PHOTOVOLTAIC POWER SYSTEMS FOR RURAL AREAS OF THE THIRD WORLD

AN OVERVIEW

NASA-LEWIS RESEARCH CENTER

CLEVELAND, OHIO

OCTOBER 1980

PHOTOVOLTAIC POWER SYSTEMS FOR RURAL AREAS OF THE THIRD WORLD

The importance of energy to the economy of nations has been underscored repeatedly in recent years. For none is energy of greater consequence, though, than for the people of the developing countries. Over one-third of the population of the world is at, or slightly above, a subsistence level of energy consumption, i.e., 8.5×10^6 Btu per year per capita or about 10% of the per capita consumption of western European countries. Further, consumption at the subsistence level is mainly in the form of non-commercial "fuels" (e.g., wood, crop residues, animal wastes and human and animal labor) with an energy utilization efficiency of about one-fifth that for commercial fuel. Thus the effective per capita energy consumption, adjusted to reflect "useful work", is in reality about 2% of that in western Europe.

There is probably no one answer for the energy dilemma of the poor nations; rather, a mix of mutually supporting technical, institutional and developmental approaches will be required. Among the technical approaches which could ameliorate the present situation, and avert a possibly dire future, is the more extensive use of renewable energy resources, specifically solar. In this regard the direct conversion of solar energy to electricity by means of solar cells is of great interest. Of all the solar technologies, photovoltaic (PV), solar cell, power systems appear to have the most flexibility for meeting a large variety of the small-scale decentralized energy needs of rural areas in underdeveloped countries. It has been acknowledged that PV systems have many desirable features; modularity (therefore scalable in size); no moving parts; low maintenance; a potentially long life. However, uncertainty has been expressed concerning cost and system reliability.

TRENDS

From 1958 to recent years the major application of solar cells has been in space where it is the power system of choice, supplying watts to several kilowatts of power to hundreds of spacecraft. In the 1960s Japan successfully employed solar cells in a number of instrument, communication, and navigational aid applications; the total peak power employed in all applications to 1976 was 22 kW. In the early 1970s U.S. firms began marketing PV power systems for communications, instrument and corrosion protection applications. By 1975 the annual terrestrial solar cell production in the U.S.

was about 100 kW peak (kWp). Production has approximately doubled each succeeding year, partly under the impetus of the U.S. Department of Energy (DOE) National PV Program and partly as a result of an expanding commercial applications market. In this same period (1975-80) solar cell module* price has dropped from about $42/Wp to $10/Wp, both in 1980 dollars. The DOE Program, currently operating with $150 million per year budget, projects module price of $0.70/Wp and system price of $1.60-2.60/Wp (1980 $) by 1986.

RELIABILITY

Nineteen experimental systems have been installed by the NASA-Lewis Research Center (LeRC) in the U.S. and overseas since 1976. Operational experience to date, representing an average of 3 years operating time, indicates the following concerning reliability.

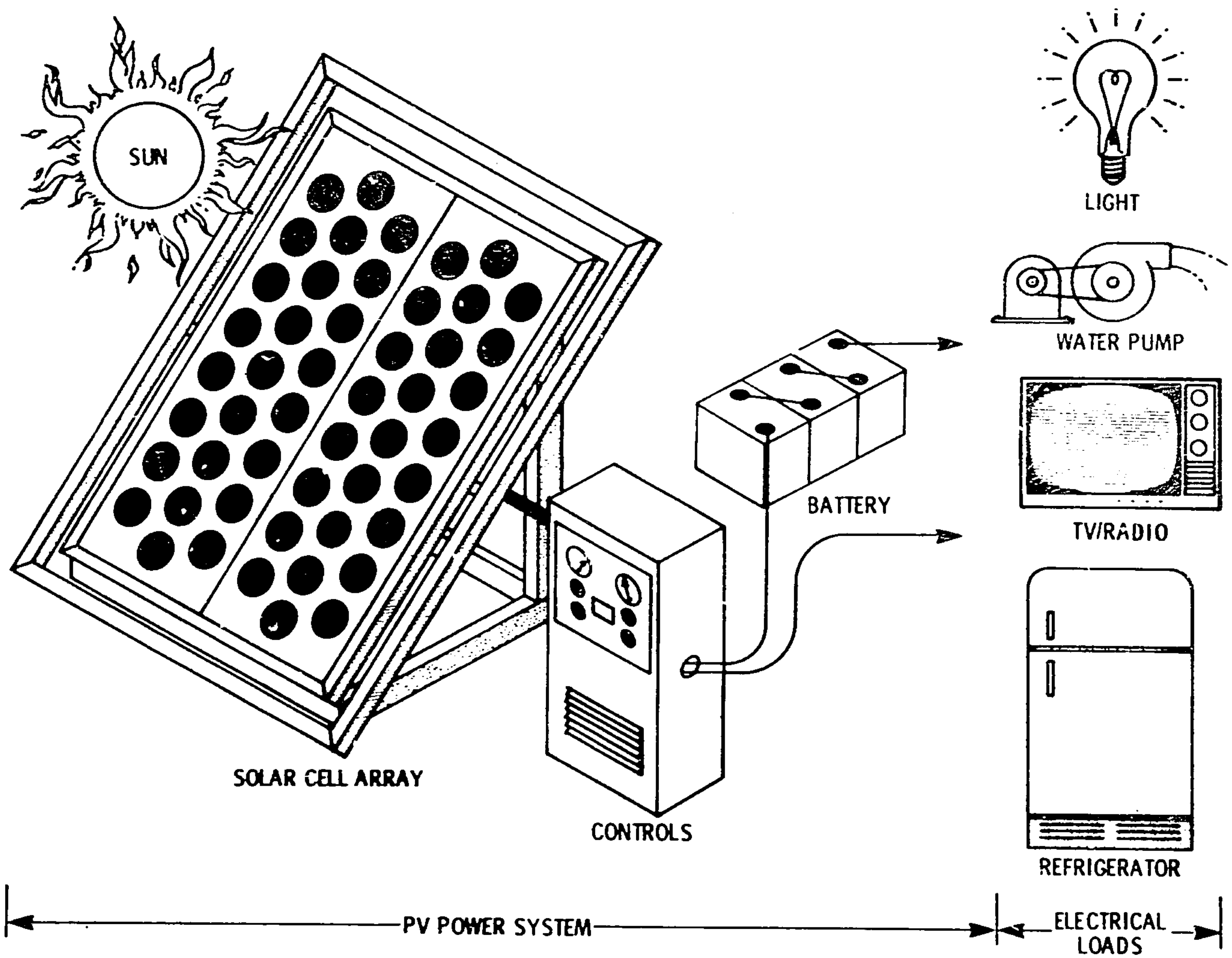
Modules. - Of a total of 2000 modules installed, approximately 1700 modules (consisting of units from three different U.S. manufacturers) evidenced less than 1% failures. The remaining 300 modules (consisting of one manufacturer's units of a single model type) exhibited 20% failures within the first 18 months of operation. Failure of these latter modules resulted from thermal stress induced fatigue cracking of the cell electrical interconnects, apparently due to an inappropriate choice of module substrate material. It may be noted that for the two PV systems (the Schuchuli and Tangaye Village Power Systems), which contained these 300 design deficient modules, there was no abrupt interruption of power. The systems continued to operate as module failures accumulated over an 18-month period, howbeit with a progressively diminished overall energy output. Full system operational output was restored by replacement of failed modules.

Other components. - The majority of the systems deployed did not exhibit any component problems. Minor, readily remedied component malfunctions or design problems (e.g., voltage regulator, refrigerator compressor motor) were experienced with seven of the systems.

Power system reliability is strongly dependent on system design and the proper selection and assembly of the components, i.e., modules, batteries, controls, regulators, structure and wiring. In general operating experience from the variety of geographically dispersed

*The module, the basic building block of the photovoltaic array, contains a number of solar cells electrically connected and encapsulated in a supporting structure.

SCHEMATIC DRAWING OF A PHOTOVOLTAIC POWER SYSTEM



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applications indicates excellent system reliability. Outage rates for photovoltaic systems are generally lower than for U.S. central station electric utility power and considerably lower than for electric utility power in many developing countries.

COST

Total photovoltaic system capital cost generally includes the following component, material, and labor costs: solar cell modules, array structure, site preparation, electrical wiring and interconnects, controls, storage battery, enclosures, design engineering, and assembly labor. For purposes of comparison with an alternative power source, such as diesel/electric, levelized annual costs and energy costs ($/kW-h) can be calculated for each system. The following assumptions are employed: for all systems - 20-year life and 15% discount rate; for diesel/electric - 4 kVA unit, $3.00/gal. fuel cost (delivered), 7%/yr. fuel escalation rate, O&M costs as specified by diesel manufacturer; photovoltaic - annual solar insolation typical of areas between 30° N and 30° S latitude (resulting in 1 Wp producing 1.6 kWh (electric) per year), levelized annual O&M costs = 15% of levelized annual capital costs.

The results indicate that for applications having an annual electrical demand of 6,000 kWh or less, the energy cost for a photovoltaic system is less than for a small diesel/electric system. Points of reference for annual electric demand are the Schuchuli Village Project, 6,000 kWh/yr. and the Tangaye Village Project, 3000 kWh/yr. Within the range of annual energy use up to 6,000 kWh lie many important applications of immediate relevance to development in rural areas of Third World countries. Furthermore, over the next several years it may be anticipated that photovoltaic system costs will continue to drop steadily. Thus within a decade it is likely that photovoltaics will become the least expensive and most reliable source for all decentralized electric power applications in the developing world.

PHOTOVOLTAIC AND DIESEL ENERGY COST COMPARISONS

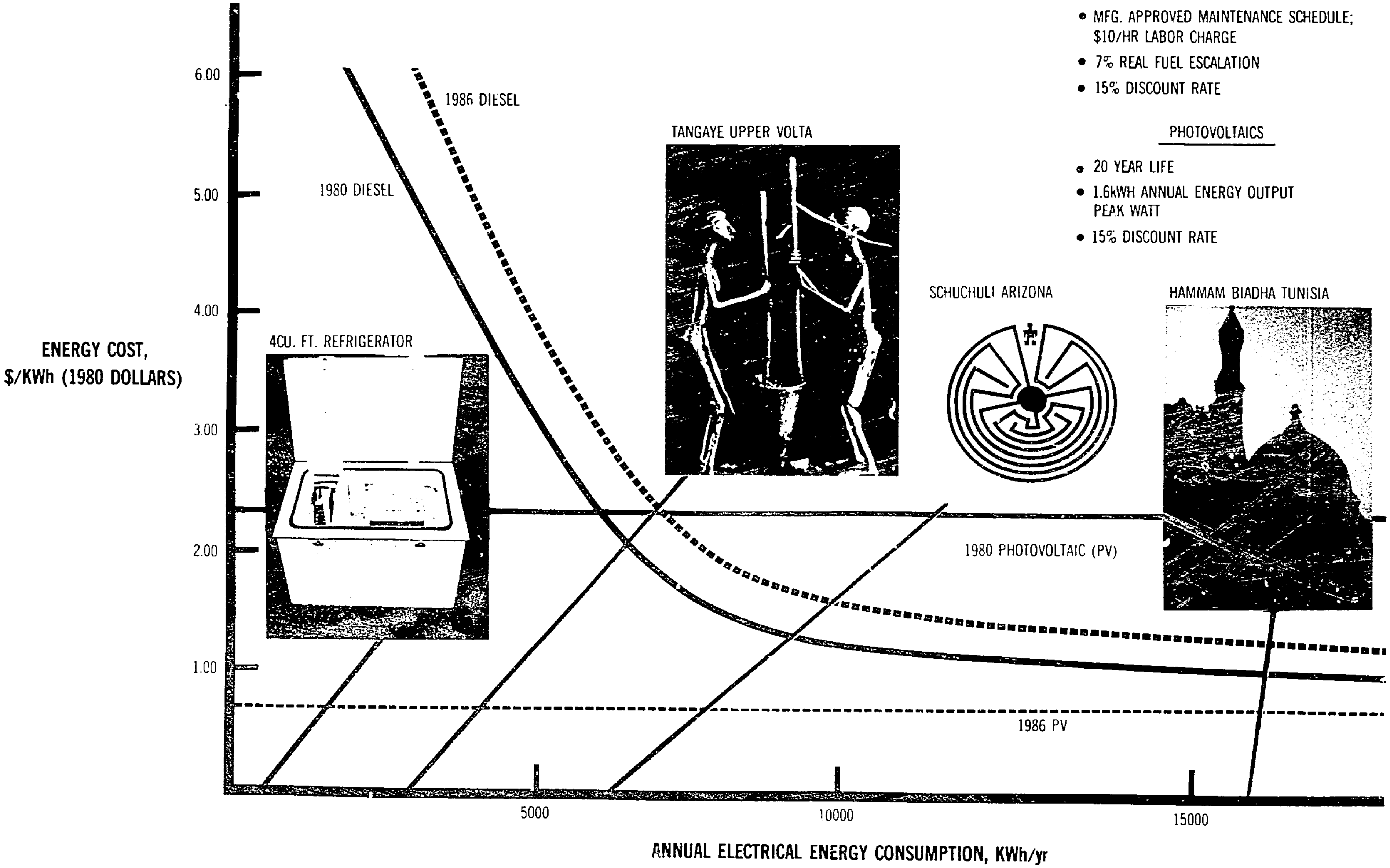
ASSUMPTIONS

DIESEL

- 20 YEAR LIFE
- $3/GALLON FIRST YEAR FUEL COST
- 4 kVA DIESEL UNIT
- MFG. APPROVED MAINTENANCE SCHEDULE; $10/HR LABOR CHARGE
- 7% REAL FUEL ESCALATION
- 15% DISCOUNT RATE

PHOTOVOLTAICS

- 20 YEAR LIFE
- 1.6kWH ANNUAL ENERGY OUTPUT PEAK WATT
- 15% DISCOUNT RATE



PHOTOVOLTAIC ACTIVITIES MANAGED BY NASA-LeRC

FOR THE DEPARTMENT OF ENERGY (DOE)

- o Photovoltaic Stand-Alone Applications Project
  - Develop and demonstrate, in partnership with users, stand-alone applications which represent a potentially large market for photovoltaics
  - Develop the supporting system, sub-system, and component technology
- o Total DOE funding of activity, since June 1976, $11.6 million

FOR THE AGENCY FOR INTERNATIONAL DEVELOPMENT (AID)

- o Photovoltaic Development and Support Program
  - Design, develop, and demonstrate with users photovoltaic (PV) power systems for select applications (e.g., health delivery, communications, education, water pumping) in rural areas of developing countries.
- o Upper Volta Photovoltaic Power System Demonstration Project
  - Provide a reliable PV system for potable water pumping and grain grinding in the village of Tangaye
- o Tunisian Renewable Energy Project
  - Provide assistance to the Government of Tunisia in the demonstration of renewable energy technology in rural settings (village of Hammam Biadha)
- o Funding
  - Upper Volta Project, since March 1978, $110K
  - PV Development and Support Project, since September 1979, $2.5 million
  - Tunisian Project, since November 1979, $1.9 million (75% AID, 25% GOT)

PARTIAL LIST OF PHOTOVOLTAIC APPLICATION DEMONSTRATIONS MANAGED BY NASA-LeRC

LOCATION	APPLICATION SECTOR	SERVICE	STATUS (AS OF SEPT.'80)	SPONSORS
SCHUCHULI, AZ., U.S.	VILLAGE: DOMESTIC & COMMUNAL	LIGHTS, REFRIGERATORS, WATER PUMP, WASHING & SEWING MACHINES	OPERATING SINCE DECEMBER 16, 1978	DOE & PAPAGO TRIBE
TANGAYE, UPPER VOLTA	VILLAGE: COMMUNAL & COMMERCIAL	WATER PUMP & GRAIN MILL	OPERATING SINCE MARCH 1, 1979	AID & UPPER VOLTA
COLOMBIA, GAMBIA, INDIA, IVORY COAST, MALDIVE IS., & PERU	HEALTH: IMMUNIZATION PROGRAMS	REFRIGERATORS FOR THE PRESERVATION OF THE COLD CHAIN OF VACCINES	OPERATION SCHEDULED FOR AUGUST 1981	DOE & CENTER FOR DISEASE CONTROL WITH COOPERATION OF PAN AMER. HEALTH ORG.
HAMMAM BIADHA, TUNISIA	VILLAGE: DOMESTIC, COMMUNAL & COMMERCIAL AGRICULTURE	WATER PUMP, LIGHTING, DOMESTIC APPLIANCES, ETC. DRIP IRRIGATION PUMP	OPERATION SCHEDULED FOR MAY 1982	AID & TUNISIA
EQUADOR, GUYANA, KENYA & ZIMBABWE	HEALTH: MEDICAL POSTS	LIGHTS, REFRIGERATOR, AUTOCLAVE, DENTAL EQUIPMENT, ETC.	PROJECT DEFINITION COMPLETE(EXCEPT FOR ZIMBABWE). OPER. MID-1982	AID & HOST COUNTRY
4 VILLAGES IN GABON	VILLAGE: COMMUNAL	DISPENSARY - LIGHTS & REFRIGERATOR SCHOOL - LIGHTS & TEACHING AIDS WATER SUPPLY - PUMP AREA LIGHTING	PROJECT DEFINITION COMPLETE. OPER. MID-1982.	DOE & GABON

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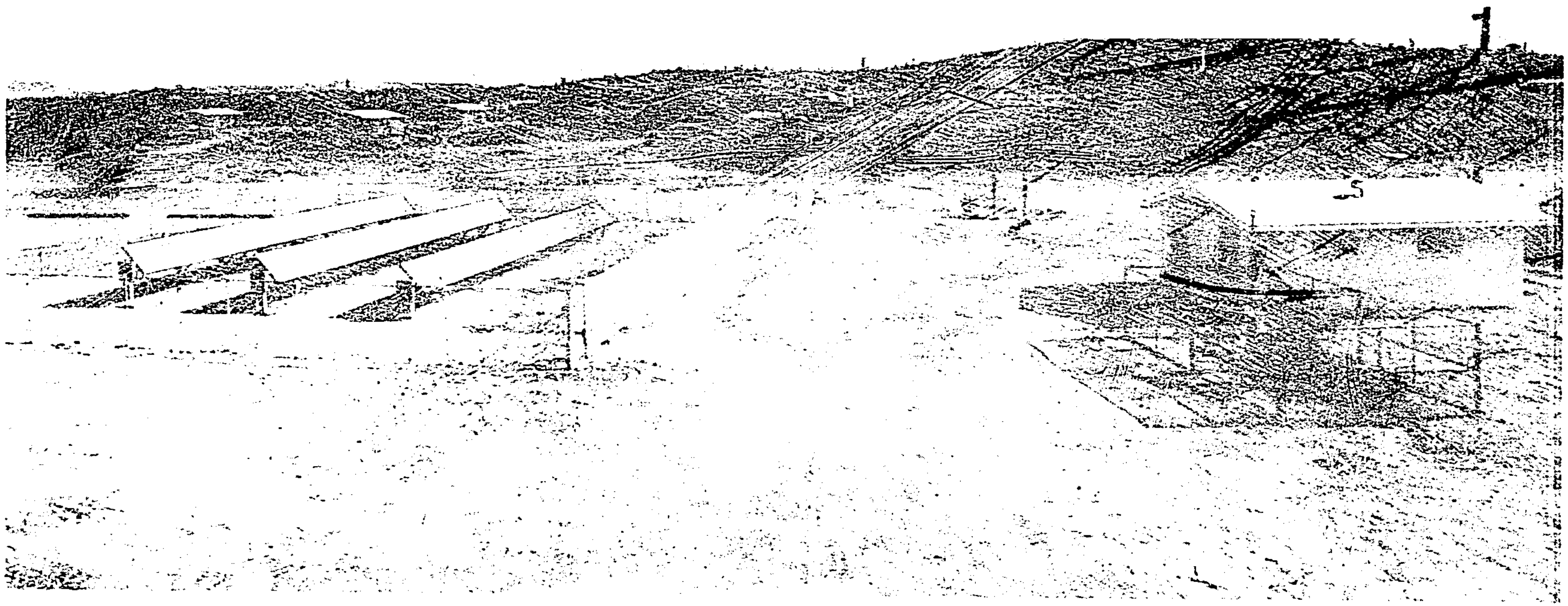
SCHUCHULI VILLAGE POWER PROJECT

The village of Schuchuli is located on the western edge of the 2,750,000 acre Papago Indian Reservation in southwestern Arizona. The village's 15 families (95 people) are 27 km (17 miles) from the nearest available electric utility power. The villager's diet has been tied to traditional (i.e., non-refrigerated) methods of food storage and preparation and includes items such as chili, beans, tortillas and commercially available non-perishable vegetables and canned foods. Cattle raising and wild game hunting provide an occasional supplemental source of food. Until the advent of the PV power system, water was provided by a diesel-powered pump; kerosene lamps and candles provided lighting in the homes.

On December 16, 1978, the world's first Village Photovoltaic Power System began operation, providing the residents of Schuchuli with the following services: electric power for potable water pumping; lights in the homes and community buildings; family refrigerators; and a communal washing machine and sewing machine. Selection of the electrical services installed was made by the village residents.

Project was cost-shared: DOE, $300K; Papago Tribe, $30K. Costs associated with the power system by itself, which includes hardware, assembly and installation, was $108K.



PHOTOVOLTAIC VILLAGE POWER PROJECT - SCHUCHULI, ARIZONA

The Schuchuli Village Photovoltaic Power System consists of a 3.5 kW, 120 volt, DC PV array, 2380 ampere-hours of battery storage, controls, regulator and instrumentation, and an overhead electrical distribution network. The batteries and controls are located in an electrical equipment building.

The system is all DC to avoid the losses associated with commercially available DC/AC inverters and to maximize system efficiency. The system voltage was set at 120 volts to limit distribution line losses and to enable use of commercially available DC switches and DC appliance motors. The load devices were individually selected on the basis of energy efficiency.

System design, exclusive of the overhead distribution network, was performed by NASA-LeRC. The overhead distribution network was designed by the Papago Tribal Utility Authority.

The PV array consists of 24, 1.22m-by-2.44m (4 ft.-by-8 ft.) panels. Each panel contains 8 modules connected in series to make up a 120 VDC series string. The panels are arranged in 3 rows of 8 and are located in a 21.3m-by-30.5m (70 ft.-by-100 ft.) fenced area. Panel frame and support structure are designed to withstand 161 km/hr (100 MPH) wind loads and are fabricated from commercially available hardware.

The battery consists of 52, 2380-ampere-hour capacity cells connected in series with a parallel arrangement of 4 pilot cells for load management. The cells were designed for operation with PV systems and have lead-calcium plates capable of deep discharge cycle operation. The batteries are housed in a separate, vented room in the electrical equipment building.

Because of unknowns in the use of the loads and variations in insolation, a load management subsystem was incorporated into the design to (1) protect the batteries from excessive discharge and potential damage, and (2) to maintain operation of the more critical loads at the expense of less critical loads. The load management subsystem sequentially disconnects loads as the battery capacity decreases to preset levels.

Since the Schuchuli village PV power system is the first of its kind it is completely instrumented to obtain a substantial amount of basic engineering data. There are two independent instrumentation subsystems: a panel meter subsystem and an automatic cassette data recorder. The panel meters are read daily by a village resident who is trained to take readings and to recognize anomalous operation. Measurements are also recorded hourly by the automatic data system. The cassettes and the panel meter data are mailed to LeRC weekly for analysis.

NASA
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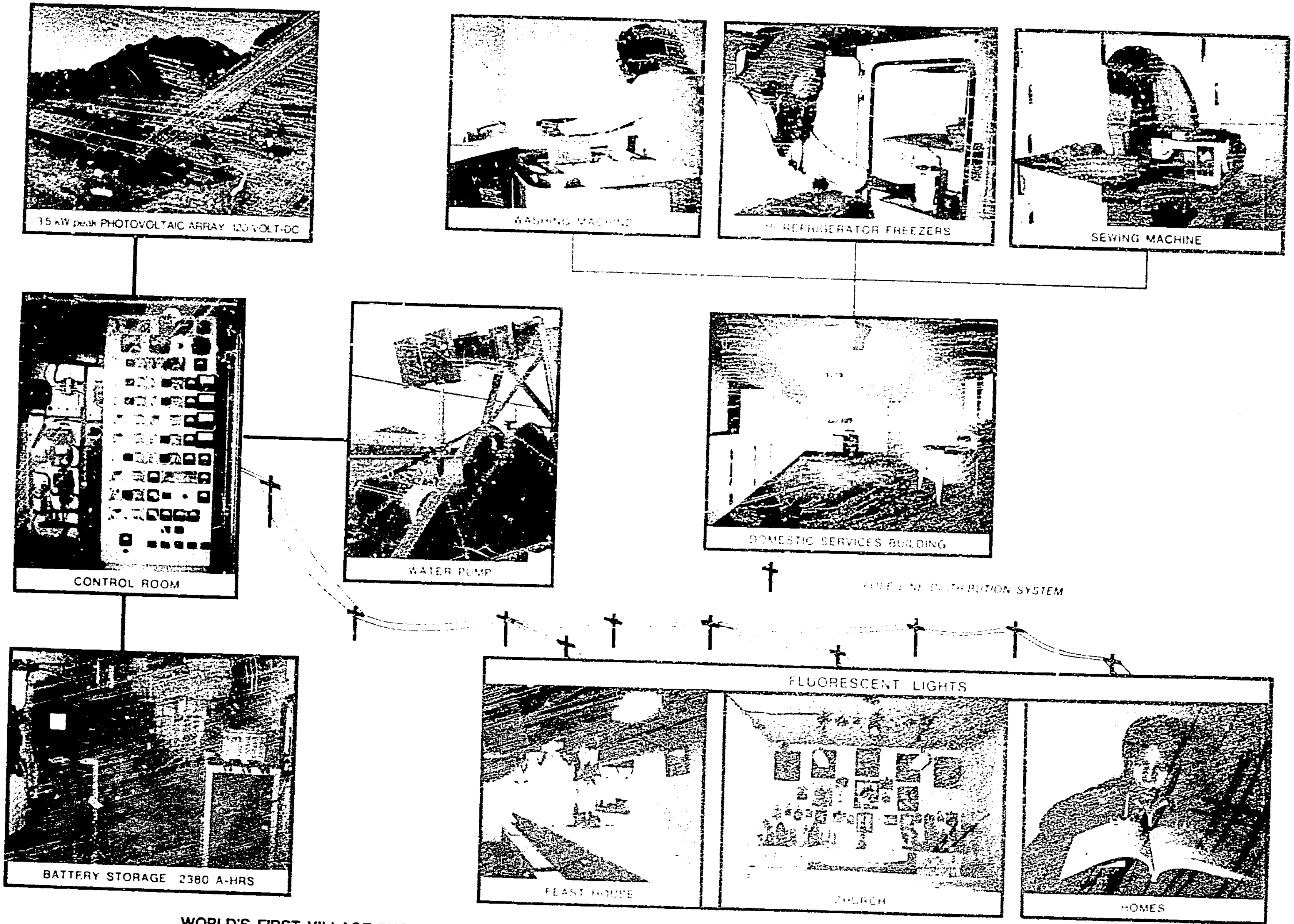


WORLD'S FIRST VILLAGE PHOTOVOLTAIC POWER SYSTEM - PAPAGO INDIAN VILLAGE OF SCHUCHULI, ARIZONA

TANGAYE VILLAGE POWER SYSTEM

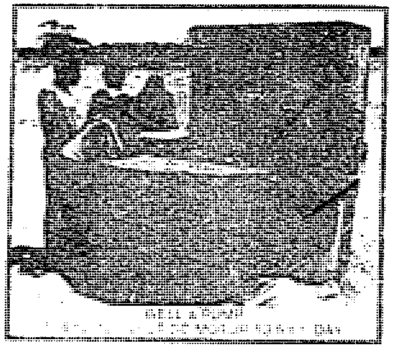
The West African village of Tangaye, Upper Volta, is located about 190 km east of Ouagadougou, the capital city. The main occupations of its 2200 inhabitants are farming and cattle raising and the main food crops are sorghum and millet. In addition to farming chores, women are responsible for all aspects of family care. This includes a number of laborious and time-consuming tasks such as drawing water and preparing of daily meals. Food preparation, for example, involves the pounding of grain (the primary source of food) into a coarse flour using a large wooden mortar and pestle. Finer flour is obtained by stone grinding the grain by hand.

As part of a project sponsored by the U.S. Agency for International Development (AID) entitled "Studies of energy needs in the food system" a PV system powering a grain mill and water pump has been installed in the village. Operation began on March 1, 1979.

The system consists of a 1.8 kWp, 120 V d.c. PV array, 540 A h of battery storage, regulator, controls and instrumentation designed by LeRC. The PV array, located in fenced-in area, provides power via underground cable to a control cabinet located in a nearby mill/battery building. Storage batteries are located in one room of the building; the mill and control cabinet are in the other. An underground cable carries power from the control cabinet to the water pump. A water storage tank and dispensing facility are located near the well. The tank was designed by LeRC and was procured and installed by Upper Volta AID Mission personnel. The mill/battery building was built by the men of Tangaye.

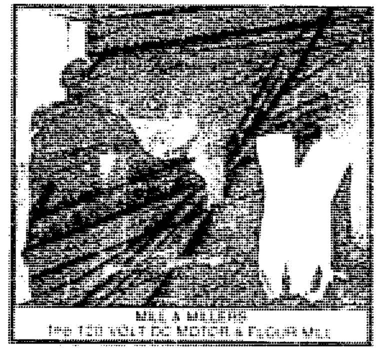
The solar derived electricity powers a commercial hammer mill with a 3 hp, 120 V d.c. motor and a positive displacement water pump with a 1/4 hp, 120 V d.c. motor. The mill operates at a throughput of 1000 kg/wk. The water pump delivers 13,600 ℓ/d at a total dynamic head of 28 m.

With the assistance of the Government of Upper Volta, Office of Rural Development, a cooperative was formed to manage the Tangaye mill. About 60 village families each invested 500 Fr CFA (about $2.35) in the enterprise. Charges for milling were set by the cooperative and are competitive with commercial, diesel driven mill in a nearby village. Milling is open to member and nonmember families alike. Proceeds from membership and milling are used to pay two full-time millers and to accumulate funds for spare parts and repairs after the first year of operation. When excess funds are accumulated, profits will be distributed to cooperative members.



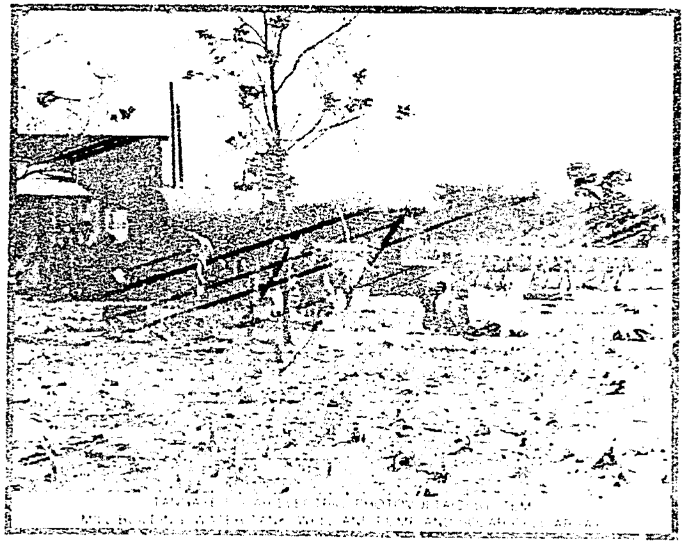
WELL & PUMP

[illegible] DC MOTOR [illegible] DAY



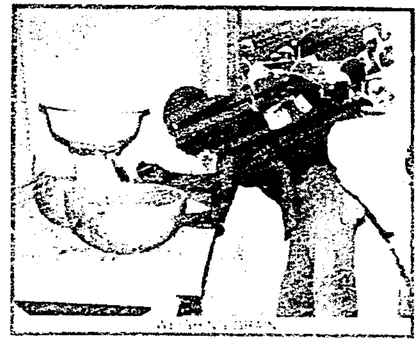
MILL & MILLERS

1hp 120 VOLT DC MOTOR & FLOUR MILL



TANGAYE [illegible] PHOTOVOLTAIC SYSTEM

[illegible] WATER TANK, WELL AND PUMP AND [illegible] ARRAY



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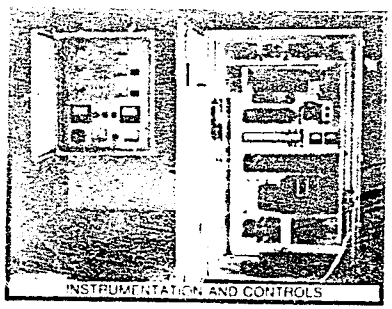
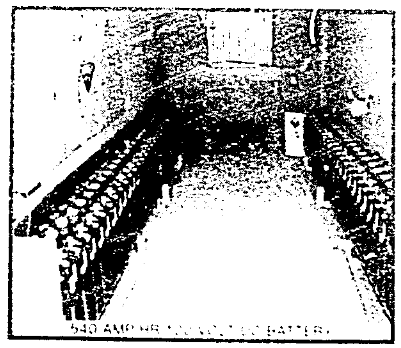


INSTRUMENTATION AND CONTROLS

1.8 KW 120 VOLT DC PHOTOVOLTAIC ARRAY



540 AMP HR [illegible] VOLT DC BATTERY

TANGAYE VILLAGE SOLAR ELECTRIC SYSTEM

PHOTOVOLTAIC-POWERED REFRIGERATOR/FREEZER FOR VACCINES

The three billion people of the less developed world suffer from a plethora of infectious diseases. Because these infections tend to flourish at the poverty level, they are important indicators of a vast state of collective ill health. The concomitant disability has an adverse effect on agricultural and industrial development, and the infant and child mortality inhibits attempts to control population growth.

Vaccination has been used extensively in developed countries over the last few decades for the prevention of a number of important communicable diseases such as poliomyelitis, diphtheria, and measles. The experiences gained in these countries are now being transferred on a gradually increasing scale to the developing world. The application of vaccination in developing countries has met with a number of problems of an economic, operational, and technological nature. One of the main problems consist in the refrigerated storag and transportation of vaccines, the so-called "cold chain".

The cold chain is a system for distributing vaccines in the potent state from the manufacturer to the actual vaccination site. Vaccines exposed to elevated temperatures suffer a permanent loss of potency. To remain efficacious most vaccines must be maintained during storage and transport at 4-8° C; with the more sensitive polio and measles vaccines, for example, -20° C temperature is recommended for extended storage times. The available technical solutions to the problem of maintaining the cold chain are mainly based on the presumption that there is a steady supply of electric power, which is frequently not the case in developing countries. The problem is much more serious for these countries in that (1) many of them have a hot tropical climate, and (2) much of the cold chain equipment produced in developed countries is unsuitable for tropical countries.

The development of an effective photovoltaic-powered refrigerator/freezer boxes peripheral units in the cold chain is seen by the World Health Organization and the Center for Disease Control (U.S. Department of Health and Human Services) as vital to the success of immunization programs in the developing countries. At present 75% of the population that is to be reached by the immunization programs are in areas not served by reliable refrigeration. Dr. Stanley O. Forster, Center for Disease Control, has estimated that 30,000 refrigeration units will be needed in the next 5 years to support present programs.

NASA-LeRC on behalf of the DOE has entered into a joint cost-shared project with the Center for Disease Control to provide PV-powered medical refrigerator/freezers which meet the World Health Organization's requirements for vaccine preservation for testing at eight locations worldwide. Deployment of these prototype test units is scheduled for August 1981.

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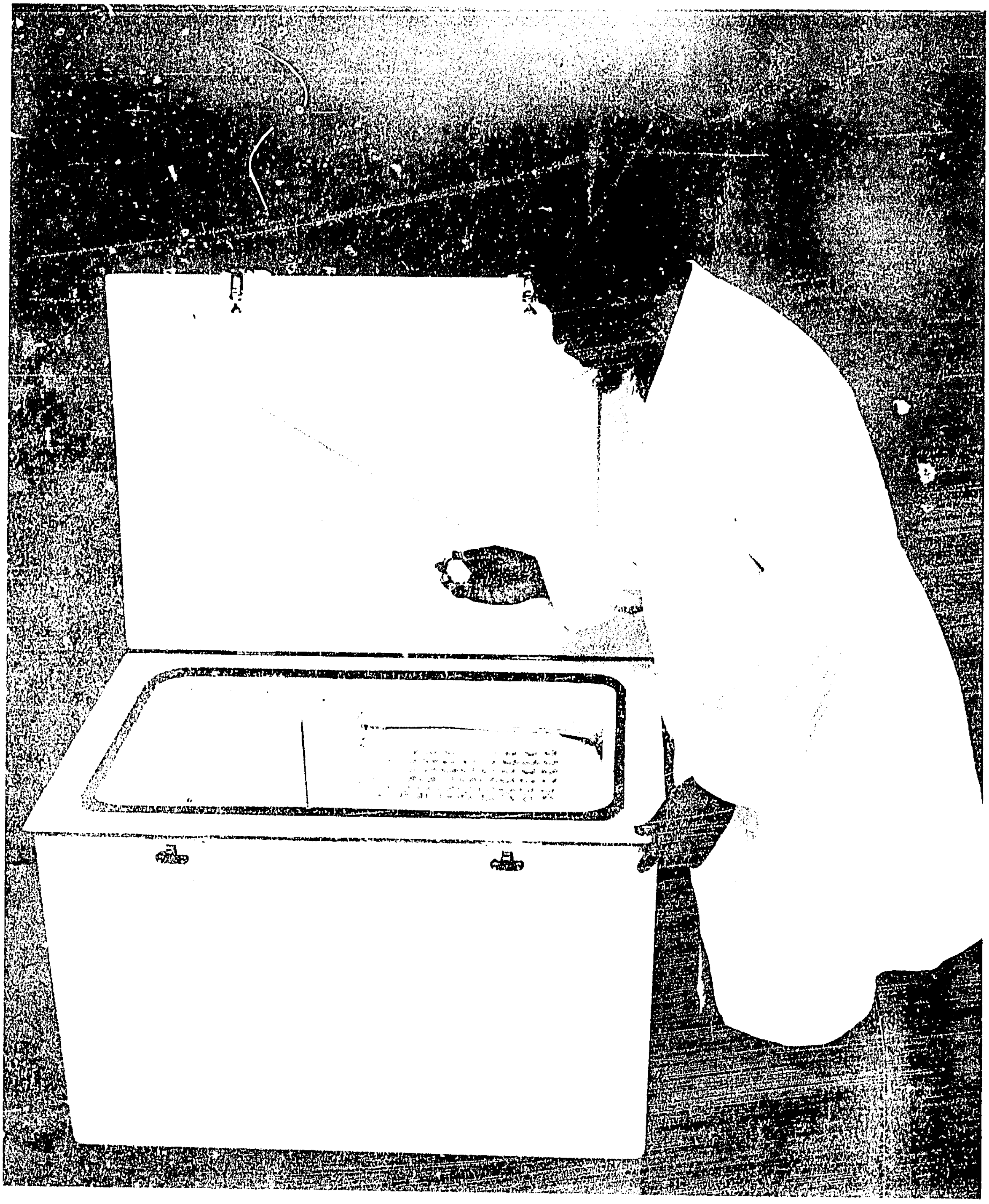


PHOTOVOLTAIC POWERED MEDICAL REFRIGERATOR FOR THE PRESERVATION OF THE COLD CHAIN OF VACCINES

MEDICAL POST APPLICATIONS

The Photovoltaic (PV) Development and Support Program, sponsored by U.S. AID and managed by NASA LeRC, is being conducted to determine the suitability of PV power systems (i.e., cost-competitiveness and reliability) for development assistance activities in rural areas of developing countries. This is being accomplished through the design, development and deployment of PV pilot tests as part of a series of non-country specific demonstration projects.

The initial application category selected by AID for PV demonstration projects is health delivery at rural health facilities. Preventative health care is generally emphasized at these sites which are typically staffed by paramedical health officers, interns and/or nurses. At present sites in four countries are under consideration for installation of PV systems.

The provision of relatively modest amounts of electricity to rural medical facilities is expected to result in a significant improvement in health delivery effectiveness. Characteristic uses of electricity include lighting, refrigeration, sterilizers and 2-way radios.

A typical medical application under this program will be at the Ikutha Health Center in Kenya. The health center, located in a semi-arid region 250 km (155 mi.) from Nairobi, consists of eight rooms, including a three-bed maternity ward, labor room, examination room, injection room and pharmacy, and serves a population of approximately 50,000. On the average, 65 people visit the center each day for health care. The Ikutha PV system is expected to be operational in early 1982.

The use of photovoltaics for meeting the basic electrical needs of health centers such as Ikutha is considered cost-effective today. For example, based on the use of $2/gal. diesel fuel (current price in Ikutha) the levelized cost of diesel-generated electricity for the health center is estimated at about $3.50 per kilowatt-hour compared to $2.30 per kilowatt-hour for PV-generated electricity.

IKUTHA MEDICAL POST - KENYA

TUNISIAN RENEWABLE ENERGY PROJECT

The goal of this cooperated, cost-shared program between the Government of Tunisia and the U.S. Agency for International Development is to demonstrate the value of alternative energy resources and technologies in assisting the development and improving the quality of life in Tunisia. Selected as the test site is the village of Hammam Biadha Sud (pop. 120) and the surrounding farm area (600 hectares) situated 130 km southwest of Tunis.

The photovoltaic portion of the project will consist of the following:

- 10-20 kWp, 220 V, 50 Hz system - to serve the domestic, public, and commercial sectors of the village
- 1 kWp system for a remote farm
- Two 600 Wp systems to power drip irrigation for a greenhouse and an orchard

Operation is scheduled for May 1982.

GABONESE PHOTOVOLTAIC DEMONSTRATION PROGRAM

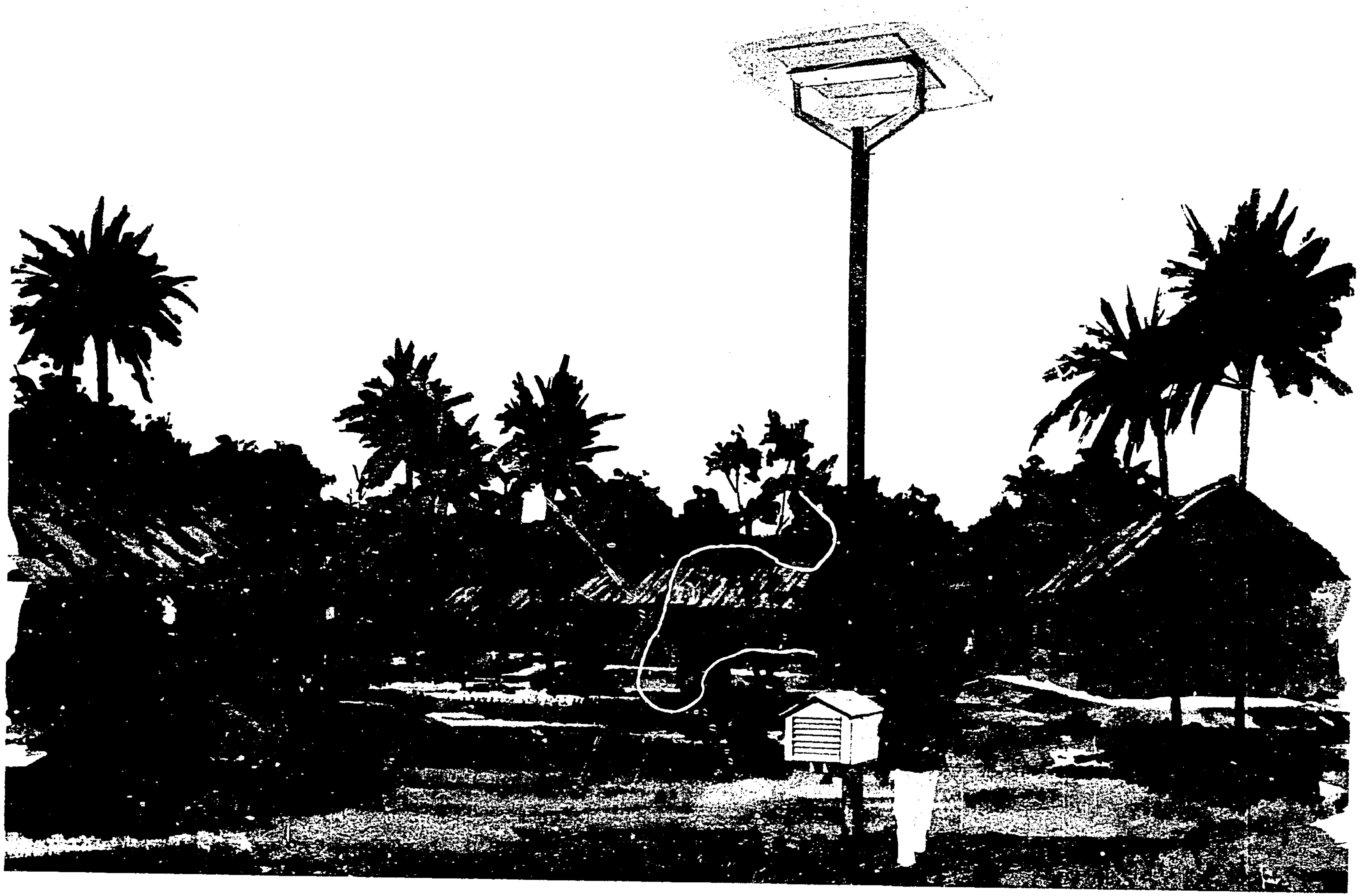
The goal of this cooperative, cost-shared program between the Government of Gabon and the U.S. Department of Energy is to demonstrate the value of photovoltaic power systems in assisting development and improving the quality of life in rural areas of Gabon. Selected as the test sites are four central villages of 1000-1500 population located in different provinces: Bougandji, Nyoli, Donguila, and Bolossoville.

Energy for four public service applications will be supplied to each village as follows:

- Health - lighting, ventilation, and medical refrigerator for the dispensary
- Education - lighting and audio-visual teaching equipment for the school
- Water supply - water pump, storage and distribution system
- Area lighting - outdoor pole light

Standard power packages and loads will be provided to all the villages for each public service application. Operation is projected for mid-1982.

SKETCH OF A PHOTOVOLTAIC POWERED VILLAGE LUMINAIRE



PHOTOVOLTAIC-POWERED ELECTRICAL PRODUCTS

From the viewpoint of the marketplace a customer has little if any use for electricity by itself; a customer seeks commodities or services. Often, though, electricity is needed to power a product which provides the desired service, e.g., lights, radios, refrigerators. Thus, in places without available or dependable electric power, electrical products must be packaged with a self-contained power supply in order to deliver the service. Such a product is exemplified by the ubiquitous portable transistor radio, battery operated.

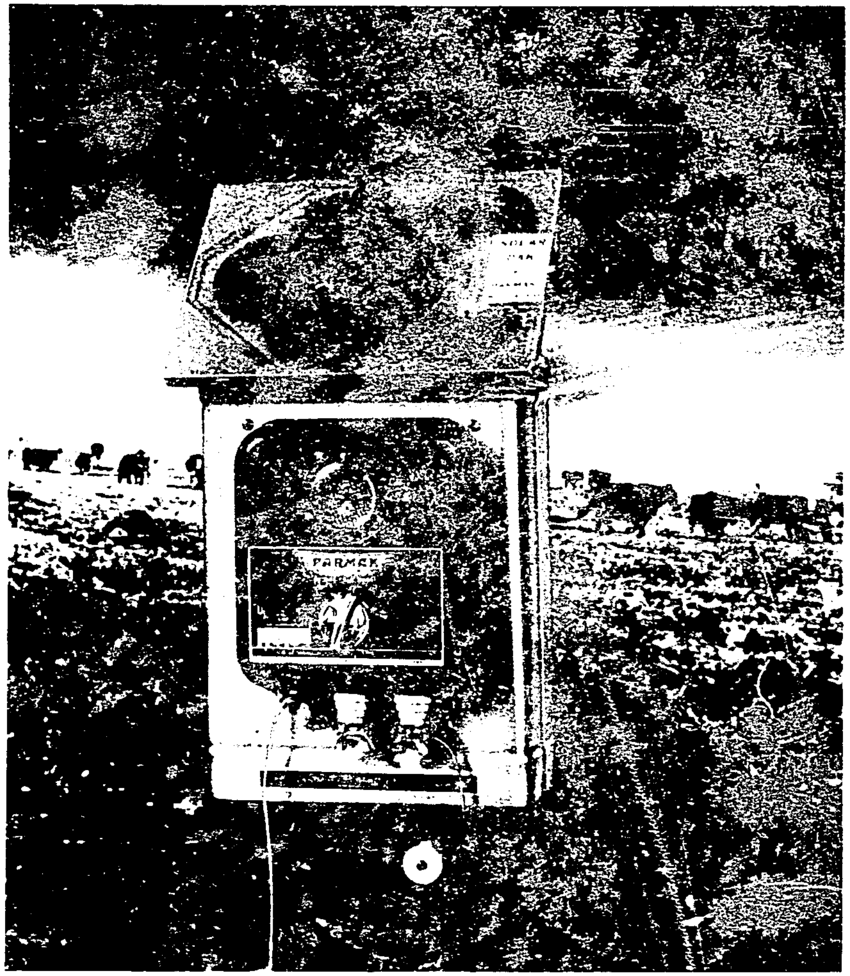
Because photovoltaic systems utilize the renewable energy of the sun, require little maintenance, are quiet and non-polluting, seldom experience an outage, and are cost competitive with small diesel generators in many applications, they are a logical power source for electrical products intended for use in rural or remote areas.

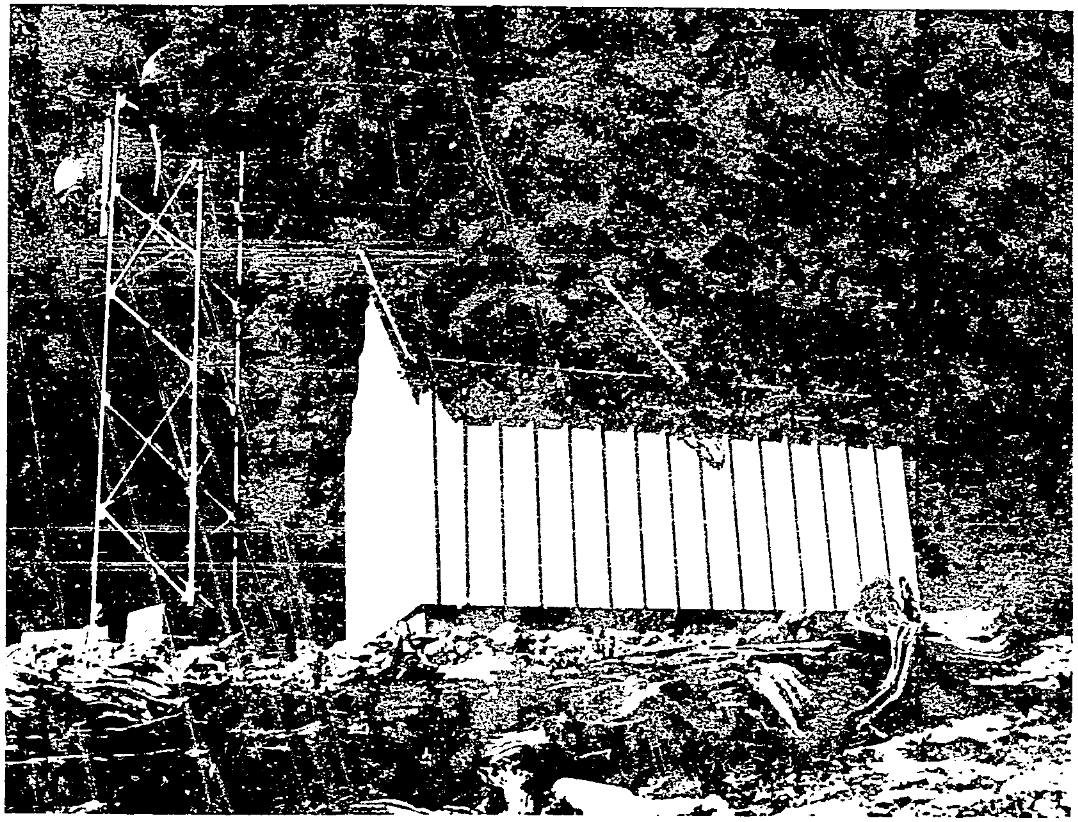
Photovoltaic-powered products now being marketed include telecommunications equipment, cathodic protection equipment, navigational aids, electric fences, and water pumps. Listed below are several photovoltaic-powered products - some as yet to be developed - likely to find markets in rural areas of the Third World, keyed to sectors most likely to use these products.

SECTOR \ PRODUCT	WATER PUMPS	LIGHTS	REFRIGERATORS	2-WAY RADIOS	TV, RADIO, TAPE PLAYERS	PORTABLE POWER UNITS	VENTILATION FANS	ELECTRIC FENCES	INSECT TRAPS
HOME	X	X	X		X		X		X
VILLAGE	X	X	X	X	X	X	X	X	X
AGRICULTURE	X	X	X			X	X	X	X
COTTAGE INDUSTRY		X				X	X		
EDUCATION		X			X		X		
HEALTH	X	X	X	X			X		X
ADMINISTRATION		X		X			X		
COMMERCIAL	X	X	X			X	X		
TOURISM/ RECREATION	X	X	X	X	X	X	X		X

SOLAR PHOTOVOLTAIC ELECTRIC FENCER

PARKER McCRORY MANUFACTURING CO.





PHOTOVOLTAIC-POWERED COMMUNICATIONS RELAY STATION

MOTOROLA COMMUNICATIONS & ELECTRONICS, INC.