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THE MEAD, NEBRASKA, 25-kW PHOTOVOLTAIC POWER SYSTEM

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ABSTRACT

In 1977 MIT/Lincoln Laboratory designed, constructed, and put into operation a 25-kW-peak solar photovoltaic power system in Mead, Nebraska. This system was to be used to provide power to an agricultural test facility operated by the University of Nebraska. The initial application of the PV system was to provide power to irrigate an 80-acre cornfield. This report describes the photovoltaic power system as it existed at the time of its inauguration, and as it will exist following the completion of presently planned modifications, which include more fully automated control and addition of an uninterruptible power supply.

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I. INTRODUCTION

As part of the MIT/Lincoln Laboratory's Field Tests and Applications Project, a 25-kW-peak solar photovoltaic power system was designed and constructed for use at an agricultural test facility. At the same time, an economic study was initiated to determine the feasibility of adopting solar photovoltaic energy systems for agricultural purposes[1]. The site chosen for this experiment is the University of Nebraska's Agricultural Field Laboratory at Mead, Nebraska (latitude 41.2°N, longitude 96.5°W). The intial application called for the use of solar power to pump water from a two-acre-foot reuse pit into a system of gated pipes which would irrigate an 80-acre field of corn. Upon completion of the irrigation season, the system would provide power for a variety of secondary applications. A major goal of the program was to identify and develop these applications, of which crop drying was the first. In October 1977, following the irrigation season, solar power was used to drive a pair of 5-HP crop-drying fans. These fans supplied ambient air to two 6000-bushel grain bins which store the corn crop. Other secondary uses are in the process of identification and development as experiments in the use of solar power for agriculture[2].

The PV power system was designed, built and installed during the first seven months of 1977. It was inaugurated on 27 July, in ceremonies conducted in part by the Governor of Nebraska, James Exon. Thereafter, the equipment was operated in a manual mode for the remainder of the irrigation season. Following its use for irrigation, a number of important modifications to the system were begun and continue at the time of this writing. The following pages will describe the system, first as it existed at the time of its inauguration, and second as it will exist upon completion of presently planned modifications.

II. THE MEAD, NEBRASKA SITE

Figure II-1 is an aerial view of the Mead site taken during the early fall. In the foreground lies the cornfield which is the object of the irrigation experiment. In the center are the two rows of solar modules constituting the array. The reuse pit, from which the water is pumped, lies directly behind the array, the rear row of which is sited on the berm of the pit. A cyclone fence surrounds the array for safety purposes.

In right center may be seen three trailers; the large (10' x 36') trailer nearest to the array houses switchgear, control circuitry, the three-phase inverter, data acquisition equipment, and other electrical and electronic appurtenances. The center (10' x 22') trailer houses a 90-kWh capacity lead-acid storage battery. The rear unit is simply an office and storage trailer. Both the battery trailer and the equipment trailer are heavily

Fig. II-1. Aerial view of the Mead, Nebraska, site.

insulated, with 6 inches of fiberglass wool in the ceiling and floor and 3-1/2 inches in the walls. Windows are fitted with storm sashes. The equipment trailer contains three combination heater/air conditioner units rated 9800 BTU/Hr(1.55 kW) cooling and 9700 BTU/Hr(3.25 kW) heating. The battery trailer contains two of these units. In addition, a vent fan rated at 175 cfm is mounted in the roof of the battery trailer to remove the hydrogen gas which is produced during battery-charging intervals.

At upper right in the photo may be seen two 6000-bushel storage bins. These bins are used to both store and dry the corn harvested from the field. For drying, each bin is supplied with air by a 5-HP fan (not visible in the photo), which is powered from the photovoltaic system. At the right end of the array is a wooden structure which forms a platform for instrumentation. Five telephone poles behind the array provide lighting for nighttime work on the array, if necessary. The poles also support air terminals and ground cables, which are strung from pole to pole, for lightning protection.

Figure II-2 shows the irrigation pump, behind which is a shelter for

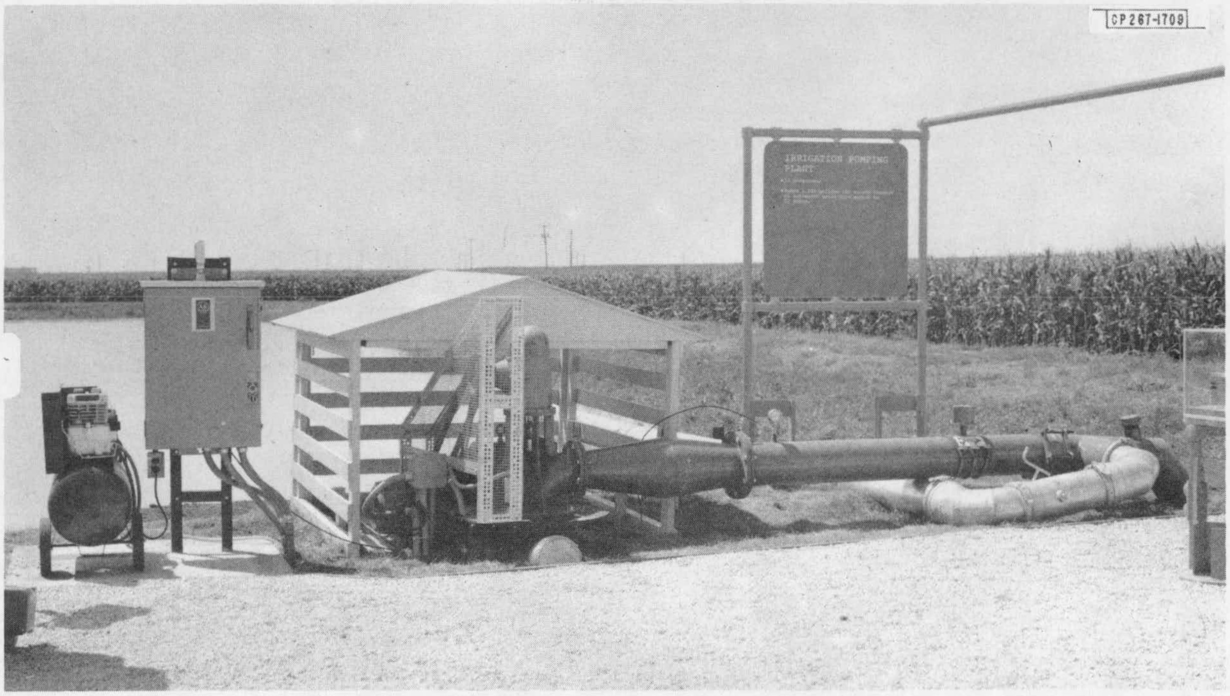


Fig. II-2. Pump and motor enclosure.

two drive motors connected to the pump via pulleys, belts and a right-angle gear head. One motor (not visible) is a 10-HP, shunt wound, 120-volt DC motor. This motor was driven from the photovoltaic system. The second motor, provided mainly for backup during periods of poor insolation (cloud or rain), is a 10-HP, three-phase, 240-volt, AC induction motor which receives its power from the utility; it is partially visible at the left of the pulley shroud.

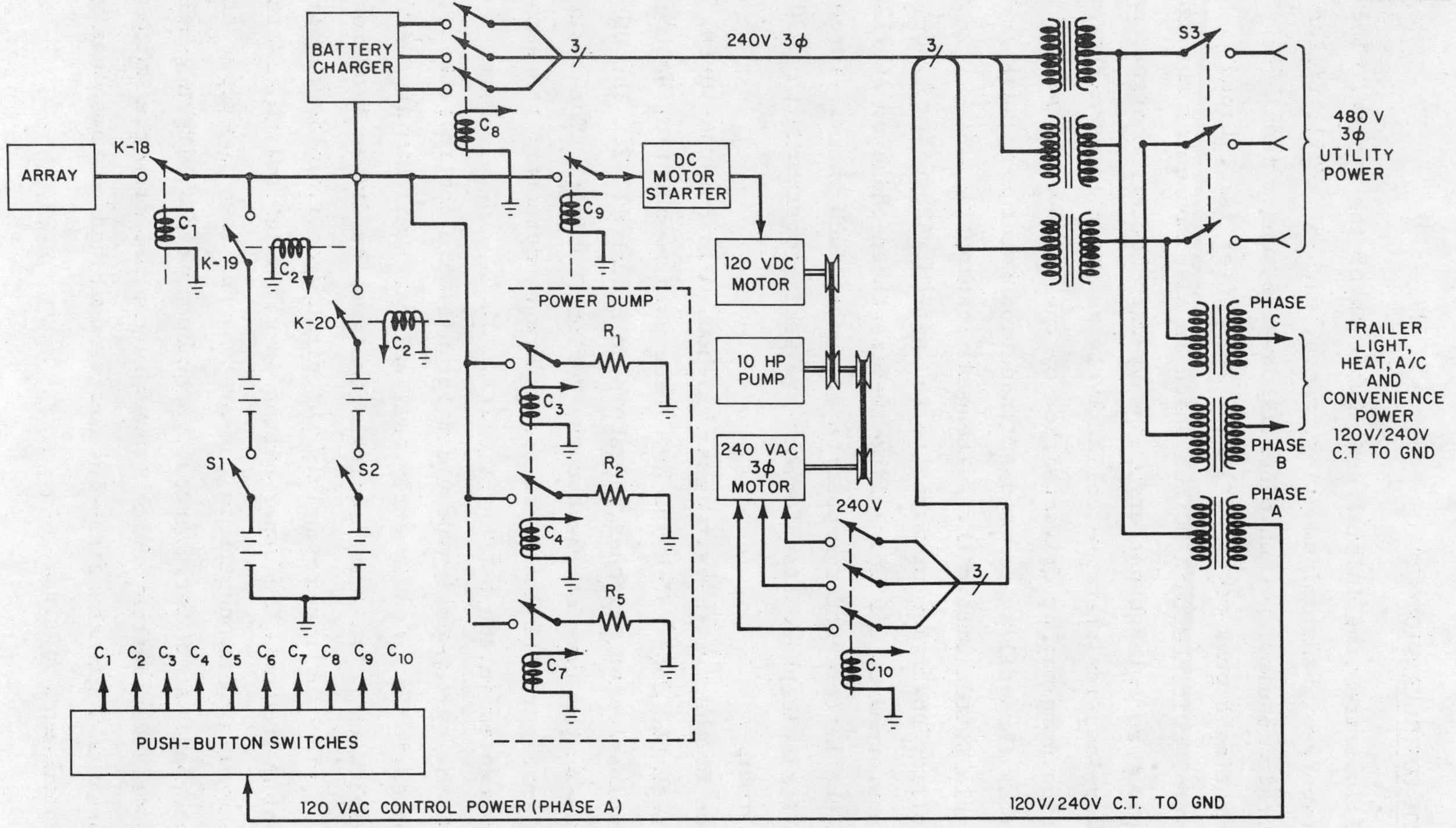
III. INITIAL SYSTEM CONFIGURATION

Figure III-1 illustrates the initial configuration of the system. The array consists of twenty-eight aluminum-alloy frames, each 8' x 25', filled with solar photovoltaic modules. Each panel is capable, under ideal conditions, of generating a peak power of 1 kW. This power is combined and fed through control switches to a DC bus which is also connected through appropriate switchgear to a large battery, a heavy-duty battery charger, and a group of high-power load resistors -- collectively referred to as a "Power Dump". The irrigation pump may be driven either by the photovoltaically powered DC motor or by the utility powered AC induction motor -- manually selectable by a toggle switch within the switchgear cabinet.

Three-phase utility power is furnished to the site at 480 volts line-to-line, and is transformed to 240 volts line-to-line three-phase or 240/120-volt single-phase, the latter center tapped to ground on each phase. Three individual 7-1/2 kVA single-phase transformers are used, together with a 30-kVA three-phase transformer.

A major portion of the system switchgear is housed in a large 10-ft. by 7-ft. Hoffman cabinet, the doors of which have been used as mounting space for meters and manual selector switches, as shown in Figure III-2. The DC motor starter stands at the far left beyond the Hoffman cabinet. The instrument at the upper right in Figure III-2 is part of a hydrogen detector; the sensor for this instrument is mounted in the battery trailer.

At the outset, the system design provided for ultimate control through some form of automated logic. Consequently, all selector switches in the system are paralleled with solid-state switches that may be driven from low-voltage (TTL) logic. The small red panel in the right center of Figure III-2 contains two control switches. The upper button is a "panic" switch. Actuation of this switch opens all interconnects in the system thus removing power from all loads, disconnecting the battery, array, power dump, etc. Directly below the "panic" switch is a key switch, which transfers control from the Hoffman cabinet to a solid-state logic chassis. The latter unit had not been designed at the time the system went on line.



NOTE:
($C_9 \oplus C_{10}$ SELECTED)
$\oplus$ DENOTES EXCLUSIVE-OR

Fig. III-1. Block diagram of the Mead PV power system as installed in 1977.

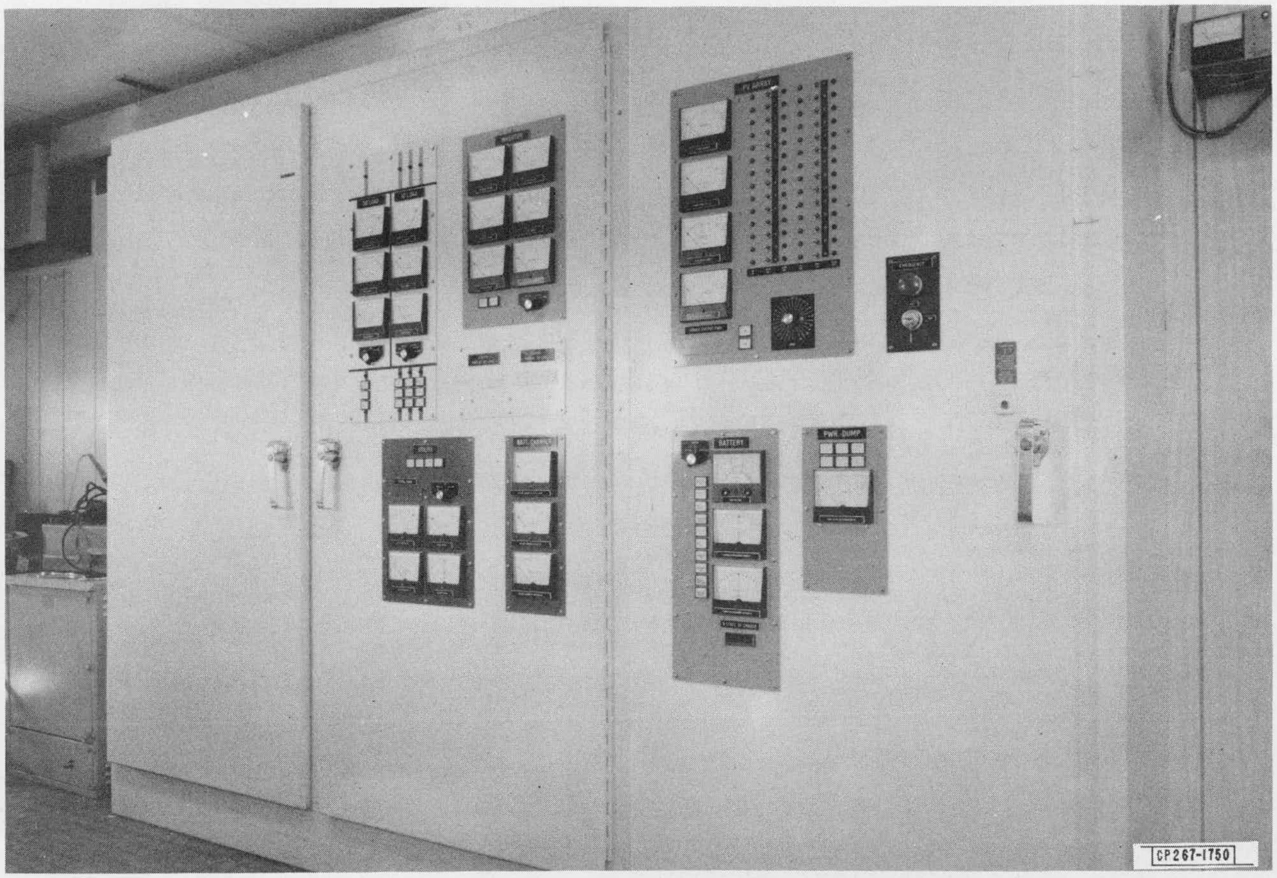


Fig. III-2. Front view of the Hoffman cabinet.

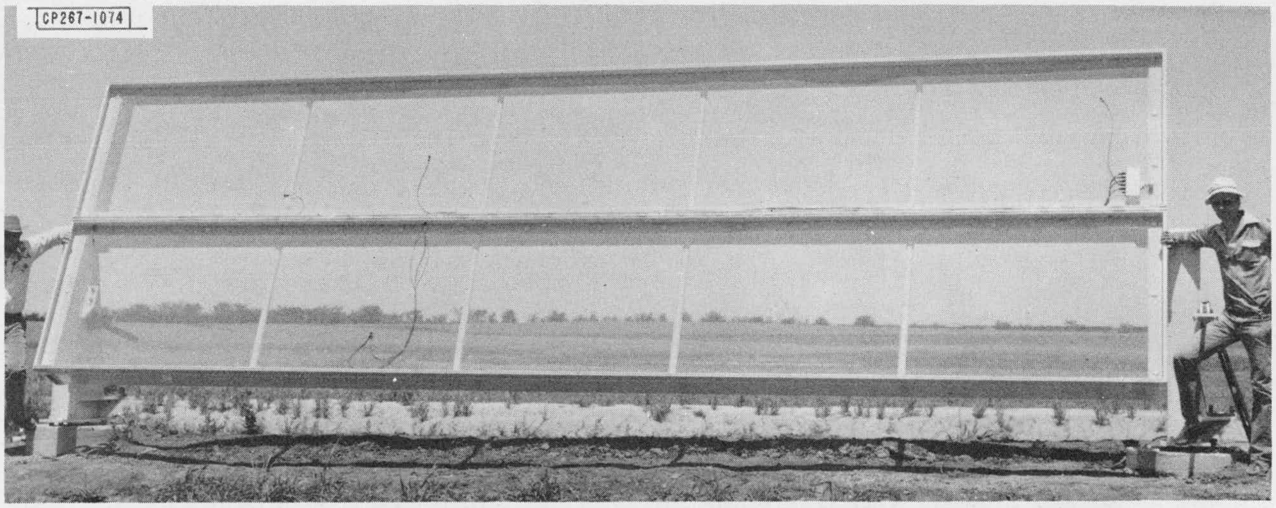


Fig. III-3. Photovoltaic frame before module installation.

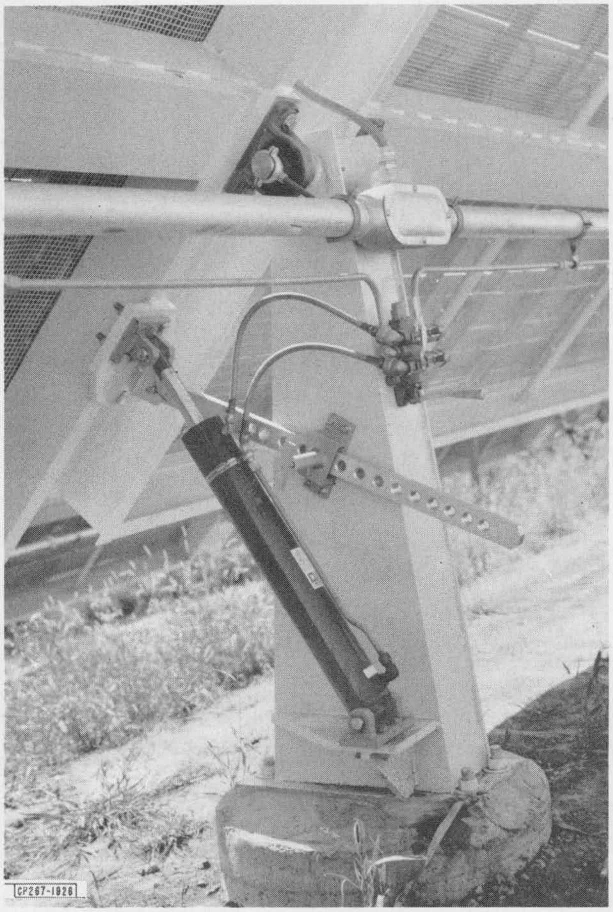
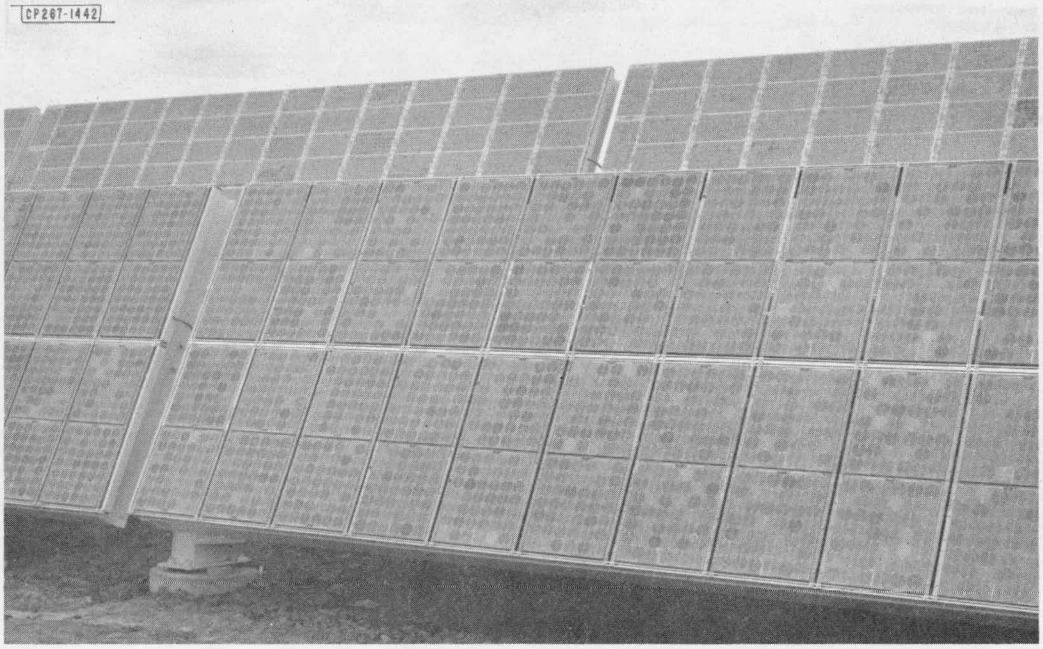


Fig. III-4. (left) Hydraulic ram and locking arm for panel tilt control.

Fig. III-5. (below) Close-up of the array.



The major components of the (initial) system will now be described in greater detail.

A. The Photovoltaic Array:

The array consists of two parallel, 370-foot rows of solar panels. The rows are parallel to the berm of the reuse pit, for practical reasons, and face true south within 10°. Each panel is approximately 8-feet wide and 25-feet long and is supported on a pair of trunnions through bearings, located at the center points of either 8-foot edge. Figure III-3 shows one of the panel frames mounted on its trunnions before installation of the photovoltaic modules. Note that the rear of the frame is entirely screened in. Note also a portion of the wiring harness for collection of the solar energy.

As an experimental feature, the frame mounting was designed to allow each panel to be tilted in elevation between 0° (horizontal) and 65° above horizontal. Limits of tilt were imposed by constraints of the hydraulic elevation control mechanism (shown in Figure III-4); however, computer simulations indicate little or no advantage in tilt angles greater than 65° for the Mead latitude.

The supporting trunnions are mounted atop reinforced concrete piers 30 inches in diameter and extending 9-1/2 feet into the soil. Construction is designed to withstand 100-MPH winds.

Figure III-5 shows the array close-up, illustrating the two different types of modules which it contains. All of these modules are taken from the ERDA/JPL Block II (130-kW) Buy of 1976. The front row contains modules manufactured by the Solarex Corporation of Rockville, Maryland. Each module is approximately 2-feet square and generates a specified power output of 16-watts minimum at 60°C for insolation of 100 mw/cm^2. Each module contains 42 series-connected, 3-inch-diameter cells; the module terminal voltage under specified conditions (maximum power) is 15.8-volts minimum.

The rear row is filled with modules manufactured by Sensor Technology Corporation, Chatsworth, California. These modules are approximately 1 foot by 2 feet, and each contains 44 series-connected cells 2-1/8 inches in diameter. Specified power is 8.17-watts minimum at 60°C for insolation which is 100 mw/cm^2. Output voltage is 16.5 volts under specified conditions. Each panel contains 108 Sensor Technology modules. Note that 4 modules are turned on end at the left edge of these panels.

B. Module Wiring:

Figures III-6 and III-7 show details of the module interconnection wiring for the two types of modules. Sensor Technology modules (Figure III-6) are paralleled in groups of 4 modules. These are referred to as "quads." Each quad has a protection diode tied across it (in parallel, not shown in the Figure) with its forward conduction in the direction of voltage rise. This feature protects against the consequences of one or more open-circuited modules. Nine quads are connected in series to form a sub-string. Each Sensor Technology panel has three sub-strings, which terminate in a junction box at the rear of the panel (center, right of Figure III-3. The junction box contains a series diode for each string in the positive side. The diode outputs of the three sub-strings are tied in parallel inside the junction box, as are the three negative leads. The output of one panel is referred to as a "string." The nominal string voltage and current for Sensor Technology panels is 5.94 amperes and 149 volts or 882-watts minimum* at maximum power, rated at 60°C and 100 mw/cm^2 insolation**. The power from each panel is brought back to the equipment trailer through separate pairs of No. 8 wire.

The wiring of the Solarex modules is shown in Figure III-7. Ten pairs of modules are connected in series to form a sub-string with pairs wired in parallel. Series and parallel diodes are employed (the parallel protection diodes are not shown in the Figure), as they are in the Sensor Technology panels. Since there are 50 active Solarex modules on each panel, 10 pairs -- or 20 modules -- make up a sub-string. There are 2-1/2 sub-strings per panel. The half sub-string from odd-numbered panels is connected in series with the half string on the adjacent even-numbered panels. Thus, the power returned from panels 1, 3, 5

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*Based on manufactures specifications; actual output is higher.

**For further details concerning module performance, refer to JPL Report #5101-36: User's Handbook for Block II Silicon Solar Cell Modules, 15 October 1977 by M. I. Smokler.

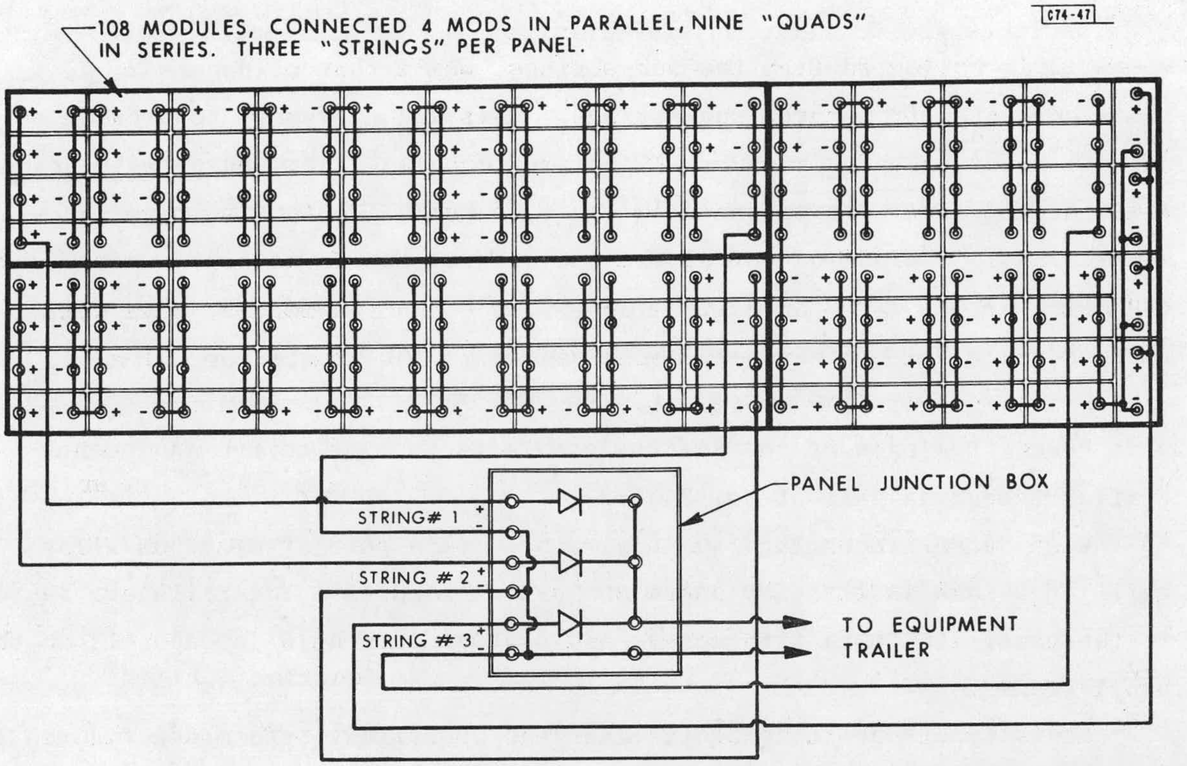
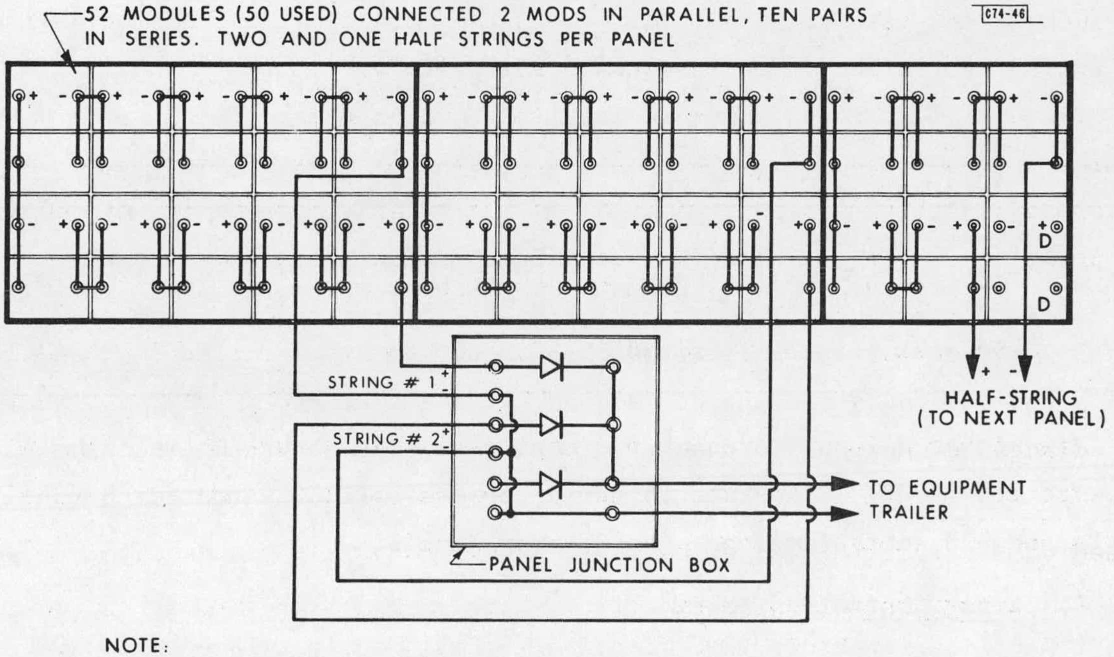


Fig. III-6. Wiring arrangement for panels containing Sensor Technology modules.



NOTE:
EVEN-NUMBERED PANELS SUPPLY POWER FROM 3 STRINGS

Fig. III-7. Wiring arrangement for panels containing Solarex modules.

- - - 13 is collected from two sub-strings, while that of panels 2, 4, 6, - - - 14 is collected from three sub-strings. This was necessary to provide a uniform mounting and wiring of all Solarex modules, i.e., as paralleled pairs, while at the same time maintaining the same nominal output voltage for all sub-strings. Nominal output of the odd Solarex panels is 4.06 amperes and 158 volts or 641 watts at maximum power, 60°C and 100 mw/cm^2. The nominal current and wattage of even-numbered panels is 50% greater or 6.1 amps, 962 watts; the open-circuit voltage is the same.

Power from each of the Solarex panels is brought to the equipment trailer through a pair of No. 8 wires.

Each Sensor Technology quad is mounted on a pair of aluminum-alloy rails; the same is true for pairs of Solarex modules. The rails are fastened to the panel structure with screws and captive nuts held in channels on the panel frames.

It is important to recognize that the specified performance figures given above are conservative for both Sensor Technology and Solarex modules. More realistic performance figures under specified conditions are:

TABLE 1

MODULE POWER AT SPECIFIC TEMPERATURE

Manufacturer	60°C	NOCT	Note
Sensor Tech	9.1 w	10.45 w	NOCT = 42.9°C
Solarex	17.08	18.56	NOCT = 47.1°C

The higher values, taken at the more realistic Normal Operating Cell Temperatures (NOCT), translate to string powers of 1130 watts for Sensor Tech panels and 928 watts (average) for Solarex panels.

C. Array Control Cabinet:

Twenty-eight pairs of wires carry power from the array to the equipment trailer. Individual strings are brought to a terminal strip through control relays and fuses as shown in Figure III-8. Provision is made at this point for measuring the short-circuit current and the open-circuit voltage of each individual string. The entire assembly is housed in a 3-foot by 4-foot by 8-inch-deep Hoffman cabinet, as shown in Fig. III-9. Note the solid-state control relays mounted on the inside door at left in the figure. As indicated in Figure III-8, the outputs of all 28 strings are combined as they leave the Array Control Cabinet to form an Array Power Bus. This bus is connected to the DC main bus via contactor K18*.

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*Contactors are identified in Table 3, Switchgear Identification.

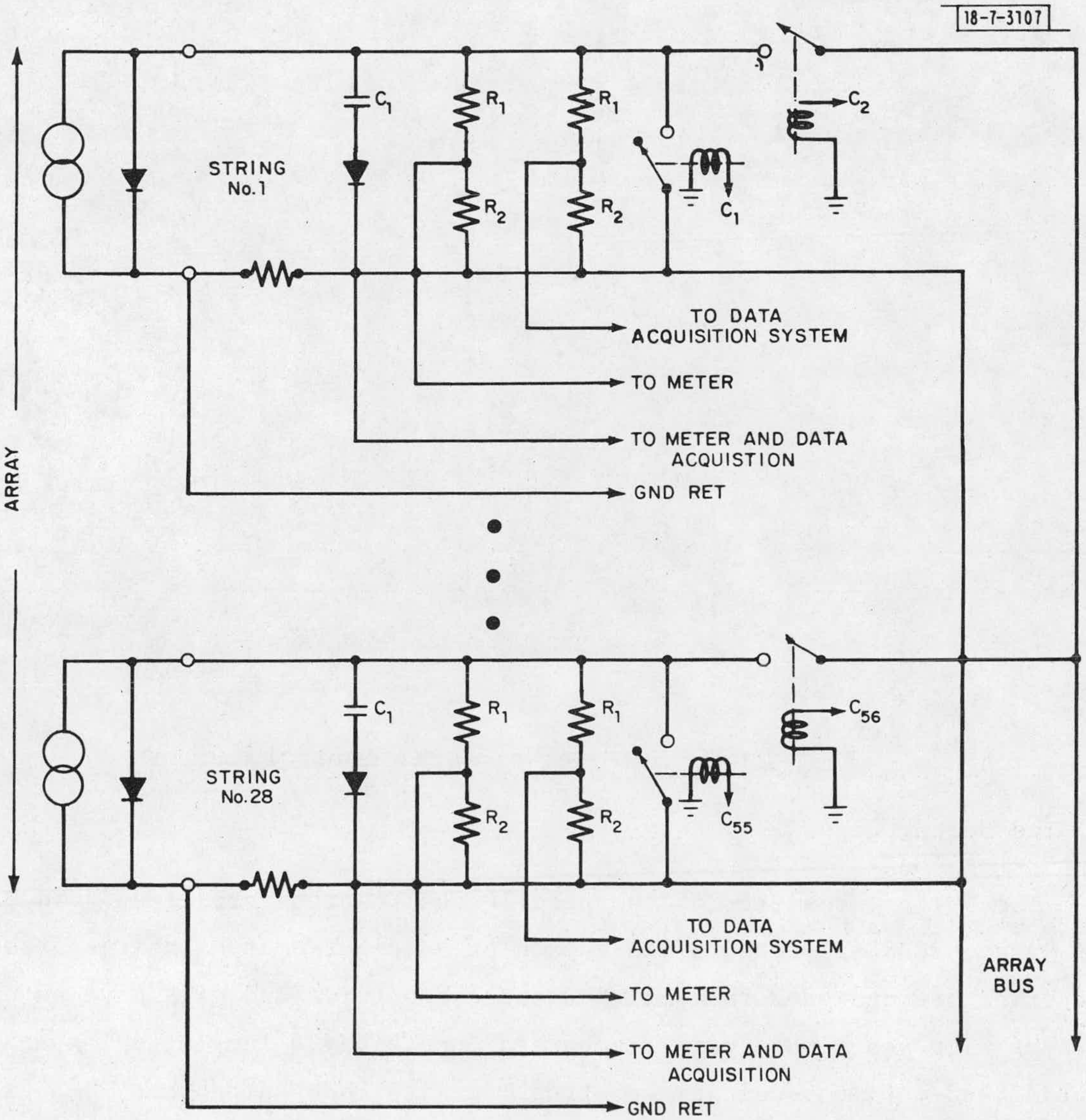

Fig. III-8. Schematic wiring diagram of array control cabinet.

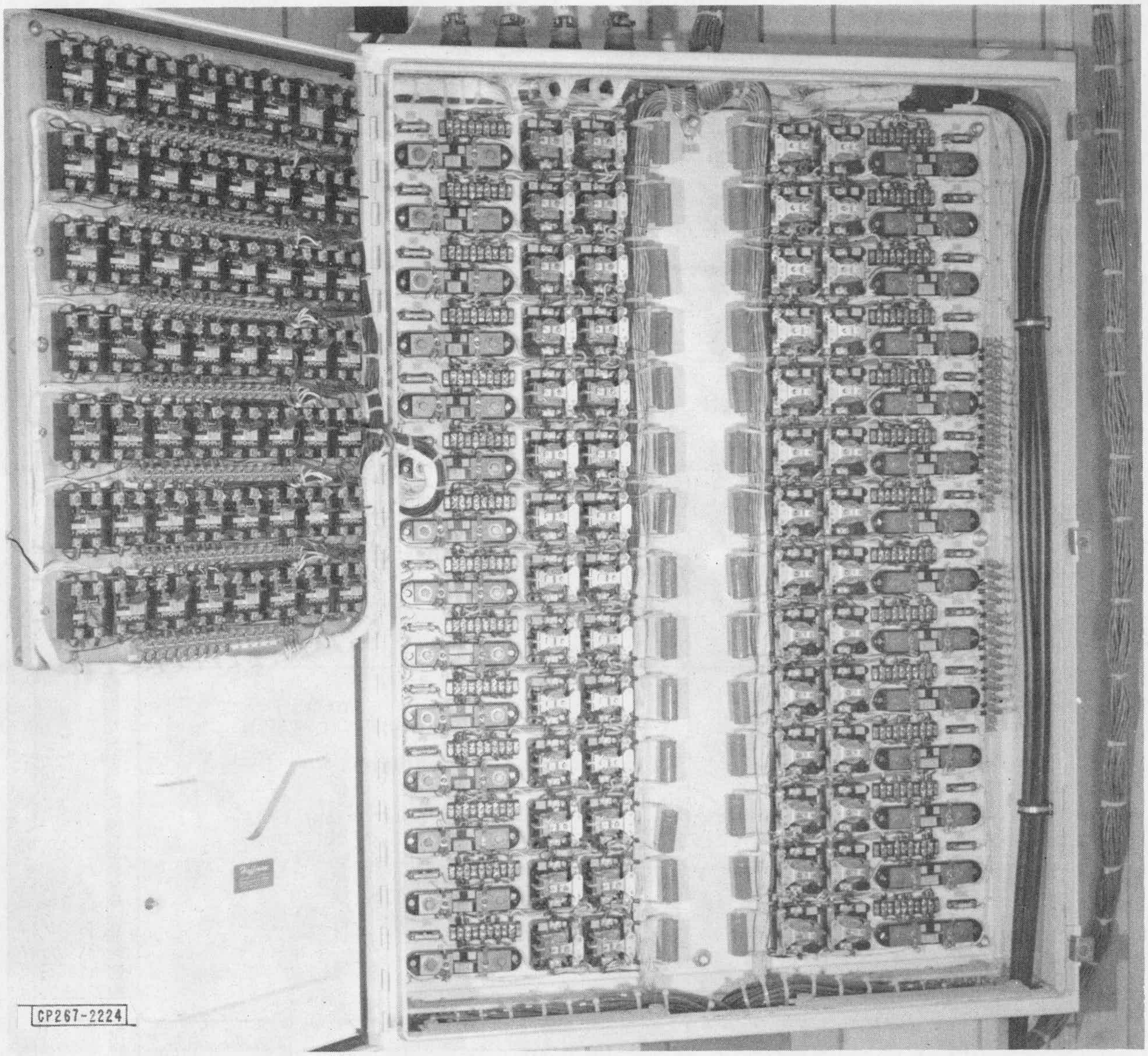

Fig. III-9. Interior of array control cabinet.

D. Battery:

The battery consists of two parallel banks of 6-volt, lead-acid batteries, C & D Type 3CBSB-11 rated 375 A-h each at an eight-hour discharge rate. These batteries are designed for railroad caboose service and will have an expected life of five years when deep discharged once a day. The batteries employ a hybrid lead-antimony-calcium construction with PbSb anodes and PbCa cathodes.

There are 20 batteries in each bank with a nominal (2-volt per cell, 3 cells per battery) terminal voltage of 120 volts and capacity of 90 kWh (72 kWh to the recommended 80% depth of discharge).

Figure III-10 is a view looking into the battery trailer. The positive and negative outputs of each bank are brought separately (via No. 0000 conductor) to the equipment trailer for switching onto the main DC bus. In addition, each bank can be divided at its midpoint by a fused disconnect in order to render the entire battery safer during periods of maintenance or for the replacement of individual units. Although not visible in Figure III-10, a hydrogen gas sensor is mounted high on the trailer's west wall. The electronics for this sensor, including an audible alarm, is located in the equipment trailer.

Fig. III-10. Interior view of the battery trailer.

The effective 70+ kWh of energy storage which are provided for in the Mead system are not intended to carry the irrigation load during day-long periods of clouds or rain. Instead, the storage accomplishes two functions: first, it buffers the system during periods of transient clouds, and second, given adequate insolation, it is intended to "square-up" the available energy during a day in which power (nominal 10 kW) is demanded for a full 12-hour period. Thus, net energy may be drawn from the battery during morning and evening hours and replaced during the mid-day period on a full-sun day. For periods of less than full sun, energy may be required from the utility.

E. Power Dump:

The operation of a PV power system requires some means of battery charge control. In particular, when the battery has reached a full state-of-charge and excess solar energy (over the load demands) is available, some means must be provided to either reduce the array output or to add additional loads. The latter method of control was chosen for the Mead PV power system and a controlled power dump was used to provide the addtional loads. This approach has the advantage over array shedding, the first techniques mentioned above, in that all sections of the array are always supplying power to the DC bus when sunlight is available. This in turn allows the continuous collection of performance data on the PV array, even during periods when the solar energy cannot be put to use either for battery charging or for supplying agricultural loads.

The power dump consists of a group of five high-power resistors, connected to the main DC bus through individual contactors K21 through K26. The resistors are arranged in two vertical stacks cooled by a pair of DC motor-driven fans. Figure III-11 shows the power dump in its weatherproof housing (white structure, center of photo) between the equipment trailer (left) and the utility transformer pad (at right). Vane switches are used to sense air flow through the power dump, and the contactor control circuits are interlocked to prevent energizing any resistor unless the fans are running.

As noted above, the purpose of the power dump is to dissipate energy from the array at times of light load, full-battery charge and high insolation.

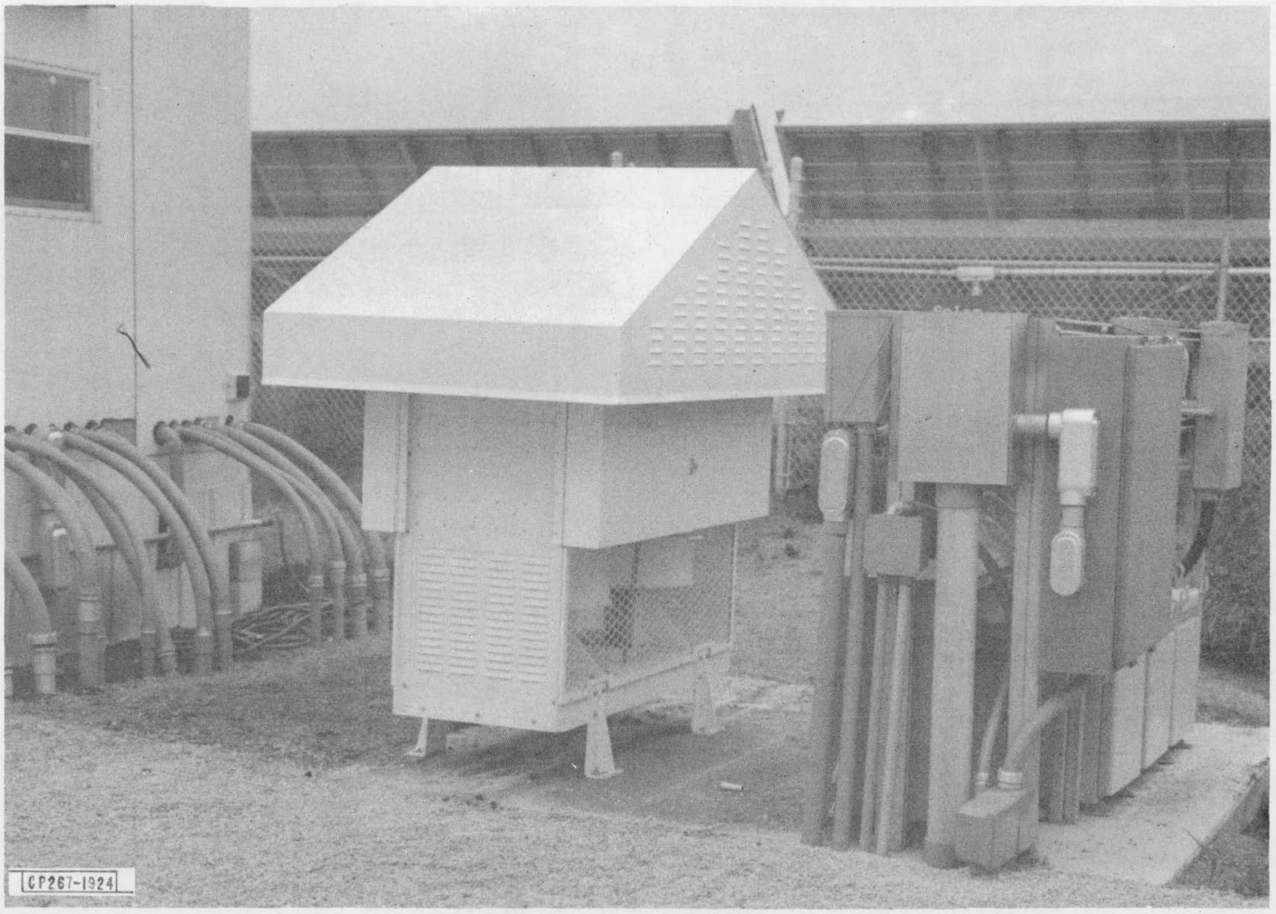

Fig. III-11. Power dump enclosure.

It was planned that the power dump should be able to absorb up to the full 25-kW (nominal peak) array output, at a bus voltage of 150 volts, corresponding to a high battery state-of-charge. Further, the five resistors are (roughly) binarily weighted so that, through switch selection, power can be expended (dumped) in 31 uniform increments of roughly 800 watts, up to the 25-kW maximum. The nominal values of the resistors, together with the actual values, are given below.

A planned modification involves an alternative use of the power dump as a part of the mechanism for collection of I-V data on the array. This is discussed at greater length in Section IV.

TABLE 2

NOMINAL VALUES OF BINARY-WEIGHTED POWER-DUMP RESISTORS

Resistor	Ideal Value	Actual Value*	Watts Dissipated (Ideal)
R_1	27.90 ohms	25.20 ohms	806
R_2	13.95	15.80	1613
R_3	6.98	6.96	3226
R_4	3.49	3.48	6432
R_5	1.74	1.73	12904

*Resistors are Square D Tab Weld Plate Resistor. R_4 consists of two 6.96-ohm resistors in parallel. R_5 consists of three 5.3-ohm resistors in parallel. The fans draw an estimated power of 750 watts at 150 volts.

F. Battery Charger:

A custom, three-phase battery charger (Fig. III-12) built by Controlled Power Co., Troy, Mich., has been provided to ensure that equalization charging of the battery can be done irrespective of weather (insolation) conditions. The charger is capable of delivering 150 A at voltages up to 160 VDC. Controls enable the charger to be set to a constant-current profile up to a set voltage, and to charge at constant voltage thereafter for a preset length of time. In addition, the charger can be prearmed to deliver an equalizing charge

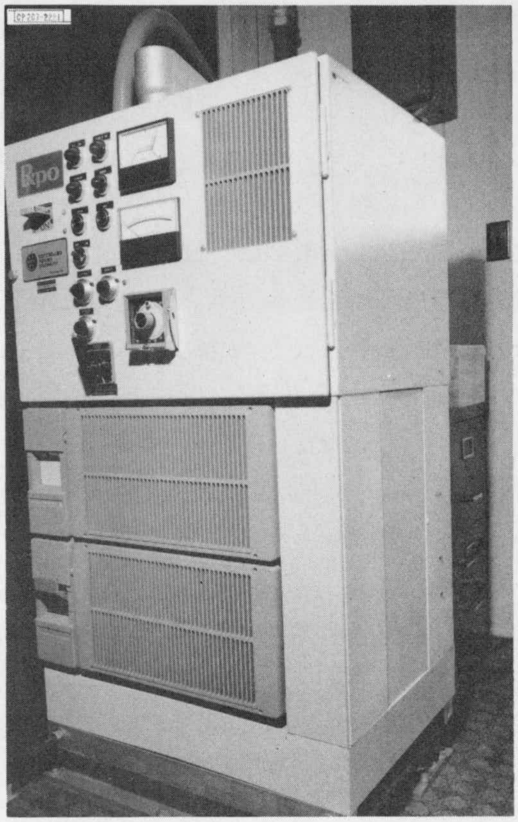

Fig. III-12. (right) Battery charger.

(with a higher voltage threshold) as soon as the standard charge voltage threshold is tripped. Another operating mode allows turn-on and turn-off of the charger from a remote control point, but current and voltage limits can only be set locally at the charger control panel.

G. Switchgear :

The primary switchgear for the system consists of electrically actuated and latched Allen-Bradley contactors* ranging in size from NEMA 1 to NEMA 5 and fitted with auxiliary contacts for holding. All coil circuits are designed for 120-volt, 60-Hz AC. Table 3 identifies the contactors used for major switchpoints in the system.

In its initial manual mode, the system was controlled primarily by momentary contact push buttons grouped with appropriate metering in sub-panels on two doors of the large Hoffman cabinet, as shown in Figure III-2. The largest sub-panel at the top of the right-hand door controls power from the array. In addition to controlling contactor K18 which ties the array bus to the main DC bus, the panel contains 28 three-position toggle switches, one for each of the strings in the array (Figure III-13). These toggle switches actuate the relays in the Array Control Cabinet previously described; they enable each string to be short-circuited, open-circuited or individually connected to the array bus.

The metering of the array sub-panel is wired through a multi-deck, 30-position switch, permitting the current and voltage of any string to be observed. In addition, a position is provided in which the voltage and current of the entire array are displayed.

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*The array string switching relays, which are Magnacraft Model W99ADBX-2, are an exception.

TABLE 3

SWITCHGEAR IDENTIFICATION

Contractor	Function	NEMA Rating
K - 3	Three-phase bus transfer between utility and PV	5
K - 4, 5, 6	Single-phase transfer (single-phase utility on/off)	2 (3 ea.)
K - 12	Connects inverter to DC main	5
K - 18	Connects array bus to DC main	5
K - 19, 20	Connects battery A, battery B banks to DC main	4 (2 ea.)
K - 21	Power Dump Switch: R_1	1
K - 22	Power Dump Switch: R_2	1
K - 23	Power Dump Switch: R_3	2
K - 24	Power Dump Switch: R_4	3
K - 25	Power Dump Switch: R_5	4
K - 26	Power Dump Fans	1
K - 29	Connects DC motor (starter) to DC main	4

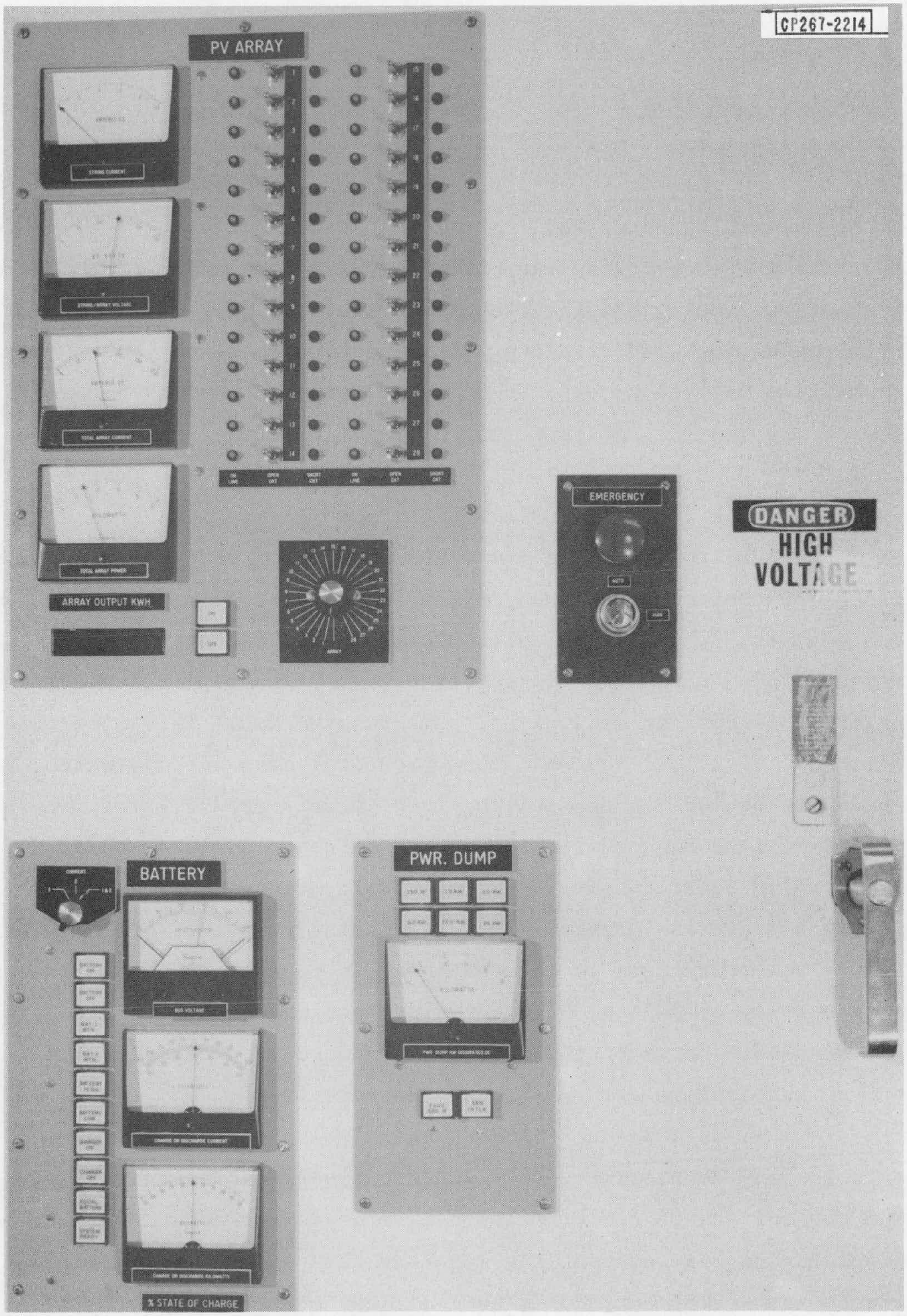


Fig. III-13. Right door of Hoffman cabinet.

IV. FINAL SYSTEM CONFIGURATION:

Subsequent to its initial period of operation, the Mead system has undergone several major modifications with other modifications currently under development. An interim three-phase power source consisting of a DC motor and three-phase alternator was installed in early October, 1977, to provide power to the two crop-drying fan motors pending completion of the inverter. After about six weeks, the inverter was installed and checked out, relegating the motor-generator with its lower efficiency to a standby role. Removal of the M-G set will be accomplished in the early spring (1978), and the details of its control and operation will not be further discussed in this report.

Following the inverter installation, a solid-state control chassis (now dubbed "solar controller") was installed which, for practical purposes, replaces the manual control mode for most of the front-panel selection switches at the Hoffman cabinet. In addition, the unit accomplishes certain system management functions through hard-wired logic circuitry. Finally, it enables the interfacing to a microprocessor, if desired, at some future time. (This will be described below in some detail; a somewhat more technical description, which provides the rationale behind its design, is given in Reference 4.)

Modifications planned for the near future include the addition of an Uninterruptible Power Supply (UPS) and modifications to the power dump to facilitate its use in gathering I-V data on the array. (The installation of Maximum Power Trackers to the system would increase the available power out of the array by 20% to 30%, depending upon insolation, ambient temperature, and the state-of-charge of the battery.) However, no decision has yet been reached on the implementation of such trackers.

Figure IV-1 is a block diagram showing the expected configuration of the system following completion of the modifications, including the two maximum power trackers (if a decision is made to implement them) listed above. This bus now includes the input to the power dump, to which a sixth resistance step (0.87-ohm, 25-kW nominal) has been added.

As of 1 November 1977, the three-phase inverter was able to power

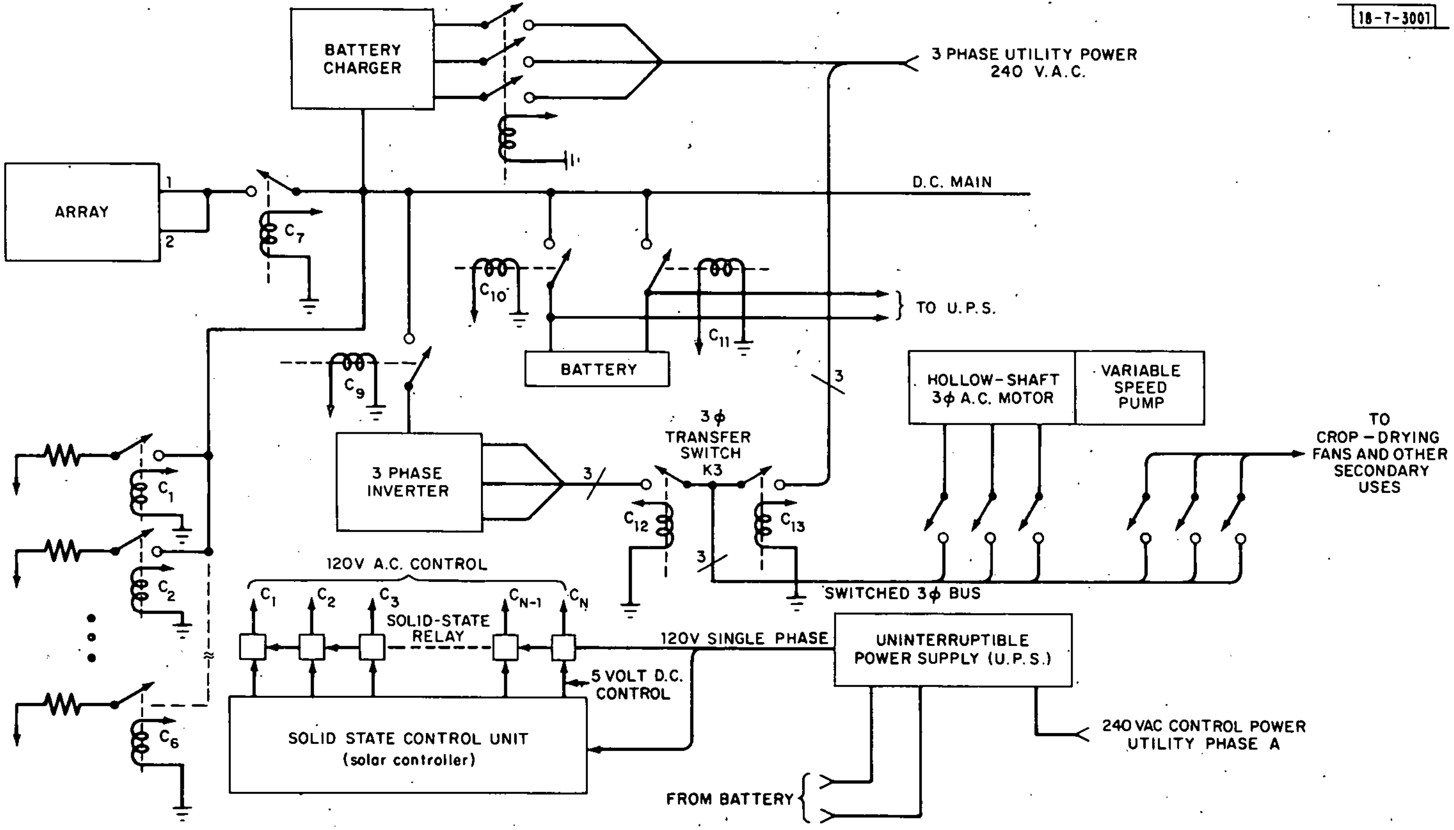


Fig. IV-1. Block diagram of the planned configuration of the Mead system.

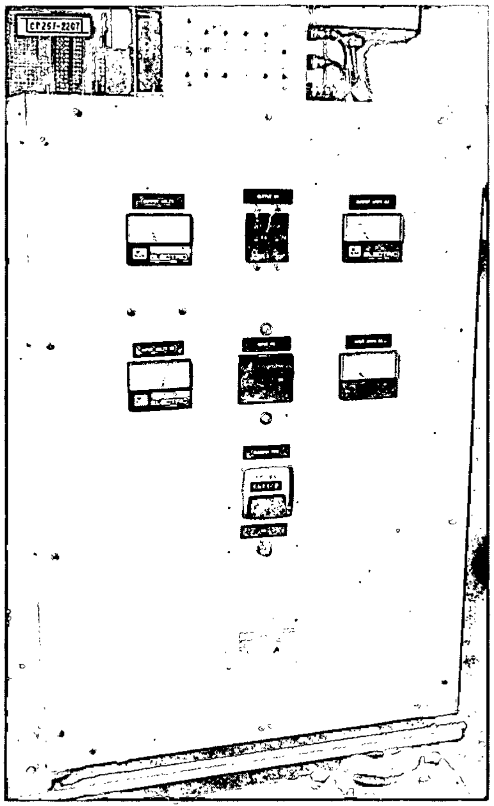
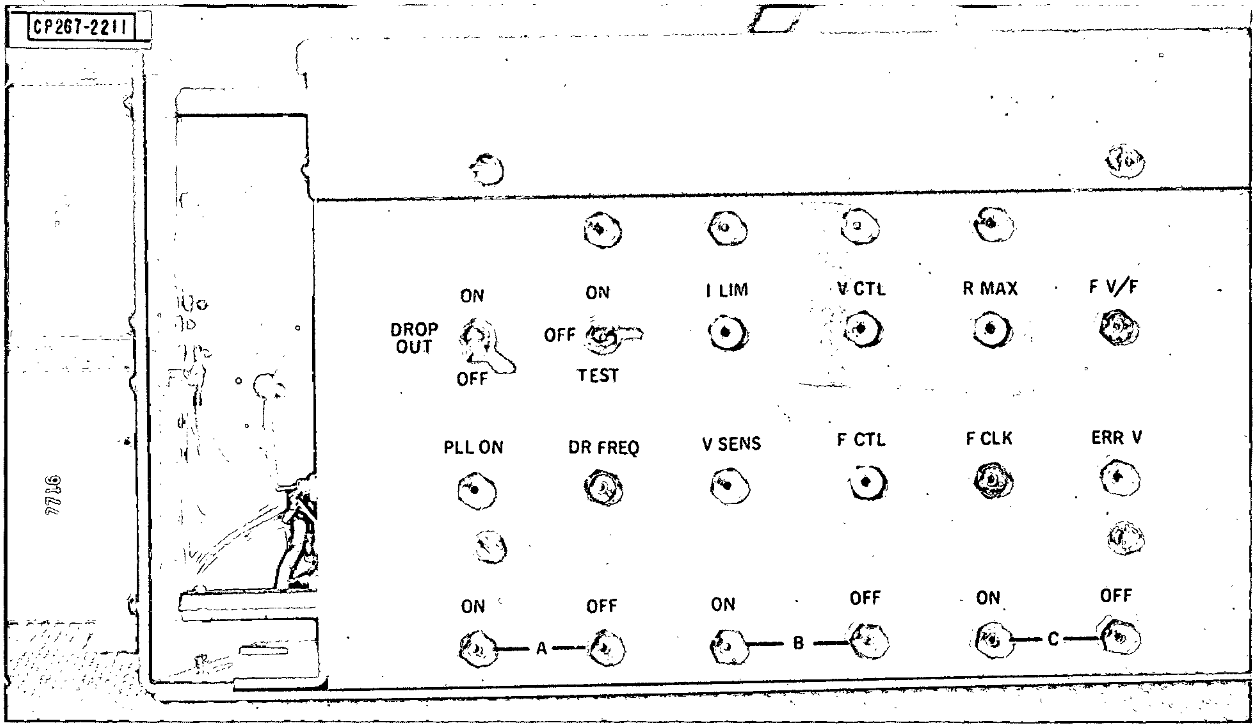


Fig. IV-2. (left) The inverter master power unit.

Fig. IV-3. (below) Close-up of inverter control chassis.



the AC irrigation pump motor. Thus the irrigation pump will, in the future, be driven directly by a three-phase, hollow-shaft induction motor replacing the pulleys, belts and gear-head of the initial system. In addition, control of the system is now exercised by the Solar Controller (SC), which actuates solid-state relays; the latter then exercise direct control of the relay and contactor coil power. This system bypasses the auxiliary holding contacts which were needed for push-button control of the large contactors when in the manual mode.

Finally, the SC and all relay and contactor coil power will soon be supplied from an Uninterruptible Power Supply (UPS) which will eliminate system crashes due to brief interruptions of the utility service, as is currently the case. These modifications will now be described in greater detail.

A. Three-Phase Inverter:

The inverter consists of three separately housed power units containing SCR switches, inductors and filters, all controlled and maintained in proper phase by custom logic circuitry designed and constructed at Lincoln Laboratory. The bulk of the control logic is housed in a central nest, complete with its own power supply driven from single-phase, 60-Hz power furnished by the utility (ultimately from the UPS). The nest is mounted atop the housing of the A (master) power unit. In addition, there is a Lincoln Laboratory-designed logic board in each power unit which provides drive pulses to the SCR's. The master power unit together with a close-up view of the control logic chassis is shown in Figures IV-2 and IV-3.

These units were purchased from NOVA Electric Mfg. Co. in Nutley, New Jersey, as constituents of a three-phase, 22.5-kVA inverter, NOVA Model 22.5K-3/6-120. In reality the power units were single-phase inverters with phase control circuitry added. Specified full-load efficiency is 87% to 91%, depending upon DC-input voltage.

Although the inverter as delivered by NOVA was specified to start a 10-HP, three-phase, code J induction motor, the unit failed to start the 10-HP induction motor at the Mead site. In order to accommodate the very large current transients which result during full-voltage motor starting, it became necessary to discard all of the NOVA-designed control logic and replace it with a more sophisticated logic* which creates a variable frequency, variable-voltage start-up sequence, bringing the motor up to speed in a current-limited condition. Figure IV-4 is a block diagram of the inverter master logic. A brief description of its operation follows.

A ramp control circuit is the basis of the motor starting sequence. The ramp control generates a slowly rising control voltage originating at zero and going to +10 volts. An inverting amplifier provides a synchronized control voltage which starts at +10 volts and decreases to zero volts. Adjustable portions of these ramps are summed and used to control the inverter frequency and voltage. A voltage-to-frequency converter circuit changes the control voltage to a corresponding frequency which is appropriately divided and used to generate the output power pulse turn-on times which are spaced 60° electrically from one another (two pulses per phase per cycle are generated). The error amplifier controls an analog-to-digital converter, the digital output of which is proportional to the integral of the difference between the inverter output voltage and the ramp control voltage. The integrated error number is loaded into a register every time the corresponding output power pulse is turned on. A constant frequency clock counts this number down to zero which terminates the output power pulse. A fast-acting output over-current detector and a low-bus-voltage detector are used to instantly terminate the power pulse and hold the inverter off as long as either condition exists. When these conditions no longer exist, the motor run-up sequence is again initiated.

The duration of the control ramp can be adjusted over wide limits to accommodate a variety of loads. At present, the ramp duration is set to one minute, consistent with the large inertia of the crop-drying fans.

B. Modifications to the Power Dump:

The Mead system design was based on the premise that adequate array performance data could be obtained by the periodic measurement of short-circuit

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*Designed by E. E. Landsman of Lincoln Laboratory.

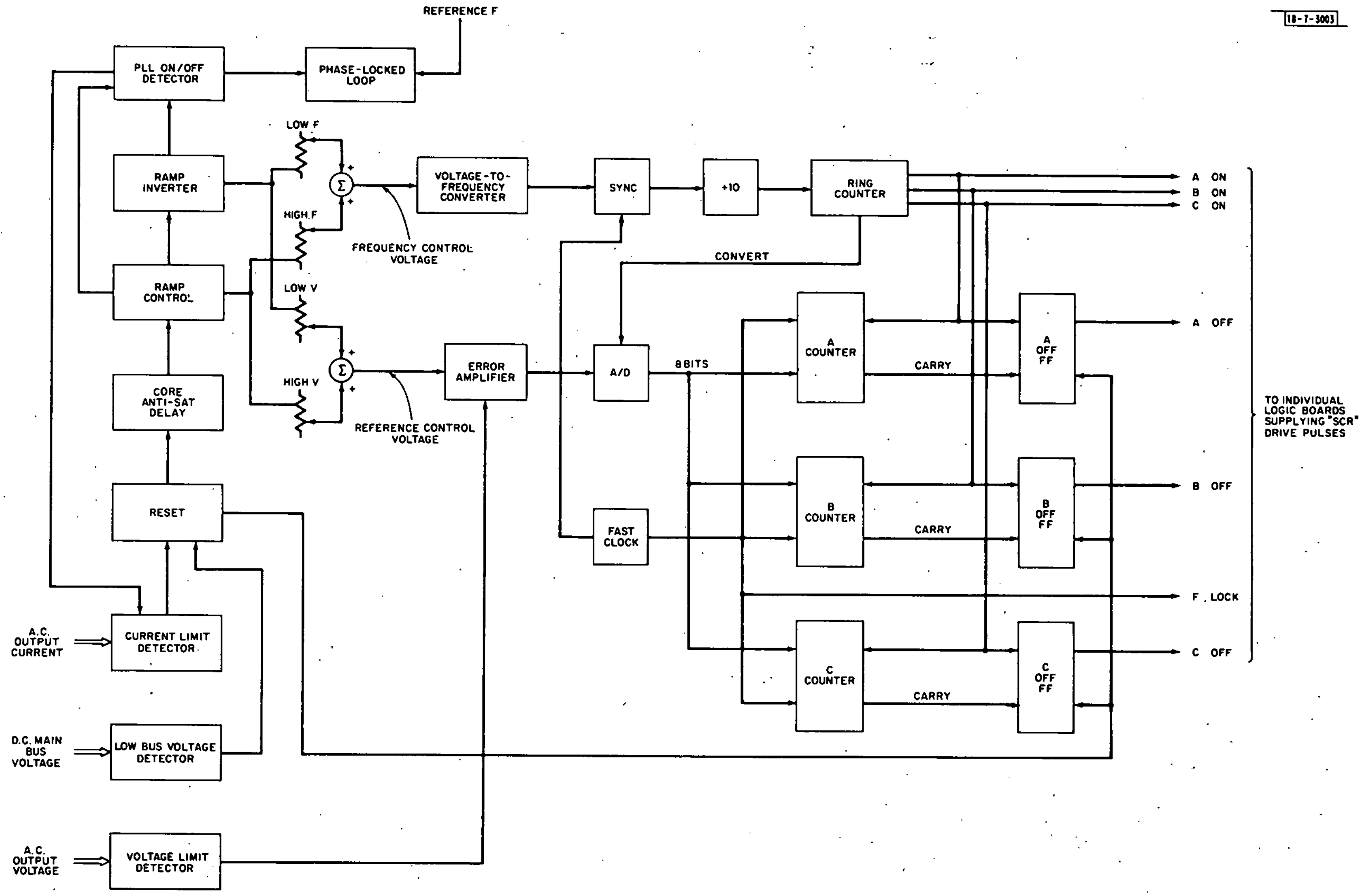

Fig. IV-4. Block diagram of inverter control logic.

current and open-circuit voltage of each string. The capability has been provided for as previously described in Section III-G. However, during the brief period that the system has been in operation, a need for obtaining complete I-V curves has become evident. By adding a sixth 0.87-ohm resistance value to the power dump, an adequate set of I-V data can be obtained for each string by using the power dump to load the entire array and disconnecting the battery from the bus.

To plot meaningful I-V curves, the data must be obtained under conditions of high and constant-intensity insolation. Therefore, the data must be gathered rapidly, with simultaneous pyranometer and temperature measurements being taken to allow the normalization of the I-V data to standard conditions. By using the power dump as a load, and measuring the individual string currents and common bus voltage, along with pyranometer and temperature data automatically through the data logger, reasonably good results should be obtained. By reconfiguring the bus structure as shown in Figure IV-1, I-V data can be gathered without interruption to the power system by opening the tie between the array bus and the DC main. The battery will support the load during the short period necessary for I-V data taking.

C. Solar Controller:

Figure IV-5 shows the front panel of the SC* as it currently exists. The originally assigned name "MANUAL CONTROL PANEL" is inappropriate for several reasons. For one thing the logic contained in the unit is capable of producing automatic control of the battery charge and discharge cycling, and of transferring load from photovoltaic power to utility power (or vice versa) as a function of the battery voltage. For another, the key switch on the Hoffman cabinet passes control to the SC when set to the "Automatic" position.

The layout of the panel no longer correctly reflects the functions performed by SC; it is therefore planned to replace it with a redesigned

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*Designed at Lincoln Laboratory by A. R. Millner.

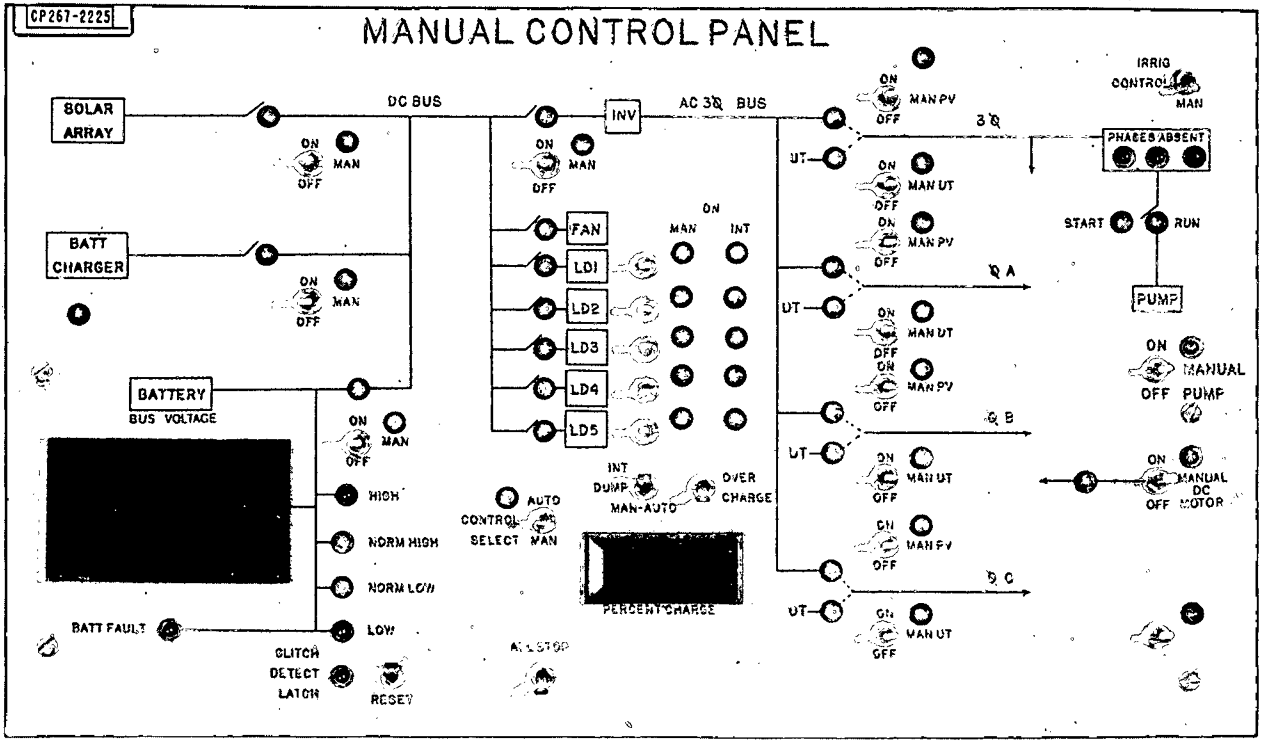

Fig. IV-5. Solar controller front panel.

panel which more accurately defines these functions. The following paragraphs will describe the present capabilities of the controller; panel switches and/or lamps which are no longer relevant to system operation will be ignored.

Referring again to Figure IV-5, it will be seen that the panel contains two digital panel meters. The larger (to the left) displays battery voltage; the small (center) reads the output of an integrating ampere-hour meter calibrated as a percent of battery full charge. This circuit is not yet properly adjusted; the displayed state-of-charge is therefore not a meaningful value.

A toggle switch marked "AUTO" above and "MAN" below the switch lever (seen to the left of the "percent charge" panel meter) provides for microprocessor control; in the AUTO position, most of the panel switches are disabled. In the MAN (manual) position, these switches duplicate push-button switches on the doors of the Hoffman cabinet. Switch functions are indicated in most cases by the line diagram on the panel, and by small lamps indicating the actual status of the system as well as the status of the switches; these can differ if the SC is in AUTO mode.

On the left side of the panel are switches to control the array bus (i.e., actuate K18 Figure IV-1), the battery (K19, K20) and battery charger. In the center are switches to put the inverter on the main DC bus (K12), and to switch on or off the power dump fans and loads (K21 through K26). The next to the right column of switches provides for switching of the three-phase AC bus between the photovoltaic (the inverter output) and the utility power line; and for energizing the three single-phase buses which supply control power (phase A) as well as power for lighting, heating and cooling of the battery and equipment trailers. The original system design provided for single-phase power, like the three-phase power, to be supplied either from the photovoltaic system or from the utility, as appropriate; this feature has been dropped so that the single-phase power is always taken from the utility.

At the bottom of the panel center are two switches marked "REST" (meaning "RESET") and "ALL STOP". The latter duplicates the function of the panic switch on the Hoffman cabinet; it shuts down the entire system and takes the array, battery, and inverter off the main DC bus. The same function will be triggered automatically by drop-out of the glitch-detect latch whose indicator lamp is seen on the immediate left of the RESET switch if the 5-volt power to the logic is interrupted.

The RESET switch resets the glitch-detector latch and the battery-fault indicator. It also presets the power dump to whatever state is manually set in by the switches.

All of the switches and lamps on the extreme right side of the panel are irrelevant to the present modes of operation of the system.

Automatic Functions of the SC:

The automatic functions which are performed by the SC logic are as follows:

1. The battery voltage is normally constrained to remain within manually adjustable limits defined as "NORMAL HIGH" and "NORMAL LOW".

The presently chosen values for these limits are 146 volts and 110 volts, respectively.

2. Should the battery exceed either of these limits and progress to a HIGH HIGH or a LOW LOW limit (marked simply "HIGH" or "LOW" on the panel), the system will be taken off line in the same manner as for the ALL STOP (PANIC) switches. In the following discussion, the battery "HIGH" limit will be referred to as "HIGH HIGH". Similarly, the "LOW" limit will be designated "LOW LOW". Nominal values are 152 volts and 100 volts, respectively.

3. Whenever the photovoltaic system is furnishing power to a three-phase load and the battery voltage drops to the "NORMAL LOW" threshold, the load is transferred to utility power and the inverter is shut off. Conversely, if load is being supplied from the utility and the battery charges to a voltage equal to the "NORMAL HIGH" threshold, the load will be transferred to the photovoltaic AC power bus and the inverter simultaneously turned on.

Management of the battery voltage, in essence, consists of removing load when the battery reaches a suitable depth of discharge and allowing the photovoltaic array to recharge the battery to a near fully charged state before reapplying load to the PV system. When the battery voltage exceeds the "NORMAL HIGH" threshold, it will pick up any three-phase load on the system, i.e., any three-phase load will be transferred from the utility bus to the PV bus. At the same time, if the DUMP switch (seen just above the PERCENT CHARGE panel meter) is set to the INT (internal) position, the power-dump loads will be programmed onto the bus sequentially in 800-watt steps. This process will continue until the battery charge current falls to zero. At that time, a logic level in the above mentioned state-of-charge circuit will switch state. This bit is used to inhibit further incrementing of the power-dump load. Assuming that the battery voltage then gradually drops as power is drained off, both by three-phase load (irrigation, crop drying, etc.) and/or by the power dump, the power-dump load will gradually be decremented, step-by-step, until it has been entirely removed.

Initial implementation of the above described logic revealed problems. For one thing, it was found that the rate at which the power dump was programmed onto the DC main bus (two seconds per 800-watt step) was too slow to hold down the battery voltage during periods of strong insolation. Consequently, battery voltage would climb to the HIGH HIGH limit, taking the entire system off line. Increasing the clock rate did not solve the problem, since the system would then proceed to hunt (oscillate) back and forth across the NORMAL HIGH threshold, imposing unacceptable cycling of the power dump switchgear.

Three logic changes were implemented to overcome these problems:

1. A selection of clock rates between 0.2 seconds and 2.5 seconds per tick was provided, such that the rate of incrementing power dump could be different (faster) than the rate of decrementing. (Both are selectable.)

2. Hysteresis was designed into the power dump increment/decrement logic so that within a dead band of approximately 3 volts above the NORMAL HIGH threshold, the power dump would neither increment nor decrement, provided that the battery charge bit was not set true (battery charging).

3. A third clock, referred to as the "Safety Clock", was installed. Now, when the HIGH HIGH threshold is tripped, the safety clock is allowed to increment a 5-bit counter, only when the counter overflows is the system taken off line. Like the power-dump increment and decrement clocks, the clock rate of the safety clock is selectable.

The above described logic has now been implemented and tested in the system with apparent success. During periods when the system power usage is light (crop-drying fans are running for only brief periods), the battery reaches a fully charged state. During periods of intense insolation, the power dump is then obliged to absorb the photovoltaic energy. In these circumstances, it sometimes happens that the sun will be briefly obscured by a cloud; insolation will decrease and the battery voltage will drop sufficiently for the power dump to decrement to zero. If the insolation increases rapidly as the cloud drifts away, the battery voltage will climb very rapidly to the HIGH HIGH threshold. In this circumstance, the safety clock allows time for the power dump to program itself on-line and to pull the battery voltage down to its normal HIGH condition.

D. Uninterruptible Power Supply:

The addition of an UPS to the Mead system was contemplated during its initial design but omitted because of the time constraint. Experience has shown that the utility power at Mead is extremely unreliable with frequent (usually brief) interruptions in service. Since the control subsystem as

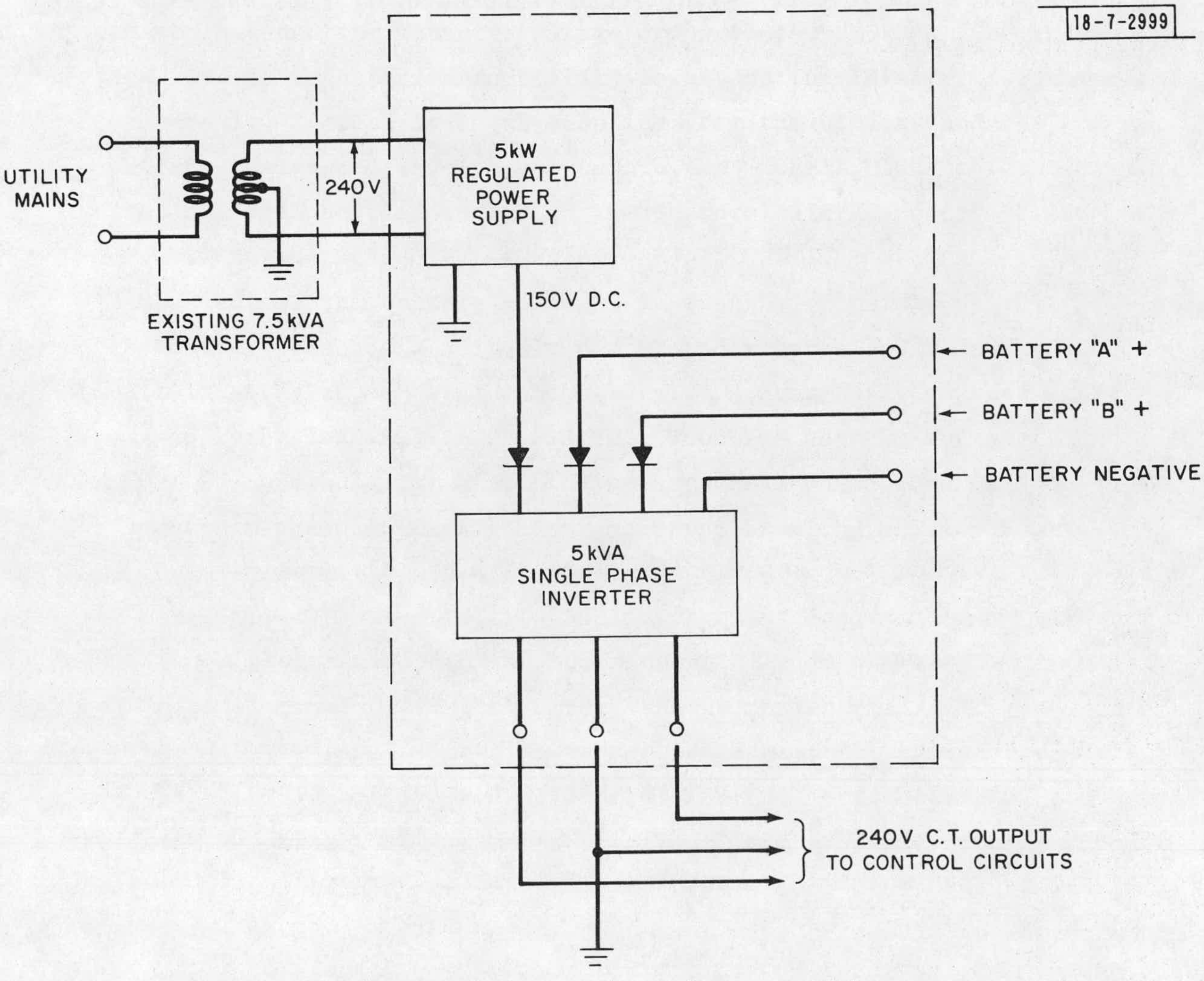

Fig. IV-6. Block diagram of the uninterruptible power supply.

well as the data acquisition depends upon utility power, any outage, however brief, takes the system down and terminates system control and data gathering pending manual re-setting. As a consequence of these problems, the addition of an uninterruptible supply, using the existing main battery as the backup power source, assumes a high priority.

Figure IV-6 shows how the UPS will be implemented. Under normal circumstances, the UPS 5-kW inverter will be fed from the utility-driven power supply, whose output will be regulated at 150 volts (above the battery's NORMAL HIGH threshold). Whenever the utility power fails, battery power will continue to drive the inverter with little or no cutover transient experienced by the control system.

V. FUTURE SYSTEM APPLICATION

The preceding is an attempt to provide a simple description of the Mead Power System. A great deal of useful engineering experience was obtained during its construction and initial period of application and will be reported elsewhere. Additional significant information remains to be acquired.

Broadly speaking, future use of the Mead system will yield at least four kinds of useful data (or experience):

1. On-site performance of the particular solar modules and/or other modules which may be retrofitted in the future.
2. Basic data on the utility and the ultimate economic viability of photovoltaic energy in an agricultural application. It is expected the an optimum mix of various seasonal uses may eventually be selected.
3. Data on the preferred system control techniques.
4. Long-term insolation records and other specific weather data relevant to module performance and aging.

The extraction of this information will not come without cost. Data acquisition and its systematic reduction will require the continued attention of skilled data processing personnel. Responsibility for the intelligent on-site management and utilization of the system must ultimately rest with the University of Nebraska. Continued periodic evaluation of the solar modules by direct inspection (as well as regular electrical testing) must be carried out by trained personnel. Finally, overall assessment of system performance will probably remain the responsibility of electrical engineers who are thoroughly familiar with the equipment and with the goals of the program.

VI. ACKNOWLEDGEMENT BY AUTHOR

The initial implementation of the Mead Photovoltaic Power System, described herein, was accomplished during a seven-month period only as a result of extreme dedication on the part of a large number of individuals. It would not be possible to credit each one by name; nevertheless, it seems appropriate to single out a few of the key contributors.

- Indispensable contributions to the overall system design, the inverter control circuitry design, and implementation were made by E. E. Landsman.
- The metering electronics was largely designed by and constructed under the direction of R. F. Hopkinson.
- The electrical power circuit layout was largely accomplished through the efforts of J. T. Kelly.
- The solar module layout planning, as well as the mechanical system design and installation, were the responsibility of A. E. Benoit.

Each of the above individuals made essential contributions to the system. In addition, the data logging and recording system design and implementation were effected by J. D. Cremin, aided by H. A. Fenton and R. F. Hopkinson.

Finally, the rapid deployment of this system at Mead was made possible in no small measure by the efforts of Professor Paul Fischbach and his assistants at the University of Nebraska Agricultural Engineering School.

Sincere thanks are extended to all of the above, as well as the many others whose efforts are not credited by name.

VII. REFERENCES

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