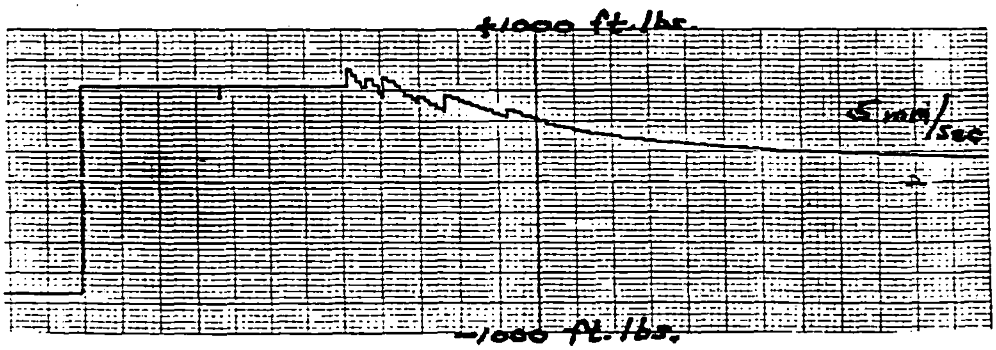
R44 SERIES FULL FIELD MODE



R44 PARALLEL FULL FIELD MODE



R44 PARALLEL 40% FIELD MODE



R44 PARALLEL 28% FIELD MODE

Figure 5-10

Torque Request Profiles vs Time for Various R44 Modes

2. Dynamic brake control and supervision.

The dynamic brake control is responsible for the regulation of the voltage across the filter capacitors during braking with a less than 100% receptive third rail or with the line switches open. The control must also be able to respond in a stable manner to sudden changes in third rail receptivity, such as a rail gap, without excessive filter capacitor voltage rise. These requirements were accomplished with the following control implementation. The filter capacitor voltage is read by the car controller and compared to the filter capacitor voltage request. The difference becomes the input to a proportional integral controller set up in software. After the proportional and integral gains are applied and the appropriate clamps and checks are applied, the output of the PI controller becomes a GTO on requirement consisting of an integer portion and a fractional portion. The ten dynamic brake GTOs (as described in Section 4) are controlled such that GTO #1 is phase controlled at a 218 HZ rate while the remaining GTOs are turned on or off as needed. Therefore, the value of the integer portion of the PI output is the number of on/off GTOs required and the fractional portion of the PI output is the percentage of on time required for the phase controlled GTO. Figure 5-11 illustrates the functional elements of the dynamic brake control.

3. Slip/Slide detection/reaction.

The car control computer is responsible for slip/slide detection and reaction. Two different criteria for slip/slide detection have been implemented. The first of these is a rate of rise test for each axle. This means that if an axle's acceleration/deceleration magnitude exceeds eight miles per hour per second, that axle will be considered to be slipping or sliding, depending on whether the mode is power or brake, and the appropriate reaction will be initiated. The second slip/slide criteria is an axle speed comparison. In this test, the relative speed of each axle is compared to the relative speed of the remaining axles and the existence of a speed differential exceeding five miles per hour will be considered a slip/slide. In this case, the axle(s) designated as the

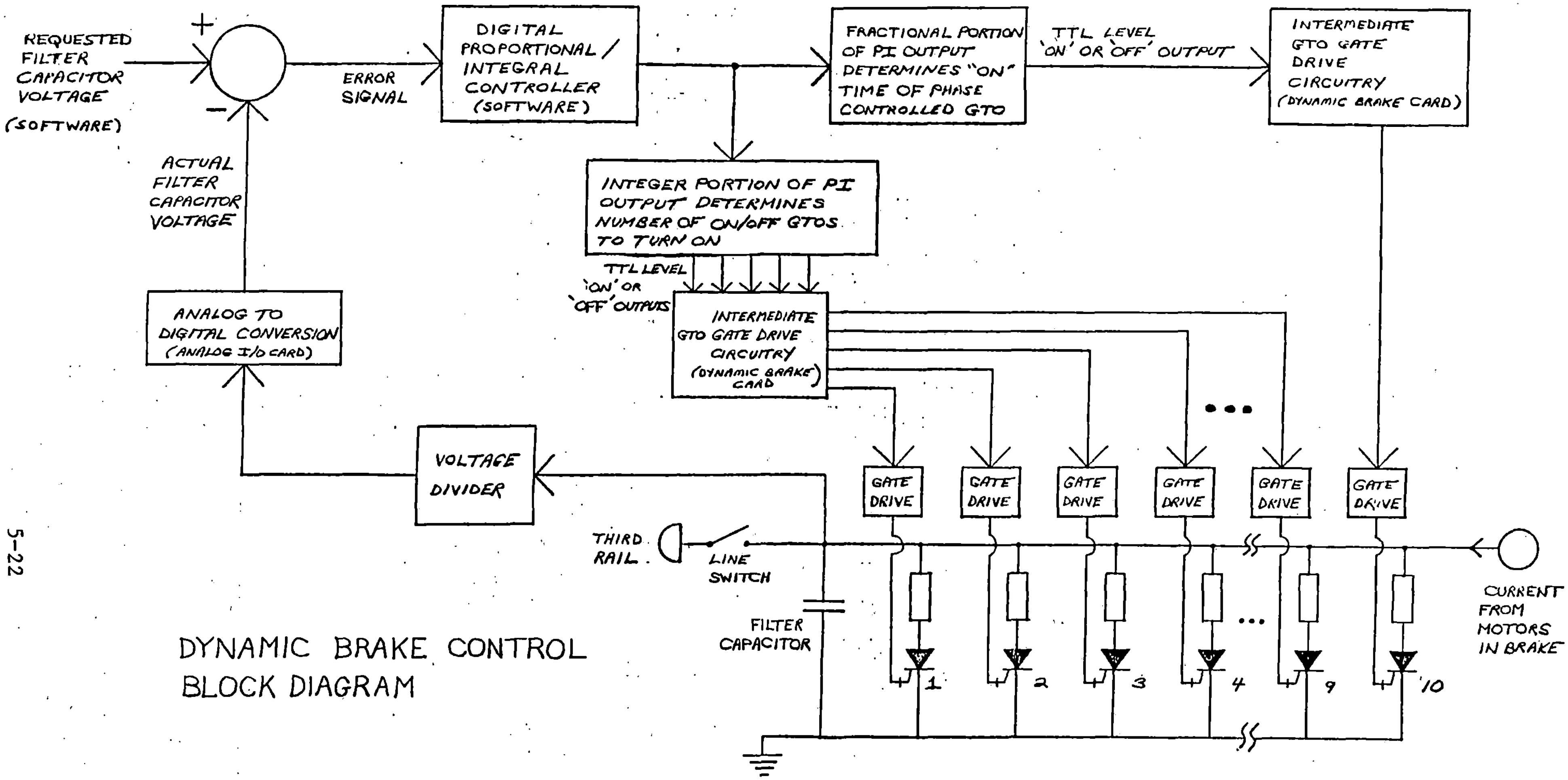


Figure 5-11

Functional Elements of Dynamic Brake Control slipping axle(s) in power will be the one(s) with the higher relative speed and the axle(s) designated as the sliding axle(s) in brake will be the one(s) with the lower relative speed. The axle speeds are compared during a low torque condition to produce a relative speed factor for each axle to compensate for RPM differences caused by wheel diameter differences. A slip or slide condition detected by either of the above tests will cause identical reactions. Regardless of which mode the vehicle is in (power or brake), the tractive effort request for the slipping/sliding axle's motor control logic is zeroed until the slip/slide is corrected. However, during a slide in brake, a per truck slide signal is sent to the friction brake supplier to provide for removal of friction brakes from the truck with the sliding axle(s). Protection circuitry will prevent friction brake removal for more than five continuous seconds.

4. Motor Control Logic coordination and communication.

Each AC motor is controlled by a motor control logic unit. These units have no knowlege of the existence of the others. Therefore, a supervisor is needed to coorindinate the performance of the individual motor control logic units. This supervisory requirement defines the primary function of the car control computer. The car controller presently communicates with each motor controller via a serial communication link (RS232 protocol). Presently, the following information is sent from the car controller to each motor controller:

a. Torque request.

This torque request is affected by the emulation function or P-signal function, whichever is active, and the slip/slide function. A positive torque request represents a motoring request while a negative torque request represents a braking request.

b. Jerk limit factor.

Since the car controller reads the load weight, it communicates a jerk limit factor to each motor control logic for use in jerk limiting of tractive effort.

c. Car control status.

The status information sent to each motor controller includes a forward/reverse direction command based on the forward/reverse trainline status, a coast command which informs the motor controllers that coast has been commanded, and an inverter enable flag and inverter recovery flag used in shutdown and recovery of an inverter.

The following information is received by the car controller from each motor control logic unit:

a. Torque estimate.

Each motor control logic calculates a torque estimate for its own purposes. However, this torque value is also transmitted to the car controller for use in dynamic brake feedback calculations, mode verifications, and inverter operation comparisons.

b. Axle RPM.

This quantity is used by the car controller, as described previously, in slip/slide detection/reaction. In addition to this use, the axle RPMs are averaged to produce a speed value used in the emulation of an R44 cam car. Also, functions such as inverter re-start and dynamic braking have axle RPM values below which they cease to be performed.

c. Axle acceleration.

This quantity is used by the car controller, as described previously, in slip/slide detection/reaction.

d. Inverter status information.

Presently, this status information consists of an indication by a motor controller to the car controller that it has shut down its inverter for an emergency off situation or run termination. Provision has been made for the motor controllers to send coded messages to the car controller describing their present modes and their reasons for initiating a shutdown when one occurs.

e. Inverter DC link current.

Presently, the polarity and magnitude of this parameter is used to determine when the motor/inverter has begun to supply DC current in brake.

The car controller is responsible for the routine start-up of the system from a stop. Upon completion of a run, or on power-up, the motor control logics send the car controller the code representing an inverter shutdown. They remain in this hold mode until the car controller sends the motor control logics an "OK to recover" message. This recovery message will be sent the instant the car controller determines that inverter recovery is both desirable and feasible. This feasibility/desirability is based upon the presence of a power request from the trainlines and closed line switches (line switches are closed if proper third rail voltage is present). When these conditions are present, the inverter recovery message is sent to each motor controller along with the appropriate torque request. If all is well, the next status report from the motor controllers should no longer indicate an inverter shutdown and the vehicle should accelerate away. During routine motoring, the appearance of an inverter shutdown message from one of the motor controllers will initiate the following recovery procedure. First, recovery feasibility/desirability will be evaluated the same as before for a power request, however for a brake request, an inverter recovery message will be sent as long as speed is above some low speed threshold (presently set at 1 MPH). If coast is being requested by the trainlines, the inverter recovery message will not be sent until the mode requested becomes power or brake. Whenever the inverter recovery message is sent to a motor controller, that unit has 300 ms to indicate to the car controller that it has re-started. If this indication has not arrived at the end of this time interval, another inverter recovery is sent by the car control computer to the motor control logic. This process is repeated until a total of three inverter recoveries have been sent without success. At this time the inverter in question is disabled and shutdown until the unit can be investigated or until a trainlined system reset signal is received.

5. P-signal type operation.

As an added feature, provision was made for the AC drive to respond to a p-signal type of trainline environment. The car controller reads the value of an analog voltage representing an acceleration/deceleration request, determines the tractive effort required for the car weight, and communicates this tractive effort request to each of the motor control logic units. The p-signal used for our purposes was scaled as follows:

0V	P-sig	4V	represents a brake request.
4V	P-sig	6V	represents a coast request.
6V	P-sig	10V	represents a power request.

maximum acceleration is 2.5 mphps at P-sig = 10V
maximum deceleration is 3.0 mphps at P-sig = 0V

Verification of the car controller's ability to produce the proper tractive effort request for a given p-signal level and load weight value is documented in Figure 5-12. The graph illustrates the linear adjustment of tractive effort request, for a given load weight, over the range of acceptable p-signal values. Also illustrated is the difference in the tractive effort request, for a given p-signal level, between an AW0 load weight and an AW2 load weight.

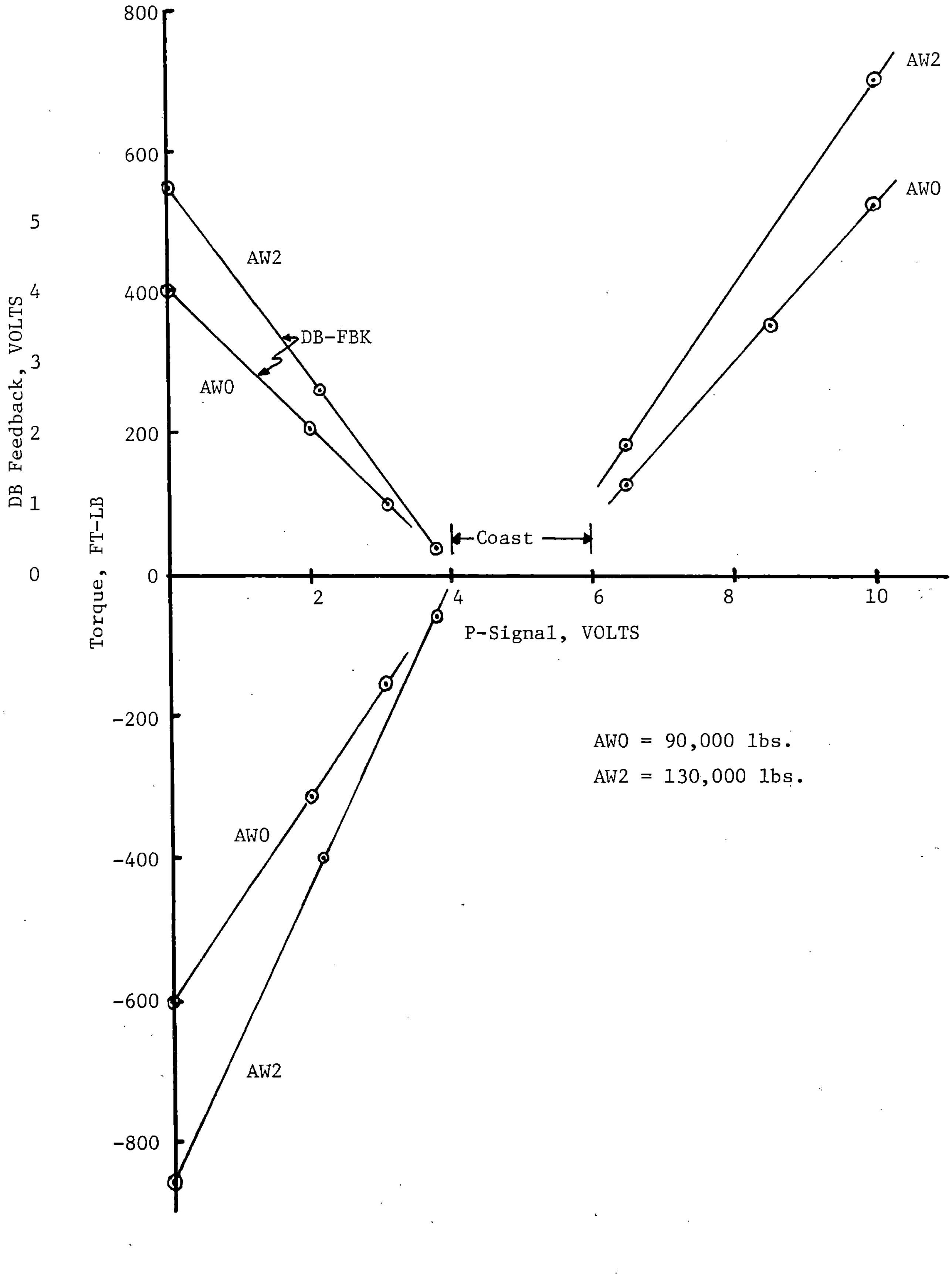


Figure 5-12
Torque vs P-Signal

6. Line switch control.

This function basically involves sensing the third rail voltage and closing the line switches if the voltage is within the specified range. During dynamic braking, the line switches will be opened and regeneration ended if the third rail voltage is out of the range of permissable regeneration voltages. In this case, the line switches would remain open until the third rail voltage is in range or power is requested. In any case, there is a two second delay in re-closing the line switches after they have been opened.

7. Dynamic brake feedback.

The car control computer provides a zero to minus ten volt output representing electric braking effort. Since the equipment was targeted for the R44 NYCTA cars, the dynamic brake feedback signal is scaled identically to the original equipment. Scaling is such that -10V = 16,048 lbs. braking effort. The total amount of electric braking present is calculated by summing the individual torque values received from the motor controllers and applying scale factors to come up with a tractive effort in pounds. The scale factors are related to wheel diameter and gear ratio. In addition to a dynamic brake feedback signal, the R44 friction brake supplier also received a speed signal from the propulsion. This zero to minus ten volt output represents zero to 100 MPH with 32.375 inch diameter wheels. Provision of this signal is therefore included in the car control computer.

8. Dead rail detection.

A dead rail detection scheme based on third rail receptivity has been implemented in the car control computer. The test states that if during dynamic braking with the line switches closed (regeneration), the regenerated current drops below fifty amps, then the line switches will be opened. The line switches will be re-closed only if proper third rail voltage is sensed.

5.4 MOTOR CONTROL LOGIC

5.4.1 INTRODUCTION

The motor control logic is responsible for controlling the motor through the application of appropriate control signals to the inverter and the auxiliary regenerative brake circuit in response to commands received from the car control computer.

5.4.2 DESIGN GOALS

The design goals of the overall propulsion control logic have been observed in the course of the design of the motor control logic. In addition the following functional design goals were established:

1. Accurate frequency waveform synthesis.
2. Torque control of a low slip AC motor suitable for use on transit vehicles.
3. Ability to provide controlled brake torque above base speed through the use of an auxiliary brake system.
4. Facilitate the transfer of information to and from the car control computer.
5. Capability of operation under environmental conditions normally experienced in transportation systems such as sudden loss of power due to rail gaps, sudden changes in line voltage, etc.

5.4.3 DESIGN DESCRIPTION

In order to meet all of the functional goals while still meeting the design goals outlined in the overall propulsion control logic section, a microprocessor based control was adopted. To satisfy all of the functional goals using traditional AC control analog circuits would require an extreme amount of very complex analog circuitry. Such a design would contradict the design goals set forth for the overall propulsion control system. A microprocessor based motor control system, on the other hand, surpasses a functionally equivalent analog design in every design goal. The circuitry necessary with a microprocessor based design is so compact that the entire motor control function can fit onto a single printed circuit board. A single board motor controller facilitates better fault isolation while reducing system mean time to repair.

The use of a microprocessor allows much more complex functions to be realized. Three types of waveform synthesis are used by the motor controller without requiring anymore hardware than one type of synthesis would take. In contrast, an analog system with three types of waveform synthesis may require as much as three times the circuitry that one type of synthesis requires. Also, using a microprocessor, a much more complicated algorithm is used to calculate the output torque from the DC line parameters (voltage and current). Such an algorithm results in no additional hardware or sensors over that needed by the waveform synthesis function. On the other hand, an analog torque calculation system requires a substantial number of additional hardware circuits and sensors.

Following is a brief discussion of some of the features of the Westinghouse AC drive motor control logic.

5.4.3.1 Waveform Synthesis (Inverter)

The inverter converts the DC voltage from the third rail into three phase AC voltage waveforms which power the AC motor. The inverter for this design consists basically of six GTO switching devices. By controlling the gating signals to these GTOs, the motor controller can vary the amplitude and frequency of the fundamental output AC voltage waveforms so as to control the torque produced by each motor. The control of the gating signals is referred to as waveform synthesis.

There are a number of synthesis techniques that can be used to produce AC waveforms from a DC source using an inverter. Each technique has its advantages and disadvantages over the other techniques. The approach used in this study consists of a combination of three of these modulation techniques. This allows the opportunity to take advantage of the particular characteristics of a modulation scheme in order to provide optimum system performance. All of the modulation schemes provide excellent frequency control. However, the voltage control capability and the harmonics produced by each technique varies.

The three types of modulation schemes used are:

1. Synchronous carrier pulse width modulation (PWM).
2. Quasi six step modulation.
3. Six step modulation.

5.4.3.1.1 PWM Synthesis

The fundamentals of PWM synthesis are well known. The implementation requires the generation of three sine wave references having the desired frequency and proper phase relationship with proportionally scaled amplitudes. The amplitude of these signals are then compared against the amplitude of a linear periodic function such as a triangular wave (also properly scaled) called "The Carrier".

The pulse pattern for the inverter switches can then be generated by adapation of the philosophy that the top switch in each phase is closed whenever the amplitude of the sine wave reference for that phase exceeds that of the reference and opened otherwise. The bottom switch of a phase is closed whenever the top switch for that phase is open. Under these operating conditions the inverter outputs a three phase AC waveform having a frequency equal to the frequency of the sine wave references and an amplitude proportional to the ratio of the amplitude of the reference to that of the carrier signal. The GTO switches will switch at a frequency equal to the frequency of the triangular waveform. Figure 5-13 shows waveforms generated by PWM synthesis. Waveforms A, B, and C show typical reference and carrier signals; waveforms Va, Vb, and Vc are the GTO firing pulse patterns; and waveforms Van, Vbn, Vcn are the resulting motor line-to-neutral voltages.

One of the characteristics of this PWM technique is that the resulting harmonics are centered around the carrier frequency which is a relatively high 350 hertz or more. It is desirable to keep the harmonics produced by the inverter at a much higher frequency than the desired fundamental as they will be filtered by the motor and thus result in only relatively small counter-torques and resistive losses. Since the harmonics produced using PWM are always centered around the carrier frequency PWM is ideal at low frequency operation (under 30 hertz). PWM also results in excellent voltage control up to about 60% to 70% of the voltage produced using six step waveform synthesis. This excellent low end voltage control makes its use almost mandatory at low fundamental frequencies where low output voltage is required.

5.4.3.1.2 Quasi Six Step

This technique is similar to six step synthesis with the exception of insertion of several strategically located notches in the generated pattern. These notches enable control of the inverter output voltage while minimizing power losses due to harmonics generated as a byproduct of the switching pattern. Several different sets of quasi six step patterns are utilized by the controller. The basic difference among these sets is the number of the switches per cycle in the pattern. This type of synthesis is utilized from about 3 hertz to 70 hertz with occasional use from 70 hertz to 200 hertz. At the lower end of the 30 to 70 hertz region, several switches per cycle can be used; however, as the fundamental putput frequency increases, the number of switches per cycle must be reduced. The number of switches per cycle used at a particular fundamental frequency is determined such that the switching frequency of the GTOs falls into the range of about 300 hertz to 600 hertz. Figure 5-14 shows waveforms generated by quasi six step synthesis. Waveforms A, B, and C show typical desired motor line-to-neutral voltages; waveforms Va, Vb, and Vc are typical GTO firing pulse patterns generated under this scheme; and waveforms Van, Vbn, and Vcn are the resulting motor line-to-neutral voltages.

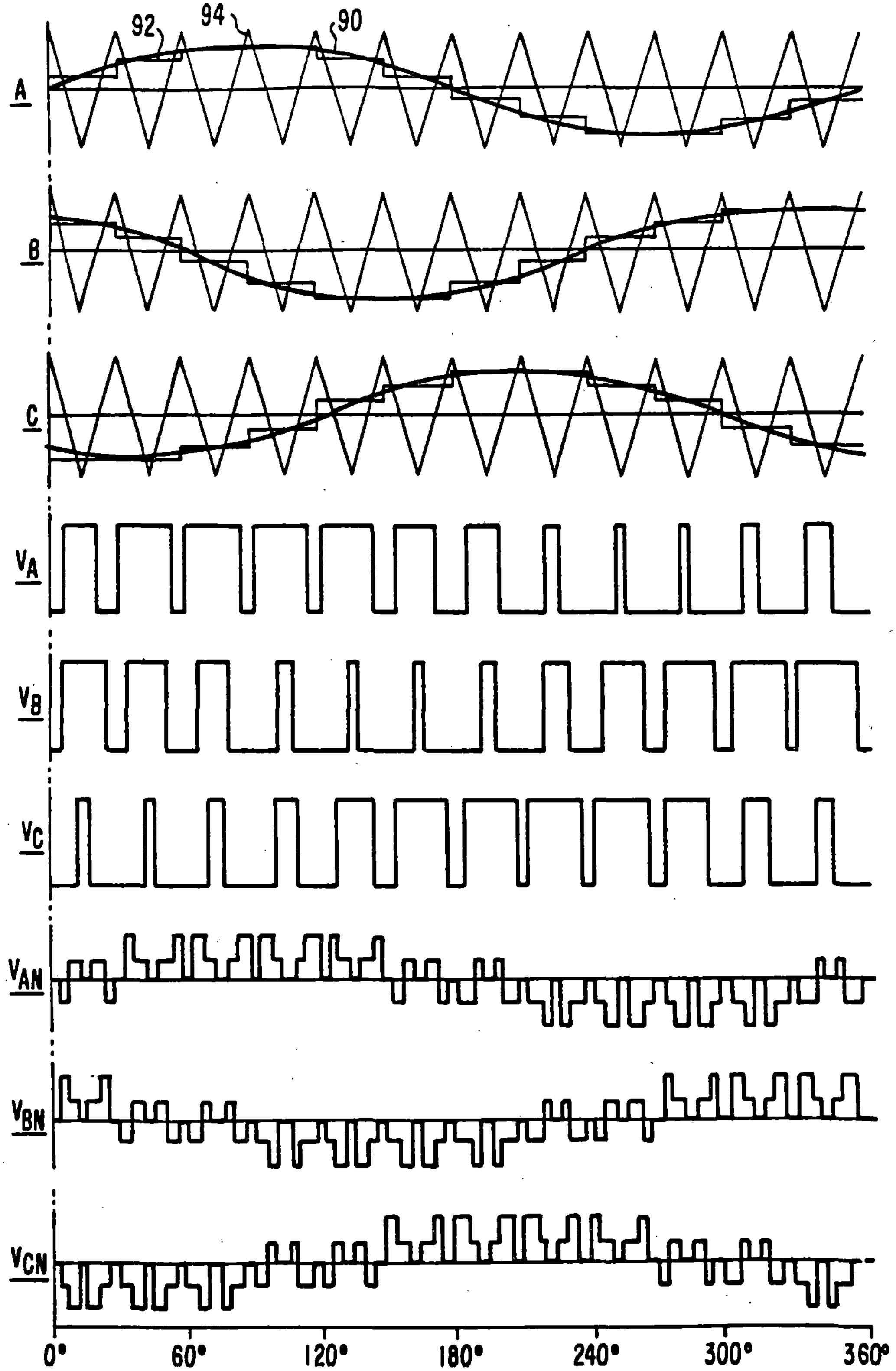


Figure 5-13

PWM Synthesis Waveforms

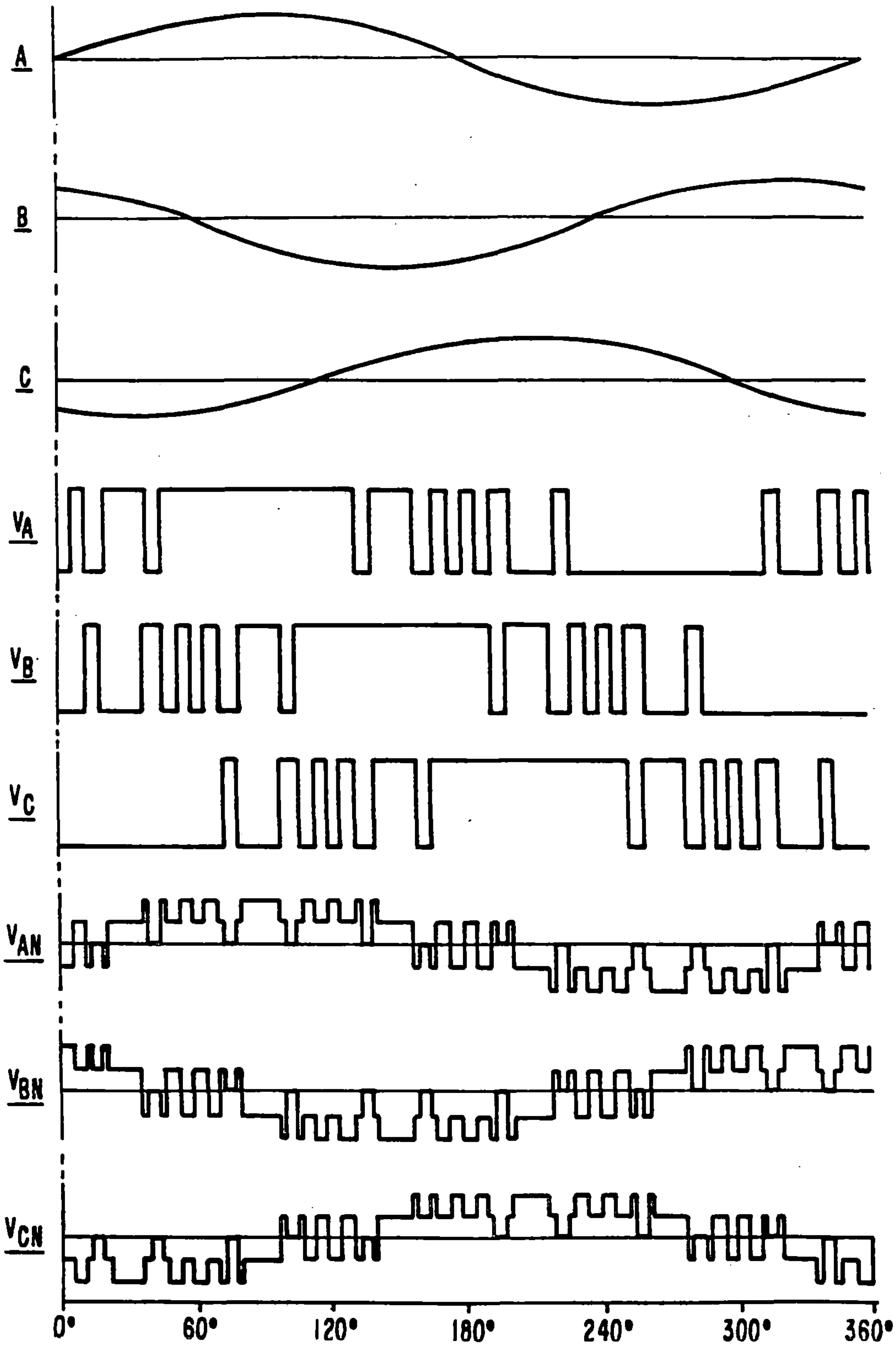


Figure 5-14

Quasi Six Step Synthesis Waveforms

The quasi six step modulation provides excellent AC output voltage control for all desirable output voltages. The harmonics generated by this scheme are located at the fifth, seventh, eleventh,... multiples of the fundamental frequency. The amplitudes of the harmonics are closely related to the ratio of desired AC output voltage to the maximum obtainable AC output voltage achievable using six step synthesis. The lower this ratio, the worse the harmonic content. At low fundamental frequencies, the harmonics produced using using quasi six step are worse than those produced using PWM. At higher frequencies, where the ratio is higher, the quasi six step harmonics eventually become better than those produced by PWM synthesis.

It should be noted that all quasi six step modulation patterns used have been optimized for lowest harmonic generation, thus resulting in lower system power consumption. This has been achieved through a special harmonic content minimization technique.

5.4.3.1.3 <u>Six Step</u>

The six step modulation only provides frequency control and generates a harmonic pattern spectrum similar to that of the quasi six step modulation; however, the harmonics produced using 98% or 99% quasi six step are somewhat better than the harmonics produced using six step. Therefore, quasi six step results in lower harmonic losses in the motor. However, these lower motor losses are somewhat offset by the increased switching losses in the inverter. Therefore, above base speed, where the desired voltage output is equal to the maximum voltage obtainable from the DC power source using six step synthesis, one must weight the benefits of quasi six step with the benefits of six step synthesis. Through testing, we have determined that the losses associated with six step synthesis are lower than those of quasi six step for fundamental frequencies above 70 hertz. Figure 5-15 shows waveforms generated by six step synthesis. Waveforms A, B, and C show typical desired motor line-to-neutral voltages; waveforms Va, Vb, and Vc are typical GTO firing pulse patterns generated under this scheme; and waveforms Van, Vbn, and Vcn are the resulting motor line-to-neutral voltages.

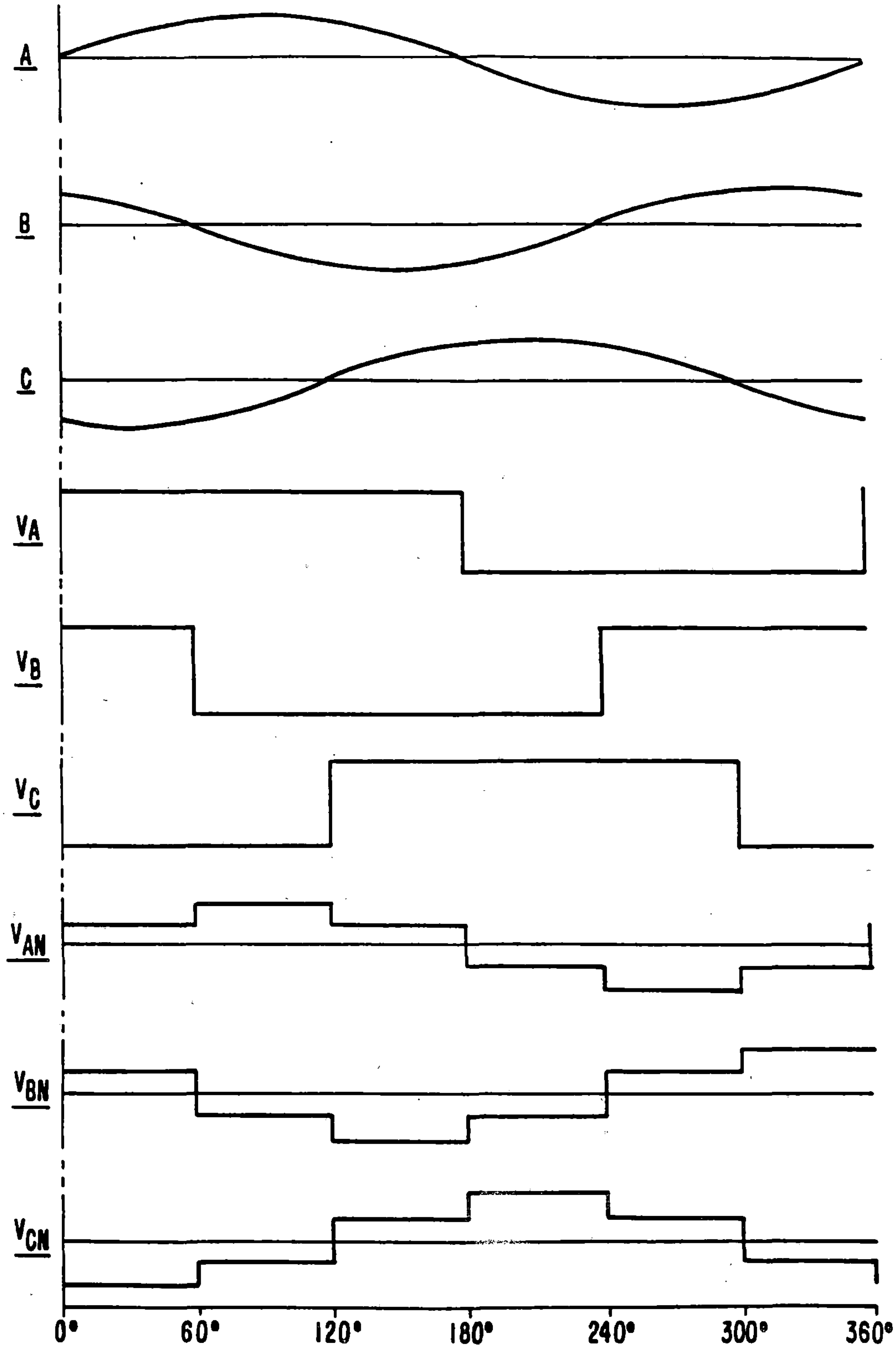


Figure 5-15

Six Step Synthesis Waveforms

As can be seen, each synthesis technique offers specific advantages while presenting certain limiting factors in the design. PWM provides excellent waveform synthesis and fast response to variations in system operating conditions; however, at fundamental frequencies above about 30 hertz, PWM's excellent synthesis begins to deteriorate and it is necessary to switch to a quasi six step type synthesis. Above 70 hertz, six step synthesis is used in order to take advantage of the lower switching losses associated with six step synthesis.

It is important to note that the waveform synthesis is digitally implemented as opposed to conventional analog implementation techniques. The reference and carrier waveforms used in PWM are not physical signals. The microprocessor is programmed with mathematical equations that represent these waveforms. Using a digital technique instead of a traditional analog technique results in a drift-free system that generates predictable, repeatable, and accurate results under all normal operating conditions, without the need for periodic calibration of the equipment.

5.4.3.2 Waveform Synthesis (Auxiliary Regenerative Brake System)

The inverter is fully regenerative and can provide slightly higher torque in brake than in power. This is generally sufficient to accomodate many transit systems. When additional electrical braking above base speed of the motor is desired, an optional auxiliary regenerative brake system is available. This option, when coupled with the inverter, can provide full electrical braking across the full speed range of the system. The extra braking achieved using this auxiliary brake system can be either partial or fully regenerative depending on the technique chosen. Using any of these additional electrical braking techniques does not result in component wearout as is the case with such systems that utilize friction brakes to achieve the extra braking effort. The auxiliary regenerative brake system provides additional motor voltage which results in increased braking effort by the motor.

5.4.3.2.1 Auxiliary Full Regenerative Brake System

This system consists of an additional 3 phase transformer that can be inserted in the power circuit on demand. By means of controlling GTO power switches on the secondary side of the transformer, additional voltage can be impressed across the motor. This additional motor voltage results in higher braking torque output from the motor. This system provides maximum energy conservation and is ideal for transit system where the power grid is highly receptive. This type of auxiliary brake system was chosen for this phase of the development in order to demonstrate the maximum regeneration capability of the AC drive system.

5.4.3.2.2 Auxiliary Partial Regenerative Brake System

With this technique, the additional voltage on the motor is developed through the use of braking resistors. This system offers lower regeneration capability when compared to the full regenerative brake system; however, the system costs are lower. This approach is ideal for transit systems where the power grid is only moderately receptive.

Regardless of the type of auxiliary brake system chosen, the inverter provides full regeneration during brake operations below base speed, with electrical braking capability at speeds as low as 1 MPH.

5.5 INVERTER CONTROLLER

The traditional control parameter for transit application is torque. In the AC drive propulsion system the control of torque is achieved by using two separate controllers for voltage and slip. The slip controller is a digitally implemented PI type. The output of this controller is the desired motor slip which is then added to the present shaft rotational frequency (measured by means of a pulsed tachometer) to derive the inverter frequency. During below base speed operation, that ouput of this controller is passed through a function generator that provides the desired inverter voltage. The familiar constant V/F type of operation is used in this range. Above base speed the slip is raised somewhat beyond the rated slip value in order to maintain the desired full torque as long as possible. Once the slip is raised to a point which will deliver no more increase in torque, the motor is operated in the reduced flux mode and the torque output is allowed to drop.

5.6 AUXILIARY REGENERATIVE BRAKE CONTROLLER

The control for the optional auxiliary regenerative brake system is achieved through an integral controller. During brake above base speed, once voltage and slip limits imposed by the slip controller have been reached, the brake voltage controller is activated. This controller controls the additional voltage provided by the auxiliary brake system in order to maintain the desired brake torque in the motor.

All controllers are implemented in the software, thus the system response is predictable, reproducible, and flexible for use on various types of systems. Also, the system reliability is enhanced while system costs are reduced due to the lack of need for any additional hardware for this implementation.

5.7 CONTROLLER FEEDBACK DETERMINATION (Torque Estimator)

One of the features of this system is the absence of multiple analog signal conditioning boards that are normally used in most AC drive systems to measure the AC side parameters. In traditional approaches to torque feedback signal generation, a minimum of two fundamental line to line voltages and two motor line currents have to be processed through fixed bandwidth, variable center frequency filters. Additional circuits are then used to arrive at the value of the same parameters for the third phase. These parameter values are then used in determination of the torque feedback signal using additional complex circuitry.

The AC drive system employes an innovative technique that involves measurements of DC side parameters (one line voltage and one line current) and shaft rotational speed to generate the torque feedback signal. Figure 5-16 is a bode plot comparing measured results of this technique against those from a high frequency response torquemeter. Operation at three different operating points (12 hz, 20 hz, and 60 hz inverter frequency) are compared in these plots. As can be seen, the frequency response of the Westinghouse technique tracks that of the torquemeter's output (gain of approximately 0 db and phase shift of approximately 0 degrees) for system disturbances of up to approximately 10 hz. At that point, even though the gain drops off, the more important phase shift still remains around 0 degrees. Since adequate control can be obtained with controllers having bandwidths of less than five hertz, the less expensive and more reliable Westinghouse torque determination technique is more than adequate for such use and is, therefore, desirable over traditional torque calculation methods.

5.8 CONTROL STABILITY

The controller response of the AC drive system has been extensively tested under various operating conditions with special attention paid to controller stability. During these tests several runs were made with different levels of torque request at various DC line voltages. The system intertia load on the motor was simulated by an appropriately sized flywheel. Test conditions included numerous boundary conditions such as low and high line voltages, and low and high torque requests. The results obtained from these tests indicate stable system operation under all conditions tested. Figure 5-17 shows a typical test run.

5.9 SYSTEM RESPONSE TO TRANSIENTS ON THE DC LINE

In order to achieve better system efficiency while reducing system size, weight, and cost, the AC drive system utilizes a single power conversion stage (an inverter). In comparison, most systems use two stages of power conversion with the first stage (a chopper) dedicated to provide desired DC voltage for use by the inverter. This normally reduces the problems associated with transients normally present on an actual DC voltage line.

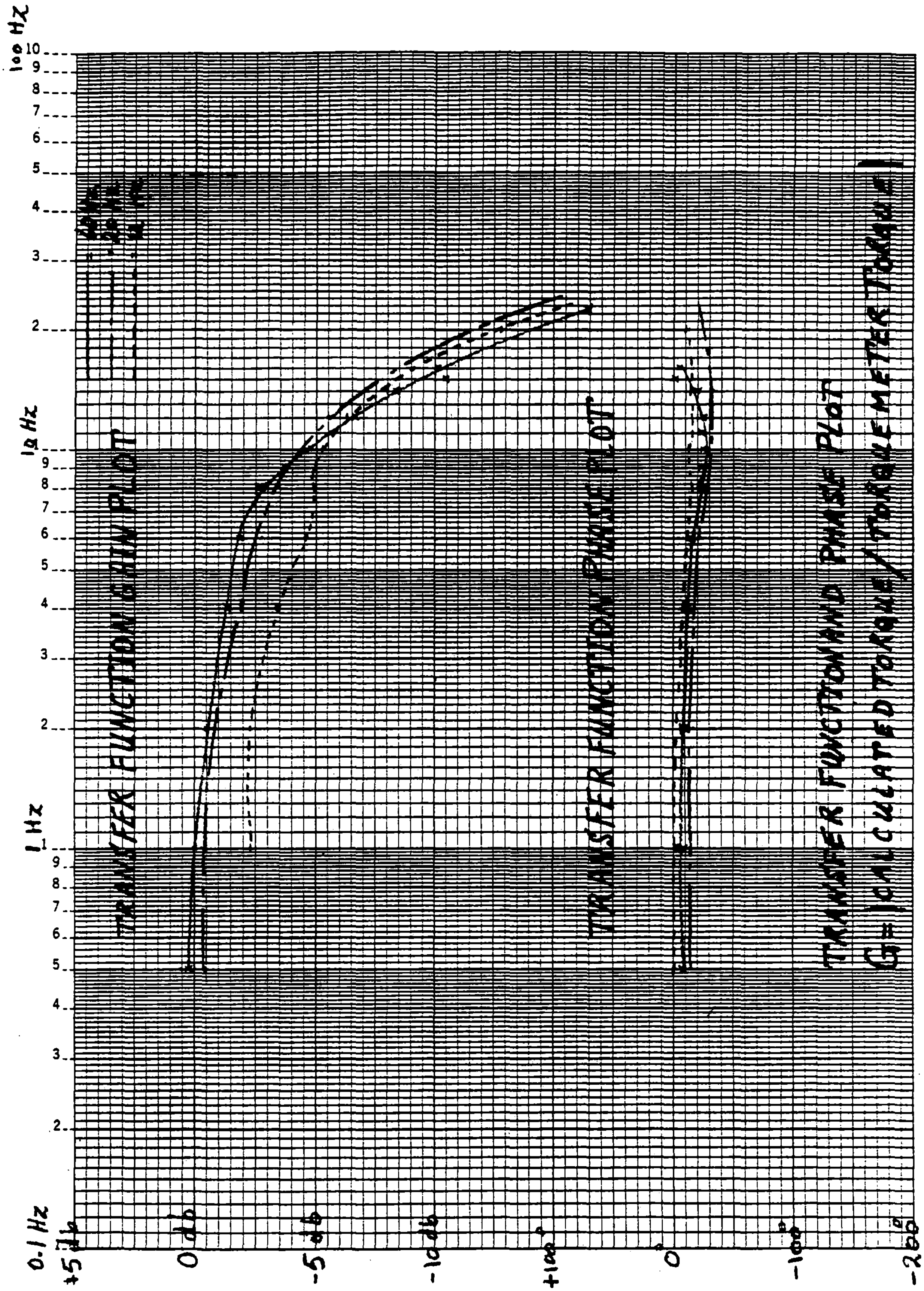


Figure 5-16

Transfer Function Gain Plot

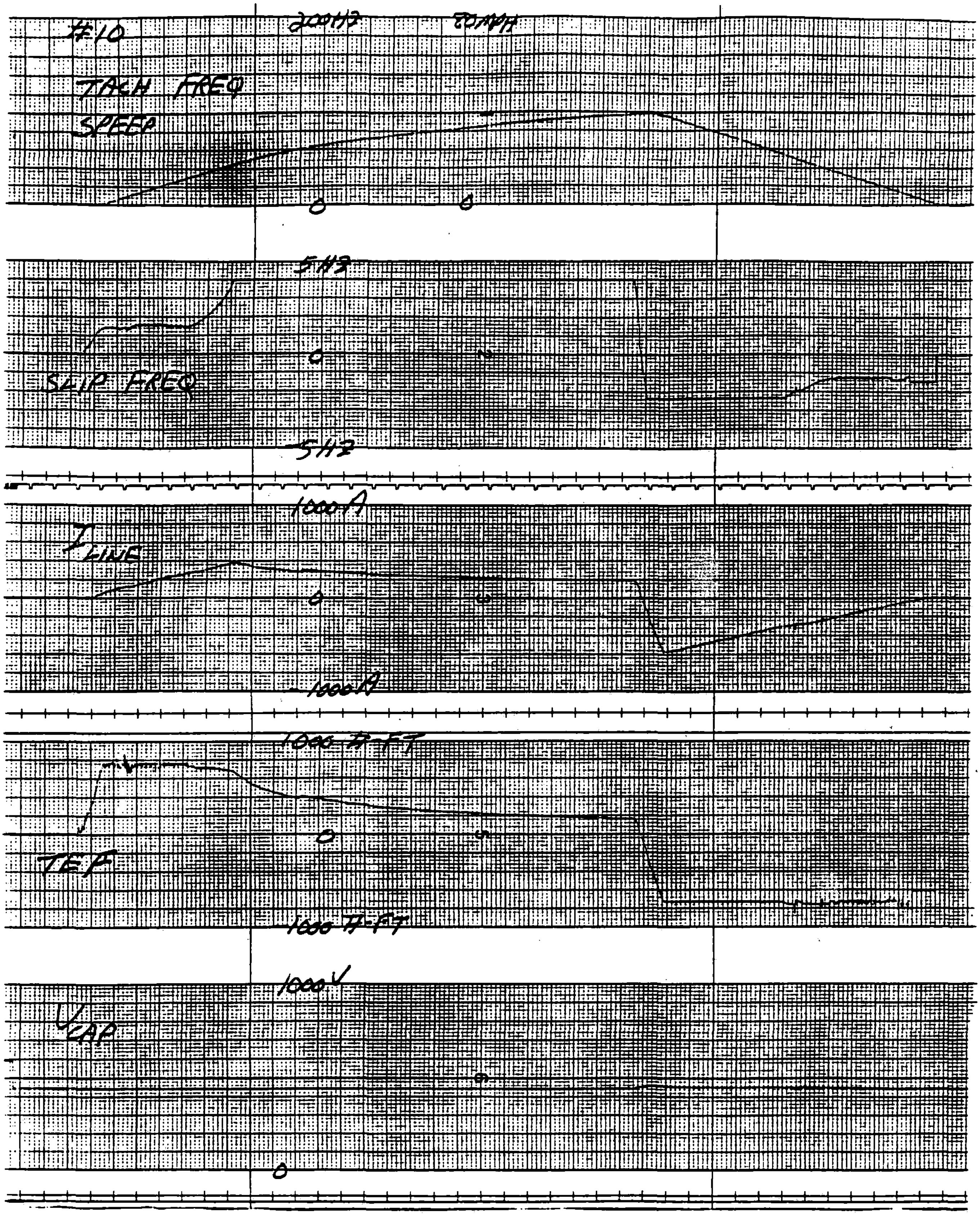


Figure 5-17

System Operation Test Results

Through a unique approach and without utilization of any additional hardware, the AC drive system provides a ride-through feature for such conditions. This feature has been tested under severe conditions such as a 300 volts rise on the DC line voltage with rate of rise of voltage of up to 25000 volts per second. Figure 5-18 shows the typical system response to such a transient condition.

5.10 FORWARD AND REVERSE OPERATION

The direction of rotation of an AC motor is determined by the phase relationshop between the rotating magnetic fields regenerated by the motor in response to the voltage imposed by the inverter. The reversal of this direction of rotation can be achieved by switching this phase relationship of the magnetic fields. Assume that phase C leads phase B which is leading phase A by 120 degrees. Application of such a field will result in a rotation of the motor in one direction, forward. The reverse direction of rotation is achieved by swapping the phase relationaships of two of the three phases, B and C. This is easily achieved through swapping the output pulse patterns generated by the synthesis for phases B and C thus eliminating the need for use of any mechanical devices (ie. contactors, reversers, ...).

5.11 ROLLBACK RECOVERY

The AC drive system can recover from rollback conditions of up to maximum system speed. However, only rollback recovery from speeds lower than 4 MPH are allowed. Due to special capabilities of the digital waveform synthesis in generation of low frequencies in both directions, the recovery is accomplished without any significant torque pulsations that could result in passenger discomfort.

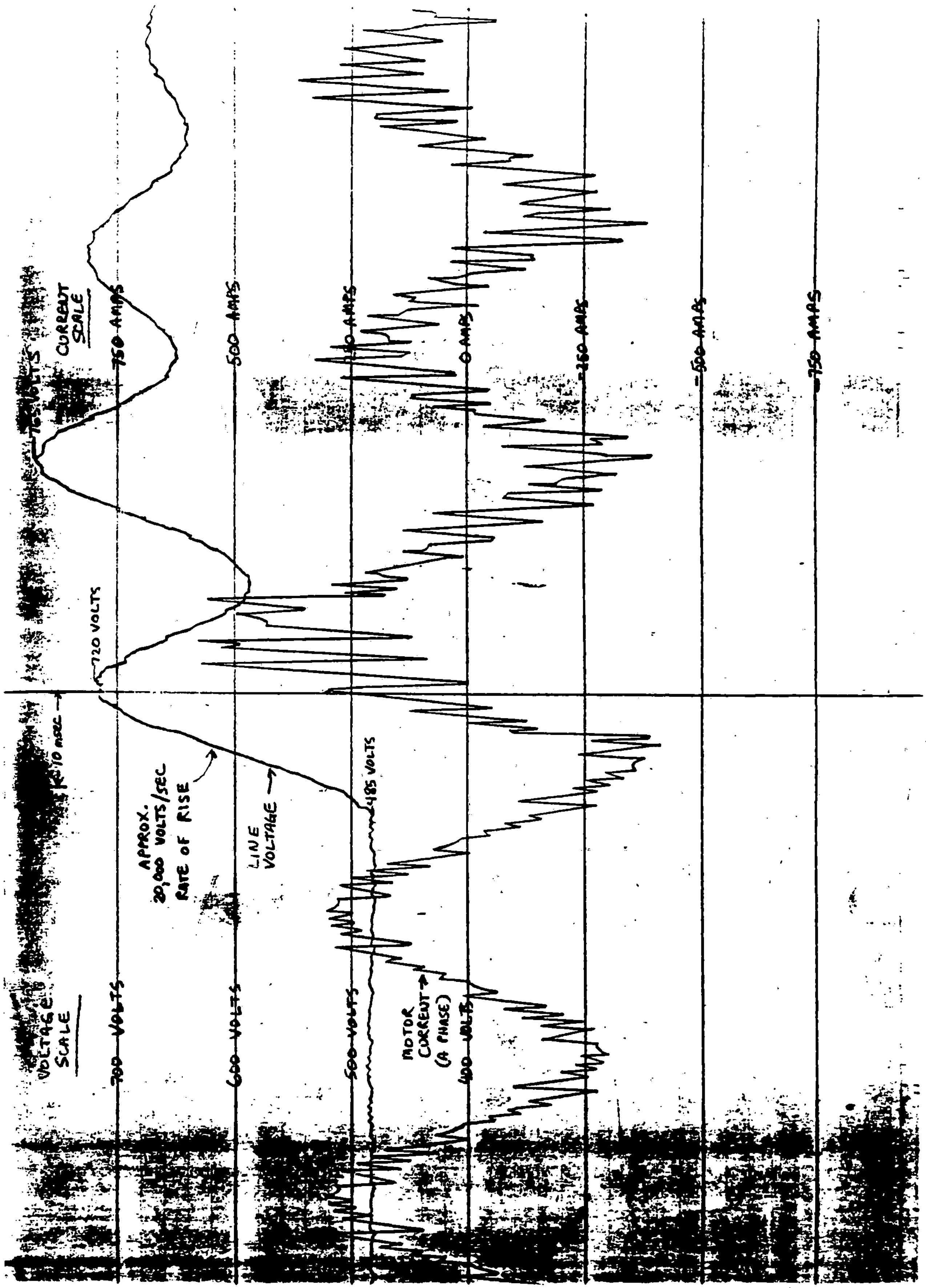


Figure 5-18

System Response to Transients

5.12 RAIL GAP/FAULT RECOVERY

In the event of a momentary power loss (ie. a rail gap), after the capacitor voltage has dropped below minimum operational voltage, the propulsion system is shut down. If the power has been restored prior to the vehicle reaching a zero speed condition, the propulsion system is energized and brought back up to its operating point. This function is accomplished through the use of a special rail gap/fault recovery procedure which allows a jerk limited restoration to full requested torque. The same procedure is also used in recovering from temporary fault conditions such as momentary overloads, system shutdowns due to over-voltage, etc. The recovery is done automatically by the microprocessor whenever the fault condition disappears.

5.13 DEAD TIME COMPENSATION

The dead time refers to that portion of time when one of the inverter switches has been opened but the other switch on the same inverter pole has not yet been closed. This period is basically needed to account for the switching times of the devices in the inverter (a switching device cannot be turned on until the other switching device in the same inverter pole is completely turned off). The insertion of dead times in the inverter control signals results in distorted AC voltage waveforms. The effect of this distortion is quite pronounced at low frequency, low voltage operation and can result in poor low speed performance such as motor cogging and poor acceleration. The Westinghouse solution to this problem is composed of several steps. The severity of the effects of dead time insertion are first reduced by reducing the dead time duration and generating identical dead time signals for all of the six inverter switches. Second, through a unique approach and without utilization of any additional hardware, the controller provides proper compensation for dead times. This is accomplished by means of the introduction of a phase change in the control signal. The implementation is completely digital, thus no periodic calibration is required. This unique process allows smooth system operation under low speed conditions.

6. BILLS OF MATERIAL AND WEIGHT ESTIMATES

This section contains several bills of material for system equipment, spare parts and test equipment as required by the Contract.

Listed in Figure 6-1 is a bill of material for the AC drive equipment, arranged in three different configurations. The various configurations allow for equipment and weight comparisons of an AC drive system with 1) full regeneration capabilities, 2) partial regeneration capabilities and 3) regeneration using only the inverter. It should be noted that all three configurations listed use a drip-proof motor in the weight estimates for equivalent comparison to the R44 cam controlled propulsion. As is noted at the bottom of Figure 6-1, should it be desired to replace a drip-proof motor with a totally enclosed motor, 350 lbs. per motor or 1400 lbs. per car should be added to the weight estimates listed.

The remaining two bills of material included in this section as Figure 6-2 and Figure 6-3 list the recommended spare parts for the AC drive system and the special test and support equipment required for field testing of the AC drive system.

Item	R44 Cam Control Equipment		AC Drive Full Regeneration Configuration		AC Drive Partial Regeneration Configuration		AC Drive Inverter-Only Configuration	
	Qty.	Total Weight (lbs.)	Qty.	Total Weight (lbs.)	Qty.	Total Weight (lbs.)	Qty.	Total Weight (lbs.)
Traction Motor (Drip-proof*)	4	6,720	4	5,400	4	5,400	4	5,400
Gear Unit	4	2,444	4	2,444	4	2,444	4	2,444
Truck Disconnect	2	50	6	150	6	150	6	150
Resistor Assembly	4	2,250	2	1,150	2	1,150	2	1,045
Knife Switch/Fuse Box	1	75	1	75	1	75	1	75
Main Cam Control Unit	1	2,075	N/A	-0-	N/A	-0-	N/A	-0-
Line Switch	N/A	-0-	1	255	1	255	1	255
Inverter	N/A	-0-	4	2,020	4	2,020	4	2,020
Regenerative Brake Circuit	N/A	-0-	4	1,520	1	960	N/A	-0-
Regenerative Brake Transformer	N/A	-0-	4	2,700	N/A	-0-	N/A	-0-
Line Filter Capacitor Box	N/A	-0-	**	-0-	**	-0-	1	450
Dynamic Brake Circuit	N/A	-0-	1	325	1	175	1	175
Line Reactor	N/A	-0-	1	475	1	475	1	475
Logic Cradle	N/A	-0-	1	35	1	35	1	35
		13,614 lbs.		16,549 lbs.		13,139 lbs.		12,524 lbs.

* Drip-proof motor frame shown for comparison - add 350 lbs./motor or 1400 lbs./car for totally-enclosed motor frame.

** Filter capacitors contained in regenerative brake circuit package for this configuration.

AC DRIVE VS. NYCTA R44 CAM CONTROL WEIGHT COMPARISON

R1661

Figure 6-1

AC Drive Recommended Spare Parts List

Quantity	Description
1	Inverter Module
1	Regenerative Brake Module
1	Brake Transformer
1	Dynamic Brake Module
1	AC Motor
1	Inverter Control Logic
1	Line Reactor
12	Line Filter Capacitor Cans (C7)
6	Line Filter Capacitor Fuses
6	Divider Resistors (R11)
6	600 Amp GTO's (GTO1)
6	Diodes (D1)
6	Capacitors (C1)
6	Diodes (D12)
6	Resistors (R4)
6	Reactors (L1)
6	Diodes (D8)
6	Resistors (R1)
1	Shunt (SH-1)
2	Gate Pulse Amplifiers (complete for 2 GTOs)
1	Reactor (L4)
1	Reactor (L5)
1	Diode (D7)
1	Diode (D11)
1	Resistor (R10)
1 set	Cards for Car Control Logic
1 set	Cards for Inverter Control Logic
1 set	Voltage Dividers
1 set	Line Switch Box Contacts
1	Tachometer Pickup
3	Main Fuses

Note: Items in parenthesis correspond to parts on attached schematic drawing 5575C13.

Figure 6-2

AC Drive Special Test and Support Equipment

Quantity	Description
1	LEM Transformer Shunt Type LA-3000-S
1	Tape Recorder for Track Circuit Test Recording
1	Spectral Dynamics SD-45 Spectrum Analyzer
1	60 Hz. Generator for Scopes and Other Equipment
1	6 Channel Recorder
1	DC Watt Hour Meter for Power Consumption
1 set	Accelerometers for Ride Comfort and Rate Tests
1 set	Standard Mechanics Tools (torque wrench included)
1 set	Standard Electricians Tools
1	Prom Programmer
2	Portable 16 Bit Microcomputers with Software
1	48 Channel Logic Analyzer
1	Emulator for MC-68000
2	Tektronics 468 Scopes
1 set	VME Modules, Cradles, Power Supplies & Boards
1	Inverter Transport Cart
1	Hand-Held Diagnostic Terminal

Figure 6-3

7. ELECTROMAGNETIC INTERFERENCE

7.1 ELECTROMAGNETIC COMPATIBILITY

Whenever propulsion traction power and track signalling share the same conductors (the running rails) there exists a potential interference problem. The main sources of noise are traction power substations and car carried propulsion equipment. The noise coupling from the car-carried propulsion equipment to the running rails can either be induced or conducted.

Induced EMI is the interference that is induced into the track circuit when the vehicle is directly over the receiver location as shown in Figure 7-1. It is primarily caused by flux produced by high di/dt circuits in the propulsion equipment.

As can be seen by the figure, induced EMI only occurs when the receiver location of a track circuit is between the two inner axles of a transit vehicle. In this situation, the track circuit is supposed to indicate that a train is present. All conventional rail signalling does this by recognizing that the track circuit receiver is not receiving its normal signal that is transmitted from the other end of the signalling block (a portion of running rail.) If the propulsion equipment could produce an interference signal that appeared to be the normal signal, then the receiver would not detect that the train is present. This would present a safety problem and must be avoided.

A second type of noise interference is conducted EMI. For this type of interference the transit vehicle is not over the receiving location of the track circuit. Instead the ripple current carried in the third rail and the ground return rail(s) produces an unwanted voltage that is picked up by the receiver. This can occur in either occupied or unoccupied signalling blocks. In an occupied signalling block conducted EMI might mimic the actual normal signal and cause the track circuit to indicate a clear state. This would cause a potential unsafe condition as was the case for the induced EMI. In an unoccupied signalling block conducted EMI could cause the normal track signal to be blocked or jammed. The receiver would then indicate that a train was in the block when actually it wasn't. This does not present a safety problem but

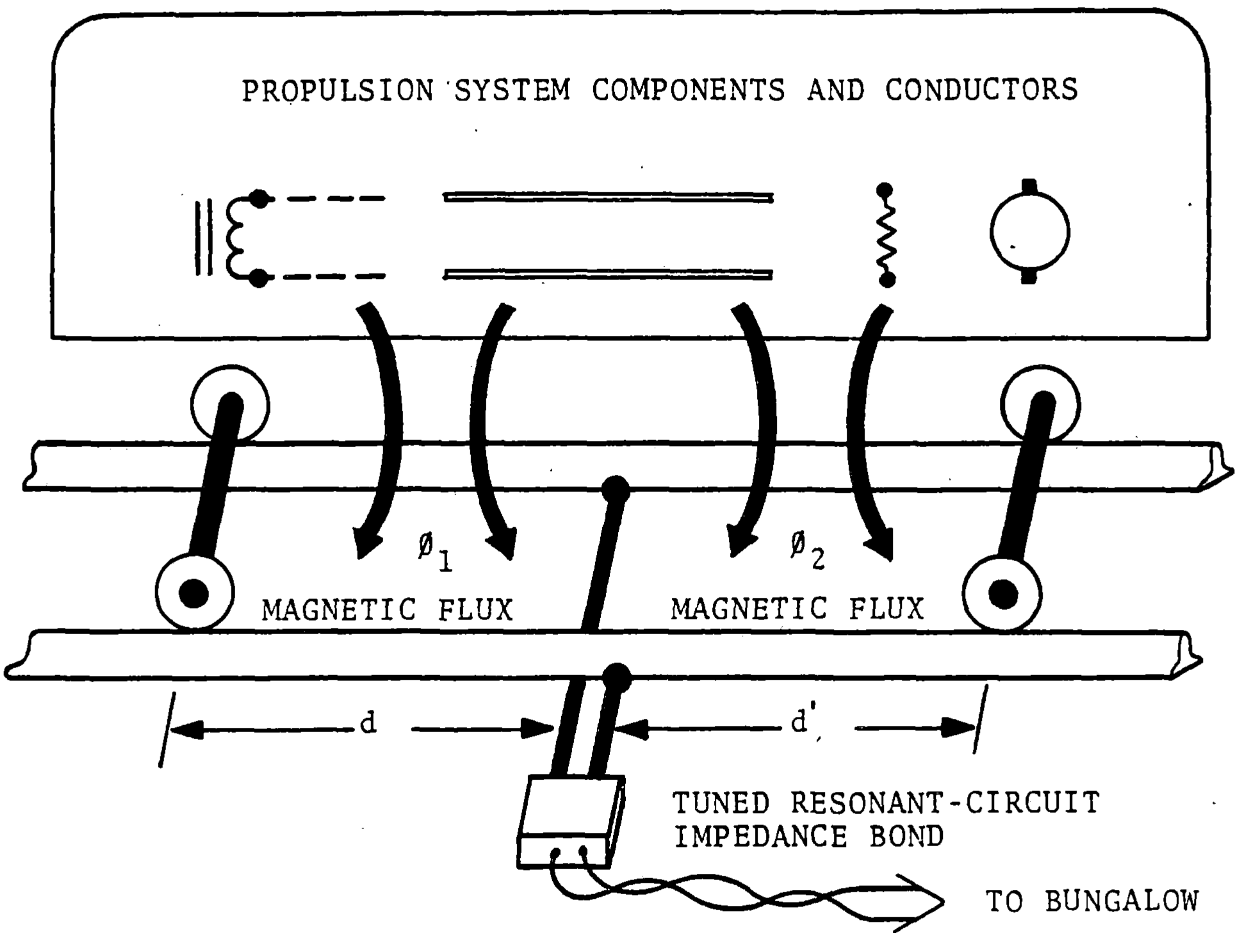


FIGURE 7-1 GENERATION OF INDUCTIVE INTERFERENCE

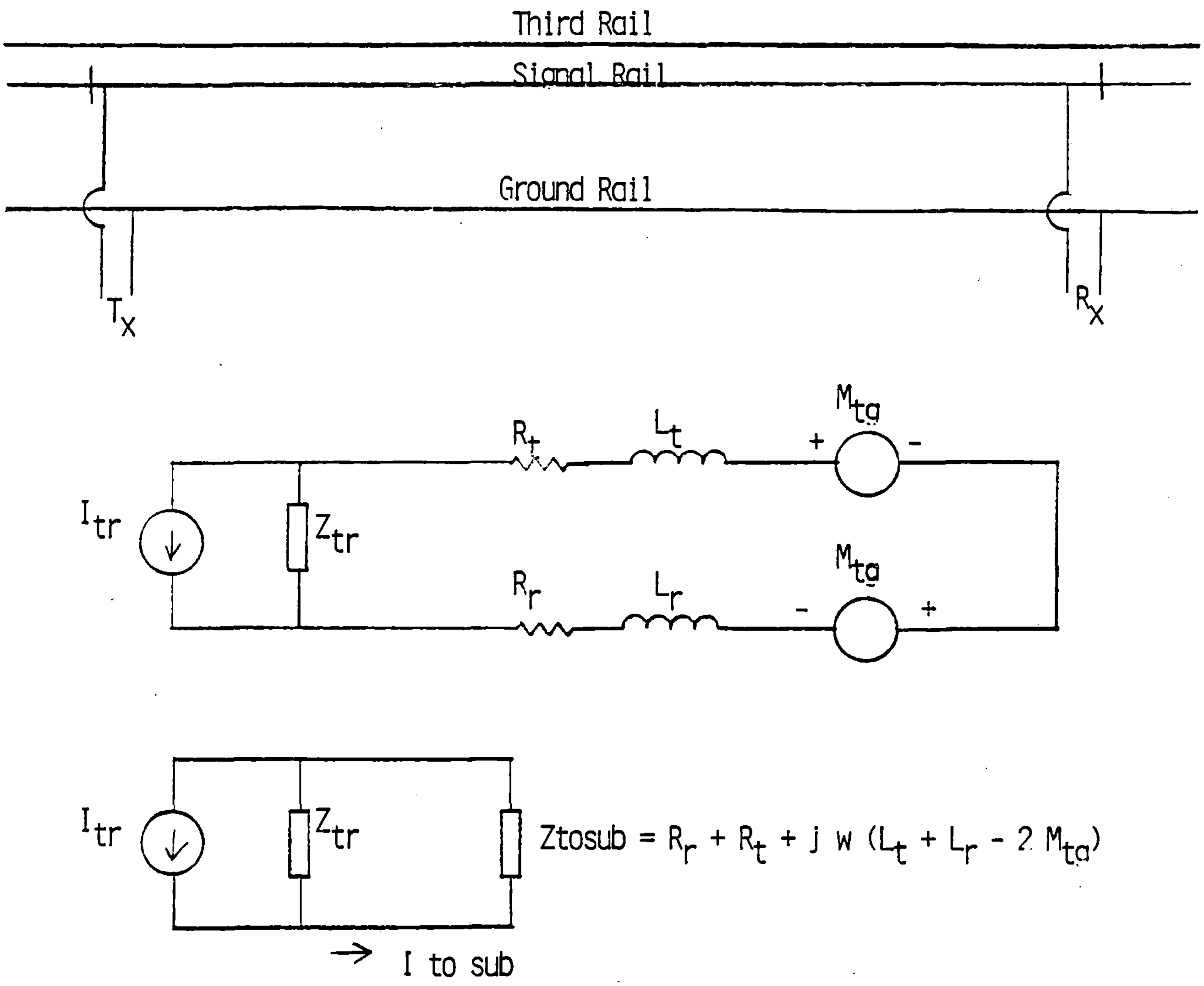
it could cause a train upstream of the interfered block to unnecessarily slow down or stop. This would disrupt passenger service and must also be avoided.

The AC drive system was designed to be compatible with the track signalling system at NYCTA for both induced and conducted EMI. Measurements have been made in the lab to test and verify the design. Measurements were also made in the lab for audio frequency conducted and induced EMI. These measurements were compared with the interference thresholds of various audio frequency track circuits to determine what steps are necessary to achieve compatibility in systems using these types of signalling systems.

7.2 CONDUCTED EMI MODELING FOR POWER FREQUENCY TRACK CIRCUITS (NYCTA)

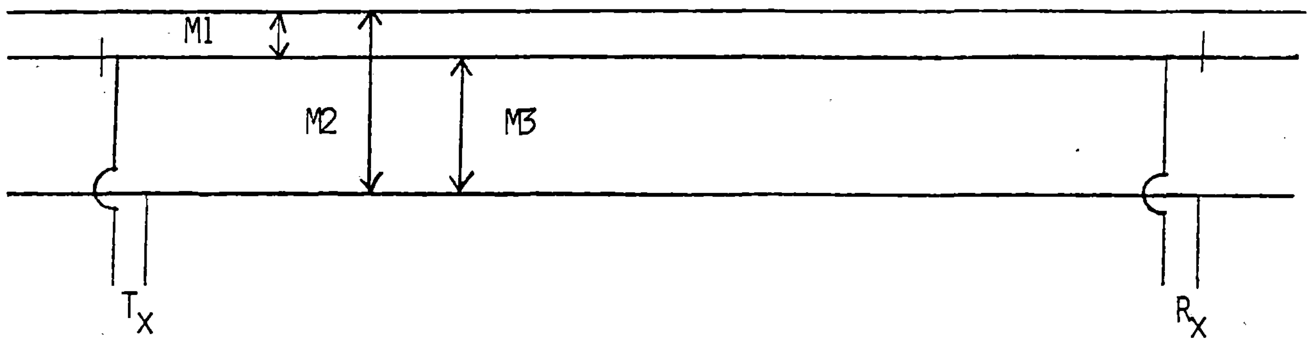
In order to determine whether or not the ripple current in the propulsion current from an AC drive propelled train could interfere with the NYCTA signalling systems, it was first necessary to understand the coupling or transfer function between the ripple in the third rail and the voltage induced into the track circuit receiver. To do this a computer model was made by Westinghouse that could determine the worst cases coupling condition. The model considers both single and double rail voltage track circuits of the type used in NYCTA.

Figures 7-2 & 7-3 show the voltage coupling mechanism for single rail voltage track circuits. For the normal signal from the transmitter to reach the receiver it must be conducted through the transmitter to reach the receiver it must be conducted through the circuit created by the ground rail and the signal rail. Voltage is applied to the signal rail at the transmitting end and the ground rail is used as the return path. Ripple components in the propulsion current cause an EMI voltage to be induced into the ground and signal rails due to mutual coupling into the signal and ground rails and the self inductance and resistance of the ground rail itself. The equations in the figure show the expression for the EMI voltage at a particular frequency as a function of the harmonic content of the propulsion current and the various rail inductances and resistance. The equations are shown for the case where the power rail is near the ground rail and the case when the power rail is near the signal rail. As it turns out, the case where the signal rail is near the third rail is always the worst case.

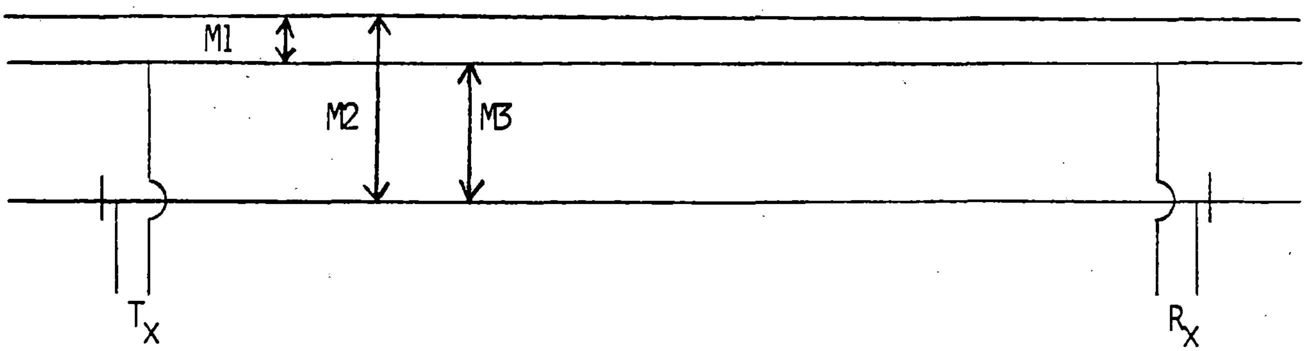


$$I\ to\ sub = I_{tr}\ (Z_{tr}\ /\ (Z_{tr} + Z_{to\ sub}))$$

FIGURE 7-2 SINGLE RAIL TRACK CIRCUIT RIPPLE CURRENT



$$V_{coup} = I \text{ to sub } (R_r + jw\,(L_r + M1 - M2 - M3))$$



$$V_{coup} - I \text{ to sub } (R_r + jw\,(L_r - M1 + M2 - M3))$$

FIGURE 7-3 SINGLE RAIL TRACK CIRCUIT VOLTAGE COUPLING

Figures 7-4 & 7-5 show the voltage coupling mechanism for a double rail voltage track circuit. For a double rail track circuit, insulated joints are found in both running rails instead of just in the signal rail which is the case with single rail voltage track circuits. The traction return current for a double rail track circuit must pass through impedance bonds attached to each end of the signalling block. The impedance bonds are center tapped to each other across block boundaries and traction return current passes through the center tap.

Referring to Figure 7-4, the impedance bonds are wound so that common mode current through them does not induce a voltage across the bond. This would be the case if I1 + I2. If the ripple current in the propulsion current would divide evenly between the two rails then there would be no interference. With the asymetrical third rail the current will not divide evenly and an interference voltage will be induced across the receiving bond. By solving the circuit equations, the induced voltage is calculated from Vtr and Ztr which represent an equivalent circuit of the train noise source. These calculations are made for both the occupied and unoccupied cases. Figure 7-5 only shows the coupling equations for the occupied case but the computer model contains both.

In order to use the models it was necessary to know the values of resistance, self inductance, and mutual inductance involved. The mutual inductances were quite easy to determine. Expressions for the mutual inductance between two parallel conductors can be found in the book 'Inductance Calculations, Working Formulas and Tables'[1] by Federick W. Grover. The expression is as follows:

M + 0.00508 * L * (ln(2*2L/S) - 1.0 + S/L) uh

L is the length of the conductors in inches

S is the spacing between the conductors in inches

M is the mutual inductance between the conductors

ln is the natural logarithm

1 Frederick W. Grover, Inductance Calculations, Working Formulas and Tables, (New York: Dover Publications 1973), pp. 31-45.

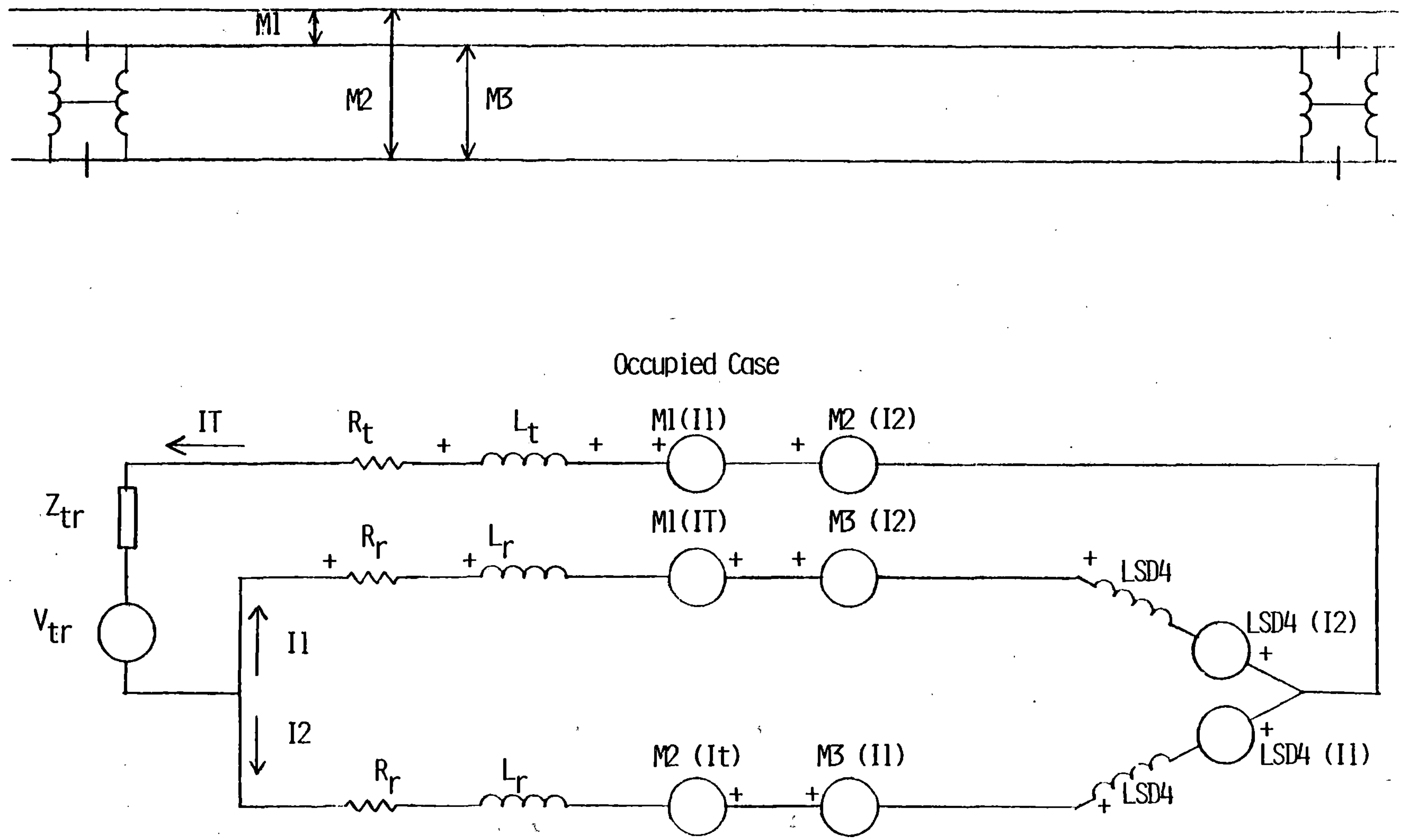


FIGURE 7-4 DOUBLE RAIL TRACK CIRCUIT EQUIVALENT CIRCUIT

$$
\begin{bmatrix} Vtr \\ Vtr \\ 0 \end{bmatrix} = \begin{bmatrix} A1 & A2 & A3 \\ B1 & B2 & B3 \\ 1 & 1 & -1 \end{bmatrix} \begin{bmatrix} I1 \\ I2 \\ IT \end{bmatrix}
$$

$$A1 = Rr + jw\,(Lr + LSD4 - M1)$$

$$A2 = jw\,(M3 - LSD4 - M2)$$

$$A3 = Rt + jw\,(Lt - M1) + Ztr$$

$$B1 = jw\,(M3 - LSD4 - M1)$$

$$B2 = Rr + jw\,(Lr + LSD4 - M2)$$

$$B3 = Rt + jw\,(Lt - M2) + Ztr$$

$$Vcoup = 2\,jw\,LSD4\,(I1 - I2)$$

FIGURE 7-5 DOUBLE RAIL TRACK CIRCUIT VOLTAGE COUPLING

There was some data on rail inductance from the AAR, but this data did not show the effect of saturation due to the dc rail current or the inductance of the 150 lb. squat rail that is used in NYCTA for contact rail.

The above referenced book by Grover also contains equations for the self inductance of conductors but not the shape of a rail. The equations are for round conductors that can be ferromagnetic or not. It was believed that if an equivalent radius of the rail were used with these equations that they would be valid.

In order to find the needed rail inductance characterization, measurements were made by members of the DOT EMI Technical Working Group and employees of DOT's Transportation System Center in Cambridge, MA.. The first set of measurements were made at the Wellington Yard of the MBTA and a second measurement technique was performed at Waltham Massachusetts near Boston. The second test yielded all of the results that were needed. It showed that the analytical expression for the inductance of a ferrous conductor found in the above mentioned book by Grover can be used to characterize the rail inductance. It also yielded the data that was needed to determine the equivalent radius of the rails. Listed below is the expression for the inductance of a ferrous conductor and the parameters of the various rail types used in NYCTA.

Lr = .00508 * L * (ln(2*L/rad) - 1.0 + u*T/4) uh

L is the length of the conductors in inches

rad is the effective radius of the conductor in inches

Lr is the self inductance of the conductor

T is a function of frequency and adds the change caused by skin effect. T + 1.0 at zero frequency and T approaches zero at high frequencies. Values for T are found in the book by Grover.

u is the relative permeability

85# Running Rail

u = 6.4

rad = 1.62 inches

Rdc = .0154 ohms/1000'

100# Running Rail

u = 9.95

rad = 1.92 inches

Rdc = .0085 homs/1000'

150# Contact Rail

u = 31.2

rad = 2.52 inches

Rdc = .0052 ohms/1000'

The change in rail inductance due to DC current levels is simulated by varying the rail permeability between the above listed values and the value of 1.0 A permeability of 1.0 would represent totally saturated iron in the rails.

The change in resistance as a function of frequency can also be found from a table in the book by Grover.

With the electrical characteristics of the rails characterized, it was then possible to write a computer program that could compute the voltage induced into a track circuit given the following:

1. Track circuit type (single or double rail)
2. Track circuit frequency
3. Track circuit transmitter and receiver impedances
4. Impedance bond inductance (double rail circuits only)
5. Track circuit length
6. Rail permeability
7. Number of cars in the train
8. Vehicle input filter element definition
    a. Line reactor inductance and resistance
    b. Filter capacitor capacitorce and resistance (ESR)
9. Substation inductance
10. Magnitude of ripple current in the DC link of each individual inverter.
11. Occupied or unoccupied track circuit.
12. For the unoccupied case the level of noise used will not be exceeded for N number of inverters at random phase 99.9% of the time. For the occupied case which would represent a

safety problem if interference occurred, the inverters are all assumed to be in phase which represents a worst case.

Appendix C contains a listing of the FORTRAN computer program that is the conducted EMI model for power frequency track circuits.

7.3 EMI DESIGN USING CONDUCTED EMI MODEL

The conducted EMI model can find the worst case condition that can exist for any combination of the above mentioned parameters for each and every track circuit from the NYCTA identified and tested at TSC. The parameters were varied in the ranges listed below.

1. Track circuit length : 75 to 1600 feet
2. Number of cars in the train : 2 to 10
3. Rail permeability : Unsaturated value listed above to 1.0

One parameter that needed to be characterized in order to determine system EMI margins was the saturation effect of the line reactor when it carries the high regeneration currents associated with high speed braking. These currents are high enough to saturate the line reactors that we normally use for chopper jobs. A reactor could be designed and built that would not saturate at these high current levels but this would increase the size and weight of the reactor 80 to 100%. Because of this it was decided to base the design on the saturated inductance value when needed. This only affected the 60 Hz track circuit calculations since the inverter only produces 25 Hz EMI at low speeds where the line currents are low and saturation does not occur. If the fully regenerative brake circuit is not used on an application, then saturation is not a problem and the EMI design can be based on the full line reactor inductance.

A test was run at he Westinghouse 2L Lab in East Pittsburgh to measure the saturation effect of a line reactor. A motor generator set was used to circulate varing degrees of DC current through the reactor under test. At the same time an AC current was circulated through the reactor. The AC voltage drop across the reactor was measured as well as the AC current. From this the reactor impedance could be measured. From the test is was determined that the fully saturated inductance of the reactor was about 6% of the unsaturated value. The line reactor inductance values that were used in the EMI design were then .5 mh for the 25 Hz track circuits and .03 mh for the 60 Hz track circuits.

A summary of the NYCTA track circuit characteristics is given in Table 7.1. This is a complete list of all of the track circuit types that were identified by NYCTA as existing on the RR line. They cover both power signalling frequencies, 25 and 60 Hz, and both single and double rail circuits. The sensitivities listed in the table were determined by measurements made at the Transportation System Center in Cambridge, Mass. The track circuit hardware was borrowed from NYCTA and MBTA in Boston.

Given the susceptibility of the track circuits, the model of interference coupling, and the estimated DC link ripple current the worst case system margin can be calculated.

These calculations yielded the values needed for the line reactor inductance and filter capacitor capacitance. From the computer model runs it was determined that 24 11000 uf 300 volt capacitors (3 series 8 parallel) per inverter and one .5 mh inductor (.03 mh saturated) would provide the needed filtering for system EMI margins.

7.4 LAB TESTING USING THE CONDUCTED EMI MODEL

In order to determine the system conducted EMI margin in the lab with the final inverter configuration the coupling model was used in conjunction with the measurements. The model yields the transfer function between single inverter DC link ripple current and the voltage induced into the track circuit by the train in the worst case situation. Listed below is the transfer function for the most sensitive 25 and 60 Hz track circuits.

Track circuit #1 60 Hz single rail circuit

1.0 A rms DC link current produces

.031 V rms rail to rail for the unoccupied case

.038 V rms rail to rail for the occupied case

Track circuit #11 25 Hz double rail circuit

1.0 A rms DC link current produces

.013 V rms rail to rail for the unoccupied case

.021 V rms rail to rail for the occupied case

In addition to the conducted EMI due to the inverter and regenerative brake circuit combination, the conducted EMI caused by the dynamic brake circuit was also measured. Since there is only one dynamic brake circuit per vehicle instead of four, there is a different transfer function to obtain the worst case rail to rail voltage at the track circuit receivers. For the two most sensitive track circuits the transfer functions for the dynamic brake are as listed below.

Track circuit #1 60 Hz single rail circuit

1.0 A rms dynamic brake current produces

.0068 V rms rail to rail for the unoccupied case

.0095 V rms rail to rail for the occupied case

Track circuit #11 25 Hz double rail circuit

1.0 A rms dynamic brake current produces

.0037 V rms rail to rail for the unoccupied case

.0053 V rms rail to rail for the occupied case

7.5 CONDUCTED EMI TEST RESULTS FOR POWER FREQUENCY TRACK CIRCUITS (NYCTA)

In order to determine the true susceptibility of the track circuits, the output of the shunt measuring the DC link ripple current was amplified and applied to the actual track relay. This is illustrated in Figure 7-6. The current measuring shunt had an output voltage of .01362 volts for one amp input. The Kepco amplifier gain was then used to adjust this voltage. With the proper gain the lab setup could produce the same voltage input to the track circuit as the worst case situation listed above for the model. For instance if 1.0 A rms DC link current were to input .032 V rms to track circuit #1 then this would be the same as the worst case unoccupied case.

If the gain of the Kepco, is further increased until interference with the track circuit occurs, then the system margin can be measured. Under these conditions an artificial condition is created where the track circuit is receiving a higher noise level than it would ever see in revenue service.

System EMI margin test were made in the lab with the two most sensitive NYCYA track circuits. The results are listed below.

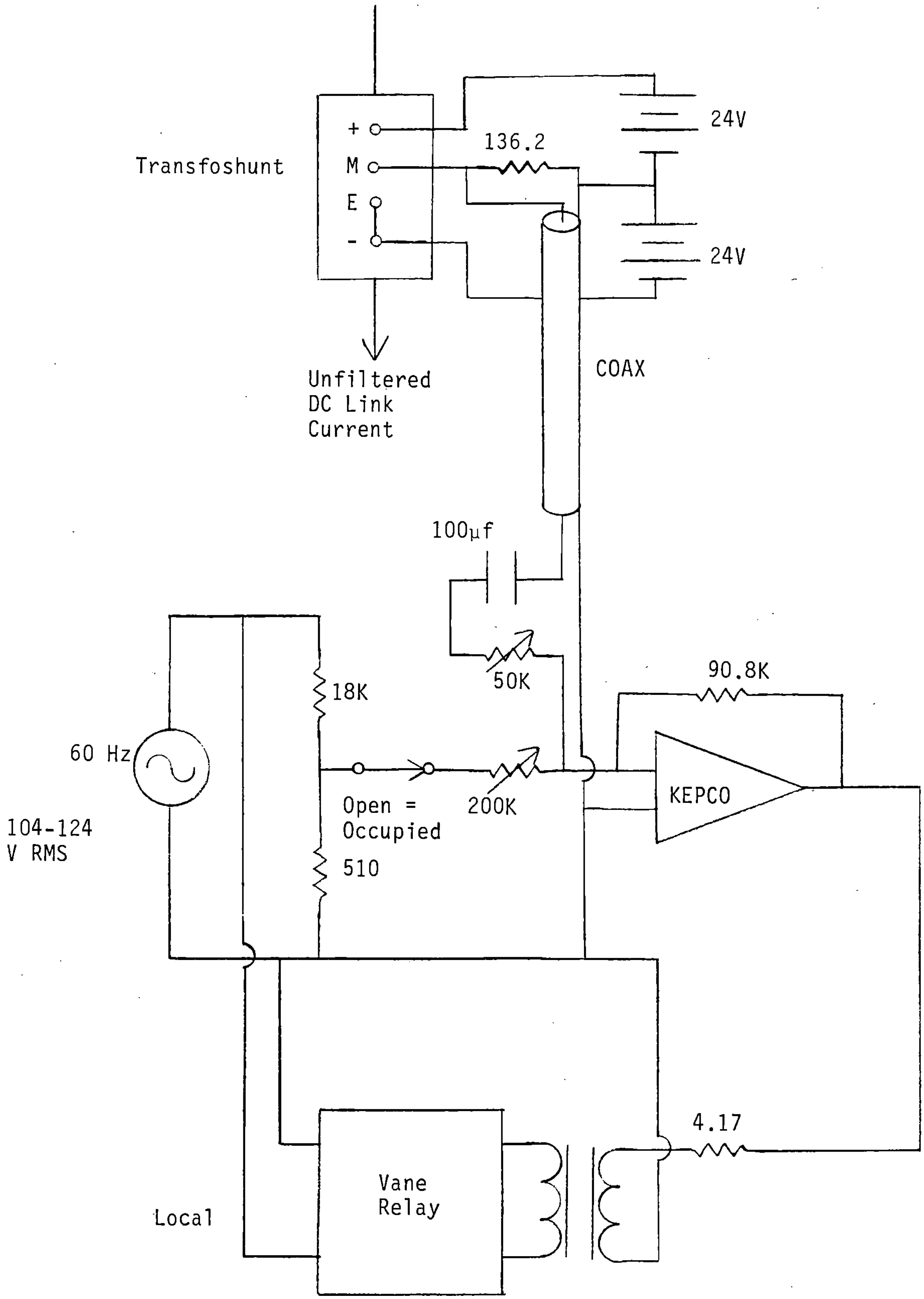


FIGURE 7-6 CONDUCTED TEST SETUP FOR GRS VANE RELAY

Track circuit #1 US&S 60 Hz Single Rail Matching transformer

Condition	Margin
Unoccupied margin	3.0 (9.6 dB)
Occupied margin	7.1 (17.1 dB)

Track circuit #11 GRS 25Hz Double Rail Direct relay receiver

Condition	Margin
Unoccupied margin	1.8 (5.2 dB)
Occupied margin	2.0 (6.0 dB)

The dynamic brake circuit consists of ten parallel resistor paths all of which are in parallel with the input filter capacitors. Each one of these resistors is controlled by a series GTO thyristor. During operation, only one of the GTOs is modulated to control the filter capacitor voltage. The others GTOs are either turned completely on or off and therefore produce no EMI.

In order to determine the conducted EMI level due to the dynamic brake circuit, the current measuring shunt was used. The dynamic brake transfer function developed in the preceding section was then used to determine the effect of this ripple current on the track circuits. Again using the maximum value storage mode of the FFT spectrum analyzer, the peak ripple current at 60 Hz was found to be 6.4 A rms. For track circuit #1, this would produce .058 V rms rail to rail for the unoccupied case and .061 V rms for the occupied case.

Since the unoccupied susceptibility threshold for this track circuit is 0.35 V rms and the occupied threshold is 2.0 V rms (see Table 7.1), it can be seen that even the measured maximum value of the dynamic brake ripple current is well beneath the interference threshold level. For the 25 Hz case, the peak ripple current was 1.9 A rms which for track circuit #11 would produce .0065 V rms for the unoccupied case and .0091 V rms for the occupied case. The unoccupied susceptibility threshold for this track circuit is .072 V rms and the occupied interference level is .148. Again the dynamic brake ripple current can be seen to not be a problem.

In summary, for the power frequency conducted EMI compatibility analysis a model has been made that relates inverter DC link current to the voltage that would be induced into the various NYCTA track circuits. This analysis determined the worst case system condition that produces the maximum EMI coupling into the track circuits for a given 25 or 60 Hz component in the DC link current. Even under these worst case conditions and with the most sensitive NYCTA track circuits, there was still positive operating and safety margin measured when the EMI was driven directly into the track circuit receiver equipment. By adding one more parallel path of capacitance to the input filter section of each inverter (3 additional cans per inverter), the system margins can be increased so that the unoccupied worst case margin for the most sensitive NYCTA track circuit (Track circuit #11) can be increased from the present 1.8 to 1 to 2.1 to 1. It is believed that there would be no problem with respect to conducted EMI when operating the Westinghouse AC Drive system in the NYCTA system.

7.6 INDUCED EMI TEST METHODS FOR POWER FREQUENCY TRACK CIRCUITS (NYCTA)

Induced EMI was measured in the laboratory using the technique shown in Figure 7-7. Figure 7-7 is found in the document 'Recommended Practice for Rail Transit Intra-System Electro-Magnetic Capability of Vehicular Electrical Power and Track Circuit Signalling Subsystems'[2] which was produced by an industry EMI technical working group. The technical working group was organized

2 U.S. Department of Transportation, Research and Special Programs Administration, Recommend Practice for Rail Transit Intra-System Electro-Magnetic Capability of Vehicular Electrical Power and Track Circuit Signalling Subsystems, 1981, Volume 1.

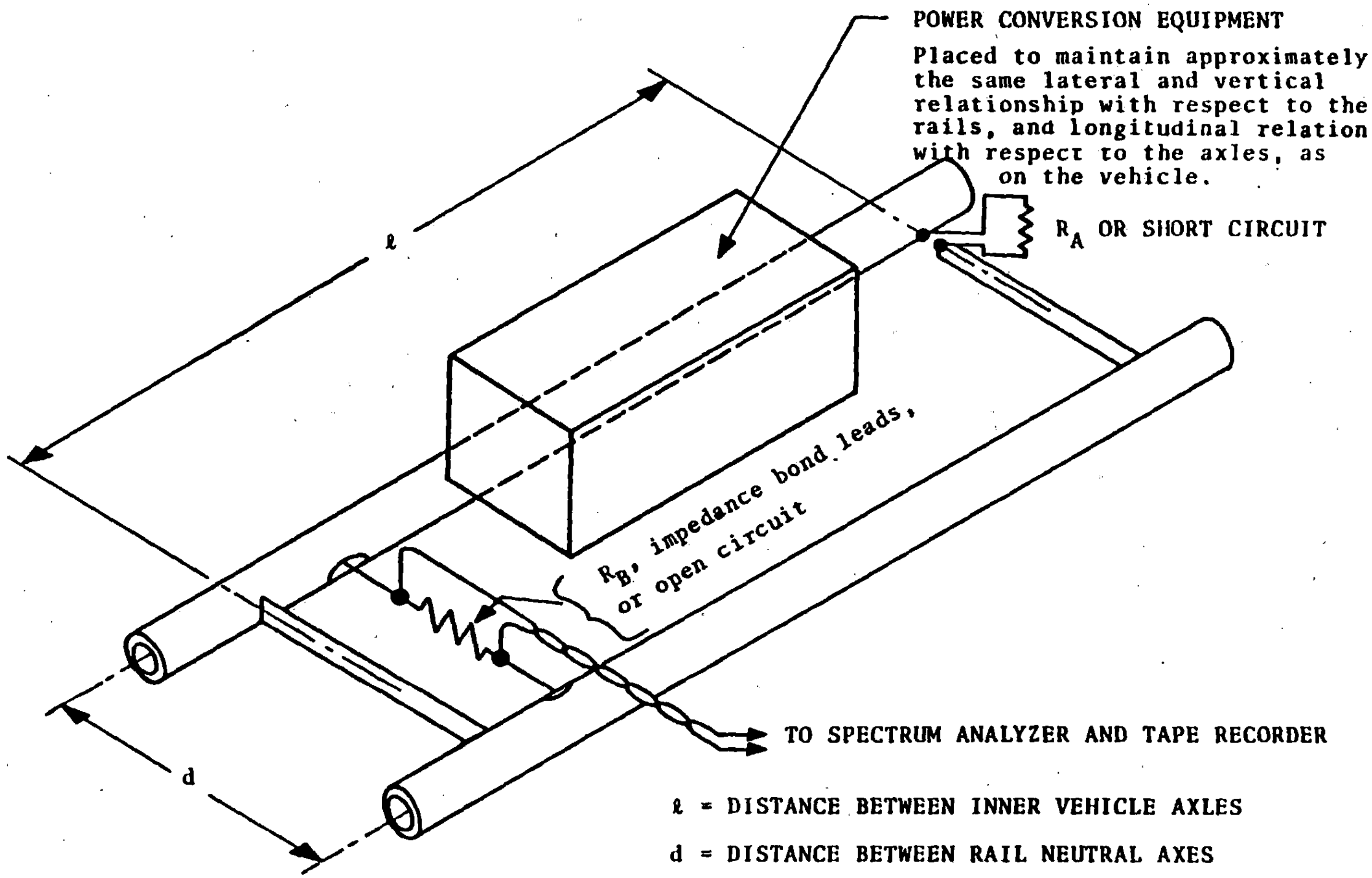


FIGURE 7-7 FIGURE RT/IE04A-1. FROM RECOMMENDED PRACTICE TEST SET-UP

through the U. S. Department of Transportation's Transportation System Center at Cambridge, Mass. The measurement technique involved emulating the running rails and inner axles of the vehicle with aluminum pipe. The power conversion equipment is placed in the same location with respect to the aluminum pipe as it would be with respect to the running rails of the actual vehicle. The power conversion equipment was then operated and the induced EMI was directly measured.

For the case of the AC drive, only half of a car set of equipment was operated in the lab. However, for the case of induced EMI the EMI levels for a whole vehicle can be calculated from the half vehicle measurements. Figure 7-8 shows the undercar layout for the AC drive equipment that could be used on the R44 vehicle on the RR line in New York. As can be seen from Figure 7-8, the inverter equipment is symmeterically located on the car around the lateral center line of the vehicle. It therefore follows that the voltage pattern in the running rails produced by inverters 1 & 2 will be a mirror image of the pattern produced by inverters 3 & 4. The pattern for inverters 3 & 4 was measured, inverted, and added to itself to find the maximum voltage coupling into the rails for a full car set of equipment. For the dynamic brake circuit, there is only one circuit that is modulated and will produce induced EMI. Therefore the dynamic brake induced EMI will not differ for a full car set of equipment.

For power frequency track circuits, there is always an insulated joint at each end of the track circuit. To simulate an insulated joint condition in the lab, one end of the aluminum pipe emulated rail is electrically open circuited.

7.7 INDUCED EMI TEST RESULTS FOR POWER FREQUENCY TRACK CIRCUITS (NYCTA)

The first measurement that was made for power frequency induced EMI was a series of measurements to determine the maximum noise coupling location under the transit vehicle as determined by measurement with the aluminum pipe emulated rail. The results of these measurements is shown in Figure 7-9. These measurements were made while running the inverter at a constant 60 Hz

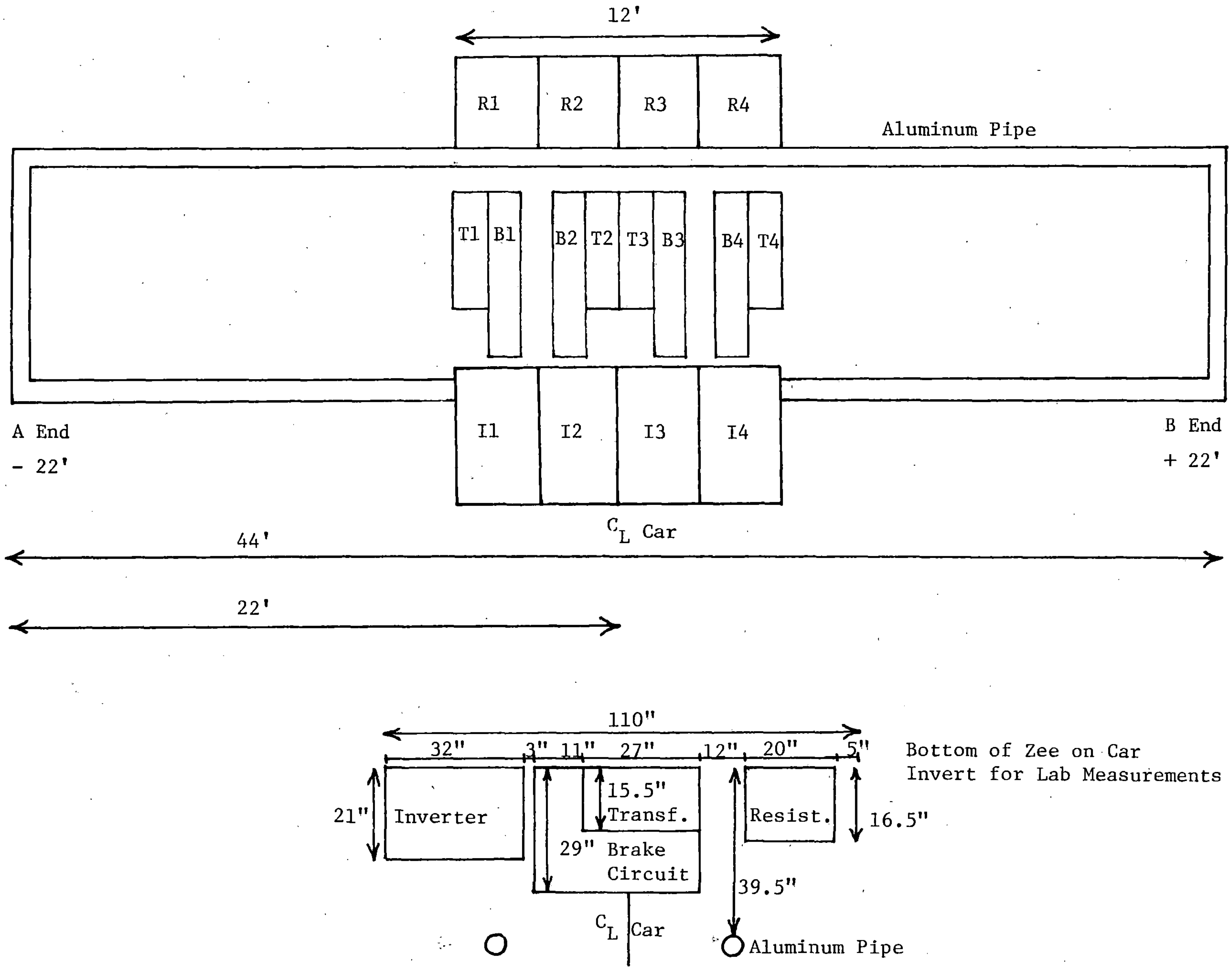


Figure 7-8

Physical Setup for Inducted EMI Measurement

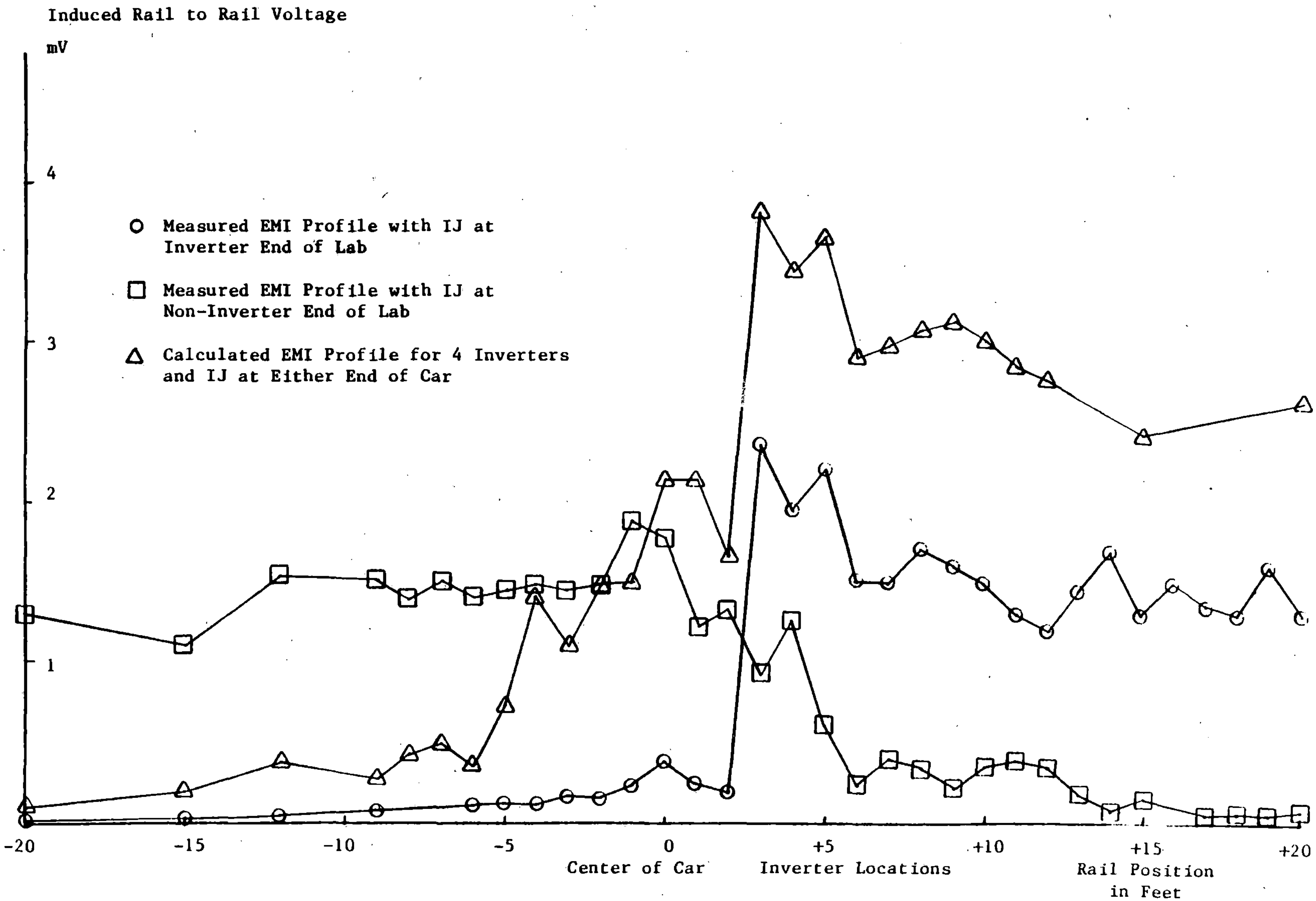


Figure 7-9

Maximum Induced Noise Coupling Position for Power Frequencies and measuring the 60 Hz induced EMI level. The series of measurements marked with circles was made with the aluminum pipe open circuited at the end of the lab setup which contained the propulsion equipment. This is a direct measure of the EMI signature for the two inverters present in the lab setup (Inverters 3 & 4 in Figure 7-8). To determine the contribution from the other two inverters the aluminum rail was open circuited at the opposite end of the lab setup. The series of measurements marked with squares shows these results. If this second set of measurements is inverted with respect to the undercar locations then it would be the same as the induced EMI produced by inverters 1 & 2 with an insulated joint at the inverter 3 & 4 side of the track circuit. This can then be added to the series of measurements marked with circles to yield the total car measurement. The total car calculation for four inverters is show in Figure 7-9 by the line labled with triangles.

The calculated induced EMI curve in Figure 7-9 shows that the maximum noise coupling location for power frequency interference is at the + 3 foot location under the vehicle. It shows how an insulated joint prevents one of the vehicle inner axles from shorting out the EMI as occurs at the inverter 1 & 2 end of the vehicle. It also shows that the measurements for a full car set of equipment can be obtained from the half car setup by taking the half car setup level at the + 3 foot location with the inverter 3 & 4 end of the aluminum pipe open circuited and multiplying by 1.61. This is a technique that was used.

Measurements were next made at the 3 foot location on the aluminum pipe to determine the inverter operating condition that produces the maximum 25 + 60 Hz induced EMI. Measurements were made with 450, 600, and 650 volts line voltage and in both power and brake. The maximum induced EMI measured at 25 Hz was 3.0 mV rms. This occurred with a 650 volt line and during braking. The maximum induced EMI level that was measured at 60 Hz was 9.9 mV rms with a 450 volt line and during braking. The lowest peak 60 Hz EMI level measured during a propulsion run was 7.2 mV rms.

Using the 1.61 multiplier described above the maximum induced EMI at 25 & 60 Hz for a four inverter carset of AC drive equipment would be 4.8 & 15.8 mV rms, respectively. From Table 7.1, it can be seen the minimum 25 Hz interference threshold is 148 mV rms for track circuit 11 and the minimum 60

Hz interference threshold is 800 mV rms for track circuit 2. The occupied case is the only one possible with induced EMI since the vehicle is over the track circuit receiver when the interference occurs. From the above data it can be seen that there is a 29.8 dB (30.8 to 1) positive operating margin for the 25 Hz case and a 34.1 dB (50.6 to 1) positive operating margin for the 25 Hz case and a 52.7 dB (432 to 1) positive operating margin for the 60 Hz case.

In the lab, the maximum noise coupling location under the car for induced EMI from the dynamic brake circuit was found and the maximum noise levels were measured. For 25 Hz the maximum level was 0.6 mV rms and for 60 Hz the maximum level was 1.85 mV rms. This would yield a 47.8 dB (247 to 1) positive operating margin for the 25 Hz case and a 52.7 dB (432 to 1) positive operating margin for the 60 Hz case.

For power frequency track circuits the induced EMI levels do not come close to the levels that would be needed to cause a problem and there is a large operating and safety margin.

7.8 CONDUCTED EMI MODEL FOR AUDIO FREQUENCY TRACK CIRCUITS

For the power frequency track circuits a model was produced to determine the voltage that would be induced into a voltage track circuit from the DC link current levels. For audio frequency track circuits a different type model is used. Since the termination for an audio frequency block is a low impedance bond or shunt the susceptibility of the track circuit receiver is usually expressed in terms of current rather than voltage. The receivers are also transparent to common mode currents in the rails, so the degree of current unbalance becomes a factor as with the double rail voltage track circuits. The magnitude of the interference current from the train, the percentage of this current that is circulated through receiving bond, and the receiver current sensitivity are needed to determine compatibility margins.

The audio frequency conducted EMI model does the following. Each car on a train has an input LC filter. For a given track circuit frequency the attenuation of the filter is computed. Substation and rail impedance cause a percentage of the conducted EMI produced by the vehicle propulsion systems to be circulated between the input filters of the vehicles rather than be conducted back to the susbstation and through the track circuit receiving bonds. The model computes this percentage from the filter, substation, and rail parameters. It is also known that the track circuit receivers are only sensitive to the percentage of ripple current conducted back to the substation that is unbalanced between the two running rails. The model uses an unbalance of 20% which is the highest unbalance that has been measured in the field. For the non-safety case of an unoccupied block it is also proper to assume that the EMI currents produced by the various inverters will not all be in phase. For an eight car train (32 inverters) a multiplier of 46.25% can be used. This factor will only be exceeded 0.1% of the time. For the case of an occupied block the worst case of all inverters in phase should be assumed.

To determine what is needed to achieve compatibility between some of the common audio frequency track circuits now in operation and the AC drive system the following was done. First, the maximum DC link ripple current was measured in the lab for the audio frequency range. Next the above mentioned model was used to compute the current that would be circulated through a receiver bond given the system parameters. Comparing this receiver conducted EMI current to the receiver interference threshold yields the expected EMI margin.

7.9 CONDUCTED EMI TEST RESULTS FOR AUDIO FREQUENCY TRACK CIRCUITS

The AC drive system was operated over a range of input voltages and in both power and brake to determine the maximum DC link inverter currents in the audio frequency range (300 to 10,000 Hz). The output of the Hall effect current transducer was monitored with the digital FFT spectrum analyzer that was used in the power frequency analysis. The spectrum analyzer was used to determinethe maximum frequency components that existed during the inverter operation. As is the case with the power frequency measurements, the DC link measurements include all of the conduced EMI effects that are produced by the regenerative brake circuit. In addition to measuring the conducted EMI from the inverter and regenerative brake circuit the unfiltered conducted EMI produced by the dynamic brake circuit was also measured.

To determine what filtering is necessary to interface with typical audio frequency track circuits measurements at certain frequencies will be analyzed. The audio frequency track circuits manufactured by Westinghouse operate at signalling frequencies above 5000 Hz. Other US signalling manufacturers use audio frequency track circuits in the 2000 - 6000 Hz range. Some applications can use frequencies as low as approximately 1000 Hz. The use of higher frequencies for track signalling has tremendous EMI compatibility advantages because the effectiveness of the input LC filter is increased as the frequency increases.

Listed below are the maximum unfiltered DC link currents that were measured in the lab under any operating conditions.

Frequency (Hz)	1000	2000	5000
Max Unfiltered DC Link Current (A rms)	129	60.9	27.2

Applying the system model for an 8 car train, the current levels conducted through the tract circuit receiving bond are as follows for various input filter inductances. These figures assume the worst case that all of the inverters are in phase. All current levels are in A rms.

Frequency (Hz)	1000	2000	5000
0.7 mh Reactor	.1188	.0208	.00362
0.5 mh Reactor	.1313	.0229	.00339
0.3 mh Reactor	.1474	.0258	.00467
0.1 mh Reactor	.1728	.0302	.00524

Acknowledging the fact that the inverters are all at random phase with respect to each other the following matrix lists the receiving bond currents that will not be exceeded more than 0.1 percent of the time. These figures are satisfactory for unoccupied block compatibility determination where rare interference would only momentarily slow down or stop a train.

Frequency (Hz)	1000	2000	5000
0.7 mh Inductor	.0549	.00962	.00167
0.5 mh Inductor	.0607	.0106	.00184
0.3 mh Inductor	.0682	.0119	.00216
0.1 mh Inductor	.0799	.0140	.00242

Interference thresholds for typical audio frequency track circuits are listed below in A rms for the unoccupied condition. The sensitivity listed in the 2000-3000 Hz range is the most sensitivity circuit known to Westinghouse in this frequency range. Another manufacturer's track circuit sensitivity is always greater than .030 V rms in this same frequency range.

			Westinghouse
Frequency (Hz)	1000	2000-3000	5000
Unoccupied INterference Threshold (V rms)	.060	.020	.017

For the case of an occupied block the typical interference sensitivities are as shown below.

			Westinghouse
Frequency (Hz)	1000	2000-3000	5000
Occupied Interference Threshold (V rms)	.120	.033	False Occupacy or False Cab Not possible

In summary the following can be said. First, it is evident that conducted EMI compatibility between AC drive propulsion systems and the Westinghouse track circuits is a simple matter. The higher frequencies used makes the LC filter very effective and the two frequency six bit code used makes the circuits immune to false pickup. For the case of the other signalling manufacturers, compatibility can be seen to be achievable with the proper input filter.

The unfiltered ripple current from the dynamic brake circuit is as listed below for one car.

Frequency (Hz)	1000	2000	5000
Max Unfiltered DC Link Current A rms)	19.2	7.22	3.42

Applying the system model for an 8 car train, the current levels conducted through the track circuit receiving bond are as follows for various input filter inductances. These figures assume the worst case that all of the dynamic brake circuits are in phase. All current levels are in A rms.

Frequency (Hz)	990	1590	2000	5000
0.7 mh Inductor	.00442	.00092	.00062	.00011
0.5 mh Inductor	.00489	.00101	.00068	.00013
0.3 mh Inductor	.00548	.00114	.00077	.00014
0.1 mh Inductor	.00643	.00133	.00090	.00016

Comparing the conducted EMI produced by the dynamic brake circuit with the various track circuit sensitivities, one can readily see that the dynamic brake circuit produces no possible conducted interference in any case.

7.10 INDUCED EMI TEST PROCEDURE FOR AUDIO FREQUENCY TRACK CIRCUITS

To measure the rail to rail induced EMI voltage produced by the AC drive propulsion system the same measurement technique was used as was used for the power frequency induced EMI measurements. The only difference between the two tests was the frequencies that were measured and the continuous rail case that is possible with audio frequency circuits.

7.11 INDUCED EMI TEST RESULTS FOR AUDIO FREQUENCY TRACK CIRCUITS

Figures 7-10 and 7-11 show the results of measurements made to find the audio frequency peak induced EMI noise location under the vehicle. The results in Figure 7-10 are for the case of an insulated joint and here the EMI that would be produced by a four inverter setup is calculated from the two inverter set up results in the same manner as described in Section 7.7. Figure 7-11 shows the induced EMI profile if the track circuit receiver is not at an insulated joint. This is the more common case with audio frequency track circuits where insulated joints are usually only needed at interlockings. Comparing the EMI levels in Figures 7-10 and 7-11, one can see that the insulated joint case is the worst case.

Based on the data shown in Figure 7-10, to find the worst case induced EMI for a full four inverter set of equipment, measurements are taken at positions approximately one foot from the inverter equipment, with the inverter end of the emulated rail open to simulate an insulated joint. The measured values are then multiplied by 1.81 to account for the contribution of the two missing inverters.

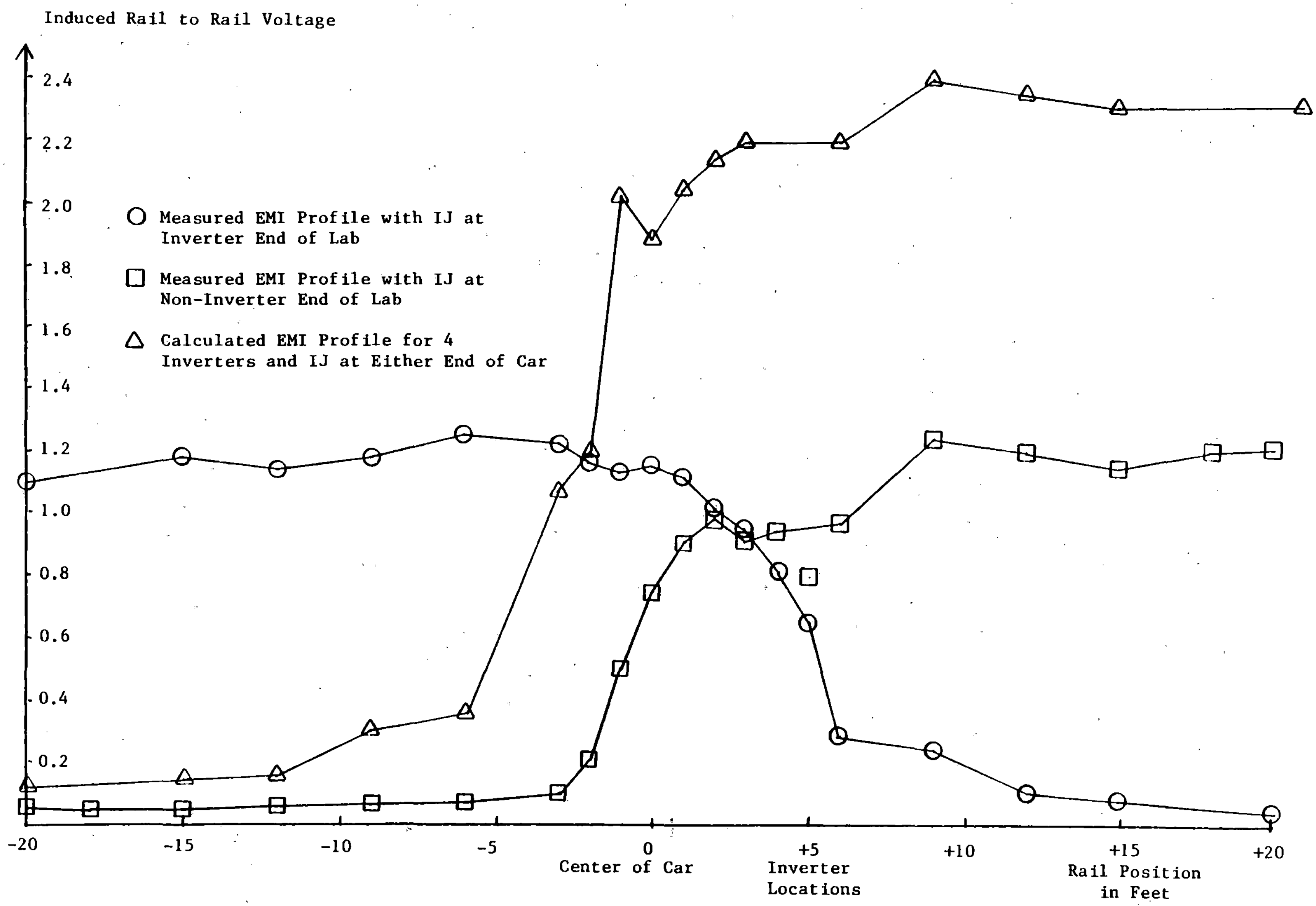


Figure 7-10
Maximum Induced Noise Coupling Position for Audio Frequencies

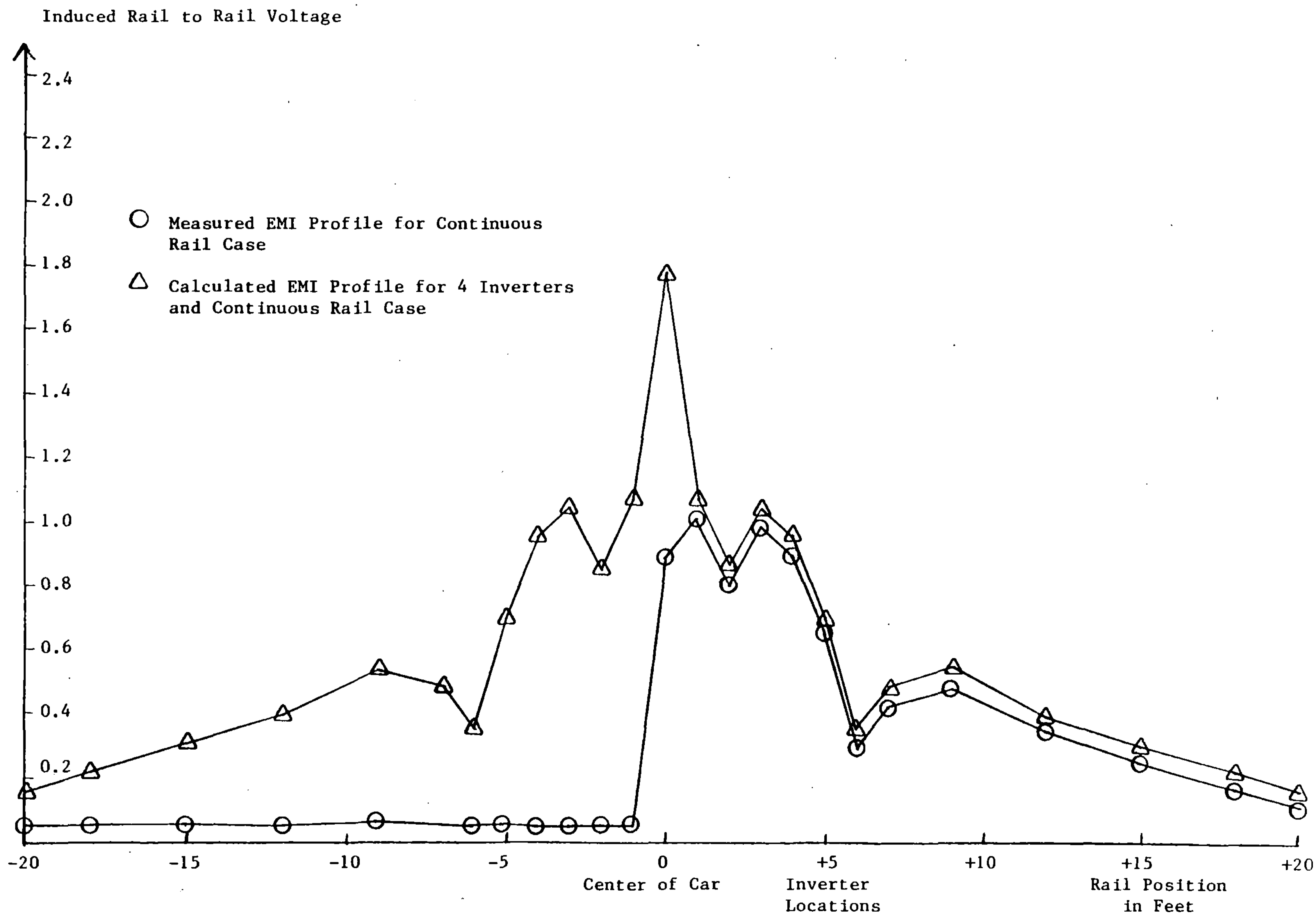


Figure 7-11

Maximum Induced Noise Coupling Position for Audio Frequencies

The maximum induced EMI occurred two feet from the center line of the vehicle setup and measured 8.0 mV rms or less at frequencies above 2000 Hz. Multiplying by 1.81 to determine the maximum induced EMI above 2000 Hz for a full car set of equipment yields 14.5 mV rms.

For the Westinghouse track circuits induced EMI can not cause a false occupancy due to the character of the six bit two frequency code that must be received. A second US signalling manufacturer has also produced a track occupancy receiver that is immune to false pickup by checking the character of the modulation of the received track signal as well as its carrier frequency.

Of the three signalling systems being investigated here only one system has the potential for interference from induced EMI. The sensitivity of these track circuits is approximately 11.5 mV rms in the worst case condition. With an induced EMI level of .0145 V rms calculated for the insulated joint case and a full car set of equipment, one can see that interference is possible. However, there are steps that could be taken to achieve compatibility. The induced EMI levels measured may be due to the reactors used to limit di/dt in the inverters. If this is the case a toroidal reactor design could reduce the EMI levels. Also, the sensitivity listed above for the most sensitive track circuit to induced EMI is with its input amplifier at its maximum gain. This amplifier gain is not needed at insulated joint locations so receiver hardware could be used that would have a lower maximum amplifier gain. Simulating a continuous rail situation in the lab yielded maximum induced EMI of .005 V rms for the two inverters or .010 V rms for the full four inverter set of equipment. This level is near but below the sensitivity of the track circuits.

The induced EMI produced by the dynamic brake circuit was also measured in the lab. The EMI produced by the dynamic brake circuit does not sweep frequency as is the case with the inverter but it does employ pulse skipping in the control scheme. By selecting the proper dynamic brake chopper frequency the main harmonics of the EMI can be made to fall outside the pass band of the track circuit receiver filters. The pulse noise may fall in the pass band of the track circuit receivers but it will do so at a level that is one half of the adjacent main harmonics. The maximum main harmonic that was measured above 2000 Hz in the lab was .0094 V rms. The maximum in band noise would be .0047 V rms. This is less than half of the induced EMI receiver sensitivity.

The dynamic brake circuit will therefore not be a source of induced EMI problems.

7.12 CONCLUSIONS

The half car setup of equipment that was operated in the West Mifflin power lab was tested to determine whether or not the Westinghouse AC drive propulsion system could be used compatibly with track signalling systems already in existence. Particular attention was made to the NYCTA power frequency voltage track circuits, but measurements were also made that show the compatibility situation for audio frequency track circuits. The results of these measurements were compared with the susceptibility levels of various types of audio frequency track circuits. Westinghouse is familiar with these various track circuits through prior successful EMI management programs with chopper control equipment. Both conducted and induced EMI was investigated.

For the case of conducted EMI and the power frequency track circuits used at NYCTA, a computer model was used in conjunction with lab measurements that used actual NYCTA track circuit hardware. The results of the testing showed a positive 1.8 to 1 margin with even the most sensitive NYCTA track circuit.

For the case of induced EMI and the power frequency track circuits used at NYCTA, there was found to be at least a 30 to 1 positive system operating and safety margin.

For the case of conducted EMI and audio frequency track circuits, it was found that compatibility with the Westinghouse track circuits was very easy. For the signalling used by another US manufacturer compatibility can be achieved with no special filtering. For the signalling at frequencies below 2000 Hz used by a third manufacturer compatibility is more difficult to achieve and requires further analysis. However, even in these cases compatibility appears to be possible.

For the case of induced EMI with audio frequency track circuits, the Westinghouse track circuits and those produced by another manufacturer are immune to interference by their very nature. The third track circuits being investigated have interference thresholds at the same general level as the AC drive is now producing under worst case conditions. There are design changes that could be made to achieve compatibility in this area.

From the analysis that has been performed it is believed that it is possible to operate an AC drive propulsion system in existing transit systems with full EMI compatibility if the proper EMI system design techniques are followed.

TABLE 7-1

NYCTA TRACK CIRCUIT CHARACTERISTICS

#	Make	Freq (Hz)	Type	Unoccupied Susceptibility V rms	Occupied Susceptibility V rms
1	US&S	60	Single rail Vane relay Matching transformer	0.4	2.0
2	GRS	60	Single rail Rotor relay Balancing reactor	0.4	0.8
3	US&S	60	Single rail Vane relay Balancing reactor	0.5	1.4
5	US&S	60	Single rail Vane relay Capacitor type	0.7	1.4
6	GRS	60	Single rail Vane relay Matching transformer	1.4	1.3
7	GRS	60	Single rail Vane relay Capacitor type	1.5	3.1
8	US&S	60	Single rail Vane relay Matching transformer	0.6	1.8
12	US&S	60	Single rail Vane relay Shielding reactor	0.4	1.85
13	US&S	60	Single rail Vane relay Shielding reactor	3.01	2.32
14	US&S	60	Single rail Vane relay Shielding reactor	2.18	1.68
17	US&S	60	Single rail Vane relay Matching transformer	0.4	2.0
4	US&S	60	Double rail Vane relay Matching transformer	0.5	1.3
9	GRS	60	Double rail Vane relay Matching transformer	0.5	1.3
10	GRS	25	Single rail Rotor relay Balancing reactor	0.9	1.0
15	US&S	25	Single rail Vane relay Resistor type	3.5	3.6
16	US&S	25	Single rail Vane relay Resistor type	0.5	1.8
11	GRS	25	Double rail Rotor relay Direct relay receiver	0.072	0.148

8. RELIABILITY STUDY

During Phase I of the Westinghouse AC Drive Development Program, Booz, Allen provided periodic updates of a reliability estimate for the equipment. A reliability block diagram was constructed and a special study conducted to estimate failure rates for the new Gate Turn Off Thyristors (GTOs). Failure rate data was gathered from sources such as MIL Handbook 217D, the BARTD management information system and Westinghouse field failure reports. The initial reliability prediction was presented at the Preliminary Design Review and updates were provided at subsequent quarterly reviews. A formal report was submitted at the scheduled end of Phase I. That report was dated February 27, 1984. The purpose of these reliability analyses was to provide guidance to the electrical designers and for estimation of corrective maintenance costs in the Economic Analysis.

Since the February 1984 report, Westinghouse has made a number of changes that impact estimated reliability. These changes include:

- Substantial redesign of the GTO gate drive circuits
- A decision to procure integrated circuits to quality level B-1 (rather than B-2)
- Removal of additional regeneration circuitry in view of its inapplicability to NYCTA RR line operations.
- Introduction of a 2-inverter-per-car configuration as an alternative, made possible by the commercial availability of higher-current-rating GTO devices and by the elimination of restrictive wheel mismatch criteria as supported by the DOT analysis of NYCTA maintenance operations.

This report updates the final reliability estimates to accommodate the changes listed above.

The remainder of the report is organized into the following sections:

- Summary
- Component failure rates
- Assembly failure rates
- Schedule reliability
- Conclusions and recommendations

8.1 SUMMARY

The Contractual Specification established the following reliability goals for the propulsion system:

Schedule Reliability: .999

Subsystem	Mean Distance Between Failures (MDBF)
Traction Motors	1,500,000 miles
Static Inverters	50,000 miles
Propulsion System Controls	50,000 miles

The reliability estimates have a fairly wide band as a result of factors that include:

1. The Gate-Turn-Off Thyristor (GTO), a device that is used extensively in the Westinghouse AC Drive design, is a recent development and definitive field reliability information is not available.

2. The "Ground Mobile" environment of MIL-HDBK-217D, mandated as a reliability prediction basis, does not appear to be fully applicable to steel-wheel-on-steel-rail transportation conditions.

3. In the absence of available operational data on totally enclosed AC induction motors in transit applications, the reliability estimates have been derived from data on conventional DC traction motors by deleting only those failures that were clearly DC-specific. The achieved reliability is likely to be higher.

Nevertheless, the reliability estimates show that the schedule reliability goals will be surpassed, that some of the subsystem MDBF goals are attainable, and that the (implied) system MDBF goal will be approached, especially in a 2-inverter-per-car configuration.

To illustrate the issue of choice of environmental factors, Westinghouse performed a MIL-HDBK-217D (parts count method) reliability estimate for three electronic packages: microcomputer, gate pulse amplifier, and analog input boards. The packages are used on SEPTA and are similar to AC Drive functions. Field failure frequency at SEPTA was found to be 55 percent of predicted values, indicating that the use of the Ground, Mobile environment leads to excessively pessimistic predictions and supporting the use of a compromise between the Ground, Mobile and Ground, Fixed factors. The use of the arithmetic mean of the factors for these two environments typically leads to failure rates slightly over one-half of the Ground, Mobile results.

Throughout the reliability estimates of this report, two sets of values -- "Baseline" and "Modified" -- are presented. For devices with failure rates determined by MIL-HDBK-217D methods alone, these values correspond to the Ground, Mobile and the compromise environment respectively. For items with directly pertinent transit experience, the baseline values are the most pessimistic and the modified values the least pessimistic. For the reasons noted above, the spread in failure rate estimates for GTOs and for traction motors is relatively large. A detailed analysis of GTO reliability considerations has been presented in a separate report.

Simulation runs for the NYCTA RR line have shown that an eight-car train will experience end-to-end delays of less than 90 seconds, and thus less than the one-half peak-period headway loss associated with the schedule reliability goal, as a result of tractive-effort reduction equivalent to the loss of seven or fewer axles. The delays are, for example, 79.9 seconds with seven axles out and 41.4 seconds with four axles out. The probability of losing more than four axles is extremely small: 0.000022 for the baseline case, 0.000004 for the modified, in the 4-inverter-per-car configuration, and less than that in the alternative. Since the AC Drive design provides for automatic cut-out of any failed axle or car, and therefore no delays are expected from corrective action, the schedule reliability goal is surpassed by a substantial margin.

MDBF estimates are displayed in Figure 8-1. Although only the modified values for propulsion system controls are very near the goals, it seems clear that satisfactory reliability levels are attainable for the AC Drive system as a whole.

8.2 COMPONENT FAILURE RATES

Failure rates used in AC Drive reliability estimates and the Economic Analysis are displayed in Figures 8-2,a and 8-2,b. For devices that are not peculiar to rail transit applications, the failure rate estimates were, with a few exceptions, derived from standard handbook sources, for example MIL-HDBK-217D. For specific rail transit components, data was provided by Westinghouse Transportation Division on previous applications of their equipment.

In Figures 8-2,a & b, both a "Baseline" and a "Modified" set of failure rates are provided. For the handbook-based failure rates, the Baseline estimates reflect the "Ground, Mobile" (G_M) environment as represented in the "Parts Count Reliability Prediction" method* of MIL-HDBK-217D; these estimates have been updated to correspond to Notice 1 (13 June 83) to the Handbook. The Modified estimates for handbook-based failure rates have the same source, but reflect the arithmetic means of the rates for the G_M and G_F ("Ground, Fixed") environments. The historical failure rates include data from the Bay Area Rapid Transit District (BARTD), the Sao Paulo Metro (SP), and the analyses for the Miami/Baltimore joint procurement (M/B) cars; the higher of the estimates appears in the Baseline column, the lower in the Modified column, and the intermediate (if applicable) under Remarks.

No specific failure rates are shown in Figure 8-2,a for integrated circuits, as the estimates vary depending on device complexity (e.g., gate count) and technology (bipolar vs. MOS); specific values are shown for each device type in the summary tables for the functional assemblies.

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* The "Part Stress Analysis" method is used for the GTO Gate Drivers, since more detailed data were available for this recently redesigned assembly.

RELIABILITY SUMMARY

	Mean Distance Between Failures (MDBF) Miles		
	Baseline Estimate	Modified Estimate	Goal
TRACTION MOTORS (4 Motors, 4 Gear Units)	250,000	1,000,000	1,500,000
INVERTERS			
• 4 Inverters per Car (4 Inverters, 24 Gate Drives, Dynamic Braking Circuit, 2 Resistor Banks)	10,300	20,000	50,000
• 2 Inverters per Car (2 Inverters, 12 Gate Drives, Dynamic Braking Circuit, 2 Resistor Banks)	20,000	38,000	
PROPULSION SYSTEM CONTROLS			
• 4 Inverters per Car (Car Computer, Knife Switch, Line Switch, Line Reactor, Filter Capacitor Box, 4 Motor Control Logic Units)	25,000	47,000	50,000
• 2 Inverters per Car (Car Computer, Knife Switch, Line Switch, Line Reactor, Filter Capacitor Box, 2 Motor Control Logic Units)	28,700	56,000	
TOTAL FOR PROPULSION SYSTEM			
• 4 Inverters per Car	7,100	13,800	24,600
• 2 Inverters per Car	11,300	22,300	

FIGURE 8-1

COMPONENT FAILURE RATES

Device Type 1. Handbook-Based	Baseline Value	Modified Value	Remarks
Integrated Circuit	various	various	B-1 quality level
Capacitor, Ceramic	.089	.0535	JAN
Electrolytic, Al	1.7	.96	JAN
Ta	.055	.0345	JANTX (M level)
Paper/Plastic	.17	.1095	JAN
Crystal	.2	.2	
Diode, Gen. Purpose	.0038	.0022	JANTX
Rectifier, Power	.095	.055	Commercial
Zener	.0126	.0075	JANTX
Fuse	.1	.1	
GTO	7.96	.471	See GTO Reliability Report
Inductor/Transformer	.37	.25	MIL
Optical Coupler	.52	.288	JANTX
Resistor, Film	.054	.0325	JAN
Network	.47	.2785	MIL
Power	.75	.435	JAN
Shunt	.0167	.0167	
Thyristor	.66	.3	JAN
Transistor, PNP	.02	.012	JANTX
Power	1.8	1.09	JANTX

FIGURE 8-2,a

Device Type

2. Historical	Baseline Value	Baseline Source	Modified Value	Modified Source	Remarks
Brake Resistor	14.4	M/B	9.76	BART	per 36-tube bank
Gear Unit/Coupler	5.83	M/B	.39	BART	5.69 Sao Paulo (SP)
Knife Switch Box	8.64	M/B	.82	SP	
Line Reactor	1.24	M/B	.79	BART	
Line Switch Box	99.79	BART	20.02	SP	36.05 M/B
Traction Motor	7.56	SP	2.7	BART	DC-peculiar failures excluded; BART data on rewound motors; M/B prediction 34.14 including DC failures

NOTES:

- All failure rates are in failures per million hours.
- For handbook-based (MIL-HDBK-217D, Notice 1) values, Baseline reflects Ground Mobile (G_M) environment, Modified reflects arithmetic mean of G_M and Ground Fixed (G_F) environments. (For GTO's, the modified environment has been applied to a failure rate prediction based on an Arrhenius model.)
- Except in the GTO and GTO Gate Driver cases, handbook-based values involve the Parts Count method of prediction.

FIGURE 8-2,b

The GTO (Gate-Turn-Off Thyristor) failure rate estimates reflect more detailed stress analysis for the Baseline and a combination of MIL-HDBK-217D environmental factors with a base failure rate derived from an Arrhenius model for the Modified value. The unusually large spread between the estimates for this device is indicative of the effects of its novelty. The detailed analysis has been presented in a separate report.

8.3 ASSEMBLY FAILURE RATES

Figure 8-3 lists the device types and quantities used in the car control computer and presents the Baseline and Modified failure rate contributions (device failure rate x quantity) for each of these. The ratio of Modified to Baseline failure rates for the car control computer is 0.67. The upgrading of integrated circuit quality level to B-1 has improved the MTBF by 75 percent compared to the Final Estimates of the February 1984 report.

Results for the remaining assemblies are presented in Figures 8-4 through 8-8. With the elimination of the separate regenerative braking circuits, the filter capacitors and associated bleeder resistors were moved to a new Filter Capacitor Box. Figure 8-8 effects these changes.

8.4 SCHEDULE RELIABILITY

For purposes of schedule reliability computation, propulsion equipment must be categorized to correspond to failure effects on tractive effort. On some properties, braking effort may be the limiting factor on achievable or allowable speed; this is not the case on the NYCTA RR line. We define as axle-specific that equipment whose failure effectively removes the tractive-effort contribution of one axle,and as car-specific that whose failure results in propulsion cut-out of the entire car. In most designs, there exists an intermediate category that may be called truck-specific; i.e., equipment whose failure removes the tractive-effort contribution of both axles on one truck. The computer program (ACRS) used for schedule reliability evaluation provides for that category, which here applies only to the 2-inverters-per-car configuration.

FAILURE RATE TABULATION
CAR CONTROL COMPUTER

Quantity	Device Type	Failure Rate Contribution (Failures per Million Hours) Baseline	Modified
1	Microprocessor	1.98	1.43
1	Multifunction Peripheral	2.07	1.47
2	EPROM	5.29	3.83
2	Static RAM	6	4.32
2	Programmable Timer	.12	.31
4	Latch	.58	.45
2	2-Way Buffer	.17	.13
4	1-Way Buffer	.34	.26
4	VCO	2.4	1.71
6	Decoder	.5	.4
3	Counter	.32	.26
4	PAL	.34	.26
1	Driver	.08	.06
1	Receiver	.11	.09
2	Bus Transceiver	.17	.13
2	3-State Buffer	.17	.13
2	Inverter Buffer	.17	.13
2	Flip-Flop	.17	.13
2	NOR	.17	.13
1	Register	.11	.09
1	Dual Multivibrator	.08	.06
5	Output Module	2.64	1.59
2	MUX	.17	.13
1	Op Amp	.21	.15
7	DAC	4.2	2.99
1	ADC	.11	.09
1	Transistor Array	.21	.15
82	Capacitor, Ceramic	7.3	4.39
24	Capacitor, Electrolytic, Ta	1.32	.83
2	Crystal	.4	.4
16	Diode	.06	.04
1	Diode, Zener	.01	.01
6	Optical Coupler	3.12	1.73
12	Resistor	.65	.39
12	Resistor Network	5.64	3.34
2	Connector	.72	.17
	TOTAL	48.4	32.21

FIGURE 8-3

FAILURE RATE TABULATION
DYNAMIC BRAKING CIRCUIT

Quantity	Device Type	Failure Rate Contribution (Failures per Million Hours) Baseline	Modified
4	Capacitor, Paper/Plastic	.68	.44
12	Diode, Rectifier	1.14	.66
4	GTO	31.84	1.88
4	Inductor	1.48	1
8	Resistor, Power	6	3.48
7	Shunt	.07	.07
	Sub-total	41.21	7.53
4	GTO Gate Drives	108.32	67.52
	TOTAL	149.53	75.05

FIGURE 8-4

FAILURE RATE TABULATION
MOTOR CONTROL LOGIC

Quantity	Device Type	Failure Rate Contribution (Failures per Million Hours) Baseline	Modified
1	Microprocessor	1.98	1.43
1	Multifunction Peripheral	2.07	1.47
2	EPROM	5.29	3.83
2	Static RAM	6	4.32
5	Programmable Timer	1.05	.77
1	Dual Port RAM	3	2.16
4	AND	.34	.26
2	Latch	.29	.23
2	2-Way Buffer	.17	.13
4	1-Way Buffer	.34	.26
2	VCO	1.2	.85
2	Decoder	.17	.13
1	Counter	.11	.09
4	PAL	.34	.26
1	DAC	.6	.43
2	Op Amp	.42	.31
1	Driver	.08	.06
1	Receiver	.11	.09
50	Capacitor	4.45	2.68
2	Crystal	.4	.4
4	Diode	.02	.01
84	Resistor	4.54	2.73
2	Transistor	.04	.02
2	Connector	.72	.17
	TOTAL	33.71	23.1

FIGURE 8-5

FAILURE RATE TABULATION
GTO GATE DRIVER

Quantity	Device Type	Failure Rate Contribution (Failures per Million Hours) Baseline	Modified
	Logic Assembly*		
1	Quad Comparator	.1838	.1466
1	Quad OP-AMP	.532	.4243
1	+6.25 Reference Chip	.062	.0494
1	+5 Volt Regulator	.0661	.0527
1	+12 Volt Regulator	.0642	.0512
1	-12 Volt Regulator	.0724	.0577
3	CMOS 556 Timer	.2235	.1783
1	HEX Buffer	.0768	.0612
1	Tri AND Gate	.0734	.0586
3	Quad NAND Schmitt	.2235	.1783
1	HEX Inverter Schmitt	.0768	.0612
2	HEX Inverter	.1536	.1225
2	Diode	.0029	.0019
12	Diode	.0171	.0114
1	19V, 5W Zener Diode	.0086	.0057
1	Opto-Isolator	.0451	.0295
1	Opto-Isolator	.0451	.0295
1	511 OHM, .25W Glass Resistor	.0374	.0244
1	14.7K, .25W Glass Resistor	.0273	.0179
42	1/8W Glass Resistor	.8526	.5076
2	5.1 OHM,.25W Carbon Resistor	.0312	.021
2	3 Resistor DIP	.1549	.1013
2	10PF Ceramic Capacitor	.006	.0036
9	47PF Ceramic Capacitor	.0318	.0191
1	82PF Ceramic Capacitor	.0038	.0023
2	1800PF Ceramic Capacitor	.0105	.0064
1	3300PF Ceramic Capacitor	.0056	.0034
4	4700PF Ceramic Capacitor	.0236	.0142
6	.01UF Ceramic Capacitor	.0382	.023
1	.033UF Ceramic Capacitor	.0073	.0044
2	100UF-30V Electrolytic Cap	1.4156	.8439
4	1UF Tantalum Capacitor	.6338	.4143
4	1UF Ceramic Capacitor	.0422	.0255
15	.1UF Decoupling Capacitor	.0955	.0575
	Subtotal	5.3442	3.6098

FIGURE 8-6,a

FAILURE RATE TABULATION
GTO GATE DRIVER

Quantity	Device Type	Failure Rate Contribution (Failures per Million Hours) Baseline	Modified
	Power Assembly*		
1	Darlington Transistor Array	.0721	.0575
1	PNP Transistor	.0013	.0009
1	PNP Darlington Transistor	.0183	.0121
1	PNP Darlington Transistor	.0194	.0128
1	HEX FET	.0361	.0239
1	PNP Transistor	.0009	.0006
1	NPN Darlington Transistor	.0062	.0041
1	Diode	.0222	.0147
1	6.8V, .5W Zener Diode	.0086	.0057
1	Thyristor	.1783	.1023
1	1.5 OHM, 5W Resistor	.2328	.1375
1	1 OHM, 25W Resistor	.1551	.0916
1	61.9 OHM, 1/2W Glass Resistor	.0294	.0192
1	215 OHM, .75W Glass Resistor	.0429	.028
16	1/8W Glass Resistor	.5709	.3733
1	51 OHM, 2W Carbon Resistor	.0149	.01
1	16VDC-350UF Electrolytic Capacitor	.5696	.3418
1	1UF Ceramic Capacitor	.0107	.0065
3	4100UF Capacitor	1.3704	.8223
	Subtotal	3.3601	2.0648
	Power Supply**		
1	Unit	18.38	11.21
	Subtotal	18.38	11.21
GTO GATE DRIVER TOTAL		27.08	16.88

* Part Stress Analysis method of MIL-HDBK-217D used for this assembly.

** Single prediction based on Ground Mobile (G_M) conditions provided by supplier; Modified prediction obtained by using multiplier of 0.61 derived from power assembly results.

FIGURE 8-6,b

FAILURE RATE TABULATION
INVERTER

Quantity	Device Type	Failure Rate Contribution (Failures per Million Hours) Baseline	Modified
36	Capacitor, Electrolytic, Al	61.2	34.56
6	Capacitor, Paper/Plastic	1.02	.66
17	Diode, Rectifier	1.62	.94
2	Fuse	.2	.2
6	GTO	47.76	2.83
4	Inductor	1.48	1
9	Resistor	.49	.29
49	Resistor, Power	36.75	21.32
6	Shunt	.1	.1
	TOTAL	150.62	61.9

FIGURE 8-7

FAILURE RATE TABULATION
FILTER CAPACITOR BOX

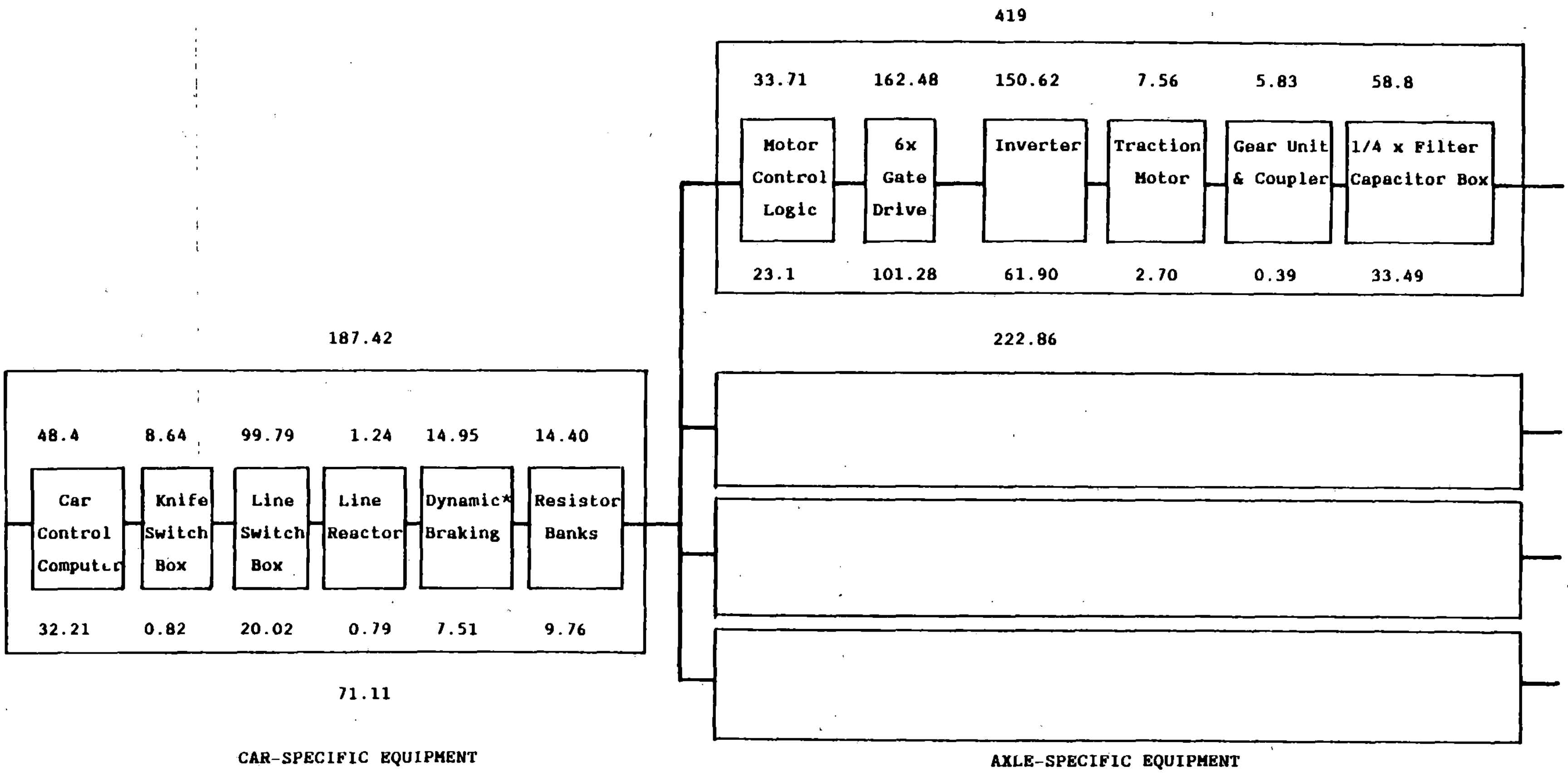
Quantity	Device Type	Failure Rate Contribution (Failures per Million Hours) Baseline	Modified
96	Capacitor, Electrolytic, Al	163.2	92.16
96	Resistor, Power	72	41.8
	TOTAL	235.2	133.96

FIGURE 8-8

The block diagrams in Figure 8-9,a and 8-9,b identify all equipment in each category. With one exception, each equipment item is labeled with the corresponding Baseline and Modified failure rates as developed in the preceding tables; the totals for the car-specific equipment and the axle-specific equipment (per axle) also are shown. The exception is the dynamic braking circuit, which has failure rates scaled to the duty cycle, approximately ten percent, associated with the RR line simulation. Since field failure rates are the source of the estimates for other components, such as braking resistors, that are subject to low duty cycles, the scaling is implicitly effected in the tabulated estimates for these.

Although the filter capacitor box is a single physical entity, the effects are represented better by allocating the capacitors among inverters, as multiple failures must occur before more than one inverter is incapacitated.

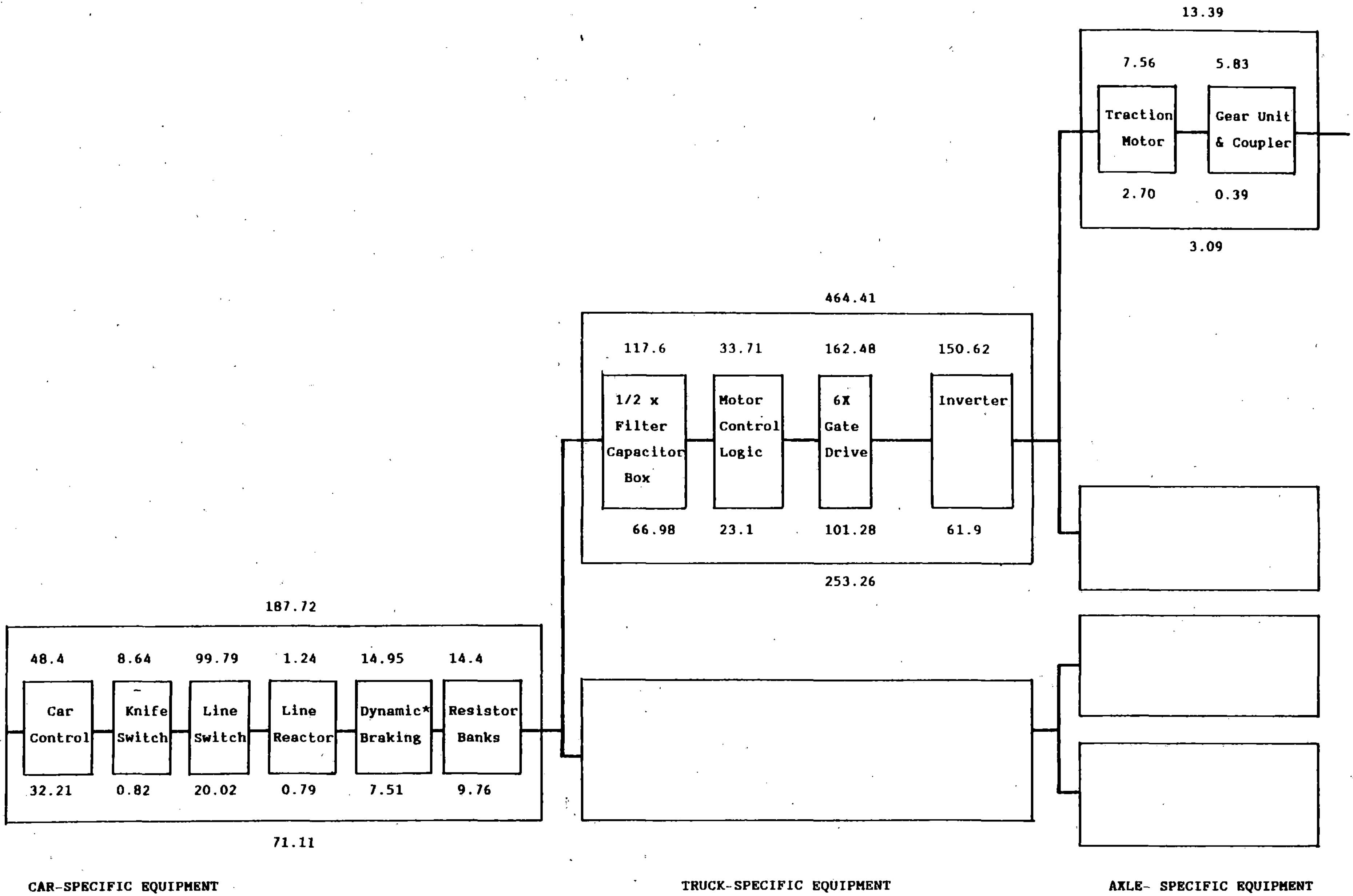
The ACRS program accepts the failure rate estimates as inputs, calculates the occurrence probability for each type of failure event for a run of the scheduled nominal end-to-end duration on the RR line, and then sums these probabilities over all combinations leading to 0, 1, 2, 3 and 4 axle outages. The results are presented, as in Figure 8-10,a and 8-10,b, as cell-by-cell and cumulative probabilities for a car and for an eight-car consist of AC Drive-equipped cars in the 4-inverters-per-car and 2-inverters-per-car configurations. The delays associated with each level of outage are determined separately from simulation results; no outage of as many as 4 axles results in the loss of half a peak-period headway on the NYCTA RR line. It thus is evident that either configuration will surpass the schedule reliability goal by a wide margin.



* Dynamic Braking subjected to 10 percent duty cycle

FIGURE 8-9,a

BLOCK DIAGRAM FOR SCHEDULE RELIABILITY COMPUTATIONS
(4 Inverters Per Car)



* Dynamic braking subject to 10 percent duty cycle

FIGURE 8-9,b

BLOCK DIAGRAM FOR RELIABILITY COMPUTATIONS
(2 Inverters Per Car)

AXLE OUTAGE PROBABILITIES
(4 Inverters Per Car)

Program ACRS
8-Car Train State Probabilities

Failrates Per Million Hours

Axle-Specific	Truck-Specific	Car-Specific
419.00	0.00	187.42

	Car		8-Car Train	
Axles Out	Prob	Cum	Prob	Cum
0	0.998D+00	0.997983	0.984D+00	0.983978
1	0.181D-02	0.999796	0.143D-01	0.998276
2	0.123D-05	0.999797	0.101D-03	0.998376
3	0.374D-09	0.999797	0.333D-06	0.998377
4	0.203D-03	1.	0.160D-02	0.999978

(A) BASELINE

Program ACRS
8-Car Train State Probabilities

Failrates Per Million Hours

Axle-Specific	Truck-Specific	Car-Specific
222.86	0.00	71.11

	Car		8-Car Train	
Axles Out	Prob	Cum	Prob	Cum
0	0.999D+00	0.998958	0.992D+00	0.991691
1	0.965D-03	0.999923	0.766D-02	0.999355
2	0.350D-06	0.999923	0.287D-04	0.999384
3	0.563D-10	0.999923	0.505D-07	0.999384
4	0.770D-04	1.	0.612D-03	0.999996

(B) MODIFIED

FIGURE 8-10,a

AXLE OUTAGE PROBABILITIES
(2 Inverters Per Car)

Program ACRS
8-Car Train State Probabilities

Failrates Per Million Hours

Axle-Specific	Truck-Specific	Car-Specific
13.39	464.41	187.42

	Car		8-Car Train	
Axles Out	Prob	Cum	Prob	Cum
0	9.999D+00	0.998733	0.990D+00	0.989913
1	0.581D-04	0.998792	0.461D-03	0.990374
2	0.101D-02	0.999797	0.797D-02	0.998344
3	0.292D-07	0.999797	0.232D-06	0.998344
4	0.203D-03	1.	0.167D-02	1.

(A) BASELINE

Program ACRS
8-Car Train State Probabilities

Failrates Per Million Probabilities

Axle-Specific	Truck-Specific	Car-Specific
3.09	253.26	71.11

	Car		8-Car Train	
Axles Out	Prob	Cum	Prob	Cum
0	0.999D+00	0.999361	0.995D+00	0.994900
1	0.133D-04	0.999374	0.106D-03	0.995006
2	0.549D-03	0.999923	0.437D-02	0.999375
3	0.366D-08	0.999923	0.292D-07	0.999375
4	0.771D-04	1.	0.631D-03	1.

(B) MODIFIED

FIGURE 8-10,b

8.5 CONCLUSIONS AND RECOMMENDATIONS

At the start of Phase I, Westinghouse Transportation Division selected the four inverter approach to provide superior performance for the DOT-specified wheel mismatch criteria. Secondary benefits were foreseen for schedule reliability. As the design progressed, however, it became clear that the additional power circuitry and control circuitry had significant adverse effect on subsystem reliability when estimated by the parts count method. Since the original four-inverter design decision, two major factors have led to reconsideration of a two-inverter approach; they are:

- The DOT cost analysis of changing wheel mismatch criteria at the NYCTA. The analysis revealed that the costs of maintaining wheel diameter on the same truck to much closer tolerances will be relatively small.

- Availability of higher power GTO devices which permits implementation of the higher power inverter without the necessity of current sharing between parallel devices.

As the four-inverter-per-car design offers improved schedule reliability and failure management, this configuration may find application on properties, such as Cleveland, where single and two car trains predominate. For NYCTA, WMATA and other high density systems where train length is four cars or more, the two-inverter-per-car appears to be the optimal choice.

The estimates of schedule reliability presented in this report exceed, by a wide margin, the reliability goals. This applies for both the four-inverter-per-car and two-inverter-per-car configurations. The two inverter-per-car offers significant improvements in subsystem reliability with corresponding cost savings in corrective and preventive maintenance.

The Booz, Allen report of February 1984 recommended the incorporation of higher power GTO's as they became available. The other recommendations that are still valid are:

- Customize the microprocessor hardware and software to the two-inverter-per-car application. While some credit has been realized in the present reliability estimates for control circuit simplication of the two-inverter design, additional design improvements are likely to be achievable in a production version.

- Continue to monitor reliability data of GTO Suppliers as device deployment increases in rail transit applications.

Finally, the reliability estimates may be updated to reflect measured and calculated stresses in target applications, including NYCTA. Inclusion of stress data in the reliability predictions is expected to result in higher reliability estimates and may also indicate areas where "overdesign" should be considered.

9. MAINTAINABILITY STUDY

A maintenance analysis has been performed as part of the system assurance program for the Westinghouse AC Drive development in the STARS AC Propulsion Project. The analysis was performed on the AC Drive System configuration as of November 8, 1983. The configuration was expressed in preproduction and breadboard prototypes of all major system elements, and in preproduction design drawings for elements built to the breadboard level.

The analysis was performed on the basis of:

- Industry and government practice in maintainability assessment
- Westinghouse Maintainability Program report, Revision B, dated September 23, 1983
- Periodic design drawing reviews
- Inspections of the prototype equipment in operation.
- Selected simulated maintenance actions
- Discussions with design, test and project engineers.

In order to complete the maintainability assessment, an audit of the as-built equipment was conducted by Booz, Allen at the Westinghouse 2L Laboratory in East Pittsburgh during November 1983.

The remainder of this report summarizes our activities and presents our findings and recommendations.

9.1 MAINTAINABILITY REQUIREMENTS

The maintainability/maintenance goals established for the propulsion system are:

(1) A minimum availability of 0.98.

(2) For basic inspection and preventive maintenance, 10,000 miles mean distance between maintenance (MDBM) with 3.0 direct manhours per car for this task.

(3) (a) To remove and install each traction motor, 2.0 manhours per unit.

(b) To remove and install each inverter module, 1.0 manhours per unit.

(c) To remove and install each propulsion control unit, 0.5 manhours per unit.

An inverter module is defined as the equipment that requires unit replacement to correct any single failure within the power electronic circuits of a single car's AC Drive system.

In order to achieve the maintainability goals, the design and construction of the AC Drive equipment has been partitioned into Line Replaceable Units (LRUs). The objective of LRU definition has been to partition the equipment into individual operating, testable units which are maintainable within the specified times. In selecting the specific partitions, the following factors were considered:

- Skill levels of the maintenance staff, and the typical responsibilities of car mechanics, electricians, and electronics technicians.
- Strength, rigidity, size, and weight of proposed LRUs.
- Ease of removal of the LRU.
- Ease of isolation of a failure to a single LRU.
- Number, type, and size of electrical and mechanical connections between the LRU and the other AC drive equipment.
- Potential of damage to the LRU or other equipment during maintenance.

The resulting LRUs are shown in Figure 9-1.

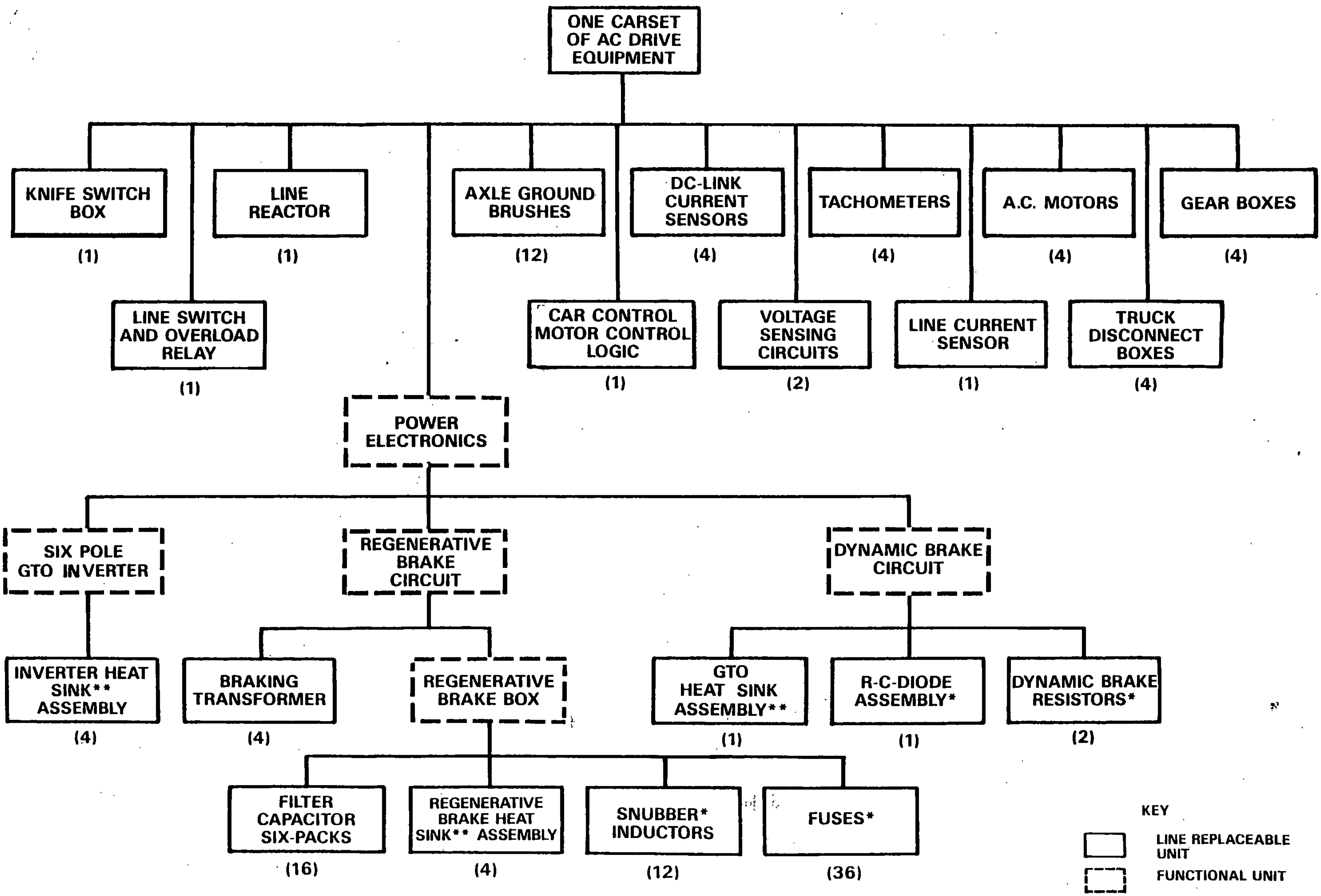


FIGURE 9-1. LINE REPLACEABLE UNITS

Assessment criteria for evaluating LRU replacement compliance were derived from the chapter on "Designing for Maintainability", from Human Engineering Guide to Equipment Design, published by the Joint Army-Navy-Air Force Steering Committee. The criteria emphasize connection, layout, labeling, and fasteners as critical maintainability elements. Within the constraints of the existing R44 car underfloor plan, the selected set of LRUs should satisfy the specification requirements with respect to the assessment criteria and the typical support equipment and staff of a transit railcar maintenance area.

In primary maintenance, before a LRU can be replaced on a failed vehicle, it must be correctly identified as the cause of the equipment failure. Further, after the failed LRU is replaced, the AC Drive System must be tested, and demonstrated to be in correct working order before returning the vehicle to revenue service. The Westinghouse Maintainability Program report describes a set of automatic, built-in test and diagnostic capabilities to be provided in the Phase II program. These test and diagnosis capabilities will be specifically designed to:

- Assess the operating condition of the equipment
- Identify the failed LRU, if present
- Provide troubleshooting or component replacement information for use in secondary maintenance.

Secondary Maintenance on failed LRUs will be performed, off the vehicle in a repair shop. Capabilities to be provided in support of LRU repairs includes:

- Test and maintenance procedures
- Diagnostic information generated by the built-in test capabilities during primary maintenance.
- An AC Drive test setup or special test equipment to permit testing of failed and repaired LRUs.

The test arrangement and equipment should permit sufficient testing to make sure that a repaired unit will operate correctly when reinstalled on a railcar.

Preventive maintenance should be performed at the intervals recommended in the Westinghouse Maintainability Program Report. Preventive maintenance work will normally be performed on equipment as installed on the vehicle; the exception is equipment scheduled for overhaul which will be removed and replaced.

9.2 MAINTENANCE CONCEPT

Booz, Allen submitted comments on Revision B of the Maintainability Program report, dated September 23, 1983, in concert with the maintainability audit performed on the prototype equipment in the Westinghouse 2L laboratory. Westinghouse has since reviewed the comments, incorporated them as appropriate, and submitted a revision of the Maintainability Program Report. In addition to the comments, the following recommendations were made for improvements to the maintenance concept:

- Careful partitioning and selection must be made for assemblies to be designated as primary maintenance LRUs. Twenty-one different types of components or assemblies are recommended to be treated as LRUs.

- The techniques for automatic built-in testing and failure diagnosis of AC Drive failures must provide identification of failed LRUs for primary maintenance action, and provide recorded troubleshooting and component-replacement information for LRU repair in secondary maintenance.

- A separate, designated AC Drive equipment secondary maintenance facility should be established to support the use of AC Drive units at the NYCTA. Under this arrangement, primary maintenance of AC Drive equipment will be provided by the same mechanics and technicians who maintain the cam-controlled dc equipment.

However, we advise against mixing the repair of sophisticated AC Drive micro-computer and power electronic assemblies with conventional electromechanical devices. Instead, trained staff should repair AC Drive LRUs in a designated facility which includes an AC Drive test setup. The test setup should consist of a minimum complement of equipment necessary to test the microcomputer and power electronic assemblies as an ensemble. The secondary repair facility should be as clean as a typical electronics repair facility, and have standard electronics tools, instruments, and materials.

- Particular design features should be changed or added in several LRUs to enhance and simplify maintainability. These include:

  - Identification marking of power cables that are disconnected for LRU removal

  - Provision of diagnostic indicators on the gate driver boards

- Protection of the gate driver boards against mechanical damage in handling

- Lamp test push button for the inverter status lights in the passenger compartment.

For subsequent AC Drive development, that is after Phase I, a comprehensive list of additional design criteria, related to maintainability, should be developed. The criteria will guide the design for the production equipment.

9.3 ANALYSIS OF UNDERCAR LAYOUT

The location of each major equipment assembly was evaluated for accessibility and relative placement on the under car. Figure 9-2 (WTD Drawing SK-RDJ102583) shows the planned locations of the power electronics equipment. Control electronics will be located in the passenger compartment. Items such as the line switch and knife switch, which are common to both CAM and AC Drive, remain in their previous locations. The findings are as follows.

The Undercar Layout Has Been Optimized Within the Constraints of the Present R-44 Undercar Equipment Arrangement

The space available for the AC power electronics results from removal of the main control group and dynamic brake resistors of the R-44 cam equipment. The space is sufficient for mounting of 4 sets of inverters, braking transformers, regenerative brake circuits and new dynamic brake resistors; however, the ease of access to the various units is mixed.

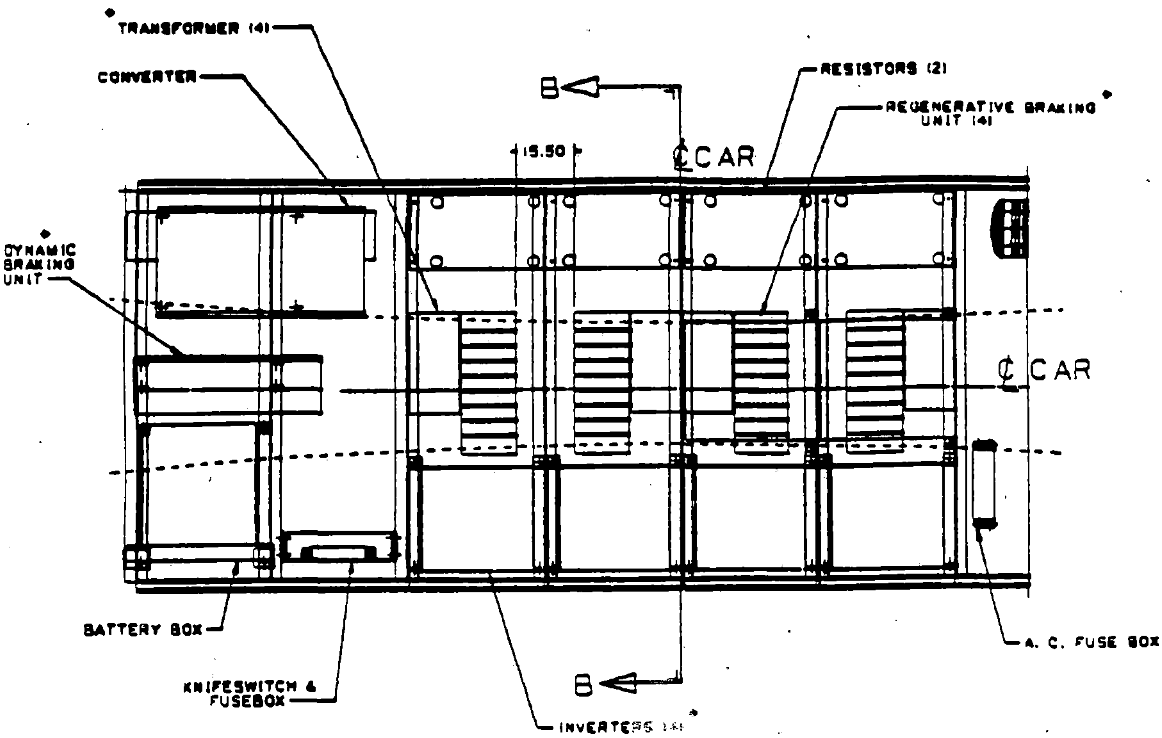
The 6 Pole PWM Inverter is Readily Accessible and Easily Replaced

As shown in Figure 9-2, the 6 pole PWM inverter units are readily accessible from the side of the car. The complete power circuit and gate drivers are integrated into a single heat sink assembly. Removal and replacement of the inverter is fast and convenient; estimated time is 15 minutes for removal and replacement. The procedure is to remove three bolts that secure the cover, disconnect seven power cables, remove four heat sink retention bolts and the slide the heat sink assembly out onto a suitable transport platform. Replacement is the inverse. Line replacement of the complete heat sink assembly is the recommended maintenance approach. The PWM inverter is highly accessible and no further maintainability design changes are foreseen for Phase II equipment.

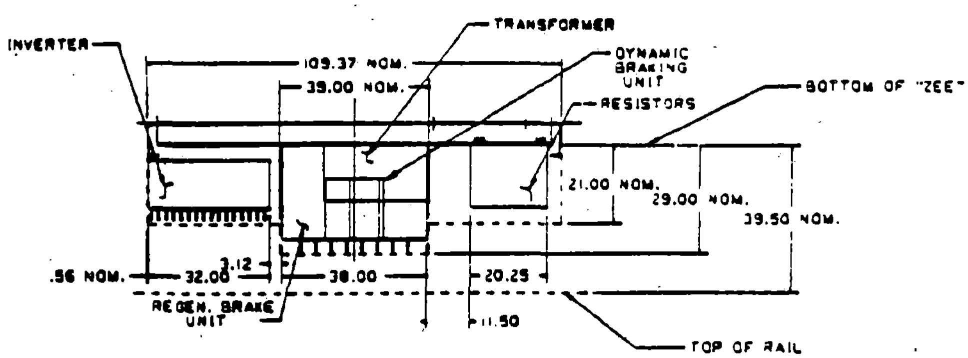
The Dynamic Brake Resistors are Placed at the Side of the Car for Maximum Heat Transfer Away from the Underfloor Equipment

The four banks of dynamic brake resistors are placed adjacent to the side of the car as shown in Figure 9-2. This location is advantageous for heat dissipation and access to the resistor assemblies. The recommended LRU for the resistors is each resistor assembly; the AC drive equipment will have two resistor assemblies per car.

FIGURE 9-2



A.C. DRIVE PROPULSION EQUIPMENT



SECTION "B-B"

STARS A.C. PROPULSION PROJECT

SK-RDJ102583

9.3.4 The Location of the Regenerative Brake Circuit Is Not Convenient for Maintenance. However Carefull Selection of the Related LRUs Permits High Maintainability

The planned location of the Regenerative Brake Circuit Boxes is close to the center line of the car as shown in Figure 9-2. This is dictated by the restrictions on vertical clearance above the running rails. It is also advantageous to locate the braking transformers on the center line because of their high weight and low maintenance requirements.

The space constraints of the R-44 car result in poor access to the Regenerative Brake Unit. However, it should be noted that access could be improved considerably if AC Drive equipment is to be supplied on a new railcar procurement.

Despite the restricted access, the maintainability goals and reduced maintenance costs can be achieved by suitable selection of LRUs within the Regenerative Circuit Box. The selected LRUs are the:

- Filter capacitor six-pac assemblies
- Heat Sink Assembly including the gate driver circuits.

Other components such as fuses, insulators and dI/dt reactors will be replaced at the component level.

An alternative which is not recommended is removal of the complete box using a lift table over a pit. This would require disconnection of 22 power connections, primarily within the box.

The braking transformer is a LRU and will require a lift table and pit for removal and replacement, however it is a high reliability item, and as such does not present a maintainability concern.

9.3.5 Adverse Reliability Effects Have Not Been Identified For the Undercar Layout Design

Contamination of heat sink surfaces was previously identified as a concern. The rate of contamination as a function of relative placement is not known. Periodic cleaning as recommended in the Preventative Maintenance Schedule will likely mitigate any adverse effects.

Large amounts of heat will be frequently dissipated by the dynamic brake resistors, however their location should alleviate any potential for adversely effecting other equipment.

9.4 DIAGNOSTICS AND TEST EQUIPMENT

For an operating AC Drive railcar, equipment failure diagnosis information is provided by four lights, which indicate the status of the four inverter/braking assemblies. When one of the inverters is not fully functional, as assessed by the built-in diagnostics, the corresponding status light is turned off. In addition, information on the cause and indication of failure is stored in the car control logic for later readout by the railcar mechanic in the primary maintenance facility.

When a railcar is taken out of service because one or more of the AC Drive inverter status lights is off, it will be brought to the primary maintenance shop. The Maintenance Concept defines a unified procedure for failure diagnosis by the same mechanics and electricians who service the rest of the fleet. The procedure entails, as a first step, connection of a hand-held printing terminal by the mechanic to a test connector of the Car Control Logic. The mechanic is then instructed in English language by the displays which inform of:

- The status of the AC Drive equipment.
- How to initiate a complete, automatic series of tests of the AC Drive equipment: the tests will be executed by the Car Control Logic and Motor Control Logic. A printed record of the test results will be printed by the terminal.

The intention of the design of the automated test sequence is to identify a failed LRU for removal and replacement by the primary maintenance mechanic. In addition, the combined built-in test diagnostics will provide printed information for LRU troubleshooting or component-replacement in the secondary maintenance shop. The printed record should be attached to the equipment trouble ticket, and sent with the failed LRU for repair.

The design of the built-in test and diagnostics in the AC Drive equipment minimizes, and almost eliminates, the need for standard or special test equipment to diagnose and verify the equipment function. Using only the hand-held terminal, the mechanic initiates a test sequence which checks:

- Car Control Logic
- Motor Control Logic
- Inverter Power Devices, Snubbers and Gate Drivers
- Regenerative Brake Power Devices, Snubbers and Gate Drivers

- Dynamic Brake Power Devices, Snubbers and Gate Drivers

- Filter Capacitors

- Line Switch

- Monitor and Support Circuits.

The tests are capable of isolating the most common components failures, and will in any event identify the failed LRU for removal and replacement.

In the secondary maintenance facility, the failed LRU, with trouble ticket and printed diagnostic test results can be repaired. Troubleshooting and test procedures will help the technician isolate the failed component, in cases where the results of the diagnostic test are not conclusive. Such procedures will require standard electronics shop equipment, including hand tools, volt-omhmeters, power supplies, and oscilloscopes. The environment of the secondary maintenance facility should be the usual standard for an electronics repair shop.

A test set-up will consist of the minimum complement of electronic AC Drive equipment necessary to test a repaired LRU in the system. The test set-up will be capable of repeating the built-in test diagnostics, both to confirm trouble reports from the primary maintenance report, and to verify correct operation of a repaired unit.

9.5 MAINTENANCE TIMES

The cost and economic analysis required development of preventative and corrective maintenance costs. Detailed preventative and corrective maintenance times are given in the WTD Maintainability Program and summary costs are shown in the Life Cycle Cost, or Economic, Analysis.

9.6 SUMMARY

Based on the maintenance time estimates developed by Westinghouse Transportation Division and reviewed by Booz, Allen, the AC equipment, as designed, will meet or exceed the contract goals for maintainability.

The maintenance concept and diagnostic features should permit adequate servicing of equipment in maintenance shops that generally deal with cam-controlled equipment.

The layout and packaging constraints that stem from the R-44 space availability should be carefully reviewed before introduction of the equipment on another railcar. Particular attention is directed towards repackaging of the regenerative brake unit to match power rating to the system specific requirements and to make the unit more accessible.

10. SYSTEM SAFETY STUDY

A Subsystem Hazard Analysis has been performed on the Westinghouse AC Drive System, following the methodology established by UMTA's System Safety Analysis, January, 1981. This Subsystem Hazard Analysis (SSHA) fulfills the requirements of Section 4.4.5.1 of Attachment B of the procurement contract. Along with the Fire Hazard Analysis, and review of EMI, the SSHA constitutes the specified preliminary safety analysis submittal.

10.1 SUBSYSTEM HAZARD ANALYSIS

The subsystem Hazard Analysis is contained in the SSHA forms attached in Figure 10-1. Analyses were performed for the following hazards, in which the AC Drive System:

- Delivers excessive tractive effort
- Delivers inadequate braking effort
- Shocks a maintenance worker
- Energizes a dead, shorted, or low-voltage section of the third rail
- Generates fire or smoke
- Causes an electric shock potential on the vehicle
- Contributes to a trauma to maintenance worker
- Sustains major equipment damage.

As specified in the analysis methodology, the hazards under consideration are investigated for cause, triggering event, potential accident, hazard category, potential accident prevention measures, and resolution.

10.2 FINDINGS AND CONCLUSIONS

Among the eight hazards identified in Figure 10-1, six have the potential to cause Category I accidents. Since Category I accidents entail the loss of life, they must be contolled by design, procedure, maintenance, or use of safety and warning devices. As shown in Figure 10-1, all eight hazards are controlled to Category III or IV by appropriate engineering, construction, operating, and maintenance practices.

Special note must be made of the hazard associated with regeneration into dead sections of the third rail. As with any regnerative propulsion system, equipment or procedures must be provided to avoid shock to maintenance workers or equipment. For the AC Drive System, the selection of dead rail detection equipment will be made in Phase II of the development program. Thus, the resolution of the hazard from Category I to Category III cannot be certified until the Phase II development and demonstration is complete.

Further, as with all operating equipment on rail transit properties, the transit operator must provide suitably skilled operators, supervision, maintenance staff, equipment, and procedures to conduct operations per accepted practices and manufacturer's recommendations.

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SUBSYSTEM HAZARD ANALYSIS

HAZARD	CAUSE OF HAZARD	TRIGGERING EVENT	POTENTIAL ACCIDENT	HAZARD CATEGORY	POTENTIAL ACCIDENT PREVENTION MEASURES	RESOLUTION
1.0 AC DRIVE SYSTEM DELIVERS TRACTIVE EFFORT ABOVE COMMANDED OR APPROPRIATE LEVEL	1.1 FAILURE OF INVERTER LOGIC OR FAILURE OF CAR CONTROL LOGIC 1.2 DESIGN ERROR IN INVERTER LOGIC OR CAR CONTROL LOGIC 1.3 TACHOMETER FAILURE	TRAIN BEARING AC DRIVE SYSTEM(S) APPROACHING SPEED RESTRICTION WHEN FAILURE OCCURS OR WHEN DESIGN ERROR CAUSES INCORRECT AC DRIVE SYSTEM RESPONSE. FAILURE IN AC DRIVE SYSTEM TRIGGERED BY ESTABLISHED STRESSES AND FAILURE MECHANISMS, OR BY EXTRAORDINARY CIRCUMSTANCES.	COLLISION, DERAILMENT, OR OTHER UNSAFE MOTION OF TRAIN.	NOMINAL CATEGORY I POTENTIAL FOR DEATH OF PATRONS AND OPERATING STAFF. HAZARD CONTROLLED AS NOTED TO CATEGORY IV.	1.1 ATP AND/OR MOTORMAN'S HANDLE OPEN LINE SWITCH AND APPLY FRICTION BRAKES WHEN BLOCK VIOLATION OR OVERSPEED IS DETECTED. 1.2 THOROUGH TESTING OF EQUIPMENT AT WESTINGHOUSE LABORATORY, AND IN R-44 CAR PRIOR TO USE IN SERVICE. ANY OBSERVED DESIGN DEFECTS WILL BE CORRECTED. 1.3 FAILURE OF A TACHOMETER TO 0 MPH WILL NOT CAUSE POWERING OF INVERTER. TACHOMETER DATA WILL BE COMPARED FOR ALL FOUR MOTORS IN CAR CONTROL LOGIC, AND INCONSISTENT MOTOR WILL BE COMMANDED OFF. DESIGN OF SPEED CONTROL ALGORITHM WILL ALSO LIMIT POWER USED BY A SINGLE FAILED INVERTER/TACHOMETER.	BOTH AUTOMATIC FAILSAFE, AND MANUAL INDEPENDENT MEANS ARE PROVIDED TO REMOVE PROPULSION POWER WHEN INAPPROPRIATE POWER APPLICATION IS MADE. AS WITH ALL PROPULSION EQUIPMENT: • ATP EQUIPMENT MUST BE MAINTAINED IN GOOD OPERATING CONDITION. • MOTORMAN MUST USE FULL VIGILANCE AGAINST UNSAFE MOVEMENTS. • LINE SWITCH AND EM RELAYS IN RAILCARS MUST BE MAINTAINED IN GOOD CONDITION.

SUBSYSTEM TITLE AC DRIVE SYSTEM

SUBSYSTEM HAZARD ANALYSIS

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HAZARD	CAUSE OF HAZARD	TRIGGERING EVENT	POTENTIAL ACCIDENT	HAZARD CATEGORY	POTENTIAL ACCIDENT PREVENTION MEASURES	RESOLUTION
2.0 AC DRIVE SYSTEM FAILS TO DELIVER COMMANDED OR APPROPRIATE BRAKING FORCE.	2.1 FAILURE OF INVERTER IN BRAKING MODE 2.2 FAILURE OF INVERTER LOGIC IN BRAKING MODE 2.3 FAILURE OF CAR CONTROL LOGIC IN BRAKING MODE 2.4 FAILURE OF REGENERATIVE BRAKING CIRCUIT 2.5 FAILURE OF DYNAMIC BRAKING CIRCUIT	TRAIN BEARING AC DRIVE SYSTEM(S) APPROACHING SPEED RESTRICTION WHEN FAILURE OCCURS OR WHEN DESIGN ERROR CAUSES INCORRECT AC DRIVE SYSTEM RESPONSE. FAILURE IN AC DRIVE SYSTEM TRIGGERED BY ESTABLISHED STRESSES AND FAILURE MECHANISMS, OR BY EXTRA-ORDINARY CIRCUMSTANCES.	COLLISION, DERAILMENT OR OTHER UNSAFE MOTION OF TRAIN.	NOMINAL CATEGORY I POTENTIAL FOR DEATH OF PATRONS AND OPERATING STAFF. HAZARD CONTROLLED AS NOTED, TO CATEGORY IV.	INDEPENDENT BRAKING SYSTEM WILL SLOW TRAIN TO SAFE SPEED IN CASE OF LOSS OF ALL OR ANY PART OR PARTS OF AC DRIVE SYSTEM ELECTRIC BRAKING CAPABILITY.	R-44 CAR PROVIDES FAILSAFE, INDEPENDENTLY CONTROLLED, AIR-ACTUATED BRAKING SYSTEM. THIS BRAKE SYSTEM WILL SAFELY CONTROL TRAIN SPEED, EVEN IN CASE OF FULL OR PARTIAL FAILURE OF AC DRIVE SYSTEM ELECTRIC BRAKING. AS WITH ALL PROPULSION EQUIPMENT, THE AIRBRAKE SYSTEM MUST BE MAINTAINED IN GOOD OPERATING CONDITION.

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HAZARD	CAUSE OF HAZARD	TRIGGERING EVENT	POTENTIAL ACCIDENT	HAZARD CATEGORY	POTENTIAL ACCIDENT PREVENTION MEASURES	RESOLUTION
3.0 HIGH VOLTAGE SHOCK TO RAILCAR MAINTENANCE PERSONNEL FROM ENERGY STORED IN FILTER AND SNUBBER CAPACITORS.	MAINTENANCE PERSONNEL MAKE CONTACT WITH GROUND AND WITH PARTS CONNECTED TO "LIVE" CAPACITOR, AS PART OF MAINTENANCE ACTION.	VEHICLE MOVED FROM THIRD RAIL TO MAINTENANCE AREA FOR SERVICE OF AC DRIVE SYSTEM OR RELATED EQUIPMENT.	ELECTROCUTION OF MAINTENANCE WORKER.	NOMINAL CATEGORY I POTENTIAL FOR DEATH OF MAINTENANCE WORKER. HAZARD CONTROLLED AS NOTED, TO CATEGORY III.	3.1 PROVISION OF BLEEDER RESISTORS ON ALL HIGH-ENERGY CAPACITORS, SO THAT ENERGY IS REMOVED FROM CAPACITORS WITHIN A SHORT TIME AFTER RAILCAR IS REMOVED FROM THIRD RAIL. 3.2 PROVISION OF WARNING INDICATORS ON ALL HIGH-ENERGY CAPACITORS, TO VISUALLY INDICATE TO THE MAINTENANCE WORKER WHEN HAZARDOUS VOLTAGES ARE PRESENT. 3.3 PROVISION OF PROMINENTLY DISPLAYED WARNING LABELS TO MAINTENANCE WORKERS, INDICATING SPECIAL STEPS AND PRECAUTIONS TO BE TAKEN WHEN WORKING AROUND HIGH-ENERGY CAPACITORS; 3.4 MAINTENANCE PROCEDURE THAT REQUIRES CHECK OF HAZARDOUS CIRCUIT WITH KNOWN GOOD VOLTMETER.	HAZARD IS RESOLVED BY PROVIDING: 1. BLEEDER RESISTORS 2. WARNING INDICATORS 3. WARNING LABLES NOTE THAT WARNING INDICATORS MAY FAIL IN TWO WAYS: • THEY MAY INDICATE A HAZARDOUS VOLTAGE IS PRESENT WHEN IT IS NOT. "FALSE ALARMS" WILL REDUCE THE UTILITY AND CREDENCE GIVEN TO THE INDICATORS. • THEY MAY FAIL TO INDICATE A HAZARDOUS VOLTAGE IS PRESENT WHEN IT ACTUALLY IS. "FALSE ALARMS" INDUCE A SECONDARY HAZARD. DESPITE THE SHORTCOMINGS OF INDICATORS THEY PROVIDE A SUBSTANTIAL OVERALL REDUCTION IN THE HAZARD TO THE MAINTENANCE STAFF. 4. MAINTENANCE PROCEDURE

SUBSYSTEM TITLE AC DRIVE SYSTEM

SUBSYSTEM HAZARD ANALYSIS

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HAZARD	CAUSE OF HAZARD	TRIGGERING EVENT	POTENTIAL ACCIDENT	HAZARD CATEGORY	POTENTIAL ACCIDENT PREVENTION MEASURES	RESOLUTION
4.0 HIGH VOLTAGE SHOCK TO TRACK MAINTENANCE PERSONNEL OR DAMAGE TO EQUIPMENT.	AC DRIVE SYSTEM REGENERATES INTO SECTION OF THIRD RAIL WHICH IS: . GROUNDED . OPEN-CIRCUITED . AT LOW POTENTIAL	VEHICLE BEARING AC DRIVE SYSTEM ENTERS SECTION OF TRACK IN WHICH THIRD RAIL IS NOT ENERGIZED. RAIL MAY BE IN ANY OF 3 NON-OPERATIONAL CONDITIONS. VEHICLE CAN REGENERATE, CONVERTING VEHICLE'S ENERGY OF MOTION INTO DANGEROUS VOLTAGE OR CURRENT IN THIRD RAIL.	ELECTROCUTION OF TRACKSIDE MAINTENANCE WORKER, OR DAMAGE TO MAINTENANCE AND OPERATING EQUIPMENT, WHICH ARE IN CONTACT WITH THIRD RAIL.	NOMINAL CATEGORY I POTENTIAL FOR DEATH OF MAINTENANCE WORKER. HAZARD IS PLANNED TO BE CONTROLLED AS NOTED, TO CATEGORY III, IN PHASE 2.	4.1 PROVISION OF A SUITABLE DEAD RAIL DETECTION MECHANISM, IN THE AC DRIVE SYSTEM, AND ON THE WAYSIDE, IF NECESSARY. 4.2 ENFORCEMENT OF PROCEDURES FOR GROUNDING THIRD RAIL SECTIONS CONTIGUOUS TO ENERGIZED, OPERATING THIRD RAIL SECTIONS. SAFETY PROCEDURE THAT REQUIRES VERIFICATION OF DE-ENERGIZED THIRD RAIL WITH A KNOWN GOOD VOLTAGE INDICATOR BEFORE GROUNDING. 4.3 ENFORCEMENT OF PROCEDURES WHICH PROHIBIT OPERATION OF TRAINS NEAR NON-ENERGIZED SECTIONS OF RAIL WHEN MAINTENANCE WORKERS ARE PRESENT.	4.1 CANDIDATE DEAD RAIL DETECTOR DESIGNS HAVE BEEN INVESTIGATED. PREFERRED APPROACH CALLS FOR WAYSIDE INJECTION OF CURRENT IN A THIRD RAIL SIGNAL LOOP. DESIGN TO BE COMPLETED AND IMPLEMENTATION MADE DURING PHASE II. . COMPLETED DESIGN MUST BE THOROUGHLY TESTED IN OPERATING ENVIRONMENT FOR ADEQUATE DETECTION OF NON-OPERATING THIRD RAIL. . DESIGN MUST TAKE ACTUAL AND PREDICTED WORST CASE SYSTEM IMPEDANCES AND NOISES INTO ACCOUNT . DEAD RAIL DETECTOR MUST BE DEMONSTRATED TO RELIABLY PREVENT REGENERATION WHEN DEAD RAIL CONDITION IS DETECTED. 4.2 AND 4.3 AS WITH OTHER REGENERATING PROPULSION EQUIPMENT, NYCTA OR OTHER OPERATING PROPERTY USING AC DRIVE SYSTEM MUST ESTABLISH AND ENFORCE SUITABLE OPERATING RULES CONCERNING GROUNDING OF DEAD RAILS, MAINTENANCE PROCEDURES AND OPERATION OF TRAINS NEAR DEAD RAIL SECTIONS UNDERGOING MAINTENANCE.

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HAZARD	CAUSE OF HAZARD	TRIGGERING EVENT	POTENTIAL ACCIDENT	HAZARD CATEGORY	POTENTIAL ACCIDENT PREVENTION MEASURES	RESOLUTION
5.0 FIRE OR SMOKE CAUSED BY UNPLANNED DISCHARGE OF PROPULSION OR BRAKING ENERGY.	FAILURE OR DESIGN ERROR IN INVERTER, LOGIC OR BRAKING CIRCUIT COMPONENTS, WIRING, OR PACKAGING.	ENERGY IS APPLIED TO AFFECTED COMPONENT(S) WHEN FAILURE OCCURS OR WHEN DESIGN ERROR CAUSES UNINTENDED ACTION.	FIRE ON RAILCAR, OR GENERATION OF SUFFOCATING OR TOXIC SMOKE.	NOMINAL CATEGORY I POTENTIAL FOR DEATH OR INJURY TO PATRONS OR STAFF, IN TRAIN OR ON NEARBY PLATFORMS. HAZARD IS CONTROLLED AS NOTES, TO CATEGORY III.	5.1 PROVISION OF OVERCURRENT SENSORS AND LOGIC, AND LINE SWITCH AND OVERLOAD RELAYS, ARRANGED TO HALT APPLICATION OF ELECTRIC POWER IN CASE OF HIGH ENERGY FAULT. 5.2 USE OF MATERIALS, COMPONENTS, AND PACKAGING TECHNIQUES WHICH MINIMIZE LIKELIHOOD OF FAILURES WHICH CAN CAUSE FIRES. 5.3 USE OF MATERIALS WITH LOW FLAMMABILITY AND TOXIC SMOKE GENERATION CAPABILITY	AS NOTED IN FIRE AND LIFE SAFETY HAZARD ANALYSIS, MEASURES TAKEN INCLUDE: 5.1 PROVISION OF OVERCURRENT PROTECTIVE DEVICES 5.2 USE OF SUITABLE MATERIALS TO PREVENT FIRE-CAUSING FAILURES 5.3 USE OF LOW FLAMMABILITY AND LOW SMOKE MATERIALS. 5.4 EQUIPMENT BOXES DO NOT CONTAIN BLOWERS WHICH COULD FAN A FIRE.

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HAZARD	CAUSE OF HAZARD	TRIGGERING EVENT	POTENTIAL ACCIDENT	HAZARD CATEGORY	POTENTIAL ACCIDENT PREVENTION MEASURES	RESOLUTION
6.0 ELECTRIC SHOCK CAUSED BY UNPLANNED DIS-CHARGE OF PROPULSION OR BRAKING ENERGY TO RAILCAR BODY.	FAILURE OR DESIGN ERROR IN INVERTER, LOGIC, OR BRAKING CIR-CUIT COMPONENTS, WIRING, OR PACKAGING.	ENERGY IS APPLIED TO AFFECTED COM-PONENT(S) WHEN FAILURE OCCURS OR WHEN DESIGN ERROR CAUSES UNINTENDED ACTION.	DANGEROUS ELECTRIC POTENTIALS GENER-ATED WITHIN RAIL-CAR GIVE ELECTRIC SHOCK TO PATRONS OR STAFF, ON TRAIN OR ON ADJACENT PLATFORMS.	NOMINAL CATEGORY I POTENTIAL FOR DEATH OR INJURY TO PATRONS OR STAFF IN TRAINS OR ON NEARLY PLAT-FORMS. HAZARD IS CONTROLLED AS NOTED, TO CATEGORY III.	6.1 PROVISION OF OVERCURRENT SENSORS, CURRENT IMBALANCE SENSORS, LOGIC, LINE SWITCH, AND OVERLOAD RELAYS, ARRANGED TO HALT APPLICA-TION OF ELECTRIC POWER IN CASE OF HIGH ENERGY FAULT. 6.2 USE OF MATERIALS, COMPONENTS, AND PACKAGING TECHNIQUES WHICH MINIMIZE LIKELIHOOD OF FAILURES WHICH CAN CAUSE ELECTRICAL FAULTS.	AS WITH ALL PROPULSION EQUIPMENT: 6.1 PROVISION OF OVERCURRENT PROTECTIVE DEVICES 6.2 USE OF SUITABLE MATERIALS AND TECHNIQUES TO MINIMIZE THE PROBABILITY OF ELECTRICAL FAULTS INVOLVING METALLIC SURFACES OF THE RAILCAR.

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HAZARD	CAUSE OF HAZARD	TRIGGERING EVENT	POTENTIAL ACCIDENT	HAZARD CATEGORY	POTENTIAL ACCIDENT PREVENTION MEASURES	RESOLUTION
7.0 INJURY TO MAINTENANCE PERSONNEL WHILE WORKING ON AC DRIVE SYSTEM EQUIPMENT.	7.1 CUT ON SHARP CORNER OR EDGE 7.2 STRIKING PART OF BODY WHILE WORKING IN RESTRICTED SPACE 7.3 DROPPING PART OF BODY ON ROTATING EQUIPMENT 7.4 STRIKING PART OF BODY ON ROTATING EQUIPMENT	UNPLANNED CONTACT WITH PORTION OF AC DRIVE SYSTEM WHILE MAINTAINING EQUIPMENT.	FRACTURE, BRUISE, CONTUSION, OR OTHER TRAUMA TO MAINTENANCE WORKER.	NOMINAL CATEGORY III POTENTIAL FOR INJURY TO MAINTENANCE WORKER. HAZARD CONTROLLED, AS NOTED, TO CATEGORY IV.	. DESIGN AND CONSTRUCTION TO: - MINIMIZE SHARP EDGES AND CORNERS - AVOID RESTRICTIVE SPACES AND/OR NEED FOR MAINTENANCE WORKER ENTRY - PROVIDE SUITABLE MOUNTING AND LIFTING ATTACHMENTS - MAKE FREQUENTLY SERVICED OR INSPECTED COMPONENTS EASY TO REACH - ROTATING EQUIPMENT IS MOUNTED ON TRACTION MOTOR DRIVE SHAFT. . PROVISION OF SUITABLE MAINTENANCE INSTRUCTIONS AND WARNINGS. . PROVISION OF SUITABLE MAINTTENANCE FACILITIES AND TOOLS. . USE OF TRAINED PERSONNEL.	. DESIGN INCORPORATES MAINTAINABILITY AND TRANSIT INDUSTRY SAFETY PROVISIONS AS DEVELOPED IN WESTINGHOUSE DESIGN PRACTICES FOR TRACTION EQUIPMENT. . REVIEWED AGAINST APPLICABLE PORTIONS OF MIL STD 272, MAINTAINABILITY PRODUCTION . A SUITABLE MAINTENANCE MANUAL IS BEING PROVIDED. . AS WITH ALL OPERATING EQUIPMENT, THE OPERATING AUTHORITY MUST PROVIDE SUITABLE FACILITIES AND TRAINED PERSONNEL TO AVOID MAINTENANCE ACCIDENTS.

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HAZARD	CAUSE OF HAZARD	TRIGGERING EVENT	POTENTIAL ACCIDENT	HAZARD CATEGORY	POTENTIAL ACCIDENT PREVENTION MEASURES	RESOLUTION
8.0 MAJOR DAMAGE TO AC DRIVE SYSTEM EQUIPMENT	FAILURE OR DESIGN ERROR IN AC DRIVE SYSTEM EQUIPMENT, CAUSING CATASTROPHIC FAILURE OF FAILING OR RELATED UNIT.	PRESENCE OF LARGE AMOUNTS OF ELECTRICAL AND KINETIC ENERGY IN EQUIPMENT WHEN FAILURE OCCURS.	DAMAGE TO EQUIPMENT REQUIRING MAJOR REWORK OR REPLACEMENT.	NOMINAL CATEGORY III POTENTIAL FOR MAJOR DAMAGE TO EQUIPMENT.	8.1 USE OF SUITABLE MATERIALS, COMPONENTS, AND TECHNIQUES, WITH APPROPRIATE DERATING, TO REDUCE STRESS ON AC DRIVE SYSTEM. 8.2 PROVISION OF OVERCURRENT AND OVERVOLTAGE PROTECTION DEVICES, THAT ARE INDEPENDENT OF THE ELECTRONIC CONTROLS, WHICH OPEN LINE SWITCH AND/OR HIGH SPEED CIRCUIT BREAKER 8.3 PROVISION OF SUITABLE MAINTENANCE PROCEDURES, EQUIPMENT AND STAFF TO ENSURE THAT EQUIPMENT IS INSPECTED AND MAINTAINED IN GOOD CONDITION.	8.1 SUITABLE MATERIALS, COMPONENTS, AND TECHNIQUES ARE USED. 8.2 INDEPENDENT MONITORING IS PROVIDED. 8.3 SUITABLE MAINTENANCE PROCEDURES, EQUIPMENT, AND STAFF TO INSPECT AND MAINTAIN EQUIPMENT ARE BEING PREPARED, AND WILL BE PROVIDED.

11. COST AND ECONOMIC ANALYSIS

Under a grant from the Urban Mass Transit Administration (UMTA), Westinghouse Transportation Division (WTD) is designing an inverter controlled AC propulsion system using induction motors and variable voltage, variable frequency inverters. The goals of the AC Propulsion Program are to:

- Demonstrate that low maintenance, energy efficient AC induction motors can be used in a transit environment
- Develop an AC system that is price competitive with existing DC chopper systems
- Demonstrate that reduced maintenance and energy savings of the AC propulsion system will show favorable life cycle cost savings over a cam-controlled propulsion system
- Design a propulsion system flexible enough to meet a wide range of transit applications
- Apply the design to the NYCTA R-44 car.

11.1 OBJECTIVES AND APPROACH

11.1.1 Objectives of the Life Cycle Cost Analysis

The primary objective of the economic analysis is to determine whether the life cycle cost of the Westinghouse AC Drive system is higher or lower than the Westinghouse cam system on the NYCTA R-44 vehicles. The analysis uses present operations on the 17.7 mile "RR" line of the NYCTA as a baseline for energy costs, and the maintenance environment of the Coney Island and Pitkin shops as a baseline for maintenance costs.

11.1.2 Approach to the Analysis

Life cycle costing is a method of estimating the total lifetime cost of acquiring, operating and maintaining a product. The life cycle cost of a product is defined as its capital cost plus the present value of a lifetime of operating and maintenance costs.

In this analysis, the emphasis is placed on the difference between the life cycle costs of the two propulsion systems. The incremental capital cost of AC Drive over the R-44 cam is viewed as an investment, and the energy and maintenance cost savings as a return on the investment.

The basic groundrules for the life cycle cost analysis were described by the UMTA contract which funded this effort. Clarifying agreements were reached between hardware contractors, Department of Transportation (DOT) representatives and consultants over the scope and approach to the life cycle cost analysis. Differences between the original contract wording and the scope of the final analysis are shown in Figure 11-1.

Contract Wording

"The acquisition cost will be based on projected production costs of the propulsion system assuming quantities of 50,100 and 200 car sets."

"The production cost estimated will cover manufacturing, materials, tooling, engineering support and warranty costs." "Industry competitive wage rates and profit margins will be assumed for the study."

"...parametric propulsion system design and production costs data will be generated for transit cars in three standard size and weight categories as follows:

- 75.0 ft long, 90,000 lbs empty, 130,000 lbs loaded
- 67.5 ft long, 76,000 lbs empty, 105,000 lbs loaded
- 48.0 ft long, 52,000 lbs empty, 74,500 lbs loaded

"Electrical energy cost will be computed for operations with and without regenerative braking."

"Typical transit industry wage rates will be used for maintenance labor costs."

FIGURE 11-1
Life Cycle Cost Analysis

Scope of Final Analysis

The acquisition cost is based on the purchase price that would be bid to a railcar manufacturer.

The quantity assumed for the analysis is the number of railcars needed to meet a schedule which requires 100 cars on line during the peak period.

Capital and life cycle cost estimates are provided for systems with 2 and 4 inverters per car.

The purchase price by a railcar manufacturer was developed by WTD based on standard pricing techniques for normal, quantity production orders.

The analysis is limited to the purchase price of a propulsion system designed for the NYCTA R-44 vehicle.

- 75 ft long, 87,000 lbs empty, 130,000 lbs loaded

Capital and life cycle cost estimates are provided for a system with regenerative braking limited to the capacity of the inverter.

A fully loaded (including fringe and overhead) labor cost of $22/hour was provided by the DOT.

The life cycle cost data for AC Drive are based on information from several sources. The cost elements have been arranged as follows:

- Operating Costs--Electrical consumption for AC propulsion is based on energy consumption measured in the WTD power lab using a profile of the "RR" line developed by Garrett.

- Preventive Maintenance Labor Costs--Labor costs for AC Drive inspection and servicing are based on the Inspection and Maintenance Schedule prepared by WTD.

- Preventive Maintenance Materials Costs--The only preventive maintenance cost for materials identified for the R-44 baseline case was for brush replacement. Because AC motors have no brushes and the inverter requires no inspection or preventive maintenance material, this cost is assumed to be zero.

- Corrective Maintenance Labor Costs--Labor costs for repair, replacement, and secondary maintenance were calculated based on the Booz, Allen Reliability Model, the WTD Corrective Maintenance Concept and the WTD Maintenance Analysis of Propulsion Equipment Line Replaceable Units.

- Corrective Maintenance Materials Cost--Costs of line replaceable units were supplied by WTD along with the "mean time to replace" for each unit. The failure rates for each component were translated into annual usage requirements for vehicles providing 40,000 car miles of revenue service.

- Capital Costs--The capital cost was based on the price that would be bid by WTD to a railcar manufacturer for each propulsion package.

Figure 11-2 depicts the data sources, analytical approach and basic assumptions of the life cycle cost analysis. All data used for the life cycle cost calculations were based on WTD or Booz, Allen analyses or studies of AC Drive. Where possible, assumptions were verified against BARTD actual maintenance costs and RMSH documentation prepared for the Miami/Baltimore chopper.

The maintenance and energy costs for a cam-controlled system are based on the cost and reliability data base[1] supplied by the DOT. It should be noted that the NYCTA is not following recommended WTD preventive maintenance and inspection schedules. Consequently, their preventive maintenance costs may be relatively low, and corrective maintenance costs relatively high, when compared with suggested or analytically derived AC propulsion maintenance costs. In theory, the reduced preventive maintenance effort should be reflected in poorer reliability and more corrective maintenance costs.

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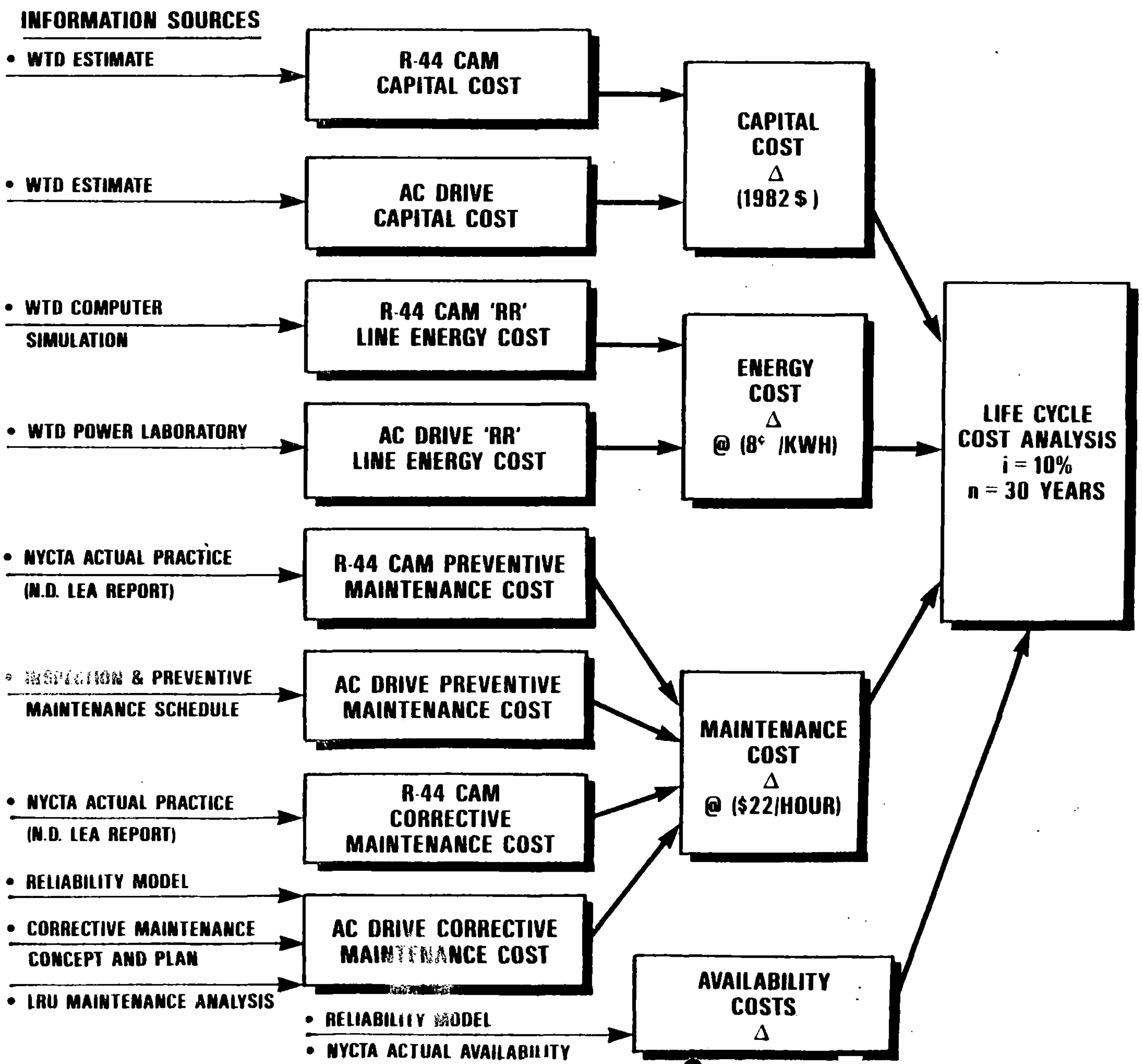
1 NYCTA R44 CAR, Cam-Controlled Propulsion System, Cost and Reliability Data Base, N.D. Lea & Associates, September 1983.

FIGURE 11-2

APPROACH TO LIFE CYCLE COST ANALYSIS



Caution should be used when comparing WTD recommended maintenance practices for AC Drive with actual NYCTA maintenance practices on their present equipment.

11.1.3 Organization of this Report

Following this introduction, each of the cost categories is discussed, and an explanation provided as to what is included and excluded from the analysis. Cost categories are:

- Capital Costs
- Energy Costs
- Preventive Maintenance Costs
- Corrective Maintenance Costs
- Availability Costs.

The life cycle cost comparison is performed consistently with DOT approved methodology. This should allow a straightforward comparison with the Garrett AC Drive system.

11.2 PROPULSION SYSTEM COSTS

11.2.1 Capital Costs

Capital costs for the WTD AC Drive Propulsion System include the following elements:

- Propulsion system purchase price
- Spare parts and warranty parts
- Spare cars needed to achieve required fleet availability.

The propulsion system purchase price and spare parts cost are discussed in this section. The effect of having a more dependable propulsion system on the number of transit vehicles a system would need to procure to provide a given level of service is discussed separately in Section 11.2.5.

11.2.1.1 Approach to Capital Cost Estimate (AC Drive)

(THE INFORMATION PRESENTED IN THIS SECTION IS SOLELY FOR THE PURPOSE OF PREPARING THE LIFE CYCLE COST ANALYSIS, AND DOES NOT CONSTITUTE AN OFFER TO SELL.)

Capital cost estimates for the AC Drive system were developed based on the following assumptions:

1. Non-recurring costs (engineering, manuals, training, RMSH and program management) are consistent with an already-developed technology. No major redesign effort is included; the estimate assumes system engineering, car layout and performance work, and startup support. Manuals, FMEA's, maintainability work, training programs, and other supporting documentation would be based on existing information modified for the specific application.

2. Manufacturing costs were estimated based on known material costs, adjusted for a quantity of 100 vehicles. Costs for GTO thyristors are based on these devices being routinely available in production quantities. The Toshiba devices currently in use are still priced relatively high, and the prices have begun to drop over the past year as more of them are sold. Estimates are based on quotations received from Mitsubishi, which are substantially lower than Toshiba's quotations, yet are based on slightly larger devices.

3. Standard WTD formulae have been applied to base cost estimates to account for warranty, division overhead and corporate overhead.

4. Industry-competitive profit margins have also been applied.

5. The base year is assumed to be 1982.

Based on these assumptions, WTD has estimated a selling price to the carbuilder of $262,000 per carset for a system with two inverters and $273,000 per carset for a system with four inverters.

To provide a perfect comparison with the existing R-44 equipment, the life cycle costs of the two systems should be compared using equally performing equipment. However, for this life cycle cost analysis, the WTD AC Drive System, as designed, is used in all cost calculations. Because the maintenance analyses and reliability prediction are based on the selected configuration, the life cycle cost comparison must also be based on the selected configuration. Improvements to the propulsion system, such as a totally enclosed motor, while increasing the capital cost, should be offset by better reliability, and therefore reduced operating or maintenance costs.

11.2.1.2 <u>Approach to Capital Cost Estimate (R-44 Cam)</u>

Capital cost estimates for the R-44 cam-controlled propulsion equipment have not changed since the Preliminary Design Review in 1982. The following assumptions were used to develop the estimate of $225,000 per carset:

- Original cost and price estimates for this program were reviewed, and factored to reflect that the quantity is reduced to 100 carsets.

- The WTD standard escalation formula was then applied to assume a base contract year of 1982.

11.2.1.3 Original Spare Part Costs

Spare part quantities and costs are generally determined by mutual agreement between transit properties and their suppliers, and are included in the vehicle contract as a capital cost.

For this analysis, however, spares provisioning as a capital cost is being excluded, at the direction of DOT. Because the R-44 fleet has long since exhausted its original spares, and spares provisioning may be viewed as a maintenance cost paid for as a capital cost, the spares requirements are considered irrelevant to this analysis.

However, in a situation where a transit property was introducing an AC Drive system into an existing cam or chopper operation, or where a new transit system was considering purchasing AC Drive or cam or chopper propulsion, the initial spares cost should be considered. The inventory level, and therefore holding costs, are influenced by equipment reliability, which is a major advantage of AC Drive. For example, a smaller percentage of spare AC motors would be required because breakdowns and time spent off the car being repaired would be less.

11.2.1.4 Warranty Costs

While there are no warranty provisions in the UMTA AC Drive contract, contracts generally require that propulsion motors, gear units, etc., be guaranteed for a period of two years.

Warranty costs represent some portion of maintenance costs that are paid for by the supplier. It would only complicate the cost analysis to increase the capital costs by a warranty cost figure, then reduce the properties' maintenance costs by the same amount of warranty cost. The capital costs of both AC Drive and the R-44 cam equipment include standard WTD formulae for warranty costs. For this analysis, annual maintenance costs for AC Drive are compared to annual maintenance costs for the R-44 cam, regardless of who actually pays the bill. In addition, the DOT life cycle cost methodology does not provide for increasing, decreasing, or variable annual maintenance costs. The approach assumes all operating costs remain constant over the life of the equipment.

11.2.2 Energy Costs

Energy costs with AC Drive are significantly less than for a cam-controlled system in operating service such as the "RR" line because:

- No power is lost in resistors during the frequent start ups.
- Regeneration is effective with closely spaced trains.

Energy consumption for the R-44 system was calculated by Westinghouse using their computer simulation[2] of the "RR" line profile and schedule. Total energy consumption, including auxiliary loads, at various car loadings was as follows:

Car Weight	R-44 Cam Energy Consumption (KwH/Car Mile) Propulsion	Auxiliaries	Total	% Trains at Each Load
AW0 = 87,000 lbs.	4.9	2.3	7.2	31%
AW1 = 98,400 lbs.	5.4	2.3	7.7	25%
AW2 = 130,000 lbs.	6.7	2.3	9.0	44%

The weighted average energy consumption is 8.12 KwH per car mile. Average energy costs for the NYCTA in 1982 were 8¢ per KwH. For a vehicle traveling 40,000 miles/year, energy costs would total:

$$8.12 \frac{\text{KwH}}{\text{Car Mile}} * 40,000 \frac{\text{Car Miles}}{\text{Year}} * .08 \frac{\text{Dollars}}{\text{KwH}} = \underline{\$25,984}$$

The energy cost to provide 5,120,000 car miles of revenue service each year would total:

$$8.12 \frac{\text{KwH}}{\text{Car Mile}} * 5,120,000 \frac{\text{Car Miles}}{\text{Year}} * .08 \frac{\text{Dollars}}{\text{KwH}} = \underline{\$3,325,952}$$

Energy consumption for the WTD AC propulsion system was measured in the Westinghouse power lab using the "Garrett Profile" of the R-44 line. Lab measurements did not include energy consumed for auxiliary loads. Results are indicated in Figure 11-3, along with comparable R-44 energy consumption. It was assumed that rush hour trains operate at AW2, midday trains at AW1 and night trains at AW0. For trains operating at AW2, it was assumed the AC propulsion system would be allowed to regenerate up to a system receptivity limit of 800 amperes/car. No regeneration savings were assumed for trains operating at AW1 or AW0 due to the longer headways during off-peak hours. Calculations are summarized below:

Car Weight	AC Drive Energy Consumption (KwH/Car Mile) Propulsion	Auxiliaries	Total	% Trains at Each Load
AW0 = 87,000 lbs.	4.0	2.3	6.3	31%
AW1 = 98,400 lbs.	4.3	2.3	6.6	25%
AW2 = 130,000 lbs.[3]	2.7	2.3	5.0	44%

2 NYCTA R-44 CAR, Cam-Controlled Propulsion System, Cost and Reliability Data Base, N. D. Lea and Associates, September 1983, page 14.

3 Regeneration permitted in this case.

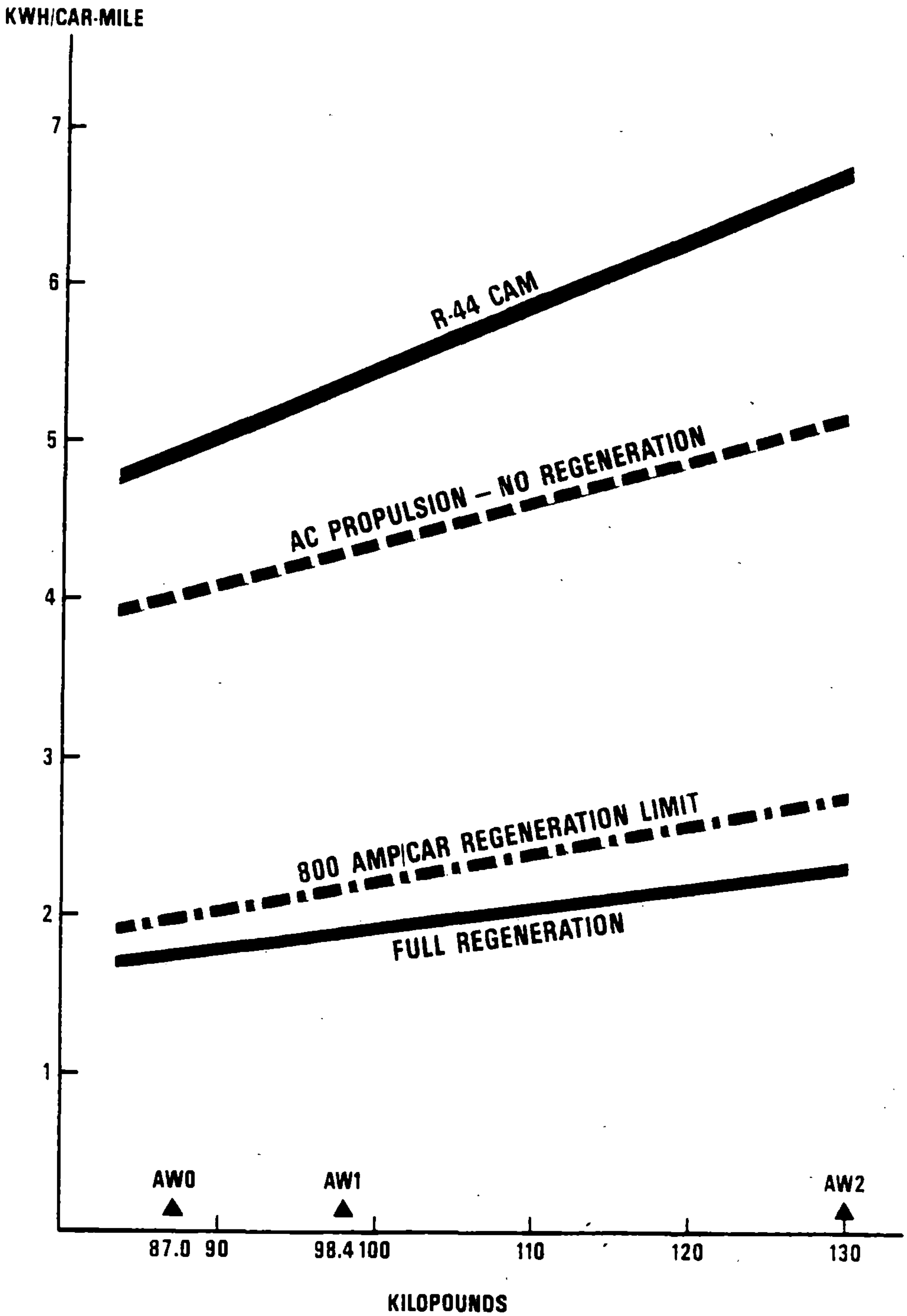


FIGURE 11-3

ENERGY CONSUMPTION COMPARISON (WITHOUT AUXILIARY LOADS)

The weighted average energy consumption is 5.80 KwH per car mile. For a vehicle traveling 40,000 miles/year, energy costs would total:

$$5.8 \frac{\text{KwH}}{\text{Car Mile}} * 40,000 \frac{\text{Car Miles}}{\text{Year}} * .08 \frac{\text{Dollars}}{\text{KwH}} = \underline{\$18,560}$$

This is $7,424/year less than a cam-controlled railcar in "RR" line service.

The energy cost to provide 5,120,000 car miles of revenue service each year would total:

$$5.8 \frac{\text{KwH}}{\text{Car Mile}} * 5,120,000 \frac{\text{Car Miles}}{\text{Year}} * .08 \frac{\text{Dollars}}{\text{KwH}} = \underline{\$2,375,680}$$

This is $950,272/year less than a fleet of cam-controlled railcars providing the same revenue-miles of service on the "RR" line. This analysis ignores the energy cost of "main-shopping" a railcar which has had a propulsion system failure.

11.2.3 Preventive Maintenance Costs

Preventive maintenance costs were calculated based on the AC Drive Inspection and Preventative Maintenance Schedule.[4] The schedule identifies preventive maintenance actions in terms of the recommended mileage interval, the time interval and the man hours required to perform each task. A corresponding NYCTA inspection class (B or C) is indicated as well as the skill level of personnel performing the maintenance. For simplicity, the DOT methodology assumes all labor to be costed at $22.00 per hour, regardless of skill level. Figure 11-4 summarizes the preventive maintenance schedule for AC Drive. Figure 11-5 separates the inspection labor from the overhaul labor as identified in Figure 11-4.

As is evident from Figure 11-5, Preventive Maintenance Requirements, a significant amount of the labor in preventive maintenance is due to overhauls, as identified in the AC Drive P.M. Schedule. Overhaul costs are not separately identified in the NYCTA data provided by the DOT. Apparent NYCTA practice is not to perform scheduled overhauls on their propulsion equipment. Therefore, to provide a fair comparison with the R-44 cam, the overhaul costs are not included in the life cycle cost analysis.

Using the "Inspection" column of Figure 11-5, the AC motor will require 3.24 hours/year/vehicle for preventive maintenance. The "control group" will require a total of 2.44 hours/year/vehicle (4 inverters) or 2.06 hours/year/vehicle (2 inverters). The control group includes the:

- Inverter
- Car Control and Motor Logic
- Resistor Assemblies

4 Revision C, April 23, 1984.

FIGURE 11-4
Annual Preventive Maintenance Hours--AC Propulsion System

Unit	Inspection and Preventive Maintenance Schedule Step	Inspection Interval (Miles)	Inspections Per 40,000 Miles	Man-Hours Per Unit	Quantity Per Vehicle	Annual Totals Per Vehicle
1. AC Motor	1.1 Inspect Air Inlets	10,000	4.000	.02	4	0.32
	1.2 Tighten All Cables	30,000	1.333	.10	4	0.53
	1.3 Perform Insulation Check	30,000	1.333	.25	4	1.33
	1.4 Lubrication	30,000	1.333	.20	4	1.06
	1.5 OVERHAUL	600,000	.067	8.00	4	2.13
						5.37
2. Gear Unit	2.1 Oil Analysis	30,000	1.333	.75	4	4.00
	2.2 Check Oil Level	10,000	4.000	.08	4	1.28
	2.3 Inspect Reservoir	10,000	4.000	.17	4	2.72
	2.4 Check Low Speed Bearing End Float	216,000	.185	.05	4	0.37
	2.5 OVERHAUL	400,000	.100	40.00	4	16.00
						24.37
3. Coupling	3.1 Check for Grease Throw Off	10,000	4.000	.01	4	0.16
	3.2 Check Lubricant Level	--	--	--	--	--
	3.3 OVERHAUL	400,000	.100	2.00	4	0.80
						0.96
4. Axle Ground Brushholder	4.1 Check Brushholder	30,000	1.333	.04	4	0.21
5. Truck Disconnect	5.1 Clean Contact Surfaces	400,000	.100	.05	4	0.020
	5.2 Check Latch	400,000	.100	.01	4	0.004
	5.3 Tighten Connections	400,000	.100	.01	4	0.004
						0.028

Annual Preventive

Unit	Inspection and Preventive Maintenance Schedule Step
6a. Inverter Box	6.1 Check Connections 6.2 Vacuum Dirt 6.3 Check Cables 6.4 Check Insulators 6.5 Check Gaskets 6.6 OVERHAUL
6b. Inverter Box	6.1 Check Connections 6.2 Vacuum Dirt 6.3 Check Cables 6.4 Check Insulators 6.5 Check Gaskets 6.6 OVERHAUL
7. Filter Capacitor Box	6.1 Check Connectors 6.2 Vacuum Dirt 6.3 Check Cables 6.4 Check Capacitors 6.5 Check Insulators 6.6 Check Gaskets 6.7 OVERHAUL
8. Line Switch Box	7.1 Blow Dirt Out 7.2 Check Air Regulator 7.3 Check Pressure Switch 7.4 OVERHAUL

FIGURE 11-4
Maintenance Hours--AC Propulsion System

Inspection Interval (Miles)	Inspections Per 40,000 Miles	Man-Hours Per Unit	Quantity Per Vehicle	Annual Totals Per Vehicle
30,000	1.333	.02	4	.107
30,000	1.333	.05	4	.267
30,000	1.333	.01	4	.053
30,000	1.333	.04	4	.213
30,000	1.333	.02	4	.107
--	--	--	--	--
				.747
30,000	1.333	.02	2	.053
30,000	1.333	.05	2	.133
30,000	1.333	.01	2	.027
30,000	1.333	.04	2	.107
30,000	1.333	.02	2	.053
--	--	--	--	--
				.374
30,000	1.333	.02	1	.027
30,000	1.333	.05	1	.067
30,000	1.333	.01	1	.013
30,000	1.333	.04	1	.053
30,000	1.333	.04	1	.053
30,000	1.333	.02	1	.027
--	--	--	--	--
				.240
30,000	1.333	.04	1	0.053
30,000	1.333	.30	1	0.400
30,000	1.333	.20	1	0.267
400,000	.100	12.00	1	1.200
				1.920

Unit	Inspection and Preventive Maintenance Schedule Step
9. Line Switches and Overload Relay	8.1 Check Connections 8.2 Check Magnet Valves 8.3 Inspect Main Contact 8.4 Inspect Interlocks 8.5 Inspect Arc Chutes 8.6 Inspect Shunts 8.7 Check Arc Chutes 8.8 OVERHAUL
10. Line Reactor	9.1 Check Connections 9.2 OVERHAUL
11. Car Control and Motor Logic	10.1 Test Logic Box 10.2 Check Harness Cable 10.3 Secure Dust Cover 10.4 Inspect LED Display
12. Knife Switch Box	11.1 Test Box 11.2 OVERHAUL
13. Resistor Assemblies	12.1 Clean Insulators 12.2 Blow Out Dirt 12.3 Check Resistor Tube 12.4 Tighten Connections

FIGURE 11-4

Maintenance Hours--AC Propulsion System

Inspection Interval (Miles)	Inspections Per 40,000 Miles	Man-Hours Per Unit	Quantity Per Vehicle	Annual Totals Per Vehicle
30,000	1.333	.01	1	0.013
30,000	1.333	.02	1	0.027
30,000	1.333	.01	1	0.013
30,000	1.333	.01	1	0.013
30,000	1.333	.01	1	0.013
30,000	1.333	.01	1	0.013
30,000	1.333	.01	1	0.013
400,000	.100	12.00	1	1.200
				1.305
75,000	.533	.05	1	0.027
400,000	.100	8.00	1	0.800
				0.827
400,000	.100	.01	1	0.001
400,000	.100	.01	1	0.001
400,000	.100	.01	1	0.001
400,000	.100	.01	1	0.001
				0.004
75,000	.533	.05	1	0.027
400,000	.100	4.00	1	0.400
				0.427
75,000	.533	.10	1	0.053
75,000	.533	.20	1	0.107
75,000	.533	.10	1	0.053
75,000	.533	.10	1	0.053
				0.266

FIGURE 11-4
Annual Preventive Maintenance Hours--AC Propulsion System

Unit	Inspection and Preventive Maintenance Schedule Step	Inspection Interval (Miles)	Inspections Per 40,000 Miles	Man-Hours Per Unit	Quantity Per Vehicle	Annual Totals Per Vehicle
14. Dynamic Brake Box	13.1 Inspect Box	30,000	1.333	.03	1	0.040
15. Tachometer	14.1 Inspect Tachometer	200,000	.200	.30	1	0.060
	14.2 Calibrate Tachometer	200,000	.200	1.00	1	0.200
						0.260
16. Voltage Sensor	No Preventive Maintenance Required					0.000

TOTAL HOURS

4 Inverters/Car	
Inspections	14.44
Overhauls	22.53
	36.97
2 Inverters/Car	
Inspections	14.07
Overhauls	22.53
	36.60

FIGURE 11-5
Preventive Maintenance Requirements
Hours/Year/40,000 Mile Vehicle

Unit	Man-Hours Per Year		
	Inspection	Overhaul	Total
1. AC Motor	3.24	2.13	5.37
2. Gear Unit	8.37	16.00	24.37
3. Coupling	0.16	0.80	0.96
4. Axle Ground Brushholder	0.21	--	0.21
* 5. Truck Disconnect	0.028	--	0.028
* 6a. 4 Inverter Boxes	0.747	--	0.747
* 6b. 2 Inverter Boxes	0.374	--	0.374
* 7. Filter Capacitor Box	0.240	--	0.240
* 8. Line Switch Box	0.72	1.20	1.92
* 9. Line Switches and Overload Relay	0.105	1.20	1.305
*10. Line Reactor	0.027	0.80	0.827
*11. Car Control and Motor Control Logic	0.004	--	0.004
12. Knife Switch Box	0.027	0.40	0.427
*13. Resistor Assemblies	0.266	--	0.266
*14. Dynamic Brake Box	0.040	--	0.040
*15. Tachometer	0.260	--	0.260
Total--4 Inverters	14.44	22.53	36.97
Total--2 Inverters	14.07	22.53	36.60

* Considered the "control group" for purposes of comparison to R-44 cam equipment. The gear unit, coupling, axle ground brushholder and knife switch box are assumed to be common equipment with the R-44 cam propulsion system and are not considered further in this cost analysis.

- Filter Capacitor Box
- Dynamic Brake Box
- Line Reactor
- Line Switch Box
- Line Switches and Overload Relay
- Tachometer
- Truck Disconnect.

Preventive maintenance costs for the R-44 cam system were provided to Westinghouse by DOT. The costs were based on actual NYCTA labor practices and maintenance capabilities. Data were also extrapolated from the 1981 UMTA Section 15 Report and TRIP. The propulsion system costs shown in Figure 11-6 reflect only control group and motor maintenance costs. Other costs for propulsion system components (e.g., gear unit, knife switch) were considered to be constant. The data on wheel inspection are not relevant to this analysis, but are included because they are part of the DOT methodology.

Inspection and preventive maintenance materials cost for the AC motor and solid state controls are considered negligible. The only material cost identified in the NYCTA/DOT data was brush replacement.

At the labor rate of $22/hour, preventive maintenance on the control group will cost $54/year (4 inverters) or $45/year (2 inverters) and on the AC drive traction motors $71/year. Wheel inspection costs are not changed. Annual preventive maintenance costs are thus reduced $739/year (4 inverters) or $748/year (2 inverters) per 40,000 mile vehicle as compared with the R-44 cam system.

11.2.4 Corrective Maintenance Costs

Figure 11-7 identifies the corrective maintenance costs for the Control Group and the AC Motor. The distance between corrective maintenance was based on the reliability analysis.

Corrective maintenance costs assume that the majority of secondary (off-line) repair work is performed by NYCTA personnel. The costs assume all printed circuit board repair will be performed by WTD, but all other work, such as trouble-shooting and repairing the inverter itself, can be performed by NYCTA using simple, commonly available equipment such as a VOM.

Corrective maintenance costs for the R-44 cam provided by the DOT are shown in Figure 11-8, along with the corresponding AC Drive corrective mainte- nance costs. As expected, significant savings are recognized in both con- trol group and motor maintenance. Annual corrective maintenance costs are thus reduced $3,792 (4 inverters) or $4,402 (2 inverters) per 40,000 mile vehicle as compared to the R-44 cam system.

FIGURE 11-6
Annual Propulsion System Preventive Maintenance
Costs for a Vehicle Traveling 40,000 Miles

Preventive Maintenance	R-44 Cam	AC Drive 4 Inverters	AC Drive 2 Inverters
• Control Group	$616	$ 54	$ 45
– Inspection Labor	616	54	45
– Inspection Materials	0	0	0
• 4 Traction Motors	248	71	71
– Inspection Labor	123	71	71
– Brushes (Materials)	125	0	0
• Wheel Inspection			
– Inspection Labor	24	24	24
Total Preventive Maintenance	$888	$149	$140
– Labor	$763	$149	$140
– Materials	$125	$ 0	$ 0

Source: R-44 Data: Booz, Allen Analysis of N. D. Lea Report, p. 7-12.

FIGURE 11-7
Corrective Maintenance Costs
(Annual Costs)

Line Replaceable Unit	Unit Distance Between Corrective Maintenance (Miles)	Quantity Per Vehicle	Failures Per Car Per Year	Remove & Replace Hours	Remove & Replace $	Repair* Costs	Average Annual C.M. Cost/ Vehicle
1a. 6-Pole GTO Inverter	103,500	4	1.546	.51	$11.22	$778	$1,220.13
1b. 6-Pole GTO Inverter	103,500	2	.773	.51	$11.22	$778	610.07
2. Filter Capacitor (6-Pack)	1,575,000	16	.406	.13	2.86	300	122.96
3. LS 2 Inductor	5.28×10^7	12	.009	.48	10.56	75	.77
4. L1 Fuse	1.32×10^8	4	.001	.35	7.70	250	.26
5. L2 Fuse	1.32×10^8	32	.010	.35	7.70	250	2.58
6. Dynamic Brake Circuit Heatsink	1,215,500	1	.033	.59	12.98	921	30.82
7. RC Diode Assembly	3,142,900	1	.013	.42	9.24	1,500	19.62
8. Power Resistors	4.33×10^7	72	.067	.58	12.76	75	5.84
9a. Control Logic (4 Inverters)	87,000	1	.460	.95	20.90	1,522	709.73
9b. Control Logic (2 Inverters)	150,000	1	.267	.95	20.90	1,522	411.95
Control Group Total							
4 Inverters							2,112.71
2 Inverters							1,204.87
AC Motor	4,272,000	4	.037	18.0	$396	$600	$36.85

* Represents labor and materials to repair the LRU.

FIGURE 11-8
Annual Propulsion System Corrective Maintenance
Costs for a Vehicle Traveling 40,000 Miles

Corrective Maintenance	R-44 Cam	AC Drive 4 Inverters	AC Drive 2 Inverters
• Control Group	$3,246	$2,113	$1,205
• 4 Traction Motors	2,696	37	37
• Wheel Servicing	953	953	1,251**
Total Corrective Maintenance	$6,895*	$3,103	$2,493

Source: R-44 Data: Booz, Allen Analysis of N. D. Lea Report, p. 20 as follows:

*	Corrective Maintenance Labor:	$3,407
	Replacement Parts Costs	3,613
	- Brushes	125
		$6,895

** Wheel servicing costs on the two inverter configuration have been increased to those required to maintain the wheel tolerance to within .250 inches, per N. D. Lea report, page 57.

11.2.5 Availability Costs

Due to the better reliability of the AC Drive system compared to the R-44 cam, fewer railcars will be needed to support peak revenue service. For the NYCTA "RR" line and schedule, a total of 128 vehicles are needed to have 100 available for peak service. Of the extra 28 vehicles, 16 are required due to propulsion system (un)availability, and the other 12 to various non-propulsion system problems.

The Reliability Study estimates a mean distance between failures of 1,068,000 miles for a carset of 4 traction motors and their gear units. This translates to a mean time between maintenance actions (MTBM) of 80,910 hours. With no other changes, this would increase the propulsion system MTBM from 141 hours for the cam control to 150 hours. As a result, the mean downtime decreases from 22.9 to 18.7 hours and the annual downtime from 492 to 379 hours. Supporting information is shown in Figure 11-9. The correspond- ing availability is 0.889, and the spare cars needed due to propulsion system availability decrease from 16.3 to 12.5. This projection does not give credit for the further reduction that may be expected as a result of the improved maintainability achievable by induction motors.

Improved maintainability of inverters as compared to cam controls should result in a substantial reduction in "control group repair" mean downtime. A very conservative estimate would be a reduction from 48 to 24 hours. This further reduces the propulsion system mean downtime to 12.5 hours and the annual downtime to 261 hours, and increases availability to 0.923. Supporting information is shown in Figure 11-10. The spare cars needed due to propulsion system availability are reduced to 8.4.

The availability analysis thus shows that several railcars could be saved (or used somewhere else) due to the improvement in the motor reliability and control group maintainability, as listed below:

- Motor only -- save 3.8 railcars
- Motor and control group -- save 7.9 railcars

The reliability of other railcar equipment being equal, a transit property could theoretically buy 120.1 AC Drive railcars[5] instead of 128 R-44 cam railcars and provide the same level of availability (i.e., 100 railcars at peak service). R-44 cars have been costed at $850,000 each, of which $225,000 is the propulsion sytem. The savings to a transit property would be 7.9 x $850,000 = $6.7 million. The railcars alone, excluding their propulsion systems, would save 7.9 x $625,000 = $4.9 million.

Because there would be fewer railcars carrying the same number of passengers the same number of miles, the average annual miles per railcar would

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5 Obviously, it is impossible to save 9/10 of a railcar. However, because this is a theoretical analysis, the railcar availability savings are based on saving 7.9 railcars.

FIGURE 11-9
Car Availability by Subsystem and Action
(Motors Only)

Operation	MTBM Hours	MDT Hours	Annual Down Time Hours	Availability
Control Group Inspection	758	6	24	.992
Control Group Repair	618	48	235	.928
Motor Inspection	758	1	4	.999
Motor Repair	80,910	96	14	.999
Wheel Inspection	758	.25	1	1.0
Wheel Servicing	939	31	101	.968
Propulsion System Total	150	18.7	379	.889

MTBM = Mean Time Between Maintenance
MDT = Mean Down Time

Source: N. D. Lea Report, Sept. 1983, page 18, modified by Booz, Allen.

FIGURE 11-10
Car Availability by Subsystem and Action
(Motors and Control Group)

Operation	MTBM Hours	MDT Hours	Annual Down Time Hours	Availability
Control Group Inspection	758	6	24	.992
Control Group Repair	618	24	117	.963
Motor Inspection	758	1	4	.999
Motor Repair	80,910	96	14	.999
Wheel Inspection	758	.25	1	1.0
Wheel Servicing	939	31	101	.968
Propulsion System Total	150	12.5	261	.923

MTBM = Mean Time Between Maintenance
MDT = Mean Down Time

Source: N. D. Lea Report, Sept. 1983, page 18, modified by Booz, Allen.

increase from 40,000 to 42,314. With present NYCTA maintenance practices, it is unclear how increasing the mileage would change preventive maintenance schedules, inventory levels and spare parts provisioning. For the life cycle cost analysis, preventive maintenance, corrective maintenance and energy savings were all mileage based for a 40,000 mile/year railcar. The "per vehicle" data shown in the next section for the life cycle cost of a propulsion system is not adjusted upward for this additional railcar usage; rather the life cycle cost of a fleet of railcars providing 5,120,000 miles of service is calculated.

11.3 LIFE CYCLE COST COMPARISON

Figure 11-11 presents the life cycle cost comparison of the R-44 cam versus the WTD AC Propulsion System. The methodology followed for the AC Drive column is consistent with the DOT approach in the R-44 column. Descriptions of how each number was arrived at are detailed below:

- Preventive Maintenance Cost--See Figure 11-6. The cost of the brushes for the DC motors is included in the replacement parts cost line.

- Corrective Maintenance Cost--See Figure 11-8. The cost(s) shown for AC Drive is the combination of the control group and traction motor maintenance shown in Figure 7, plus the $953 or $1,251 of wheel servicing costs. Corresponding D.C. costs were provided in the N. D. Lea Report on Page 20. Replacement parts costs for AC Propulsion are not identified as are the R-44 costs.

- Present Value of the Annual Maintenance Costs--The present value of 30 years of annual maintenance costs for AC Drive is $30,656 (4 inverters) or $24,821 (2 inverters), given a discount rate of 10%.

- Annual Energy Costs--See the calculations in Section 11.2.2. As is evident, and expected, significant savings occur in this area, on the average of $7,500/year per 40,000 mile railcar.

- Present Value of the Annual Energy Costs--Using the DOT prescribed Department of Energy Region 2 Present Worth Factor, the present value of 30 years of energy savings totals $188,198.

- Present Value of Recurring Expenses--This is the sum of the present values of the maintenance and energy costs. With AC Drive, a maintenance and energy cost savings of $118,000 (4 inverters) or $124,000 (2 inverters) is expected as compared to a similarly operated and maintained R-44 cam system.

- Capital Cost--These items were explained in Section 11.2.1. The purchase price of the AC Drive system is $48,000 (4 inverters) or $37,000 (2 inverters) more than the purchase price of an R-44 cam system.

FIGURE 11-11
Life Cycle Cost Summary

Cost Element	Per Car		
		AC Drive	
	R-44 Cam	4 Inverters	2 Inverters
Preventive Maintenance Cost	$ 763	$ 149	$ 140
Corrective Maintenance Cost	3,407	3,103	2,493
Replacement Parts Cost	3,613	incl.	incl.
Annual Maintenance Cost/Car	7,783	3,252	2,633
PV of Maintenance Costs	73,394	30,656	24,821
Annual Energy Cost	25,984	18,560	18,560
PV of Energy Costs	263,478	188,198	188,198
PV of Recurring Expenses	336,872	218,854	213,019
Capital Cost	225,000	273,000	262,000
Life Cycle Cost/Propulsion System	561,872	491,524	475,019

Number of Systems Times Mileage Adjustment	128	$\frac{(120.1)(128)}{(120.1)}$	
Total Cost of Propulsion Systems	$71,919,616	$62,915,072	$60,802,432
Cost of Spare Cars	$13,907,792	$7,040,820	$7,040,820
Life Cycle Cost	$85,827,408	$69,955,892	$67,843,252
Per Peak Period Car	$858,274	$699,559	$678,432

- Life Cycle Cost of Propulsion System--The life cycle cost of each system, $561,872 for the cam and $491,524 (4 inverters) or $475,019 (2 inverters) for the AC Drive, is the sum of the Present Value of the Recurring Expenses and the capital costs. A life cycle cost savings of about $70,000 (4 inverters) or $87,000 (2 inverters) should be expected. With an annual maintenance and operating cost savings of about $12,000, a capital cost penalty of $37,000 to $48,000 and an interest rate of 10%, the discounted payback period on an AC propulsion system would be in the range of 4-5 years.

- Number of Systems Times Mileage Adjustment--Per the DOT base data, 128 railcars are needed to provide 100 cars for peak service. The discussion in Section 11.2.5 demonstrates 7.9 railcars could be saved due to better AC Drive availability. However, the railcars would each travel additional mileage, consuming more maintenance and energy resources. The 30 year life of the propulsion system might also be shortened. Consequently, a mileage adjustment of 128/120.1 is multiplied by the carsets needed to provide the cost of a fleet of propulsion systems providing the required revenue service.

- Total Cost of Propulsion Systems--About $9-11 million would be saved for a "fleet of propulsion systems" providing 5,120,000 miles of service annually, relative to a R-44 cam system.

- Cost of Spare Cars--Per the N. D. Lea Report, the life cycle cost of a spare railcar is $869,237. Sixteen R-44 cam cars would cost $13,907,792. Only 8.1 AC Propulsion railcars would be needed, reducing the cost to $869,237 (8.1) = $7,040,820.

- Life Cycle Cost--The sum of the propulsion system cost and spare cars needed due to propulsion system unavailability is defined as the life cycle cost. Consequently, AC propulsion reduces the life cycle cost/peak period car from $858K to $699K (4 inverters) or $678K (2 inverters), a savings of 18%-21%.

12. ENERGY CONSUMPTION TEST DATA

The "Garrett profile" was adopted as the RR Line profile for demonstration purposes and is shown in Figure 12-1. This route profile was developed by Garrett AiResearch Corporation as a common basis for evaluation. It is equivalent in thermal duty (i.e. RMS currents) to the NYCTA RR Line. The profile consists of three sections. The first two sections (1 & 2) are identical low speed runs with a coast interval. Section 3 is a higher speed run consisting of maximum acceleration followed immediately by braking. Repeated runs of 1, followed by 2 and 3 were made to simulate the entire RR Line profile.

Additional runs were also made using the so-called "Miller profile", which simulates more severe thermal duty and includes high-speed braking. However, the energy measurements described in this section are for the purpose of input to the Cost & Economic Analysis (Section 11) and therefore are based solely on the RR Line-equivalent Garrett profile.

12.1 TEST RESULTS

During these runs, the car control computer calculated the energy consumed and the distance traveled. It calculated the energy consumed by summing the product of the line current, the line voltage and the delta time (1/109 sec.). The tests were run with the line fully receptive to all the regenerative energy the inverter could supply. The car control computer displayed this number at the end of each run, along with the energy consumed assuming no regeneration by excluding negative line currents from the summation. The computer also displayed the energy consumed when the line current was limited to 800 Amps per car by limiting the line current used in the summations to 800 Amps in regeneration. The car control computer calculated the distance by summing the product of the RPM from the tachometer, the delta time and an appropriate scale factor for the gear ratio and wheel diameter. From these numbers, the energy consumed in terms of kilowatt-hours per car mile was calculated and plotted on the graph shown in Figure 12-2.

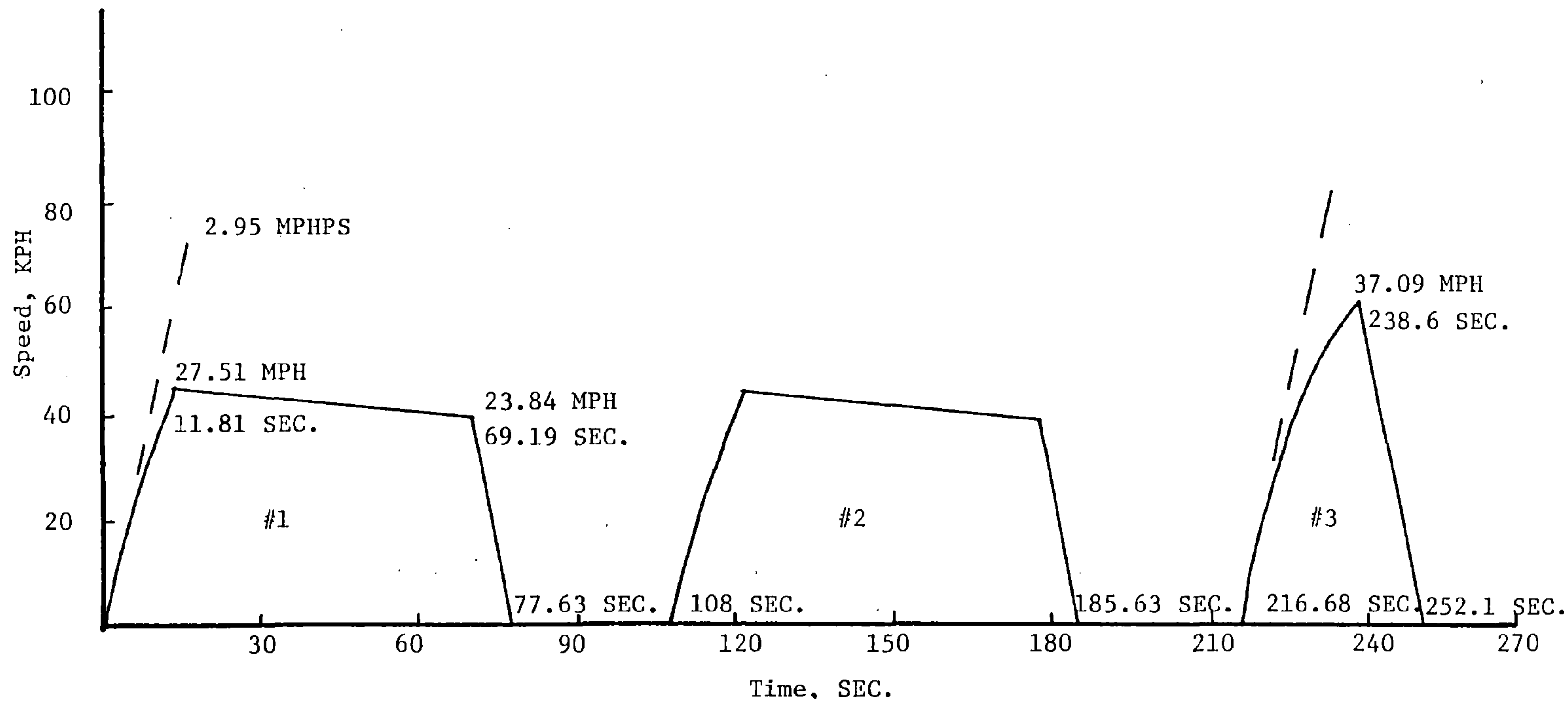


Figure 12-1

Garrett Synthetic Profile

The tests were run for car weights of 90,000 and 130,000 lbs., thus covering the range of an empty car to a crush-loaded car.

For comparison, the energy consumed by a cam-controlled car is also shown in Figure 12-2. These particular values were calculated using a Westinghouse train performance program which simulated the same profile.

12.2 COMMENTS

Even without regeneration, the AC drive proved to be more efficient than the cam controlled cars due to the lack of resistors in the control of the motors. The AC drive would be similar to the chopper for this case.

The energy consumption with regeneration is approximately 50% of that without regeneration, whether the 800 Amp limit is considered or not. This is mainly due to the relatively low speeds used in the simulation compared to the speeds for which the equipment was designed. The maximum design speed is 80 MPH while the maximum profile speed was 37 MPH. With higher speeds, the 800 Amp limit would prove to be a more severe penalty. With the speeds used in the profile, the line current rarely exceeded 800 Amps per car. However, the AC drive would still be very efficient and would show a significant reduction in total energy consumed due to its high regeneration capacity.

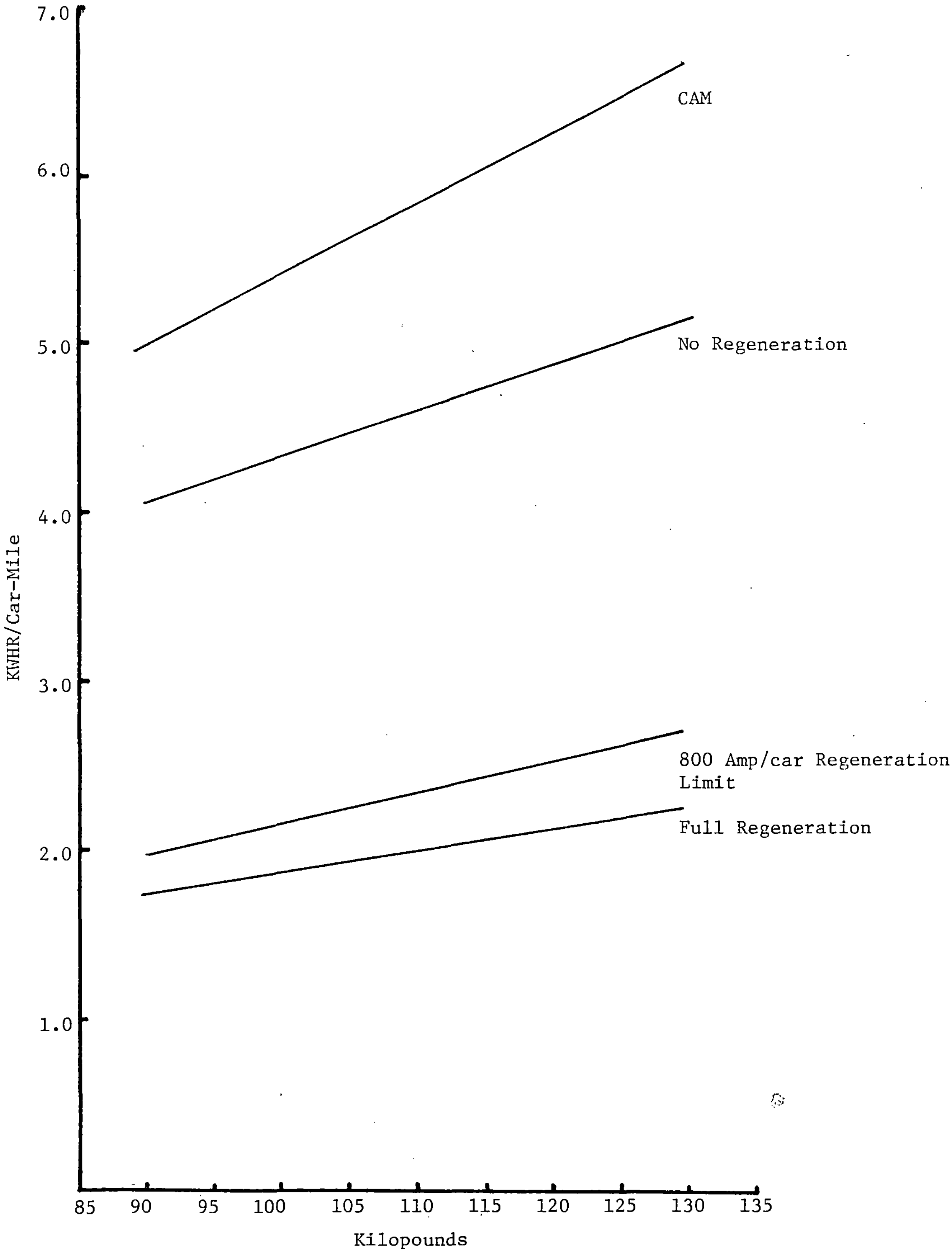


Figure 12-2

Propulsion System Energy Consumption
(Garrett Profile)

13. AC DRIVE TROUBLESHOOTING CONCEPT

The AC drive system consists of the following vehicle elements.

1. Knife Switch Box
2. Line Switch and OLR
3. Line Reactor
4. Dynamic Brake Chopper
5. Dynamic Brake Resistors
6. Regenerative Brake Circuit
7. Regenerative Brake Circuit Transformer
8. Line Filter Capacitors
9. Inverter
10. Gate Drivers
11. Current Sensors
12. Voltage Sensing Circuit
13. Tachometers
14. Axle Ground Brushes
15. AC Motor
16. Gears and Coupler
17. Logic
18. Truck Disconnect
19. Converter
20. Master Controller

The troubleshooting concept for each element is described below. The concepts are simple and straightforward making maintenance of the AC drive system an easy matter.

13.1 VEHICLE MICROPROCESSOR FAULT REPORTING

In the passenger compartment of each vehicle will be 4 lights indicating whether or not the inverters are operational. The light will indicate that all of the equipment needed to propel and brake one axle is fully operational. If the light is extinguished, it does not mean, however, that the equipment is not still being used in whatever way it is still functional. These lights will be latching and will be commanded from the CCL (car control logic).

Each day the lights should be checked and a note made of the number of failed inverters. The following action should be taken depending on the number of failed inverters:

0	failed inverters	fully operational
1 to 3	failed inverters	repair at the earliest convenient time
4 to 5	failed inverters	remove from service at the end of the day
6 to 8	failed inverters	remove from service at the end of the run

These guidelines are based on an 8 car train and NYCTA duty.

As abnormal conditions are detected by the CCL (car control logic) or reported to the CCL from the MCL (motor control logic) they will be retained in non-volatile memory. When it has been determined by the CCL that the car or an inverter must be shut down this will be automatically done by the CCL and the reason for the shutdown will be stored in the non-volatile RAM. As mentioned above the inverter go light will be extinguished.

The first thing that the maintenance personnel will do to troubleshoot a failed inverter (by failed inverter is meant a failure of anything needed to drive one axle in both power and brake as indicated by the extinguished go light) is to attach a handheld terminal to an I/O Port of the CCL and ask the CCL to tell in English why the equipment was taken out of service. The CCL will respond and the reason will be printed on the printer of the handheld terminal. This printout will be part of the maintenance report. Next the maintenance personnel will initiate microprocessor self diagnostics through the handheld terminal. This will be accomplished with a simple command or a dedicated button on the terminal. The series of tests that will then be executed by the microprocessor will further define the problem; nearly to the component level. After the microprocessor has completed the self diagnostics it will list any abnormal conditions again on the terminal of the printer.

In some cases it will be necessary to use an oscilloscope or ohmmeter in conjunction with the microprocessor diagnostics to isolate the failure. This is true when a switching device is found to fail to turn on. The failure could be the logic, the gate driver, or the device. In this case the signal must be traced by looking at the input and output of the gate driver board while having the microprocessor output a continuous stream of gate commands. These cases are described below.

With the microprocessor diagnostics, it may be possible to change components on the car without taking the inverter or brake circuit to the bench for troubleshooting. Other failures may not be definable to the component level and will require bench testing.

The microprocessor diagnostics should also be used after any part or module replacement to verify that the problem is corrected.

13.3 VEHICLE MICROPROCESSOR SELF DIAGNOSTICS

13.3.1 Microprocessor Check

a. Plug the handheld maintenance terminal into the interface port connected to the car control logic cradle.

b. Initiate the computer check. This check will first verify that the car control logic is responding to the terminal and then that each motor control logic can communicate with the car control logic over the dual port ram interface.

Checks can now be made to identify failed components in the inverter and the brake circuit. These checks will be made by the microprocessors themselves as initiated from the handheld maintenance terminal. The tests involve commands from the car control logic to a particular motor control logic to quickly turn on and off a switching device. The car control logic then monitors the response of the inverter input current or voltage to conclude whether a device is operational or not. All that is required of the maintenance person is to initiate the test and then read the results of the test on the handheld terminal. He is not required to measure any rise times of the voltages or currents. This will be done by the car control logic internally.

The major advantage of the self diagnostics is that it can localize the problem to a small enough area that the failed component can be identified and replaced on the vehicle. This can help solve the problem of tied up inventory of failed components near the work bench. It is also advantageous to troubleshoot the failed component in the total system. If the faulty device can be identified quickly enough then component changing on the car is practical. Even if an authority would not choose to change components on the car, the self diagnostics can be used to identify the failed module with great accuracy. After the module has been replaced the self diagnostics can be used to verify that the vehicle is fully operational. The personnel repairing the module on the bench will also be provided with a localized failure report rather than a vague statement which only states that the module is defective.

The device names that are used in the explanation below are those found on Figure 13-1 "Schematic of Inverter Motor and Regenerative Braking Circuit".

13.3.2 Inverter Check

This test will be done with voltage applied to the inverter. The pulse duration of the firing pulses will be approximately one millisecond. This will produce current pulses that are well beneath the device ratings.

a. Check for Short Circuits in the GTO's.

The CCL (car control logic) will command the MCL (motor control logic) to individually fire GTO's 1 through 6. The CCL should not measure any current in the DC link.

If current is measured the magnitude of the current will reveal which GTO has failed. If GTO-3 were fired and the current rise was sharp, then GTO-4 would be expected to be shorted. If the current rise was slow then GTO-2 or GTO-6 would be expected to be shorted. A determination of which GTO is shorted is evident after all the GTO's have been fired. It should be noted that the absolute value of the current rise does not have to be predicted ahead of time. Only the relative rise time is needed. Although this short has been referred to as a GTO short the short could also be in the snubber circuit around the GTO.

Also, with the gate driver board design shorted GTO's can be detected in another manner. A shorted GTO will pull down the power supply on the gate driver board and result in an SOS (low voltage indication).

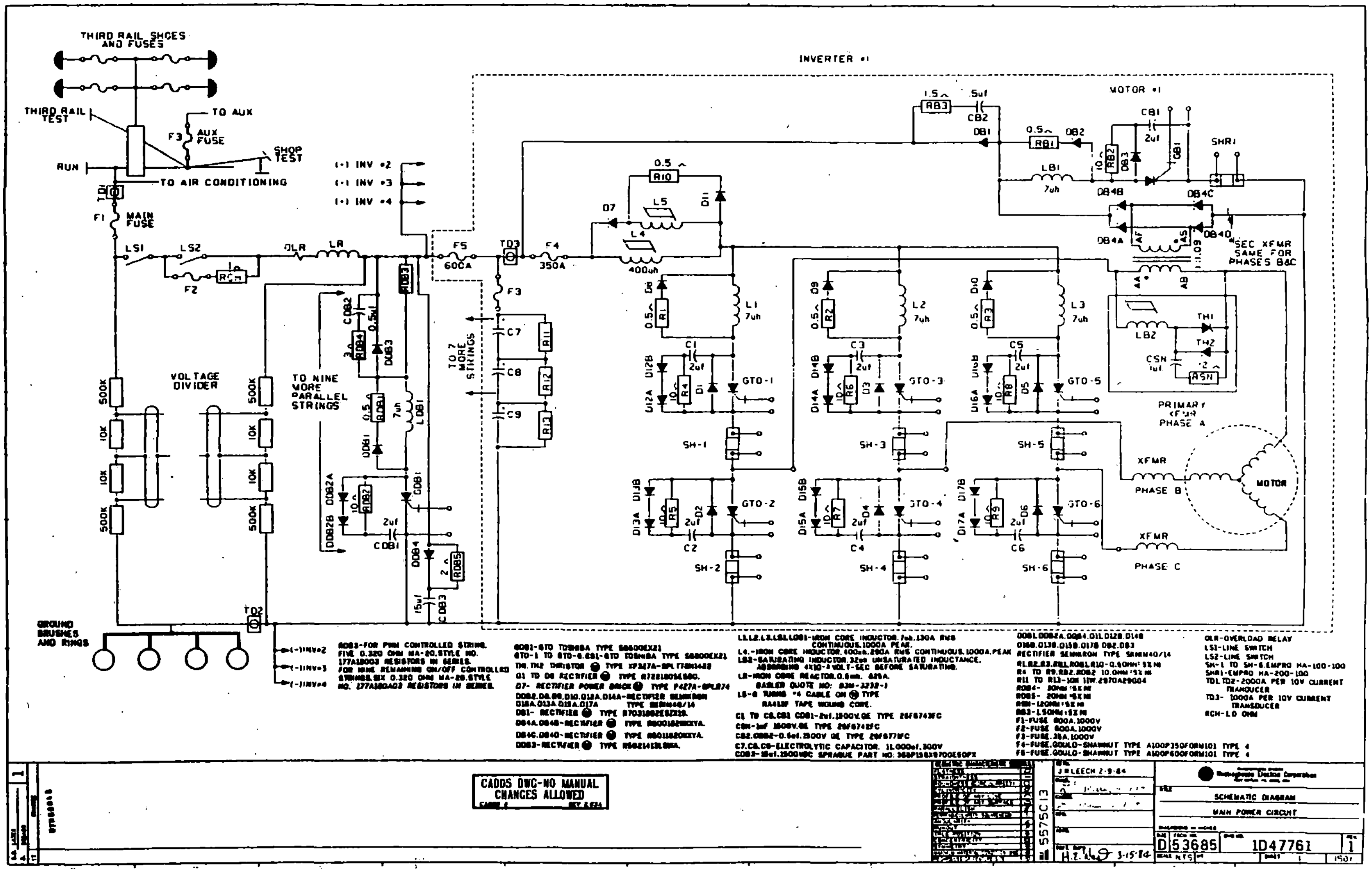


Figure 13-1
Main Power Schematic

This SOS signal will exist even if the GTO's are not being fired. The SOS signal would be reported to the CCL.

b. Check for GTO's That Will Not Fire.

The GTO's will be commanded to fire two at a time for a short pulse duration. This will be done with voltage applied to the inverter. The GTO pairs will be opposite but not in the same pole. If a current rise is not seen by the CCL while the GTO's are fired, then a GTO did not fire. The particular faulty GTO can be located by checking the appropriate combinations. For instance, if GTO-1 and GTO-4 were fired and no currents were measured then one or the other would be faulty. If the firing of GTO-1 and GTO-6 resulted in a current rise, then it would be established that GTO-4 is the faulty device.

This test establishes that GTO's can or cannot fire but it does not reveal the reason why. Further testing is needed to determine this. The problem could be the MCL, the gate driver board, the GTO, or connections in between.

c. GTO Gate Drive Test.

This test is used to troubleshoot the failure of a GTO to fire.

The maintenance personnel will command the logic to enter a mode that will produce a continuous string of gate drive pulses to an unpowered inverter. The troubleshooter will then use an oscilloscope to determine where the failure occurred. Looking at the input and output of the gate driver board will show if the gate driver signal is being sent from the logic and whether or not the gate driver board is sending gate pulses to the GTO. This will isolate the failure to the logic, the gate driver, or the GTO.

13.3.3 Regenerative Brake Circuit Check

The check of the regenerative brake circuit is contingent upon having a functioning inverter. The inverter functional checkout described in steps 13.3.2.a & b must proceed this test and be successfully passed.

All of the tests for the brake circuit involve applying pulses of voltage phase to phase and measuring the rise in the DC link current. Firing various elements in the brake circuit will change the series impedance of the phase to phase path and change the rise time of the measured currents. Since only a relative rise time is needed the measurement by the microprocessor is as simple as measuring the DC link current at a fixed time after the GTO's are fired and then comparing the results. This measurement will be made internally by the CCL. The maintenance personnel will simply be told that the circuit has failed a particular test step and what the possible failures could be.

a. Check for Single Device Failures in the Diode Bridge DB4.

A short of a single diode in the diode bridges DB4 needs to be checked first because it can greatly complicate the testing if it exists and has not yet been identified.

If a DB4 diode is shorted the secondary of the brake circuit transformer will be shorted when one polarity of voltage is applied to the transformer and open when the other polarity is applied.

Apply a pulse of voltage from the A to B phases of the motor using GTO-1 and GTO-4 and measure the current response.

Apply a pulse of voltage from the B to A phases of the motor using GTO-3 and GTO-2 and measure the current response.

If the response of the two steps differs by more than a predetermined amount that a DB4 diode has shorted in either the A or B phases. By performing the same test between the other two phase combinations the phase with the shorted diode can be identified.

b. Check for shorted devices across either the primary or secondary of the regenerative brake circuit transformer.

This check can be made with the same data that is stored in the microprocessor from step A. If one phase of the brake circuit has a short of the transformer then the current rise times measured involving that phase will be faster (a higher current will be recorded) than the rise time when the voltage was applied to the other two phases. If two phases had a short, then the combination of the two shorted phases would result in a rise time higher than the other two combinations. In the unlikely event that all three phases were shorted the test would fail.

The following devices could short the transformer: TH1, TH2, two diodes in DB4, GB1, CB1, and the transformer primary itself.

Shorted windings in the traction motor would also show up in this test in the same manner. The motor failure is less likely and troubleshooting should begin with the brake circuit. However if no problem is found with the brake circuit an ohmmeter check should be made on the motor to check for shorted windings.

Successful passage of steps A and B are necessary to proceed on to the following steps and the microprocessor would be programmed in this manner.

c. Check for TH1 and TH2 Firing.

To illustrate how TH1 and TH2 are checked the A phase will be used as the example.

GTO-1, GTO-4, and GTO-6 will be fired together and the current rise measured by the CCL.

GTO-1, GTO-4, and GTO-6 will be fired together again but this time also firing TH1 in the A phase.

Firing TH1 will reduce the inductance of the current path by shorting out the A phase transformer primary inductance and a change in the current rise time measured by the CCL should occur.

If no change is measured then TH1 failed to fire.

Next the CCL would command GTO-3, GTO-2, and GTO-6 to be fired together with and without firing TH2 and measure the differences in the current rises.

If no change is measured then TH2 failed to fire.

d. Check for GB1 firing and DB4.

To illustrate how GB1 and DB4 are checked the A phase will be used as the example.

GTO-1, GTO-4, and GTO-6 will be fired together and the current rise measured by the CCL.

GTO-1, GTO-4, and GTO-6 will be fired together again but this time also firing GB1 in the A phase.

Firing GB1 will reduce the inductance of the current path by shorting the A phase transformer secondary and a change in the current rise time measured by the CCL should occur.

Next the CCL would command GTO-2, GTO-3, and GTO-5 to be fired together with and without firing GB1 and measure the differences in the current rises.

If no change is measured in either step then GB1 failed to fire or two diodes are open in DB4, the GB1 failure is most likely. If no change is measured in one step but is in another then a diode in DB4 is open.

e. GTO or Thyristor Gate Drive Test.

This test is used to troubleshoot the failure of a GTO or thyristor to fire.

The maintenance personnel will command the logic to enter a mode that will produce a continuous string of gate drive pulses to an unpowered brake circuit. The troubleshooter will then use an oscilloscope to determine where the failure occurred. Looking at the input and output of the gate driver board will show if the gate drive signal is being sent from the logic and whether or not the gate driver board is sending gate pulses to the GTO or thyristor. This will isolate the failure to the logic, the gate driver, or the GTO or thyristor.

For the thyristors the gate driver is normally called a gate pulse amplifier.

13.3.4 Dynamic Brake Circuit Check

To check the dynamic brake circuit the line filter capacitors will be charged and then the line switch will be opened.

If a brake control GTO has failed as a short, then the capacitor voltage will be gone in about one second.

If the capacitor voltage holds (relatively speaking since there are bleed down resistors on the capacitors, these resistors bleed down the voltage with a time constant of about 100 seconds) then the GTO's will be pulsed on and off for a short time interval. If a drop in the capacitor voltage is measured when the GTO is pulsed then the GTO is operating. All of the eight paths will be checked in this manner.

To troubleshoot the failure of a GTO to fire do the following:

The maintenance personnel will command the logic to enter a mode that will produce a continuous string of gate drive pulses to an unpowered dynamic brake circuit. The troubleshooter will then use an oscilloscope to determine where the failure occurred.

Looking at the input and output of the gate driver board will show if the gate drive signal is being sent from the CCL and whether or not the gate driver board is sending gate pulses to the GTO. This will isolate the failure to the logic, the gate driver, or the GTO.

13.3.5 Parameter Monitoring

In addition to initiating diagnostic test procedures, the handheld terminal could also be used to minitor the value of any parameter measured or calculated by the computers. On a slow basis (once a second or once every half second) the value of the parameter could be updated on the terminal display.

13.4 TROUBLESHOOTING PROCEDURES FOR THE VEHICLE ELEMENTS

13.4.1 Knife Switch Box

a. Failure Modes

1) Open Fuse

2) Burned Switch Blade or Contacts

b. Diagnostics

The CCL will measure zero volts on the line filter capacitors even after the line switch has closed. An unpowered ohhmeter check will reveal the state of the fuse. A visual check of the switch will show its condition.

c. Maintenance Action

Repair on the vehicle.

13.4.2 Line Switch and OLR

a. Failure Modes

1) Faulty Magnet Valve

2) Faulty Cylinder

3) Faulty Air Regulator

4) Bad Contact Tips

5) Bad Magnet Valve Coil

6) Open Fuse

13) Open or Shorted 1 OHM Charging Resistor

8) Charging Resistor Switch Failure

b. Diagnostics

Failures of the switch to close or open will be detected by the CCL as it monitors the status of the auxiliary contacts. This failure will be reported to the maintenance personnel when he attaches the handheld terminal and asks for the known cause of failure.

Failures of the charging resistor and its switch will also be detected by the CCL. If the resistor is not inserted into the circuit when the line switch is closed then a rapid rise in the line filter capacitor voltage will be detected by the CCL.

c. Maintenance Action

Repair on the vehicle.

13.4.3 Line Reactor

a. Failure Modes

1) Shorted Winding (full or partial)

2) Open Winding

3) Bad Connection

b. Diagnostics

Failures of the line reactor are very few. It is one of the least likely items to fail on the car. For this reason the diagnostics of its failures will be limited to an ohmmeter check.

Shorted windings would reduce the inductance of the reactor and this would be very hard to detect by the onboard logic. On a scheduled bases though the reactor should be disconnected and its inductance measured.

An open winding would result in the loss of voltage to the inverter and would be detected. However, fuses would be checked first before the failed reactor would be found.

A bad connection would heat up and show visual signs of failure.

c. Maintenance Action

A failed reactor would be removed and replaced. The failed reactor would be sent to the vendor or an outside shop for repair.

13.4.4 Dynamic Brake Chopper

a. Failure Modes

1) Shorted GTO or Snubber Capacitor

2) Failure of GTO to Turn On

3) Other Failures in the Snubber Circuit

b. Diagnostics

A shorted GTO or snubber capacitor will be detected in the microprocessor self diagnostics.

The failure of a GTO to turn on will be detected in the microprocessor self diagnostics.

Other failures in the snubber circuit can go undetected until they cause the failure of the GTO. For this reason the snubber circuit devices should all be checked whenever a GTO is changed.

c. Maintenance Action

Since the failures can be localized to a small area the failed device can be identified quickly and changed on the car. Failed parts would be disposed of.

13.4.5 Dynamic Brake Resistors

a. Failure Modes

1) Broken or Damaged Brake Resistors

2) Shorted or Open Windings of the DI/DT Reactor

3) Failures in the Freewheeling Circuit

b. Diagnostics

An open resistor or DI/DT reactor would appear to the microprocessor diagostics the same as the failure of the GTO to turn on. An ohmmeter could quickly determine which had failed. A visual inspection of the resistors might also show a failed resistor.

Resistors with changed resistance values would still operate and would be detected at a given maintenance interval when they were measured. A shorted DI/DT reactor and other component failures in the freewheeling circuit would go undetectd until it caused the failure of the GTO. For this reason the devices in the freewheeling circuit should be checked with an ohmmeter whenever a GTO is changed.

c. Maintenance Action

Since the failures can be localized to a small area the failed device can be identified quickly and changed on the car. Failed parts would be disposed of.

13.4.6 Regenerative Brake Circuit

a. Failure Modes

1) Shorted Semiconductor Switching Devices

2) Failure of Semiconductor Switching Devices to Turn On

3) Snubber Device Failures

4) Shorted or Open Windings in the DI/DT Reactors

b. Diagnostics

The existance of a shorted switching device will be detected by the microprocessor diagnostics and isolated to the particular phase. An ohmmeter will then be used to identify the particular failed device. Failure of GB1, TH1, TH2, and the diodes in DB4 to conduct can be detected by the microprocessor diagnostics. Failure of CB1 to a short would appear the same as a GB1 short to the microprocessor diagnostics except it would not result in a continuous SOS message from the gate driver board. Other snubber failures would go undetected until they would cause a GTO or thyristor failure. For this reason the snubber circuit devices should all be checked whenever a GTO or thyristor is changed.

Open windings on the DI/DT reactors would appear the same as a device failure to turn on. An ohmmeter would be used to check the reactor. A shorted DI/DT reactor and other component failures in the freewheeling circuit would go undetected until it caused the failure of the GTO or thyristor. For this reason the devices in the freewheeling circuit should be checked with an ohmmeter whenever a GTO or thyristor is changed.

c. Maintenance Action

Since the failures can be localized to a small area the failed device can be identified quickly and changed on the car. Failed parts would be disposed of.

13.4.7 <u>Regenerative Brake Circuit Transformer</u>

a. Failure Modes

1) Shorted or Open Windings

2) Primary to Secondary Shorts

b. Diagnostics

Partially shorted windings that change the transformer turns ration and primary to secondary shorts would cause unbalanced currents in braking. This is not detectable by the microprocessor diagnostics but it is a rare failure. Shorted windings would appear to the microprocessor diagnostics to be the same as a shorted device across the winding.

An ohmmeter will be used to identify the transformer as failed.

c. Maintenance Action

A failed transformer would be removed and replaced. The failed transformer would be sent to the vendor or an outside shop for repair.

13.4.8 Line Filter Capacitors

a. Failure Modes

1) Open F2 Fuse

2) Failed Capacitor to Open or Short

b. Diagnostics — The fuse counter circuit will detect open fuses by detecting a loss of voltage at the positive end of each capacitor string. This will be reported to the maintenance personnel when the CCL is initially interrogated.

Failed capacitors will be detected by visual inspection. A rough check of the total capacitance of the vehicle is possible by measuring the voltage delay time during the dynamic brake microprocessor test. At a scheduled maintenance interval the capacitors should all be checked for capacitance value and ESR. This interval would be several years.

c. Maintenance Action

Remove and replace the failed component on the vehicle.

13.4.9 Inverter

a. Failure modes

1) Shorted GTO's

2) GTO's That Fail to Fire

3) Snubber Circuit Failures

4) DI/DT Reactor Failures

5) Freewheeling Circuit Failures

b. Diagnostics

The microprocessor diagnostics will be able to identify a shorted GTO. Also the continuous SOS signal from the gate driver board because of the shorted gate to cathode will also identify a shorted GTO and will be reported by the microprocessor diagnostics.

The microprocessor diagnostics will be able to identify a GTO that fails to fire with the help of an oscilloscope.

Shorts in the GTO snubber capacitor or the reverse diode (Cl & Dl for GTO-1) will look like a shorted GTO but without the continuous SOS signal from the gate driver board. An ohmmeter will identify the failed device.

An open freewheeling reactor would be diagnosed as being the failure of a switching device to turn on. These failures are rare.

Other snubber circuit failures and freewheeling circuit failures will be undetectable until they cause a GTO failure.

Whenever a GTO is changed the snubber circuit and freewheeling circuit should be checked with an ohmmeter.

c. Maintenance Action

Since the failures can be localized to a small area the failed device can be identified quickly and changed on the car. Failed parts would be disposed of.

13.4.10 <u>Gate Drivers</u>

a. Failure Modes

1) Command signals are received from the logic but improper gate drive pulses are produced.

b. Diagnostics

The maintenance personnel will be able to identify a failed gate driver board with the help of an oscilloscope check and the continuous string of firing commands from the microprocessor.

c. Maintenance Action

Remove and replace the failed gate driver board.

Return the failed PCB to West Mifflin for repair.

13.4.11 <u>Current Sensors</u>

a. Failure Modes

1) Incorrect Output From the Hall Effect Current Measuring Device

b. Diagnostics

If the four DC link currents do not add up to the ground return current then there is either a ground fault or a sensor failure. Using the microprocessor diagnostics the sensors can be tested one at a time to find the failed sensor.

The failure could also be caused by the input circuit of the CCL.

c. Maintenance Action

Remove and replace the failed sensor.

13.4.12 <u>Voltage Sensing Circuit</u>

a. Failure Modes

1) Incorrect Output From the Voltage Sensing Circuit

b. Diagnostics

Failure of the voltage circuit will result in overvoltage or undervoltage shutdown of the vehicle.

The failure could also be caused by the input circuit of the CCL.

c. Maintenance Action

Remove and replace the failed voltage sensing circuit.

Return the failed circuit to West Mifflin for repair.

13.4.13 Tachometers

a. Failure Modes

1) No Output From the Tach When the Train is Moving According to the Other Tachometers

b. Diagnostics

The CCL will note that one tachometer is not working.

The failure could also be in the MCL that reads and counts the tach pulses.

c. Maintenance Action

Remove and replace the failed tachometer.

13.4.14 Axle Ground Brushes

a. Failure Modes

1) Bad Brushes

2) Broken Connection

b. Diagnostics

Visual inspection at a regular maintenance interval.

c. Maintenance Action

Remove and replace brushes and tighten connections.

13.4.15 AC Motor

a. Failure Modes

1) Winding Insulation Failure (winding short)

2) Bad Connection

3) Open Winding

b. Diagnostics

Any failure in one stator winding phase will cause current unbalances and inverter performance that is noticeably different than the other inverter/motor systems.

Shorted windings will cause the step in the regenerative brake circuit microprocessor diagnostics which checks for shorts across the braking transformer primary to fail. The braking transformer and the motor are in series so a change in the impedance of either one with respect to the other phases would be detected. An ohmmeter check can differentiate between the two failures. The motor would be checked last since its failure is less likely.

c. Maintenance Action

Remove and replace the motor.

Send the failed motor to the vendor for repair.

13.4.16 Gears and Coupler

a. Failure Modes

1) Failed Bearing

2) Worn Gearing

3) Worn Coupling Teeth

b. Diagnostics

At a scheduled maintenance interval do the following:

Remove the reservoir cover and check the magnet for chips. Gold or copper colored particles in the oil is also indicative of a bearing failure.

Check the gearing backlash.

Check the coupling backlash.

c. Maintenance Action

Remove and replace worn out units.

Overhaul the removed unit.

13.4.17 Logic

a. Failure Modes

1) Improper Output Logic Levels with Proper Input Commands

b. Diagnostics

Begin with the self check initiated with the maintenance handheld computer.

If the logic is suspected of incorrectly reading a parameter, the parameter can be measured on an oscilloscope while monitoring the internal value of the parameter with the handheld terminal. The failure of the logic to output gate control signals is tested in the microprocessor diagnostics and with the use of an oscilloscope. If a logic problem is suspected replace the module with a known working unit and retest.

c. Maintenance Action

Remove and replace the failed logic module.

Identify the failed PCB's on a bench tester.

Return the failed PCB's to West Mifflin for repair.

13.4.18 Truck Disconnect

a. Failure Modes

1) Bad Contacts

b. Diagnostics

Bad contacts would increase the impedance of one of the motor phases. However, failures of the truck disconnect are extremely rare and it would be one of the last things to check.

c. Maintenance Action

Visually inspect for evidence of overheated contacts.

Replace contacts or springs as needed.

13.4.19 Converter

a. Failure Modes

1) Input Circuit Breaker is Tripped.

a) Shorted Thyristor

b) Defective Control Logic Plug-In Module

c) Shorted Line Filter C1

d) Shorted Transformer T1

e) Shorted Inductor L4

f) Open Circuit Between Power Components and Logic Module

2) Fuses F1 or F2 are blown

a) Capacitor C5 is Failed

b) Shorted Diode Bridge

c) Shorted Inductor L4

3) Overvoltage Shutdown

a) Defective Control Logic Plug-In Module

b. Diagnostics

Use an ohmmeter to check thyristors and diodes.

Replace the control module with a known working unit.

Visually check for capacitor swelling.

Visually check for transformer overheating.

Visually check for inductor overheating.

Check circuit with ohmmeter.

Check L4 inductor resistance to ground. Should exceed 100k.

c. Maintenance

Remove and replace failed components.

Return inductors and transformers to vendor for repair.

Return control module to West Mifflin for repair.

13.4.20 <u>Master Controller</u>

a. Failure Modes

1) Train Line Signals are Incorrect

b. Diagnostics

Troubleshoot with VOM.

c. Maintenance

Repair failed controller.

APPENDIX A

INVERTER VOLTAGE AND CURRENT WAVEFORMS TEST PROCEDURE

STARS AC PROULSION PROJECT

LAB TEST PROCEDURE

TEST TITLE: I-1C REVISION NO.: 2
INVERTER VOLTAGE AND CURRENT WAVEFORMS

WRITTEN BY: PAUL MERLINO REVISION DATE: 09/26/84

TEST OBJECTIVE:

TO EVALUATE THE DESIGN OF THE INVERTER BY MONITORING THE VOLTAGES AND CURRENTS OF THE POWER DEVICES, AND DETERMINING THE WORST CASE CONDITIONS. TO NOTE AND CORRECT ANY UNUSUAL CONDITION, SUCH AS: HIGH VD, DV/DT, DI/DT, OR HEAT BUILD-UP. ALSO, DETERMINE WORST CASE PEAK INSTANTANEOUS MOTOR LINE CURRENT.

TEST DESCRIPTION:

USING THE MOTOR CONTROL LOGIC DEVELOPED FOR THE AC DRIVE, THE MOTOR CAN BE CYCLED UP AND DOWN, AND LOCKED AT ANY SPEED (FREQUENCY). VOLTAGE AND CURRENT WAVEFORMS WILL BY TAKEN OF THE VARIOUS COMPONENTS, AND THE WORST CASE CONDITIONS NOTED. A COMBINATION OF THE FOLLOWING VARIABLES WILL BE TESTED:
LINE VOLTAGE WILL VARY FROM 425 TO 750 VOLTS. (SPEC. 2.2.1.1 AND 2.8)
SET FREQUENCIES WILL VARY FROM 1 TO 200 HZ. (0 TO 6000 RPM)
LOAD WILL VARY FROM "NO-LOAD" TO +/- 1 P.U. SHAFT TROQUE (745 FT-LBS).

STATUS: COMPLETE

1. NONE OF THE DEVICES WERE STRESSED OVER THE SPEC SHEET LIMITS.
2. THE CRITICAL PARAMETERS FOR THE GTO'S ARE:
   A. MAX DV/DT ALLOWED IS 350 V/US, WE HAD 200 V/US WORST CASE.
   B. MAX V-PEAK (VDRM) ALLOWED IS 2500 VOLTS, WE HAD 1160 VOLTS MAX.
   C. MAX VD (SEE PG. 6,7) ALLOWED IS 600 VOLTS, WE HAD 120 VOLTS MAX.
3. THE WORST CASE IS AT HIGH LINE OF 750 VOLTS.
4. THE WORST CASE IS AT FULL TORQUE, WHICH IS DRAWING MAX CURRENT.
5. THE HIGHEST MOTOR CURRENT OCCURS WHEN YOU FIRST GO INTO 6-STEP.
6. ~~THE TRANSITION FROM PWM TO QUASI-SIX STEP CAUSES THE WORST LINE~~ DISTURBANCE.
7. THE HEATSINK REMAINED COOL THROUGH ALL OF THESE TESTS.
8. THE VOLTAGES AND CURRENTS WERE LOOKED AT FOR THE NEW MOTOR, AND

THERE WASN'T MUCH DIFFERENCE. SO ONLY A FEW OF THE WAVEFORMS WERE TAKEN.

PROCEDURE:

<u>PRELIMINARY</u> (PRE-TEST)

1. CALIBRATE INSTRUMENTATION.
2. INSERT T&M RESEARCH 2M-8 .004922 OHM SHUNT IN SERIES WITH SH-1.
3. INSERT T&M RESEARCH 2M-8 .004908 OHM SHUNT IN SERIES WITH SH-2.
4. INSERT T&M RESEARCH .00049 OHM SHUNT IN SERIES WITH MOTOR-A.
5. SET UP OSCILLOSCOPE AND SCOPE CAMERA.
6. SET UP TORQUE AND SPEED INSTRUMENTATION.

<u>OPERATION</u> (AT 2L LAB, AND AT POWER LAB AT WEST MIFFLIN)

1. ATTACH VOLTAGE PROBE OR CURRENT LEAD TO THE DEVICE BEING MEASURED.
2. ACCELERATE THE MOTOR TO THE DESIRED SPEED, PHOTOGRAPH THE WAVEFORM FROM THE OSCILLOSCOPE, AND RECORD THE LINE VOLTAGE, FREQUENCY, AND LOAD.
3. REPEAT STEP 2 UNTIL AN ACCURATE REPRESENTATION OF THE WAVEFORMS IS ACHIEVED.
4. REPEAT STEP 2 FOR THE WORST CASE CONDITION.

EQUIPMENT:

2L LAB LOAD SIMULATOR OR LCS POWER LAB CONSISTING OF:

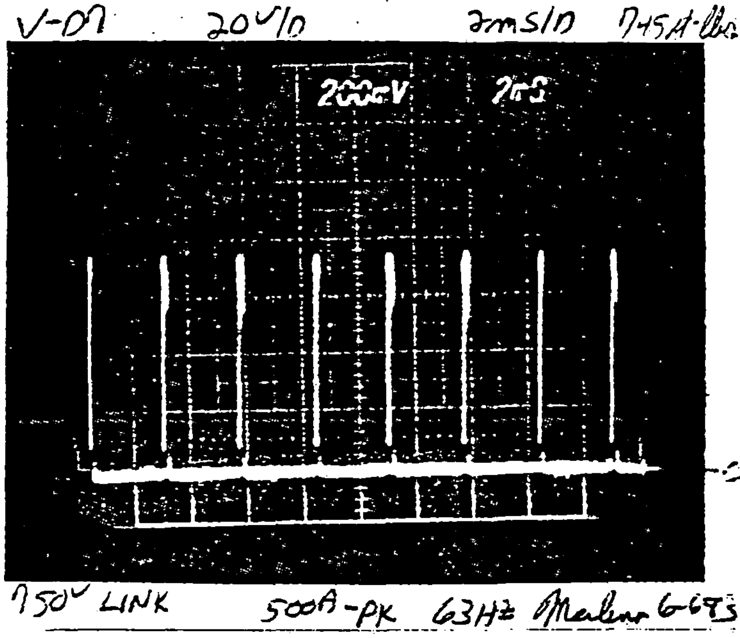
A) 0 - 1000 VOLT DC POWER SUPPLY CAPABLE OF REGENERATING.
B) DC LOADING MACHINE OR DUAL CONVERTERS FOR LOADING AC MOTOR.
C) SHAFT TORQUE TRANSDUCER WITH METER.
D) LOADING MACHINE CONTROLLER (SIMULATOR).
E) SHAFT SPEED COUNTER.
F) METERING TO MEASURE DC LINK VOLTAGE AND CURRENT.

INSTRUMENTATION:

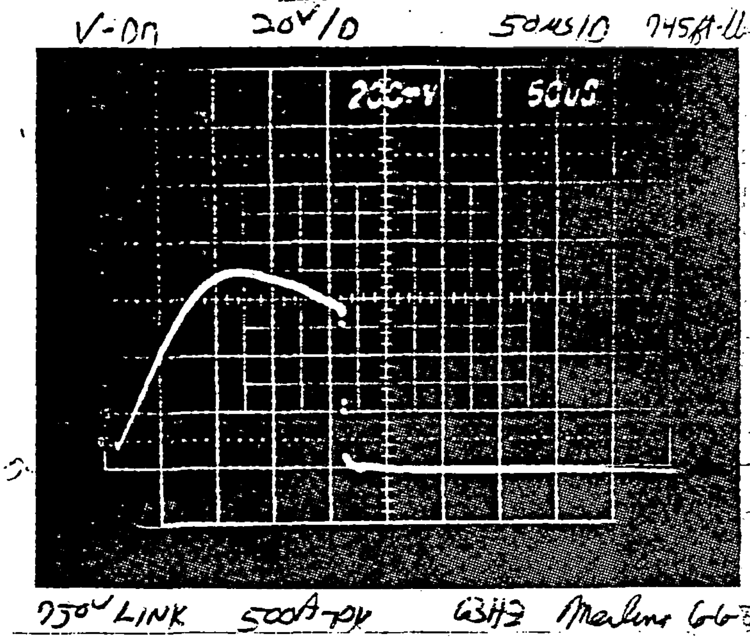
MEASURE THE VOLTAGE OR CURRENT OF THE FOLLOWING DEVICES INDEPENDENT OF EACH OTHER.

1. VOLTAGE ACROSS D7.
2. VOLTAGE ACROSS D11.
3. VOLTAGE ACROSS D8.
4. VOLTAGE ACROSS D12.
5. VOLTAGE ACROSS GTO-1/D1.
6. CURRENT THROUGH SH-1 (GTO-1/D1)
7. VOLTAGE ACROSS GTO-2/D2.
8. CURRENT THROUGH SH-2 (GTO-2/D2)
9. VOLTAGE ACROSS D13.
10. VOLTAGE ACROSS L1.
11. CURRENT THROUGH MOTOR LEAD A.

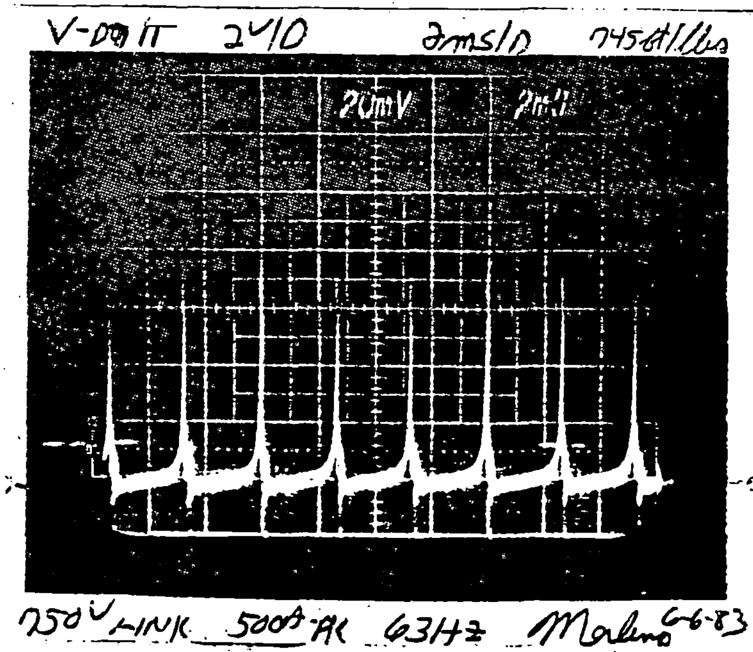
OUTPUTS: SCOPE WAVEFORMS OF THE VARIOUS DEVICES.



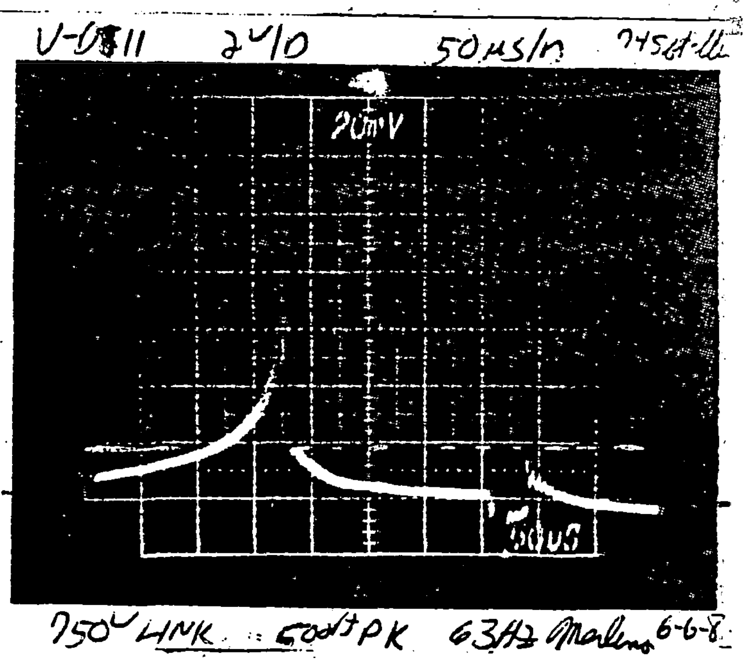
VOLTAGE ACROSS D7



VOLTAGE ACROSS D7



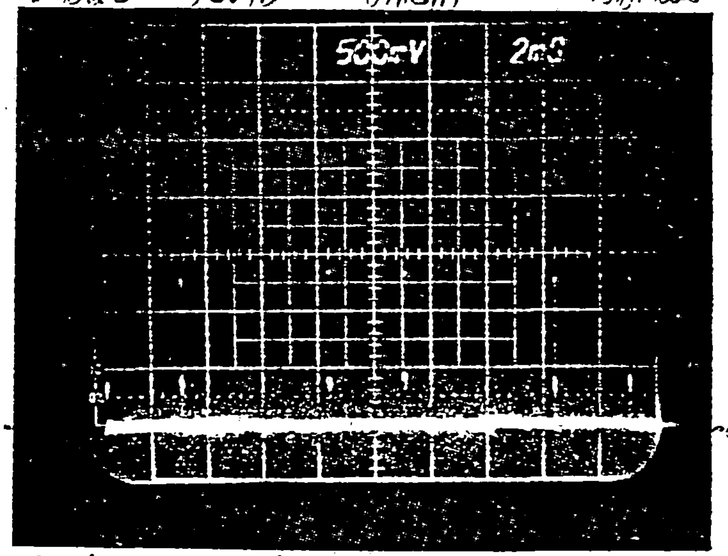
VOLTAGE ACROSS D11



VOLTAGE ACROSS D11

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

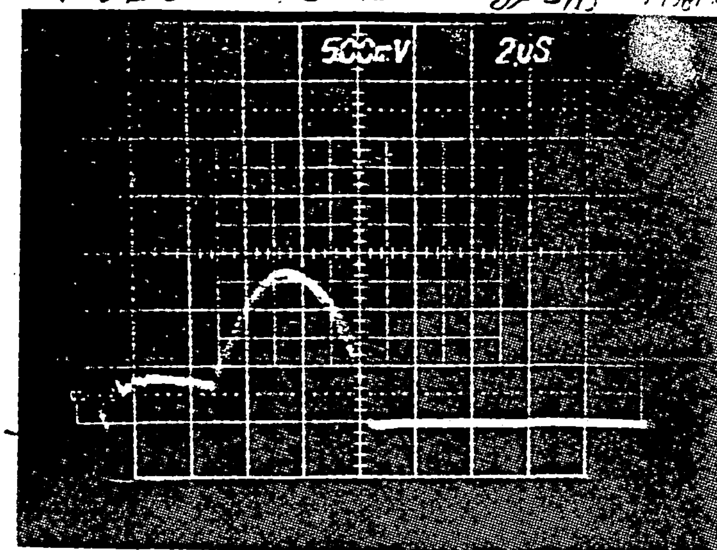
V-D8 50V/D 2mS/D 745ft-lbs



750V-LINK 500A-PK 63Hz Marlens 6-6-83

VOLTAGE ACROSS D8

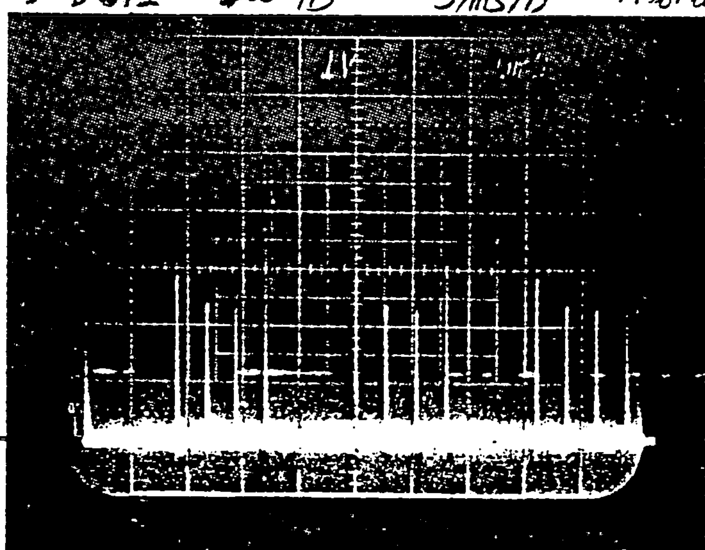
V-D8 50V/D 2µS/D 745ft-lbs



750V-LINK 500A-PK 63Hz Marlens 6-6-83

VOLTAGE ACROSS D8

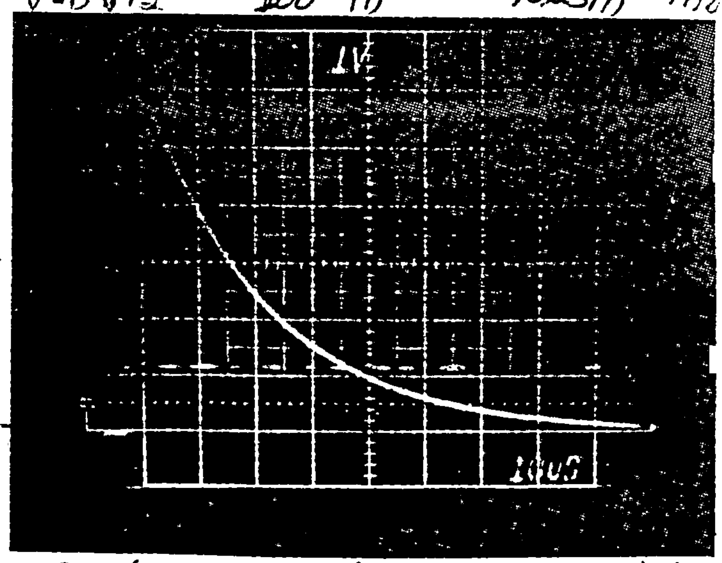
V-D12 200V/D 5mS/D 745ft-lbs



750V LINK 500A-PK 63Hz Marlens 6-6-83

VOLTAGE ACROSS D12

V-D12 200V/D 10µS/D 745ft-lbs

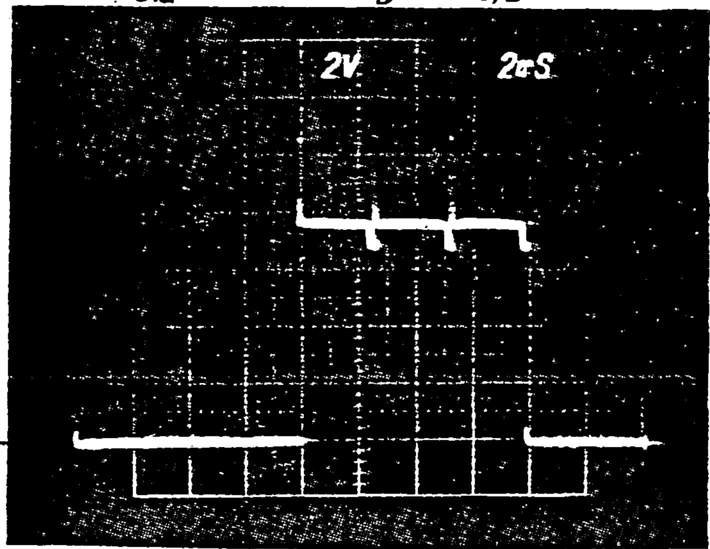


750V LINK 500A-PK 63Hz Marlens 6-6-83

VOLTAGE ACROSS D12

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

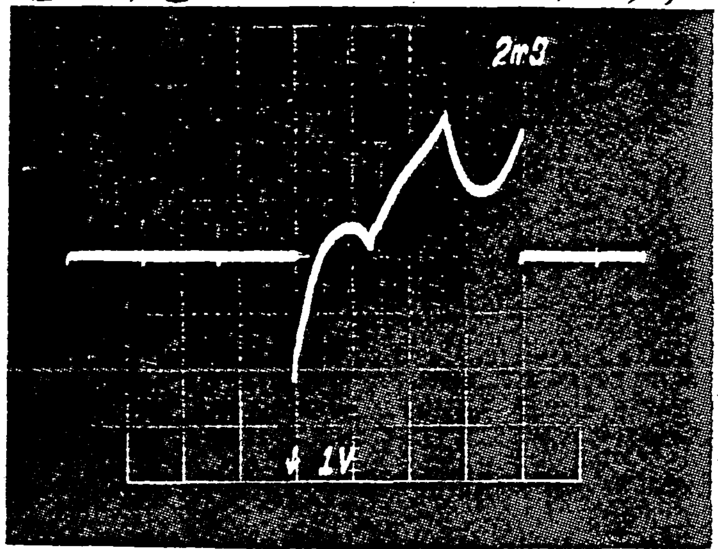
V-GTO1 200V/D 2ms/D 6-6-83



750V-LINK 500A-PK 63HZ Marlins

VOLTAGE ACROSS GTO-1/D1

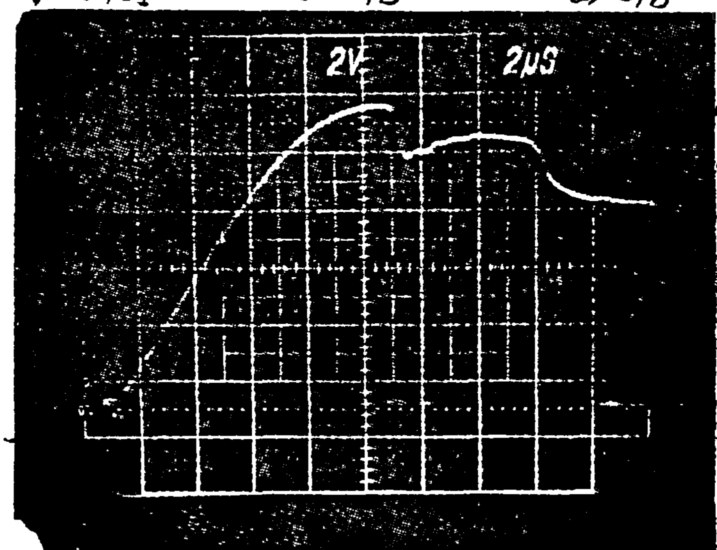
I-GTO1 200A/D 2ms/D



750V-LINK 500A-PK 63HZ Marlins 6-6-83

CURRENT THROUGH SH-1 (GTO-1/D1)

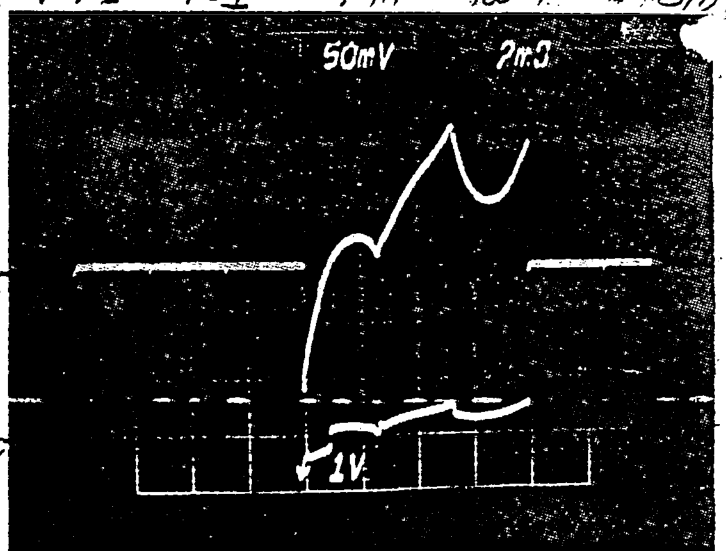
V-GTO1 200V/D 2µs/D



750V-LINK 500A-PK 63HZ Marlins 6-6-83

VOLTAGE ACROSS GTO-1/D1
VD = 120V, DV/DT = 200 V/US

V+I-GTO1 5V/D 200A/D 2ms/D

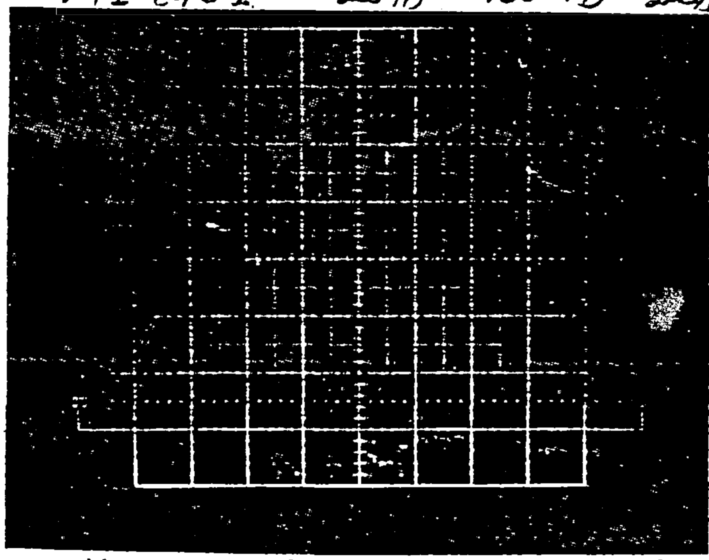


750V-LINK 500A-PK 63HZ Marlins 6-6-83

VOLTAGE AND CURRENT (GTO-1/D1)

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

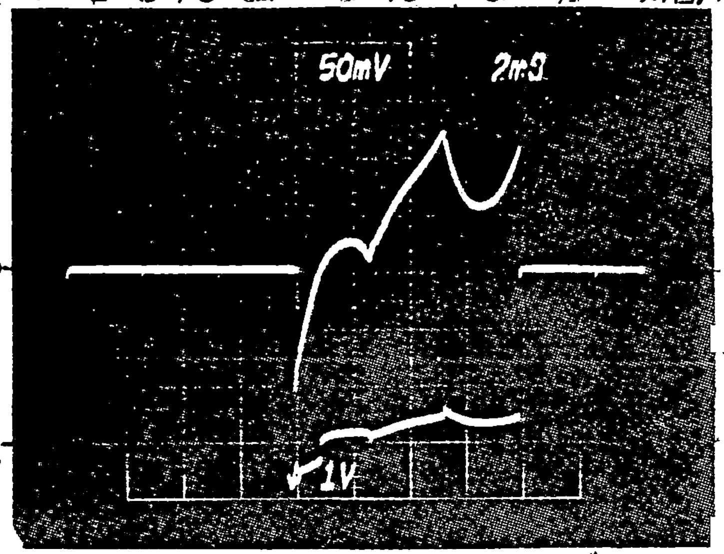
V+I-GTO2 200V/D 100A/D 2uS/D



750V LINK 500A-PK 63HZ Merlino

VOLTAGE AND CURRENT (GTO-2/D2)

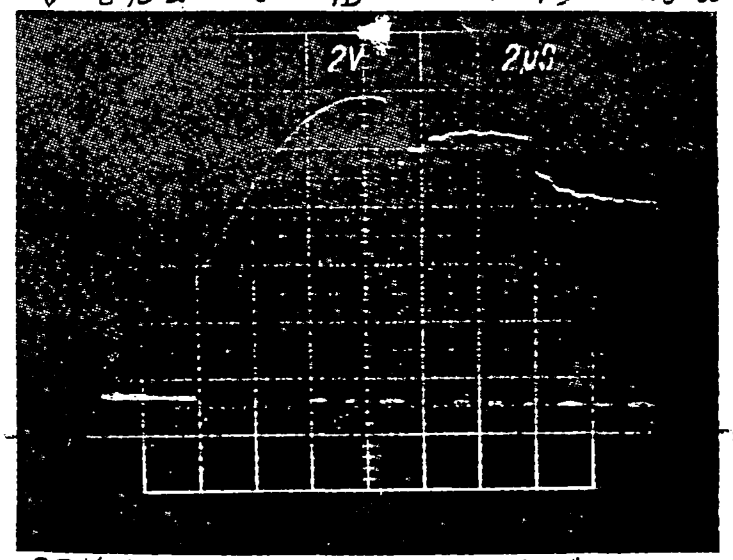
V+I GTO-2 5V/D 200A/D 2ms/



750V LINK 500A-PK 63HZ Merlino 6-6-8

VOLTAGE AND CURRENT (GTO-2/D2)

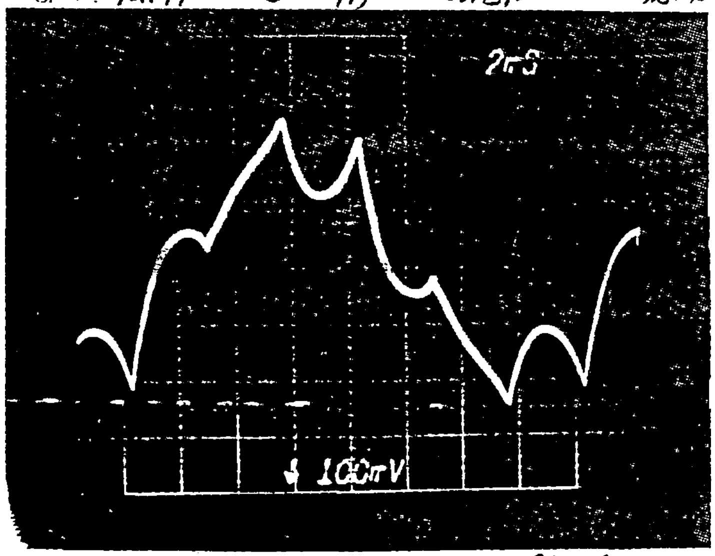
V-GTO2 200V/D 2uS/D 745H-Wo



750V-LINK 500A-PK 63HZ Merlino 6-6-83

VOLTAGE ACROSS GTO-2/D2
VD = 120V, DV/DT = 200 V/US

I-MOTOR A 200A/D 2mS/D 745H-W

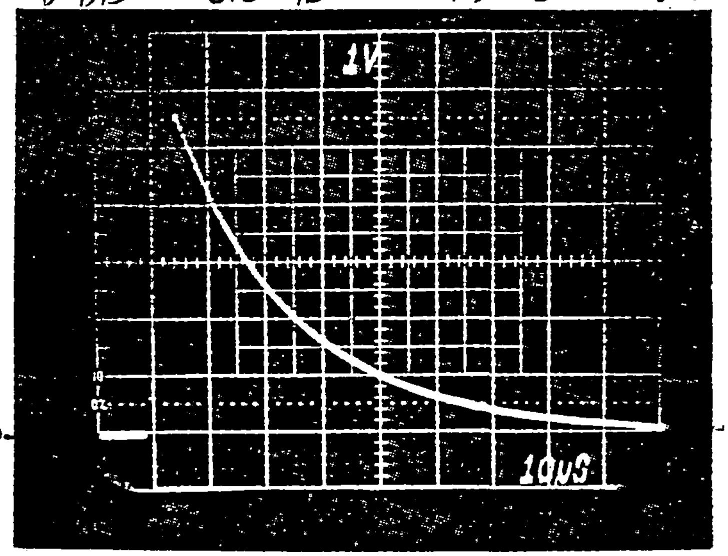


750V LINK 500A-PK 63HZ Merlino

CURRENT THROUGH MOTOR-A

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

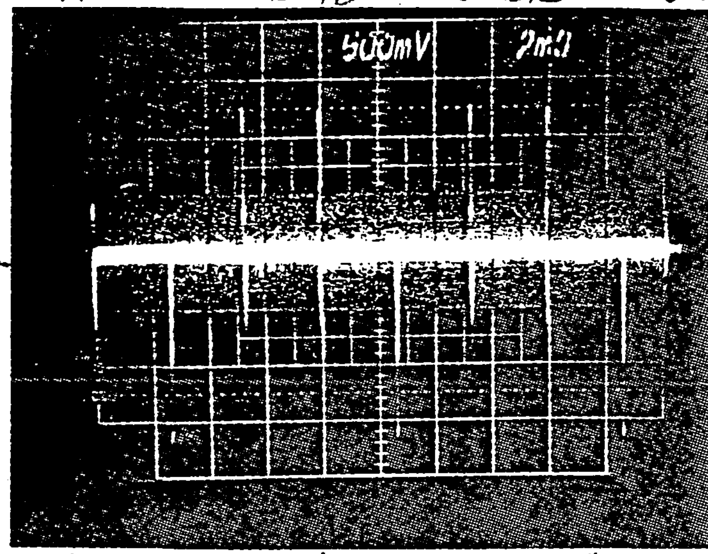
V-D13 100V/D 10µS/D 745ft-lbs



750V LINK 500A-PK 63HZ Marlene 6-6-83

VOLTAGE ACROSS D13

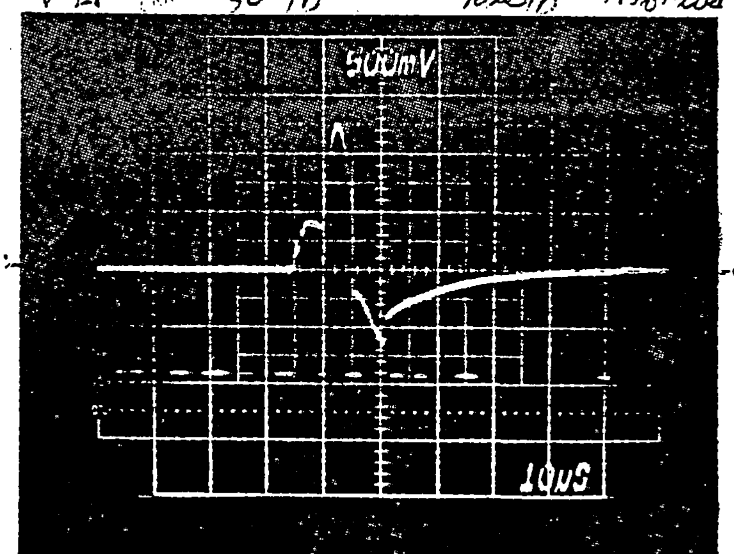
V-L1 50V/D 2mS/D 745ft-lbs



750V-LINK 500A-PK 63HZ Marlene 6-6-83

VOLTAGE ACROSS L1

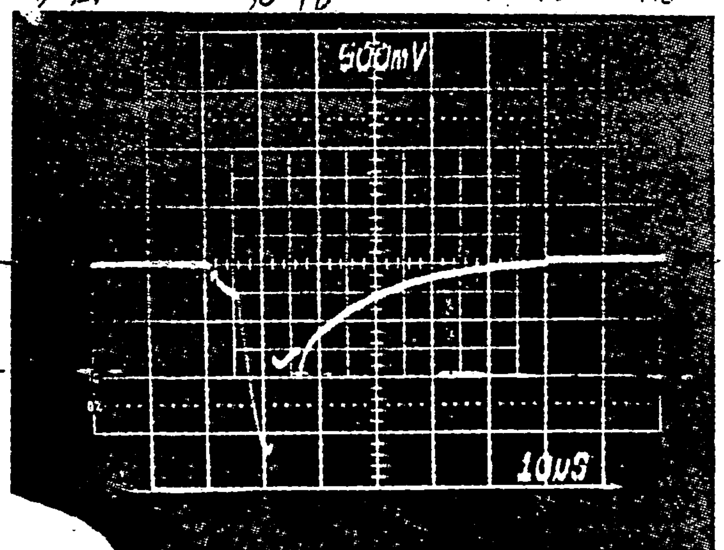
V-L1 50V/D 10µS/D 745ft-lbs



750V LINK 500A-PK 63HZ Marlene 6-6-83

VOLTAGE ACROSS L1

V-L1 50V/D 10µS/D 745ft-lbs

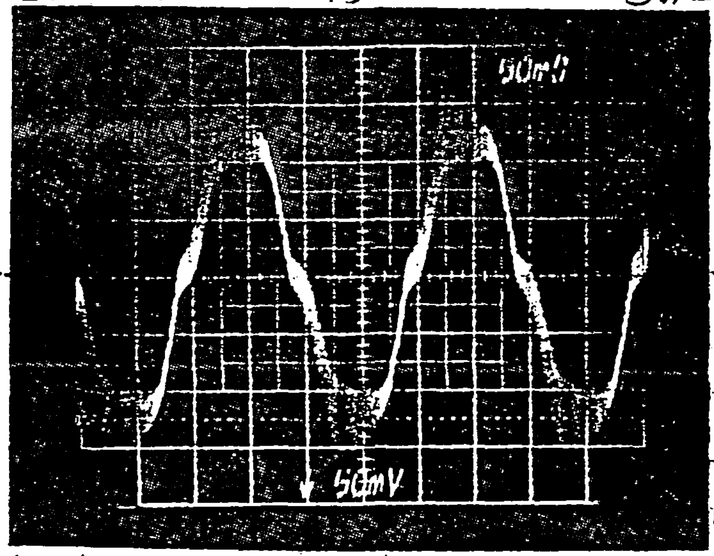


750V LINK 500A-PK 63HZ Marlene 6-6-83

VOLTAGE ACROSS L1

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

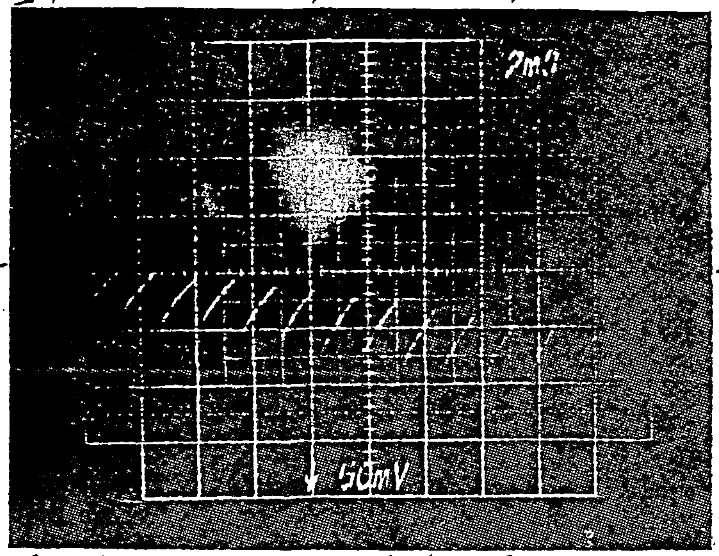
I-MOTOR A 100A/D 50mS/D 5HZ



600 V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

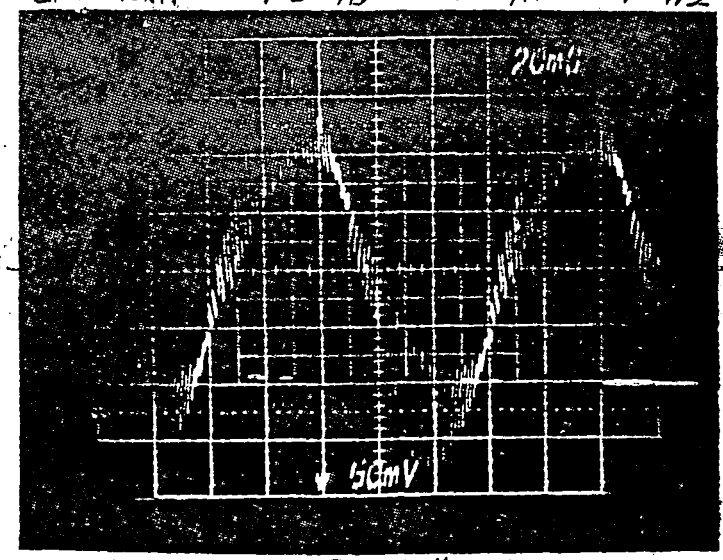
I-MOTOR A 100A/D 2mS/D 5HZ



600 V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

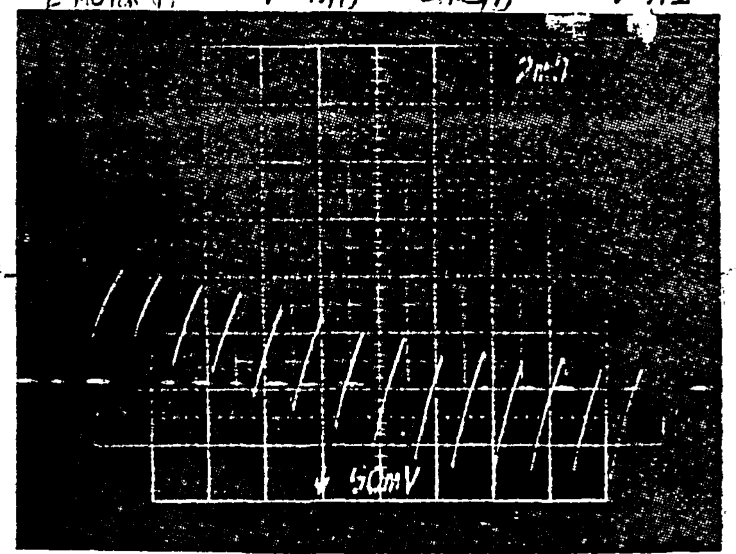
I-MOTOR A 100A/D 20mS/D 10HZ



600 V LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

I-MOTOR A 100A/D 2mS/D 10HZ

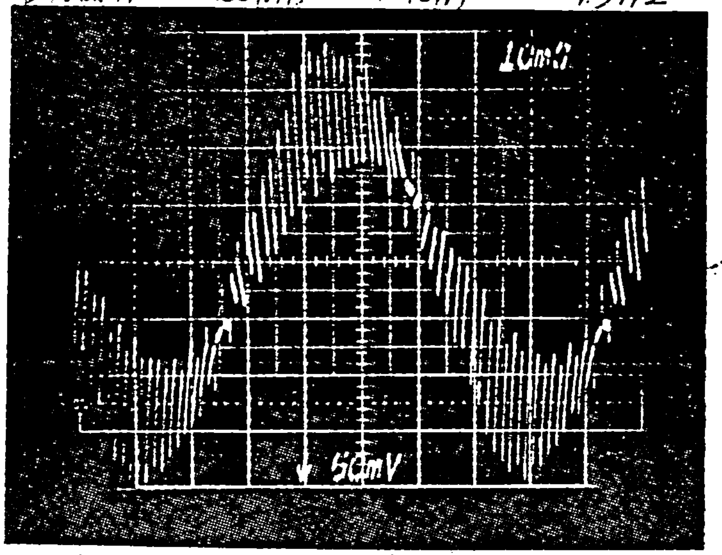


600 V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

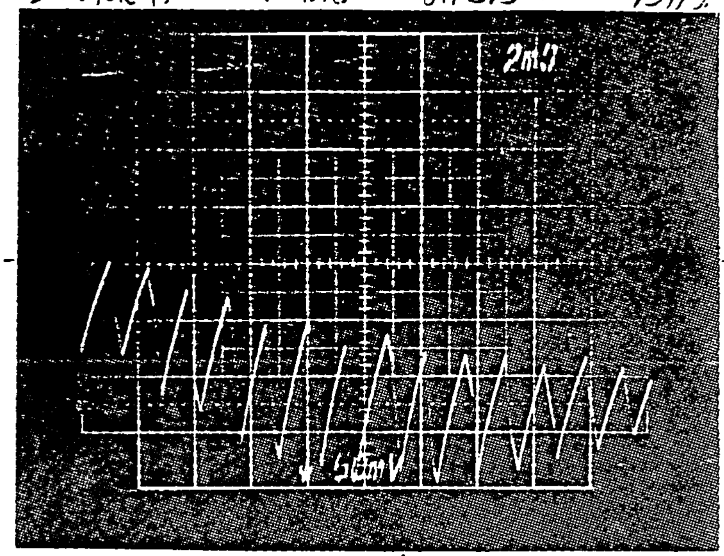
I-MOTOR-A 100A/D 10mS/D 15HZ



600V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

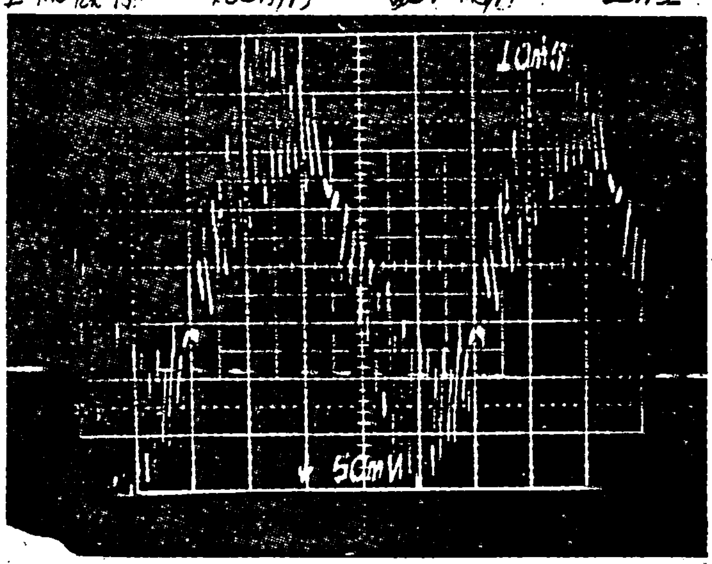
I-MOTOR-A 100A/D 2mS/D 15HZ



600V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

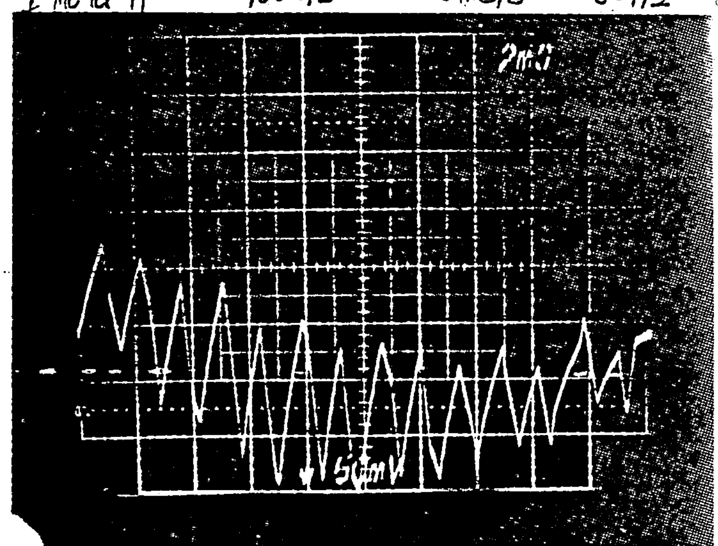
I-MOTOR-A 100A/D 10mS/D 20HZ



600V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

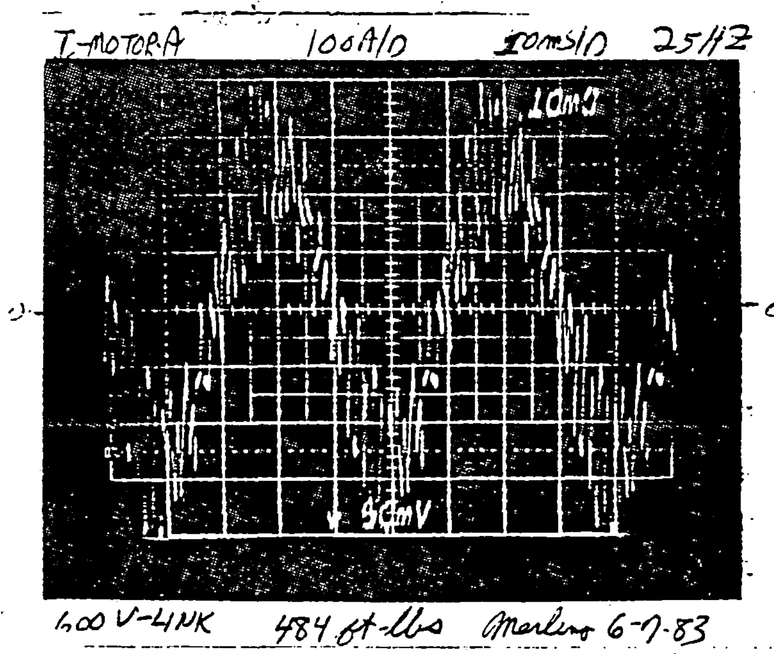
I-MOTOR-A 100A/D 2mS/D 20HZ



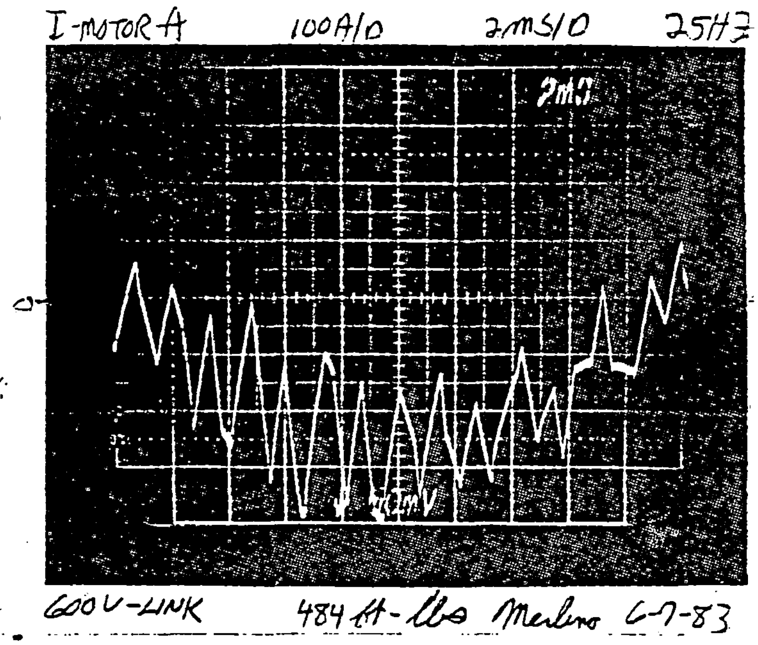
600V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

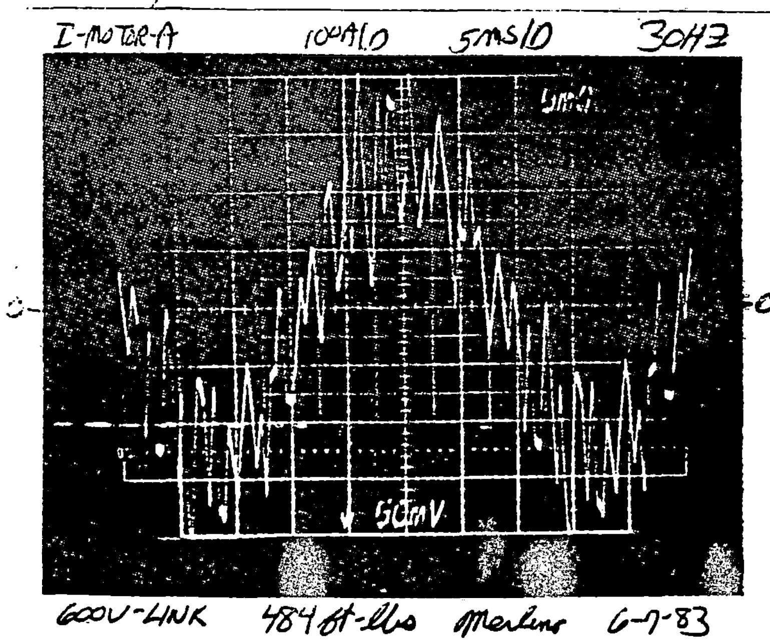
OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.



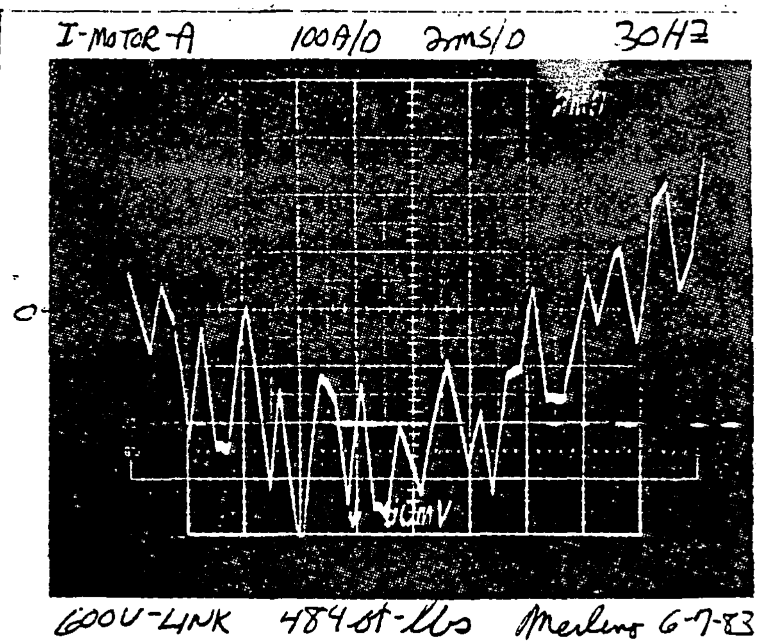
CURRENT THROUGH MOTOR-A



CURRENT THROUGH MOTOR-A



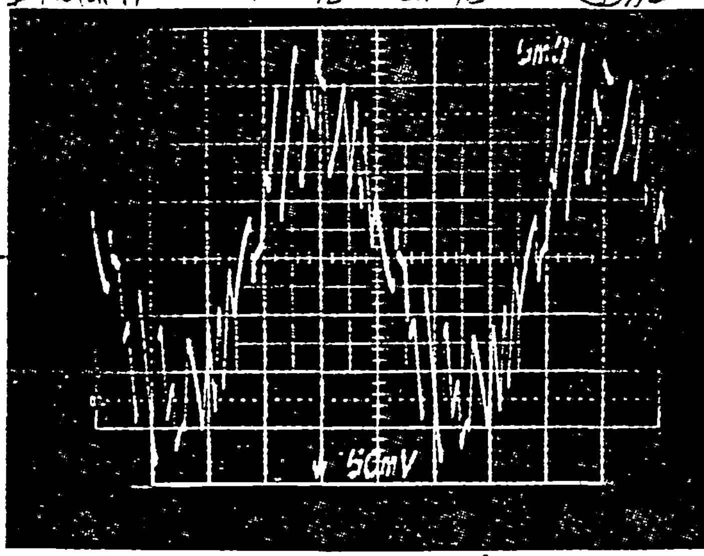
CURRENT THROUGH MOTOR-A



CURRENT THROUGH MOTOR-A

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

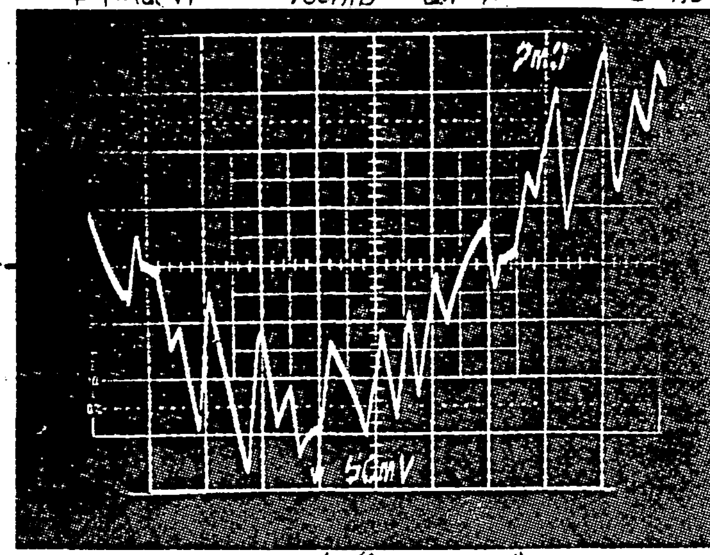
I-MOTOR-A 100A/D 5ms/D 35HZ



..V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

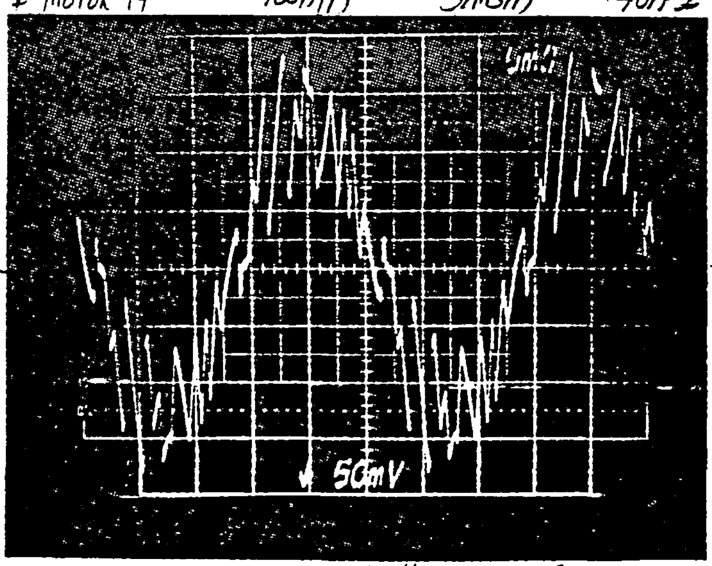
I-MOTOR-A 100A/D 2ms/D 35HZ



600V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

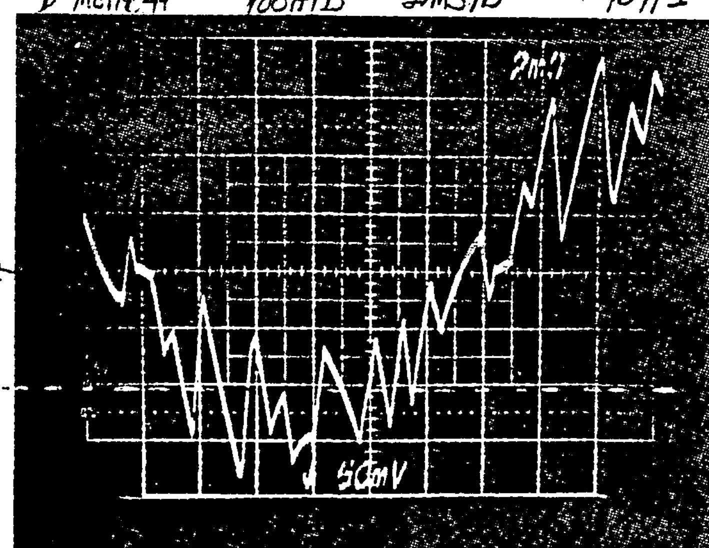
I-MOTOR-A 100A/D 5ms/D 40HZ



600V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

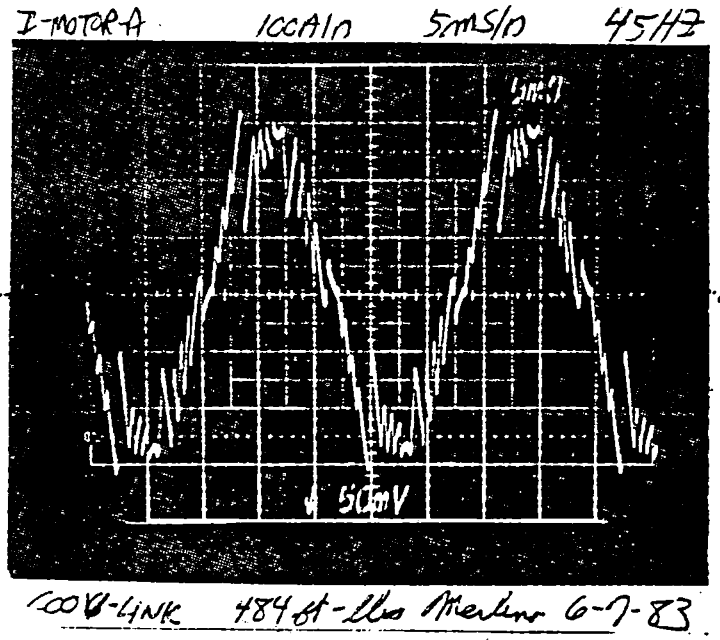
I-MOTOR-A 100A/D 2ms/D 40HZ



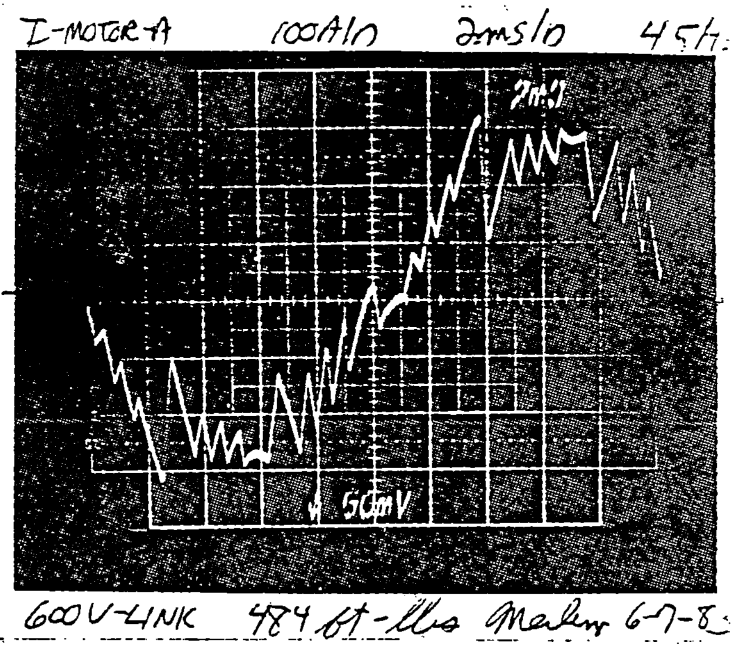
600V-LINK 484 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

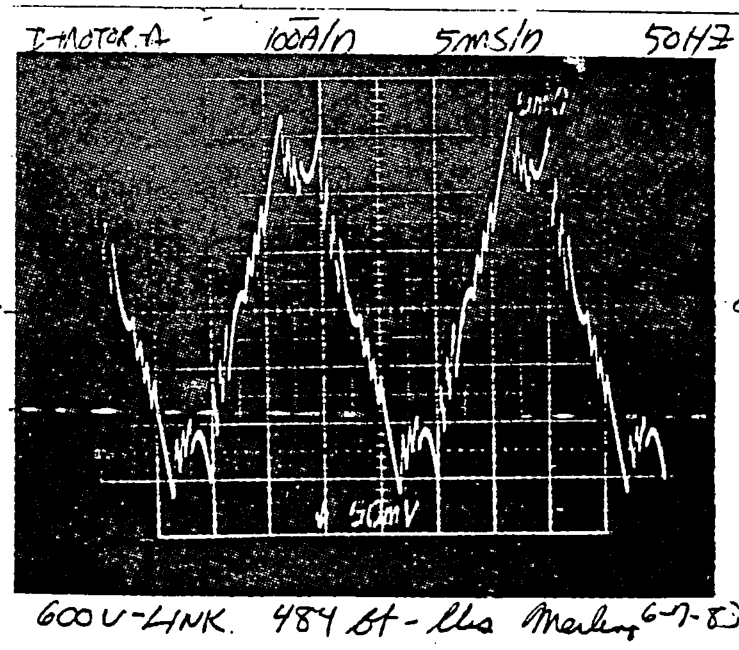
OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.



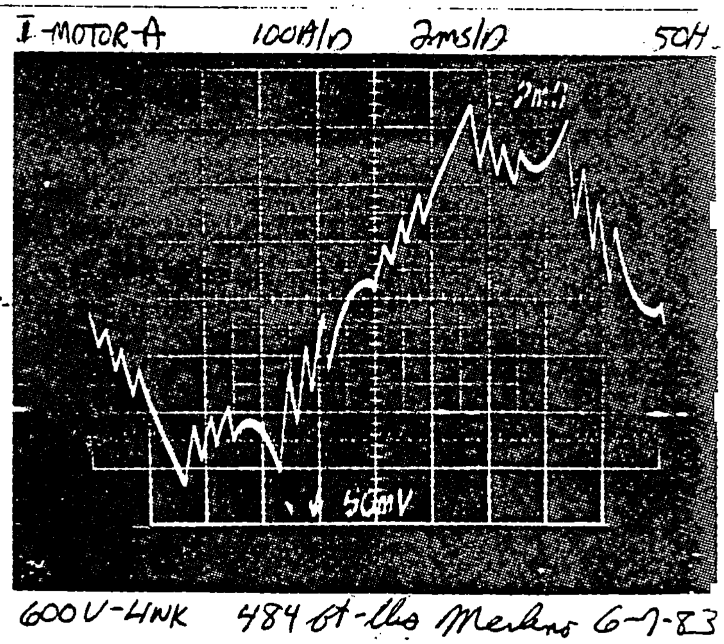
CURRENT THROUGH MOTOR-A



CURRENT THROUGH MOTOR-A



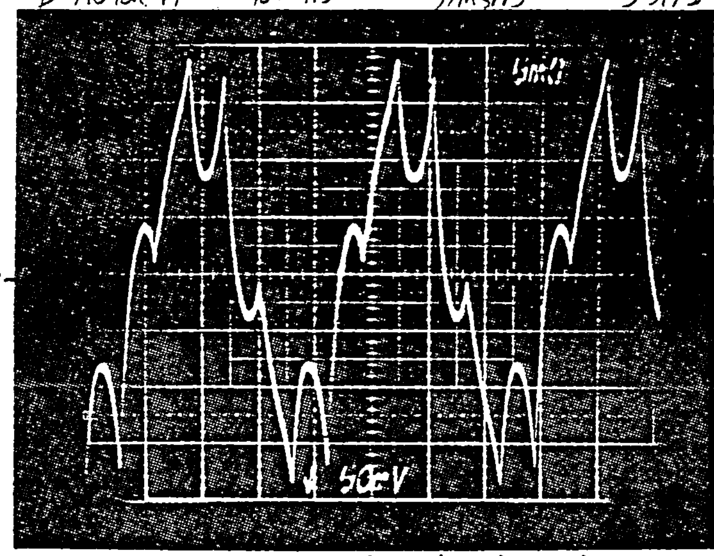
CURRENT THROUGH MOTOR-A



CURRENT THROUGH MOTOR-A

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

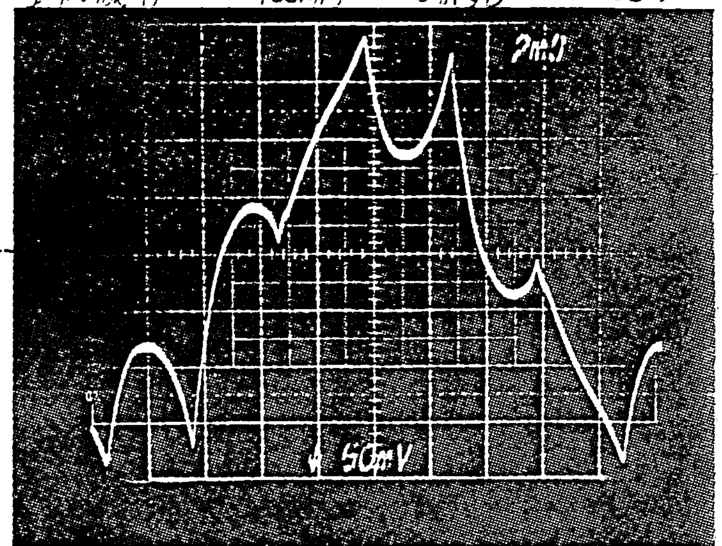
I-MOTOR-A 100A/D 5mS/D 55HZ



600V-LINK 484 ft-lbs Marlin 6-7-83

CURRENT THROUGH MOTOR-A

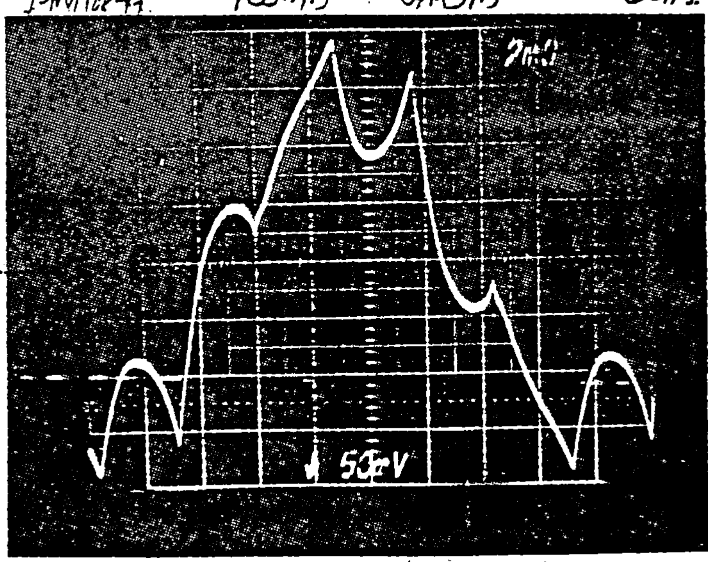
I-MOTOR-A 100A/D 2mS/D 55HZ



600V-LINK 484 ft-lbs Marlin 6-7-83

CURRENT THROUGH MOTOR-A

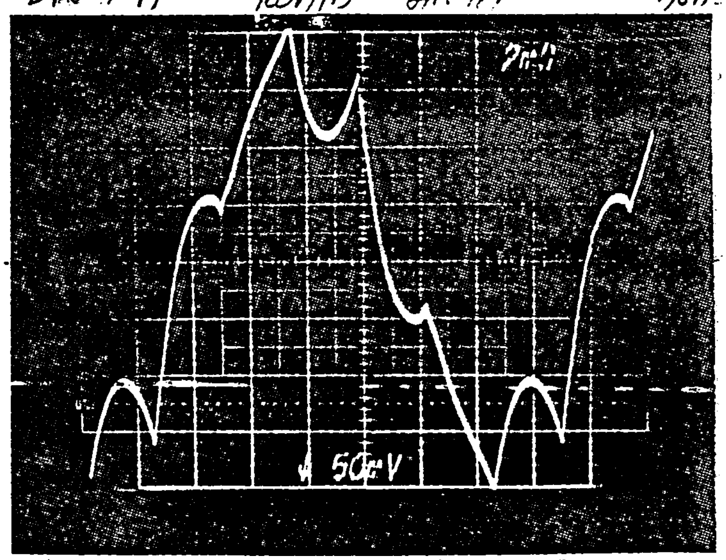
I-MOTOR-A 100A/D 2mS/D 60HZ



600 V-LINK 484 ft-lbs Marlin 6-7-83

CURRENT THROUGH MOTOR-A

I-MOTOR-A 100A/D 2mS/D 70HZ

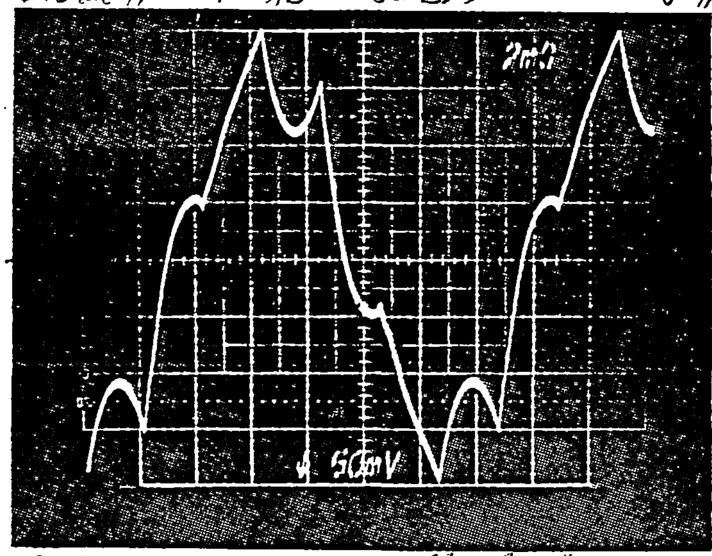


600 V-LINK 484 ft-lbs Marlin 6-7-83

CURRENT THROUGH MOTOR-A

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

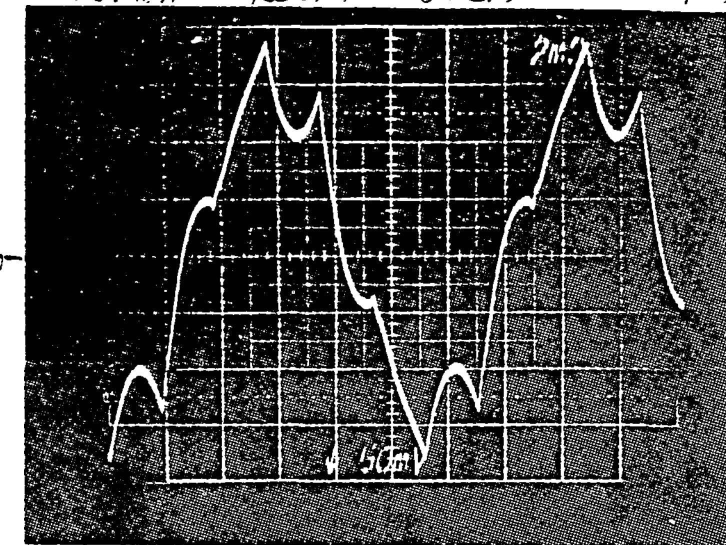
I-MOTOR-A 100A/D 2ms/D 80Hz



600 V-LINK 400 ft-lbs Merlino 6-7-83

CURRENT THROUGH MOTOR-A

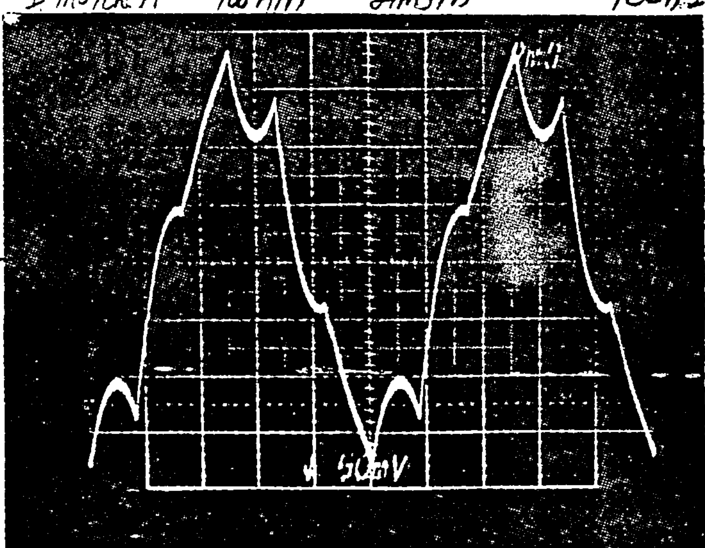
I-MOTOR-A 100A/D 2ms/D 90Hz



600 V-LINK 320 ft-lb Merlino 6-7-83

CURRENT THROUGH MOTOR-A

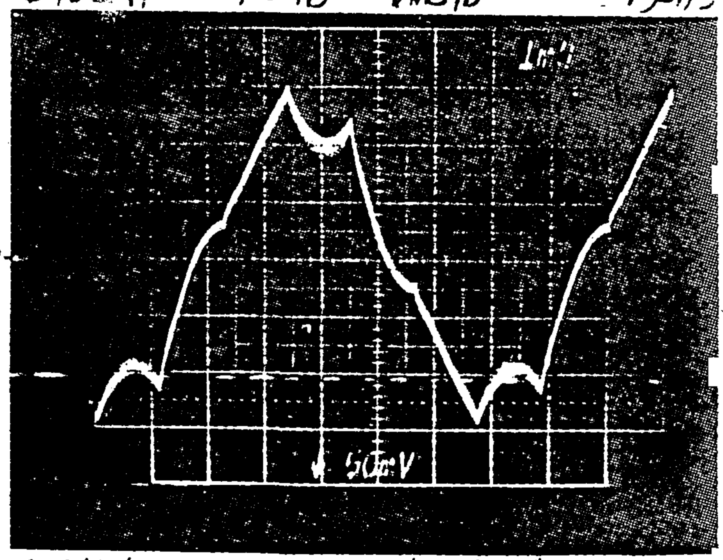
I-MOTOR-A 100A/D 2ms/D 100Hz



600 V-LINK 280 ft-lb Merlino 6-7-83

CURRENT THROUGH MOTOR-A

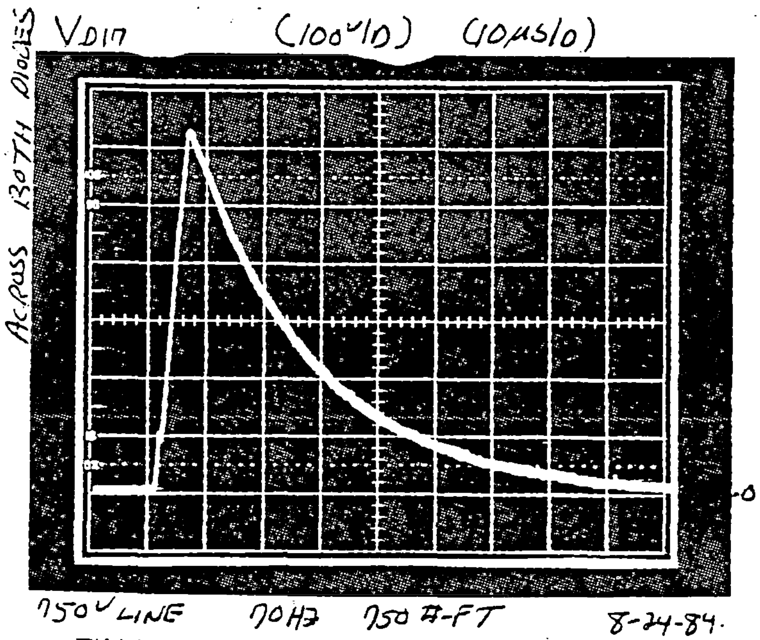
I-MOTOR-A 100A/D 1ms/D 150Hz



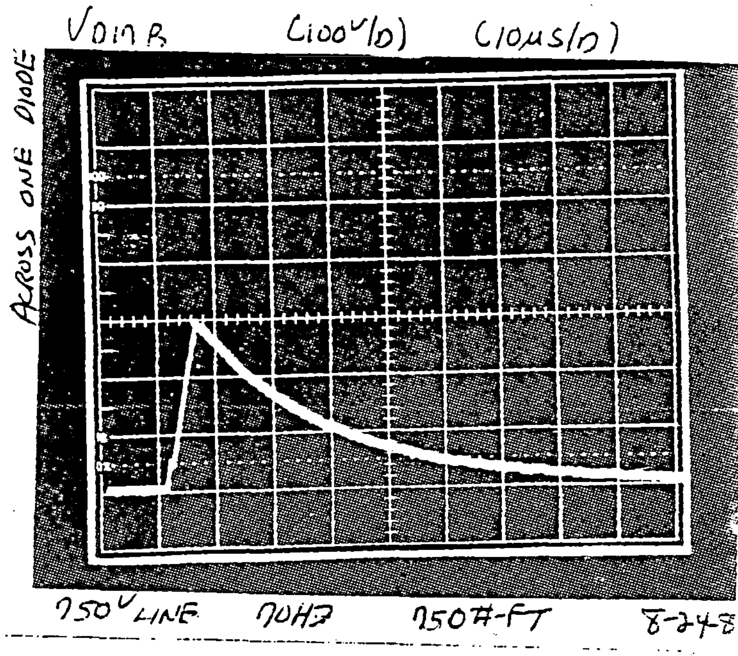
600 V-LINK 130 ft-lb Merlino 6-7-83

CURRENT THROUGH MOTOR-A

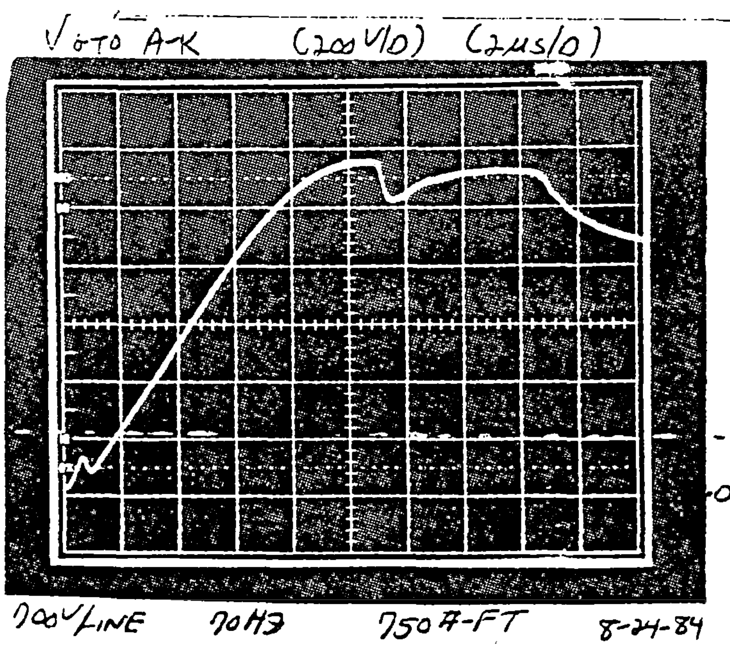
OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.



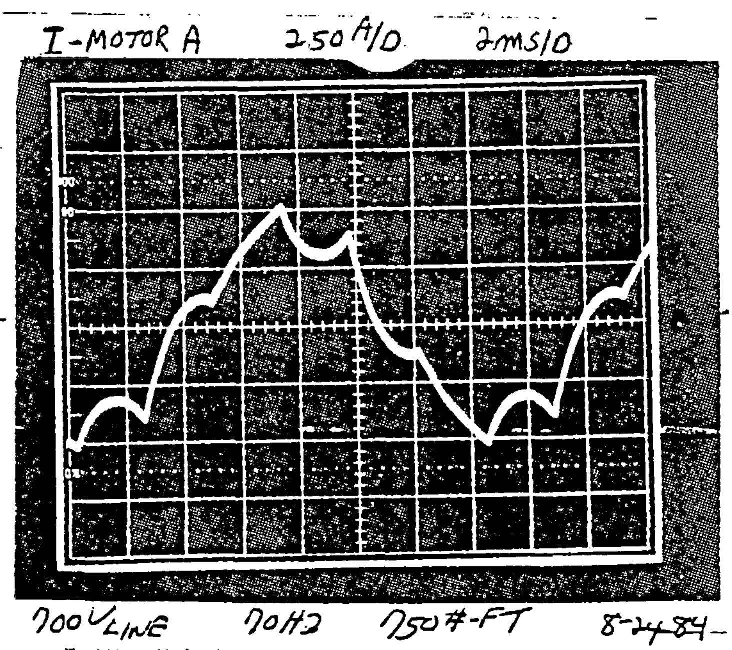
VOLTAGE ACROSS D17 (BOTH)



VOLTAGE ACROSS D17B (ONE)

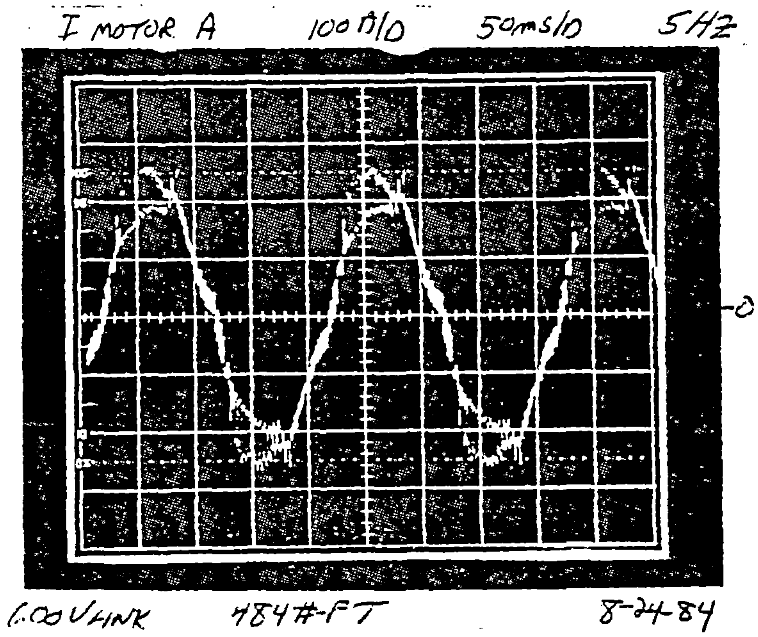


VOLTAGE ACROSS GTO-1/D1
~~VD = 120V, DV/DT < 200 V/US~~

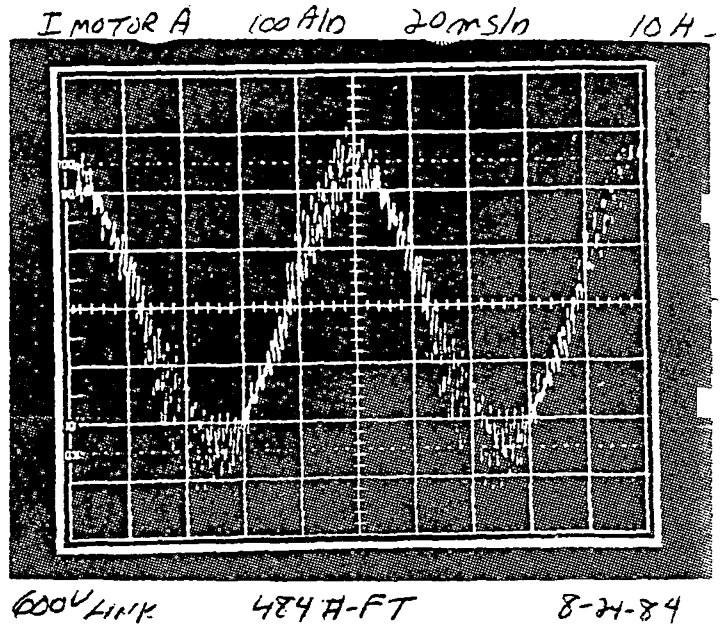


CURRENT THROUGH MOTOR-A

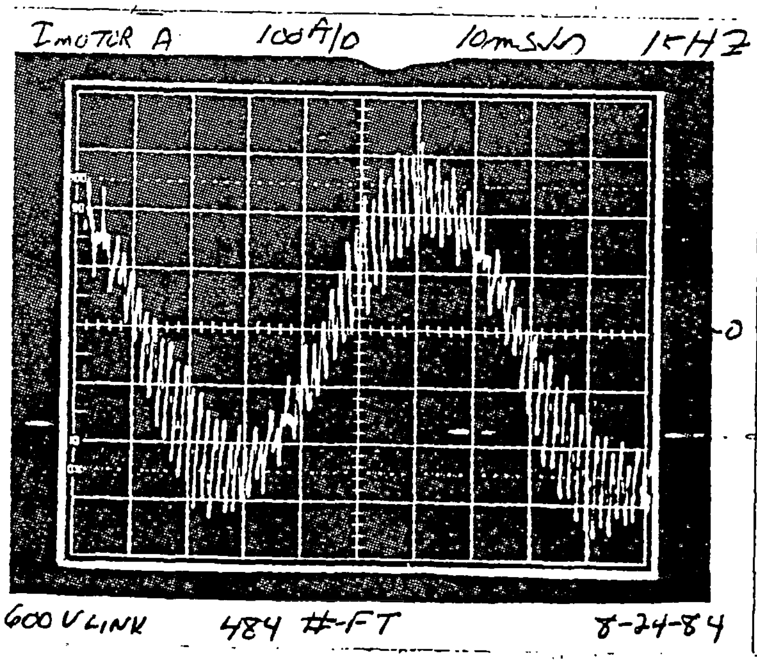
OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.



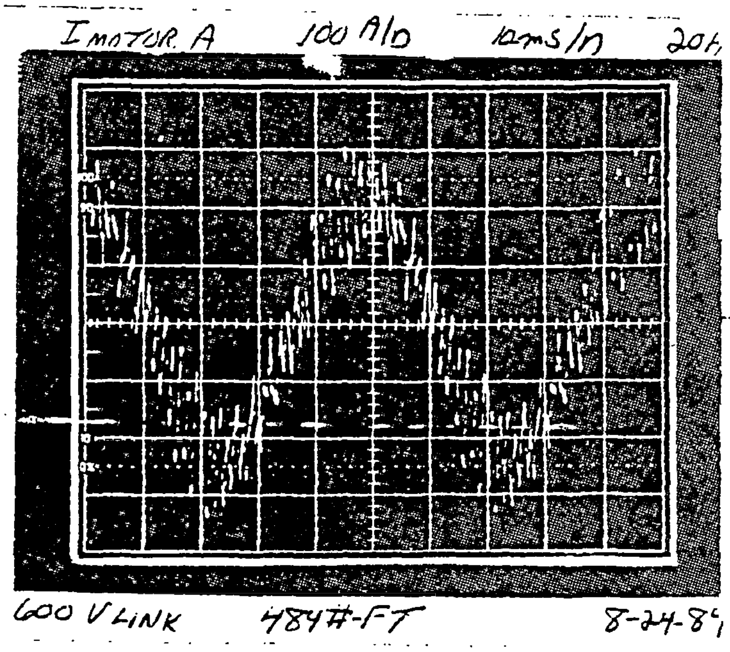
CURRENT THROUGH MOTOR-A



CURRENT THROUGH MOTOR-A

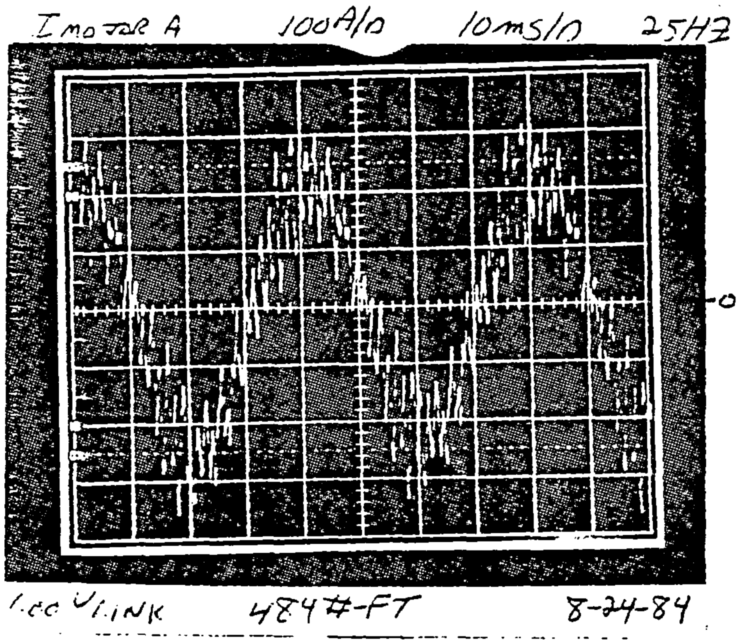


CURRENT THROUGH MOTOR-A

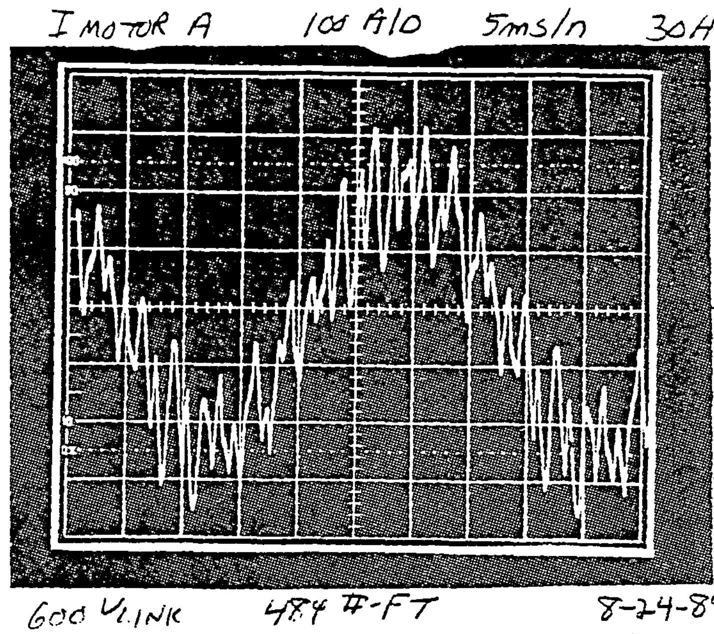


CURRENT THROUGH MOTOR-A

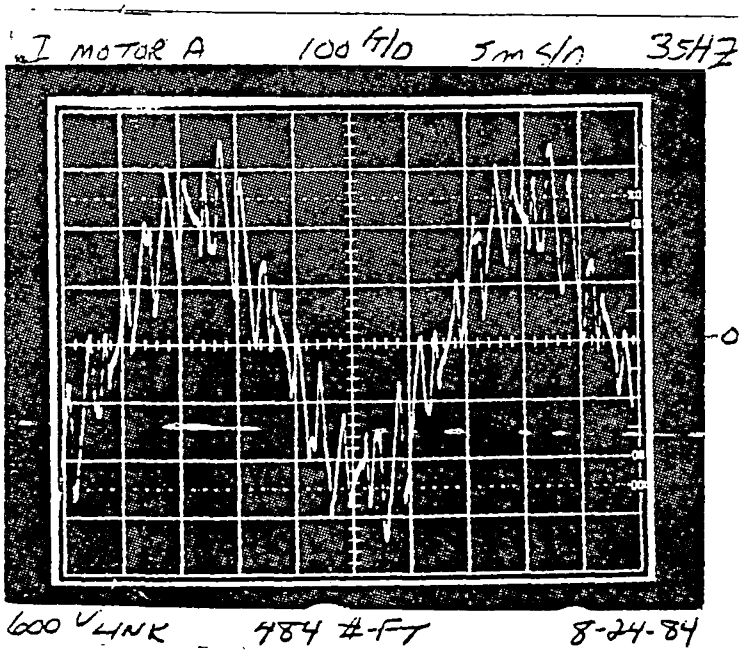
OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.



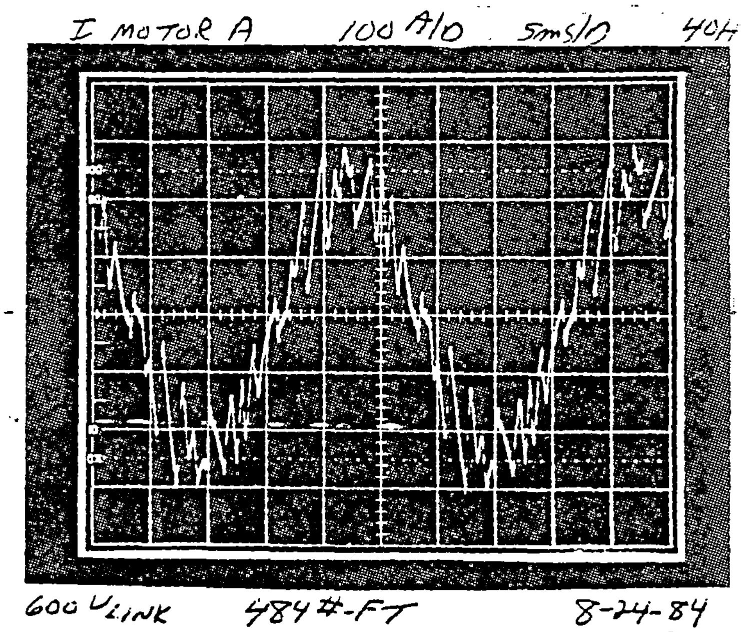
CURRENT THROUGH MOTOR-A



CURRENT THROUGH MOTOR-A



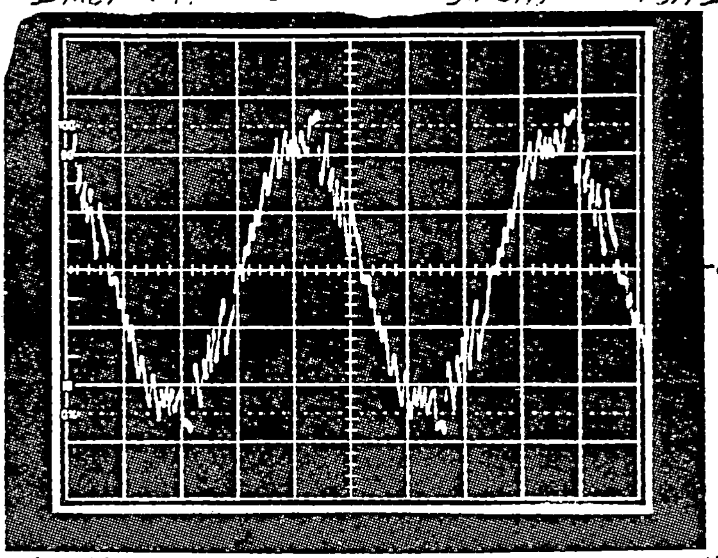
CURRENT THROUGH MOTOR-A



CURRENT THROUGH MOTOR-A

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

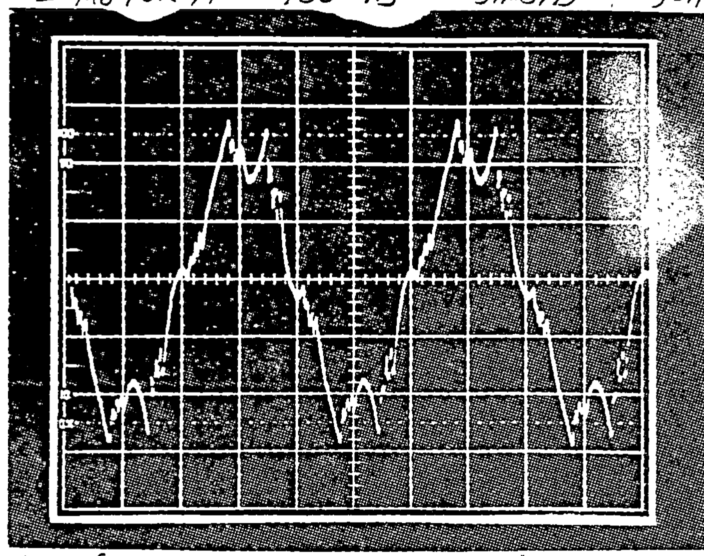
I MOTOR A 100 A/D 5ms/D 45HZ



600 V LINK 484 #-FT 8-24-84

CURRENT THROUGH MOTOR-A

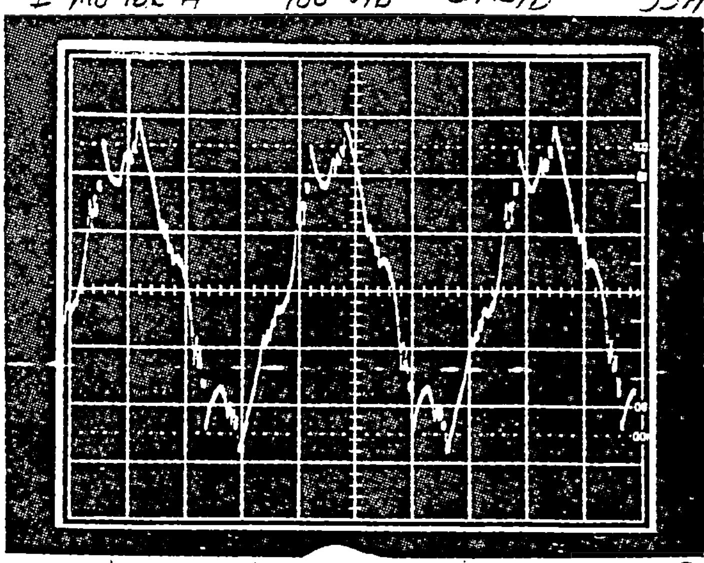
I MOTOR A 100 A/D 5ms/D 50H



600 V LINK 484 #-FT 8-24-8

CURRENT THROUGH MOTOR-A

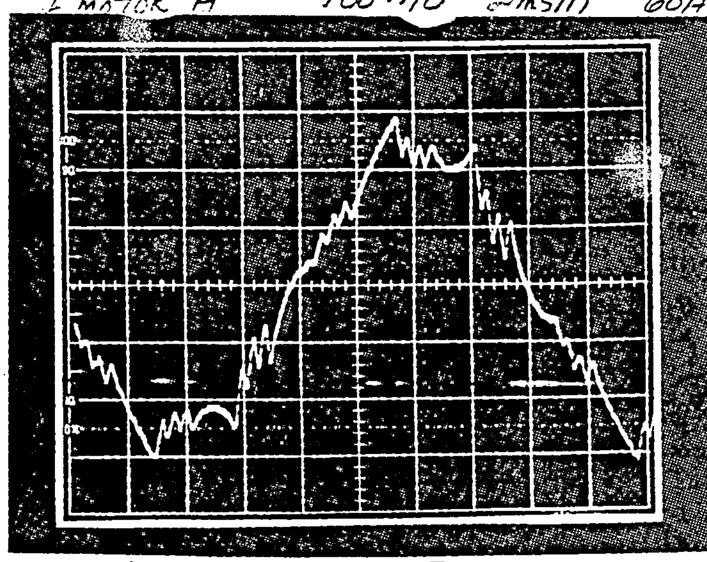
I MOTOR A 100 A/D 5ms/D 55HZ



600 V LINK 484 #-FT 8-24-84

CURRENT THROUGH MOTOR-A

I MOTOR A 100 A/D 2ms/D 60H

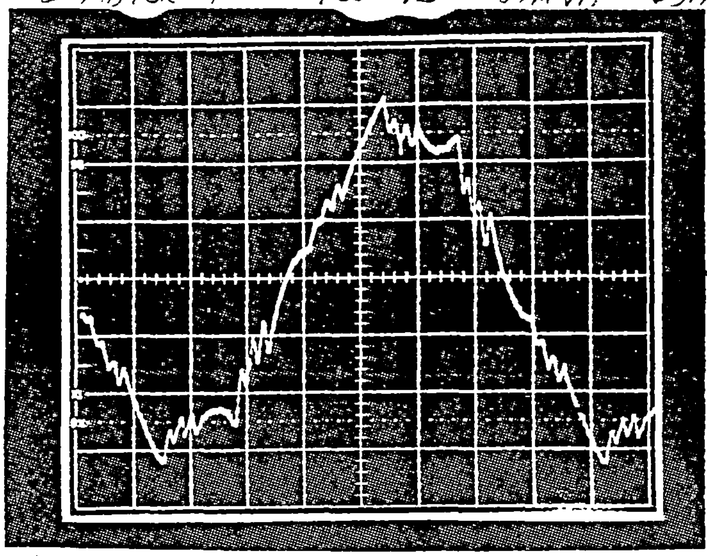


600 V LINK 484 #-FT 8-24-8

CURRENT THROUGH MOTOR-A

OUTPUTS: WAVEFORMS OF THE VARIOUS DEVICES.

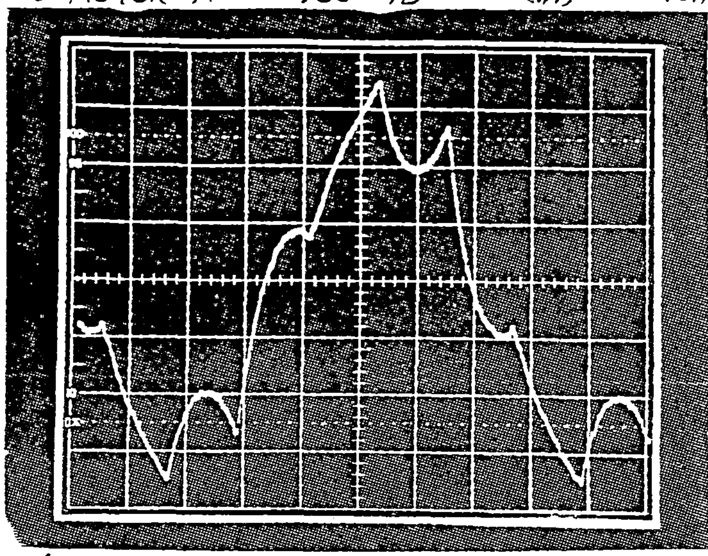
I MOTOR A 100 A/D 2ms/D 65HZ



600 V LINK 484 #-FT 8-24-84

CURRENT THROUGH MOTOR-A

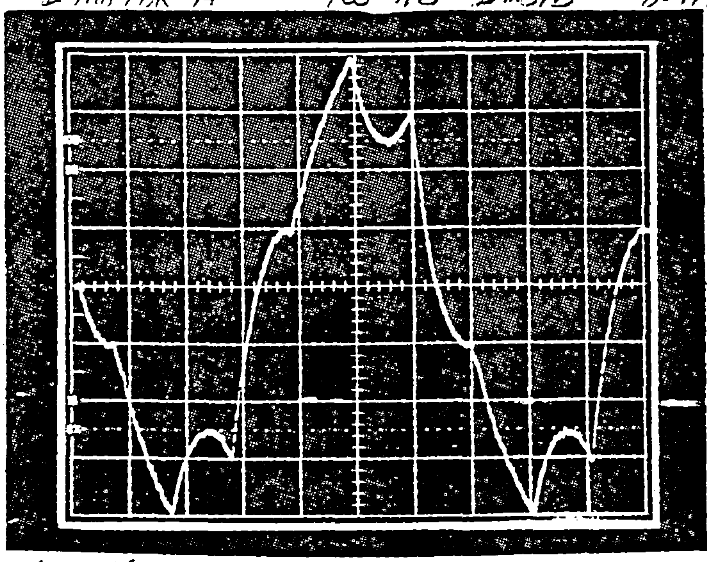
I MOTOR A 100 A/D 2ms/D 70H



600 V LINK 484 #-FT 8-24-84

CURRENT THROUGH MOTOR-A

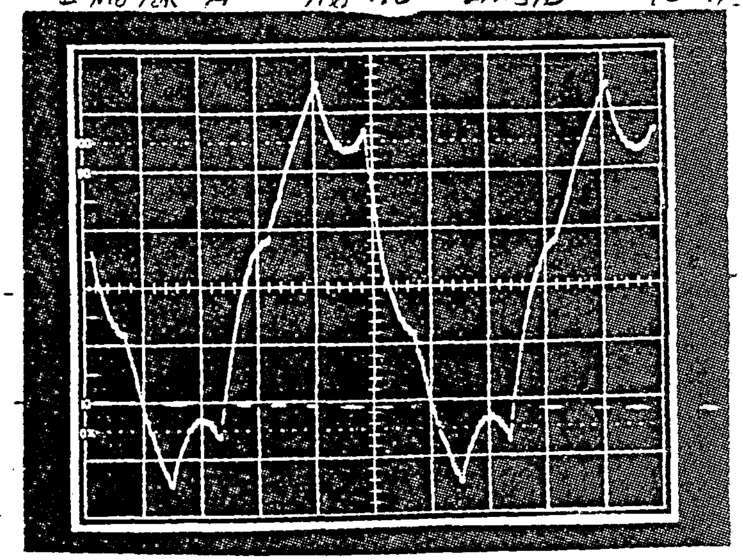
I MOTOR A 100 A/D 2ms/D 80HZ



600 V LINK 484 #-FT 8-24-84

CURRENT THROUGH MOTOR-A

I MOTOR A 100 A/D 2ms/D 100H



600 V LINK 280 #-FT 8-24-8

CURRENT THROUGH MOTOR-A

APPENDIX B

GTO GATE DRIVER BOARD DESCRIPTION

Due to the newness of GTOs, and the lack of a GTO gate driver that could handle the currents and frequencies experienced in the PWM inverter, we opted to custom design a gate driver board.

B.1 GTO DRIVE SPECIFICATIONS

Before designing the board, the drive specification for the three GTOs to be used in the inverter were considered. They are, the Toshiba SG800EX21 and SG1400EX21, and the Mitsubishi FG1000A. The turn on and the turn off characteristics are as follows:

	SG800EX21	SG1400EX21	FG1000A	GTO DRIVER
Turn On:				
DIG/DT	> 5 A/us	> 5 A/us	> 5 A/us	10 A/us
IFGM	5 - 10 A	10 - 20 A	15 - 30 A	12 A
IFG	> 2 A	> 3 A	> 3 A	3 A
TGT	20 us	20 us	20 us	25 us
Turn Off:				
DIRG/DT	20 - 30 A/us	30 A/us	> 30 A/us	30 A/us
IRG	220 A	300 - 350 A	350 A	---
TS	15 us	20 us	18 us	---
TGQ	18 us	25 us	20 us	---

B.2 GTO GATE DRIVER CHARACTERISTICS (See Figures B-1 & B-2)

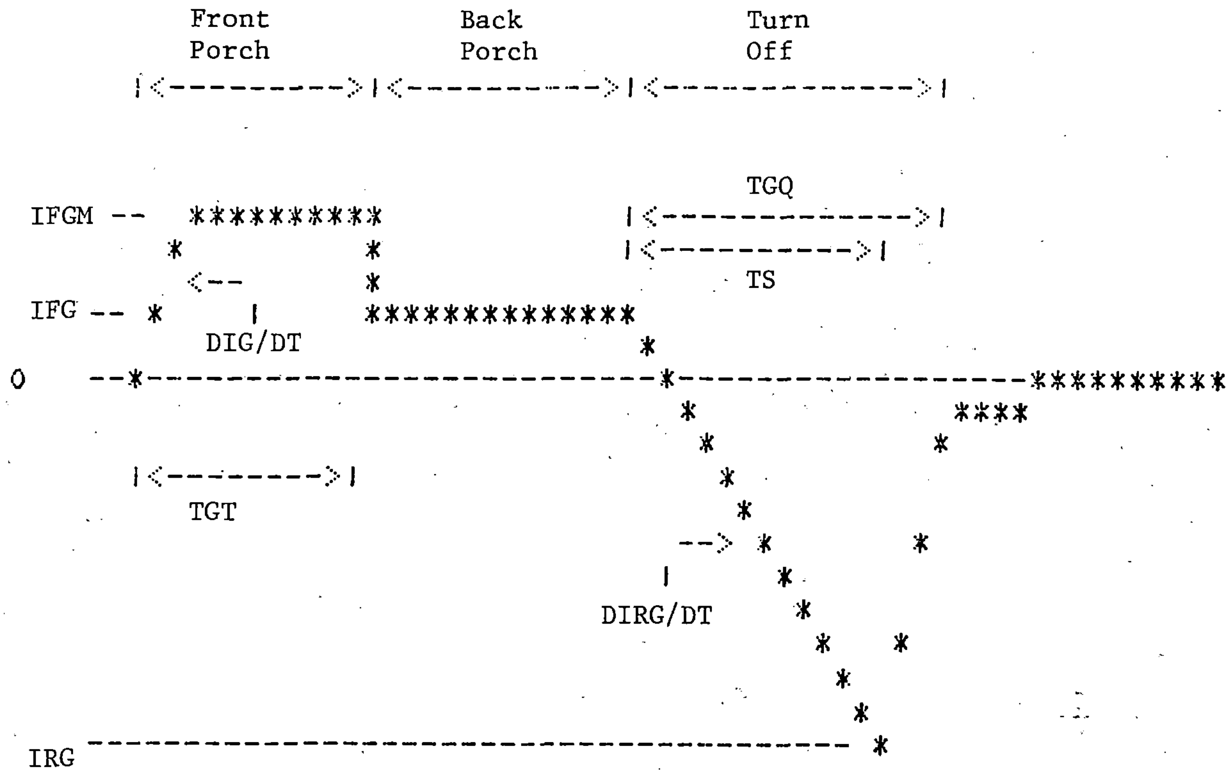
B.2.1 TURN ON CHARACTERISTICS

A. Referring to the previous section, it can be seen that all turn on specifications are either met or exceeded. The front porch has a 10 amps/microsecond rise time to 12 amps for 25 microseconds, with a back porch of 3 amps. The current levels can easily be changed by selecting different resistor values. Since the "ON" pulse is driven from two power supplies, +16 VDC and +6 VDC, the front and back porch drives are independent of each other. This also decreases the power consumption, since the back porch is driven by the +6 VDC power supply, instead of what is typically done, which is to drive it from the higher voltage and drop the voltage across a resistor.

B.2.2 TURN OFF CHARACTERISTICS

A. Again referring to the previous section, it can be seen that the 30 amps/microsecond rise time for the turn off current is met. The peak current (IRG), storage time (TS), and turn off time (TGQ) are all functions of the device and load current through the device.

B. The reverse bias is -6 VDC, which increases the DV/DT withstanding capability of the device.



Gate Current Through the GTO

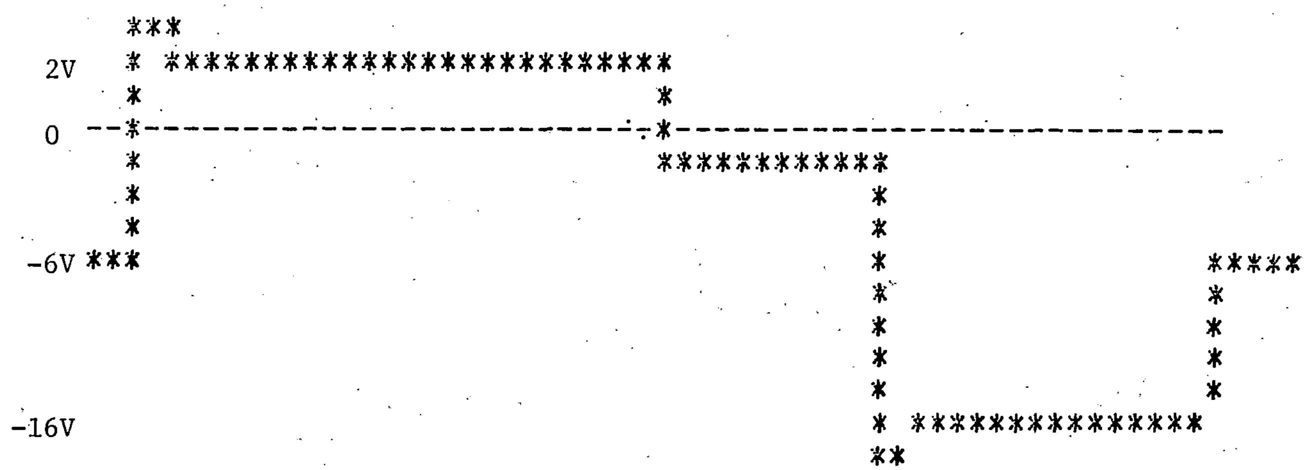
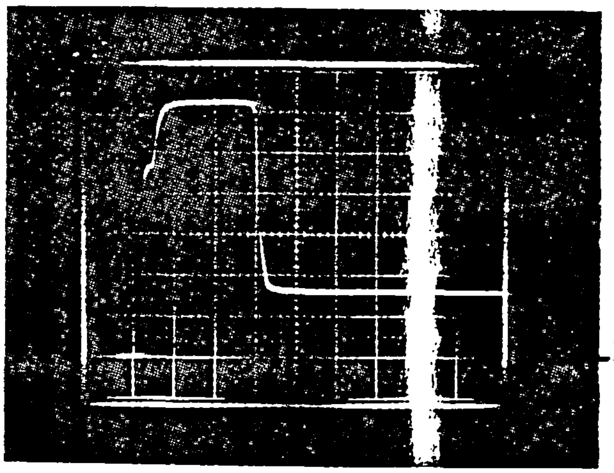


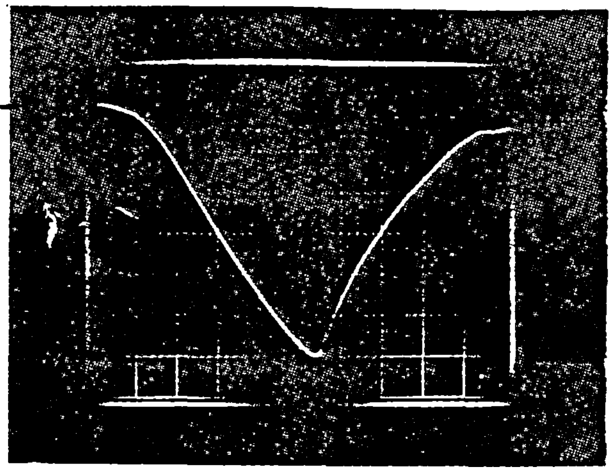
Figure B-1

Voltage Across the GTO (Gate - Cathode)



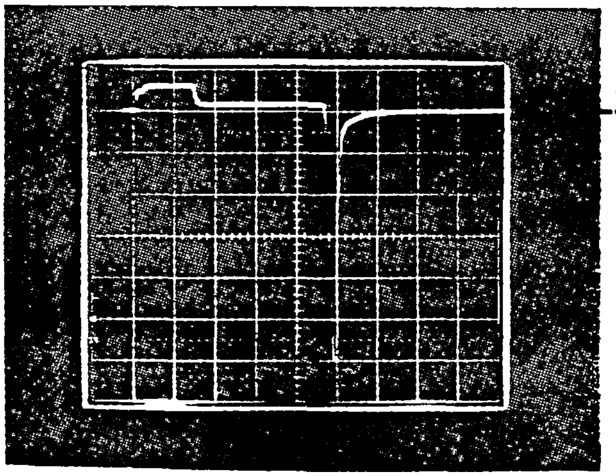
(a)

Current through GTO G-K
2 AMPS/DIV
10 MICROSECONDS/DIV



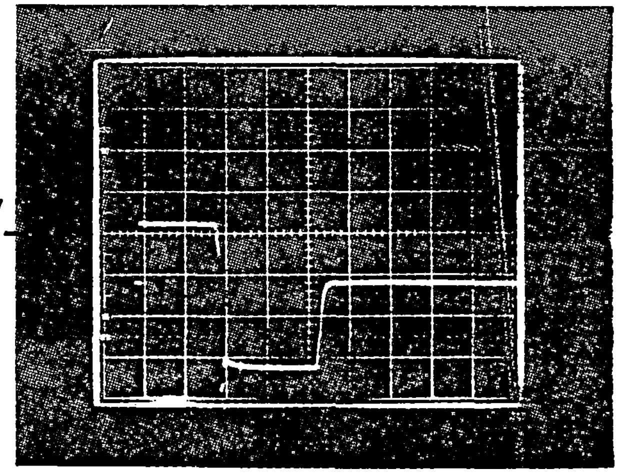
(b)

Current through GTO G-K
20 AMPS/DIV
1 MICROSECOND/DIV



(c)

Current through GTO G-K
20 AMPS/DIV
20 MICROSECONDS/DIV



(d)

Voltage across GTO G-K
5 VOLTS/DIV
50 MICROSECONDS/DIV

Figure B-2

B.2.3 DRIVE CAPABILITY

A. The board is capable of turning on and off the designated devices (SG800EX21, SG1400EX21, FG1000A, or any other device with similar specifications) under full load current, upto an 800 Hz rate.

B.2.4 POWER SUPPLIES

A. The board is powered by a DC input voltage ranging from 20 to 80 VDC, which is compatible with most mass transit low voltage battery sources. The power draw is dependent on the GTO being used, the load current, frequency, and the duty cycle. If we assume that the SG800EX21 GTO is used at full rated current, 300 Hertz, and 50% continuous duty, the power consumption is:

Front Porch	+	Back Porch	+	Turn Off	=
(12A*16V*25US*300Hz)	+	(3A*6V*.5)	+	(.5*15US*220A*16V*300Hz)	=
144 W	+	9 W	+	7.92 W	=

= 18.36 Watts/Gate Driver Board

B.2.5 PROTECTION

A. There is a shunt in series with the GTO and its signal is brought up to the GTO driver board. On an overcurrent trip, the GTO driver board will either turn the GTO on or off, depending on where the two jumpers are placed on the board.

B. The gate driver board monitors the +/- 16 volts on board power supply outputs, and trips out at +/- 13.5 volts.

C. The drive to the GTO is positively removed when the +16 V power supply drops below 8 volts to handle the power-up and power-down situations.

D. The power supplies are current limited such that if a GTO shorts, there is no harm to the driver board or to the main battery and wires.

E. All timing and delays are done by the motor controller, however, the driver board protects the GTO from too short of an "ON" or "OFF" pulse.

B.2.6 DELAYS

A. The driver board is basically a slave with its own protection on board. Therefore, there is very little phase distortion for the motor controller. The "ON" delay is less than 7 microseconds, and the "OFF" delay is less than 11 microseconds.

B.2.7 MANUFACTURABILITY

A. There are no POTs or SOTs on the board, therefore allowing ease of manufacturability.

B.2.8 NOISE IMMUNITY

A. CMOS was used for the logic chips and Schmitt triggered inverters were used where appropriate for optimal noise immunity.

B. The logic power is filtered from the power section, and series regulated to +5 and +/- 12 volts.

C. The current feedback is fed into a differential amplifier and compared to an accurate threshold. There is also a 25 microsecond delay on the overcurrent trip to ride through the increased current due to the recovery of the back diodes and for noise spikes.

D. There is a ground plane under each section of the board for noise immunity; the power section, the logic section, and the power supply section. The ground planes are then tied together at the power supply section.

B.2.9 RELIABILITY

A. Throughout testing in the power lab with the driver boards in the inverter, the regenerative braking unit, and the dynamic braking unit, the only reliability related problems encountered was with the +/- 6 volt power supply. The power supplies currently used are off the shelf items with commercial parts. In the final design, a different power supply will be implemented, one with more margin and industrial parts (no plastic parts).

B. The components were sized for continuous duty at 800 Hz and full load current. Under normal conditions the frequency will average less than 300 Hz and less than full load current; thereby providing ample margin for the power components, especially the transistors and capacitors.

C. The most temperature sensitive components are the drive capacitors, which are rated at 85 degrees centigrade at full load.

D. All logic chips are industrial grade (-40 to +85 degrees cent.), ceramic, and hermetically sealed.

E. All inputs and outputs to the outside world are adequately protected.

B.3 CIRCUIT DESCRIPTION

A. Refer to the block diagram in Figure B-3.

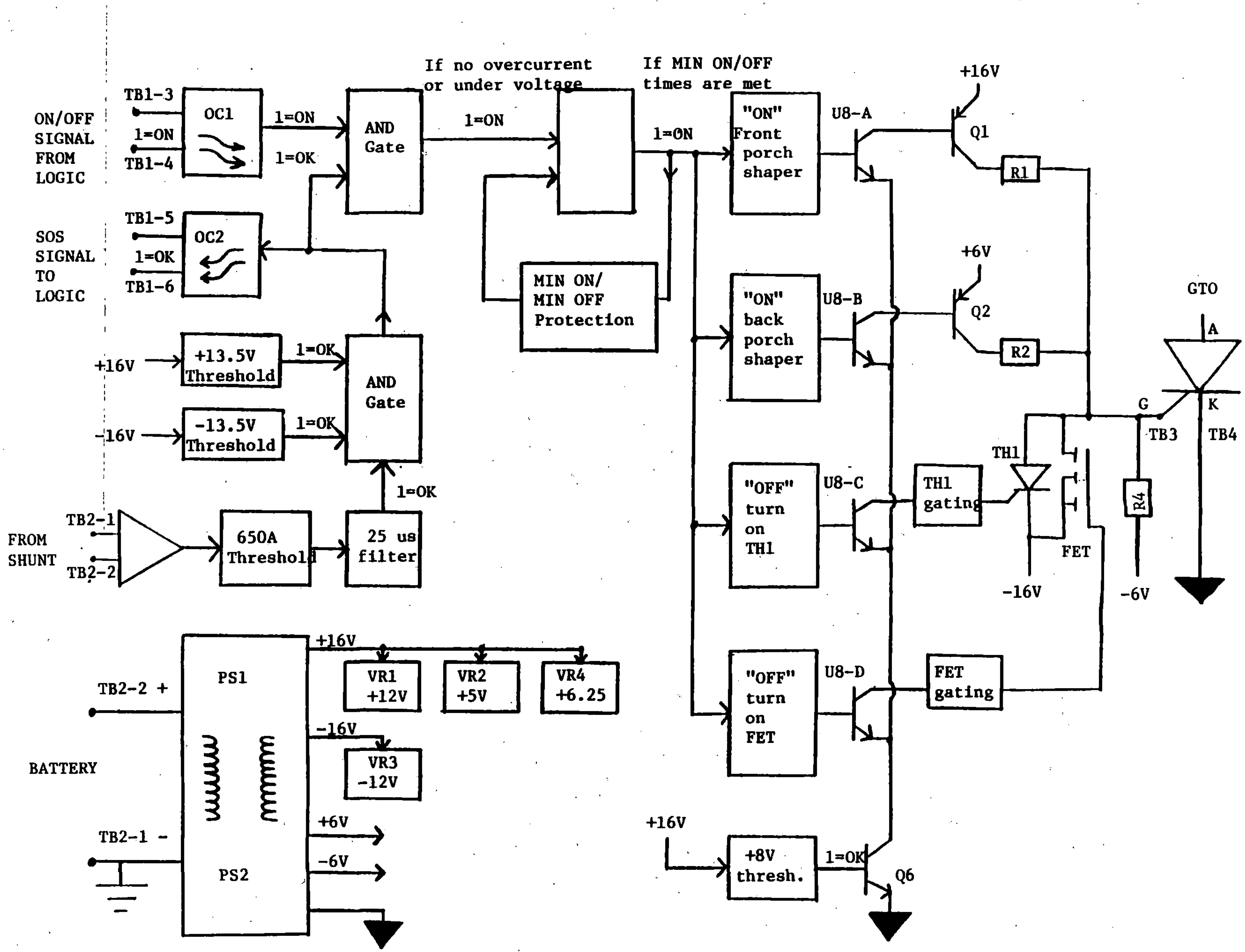


Figure B-3

GTO Gate Driver Block Diagram

B.3.1 POWER SUPPLY

A. Power is supplied from the battery to the board via TB1-2,1. PS1 and PS2 are 30 watt power supplies at +/- 16 and +/- 6 volts. These particular power supplies are only capable for 1500 volts isolation. The final design configuration will have one power supply with +/- 16 and +/- 6 volt outputs, and will be designed to handle 5000 volts isolation. The response time is critical for these power supplies, since the load from the +6 volt output is a step from 0 to 3.5 amps, at an average frequency of 200 Hz, with a peak of 600 Hz. (There is a 350 microfarad capacitor across its output). The output of the + 16 volt power supply is 10 amps for 25 microseconds with the same frequencies as above. (There is a 4100 microfarad, low ESR capacitor across its output.) The output of the -16 volts power supply is 250 amps for 20 microseconds with the same frequencies as above. (There are two 4100 microfarad, low ESR capacitors in parallel across its output.)

B.3.2 LOGIC SECTION POWER SUPPLIES

A. The +16 volts which is used by the power section is filtered by an R-C circuit which is used by the logic section.

B. The -16 volts, which is used by the power section, is filtered by an R-C circuit which is used by the logic section.

C. The +12 (VR1), +5 (VR2), and -12 (VR3) voltage regulators come off of the +/- 16 volt filtered power supplies to provide the necessary power for the logic section.

D. A precision reference 6.25 volts (VR4) is also derived from the +16A power supply.

B.3.3 OVERCURRENT PROTECTION

A. Attached to the aluminum block at the cathode end of the GTO is a 200A/100MV two blade shunt. A coaxial wire (1 conductor with shield) is routed from the shunt, where the wire is tight against the shunt, to the board at TB2-1,2. Throughout testing of the inverter, one of the coaxial wires was replaced with a twisted pair (no shield) with no appreciable difference detected.

B. The shunt signal is filtered by an R-C filter (which changes the current trip level by 464K/474K = 97.89% of its value), and is clamped to +/- 12 volts for board protection.

C. The shunt signal is received by a high impedance differential Op Amp circuitry and amplified by a factor of 10.

D. The amplified shunt signal is then compared against a set threshold.

E. After testing the 30 prototype boards, the current trips were measured to be; between 642 and 672 amps on rising (average of 657 amps) and between 602 and 630 amps on falling (average of 616 amps), with an hysterysis of 41 amps.

F. The threshold signal is then filtered for 25 microseconds such that the inductive effects of the shunt and the power circuit are ignored.

B.3.4 POWER SUPPLY LOW VOLTAGE PROTECTION

A. When the filtered +16V supply drops below 13.5 volts, a fault is detected.

B. When the filtered -16V supply drops below -13.5 volts, a fault is detected.

B.3.5 FAULT PROTECTION

A. If any of the protection circuits are tripped (shunt current, filtered +16 voltage, or filtered -16 voltage), a fault is detected and latched for 218 microseconds.

B.3.6 SOS SIGNAL TO THE LOGIC

A. The latched fault opens the optical coupler OC2, which cuts off the signal back to logic via TB1-5,6. (NOTE: An active SOS signal means everything is OK.)

B.3.7 ON-OFF SIGNAL FROM THE LOGIC

A. The ON-OFF signal from the logic comes on the board at TB1-3,4.

B. The optical coupler (OC1) provides the voltage isolation between the logic and the gate driver board. The optical coupler also provides for good noise immunity since it is a current driven device.

B.3.8 ON-OFF SIGNAL

A. If there are no overcurrent or undervoltage conditions, the ON signal continues through the "AND" gate.

B.3.9 MINIMUM "ON" AND "OFF" TIME PROTECTION

A. This circuit provides a minimum "ON" time for the GTO. It inhibits any off pulses for 68 microseconds after an "ON" pulse is recognized, to allow for the GTO snubber to discharge sufficeintly. This circuit also provides a minimum "OFF" time for the GTO. It inhibits any "ON" pulses for 148 microseconds after an "OFF" pulse is recognized, to allow for the thyristor TH1 to recover.

B.3.10 "ON" SIGNAL (FRONT PORCH)

A. The "ON" Front Porch Shaper block generates a 25 microsecond pulse.

B. U8A provides the drive for Q1.

C. The "ON" pulse front porch (10 amps), for turning the GTO "ON", is provided by +16V, Q1 and R1.

B.3.11 "ON" SIGNAL (BACK PORCH)

A. The "ON" Back Porch Shaper block generates the DC level.

B. U8B provides the drive for Q2.

C. The "ON" pulse back porch (3 amps), for turning the GTO "ON", is provided by +6V, Q2 and R2.

B.3.12 OFF PULSE (THYRISTOR TH1)

A. The "OFF" turn on TH1 block generates the 20US thyristor firing pulse.

B. U8-C and the TH1 gating block provides the drive for TH1.

C. The OFF pulse waveform (250 amps), for turning the GTO "OFF", is provided by -16V and TH1.

B.3.13 OFF PULSE (FET)

A. The "OFF" turn on FET block generates the 122 microsecond FET firing pulse.

B. U8-D and the FET Gating block provides the drive for FET.

C. The FET is used to shunt the thyristor TH1 to decrease its turnoff time. The FET has an "ON" resistance of .18 ohms.

B.3.14 OFF STATE REVERSE BIAS

A. R4 is used to maintain -6 volts on the GTO gate in the "OFF" state. Note that current is always flowing in R4, however is so small that it is negligible.

B.3.15 START-UP AND SHUTDOWN PROTECTION

A. Q6 connects the emitters of all NPN Darlington transistors in U8 to ground. When Q6 is "OFF" (the +16 volt supply falls below 8 volts) the emitters of U8 are floating, thereby disabling all outputs.

APPENDIX C

POWER FREQUENCY CONDUCTED EMI MODEL

```
C
C
C THIS PROGRAM COMPUTES THE SYSTEM MARGIN FOR EITHER SINGLE OR DOUBLE
C RAIL POWER FREQUENCY TRACK CIRCUITS GIVEN A DC LINK RIPPLE CURRENT OF
C ONE AMP RMS AT EITHER 25 OR 60 HZ.
C
C THE PROGRAM IS INTERACTIVE AND ASKS FOR THE TRACK CIRCUIT CHARACTERISTICS
C NEEDED TO DETERMINE THE SAFETY AND OPERATING MARGINS.
C
C THE PROGRAM CONTAINS A SUBROUTINE TO COMPUTE THE INDUCTANCE AND RESISTANCE
C OF VARIOUS TRACK CIRCUIT LENGTHS AND RAIL CONFIGURATIONS. IT THEN COMPUTES
C THE COUPLING INTO THE TRACK CIRCUIT FOR ONE AMP RIPPLE CURRENT IN THE
C INVERTER DC LINK FOR THE REQUESTED TRACK CIRCUIT.
C
C FOR THE CASE OF AN OCCUPIED TRACK CIRCUIT IT IS ASSUMED THAT ALL THE
C INVERTERS IN THE TRAIN ARE IN PHASE. FOR THE UNOCCUPIED CASE A MULTIPLIER
C IS USED THAT WILL NOT BE EXCEEDED MORE THAN 0.1 % OF THE TIME.
C
C NOT ALL OF THE PARAMETERS NEEDED IN THE CALCULATIONS ARE INPUTTED
C INTERACTIVELY. MANY ARE LISTED IN DATA AND DECLARATION STATEMENTS.
C
C

      DIMENSION TRACK_CKT_LENGTH(14), THIRD_TO_GROUND(2), FREQ(2),
     1 PERMR(6), PERMT(6), TRKLENMAX(10), TRDTOGRDMAX(10),
     1 PERMMAX(10), COUPMAX(10), RVMAX(10), RAILCUR(10), RECVOLT(10),
     1 PROBFAC(10),CFV(6),RECCUR(10),CURTHRD(10),AMAXTHRD(10)
      COMPLEX*8 Z,CJ,VCOUP,RCUR,ZINCAR,ZTOSUB,ZB,ZWORK,IWORK,
     1 ZSERIES,A1,A2,A3,A4,B1,B2,B3,B4,V,DD,D1,D2,Z1000,Z01000,GAMMA,
     1 SINHGAMMAD,COSHGAMMAD,Z1,Z2,ZT,ZR,E,EIND,GAMMAD,ZX,DT,
     1 Z1PARZTPARZX,Z1PARZRPARZX,C1,C2,C3,C4,ZS,ANIR,D3,D4,ANIT,ITHRD
      REAL LRE,LT,LR,LG,M1,M2,M3,LF,LB,LFV(6),MB,LSD4,LS,LR1000,
     1 LT1000,M11000,M21000,M31000,M3LOOP
      DATA TRACK_CKT_LENGTH/1600.,1450.,1300.,1150.,1000.,850.,
     1 700.,600.,500.,400.,300.,
     1 225.,150.,75./,THIRD_TO_GROUND/26.28,85.41/,FREQ/25.,60./,
     1 PERMR/20.,16.,8.,4.,2.,1./,PERMT/35.,22.,15.,10.,5.,1./,
     1 LFV/.0005,.00003,.00003,.000,.000,.000/,
     1 PROBFAC/0.0,0.8375,0.0,0.625,0.0,0.52083333,0.0,0.4625,0.,.44/,
     1 CFV/.146667,.117333,.106667,.048,0.,0./
      DIMENSION RI(2),THRES(2)
C
       OPEN (UNIT=8, FILE='NYCTA.DAT', STATUS='NEW')
C
C AR IS THE EFFECTIVE RADIUS OF THE RUNNING RAIL.
C AT IS THE EFFECTIVE RADIUS OF THE THIRD RAIL.
C DCRR IS THE DC RESISTANCE FOR A 1000 FOOT RUNNING RAIL (ONE WAY).
C DCRT IS THE DC RESISTANCE FOR A 1000 FOOT THIRD RAIL (ONE WAY).
C RI(1) IS THE MAXIMUM INVERTER RIPPLE CURRENT IN AMPS RMSFOR 25 HZ.
C RI(2) IS THE MAXIMUM INVERTER RIPPLE CURRENT IN AMPS RMSFOR 60 HZ.
C THRES(1) IS THE TRACK CKT R TO R REC THRESHOLD IN V RMS. UNOCCUPIED.
C THRES(2) IS THE 25 HZ TRACK CKT R TO R REC THRESHOLD IN V RMS. OCCUPIED.
C BAL IS THE BALLAST RESISTANCE FOR 1000 FEET IN MHOS.
C ZT IS THE TRANSMITTER IMPEDANCE.
C ZR IS THE INPUT IMPEDANCE OF THE RECEIVER AS SEEN AT THE TRACK.
```

```
C ZS IS THE SUBSTATION IMPEDANCE CALCULATED FROM ZSR AND ZSL AFTER FREQ INPUT.
C
      AR = .187
      AT = .182
      DCRR = .0085
      DCRT = .0052
      RI(1) = 1.0
      RI(2) = 1.0
      ZSR = .55E-3
      ZSL = 200.E-6
      CJ = CMPLX(0.0,1.0)
      WRITE(8,*)' '
 1000 CONTINUE
      WRITE(6,*)' INPUT TRACK CIRCUIT NUMBER'
      READ(5,*) NTCK
      WRITE(8,*)' '
      WRITE(8,*)' THIS IS TRACK CIRCUIT NUMBER ',NTCK
      WRITE(6,*)' INPUT THE UNOCCUPIED INTERFERRENCE THRESHOLD.'
      READ(5,*)THRES(1)
      WRITE(6,*)' INPUT THE OCCUPIED INTERFERRENCE THRESHOLD.'
      READ(5,*)THRES(2)
      WRITE(6,*)' INPUT 1 FOR SINGLE RAIL OR 2 FOR DOUBLE RAIL.'
      READ(5,*)ISD
      WRITE(6,*)' INPUT 1 FOR 25 HZ OR 2 FOR 60 HZ.'
      READ(5,*)K
      W = 2.*3.1415927*FREQ(K)
      ZS = ZSR + CJ*W* ZSL
      LSD4 = 0.
      LS = 0.
      IF (ISD .EQ. 2) THEN
       WRITE(6,*)' INPUT Z-BOND INDUCTANCE'
       READ(5,*)LS
       LSD4 = LS/4.
      ELSE
       WRITE(6,*)' INPUT 2 FOR THIRD NEAR SIGNAL RAIL OR 1 FOR OTHER'
       READ(5,*)J
      END IF
      WRITE(6,*)' INPUT TRANSMITTER IMPEDANCE IN OHMS'
      READ(5,*)ZTX
      ZT = ZTX
      WRITE(6,*)' INPUT RECEIVER IMPEDANCE MAGNITUDE IN OHMS'
      READ(5,*)ZRX
      WRITE(6,*)' INPUT RECEIVER IMPEDANCE ANGLE IN DEGREES'
      READ(5,*)ZRA
      ZRAR = ZRA*3.1415927/180.
      ZR = ZRX*COS(ZRAR)+CJ*ZRX*SIN(ZRAR)
C
      DIST_B = 75.
      IPLOT = 0
C
C THIS LOOP IS TO MAKE OCCUPIED AND UNOCCUPIED RUNS.
C
     DO 508 IOC = 1,2
C
     WRITE(6,300)AR,PERMR(1),AT,PERMT(1),DCRR,DCRT,LS,DIST_B,
```

```
     1 PROBFAC(8),RI(K),FREQ(K),THIRD_TO_GROUND(J),THRES(IOC),ZT,ZR,
     1 ZS
      WRITE(8,300)AR,PERMR(1),AT,PERMT(1),DCRR,DCRT,LS,DIST_B,
     1 PROBFAC(8),RI(K),FREQ(K),THIRD_TO_GROUND(J),THRES(IOC),ZT,ZR,
     1 ZS
 300    FORMAT(' EFFECTIVE RADIUS OF RUNNING RAIL IN FEET',F10.4/
     1 ' MAXIMUM VALUE OF PERMEABILITY FOR THE RUNNING RAIL',F10.4/
     1 ' EFFECTIVE RADIUS OF THIRD RAIL IN FEET',F10.4/
     1 ' MAXIMUM VALUE OF PERMEABILITY FOR THE THIRD RAIL',F10.4/
     1 ' DC RESISTANCE FOR A 1000 FOOT RUNNING RAIL (ONE WAY)',F10.4/
     1 ' DC RESISTANCE FOR A 1000 FOOT THIRD  RAIL (ONE WAY)',F10.4/
     1 ' RAIL INDUCTANCE AND AC RESISTANCE ARE BOTH COMPUTED USING'/
     1 ' EQUATIONS AND APPROXIMATED TABLES FOUND IN GROVER.'/
     1 ' IMPEDANCE BOND INDUCTANCE',F10.6/
     1 ' CAR LENGTH = ',F10.2/
     1 ' PROBABILITY FACTOR FOR AN 8 CAR TRAIN',F10.5/
     1 ' MAXIMUM INVERTER RIPPLE CURRENT'/
     1  F10.5,' AMPS RMS AT ',F4.1,' HZ'/
     1 ' THIRD RAIL TO GROUND RAIL DISTANCE',F10.5/
     1 ' RAIL TO RAIL TRACK CIRCUIT RECEIVER INTERFERENCE THRESHOLD'/
     1  F10.5,' VOLTS RMS '/
     1 ' TRANSMITTER IMPEDANCE',2F10.4/
     1 ' RECEIVER IMPEDANCE',F13.4,F10.4/
     1 ' SUBSTATION IMPEDANCE',F10.5,F10.5)
C
C FOR INDUCTANCE .0005 AT 25 HZ AND .00003 AT 60 HZ.
C
        LF = LFV(K)
        RL = .0011
C
C THIS LOOP VARIES THE CAPACITANCE OF THE FILTER.
C
        DO 502 IC = 2,2
        CF = CFV(IC)
        RC = .0005625*.096/CF
C
        WRITE(6,600)LF,CF,RL,RC
        WRITE(8,600)LF,CF,RL,RC
 600    FORMAT(/' LF = ',F7.5,' CF = ',F7.5,' RL = ',F7.5,' RC = ',F7.5)
C
C THIS LOOP SETS TO ZERO THE MAX VOLTAGES INDUCED INTO THE TRACK CIRCUIT,
C
        DO III = 1,10
         RVMAX(III)=0.
        END DO
C
C THIS LOOP VARIES THE PERMEABILITY.
C
        DO 505 L = 1,6
C
C THIS LOOP VARIES THE TRACK CIRCUIT LENGTH.
C
         DO 506 I = 1,14
C
C IF IOC = 1 THEN THE TRACK CIRCUIT IS UNOCCUPIED.
```

```
C IF IOC = 2 THEN THE TRACK CIRCUIT IS OCCUPIED.
C
C THESE STATEMENTS COMPUTE THE INDUCTANCES AND RESISTANCES NEEDED.
C
         CALL GROVER (LR,RR,PERMR(L),FREQ(K),AR,TRACK_CKT_LENGTH(I),
     1   DCRR,20880.)
         CALL GROVER (LT,RT,PERMT(L),FREQ(K),AT,TRACK_CKT_LENGTH(I),
     1   DCRT,11809.)
C
         M1 = .00508*TRACK_CKT_LENGTH(I)*12.*(LOG(2.*TRACK_CKT_LENGTH(I)
     1 *12./26.28)-1+26.28/TRACK_CKT_LENGTH(I)/12.)*1.E-6
         M2 = .00508*TRACK_CKT_LENGTH(I)*12.*(LOG(2.*TRACK_CKT_LENGTH(I)
     1 *12./85.41)-1+85.41/TRACK_CKT_LENGTH(I)/12.)*1.E-6
         M3 = .00508*TRACK_CKT_LENGTH(I)*12.*(LOG(2.*TRACK_CKT_LENGTH(I)
     1 *12./57.48)-1+57.48/TRACK_CKT_LENGTH(I)/12.)*1.E-6
C
C THE CURRENT CIRCULATED BACK TO THE SUBSTATION IS COMPUTED BELOW.
C
        ZINCAR = RL+RC + CJ*(W*LF-1./W/CF)
        RCUR = 4.*(RC-CJ/W/CF)/ZINCAR
        CALL GROVER (LB,RB,PERMR(L),FREQ(K),AR,DIST_B,DCRR,20880.)
        MB = .00508*DIST_B*12.*(LOG(2.*DIST_B*12./57.48)
     1 -1+57.48/DIST_B/12.)*1.E-6
        LB = LB*2.-2.*MB
        RB = RB*2.
        ZB = RB + CJ*W*LB
C        ZB = CJ*0.
C
        NUMCARS = 2
        ASSIGN 1 TO IAD
        GO TO 110
 1      RECCUR(NUMCARS) = CABS(IWORK)
        CURTHRD(NUMCARS) = CABS(ITHRD)
        NUMCARS = 4
        ASSIGN 2 TO IAD
        GO TO 110
 2      RECCUR(NUMCARS) = CABS(IWORK)
        CURTHRD(NUMCARS) = CABS(ITHRD)
        NUMCARS = 6
        ASSIGN 3 TO IAD
        GO TO 110
 3      RECCUR(NUMCARS) = CABS(IWORK)
        CURTHRD(NUMCARS) = CABS(ITHRD)
        NUMCARS = 8
        ASSIGN 4 TO IAD
        GO TO 110
 4      RECCUR(NUMCARS) = CABS(IWORK)
        CURTHRD(NUMCARS) = CABS(ITHRD)
        NUMCARS = 10
        ASSIGN 5 TO IAD
        GO TO 110
 5      RECCUR(NUMCARS) = CABS(IWORK)
        CURTHRD(NUMCARS) = CABS(ITHRD)
        GO TO 55
C
```

```
 110    IWORK = RCUR
        ZWORK = ZINCAR
C
C       THIS LOOP COMPUTES AN EQUIVALENT CIRCUIT FOR THE TRAIN
C       ZWORK IS THE INPUT IMPEDANCE OF THE TRAIN
C       IWORK IS THE PARALLEL CURRENT SOURCE FOR THE TRAIN
C       V IS THE VOLTAGE SOURCE EQUIVALENT FOR IWORK
C
        NUMCARSM1 = NUMCARS-1
        DO 120 II = 1,NUMCARSM1
        IWORK = IWORK*ZWORK/(ZWORK+ZB)
        ZWORK = ZWORK + ZB
        IWORK = IWORK+RCUR
        ZWORK = ZWORK*ZINCAR/(ZWORK+ZINCAR)
 120    CONTINUE
        V = IWORK*ZWORK
C
C       THIS CODE COMPUTES THE RECEIVER CURRENT FOR THE TRACK CIRCUIT.
C
        IF (ISD .EQ. 1) THEN
C
C THIS IS FOR SINGLE RAIL CIRCUITS
C
         IF (J .EQ. 1) THEN
C
C THIS IS FOR SINGLE RAIL CIRCUITS WITH THE THIRD RAIL NEAR THE GROUND RAIL.
C
          A1 = ZT + ZR + RR + CJ*W* (LR - M2)
          A2 = CJ*W* (M3 - M1)
          A3 = ZS + ZWORK + RT + CJ*W* (LT - M2)
          B1 = CJ*W* (M3 - M2)
          B2 = RR + CJ*W* (LR - M1)
          B3 = ZS + ZWORK + RT + CJ*W* (-M1 + LT)
          DD = A2*(B1+B3)-A1*(B2+B3)+A3*(B1-B2)
          ANIR = V * ( A2 + A3 - B2 - B3 )
          IWORK = ANIR/DD
          ANIT = -V * (B1 - B2) + V * (A1 - A2)
          ITHRD = ANIT / DD
          GO TO IAD
C
         ELSE
C
C THIS IS FOR SINGLE RAIL CIRCUITS WITH THE THIRD RAIL FAR FROM GROUND RAIL.
C
          A1 = ZT + ZR + RR + CJ*W* ( LR - M1)
          A2 = CJ*W* ( M3 - M2)
          A3 = ZS + ZWORK + RT + CJ*W* (-M1 + LT)
          B1 = CJ*W* (M3 - M1)
          B2 = RR + CJ*W* (LR - M2)
          B3 = ZS + ZWORK + RT + CJ*W* (LT - M2)
          DD = A2*(B1+B3)-A1*(B2+B3)+A3*(B1-B2)
          ANIR = V * ( A2 + A3 - B2 - B3 )
          IWORK = ANIR/DD
          ANIT = -V * (B1 - B2) + V * (A1 - A2)
          ITHRD = ANIT / DD
```

```
          GO TO IAD
C
         END IF
C
        ELSE
C
C  THIS IS FOR DOUBLE RAIL CIRCUITS
C
         IF (IOC .EQ. 1) THEN
          A1 = RR + ZS + ZWORK + RT + CJ*W* (2.*LSD4 + LR + LT - 2.*M2)
          A2 = -RR + CJ*W* (-4.*LSD4 - LR + M3 + M2 - M1)
          A3 = -RR + CJ*W* (-LR + M3 -2.*LSD4 + M2 - M1)
          A4 = CJ*W* ( 2.*LSD4 )
          B1 = ZS + ZWORK +  RT + CJ*W* (-2.*LSD4 + LT + M3 - M1 - M2)
          B2 = RR + CJ*W* (4.*LSD4 + LR - M3 + M2 - M1)
          B3 = RR + CJ*W* (2.*LSD4 + LR - M3 + M2 - M1)
          B4 = CJ*W* (-2.*LSD4)
          C1 = -RR + CJ*W* (M3 + M2 - LR)
          C2 = 2.*RR + CJ*W* (2.*LR - 2.*M3)
          C3 = ZT + 2.*RR + CJ*W* (2.*LR - 2.*M3)
          C4 = ZR
          D1 = CJ*W* (2.*LSD4)
          D2 = CJ*W* (-4.*LSD4)
          D3 = CJ*W* (-4.*LSD4)
          D4 = ZR + CJ*W* (4.*LSD4)
         ELSE
          ZT = 1000000.
          A1 = RR + ZS + ZWORK + RT + CJ*W* (1.*LSD4 + LR + LT - 2.*M2)
          A2 = -RR + CJ*W* (-2.*LSD4 - LR + M3 + M2 - M1)
          A3 = -RR + CJ*W* (-LR + M3 -2.*LSD4 + M2 - M1)
          A4 = CJ*W* ( 2.*LSD4 )
          B1 = ZS + ZWORK +  RT + CJ*W* (-1.*LSD4 + LT + M3 - M1 - M2)
          B2 = RR + CJ*W* (2.*LSD4 + LR - M3 + M2 - M1)
          B3 = RR + CJ*W* (2.*LSD4 + LR - M3 + M2 - M1)
          B4 = CJ*W* (-2.*LSD4)
          C1 = -RR + CJ*W* (M3 + M2 - LR)
          C2 = 2.*RR + CJ*W* (2.*LR - 2.*M3)
          C3 = ZT + 2.*RR + CJ*W* (2.*LR - 2.*M3)
          C4 = ZR
          D1 = CJ*W* (2.*LSD4)
          D2 = CJ*W* (-4.*LSD4)
          D3 = CJ*W* (-4.*LSD4)
          D4 = ZR + CJ*W* (4.*LSD4)
         END IF
         DD = A1*(B2*(C3*D4-C4*D3)-C2*(B3*D4-B4*D3)+D2*(B3*C4-B4*C3))
     1       -B1*(A2*(C3*D4-C4*D3)-C2*(A3*D4-A4*D3)+D2*(A3*C4-A4*C3))
     1       +C1*(A2*(B3*D4-B4*D3)-B2*(A3*D4-A4*D3)+D2*(A3*B4-A4*B3))
     1       -D1*(A2*(B3*C4-B4*C3)-B2*(A3*C4-A4*C3)+C3*(A3*B4-A4*B3))
         ANIR = -V*(B1*(C2*D3-C3*D2)-C1*(B2*D3-B3*D2)+D1*(B2*C3-B3*C2))
     1          +V*(A1*(C2*D3-C3*D2)-C1*(A2*D3-A3*D2)+D1*(A2*C3-A3*C2))
         IWORK = ANIR/DD
         ANIT =  V*(B2*(C3*D4-C4*D3)-C2*(B3*D4-B4*D3)+D2*(B3*C4-B4*C3))
     1          -V*(A2*(C3*D4-C4*D3)-C2*(A3*D4-A4*D3)+D2*(A3*C4-A4*C3))
         ITHRD = ANIT / DD
         GO TO IAD
```

```
C
      END IF
C
55    RECVOLT(2) = RECCUR(2) * CABS(ZR) * PROBFAC(2)
      RECVOLT(4) = RECCUR(4) * CABS(ZR) * PROBFAC(4)
      RECVOLT(6) = RECCUR(6) * CABS(ZR) * PROBFAC(6)
      RECVOLT(8) = RECCUR(8) * CABS(ZR) * PROBFAC(8)
      RECVOLT(10) = RECCUR(10) * CABS(ZR) * PROBFAC(10)
      IF (IOC .EQ. 2) THEN
      RECVOLT(2) = RECCUR(2) * CABS(ZR)
      RECVOLT(4) = RECCUR(4) * CABS(ZR)
      RECVOLT(6) = RECCUR(6) * CABS(ZR)
      RECVOLT(8) = RECCUR(8) * CABS(ZR)
      RECVOLT(10) = RECCUR(10) * CABS(ZR)
      END IF
C
 100  FORMAT(' ',3F10.1,F10.2,9F10.5)
 200  FORMAT(/' ','TRACK CKT ','THIRD TO  ','FREQUENCY ',
     1 'PERM(REL) ','COUPLING  ','RAIL CUR  '
     1 ,'RAIL CUR  ','RAIL CUR  ','RAIL CUR  ','REC VOLTS ',
     1 'REC VOLTS ','REC VOLTS ','REC VOLTS '
     1 /' LENGTH    ','GROUND    ',10X,
     1 20X,'1 CAR     ','2 CARS    ','4 CARS    ','8 CARS    ',
     1 '1 CAR     ','2 CARS    ','4 CARS    ','8 CARS    ')
C
      IF (RECVOLT(2) .GT. RVMAX(2)) THEN
       RVMAX(2) = RECVOLT(2)
       TRKLENMAX(2) = TRACK_CKT_LENGTH(I)
       PERMMAX(2) = PERMR(L)
       AMAXTHRD(2) = CURTHRD(2)
      END IF
C
      IF (RECVOLT(4) .GT. RVMAX(4)) THEN
       RVMAX(4) = RECVOLT(4)
       TRKLENMAX(4) = TRACK_CKT_LENGTH(I)
       PERMMAX(4) = PERMR(L)
       AMAXTHRD(4) = CURTHRD(4)
      END IF
C
      IF (RECVOLT(6) .GT. RVMAX(6)) THEN
       RVMAX(6) = RECVOLT(6)
       TRKLENMAX(6) = TRACK_CKT_LENGTH(I)
       PERMMAX(6) = PERMR(L)
       AMAXTHRD(6) = CURTHRD(6)
      END IF
C
      IF (RECVOLT(8) .GT. RVMAX(8)) THEN
       RVMAX(8) = RECVOLT(8)
       TRKLENMAX(8) = TRACK_CKT_LENGTH(I)
       PERMMAX(8) = PERMR(L)
       AMAXTHRD(8) = CURTHRD(8)
      END IF
C
      IF (RECVOLT(10) .GT. RVMAX(10)) THEN
       RVMAX(10) = RECVOLT(10)
```

```
        TRKLENMAX(10) = TRACK_CKT_LENGTH(I)
        PERMMAX(10) = PERMR(L)
        AMAXTHRD(10) = CURTHRD(10)
       END IF
C
 506   CONTINUE
 505   CONTINUE
 504   CONTINUE
C
 400   FORMAT(' ',I10,F10.5,F10.1,F10.2,F10.3,F10.5,F10.3)
 500   FORMAT(' ','  NUM CARS',' MAX CURTHRD',' TRK LEN',
     1 '       PERM',' IND VOLTS',' DB MARGIN','  FREQUENCY =',F5.1,
     1 '  UNOCCUPIED BLOCK')
 700   FORMAT(' ','  NUM CARS',' MAX CURTHRD',' TRK LEN',
     1 '       PERM',' IND VOLTS',' DB MARGIN','  FREQUENCY =',F5.1,
     1 '  OCCUPIED BLOCK')
       IF(IPLOT .EQ. 1) GO TO 12
       IF (IOC .EQ. 1) THEN
        WRITE(6,500) FREQ(K)
        WRITE(8,500) FREQ(K)
       ELSE
        WRITE(6,700) FREQ(K)
        WRITE(8,700) FREQ(K)
       END IF
       DO III = 2,10,2
        VINDUCED = RVMAX(III)*RI(K)
        AMARGIN = THRES(IOC)/VINDUCED
        AMARGIN = 20.*LOG(AMARGIN)/2.30258
        WRITE(6,400)III,AMAXTHRD(III),TRKLENMAX(III),
     1  PERMMAX(III),VINDUCED,AMARGIN
        WRITE(8,400)III,AMAXTHRD(III),TRKLENMAX(III),
     1  PERMMAX(III),VINDUCED,AMARGIN
       END DO
 12    CONTINUE
 503   CONTINUE
 502   CONTINUE
 501   CONTINUE
C
 508   CONTINUE
       IF (FREQ(K) .LT. 1000.) GO TO 1000
       END
C
        SUBROUTINE GROVER (L,R,PERM,FREQ,A,TRACK_CKT_LENGTH,DCR,SIG)
C
        DIMENSION RRA(2,8),TA(2,8)
        REAL L
C
C THE FOLLOWING IS USED TO CALCULATE ONE WAY RAIL INDUCTANCE FROM
C THE RAIL LENGTH, EFFECTIVE RADIUS, AND PERMEABILITY.
C
C THE ARRAYS BELOW ARE USED TO TABULATE A TABLE FOUND IN GROVERS BOOK OF
C INDUCTANCE CALCULATIONS.
C
        RRA(1,1) = 0.
        RRA(1,2) = 2.
```

```
      RRA(1,3) = 3.
      RRA(1,4) = 5.
      RRA(1,5) = 10.
      RRA(1,6) = 30.
      RRA(1,7) = 50.
      RRA(1,8) = 100.
      RRA(2,1) = 1.00
      RRA(2,2) = 1.078
      RRA(2,3) = 1.318
      RRA(2,4) = 2.043
      RRA(2,5) = 3.799
      RRA(2,6) = 10.86
      RRA(2,7) = 17.93
      RRA(2,8) = 35.61
      TA(1,1) = 0.
      TA(1,2) = 1.
      TA(1,3) = 2.
      TA(1,4) = 5.
      TA(1,5) = 7.
      TA(1,6) = 10.
      TA(1,7) = 15.
      TA(1,8) = 25.
      TA(1,9) = 38.
      TA(1,10) = 50.
      TA(2,1) = 1.0
      TA(2,2) = .9974
      TA(2,3) = .9611
      TA(2,4) = .5560
      TA(2,5) = .4002
      TA(2,6) = .2816
      TA(2,7) = .1882
      TA(2,8) = .1131
      TA(2,9) = .0744
      TA(2,10) = .0566
C
C X IS COMPUTED HERE.
C
      X = 60.96*3.1415927*A*SQRT(2.*PERM*FREQ/SIG)
C
C THE FOLLOWING CODE COMPUTES EQUATION PARAMETERS FROM THE COMPUTED VALUES OF X.
C
      IF (X .GT. RRA(1,8)) THEN
       RR = RRA(2,8) + (X-RRA(1,8))/10.*3.535
      ELSE
       IX = 7
 5     IF (X .GT. RRA(1,IX)) GO TO 10
       IX = IX - 1
       GO TO 5
 10    RR = RRA(2,IX) + (X-RRA(1,IX))/(RRA(1,IX+1)-RRA(1,IX))*
     1  (RRA(2,IX+1)-RRA(2,IX))
      END IF
C
      IF (X .GT. TA(1,8)) THEN
       T = 2.83/X
      ELSE
```

```
          IX = 7
 15       IF (X .GT. TA(1,IX)) GO TO 20
          IX = IX - 1
          GO TO 15
 20       T = TA(2,IX) + (X-TA(1,IX))/(TA(1,IX+1)-TA(1,IX))*
     1     (TA(2,IX+1)-TA(2,IX))
         END IF
C
C THIS CODE COMPUTES THE INDUCTANCE AND RESISTANCE ONE DIRECTION.
C
         L = .06096 * TRACK_CKT_LENGTH*(LOG(2.*
     1 TRACK_CKT_LENGTH/A)-1.+PERM*T*.25)*1.E-6
         R = RR * DCR * TRACK_CKT_LENGTH / 1000.
C
         RETURN
         END
```

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