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DEVELOPMENT, FABRICATION, AND TESTING OF INVERTER POWER SYSTEM FOR METROLINER

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FINAL REPORT

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16. Abstract

This report documents the development and subsequent fabrication of a solid state auxiliary power conditioning unit for the upgraded Metroliner. The APCU is an inverter of the pulse width modulated type having multiple parallel transistors in a three phase double way bridge configuration. The APCU is packaged to be tested and evaluated in a laboratory environment and proposed to be a prototype of units suitable for replacement of rotary type APU's presently installed in General Electric power system equipped Metroliners.

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PREFACE

This program was carried out under the sponsorship and guidance of the Transportation Systems Center, Kendall Square, Cambridge, MA, Department of Transportation.

Messrs. Frank Raposa and Raymond Wlodyka of TSC were the Program Manager and Project Engineer, respectively, providing technical guidance throughout the program. Dr. John W. Marchetti, AMTRAK consultant, provided invaluable assistance regarding details of the upgraded Metroliner vehicles and their operating environment.

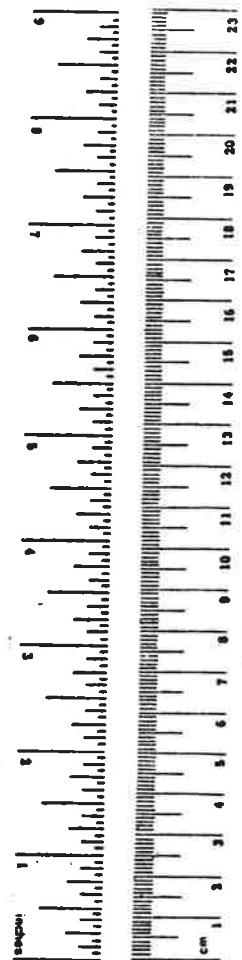
Overall program responsibility at Rohr was vested in the Advanced Transportation Systems Group under the direction of Mr. K.W. Tantlinger. The Program Manager was Mr. C. Theodore, succeeded by Mr. W.J. Holt, Director of Engineering.

Principal contributors to the design and development were J.A. Ross, systems design; A. Nerem and C. Ickes, electronics; R. Clary, magnetics and testing; J.A. Houdyshel, thermal and magnetics; R. Cariola, mechanical design.

METRIC CONVERSION FACTORS

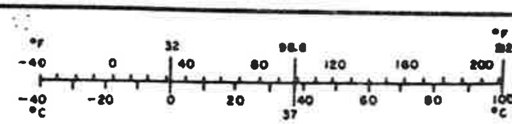
Approximate Conversions to Metric Measures

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	20	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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1. INTRODUCTION

This report describes the development, fabrication and testing of a static Auxiliary Power Conditioning Unit designed to operate in the electrical environment typical of an upgraded Metroliner vehicle.

The Metroliner vehicles, as furnished by the Budd Company, were equipped with power systems supplied by General Electric and Westinghouse. The motor-alternator and its associated power system have been, according to DOT reports, a source of maintenance problems and poor reliability. Various methods of motor-alternator replacements have been studied, and as a result of such studies, a two-phase contract was awarded to Rohr Industries, Inc., in 1976 for the development of two static inverters to be designed and fabricated and then installed and field-evaluated.

These static inverters were to be installed on two Metroliner vehicles, one on a General Electric vehicle and the second on a Westinghouse vehicle. These vehicles were then to be operated by AMTRAK in their normal environment on the Northeast corridor system for an evaluation period of twelve months.

A subsequent contract modification revised the contract to the extent that only one static inverter would be fabricated.

A further contract modification revised the program so that in the interest of overall economy the inverter would not be an environmentally packaged unit installed into an operating vehicle but instead would be a laboratory assembly.

2. SUMMARY

The static inverter Auxiliary Power Conditioning Unit as finally configured for evaluation by the Transportation Systems Center is a single 183 KVA, three-phase, 230 VAC, 60 Hertz power supply.

The input to this inverter was designed to accept the D.C. link voltage as provided by the General Electric equipped vehicle with the line variations common to the Penn Central 11 KV, 25 HZ catenary system.

The basic power conditioner consists of three class "D" transistor switching amplifiers arranged for three-phase bidirectional conduction, which is an outgrowth of Rohr's propulsion technology developed for magnetic levitation systems.

The assembly is housed in two 19-inch equipment enclosures, forced air cooled, which with minor vehicle seating modification may be installed into the interior of a G.E. equipped Metroliner vehicle if field-testing under the catenary environment is considered appropriate.

Performance tests at Rohr Industries' Chula Vista facility successfully demonstrated conformance with the design criteria and also demonstrated the feasibility of large high-efficiency static power systems employing multiple parallel transistors.

3. SYSTEM DESCRIPTION

3.1 Performance Specifications

INPUT VOLTAGE	325 to 590 VDC for specified output voltage. 265 to 325 VDC with reduced output voltage.
OUTPUT VOLTAGE	230 VAC three phase.
OUTPUT FREQUENCY	60 Hertz.
OUTPUT POWER	183 kVA peak for 1 minute. 100 kVA continuous @ 0.8 power factor.
CURRENT WAVEFORM	Sinusoidal.
VOLTAGE WAVEFORM	Square (pulse width modulated 4kHz carrier).
PHYSICAL SIZE	1120 mm wide x 610 mm deep x 1676 mm high.
WEIGHT	500 kilograms.

3.2 Power Rating

The kVA capacity of the inverter was determined by an analysis of all the power loads on the G.E. vehicle, the peak kVA requirement being that necessary to start (provide inrush current) the largest single motor load (Freon compressor) after all other loads are on OK at maximum load.

3.3 Original Scope of Work

The APCU static inverters were originally intended to be as identical as possible. They were to be designed and fabricated under Phase 1 and then incorporated into the G.E. and Westinghouse equipped vehicles for a period of field-testing and evaluation under Phase 2. Later, they were to be returned to their former motor-alternator configuration.

Upon detailed examination, however, it became apparent that the variations in the two types of vehicles were significant enough that the two inverters would be substantially different.

The major difficulty was with the undercarbody equipment arrangement which precluded the concept of a single inverter package which would fit both vehicles. Inasmuch as the G.E. and Westinghouse power systems were electrically similar, it was decided to construct a single inverter package and install it in the G.E. equipped vehicle. No economically justifiable purpose would have been served by field-evaluating two nearly identical systems and the effort would have become largely a packaging exercise.

The Metroliner vehicles were inspected during the severe winter of 1976-77, and it was found that most of the vehicles taken out of service were taken out for reasons of inoperative electrical equipment resulting from impacted ice and snow in open ventilated assemblies. For this reason it was recommended that the APCU would have to be either a completely sealed unit with a closed loop cooling system or a flow-through system incorporated into the roof air induction system installed on the upgraded G.E. vehicle.

This concept was pursued and working designs were completed for an environmentally packaged assembly which was intended for direct replacement of the motor-alternator in the existing underfloor space envelope.

Subsequently, in the interests of overall economy a decision was made to cancel Phase 2 (the installation and field evaluation aboard a Metroliner vehicle) and to concentrate on a more conventional and economical assembly which would operate in a benign laboratory environment and would be evaluated with a 100 horsepower electric motor dynamometer test assembly.

3.4 Final Implementation

The APCU assembly configuration as finally implemented was an attempt to use the components and subassemblies as they were initially developed and configured for the proposed environmentally packaged assembly. Particular emphasis was given to the power module section in order to establish criteria for forced air cooling requirements, voltage spacing, power and signal circuits proximity, and general mechanical and structural integrity.

The resulting configuration is a low-density assembly of simple construction, with good accessibility for easy maintenance. However, the power module section, being an air-insulated assembly, is as densely packaged as is considered to be practical from a reliability standpoint without employing exotic insulating fluids in a sealed unit.

3.5 Reliability

Reliability of the APCU is improved by providing redundant power modules in the inverter power assembly. The failure of any component in a power module results in blowing a fuse in that module, which isolates it from the rest of the operating power modules. With the isolation of the failed module, operation of the APCU continues without interruption with its available reserve power reduced only by the contribution of that single failed module.

The result then of providing additional modules is to maintain uninterrupted operation so that module replacement is not necessary until scheduled maintenance is performed at the next routine interval.

A reliability prediction study was conducted prior to the Metroliner APCU contract and was subsequently verified to a 90% statistical confidence by life testing. For the life test a precursor to the Metroliner APCU was constructed using 25 prototype power modules with a rating of approximately 100 KVA. This test assembly was operated continuously for over 10,000 hours from a 600 Vdc source into an inductive load with only minor infantile failures in the first 100 hours.

The power transistors employed in the modules are of the glass-passivated, triple-diffused, silicon type and have demonstrated extremely high reliability.

4. SWITCHING AMPLIFIER CONCEPT

4.1 General

The basic power conditioner used in the APCU is a transistorized pulse width modulated (PWM) type. This power conditioner concept is fundamentally different from conventional AC motor drives in that power transistors are used rather than thyristors (SCR's). The power transistor offers a decided advantage over the SCR in the reduction of circuit complexity and packaging volume because it does not require complicated turn-off circuitry. In addition, it allows high frequency modulation, thus reducing the carrier ripple current in the load and the requirement for large smoothing reactors. The pulse width modulation frequency employed in the APCU is 4 kilo Hertz. Also the acoustic noise level (at 2 times the modulation frequency) is very low due to the reduced energy at the higher frequencies.

Many small (To-3 case size) transistors are connected in parallel to produce the high current capacity for large KVA loads. The use of multiple, relatively small transistor junctions is a sound approach from a volume and weight standpoint since it avoids the thermal problems associated with high current, physically large, power SCR junctions with their high heat flux concentration. Mounting a number of smaller junctions on light weight heat sinks maintains low junction to air temperature gradients by spreading of the heat-generating areas, thus affording short thermal paths with thin heat conducting sections at modest air velocity requirements.

Since thermal shock and extreme thermal cycling are primary causes of semiconductor failures, it is appropriate to limit the temperature differentials to low values to maintain generous safety margins. By the method employed here, these junction to air temperature gradients are typically within 20 degrees Centigrade.

4.2 Operation of Switching Amplifier

Figure 1 shows the basic inverter element, a Class D(PWM) transistor switching amplifier. Figure 2 shows a three-phase power conditioning unit consisting of three identical stages of this element driving an induction motor. Each stage is capable of switching current and voltage with any arbitrary phase relationship. As indicated in the diagram, a positive output current is provided by the top transistor and the bottom freewheeling diode. A negative output current is provided by the bottom transistor and the top freewheeling diode.

Figure 3 illustrates the function of a stage in the transistor switching amplifier. Four load conditions are shown for the stage, and the active current-carrying circuit elements are shown for each condition. Since the phase voltage and phase current relationship is load-dependent, the base voltage waveform and the phase output current waveform are not shown to be in phase with respect to each other.

4.3 Ancillary Circuits

Several unique ancillary circuits described below are necessarily incorporated along with the basic switching amplifier into the APCU inverter system to provide safe, efficient operation.

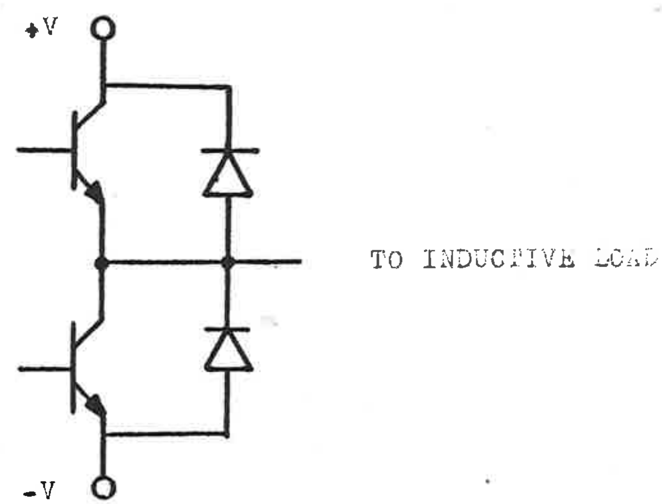


FIGURE 1. BASIC INVERTER ELEMENT

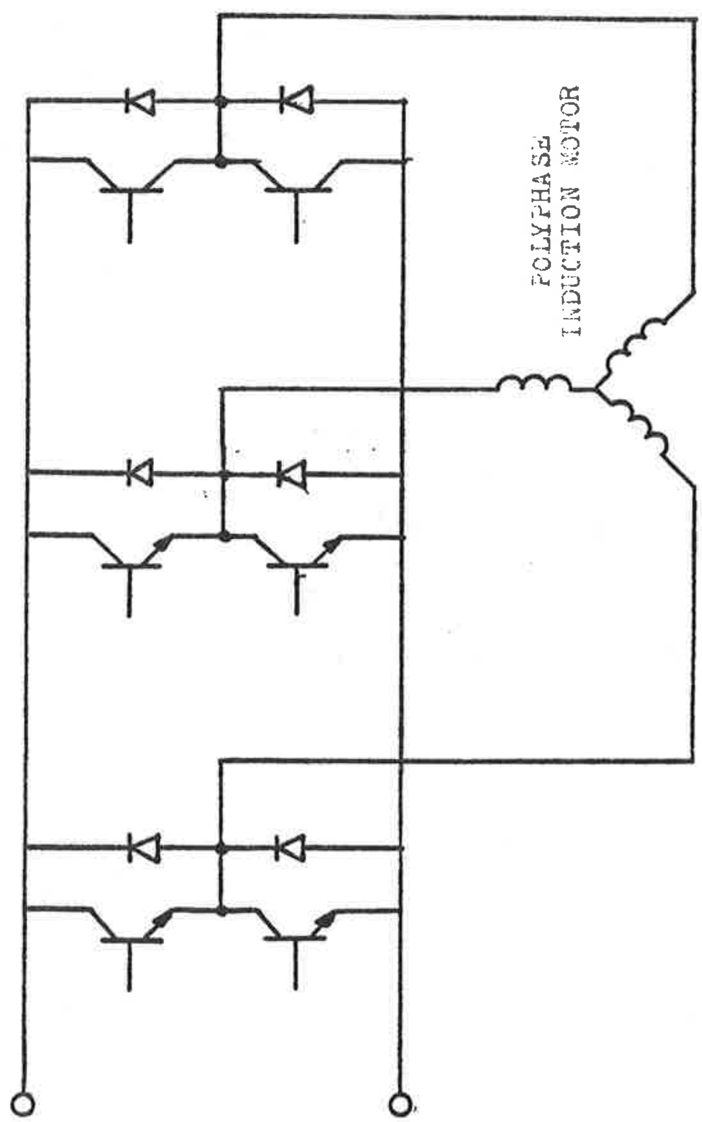


FIGURE 2. THREE PHASE POWER CONDITIONING UNIT

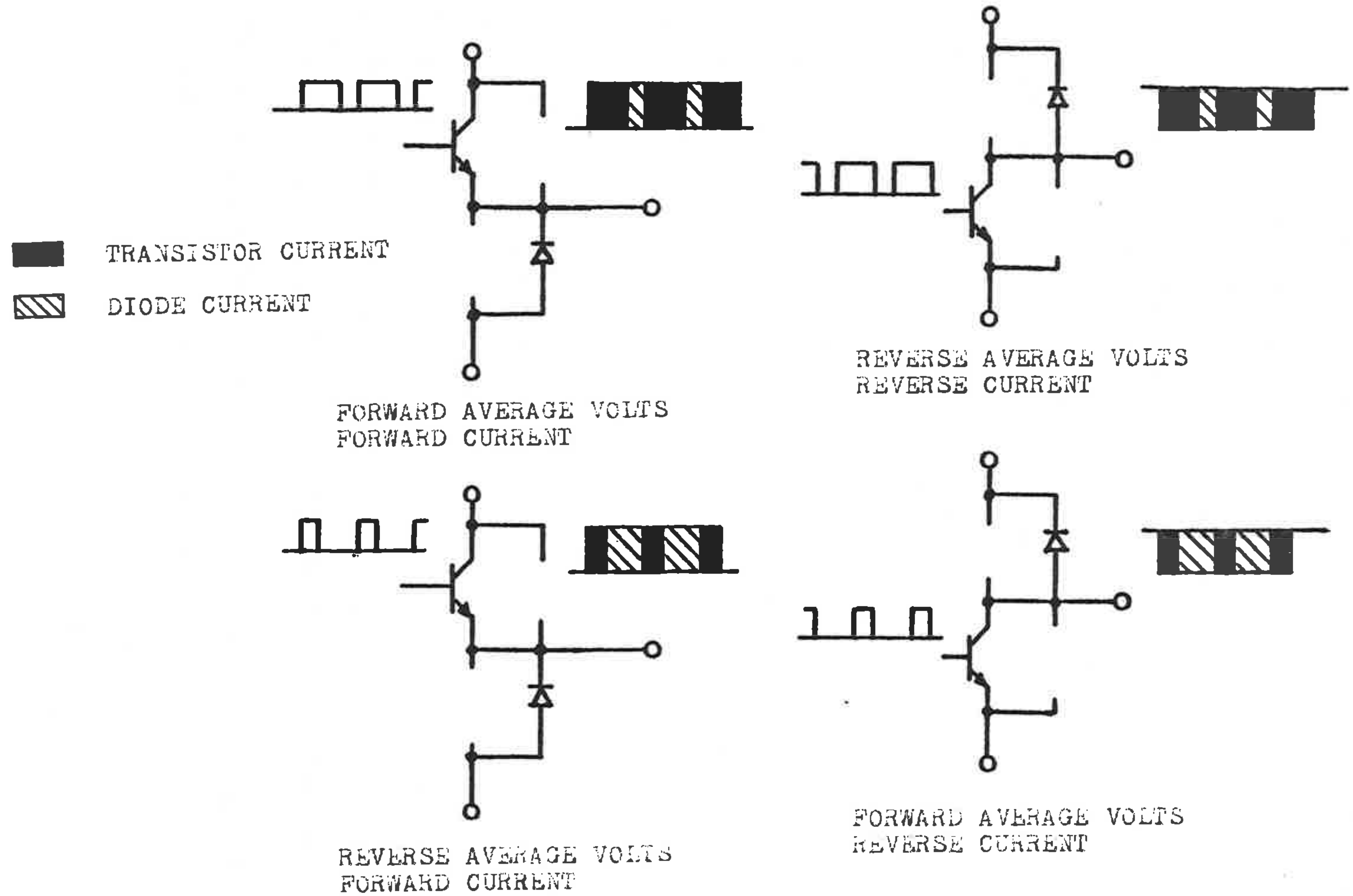


FIGURE 3. FOUR QUADRANT SWITCHING AMPLIFIER OPERATION

4.3.1 A third harmonic (distorted sine wave) voltage is added to the fundamental voltage which allows the peak-to-peak value of output voltage to be greater than the D.C. supply voltage.

4.3.2 Overvoltage (overconduction) circuits turn off the power conditioner when an overload is detected to be longer than 10 microseconds duration.

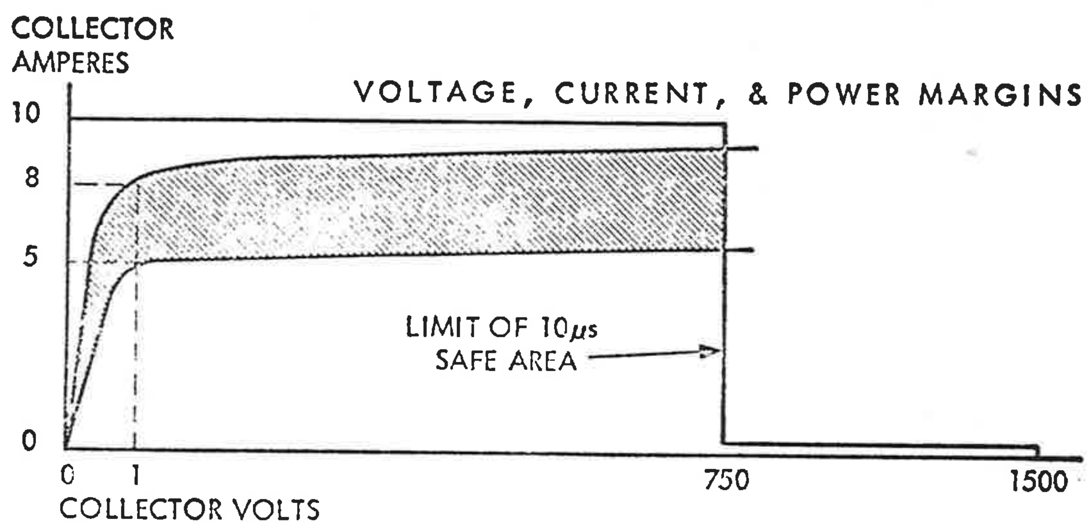
4.3.3 Dynamic base drive regulation is provided to control saturation levels in the driver and power transistors and to conserve base drive power.

4.3.4 The direction of current flow (into or out of the power conditioner) is monitored, and the base drive to the non-conduction transistor is inhibited to conserve base drive power.

4.4 Transistor Switching Characteristics

Switching characteristics of the presently available transistors used in this application (voltage ratings, current ratings, and power margins) clearly demonstrate the feasibility of switching amplifiers which can operate from dc power sources of up to 750 Volts (600 Volts as a practical application limit).

The power conditioner presently used in the APCU employs parallel connected transistors of the glass-passivated, triple-diffused silicon type. The safe area characteristic curve for a semiconductor device of this type is shown in Figure 4.



SPREAD OF COLLECTOR CURRENT FOR CONSTANT BASE VOLTAGE OF 1.3 VOLTS (95% OF UNITS)

FIGURE 4. SAFE AREA CHARACTERISTICS

4.5 Current Limiting

In the parallel connected arrangement of transistors presently used in the APCU operating voltages up to 600 Volts dc are achieved (750 Vdc as a peak limit) with nonoperating voltages of up to 1500 Vdc permissible. The power conditioner unit maintains safe area operation for the main power transistors by monitoring the status of the collector voltage during the "on" state. If the voltage across a transistor exceeds a safe "on" limit voltage for a predetermined time (10 microseconds) during its conduction cycle, the transistor is shut off immediately and allowed to rest prior to being turned on again. This protects the power conditioner from short circuits or momentary overloads. Figure 5 illustrates this current limiting action.

CURRENT LIMITING ACTION

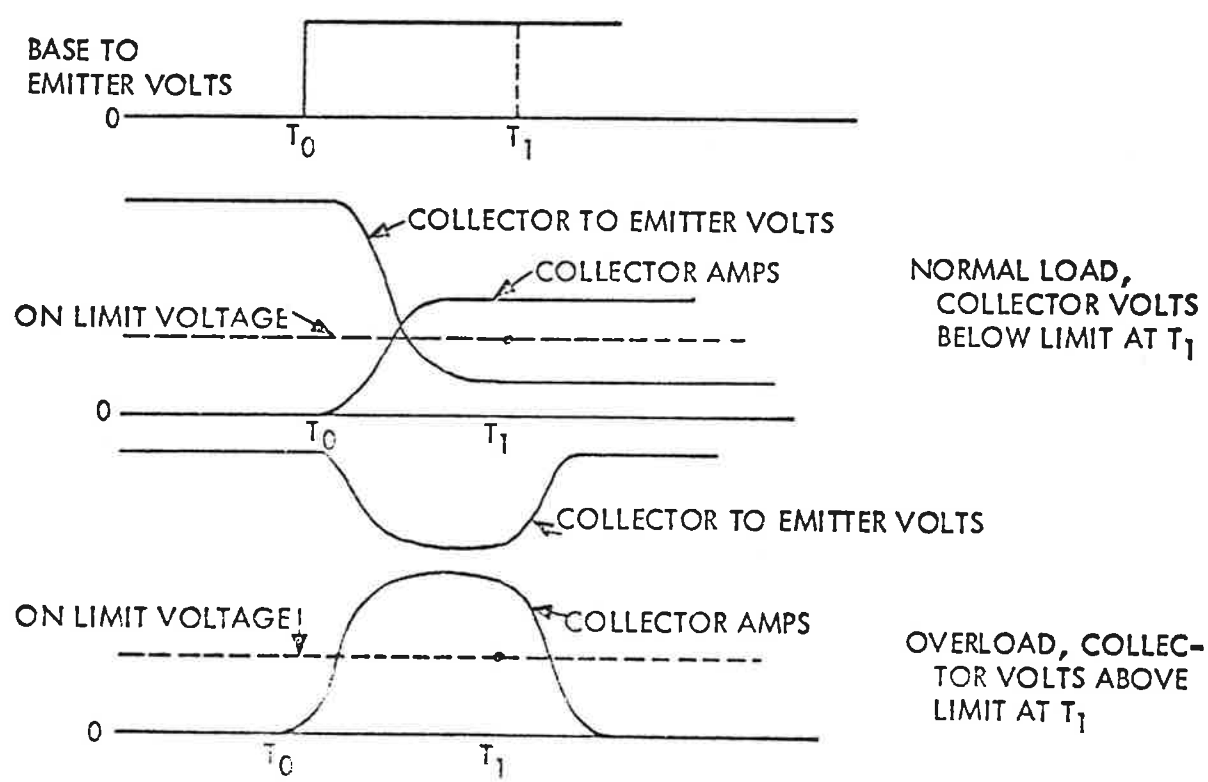


FIGURE 5. CURRENT LIMITING ACTION

5. APCU DEVELOPMENT

5.1 Prior Development Work

The Auxiliary Power Conditioning Unit (APCU) developed for the Metroliner is based on the inverter technology developed at Rohr for variable-voltage, variable-frequency linear and rotary induction motor control. The previous power conditioners were developed for use in systems requiring 40 to 800 KVA output power capacity for vehicle propulsion and machine tool spindle drives. A technique allowing soft failure modes in the inverter by isolating power components on individual power modules was previously developed. Also methods of paralleling multiple power modules to increase current capability to high levels were previously developed.

5.2 Development Work during Contract

Analysis of the load requirements of the upgraded General Electric cars showed that the highest momentary KVA requirement of the inverter occurs when all loads except the freon compressor are running and the freon compressor contactor closes. Under this condition, a steady state load of 120 amperes exists. When the freon compressor contactor closes, the load current momentarily increases to 460 amperes. A design goal of 540 amperes rms was selected utilizing 54 modules of 10 amperes rms each.

A system of internal logic and driver power supplies was developed utilizing the main rectified DC as source voltage. The power supplies developed provide stable logic supply voltages as the input rectified voltage varies from 200 to 700 volts DC.

This range corresponds to a catenary voltage range of 5,500 volts to 19,250 volts for the upgraded GE cars. The driver voltage regulator developed provides stable regulated driver stage dc power for 260 to 491 volts rectified dc input (7.0 KV to 13.5 KV catenary). The power supplies were coordinated so that the inverter operates safely without hazard to internal components with any input rectified voltage from zero to 900 volts dc. The inverter self-protects by reverting to a nonoperating mode at supply voltage below 265 volts dc and above 590 volts dc.

Analog simulation of the system transients showed a possible source of voltage instability at the filter capacitor bank. The inverter output voltage can be maintained at a constant level as the rectified voltage varies. The result is a negative impedance load at the inverter input. Sustained power supply oscillation can result. A circuit was developed and implemented which increases the inverter output voltage and frequency slightly as the rectified input voltage increases. This provides active damping to the dc filter circuit.

6. CIRCUITS DESCRIPTION

6.1 Internal Power Supplies. (Refer to Figure 6.)

The inverter is a self-contained, self-starting power source. A source of rectified voltage applied to the input power terminals results in sequential starting of internal power supply circuits, resulting in a regulated three-phase 230 Volt, 60 Hertz output.

The initiating supply inverter self-oscillates at any power input voltage between approximately 50 and 700 Volts. At inputs above 200 Volts the output voltage at the terminals is regulated at 20 Volts. The sole purpose of this small inverter is to provide an initial 20 Volt input to the 22 Volt, 40 Amp inverter.

This 20 Volts is the initial logic supply voltage for the 22-Volt power supply. The output section power module is identical with the power modules used in the main inverter power output section. This power module drives a power transformer and rectifier. The output from the rectifier provides the feedback for the pulse width modulated power supply regulator.

The resulting regulated 22 Volts provides the permanent power source for its own logic and the power source for the system control logic. The same 22 Volt power supply is also used as the starting input for both the 5 Volt, 80 Amp and 27 Volt, 160 Amp power supplies. These last two power supplies are also pulse width modulated. They use as permanent driver stage input voltage the regulated 27 Volts dc from the 160 Amp power supply.

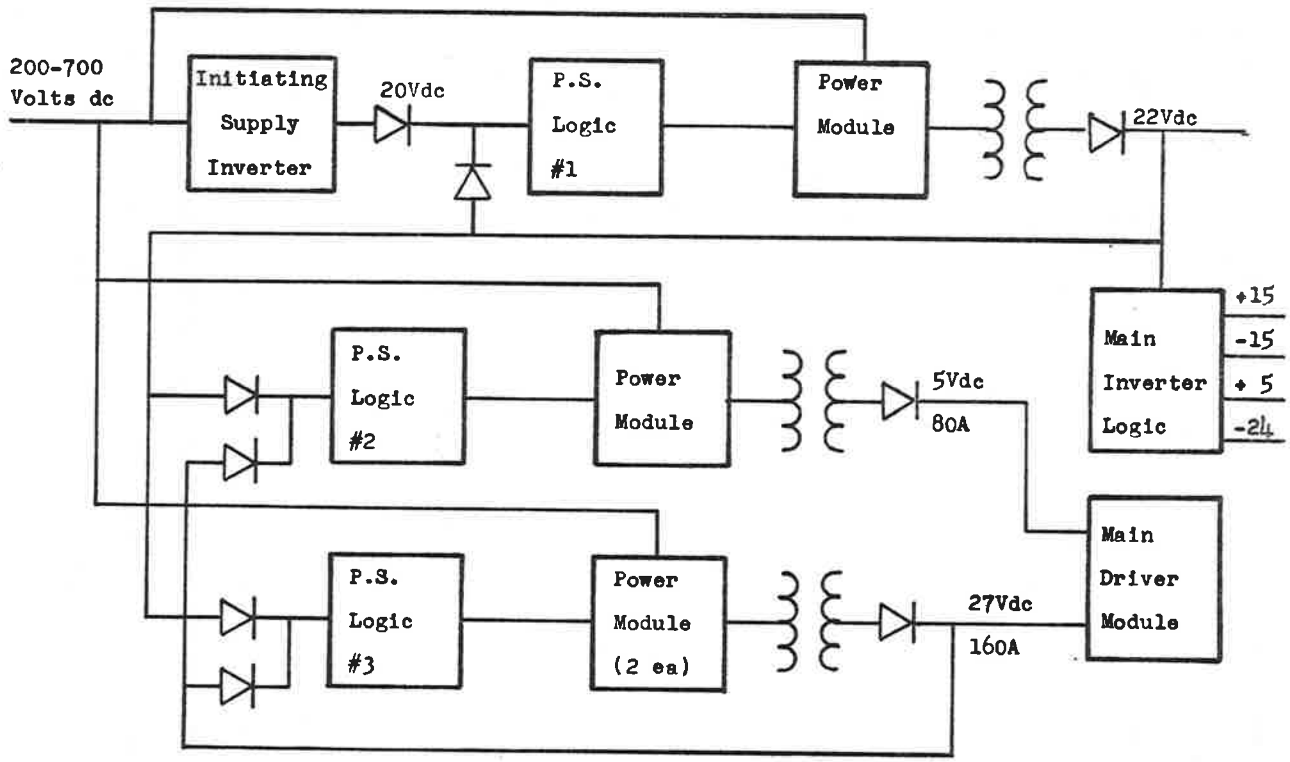


FIGURE 6. INTERNAL POWER SUPPLIES DIAGRAM

The 5 Volt, 40 Amp and 27 Volt, 160 Amp power supplies are used by the driver modules. The driver modules generate bursts of 140 kilo-Hertz waves to the output power modules. The current demand on the 27 Volt power supply varies as the 60 Hertz inverter load current varies.

6.2 Explanation of Block Diagram. (Refer to Figure 7.)

Figure 4 is a block diagram of the signal generation and power amplification sections of the Auxiliary Power Conditioning Unit (APCU). The circuitry involving conversion of unregulated rectified input voltage to internal logic power and regulated internal drive power is described in Section 6 and detailed in Section 9.

The FREQUENCY CONTROL is a front panel control whose setting determines the final operating frequency after start. A precision reference voltage serves as the input to this control so that the output voltage is stable to within 0.1% over the range of rectified input voltage variation of from 200 to 600 Volts.

The RATE LIMITER is a front panel control whose setting determines the rate at which the output frequency increases after startup. The RATE LIMITER output voltage is automatically set to zero during each start-up so that the initial output frequency and voltage are near zero during the energizing cycle. This prevents saturation of transformer loads and allows any connected motor loads to start without high inrush currents.

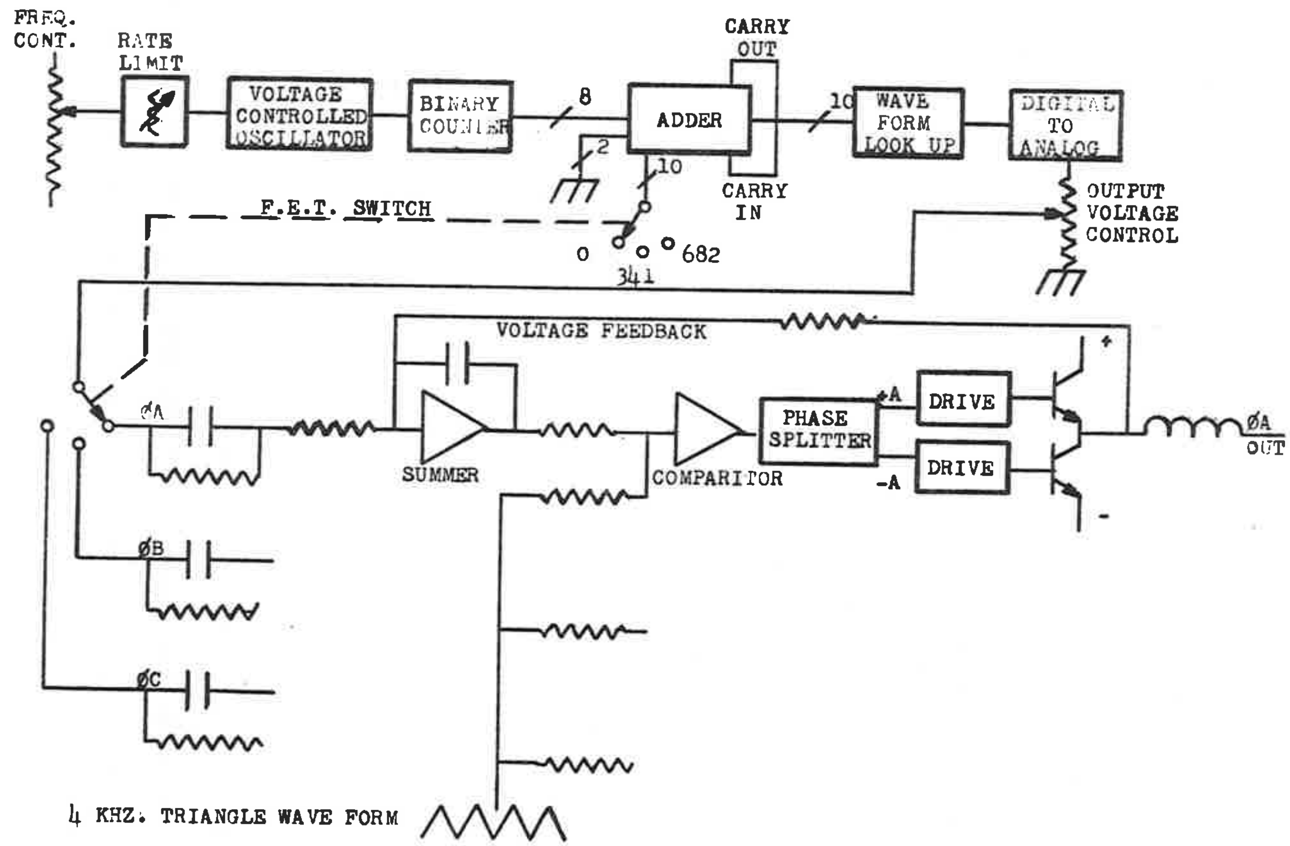


FIGURE 7. APCU BLOCK DIAGRAM

The VOLTAGE CONTROLLED OSCILLATOR generates a pulse train whose frequency is determined by the analog input voltage from the rate limiter. This frequency is 256 times the final system output frequency.

The 8-bit BINARY COUNTER provides the most significant 8-bit to the 10-bit ADDER. The other input to the ADDER is sequentially the binary equivalent of 0, 341, or 682. This generates 0, 1/3, or 2/3 of a cycle in addition to the phase angle equivalent to the binary counter output. The resulting 0 degrees, 120 degrees, and 240 degrees time information is synchronized and available for addressing the WAVE FORM LOOK UP table.

The WAVE FORM LOOK UP table is a Read Only Memory whose input address results in an output binary number proportional to the desired harmonic amplitude-vs-time.

The 10-bit DIGITAL TO ANALOG converter provides sequentially the three phase reference waveforms. This provides an analog voltage output whose instantaneous amplitude is equal to the sine of the angle represented by the binary number at the output of the counter or that binary number plus 120 degrees or that binary number plus 240 degrees.

The OUTPUT VOLTAGE CONTROL allows simultaneous adjustment of all phases since this control is ahead of the synchronized FIELD EFFECT TRANSISTOR (F.E.T.) distributor switch.

The three separated phases are individually differentiated to provide an increasing output with frequency.

The SUMMER allows output VOLTAGE FEEDBACK. A large amount of VOLTAGE FEEDBACK is used so that the actual phase power frequency voltage variation with respect to the rectified supply voltage variation is small. The SUMMER integrating capacitor provides the constant roll-off slope desired for system stability and very high zero frequency loop gain to eliminate dc offset voltages.

Pulse width modulation at a 4 kiloHertz rate is achieved by adding a triangular waveform to the summer output into a COMPARATOR.

The PHASE SPLITTER directs positive COMPARATOR outputs which result in turning on the transistors connecting the output to the positive power supply terminal. Conversly negative COMPARATOR output results in turning on the transistors connecting the output to the negative power supply terminal.

The output reactor reduces the magnitude of the resulting 8 kiloHertz current flowing in the load.

Output phases B and C are generated in a similar manner by using the B and C signals as references, by adding voltage feedbacks, and by modulating the B and C signals with the same 4 kilohertz carrier frequency traingular waveform. By utilizing a common carrier waveform, carrier chop between phases is minimized.

The waveform look up ROM is programmed with the proper magnitude of triple output frequency harmonic so that the phase-to-phase output voltage is a pure sine wave with maximum amplitude without clipping for rectified input voltages as low as 340 Volts dc.

7. APCU ASSEMPLY DESCRIPTION

7.1 General Arrangement

All elements of the APCU assembly are contained in two standard 19-inch panel equipment enclosures permanently jointed together. (See illustrations, Figures 8 and 9.) The main power module assembly section is in one enclosure with a plenum chamber and input capacitor energy storage bank mounted on the bottom. (See illustration, Figure 10.) The second enclosure contains three regulated power supply assemblies for the driver and logic power in two draw-out chassis, a draw-out motor control logic chassis, along with three iron core output inductors and a low speed centrifugal air blower at the bottom. (See illustration, Figure 11.) The blower in the power supply and logic section enclosure pressurizes the main power module section in the adjacent enclosure.

7.2 Main Output Power Assembly

The power module assembly is comprised of three identical power module units mounted together in the enclosure. (See illustration, Figure 10.) Each unit has a mother printed circuit board onto which are mounted twenty-two heavy duty industrial type sockets (2 rows of 11 sockets). (See illustration, Figure 12.) Eighteen of these sockets (9 per row) are 24-pin to accept the printed circuit power modules, and 4 of the sockets (2 per row) are 30-pin to accept the printed circuit power modules. The three mother printed circuit board units just described then provide for a total of 54 power modules and 12 driver modules (1 positive and 1 negative driver for each 9 power modules.)

Each of the 22 receptacles mounted onto the mother circuit board are integral with the card guide/slides so as to insure proper alignment when inserting a power or driver module. (See illustration, Figure 14.) The mother printed circuit board contains logic, driver, and power circuits distributed to the individual receptacles. (See illustration, Figure 12.) Collection of high current from individual power module outputs is made by heavy bus bar networks located on the backplane of the board along with the input power bus bars, driver logic connector, and certain other hard wiring. (See illustration, Figure 13.) This board with its assembled hardware is a foundation item and not removeable from the assembly. Feedback signals for output voltage and frequency control are supplied from an attenuator board (illustration, Figure 18) mounted adjacent to the mother board assembly.

7.3 Power Module

The power module itself is a printed circuit card 150 millimeters wide by 406 millimeters long with 24 double-sided connections on one end. It is fabricated from 1.6 mm thick NEMA grade G-10 epoxy glass laminate with 3-ounce copper cladding on each side. The power module contains all the high current power handling components such as D.C. input line fuses, D.C. filter capacitors, power switching transistors, free wheeling diodes, heat sinks, A.C. output phase fuses. With all the components assembled onto one side of the printed circuit board, the finished module is 35 mm high. (See illustration, Figure 15.) A second printed circuit card, called a piggy back module, contains the low-level circuitry and plugs into the center of the power module. (See illustration, Figure 16.)

At the rear edge of the power module are mounted neon lamps which indicate a blown input fuse and thereby identify a faulty power module. When mounted into the enclosure, the neon lamps at the rear of each module are visible behind the clear plexiglas air screen.

To realize the maximum current rating of 10 Amperes r.m.s. per phase, the power module requires the application of forced air across the power transistor heat sinks.

7.4 Driver Module

The driver module is similar in construction to the power module. (See illustration, Figure 17.) It is the same basic printed circuit card size with 30 double aided connections. It contains the power handling components necessary for distribution of the base drive to the power module with the exception of the large raw power components housed in the separate power supply section. The finished module is 23 mm high, and like the power module it is intended for forced air cooling.

Each module (power and driver) is fitted with locking ejector tabs located at the rear edge for ease of withdrawing and securing the modules.

7.5 Input Capacitor Bank

Below the power module assembly in the air plenum chamber is mounted the input energy storage bank consisting of 30 aluminum electrolytic computer grade capacitors of 1900 microFarads @ 450 Vdc each. (See illustration, Figure 29.)

The capacitors are in series-parallel with individual fusing of each series pair and individual resistors across each capacitor. The total capacity is 14,250 microFarads @ 900 Vdc. The capacitor cans are mounted onto an insulated panel.

7.6 Power Supplies Section

In the enclosure adjacent to the power module section are housed the regulated power supplies and logic assemblies. (See illustration, Figures 10 and 11.) The driver power supply assembly is contained in two separate chassis. The first chassis contains four power modules (identical with the main power modules); three power supply logic/drive modules (illustration, Figure 23); and one logic power supply module (illustration, Figure 24); all of which are printed circuit card modules which plug into connectors on the power supply mother printed circuit board (illustration, Figures 20, 21 and 22.)

The second driver power supply assembly chasis contains three power transformers, diode rectifier bridges, inductors, and filter capacitors for the 5 Volt @ 80 Ampere, 22 Volt @ 40 Ampere, and 27 Volt @ 160 Ampere regulated supplies. (See illustration, Figures 25, 26, 27 and 28.)

The logic assembly is contained in a small chassis with the three multiturn potentiometer controls on the front panel for voltage control, frequency control, and rate limit control. (See illustration, Figure 19.)

7.7 Output Inductors

Mounted beneath the power supply chassis are the three output phase reactors. These iron core inductors are rated for 69 microHenries at 697 Amperes peak and 234 Amperes continuous. They are constructed from 4 mil silicon steel tape wound cores and multistrand No. 20 gauge film wire.

7.8 Forced Air System

At the bottom of the power supply section is mounted a centrifugal blower which provides air to the adjacent enclosure for power module cooling. The inlet air to the blower is drawn from several filtered locations so that some air is drawn through the power supply and logic section. The outlet air pressurizes the plenum chamber below the power module assembly and exhausts at the top of the enclosure.

The squirrel cage blower operates at 1100 r.p.m. driven from a 3/4 horsepower motor powered by the output of the APCU and delivers 1200 cubic feet per minute against a 1.3 inch water column static pressure head. The blower and air moving acoustic noise level is moderately low.

8. PHOTOGRAPHS

8. PHOTOGRAPHS (CONT)

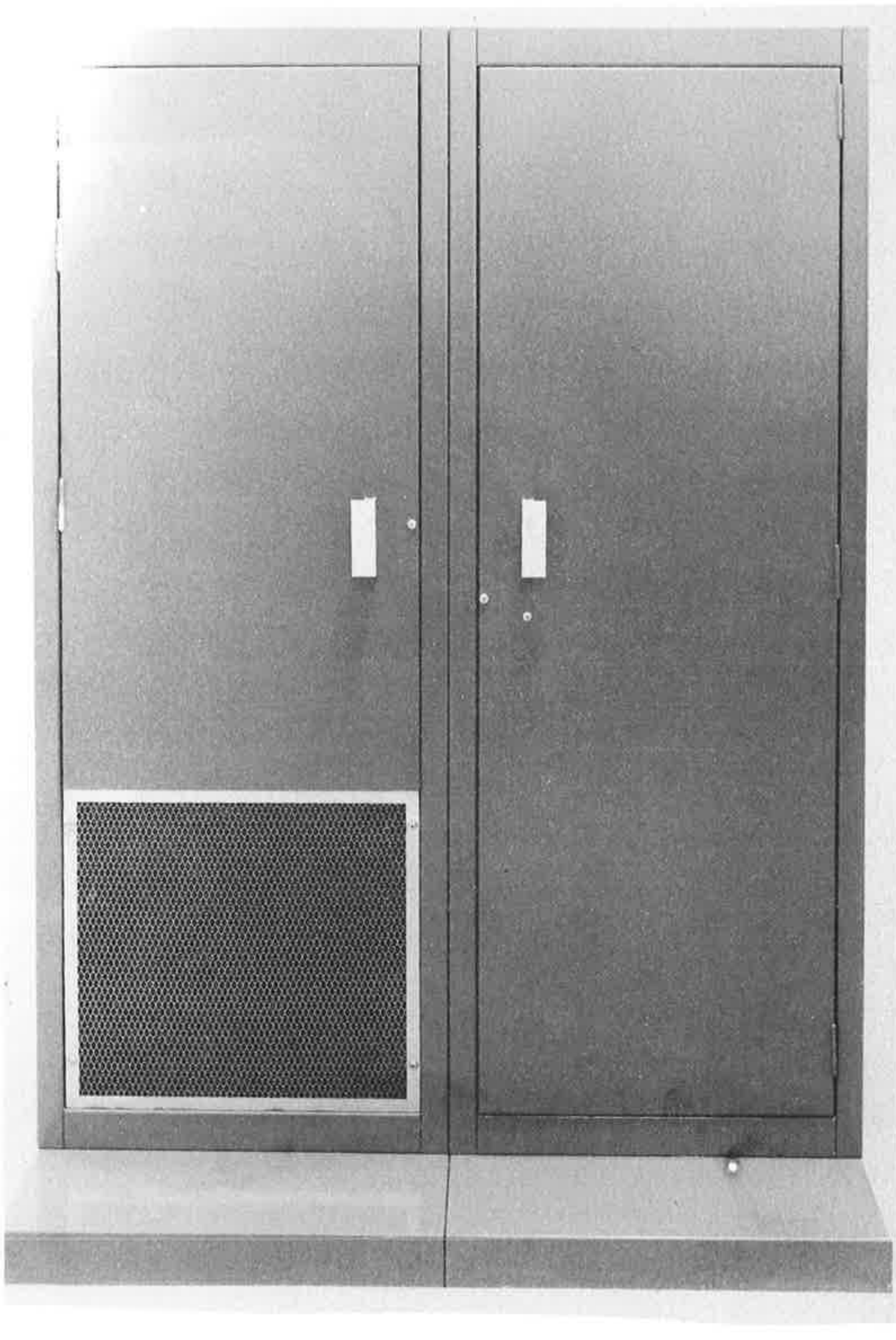


FIGURE 8. FRONT VIEW OF APCU ENCLOSURE

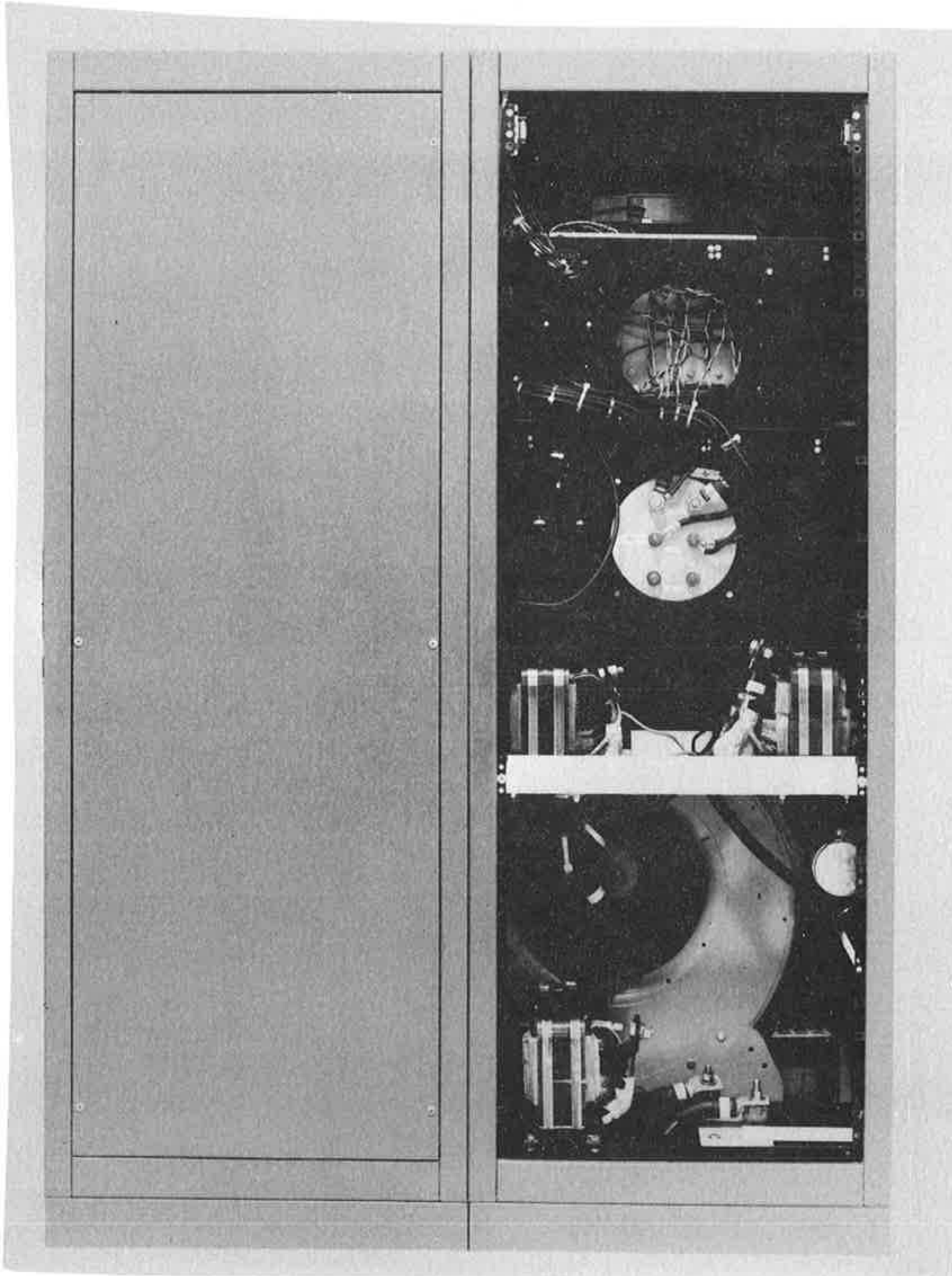


FIGURE 11. REAR VIEW OF ENCLOSURE

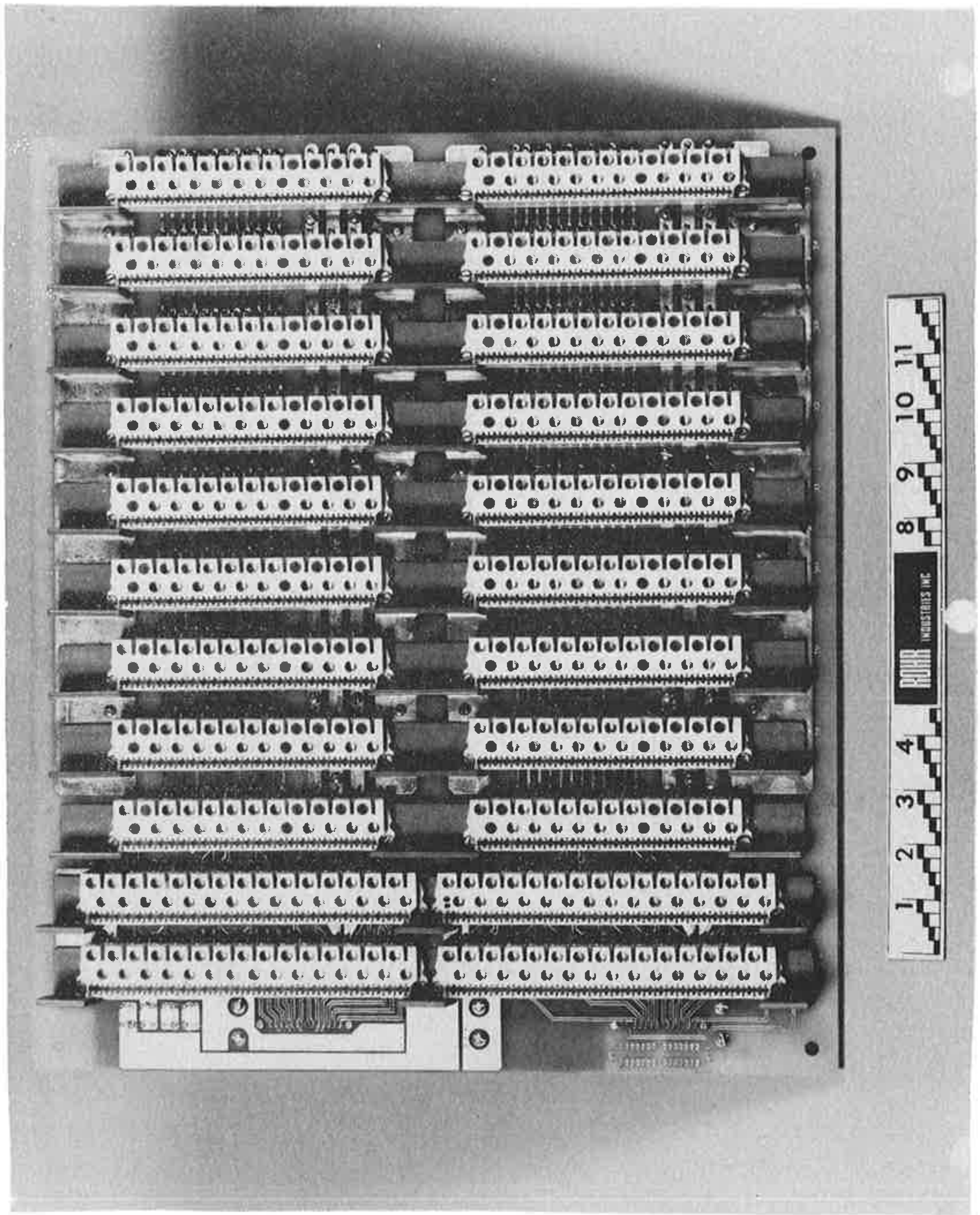


FIGURE 12. MOTHER P.C. BOARD

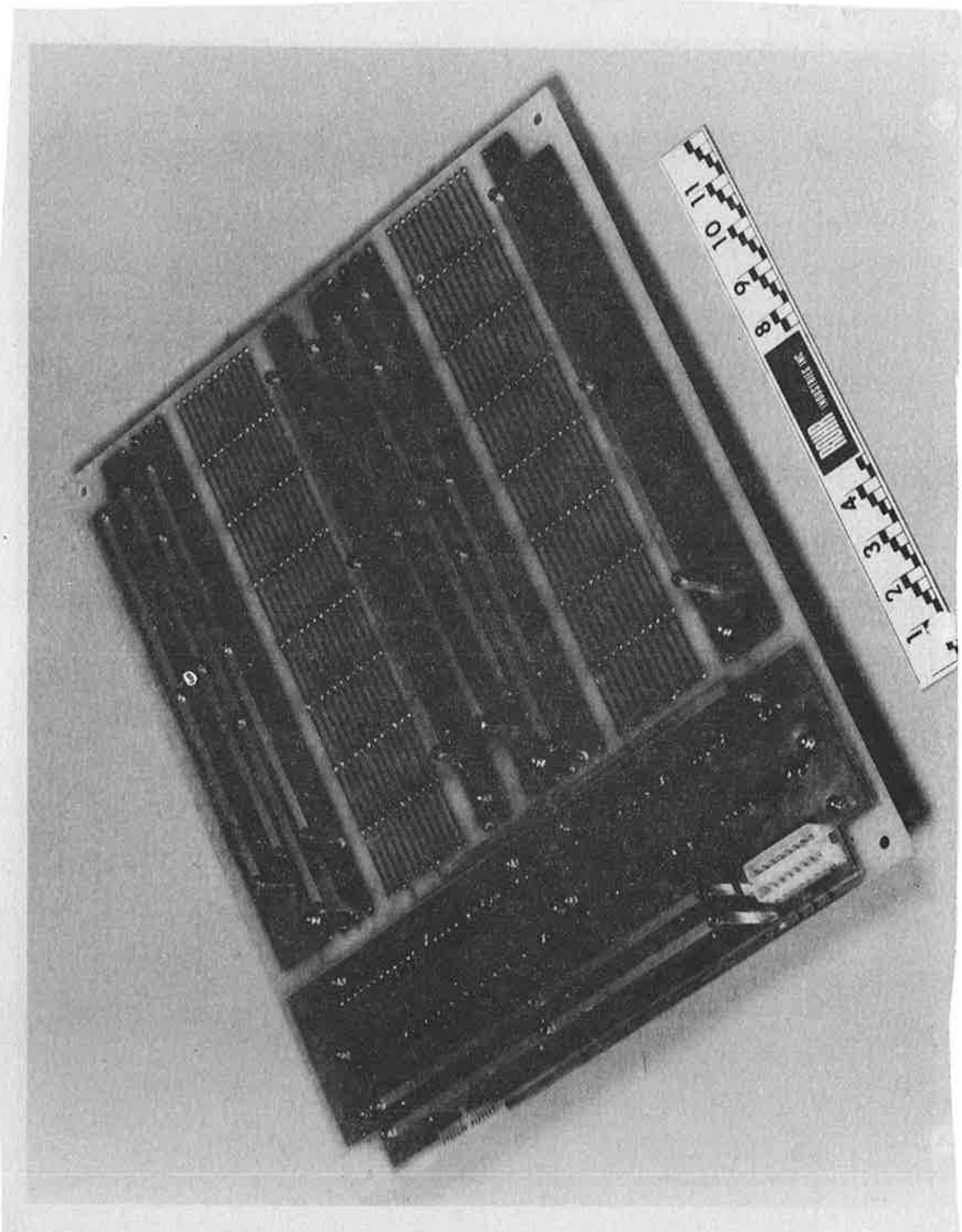


FIGURE 13. MOTHER P.C. BOARD BACKPLANE

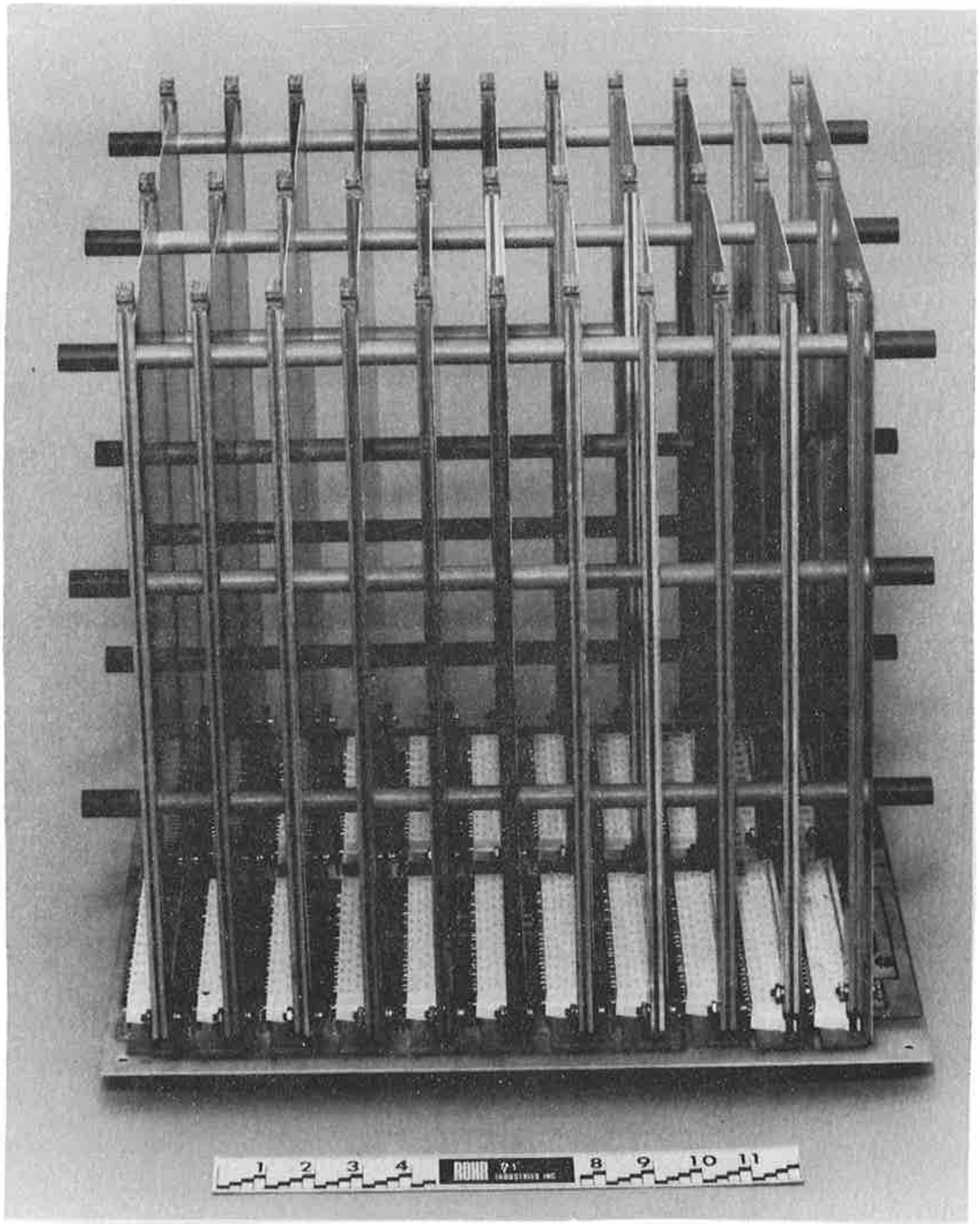


FIGURE 14. MOTHER P.C. BOARD ASSEMBLY

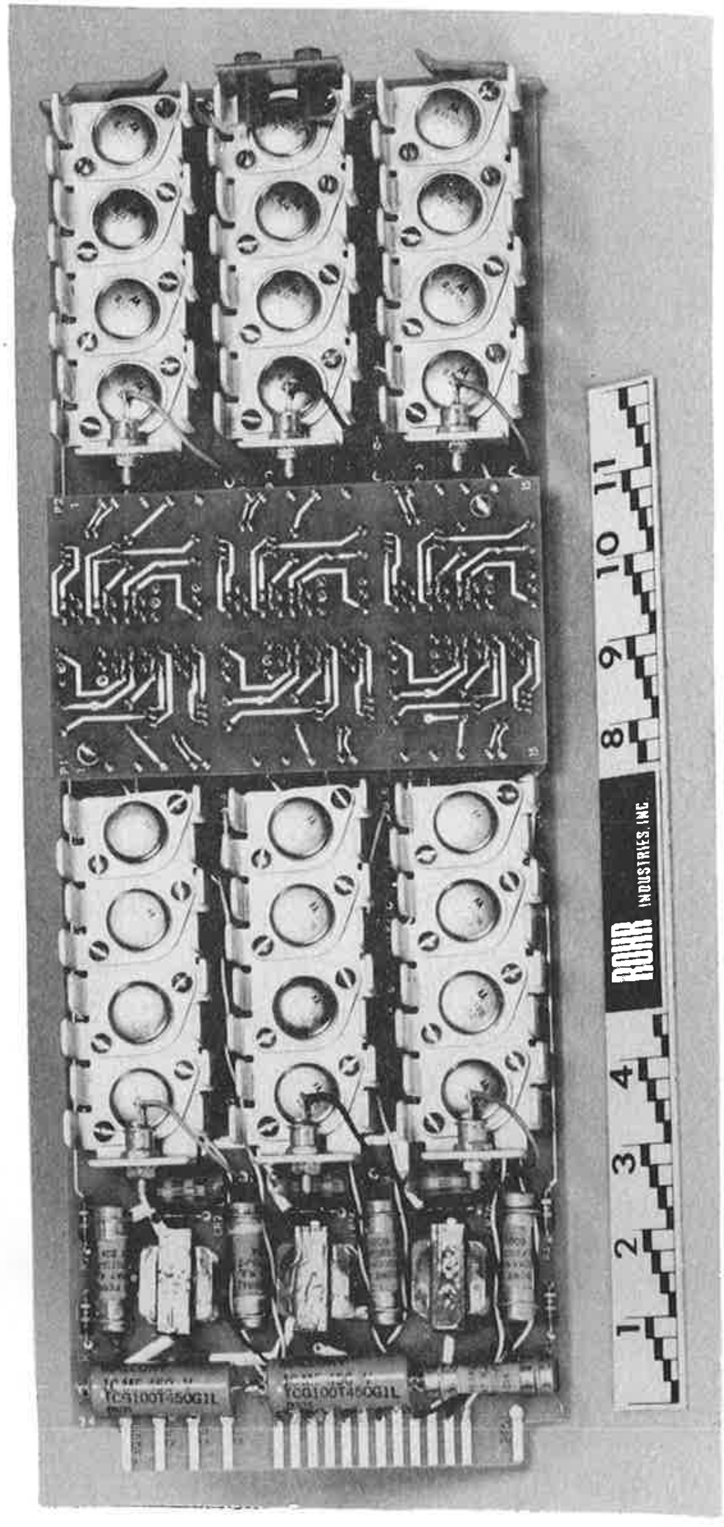


FIGURE 15. POWER MODULE ASSEMBLY

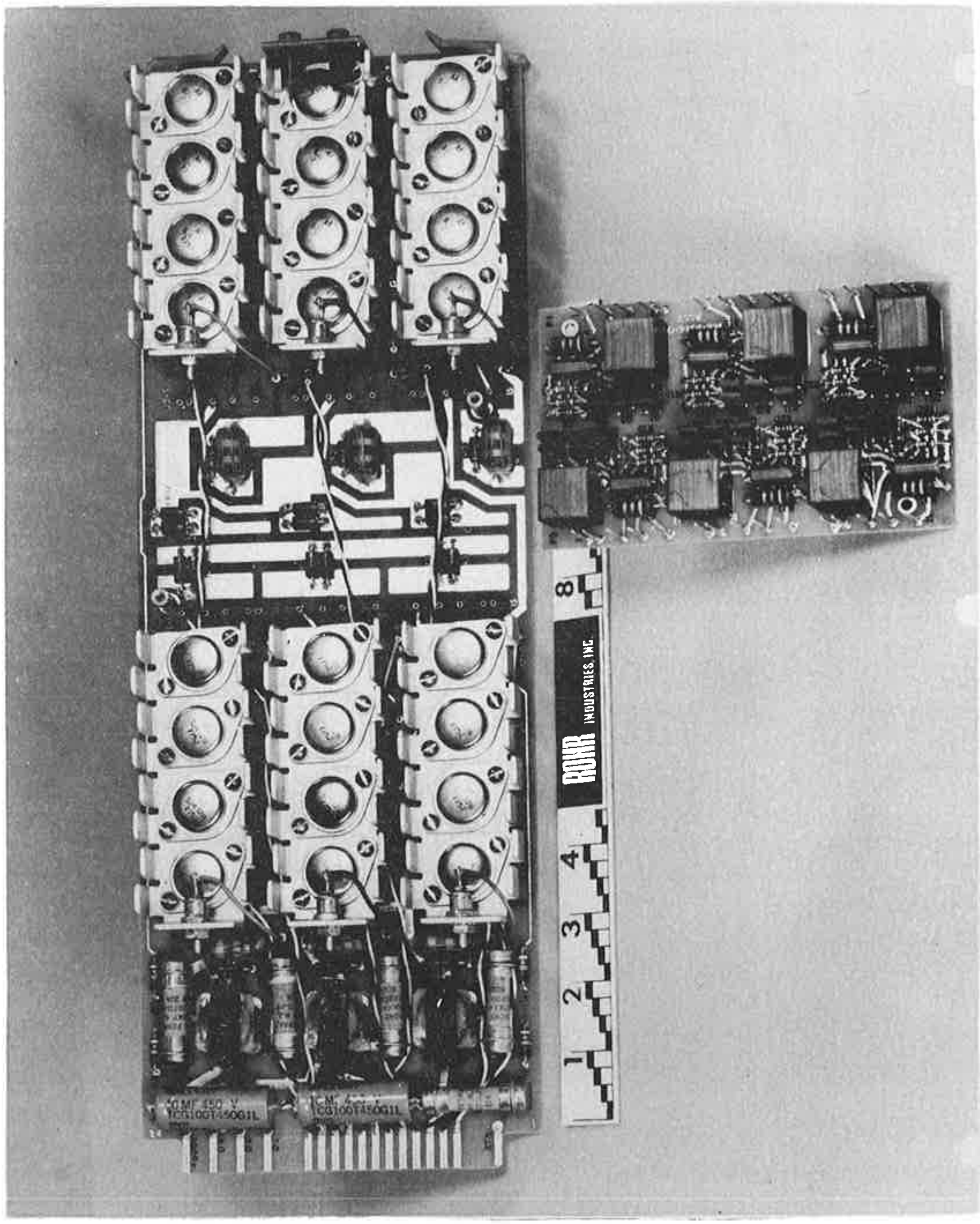


FIGURE 16. POWER MODULE ASSEMBLY WITH PIGGY BACK MODULE

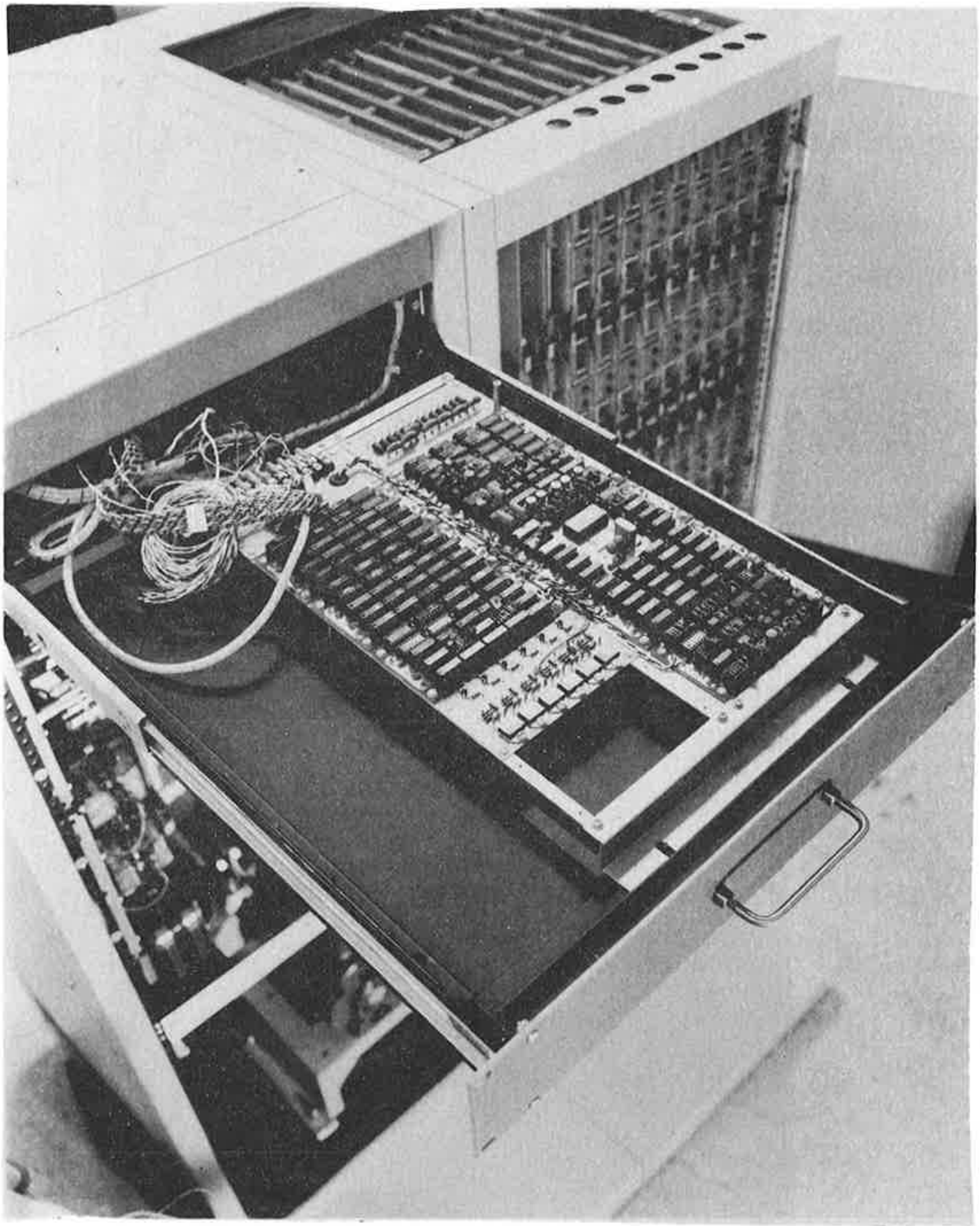


FIGURE 19. LOGIC ASSEMBLY

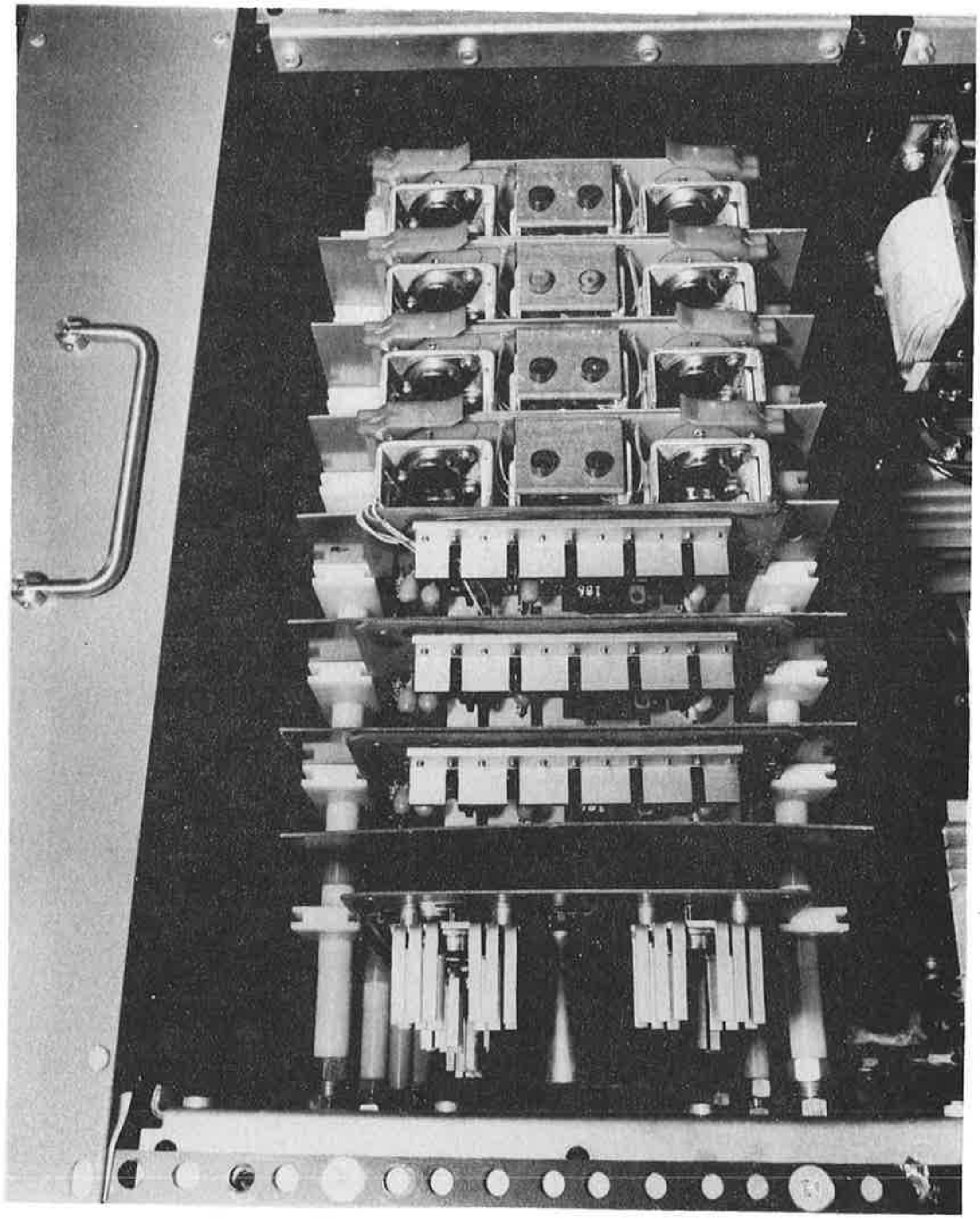


FIGURE 20. DRIVER POWER SUPPLY ASSEMBLY NO. 1

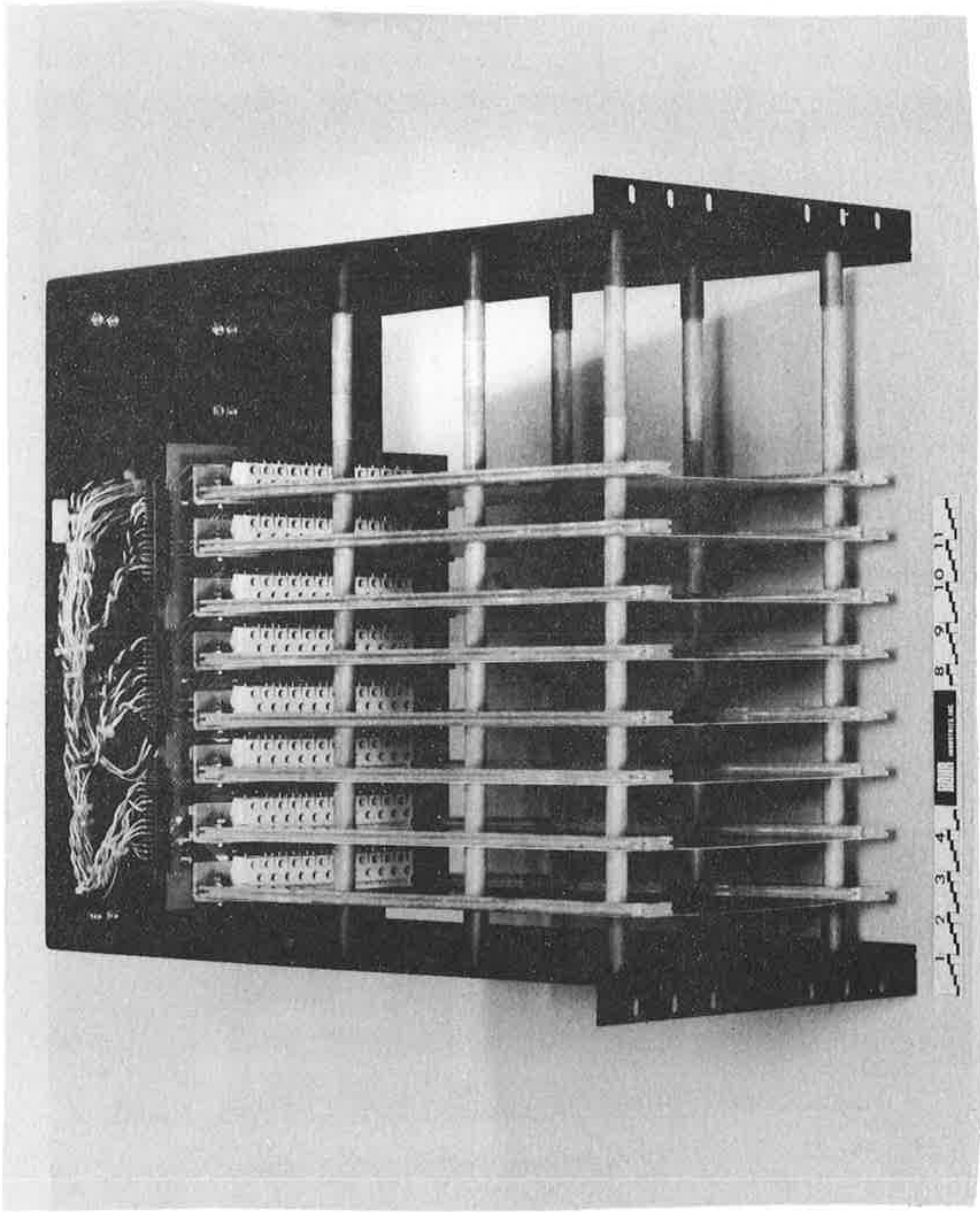


FIGURE 21. INSIDE OF DRIVER POWER SUPPLY ASSEMLBY NO. 1

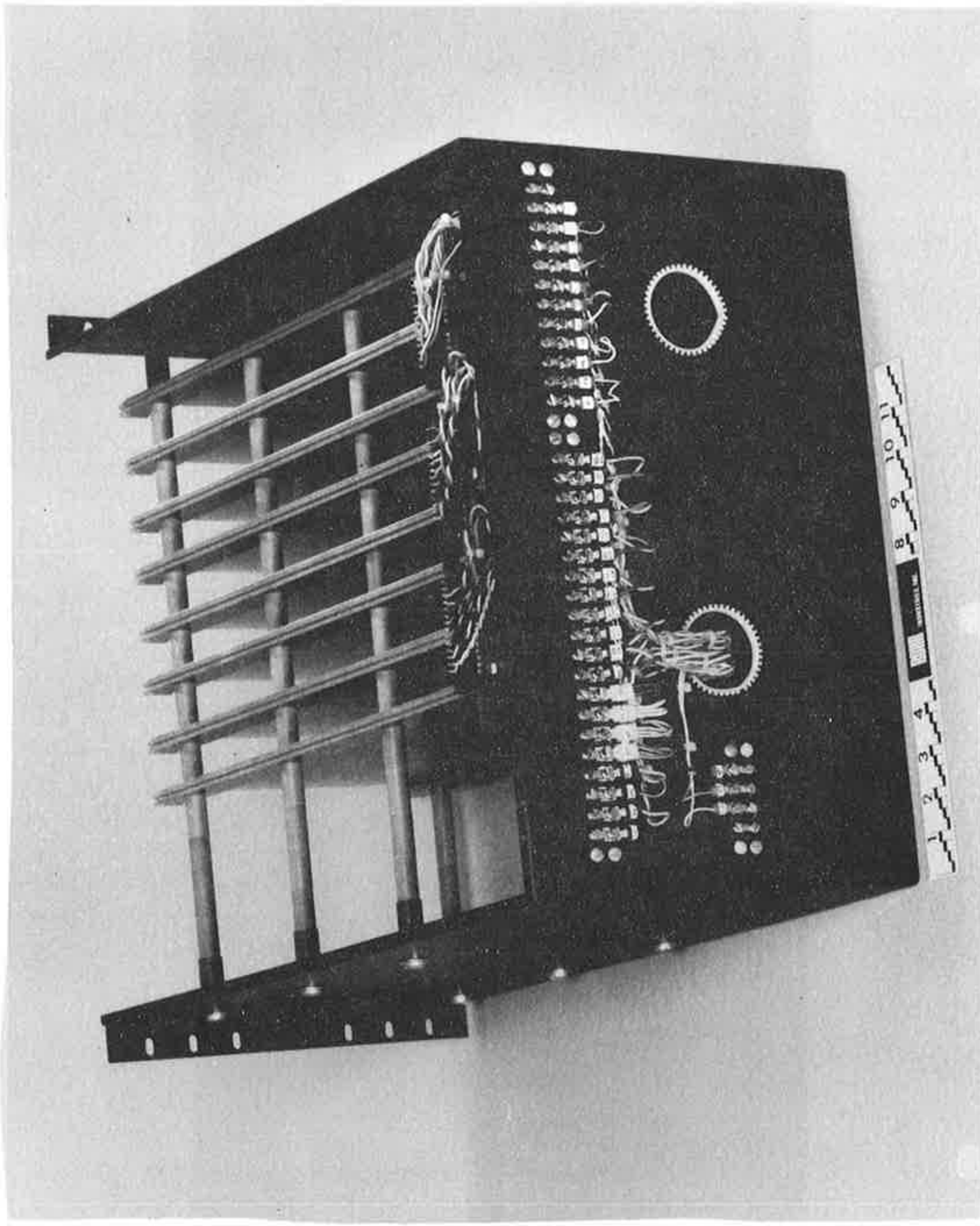


FIGURE 22. REAR OF DRIVER POWER SUPPLY ASSEMBLY NO. 1

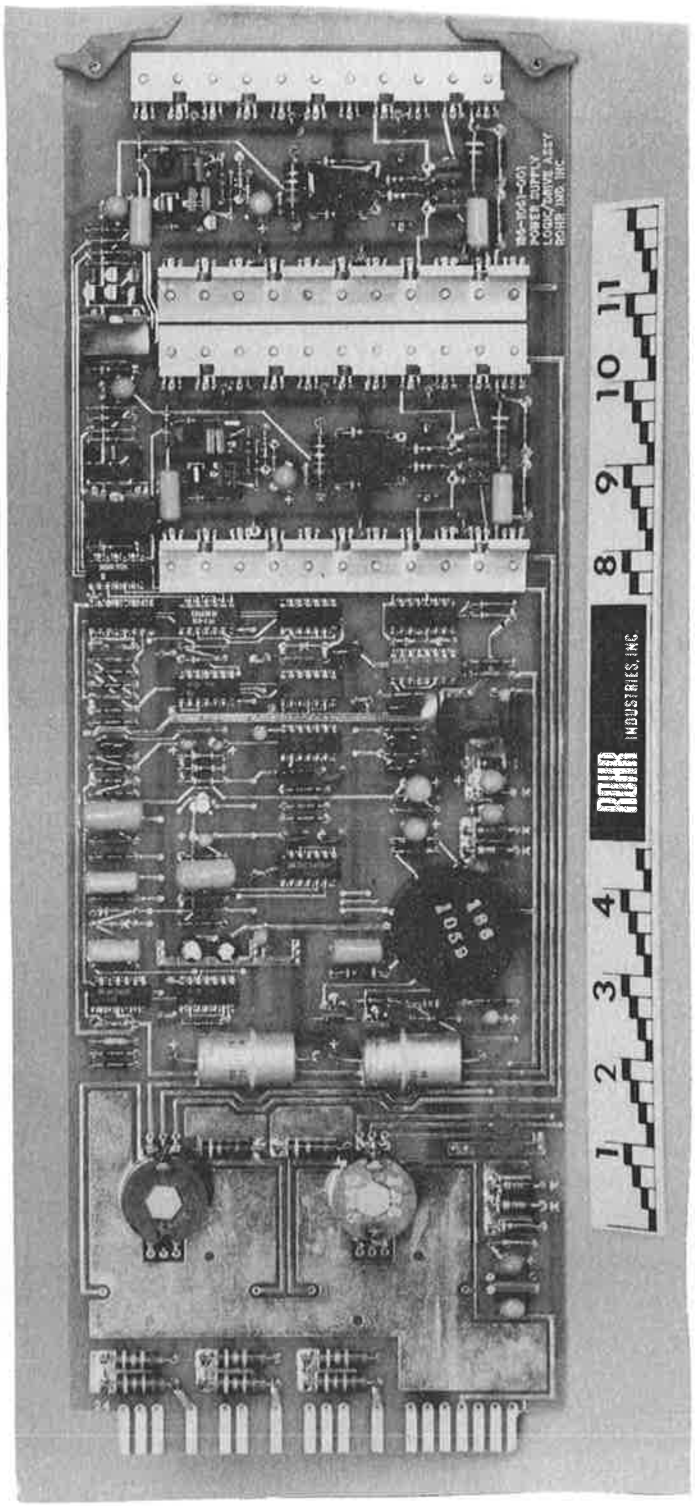


FIGURE 23. POWER SUPPLY MODULE, LOGIC/DRIVER ASSEMBLY

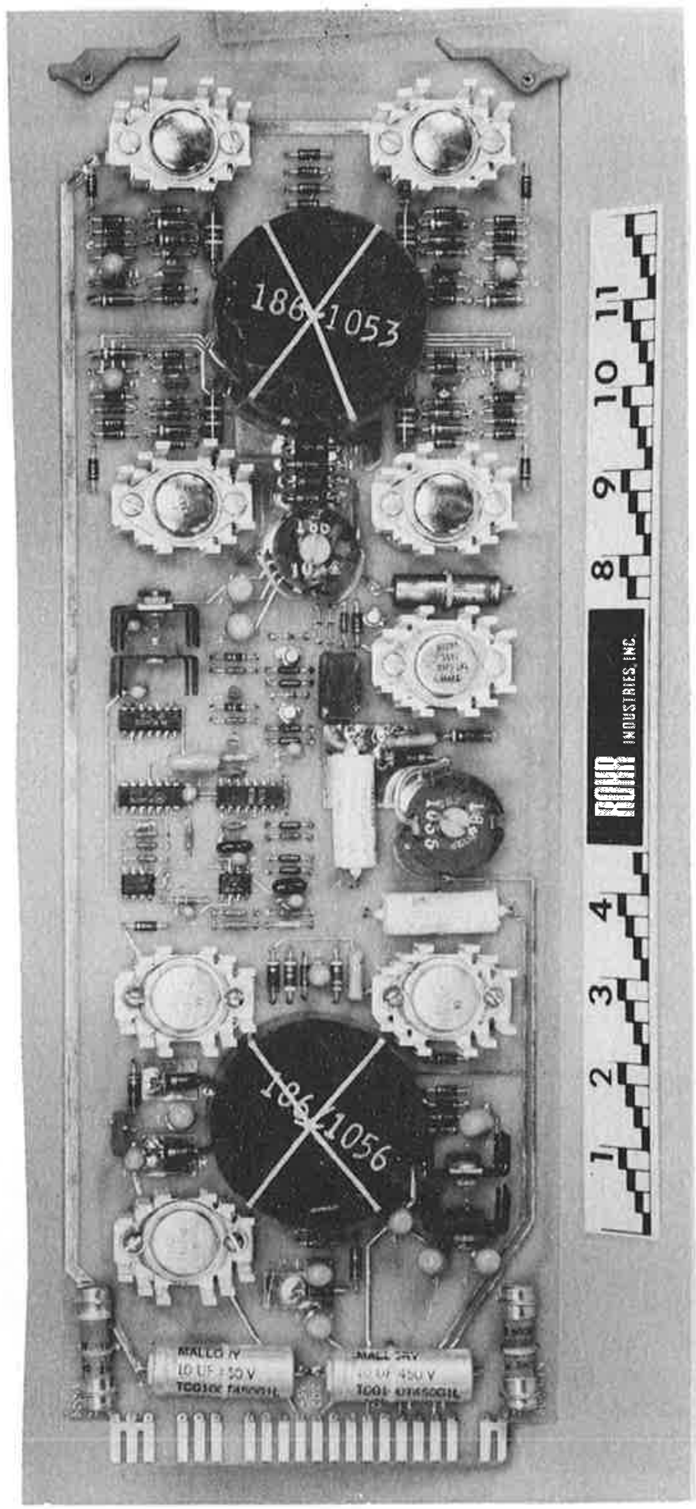


FIGURE 24. LOGIC POWER SUPPLY MODULE

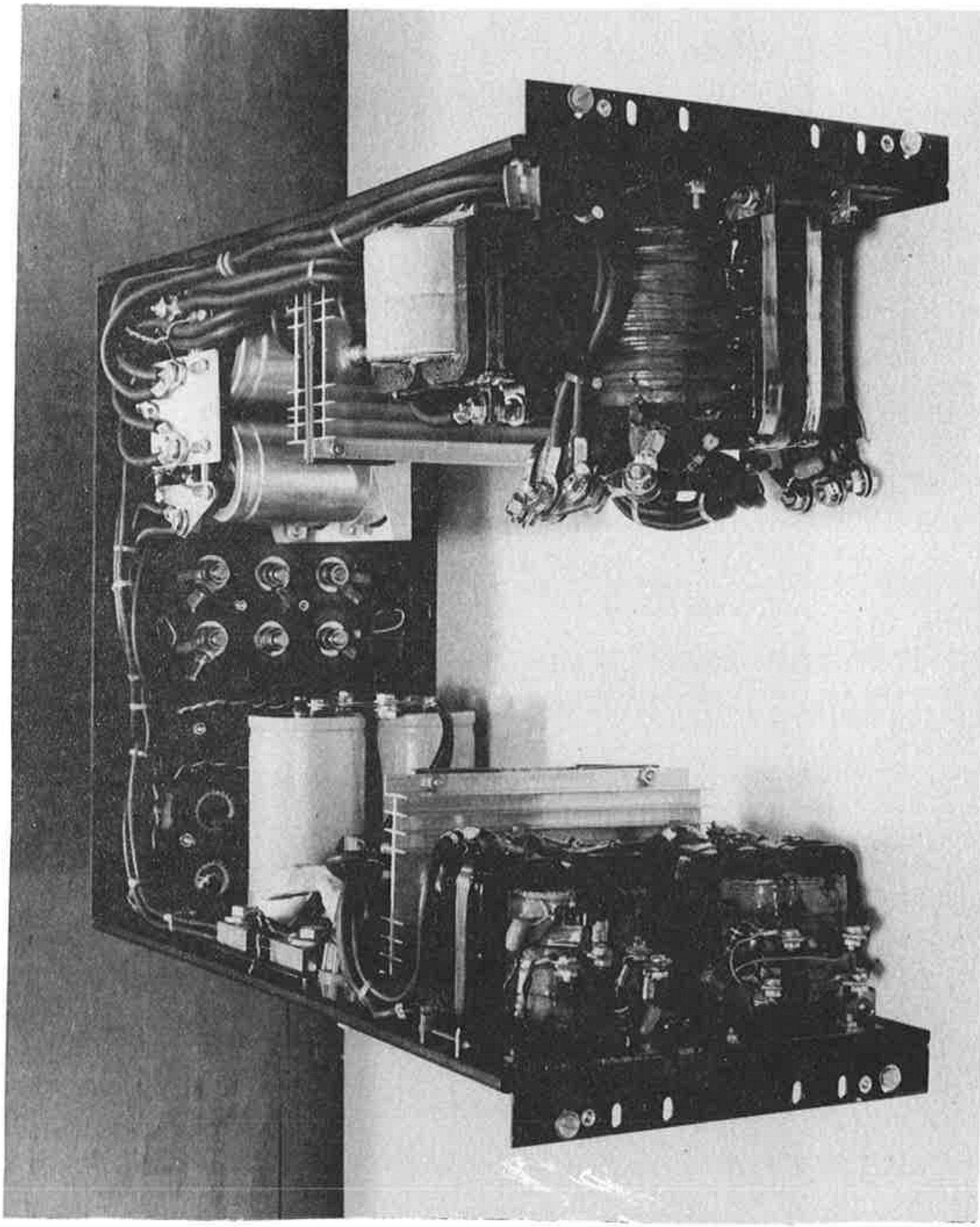


FIGURE 25. INSIDE OF DRIVER POWER SUPPLY ASSEMBLY NO. 2

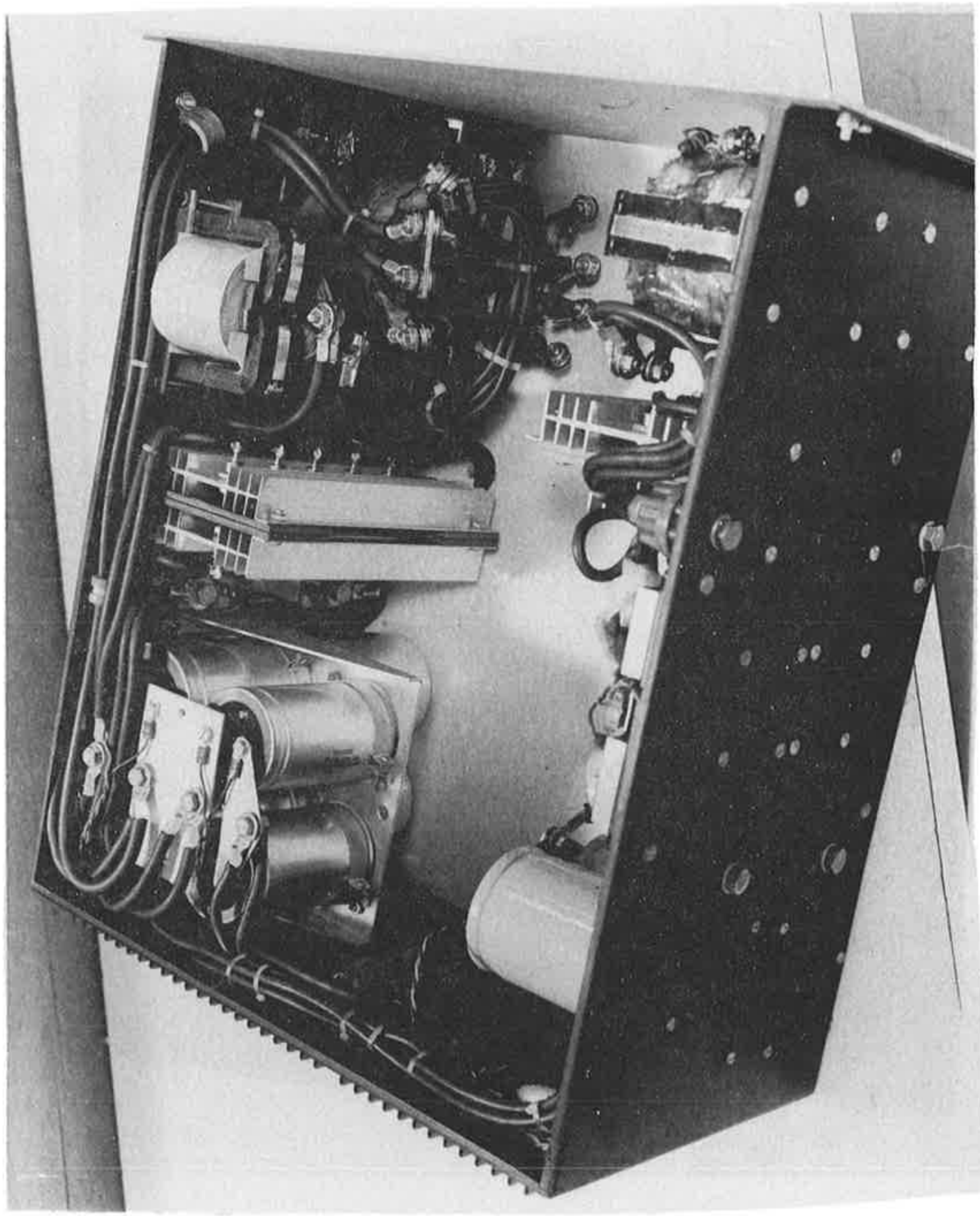


FIGURE 26. INSIDE OF DRIVER POWER SUPPLY ASSEMBLY NO. 2

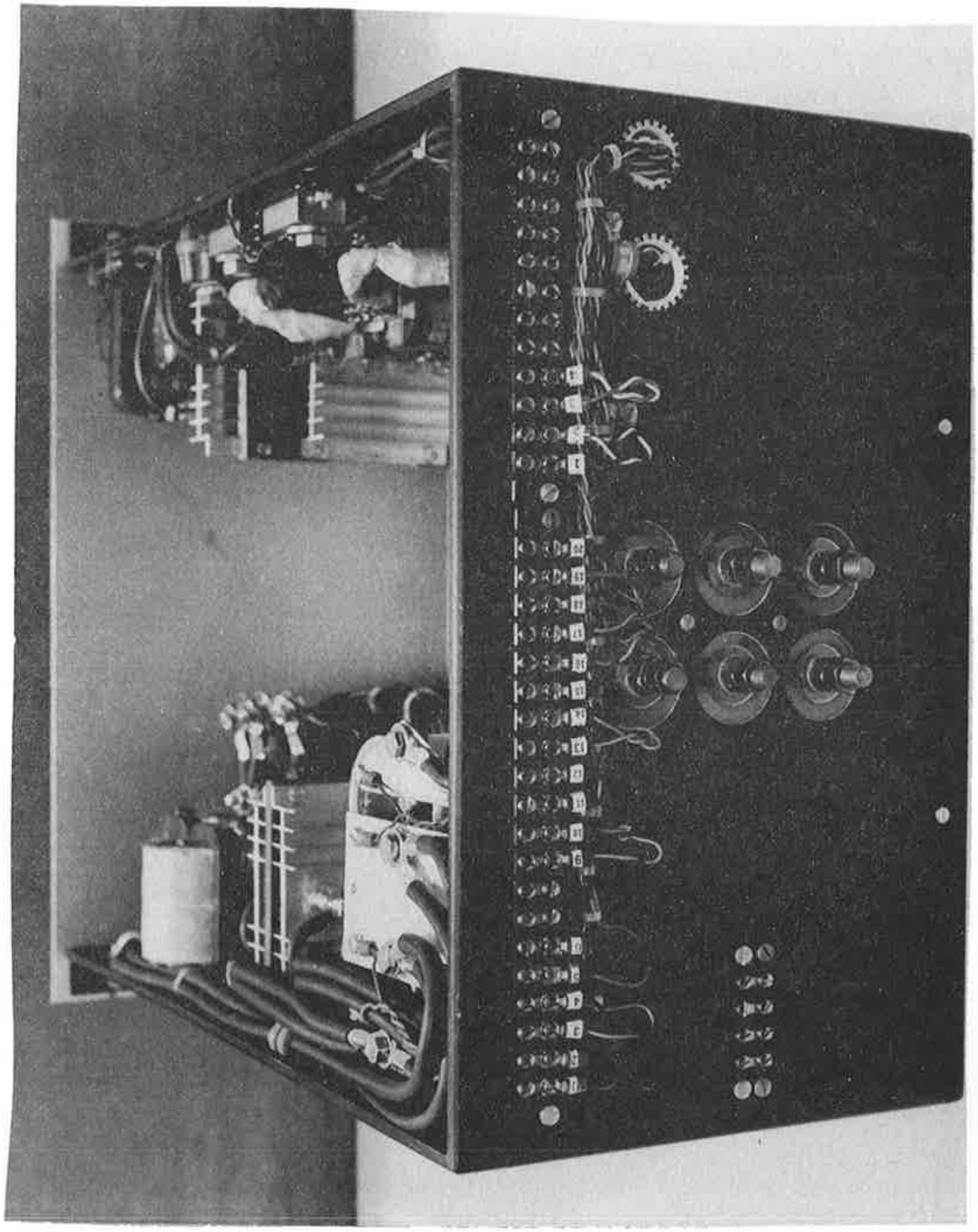


FIGURE 27. REAR OF DRIVER POWER SUPPLY ASSEMBLY NO. 2

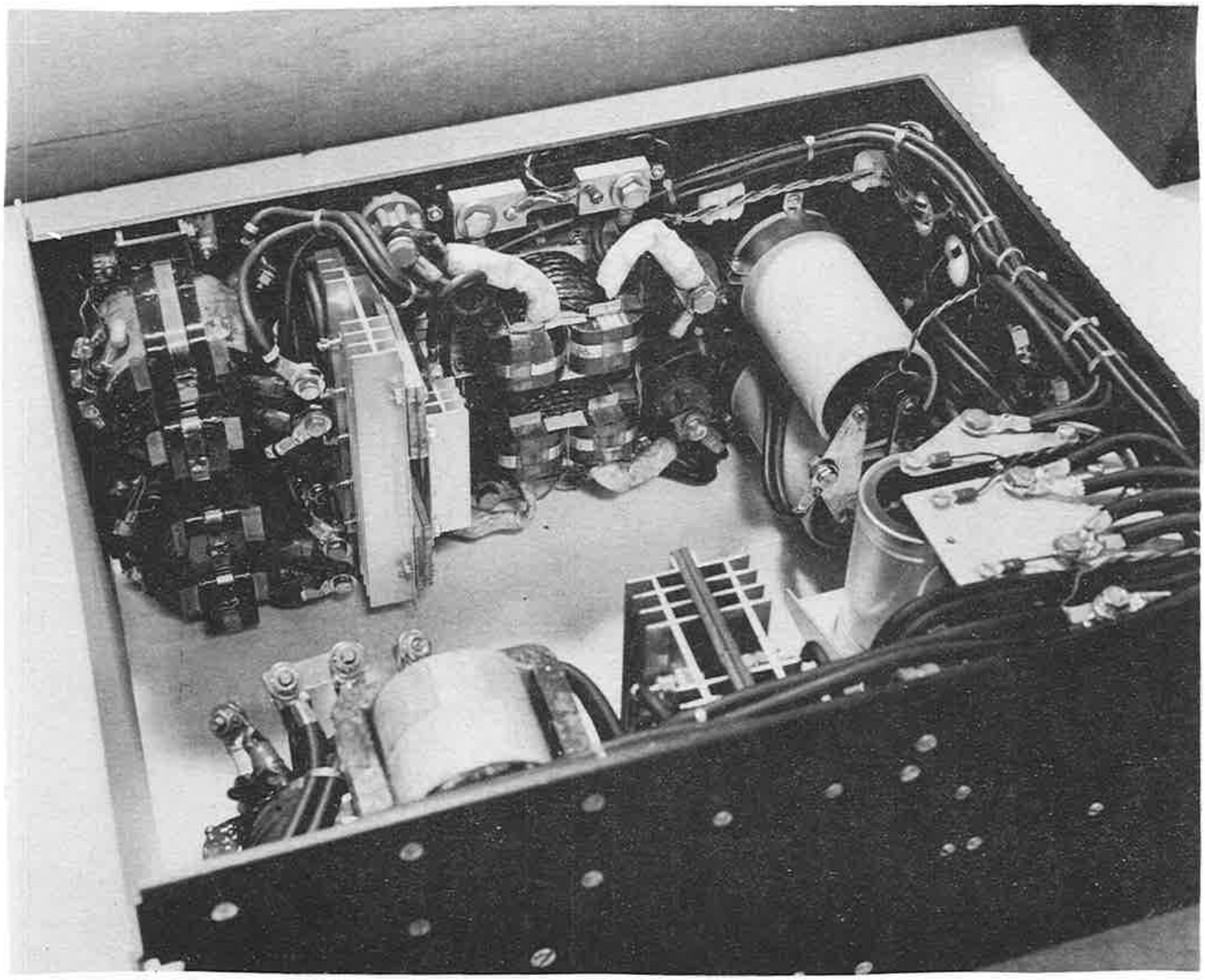


FIGURE 28. INSIDE OF DRIVER POWER SUPPLY ASSEMBLY NO. 2

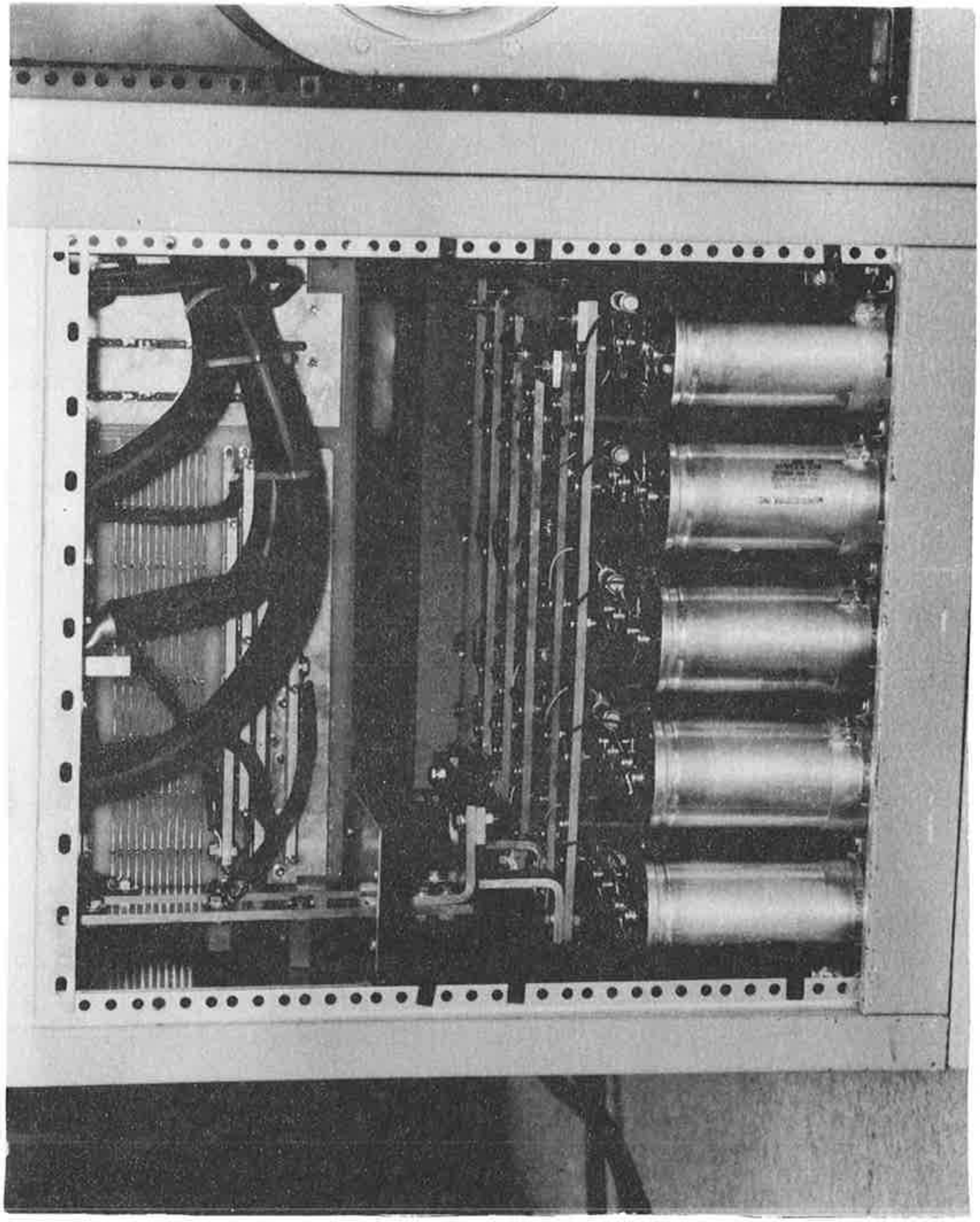


FIGURE 29. REAR OF LOWER LEFT ENCLOSURE

APPENDIX A

PATENT RIGHTS

Patent Rights - Acquisition by the Government

Inventions conceived and first reduced to practice during the course of subject contract:

TITLE:	Method to Regulate AC/DC Converter
INVENTOR:	Richard J. Clary
ASSIGNEE:	U.S. Department of Transportation
DOCKET NUMBER:	77044
DATE OF DISCLOSURE:	9-28-77

TITLE:	Drive Regulated Free-Running Inverter
INVENTOR:	Arne Nerem
ASSIGNEE:	U.S. Department of Transportation
DOCKET NUMBER:	77045
DATE OF DISCLOSURE:	9-29-77

APPENDIX B

REVISED
METROLINER APCU
ACCEPTANCE TEST PLAN

1.1 INTRODUCTION

The APCU for the Metroliner is comprised of two racks mounted together. The PCU Power Assembly is contained in one rack, and the Logic and Power Supply Assemblies are contained in the second rack. A blower unit is provided for cooling of the power section of the PCU and is shared with the logic and power supply section.

POWER ASSEMBLY

The PCU Propulsion Power Assembly is comprised of a multiplicity of identical modules. These modules are of the plug-in printed circuit card type. There are two distinct types of modules in this assembly--power modules and driver modules.

The power and driver modules are grouped together in groups of 18 power modules and 4 driver modules which are mounted onto a mother printed circuit (PC) board. The mother PC board assembly is mounted into an enclosure which accommodates 3 identical mother board assemblies.

The rear edge of the power modules has a blown fuse indicator in the form of neon lamps so that a faulty module can be readily identified. (See Figure B-1.) The power and driver modules are mounted vertically on edge and are withdrawn from the enclosure by lifting the locking ejector tab located on the two rear corners of each module to disconnect the card from the receptacle at the opposite end of the module. The module may then be withdrawn horizontally from the enclosure. To reinstall the module, simply line up the edge of the module printed circuit card and slide it into the groove of the guide/slide and depress firmly the locking ejector handle to seat the card connector into the receptacle.

The 22 individual receptacles mounted into each of the mother circuit boards are integral with the card guide/slide so as to assure proper alignment when inserting a module. All hard wiring, input/output connections, and bus bar interconnections are located at the back of the mother board. The mother board assembly is not removable from the enclosure and no servicing is required.

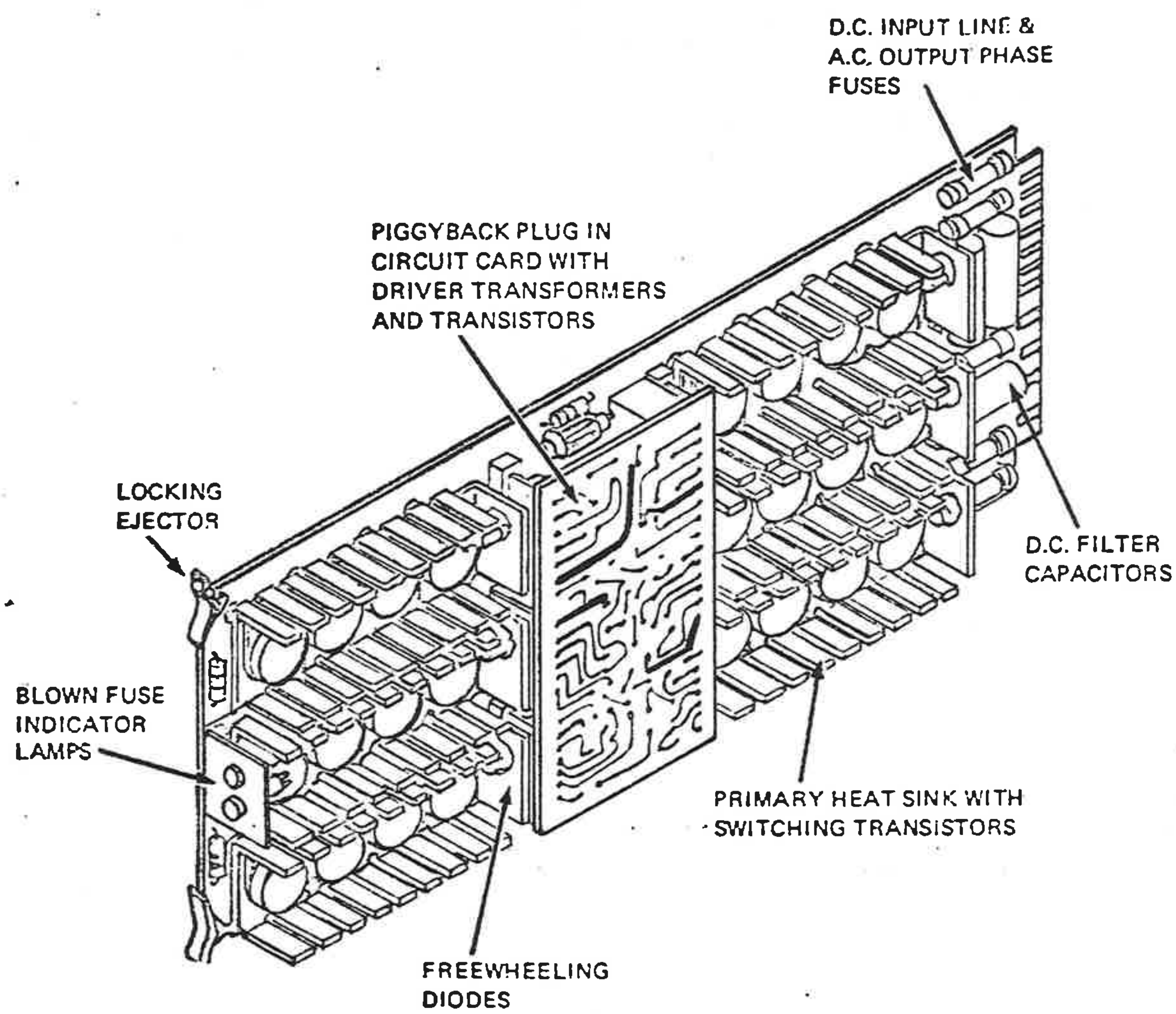


FIGURE B-1. PCU POWER MODULE

LOGIC ASSEMBLY

The logic section consists of a control circuit panel, logic power supplies, and drive power supplies. These assemblies are mounted in standard rack panel chassis and are mounted in the rack adjacent to the power assembly section.

OPERATION

The APCU is configured for operation from a 400 VDC source, and contains the required startup and shutdown sequence circuits for complete automatic operation.

Figure B-2 represents APCU operation from 400 VDC service filtered with a capacitor bank with .25 farad storage capacity.

This capacitor bank is to be supplied by the user of the APCU, and in the absence of such a capacitor bank, the APCU is connected for constant-frequency, constant-voltage operation. Output voltage varies as a function of dc service voltage.

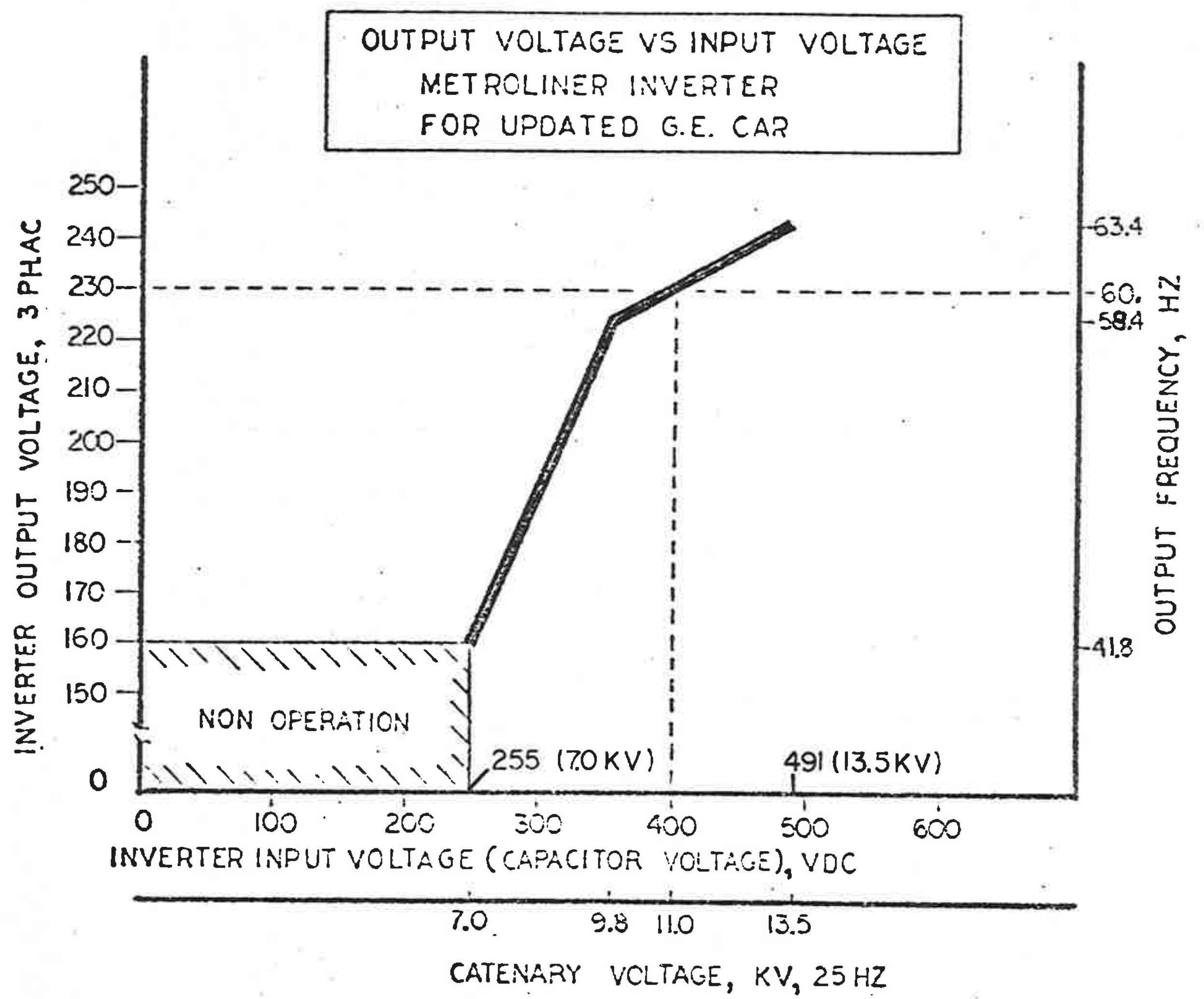


FIGURE B-2. OUTPUT VOLTAGE VERSUS INPUT VOLTAGE

1.2 TEST OBJECTIVES

An acceptance test will be conducted at Rohr Industries and will, to the extent possible, simulate operation under actual conditions as anticipated from available load profiles.

Tests of motor start capabilities with respect to surge currents, steady state load conditions, and undervoltage/overvoltage and overcurrent shutdowns will be conducted. No environmental tests will be conducted as part of this program.

2.0 TEST SET-UP

The APCU will be connected to a variable voltage DC source. The output will be connected to a 100 HP motor shaft coupled to a second 100 HP motor. The second motor will be operated from utility line power. (See Figure B-3.)

2.1 ACCEPTANCE TEST DESCRIPTION

The tests will be organized in two classes - functional tests at no load and performance tests at varying loads.

The variable voltage test will be performed during the functional tests while the power source is derived from a 3-phase variac.

The load tests will be conducted at 400 VDC power from a 333 kW DC power supply connected to utility line power.

Variation of loads will be accomplished by varying the slip frequency between the two motors as achieved by varying the output frequency of the APCU.

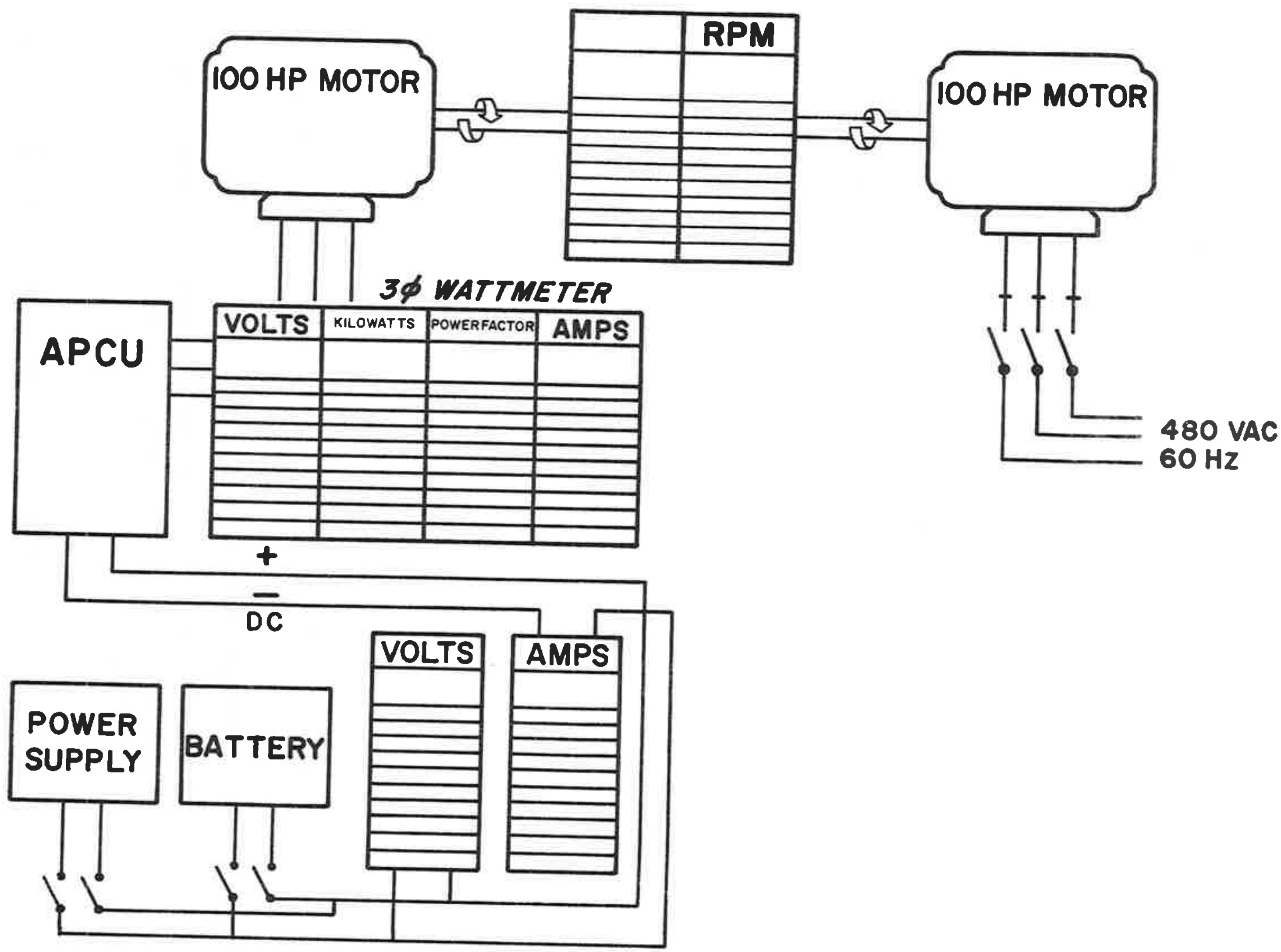


FIGURE B-3. TEST SETUP AND SAMPLE DATA SHEET

3.1 APCU ACCEPTANCE TEST

A. Functional Tests

1. Apply 400 VDC to APCU operating 100 HP dynamometer at no load.
    a. Measure output voltage and verify that it is adjustable 0 to 250 V RMS, at 60 Hz.
    b. Measure output frequency and verify that it is adjustable 0 to 65 Hz.
2. Undervoltage/Overvoltage Shutdown/Reset
    a. Operate APCU at approximately 400 VDC.
    b. Reduce input DC voltage until APCU shuts down (265 V max.).
    c. Record input DC voltage.
    d. Restart unit at approximately 400 VDC by pushing panel reset button.
    e. Increase input DC voltage until APCU shuts down (590 V min.).
    f. Record input DC voltage.
    g. Reduce input DC voltage to 580 VDC and start APCU by pushing reset button.
3. Measurement of 100% Modulation Point
    a. Apply increasing DC input to APCU and observe startup.
    b. Record input voltage at point unit starts.
    c. Observe output voltage waveform and continue to increase DC voltage to point where 100% modulation occurs for 230 V RMS output, 60 Hz.
    d. Record DC voltage.
    e. Record output voltage.
    f. Record output frequency.
    g. Reduce input DC voltage and record voltage at which output begins to decay.
4. Constant Volts per Hertz Startup
    a. Demonstrate startup at 400 V input for acceleration potentiometer settings of 1.0, 2.0, 3.0, 4.0, and 5.0.
5. Overcurrent Protection
    a. Set acceleration potentiometer to 6.0.
    b. For approximately 400 VDC input, operate the APCU into a 100 HP dynamometer at no load.

c. Observe that the high starting transient will stop the APCU and that it does not try to restart.

d. Reduce acceleration potentiometer to 2.0 and start the unit by pushing the reset button - observe normal operation.

6. Fuse Protection of PCU Cards

a. Remove one of the PCU cards and wire a short around one of the output transistors.

b. Reinsert the card and start the unit for approximately 400 VDC input.

c. Note that unit starts properly and that the fuse indicator lights on the shorted PCU card are lighted.

d. Remove card, remove short, and replace blown fuses on the card.

B. Operation at Load

1. Cycling Loads

a. Simulate the startup of a Metroliner freon compressor while APCU is supplying a steady state load of 120 A.

- o Set up 100 HP dynamometer to 120 A load.
- o Line start 20 HP motor to simulate start of freon compressor.
- o Record DC input, APCU output voltage, and current during the start cycle.

2. Steady State Operation

a. Operate APCU for one hour or until temperature stabilization, 400 VDC input, 240 A RMS output.

b. Prior to test, apply 150°F temperature tabs on PCU transistor collector and driver power supply transistor collector.

c. Record the following data:

(1) DC input voltage

(2) DC input current

(3) Output phase voltage (A-B, B-C, C-A)

(4) Output phase current (A, B, C)

(5) Output kW

(6) Output power factor

(7) Case temperature of one heat sink (PCU card)

(8) Inlet and outlet air temperature

(9) Time and date of measurement.

3. Repeat items B.2. a, b, and c for 590 V input until temperatures stabilize. In 2c(7), measure heat sink in Driver Power Supply PCU card.

4.1 DATA REDUCTION

Calculate input power, output power, efficiency per data sheet, and record on report table.

5.1 FAILURE LOG, FAILURE ANALYSIS

6.1 CONCLUSIONS

7.1 RECOMMENDATIONS

APCU SPECIFICATIONS

Input:	260 VDC - 600 VDC
Output:	230 VAC 60 Hz 3-Phase (Figure 2) At 230 VAC, input must be 325 VDC or greater
Rating:	183 kVA peak for 1 minute 100 kVA at .8 power factor continuous
Current Waveform:	Sinusoidal (inductive load)
Voltage Waveform:	PWM square wave, carrier frequency 4 kHZ
Dimensions:	44" wide, 37.5" deep, 66" high

Note: 3/4 HP cooling fan operates from APCU output - can be supplied from 115 VAC, 60 Hz, 1 Phase external supply if desired.

INSTRUMENT LIST

The following list of items comprise the test instrumentation used in the PCU Life Test:

- Weston Industrial Analyzer Model 639
- Honeywell Visicorder CRT 1858
- Tektronix Oscilloscope Model 7623 or equivalent
- Tektronix Vertical Plug-In Model 7A13 or equivalent
- Tektronix Vertical Plug-In Model 7A12 or equivalent
- Tektronix Horizontal Plug-In Model 7B92 or equivalent
- Tektronix Current Probe Model P6042
- Simpson Thermometer Model 388 or equivalent
- Variable Voltage DC Source
- Rohr ROMAG 333 kW Power Supply 186-0725, Variable Voltage DC Source
- Current Transformer
- Line Disconnect Switch
- Frequency Counter
- Clamp-on Ammeter
- 100 HP AC Polyphase Motors, two, shaft connected for dynamometer load
- Motor Couplings and Base Mount
- DC Voltmeter
- DC Current Meter
- Variac 50 Amp 3-phase 480 VAC

APPENDIX C

TEST RESULTS
IN ACCORDANCE WITH THE
REVISED METROLINER APCU
ACCEPTANCE TEST PLAN
JULY 20, 1978

APCU ACCEPTANCE TEST RESULTS

A. Functional Tests

A load for the unit was provided by two 100 HP 3-phase, 3600 rpm induction motors, shaft-connected. One motor was fed from the APCU and the other was connected to the in-house 60 Hz power line. By controlling the speed of the driving motor, the generating motor pumps power into the 60 Hz line and becomes the APCU load. This arrangement is depicted in Figure C-3 of the Test Plan. The power supply used to provide DC input power was a 3-phase full wave bridge rectifier operating from a 480 V 3-Phase 60 Hz tapped transformer. A Weston Industrial Analyzer Model 639 was used to measure the output of the APCU.

1. Voltage and Frequency Verification

   a. 400 VDC was applied to the unit and with the 100 HP dynamometer operating at no load, the output voltage was varied from 32 V to 250 V line to line. (Note: An offset bias is provided in the voltage potentiometer so that motor torque can be applied at zero speed). The output voltage was set at 230 V line to line with the output frequency at 60 Hz.

   b. The output frequency potentiometer was varied over the 0-65 Hz range. This must be done with the voltage potentiometer set at its low value in order not to saturate the motor load. Figure C-12 shows the variation of output voltage and frequency as functions of potentiometer settings.

2. Undervoltage/Overvoltage Shutdown/Reset

   a. The undervoltage dropout test is shown as recorded in Figure C-1. With the input set at 380 VDC the unit was started and the load current allowed to stabilize. (Time markers are 1-second intervals, and the timing is from right to left on the charts.) The drop in input voltage during start is the regulation of the DC power supply. In order to vary the input voltage, a three-phase VARIAC was used on the input to the power supply which increased the supply impedance.

b. After the output stabilized, the input DC voltage was reduced manually until the unit dropped out and the dropout indicator light went on.

c. The dropout occurred at 240 VDC as shown in Figure C-1 and is below the maximum value of 265 V required by the test plan.

d. The input was returned to 380 VDC and the unit restarted by pushing the RESET button on the front panel.

e. Input voltage was increased manually as shown in Figure C-2 until the unit dropped out because of overvoltage. The RESET light showed ON.

f. The overvoltage dropout point was recorded as 595 V, which is above the minimum specified value of 590 VDC.

g. The input voltage was lowered to 580 VDC as shown in Figure C-3 and the unit restarted by pushing the RESET button.

3. Measurement of 100% Modulation Point

a. The input voltage was raised manually from zero to a point at which the unit started (Figure C-4).

b. The start voltage was recorded as 230 VDC.

c. thru g.

The input voltage was increased to the point at which 100% modulation occurred for 230 V RMS line to line 60 Hz output. The input voltage was then gradually reduced until the output voltage began to decay with input voltage (Figure C-4A). This point was recorded as 325 VDC input.

4. Constant Volts per Hertz Startup

a. At startup, the output frequency and voltage are internally programmed to start at a very low value and then are raised together in such a way as to keep the ratio of voltage to frequency essentially constant. This prevents motor loads from saturating and producing high inrush starting currents. In addition, full starting torque is available at zero speed. The rate at which the voltage and frequency are raised to their final values is determined by the acceleration potentiometer marked ACC LIM.

Figures C-5, C-6, C-7, C-8, and C-9 show the relationship of the acceleration potentiometer setting and the time required for the output voltage to reach its final value with 400 VDC input and the 100 HP dynamometer operating at no load.

As the acceleration rate is increased, the starting time is progressively shorter, causing the motor current to increase during start. It should be noted in Figure C-9, with an ACC LIM potentiometer setting of 5.0, that the starting current was high enough to trip the overcurrent protection circuit and that the unit would not start.

5. Overcurrent Protection

   a. - d. As noted in the previous test, the overcurrent protection circuit was tripped for an ACC LIM setting of 5.0. To further test this feature, the ACC LIM was set to 6.0. The input was set as 400 VDC and the unit started into the 100 HP dynamometer (at no load). The overcurrent protection circuit tripped and the unit did not start. With the 400 VDC still applied, the LIM ACC potentiometer was lowered to a setting of 2.0 and the unit restarted by pushing the RESET button. Operation was normal.

6. Fuse Protection of PCU Cards

   a. A PCU card was removed from the unit and a shorting wire was soldered around an output transistor in phase A on the card.

   b. The card was reinserted and the unit started with the input at approximately 400 VDC.

   c. The unit started properly, the fuses on the modified card were blown, and the fuse indicator lights on the card were ON. (Note: under normal operation the neon fuse indicator lights will sometimes glow softly at the higher input voltages. A blown fuse, however, will cause the lights to light brilliantly). The unit continued to operate properly, the PCU card having cleared itself from the circuit. There are 54 PCU output cards in the unit, so under this condition the rating of the unit was reduced by 1/54, or less than 2%.

   d. The card was removed and inspected. The phase A fuse and one of the DC input fuses was open. These fuses were replaced, the short on the transistor removed, and the card replaced. The APCU was restarted and operated normally.

B. Operation at Load.

1. Cycling Loads

a. The largest cycling load on the Metroliner car is the freon compressor for the air conditioner. To simulate this load, a 20 HP motor was line-started on the APCU while it was supplying a steady state 120 A load (48 KVA) to the 100 HP dynomometer. This test is shown in Figure C-10. The peak current during the 20 HP motor start was recorded as 370 A RMS. During this starting transient the output voltage dropped approximately 8% from its steady state value of 230 V RMS. This regulation is caused primarily by the reactive drop across the output reactors in the APCU. At an output of 370 A and 230 V, this represents a peak load of 147.4 KVA. In order to show the peak capabilities of the unit a further test was performed and is recorded in Figure C-11. Here the 100 HP motor was started at reduced voltage and at a high acceleration rate. Under these conditions the time required for the motor to reach its synchronous speed is increased and the starting current is high. As shown in Figure C-11, the peak current recorded was 480 A RMS. At the nominal output voltage this represents a peak load of 191.2 KVA.

It should be noted that at 400 VDC input, the unit is capable of supplying an output voltage of 282.8 V RMS, which at the peak current rating of the unit of 540 A represents a peak capability of 264.5 KVA.

2. Steady State Operation (400 VDC Input)

a. The unit was operated for approximately one hour into the 100HP dynamometer with 400 VDC input. The data for this test is shown in Figure C-13

b. At the conclusion of the test the 150°F temperature tabs on the PCU transistor collectors and driver power supply transistor collectors were inspected and none of the tabs had reached 150°F.

c(7)(8) A plot of the inlet and outlet air temperature and the case temperature of a PCU card transistor is shown in Figure C-14. It is interesting to note that the temperature rise over ambient air of the transistor heatsink remains essentially constant at 20°C after 15 minutes running time. The air inlet temperature continued to rise during this test because of the confined quarters in the test cell where the test was performed.

3. Steady State Operation (560 VDC Input).

The steady state run of item B.2 was repeated for an input voltage of 560 VDC. These data are shown in Figure C-15. The heatsink temperature of the driver power supply power card was measured during the run. At the conclusion of the test the 150°F temperature tabs were examined on the power cards and driver power supply cards and found to be unchanged.

The readings obtained on this run were somewhat erratic due to the dynamometer load drifting with temperature. The load was readjusted on two occasions to bring it back to approximately 100 KW as measured on the wattmeter. Apparently this caused some reading errors, as indicated by the high efficiency indicated on lines 2, 3, and 4 of Figure C-15.

These temperature data are plotted in Figure C-16.

4.1 Data Reduction

The output power of the APCU in the steady state runs of B.1, B.2, and B.3 was calculated using the average of the current and voltage of the three phases.

This will introduce a slight error, but it is generally within the meter accuracies of 1%. The output KW was measured with the Weston Industrial Analyzer and also calculated from the three phase voltage and current measurements. In the 400 VDC input steady state run the two efficiency calculations (wattmeter vs calculated) averaged a difference of 1.6%. In the 560 VDC input steady state run, the varying load and current due to heating made it difficult to obtain accurate readings, and the efficiency readings in some instances are too high.

5.1 Failure Analysis

No failures were observed during the acceptance test runs. The steady state run at 560 VDC input was interrupted by an input line transient which caused the overvoltage protector circuit to trip. The unit was restarted without incident, but the run was not continued since the APCU had reached temperature stabilization.

Prior to this program, a laboratory 100 KVA unit was placed on life test. There was no component selection in the construction of the unit. After three infant mortality failures occurring at the beginning of the test, the unit ran in excess of 10,000 hours without failure.

6.1 Conclusions

The acceptance test of the Rohr APCU demonstrated that it could operate over the complete input range of 240 VDC to 590 VDC.

The unit will produce a 60 Hz, 230 V 3 phase output for a minimum input of 325 VDC.

The unit will accept the steady state and transient loads of the G.E. Metroliner car.

The unit will shut itself off for a decreasing input voltage lower than 240 VDC and an increasing input voltage higher than 595 VDC. When the voltage returns within these limits, the unit may be manually restarted by pushing the RESET button. These limits represent a catenary voltage of the 25 Hz Metroliner input of 6,600 VAC to 16,363 VAC where normal input would be 11,000 VAC for the 400 VDC input to the APCU. The catenary voltage has been measured to vary from 7000 VAC to 13,500 VAC on the Metroliner catenary.

For 230 VAC output the unit demonstrated a capability of delivering a peak output of 191 KVA. Operating at 400 V input at peak output voltage of 283 VRMS and peak current rating of 540 ARMS, the unit is capable of delivering 264.5 KVA.

The unit demonstrated that it will operate with a PCU card which has shorted and blown its own fuses. This prevents a catastrophic failure when a short occurs on one of the cards and allows a routine inspection procedure for replacement of failed cards.

Efficiency, Losses Per KVA

Using the calculations shown on Figure C-13 for the 400 VDC input steady state run, the average efficiency of the APCU was 93.8%. Assuming an output of 90.0 KW the input would then be 95.95 KW, a total loss of 5.95 KW.

The power consumed by the cooling fans is 826 watts; and therefore, the net electrical losses of the unit are:

5,948 W - 826 W = 5,122 W for an output current of 235 ARMS.

At 230 V output, this represents an output of 94.0 KVA, with a loss of 5122 W/94.0 KVA = 5.4 W/KVA.

For full output voltage at 400 VDC input of 283 VAC, the output is 115.6 KVA and the loss per KVA of output is 4.4 W/KVA.

7.1 Recommendations

The Rohr APCU has demonstrated that it will operate over the same input and load conditions as are encountered on the G.E. Metroliner car. After laboratory check out at TSC, it is recommended that the unit be installed in the passenger compartment of the G.E. Metroliner car for testing under the actual conditions.

Prior packaging design work has shown that a unit of this type can be installed in the same envelope as the present motor - alternator set. Cooling can be provided from the car cooling system, thus eliminating the cooling fans now provided.

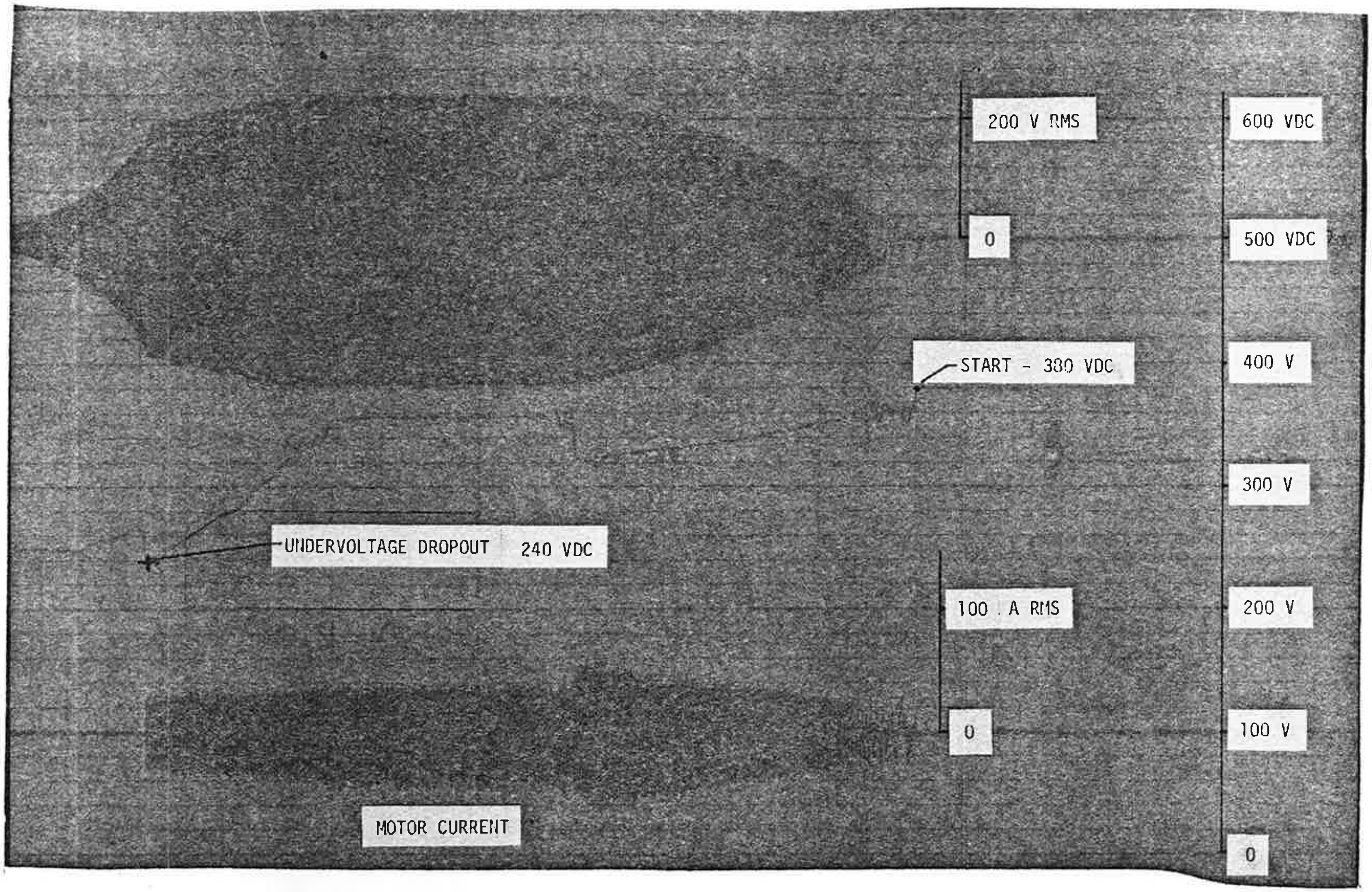


FIGURE C-1. UNDERVOLTAGE DROPOUT TEST

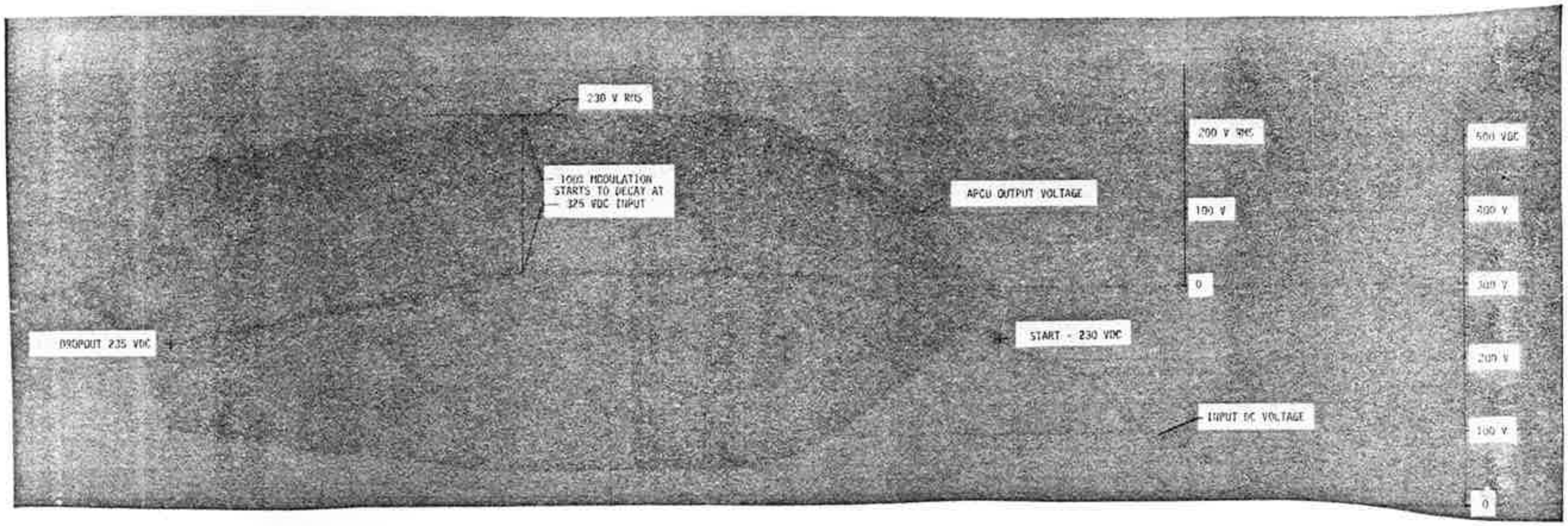


FIGURE C-4. 100% MODULATION TEST

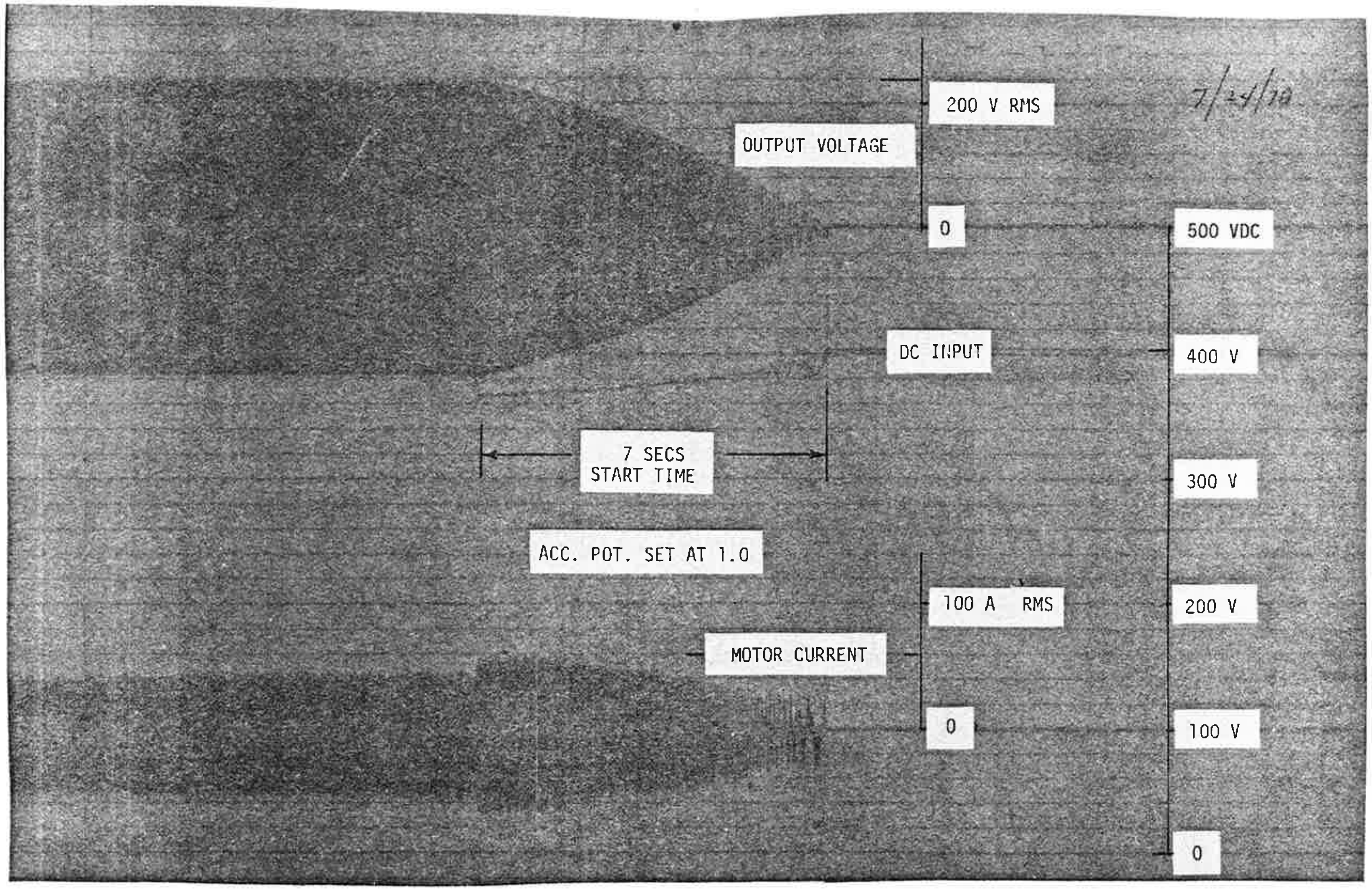


FIGURE C-5. STARTING RAMP TEST

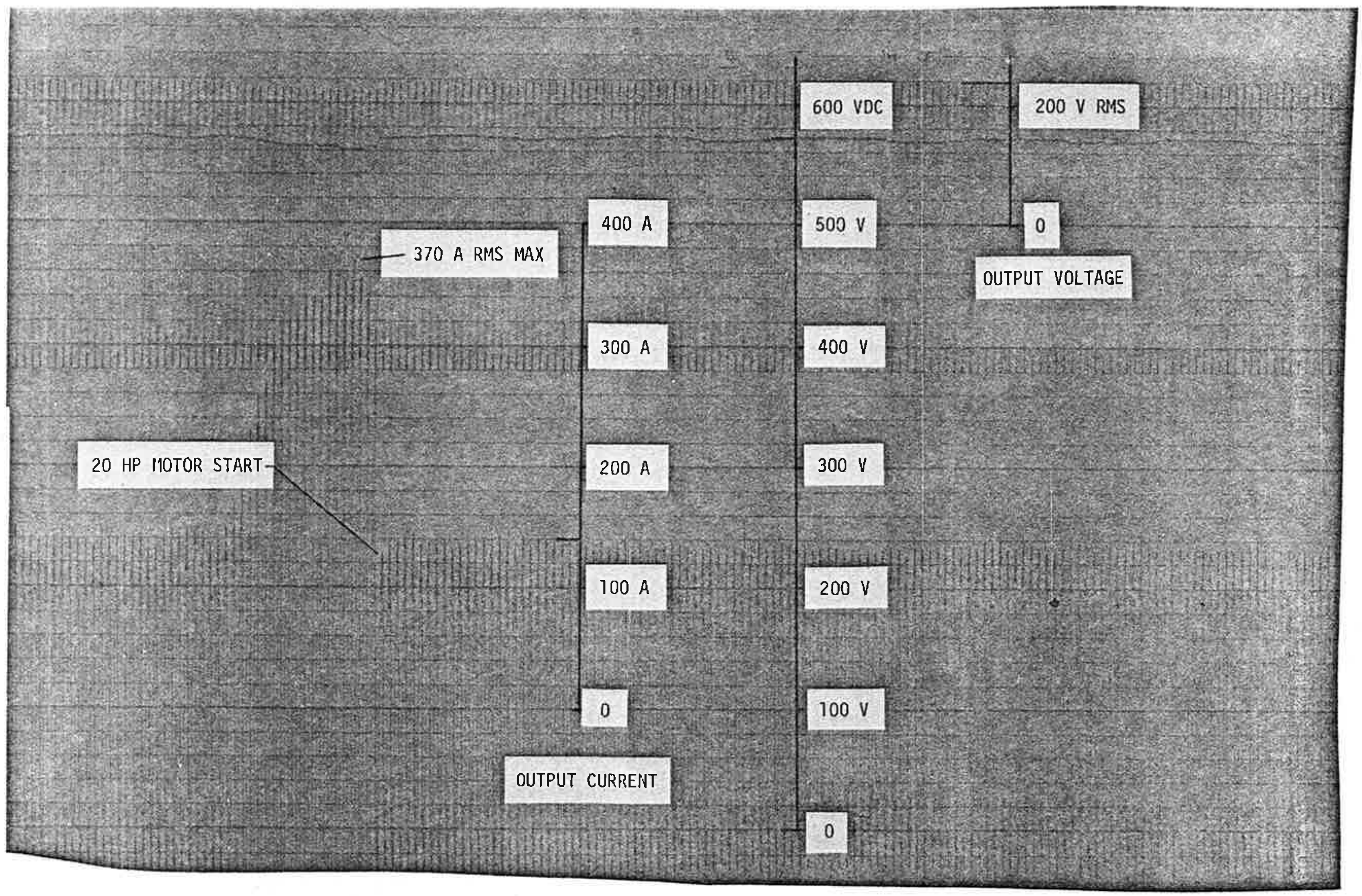


FIGURE C-10. FREON COMPRESSOR START SIMULATION

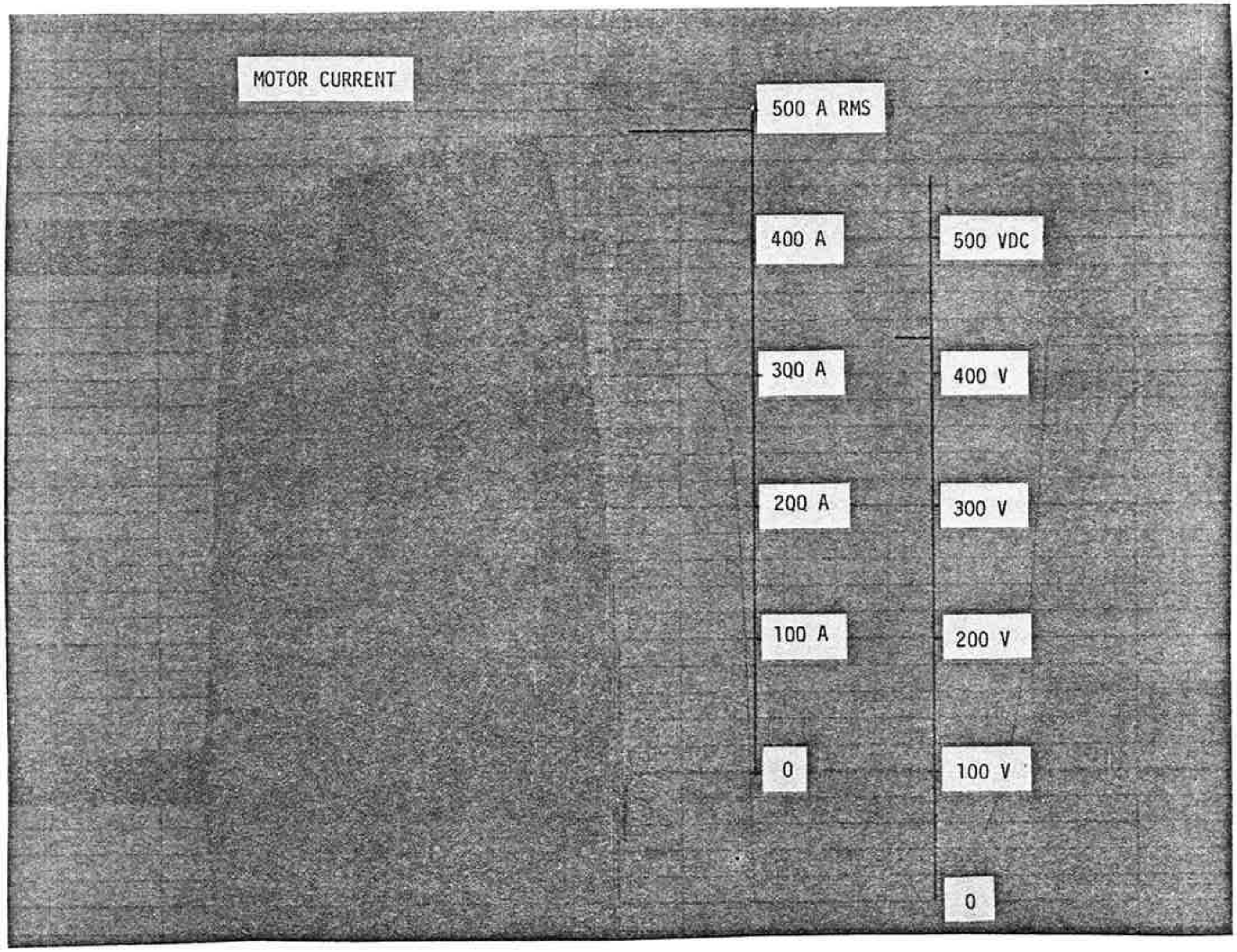


FIGURE C-11. PEAK CURRENT TEST

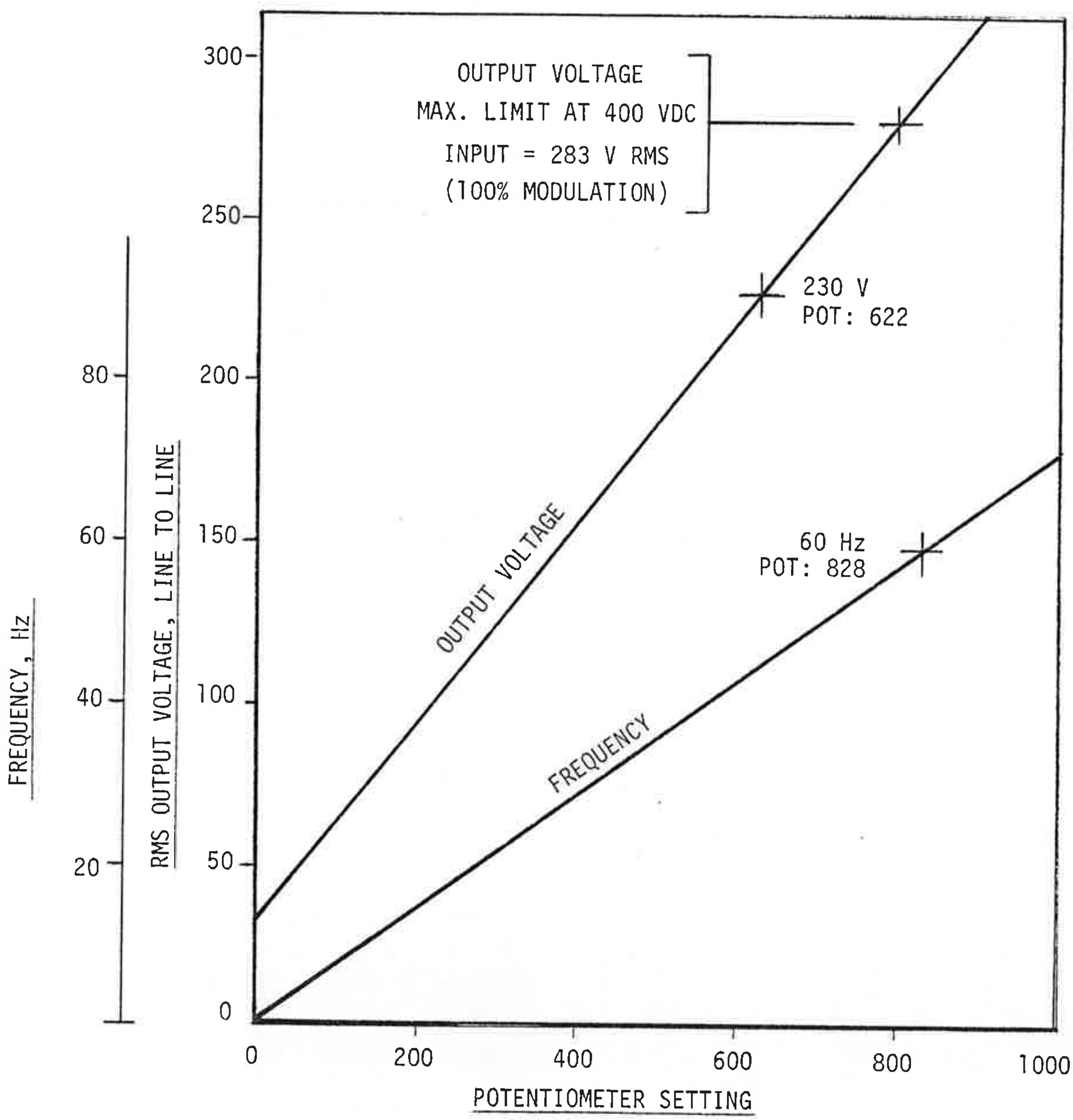


FIGURE C-12. OUTPUT VOLTAGE AND FREQUENCY AS A FUNCTION OF PANEL POTENTIOMETER SETTINGS

DATA

	TIME P.M.	TIME (ELAPSED) (Min.)	INPUT DC V	INPUT AMPS	OUTPUT CURRENT Scale X 150 Ph. A	Ph. B	Ph. C	OUTPUT VOLTS A-B	B-C	C-A	KW X 300	P.F.	TEMPERATURE °C AIR IN	AIR OUT	HEATSINK
1.	1:45	0											22.2		29.5
2.	1:50	5	400	242	1.55	1.60	1.60	237	240	240	.30	.935	22.2	30.0	44.0
3.	2:05	20	405	235	1.50	1.50	1.60	238	240	240	.30	.940	28.9	34.4	48.5
4.	2:25	40	400	234	1.48	1.52	1.58	238	240	240	.29	.940	28.9	37.8	49.5
5.	2:37	52	400	240	1.53	1.58	1.61	238	240	240	.30	.935	30.6	43.9	50.0
6.	2:50	65	400	240	1.49	1.52	1.58	238	240	240	.29	.940	31.1	44.4	51.0

NOTE: Line 1. - Heatsink temperature above ambient at start because of other tests prior to heat run. See Fig. C-14 for temperature plot.

Line 2. - Output data measured with Weston Model 639 Industrial Analyzer.

ANALYSIS

	INPUT KW E • I	OUTPUT KW (WATTMETER)	OUTPUT (Avg. of 3 Phases) AMPS	VOLTS	OUTPUT (Calculated) KVA $\sqrt{3} \cdot E \cdot I$	KW (KVA•P.F.)	EFF. % (Wattmeter)	EFF. % (Calc. Data)
2.	96.8	90.0	237.5	239.0	98.3	91.9	93.0	95.0
3.	95.2	90.0	230.0	239.3	95.3	89.6	94.5	94.2
4.	93.6	87.0	229.0	239.3	94.9	89.2	93.0	95.3
5.	96.0	90.0	236.0	239.3	97.8	91.5	93.8	95.3
6.	96.0	87.0	229.5	239.3	95.1	89.4	90.6	93.1
							93.0 Avg.	94.6 Avg.

FIGURE C-13. APCU STEADY STATE OPERATION - 400VDC INPUT