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A Simple Economic Evaluation and Applications Experiments for Photovoltaic Systems for Remote Sites

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ABSTRACT

A simple evaluation of the cost effectiveness of photovoltaic systems is presented. The evaluation is based on a calculation of breakeven costs of photovoltaics (PV) arrays with the levelized costs of two alternative energy sources - (1) extension of the utility grid and (2) diesel generators. A selected number of PV applications experiments that are in progress in remote areas of the U. S. are summarized. These applications experiments range from a 23 watt insect survey trap to a 100 kW PV system for a national park complex. It is concluded that PV systems for remote areas are now cost effective in remote small applications with commercially available technology and will be cost competitive for intermediate scale systems (~10 kW) in the 1980s if the DOE 1986 Commercial Readiness Goals are achieved.

DISCLAIMER

INTRODUCTION

Applications analysis of photovoltaics (PV) as an alternative source of electricity in the US are generally categorized in the following four energy sectors of the economy:

SMALL REMOTE

RESIDENTIAL

INTERMEDIATE

- Agricultural
- Service/Commercial/Institutional
- Industrial
- Residential Load Centers

UTILITY CENTRAL STATIONS

Figure 1 illustrates that almost all (97%) of the electricity produced in the US is consumed in the intermediate (industrial/commercial) and residential sectors. Thus, in order for PVs to displace a significant fraction of the fossil fuels that are currently used to generate electricity in the US, photovoltaics technology must be developed to the point where systems can be economically competitive in these two sectors. The US National Photovoltaics Program administered by the US Department of Energy (DOE) that is intended to assist the technology development and commercialization of PV is briefly discussed elsewhere.[1] This presentation, however, is an overview of the PV applications experiments in remote areas sponsored by the DOE in the US. The motivation for a discussion of PV remote applications stems from the fact that silicon flat-plate PV technology is sufficiently mature to be cost competitive in applications at sites that are not connected to the grid.

PRONOSTICO PARA CONSUMO DE PODER ELECTRICO PARA 1978*
BILLONES DE KWH

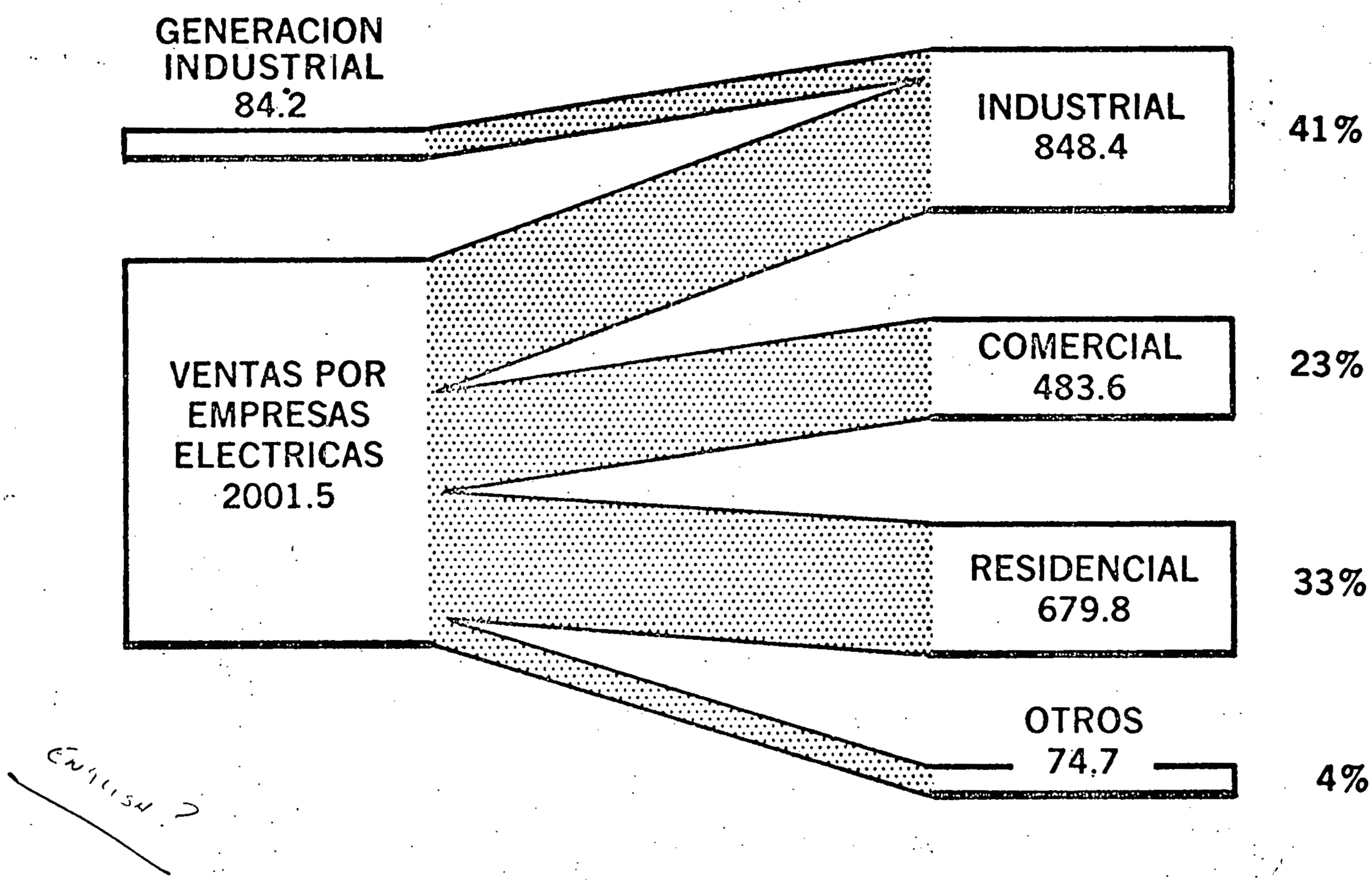

FIGURA 1

*ELECTRICAL WORLD, 15 DE SEPTIEMBRE DE 1978

ECONOMICS

Studies[2] in the US have identified a broad spectrum of applications at remote sites. A summary of some potential applications is given in Table 1. In order to estimate cost competitiveness with ~~their~~ other sources of electricity, breakeven array prices for PV systems for some applications in Table 1 have been calculated by Rattin[2]. Breakeven prices were computed for rough conceptual designs, both for PV and its alternatives - batteries, extension of the grid, or engine generators. Duty cycle and average electrical load demand were used to determine equivalent continuous load for the application. The applications were assumed to be in the Southwestern US where the ratio of array peak power* to equivalent continuous load is about 7.2. The comparisons presented are for flat-plate arrays only with three-day lead-acid battery storage at the equivalent continuous load. A 20 year life cycle was assumed for photovoltaics as well as for the two alternatives presented here - extensions of the grid and engine generators. A five year life was assumed for secondary storage batteries.

Economic decisions to buy are based on considerations that can vary significantly from buyer to buyer. Government and industrial/commercial organizations buying several units at a time may tend to base their decision on competitive life-cycle costing. On the other hand, consumers may base their decision on payback period considerations - namely, they may be persuaded to tolerate a higher

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*Array peak power (W_p) is measured under an insolation of 1 kW/m^2.

TABLA 1

ALGUNAS APLICACIONES FOTOVOLTAICAS CONSIDERADAS EN ESTUDIOS PUBLICADOS DEL MERCADO PARA AREAS REMOTAS Y RURALES

Aplicaciones/ Categoría	Aplicación			
Sensores/Procesamiento y Transmición de Datos	Residencial Estación Meteorológica Sismología	Control de Ganado y Animales Silvestres	Televisión de Circuito Cerrado	Estación Remota de Datos Meteorológicos
		Contaminación	Acumulación de Gas	Hidrología
Comunicaciones	Equipo Telefónico de Emergencia	Vigilia y Control de Radio	Control de Tráfico Ferrocarril/ Aereo	Abastecimiento de Agua
				Mando y Control
	Repetidores	Televisión Educativa	Transmisores	Control de Irrigación
	Rescate	Receptores de Televisión	Radiofaros	Radios Portátiles
	Repetidores de Microonda	Sistema de Comunicación para Oleoductos	Comunicación de Silvicultura	Radio Telemétrico
Señales	Ayudas Navegacionales para Costas e Interior	Luces de Aeropuerto	Radiofaros de Emergencia	Carteleras
	Señales de Tránsito	Luz de Destellos Agrupados para Carretera	Ferrocarril	
Potencia General/ Iluminación	Potencia Portátil	Iluminación de Emergencia	Refrigeración	Potencia de Reserva
	Desalinización de Agua	Cargar Baterías	Sacar Agua con Bomba	Estación de Despacho de Trenes
	Casas Remotas	Industrias Aisladas	Utensilios Eléctricos Pequeños	Purificación de Agua
	Preparación de Comestibles	Procesamiento de Residuos Cloacales	Refinamiento de Cobre	Dispensador de Insecticida
	Protección Catódica	Iluminación Municipal	Potencia para Hospital	Casas Móviles

initial cost* if the investment can be recovered in a relatively short period through operating savings.

The economics of a PV system can be estimated over the life cycle of the system. By setting equal the present value costs of owning and operating several alternative power generation sytems, a photovoltaic array price can be determined at which the system containing the array can price-compete (cost break-even) with the alternate power sources.

Equations (1) and (2) give the formulas used by Rattin[2] to arrive at the present-value costs of the systems to be compared:

Present value of capital investment, CI

$$CI_{pv} = (1 + g)^p \sum_t \left[CI \left(\frac{1 + g}{1 + k} \right)^t \right] \qquad (1)$$

Present value of a stream of annual recurring costs, RC

$$RC_{pv} = (1 + g)^p \; RC \left(\frac{1 + g}{k - g} \right) \left[1 - \left(\frac{1 + g}{1 + k} \right)^N \right] \qquad (2)$$

where

p = Number of years from beginning of pricing year to beginning of first year of operation

g = Escalation rate (inflation plus real cost growth), assumed constant over the life of the system

k = Discount or interest rate

N = Total system life in years

t = years between initial year of system operation and year of purchase

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*It should be noted the term cost in this text is synonymous with price to the consumer.

The exponent (t) equals zero when the capital investment occurs in the same year in which the power generation system begins its operation. In the instance of the photovoltaic array, for example, (t) would be zero when total system life and the array life are both assumed to be 20 years. In the case of the secondary batteries associated with the photovoltaic system, with an assumed life of only 5 years, the present value factor $\left(\frac{1 + g}{1 + k}\right)^t$ would be computed for 4 different investment years and then summed before multiplying the one-time investment cost of batteries, CI, to determine the present value of this stream of intermittent investments. The years for which the present value factor would be computed for the batteries in this example are years 0, 5, 10 and 15, since the total system life was assumed to be 20 years.

The exponent (p) also was set equal to zero for the cost break-even calculations. The prices and costs for the grid extension calculations are expressed in 1975 dollars. Setting (p) equal to zero is equivalent to choosing to carry out the break-even calculation in 1975 dollars and the result is valid for any year of initial operation, provided that the cost elements in the calculation are all escalated at the same rate between 1975 and the first year of operation. In the engine generator case, the calculation was carried out in 1980 dollars.

As stated, present-value costs for the photovoltaic system were computed by Ratlin with the cost of the array itself remaining unknown, to be determined when the cost of the competing system was set equal to that of the photovoltaic system. Land costs, site preparation costs, structural costs associated with equipment housing, and so forth, were not included in the capital investment costs assumed for this study (except for the analysis of generator sets) because the relatively small power level of many potential applications make these negligible. The largest error will be for the 1 kW load calculation but the crude estimate of break-even costs is instructive nonetheless. Costs for photovoltaic system maintenance, such as array washing, also were not included except for the special analysis of generator sets. Engine generator set operating and maintenance costs were included, but were based on manufacturers data, and may therefore be somewhat optimistic.

Cost escalation was assumed to be uniform over the lifetime of all systems installations and covered both inflation and real cost growth. A value of 5% was used for this purpose. The cost of money, the discount rate, was set at 9%, based on bond yields prevailing in early 1976. Present value costs were calculated as of the first year of operation.

PV BREAKEVEN COSTS WITH UTILITY POWER EXTENSION

Costs for extending the grid to remote sites with 12 kV service ranged from $3,730/kM for an REA* in the midwest to about $9,320/kM for commercial utilities on the east or west coast. Utility line extension costs over hilly or mountainous terrain were as high as $21,850/kM. Burying the power lines over mountainous terrain can double these costs. The PV breakeven costs presented here were calculated on the basis of $9,320/kM for power lines.

Other costs associated with power line service are those of power conditioning and the actual charge for energy. Table 2 shows the rates charged for electric energy in Arizona for rural commercial service, which were taken as sufficiently representative for the Southwest and thus used for this study.

Other costs include the service connection which is charged at $250 and covers fuse box, meter holder, outlets, and miscellaneous hardware. AC/DC rectification equipment cost is dependent on voltage and power rating desired, and will range from about $500 for 100 watts to about $1500 for 5-10 kW without filtering, and up to $6000 at 10 kW with filtering. Regulation of DC power to the battery, and from battery to load, is costed at $20 each for the purpose of this study. If the load is small, the utility will also charge for the transformer from line voltage to 115 V (or other voltage) at $150-$200. These rather large investment costs explain why photovoltaic systems for very low power loads are so competitive with the energy from the utility grid; they are so even in urban situations where no power line extension

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*Rural Electrification Administration

is needed and where the application is situated near a power pole or on it. However, when house current at 115 V can be used and is available from a conventional outlet, equipment costs are considerably less, ranging from about $5 to $15 for a combined transformer/rectifier at power levels up to 5 W. In such instances, photovoltaic systems are far less competitive.

Table 2

RURAL COMMERCIAL ELECTRIC ENERGY RATES FOR ARIZONA

Load, kW	Annual Energy, kWh	Annual Cost, $	Average Cost, Cents/kWh
0.01	87.6	18.6	21.2
0.02	175.2	20.1	11.4
0.10	876.0	55.0	6.3
0.20	1752.0	99.0	5.6
1.0	8760.0	428.0	4.9

The photovoltaic system was assumed to require 3 days storage capacity, sized by the equivalent continuous load determined for the application. The utility power was backed up by 1 day of storage. In both instances, lead-acid secondary batteries were costed. A blocking diode was the only charge control assumed for the photovoltaic system. As in the previous example, service calls were not costed, the assumption being that these would be required for both systems to a similar degree.

The following cost assumptions were used:

Power line cost	= \$9,320/kM (proportional for fractions of a kilometer)
Utility connection charge	= \$250 (fuse box, meter holder, electrical fittings and hardware, installation)
Transformer cost	= \$150
Rectifier cost	= \$20 for 1 W of load
	\$40 for 10 W of load
	\$200 for 100 W of load
	\$1200 for 1000 W of load
Secondary Battery cost	= \$50 per kWh (investment cost)
Energy charge	= Variable (see Table 2)

The break-even cost equation, using present value costs, becomes:

$$CI_{array} = CI_{power\ line+connection+transformer+rectifier} + CI_{battery\ backup\ (utility)} - CI_{battery\ storage(PV)} + RC_{energy\ charge}$$

The present value factors are 3.07 for the secondary batteries and 13.8 for the annual recurring energy charges over a 20-year period. The same escalation and interest charges were used. This equation reduces to:

$$CI_{array} = 9{,}320\ (D) + 400 + CI_{rectifier} - 7370\ (P) + 13.8\ RC_{energy} \quad (4)$$

where D = power line length, in miles, and P = load, in kW.

Figure 2 shows the break-even array costs calculated* with Equation 4 for three continuous equivalent loads as a function of

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*The breakeven costs for the 1000W array were calculated by the author.

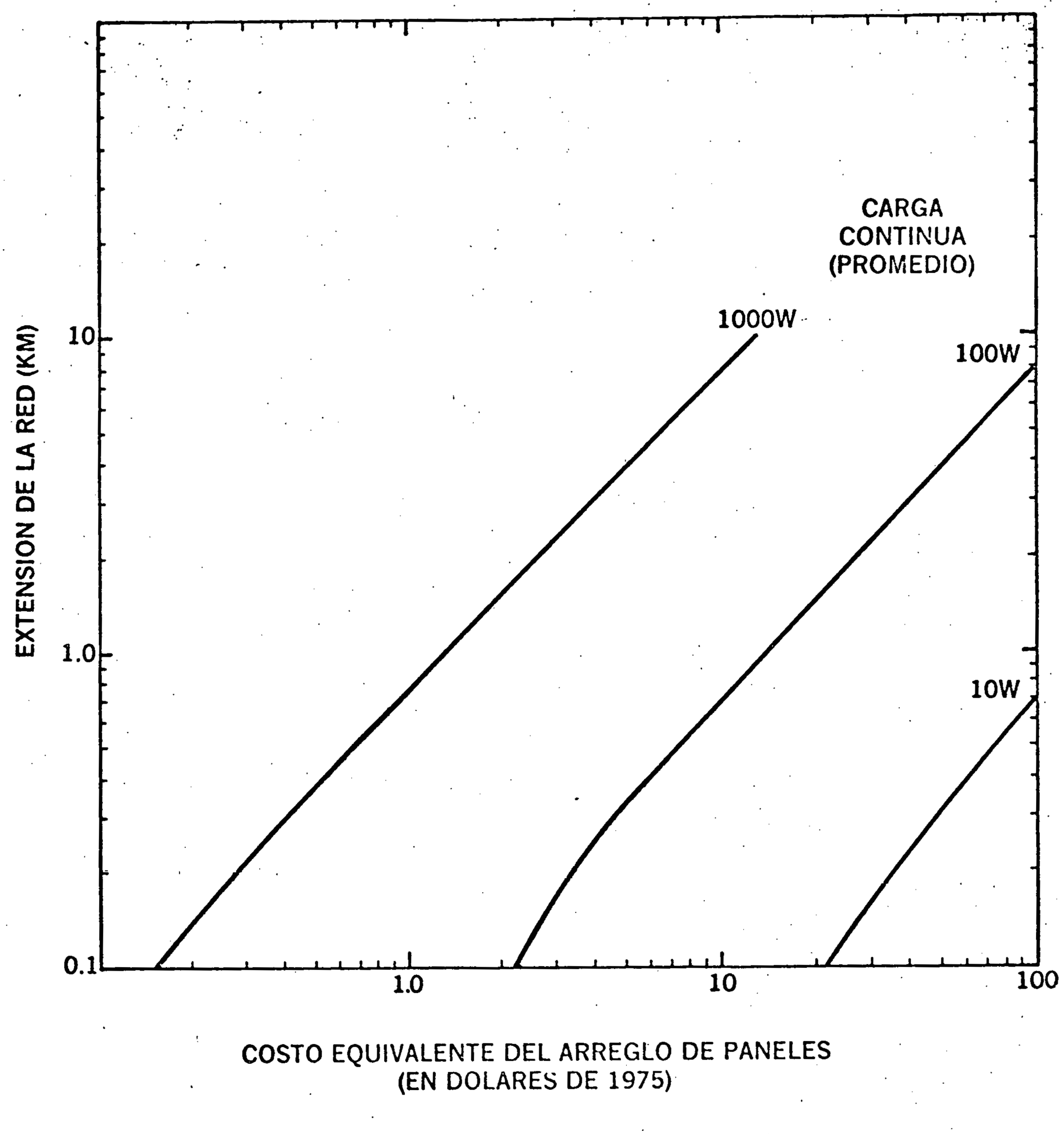

CARGA
CONTINUA
(PROMEDIO)
1000W
100W
10W
10
1.0
0.1
1.0
10
100
EXTENSION DE LA RED (KM)
COSTO EQUIVALENTE DEL ARREGLO DE PANELES
(EN DOLARES DE 1975)

FIGURA 2

the power line extension distance for utility power. There are several significant points to be gleaned from the graphs. The longer the extension of the utility grid to the remote site, the higher the breakeven cost of the array. The higher the continuous equivalent load, however, the longer the permissible power line extension. It should be kept in mind, however, that the 1 kW equivalent continuous load corresponds to about a 7.2 kW_p array in the southwestern US. This is a moderate size array capable of producing sufficient energy for very useful general power/lighting applications such as water pumping, water purification and isolated industries. At 10 kM, the 1000 W load in Figure 2 has an array breakeven cost of $13*.

If we assume a 10% escalation rate for costs since 1975, the array breakeven costs are about $21 at 10 kM in 1980 dollars. The expected array costs for the intermediate flat plate experiments[1] currently under construction in the US range from $\$8/W_p$ to $\$11/W_p$. This very strongly suggests that PV is already more cost effective than extending the grid for a remote application of this type in the US for areas separated from the grid by more than about 10 kM.

*1975 dollars

PV BREAKEVEN COSTS WITH ENGINE GENERATED POWER

A second alternate to PV applications in remote areas is an engine generator system. Rattin[2] has also performed a simple economics comparison of these two electrical power systems by computing the levelized costs of energy as a function of electrical load. These calculations were carried out for four different array costs. The cost and fuel consumption data used for engine generators was obtained from manufacturers and is given in Tables 3 and 4 respectively. Other costs and operating assumptions are given in Table 5. Table 5 also shows the parameters used for the PV system.

The present value costs for the comparison were derived using the life cycle costing methodology of Doane et al.[3] The costs shown in Table 3 are in 1976 dollars whereas the costs shown in Table 5 are in 1975 dollars. Since the comparison for the two energy supplies were made for a 1980 diesel fuel cost of $0.26/litre ($1.00/gal), the 1975 and 1976 costs were escalated to 1980. The comparison is thus for 1980 as the initial operating year. The levelized costs were computed by calculating present value costs for a 20 year life for both systems, and then multiplying these costs by the capital recovery factor to annualize them and then dividing by the total power produced per year. The costs were computed for two different diesel fuel escalation rates - 5% and 10% - while all other costs were escalated at 5%.

The present value equations for this comparison is given by

$$X_{pv} = CI_{pv} + CO_{pv} + CM_{pv} + COV_{pv} \qquad (5)$$

Table 3

ENGINE GENERATOR SET PRICES

Type of Engine Generator and Rated Power	Average Price in $/kW (1976 Dollars)
Gasoline Sets	
0-5 kW	200
5-15 kW	320
Diesel Sets	
0-15 kW	350
15-100 kW	185
100-500 kW	120
500-3000 kW	135

Average price includes:
- Engine
- Generator
- Base
- Fuel Tank
- Electrical Control

Note (1) Radiator for liquid-cooled sets is additive and will be required for higher power diesel engine sets (above 15 kW)

(2) Equipment is assembled on single base.

Table 4

DIESEL GENERATOR FUEL CONSUMPTION (SFC)

Rating in kW	100% Load, in gal/kWh Aerospace	Army
1	0.122	NA
3	0.112	NA
5	0.105	0.13
10	0.094	0.11
15	0.090	0.11
60	0.074	0.09

Aerospace data based on manufacturers' input.

Note: The Army data are presumably based on actual experience with older machines and consequently lower levels of operating efficiency.

Table 5

OVERALL COST ASSUMPTIONS

Present Value Costs: $X_{pv} = CI_{pv} + CO_{pv} + CM_{pv} + COV_{pv}$

Capital Recovery Factor $= \dfrac{k}{1 - (1 + k)^{-N}}$

No Tax Considerations?

No Discount Rate?

	Engine Generator	Photovoltaic System
Capital Investment - CI	Equipment Cost Plus Installation Cost	Same as for engine generator, including battery replacements
Annual Operating Cost = CO	$F_f \times P \times 8760$ hr/yr where F_f = (Fuel Price) P = continuous load in kW	NA
Annual Maintenance Cost = CM	0.05 (CI) + 0.05 (CO)	$400/yr
Annual Overhaul Cost = COV	0.25 [CI(Overhaul Factor)]*	NA
Year of Initial Operation	1980	1980
Inflation, %	5	5
Interest, %	9	9
Fuel Cost Escalation, %	5,10	NA
Life of Installation, years (other than Batteries)	20	20
1980 Fuel Cost, $/gal	0.50, 1.00	NA
Storage Battery Cost, $/kWh	NA	50
Battery Storage Capacity, days	NA (Starting only)	3
Battery Service Life, years	5	5
Backup	1 on 1 with generator	Storage
Power Conditioning	AC/DC Converter	None
Equipment Housing, $\$/ft^2$	30	5 (Battery only)
Array Support Structure Cost, $\$/m^2$	NA	15

*Where Overhaul Factor is determined from:

Size of Generator in kW	Overhaul Factor
0-15	3
5-10	1.5
10-15	1

Notes: (1) Operating cost consists of only the fuel cost. Fueling operations oil servicing, etc., are charged as maintenance cost, together with routine mechanical maintenance. Major maintenance involving parts repair or replacement are included in overhaul cost.

(2) The overhaul factor represents the need to replace worn parts on a regularly scheduled basis and is a function of both operating time and engine size. Smaller engines exhibit shorter operating lives with consequently higher overhaul factors per unit time.

(3) Maintenance cost for photovoltaic arrays represents 2 visits per year to a remote site for array cleaning and battery maintenance.

(4) NA = Not Applicable

Equations (1) and (2) above were used to determine present values of all of the cost streams, with operating cost, maintenance cost, and overhaul cost treated as recurring costs. The operating, maintenance, and overhaul cost factors shown in the table are based on manufacturers' data. These may be optimistic for applications such as those military ones in which the generators are operated and stored outdoors under inimical environmental conditions, and where, as a consequence, maintenance and overhaul costs may be higher. Additionally, the cost differentials which exist as a result of differences in operational modes, such as between base-load and peaking load operation versus standby operation, have not been investigated in detail by this study and are therefore not reflected in the reported costs.

For the purpose of this cost comparison, a remote, unmanned installation such as a radio relay station was postulated in which the load required a 24V DC supply. This required the use of a converter in the instance of the engine generator, while no power conditioning was assumed for the photovoltaic system. This type of installation also required a backup for the engine generator which was postulated to consist of an identical engine generator set. Other methods of backup exist, including enough battery storage to permit repair or replacement of the generator set in the event of failure. No trade-offs to determine optimum backup concepts were made. The battery storage associated with the photovoltaic system was considered to serve also as its backup, an optimistic assumption. The location was assumed to be in the Southwest, and only a 3-day storge requirement was postulated. This assumption also probably favors the photovoltaic system. A continuous duty requirement was assumed. The engine generator and associated equipment was assumed to be housed in a structure capable of providing environmental protection, as well as protection against vandalism, in order to permit unattended operation. In the case of the photovoltaic system, only the storage batteries could be so protected.

Figure 3 shows the results of the analysis performed for this study. Displayed are 1980 costs for electric energy from diesel generators for two different fuel cost escalation rates. Also shown in the figure are the costs of energy from photovoltaic power systems at four different array price assumptions overlaid on the generator-based cost curves. This graph suggests that photovoltaic systems could begin to compete with engine generator power at array prices of \$2.00/W_{pk} under continuous duty assumptions. The lower the array price, the higher the load for which photovoltaics are competitive. When a price of \$0.50/W_p is reached, a fuel price escalation of 10% in the post 1980 time period may permit photovoltaics to compete with engine generators in baseload applications up to at least 15 kW. As a point of reference, diesel fuel prices in Albuquerque, NM are currently about \$0.26/litre (\$1.00/gal) and although array prices are still at about \$10/W_p, the DOE 1986 Commercial Readiness goal for 1986 is \$0.70/W_p (factory) for arrays. Thus, for small scale applications a more refined analysis may show that, in the near term, photovoltaics will be cost competitive with engine generator systems in the Southwestern U. S. for applications up to about 1 kW.

COSTOS DE ENERGIA PARA EL GENERADOR DE MOTOR COMPARADOS A COSTOS DE ENERGIA FOTOVOLTAICA

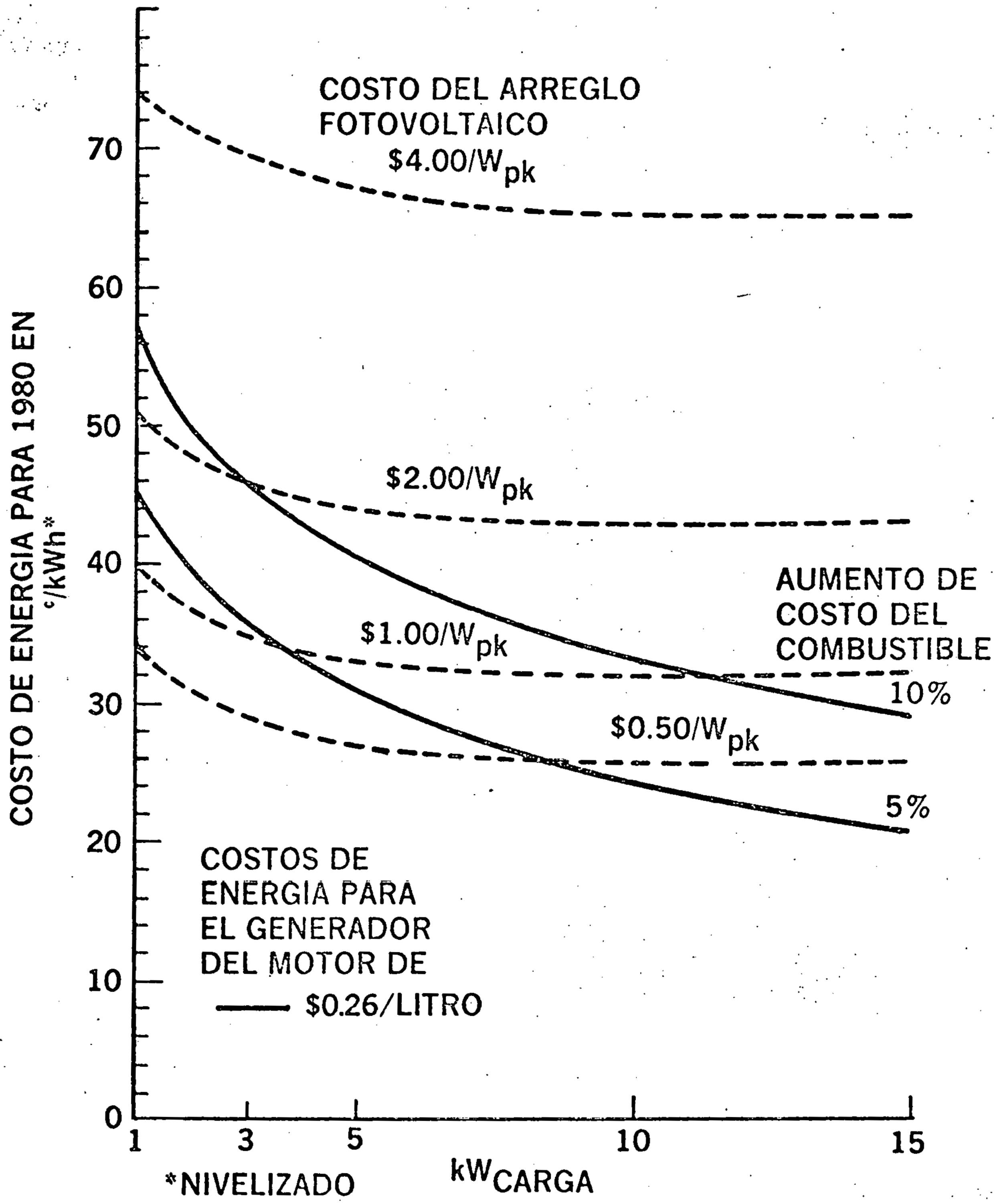


FIGURA 3

SMALL AND REMOTE APPLICATIONS EXPERIMENTS

A variety of small and remote applications experiments are in progress or under construction in the U. S. Some examples[4] of these systems are presented here to illustrate the potential of PV systems in remote and rural applications. All systems discussed here utilize silicon cells in flat plate arrays. Figure 4 shows some flat plate silicon modules that are commercially available in the U. S.

Figure 5 shows a portable water pump that may be of some use in rural areas. As can be seen, the panel, motor and electronics are all mobile with the system.

Figure 6 shows a dust storm warning sign that has been in place since April of 1977 on Interstate Highway 10 between Phoenix and Tucson, Arizona. The principal characteristics of the system are as follows:

PEAK ARRAY POWER:	116 watts	STORAGE CAPACITY:	200 amp hours
PEAK CURRENT:	5 amps	PEAK VOLTAGE:	12V DC
ARRAY AREA:	1.8 m^2	MODULES:	20 (5.8 Watts-6V)

The load consists of a changeable drive mechanism, sign lighting, and radio receiver. The panels are fixed at a declination angle of 33.5°. The cost of the system was $21.50/$W_p$ for modules and $49.04/W for the balance of system (BOS) (excluding experiment related items) for a total of $8,183.

Figures 7 and 8 show a PV insect survey trap used to monitor insect population patterns to determine required pest control measures. Two types of traps--fluorescent black light and changed grid--have traditionally been utility powered with long extension

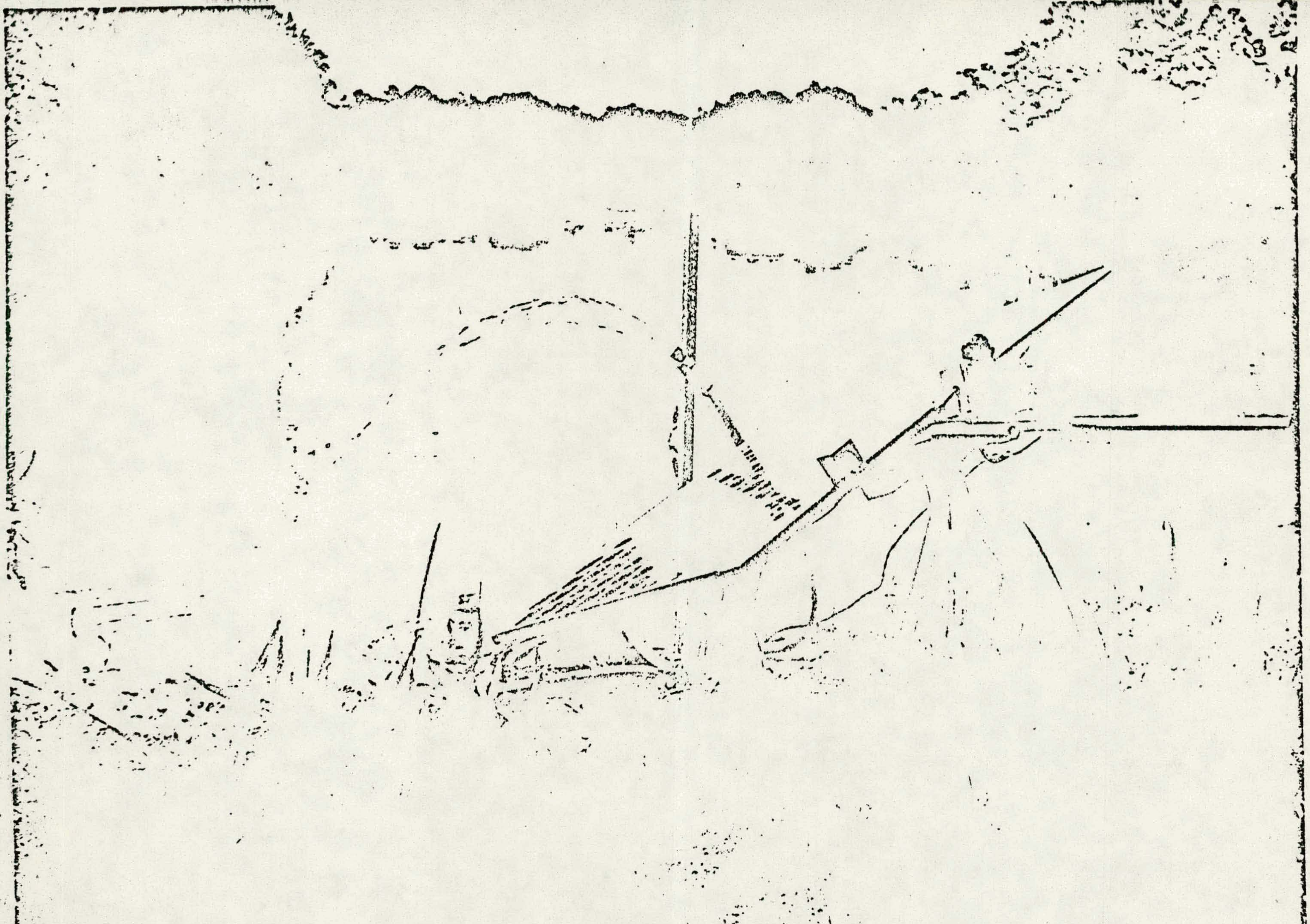


Figure 5

Portable Micro-Pumping Experiment/Display. An Inexpensive Method for Irrigation in the Field.

PHOTOVOLTAIC POWERED DUST STORM WARNING SIGN

ON INTERSTATE 10 NEAR CASA GRANDE, ARIZONA

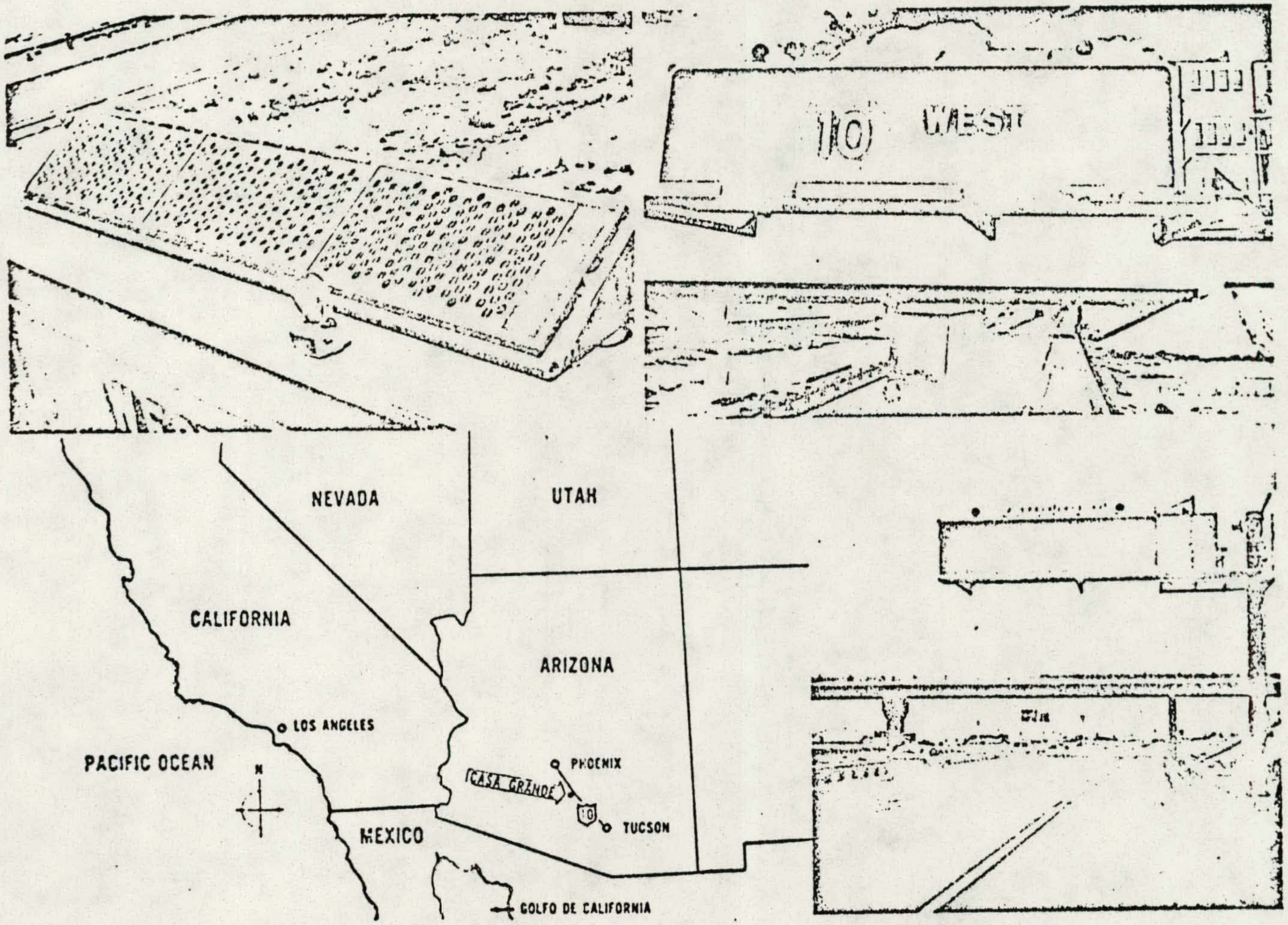


Figure 6

PHOTOVOLTAIC POWERED INSECT SURVEY TRAPS

NEAR COLLEGE STATION AND NAVASOTA, TEXAS

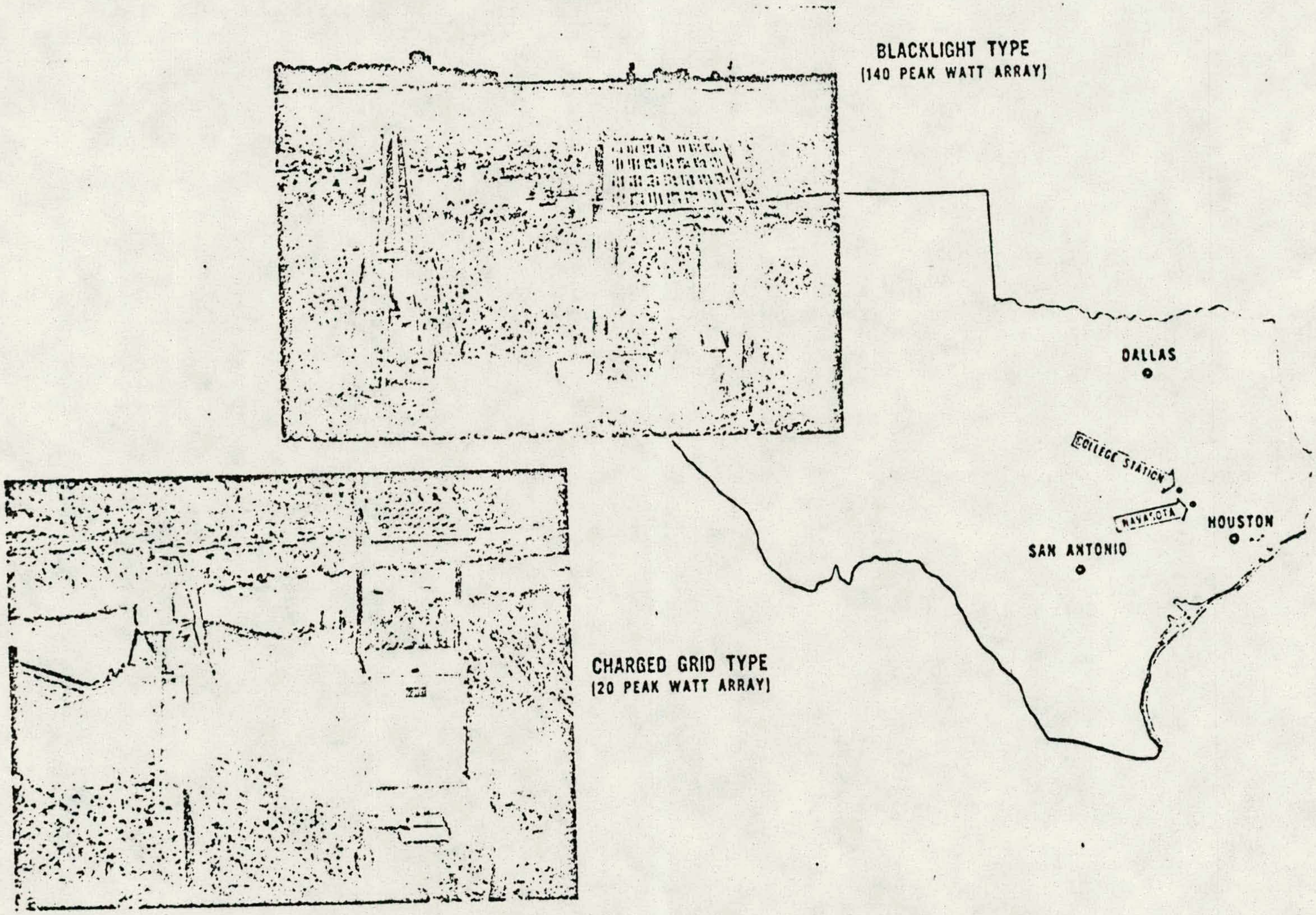
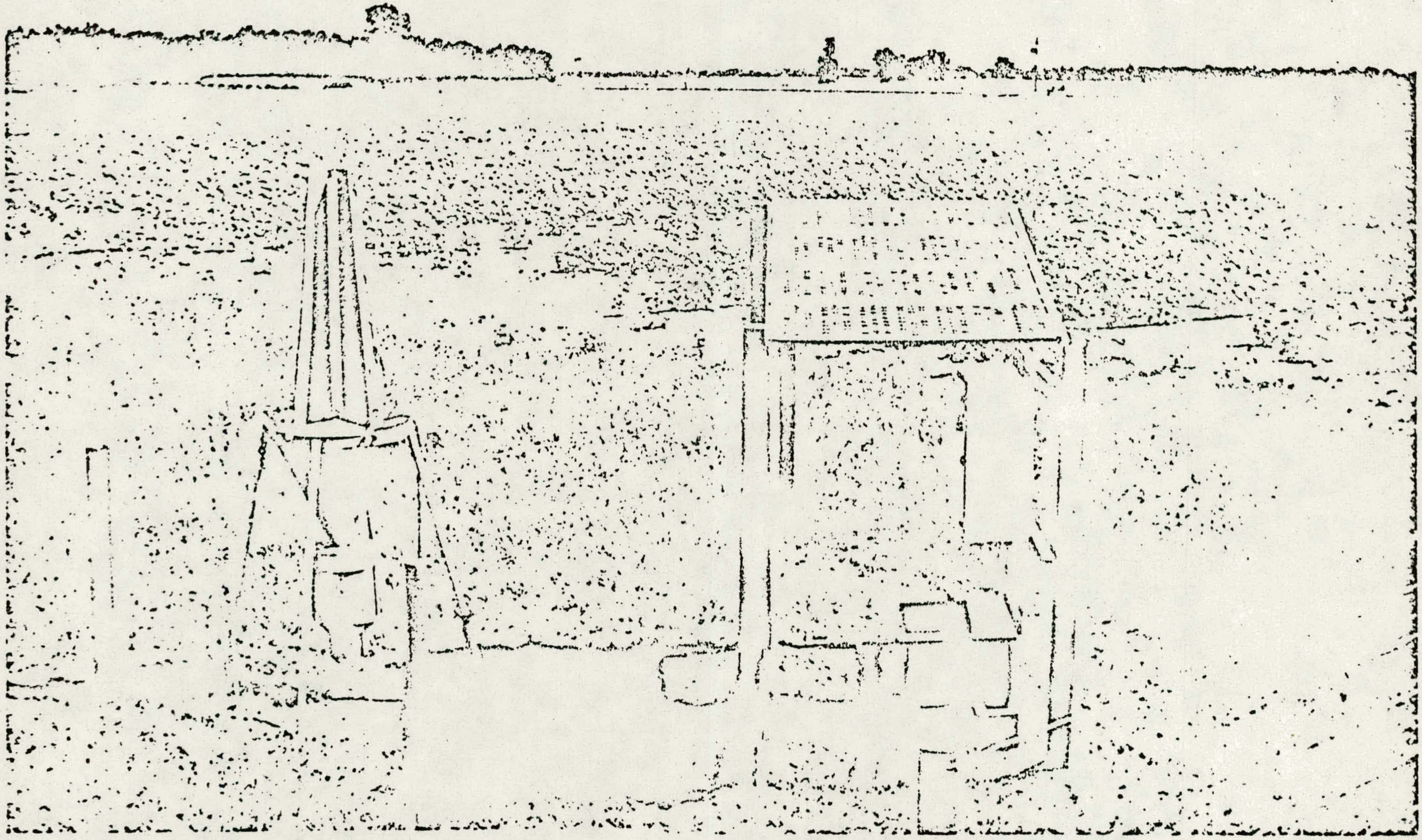


Figure 7



PV Powered Insect Survey Traps Near College Station and Navasota, Texas. Summer 1977 (Blacklight Type, 140 Watt array)

Figure 8

cords thus greatly reducing flexibility of siting. The main features of the two systems being tested are as follows:

	FLUORESCENT BLACK LIGHT	CHARGED GRID
PEAK ARRAY POWER:	163 watts	23 watts
STORAGE CAPACITY:	400 amp hours	100 amp hours
PEAK CURRENT:	7 amps	1 amp
PEAK VOLTAGE:	12 VDC	12V DC
ARRAY AREA:	2.64 m^2	0.38 m^2
MODULES:	28(5.8 Watt-6V)	4(5.8 Watt-6V)
LOAD:	Fluorescent Light	Charged Grid

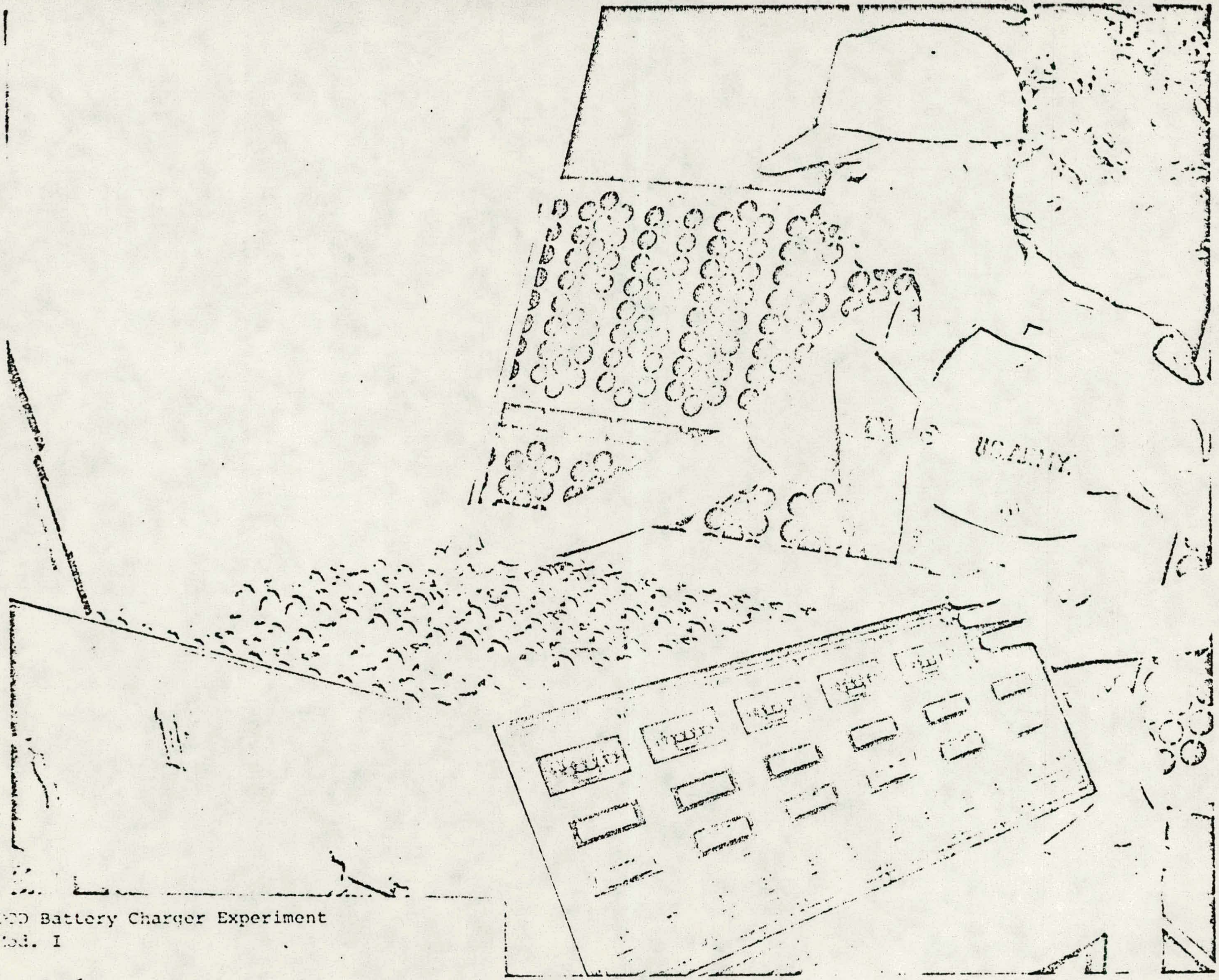
Both systems are fixed at a declination of 15°. The costs of the systems were $7,271 ($21.50/W, $23.20/W for BOS), and $3,680 ($21.50/W, $137.33 for BOS), excluding experiment related items, for the Black Light and Charged Grid systems, respectively.

These two systems have been operating since May, 1977. One module failed due to open circuit immediately after operation commenced. The module was replaced and the systems were operating satisfactorily as of August 1978.

Figure 9 shows the battery charging system that is being tested at Nellis AFB, Nevada since July 1976. Four PV systems are designed to provide power for four of the battery charging units shown in the figure. Each unit is capable of holding 84 D size Ni Cd batteries. The principle design features of the system are:

PEAK ARRAY POWER:	163 watts	STORAGE CAPACITY:	None
PEAK CURRENT:	1.2 amps	PEAK VOLTAGE:	20V DC
ARRAY AREA:	5.9 m^2	MODULES:	28 For 1, 18 for 3

Figure 10 shows the PV refrigeration system at the Sil Nakaya village on the Papago Indian Reservation in Arizona. This system provides power for refrigeration of medicine and foods in a remote



[illegible] Battery Charger Experiment
Mod. I

Figure 9

PHOTOVOLTAIC POWERED REFRIGERATOR

AT PAPAGO INDIAN VILLAGE OF SIL NAKYA, ARIZONA

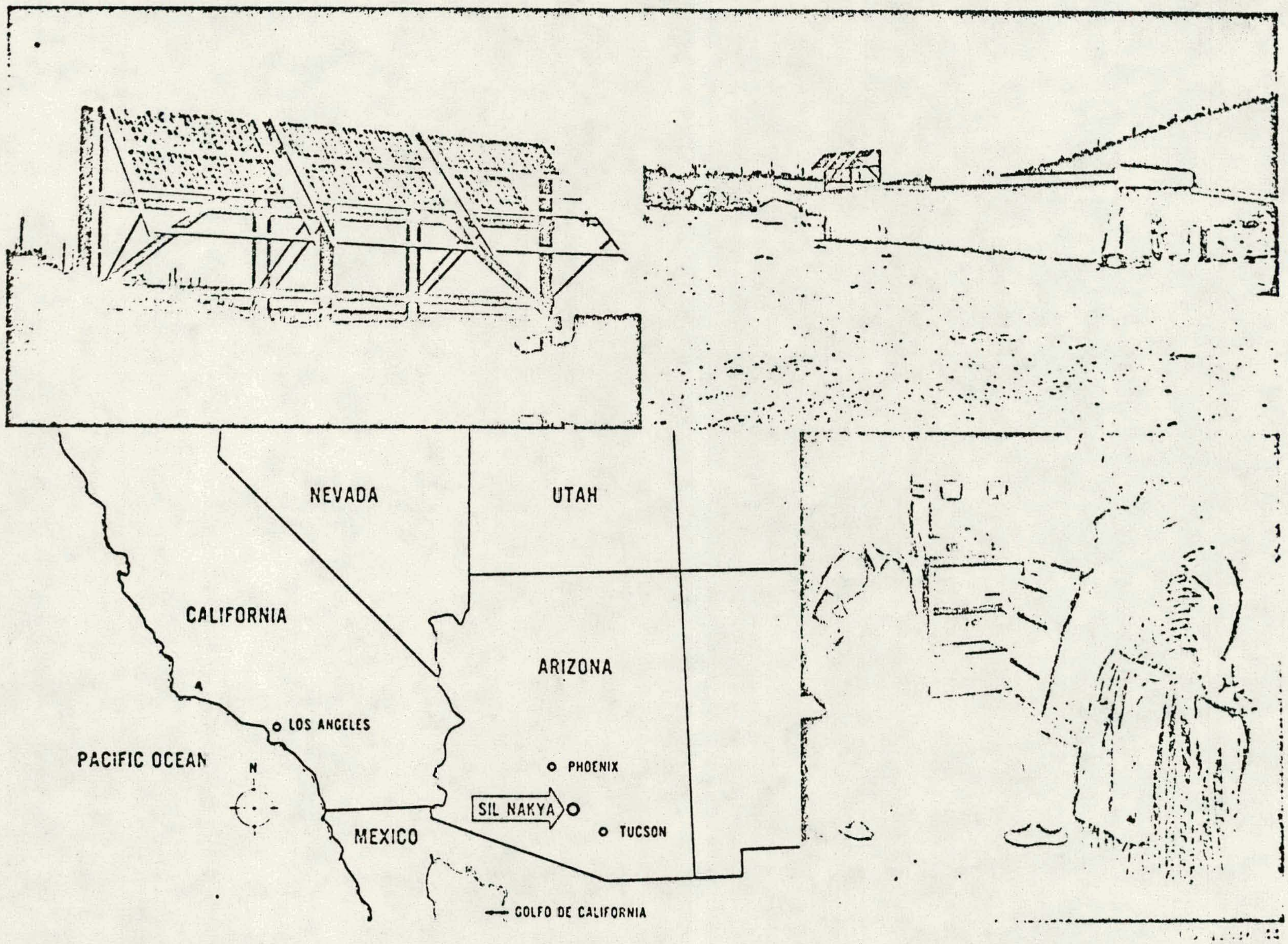


Figure 10

village that is not connected to the grid. The basic design features of the system are:

PEAK ARRAY POWER:	330 watts	STORAGE CAPACITY:	600 amp hours
PEAK CURRENT:	18 amps	PEAK VOLTAGE:	12V DC
ARRAY AREA:	4.75 m^2	MODULES:	36 (9.2 Watt-6V)

The load is a commercial recreational vehicle refrigerator with a volume of 0.11 m^3. The orientation of the array is fixed at a declination of 11°. The cost of the system was $11,218 (modules at $21.50/$W_p$, $12.49/$W_p$ for BOS), excluding experiment items.

The refrigerator system was installed in July of 1976. The system operated satisfactorily until May of 1977 when the higher than anticipated summer demand for power, due to high local ambient temperatures, required a change in the tilt angle and addition of modules to increase the power to 330 watts. During the second year of operation, one of the modules developed an intermittent open cirucit and was replaced. The refrigerator is operating satisfactorily with summer daytime temperatures consistently over 100°F (38°C).

Figure 11 shows a PV array for a forest lookout station at Antelope Peak at Larson National Forest. This PV system became operational in October of 1976 and provides sufficient electrical power to operate the tower's refrigerator, lights, water pump, TV, and radio communication sets. The basic design features are:

PEAK ARRAY POWER:	294 watts	STORAGE CAPACITY:	3,015 amp hours
PEAK CURRENT:	16 amps	PEAK VOLTAGE:	12V DC
ARRAY AREA:	6.2 m^2	MODULES:	32(9.2 Watt-6V)

PHOTOVOLTAIC POWERED FOREST LOOKOUTS

LASSEN AND PLUMAS NATIONAL FORESTS, CALIFORNIA

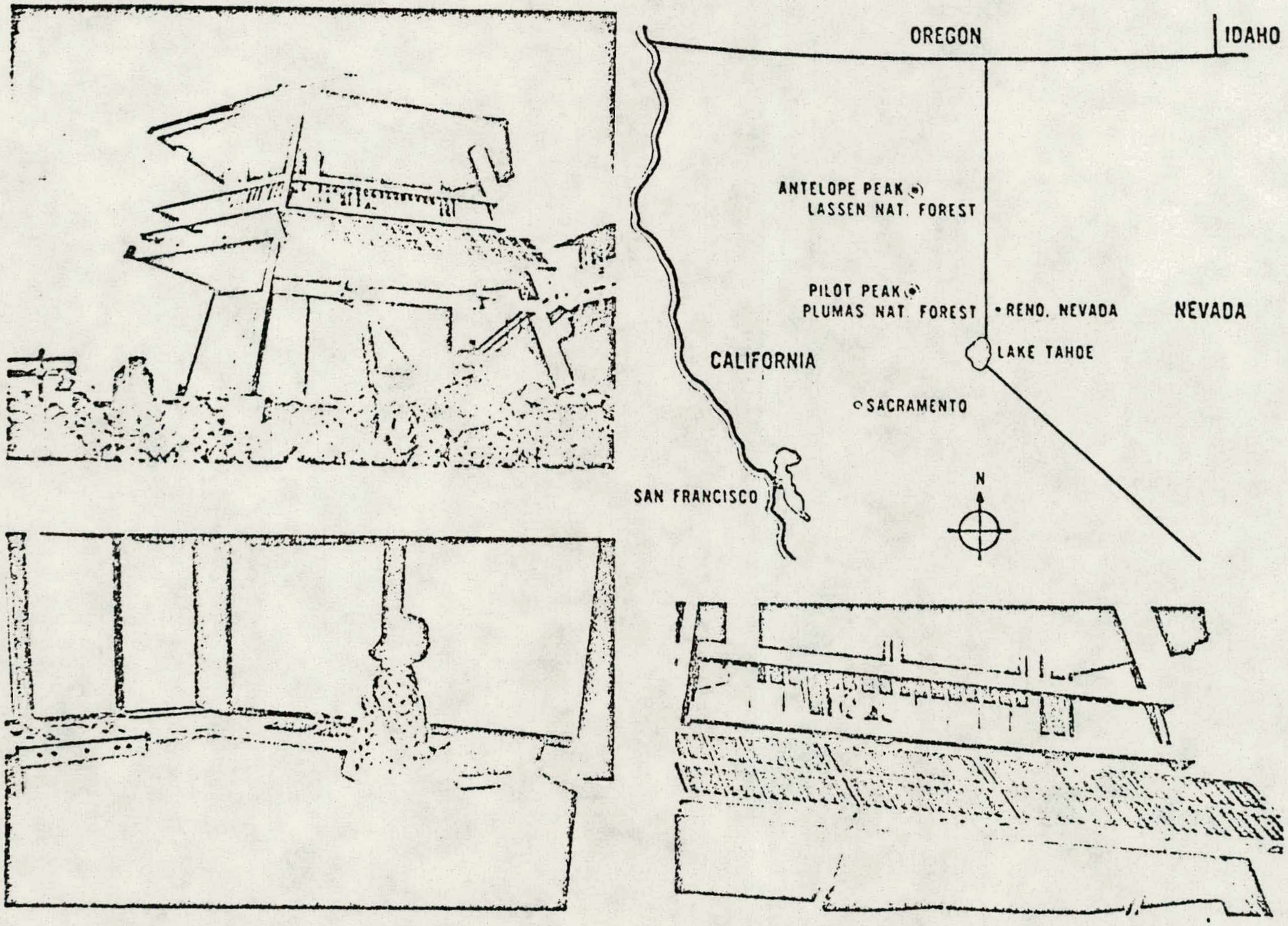


Figure 11.

The array is fixed at a declination of 36° and the system cost $19,690 (modules at $21.50/W and BOS costs at $45.47/W), excluding experiment related items. The system is used continually from May to September each year and is used only to charge the batteries during the winter and provide power for the radio receiver.

Figure 12 shows a PV array on two army trucks (vans) that serve as a mobile telephone central unit at several military bases. The basic design features of the PV system are:

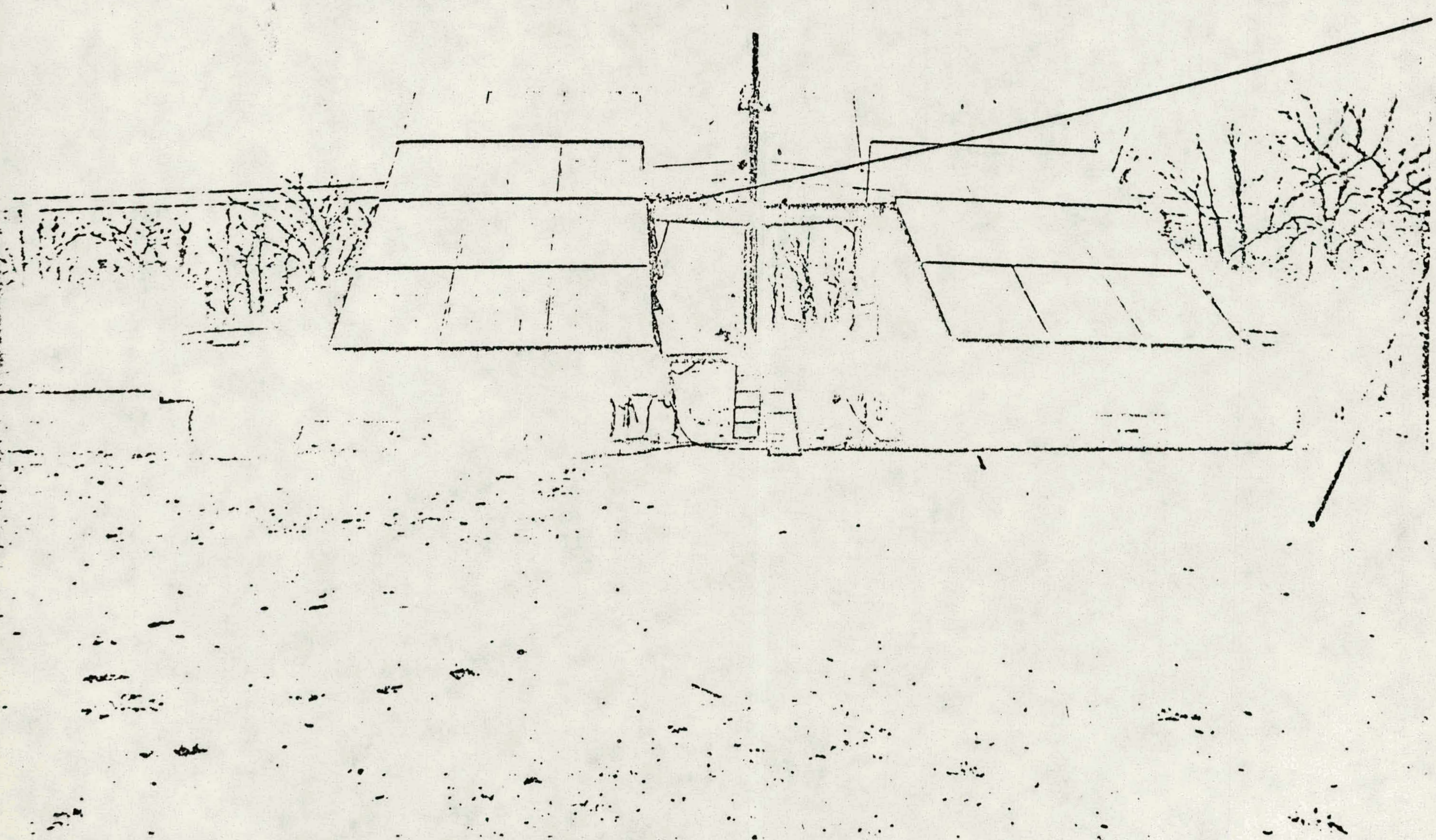
PEAK ARRAY POWER:	2.65 kW	STORAGE CAPACITY:	375 amp hours
PEAK CURRENT:	22 amps	PEAK VOLTAGE	56V DC
ARRAY AREA:	44.6 m^2	MODULES:	288

The array is non-tracking but is adjustable on the vans to a declination of 15° - 60°. The installed system cost was $81,200. Some of the vans have been driven over 10,000 miles across country with no harmful effects to the system.

Figure 13 shows a PV array for electrical power for the remote Indian village of Schuchuli on the Papago Indian Reservation in Arizona. The village has 15 families totaling 95 inhabitants. This experiment is a joint project of the Papago tribe and the Public Health Service that has been operational since December of 1978. The basic features of the system are:

PEAK POWER:	3.5 kW	STORAGE CAPACITY:	2380 amp hours
PEAK CURRENT:	29 amps	PEAK VOLTAGE:	120V DC
ARRAY AREA:	71.4 m^2	MODULES:	192

The tilt angle is adjusted four times per year: 3.5° (summer), 26° (spring and fall), and 48° (winter). The village had no electricity prior to installation of the PV system. A 7HP diesel engine was used to power a village water pump.



Van-mounted Solar Arrays used in DOD's Telephone Central Van Experiment.

Figure 12

Village of Schuchuli, Arizona, in the Papago Indian Reservation. Dec. 1978

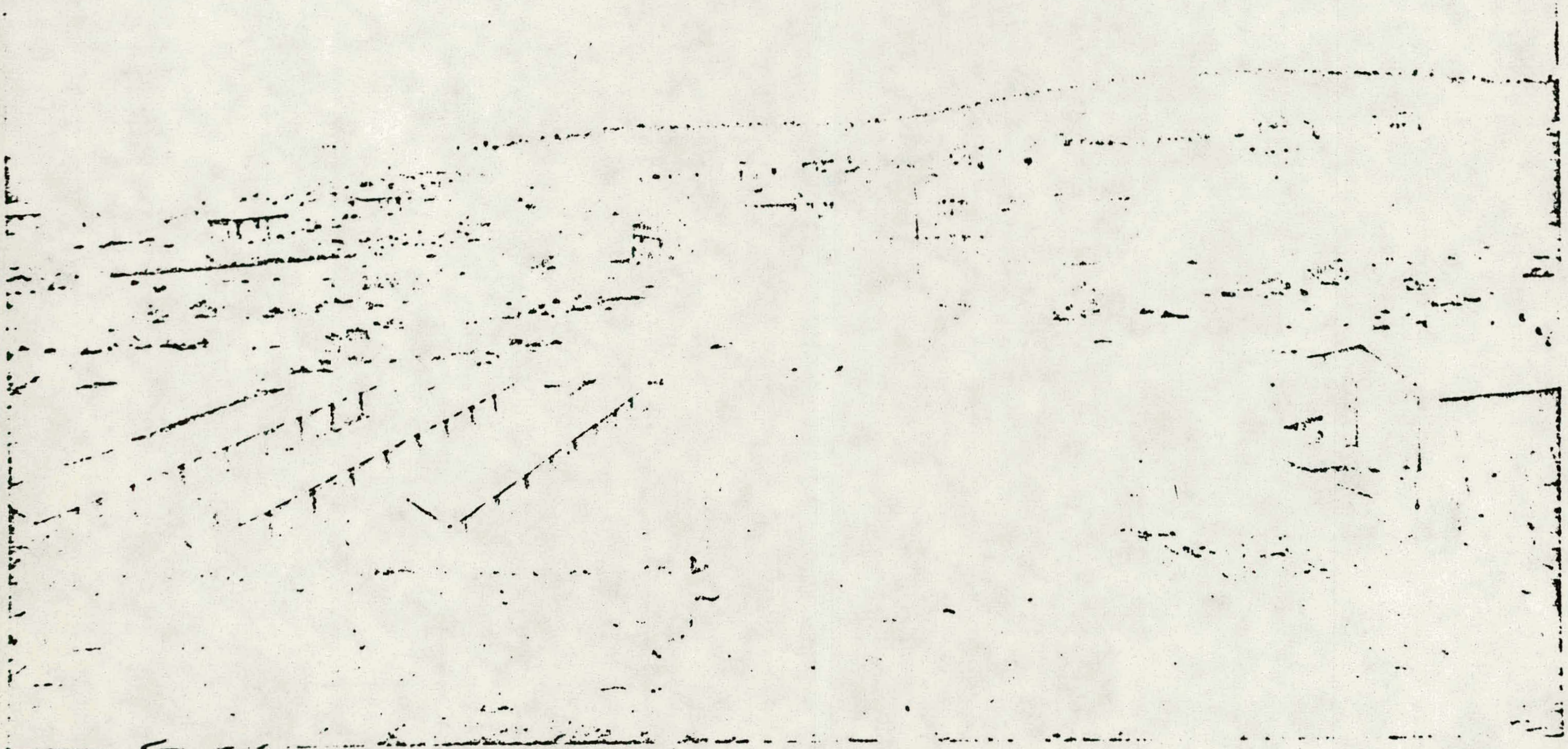


Figure 13

An all DC system was selected to avoid the losses associated with commercially available AC/DC inverters. There are 15 individual homes, a church, a feast house, a domestic services building, and an electrical equipment building. The villagers selected the loads to be powered and assigned priorities to the loads. Some load devices (appliances) are used in communal fashion. The prioritized list of the loads is as follows.

1. WATER PUMP - A 2HP permanent magnet 120V DC motor will be used to power an existing jack pump on the main well. The pump delivers about 4,163 litre/hour to the village water distribution system. The water consumption rate for villagers and livestock is estimated to range from 9,460 litres/day in the winter to 18,925 litres/day during the summer. The communal clothes washer was estimated to require 3,633 litres/day. Thus total water pumping time ranges from 3.1 hours/day to 5.4 hours/day in the summer. A control system limits pumping to daylight hours centered around noon.

2. LIGHTS - A total of 44 20 watt/120V DC fluorescent lights were installed in the following priority:

    - 2 lights in each of the 15 homes,
    - 6 lights in the feast house
    - 2 lights in the domestic services building
    - 2 lights in the church
    - 4 lights in the electrical equipment building

3. REFRIGERATORS - A total of fifteen (15) 4 cubic foot refrigerators are available in the domestic services building. The refrigerators are assembled in groups of three and powered as a unit from a single compressor with a 1/8 HP 120V DC

permanent magnet motor. The duty cycle is about 25% "on" in a 110°F (43°C) ambient temperature.

4. CLOTHES WASHER - A standard wringer type washer fitted with a 1/4 HP 120 VDC motor was installed. The washer can be run for 12 hours per day seven days/week. At 1/2 hour/load, this provides about 1.75 loads/person/week for the 96 villagers.

5. SEWING MACHINE - A commercially available sewing machine with a 1/8 HP 120V motor was installed. The unit was assumed to operate about 3 hours/day in the afternoon.

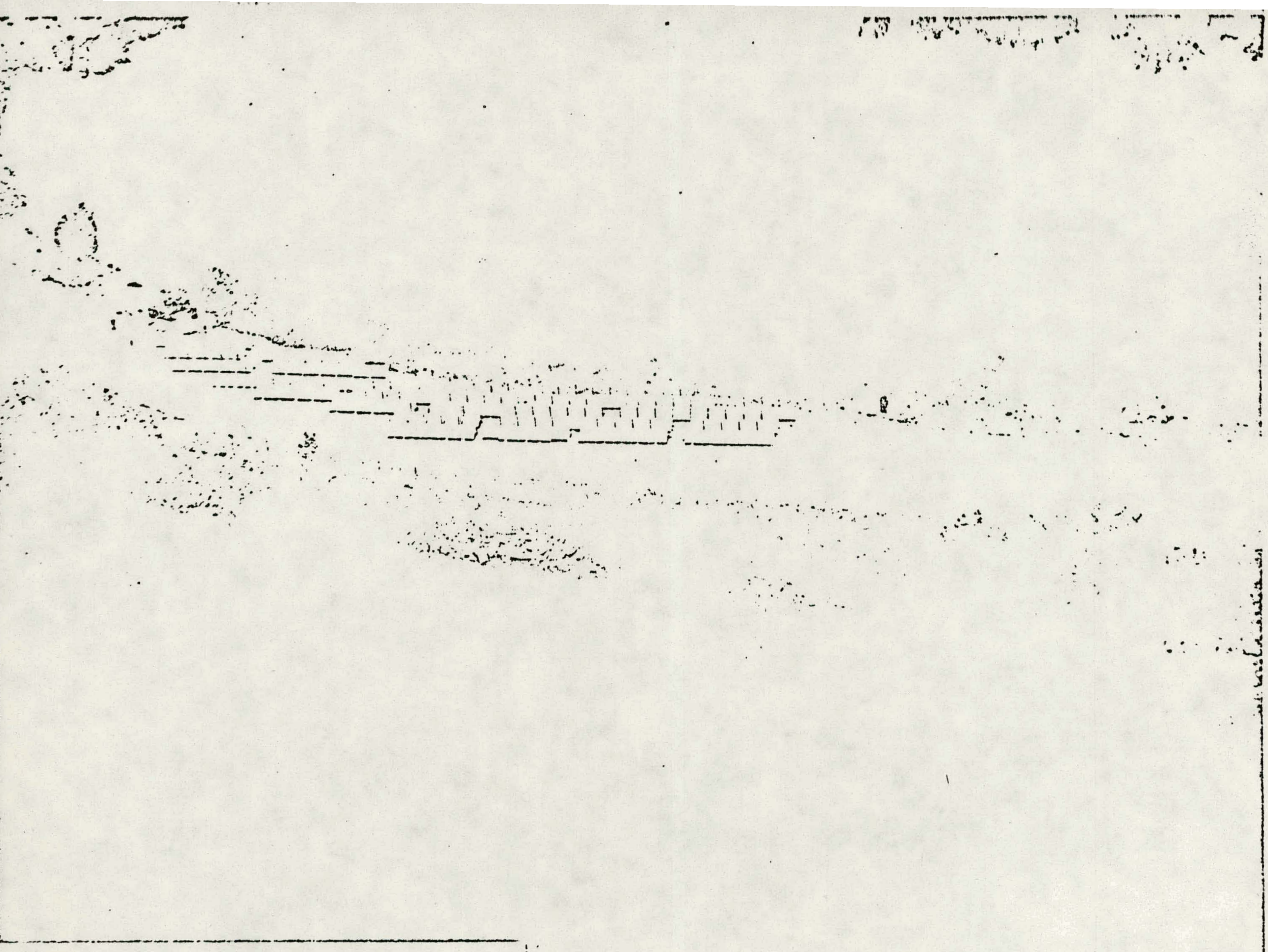
Because of unknowns in the use of loads and variation in insolation, a load management subsystem was incorporated in the design in order to:

- Protect the batteries from excessive discharge and potential damage
- Maintain operation of the more critical loads

The load management subsystem sequentially disconnects loads as the battery capacity decreases to preset levels. At 50% discharge, the washing and sewing machines are discharged at 60% the lights, at 70% the water pump motor and at 80% the refrigerators. As the batteries are recharged, the loads are sequentially reconnected.

Figure 14 shows a PV array for a reverse osmosis water purification system installed in April of 1977 at Ft. Belvoir, Virginia. The basic characteristics of the PV system are:

PEAK ARRAY POWER:	10.63 watts	STORAGE CAPACITY:	90 amp hours
PEAK CURRENT:		PEAK VOLTAGE:	240V DC
ARRAY AREA:	198 m^2	MODULES:	931



Water Purification System Experiment,
Ft. Belvoir, Virginia

Figure 14

This experiment involved a high power PV array to provide power for a large mobile reverse osmosis water purification unit. Design operating period was eight hours per day with an energy storage of two hours. The declination of the panels was variable from 15° to 62°.

The system worked satisfactorily without failures or system degradation for about two years. The array has now been converted to a fork lift-truck battery charging demonstration.

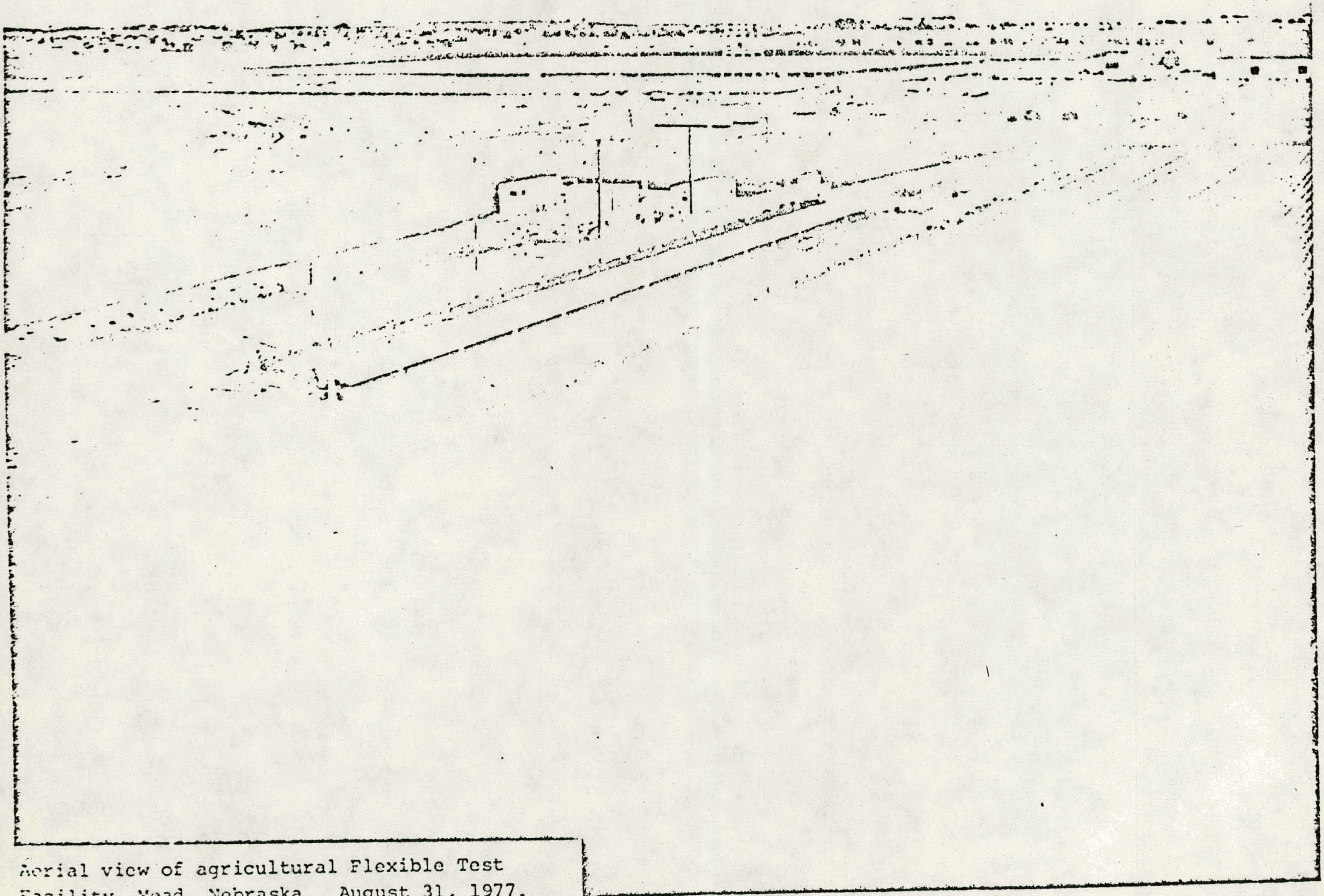
Figure 15 shows the PV array for an irrigation and crop drying system on a farm in Mead, Nebraska. The design parameters for the system include:

PEAK ARRAY POWER:	25 kW	STORAGE CAPACITY:	90 kWh (forty 6V batteries at 375 amp hrs. each)
PEAK CURRENT:	28 panels at 6.3 amps each	PEAK VOLTAGE:	28 panels at 160V each
ARRAY AREA:	520 m^2	MODULES:	Front row 728, back row 1512

The tilt angle of the system is changed once per month and ranges from 0° to 65°.

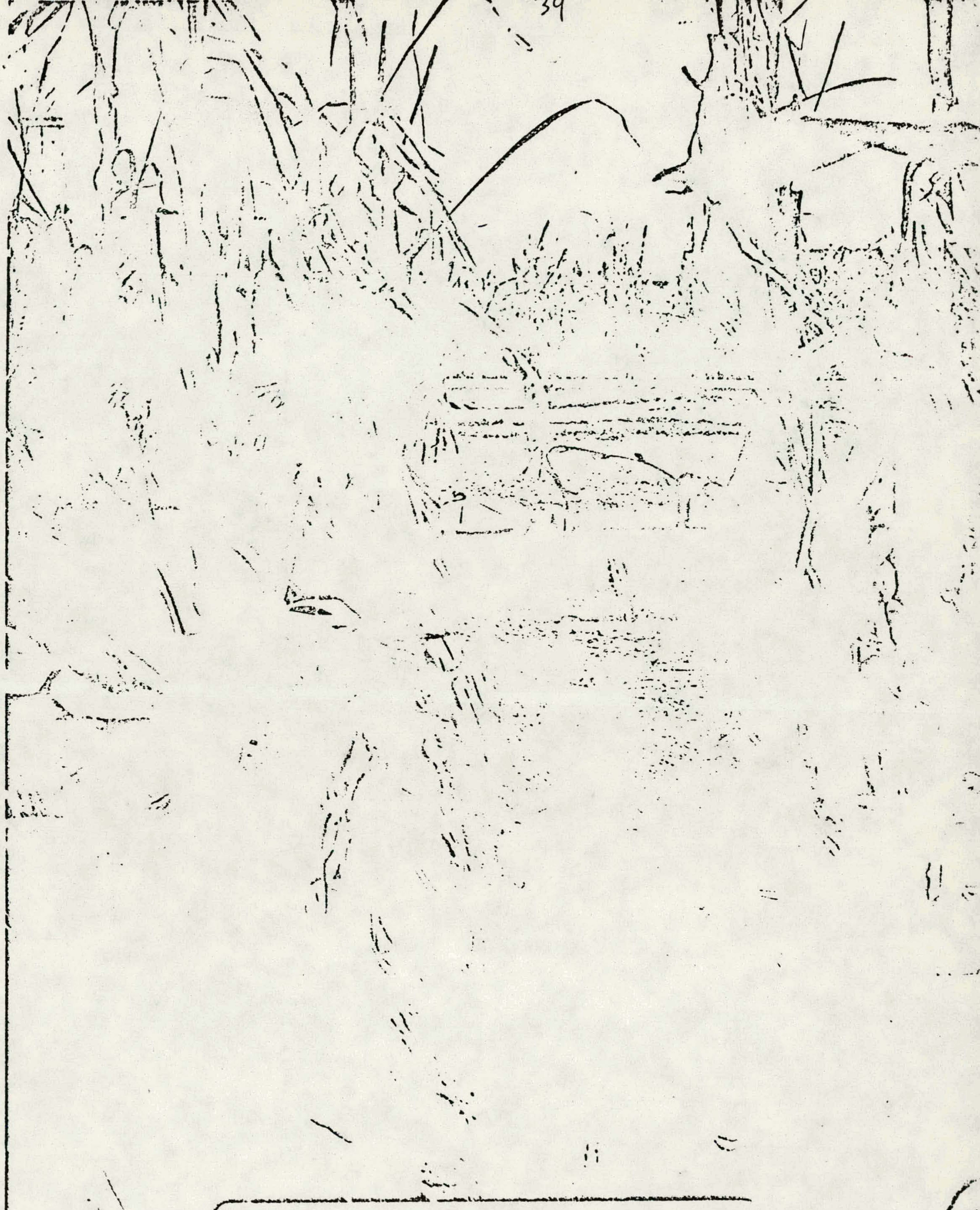
A center-pivot irrigation system can be seen in the background of Figure 15. The center pivot system requires more than twice the energy used by the grated pipe system coupled to the PV system and shown in Figure 16.

The 25 kW system provides power for a 3,783 litre/minute pump since July of 1977. The system has exhibited fair reliability with 19 (out of 2000) panel failures during the first fourteen months of operation and an overall system degradation of 1%. The system efficiency is 10% based on cell area and 6% based on array



Aerial view of agricultural Flexible Test Facility, Mead, Nebraska. August 31, 1977.

Figure 15



View of Grated Pipe Irrigation System,
Mead, Nebraska

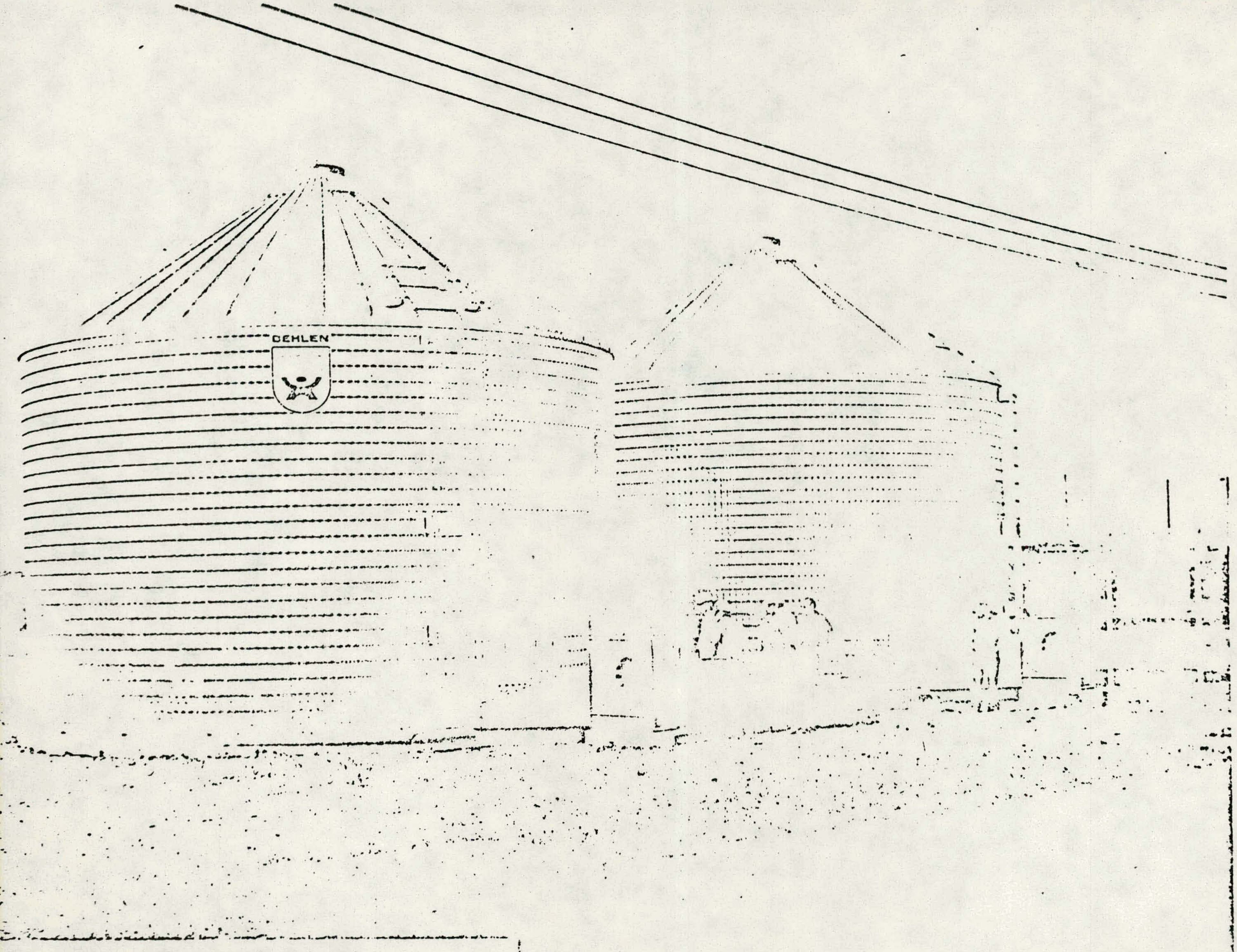
Figure 16

area. Part of the energy is used to dry corn in the bins shown in Figure 17. The two grain bins shown housed 12,000 bushels of corn harvested from the 80 acres that were irrigated. The corn must be dried to about 15% moisture so it will not sprout or rot when the weather turns warm in the spring. The conventional method of drying the grain is to force hot air through the grain, thus requiring combustible fuels or electric resistance heating. The method used with the PV system is to force larger quantities of air at ambient temperatures and humidity through the grain. The two approaches are roughly equivalent in terms of total energy consumption.

Other uses being explored for this PV system include electric power for fans and lighting for animal husbandry, on site production of fertilizer, and grain grinding.

Figure 18 shows an aerial view of Natural Bridges National Monument (NBNM) in Canyon Lands National Park in the state of Utah. A 100 kW PV system is currently under construction at this site. The PV system will provide power for a diversified load that is typical of a small community in a remote area that is not connected to the grid.

The load of the PV system will consist of the entire park's electrical demand, including two rangers' residences, a dormitory that holds a staff of 20 summer workers, a visitor's center and various maintenance shops. The basic design features of the array include:



Grain Drying Bins, Mead, Nebraska

Figure 17

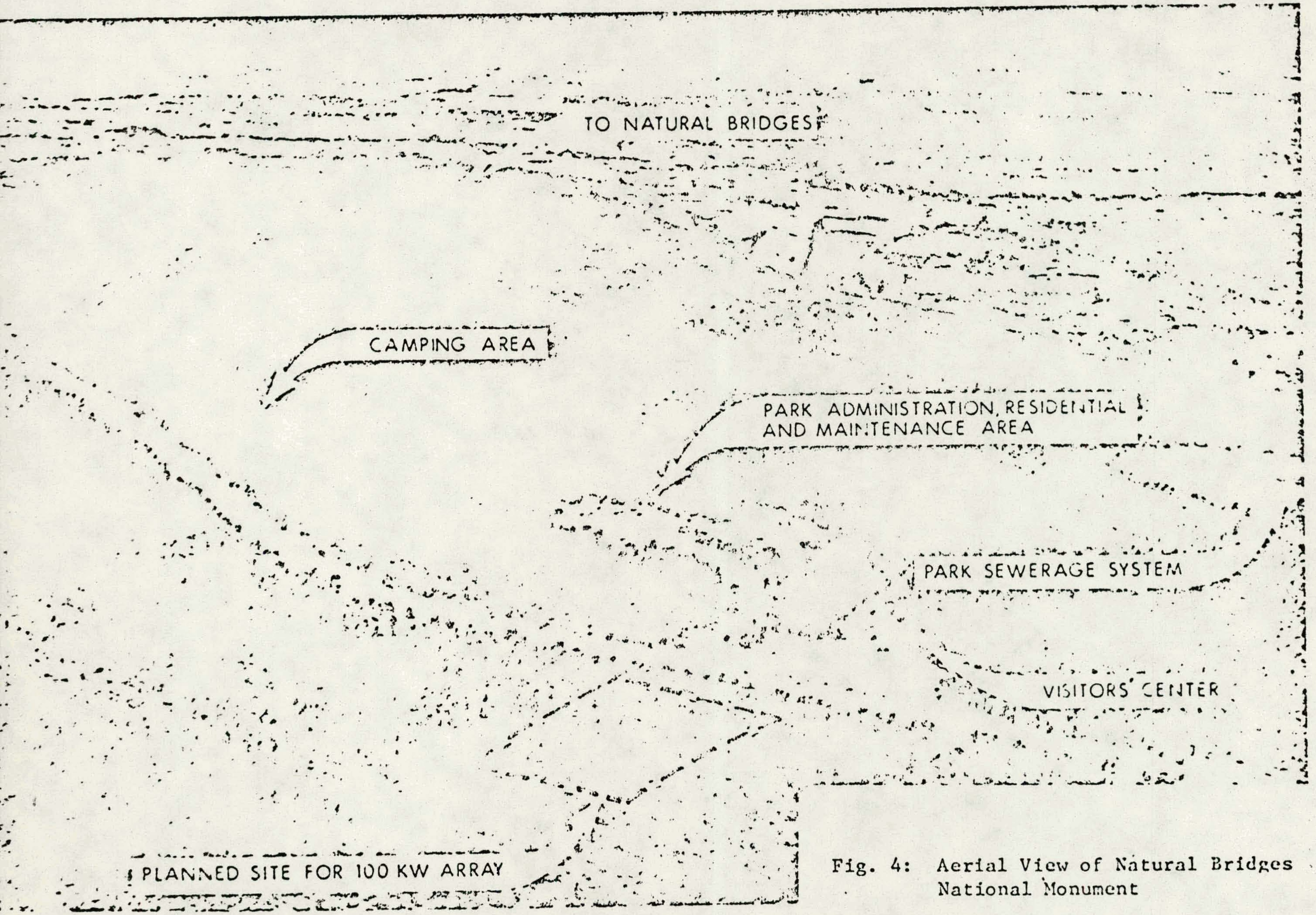


Fig. 4: Aerial View of Natural Bridges National Monument

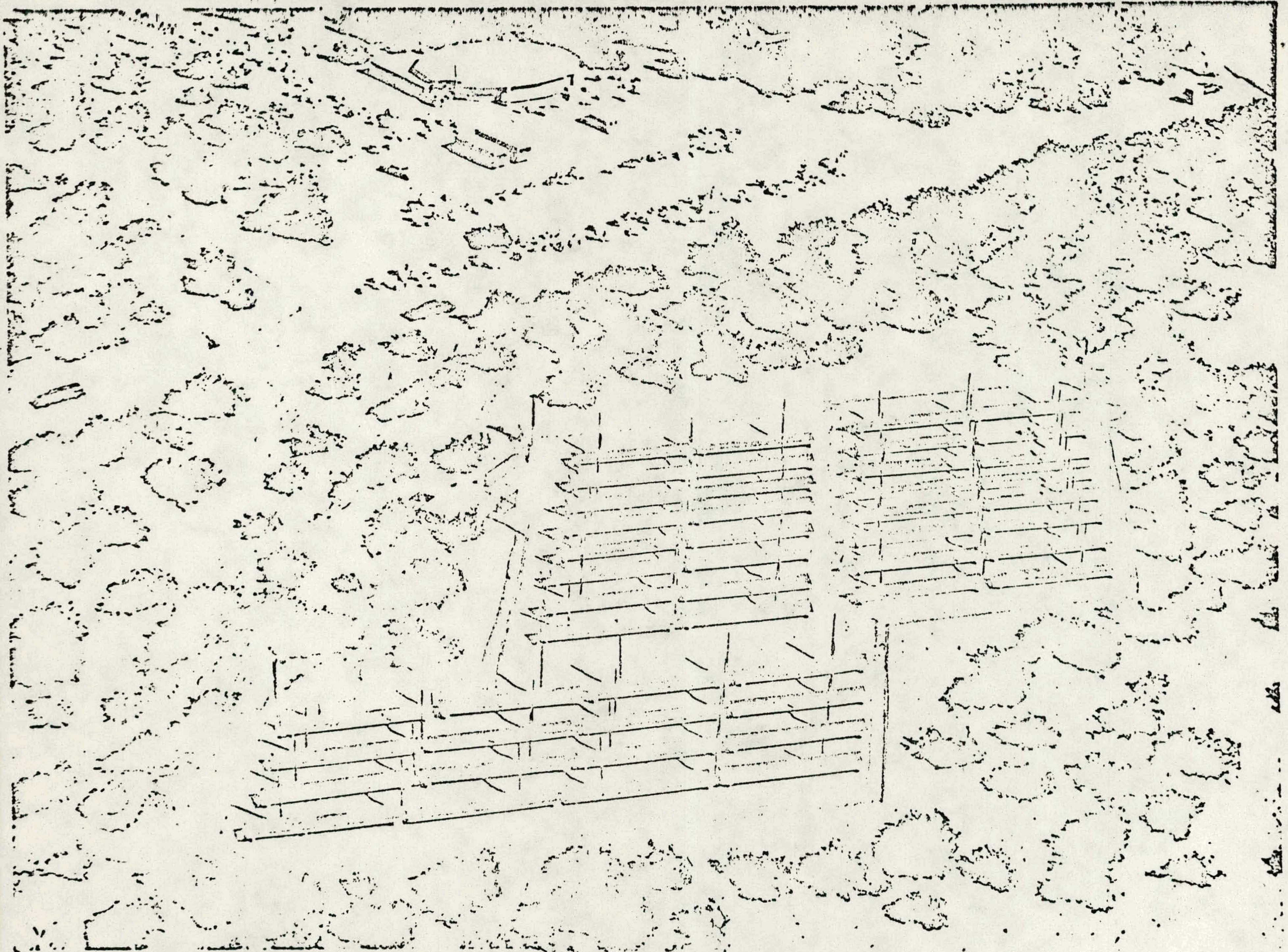
Figure 18

PEAK ARRAY POWER:	100 kW	STORAGE CAPACITY:	600 kWh lead acid battery bank
PEAK CURRENT:	210 amps	PEAK VOLTAGE:	240V DC, 240V AC
ARRAY AREA:	1712 m^2	MODULES:	4762 (3 manufacturers)

DECLINATION: 20° and 40° from horizontal (changed seasonally), non-tracking

To retain the park's aesthetics, the array will be designed so as not to protrude above the surrounding natural shrubs. The array is illustrated in Figure 9. The vegetation consists mainly of shrubs shorter than 5 meters.

Placement of a photovoltaic test bed in a U. S. National Park is of interest for several reasons. For one thing, the National Park Service (NPS) offers a modest near-term market for solar cells at an array price of one to two dollars per peak watt. The initial size of this market is approximately 15 peak megawatts, and it should become realizable in the early 1980's if the DOE Price goals are met. This market size is conservatively based on utilizing PV only at those Park Service installations which are remotely located and presently use diesel-electric generators. (The total Park Service demand is much larger than this - in the range 200 to 300 megawatts peak - but is supplied largely from the electric utility grid.) An NPS experiment is also of interest because it typifies the use of photovoltaics in load center applications, both in the Service, Commercial and Institutional sectors of the U. S. Economy, and in on-site generation systems for less developed countries. Finally, the large visitation to the National Parks offers good visibility



Miniature Replica of Natural Bridges Field
Array and Visitor Overlook

Figure 19

to the general public for such an experiment.

NBNM was judged to be the most attractive site for the first PV system in the Park Service. NBNM contains several huge stone arches which were carved by wind and water erosion from the surrounding sandstone rock. The park lies at an average elevation of 6,600 feet and is in a semi-arid region characterized by infrequent (but sometimes violent) rain and snow falls. Because of the remoteness of NBNM and because there was no possibility of upgrading the limited radio telephone system that was in place, a communication system is being installed for voice communication and for transmission of PV system performance data.

MIT/Lincoln Laboratory will supervise the development of technical material and a training course for NPS personnel. This course will be designed to provide operation and maintenance personnel with a basis for dealing with PV power systems and will support the NPS goal of evaluating the potential role of photovoltaics in future NPS energy planning. Additionally, the training course will provide an opportunity to evaluate the problems of technology transfer of photovoltaics to the ranks of people who will be responsible for the daily operation and maintenance of PV power systems.

The estimated cost of the array is \$1.1 million (~\$1.10/kW_p) and the total installed system cost is estimated to be \$3.1 million.

CONCLUSION

It should be apparent that Photovoltaics provides flexibility to meet a variety of small to intermediate needs in rural and remote areas. The modularity makes the technology scalable in size with no moving parts, low maintenance, and potentially long life. The modularity also allows for some increments of power as future needs require or as resources allow.

Capital costs for arrays have been decreasing from about $35/$W_p$ in 1975 (78 dollars) to an estimated $8-11 in 1980 (80 dollars) thus making PV more affordable for developing countries as well as more cost competitive with alternatives. The reliability has also been increasing. The examples presented in this paper probably represent more than 1000 module years of operation with relatively few module failures. Furthermore, the components for the PV systems of the type disucssed in this paper are commercially available.

It is concluded, therefore, that PV is already a viable energy alternative for small scale applications in remote and rural areas, and will be a cost effective alternative for intermediate applications (tens of kilowatts) in the near term (1986-1990) if the 1986 DOE commercial readiness goal of $0.70/$W_p$ is achieved.

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