

N77-22609

ERDA/NASA 1022/77/12  
NASA TM X-73641

ERDA/LEWIS RESEARCH CENTER PHOTOVOLTAIC  
SYSTEMS TEST FACILITY

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April 1977

Prepared for  
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION  
Office of the Assistant Administrator for  
Solar, Geothermal, and Advanced Energy Systems  
Division of Solar Energy  
Under Interagency Agreement E(49-26)-1022

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1. Report No. <b>NASA TM X-73641</b>	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle <b>ERDA/LEWIS RESEARCH CENTER PHOTOVOLTAIC SYSTEMS TEST FACILITY</b>		5. Report Date <b>April 1977</b>	
		6. Performing Organization Code	
7. Author(s) <b>A. Forestieri, J. Johnson, W. Knapp, H. Rigo, J. Stover, and R. Suhay</b>		8. Performing Organization Report No. <b>E-9147</b>	
		10. Work Unit No.	
9. Performing Organization Name and Address <b>Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135</b>		11. Contract or Grant No.	
		13. Type of Report and Period Covered <b>Technical Memorandum</b>	
12. Sponsoring Agency Name and Address <b>Energy Research and Development Administration Division of Solar Energy Washington, D. C. 20545</b>		14. Sponsoring Agency Code Report No. <b>ERDA/NASA 1022/77/12</b>	
		15. Supplementary Notes <b>This report was prepared under Interagency Agreement E(49-26)-1022.</b>	
16. Abstract  <b>A national photovoltaic power systems test facility (of initial 10-kW and final 40-kW peak power rating) is described. It consists of a solar array to generate electrical power, test-hardware for several alternate methods of power conversion, electrical energy storage systems, and an instrumentation and data acquisition system. The facility was built for and is operated in support of the ERDA National Photovoltaic Conversion Program by the NASA Lewis Research Center.</b>			
17. Key Words (Suggested by Author(s))		18. Distribution Statement <b>Unclassified - unlimited STAR category 44 ERDA category UC-63</b>	
19. Security Classif. (of this report) <b>Unclassified</b>	20. Security Classif. (of this page) <b>Unclassified</b>	21. No. of Pages	22. Price*

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SUMMARY

A national photovoltaic power systems test facility (of initial 10-kW and final 40-kW peak power rating) is described. It consists of a solar array to generate electrical power, test-hardware for several alternate methods of power conversion, electrical energy storage systems, and an instrumentation and data acquisition system. The facility was built for and is operated in support of the ERDA National Photovoltaic Conversion Program by the NASA-Lewis Research Center.

INTRODUCTION

Photovoltaic power systems for many applications envisioned by the ERDA National Photovoltaic Conversion Program present new engineering challenges. As requirements for these systems emerge and plans for appropriate tests and demonstrations are proposed, a facility is required to breadboard and test various designs and concepts. Data is needed to evaluate photovoltaic systems, subsystems, and components design methods, operating characteristics,



and overall performance. A breadboard photovoltaic systems test facility should provide a versatile deployment of basic equipment to permit reconfiguration for a variety of possible alternate systems. Also, it should accommodate simultaneous testing of two or more photovoltaic power system designs.

This report describes the ERDA/LeRC Photovoltaic Systems Test Facility (STF), located at the Lewis Research Center, which meets the above-outlined needs. The facility was built for, and is being operated, in support of the ERDA National Photovoltaic Conversion Program.

#### OVERVIEW

The ERDA/LeRC Photovoltaic Systems Test Facility is structured around two basic parts: a photovoltaic power system (PPS) and an instrumentation and data acquisition system (IDAS). Figure 1 shows the basic elements of a PPS. Included are a solar cell array, energy storage equipment, power conditioning equipment (inverter, battery charger, controls), electrical loads, and electric utility interface equipment. The IDAS includes transducers for measuring electrical parameters (voltage, current, power, reactive power), temperatures, weather parameters (windspeed, wind direction, air temperature, humidity), and insolation. It also includes data logging equipment and an interface with data storage and processing facilities.

Two basic PPS have been prepared for use in the initial operation of the ERDA/LeRC STF. The first PPS (Figure 2) consists of a solar array with output filter and a 60-Hz single-phase line-commutated inverter which is transformer coupled to an electric utility distribution network.

In Figure 3 is shown the second PPS prepared for initial operation with the STF. It consists of a solar array with output filter, an electric storage battery, battery charger, and a 60-Hz single-phase self-commutated inverter which is transformer coupled to its load. Inherently this type of PPS permits operation without interconnection with an electric utility grid. The inverter initially used was not designed for parallel operation with a utility grid. A self-commutated inverter that would permit parallel operation is under development. In Figure 3, the loads are automatically switched from the PPS to the utility grid when the photovoltaic system is unable to supply the load.

The ERDA/LeRC STF is located near the LeRC Energy Conversion Laboratory, which houses photovoltaic research facilities and other facilities related to the ERDA/LeRC Photovoltaic Tests and Applications Project. Figure 4 shows a retouched aerial view of the STF area. In it are depicted eight rows of a 4-foot-by-8-foot south-facing inclined flat solar cell panels that will comprise the 40-kW peak power solar array when complete. Also shown are two trailers which house system controls, instrumentation, and electric equipment. Near the trailers can be seen also an electric storage battery shed and an electric utility distribution substation.

The photograph in Figure 5 shows a ground level view looking east along the most southerly row of the solar array, with one equipment trailer visible in the background. In Figure 6 is a closer view of the trailers and adjacent battery shed. The series solar cell strings are separately wired into the trailers through 20 ducts that extend underground a distance of 350 feet between the array and the trailers.

Layout of STF controls, instrumentation, and electric equipment is shown in the plan view drawing Figure 7. Array series solar cell string and panel wire terminations, output filters, battery chargers, inverters, controls, instrumentation, and utility interface transformers are located within the trailers. Space for additional equipment and instrumentation has been provided. Outside the trailers are two 10-kW resistive load banks, with provision for an additional 20-kW of load bank equipment. In the nearby shed is housed 48-kWh of electric storage batteries.

Figure 8 is a photograph of the inside of the trailer inverter room, showing special instrumentation that was used during initial operation of the STF with the PPS configuration of Figure 2. The 60-Hz single-phase line-commutated inverter can be seen at the left rear, in Figure 8.

Trailer instrument and control panels are shown in Figure 9. In the upper center of the photograph are visible the Hall effect watt-hour meters used in the STF. These instruments are capable of responding to a wide range of frequencies and also provide

signal outputs compatible with the automatic data acquisition system.

### SOLAR ARRAY

In Figure 10 is shown schematically the 40-kW peak power array of 8 rows of 30 4-foot-by-8-foot solar cell panel frames, and the designation of rows and files within the array. The two rows on the south are fitted out with solar cell modules built by three manufacturers; peak power rating of these two rows is 10-kW. The remaining six rows are planned to be fitted out with solar cell modules in 1977.

Figure 11 shows the electrical schematic diagram of 59 solar panels interconnected into series strings for use with the PPS configuration of Figure 2. All modules comprising a series string are from the same manufacturer. Four wires per panel have been provided to the trailers to ensure a versatile electrical configuration. Panel wiring is weatherproof; it is routed along wiring trays, which lie behind each row, and through underground ducts to the equipment and control trailers. Series solar cell strings are connected through isolation diodes, fuses, and disconnect switches to a solar array busbar, inside the equipment trailers. The solar array can be electrically reconfigured to change its output voltage. Also the 40-kW peak power array will be able to

be electrically split into several independent arrays. Figures 12, 13 and 14 show the different types of modules mounted on 4-foot-by-8-foot solar panel frames.

In Figure 15 can be seen the 60-Hz, 120-volt conduit and service outlet boxes provided to the panel rows for construction, maintenance, and temporary field instrumentation power. Also shown are separate conduits to connect eight copper-constantan thermocouples per row (for measuring module temperatures) to the trailers, and for connecting the No. 12 AWG copper panel leads (four wires per panel) in 19 conductor cables to the trailers. Wiring from the field to the trailers is routed underground through twenty 350-foot ducts.

Part of the detail discussed above is also seen in the photograph of Figure 16; also shown is the adjustable elevation angle panel frame. The frames are made of steel channel and are connected through a buried copper cable network and driven ground rods to array field ground. Frame ground is partially to protect the arrays from lightning and partially for personnel safety. The dc terminal cabinets shown in Figure 16 are grounded and locked, also as a personnel safety precaution.

### BATTERIES

The photovoltaic system illustrated in Figure 3, and some other proposed systems require on-site energy storage. Figure 17 shows a

48-kWh electric lead-acid storage battery provided for the STF. The battery cells are of a deep discharge cycle duty type, with lead-antimony positive plate grids and calcium alloy negative plate grids. Loss of positive battery shed ventilation triggers a safety alarm. Plastic acid-resistant trays are provided to contain accidental acid spills. Provisions have been made to expand on-site storage possibly as high as 500-kWh.

The battery may be recharged from either the electric utility distribution network or from the solar array. Commercial battery chargers used for recharging from the utility are shown in Figure 18. Separate chargers are required to recharge the batteries from the solar array; equipment required depends upon the electrical system configuration. For the system configuration of Figure 3, a shunt battery charge controller has been provided.

#### EXAMPLES OF STF CONFIGURATIONS

Basic elements of the STF, a sample PPS and an appropriate IDAS, are illustrated in the two STF configurations shown in Figures 19 and 20.

Figure 19 is a more detailed schematic electrical diagram of the equipment and instrumentation required for testing the photovoltaic power system of Figure 2. Shown is the solar array connected to the single-phase 8-kW line-commutated inverter, which is transformer coupled both to a load bank and to an electric utility distribution network. Also shown are voltage, current, power, reactive power, energy, wind speed, wind direction, insolation, and temperature

transducers deployed to measure system performance. The data logging, storage, and processing interface is shown also.

Similar instrumentation and data interface equipment are shown in Figure 20, which is a more detailed schematic electrical diagram of the gear required for testing the PPS of Figure 3. In this system an electric storage battery and its chargers are used to store energy; here the electric utility distribution network serves only as a standby power source, rather than serving as a parallel source with virtual energy storage capability as it does in the system of Figure 19.

#### INSTRUMENTATION AND DATA ACQUISITION SYSTEM

Table I lists the complement of instruments provided for the two STF configurations illustrated in Figure 19 and 20. Listed are the parameters measured, units of measurement, range, and full-scale output of each transducer; they are listed in the order of data logger channel assignment. Figure 21 shows a block diagram of the initial data acquisition system, which is a Fluke type 2240A data logger interfaced with the LeRC IBM-360 computer. Capabilities of the initial data acquisition system are summarized in Table II.

A micro-minicomputer data acquisition and display system with some control capability (PDP 11/34) has been purchased for dedicated use on STF. It will complement the initial system by providing on-line results during STF operation.

Of particular interest is the provision for energy balance measurements on the sample photovoltaic power systems of Figures 19 and 20. For example, in Figure 20 (and correspondingly in Table I) is shown instrumentation to measure insolation, total energy from the solar array, and energy to the shunt controller, the battery, the load, both to and from the inverter, and from the electric utility. The electric energy measurements are made with Hall effect-type watt-hour meters. These transducers provide a time integrated product of instantaneous circuit voltage and current.

#### SAFETY CONSIDERATIONS

General LeRC safety procedures with regard to both ac and dc circuits of comparable current and voltage are also applicable to the STF. The solar array field is regarded as a dc substation and is enclosed on all four sides by an 8-foot-high chain-link fence. Solar cell panel mounting frames are connected through a buried copper cable network and driven ground rods to array field ground. Negative terminals of the series strings of solar array modules are connected to the array field ground.

Of particular interest are the safety procedures applicable to the solar cell array and its panels. Each series string of the array is connected to the solar array busbar through disconnect switches. These switches are opened and tagged when work is being done on panels within the series strings. Installation, maintenance



and inspection is done on 4-foot-by-4-foot half-panels. Their voltage may be 60 to 180 volts and their current may be as high as  $1\frac{1}{2}$  amperes. Prior to work on a panel the current and voltage are eliminated by shutting off the light to the solar cells. During the daylight this is done by covering the half-panel face with special reinforced black plastic, held in place by elastic cord. Half-panel output terminals are also short-circuited.



TABLE II. - DATA ACQUISITION SYSTEM CAPABILITIES

- 60 full guarded analog input channels, expandable to 1000 channels.
- d-c volts and thermocouple inputs, 40 mV, 400 mV, 4V, 40 V ranges.
- digital inputs with parallel BCD format.
- scan rates  $2\frac{1}{2}$  to 15 channels per second,  $2\frac{1}{2}$  line per second printer.
- paper tape punch interface.
- keyboard programming of range, function, skip, alarm limits, and heading data.
- monitor inputs continuously and record on alarms and/or at predetermined intervals - scan intervals programmable from 1 second to 24 hours.
- program list printout available.

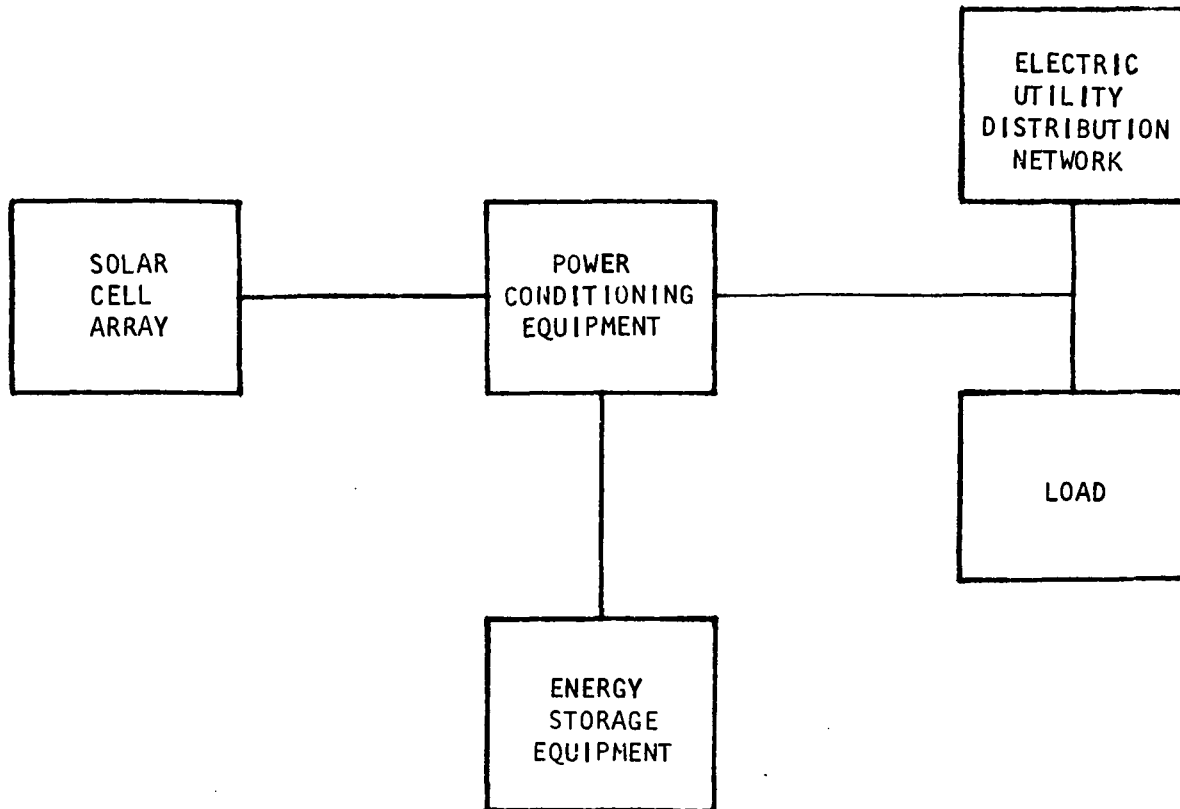


Figure 1. - Elements of a Photovoltaic Power System

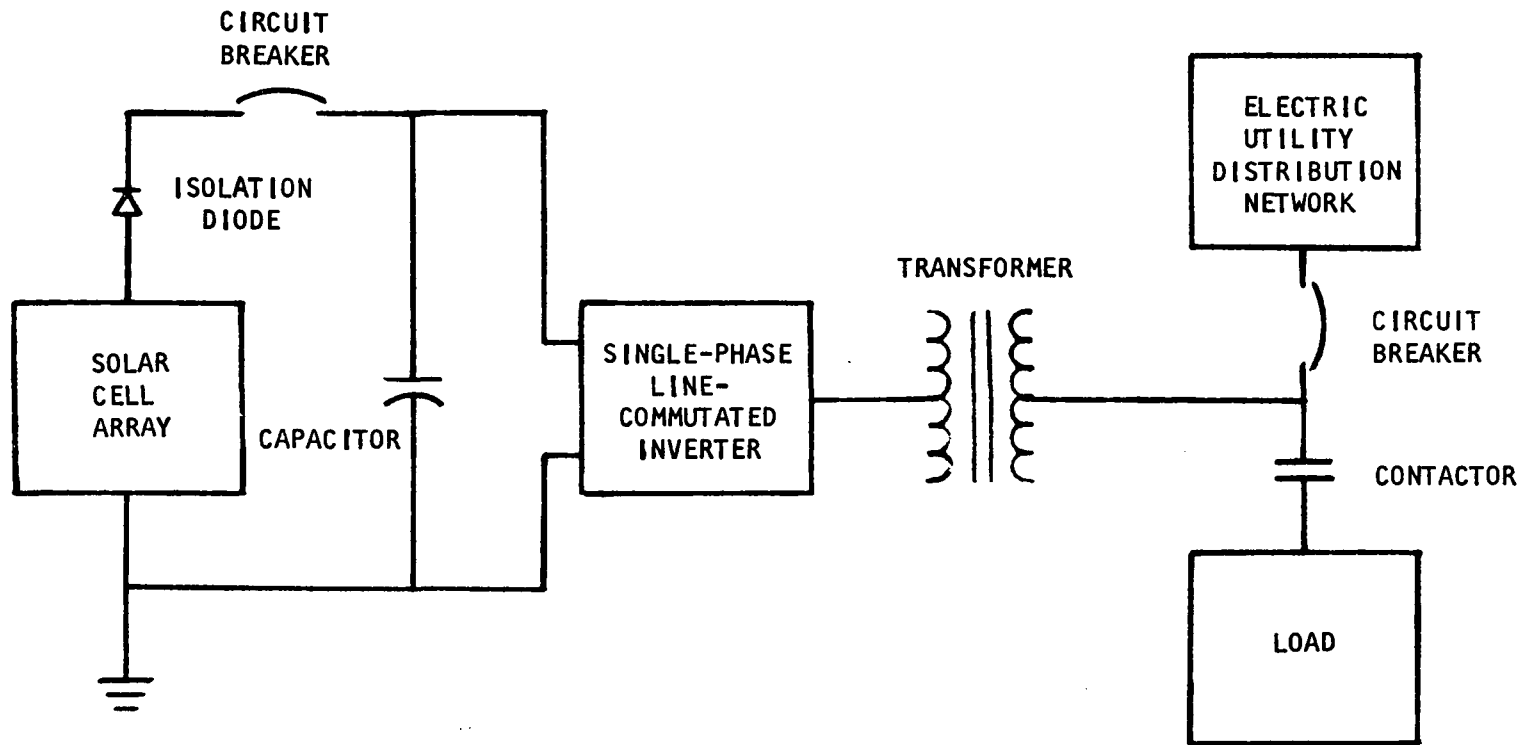


Figure 2. - Basic photovoltaic power system prepared for initial operation of the ERDA/ LeRC Systems Test Facility

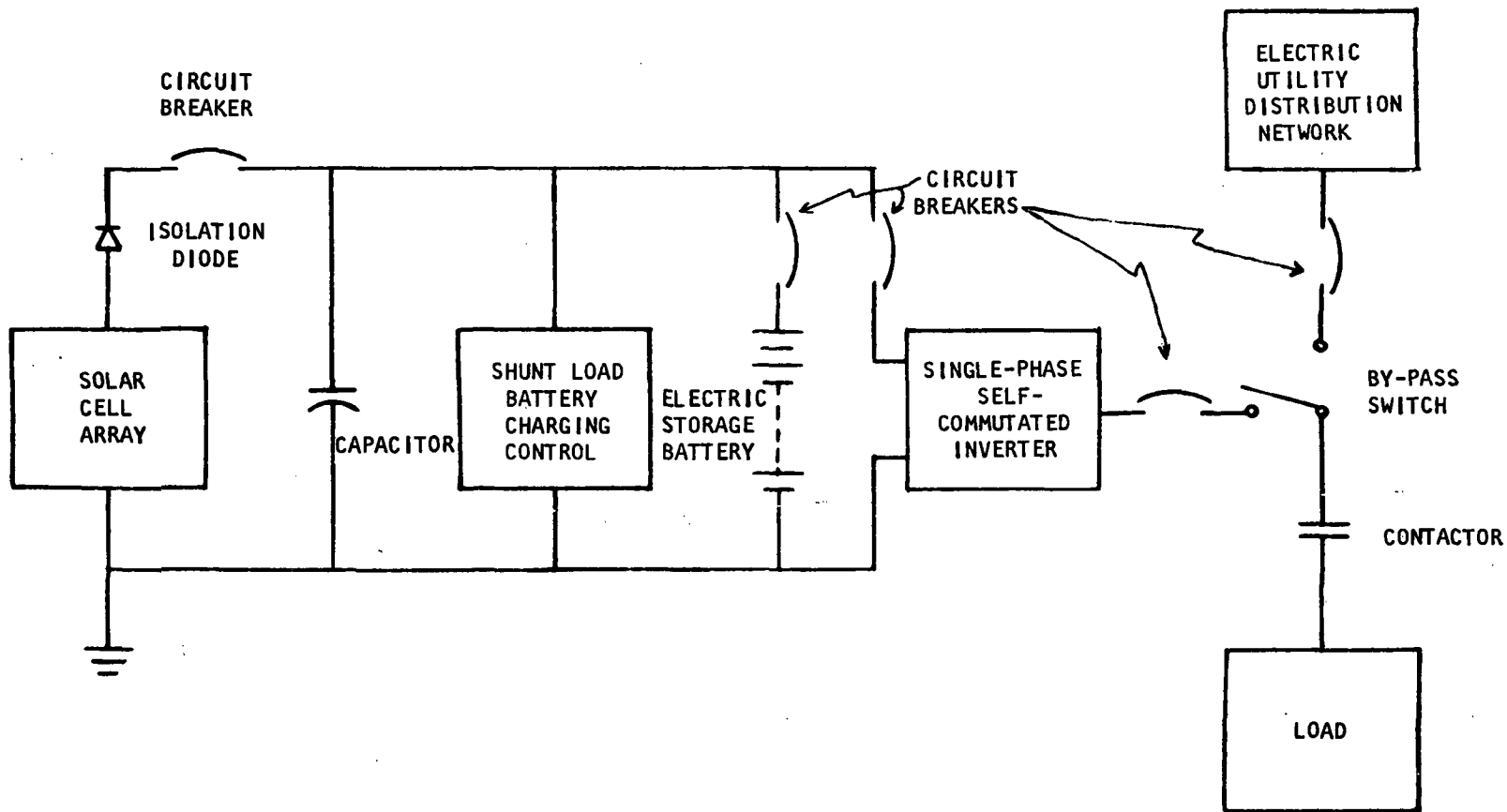


Figure 3. - Alternate basic photovoltaic power system prepared for initial operation of the ERDA/ LeRC Systems Test Facility

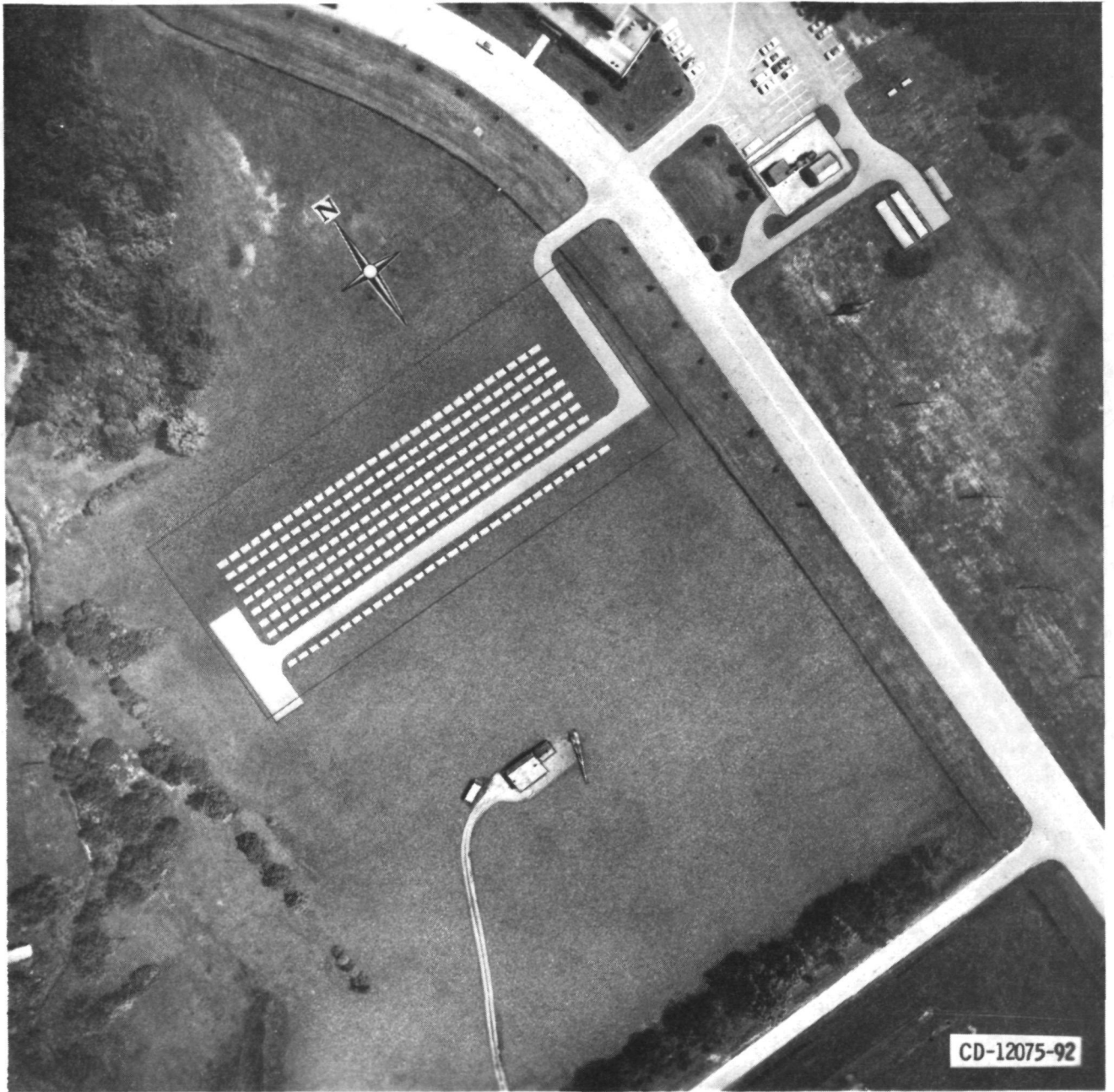


Figure 4. - Aerial view of ERDA/LeRC Systems Test Facility area (retouched)

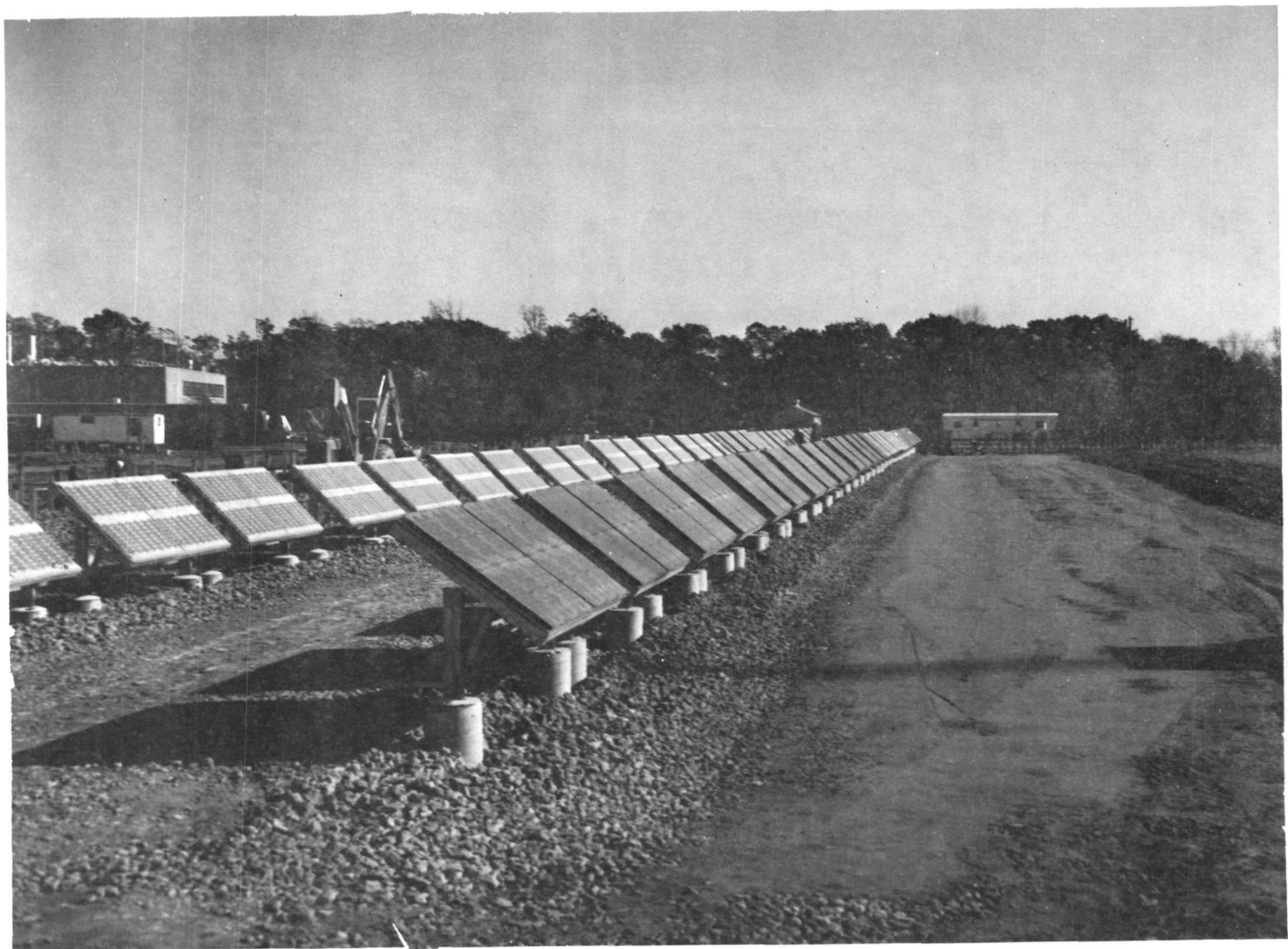


Figure 5. - View along most southerly row of solar array for ERDA/LeRC Systems Test Facility.



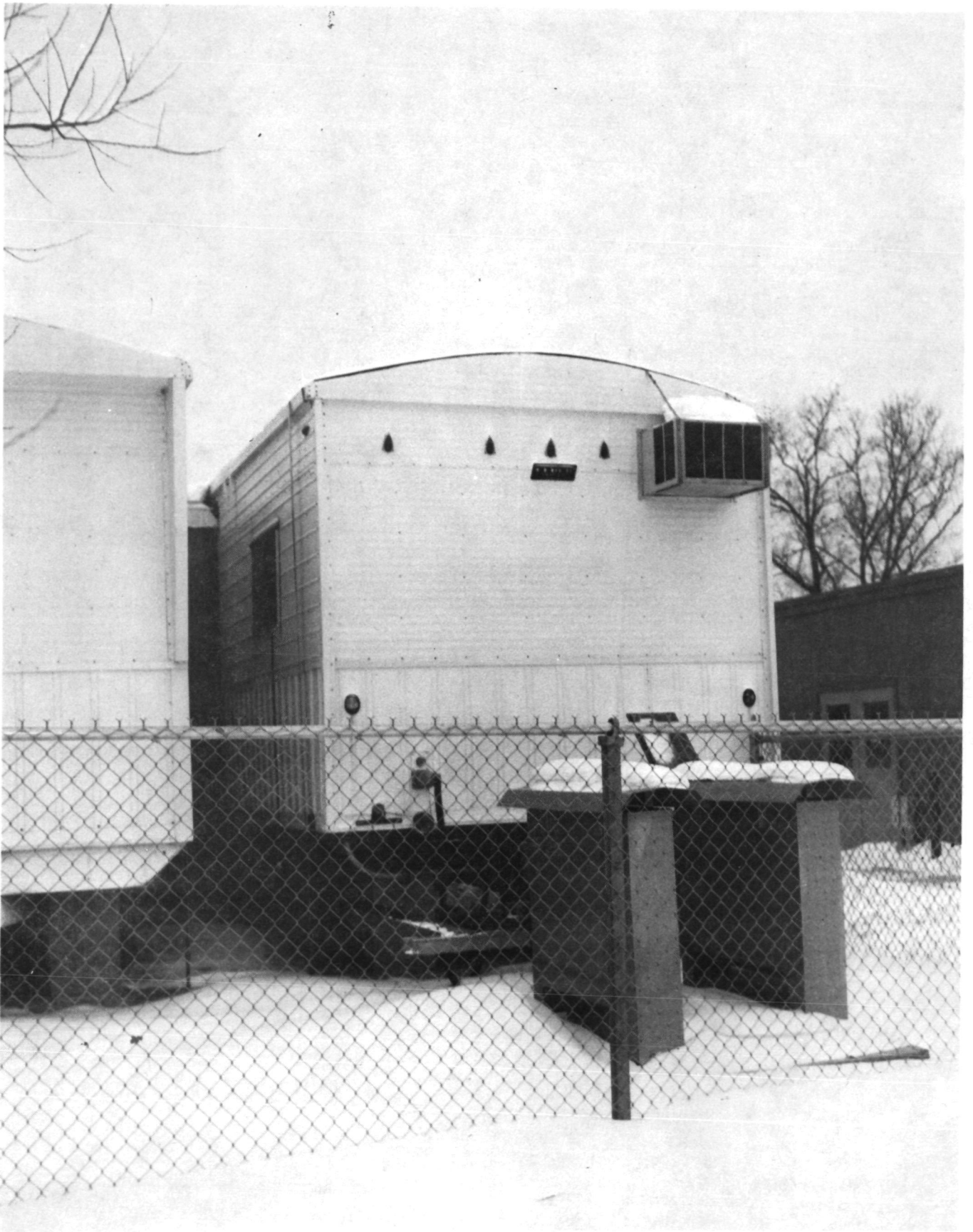


Figure 6. - Equipment trailers and battery shed for ERDA/LeRC Systems Test Facility.

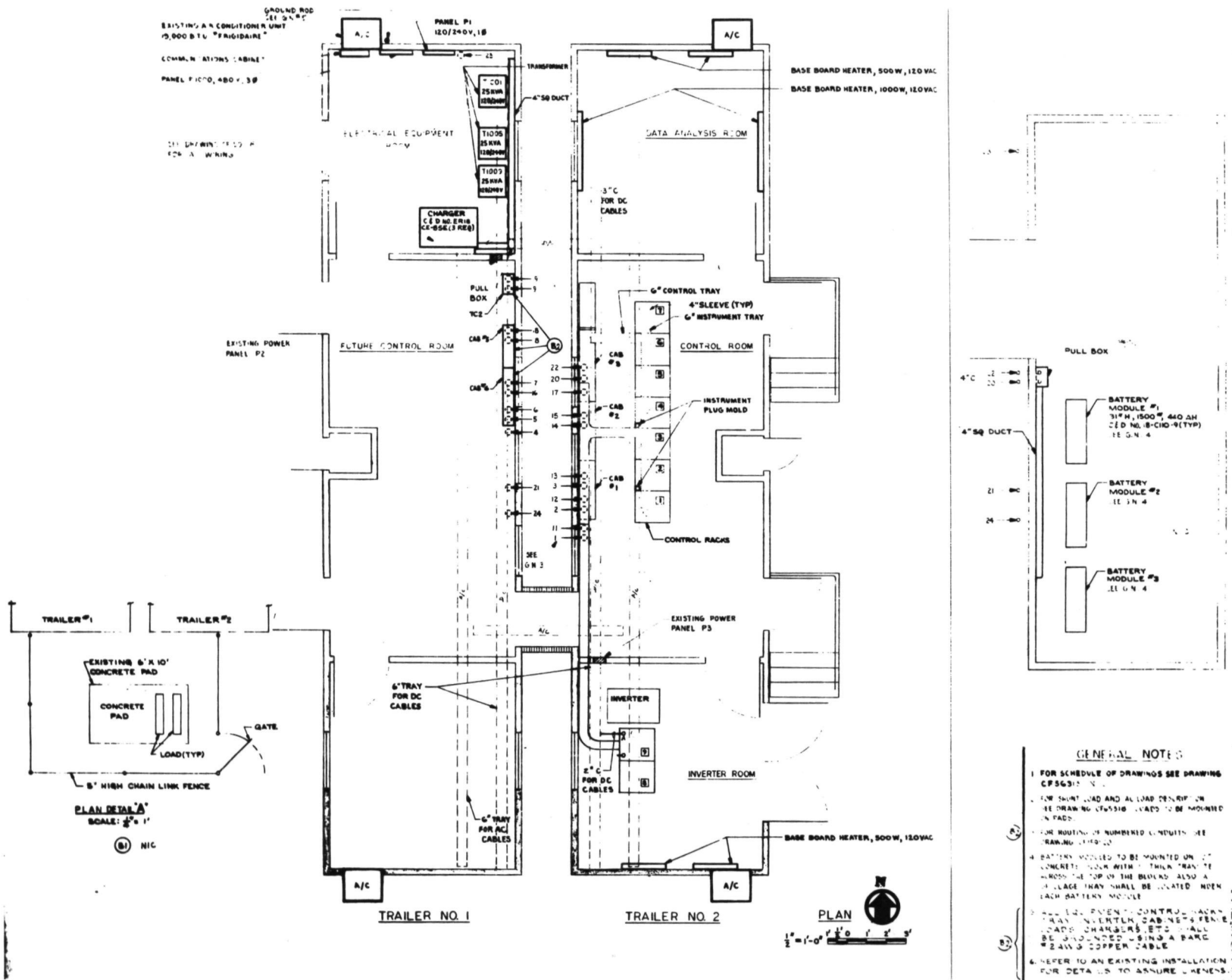


Figure 7. - Trailers and battery shed equipment layout for ERDA/LeRC Systems Test Facility.

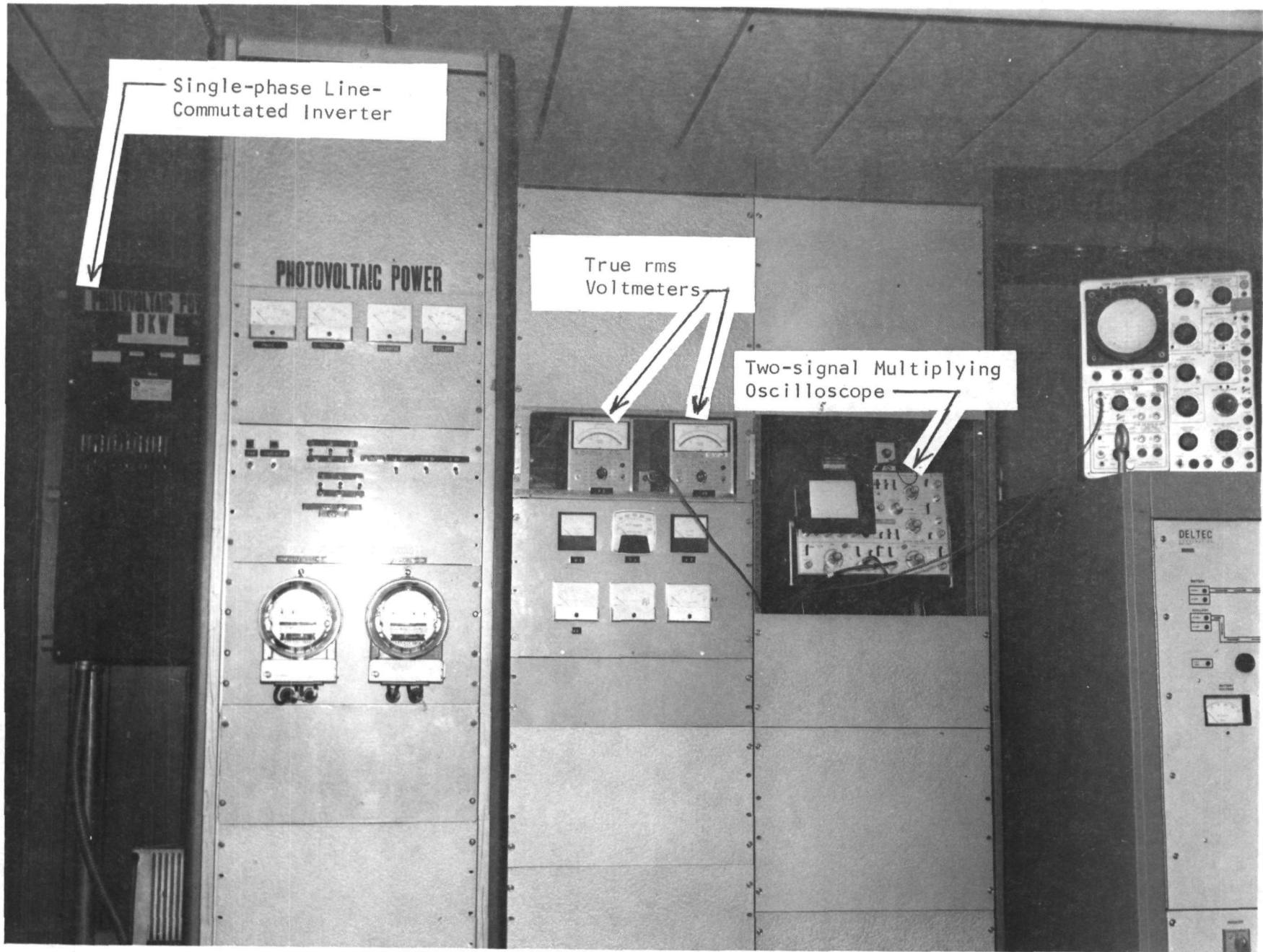


Figure 8. - Trailer inverter room for ERDA/LeRC Systems Test Facility.

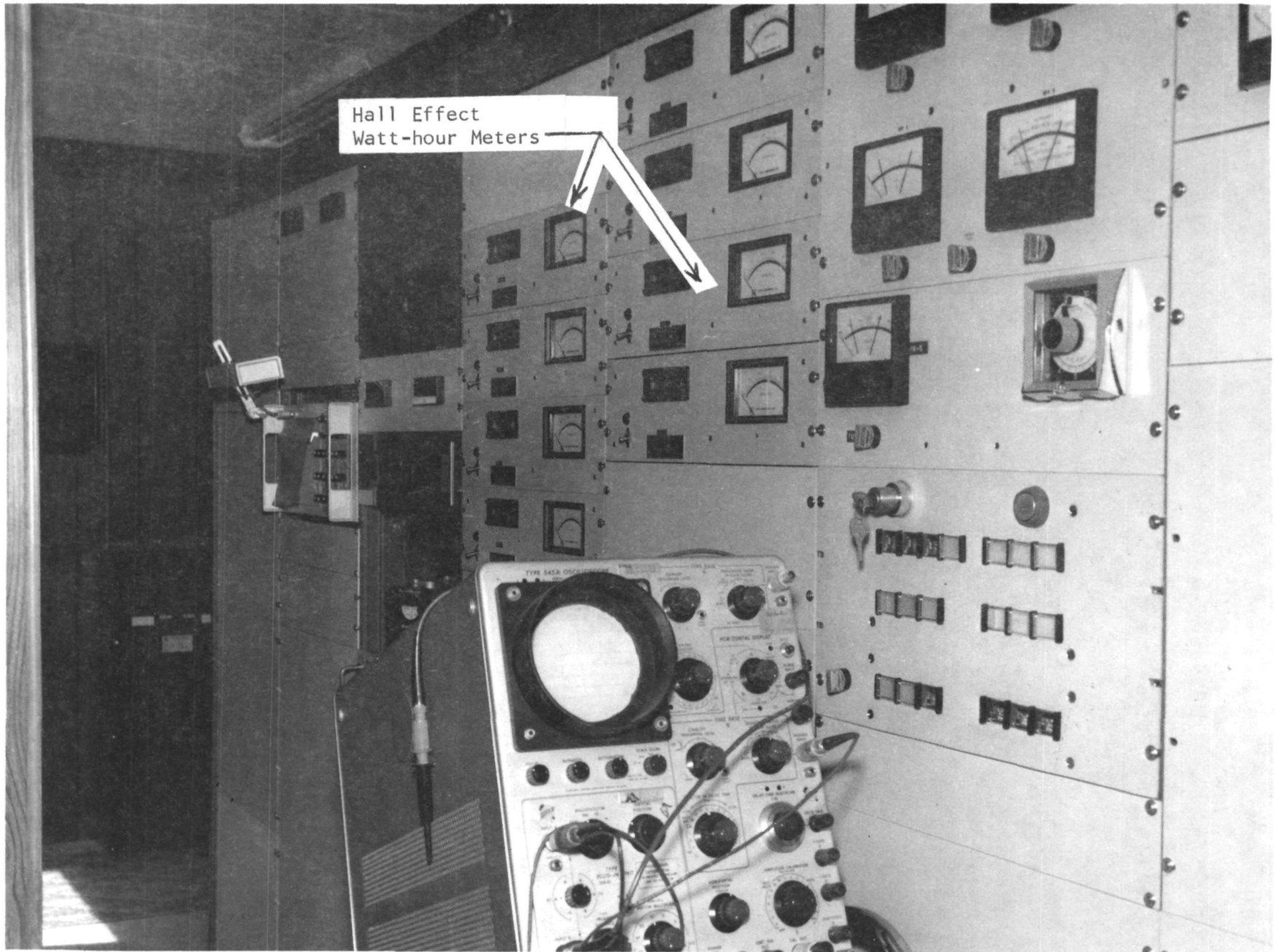


Figure 9. - Trailer instrument and control room for ERDA/LeRC Systems Test Facility.

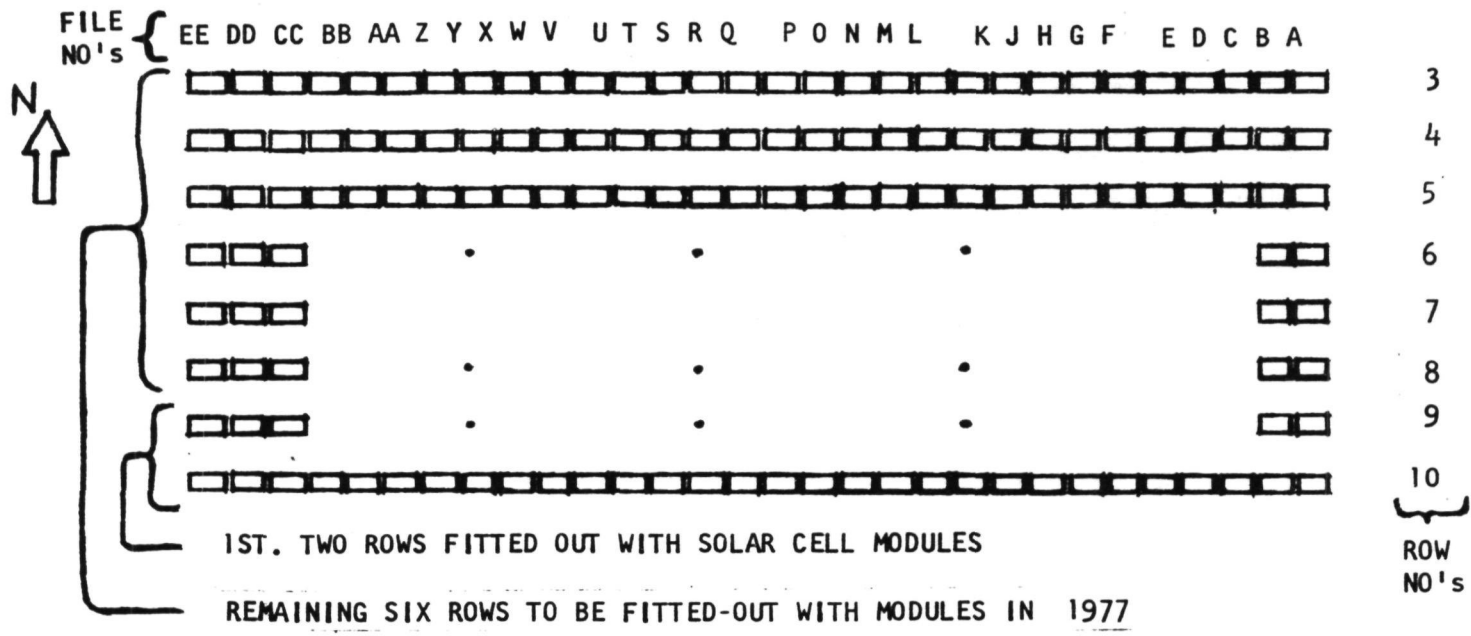


Figure 10. - Layout of Solar Panels for ERDA/LeRC Systems Test Facility



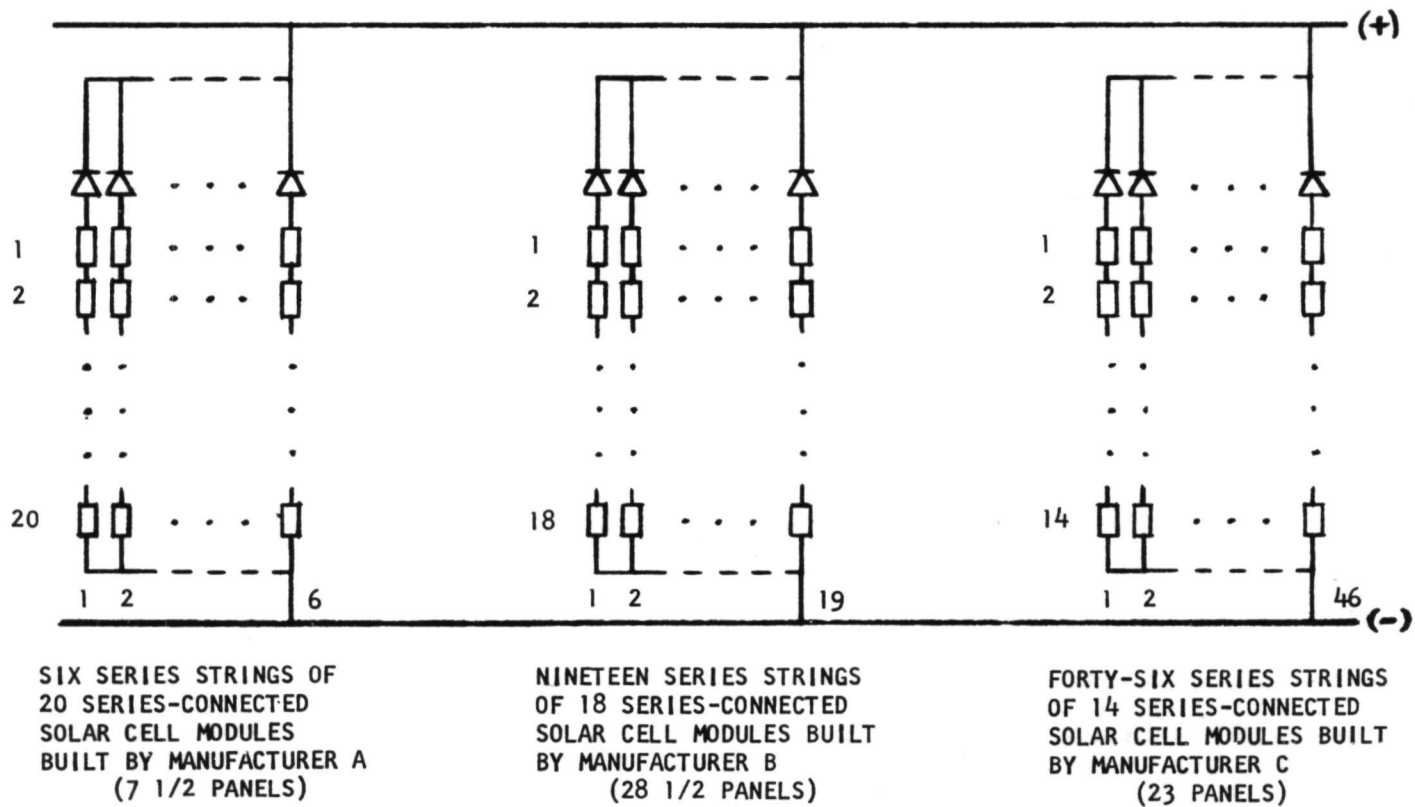


Figure 11. - Electrical configuration of solar cell modules for initial operation of ERDA/LeRC Systems Test Facility

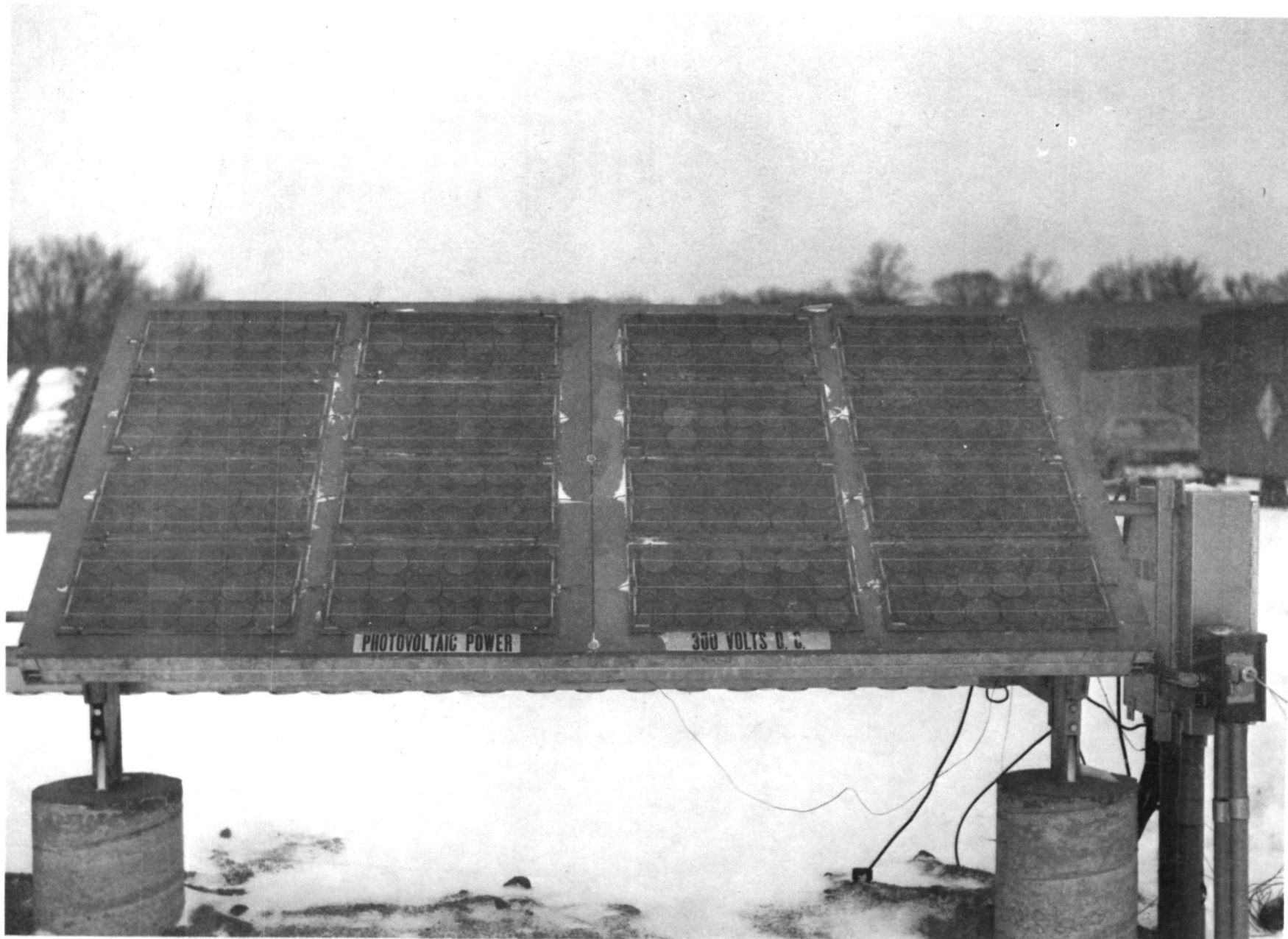


Figure 12. - Layout of Manufacturer A solar cell modules on 4' x 8' solar array panel for ERDA/LeRC Systems Test Facility.

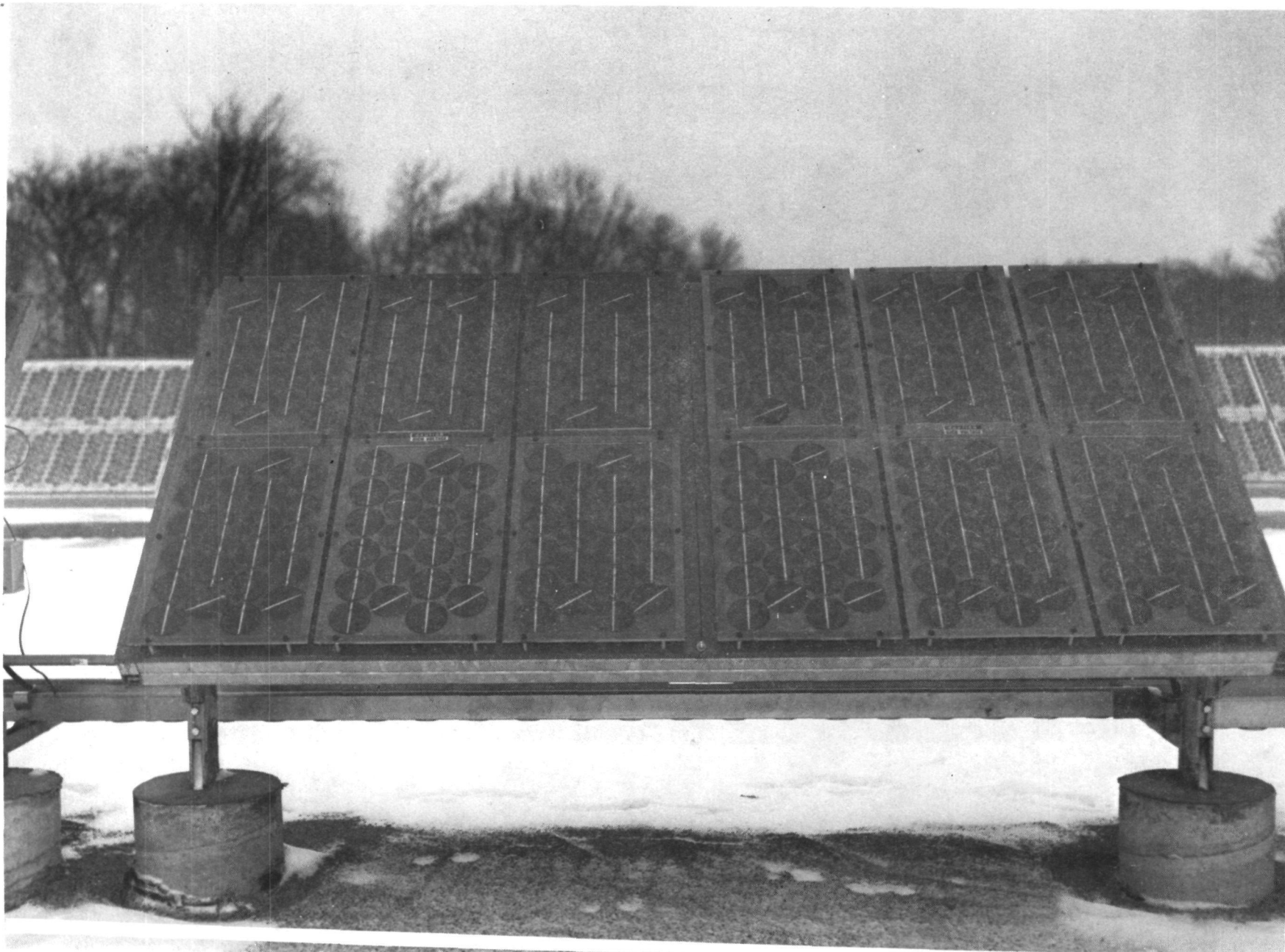


Figure 13. - Layout of Manufacturer B solar cell modules on 4' x 8' solar array panel for ERDA/LeRC Systems Test Facility.



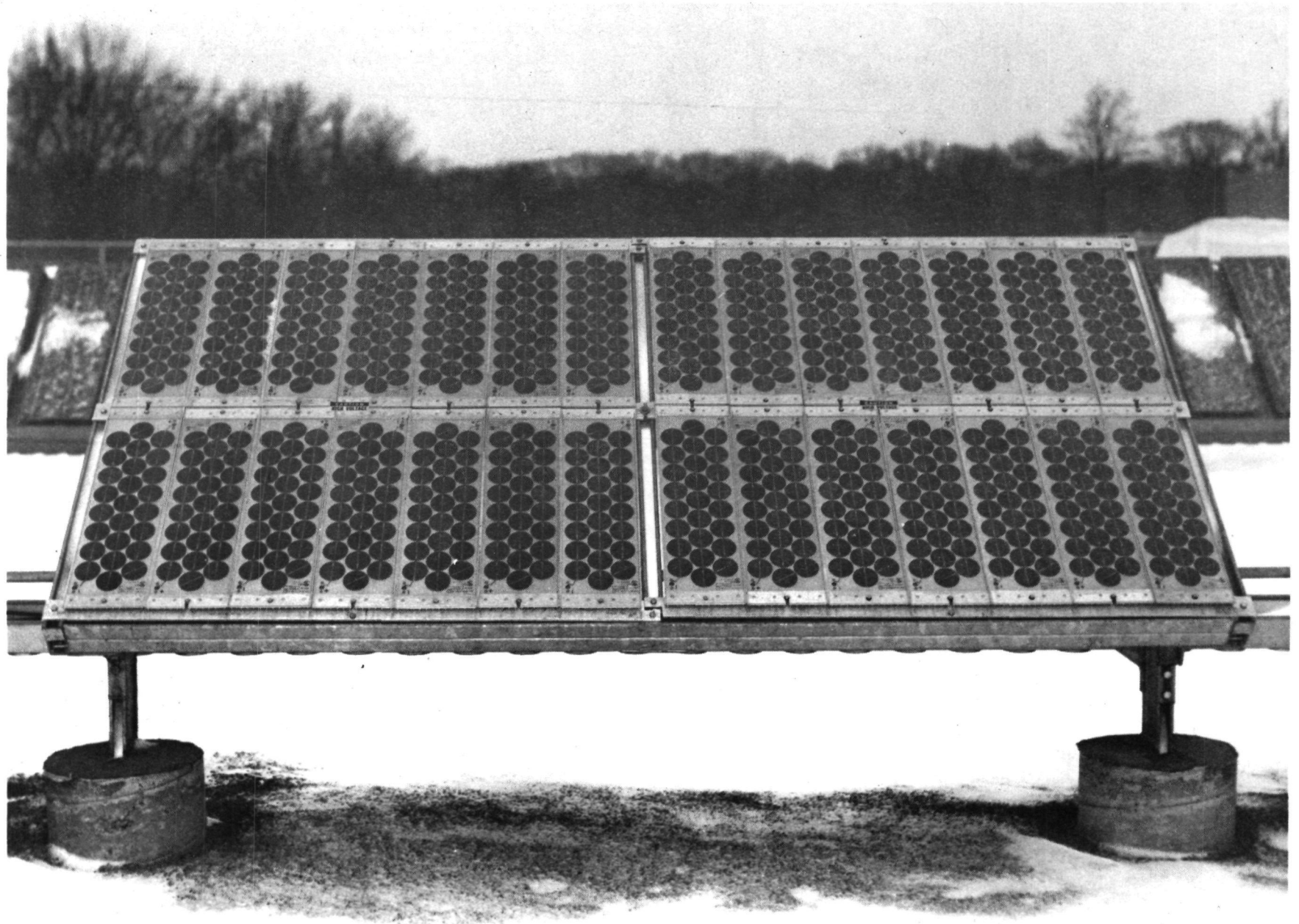


Figure 14. - Layout of Manufacturer C solar cell modules on 4' x 8' solar array panel for ERDA/LeRC Systems Test Facility.

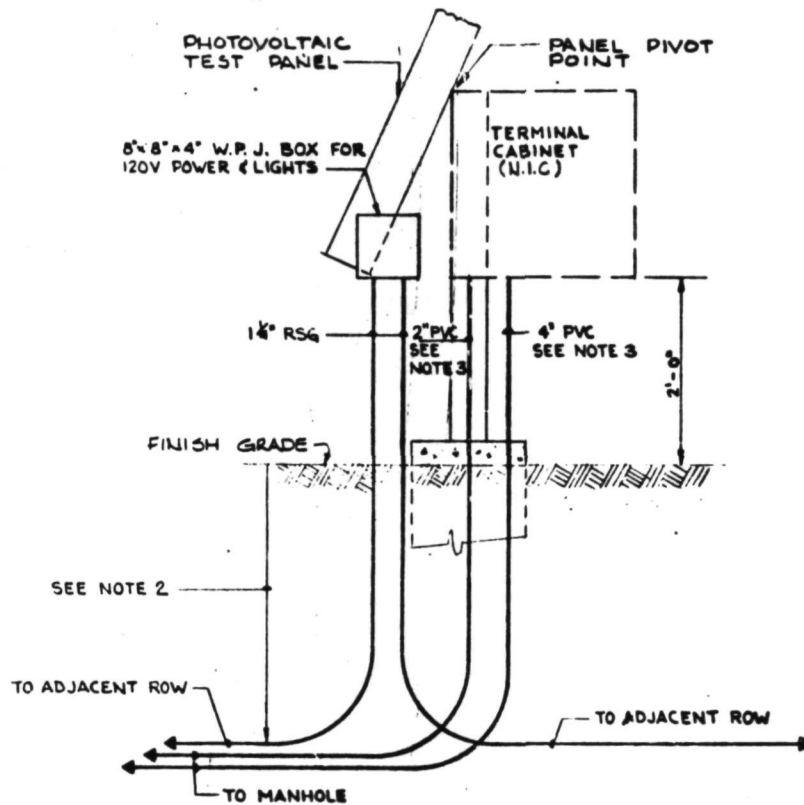


Figure 15. - Details of ducts at solar array terminal cabinets for ERDA/LeRC Systems Test Facility

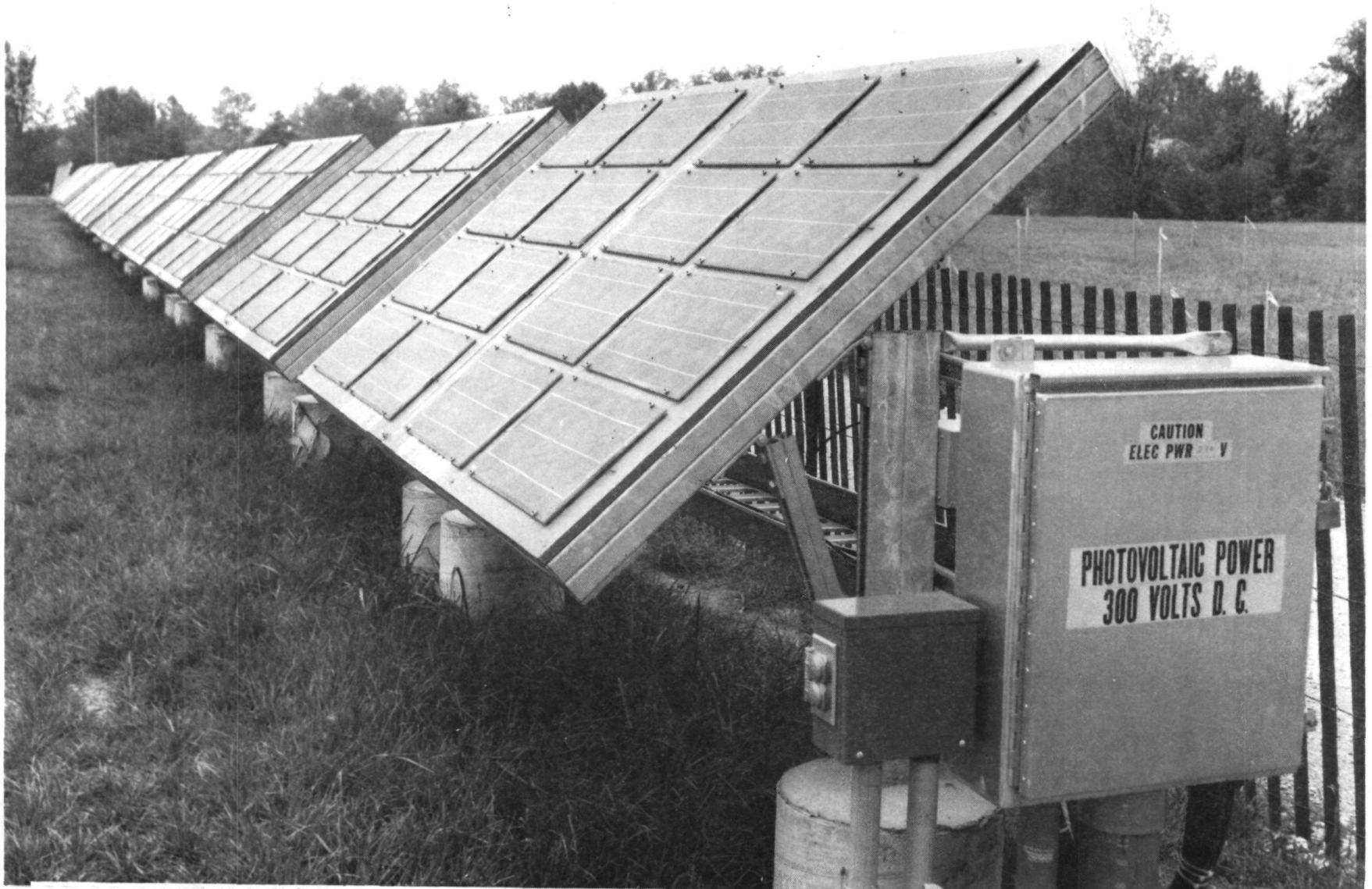


Figure 16. - Details of solar array terminal cabinets and inclined solar panels for ERDA/LeRC Systems Test Facility.

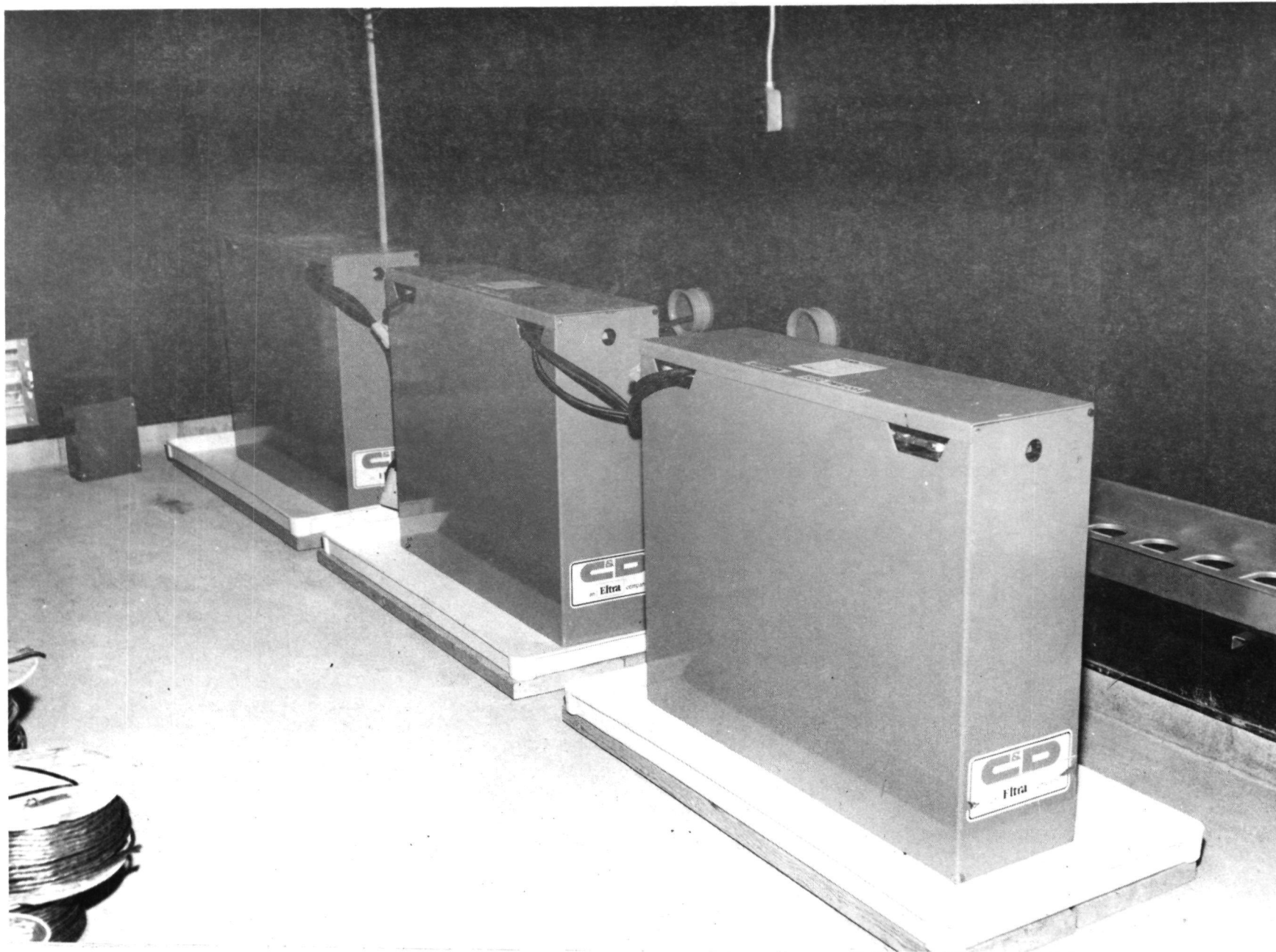


Figure 17. - 48-kilowatt hour lead acid electric storage battery for ERDA/LeRC Systems Test Facility.



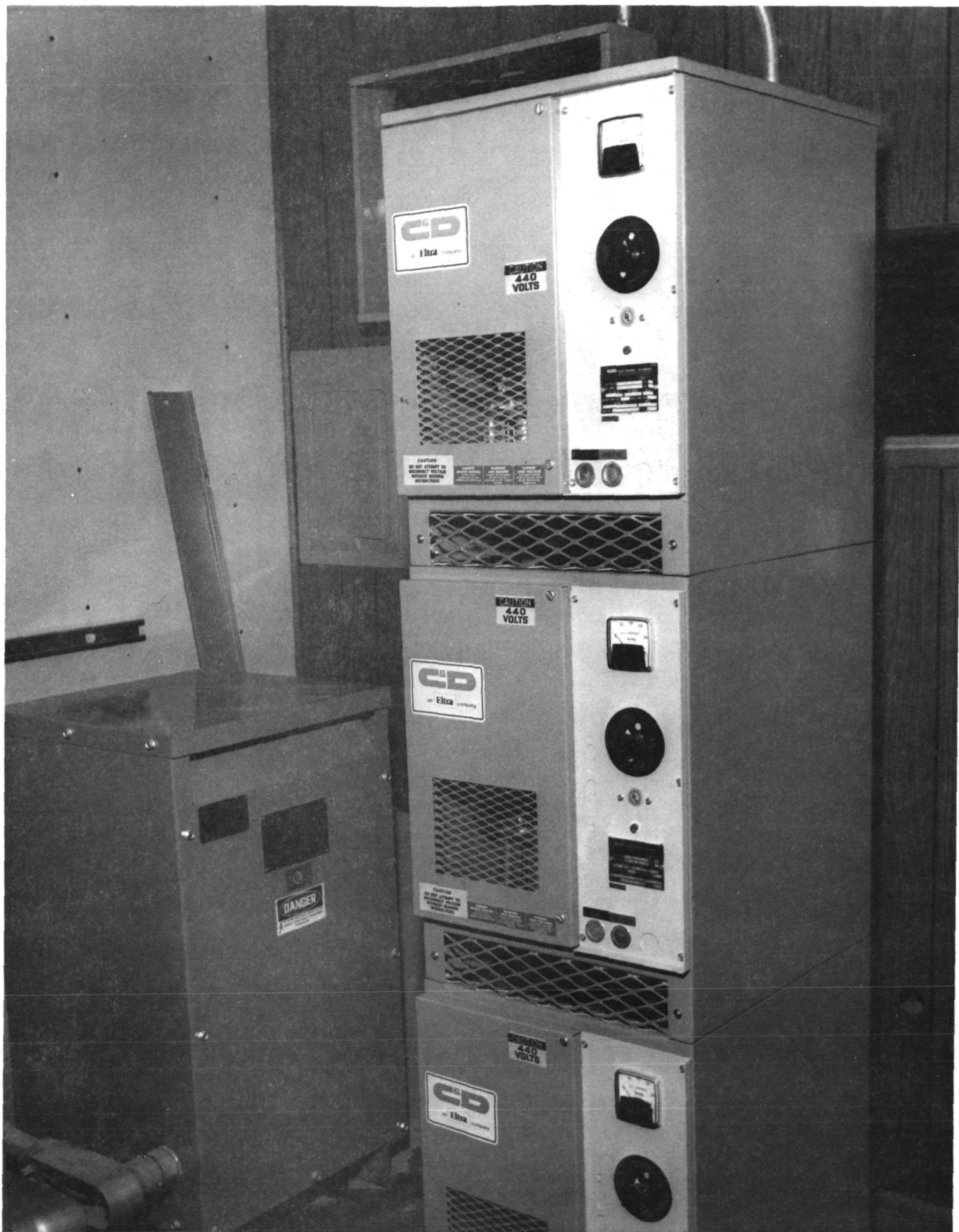
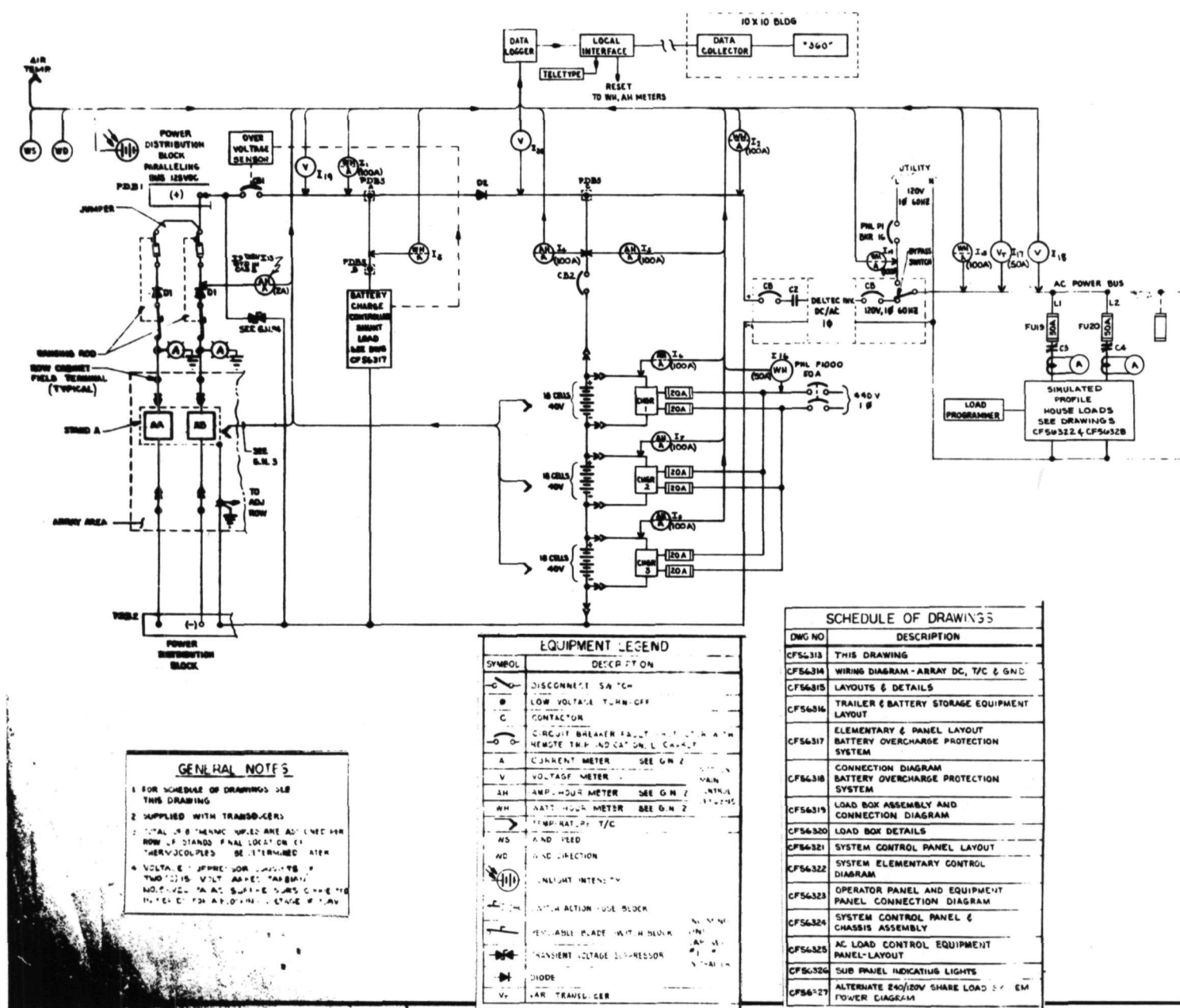


Figure 18. - Electric utility powered battery chargers for ERDA/LeRC Systems Test Facility.





**GENERAL NOTES**

1. FOR SCHEDULE OF DRAWINGS SEE THIS DRAWING
2. SUPPLIED WITH TRANSFORMERS
3. TOTAL 18 12" MENMC WIPES ARE ADJ. LINED FOR ROW OF STANDS FINAL LOCATION OF THERMOCOUPLES BE DETERMINED AFTER
4. VOLTAGE APPROXIMATIONS OF TWO CELLS MUST APPLIED TO ARRAY AND CHECKED IN AC SUPPLY SYSTEMS CHECK THE INSTRUMENT FOR APPROXIMATE STAGE PLANT

EQUIPMENT LEGEND	
SYMBOL	DESCRIPTION
	DISCONNECT SWITCH
	LOW VOLTAGE TURN-OFF CONTACTOR
	CIRCUIT BREAKER FAULT INDICATOR WITH REMOTE TRIP INDICATION CAPABLE
	CURRENT METER SEE G.N. 2
	VOLTAGE METER SEE G.N. 2
	AMP-HOUR METER SEE G.N. 2
	WATT-HOUR METER SEE G.N. 2
	TEMPERATURE T/C
	WIND AND SPEED
	WIND DIRECTION
	SUNLIGHT INTENSITY
	DATA ACTION FUSE BLOCK
	REMOVABLE BLADE WITH BLOCK
	TRANSIENT VOLTAGE SUPPRESSOR
	DIODE
	AIR TRANSDUCER

SCHEDULE OF DRAWINGS	
DWG NO.	DESCRIPTION
CF56313	THIS DRAWING
CF56314	WIRING DIAGRAM - ARRAY DC, T/C & GND
CF56315	LAYOUTS & DETAILS
CF56316	TRAILER & BATTERY STORAGE EQUIPMENT LAYOUT
CF56317	ELEMENTARY & PANEL LAYOUT BATTERY OVERCHARGE PROTECTION SYSTEM
CF56318	CONNECTION DIAGRAM BATTERY OVERCHARGE PROTECTION SYSTEM
CF56319	LOAD BOX ASSEMBLY AND CONNECTION DIAGRAM
CF56320	LOAD BOX DETAILS
CF56321	SYSTEM CONTROL PANEL LAYOUT
CF56322	SYSTEM ELEMENTARY CONTROL DIAGRAM
CF56323	OPERATOR PANEL AND EQUIPMENT PANEL CONNECTION DIAGRAM
CF56324	SYSTEM CONTROL PANEL & CHASSIS ASSEMBLY
CF56325	AC LOAD CONTROL EQUIPMENT PANEL-LAYOUT
CF56326	SUB PANEL INDICATING LIGHTS
CF56327	ALTERNATE 240/120V SHARE LOAD SYSTEM POWER DIAGRAM

Figure 20. - Electrical diagram of alternate basic photovoltaic power system prepared for initial operation of the ERDA/LeRC Systems Test Facility.

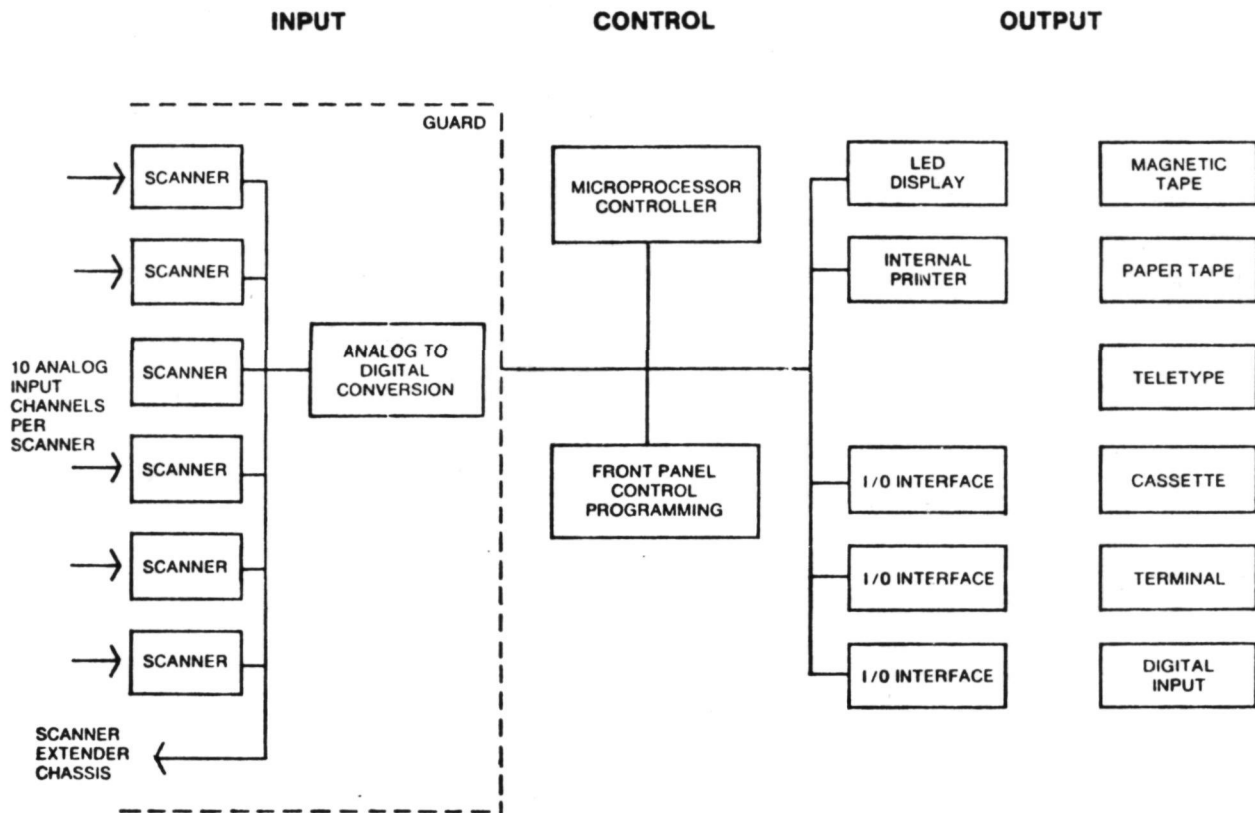


Figure 21. - Block diagram of initial data acquisition system for ERDA/LeRC Systems Test Facility