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LEAD–ACID BATTERIES FOR REMOTE PHOTOVOLTAIC APPLICATIONS*

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Summary

The various load profile characteristics most commonly encountered in photovoltaic installations are analyzed in conjunction with solar array and battery performance data and used to generate battery specifications with particular respect to operating characteristics and cycle life requirements.

The design of lead–acid batteries for photovoltaic applications is discussed and illustrated with both operating, maintenance, and cycle life data. Other performance characteristics of lead–acid photovoltaic batteries are described including the effects of operating temperature and the correct choice of charging method for various operational requirements.

Introduction

Scientists have, for many years, dreamed about capturing and effectively utilizing the energy from the sun. This thought more or less remained a dream until the invention of the solar cell by Bell Telephone Laboratories in 1953. Silicon solar cells made from abundantly available raw material now make it possible to install relatively low cost energy systems in areas that were previously too remote and inaccessible to be supplied with commercial electrical power. Such photovoltaic energy systems are now found in such widespread applications as cathodic pipeline protection, ranger stations, telemetering and microwave transmitters and receivers, railroad crossing gate operations, and providing power for remote communities.

At the present time the market for photovoltaic systems is small, about 750 kWp in 1977. This is principally due to the high cost of solar panels which has averaged approximately $15/Wp in 1977.

Major efforts are underway to reduce the cost of solar cells and the Department of Energy has established a National Photovoltaic Conversion Program with the specific objective of developing a viable photovoltaic system industry. In this regard cost goals for solar arrays have been established as shown in Fig. 1 [1].

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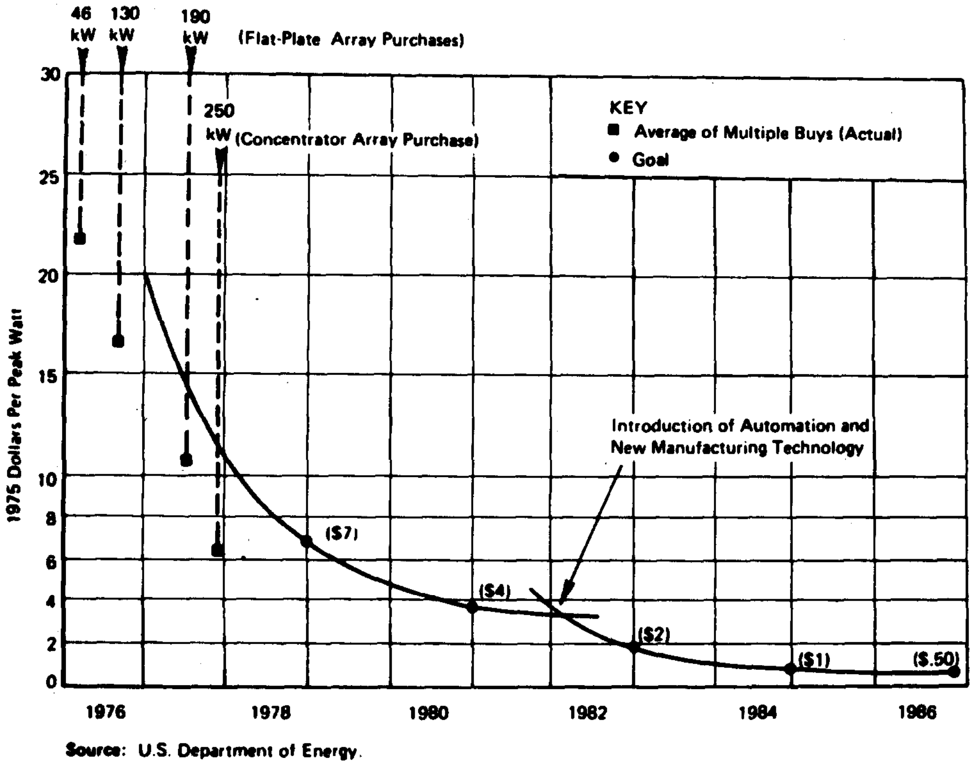

Fig. 1. Recent solar array prices and goals to 1986.

As the cost of solar panels is reduced the market should grow at a rapid rate and has been estimated to reach 500 000 kWp/yr by 1986.

While the modern photovoltaic cell does answer one problem, it also poses another. How does one supply a continuous demand for energy from a source which is discontinuous? A device to store the excess energy available during periods of sunlight and to dispense this energy during periods of darkness and inclement weather must be found. The obvious answer is a lead–acid storage battery — a proven reservoir of electrochemical energy. Such batteries are capable of operating over a wide range of temperatures and duty cycles, feature long cycle life, ease of maintenance, extremely high reliability, and low initial cost.

A typical photovoltaic installation showing the interconnections of the battery, the load, and the solar panel is shown in Fig. 2.

A typical photovoltaic conversion system consists of arrays of solar cells, which may be either flat arrays or solar cells combined with solar concentrators, mounted to face the sun. The mount may be stationary or may follow the sun. Solar cell arrays are arranged in series or parallel to obtain a required output voltage; a controller maintains the required voltage and a uniform flow of power to the load; a battery stores power for future

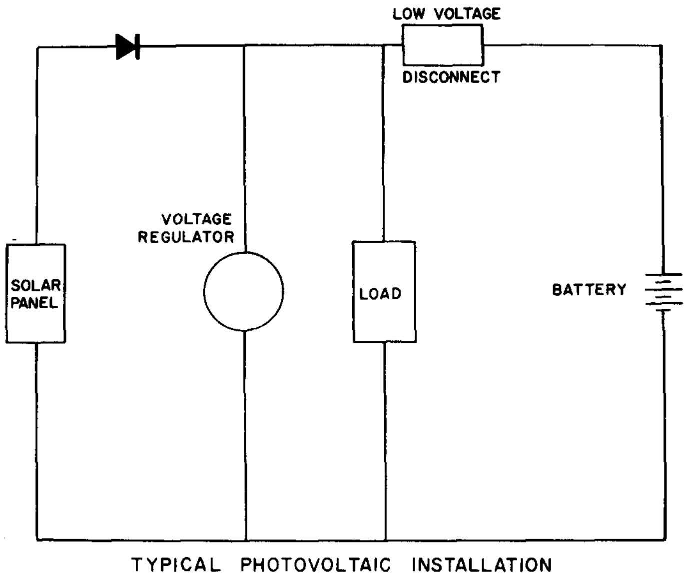

Fig. 2. Typical photovoltaic installation.

use. The d.c. output from the solar cell array can either be used to charge the battery or be transmitted directly to the load. Where an a.c. output is necessary an inverter must be incorporated into the system.

The state-of-charge (SOC) of a typical photovoltaic battery varies seasonally as is shown in Fig. 3. During the summer months when days are long and sunlight is most intense, the energy output of the solar array exceeds that of the load, and the excess energy is used to maintain the battery in a fully charged state. However, as autumn approaches and the

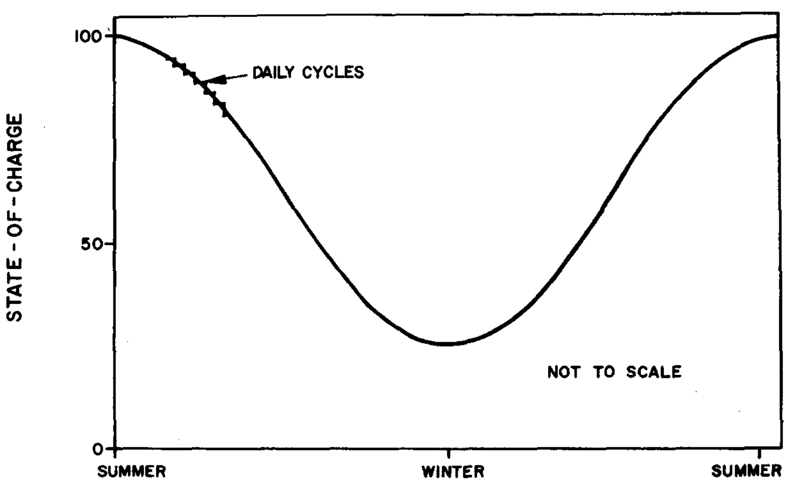

Fig. 3. State-of-charge of a photovoltaic battery *vs.* time.

days grow shorter less energy is produced by the array and the battery is called upon to reach into its reserve capacity and make up any energy deficiencies that the array cannot supply. Thus the battery SOC gradually decreases throughout the winter season and remains low until the lengthening days of spring tend to reverse the trend and restore more energy than is being removed. Thus the SOC curve tends to resemble the insolation pattern of the incident sunlight.

Environmental conditions

Photovoltaic batteries are frequently installed in locations where extreme environmental conditions are encountered. Seasonal temperature excursions of 55 °C are not uncommon. Batteries must be protected against the incursion of very fine sand and dust particulate matter such as is found in desert regions. Salt spray is common in coastal areas and relative humidity may vary from almost zero in very arid climes to one hundred percent. in jungles. Coupled with these static extremes, the battery must be built and packaged to withstand the dynamic shipping and handling hazards produced by methods of transportation as diverse as helicopter and pack mules. Batteries must be delivered in perfect condition as there are no repairmen or battery service stations in remote areas.

Not only must the batteries be installed in perfect condition, but they must operate reliably under the same environmental parameters of temperature, altitude, humidity, and sand and dust with little or no maintenance. These features must be designed and built into the battery.

Battery design considerations

The batteries provided for photovoltaic installations are designed specifically for the intended application. The grids are made from calcium–lead alloy instead of the antimonial–lead alloy used in conventional batteries. The use of calcium as the alloying agent instead of antimony has four very significant effects. First, it reduces open circuit stand losses by almost an order of magnitude (see Fig. 4). This means less self-discharge and more available capacity when the battery is operated for long periods of time in a less than fully charged condition. Second, it means longer intervals between water additions (less maintenance) throughout the life of the battery. Third, by eliminating the poisoning effect of antimony transfer, lower charge currents can be used, and, since charge current is a major factor in determining a battery's life, longer life. Fourth, lead–calcium batteries, when operated at the recommended float potential, never require equalizing charges. All these factors are of primary importance when cells are located in remote locations.

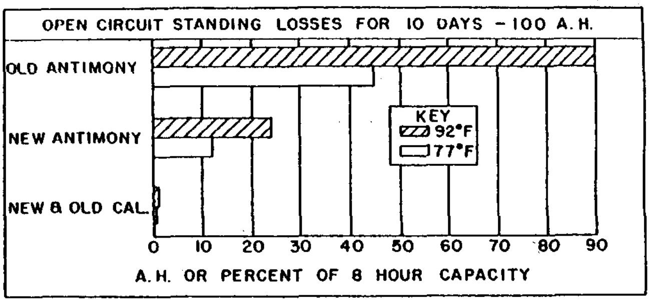

Fig. 4. Open circuit standing losses for 10 days, 100 A h (92 °F = 33 °C, 77 °F = 25 °C).

In addition to the calcium–lead alloy grids, photovoltaic batteries also differ from conventional lead–acid batteries in two other ways — the choice of plate insulation and the specific gravity of the cells. The insulation of photovoltaic batteries more closely approximates that of the motive power or traction battery than that of a typical stationary or standby battery. The incorporation of highly retentive Slyver® glass mats effectively minimizes the shedding of the positive active material and permits the battery to be capable of cycle service operation.

To withstand the rigors of transportation, batteries are frequently packaged in impact resistant epoxy-powder-coated steel or glass reinforced plastic trays capable of withstanding high levels of shock and vibration as might be encountered during shipment and installation.

Protection against sand and dust particulate matter is provided by replaceable open foam or fiberglass filters that allow the battery to "breathe" and exhaust gaseous hydrogen and oxygen produced during charge, but prevent the incursion of very small granules. By coating the trays with an oven baked epoxy powder coating the battery is effectively protected against dust, salt spray, and high humidity.

In areas of extremely low ambient temperatures the battery can be given a longer survival time by packaging it inside a layer of low-heat-conducting, closed cell plastic foam to minimize the dissipation of the battery's heat into the surrounding atmosphere.

Another optional feature that can be incorporated into the battery design is a special low evaporation vent suitable for those installations that may experience extremely high temperatures coupled with low humidity. These same vents can also be utilized in high altitude installations.

To provide the additional electrolyte necessary to enable the battery to deliver its maximum low rate discharge capacity, individual cells are often installed in oversized containers, thus increasing the utilization of the active material. For those installations where low temperature operations are specified, the concentration of the electrolyte is increased to prevent it from freezing during discharge. A curve showing the relationship between electrolyte concentration (specific gravity) and the freeze point is shown in Fig. 5.

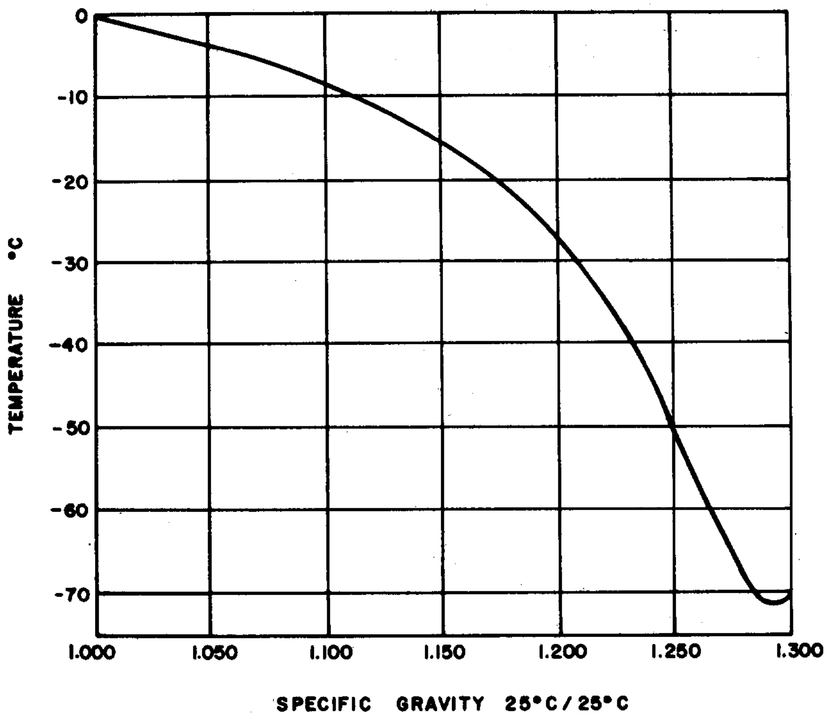

Fig. 5. Freezing point of H_2SO_4 electrolyte *vs.* specific gravity.

Figure 6 shows the approximate percentage of the 500 Hour Rated Capacity remaining as a function of the specific gravity of the electrolyte.

At this point it is in order to review some of the operating characteristics of a photovoltaic storage battery.

The capacity of a lead–acid battery is dependent upon numerous factors. They include the weight of active materials present within the cell; the volume and concentration of the electrolyte; the thickness of the plates; the temperature of the cell; the rate of discharge, and the final voltage of the discharge.

The relationship between the weight of active materials, the volume and specific gravity of the electrolyte, and the thickness of the plates is a rather complex one and will be touched on rather briefly. As a general rule, thick plates, those greater than 6.35 mm, are used in industrial batteries where long life rather than high rate capability is of paramount consideration. The thicker the plates, the more active material present, the greater the per plate capacity and the longer their life. Most conventional lead–acid batteries are acid limited. By this is meant that the ultimate capacity of the cell is limited by the amount and concentration of the acid electrolyte present within the cell. The cells specifically designed for photovoltaic application have overcome this shortcoming by increasing both the volume of available electrolyte as well as its concentration. These two factors not only improve the capacity

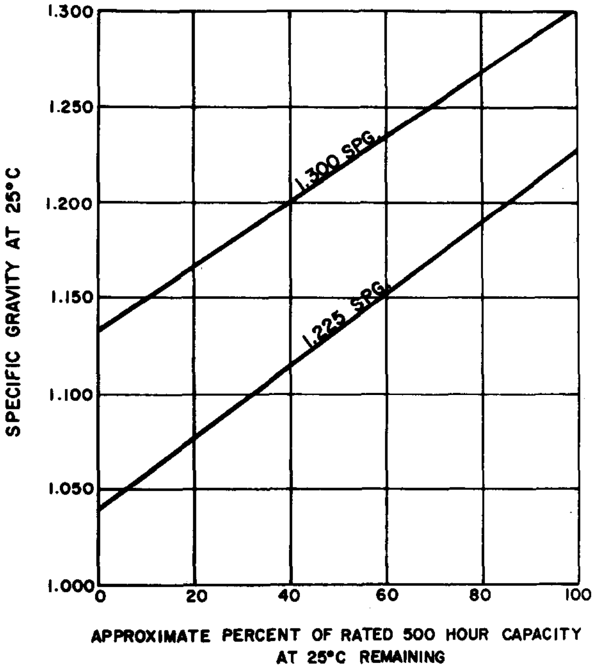

Fig. 6. Approximate 500 H Rated Capacity remaining *vs.* specific gravity.

but also serve to prevent freezing of the electrolyte when the cells are in a deeply discharged condition.

The rate of discharge and the final or cut-off voltage are also interrelated. During the discharge of any cell the voltage starts off at a predetermined value dependent upon the rate of discharge. As the discharge progresses this voltage gradually decreases until it reaches a point, called the knee of the discharge curve, following which it falls off very rapidly. Once this knee has been reached the energy that is subsequently delivered is not considered to be useful since the wattage (product of the cell current and voltage) is negligible. The lower the rate of discharge the longer the cell will deliver energy and the greater will be its ampere hour capacity. Thus, a cell being discharged at its 500 hour rate will deliver almost twice as many ampere hours as the same cell when discharged at its 8 hour rate. Figure 7 illustrates this relationship.

The temperature of a cell affects both its ampere hour capacity and its ability to accept recharge. Figure 8 shows the relation between cell temperature and battery capacity. Thus, a cell operating at −18 °C will deliver about 47% of its rated 8 hour, 25 °C capacity or 70% of its 500 hour rated capacity. It is most important that cognizance of this reduced capability is taken into account when sizing a battery for photovoltaic applications where temperatures less than 25 °C are anticipated.

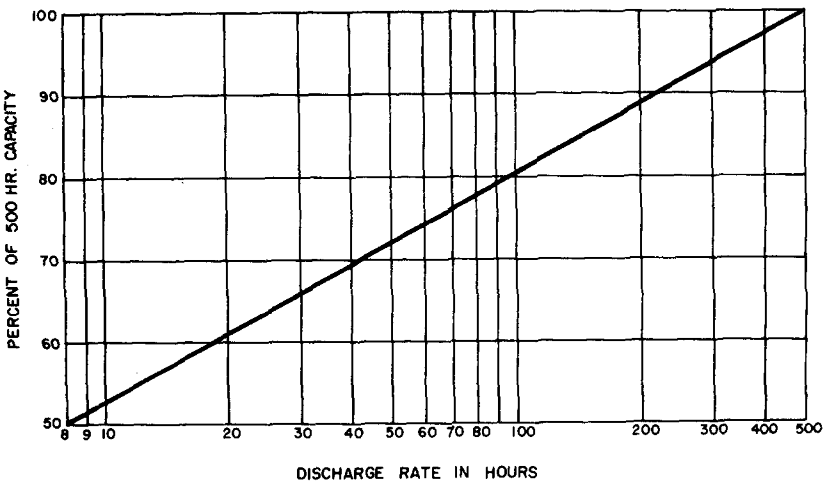

Fig. 7. Discharge rate *vs.* percent. of nominal 500 hour capacity — photovoltaic cells; 1.225 Sp. gr. at 25 °C.

Figure 9 shows the relationship between recommended float voltage and cell temperature. Higher voltages are required when cell temperatures are low. It is thus desirable that temperature compensated voltage regulators be utilized in those photovoltaic systems where large temperature fluctuations are anticipated. By incorporating this feature battery charging will be optimized regardless of thermal conditions.

The cycling ability of a lead–calcium battery is graphically illustrated in Fig. 10 [2]. These data demonstrate the fact that a lead–calcium traction battery successfully delivered 1600 life cycles when tested in accordance with Federal Specification WB-133. The test routine consists of two 80% depth-of-discharge cycles per day each followed by a modified constant

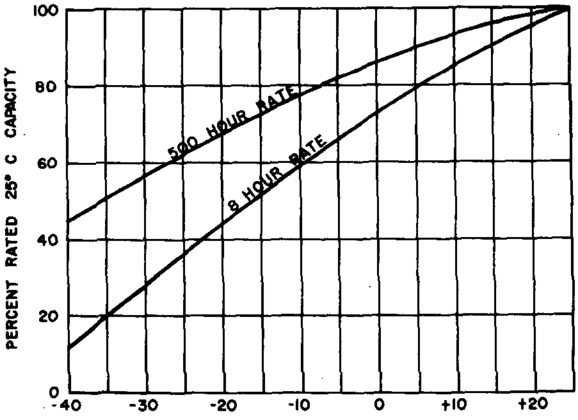

Fig. 8. Typical photovoltaic cell capacity *vs.* cell temperature.

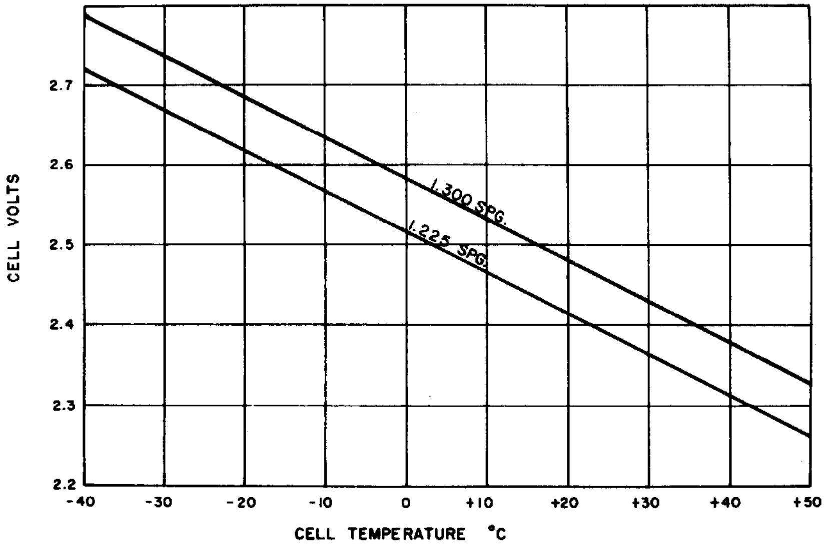

Fig. 9. Recommended float voltages for photovoltaic cells at various temperatures.

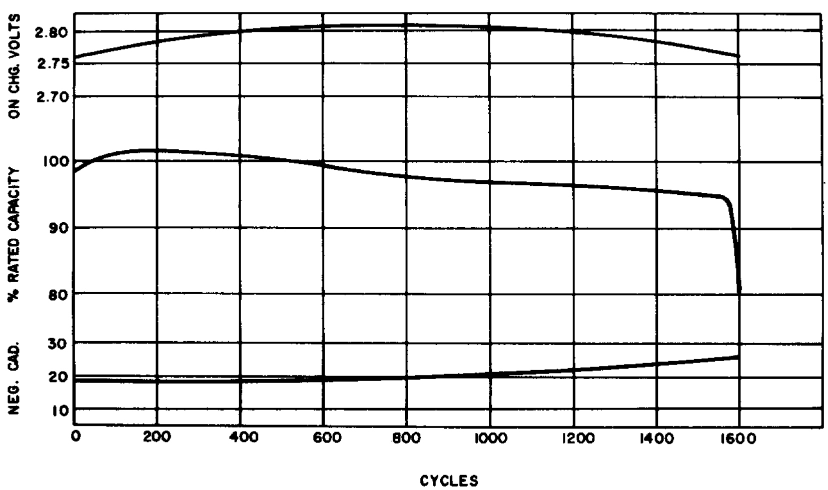

Fig. 10. Life cycle characteristics of a calcium–lead motive power battery.

potential recharge which returns 104 - 107% of the ampere hours removed. Batteries must demonstrate a minimum of 1 500 such cycles in order to qualify for inclusion on the Federal Supply Schedule.

When properly sized and floated in accordance with the values recommended in Fig. 9 the photovoltaic battery will require a minimum of maintenance. This is most important when the battery is installed in a remote and often inaccessible location. Inspection and maintenance intervals of two to three years are recommended. While performing such a routine the batteries are inspected for loose connections, accumulated dirt, and the electrolyte levels are adjusted to their specified height by adding battery grade water. Dissociative water losses are low because the battery is operated for long periods of time in a less than fully charged condition, as explained earlier. The dissociation of water cannot occur unless the battery is overcharged while in a fully charged state. Evaporative water losses are difficult to predict because of the varying conditions of temperature, relative humidity, and altitude encountered in different locations.

The sizing of batteries for photovoltaic service is a complex task. Consideration must be given not only to the magnitude of the load but also to such parameters as minimum operating temperatures and the vagaries of sunlight. Normally, the array manufacturer, through the use of insolation and climatic tables, can estimate worst case conditions of temperature and array output which predicate how long the load must be sustained by the battery. This information, consisting of the magnitude and duration of the load and the minimum operating temperature, is forwarded to the battery manufacturer and used to size the battery.

When properly sized and matched, the photovoltaic system, consisting of the array, the battery, and associated controls, will give years of trouble free service.

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