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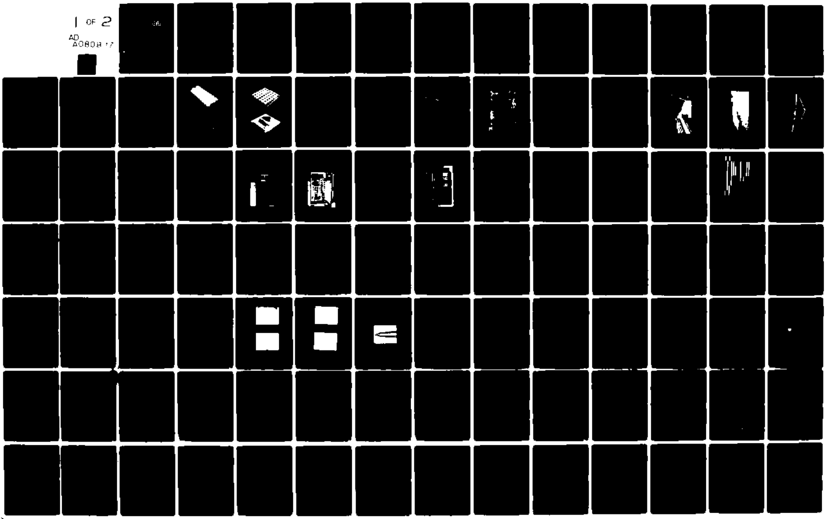

Report DECC-61211-003

DESIGN, CONSTRUCTION AND TESTING OF A 60 KW SOLAR ARRAY AND POWER CONVERSION SYSTEM

Final Report

J.S. Suelzle
Delta Electronic Control Corporation
2801 S.E. Main Street
Irvine, California 92714

August 1979

Prepared for

Department of the Army
Mobility Equipment Research and Development Command
Fort Belvoir, Virginia 22060

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A 60 kW photovoltaic array and power conversion system was designed, constructed, tested and installed by Delta Electronic Control Corporation. The system is currently operative, augmenting a remote diesel power generating station at Mt. Laguna Air Force Station. The system, which operates without on-site energy storage, operates unattended, extracting the maximum available power from the solar array.

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PREFACE

The work reported herein was performed by DECC (Delta Electronic Control Corporation) under contract to the United States Army Mobility Equipment Research and Development Command (contract DAAK70-78-C-0018). The Contracting Officer's Representative is Donal Faehn at Fort Belvoir, Virginia. The work was sponsored by the U.S. Department of Energy and the U.S. Air Force. The entire project was under the direction of the Defense Photovoltaic Program Office, U.S. Army MERADCOM.

Appreciation is expressed to Dietrich J. Roesler, presently of the Department of Energy, for his efforts as Contracting Officer's Representative during the early stages of the contract.

SUMMARY

The objective of the effort described in this report was to demonstrate that a dc-ac photovoltaic energy conversion system without on-site energy storage could effectively augment a utility, e.g. a remote military grid. Delta Electronic Control Corporation (DECC) designed, constructed and installed such a system using photovoltaic modules provided by Jet Propulsion Laboratories under the Low-Cost Solar Array Project. The 60 kW photovoltaic system is installed at Mt. Laguna Air Force Station where it augments a remote diesel power plant. The system is entirely automatic, coming on-line when there is sufficient solar power available in the morning, and returning to a stand-by state when the solar power is insufficient to operate the system. The system is designed to extract the maximum power available from the photovoltaic modules and operates unmanned for extended periods of time. All observations to date support the conclusion that such a system can effectively augment a utility.

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1.0 INTRODUCTION

This report discusses the design, fabrication and testing of a photovoltaic power generation system. The system consists of a 60 kW photovoltaic (PV) array, a 75 kVA solid-state power inverter, and interconnecting, control and monitoring equipment. The output of the inverter drives the local utility grid in parallel with existing diesel generators, providing up to 10% of the grid power. The effort is part of the Military Applications of Photovoltaic Systems project, a joint effort of the Department of Energy and the Department of Defense.

The objective of the effort has been to demonstrate that a dc-ac photovoltaic energy conversion system without on-site storage can effectively augment a remote military power grid.

The system was originally assembled and tested at the Delta Electronic Control Corporation (DECC) facility. Because of time considerations and the delivery schedule for PV modules, the tests at DECC were performed with a half-power (30 kW) array. At DECC the power conversion equipment operated into the local utility grid.

2.0 DESIGN AND CONSTRUCTION

2.1 THE SYSTEM. Figure 2-1 is a simplified block diagram of the photovoltaic power system. Power from the PV array is fed to the dc-ac power conversion unit through a paralleling and monitoring panel (PMP). The power conversion unit operates from the dc array voltage and provides ac power suitable for transmission to the utility grid (main diesel generator bus). The power conversion unit has the following features:

(1) Dynamic peak power tracking (PPT) to extract the maximum available power from the array at any time and feed all available power to the grid;

(2) Output power control circuitry to synchronize the output to the grid and to control the real and reactive components of the output power;

(3) Automatic start-up and shut-down controls for unmanned operation;

(4) Automatic protection circuitry.

The major parameters of the system are listed in Table 2-1.

2.2 THE ARRAY. The photovoltaic array is rated at 60 kW at 50°C ambient and 1000 W/m^2 insolation. It is composed of 169 strings of PV modules, each string consisting of 14 seriesed modules. A reverse diode installed across each module bypasses and protects the module during occlusion or malfunction.

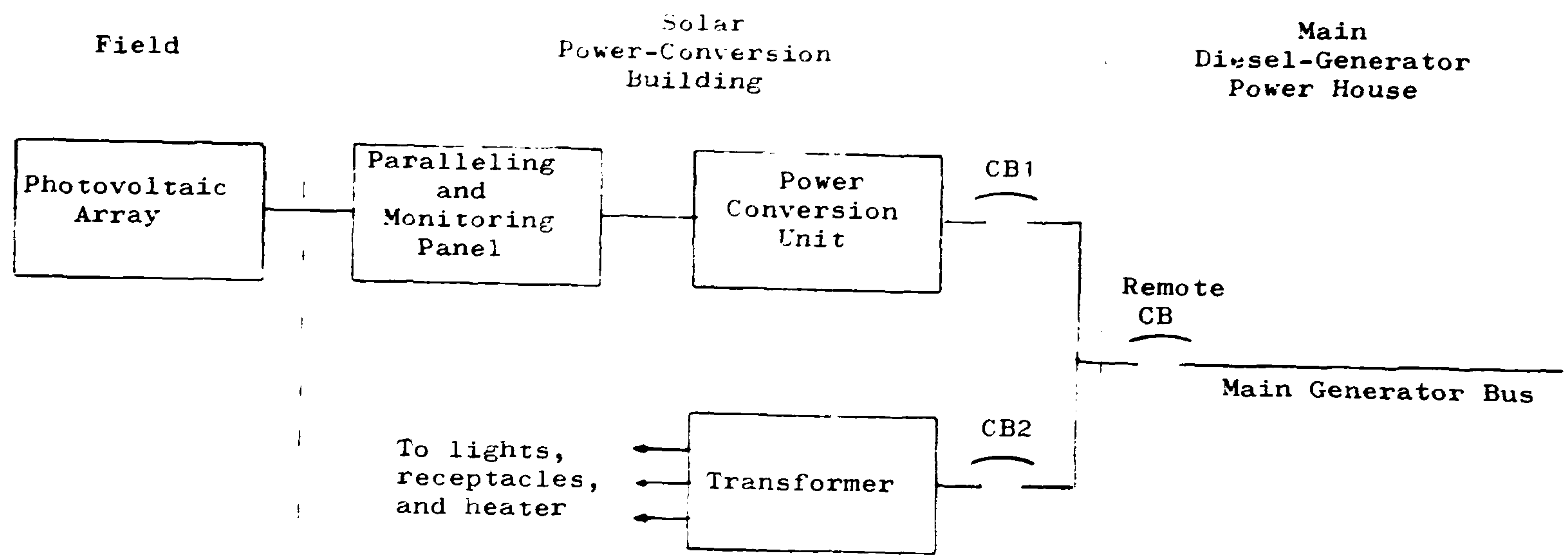


FIGURE 2-1. BLOCK DIAGRAM OF THE PHOTOVOLTAIC POWER GENERATION SYSTEM

TABLE 2-1. SOLAR POWER SYSTEM CHARACTERISTICS

ARRAY	
COMPOSITION	
Vendor Code Z modules	756 (13 kWp)
Vendor Code Y modules	1610 (47 kWp)
Number of modules per series string	14
Number of series strings	169
ELECTRICAL	
Output power @ 50°C, $1kW/m^2$	60 kW
Normal operating output voltage	180-290 Vdc
Estimated annual energy output	120,000 kWhr
POWER CONVERSION SYSTEM	
MECHANICAL	
PMP	76"h x 36"w x 32"d
Power conversion unit	79"h x 86"w x 32"d
Cooling	Blowers integral to power conversion unit
ELECTRICAL	
Input voltage	180-290 Vdc operation, 400 Vdc maximum
Output power	75 kW
Output frequency	Matched to grid (60 Hz)
Output voltage	Matched to grid (277/480 Vac, 3-phase)
Efficiency	92% @ 60 kW 91% @ 30 kW
Output current distortion(THD)	2.6% @ 60 kW

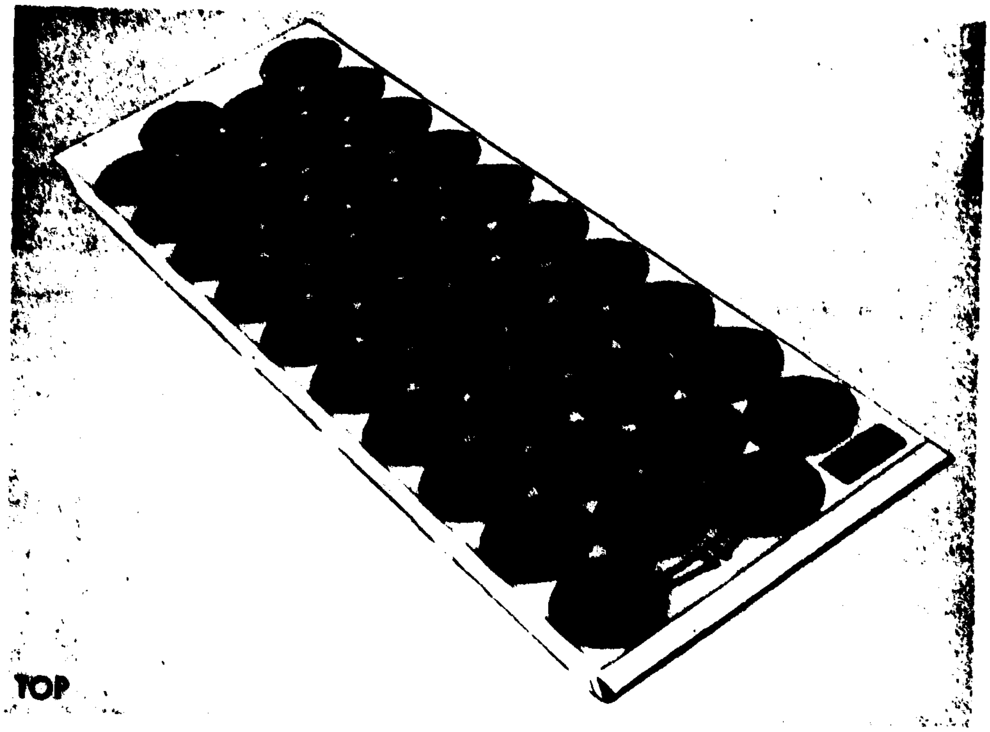
2.2.1 <u>The Modules</u>. The modules are of two types: the vendor Code Z[1] modules shown in Figure 2-2 comprise 115 of the strings (78% of the rated power); and the vendor Code Y[1] modules shown in Figure 2-3 comprise 54 strings (22% of the rated power). These two types of Block III[2] modules differ in almost all parameters including electrical output and physical dimensions. Table 2-2 lists the major characteristics of the two types of modules and Figures 2-4 and 2-5 show typical I-V curves for the two types of modules.

The modules of each series string were matched for output current characteristics so that the higher-current modules would not be limited by low-current modules in series. The short-circuit current data provided by the manufacturers were used for current matching.

2.2.2 <u>Module Frames</u>. Support frames were designed for the two types PV modules. The frames for both were constructed from rectangular steel tubing with T-section or right angle cross braces. Figure 2-6 shows one of the Code Z module frames being welded on a jig developed at DECC for that purpose. After construction, the frames were hot-dip galvanized for protection against the environment. The Code Z support frames hold 7 modules (half of a string) and the Code Y support frames hold 14 modules

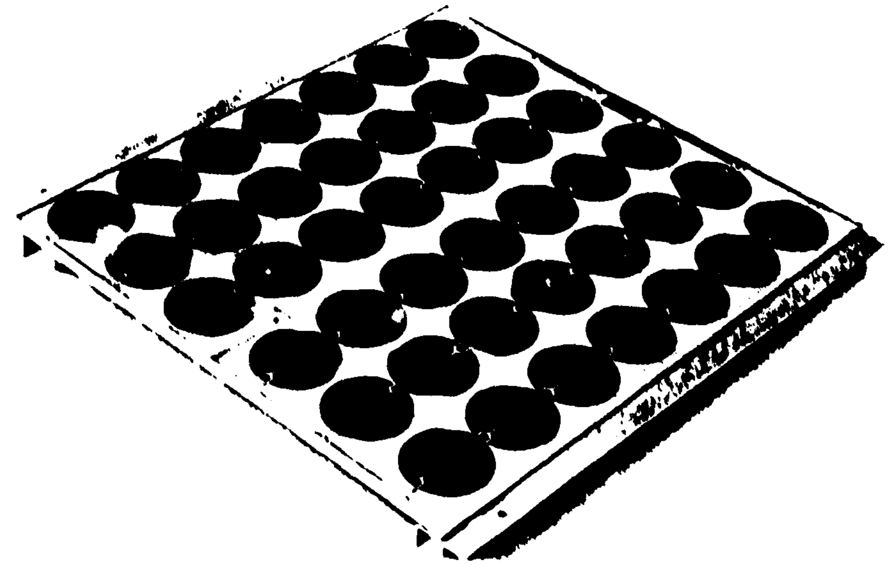
1 Refer to Report Number DOE/JPL-1012-30, "Environmental Testing of Block III Solar Cell Modules," September 1, 1979, prepared by Jet Propulsion Laboratory (JPL).

2 JPL designation.



Photos courtesy of JPL

FIGURE 2-2. CODE Z MODULE



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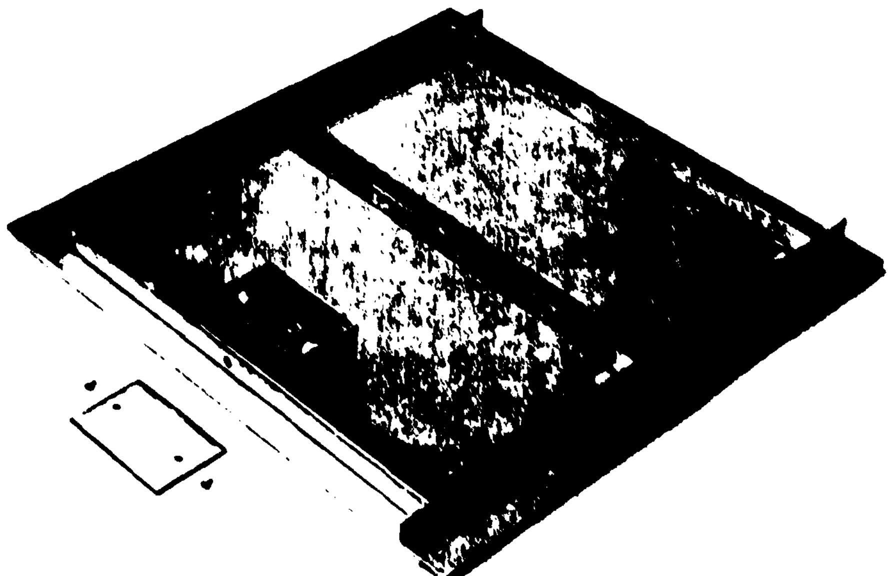

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Photos courtesy of JPL

FIGURE 2-3. CODE Y MODULE

TABLE 2-2. PHOTOVOLTAIC MODULE CHARACTERISTICS

	CODE Y	CODE Z
PHYSICAL		
Dimensions		
Length	22.9"	46"
Width	22.9"	15.3"
Height	1.8"	1.9"
Weight	9 lbs.	16.7 lbs
Number of cells	42	40
Cell diameter	3"	4"
Cell type	N-P	P-N
ELECTRICAL		
Rated voltage	15.8 V	15.8 V
Rated current	1.18 A	1.81 A
Rated power	18.6 W	28.6 W

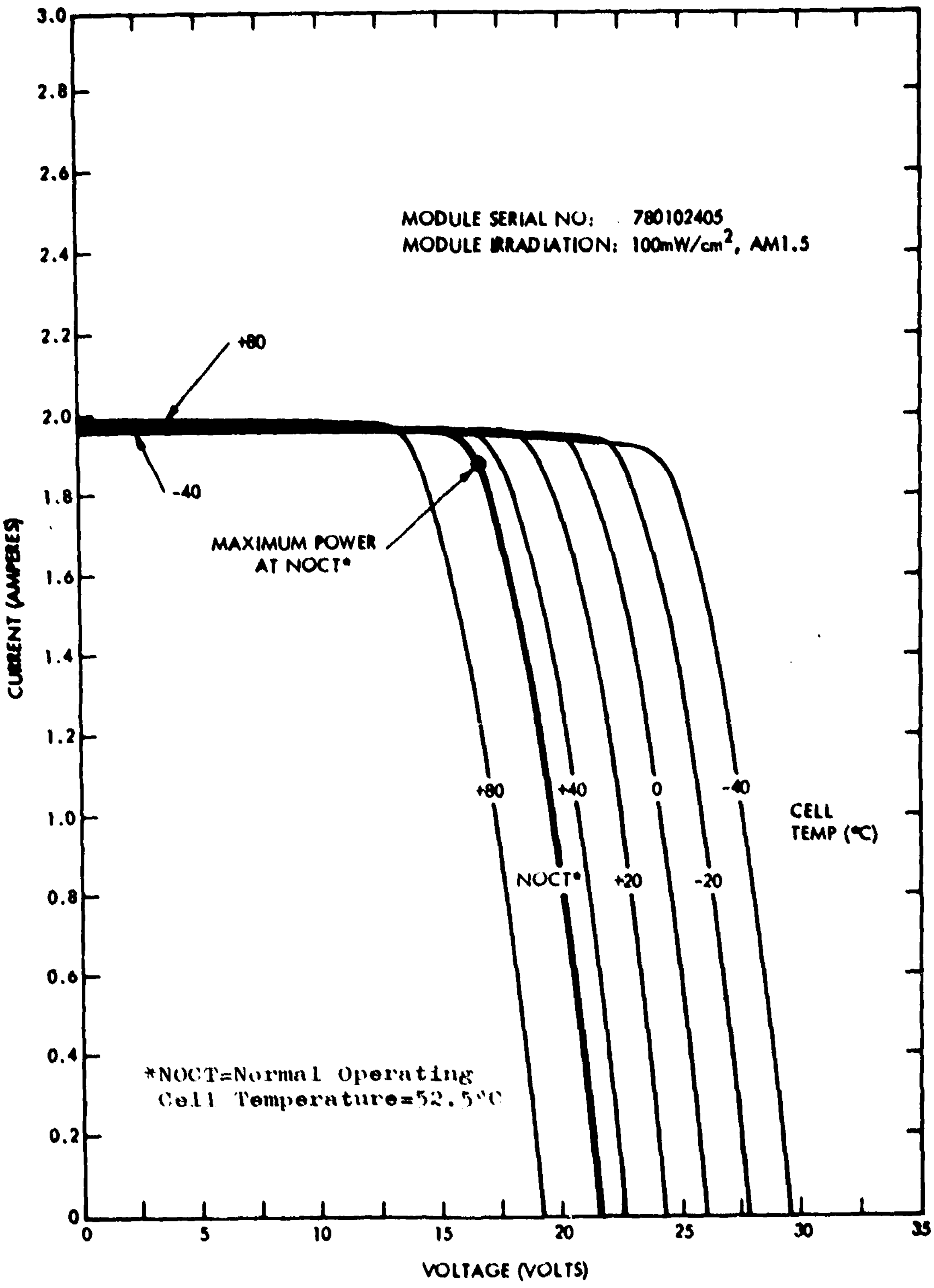


FIGURE 2-4. CODE Z MODULE: I-V CURVES

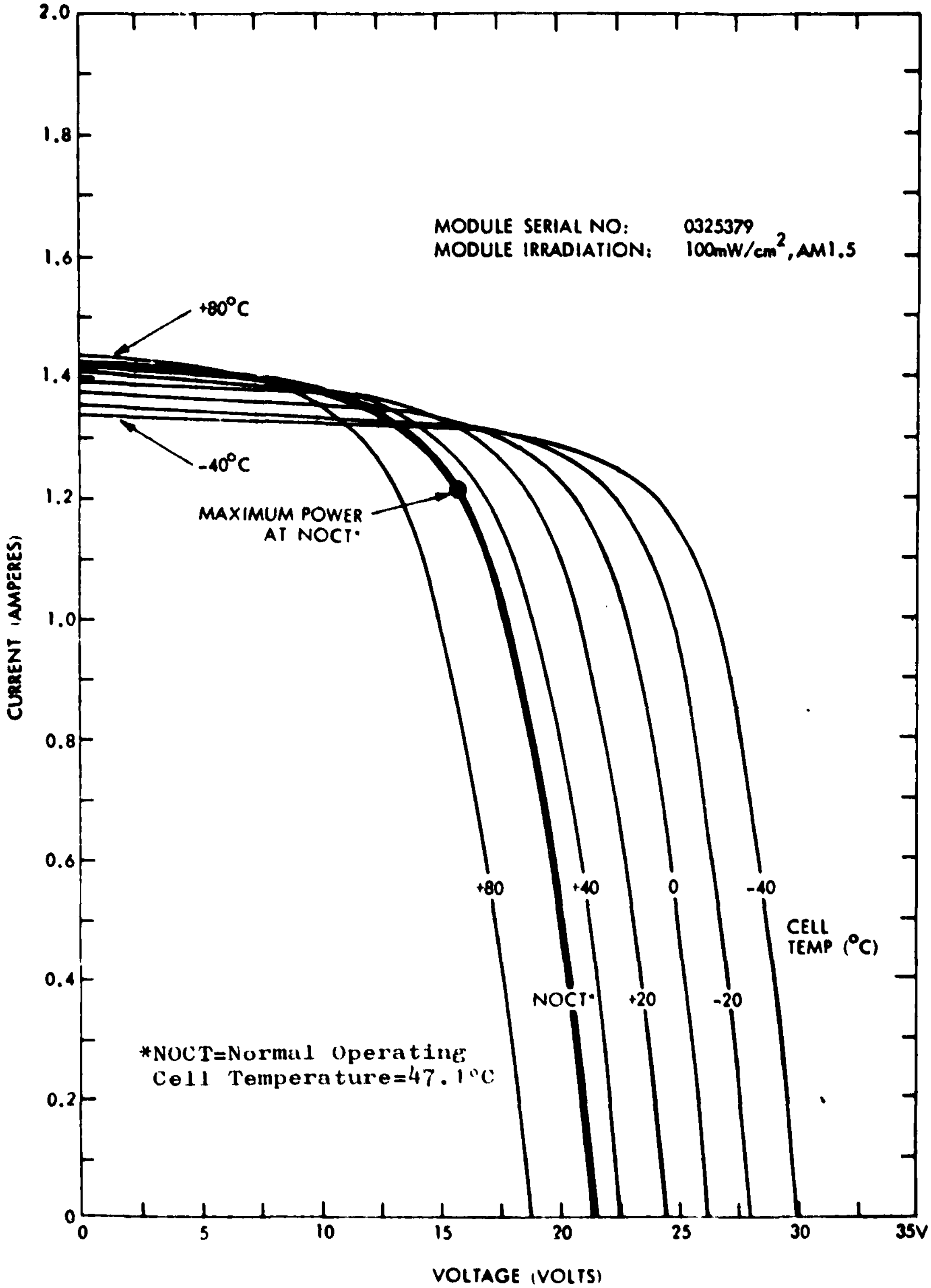


FIGURE 2-5. CODE Y MODULE: I-V CURVES

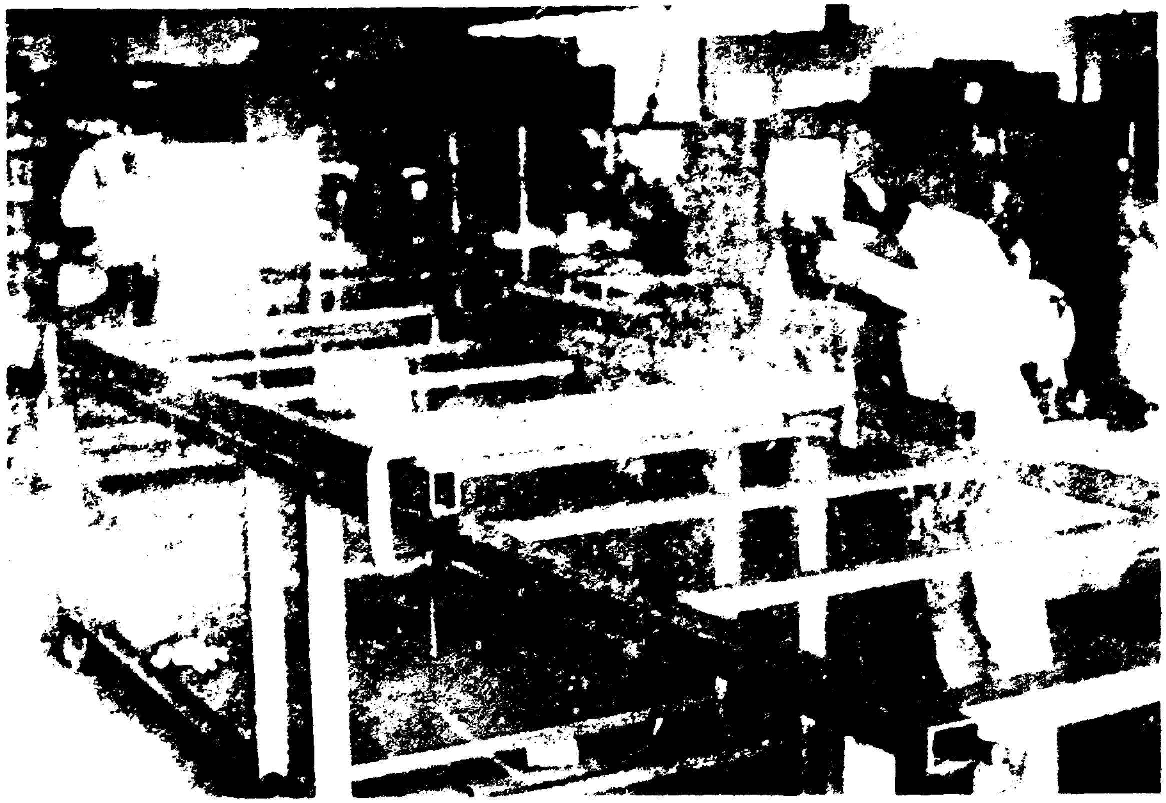


FIGURE 2-6. WELDING OF A FRAME FOR A CODE Z MODULE

(one string). See Figure 2-7.

2.2.3 **Supports**. The module frames are supported by wooden shear panels as shown in Figure 2-8. At the DECC temporary installation these shear panels were placed directly on the ground. At the permanent site they are mounted to concrete footings to withstand 120 knot winds.

The 25° tilt angle of the panels was selected to provide the maximum integrated annual output power at the 32.5° latitude of the permanent site.

2.2.4 **Permanent Site Preparation and Footings**. Figure 2-9 shows the permanent site for the solar installation after grading and trenching. Concrete footings, 12" x 12" in cross section and 19' to 28' in length, were cast at a remote location, transported to the array site and set into the soil. Splices between footings were poured in place. The wooden shear panels are bolted and braced to the concrete footings, and the frames are bolted to the shear panels.

Figure 2-10 is a photograph of the installed array.

2.2.5 **Electrical Interconnection of Panels**. Each row of PV modules consists of several strings (typically 12 for Code Y and 9 for Code Z). The outputs of the series connected strings are wired to a row terminal

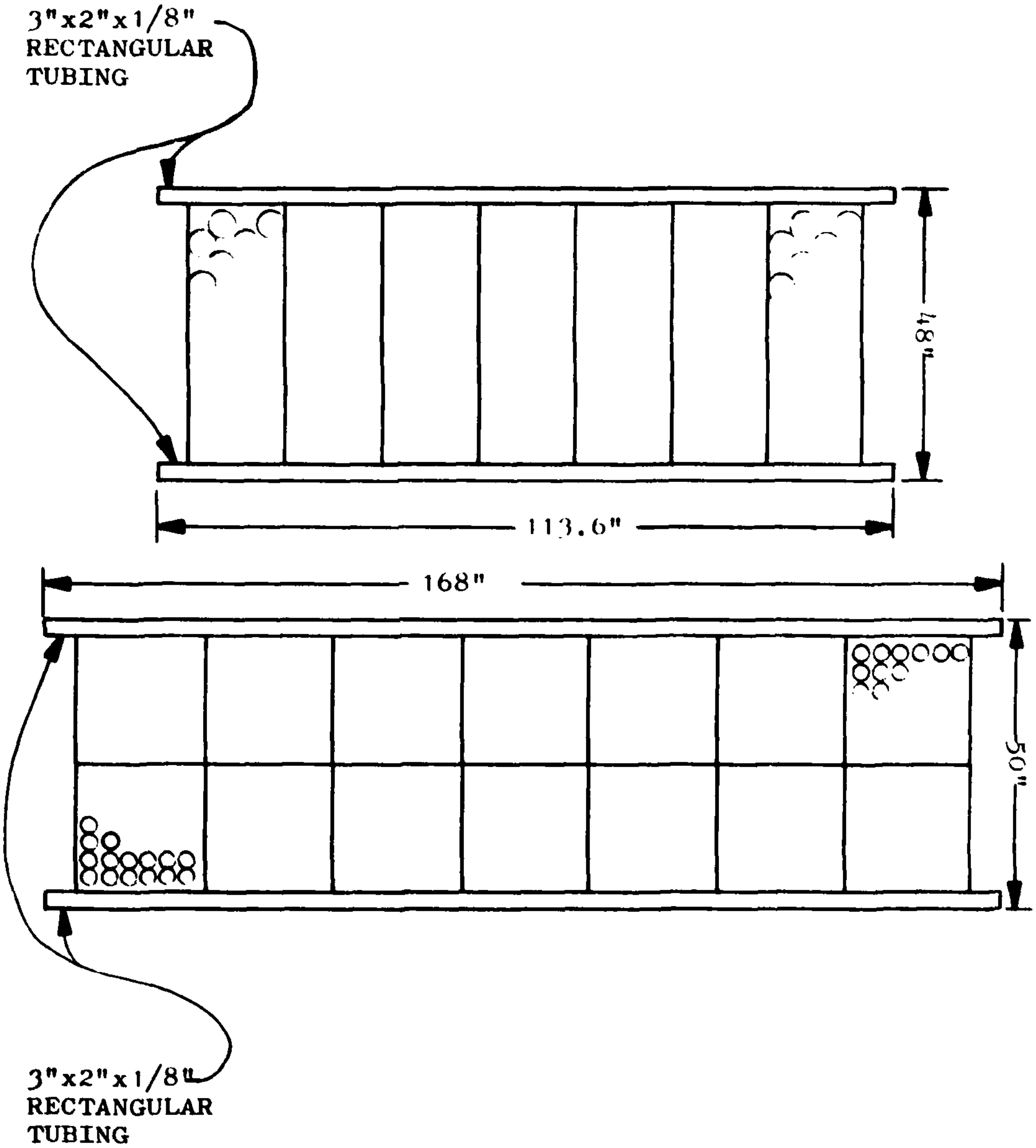


FIGURE 2-7. CODE Z AND CODE Y FRAME ASSEMBLIES

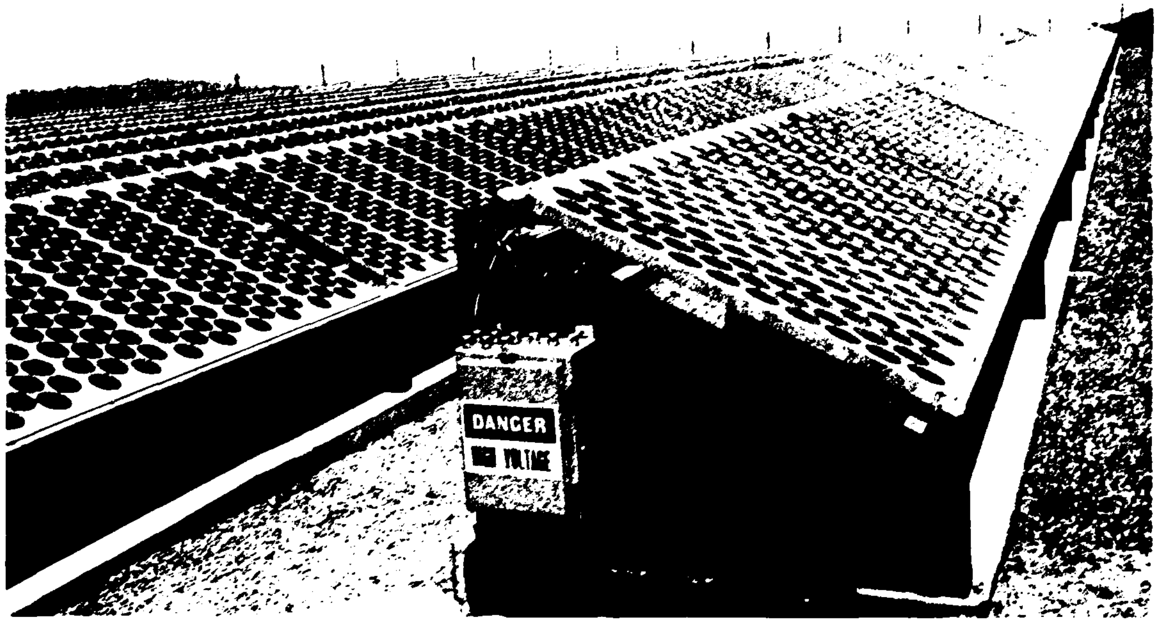


FIGURE 2-8. FRAMES MOUNTED ON SHEAR PANELS
(SHOWING ROW TERMINAL BOX)

FIGURE 2-9. PERMANENT SITE AFTER GRADING AND TRENCHING (RADAR FACILITY SHOWN IN BACKGROUND)

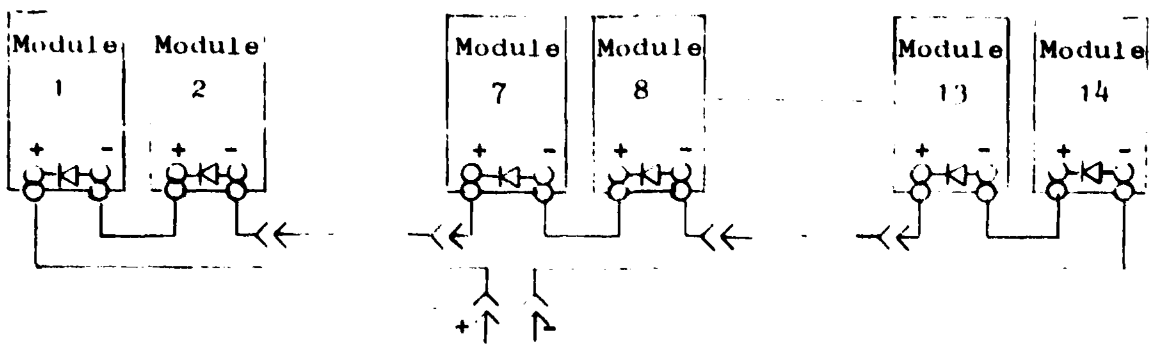
FIGURE 2-10. PHOTOVOLTAIC ARRAY INSTALLED AT MT. LAGUNA

box. In addition to providing a termination point for array wiring, the row terminal box contains surge suppressors for lightning protection and test plugs for monitoring individual string voltages. The array interconnections are depicted in Figure 2-11.

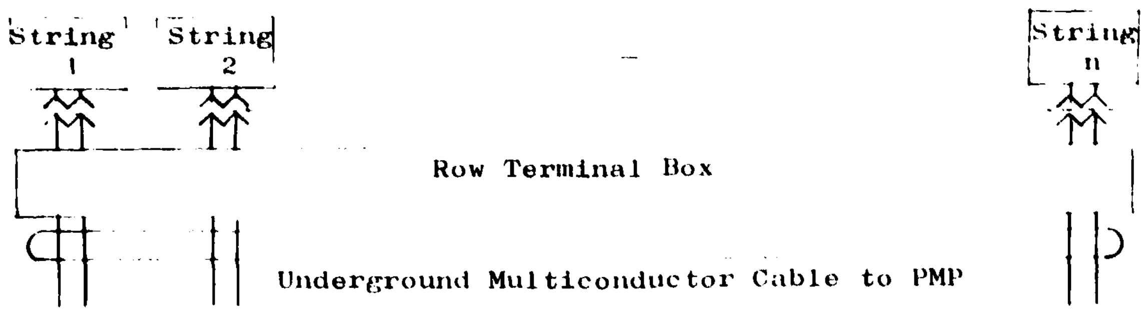
Underground multiconductor cables from the row terminal boxes connect the series-string outputs to the paralleling and monitoring panel. The paralleling and monitoring panel is located in a building with the power conversion unit. The power conversion building is visible at the left side of Figure 2-10.

2.2.6 Grounding. The PV module frames of each row are connected together and to a buried ground bus which runs along the west end of the array. The ground bus also circles the power conversion building to provide a ground for the power conversion equipment. It is connected to the diesel power plant ground.

2.3 PARALLELING AND MONITORING PANEL. Figure 2-12 is a simplified schematic diagram of the paralleling and monitoring panel. The output of each string of PV modules is normally connected to the common bus through a fuse represented by F1, a blocking diode CR1 and a switch S1. Meters M1, M2, M3, and M6 monitor the operation of the entire array: output voltage, current, power and accumulated kilowatt-hours. The 169 switches represented by



A. Intra-String Wiring



B. Inter-String Wiring, One of Eighteen Rows

FIGURE 2-11. ARRAY INTERCONNECTIONS

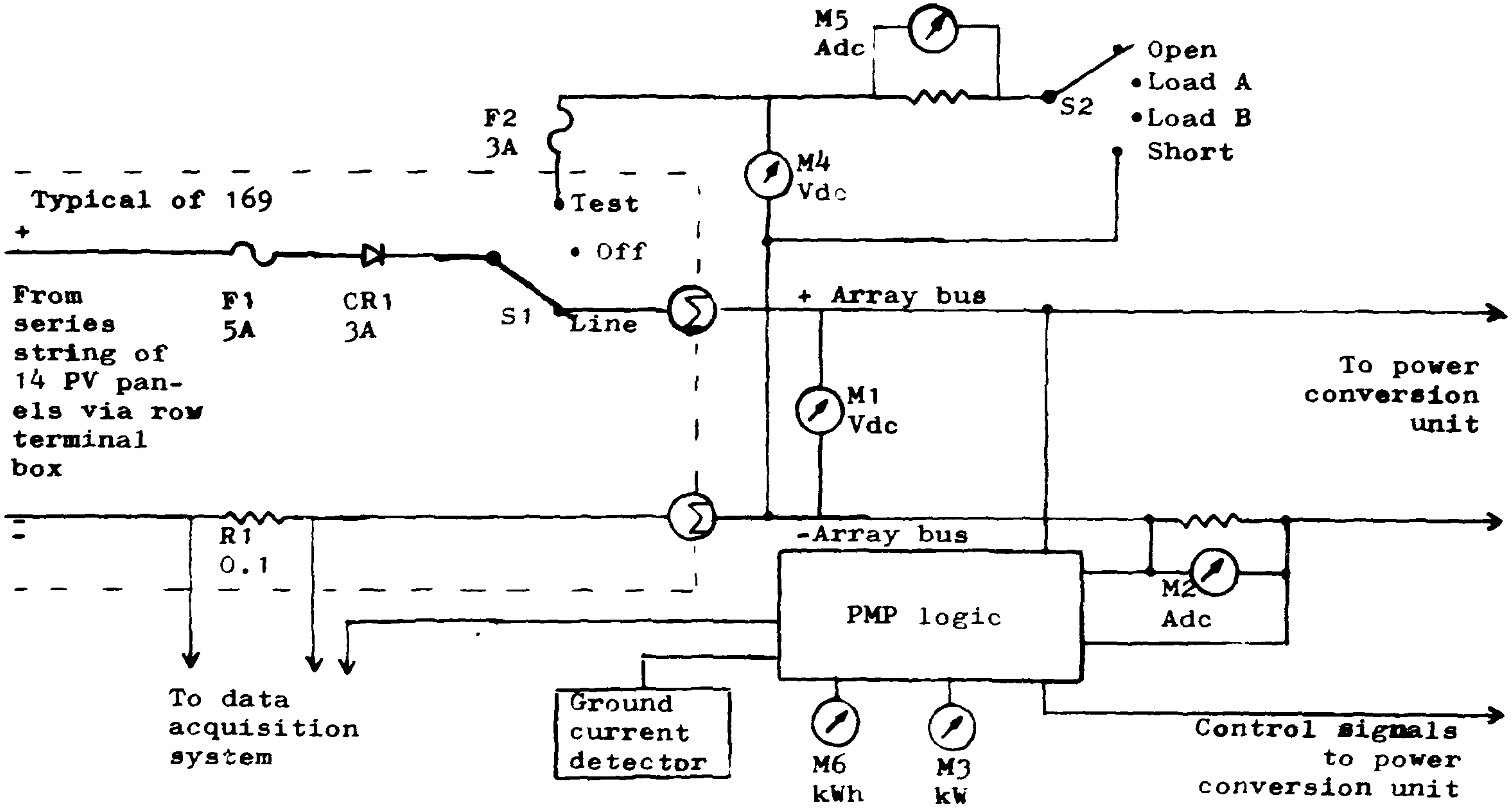


FIGURE 2-12. SCHEMATIC DIAGRAM OF THE PARALLELING AND MONITORING PANEL

S1 are three-position switches. In the normal "line" position each switch connects the corresponding string to the common bus. In the "off" position, the switch disconnects the string from the remainder of the system. In the "test" position the switch connects the string to a test bus for evaluation. M4 and M5 provide measurement of the test-string voltage and current into a load selected by S2: open, shorted, load A or load B. Loads A and B are the average peak-power loads for the Code Z and Code Y strings respectively.

A shunt resistor represented by R1 is incorporated in each string to provide individual string-current information to a data acquisition system provided under separate contract. (For more details see paragraph 2.5)

Figures 2-13 and 2-14 show the front panel and interior construction of the paralleling and monitoring panel. The wheel-like construction at the back of the cabinet is the "- array bus" shown in Figure 2-12. The resistors R1 can be seen radiating outward from it.

A ground fault detector is included in the paralleling and monitoring panel. The detector transmits a fault signal to the power conversion module to operate a warning lamp.

2.4 POWER CONVERSION UNIT. The power conversion unit, shown

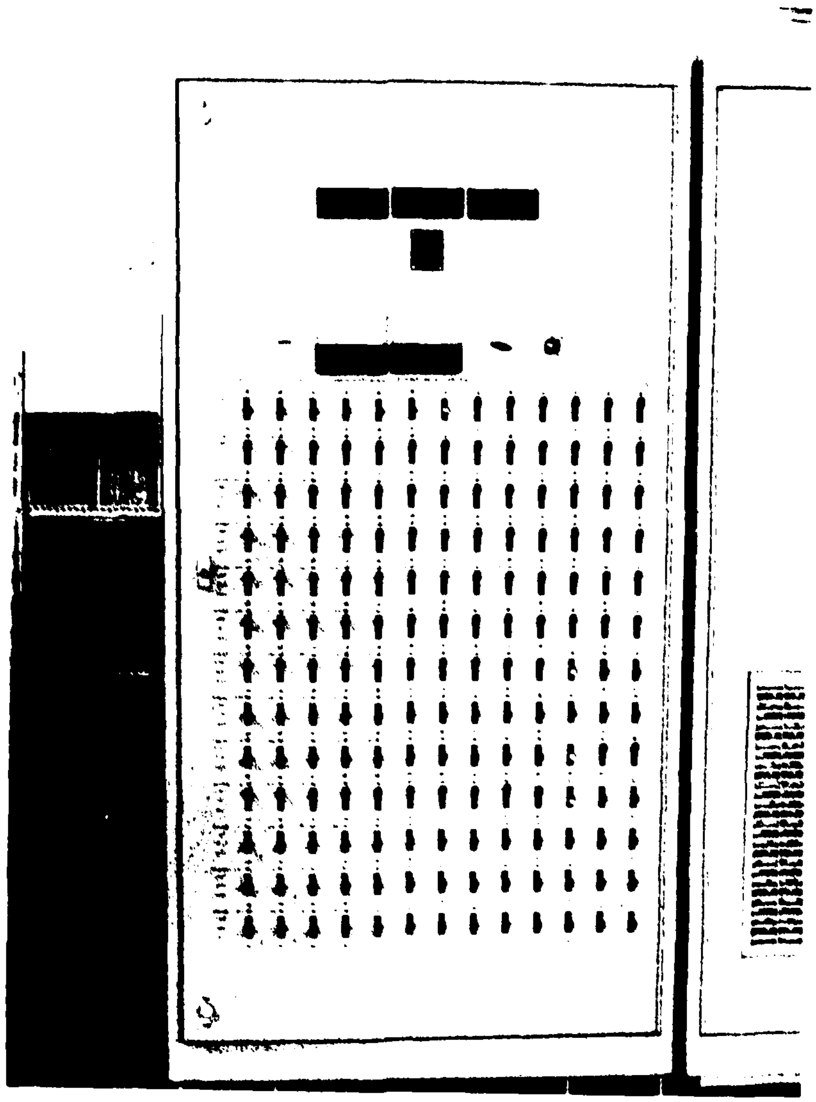


FIGURE 2-13. PARALLELING AND MONITORING PANEL, FRONT VIEW

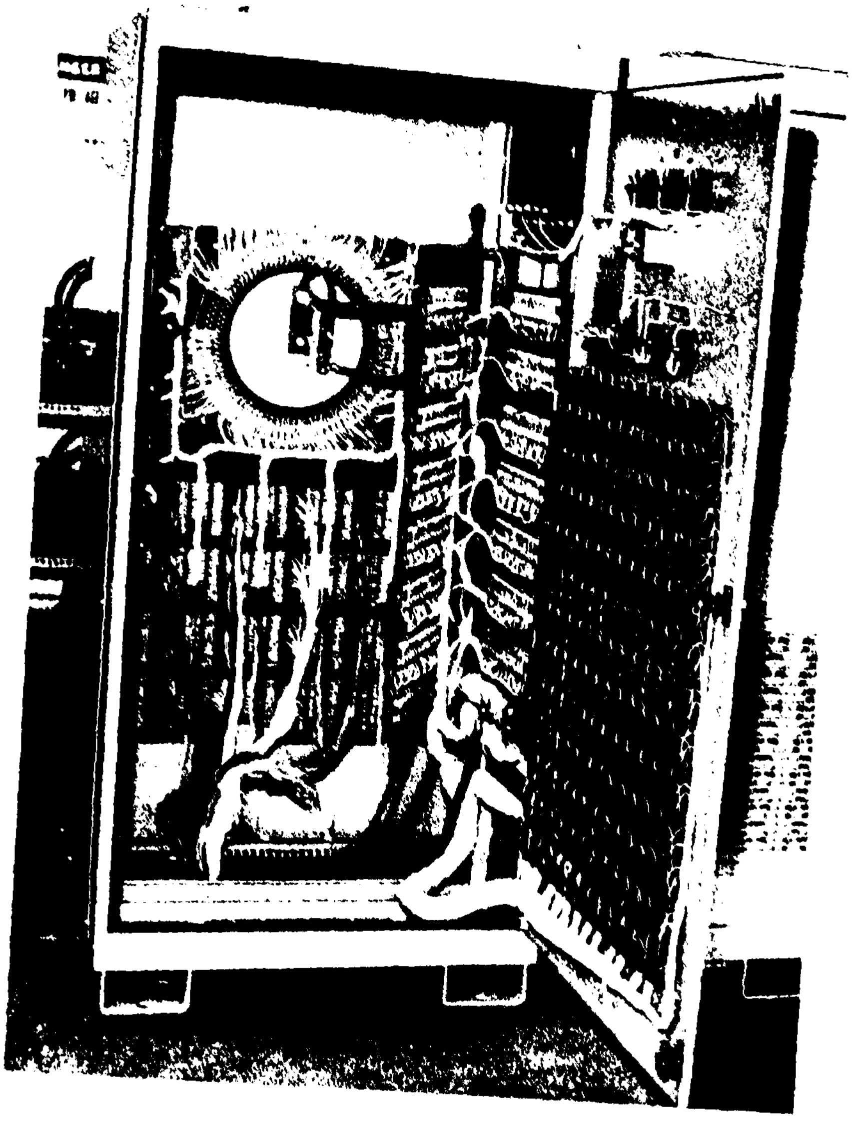


FIGURE 2-14. PARALLELING AND MONITORING PANEL, INTERIOR VIEW

in Figure 2-15, includes input and output contactors, an input voltage limiter, a dc-ac inverter, and system control circuitry. Figure 2-16 is a simplified block diagram of the power conversion unit.

2.4.1 Input and Output Contactors. Input contactor K1 is operated to short the PV array and disconnect the array from the pre-regulator when the inverter is off for any reason. Output contactor K2 is operated to isolate the inverter from the grid when the inverter is off. K1 and K2 are used in the automatic start-up and shut-down sequences.

2.4.2 Voltage Limiter. The preregulator limits the maximum inverter input voltage to 290 Vdc. During normal operation this thyristor buck-type regulator is in the "full on" condition and dissipates very little power (less than 1%). The limiter protects the inverter during the start-up sequence between the time K1 is activated and the time K2 is activated. During this period the input voltage from the unloaded array can be as high as 400 Vdc.

2.4.3 DC-AC Inverter. The dc-ac inverter is the same inverter used by DECC in its Uninterruptible Power Supplies. This self-commutated power inverter uses pulse-width modulation techniques to generate a 3-phase, 12-step sine-wave synthesis. The pulse-width modulation provides control of the dc/ac voltage ratio. The lowest order harmonic

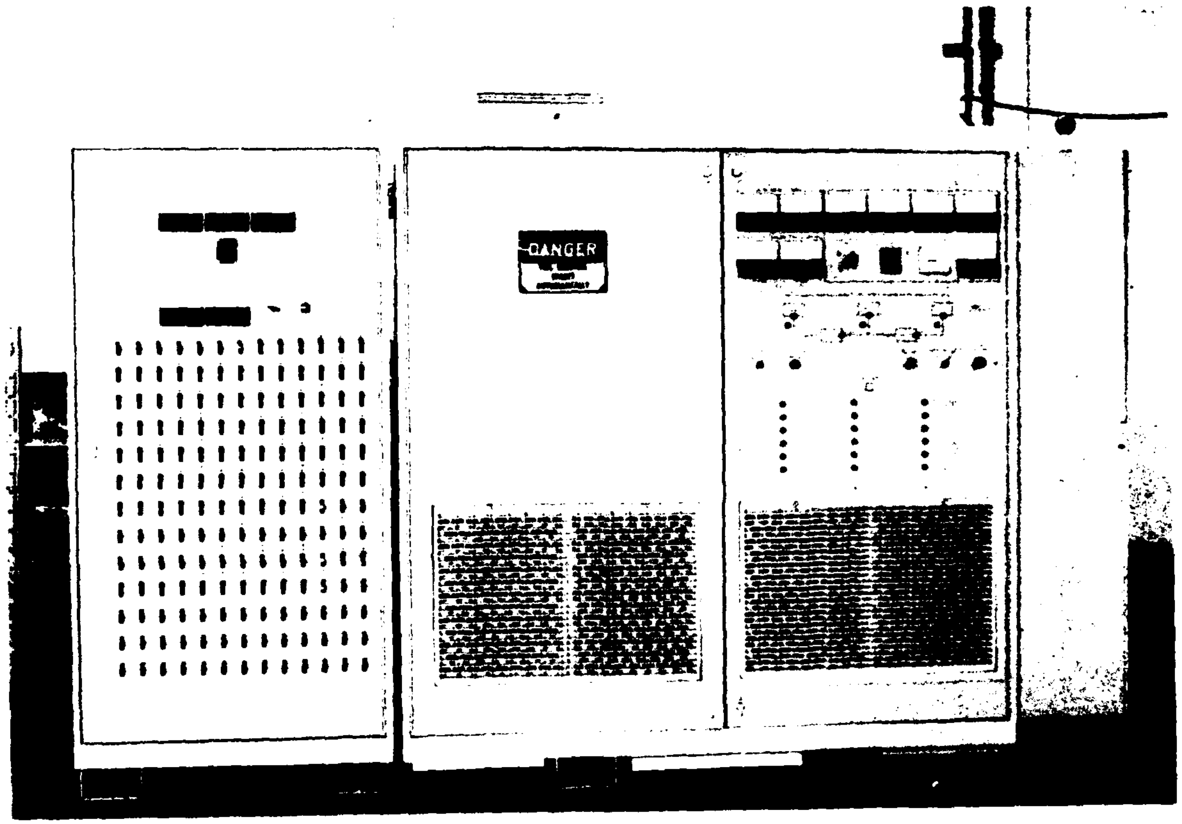


FIGURE 2-15. POWER CONVERSION EQUIPMENT

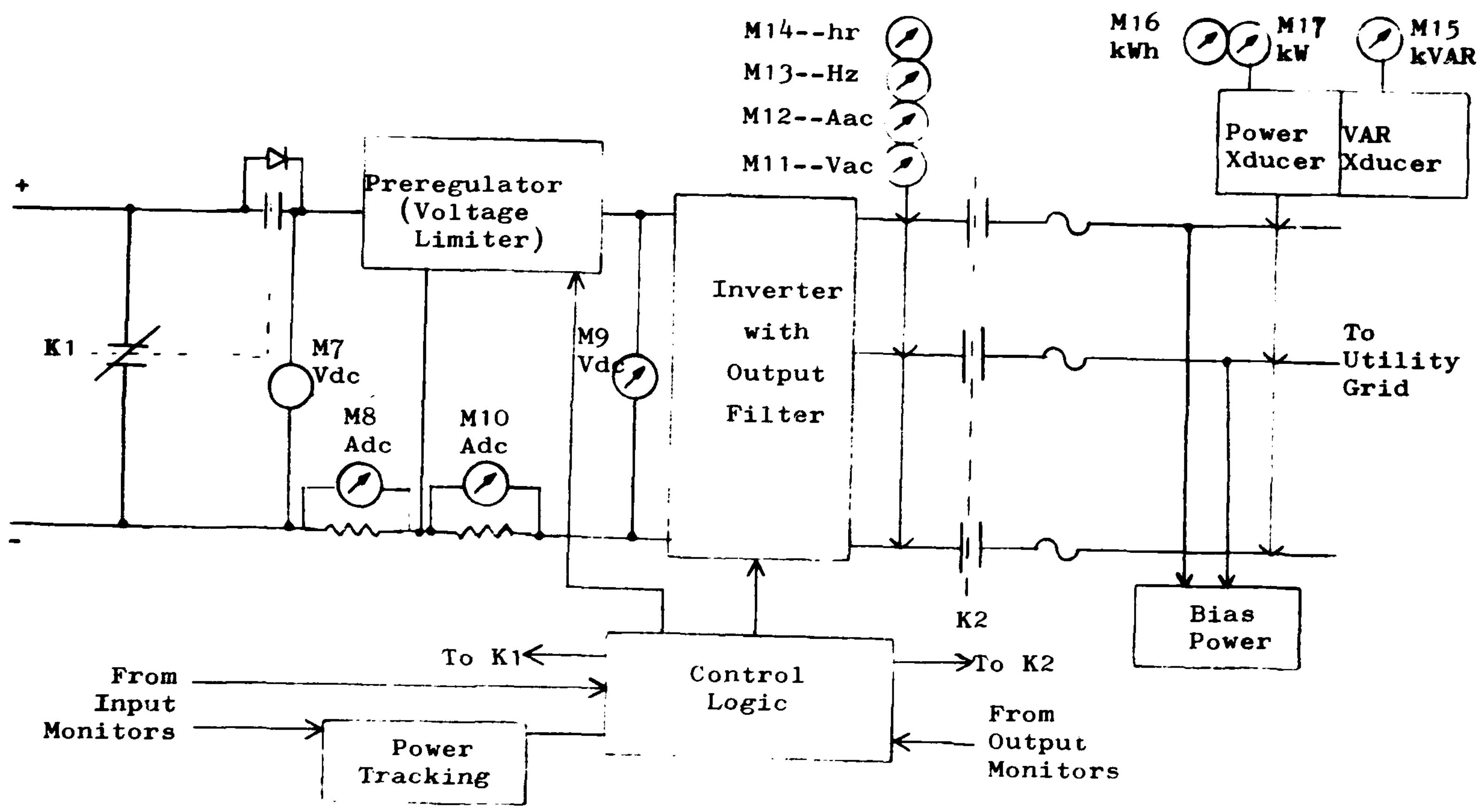


FIGURE 2-16. BLOCK DIAGRAM OF THE POWER CONVERSION UNIT

produced by the synthesis is the eleventh. Only minimal filtering is required to ensure a total harmonic distortion of less than 3%. The series inductive component of the output filter is also used in power flow control.

2.4.4 <u>System Control Circuitry</u>. The system control includes array peak power tracking and output power control, automatic start-up and shut-down controls, automatic safety and protection circuitry, remote shut-down control, and status monitors.

2.4.4.1 Peak Power Tracking and Power Flow Control. Peak power tracking and power flow controls extract the maximum available power from the array, provide stability in the face of changing array conditions, and minimize the reactive output power.

The primary control loop generates a phase difference, φ, across the series inductive component of the output filter, resulting in the flow of power to the grid and loading of the array.

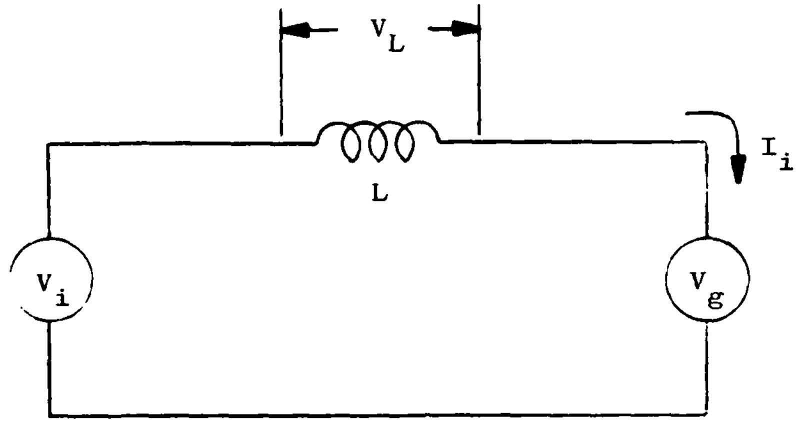
A secondary control loop provides the peak power tracking. Control circuitry applies a half-Hertz modulation to the phase difference, φ, and the pulse-width modulation index of the inverter, and monitors the derivative dP/dV at the array output. The phase difference and pulse width modulation index are adjusted to set dP/dV equal to zero, i.e.

the peak power point.

A tertiary control loop adjusts the output ac voltage from the inverter for zero reactive power as depicted in Figure 2-17.

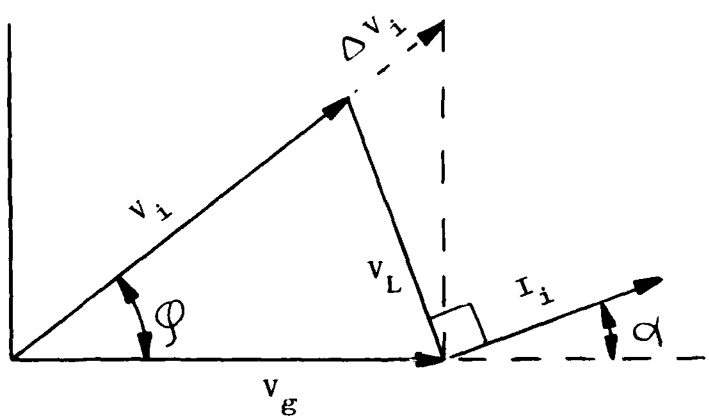
2.4.4.2 Automatic Start-Up. The solar power conversion system was designed to allow unattended operation over long periods of time; operation is entirely automatic from start-up to shut-down. The operation sequencing is depicted in Figure 2-18. When there is insufficient solar power available to support the system losses, (e.g. at night) the power conversion unit turns off automatically. When the power conversion unit is off, the input contactor K1 is deactivated, shorting the array. A small amount of power (65 watts) is drawn from the utility grid to power stand-by circuitry. In the course of a normal day, as the insolation increases, the array output current through K1 increases. When this current reaches 10% of the peak current, the start-up sequence is initiated. If the grid voltage is not within 10% of the nominal value, start-up is delayed until the grid returns to that range.

When the start-up conditions are met, the start-up sequence is initiated (T_0). At T_0, bias power supplies are energized. Five seconds later (T_0+5), the input contactor is energized, unshorting the array. The input



V_i = Inverter output voltage
V_g = Grid voltage
V_L = Voltage across L
L = Effective series inductance of output filter

a. Single-Phase Equivalent Circuit

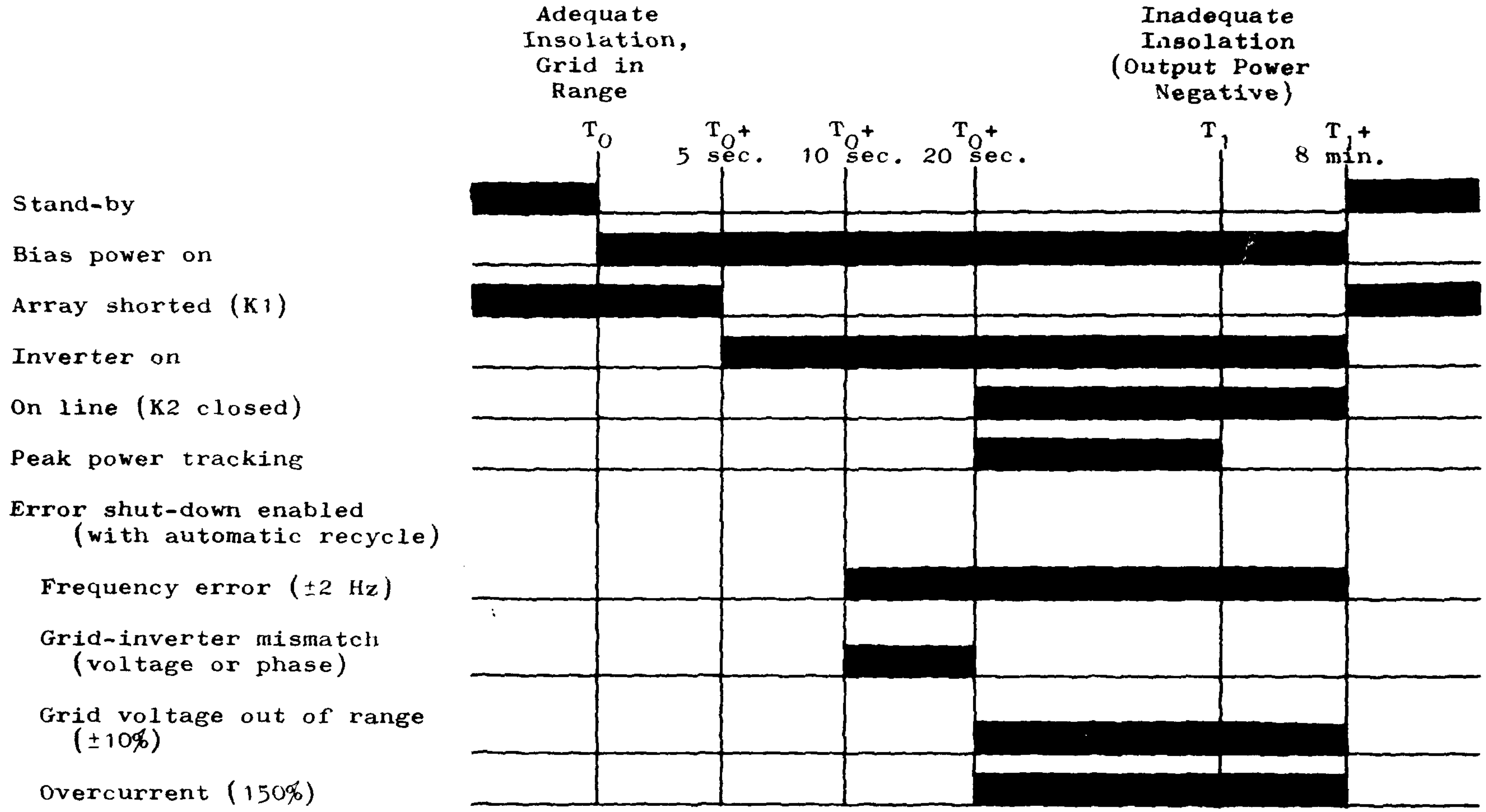


φ : power flow control
α : power factor angle

ΔV_i: adjusted to set $\alpha = 0$

b. Vector Diagram

FIGURE 2-17. FOUR-QUADRANT POWER CONTROL



Fault Shut-downs Requiring Manual Reset

- Blown fuse
- DC overvoltage
- Overtemperature
- Excessive reverse power

Fault Shut-down with Automatic Reset when Fault is Cleared

- Interlock loop open

FIGURE 2-18. START-UP SEQUENCING

voltage to the power conversion unit rises and the preregulator and inverter commence operation. Control circuitry synchronizes the inverter output to the grid and controls the inverter output voltage. The preregulator limits the input voltage to 290 Vdc.

Ten seconds later (T_0+15), frequency error and line match error detectors are activated. If the output frequency deviates from the range of 60±2 Hz at any time after T_0+15, the power conversion unit is gated off and "error recycle" sequence is initiated (see paragraph 2.4.4.3)

At T_0+20, the three-phase output contactor K2 closes. Closure is prevented, however, if the voltage across K2 (any phase) is greater than 7% of the nominal line-to-neutral voltage. This assures that the inverter output is matched to the grid in voltage and phase.

After T_0+20, the power conversion unit is in the operational mode; all power flow control and fault detection circuitry is activated.

2.4.4.3 Shut-Down. There are six basic types of shut-down for the power conversion unit:

(1) Manual Shut-down in Response to the On-Off Control Switch. When the Inverter Power System on-off switch on the front panel of the power conversion unit is turned

to the "off" position, normal shut-down occurs. The power conversion unit remains off until the switch is turned to the "on" position. The power conversion unit then starts up if the normal start-up conditions are met.

(2) Manual Shut-down in Response to the Emergency Off Switch. Pulling the momentary Emergency Off switch initiates an orderly shut-down as the on-off switch does, and also opens an external circuit breaker, removing all ac power from the unit. The circuit breaker is mounted on the wall of the power conversion building and must be reclosed manually to reinitiate operation.

(3) Shut-down Due to Insufficient Solar Power. When the power available from the PV array is insufficient to operate the power conversion system, the primary stabilizing power-flow-control circuitry causes a small amount of power to flow into the inverter from the grid. If this reverse power flow persists for more than 10 minutes, the power conversion unit shuts down from insufficient solar power. The unit turns on again when normal turn-on requirements are met. The turn-off delay provides hysteresis and prevents nuisance shut-downs and on-off cycling during marginal insolation.

(4) Shut-down with Automatic Restart when the Fault is Cleared. An interlock circuit turns the power conversion unit off if an interlock loop is opened. The interlock

loop includes auxiliary contacts on the major system switches, including the remote circuit breaker. The unit restarts automatically when the loop is closed, provided the normal start-up conditions are met.

(5) Shut-down with Automatic Recycling. Many system faults, such as utility net disturbances, tend to be transient in nature. The power conversion unit protects itself against these faults by shutting down. To avoid unnecessary operator intervention, the power conversion unit is designed to start-up again automatically 30 seconds after shut-down. If the start-up conditions are not met, the restart is delayed until they are. If any of the associated faults recurs after start-up and within 80 seconds of the original fault, the power conversion unit shuts down until reset manually. The faults which cause shut-down with recycling are:

(a) Utility grid frequency out of range (60±2 Hz),

(b) Utility grid voltage out of range (nominal ± 10%),

(c) Excessive output current from the power conversion unit (greater than 100 amps for 100 milliseconds or greater than 175 amps peak instantaneous on any phase), and

(d) Mismatch between utility grid and inverter at start-up.

(6) Shut-down Requiring Manual Reset. Seven fault conditions cause the power conversion unit to shut down

until reset manually. These are faults which require attention by service personnel. They include:

(a) Overvoltage at the dc bus-- input voltage regulator not operating properly,

(b) Output undervoltage during start-up sequence--inverter has not produced full output voltage by the expected point in the sequence,

(c) Open fuse--at output or at inverter power stage,

(d) Excessive reverse power into the inverter from the grid--power flow control circuitry not operating properly,

(e) Overtemperature within the power conversion unit, and

(f) Incorrect bias voltages--bias supplies not operating properly.

All six types of shut-down deactivate K1, shorting the array, and open the output contactor K2. Bias supplies remain activated for a short time to assure orderly shut-down.

2.4.5 Monitors. The solar power conversion system includes meters and status lamps for monitoring of normal and abnormal operation. The PMP has six meters; the power conversion unit has eleven meters and twenty-six status lamps. Generally, fault condition indicator lamps remain lit after shut down to assist in fault diagnosis.

The monitors and their functions are listed in Table 2-3. No audible alarm is included in this system which is installed in an unmanned building.

2.5 DATA ACQUISITION SYSTEM. A data acquisition system, provided under separate contract, processes digital and analog outputs from the power conversion system for local monitoring or for recording on magnetic tape. The outputs provided by the power conversion system are listed in Table 2-4. The data acquisition system will also monitor a weather station to be installed at a later data; an insolometer has been installed already. The data acquisition system includes data scanners, a programmable computer, input keyboard, CRT display, printer, and a dynamic load. Figures 2-19 through 2-22 are typical of the types of output available at the CRT and printer. Figure 2-22 is an I-V curve for a single Code Z string. The curve is generated using the dynamic load.

The data acquisition system was provided by Sandia Laboratories.

TABLE 2-3. MONITORS

Monitor	Location	Parameter or Condition
M1	Paralleling and Monitoring Panel	Array output voltage
M2	Paralleling and Monitoring Panel	Array output current
M3	Paralleling and Monitoring Panel	Array output power
M4	Paralleling and Monitoring Panel	Test string voltage
M5	Paralleling and Monitoring Panel	Test string current
M6	Paralleling and Monitoring Panel	Array output kWhr
M7	Power Conversion Unit	Input voltage from array
M8	Power Conversion Unit	Input current from array
M9	Power Conversion Unit	Input voltage to inverter
M10	Power Conversion Unit	Input current to inverter
M11	Power Conversion Unit	Output ac voltage
M12	Power Conversion Unit	Output ac current
M13	Power Conversion Unit	Output frequency
M14	Power Conversion Unit	Running time
M15	Power Conversion Unit	Output reactive power
M16	Power Conversion Unit	Output kWhr
M17	Power Conversion Unit	Output real power
DS1	Power Conversion Unit-Mimic Bus	Sufficient solar power
DS2	Power Conversion Unit-Mimic Bus	K1 activated
DS3	Power Conversion Unit-Mimic Bus	DC-DC converter activated
DS4	Power Conversion Unit-Mimic Bus	Adequate battery voltage (not used mode 1)
DS5	Power Conversion Unit-Mimic Bus	Battery contactor activated (not used mode 1)
DS6	Power Conversion Unit-Mimic Bus	Proper inverter output voltage
DS7	Power Conversion Unit-Mimic Bus	K2 activated
DS8	Power Conversion Unit-Mimic Bus	Utility grid connected
DS9	Power Conversion Unit	Power conversion unit on
DS10	Power Conversion Unit	Off--insufficient solar power
DS11	Power Conversion Unit	Off--error, recycling
DS12	Power Conversion Unit	Off--error shut-down
DS13	Power Conversion Unit	Overvoltage at dc bus
DS14	Power Conversion Unit	Inverter undervoltage during start-up
DS15	Power Conversion Unit	Grid frequency out of range
DS16	Power Conversion Unit	Synchronization error at start-up
DS17	Power Conversion Unit	Grid voltage out of range

TABLE 2-3. MONITORS (cont'd)

Monitor	Location	Parameter or Condition
DS18	Power Conversion Unit	Output fuse open
DS19	Power Conversion Unit	Inverter fuse open
DS20	Power Conversion Unit	Excessive power flow, grid to inverter
DS21	Power Conversion Unit	Excessive output current
DS22	Power Conversion Unit	Overtemperature
DS23	Power Conversion Unit	Incorrect bias voltages
DS24	Power Conversion Unit	Blower failure
DS25	Power Conversion Unit	Ground fault
DS26	Power Conversion Unit	Interlock loop open

TABLE 2-4. OUTPUTS TO THE

DATA ACQUISITION SYSTEM

Output	Type	Voltage
Series string current (169 outputs)	Analog	100mV/A
Array current	Conditioned analog	5V/300A
Array voltage	Conditioned analog	5V/500V
Array power	Conditioned analog	5V/100kW
Array kWhr	BCD	0/14 V
Output power	Conditioned analog	5V/100kW
Output kWhr	BCD	0/14 V
On/Off	Binary	0/14 V
Off--insufficient solar power	Binary	0/14 V
Off--error shutdown	Binary	0/14 V
Off--error recycle	Binary	0/14 V

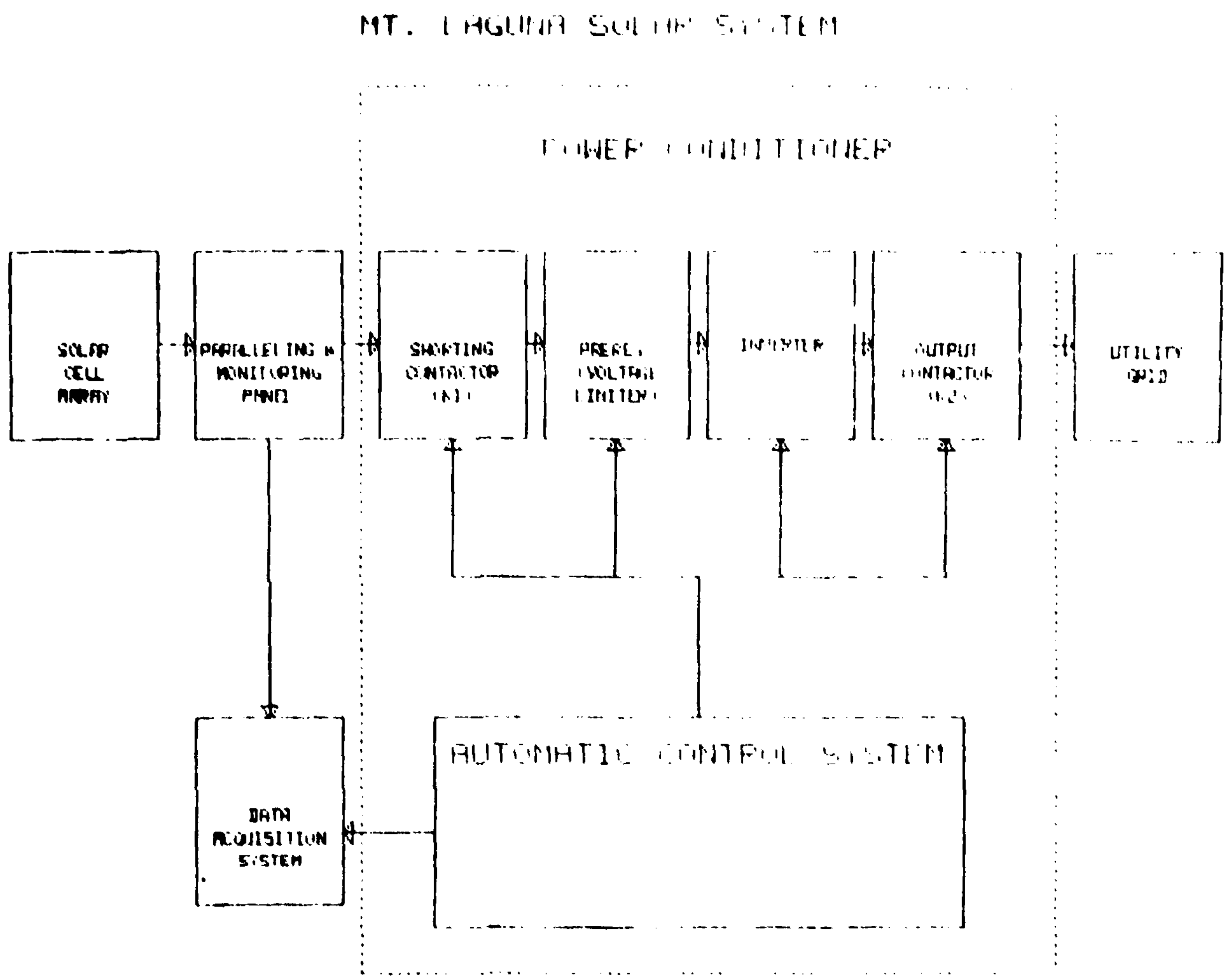


FIGURE 2-19. OUTPUT FROM DEMONSTRATION PROGRAM ON DATA ACQUISITION SYSTEM

Aug 14,1979 at 12:38:23

SYSTEM STATUS

SYSTEM IS ON

SYSTEM CONDITIONS

SOLAR INSOLATION IS	1000.8 WATTS PER SQUARE METER
THE AMBIENT AIR TEMPERATURE IS	68.0 DEGREES F
ARRAY OUTPUT CURRENT IS	250.9 AMPS
ARRAY OUTPUT VOLTAGE IS	227.4 VOLTS
ARRAY OUTPUT POWER IS	57.6 KILOWATTS
CONVERTER OUTPUT POWER IS	52.0 KILOWATTS
ARRAY METER READING IS	1066 KWH
CONVERTER METER READING IS	899 KWH

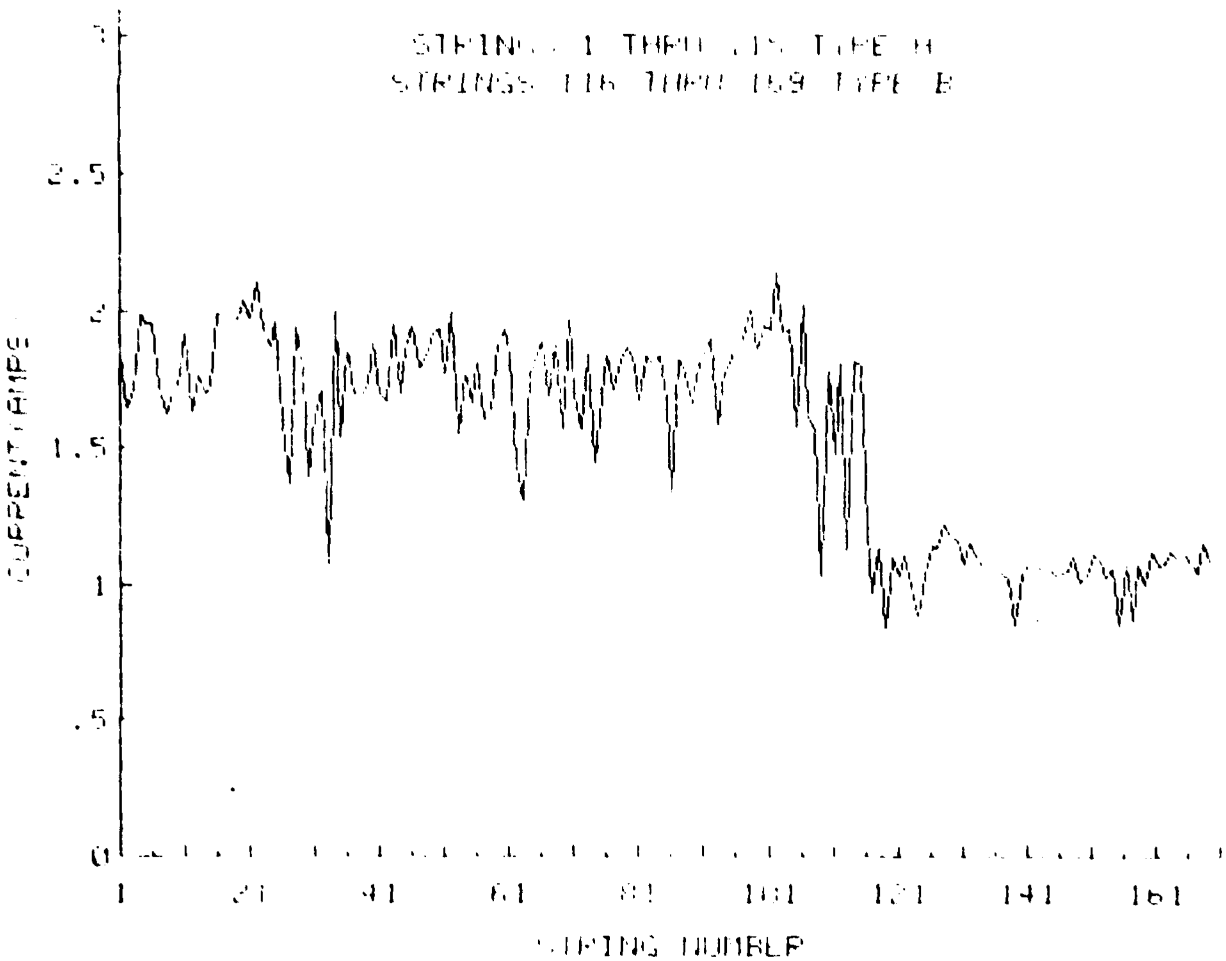
TABULATION OF STRING CURRENTS FROM THE ARRAY

Aug 14,1979 at 12:38:32 TIME AT START OF SCAN

1.90	1.68	1.74	2.02	1.98	1.98	1.75	1.67	1.75	1.7[illegible]
1.97	1.65	1.80	1.72	1.77	2.03	2.00	2.01	2.02	2.0[illegible]
1.99	2.13	1.94	1.72	1.99	1.62	1.21	2.00	1.81	1.9[illegible]
1.67	1.73	1.17	2.03	1.59	1.94	1.64	1.90	1.74	1.9[illegible]
1.74	1.64	1.98	1.72	1.88	1.96	1.84	1.86	1.94	1.9[illegible]
1.74	2.01	1.57	1.79	1.68	1.85	1.60	1.64	1.93	1.95
1.91	1.45	1.33	1.81	1.89	1.65	1.72	1.94	1.60	1.9[illegible]
1.77	1.59	1.90	1.47	1.52	1.91	1.71	1.88	1.91	1.81
1.70	1.80	1.85	1.86	1.64	1.37	1.86	1.82	1.71	1.8[illegible]
1.94	1.95	1.59	1.81	1.38	1.94	1.94	2.06	1.93	2.06
1.97	2.20	1.66	1.98	1.72	2.08	1.63	1.60	1.13	1.8[illegible]
1.5[illegible]	1.06	1.17	1.87	1.86	1.23	1.01	1.16	.87	1.14
1.06	1.14	1.01	.92	1.03	1.16	1.15	1.23	1.21	1.18
1.11	1.20	1.14	1.11	1.13	1.10	1.09	1.05	.90	1.07
1.10	1.11	1.07	1.09	1.04	1.05	1.08	1.13	1.04	1.0[illegible]
1.14	1.12	1.06	1.09	.89	1.09	.92	1.09	1.03	1.1[illegible]
1.11	1.10	1.16	1.11	1.15	1.12	1.08	1.19	1.13	

Aug 14,1979 at 12:38:45 TIME AT END OF SCAN

FIGURE 2-20. DATA ACQUISITION SYSTEM OUTPUT



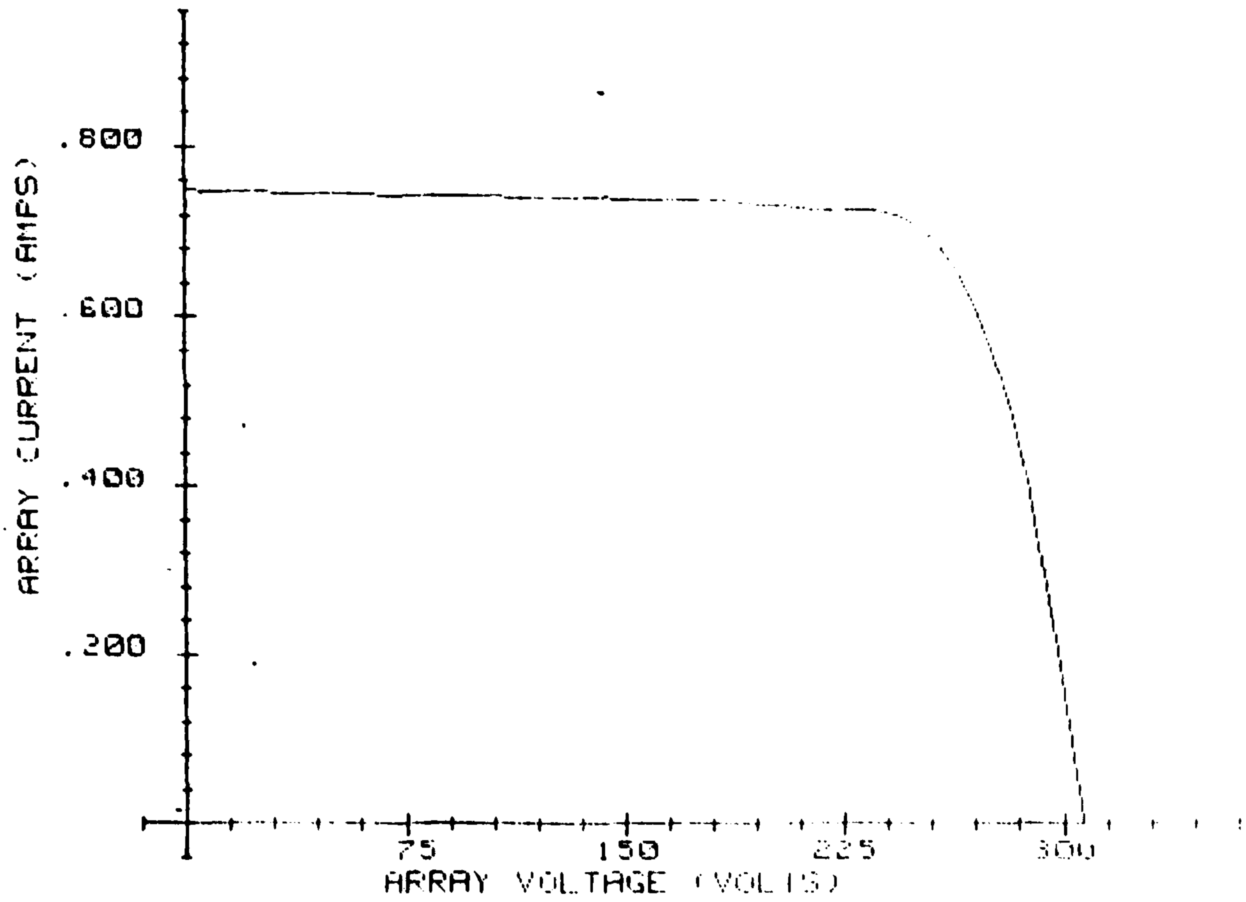
END OF DEMONSTRATION PROGRAM

FIGURE 2-21. DATA ACQUISITION SYSTEM OUTPUT

Aug 13,1979 at 17:11:54

Open circuit voltage is 306.92 Volts
Short circuit current is .77 Amps

Maximum power of string is 176.617 Watts
with 250.876 Volts @ .704 Amps



Run on Aug 13,1979 at 17:12:02

FIGURE 2-22. TYPICAL DATA ACQUISITION SYSTEM OUTPUT-- I-V CURVE FOR A CODE Y STRING

3.0 RESULTS

Since the first testing of the power conversion unit in September of 1978, the results have been extremely gratifying.

3.1 OPERATION OF THE POWER CONVERSION UNIT FROM AN ARRAY SIMULATOR. In early September, 1978, construction of the power circuitry and basic control circuitry of the power conversion unit were completed. Normal operation of the power circuitry was verified in September. In early October, the power conversion unit, operating from a current-source array simulator, delivered power into the Southern California Edison Company utility grid. The tests demonstrated the stability of the power control circuitry and the operation of the peak power tracking circuitry. The tests performed were primarily qualitative and the unit met design goals, operating stably and tracking peak power to within 1%.

3.2 FIELD TESTS WITH PV ARRAY AT THE DECC FACILITY. During the autumn of 1978, a partial array was installed at DECC to allow system testing. The array consisted of some Code Z and some Code Y PV modules mounted to their frames and interconnected as they would be at the permanent site at Mt. Laguna. Some of the module frames were mounted to shear panels while the remainder of the shear panels were being installed at the permanent site.

By January 10, 1979, enough strings of PV modules were installed to begin system testing. There were no surprises when the system was operated in its normal mode, extracting power from the array and providing power to the local utility grid. By March, 1979, the system had operated successfully at array power levels up to 27 kW (the maximum available from the partial array). The system operated normally, without unnecessary operator intervention for 43 days (414 operating hours) at the DECC facility, extracting a total of 6218 kWhr from the array and providing a total of 4861 kWhr to the utility grid. Because the testing was performed during a southern-California winter, the array was exposed to a variety of environmental conditions: temperatures from 34-90°F, bright sun, dark clouds, thick fog, heavy rain, and hail with stones up to 3/8 inch in diameter driven by strong winds. The only environmental damage observed was the flooding of some temporary underground cables from the array to the power conversion system. Because of the temporary nature of the installation, and the expectation that the underground conduit would remain dry, the temporary cables had not been designed for submerged operation. Thoughout the testing at DECC the power conversion system operated without failure. The entire system operated through an hour-long series of intermittent brown-outs and black-outs of the local utility grid, shutting down for self-protection when necessary and restarting automatioally when appropriate.

3.3 OPERATION AT THE PERMANENT SITE. On May 29, 1979, the power conversion unit, PMP and a few remaining array elements were shipped to the permanent site at Mt. Laguna Air Force Station. Most of the PV array and system interconnect wiring had already been installed at that time. The power conversion equipment was installed and operational within a week. Since completion of the installation in July, the system has been tested and operated under the local conditions. A formal acceptance test was performed to verify conformance of the system to the primary requirements of the purchase description. A copy of the procedure and results of the system tests at Mt. Laguna and at DECC are discussed below.

3.4 SYSTEM PERFORMANCE. Tests performed at DECC and at the permanent site verified that the photovoltaic power conversion system met all of the primary requirements of the purchase description. Although the formal acceptance test (Appendix A) was performed during a brief two day period and under the prevailing environmental conditions, additional data were taken during later operation and are reported here. The data acquisition system was particularly helpful in taking approximately concurrent readings of the monitored parameters. At the time of the observations, the data acquisition system was programmed to provide "hard copy" data printouts on request.

3.4.1 **Modes of Operation.** The purchase description for the PV system called for a power conversion unit capable of operating in two distinctly different modes with only minor modifications of the circuitry: (1) the augmentation mode, with the system operating in parallel with a utility grid and no battery storage, and (2) the stand-alone mode, independent of utility power, with battery storage and operation into a dedicated load.

The power conversion system was tested in mode 1, the augmentation mode, only. The results of these tests are reported below. The power circuitry of the system, including the dc-dc converter (input regulator/voltage limiter) and dc-ac inverter are those used by DECC in its 62.5 Uninterruptible Power Supplies (UPSs). The UPS operates like a mode 2 PV power conversion system, except that the input dc-dc converter operates from rectified utility power rather than solar power. Only the control circuitry would have to be modified to convert the PV system from mode 1 to mode 2 operation. The 62.5 kW UPS characteristics are described below as an indication of the performance which can be expected in a stand-alone operation of the PV power conversion system.

3.4.2 **The Power Conversion System.**

3.4.2.1 Input Power. The power conversion system operated properly throughout the range from no input power up to the maximum observed input power, 69kW. The power conversion system tracked the array peak power to within 1% (typically 0.5%) over the input power range of 10-60 kW.

3.4.2.2 Input Voltage. The power conversion system operated properly over the range of peak power points encountered, and protected itself against unloaded array voltage. The system was tested at input voltages 20% above and below the peak power point by operating the manual override adjustment. The system operated stably both above and below the peak power point.

3.4.2.3 Output Power. Operation of the power conversion system has been demonstrated at output power levels up to 60 kW.

3.4.2.4 Output Voltage. As tested in mode 1 operation, the power conversion system output voltage is equal to the utility grid voltage by identity. The system operated properly over all in-range grid conditions encountered during testing.

When the same inverter has been used in UPS applications it has demonstrated excellent output characteristics. The voltage regulation is typically ± 1% with a phase imbalance of less than 0.3% of the line-to-neutral voltage. The phase displacement is 120±3° for load imbalance up to 30%.

3.4.2.5 Efficiency. The measured efficiency of the system is plotted as a function of output power in Figure 3-1. The overall power conversion efficiency is 92% at 60 kW and 91% at 30 kW. The no-load losses (input power from array with zero output power) are less than 2.6 kW at all normal array input voltages. The stand-by losses are approximately 65 kW.

3.4.2.6 Harmonic Distortion and Waveform. The measured total harmonic distortion of the output current in mode 1 operation is 2.6% over the output power range of 30-60 kW. Below 30 kW the distortion amplitude remains relatively constant (approximately 1.3% of the full power output). The output current waveforms at 14 kW and 45 kW are shown in Figure 3-2. There is no observable disturbance to the utility grid voltage. Figure 3-3 shows the grid voltage (a) with the power conversion system off, and (b) with the power conversion system on and delivering 40 kW to the grid.

The output voltage of the same inverter operating as an UPS has a total harmonic distortion of less than 3% with a maximum single harmonic distortion of less than 2%.

3.4.2.7 System-Grid Interaction. The power conversion system incorporates soft-start characteristics to avoid

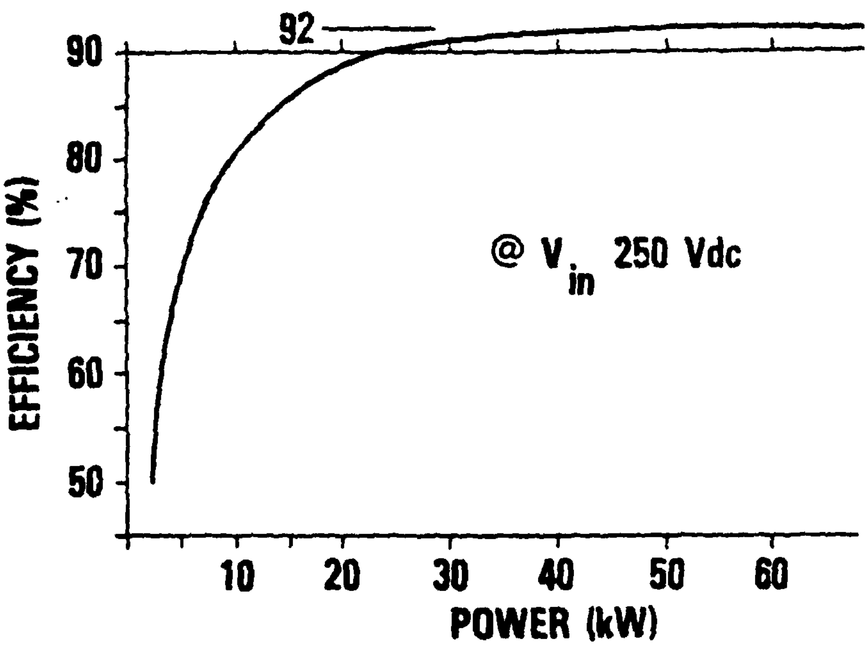
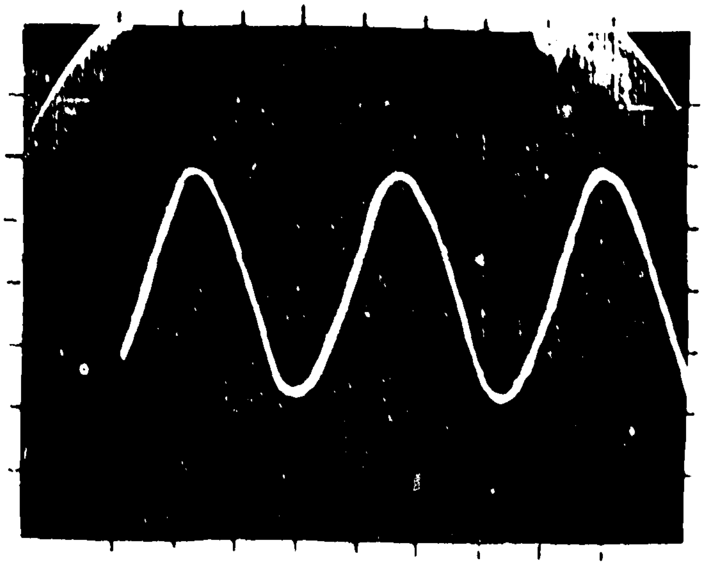
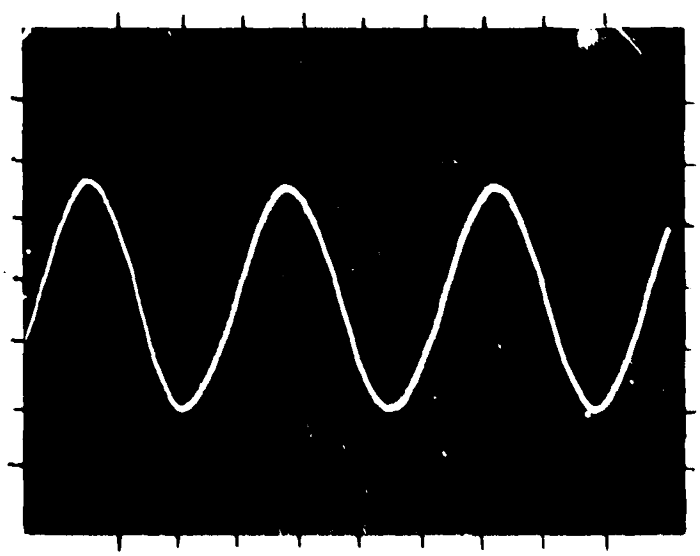


FIGURE 3-1. POWER CONVERSION SYSTEM EFFICIENCY AS A FUNCTION OF OUTPUT POWER

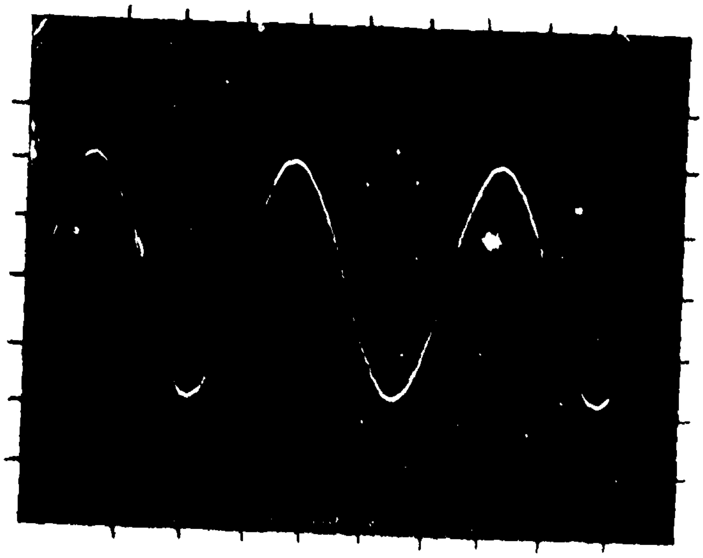


a. [illegible] kW [illegible]
Vertical [illegible]
Hori[illegible]

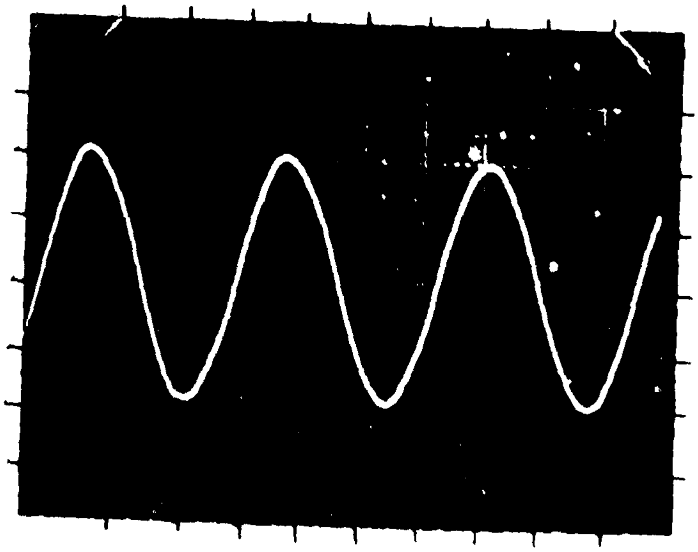


b. [illegible] kW Output [illegible]
Vertical [illegible] 100 V[illegible] division
Horizontal [illegible] division

FIGURE [illegible] WAVEFORM



a. [illegible] kW Output Power
Vertical Scale: [illegible] V/Division
Horizontal Scale: [illegible]/Division



b. [illegible] kW Output Power
Vertical Scale: [illegible] V/Division
Horizontal Scale: [illegible]/Division

FIGURE [illegible]. [illegible] VOLTAGE WAVEFORM
AT [illegible] RPM [illegible]

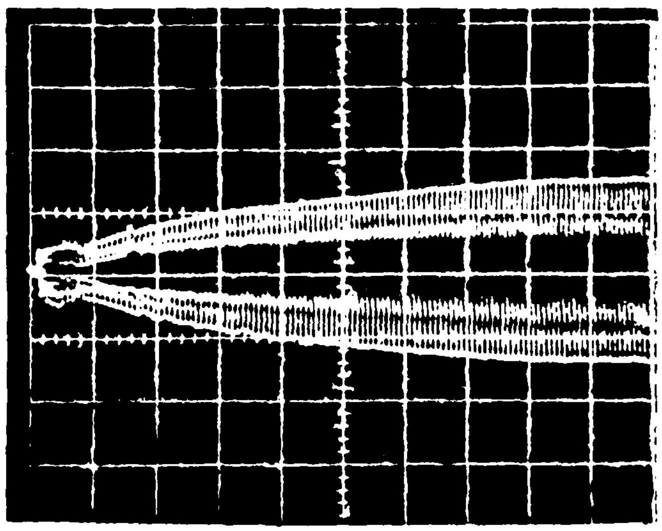


FIGURE 3-4. RATE OF RISE OF OUTPUT CURRENT AT TURN-ON,
30 kW ARRAY POWER AVAILABLE
HORIZONTAL SCALE: 0.2 SECONDS/DIVISION
VERTICAL SCALE: 25 AMPS/DIVISION

disturbance of the grid at turn-on. Figure 3-4 shows the typical rate of rise of the output current at turn-on. The small mismatch in voltage and phase across the output contactor is responsible for the discontinuity seen at the point of turn-on. There is no observable disturbance to the grid at turn-on.

There was some initial concern that the abrupt current change at turn-off would affect the Mt. Laguna grid. Fault shut-down during high-power operation was of particular concern. DECC planned to perform a set of tests, shutting the system off, first at very low power, and then at higher power levels to determine the affect on the grid. During the first day of testing, however, the system was accidently shut down with 65 kW output to the grid. Since no significant disturbance was observed at the main power station, no further tests were deemed necessary.

3.4.2.8 Protective System. The protective circuitry of the PV system includes, but is not limited to, that required by the purchase description for the system. (See paragraph 2.4.4.) All protection circuitry operated properly and workable fault thresholds were established for all protective circuits.

During the design phase it was hoped that the ground fault detector could be operated to provide an additional measure of personnel protection by initiating the shut-down and array-shorting sequence when potentially dangerous ground fault currents (more than 50 mA) were detected. During tests at DECC, however, it was found that whereas the normal ground current on a dry day was approximately 2 mA, the total array ground current on wet days frequently reached 50 mA. Thus the ground fault detector, as delivered, operates to provide an indication of excessive ground current only.

3.4.2.9 Expansion Capability. The power conversion system meets the purchase description requirements for expandability in either operating mode. In mode 1, adding another independent power conversion system is completely straightforward. Each system is independently controlled to operate into the utility grid.

In mode 2, combination of two units may be achieved by operating in a master-slave mode. The inverter has been operated in this manner in many UPS installations.

3.4.2.10 Electromagnetic Interference. As mentioned above, the power conversion circuitry and cabinet design of the PV system are identical to those of DECC's 62.5 kVA UPSs. The results of EMI tests performed on one such UPS unit are given in Appendix B of this report. The PV power conversion unit includes additional input and output filtering which should result in even lower conducted emissions, and the removal of input rectifiers should result in a slightly lower radiated emission in the PV unit. Because of the low EMI levels, the low frequency of the emissions, and the 200 yard distance between the power conversion building and the nearest sensitive equipment (with its 100 MHz to several GHz operating range), there should be no significant interference with that equipment. None has been reported.

3.4.2.11 Audible Noise. No actual acoustic noise measurements were made on the power conversion system. An uninterruptible power supply using the same inverter, converter, cabinet and blowers has a maximum acoustic noise of 85dB measured at 6 feet from the cabinet. Two cooling fans mounted in the ceiling of the power conversion building produce a negligible increase in the sound level.

3.4.3 The Array. Although the emphasis of this contract is on the development and operation of the power conversion system, some significant observations have been made about the PV array itself.

3.4.4.1 Output Power. The measured array output power reached a peak value of 69 kW. This higher-than-rated array power was observed at a time when the insolation was enhanced by reflection from nearby clouds. On a clear

August day with 1016 W/M^2 insolation and 71°F ambient temperature, the array output power was 58 kW. When the data from the data acquisition system is reduced, extensive detailed information on output power as a function of insolation and temperature will be available from Sandia Laboratories.

3.4.4.2 The PV Modules. The only major problem which has arisen in the system is with the Code Z PV modules. During the system tests at the DECC facility, it was observed that some of the Code Z PV cells operated at a considerably higher temperature than others. The heating effect was observed both with the array shorted and with the array providing power to the power conversion system.

When the PV modules were shipped to Mt. Laguna, the technicians installing them began to notice bulges, or "bursts" in some of the cells. New bursts are still appearing at the time of this report. Although there has been no appreciable reduction in the output power of the array, it is clear that the continued development of bursts will eventually cause deterioration of module performance and failure of some modules to produce power.

The tendency of cells to develop bursts appears to be correlated to the presence of high temperatures. The bursts may be caused by even or uneven expansion of the cells or of gasses trapped under the cells during encapsulation.

Jet Propulsion Laboratory (JPL), who provided the PV modules under contract with the Department of Energy, is studying the temperature and burst problems and will be publishing a full report of their findings. They have found that the temperature of some cells exceeds the temperature of others by as much as 80°C. Two heating mechanisms are responsible for the high temperatures: heating due to photocurrents in reverse biased cells, and heating due to leakage or breakdown in reverse biased cells. A cell of a loaded module becomes reverse biased when its current production capability is significantly less than that of the cells connected in series with it. The first heating mechanism occurs in any reverse biased cell: the power dissipated by this mechanism is equal to the photocurrent generated in the cell times the bias voltage and may be as much as the peak available power of the rest of the cells of the module. The power, however, is distributed over the entire photocurrent-generating area of the cell for maximum power densities of approximately three watts per square inch.

The second heating mechanism does not occur in all cells, but does result in much higher power densities. Uneven heating in some cells led DECC to investigate the reverse breakdown characteristics of the PV cells. Tests were performed on eight Code Z modules (320 cells). The test set-up is shown in Figure 3-5. With a module shorted, its cells were occluded one at a time by an opaque disc. Ideally, covering one cell in the series set should result in an open circuit and zero current through an external short. In actuality, electrical leakage and leakage of light around and under the covering disc result in some output current. For most cells, the "dark" current was between 10 and 100 milliamps. Sixteen percent of the cells, however, had "dark" currents in excess of 200 milliamps, 7.8% had "dark" currents in excess of 500 milliamps, and 2.2% had "dark" currents in excess of one amp. The cells exhibiting "dark" currents of more than 500 milliamps became discernably hotter than the other cells. In general the heating occurred in a very small area of the cell, causing an extremely rapid rise in temperature. In one case, when the opaque disc was inadvertently left in place too long, the surface of the module reached a temperature of the order of 80-100°C. The result was visible melting of the solder and of either the plastic or the adhesive material under the cell. The cell became physically distorted at the hot spot. These tests, performed with totally occluded cells, resulted in greater localization of the dissipation than would normally occur. Under normal partial occlusion, the power dissipated in a cell would be shared by the distributed photocurrent dissipation and the localized breakdown dissipation.

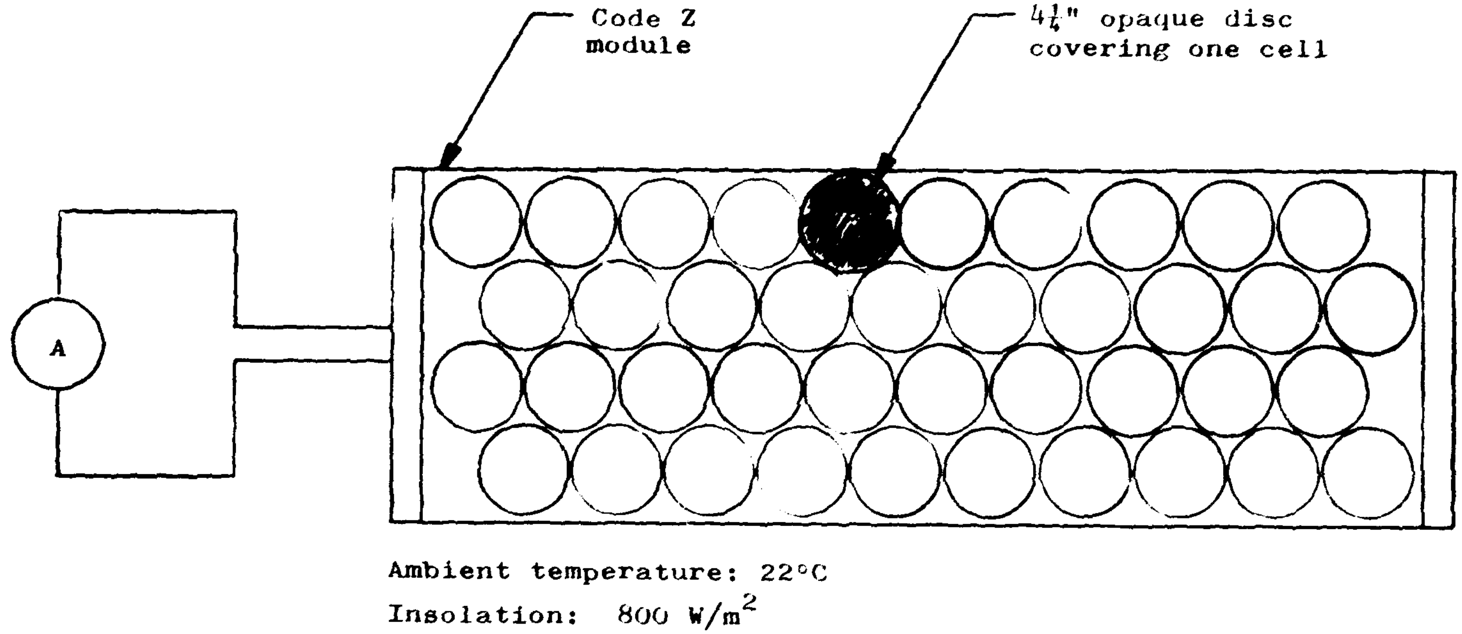


FIGURE 3-5. TEST SET-UP FOR
CELL BREAKDOWN TESTS

The Code Z modules are particularly prone to reverse biasing. The I-V characteristics for the two types of cells are different as seen in Figure 3-6. Vendor Z has attained a very sharp I-V curve with a consequent high cell efficiency. The penalty paid for this characteristic is the strong dependence of the voltage on the current at high currents. If one cell can't produce as much current as the other cells of the module, the remainder of the module may apply a significant reverse voltage to the limiting cell (through the load).

Tests at DECC verified what the curves predict: with the module operating into a normal load, a 20% deficiency in the current capability of one cell causes a significant (10-20 Vdc) reverse voltage across the cell and significant power dissipation in the cell. Operating into a short circuit, however, a current deficiency on only 10% will have the same effect.

Unfortunately, several real field conditions can result in 10-20% insolation variations between cells of a module. Single cells may become shadowed due to weed growth, and dirt distribution is not necessarily even. Condensed or precipitated water on the modules sometimes causes dirt to collect on the lower cells. Bird droppings are not evenly distributed.

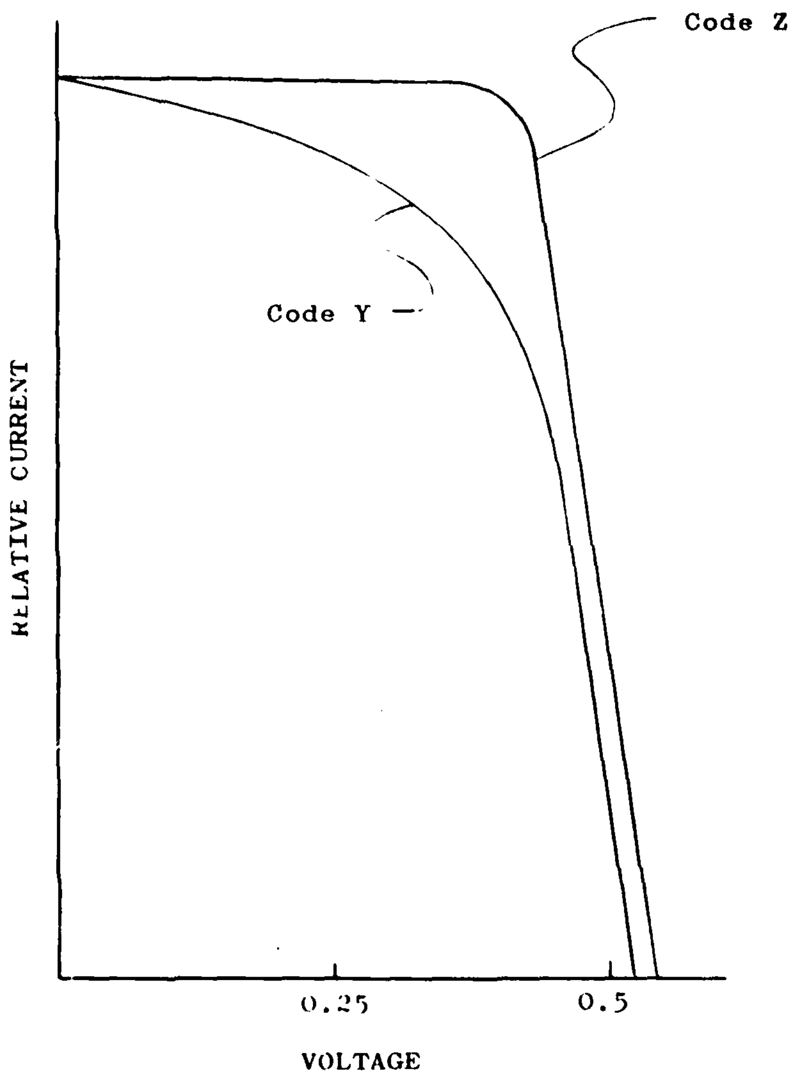


FIGURE 3-6. COMPARISON OF CURRENT-NORMALIZED I-V CURVES FOR SOLAR POWER AND SOLAREX PHOTOVOLTAIC CELLS

4.0 CONCLUSIONS AND RECOMMENDATIONS

With the exception of the problems with the Code Z photovoltaic modules, the operation of the 60 kW Solar Array and Power Conversion System has been more than satisfactory in every way. The array has produced power in excess of its rated output, and the power conversion system has operated within its design goals and without failure during months of testing at DECC and at Mt. Laguna. Much more information concerning long term system operation will become available as the system continues to operate at Mt. Laguna and data become available from the data acquisition system.

Even a system as totally successful as this one must be evaluated carefully at completion with an eye to possible improvements in future systems. Some of DECC's observations and conclusions on the Mt. Laguna system are discussed below along with some recommendations for future systems.

4.1 THE ARRAY STRUCTURE. The mounting frames for the PV modules were designed to support and protect the modules during winds of up to 120 knots. The frames were sized on the basis of series string size, the Code Y frames holding a complete string and the Code Z frames holding half a string. The PV modules could then be installed on the frames and the intra-string wiring performed indoors with the panels not exposed to sunlight. Although the assembled frames proved rather too large and heavy to be carried by two men, this sizing of frames proved especially convenient in this application where part of the array was installed at DECC, disassembled, and moved to Mt. Laguna. For systems to be installed in a more benign environment, some savings in weight and cost might be achieved by redesigning the frames. The frames were easy to construct using welding jigs developed for that purpose, and a complete Code Y frame could be assembled in approximately one hour by an experienced welder.

In future systems, the use of wood for the shear panels should be evaluated in terms of ease of installation and site environment. Mechanical alignment of the long rows of modules was difficult, and many mounting holes had to be redrilled. The use of adjustable U-channel mountings would ease the installation of large arrays. The ability of the wood panels to withstand the harsh Mt. Laguna environment should be evaluated after a few years of exposure.

4.2 ARRAY WIRING. In this system, approximately 1000 cable-mounted disconnect plugs were installed within the series strings to allow isolation of pairs of modules and reduction of the maximum daytime service-point voltage to 50 Vdc. The protection provided by these plugs is redundant. Servicing can be performed safely during periods of low insolation or with the panels covered by opaque covers supplied for that purpose. In future systems, the impact of these plugs on construction time, cost and reliability should be weighed carefully against the questionable contribution to safety.

Ideally, future PV modules should be fabricated with the reverse diode installed internally and all connections made through a connector molded into the unit. This would drastically reduce the time required to install large arrays and eliminate the need for additional disconnect plugs by eliminating any exposed terminals. At the very least, the junction box covers should snap into place, rather than be held in place by four screws. Using time estimates from MIL-HDBK-472, more than 169 man-hours were required just to remove and replace the covers of the junction boxes during wiring of this array. Location of a faulty reverse diode within a string could take as long as an hour because of the time required to gain access to the diodes in the junction boxes.

In the Mt. Laguna installation, the intra-string connecting wires were mounted to the module support frames with metal U-clips to reduce wind damage to the wires. In the design of future installations, some thought might be given to the provision of mounting holes or anchors for tie wraps or other cable mounts.

4.3 ROW TERMINAL BOXES. The row terminal boxes on the array provide a termination point for series string outputs and underground cables, and include surge suppressors for lightning protection. They also include test jacks for measuring the outputs of all strings in that row. Since the same information is available at the PMP, or at the string output connector mounted to the PV module frame, these terminals appear to be superfluous. Throughout installation, checkout and testing of the system no engineer or technician used these test jacks.

4.4 SOLAR POWER MODULES. There are two distinct problems to be addressed concerning the Solar Power modules: (1) how future module design might overcome the problems observed with these modules, and (2) what might be done to improve the operation and lifetime of existing modules.

The solution of the first problem is generally understood. Both dissipation mechanisms described above can be minimized by the addition of reverse diodes across subsets of cells of a module. The number of cells in a subset, "n", must be chosen such that (1) the peak power of n-1 cells can be dissipated by the nth cell without damage to the cell, and (2) the maximum voltage of n-1 series cells does not cause reverse breakdown in the nth cell.

From the construction of the Solar Power modules, it appears to be relatively easy to install two reverse diodes in the module, each diode across 20 of the cells. Installation of these diodes would reduce the maximum photocurrent dissipation in a cell by a factor of two, and eliminate breakdown in all but a small fraction of the cells. DECC estimates that the cost of installing these diodes would be approximately $30 per module. Some consideration might be given to installing four diodes, each across 10 cells. This modification would be more difficult and the cost would be more than twice the cost of installing 2 diodes. Further studies by JPL should determine whether it is necessary to reduce the maximum power by more than a factor of two, and whether installation of the diodes could be performed without adversely affecting the reliability of the module.

4.5 ARRAY SHORTING. The input contactor K1 of the power conversion system shorts the array whenever the power conversion unit is off. The purpose of this is twofold.

Firstly, with the power conversion system off and the array unshorted, the voltage at the unloaded array can be as high as 400 Vdc. Shorting the array removes the high voltage for the connected strings providing added protection for service personnel. Shorting could be particularly useful in the case of a ground fault due to personnel contact between high voltage and ground.

Secondly, the current through the shorting circuit breaker is monitored to detect the presence of sufficient solar power for start-up.

In view of the problems with the Solar Power modules, the wisdom of shorting PV arrays has been questioned. Although it would alleviate the problem somewhat, eliminating the shorting of the array will not solve the problem of the Solar Power modules. Occluded cells are being reverse biased whether the array is operating into a short or into the power conversion system. There are, however, other arguments for leaving the array open. The high current contactor required for shorting the array is generally quite expensive. It must be rated for interruption of the entire short circuit current. An insolometer or two redundant insolometers could be used to sense the presence of sufficient power for turn on. A shorting switch or connector could be provided to allow shorting of individual series strings or subarrays during servicing.

DECC does not recommend that the present Mt. Laguna system be modified to operate with an open array. In normal operation, the array will be shorted only when there is insufficient solar power available, and the stress on the PV cells is minimal. If the system is to remain off for extended periods of high insolation, the individual strings can be unshorted manually at the string select switches in the PMP. In the design of future systems, the tradeoff between cost and safety will have to be evaluated. Some of the factors affecting the decision will be the array voltage, array current, and PV cell characteristics.

4.6 THE PMP. Prior to the installation of the data acquisition system, the PMP was invaluable in identifying faulty or inoperative strings of PV modules. One improvement which might be made in future systems would be to replace the fixed loads with a variable load (static or dynamic) to allow plotting of the I-V curves of individual strings.

4.7 POWER CONVERSION UNIT. To allow mode 2 stand-alone operation as required by the purchase description, the power conversion unit had to include an input dc-dc power conversion stage to supply a regulated charge voltage to the battery. In the augmentation mode, though, the dc-dc converter is operated only to protect the power inverter from the high array voltages present at start-up. For future systems operating in the augmentation mode only, consideration should be given to redesigning the inverter using components capable of operating at the maximum array voltage. Improvements in cost, efficiency and simplicity would result from elimination of the dc-dc conversion stage.

4.8 GROUND-FAULT PROTECTION. Because of the ground current measurements made during tests at the temporary site at DECC (paragraph 3.4.2.8), the ground-fault detector does not initiate a shut-down and array-shorting sequence. Although the 50 mA protection threshold was frequently exceeded at the temporary installation, it will not necessarily be exceeded with the system properly installed at the permanent site, even during wet weather. DECC recommends that operating personnel at Mt. Laguna monitor the "ground fault" status lamp periodically during the coming wet season, when the soil around the underground cables is saturated with water. If the ground current does not exceed 50 mA during these operating conditions, the ground fault circuit should be modified. Addition of a single wire will change the control circuitry so that a ground fault indication initiates a shut-down, shorting the array and removing high voltage from the array.

4.9 OPERATION. To date the system has operated reliably without fault shutdowns. The power conversion system, however, is located in an unmanned building and service personnel must be dispatched periodically to verify that the system is operating. It is therefore possible that the system may remain off, with the array shorted, for some period of time.

When the system wiring was done, extra wires were strung through the conduit from the power conversion building to the manned, diesel power generating station. It is recommended that these wires be connected such that on/off status contacts in the power conversion unit are operative to drive a lamp or other indicator in the manned diesel power station. In this way, system shutdowns can be attended to promptly without unnecessary stress on the array or loss of solar power.

4.10 CONCLUSION. The 60 kW solar power array and power conversion system is the first of its type: designed to be a working component of a power generating station and to provide a significant portion of the station power. The primary design emphases were making the system stable, efficient, self-protected, self-sufficient, and automatic. Unlike previous research and development systems, the Mt. Laguna solar power plant was designed to operate completely unmanned over extended periods of time.

No major technical difficulties were encountered in the development of the system. The design of the control circuitry avoided the instabilities which have plagued so many photovoltaic systems. All observations to date support the belief that a dc-ac photovoltaic energy conversion system without on-site energy storage can effectively augment a utility grid, even in a remote location. Continuing long-term operation and observation of the system in the future will determine the system lifetime, maintenance requirements and the actual fuel savings resulting from system operation.

APPENDIX A

ACCEPTANCE TEST

ACCEPTANCE TEST PROCEDURE

FOR THE

MODEL 64211

SOLAR POWER CONVERSION SYSTEM

CONTRACT	**DELTA ELECTRONIC CONTROL CORP** IRVINE, CALIFORNIA, U S A DECC
DRAWN J. Suetzle	
CHECK	
MFG	
APPROVED	
APPROVED	SIZE	CODE IDENT NO 33434	DRAWING NO. 570-1007	REV LTR
APPROVED	SCALE	WT	SHEET

SHOP GRAPHICS/ACCUPRESS
ORDER NO A-0644

1.0 SCOPE

The purpose of this test procedure is to verify proper operation of the Photovoltaic Power Conversion System, DECC Model 61211, provided under U.S. Army MERADCOM Contract DAAK70-78-C-0018. The tests to be performed fall into three main categories: (1) tests of the inverter and PMP operation, (2) system tests at the DECC facility (with a partial array), and (3) field tests of the final installation.

2.0 APPLICABLE DOCUMENTS

MERADCOM Contract DAAK70-78-C-0018, Purchase Description

DECC Workmanship Standards Manual

3.0 TEST REQUIREMENTS

3.1 GENERAL. Unless otherwise noted, all tests are to be performed at ambient conditions. The test equipment in Table 1 shall be used. Substitution of equivalent equipment shall be allowed only when approved by the DECC QA manager, and all equipment substitution shall be noted on the data sheets. All test equipment shall have a sticker or tag showing the calibration date and the date the next calibration is due. No equipment shall be used beyond the date the calibration is due. Power sources and loads need not be calibrated if adequately monitored by calibrated equipme . Measurements are to be performed and the data recorded as indicated in Section 4.

3.2 INSPECTION. All equipment shall be inspected for conformance to drawing and to the DECC workmanship standards and shall be inspected for general appearance.

3.3 ISOLATION TEST OF THE INVERTER AND PMP. This test verifies that the inverter and PMP have the required electrical isolation. Disconnect the PMP and the inverter from any input power source or load. Disconnect the input return from the chassis (at ground fault detector). Short together the input power leads and measure the leakage current from the leads to the chassis at 200 Vdc. Reconnect the input return to the chassis. Short together the output leads and measure the current from the leads to the chassis at 1500 Vdc. Unshort the leads. Test the inverter (qualitatively) from a current-source array simulator and with utility interface to verify proper operation and stability.

...ACY, INVERTER AND PMP. Using 0.1% meters, ... meters monitored by each of the inverter and PMP meters (Table 2). Calculate the percentage deviation of each panel meter reading from the calibration source and record as indicated in Table 2. Meter locations are shown in Figure 1.

3.5 TESTS WITH PARTIAL ARRAY. These tests are to be performed at the DECC facility using a partial array (consisting of both types of PV panels) and the Southern California Edison Company utility grid. See Figure 2. The purpose of these tests is to verify proper and stable operation with a photovoltaic source and utility interface. Perform the measurements and record the data as indicated in Section 4 (Tables 3 and 4).

3.6 EXTENDED OPERATION. Following the formal tests at the DECC facility, operate the system from the array and into the utility until the permanent site is ready. Keep an operation log to note any unusual operating conditions or system malfunctions. Append the log to the test data as Table 5. Note primary array parameters under various weather conditions.

3.7 TESTS AT THE PERMANENT SITE. These tests verify proper installation and operation at the permanent site. The tests include verification of proper interconnection of the array and PMP, verification of stability with full power array and local grid, and check of protection circuitry. Perform the measurements and record the data as indicated in Section 4, Tables 6, 7, and 8.

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Date 4/27/78

By ____

QA ____

4.0 TEST PROCEDURES

4.1 INSPECTION. Inspect all equipment for conformance to drawing and DECC workmanship standards. Inspect for general appearance. Attach to this procedure a list of all non-conformances. If there are none, indicate so below.

No non-conformance ✓

4.2 ISOLATION TEST OF THE INVERTER AND PMP. Perform the procedure described in paragraph 3.3. Record the measured leakage currents below.

Leakage from input leads to chassis 0.3 mA

Leakage from output leads to chassis 0.1 mA

4.3 METER ACCURACY, INVERTER AND PMP. Verify the accuracy of the inverter and PMP panel meters as described in paragraph 3.4. Record data in Table 2.

4.4 TESTS WITH A PARTIAL ARRAY.

Note: Except where noted, measurements are to be made with the inverter in the AUTO mode.

4.4.1 Standby Power and Current. Connect the system in the normal fashion with the partial array and the local grid. Place all string switches on the PMP in the center (off) position. With external meters, measure the input current and the input power from the utility grid with the system off. Record the measurements in Table 3.

4.4.2 Start-Up. On a sunny day, switch the string switches to the LINE position one at a time. Each switch action should result in an increase in the input current (M2). The inverter will eventually start up. Record the input current (M2) just prior to start-up. After start-up, record the input power (M3) and the output power (M17). Calculate the power loss in the system (M3-M17).

4.4.3 Operation. Perform the measurements indicated in Table 3 and record the results in Table 3.

4.4.4 Fault Protection and Automatic Shut-Down. Test the fault protection and shut-down features and verify operation as indicated in Table 4. List any failures or unusual operations or conditions in the comments column.

4.5 TESTS AFTER FINAL INSTALLATION.

Note: Except where noted, measurements are to be made with the inverter in the AUTO mode.

4.5.1 Start-Up. On a sunny day, switch the string switches to the LINE position one at a time. Verify that each switch action results in an increase in the input current (M2). Verify that the inverter starts up at approximately 35 amps input current.

4.5.2 Operation. Perform the measurements indicated in Table 6 and record the data in Table 6.

4.5.3 Fault Protection and Automatic Shut-Down. Test fault protection and shut-down features and verify operation as indicated in Table 7. Perform interlock test by opening and closing the remote circuit breaker. List any failures or unusual conditions in the comments column.

4.5.4 Comparison of Solar Cell String Outputs. This test is to be performed under conditions of stable insolation. If possible it should be performed under conditions of maximum insolation (between 11 A.M. and 1 P.M. Pacific Standard Time on a clear sunny day.) Select one Solar Power string and one Solarex string to serve as a reference. Operate the system in the normal manner from the full array and into the utility net. Using the outputs to the data acquisition system, measure the output current from each string compared to the reference string. Record the current of both and the ratio of the measured string current to the reference string current.

4.5.5 Outputs to Data Acquisition System. The presence of string current outputs has been verified. Check calibration of analog outputs and presence of proper digital outputs as indicated in Table 8.

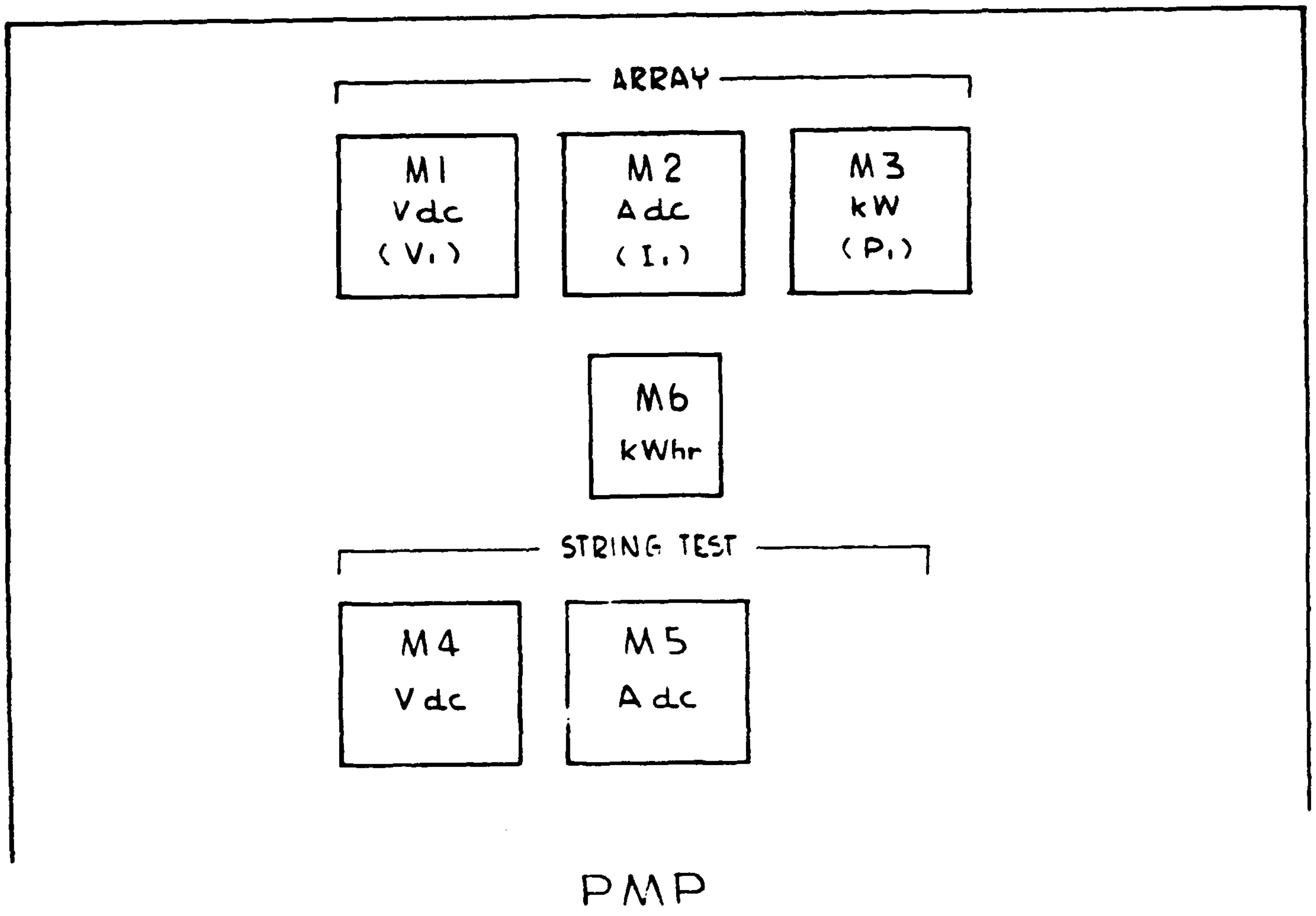

FIGURE 1a. METERS

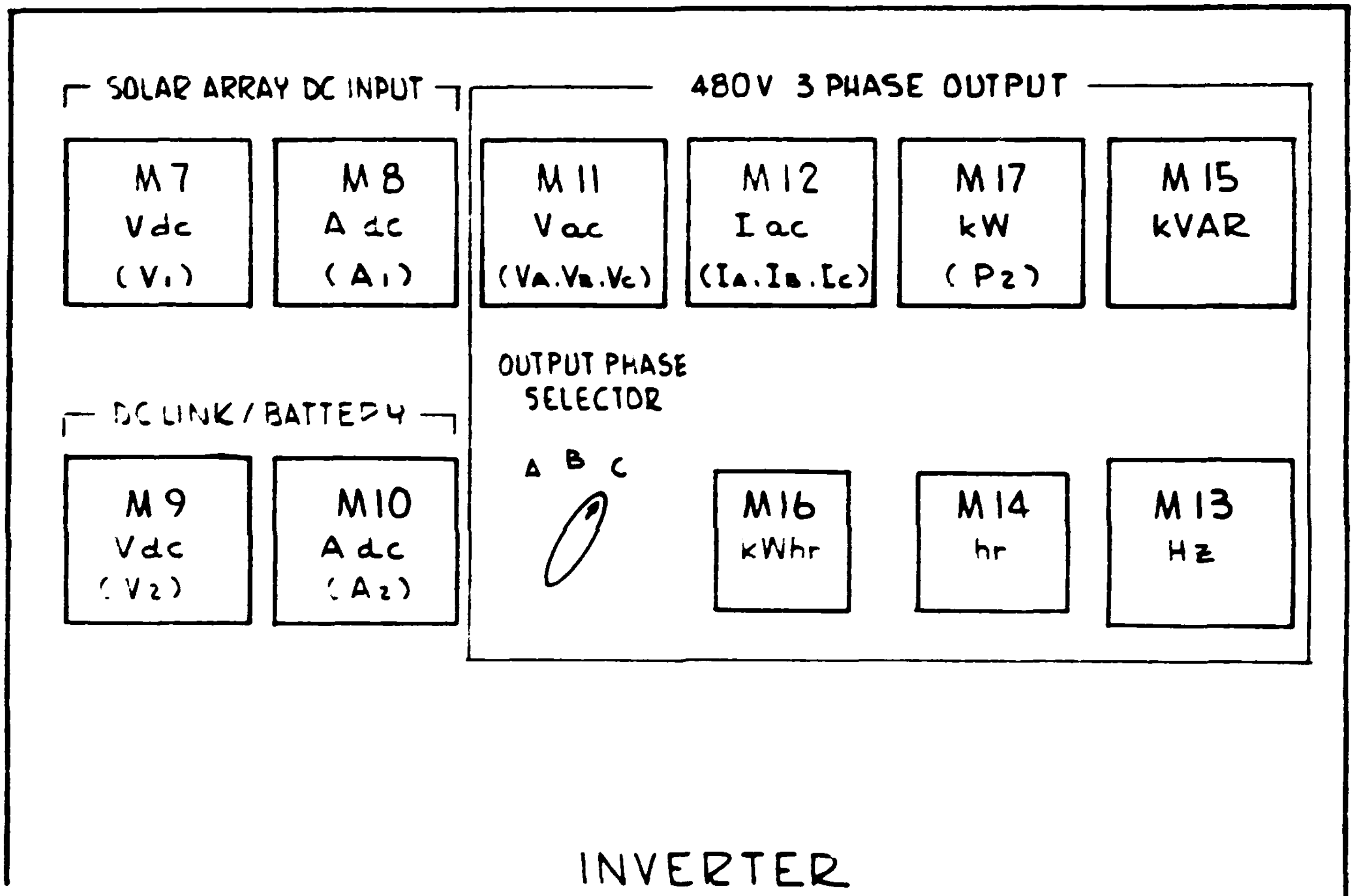

FIGURE 1b. METERS

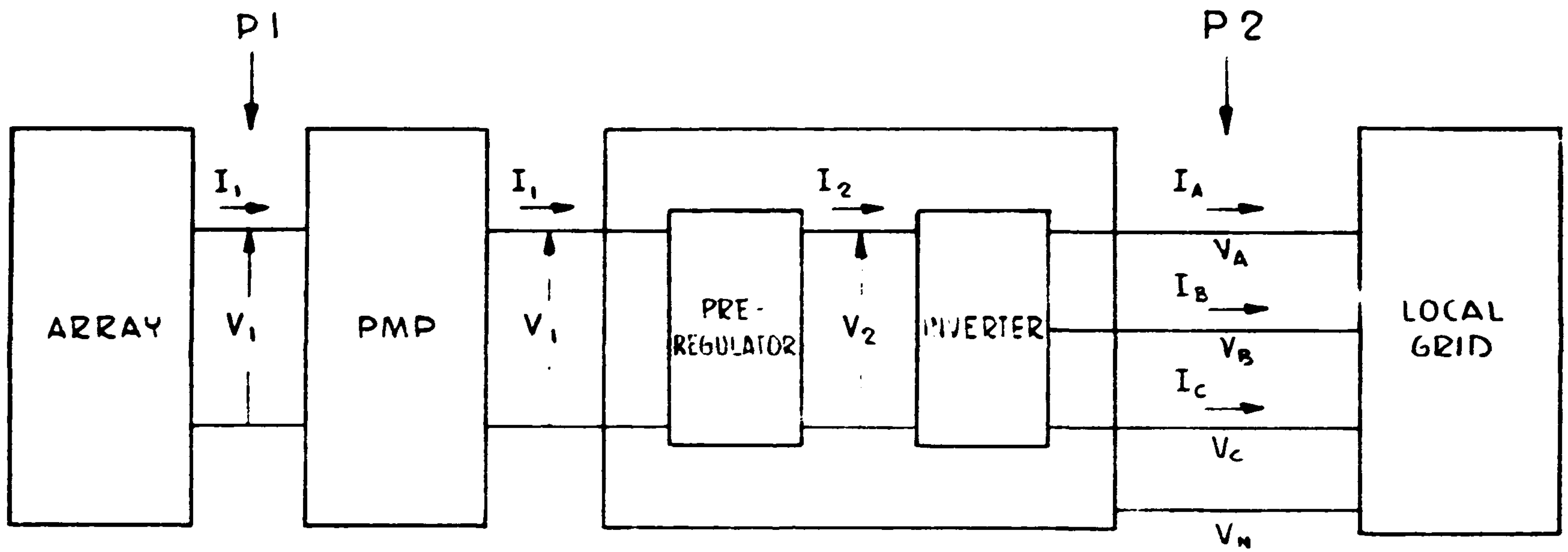

FIGURE 2. TEST SET UP

Table 1. Test Equipment

DC Insulation Tester	DECC Model 61107
Digital multimeter	Dana 4200 or equivalent
Distortion analyzer	HP 331A or equivalent
Oscilloscope	Tektronix 543B or equivalent
Oscilloscope camera	Tektronix C-12
Power meter	Scientific Columbus DL-A2-6096 or equivalent
Stopwatch	Accurate to 0.5%

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TABLE 2. METERS

	LABEL	FUNCTION	LOCATION	SCALE	FULL-SCALE ACCURACY	HALF-SCALE ACCURACY
						% full scale
M1	ARRAY VOLTAGE	Array output voltage (dc)	PMP	0-500V	≈ 0.5%	- - -
M2	ARRAY CURRENT	Array output current (dc)	PMP	0-300A	≈ 0.5%	< 0.5%
M3	ARRAY POWER	Array output power	PMP	0-100 kW	0.8% calibrated	< 0.5%
M4	STRING TEST VOLTAGE	Individual string output voltage (dc)	PMP	0-500V	0.5%	- - -
M5	STRING TEST CURRENT	Individual string output current (dc)	PMP	0-3A	- - -	- - -
M6	KWH	Array output power	PMP	0- 99,999kWhr	Verified ✓	- - -
M7	SOLAR ARRAY DC INPUT D-C VOLTS	Array output voltage (dc)	Inverter	0-500V	≈ 0.5%	- - -
M8	SOLAR ARRAY DC INPUT D-C AMPERES	Array output current (dc)	Inverter	0-300A	< 1%	< 0.5%
M9	DC LINK/BATTERY VOLTAGE	DC link voltage	Inverter	0-300V	< 1%	- - -
M10	DC LINK/BATTERY CURRENT	DC link current	Inverter	500-0-500A	- - -	- - -
M11	480 PHASE OUTPUT A-C VOLTS	Inverter output voltage (line to neutral)	Inverter	0-300V	< 1%	- - -

Note: Tests were actually performed after installation at Mt. Laguna

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TABLE 2 (cont'd)

	LABEL	FUNCTION	LOCATION	SCALE	FULL-SCALE ACCURACY	HALF-SCALE ACCURACY
M12	480 3 PHASE OUTPUT A-C AMPERES	Inverter output current (1 phase)	Inverter	0-150A	- - -	- - -
M13	HERTZ	Inverter output frequency	Inverter	55-65 Hz	< 0.2 Hz	- - -
M14	480 3 PHASE OUT-PUT ELAPSED TIME	Elapsed Time	Inverter	0-99,999 hr	No observable deviation	- - -
M15	480 3 PHASE OUTPUT KVAR	Inverter output VAR	Inverter	100-0-100	< 1% calibrated	- - -
M16	480 3 PHASE KWH	Inverter output kWH	Inverter	99,999 kWhr	Verified	- - -
M17	480 3 PHASE OUT-PUT KILOWATTS	Inverter output kW	Inverter	10-0-100	< 1%	- - -
						Zero point No observable deviation

Note: Tests were actually performed after installation at Mt. Laguna

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Date 5/1/79

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Table 3. Test Data

Describe environmental conditions at the time of test, including approximate ambient temperature of the array.

Sunny, some haze, 70°F, 13:00 PDT

Test Para.	Test Description	Parameter	Meter	Units	Nom. or set value	Meas. value	Limits	Comments
4.4.1	STAND-BY							
	Standby current	I_A	---	Aac	---	3.2	---	Primarily reactive
	Standby power	P2	---	W	---	65	---	
4.4.2	START-UP							
	Start-up current	I1	M2	Adc	35	35	---	
	Input power	P1	M3	kW	---	7	---	
	Output power (auto mode)	P2	M17	kW	---	4.5	---	
	Power loss (P1-P2)	---	Calc.	kW	---	2.5	---	
	Number of Solarex strings	---	---	---	---	14	---	
	Number of Solar Power strings	---	---	---	---	53	---	
	Total harmonic distortion, output current I_A	---	---	%	---	---	---	

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DESIGN, CONSTRUCTION AND TESTING OF A 60 KW SOLAR ARRAY AND POW--ETC(U)
AUG 79   J S SUELZLE   DAAK70-78-C-0018
UNCLASSIFIED   DECC-61211-003   NL

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Table 3. Test Data (cont'd)

Describe environmental conditions at the time of test, including approximate ambient temperature of the array.

Sunny, some haze, 70°F, 13:00 PDT

Test Para.	Test Description	Para-meter	Meter	Units	Nom. or set value	Meas. value	Limits	Comments
4.4.3	OPERATION							
	Switch remainder of strings on line	V1	M1	Vdc	---	248	---	
		I1	M2	Idc	---	110	---	
		P1	M3	kW	---	27.5	---	
		P2	M17	kW	---	24.5	---	
		VAR	M15	kVAR	---	-0.7	---	
		V_A	M11	Vac	277	280	---	
		I_A	M12	Aac	---	29	---	
	Efficiency= $\frac{P2}{P1}$ x 100	Eff.	---	%	---	89.4	---	
	Switch to manual mode, maximize P2	P2	17	kW	---	→	P2 auto + 1 (max)	No visible improvement possible

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TABLE 4. Fault Protection Circuitry Test

FAULT	TEST METHOD	CHECK OR DATA	ERROR RECYCLE LAMP	ERROR SHUTDOWN LAMP	COMMENTS
Insufficient Solar Power	Switch Strings off line	✓	---	---	
DC Overvolts	Simulate @ logic level	✓	---	✓	
Output Undervoltage	Simulate @ logic level	✓	---	✓	
Frequency Error	Disable interlock loop, remove ac power (record trip frequency)	±2 Hz	✓	---	
Synchronization Error	Offset output voltage adjustment	✓	✓	---	
Net Voltage Error	Simulate @ logic level	✓	✓	---	
Output Fuse Open	Actuate fuse detector	✓	---	✓	
Inverter Fuse Open	Open one fuse	✓	---	✓	
Excessive Reverse Power	Simulate @ logic level	✓	---	✓	
Output Overcurrent	Simulate @ logic level	✓	✓	---	
Overtemp	Heat thermal sensor	✓	---	✓	
Logic Power Error	Simulate @ logic level	✓	---	✓	
Blower Failure	On monentarily @ turn-on	✓	---	---	
Ground Fault	Apply fault current (record trip level)	50 mA	---	Not set to shut down	
Interlock	Open interlock chain	✓	---	---	

Date__________

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TABLE 5. OPERATION LOG

DATE	TIME ON	START kWhr IN	START kWhr OUT	START ELAPS. HR	PEAK POWER (NOON)--kW	TIME OFF	COMMENTS AND WEATHER CONDITIONS
See insert, next page							

INSERT

Data for Model 61211 Solar Power Conversion System

SN 001

The data log for system operation at the DECC facility was lost during the move of the system from DECC to Mt. Laguna. The following summary data are available:

Total input kWH at DECC	6218
Total output kWH at DECC	4861
Total running time at DECC	413.6 H

The system was operated for 43 days, not including down-time due to flooding of the temporary wiring from the array to the PMP.

More extensive data will be available from Sandia when Data Acquisition System output data are reduced.

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Date 7/19/79

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Table 6. Test Data

Describe environmental conditions at the time of test, including approximate ambient temperature of the array.

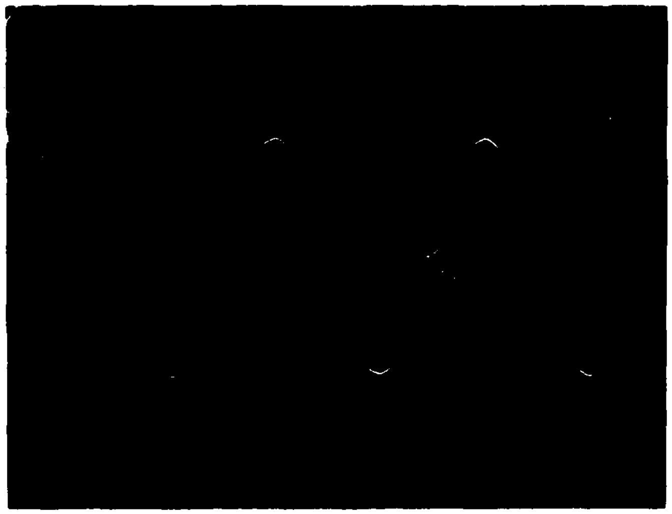
Partially cloudy, with rapidly varying insolation; 80°F, 10:00 PDT

Test Para.	Test Description	Parameter	Meter	Units	Nom. or set value	Meas. value	Limits	Comments
4.5.1	START-UP							
	Start-up current	I1	M2	Adc	35	35	---	
	Input power	P1	M?	kw	---	8	---	
	Output power (auto mode)	P2	M17	kw	---	6.5	---	
	Power loss (P1-P2)	---	Calc.	kw	---	2.5	---	
	Number of Solarex strings	---	---	---	54	54	---	# of strings available
	Number of Solar Power strings	---	---	---	115	115	---	# of strings available

Attach oscillogram of V_A prior to start-up

SN 001
Date 7/19/79
By
QA

Utility Net Without Solar Input



SCALE
V/cm 200
Sec/cm 5 ms

V_A

001
Date 7/19/79
By ____
QA ____

Table 6. Test Data (cont'd)

Describe environmental conditions at the time of test, including approximate ambient temperature of the array.

Overcast, 65°F, 15:00 PDT

Test Para.	Test Description	Para-meter	Meter	Units	Nom. or set value	Meas. value	Limits	Comments
4.5.2	OPERATION							
	Switch strings to LINE position to set P2 to approximately 10 kW	V1	M1	Vdc	---	250	---	
		I1	M2	Idc	---	60	---	
		P1	M3	kW	---	16	---	
		P2	M17	kW	10	14	---	
		VAR	M15	kVAR	---	0	---	
		V_A	M11	Vac	277	280	---	
		I_A	M12	Aac	---	16.5	---	
	Efficiency= $\frac{P2}{P1} \times 100$	Eff.	---	%	---	87.5	---	
	Switch to manual mode, maximize P2	P2	M17	kW	---	14	P2 auto + 1% (max)	No visible improvement possible

001
Date 7/19/79
By________
QA________

Table 6. Test Data (cont'd)

Describe environmental conditions at the time of test, including approximate ambient temperature of the array.

Overcast, 65°F, 15:00 PDT

Test Para.	Test Description	Para-meter	Meter	Units	Nom. or set value	Meas. value	Limits	Comments
4.3.2	OPERATION							
	Switch strings to LINE position to set P2 to approximately 30 kW	V1	M1	Vdc	---	258	---	
		I1	M2	Idc	---	160	---	
		P1	M3	kW	---	41	---	
		P2	M[illegible]	kW	30	37	---	
		VAR	M[illegible]	kVAR	---	0	---	
		V_A	M[illegible]	Vac	[illegible]	279	---	
		I_A	[illegible]	Iac	---	44	---	
	Efficiency= $\frac{P2}{P1}$ x 100	Eff.	---	%	---	90	---	
	Switch to manual mode, maximize P2	P2	M[illegible]	kW	---	37	P2 auto + [illegible] (max)	No visible improvement possible
	[illegible] output current I.	---	---		---	2.6%	---	

Attach oscillograms of V_A and I_A.

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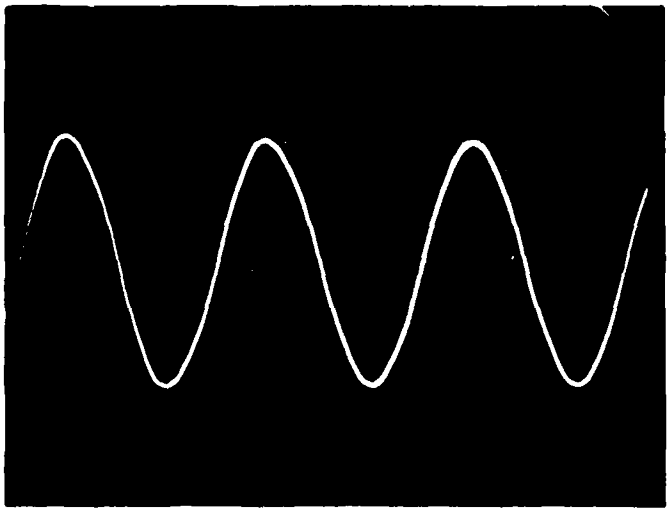
Output Power 37 kW

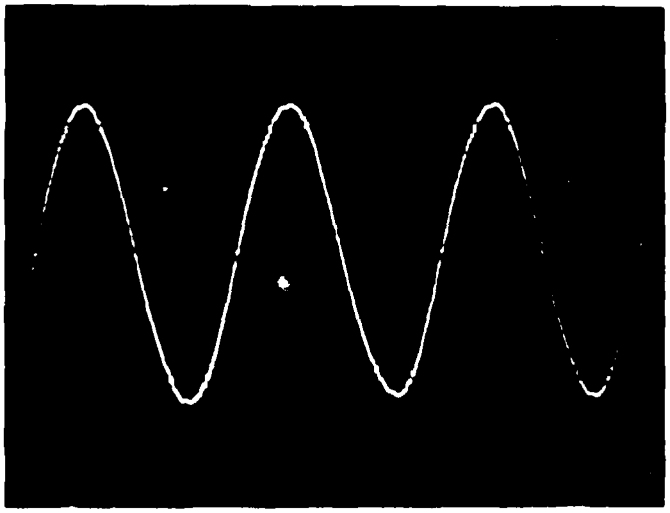


SCALE

V/cm 200 V

Sec/cm 5 mS

V_A



SCALE

I/cm 20

Sec/cm 5 mS

I_A

Comments:

001

Date 7/19/79

By

QA

Table 6. Test Data (cont'd)

Describe environmental conditions at the time of test, including approximate ambient temperature of the array.

Overcast, 65°F, 15:30 PDT

Test Para.	Test Description	Parameter	Meter	Units	Nom. or set value	Meas. value	Limits	Comments
4.5.2	OPERATION							
	Switch strings to LINE position to set P2 to approximately 45 kW	V1	M1	Vdc	---	245	---	
		I1	M2	Idc	---	186	---	
		P1	M2	kW	---	45.5	---	
		P2	M7	kW	45	42.0	---	
		VAR	M15	kVAR	---	0	---	
		V_A	M11	Vac	277	279	---	
		I_A	M[illegible]	Aac	---	50	---	
	Efficiency= $\frac{P2}{P1}$ x 100	Eff.	---	%	---	92	---	
	Switch to manual mode, maximize P2	P2	M7	[illegible]	---	42.0	P2 auto + [illegible]	No visible improvement possible

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By ________

QA ________

Table 6. Test Data (cont'd)

Describe environmental conditions at the time of test, including approximate ambient temperature of the array.

Overcast, 65°F, 11:30 PDT

Test Para.	Test Description	Para-meter	Meter	Units	Nom. or Set Value	Meas. Value	Limits	Comments
4.5.2	OPERATION							
	Switch remainder of strings on line	V1	M1	Vdc	---	210	---	
		I1	M2	Idc	---	240	---	
		P1	[illegible]	kW	---	50	---	
		P2	[illegible]	kW		46	---	
		VAR	M15	KVAR	---	0	---	
		V_A	M11	Vac	277	279	---	
		I_A	M12	Aac	---	55	---	
	Efficiency= $\frac{P2}{P1}$ x 100	Eff.	---	%	---	92	---	
	Switch to manual mode, maximize P2	P2	M17	kW	---	46	P2 auto - [illegible] max)	No visible improvement possible
	Total harmonic distortion, output current I_A	---	---	%	---	2.6	---	

Attach oscillograms of V_A and I_A

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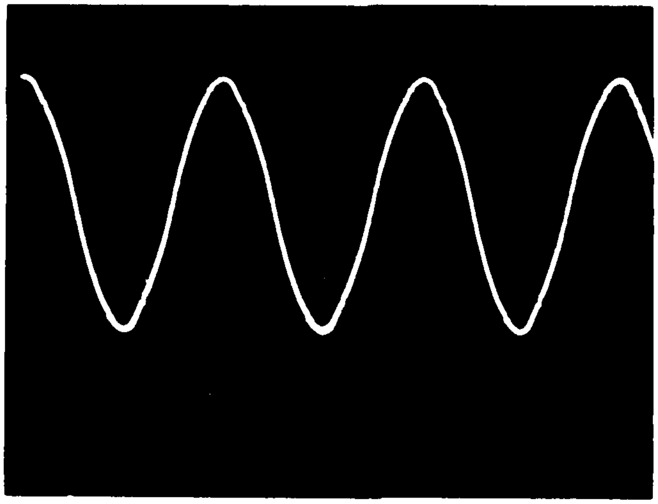
Date 7 19 79

By

A

Output Power [illegible] kW

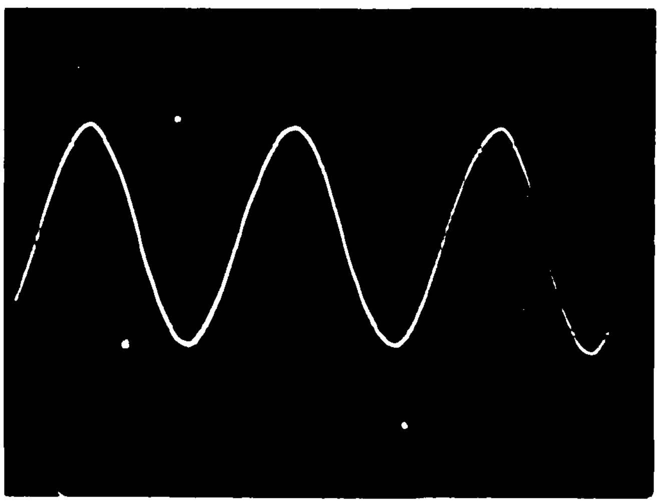


SCALE

V/cm 200 V

sec/cm 5 ms

V_A



SCALE

I/cm 40 A

sec/cm 5 ms

I_A

Comments:

001

Date 7/20/79

By

QA

TABLE 7. Fault Protection Circuitry Test

FAULT	TEST METHOD	CHECK OR DATA	ERROR RECYCLE LAMP	ERROR SHUTDOWN LAMP	COMMENTS
Insufficient Solar Power	Switch Strings off line	✓	---	---	
DC Overvolts	Simulate @ logic level	✓	---	✓	
Output Undervoltage	Simulate @ logic level	✓	---	✓	
Frequency Error	Disable interlock loop, remove ac power (record trip frequency)	±2 Hz	✓	---	
Synchronization Error	Offset output voltage adjustment	✓	✓	---	
Net Voltage Error	Simulate @ logic level	✓	✓	---	
Output Fuse Open	Actuate fuse detector	✓	---	✓	
Inverter Fuse Open	Open one fuse	✓	---	✓	
Excessive Reverse Power	Simulate @ logic level	✓	---	✓	
Output Overcurrent	Simulate @ logic level	✓	✓	---	
Overtemp	Hea thermal sensor	✓	---	✓	
Logic Power Error	Simulate @ logic level	✓	---	✓	
Blower Failure	On momentarily @ turn-on	✓	---	---	
Ground Fault	Apply fault current (record trip level)	51 mA	---	Not set to shut down	
Interlock	Open interlock chain	✓	---	---	

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Data taken using Data Acquisition System

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QA

Table 8. Comparison of String Output

Solar Power Reference String Number 40

Sky clear, ambient temperature 80-90°F

String No.	String Output	Refer. String Output	Ratio	String No.	String Output	Refer. String Output	Ratio
1	1.91	1.82	1.05	24	1.58	1.82	.87
2	1.90		1.04	25	1.82		1.00
3	1.62		.89	26	1.57		.86
4	1.90		1.04	27	1.45		.80
5	1.83		1.00	28	1.86		1.02
6	1.84		1.01	29	1.68		.92
7	1.61		.88	30	1.42		.78
8	1.55		.85	31	1.52		.84
9	1.62		.89	32	1.58		.87
10	1.62		.89	33	1.31		.72
11	1.83		1.00	34	1.54		.85
12	1.51		.83	35	1.58		.87
13	1.65		.91	36	1.76		.97
14	1.65		.91	37	1.62		.89
15	1.65		.91	38	1.77		.97
16	1.86		1.02	39	1.36		.75
17	1.92		1.05	40	1.82		1.00
18	1.92		1.05	41	1.68		.92
19	1.91		1.05	42	1.70		.93
20	1.96		1.08	43	1.77		.97
21	1.89		1.04	44	1.65		.91
22	1.89		1.04	45	1.80		.99
23	1.80		.99	46	1.85		1.02

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By

QA

Table 8. Comparison of String Outputs (cont'd)

Solar Power Reference String Number 40

String No.	String Output	Refer. String Output	Ratio	String No.	String Output	Refer. String Output	Ratio
47	1.74	1.82	.96	70	1.84	1.82	1.01
48	1.79	↓	.98	71	1.67	↓	.92
49	1.84		1.01	72	1.57		.86
50	1.82		1.00	73	1.76		.97
51	1.74		.96	74	1.65		.91
52	1.82		1.00	75	1.42		.78
53	1.53		.84	76	1.63		.90
54	1.63		.90	77	1.43		.79
55	1.54		.85	78	1.76		.97
56	1.74		.96	79	1.60		.88
57	1.49		.82	80	1.69		.93
58	1.64		.90	81	1.61		.88
59	1.80		.99	82	1.76		.97
60	1.85		1.02	83	1.73		.95
61	1.63		.90	84	1.79		.98
62	1.32		.73	85	1.65		.91
63	1.20		.66	86	1.60		.88
64	1.84		1.01	87	1.72		.94
65	1.78		.98	88	1.68		.92
66	1.66		.91	89	1.69		.93
67	1.63		.90	90	1.71		.94
68	1.82		1.00	91	1.80		.99
69	1.49	↓	.82	92	1.84	↓	1.01

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QA

Table 8. Comparison of String Outputs (cont'd)

Solar Power Reference String Number 40

String No.	String Output	Refer. String Output	Ratio
93	1.76	1.82	.97
94	1.82		1.00
95	1.78		.98
96	1.79		.98
97	1.78		.98
98	1.93		1.06
99	1.87		1.03
100	1.91		1.05
101	2.03		1.12
102	2.07		1.14
103	1.83		1.00
104	1.87		1.03
105	1.69		.93
106	1.90		1.04
107	1.52		.84
108	1.46		.80
109	1.12		.62
110	1.39		.76
111	1.20		.66
112	1.73		.95
113	1.43		.79
114	1.65		.91
115	1.64		.90

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QA

Table 8. Comparison of String Outputs (cont'd)

Solarex Reference String Number 136

String No.	String Output	Refer. String Output	Ratio	String No.	String Output	Refer. String Output	Ratio
116	1.09	1.00	1.09	139	.76	1.0	.76
117	.91	↓	.91	140	.97	↓	.97
118	1.09		1.09	141	1.10		1.10
119	.83		.83	142	1.05		1.05
120	1.06		1.06	143	1.02		1.02
121	.97		.97	144	1.04		1.04
122	1.06		1.06	145	.98		.98
123	.96		.96	146	1.02		1.02
124	.85		.85	147	1.01		1.01
125	.95		.95	148	1.06		1.06
126	1.06		1.06	149	.95		.95
127	1.03		1.03	150	.96		.96
128	1.11		1.11	151	1.04		1.04
129	1.10		1.10	152	1.01		1.01
130	1.09		1.09	153	.96		.96
131	1.01		1.01	154	.99		.99
132	1.09		1.09	155	.81		.81
133	1.06		1.06	156	1.02		1.02
134	1.01		1.01	157	.86		.86
135	1.03		1.03	158	1.03		1.03
136	1.00		1.00	159	.96		.96
137	1.01		1.01	160	1.06		1.06
138	.98	↓	.98	161	1.02	↓	1.02

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Table 8. Comparison of String Outputs (cont'd)

Solarex Reference String Number 136

String No.	String Output	Refer. String Output	Ratio
162	1.01	1.00	1.01
163	1.05		1.05
164	1.01		1.01
165	1.05		1.05
166	1.01		1.01
167	.99		.99
168	1.10		1.10
169	1.04		1.04

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QA

Table 8. Outputs to Data Acquisition System

Analog

	Meas'd Value	Input to D.A.S.	% Calib.
Input voltage	Meters compared to actual Data Acquisition System printout		< 1%
Input current			< 1%
Input power			< 1%
Output power			< 1%

BCD

	Verified
Input KWH meter	✓
Output KWH meter	✓

Status (Digital)

	Verified
Off	✓
Off--Insufficient Solar Power	✓
Off--Shut Down	✓
Off--Error Recycle	✓

APPENDIX B

EMI TESTS ON COMPARABLE POWER CONVERSION EQUIPMENT

28 JAN 1975

QUALIFICATION TEST REPORT

ELECTROMAGNETIC INTERFERENCE TESTS

ON

UNINTERRUPTABLE POWER SUPPLY SYSTEM

Prepared For:

STATIC POWER INC.
3800 Campus Boulevard
Newport Beach, California

by

HOPKINS ENGINEERING COMPANY
12900 Foothill Boulevard
San Fernando, Calif. 91342

Prepared by: John J. Walls
EMI Specialist

Verified by: Martin J. Nemiroff
Vice President-Operations
Hopkins Engineering Company

Approved: Ronald N. Zachello
Vice President-Quality Control

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REPORT SUMMARY

PURPOSE: Electromagnetic interference tests were performed on the Uninterruptable Power Supply (UPS) to verify that the UPS system provides adequate compliance with the applicable electromagnetic compatibility control requirements.

TEST ITEMS:	Uninterruptable Power Supply 62.5 KVA
MANUFACTURED BY:	Static Power Inc. Newport Beach, California
SPECIFICATION:	MIL-STD-461A/462 Notice 3
TEST PERFORMED BY:	HOPKINS ENGINEERING COMPANY San Fernando, California 91342
TEST PERFORMED AT:	STATIC POWER Newport Beach, California
AUTHORIZED BY:	STI Purchase Order #4864 dated 12-11-74
TEST COMPLETION:	12-18-74
SECURITY CLASSIFICATION:	Unclassified
SUMMARY OF RESULTS:	The Uninterruptable Power Supply was found to be in compliance with all applicable electromagnetic control requirements when tested in accordance with MIL-SLD-461A Notice 3, Para. C E 0 2, R E 0 2 & R E 0 4.

QUALIFICATION TEST REPORT

1.0 SCOPE

This report presents the results of the electromagnetic interference test performed on the UPS 62.5KW manufactured by SPI, Newport Beach, California, and compares these results with the applicable requirements of the specification.

2.0 APPLICABLE DOCUMENTS

Military Standards

MIL-STD-461A Notice 3	Electromagnetic Interference Characteristics, requirements for Equipment.
MIL-STD-462 Notice 3	Electromagnetic Interference Characteristics, Measurement of.

APPROVED TEST PROCEDURE

Prior to conducting the Radiated Emissions Test the perifery of the system was probed to determine the position of maximum radiation according to approved test procedure of MIL/STD-462. The antennaes were then positioned as specified and all radiated measurement taken at this location. Conducted measurements were made using a current probe on input and output power 3 phases and neutral.

3.0 GENERAL

3.1 TEST SAMPLE IDENTIFICATION

The test sample system consisted of one console and applicable load.

3.2 SUMMARY OF TEST METHODS PERFORMED

The test sample system was subjected to the following applicable test methods of MIL/STD-461A/462 Notice 3.

METHOD	TYPE OF TEST	Freq. Range
CE02	Conducted Emissions, Power Lines (Input & output)	14KHz-50MHz
RE02	Radiated Emissions, E Field	14KHz-1000MHz
RE04	Radiated Emissions, H Field	20Hz - 50KHz

3.3 TEST DATES

These tests were started on 12/18/74 and completed on 12/18/74.

4.0 TEST PROCEDURES

4.1 TEST SITE

The test program was conducted at S.T.I. facility at 3800 Campus Boulevard, Newport Beach, California. Since the test sample could not feasibly be housed in a shielded enclosure, radiated tests were run after 11:00 PM because of day time Hi Ambient fields. Conducted tests were run after factory shut down.

4.2 OPERATIONAL PROCEDURES

All test sequences were performed with the UPS operating load, 50 KVA.

4.3 TEST INSTRUMENTATION

The test instruments used during this test program are listed in Appendix A along with their applicable model numbers, serial numbers and calibration dates.

5.0 TEST RESULTS

5.1 CE02 Conducted Emissions, Phase A.B.C. & Neutral input and output 14KHz-50MHz.

5.1.1 Broadband emissions on both input & output all phase were within specification limits.
(See Graphs Fig. #1 thro 8)
There were no measureable Narrowband Emissions.

5.2 RE02 RADIATED EMISSIONS, E-FIELD (14KHz-1000MHz)

Broadband radiatad emission were within specification limits all frequencies. (See Graphs Fig. 9)
There were no measureable Narrowband Emissions.

5.3 RE04 RADIATED EMISSIONS, H-FIELD (20Hz - 50KHz)

There was no measureable H-Field emission.

6.0 CONCLUSIONS

When tested in accordance with MIL-STD-462 the Uninterruptible Power Supply conplied with all applicable Class 1 C requirements of MIL-STD-461A Notice 3 Test Method CE02, RE02 and RE04.

APPENDIX A

TEST EQUIPMENT

The following primary meters were used during this test program:

RECEIVERS/METERS

Noise and Field Intensity Meter, Singer/Empire Model NF105 S/N 2083
Calibration date 2-5-75. Stoddart N M 40 S/N 1
Calibration date 5-17-75.

CURRENT PROBE

Stoddart Radio No. - 91550-1 S/n BF231

ANTENNAES

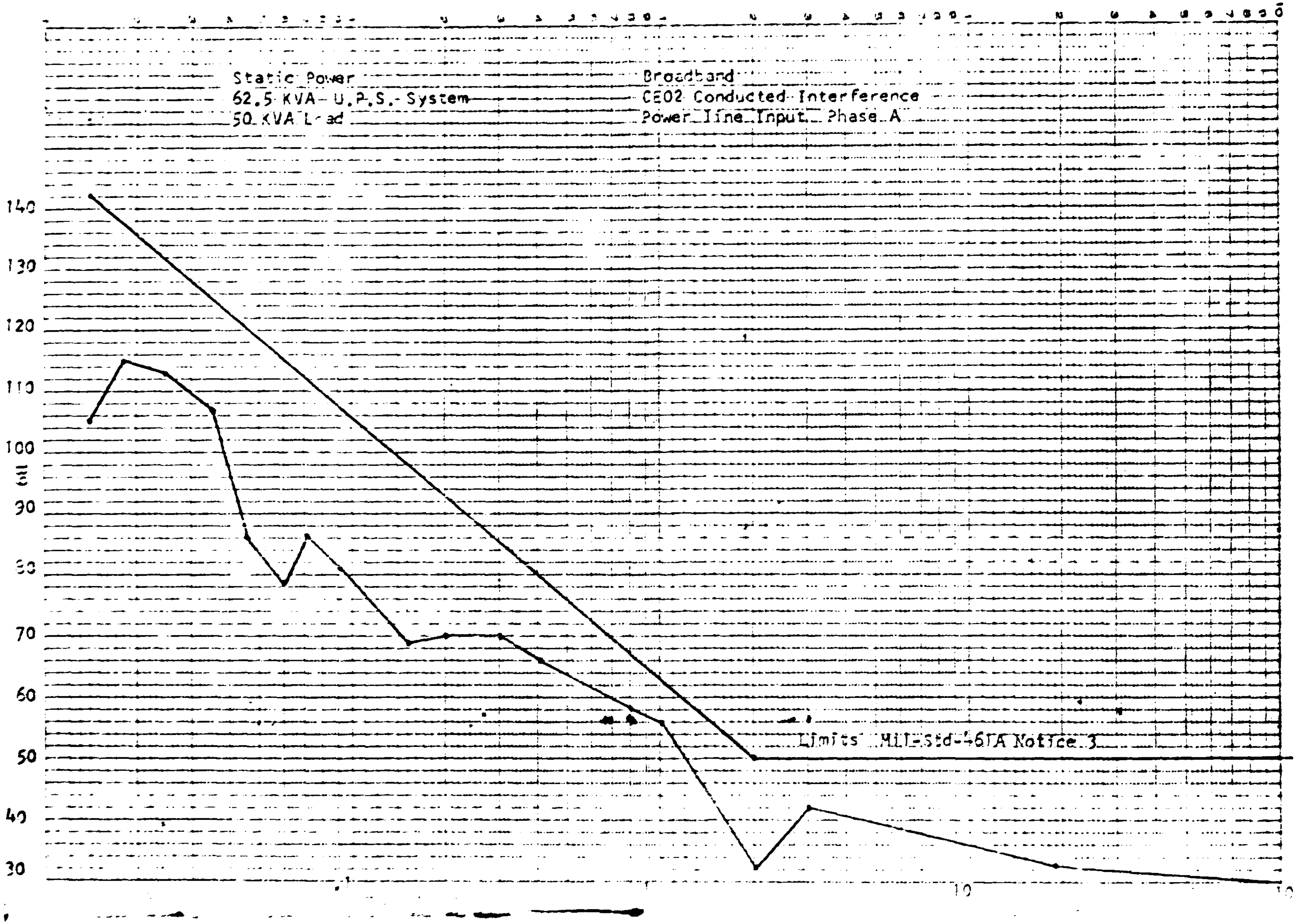
Singer/Empire . VX - 105

Singer/Empire VA - 105

Honeywell Bi Conical Model 7825

Electro Magnetics Conical Log Spiral Model CLP-1A

Loop Antenna Model 90114-3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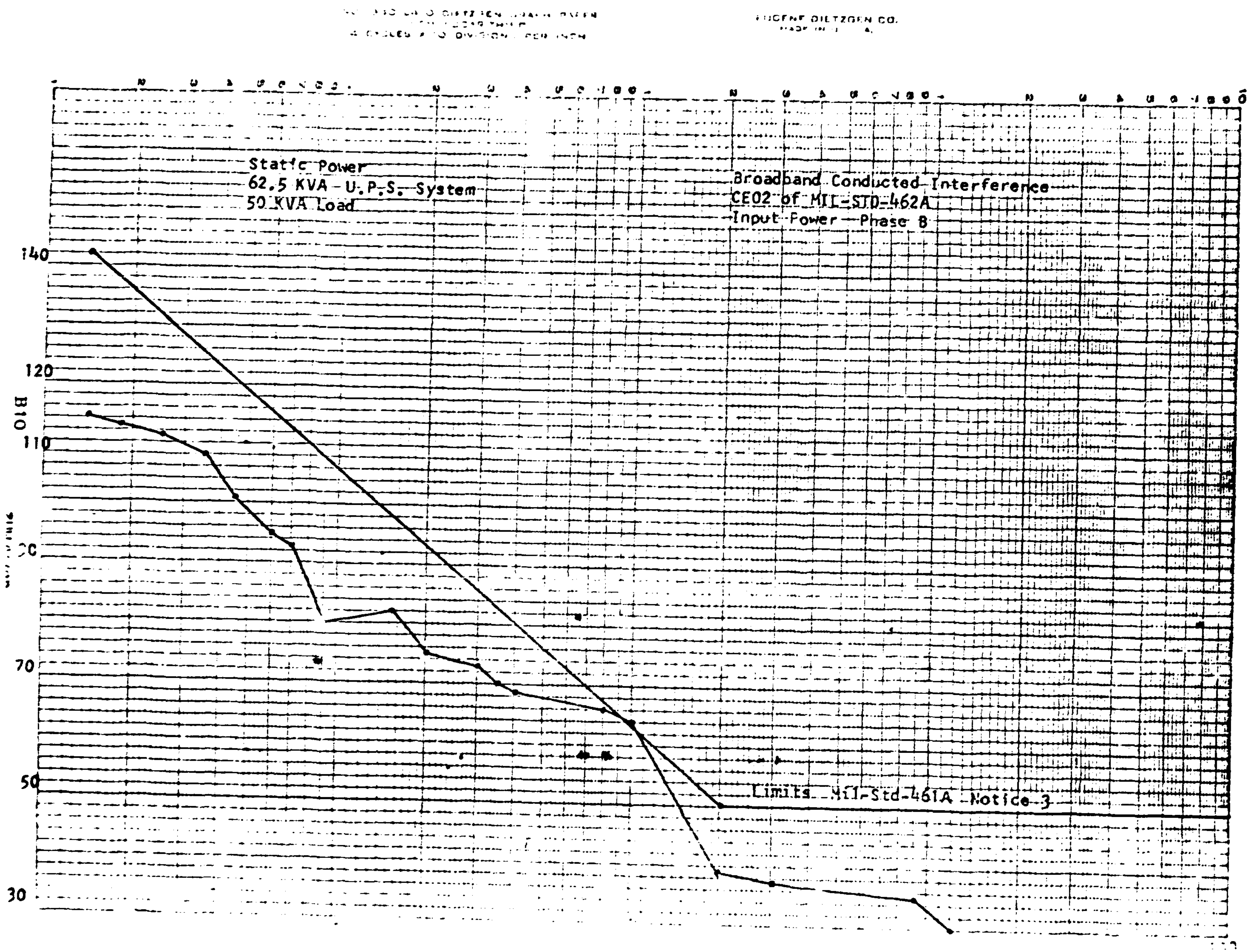
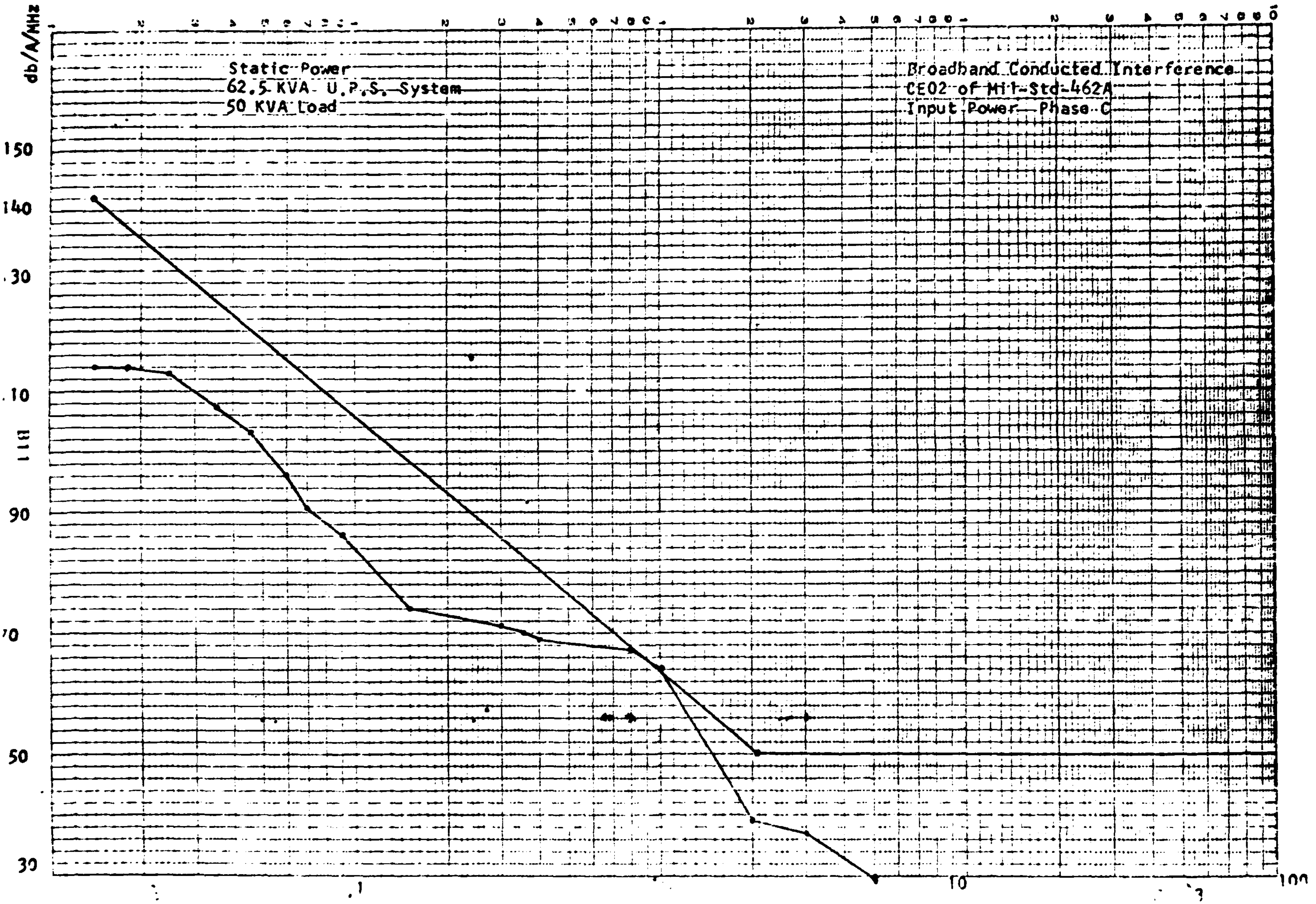
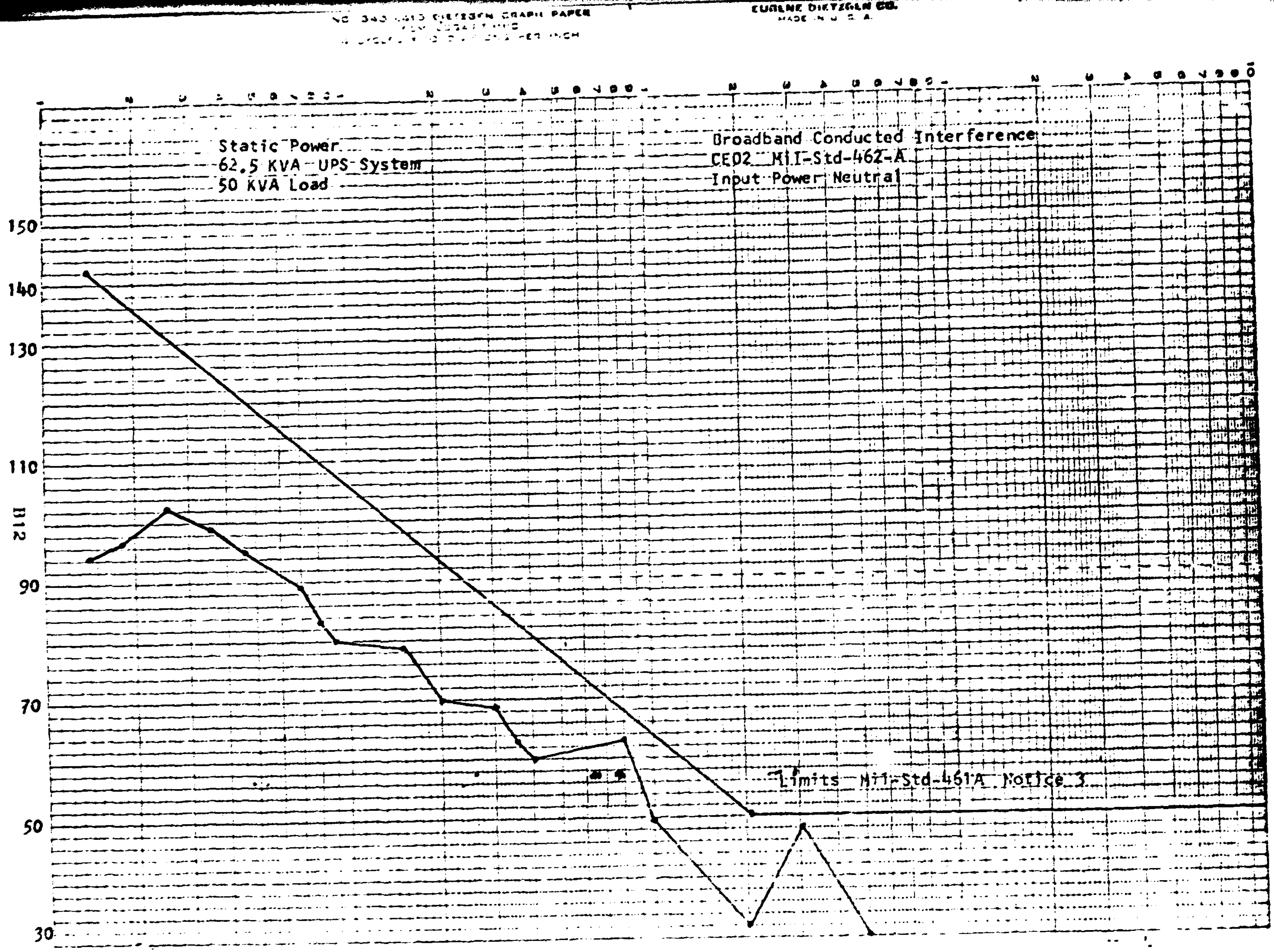
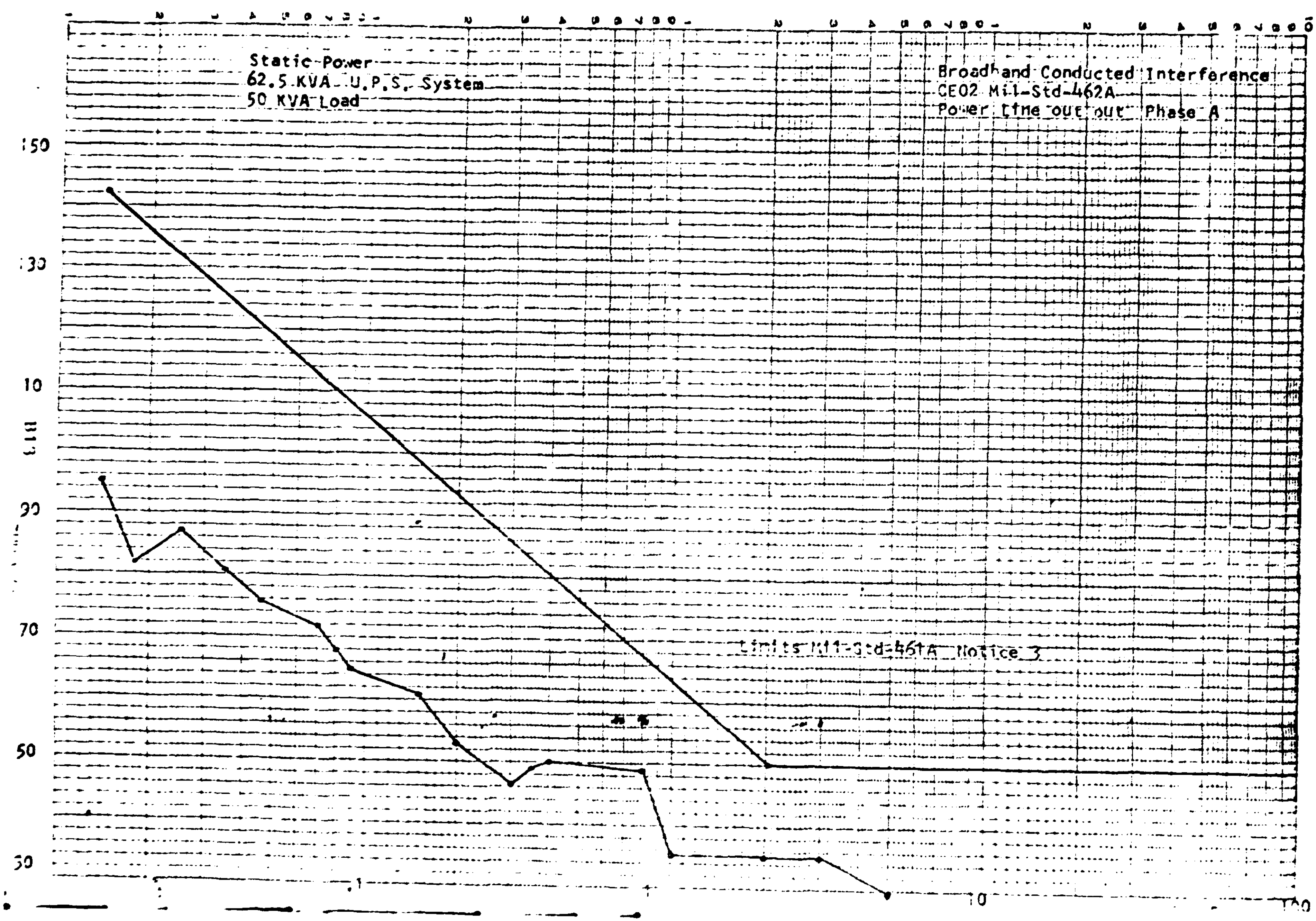
62.5 KVA U.P.S. System
50 KVA L-ad
Broadband
CE02 Conducted Interference
Power line Input Phase A
Limits Mil-Std-461A Notice 3
140
130
120
110
100
90
70
60
50
40
30
10
100

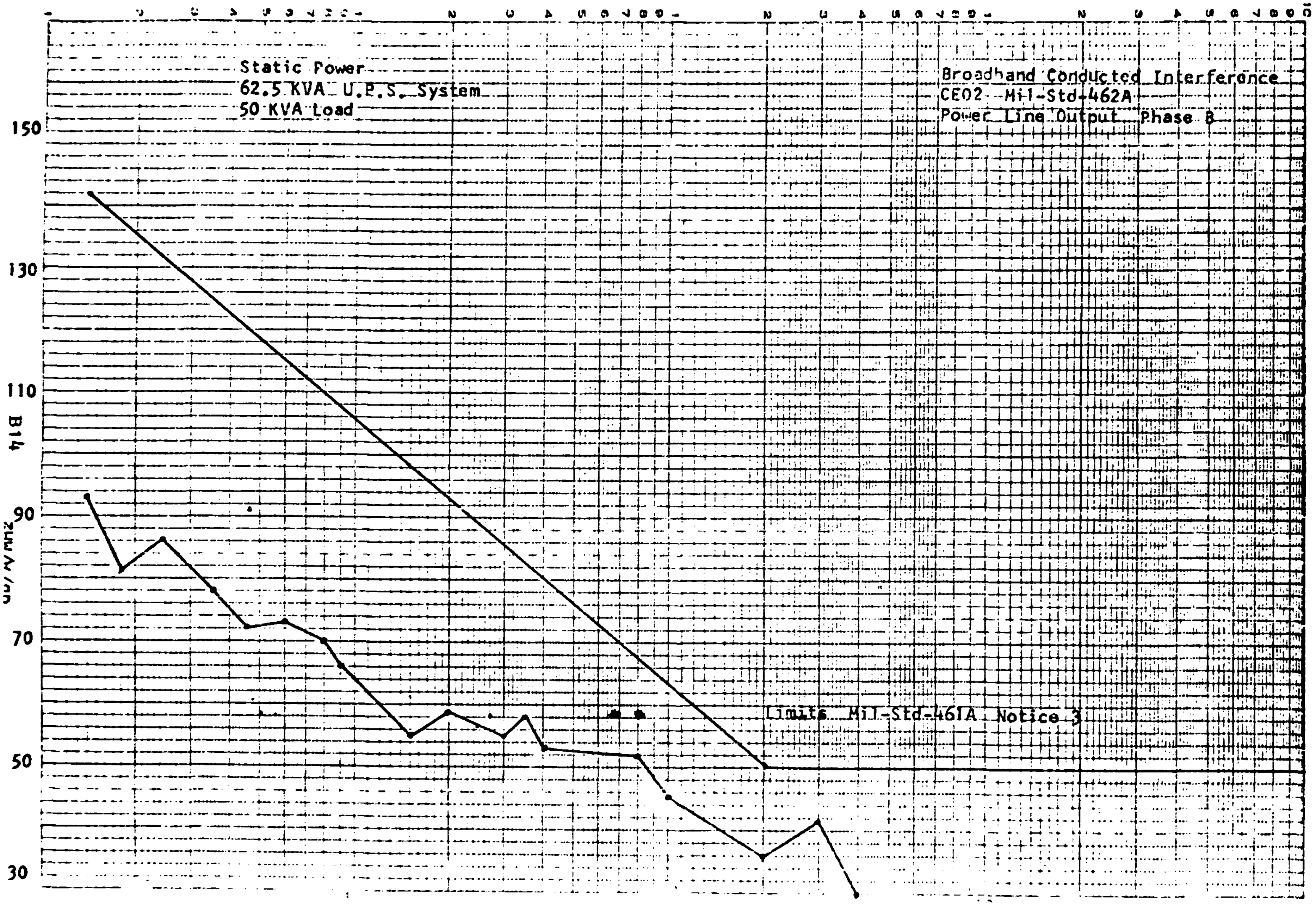

EUGENE DIETZGEN CO.
Static Power
62.5 KVA U.P.S. System
50 KVA Load
Broadband Conducted Interference
CE02 of MIL-STD-462A
Input Power Phase B
Limits MIL-Std-461A Notice 3
140
120
110
70
50
30

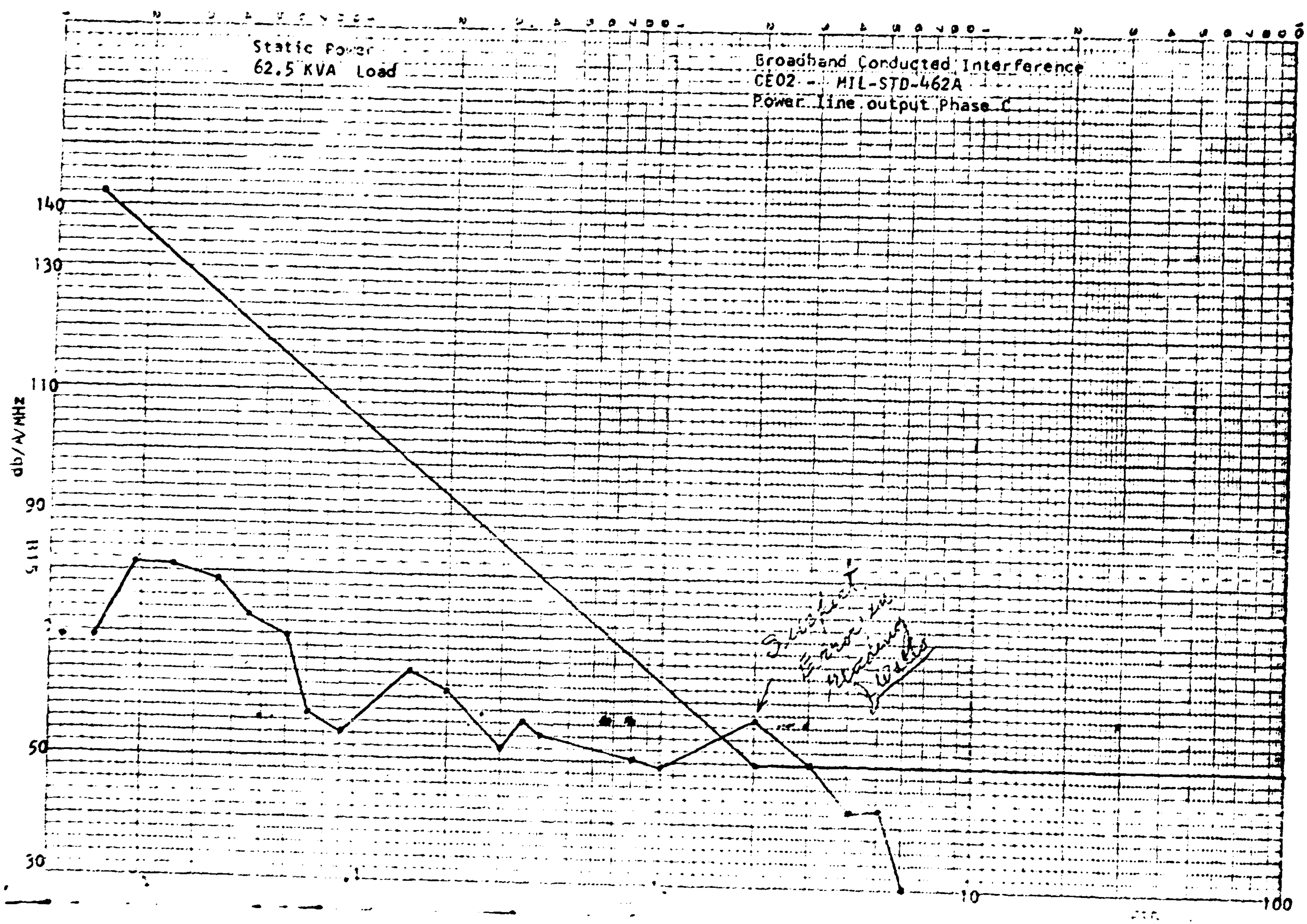


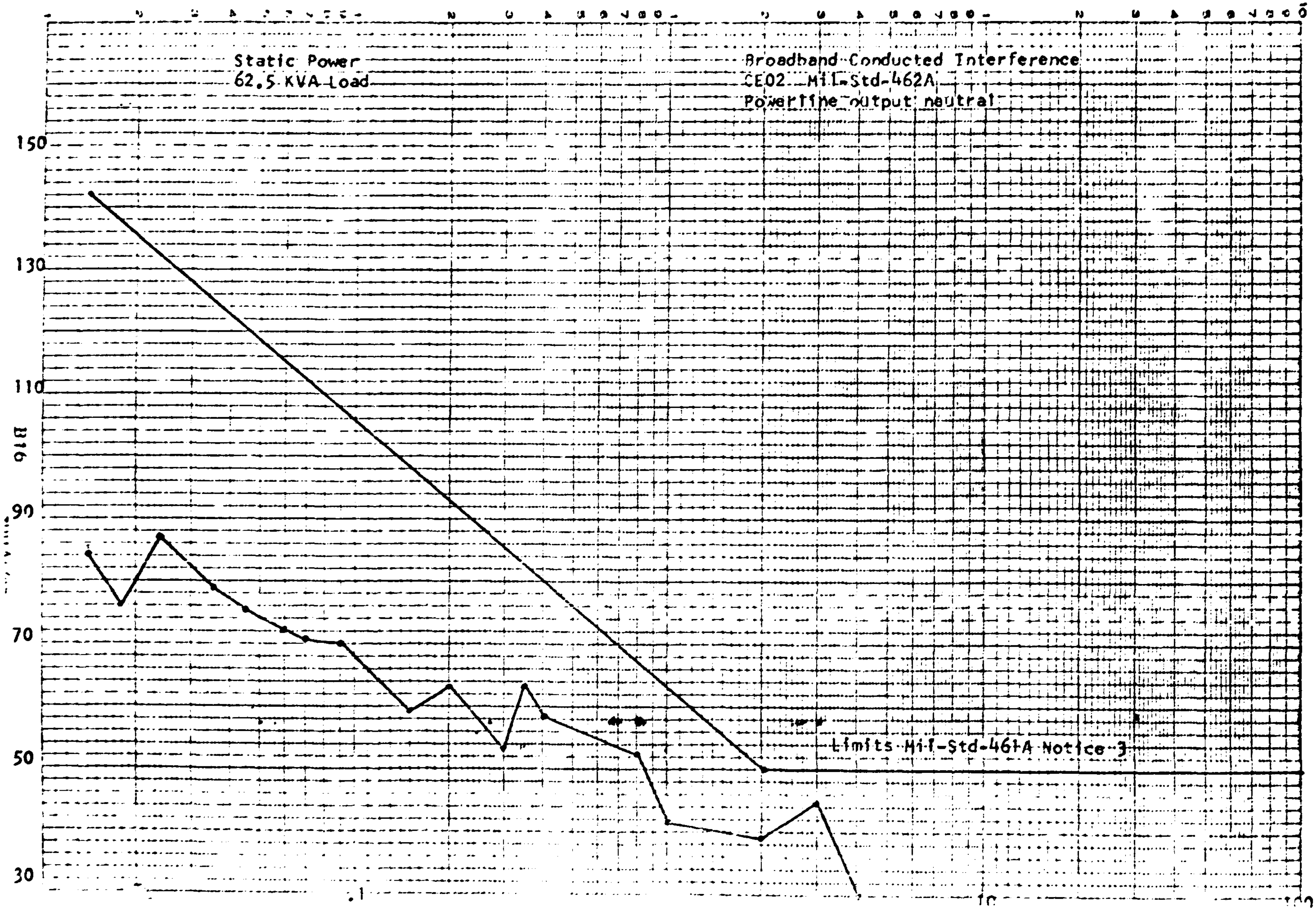
Static Power
62.5 KVA U.P.S. System
50 KVA Load
Broadband Conducted Interference
CE02 of Mil-Std-462A
Input Power Phase C
db/A/MHz
150
140
130
110
90
70
50
30
.1
1
10
100

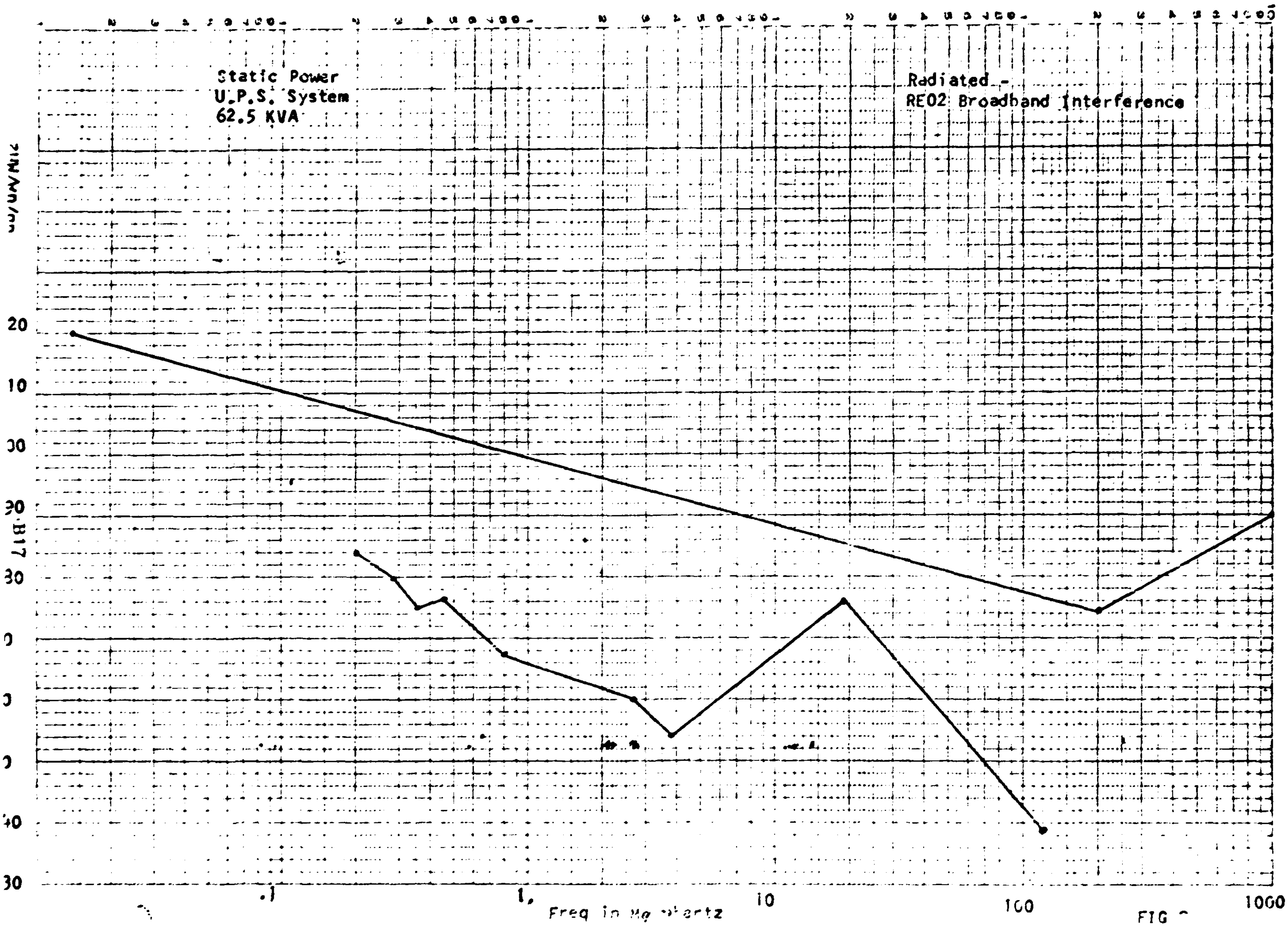

NO. 340 DIETZGEN GRAPH PAPER
EUGENE DIETZGEN CO.
MADE IN U.S.A.
Static Power
62.5 KVA UPS System
50 KVA Load
Broadband Conducted Interference
CE02 Mil-Std-462-A
Input Power Neutral
Limits Mil-Std-461A Notice 3
150
140
130
110
90
70
50
30


Static Power
62.5 KVA U.P.S. System
50 KVA Load
Broadband Conducted Interference
CE02 Mil-Std-462A
Power Line out Phase A
Limits Mil-Std-461A Notice 3
150
130
10
90
70
50
30
1
10
100


Static Power
62.5 KVA U.P.S. System
50 KVA Load
Broadband Conducted Interference
CE02 Mil-Std-462A
Power Line Output Phase B
Limits Mil-Std-461A Notice 3
150
130
110
90
70
50
30
dB μV/MHz


Static Power
62.5 KVA Load
Broadband Conducted Interference
CE02 - MIL-STD-462A
Power line output Phase C
140
130
110
90
50
30
db/A/MHz
10
100


Static Power
62.5 KVA Load
Broadband Conducted Interference
CE02 Mil-Std-462A
Powerline output neutral
Limits Mil-Std-461A Notice 3
150
130
110
90
70
50
30
.1
10
100



Static Power
U.P.S. System
62.5 KVA
Radiated -
RE02 Broadband Interference
20
10
.1
1,
10
100
1000
Freq in

FIG

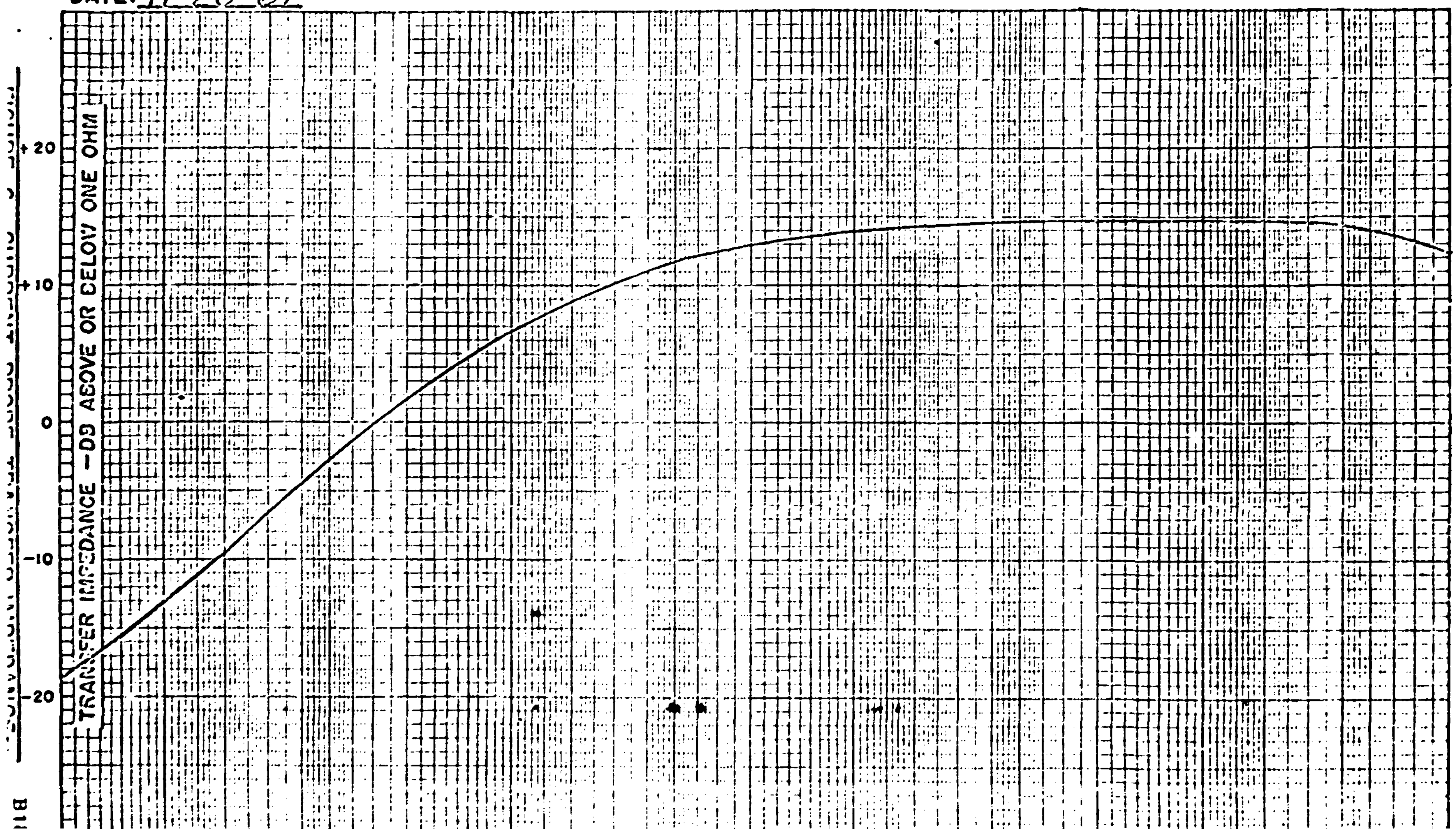
B17

CALIBRATING ENGINEER: R. GAONA

DATE: 11-20-67

CURRENT PROBE 91550-1

SERIAL NO. BF 231



Trial 50KVA.

HOPKINS ENGINEERING COMPANY

ELECTROMAGNETIC INTERFERENCE DATA SHEET

PROJECT Static Power TEST ITEM UPS 62.5 KVA

TEST SPEC. 461A — PARAGRAPH CE03 TEST POINT

TEST EQUIPMENT NF105- TESTED BY John W DATE 12-18-74

TYPE OF TEST				SIGNAL
	☑ BROADBAND	☑ CONDUCTED	☑ EMISSION	☐ RECEIVED BY ☐ XMITTED BY
	☐ NARROWBAND	☐ RADIATED	☐ SUSCEPTIBILITY	☑ CURRENT PROBE ☐ LISN ☐ ROD ☐ DIPOLE
	☐	☐	☐	☐ BI-CONICAL ☐ SPIRAL ☐ HORN ☐ LOOP

TEST MODE ☐ STEADY STATE ☐ TRANSIENT ☐

FREQ. KHz	Ø A db	Ø B db	Ø C db	NEUT	Ø A Corrected db/A	Ø B Corrected db/A	Ø C Corrected db/A	Neut Corrected db/A	
14	90	99	99	79	105	114	114	94	
18	102	100	101	83	115	113	114	97	
25	102	100	102	91	113	111	113	102	
35	99	100	99	91	107	108	107	99	
45	81	96	98	90	86	101	103	95	
60	76	92	93	86	79	95	96	89	
70	85	92	90	82	86	93	91	83	
90	82	87	87	81	81	80	86	80	
150	74	87	79	84	69	82	74	79	
.2	77	82	83	77	70	75	76	70	
.3	79	82	80	76	70	75	71	69	
.35	78	80	80	73	65	70	70	63	
.4	76	79	79	70	66	69	69	60	
* .62	72	75	76	67	60	63	64	52	
.8	70	80	80	75	58	68	68	63	
1.0	69	74	77	62	56	61	64	49	
2.0	48	46	53	46	34	32	39	32	
3.0	56	57	51	62	42	40	37	48	
5.0	29	40	39	35	15	26	25	21	

NOTES:

* Broadcast Station

SHEET OF

HOPKINS ENGINEERING COMPANY

ELECTROMAGNETIC INTERFERENCE DATA SHEET

LOAD 50 KVA

PROJECT Static Power TEST ITEM U.P.S. 62.5 KVA

TEST SPEC. 461 A PARAGRAPH CE 03 TEST POINT

TEST EQUIPMENT NF 105 TESTED BY DATE 12-18-74

TYPE OF TEST				
	☑ BROADBAND	☑ CONDUCTED	☑ EMISSION	SIGNAL ☐ RECEIVED BY ☐ XMITTED BY
	☐ NARROWBAND	☐ RADIATED	☐ SUSCEPTIBILITY	☑ CURRENT PROBE ☐ LISN ☐ ROD ☐ DIPOLE
	☐	☐	☐	☐ BI-CONICAL ☐ SPIRAL ☐ HORN ☐ LOOP

TEST MODE ☐ STEADY STATE ☐ TRANSIENT ☐

FREQ. MHZ	ØA db	ØB db	ØC db	NEUT	ØA Corrected dB/A	ØB Corrected dB/A	ØC Corrected dB/A	neut corrected dB/A	
4.0	29	40	40	37	15	26	26	23	
6.0	37	35	26	30	22	20	11	15	
7.0	25	25	31	29	10	10	16	14	
11.0	27	36	38	33	12	21	23	18	
17	48	50	49	19	33	35	34	4	
24	25	26	15	26	10	11	0	11	
30	4	16	0	17	0	1	0	2	
40	8	9	25	26	0	0	10	11	
50	4	10	20	20	0	0	5	5	
55	24								
65	14								
90	28								

NOTES:

SHEET OF

HOPKINS ENGINEERING COMPANY

ELECTROMAGNETIC INTERFERENCE DATA SHEET

PROJECT Static Power TEST ITEM UPS 62.5 KVA (Load 50 KVA)

TEST SPEC. 461A PARAGRAPH ______ TEST POINT Panel output.

TEST EQUIPMENT NF105- TESTED BY [illegible] DATE 12-18-79

TYPE OF TEST: ☐ BROADBAND ☐ NARROWBAND ☐ | ☒ CONDUCTED ☐ RADIATED ☐ | ☐ EMISSION ☐ SUSCEPTIBILITY ☐

SIGNAL ☐ RECEIVED BY ☐ XMITTED BY ☒ CURRENT PROBE ☐ LISN ☐ ROD ☐ DIPOLE ☐ BI-CONICAL ☐ SPIRAL ☐ HORN ☐ LOOP

TEST MODE ______ ☐ STEADY STATE ☐ TRANSIENT ☐

FREQ. KHz	φA	Corrected Reading dB/µA	φB	Corrected Reading dB/µA	φC	Corrected Reading dB/µA	Neut	Corrected Reading dB/µA
14	80	95	78	93	54	69	69	84
18	77	81	77	81	77	81	72	76
25	76	87	75	86	70	81	76	87
35	73	81	70	78	71	79	71	79
45	71	76	67	72	68	73	72	77
60	69	72	70	73	67	70	69	72
70	67	68	69	70	56	57	70	71
90	66	65	67	66	55	54	71	70
150	66	61	60	55	69	64	64	59
.2	60	53	66	59	68	61	70	63
.3	55	46	64	55	60	51	62	53
.35	59	49	68	58	66	56	73	63
.4	60	58	63	53	64	54	68	58
.62	60		62		67		66	
.8	61	49	64	52	62	50	60	52
1	48	35	58	45	62	49	54	41
2	49	35	50	36	71	57	53	39
3	49	35	55	41	64	50	61	47

Radio Station

NOTES: .62 MHz Local Radio Station

SHEET ____ OF ____

HOPKINS ENGINEERING COMPANY

ELECTROMAGNETIC INTERFERENCE DATA SHEET

PROJECT Static Power TEST ITEM UPS 62.5 KVA (Load 50 KVA)

TEST SPEC. 461A- PARAGRAPH ______ TEST POINT ______

TEST EQUIPMENT NF105- TESTED BY JJ Wells DATE 12-18-74

TYPE OF TEST				
☐ BROADBAND	☒ CONDUCTED	☐ EMISSION	SIGNAL ☐ RECEIVED BY ☐ XMITTED BY	
☐ NARROWBAND	☐ RADIATED	☐ SUSCEPTIBILITY	☒ CURRENT PROBE ☐ LISN ☐ ROD ☐ DIPOLE	
☐	☐	☐	☐ BI-CONICAL ☐ SPIRAL ☐ HORN ☐ LOOP	

TEST MODE ______ ☐ STEADY STATE ☐ TRANSIENT ☐ ______

FREQ. MHz	ΦA	Corrected Reading dB/µA	ΦB	Corrected Reading dB/µA	ΦC		NEUT		
4	39	24 ~~55~~	42	27 ~~56~~	56	42 ~~90~~	41	27 ~~56~~	
5	38	24 ~~53~~	45	30 ~~60~~	57	42 ~~73~~	46	31 ~~61~~	
6	36	21	33	17	42	27	32	17	
9	28	13	36	21	34	19	20	5	
11	25	10	27	12	35	20	25	10	
19	44	29	45	30	5	0	20	5	
24	15	0	0	0	25	10	0	0	
30	14	0	0	0	22	7	15	0	
40	7	0	16	0	17	2	18	3	
50	4	0	4	0	4	0	10	0	

NOTES:

SHEET ___ OF ___

HOPKINS ENGINEERING COMPANY

ELECTROMAGNETIC INTERFERENCE DATA SHEET

PROJECT State Power TEST ITEM UPS - 62.5 KVA System

TEST SPEC. 461A - Notice 3 PARAGRAPH RE02-RE04 TEST POINT Rear Console

TEST EQUIPMENT NE 105 TESTED BY John Wells DATE 12-18-74

TYPE OF TEST: ☑ BROADBAND ☐ NARROWBAND ☐ | ☐ CONDUCTED ☑ RADIATED ☐ | ☐ EMISSION ☐ SUSCEPTIBILITY ☐

SIGNAL ☐ RECEIVED BY ☐ XMITTED BY
☐ CURRENT PROBE ☐ LISN ☑ ROD ☐ DIPOLE
☑ BI-CONICAL ☐ SPIRAL ☐ HORN ☐ LOOP

TEST MODE ____ ☐ STEADY STATE ☐ TRANSIENT ☐ ____

FREQ. MHz	db	Corrected Readings							
~~.28~~									
.2	46	84							
.28	42	80							
.35	40	78							
.45	44	76							
.8	32	64							
2.7	36	60							
3.7	30	54							
19	59	76							
24	10	26							
40	12	25							
120	23	39							

NOTES: There were no measurable narrow band ~~readings~~ signals
No measurable Magnetic Fields -

SHEET OF