The Value of PV Systems Experiments: Volume I
A Preliminary Assessment of the Lessons Learned from Nine Intermediate-Size Systems

Mike Thomas

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
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The Value of PV Systems Experiments: Volume I
A Preliminary Assessment of the Lessons Learned from Nine Intermediate-Size Systems

Mike Thomas
Systems Evaluation Project
Sandia National Laboratories
Albuquerque, NM 87185
Contributors: E. L. Burgess
J. Fernandez
M. L. Fuentes
T. D. Harrison
D. M. Menicucci

Abstract
This report reviews nine intermediate-size photovoltaic (PV) experiments sponsored by the US Department of Energy (DOE). Five variations of PV technology were represented in the experiments: (1) flat plate, (2) flat plate with mirror enhancement, (3) combined photovoltaic/thermal (PV/T) parabolic trough concentrator, (4) combined line-focus Fresnel lens concentrator and thermal, and (5) point-focus Fresnel lens concentrator. The system costs and installation costs are reviewed. The characteristics and electrical performance of the systems are described. Operation and maintenance data are given.
ILLUSTRATIONS (Continued)

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In the late 1970s, the Department of Energy (DOE) fielded nine photovoltaic systems of intermediate size in commercial and institutional applications. These experiments were to serve as the initial test beds to gain the necessary experience of fielding and operating PV systems in anticipation of the larger commercial deployment of similar systems when they reached economic feasibility. The experiments have provided a large data base for the technical evaluation of PV systems. The data are now being analyzed, and the results are being disseminated. This is the first of a series of reports presenting the results of the technical evaluation of and the lessons learned from these experiments.

The systems were designed and installed by teams consisting primarily of commercial firms. Brief details of the systems are:

1. The Beverly project is a 100-kilowatt peak power (kW) flat-plate array located on a south-sloping hillside at the Beverly High School, Beverly, MA; operational since March 1981.

2. The Dallas-Ft. Worth (DFW) Airport project is a combined photovoltaic/thermal (PV/T) experiment that utilizes line-focus Fresnel concentrator technology rated at 24 kW of electric energy and 140 kW of thermal energy; operational since April 1982.

3. A combined PV/T parabolic system rated at 35 kW electrical energy and 230 kW of thermal energy was located adjacent to the G. N. Wilcox Memorial Hospital of Kauai, HI. The formal dedication of this experiment was in January 1982.

4. A 100-kW flat-plate array was installed in Lovington, NM, and has been operational since March 1981.

5. A 20-kW flat-plate array has been integrated into the uninterruptible power supply at the El Paso Electric Company's Newman Power Station, outside of El Paso, TX. This dc power system has been operational since January 1981.

6. A 135-kW, mirror-enhanced, fixed-plate array was installed on the roof of the Oklahoma Center for Science and Art. The system operates at 400 Vdc, the highest voltage of the intermediate experiments.

7. The San Bernardino Project is a 25-kW flat-plate array located on the roof of the light manufacturing facility of the San Bernardino West Side Community Development Corporation. The system first provided power in July 1981.

8. Arizona Public Service Company operates a 225-kW ground-mounted, point-focus, Fresnel concentrator system at the Sky Harbor Airport, Phoenix, AZ. This system has been operating since April 1982.

9. A combined PV/T 47-kW electrical and 280-kW parabolic trough concentrator array is located on the roof of the BDM Corporation offices in Albuquerque, NM, and was dedicated in July of 1982.

10. These experiments were the first in a planned series of projects. The DOE has not followed these systems experiments with a second generation, but the private sector has, to a limited extent. Continued operation of the intermediate experiments and new projects by industry are continuing to provide data needed to advance the technology. The actual energy produced for a year by these systems ranges from ~27,000 kWh at San Bernardino to ~200,000 kWh at Lovington (see Table 9).
Experience with the intermediate experiments has shown little or no system degradation. Failures have apparently all (or nearly all) resulted from manufacturing deficiencies, not a rate process that would result in the ultimate demise of the module. The most probable area of failure, inherent in design, would be in the area of insulation breakdown. The Oklahoma City experiment utilizes the highest operating voltage of any of the PV systems (~400-Vdc nominal operating voltage with a 540-Vdc open circuit voltage). Only 5 modules have failed at this site (out of 1500) and all failures occurred in random positions within the source circuits, indicating no relation to voltage. The two major points have been

- The quality control of module manufacturers must be improved and standardized. Manufacturers must also provide warranties on their products.

- Module lifetimes may indeed already be as large as desired (20 to 30 yr), but the determination of a lifetime is confounded by many intervening variables.

A number of the projects were collocated with a load to test the potential for commercial applications. The Science and Art Center, DFW Airport, and BDM projects have been rooftop experiments that have experienced difficulties. Structural members have required reinforcement. Wind velocities near the edges of multistory buildings have caused array damage. Area is limited and can prevent the system from providing a significant part of the electrical requirements and may result in additional load on structures. The BDM array does not even satisfy site baseload.

The BDM, Kauai, and DFW experiments have used combined PV/T concentrator collectors. The added complexity of the liquid cooling systems has increased operation and maintenance (O&M) costs and caused extra start-up problems. Even beyond these difficulties, perhaps the most important concern for PV/T technology is matching the thermal load, a point beyond the scope of the experiments.

Kauai and BDM were both parabolic trough concentrating systems. This technology was questionable when fielded. Continual adjustment to improve the accuracy of focusing the parabolic mirrors resulted in increased costs, but the systems never reached design specifications. The tracking systems at BDM used sophisticated controls that proved to be more than needed and actually resulted in reduced energy collection.

The Kauai experiment showed the importance of local microclimate. The design was based on climatic data from a nearby site. The Kauai site, however, had much more diffuse radiation. Because concentrators utilize direct normal insolation, this site proved to be inappropriate.

Mechanical problems associated with tracking structures have been observed at several of the concentrator sites, but have been most evident at the Sky Harbor experiment. Here, subcontractor supplied mechanical members that did not meet procurement specifications have failed. Electrical failure also occurred as a result of slippage of mechanical members caused by lubricants leaking from overheated bearings.

Site preparation for ground-mounted systems must be kept to a minimum. Leveling or paving of sites is unnecessary for PV systems. Sites where there was extensive site preparation (e.g., Lovington and Beverly) cost an additional ~$2.00/W, about the estimated cost for the entire system of the future.

Except for correction for design deficiencies, little O&M has been required. A problem in all the systems has been the inverters. Most troublesome were those modified for PV use from uninterruptable power supply (UPS) systems. These inverters have been responsible...
for much system downtime. Helionetics inverters at Lovington, Beverly, and San Bernardino were built for PV application and have performed much more reliably. Even for these inverters, the attempt to provide personnel safety via ground fault interrupters has caused much downtime. This difficulty, however, does not reflect a difficulty with the inverters.

The mirror augmentation experiment at Oklahoma City has had a combination of difficulties. The system has consistently performed much below expectations. The system was designed with 100 kW of semicrystalline modules. Mirrors were installed to enhance the insolation falling on the array by 30%. Instead of a 130-kW output, only about 100 kW has been obtained. The reduced power output is easily explained, however. First, the modules were overrated by ~10%, quite typical in the industry. Second, the rating was performed at a temperature 30°C to 40°C lower than the array operating temperature. This ΔT results in another 10% power reduction. Thus, the 100-kW design was 90 kW (rating inaccuracy)\(^p\), which was lowered to 80 kW because of relatively high operating temperatures. Now, by enhancing 80 kW 30% with mirrors, we have an ~100-kW\(^p\) system.

The San Bernardino experiment provided another discrepancy between the original design and observed output. Here, in a 35-kW system design, the modules produced only 90% of their rating, or ~31 kW\(^p\). A large PCS unit (60 kW), the same used for the 50-kW subfields at Lovington and Beverly, was used for inversion. The relatively large tare losses (4 to 5 kW) resulted in ~70% inversion efficiency, or a >25-kW\(^p\) system.

The use of power ratings, as in the above examples, has also plagued technical transfer to the end users. The value of the system is based upon the value (utility rate) of the energy (power over time), or $/kWh, not kW\(^p\). The amount of energy produced is related to the amount of energy into the system, a site-dependent variable, whereas peak power can be used more directly to measure system performance. The 100-kW array at Lovington produces about 1700 kWh/kW\(^p\), the 225-kW array at Sky Harbor produces about 1900 kWh/kW\(^p\), and the 100-kW array at Beverly about 1000 kWh/kW\(^p\).

All in all, the intermediate experiments have reached and exceeded original expectations. All systems fielded have worked. System problems have been identified, and current large-field designs have incorporated the lessons learned from the experiments to eliminate many of the systems-level problems. There have been many difficulties with the installation and operation of these experiments, but in almost all cases, this has been a result of the prototype status of the componentry. This was also the original motivation for the experiments. The concentrator technology, the dc-ac inverters, and many of the interconnections had never been field-tested, even at the component level, for PV applications prior to the intermediate experiments. Major lessons learned and actions taken and incorporated into new designs have been as follows:

- Individualized engineering designs are too costly. In addition, installation costs based on individual components are prohibitive. Modular building blocks for flat-plate and concentrator designs have reduced costs to acceptable levels.
- High-efficiency, highly reliable power conditioners are absolutely required for economical operations. A current research project is addressing power conditioners that will provide this type of operation.
- Parabolic trough technology is inadequate for PV applications. Focusing difficulties and trough manufacturing produce costly, low-efficiency components.
• Rooftop systems are troublesome. This type of application should be avoided.

• Personnel protection through ground-fault interruption (GFI) has resulted in a large amount of downtime. Ground-fault detection may be useful as a diagnostic tool, but current large facilities do not incorporate interruption.

• Little difference in systems performance (energy production, degradation, or O&M) has been experienced due to climatic variation. Upon study over longer times, this hypothesis may need to be revised.

• Choice of specific site is extremely important. Microclimate at each location must be known before systems are designed. Concentrating arrays are not appropriate for areas with inadequate direct normal insolation. Major site preparation (e.g., grading, paving) are too costly to be considered for a PV site.

• Accurate module ratings are important for system design. In addition, energy ratings will assist the end users in feasibility assessments.
THE VALUE OF PV SYSTEMS EXPERIMENTS: VOLUME I
A PRELIMINARY ASSESSMENT OF THE LESSONS LEARNED
FROM NINE INTERMEDIATE-SIZED SYSTEMS

INTRODUCTION

During the late 1970s, the U.S. Department of Energy (DOE) funded the deployment of nine intermediate-size photovoltaic (PV) systems for commercial and institutional applications. The objective of these experiments was to gain field experience and performance data to guide the design of future generations of PV equipment. The nine experiments represented a broad range of sizes, applications, and collector technologies. The basic characteristics of each experiment are shown in Table 1. This report documents the results of the initial evaluations of these systems, lists the "lessons learned," and describes how these lessons have been incorporated into large system designs.

The prime contractors for the PV experiments were selected by a competitive evaluation process conducted by DOE. The selected prime contractors, with the assistance of their respective subcontracts, were responsible for the conceptual and site-specific detailed designs of the PV system. These design teams ranged in experience from no previous PV experience to active participants in the DOE program and included commercial suppliers of PV equipment. Local general contractors as well as large, national engineering firms were represented. This wide variety of experience and talent provided the opportunity to observe and investigate numerous approaches to PV system design.

The detailed designs developed were considerably different among the nine projects. Four were roof-mounted and five were ground-mounted; four were flat-plate collectors, one was mirror-enhanced flat plate, and four were concentrators of various types (Table 1). Figure 1 shows the ground-mounted parabolic collectors for the Wilcox Hospital project. Figure 2 shows the roof-mounted flat-plate collectors for the San Bernardino project. Various wiring systems were used (see Appendix A for one-line wiring diagrams). The design efforts for all of the experiments were very expensive (on the order of one-third or more of the total system cost) and represent a cost that cannot be supported for privately funded PV applications.

When these PV experiments were first conceived, "intermediate" systems were perceived as operating at lower voltages than "central station" systems. The intermediate systems were directly associated with a local on-site load. Now, we recognize no inherent differences between intermediate and central station systems. Intermediate systems may be used as building blocks for larger systems. However, a PV system associated with an on-site load may be less favorable economically than a system that sells electricity to a utility.

The economics of a PV system are dependent upon the difference between the system costs and the value of the energy produced. The system costs can be subdivided into capital costs (financing) (C), installation costs (I), equipment costs (E), and operation and maintenance costs (O&M). The value of the energy produced (V) can be computed from the rate at which the local utility
<table>
<thead>
<tr>
<th>Name of Project</th>
<th>Location</th>
<th>Electric Peak Power ($kW_p$)</th>
<th>Thermal Power ($kW_t$)</th>
<th>Type of Collector</th>
<th>Operational Date</th>
<th>Mounting</th>
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<tr>
<td>Beverly High School</td>
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<td>100</td>
<td>24</td>
<td>Flat-plate</td>
<td>March 1981</td>
<td>Ground fixed</td>
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<td>DFW Airport</td>
<td>Dallas-Ft. Worth, TX</td>
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<td>140</td>
<td>Fresnel, Line-focus</td>
<td>April 1982</td>
<td>Roof</td>
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<td>Wilcox Memorial Hospital</td>
<td>Kauai, HI</td>
<td>35</td>
<td>230</td>
<td>Parabolic, Line-focus</td>
<td>January 1982</td>
<td>Ground</td>
</tr>
<tr>
<td>Lovingston Shopping Center</td>
<td>Lovingston, NM</td>
<td>100</td>
<td></td>
<td>Flat-plate</td>
<td>March 1981</td>
<td>Ground fixed</td>
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<td>Newman Power Station</td>
<td>El Paso, TX</td>
<td>18</td>
<td></td>
<td>Flat-plate</td>
<td>January 1981</td>
<td>Ground fixed</td>
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<td>Science and Art Center</td>
<td>Oklahoma City, OK</td>
<td>135</td>
<td></td>
<td>Flat-plate, Mirror-enhanced</td>
<td>February 1982</td>
<td>Roof fixed</td>
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<td>San Bernardino Community</td>
<td>San Bernardino, CA</td>
<td>35</td>
<td></td>
<td>Flat-plate</td>
<td>July 1981</td>
<td>Roof fixed</td>
</tr>
<tr>
<td>Sky Harbor Airport</td>
<td>Phoenix, AZ</td>
<td>225</td>
<td></td>
<td>Fresnel, Point-focus</td>
<td>April 1982</td>
<td>Ground</td>
</tr>
<tr>
<td>BDM Corporation</td>
<td>Albuquerque, NM</td>
<td>47</td>
<td>280</td>
<td>Parabolic, Line-focus</td>
<td>July 1982</td>
<td>Roof</td>
</tr>
</tbody>
</table>
Figure 1. Ground-Mounted Parabolic Collectors at Kauai, HI
Figure 2. Roof-Mounted Flat-Plate Collectors at San Bernardino
purchases electric power. This rate may vary with time. If the costs and energy value are integrated over the lifetime of the PV system, then economic viability is determined when

\[ V > C + I + E + O&M \]

The remainder of this report is structured to provide as much detail as possible about these factors that affect system performance. The reader should recognize that (1) these systems are experimental or prototype and are not necessarily state-of-the-art; (2) these systems have not attained steady-state operation, and the data must be considered only tentative; and (3) extrapolation to future systems is possible but is the subject of a subsequent report.

GENERAL CHARACTERISTICS

The nine intermediate experiments represent a wide range of characteristics that affect PV system performance and economics. The design power ratings range from 18 to 225 kW. Both flat-plate and concentrator technologies are used. Among the concentrator group, parabolic trough, line-focus Fresnel lens, and point-focus Fresnel lens systems are represented. The flat-plate system for the Science and Art Center experiment achieves a modest degree of concentration by use of mirror enhancement. The flat-plate systems have operated reliably for several years and represent a more fully developed technology than the concentrator systems. Although the PV experiments were conceived and designed by many different contractors, the resulting systems all have the same basic design (Figure 3). A detailed summary of the characteristics of each experiment, including one-line electrical drawings, is given in Appendix A.

Geographic Distribution

The geographic distribution of the nine experiments (Figure 4) provides for the different experiments a wide range in the amount of insolation available to the collector and also in the fraction of this insolation that appears as the diffuse component. A standard measure of insolation is the monthly average of energy incident upon a horizontal surface in 1 day, \( H \), measured in kilowatt-hours per square meter per day (kW·h/m²·day). The diffuse component of the insolation can be inferred from the monthly average clearness index, \( K_T \), which is the ratio of \( H \) to \( H_0 \), where \( H_0 \) is the monthly average extraterrestrial radiation on a horizontal surface. The clearness index is essentially a measure of the radiation intercepted by the earth's atmosphere; however, much of the intercepted radiation is scattered and reaches the earth's surface as the diffuse component of insolation. The clearness index is therefore a indicator of diffuse radiation; the diffuse component of insolation increases as \( K_T \) decreases. Table 2 lists the range of \( H \) and the range of \( K_T \) for an average year for all the experiment sites except Kauai, for which this long-term average information is not available.

The southwest regions have relatively clear skies, and a large fraction of the radiation is received as the direct component. In Massachusetts, the magnitude of \( H \) is generally less, and the diffuse fraction is greater. The amount of insolation available for collection can be determined by measurements at the experiment site. For concentrating collectors, a pyrhemeter, which measures only the direct normal component, is used. For flat-plate collectors, a pyranometer, which measures the total hemispheric insolation (direct plus diffuse), mounted in the plane of the collector, is used. The data for the period October 1982 through September 1983 are listed in Table 3. No entries are made for the BDM or Wilcox Hospital experiments because of their poor performance during this period. The Hawaii site is a clear mismatch of type of insolation versus system. The Wilcox Hospital site, for the day of the
Figure 3. Basic Design of the PV Experiments

Figure 4. Geographic Distribution of the PV Experiments
# Table 2

**Long-Term Insolation Data for the Experiment Sites**

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Range of $H$ (kW·h/kWh/m²·day)</th>
<th>$K_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beverly High School&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Beverly, MA</td>
<td>1.77 to 5.73</td>
<td>0.38 to 0.50</td>
</tr>
<tr>
<td>DFW Airport</td>
<td>Dallas, TX</td>
<td>2.46 to 6.73</td>
<td>0.49 to 0.60</td>
</tr>
<tr>
<td>Lovington Shopping Center&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Lovington, NM</td>
<td>3.00 to 8.23</td>
<td>0.61 to 0.72</td>
</tr>
<tr>
<td>Newman Power Station</td>
<td>El Paso, TX</td>
<td>3.25 to 8.46</td>
<td>0.63 to 0.75</td>
</tr>
<tr>
<td>Science and Art Center</td>
<td>Oklahoma City, OK</td>
<td>2.29 to 6.76</td>
<td>0.50 to 0.60</td>
</tr>
<tr>
<td>Community Dev. Center&lt;sup&gt;c&lt;/sup&gt;</td>
<td>San Bernardino, CA</td>
<td>3.14 to 7.91</td>
<td>0.62 to 0.70</td>
</tr>
<tr>
<td>Sky Harbor Airport</td>
<td>Phoenix, AZ</td>
<td>2.94 to 8.64</td>
<td>0.60 to 0.77</td>
</tr>
<tr>
<td>BDM Corporation</td>
<td>Albuquerque, NM</td>
<td>2.92 to 8.45</td>
<td>0.63 to 0.74</td>
</tr>
</tbody>
</table>

<sup>a</sup>Boston, MA, data  
<sup>b</sup>Roswell, NM, data  
<sup>c</sup>Riverside, CA, data

# Table 3

**Available Insolation at the Experiment Sites**  
*for the Period October 1982 through September 1983*

<table>
<thead>
<tr>
<th>Site</th>
<th>Location</th>
<th>Type of Measurement</th>
<th>Insolation (kW·h/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beverly High School</td>
<td>Beverly, MA</td>
<td>Total hemispheric, pyranometer in plane of array</td>
<td>1210</td>
</tr>
<tr>
<td>DFW Airport</td>
<td>Dallas, TX</td>
<td>Normal incidence pyrheliometer (NIP)</td>
<td>1350</td>
</tr>
<tr>
<td>Lovington Shopping Center</td>
<td>Lovington, NM</td>
<td>Total hemispheric, pyranometer in plane of array</td>
<td>1970</td>
</tr>
<tr>
<td>Newman Power Station</td>
<td>El Paso, TX</td>
<td>Total hemispheric, pyranometer in plane of array</td>
<td>2100</td>
</tr>
<tr>
<td>Science and Art Center</td>
<td>Oklahoma City, OK</td>
<td>Total hemispheric, pyranometer in plane of array</td>
<td>1550</td>
</tr>
<tr>
<td>Community Dev. Center</td>
<td>San Bernardino, CA</td>
<td>Total hemispheric, pyranometer in plane of array</td>
<td>1630</td>
</tr>
<tr>
<td>Sky Harbor Airport</td>
<td>Phoenix, AZ</td>
<td>Direct normal, pyrheliometer</td>
<td>1460</td>
</tr>
</tbody>
</table>
summer solstice, received only 50% of the amount of direct normal insolation received at DFW Airport and only 33% of the amount at Sky Harbor Airport. For this climate, a flat-plate system (fixed or tracking) is preferred; in fact, it is the only reasonable choice. In the design of this system, average weather data from a nearby site were used. This assumption was inappropriate and serves to show that actual site data are best for design purposes.

The Lovington and Beverly High School systems are almost identical. However, the climatic differences between the two sites are very great and offer the opportunity to study how climatic differences affect performance and O&M costs.

Integration with Public Utilities

Three of these experiments (Lovington, Sky Harbor, and Newman) are closely integrated with public utility systems. The Lea County Electric Cooperative is a prime contractor for the Lovington Shopping Center site, and the Arizona Public Service Company is the prime contractor for the Sky Harbor Airport site. The El Paso Gas and Electric Company operates the Newman Power Station, into which the Newman project is closely integrated as part of the UPS for the generator control system. Because the utilities are either directly or indirectly involved with the energy generated from these systems, the reliability, safety and protection, and power quality have become major current program issues.

The San Bernardino site has been installed and operated by crews totally inexperienced in PV technology. Many errors have occurred in the installation of the system, requiring extensive time for retrofitting and causing problems in the operation of the system. These experiences clearly show that unfamiliarity can cause poor performance outside the technical details of design.

DESIGN EXAMPLE

To understand the significance of energy production from a PV system, one must possess a nominal understanding of system design. A single example can expedite this understanding and will be used for this report.

Consider two sites, Beverly, Massachusetts, and Lovington, New Mexico. The designer can make a rather arbitrary decision as to the desired system output. For our example, this is 100 kW. This is the instantaneous power output of the system rather than an energy rating, which would have units of KWh. Kilowatts are used because we need to select a power conditioner of the proper size to convert the dc power into ac power. A 100-kW power conditioner is not available, but two 60-kW units are available. If the system produces higher power levels, the excess energy will be dissipated and lost. Since two power conditioners must be used, the system design must assume the form shown in Figure 5.

The next step is to select a PV module to make up the two 50-kW subfields. The Solar Power Co. modules are rated at 31.2 W under nominal operating cell temperature (NOCT) conditions. Since Beverly, MA, has a relatively cool climate, it can be assumed that the NOCT will not be exceeded (on the average), and the module will perform at its rated output of 31.2 W at 15.6 V and 2 A. For each subfield of 50 kW, we need 1600 modules (50,000/31.2 ~ 1600). A group of five modules wired in parallel, forms a block. The blocks must be connected to provide a voltage output that matches the power conditioner input specification, which is 250 V. A series string of 16 blocks meets this requirement (16 x 15.6 ~ 250). Twenty of these strings, wired in parallel, form a subfield. The output of each of the two subfields is 50 kW at 250 V and 200 A. The components of the array are shown in Figure 6.
SYSTEM PERFORMANCE

Since the systems are constructed from different components and located at widely separated sites subject to different levels of insolation, a standard rating parameter must be developed to compare the performance of the systems on an equivalent and realistic basis.

Systems Performance Parameter

Such a parameter is the ratio of annual average efficiency, $\bar{\eta}$, to peak efficiency, $\eta_p$. [3] A formula for calculating the value of this parameter from test data is derived from the following definitions.

Instantaneous PV system efficiency, $\eta(t)$:

$$\eta(t) = \frac{P}{AI} \quad (1)$$

where

- $P$ = array power (W)
- $A$ = array aperture area ($m^2$)
- $I$ = insolation ($W/m^2$)

Average PV array efficiency, $\bar{\eta}$:

$$\bar{\eta} = \frac{\int_{t_1}^{t_2} P(t) dt}{\int_{t_1}^{t_2} I(t) dt} = \frac{E_{out}}{AS} \quad (2)$$

where

- $t$ = time (h)
- $E_{out}$ = the energy produced by the array ($W*h$)
- $S$ = solar input energy per unit area ($W*h/m^2$)
Figure 6. Components of the Example Array

MODULE
36 CELLS IN SERIES

BLOCK
5 MODULES IN PARALLEL

STRING
16 BLOCKS IN SERIES

SUBFIELD
20 (21) STRINGS IN PARALLEL
If \( t_2 - t_1 \) is 1 yr, then \( \bar{\eta} \) is the annual efficiency during that year. (Note that \( \bar{\eta} \) measures the efficiency of the array only and does not account for the power conditioner.)

Peak efficiency, \( \eta_p \):

\[
\eta_p = \frac{R}{1000 \ A} \tag{3}
\]

where

\[ R = \text{the system power rating (W), calculated from module specifications under peak rating conditions.} \]

The factor 1000 represents an insolation rate of 1000 W/m², and it is assumed that the PV cells are operating at NOCT (i.e., standard conditions for system operation are assumed).

Dividing Eq. 2 by Eq. 3 gives

\[
\frac{\bar{\eta}}{\eta_p} = \frac{1000 \ E_{\text{out}}}{E_{\text{SR}}} \tag{4}
\]

This ratio and the data for calculating it are tabulated in Table 4. The data are listed for the fiscal year September 1, 1982 to September 1, 1983. Annual figures are given as well as data for the day of the summer solstice. Insufficient data were available for the HIM and Wilcox Hospital sites. These two sites have performed very poorly, in contrast to design energy estimates.

The values listed for the ratio \( \frac{\bar{\eta}}{\eta_p} \) are all less than one because all the systems operate with an average cell temperature greater than NOCT, reducing their efficiency. Experience gathered in this program indicates that the relationship between \( \bar{\eta} \) and \( \eta_p \) is given by

\[
\bar{\eta} = \eta_p \left[ 1 - 0.005(\bar{T} - 28) \right] - 0.03 \ \eta_p \tag{5}
\]

where

\[ \bar{T} = \text{average array cell temperature (°C)} \]

The 3% loss accounts for wiring losses and cell mismatching. This relation assumes that NOCT is 28°C. Eq. 5 can be simplified to

\[
\frac{\bar{\eta}}{\eta_p} = 0.97 - 0.005 (\bar{T} - 28) \tag{6}
\]

so that the ratio \( \frac{\bar{\eta}}{\eta_p} \) can be calculated if \( \bar{T} \) is known. If the value of \( \frac{\bar{\eta}}{\eta_p} \) calculated from Eq. 6 is within ±0.05 (i.e., 5 percentage points) of the value from Eq. 4, then the array performance is acceptable. This value judgment does not indicate error in the equations, but rather the uncertainty in the data.

If the efficiency of the power conversion system is \( \eta_{pc} \), then the efficiency for the production of ac power, \( \eta_{ac} \), can be found from

\[
\eta_{ac} = \bar{\eta} \cdot \eta_{pc} \tag{7}
\]

The average annual value for \( \bar{\eta} \) is 0.88 and Eq. 6 can then be rewritten as

\[
\frac{\bar{\eta}}{\eta_p} = 0.85 - 0.0044(\bar{T} - 28) \tag{8}
\]

and the data for ac power production can be used as the basis for intersystem comparison.

Power Conversion Subsystem Performance

The power conversion subsystem (PCS) converts the dc power from the PV array into ac power compatible with the local utility grid. It also provides the disconnect function when the utility is
Table 4
Performance and Efficiency Data for PV Systems

<table>
<thead>
<tr>
<th>Site</th>
<th>Array Rating (kWp)</th>
<th>A (m²)</th>
<th>Period (Annual) (Summer Solstice)</th>
<th>Insolation (kW·h)</th>
<th>Array Energy (kW·h)</th>
<th>Efficiency</th>
<th>n/np</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newman</td>
<td>18</td>
<td>258</td>
<td>Annual</td>
<td>538110</td>
<td>31962</td>
<td>0.0594</td>
<td>0.851</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>1706</td>
<td>96</td>
<td>0.0563</td>
<td>0.807</td>
</tr>
<tr>
<td>Beverly, A &amp; B</td>
<td>100</td>
<td>1432</td>
<td>Annual</td>
<td>1738900</td>
<td>102379</td>
<td>0.0589</td>
<td>0.843</td>
</tr>
<tr>
<td>B</td>
<td>50</td>
<td>716</td>
<td>Annual</td>
<td>3814</td>
<td>219</td>
<td>0.0574</td>
<td>0.822</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Annual</td>
<td>3814</td>
<td>219</td>
<td>0.0574</td>
<td>0.822</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Lovington A</td>
<td>50</td>
<td>752</td>
<td>Annual</td>
<td>1481979</td>
<td>83367</td>
<td>0.0563</td>
<td>0.846</td>
</tr>
<tr>
<td>B</td>
<td>50</td>
<td>752</td>
<td>Annual</td>
<td>1481979</td>
<td>91230</td>
<td>0.0616</td>
<td>0.926</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>5366</td>
<td>318</td>
<td>0.0593</td>
<td>0.891</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Annual</td>
<td>5366</td>
<td>318</td>
<td>0.0593</td>
<td>0.891</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Annual</td>
<td>5366</td>
<td>318</td>
<td>0.0593</td>
<td>0.891</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>A &amp; B</td>
<td>100</td>
<td>1503</td>
<td>Annual</td>
<td>2963958</td>
<td>174597</td>
<td>0.0589</td>
<td>0.886</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>10732</td>
<td>645</td>
<td>0.0601</td>
<td>0.904</td>
</tr>
<tr>
<td>Oklahoma City</td>
<td>135</td>
<td>1266</td>
<td>Annual</td>
<td>1966002</td>
<td>109683</td>
<td>0.0558</td>
<td>0.523</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>8833</td>
<td>594</td>
<td>0.0672</td>
<td>0.631</td>
</tr>
<tr>
<td>DFW Airport</td>
<td>27</td>
<td>245</td>
<td>Annual</td>
<td>330743</td>
<td>26195</td>
<td>0.0792</td>
<td>0.719</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>1451</td>
<td>106</td>
<td>0.0792</td>
<td>0.719</td>
</tr>
<tr>
<td>Sky Harbor Airport</td>
<td>225</td>
<td>2022</td>
<td>Annual</td>
<td>3943583</td>
<td>242853</td>
<td>0.0616</td>
<td>0.553</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>192388</td>
<td>1711</td>
<td>0.0887</td>
<td>0.797</td>
</tr>
<tr>
<td>San Bernardino</td>
<td>35</td>
<td>323</td>
<td>Annual</td>
<td>526050</td>
<td>27032</td>
<td>0.0514</td>
<td>0.474</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solstice</td>
<td>2289</td>
<td>131</td>
<td>0.0572</td>
<td>0.528</td>
</tr>
</tbody>
</table>
inoperative. Because the PCS contains switching circuits and a control microprocessor, it also provides fault sensing, power interruption, and maximum power tracking and acts as an isolation transformer for matching the utility voltage. The PCS serves as the control unit for the entire PV system. The major specifications for a typical PCS are given in Appendix B.

Table 5 presents the efficiency as well as other characteristics of the power-conditioning systems at the various sites. These efficiencies are acceptable even though efficiency goals are higher. Power inversion and power quality have not been problems, and therefore potential utility interface difficulties have been avoided. More important to the operation of the subsystem has been a reliability question. The power conditioners have been highly susceptible to tripping. There has been little development of power conditioners for PV, especially at this intermediate-size range. One requirement for these experiments, which was included as part of the power-conditioning package, was some sort of personnel protection. Ground-fault interruption (GFI) in the mA range (to protect people) is also sensitive enough to detect induced fields (the array is essentially a large antenna), instrumentation-induced imbalances, and possibly even voltage variation on the ac side. Over the course of the experiments, the GFIs have been desensitized to 30 to 40 mA to reduce the number of these nuisance trips.

There has also been difficulty with maximum power tracking. Estimates indicate that ~2% increase in energy can be obtained from the maximum power tracking operation. Should the maximum power tracker operate poorly, more than 2% can be lost. The maximum power tracker at the Science and Art project appears to behave erratically. Certain data show a decrease in output power at increased energy, which indicates a tracking problem.

INSTALLATION AND SYSTEM COSTS

The installation of a variety of systems provided insight into certain features of particular detailed designs. Installation can be divided into a number of different steps: site preparation, array foundations and structure, electrical subsystem, and the thermal subsystem for the photovoltaic/thermal (PV/T) collectors. Each of these is discussed in this section with particular emphasis placed on the lessons learned.

Site Preparation

The PV arrays may be either ground-mounted or roof-mounted. The costs associated with site preparation for a ground-mounted system include mobilizing and demobilizing the work force; clearing, filling, and leveling the site; excavating and backfilling the cable trenches; and providing a ground cover, site fencing, necessary paving, and utility hookups. In the case of roof-mounted systems, the costs include any special roof support, access to the roof, and roof repair required because of damage incurred during system installation. Roof penetration costs are included as foundation costs, although this is somewhat arbitrary. The cost of land is not included in these costs because the site owners provided the land at no cost to the project. The costs for site preparation ranged from $36 to $248/m^2 of collector area and are listed for each site in Table 6. These costs far exceed those that will be necessary to achieve economic viability for PV systems.

The site preparation costs and the associated designs and construction experiences indicate that the two lowest costs are for ground-mounted systems that were installed on very level sites that required no clearing, filling, or leveling (Newman and Sky Harbor). The Lea County (Lovington) system was also installed on a comparable site, but the
Table 5

PV System Data for Standard Operating Conditions*

<table>
<thead>
<tr>
<th>Site and Period</th>
<th>SOC dc Power (RW)</th>
<th>SOC ac Power (RW)</th>
<th>SOC Power Conditioner Efficiency (%)</th>
<th>SOC dc Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Bernardino</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Jan 82 to 26 May 82</td>
<td>15.64</td>
<td>9.29</td>
<td>56.43</td>
<td>6.72</td>
</tr>
<tr>
<td>1 Jun 82 to 24 May 83</td>
<td>16.42</td>
<td>13.55</td>
<td>79.33</td>
<td>7.14</td>
</tr>
<tr>
<td>1 Jun 83 to 17 Aug 83</td>
<td>16.11</td>
<td>13.39</td>
<td>80.18</td>
<td>6.43</td>
</tr>
<tr>
<td>El Paso</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Jun 81 to 29 May 82</td>
<td>11.78</td>
<td>-</td>
<td>-</td>
<td>6.47</td>
</tr>
<tr>
<td>29 May 82 to 29 May 83</td>
<td>11.84</td>
<td>-</td>
<td>-</td>
<td>6.36</td>
</tr>
<tr>
<td>29 May 83 to 18 Aug 83</td>
<td>10.60</td>
<td>-</td>
<td>-</td>
<td>5.86</td>
</tr>
<tr>
<td>Lovington, B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Jun 81 to 26 May 82</td>
<td>36.01</td>
<td>32.53</td>
<td>87.13</td>
<td>6.45</td>
</tr>
<tr>
<td>3 Jun 82 to 29 May 83</td>
<td>35.74</td>
<td>31.52</td>
<td>86.01</td>
<td>6.37</td>
</tr>
<tr>
<td>29 May 83 to 18 Aug 83</td>
<td>33.37</td>
<td>29.79</td>
<td>87.22</td>
<td>6.25</td>
</tr>
<tr>
<td>Lovington, A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Jun 81 to 26 May 82</td>
<td>36.64</td>
<td>33.74</td>
<td>88.97</td>
<td>6.55</td>
</tr>
<tr>
<td>3 Jun 82 to 29 May 83</td>
<td>35.47</td>
<td>32.05</td>
<td>88.55</td>
<td>6.29</td>
</tr>
<tr>
<td>3 June 82 to 18 Aug 83</td>
<td>34.85</td>
<td>31.53</td>
<td>88.71</td>
<td>6.25</td>
</tr>
<tr>
<td>Beverly, A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Jun 81 to 7 May 82</td>
<td>32.60</td>
<td>28.57</td>
<td>84.39</td>
<td>6.36</td>
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<tr>
<td>3 Jun 82 to 18 Aug 83</td>
<td>26.92</td>
<td>23.42</td>
<td>83.84</td>
<td>6.06</td>
</tr>
<tr>
<td>3 Jun 82 to 29 May 83</td>
<td>29.79</td>
<td>25.80</td>
<td>85.11</td>
<td>6.56</td>
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<tr>
<td>Beverly, B</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 Jun 81 to 7 May 82</td>
<td>32.64</td>
<td>29.88</td>
<td>88.44</td>
<td>6.27</td>
</tr>
<tr>
<td>3 Jun 82 to 29 May 83</td>
<td>29.43</td>
<td>26.37</td>
<td>86.41</td>
<td>6.40</td>
</tr>
<tr>
<td>29 May 83 to 18 Aug 83</td>
<td>26.20</td>
<td>23.22</td>
<td>86.03</td>
<td>5.86</td>
</tr>
<tr>
<td>Phoenix</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 April 82 to 28 May 82</td>
<td>150.02</td>
<td>133.29</td>
<td>88.56</td>
<td>9.95</td>
</tr>
<tr>
<td>2 Jun 82 to 29 May 83</td>
<td>144.64</td>
<td>127.64</td>
<td>87.78</td>
<td>9.87</td>
</tr>
<tr>
<td>29 May 83 to 18 Aug 83</td>
<td>141.92</td>
<td>125.74</td>
<td>88.37</td>
<td>9.80</td>
</tr>
<tr>
<td>Dallas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 Jul 82 to 29 May 83</td>
<td>14.75</td>
<td>-</td>
<td>-</td>
<td>8.65</td>
</tr>
<tr>
<td>29 May 83 to 18 Aug 83</td>
<td>14.33</td>
<td>-</td>
<td>-</td>
<td>8.97</td>
</tr>
</tbody>
</table>

*The Standard operating Conditions (SOC) data are weighted averages with dc power as the weighting factor.

For example: \( \text{SOC ac Power} = \frac{\sum P_{\text{ac}} \cdot P_{\text{dc}}}{\sum P_{\text{dc}}} \)
cost was four times as much on a dollar per kilowatt ($/kW) basis. This site had a 3-ft elevation difference across the 600-ft site and, for aesthetic reasons, was made nearly level. The leveling was not required for the construction of the PV system, and the cost was excessive. The two other ground-mounted systems were installed on sites requiring considerable excavations because of a hillside location (Beverly) and a large drainage ditch (G. N. Wilcox), requiring filling and culverts. These "unfavorable" sites contributed significantly to the site preparation costs.

Table 6
Site Preparation Costs for Ground-Mounted Systems

<table>
<thead>
<tr>
<th>Project</th>
<th>$/m²</th>
<th>$/Wp</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLM Corp.</td>
<td>71</td>
<td>1.06</td>
</tr>
<tr>
<td>Beverly H.S.</td>
<td>166</td>
<td>2.75</td>
</tr>
<tr>
<td>DFW Airport</td>
<td>245</td>
<td>2.22</td>
</tr>
<tr>
<td>Newman</td>
<td>36</td>
<td>0.57</td>
</tr>
<tr>
<td>Wilcox</td>
<td>248</td>
<td>3.17</td>
</tr>
<tr>
<td>Lovington</td>
<td>122</td>
<td>1.98</td>
</tr>
<tr>
<td>Science and Art</td>
<td>211</td>
<td>1.73</td>
</tr>
<tr>
<td>Sky Harbor</td>
<td>62</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Note: Site preparation costs for the San Bernardino project were not accounted separately and hence are not included in this table.

The roof-mounted systems were considerably more complex. Many commercial and industrial roofs are not structurally adequate to support the additional loadings associated with installation of a PV system. Expensive superstructures are necessary to support the PV system.

The BDM and Science and Art Center installations both have complex superstructures. The site preparation costs reflect these expensive structures. The BDM cost is somewhat lower than the Science and Art Center cost because some costs were a result of building design discrepancies that were corrected and paid for by the builder.

In addition, skylights, and heating, ventilation, and air-conditioning equipment often obstruct roof space and complicate the design and construction of PV systems. Significant numbers of roof penetrations for PV structures increase the probability of roof leaks and resultant water damage. Conversely, a roof-mounted PV system makes access to existing roof equipment more difficult and hampers reroofing. Existing roofing may need to be replaced at the time of installation of a PV system since it is not designed to handle the large amount of traffic on the roof during system construction. This was the case in both the DFW and Science and Art Center projects and accounts for a significant amount of those costs.

Roof-mounting may expose a PV system to amplified wind conditions. The BDM system illustrates this situation. A strong wind (~80 mph) directly from the east was amplified as the wind streamed up and over the multistory BDM office building. The parabolic trough collectors were in a stowed position, and the wind caught the upper edge of the collector; the lower edge was protected from the wind by a parapet around the top of the building. The resulting high torque exceeded the design load of the collectors and caused extensive damage on the east row of collectors. This problem has been solved by changing the stow position of the collectors. The effectiveness of the solution was verified with wind tunnel tests on a scale model.

Several general conclusions can be made about site selection and preparation:
1. Ground-mounted systems on a relatively level site are considerably less expensive,
2. Site leveling should be avoided if at all possible,
3. Roof-mounted systems are less desirable because of the above-mentioned reasons, and
4. Roof-mounted systems are also less adaptable to a "standard" modular design, a feature that can reduce PV system costs considerably.

Array Foundations

The specific design approach to foundations and structures greatly affects cost. Table 7 shows the range of costs for the foundation alone for the various projects. In general, the high-cost foundations are either roof-mounts or shallow-footing ground-mounts. The problems with roof-mounting have been discussed above. Shallow-footing ground-mount designs are dominated by sliding resistance and tipping force requirements that result from wind loads. The Lovington array is an example of a shallow-footing foundation. A large amount of concrete was required to prevent it from sliding or tipping in the 90-mph design wind. The Beverly foundation design is similar, and the costs reflect the high concrete costs. In addition, the Beverly footings have "steps" in the concrete pours, which further increase costs. In contrast, the Sky Harbor foundations (deep-footing design) are one-half to one-fourth the cost per unit aperture area.

The Newman costs are low because essentially prefabricated materials were used.

Mounting Structures

For the flat-plate PV systems reported here, the mounting structure was not an integral part of the PV module. Subsequent experience has shown that it is wise to integrate the two designs. The mounting structure costs for the flat-plate projects are listed in Table 8.

<table>
<thead>
<tr>
<th>Project</th>
<th>$/m²</th>
<th>$/Wp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beverly</td>
<td>113</td>
<td>1.87</td>
</tr>
<tr>
<td>San Bernardino</td>
<td>121</td>
<td>1.14</td>
</tr>
<tr>
<td>Newman</td>
<td>18</td>
<td>0.29</td>
</tr>
<tr>
<td>G. N. Wilcox</td>
<td>67</td>
<td>0.86</td>
</tr>
<tr>
<td>Lovington</td>
<td>62</td>
<td>1.01</td>
</tr>
<tr>
<td>Science and Art</td>
<td>91</td>
<td>0.75</td>
</tr>
<tr>
<td>Sky Harbor</td>
<td>30</td>
<td>0.27</td>
</tr>
</tbody>
</table>

The highest cost flat-plate structures (San Bernardino and Science and Art Center) are roof-mounted designs with many piece parts, much welding, and considerable in-field handling. The two lowest cost systems (Beverly and Lovington) were well designed and were "factory-assembled" into 10-module panels. These panels were shipped to the site and installed by direct attachment to the foundation along the front edge and to metal struts at the back. The Newman
mounting structure design follows the same "factory-assembly" design philosophy and, in larger quantities, would compete with the two lowest cost designs. However, these wooden structures have not exhibited good long-term dimensional stability. Additional bracing was necessary, after a period of time, to help maintain the structural integrity. Wood may not be the best material to use as the main support members, but in combination it provides low costs and flexibility.

For concentrator systems, the mounting structure is complementary to and integrated with the module itself, and the costs cannot be clearly separated. The costs for concentrator system mounting structures are therefore not discussed here.

Thermal Subsystems

Three of the four concentrator projects use actively cooled collectors. The thermal subsystem cools the PV cells and can also be useful to provide thermal energy for on-site thermal loads. Use of the thermal energy significantly increases the efficiency of converting sunlight to useful energy. Ordinarily, a flat-plate or concentrating PV collector will operate at an electrical efficiency of 5% to 12%. Most of the actively cooled concentrators achieve additional thermal efficiencies of 40% to 60%. This thermal energy is collected at temperatures below 100°C.

The BDM project makes use of the thermal energy as an input to the experimental heat pump used in the building. During the nonheating portion of the year, the thermal energy is dissipated using a cooling tower.

In the G. N. Wilcox project, the collector thermal energy is supplied to the hospital for domestic hot water needs. Cooling convectors dissipate heat in excess of that required.

The DFW Airport project planned to supply thermal energy as a preheat to boiler feedwater in the DFW Airport air-conditioning system. These boilers generate steam to be used in a Rankine cycle to operate centrifugal chillers supplying chilled water throughout the airport. During the brief periods of the year when air-conditioning is not required, the thermal energy was to be dumped into an 18,000-gal treated boiler feedwater makeup tank. However, as part of the energy management program of the airport, an electrical air-conditioning system was installed. The thermal energy is now flowing to the hot water system of a hotel at the airport.

For the most part, the costs associated with the actively cooled systems are a requirement for the operation of the concentrators described, whether or not the thermal energy is used. The costs associated with the purchase and installation of the actively cooled components are listed in Table 9.

Table 9
Active Cooling System Costs for Concentrating PV Collectors

<table>
<thead>
<tr>
<th>Project</th>
<th>$/m²</th>
<th>$/Wp</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDM</td>
<td>78</td>
<td>1.17</td>
</tr>
<tr>
<td>DFW</td>
<td>383</td>
<td>3.48</td>
</tr>
<tr>
<td>G. N. Wilcox</td>
<td>36</td>
<td>0.57</td>
</tr>
</tbody>
</table>

The problems encountered with the active thermal systems include

1. A change in the nature of the thermal load at the DFW Airport, which required additional work and expense.
2. The poor seasonal use of thermal energy in the BDM project, and
3. The requirement for proximity of the thermal system to the load, which affected the siting of the G. N. Wilcox project.

Because four to five times as much thermal as electrical energy is available from these combined systems, it is difficult to find applications that can make use of all of the low-grade thermal energy that is available from a system supplying a significant amount of electric power. Also, standardized thermal subsystem designs are less likely to be practical because of the varying site-specific design requirements. In fact, a major limitation (from the PV perspective) is that PV/T systems are designed to meet the thermal load, with the electricity as a by-product.

**Electrical Subsystems**

The electrical subsystem includes all dc and ac system electrical wiring, lightning protection, and instrumentation and control wiring. The discussion emphasizes the wiring from the array to the PCS. Lightning protection has been discussed in other reports. The total electrical subsystem costs are detailed in Table 10.

**Table 10**  

<table>
<thead>
<tr>
<th>Project</th>
<th>$/m²</th>
<th>$/Wp</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDM</td>
<td>73</td>
<td>1.09</td>
</tr>
<tr>
<td>Beverly</td>
<td>216</td>
<td>3.57</td>
</tr>
<tr>
<td>San Bernardino</td>
<td>76</td>
<td>0.71</td>
</tr>
<tr>
<td>DFW</td>
<td>326</td>
<td>2.96</td>
</tr>
<tr>
<td>Newman</td>
<td>399</td>
<td>6.34</td>
</tr>
<tr>
<td>G. N. Wilcox</td>
<td>195</td>
<td>2.49</td>
</tr>
<tr>
<td>Lovington</td>
<td>153</td>
<td>2.50</td>
</tr>
<tr>
<td>Science and Art</td>
<td>113</td>
<td>0.93</td>
</tr>
<tr>
<td>Sky Harbor</td>
<td>118</td>
<td>1.06</td>
</tr>
</tbody>
</table>

The Beverly and Lovington Projects illustrate vividly why the wiring costs for most of these systems exceed the economically acceptable limits. In keeping with standard construction practices and electrical codes (in the absence of PV-specific National Electrical Code [NEC]), the system designs included numerous electrical junction boxes and rigid metal conduit. This resulted in high material and labor expenses. The lower cost systems made use of "daisy-chaining" techniques for module wiring. Techniques like these are necessary to bring wiring costs to reasonable levels.

Although it is too early to critique electrical designs for the concentrator PV systems, the flat-plate systems have been reviewed recently.[5] The general conclusions from the review are as follows:

1. Modular design allows for partial operation under fault or maintenance conditions.
2. Plug-in modules provide easy installation.
3. Protection from direct lightning strikes is not cost effective.
4. Metal oxide varistors appear to be adequate for surge protection.
5. Redundant junction boxes are unnecessary; one junction box or less per source circuit is more appropriate.
6. Incorporation of ground-fault interruption for personnel safety greatly reduces system reliability.

Grounding techniques and diagnostic instrumentation are unresolved issues still being studied. Both of these issues depend upon anticipated failure rates. Current module failure rates are low (the Science and Art Center system, which has the highest operating voltage, has a module failure rate of 5 per 1500). None of the systems is large enough to establish a "real" failure rate.
Conclusions and Lessons Learned

Much of this section has dealt with the problem of high cost for the various subsystems. Careful analyses of the cost items have led to subsequent work in balance-of-system engineering, which promises to significantly reduce the cost of second-generation systems. This work is presented in detail by Post et al. A brief summary of the approach is presented here.

1. Develop standardized array field designs and building block hardware,
2. Minimize site-specific work,
3. Select sites with favorable conditions (minimal clearing and excavating work),
4. Use low-cost foundations,
5. Develop integrated module/structure approach and maximize factory assembly, and
6. Minimize electrical junction boxes and conduit.

Incorporating this approach into optimized subsystem designs has led to much lower costs. Two such flat-plate building block designs have been installed at the Sandia test facility. The experience to date for these systems has been very good. Briefly,

1. The original total installation cost (exclusive of PV modules) for 30 kWP of each array subsystem design was about $150/m².
2. One contractor had such good experience that he indicated he would repeat the job for $78/m².
3. Both designs are projected to cost about $50/m² in 1-MW or greater quantities per year. The initial installation seems to support this projection.

The experience from the nine experiments was invaluable in developing the subsequent low-cost designs.

OPERATION AND MAINTENANCE

Data on O&M of PV systems has been collected for nearly 3 yr. The summary of these data given here is shown in the histograms in Figures 7 through 16, displaying for each system the time spent in each of four categories of operational status, the output energy, and the energy lost, broken down by month.

Flat-Plate Systems

For the Newman, Beverly, and Lovington systems, the histograms show a loss of a few percent of the energy each month due to insufficient insolation, which is usually caused by low sun angle (high angle of incidence) or by bad weather. The PCS is the primary cause of energy loss and of downtime for the Beverly and Lovington systems. The difficulty with the PCS was caused by a requirement to repair the inverter. There was a delay in obtaining the proper service, but the PCS was then quickly repaired. Even with the delay, the energy lost was only ~20% of the monthly total and was less than 2% of the annual total. The repair expenses for the PCU were $3000, which represents virtually all of the maintenance expenses at this site. The cost of the energy lost due to the downtime caused by the failure of the PCS was insignificant in comparison to the repair expense.

Significant loss of energy has occurred at the Lovington, Beverly, and San Bernardino sites due to tripping of the GFIs. The GFIs have since been desensitized to a level of approximately 30 to 40 mA, which has greatly improved the reliability of these systems.

The operational expenses for flat-plate PV systems identified in these experiments have been limited to the three categories listed in Table 11. The
Figure 7. Operational and Energy Production Data for Beverly A Subfield
Figure 8. Operational and Energy Production Data for Beverly B Subfield
Figure 9. Operational and Energy Production Data for Lovington A Subfield
Figure 10. Operational and Energy Production Data for Lovington B Subfield
Figure 11. Operational and Energy Production Data for San Bernardino
Figure 12. Operational and Energy Production Data for Science and Art Center
Figure 13. Operational and Energy Production Data for Newman Power Station
Figure 14. Operational and Energy Production Data for Dallas-Ft. Worth Airport
Figure 15. Operational and Energy Production Data for Sky Harbor Airport
Figure 16. Operational and Energy Production Data for BDM Office Building
Table 11
Operational Costs for Flat-Plate Systems

<table>
<thead>
<tr>
<th>Category</th>
<th>Cost ($/kW)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array washing</td>
<td>5</td>
<td>Not needed</td>
</tr>
<tr>
<td>Change of array</td>
<td>5-10</td>
<td>Not needed</td>
</tr>
<tr>
<td>tilt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walk-Through</td>
<td>10-15</td>
<td>Required</td>
</tr>
</tbody>
</table>

Washing of flat-plate arrays is not necessary even in climates as arid as that at the Newman project; the infrequent rains adequately remove the accumulated dust. The Newman and Lovington systems were designed to allow adjustment of the tilt of the flat-plate arrays for more efficient seasonal operation. Experience has indicated the increased efficiency of array performance does not produce sufficient additional power production to offset the operational cost of changing the array tilt twice a year. A biannual visual check (walk-through) of the array and its subsystems may be the only required operational expense for a flat-plate PV system. The walk-through is a routine check of the operational status of the components and subsystems. If problems are noted, then some maintenance will be required. It may be possible to perform these routine checks remotely, and equipment monitors with automatic annunciators are currently being developed for this purpose.

Maintenance costs for flat-plate arrays have not been as clearly defined as the operational costs. Many deficiencies were discovered during initial operation of the experiments, including poor quality control for module manufacture and inappropriate connectors. After these initial deficiencies were corrected, only a few maintenance requirements have been identified. The categories of maintenance requirements are listed in Table 12. The sum of these operation and maintenance costs ranges from $40 to $50 per peak kilowatt, with the required being about $30 per peak kilowatt. For those systems that operate at approximately 6% efficiency the equivalent cost is about $2/m². A southwest site might produce \(~2000\) kWh/kW and have an energy cost of $0.10/kWh, with a resulting O&M cost of about 15%/yr.

Table 12
Maintenance Requirements for Flat-Plate Systems

<table>
<thead>
<tr>
<th>Category</th>
<th>Cost ($/kW)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weed control</td>
<td>5</td>
<td>Depends on site</td>
</tr>
<tr>
<td>Module replacement</td>
<td>1-2</td>
<td>Needed for failure rates greater than 0.01 per year</td>
</tr>
<tr>
<td>Short or open circuit isolation</td>
<td>1-2</td>
<td>Required</td>
</tr>
<tr>
<td>PCS repair</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Servicing of control instrumentation</td>
<td>1-2</td>
<td>Optional</td>
</tr>
</tbody>
</table>
Concentrator Systems

The lessons learned from the O&M experiences for concentrator systems are not as clear-cut as for the flat-plate systems. The concentrator systems represented in this group of intermediate experiments are the first concentrator systems operated under field conditions, and their O&M records reflect the developmental processes that have taken place.

The histogram summaries for the DFW Airport project show that the system was inoperative 30% to 50% of the year; however, the available energy loss was not appreciable. The major portion of the inoperative time was caused by insufficient direct normal insolation, and during these periods, very little energy is lost. The losses for other reasons are less than 2% and are due to servicing of the PCS and array components.

The histogram summaries for the BDM project show the largest losses of energy. The system control logic was responsible for some of these losses because cloud shadowing consistently caused the collectors to orient in the stow position for an extended period even if the shadowing was momentary. The system was grounded improperly and formed a potentially hazardous ground loop. The major loss of energy was caused by the poor focusing of the sunlight onto the PV cells. For even the best constructed troughs, any stress causes defocusing. During the period of this experiment, the best performance of the system was only 60% to 70% of the design peak power.

The Sky Harbor Airport system operated erratically during the period October 1982 through March 1983. The difficulties were caused by faulty PCS operation and by inconsistent array tracking. In late spring 1983, a slippage developed in the gear box, which aggravated the tracking problem, but energy loss was minimized by manually resetting the arrays. In early summer, the PCS began to fail frequently and by the end of the summer little energy was produced by the system. The mechanical problems have been severe and appear to be caused by poor design rather than by inherent tracking flaws. A PV system constructed in Saudi Arabia, using the same concentrator technology, has not experienced problems with tracking. The PCS problems are apparently also due to poor design. The PCS at Sky Harbor is a one-of-a-kind system.

A recent survey at the APS site identified a number of problems in the array. The major difficulties are

1. Modules leak water
2. Many open circuits have been identified, and
3. Ground faults are numerous.

These problems appear to have been present in the field since installation. Our estimates suggest between 5% to 10% energy loss due to those manufacturing flaws. No degradation or other problems that are directly related to module performance have been observed.

We have concluded from the experiences gathered from these concentrator systems that the operational maintenance of a concentrator system is more complex and the costs will be higher than for fixed flat-plate systems. However, these issues will also relate to tracking flat-plate systems, but this technology was not employed in any of these experiments.

ON-SITE DATA ACQUISITION SYSTEM

An on-site data acquisition system (ODAS) was provided at each experiment site by Sandia National Laboratories, Albuquerque (SNLA). The ODAS sampled, averaged, and recorded up to 84 values from sensors located throughout the PV system. The ODAS sampled the sensors at different rates dependent on their importance and the operational status of the PV system. All recorded data were
stored on magnetic tape in a small computer that controlled the ODAS operation. Several days of data could be stored on a single tape cartridge.

The ODAS, upon external telephone query, transferred data to qualified users.

The Boeing Computer Services (BCS) regularly collected data from the ODAS at each experiment site. Table 13 lists a typical set of parameters recorded by the ODAS.

Table 13

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sample Interval (min)</th>
<th>Record Interval (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>64 Panel String Currents</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>6 Cell Temperatures</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 System Mode Detection</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1 Array Power</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 Array Voltage</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 Array Current</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 Wind Speed Peak</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 Wind Direction</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 Barometric Pressure</td>
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<td>10</td>
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<tr>
<td>1 Ambient Temperature</td>
<td>1</td>
<td>10</td>
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<tr>
<td>1 Dew Point</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 Rainfall</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 Plane of Array Insolation</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 Horizontal Insolation</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 Direct Normal Insolation</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>1 Reference Cell Insolation</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>
REFERENCES


APPENDIX A

Intermediate Photovoltaic Experiment Descriptions

BDM OFFICE BUILDING PROJECT
ALBUQUERQUE, NM

Description

The BDM PV experiment consists of 54 parabolic trough concentrators installed on the roof of the BDM Corporation office building. The system is composed of nine rows of T-700 Solar Kinetics 40X troughs with six of the 20-ft troughs in each row. The receiver on each trough is a 20-ft long, hollow, inner extrusion with four 5-ft-long outer extrusion sections clamped over the inner extrusion. The PV cells are mounted on the outer extrusion. Power from the array is delivered to an inverter. The output from the inverter is delivered to several building loads in parallel with power supplied from the Public Service Company of New Mexico. Heat from the receivers is transferred by a mixture of ethylene glycol and water pumped through the cavity in the receiver to supplement the building heating load in the winter or is rejected to the atmosphere by a closed-circuit cooling tower in the summer. The thermal energy from the PV system provides approximately 50% of the building's winter heating load.
**BDM Office Building Project Characteristics**

<table>
<thead>
<tr>
<th><strong>FIRMS INVOLVED</strong></th>
<th><strong>The BDM Corporation</strong></th>
<th><strong>The BDM Corporation</strong></th>
<th><strong>Bridgers and Paxton and the BDM Corporation</strong></th>
<th><strong>BDM</strong></th>
<th><strong>Public Service Company of New Mexico</strong></th>
<th><strong>Craddock Development Company</strong></th>
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</thead>
<tbody>
<tr>
<td>Prime contractor</td>
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<tr>
<td>Design</td>
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<tr>
<td>Construction</td>
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<td></td>
</tr>
<tr>
<td>Operation</td>
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<tr>
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<td></td>
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<td><strong>APPLICATION</strong></td>
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<tr>
<td><strong>OPERATIONAL DATE</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>ARRAY TECHNOLOGY</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ENERGY USE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
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<tr>
<td><strong>SIZE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy output (kW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Electrical</td>
<td>47</td>
<td></td>
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<tr>
<td>Thermal</td>
<td>280</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Aperture area (m²)</td>
<td>702</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Silicon area (m²)</td>
<td>8.8</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>POWER-CONDITIONING UNIT</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Westinghouse 62.5 kVA unit. Output is</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>277/480 V three-phase, 60 Hertz</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>ENERGY STORAGE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Thermal input to ground-coupled heat pump system. This exchange is through a 10,000-gal tank. Assuming a 20°F temperature change provides about 490 kWh of thermal storage.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>TRACKING</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single axis, diurnal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CONCENTRATION</strong></td>
<td>32X</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>COOLING</strong></td>
<td>Active, 50% ethylene glycol and water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>COST (1980 $)</strong></td>
<td>$31.60/W (estimated system costs)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure A-1. One-Line Diagram for BDM Office Building PV Site
Description

This PV flat-plate array, installed on a south-sloping hillside at the Beverly High School, consists of two subfields each with 1600 modules. Each 50-kW subfield supplies a separate PCU with 250 V and 200 A and is divided into 20 subarrays of 80 modules wired 5 in parallel by 16 in series. Solar Power, G-361, 36-cell, glass superstrate modules are utilized and operate at 2 A and 15.6 V.

The dc power from each subfield is converted by inverters and is then delivered to a three-phase step-up transformer whose output is fed directly to the main 4160-V utility feeder line in one of the school's electric distribution vaults. Rachet-type watt-hour and Q-hour meters are installed in this feeder line where the utility service enters the building. These meters interface with the ODAS to measure and record electric energy bought and sold.
# Beverly High School Project Characteristics

## FIRMS INVOLVED

<table>
<thead>
<tr>
<th>Prime contractor</th>
<th>Design</th>
<th>Construction</th>
<th>Operation</th>
<th>Utility</th>
<th>Site</th>
</tr>
</thead>
</table>

## LOCATION

Beverly, Massachusetts

## APPLICATION

Electric power to high school

## OPERATIONAL DATE

April 1981

## ARRAY TECHNOLOGY

Ground-mounted flat-plate array using Solar Power single-crystal silicon modules, tilted to 40 degrees from horizontal, facing south, passive cooling.

## ENERGY USE

<table>
<thead>
<tr>
<th>Energy type</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>Reduce grid-supplied load</td>
</tr>
<tr>
<td>Thermal</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

## SIZE

<table>
<thead>
<tr>
<th>Energy type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>100</td>
</tr>
<tr>
<td>Thermal</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Aperture area</td>
<td>1431</td>
</tr>
<tr>
<td>Silicon area</td>
<td>905</td>
</tr>
</tbody>
</table>

## POWER-CONDITIONING UNIT

Two DECC 60 kVA units. Output is three-phase 277/480 V, 60 hertz.

## ENERGY STORAGE

None

## TRACKING

None

## CONCENTRATION

None

## COOLING

None

## COST (1980 $)

$33.00/W (estimated system costs)
Figure A-3. One-Line Diagram for Beverly PV Site (Electrical)
Description

A line-focus Fresnel lens concentrator with a concentration ratio of 25X is used in conjunction with silicon solar cells to generate 24 kW_e and 140 kW. This energy is supplied to the central utility plant at the DFW Airport. Electricity from the array, which is located on the roof of the utility plant, is used by small motors and lights within the plant. Heat from the solar array preheats boiler feedwater for the steam plant. The heat-transfer fluid is relatively cool so that the solar cells will stay at a low mean temperature and hence have a relatively high conversion efficiency.
DFW Airport Project Characteristics

**Firms Involved**
- **Prime contractor**: E-Systems
- **Design**: E-Systems
- **Construction**: JUD mechanical
- **Operation**: DFW Airport
- **Utility**: Texas Power & Light
- **Site**: DFW Airport

**Location**: Dallas, Texas

**Application**: Electric power and hot water to Airport Utility Plant

**Operational Date**: July 1982

**Array Technology**: Roof-mounted, concentrating array with E-systems linear Fresnel lens modules and ASE2 silicon single-crystal cells.

**Energy Use**
- **Electrical**: Power utility plant emergency lighting system
- **Thermal**: Preheat boiler feedwater

**Size**
- **Energy output (kW)**
  - **Electrical**: 24 kW
  - **Thermal**: 140 kW
- **Aperture area (m²)**: 245
- **Silicon area (m²)**: 10

**Power-Conditioning Unit**: Unique, fully transistorized 30 kVA inverter designed by J. A. Ross, 260 Vdc input, 480 VAC three-phase output

**Energy Storage**: Electrical - none
- **Thermal**: 11,500-gal feedwater tank

**Tracking**: Two axis, rack and roll

**Concentration**: 25x

**Cooling**: Actively cooled by 50% ethylene glycol and water

**Cost (1980 $)**: $47.00/W (estimated system costs)
Figure A-5. One-Line Diagram for DFW Airport PV Site (Electrical)
Figure A-6. DFW Airport Project
Description

This project is an applications experiment to supply both electricity and water heating to the G. N. Wilcox Hospital in Hawaii, using 80 parabolic trough concentrators. The array is comprised of ten rows of parabolic trough concentrators with a total of 1458 modules. A cooling system, consisting of water sent through the receiver tubes that contain the cells, is required. This system maintains an effective operating temperature and also provides recoverable thermal energy in the form of hot water. The design peak array output is 35 kW electrical plus 230 kW thermal.
# G. N. Wilcox Hospital Project Characteristics

**FIRMS INVOLVED**

<table>
<thead>
<tr>
<th>Firm</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acurex Corp.</td>
<td>Prime contractor</td>
</tr>
<tr>
<td>Acurex Corp.</td>
<td>Design</td>
</tr>
<tr>
<td>Acurex with local subcontractors</td>
<td>Construction</td>
</tr>
<tr>
<td>Acurex Corp. and Hawaii Natural Energy Institute</td>
<td>Operation</td>
</tr>
<tr>
<td>Kauai Electric Company</td>
<td>Utility</td>
</tr>
<tr>
<td>G. N. Wilcox Hospital</td>
<td>Site</td>
</tr>
</tbody>
</table>

**LOCATION**

Lihue, Kauai, Hawaii

**APPLICATION**

Hospital

**OPERATIONAL DATE**

January 1982

**ARRAY TECHNOLOGY**

Ground-mounted, single-axis Acurex parabolic trough, NS orientation, single crystalline silicon ASE cells, actively cooled receiver, concentration ratio is 30:1

**ENERGY USE**

- **Electrical**: Reduce grid-supplied building load
- **Thermal**: Provide hot water for hospital

**SIZE**

<table>
<thead>
<tr>
<th>Energy output (kW)</th>
<th>Electrical</th>
<th>35</th>
</tr>
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<tr>
<td></td>
<td>Thermal</td>
<td>230</td>
</tr>
<tr>
<td>Aperture area (m²)</td>
<td>446</td>
<td></td>
</tr>
<tr>
<td>Silicon area (m²)</td>
<td>10.94</td>
<td></td>
</tr>
</tbody>
</table>

**POWER-CONDITIONING UNIT**

Westinghouse 62.5 kVA. Output is 277/480 V three-phase, 60 hertz

**ENERGY STORAGE**

325 kWh thermal, hot water

**TRACKING**

Single axis, diurnal

**CONCENTRATION**

30X

**COOLING**

Active water cooling

**COST (1980 $)**

$57.30/W (estimated system costs)
Figure A-7. One-Line Diagram for G. N. Wilcox Hospital PV Site (Electrical)
Figure A-8. G. N. Wilcox Hospital Project
Description

The 100-kW flat-plate grid-connected PV system is composed of two 50-kW subfields, each with a dedicated PCU. A subfield contains 21 subarrays, 80 modules each. Oriented due south, the total panel area may be adjusted manually to 10, 30, or 40 degrees from horizontal.
## Lovington Square Shopping Center Project Characteristics

**FIRMS INVOLVED**
- **Prime contractor**: Lea County Electric Cooperative
- **Design**: Stone and Webster
- **Construction**: Foster Builders and Kirk Meyer Electric
- **Operation**: Lea County Electric Cooperative
- **Utility**: Lea County Electric Cooperative
- **Site**: Lea County Electric Cooperative

**LOCATION**
- Lovington, New Mexico

**APPLICATION**
- Shopping Center

**OPERATIONAL DATE**
- March 1981

**ARRAY TECHNOLOGY**
- Ground-mounted, flat-plate array, adjustable tilt, facing south, single-crystal silicon Solar Power Modules, passive cooling

**ENERGY USE**
- **Electrical**: Reduce grid load to shopping center
- **Thermal**: Not applicable

**SIZE**
- **Energy output (kW)**
  - Electrical: 100
  - Thermal: Not applicable
- **Aperture area (m²)**
  - 1684
- **Silicon area (m²)**
  - 980

**POWER-CONDITIONING UNIT**
- Two DECC 60 kVA units. Output is three-phase 277/480 V, 60 hertz

**ENERGY STORAGE**
- None

**TRACKING**
- None

**CONCENTRATION**
- None

**COOLING**
- None

**COST (1980 $)**
- $31.20/W (estimated system costs)
Figure A-9. One-Line Diagram for Lovington PV Site (Electrical)
Figure A-10. Lovington Square Shopping Center Project
Description

This flat-plate PV system was designed, constructed, and integrated onto an existing UPS at El Paso Electric Company's Newman Power Station. The system consists of 64 parallel-connected panels, each panel containing 9 series-connected modules. The panels face due south and are tilted at a fixed 26 degrees from horizontal. The electrical output from the array is supplied directly to the load at a fixed voltage of 134 Vdc.
### Newman Power Station Project Characteristics

#### FIRMS INVOLVED
- **Prime contractor**
  - Design: New Mexico Solar Energy Institute, Fouts, Lopez, Gomez and Moore, and Golucke Engineering
  - Construction: Callaghan Electric Co. and Ponsford Brothers
  - Operation: New Mexico Solar Energy Institute
  - Site: Newman Power Station

#### LOCATION
- El Paso, Texas

#### APPLICATION
- Uninterruptible Power Supply (UPS)

#### OPERATIONAL DATE
- January 1981

#### ARRAY TECHNOLOGY
- Ground-mounted, flat-plate array, facing south, single-crystal silicon Solar Power modules, passive cooling

#### ENERGY USE
- **Electrical**: Reduce grid-supplied load
- **Thermal**: Not applicable

#### SIZE
- **Energy output (kW)**: 20
- **Electrical**: Not applicable
- **Thermal**: Not applicable
- **Aperture area (m²)**: 279
- **Silicon area (m²)**: 168.11

#### POWER-CONDITIONING UNIT
- None, supplies direct current needed by UPS

#### ENERGY STORAGE
- None (Batteries included in UPS)

#### TRACKING
- None, fixed at 26° elevation

#### CONCENTRATION
- None

#### COOLING
- None

#### COST (1980 $)
- $34.10/W
Figure A-11. One-Line Diagram for Newman Power Station PV Site (Electrical)
Figure A-12. Newman Power Station Project
Description

This fixed, flat-plate roof-mounted array contains several unique features including polycrystalline solar cells, reflectors to augment insolation, and an innovative module design. The module has no frame. The 12-series- by 6-parallel-cell configuration includes 100% parallel connections to enhance reliability. The PCU is interfaced to the ac bus through a transformer so that the array voltage is always less than 600 V, allowing the use of low-voltage wiring. Also, dc components are completely isolated from the ac line. The supporting structures are steel.
### Oklahoma Center for Science and Art Project Characteristics

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<thead>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>The Benham Group</td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>Science Applications, Inc., and Oklahoma Center for Science and Art</td>
<td></td>
</tr>
<tr>
<td>Operation</td>
<td>Oklahoma Gas and Electric</td>
<td>Oklahoma Center for Science and Art</td>
</tr>
<tr>
<td>Utility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| LOCATION | Oklahoma City, Oklahoma |
| APPLICATION | Museum |
| OPERATIONAL DATE | February 1982 |
| ARRAY TECHNOLOGY | Roof-mounted, flat-plate array, tilted 39° from horizontal, facing south, mirror enhanced, polycrystalline silicon Solarex modules, passive cooling |

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<thead>
<tr>
<th>ENERGY USE</th>
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<tbody>
<tr>
<td>Electrical</td>
<td>Reduce grid-supplied load</td>
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<tr>
<td>Thermal</td>
<td>Not applicable</td>
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</table>

<table>
<thead>
<tr>
<th>SIZE</th>
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</thead>
<tbody>
<tr>
<td>Energy output (kW)</td>
<td>135 with mirror enhancement</td>
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<tr>
<td>Electrical</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Aperture area (m²)</td>
<td>1273</td>
</tr>
<tr>
<td>Silicon area (m²)</td>
<td>961</td>
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<table>
<thead>
<tr>
<th>POWER-CONDITIONING UNIT</th>
<th>Windworks</th>
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<tbody>
<tr>
<td>ENERGY STORAGE</td>
<td>None</td>
</tr>
<tr>
<td>TRACKING</td>
<td>Fixed</td>
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<tr>
<td>CONCENTRATION</td>
<td>1.2X</td>
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<tr>
<td>COOLING</td>
<td>None</td>
</tr>
<tr>
<td>COST (1980 $)</td>
<td>$20.20/W (estimated system cost)</td>
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</tbody>
</table>
SUBFIELD 1
- 72 CELLS PER MODULE
- 84 MODULES PER STRING
- MODULES IN SERIES
- 9 STRINGS PER SUBFIELD
- STRINGS IN PARALLEL

SUBFIELD 2
(SAME AS SUBFIELD 1)

Figure A-13. One-Line Diagram for Oklahoma Center for Science and Art PV Site (Electrical)
Figure A-14. Oklahoma Center for Science and Art Project
Description

This flat-plate PV array is located on the roof of the San Bernardino West Side Community Development Corporation's light manufacturing facility. The high-density modules are mounted at a fixed-tilt of 25 degrees to the horizontal. The system is interactive with the utility grid and has no storage.
### San Bernardino Project Characteristics

| FIRMS INVOLVED | San Bernardino West Side Community Development Corp.  
| Design | Dukes, Dukes & Associates  
| Construction | San Bernardino W.C.D.C.  
| Operation | DECC Div. of Helionetics  
| Utility | Southern Calif. Edison  
| Site | San Bernardino Industrial Park  
| LOCATION | San Bernardino, California  
| APPLICATION | Electric power to light manufacturing facility  
| OPERATIONAL DATE | March 1982  
| ARRAY TECHNOLOGY | Roof-mounted, flat-plate, south-facing, single-crystal silicon Solorex modules tilted 25° from horizontal  
| ENERGY USE | Reduce grid-supplied load  
| Electrical | Not applicable  
| Thermal | Not applicable  
| SIZE |  
| Energy output (kW) | 35  
| Electrical | Not applicable  
| Thermal | Not applicable  
| Aperture area (m²) | 328 m²  
| Silicon area (m²) | 270 m²  
| POWER-CONDITIONING UNIT | DECC 75 kVA unit, 480 Vac three-phase  
| ENERGY STORAGE | None  
| TRACKING | None, fixed tilt  
| CONCENTRATION | None  
| COOLING | None  
| COST (1980 $) | $22.10/W (estimated system cost)  


Figure A-15. One-Line Diagram for San Bernardino PV Site (Electrical)
Figure A-16. San Bernardino Project
Description

This 225 kW ground-mounted concentrator PV power system consists of 80 pedestal-mounted arrays. Modules are mounted on a horizontal torque tube. The arrays are passively cooled and track the sun in two axes. These arrays use Fresnel lens for sunlight concentration of 33X on a silicon solar cell 5.7 cm in diameter. Each acrylic lens is 30.5 cm by 122.0 cm and contains four point-focusing patterns. A plastic housing supports the lenses. Eight cells are mounted on an aluminum heat exchanger for passive cooling. Each pedestal supports 272 cells and produces 2.8 kW at standard operating conditions. The dc input from the array is converted by the PCU and delivered through a step-up transformer to a utility distribution line that feeds one of the buildings at the airport.
## Sky Harbor Airport Project Characteristics

<table>
<thead>
<tr>
<th><strong>FIRMS INVOLVED</strong></th>
<th><strong>Arizona Public Service</strong></th>
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</thead>
<tbody>
<tr>
<td>Prime contractor</td>
<td>APS and Martin Marietta</td>
</tr>
<tr>
<td>Design</td>
<td>H. P. Foley</td>
</tr>
<tr>
<td>Construction</td>
<td>Arizona Public Service</td>
</tr>
<tr>
<td>Operation</td>
<td>Arizona Public Service</td>
</tr>
<tr>
<td>Utility</td>
<td>City of Phoenix, Arizona</td>
</tr>
</tbody>
</table>

| **LOCATION** | Phoenix, Arizona |
| **APPLICATION** | Airport building loads |
| **OPERATIONAL DATE** | May 1982 |
| **ARRAY TECHNOLOGY** | Martin Marietta point-focus Fresnel system with two-axis tracking. Single-crystal silicon cells, passive cooling. |

| **ENERGY USE** | **Electrical** 225 kW |
| **Thermal**    | None |

| **SIZE** | **Energy output (kW)** 225 kW |
| **Electrical** | 0 |
| **Thermal** | |
| **Aperture area (m²)** 2022 |
| **Silicon area (m²)** 61.3 |

| **POWER-CONDITIONING UNIT** | Power Systems and Controls 250 kVA unit, 277/480 V three-phase |

| **ENERGY STORAGE** | None |

| **TRACKING** | Two axis azimuth-elevation pedestal |

| **CONCENTRATION** | 33X |

| **COOLING** | Passive heat sink |

| **COST (1980 $)** | $21.20/W (estimated system cost) |
SUBFIELD 1
- 4 LENS-CELLS IN SERIES PER MODULE
- 85 MODULES IN SERIES PER STRING
- 8 STRINGS IN PARALLEL PER SUBFIELD

SUBFIELDS 2-4
(SAME AS SUBFIELD 1)

300Vdc (NOMINAL)

INVERTER

480Vac

PV ARRAY
PARASITIC

PV SITE BUILDING

ARIZONA PUBLIC SERVICE

Figure A-17. One-Line Diagram for Sky Harbor Airport PV Site (Electrical)
Figure A-18. Sky Harbor Airport Project
APPENDIX B

Typical Specification for a PCS

CONTROL FEATURES

1. AUTOMATIC START-UP AND SHUTDOWN in response to the presence or absence of sufficient solar power. In order to avoid nuisance shutdowns during marginal insolation, the PCS remains on-line for a period of time (5 to 8 min typical) after loss of sufficient solar power. The inverter in the PCS, with its bilateral power-flow capability, can run in a stable mode (drawing standby power from the utility grid), even with complete loss of input solar power.

2. SHORTING OF THE PV ARRAY and disconnection of the array from the PCS during shutdown. A shorting contactor is provided to short the array for personnel protection. When operated in this mode, the control circuitry monitors the short-circuit current to determine the presence of sufficient solar power for start-up. (The unit can also function with the array open during shutdown, starting up in response to array voltage or to an externally provided signal—a capability not used at either Beverly or Lovington.)

3. AUTOMATIC PEAK-POWER TRACKING within 1% over the entire power range of 10% to 100% of rated power.

4. ARRAY GROUND-FAULT DETECTION for increased personnel safety. A ground-fault sensor senses ground faults in the array and shuts down the PCS, shorting the array through the input contactor.

5. SYNCHRONIZATION to the grid and prevention of connection between mismatched PCS output and utility grid.

6. AUTOMATIC DISCONNECTION of the PCS from the grid when the grid exceeds set tolerances in frequency and voltage (PCS automatically restarts once after a time delay unless grid fault is repeated).

7. FAULT DETECTION AND PROTECTION circuitry for input overvoltage, PCS overtemperature, grid voltage out of range, excessive reverse power flow, blown fuses, and improper output current. Sophisticated current sensing circuitry detects excessive peak current (output is current-limited), excessive average current, excessive rate-of-rise of current, and excessive phase imbalance in the output current.

8. STANDARD CONTROL PANEL METERING of the Model 61264 PCS includes input power, input voltage, input current, input kWh (totalizing counter), output voltage, output current, output power, output volt-ampere reactive (VAR), and total running time. Twenty-one status and fault indicator lamps allow quick visual determination of the status of the PCS.
APPENDIX B (cont.)

Typical Specifications for a PCS

9. DATA INTERFACE signals are provided. These include digital PCS status signals and 0- to 10-Vdc analog signals for monitoring of input and output parameters (voltage, current, power).

**INPUT**

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<th>SPECIFICATIONS</th>
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<td>Maximum voltage</td>
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<td>Normal operating range, loaded</td>
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<th>OUTPUT</th>
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<tbody>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Rated Power</td>
</tr>
<tr>
<td>kVAR</td>
</tr>
<tr>
<td>Efficiency</td>
</tr>
<tr>
<td>No load losses</td>
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<tr>
<td>Efficiency at 37 kW</td>
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<tr>
<td>Efficiency at 75 kW</td>
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<tr>
<td>Standby power drain from utility</td>
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<tr>
<td>Output current distortion, full load</td>
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<td>Frequency synchronization range</td>
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<th>PHYSICAL CONFIGURATION</th>
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<td>Humidity</td>
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<th>OUTPUTS TO DATA ACQUISITION SYSTEM</th>
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<tbody>
<tr>
<td>Standard level analog and digital signals</td>
</tr>
</tbody>
</table>
INTER SOL POWER CORPORATION (2)
11901 W. Cedar Ave.
Lakewood, CO 80228
Attn: John Sanders
Dick Stegeman

J. C. SCHUMACHER (2)
580 Airport Road
Oceanside, CA 92054
Attn: Stephen M. Lord
Joseph C. Schumacher

JET PROPULSION LABORATORY (8)
4800 Oak Grove Drive
Pasadena, CA 91109
Attn: Bud Powell
Gerald Praver
Russ Sugimura
Anthony Pearson
Kent Volkmer
Len Reiter
W. T. Callaghan
Ron Ross

KELLAM, BIRD, JOHNSON, INC.
612 North Park Street
Columbus, OH 43215
Attn: John Ayres

KYOCERA (3)
8611 Balboa Avenue
San Diego, CA 92123-1580
Attn: William Everitt
R. Alan Panton
Luis Alvarez

LOS ANGELES DEPT. OF WATER & POWER
111 North Hope Street
Los Angeles, CA 90051
Attn: William W. Engels
Kevin G. McAvoy

MC DONNELL DOUGLAS ASTRONAUTICS CO.
5301 Bolsa Avenue, M/S 431, 10-3
Huntington Beach, CA 92647
Attn: Lloyd E. Sanchez

MARTIN MARIETTA (3)
P. O. Box 179
Denver, CO 80201
Attn: H. Wroton
Bob Hein
Matt Imamura

MERIDAN CORP. (2)
5113 Leesburg Pike
Suite 700
Falls Church, VA 22041
Attn: Brad MacLeer
Judy Hogan

METAL IRON CO.
P. O. Box 4590
Ft. Worth, TX 76106
Attn: Arthur Varnoos

MIT/ENERGY LAB-NE RES (3)
711 Virginia Road
Concord, MA 01742
Attn: Miles Russell
Daniel Bergman
Ed Kern

MOBIL SOLAR ENERGY CORP. (4)
16 Hickory Dr.
Waltham, MA 02254
Attn: Bob L. Hammond
Catherine M. Joyce
Juris P. Kalejs
Fritz V. Wald

MONOSOLAR, INC.
8635 Aviation Blvd.
Inglewood, CA 90301
Attn: Bulent M. Basol

MONSANTO ELECTRONIC MATERIALS
COMPANY (2)
P. O. Box 8 Hwy 79 North
St. Peters, MO 63376
Attn: Harold R. Patton
Robert M. Sandfort

NASA HEADQUARTERS - Code RJE
600 Independence Ave., SW
Washington, DC 20546
Attn: Don H. Calahan

NATIONAL RESEARCH COUNCIL (2)
Montreal Road
Ottawa, ONTARIO, Canada K1A 0R6
Attn: Siegfried Karius
Glen Rumbold

NMSEI (2)
P. O. Box 3SOL
Las Cruces, NM 88003
Attn: Vern Risser
Harry Zwibel
NMSIDC
5301 Central NE
Suite 705
Albuquerque, NM 87108
Attn: Leland Alhorn

OAK RIDGE NATIONAL LAB
P. O. Box X
Oak Ridge, TN 37830
Attn: John Stovall
Stephen I. Kaplan

ONTARIO MINISTRY OF ENERGY
56 Wellesley Street West
Toronto, Canada M7A 237
Attn: Ian Lewis

ONTARIO RESEARCH FOUNDATION
Engineering Science Division
Sheridan Park Res. Community
Mississauga, Ontario, Canada L5K1B3
Attn: Michael Westcott

OSTRACO PHOTOLTAIC CO. (2)
Phillip Drive
Princeton, NJ 08540
Attn: Jeremiah P. Ostriker
Robert B. Strassler

PG&E (2)
3400 Crow Canyon Road
San Ramon, CA 94583
Attn: Steve Hester
Kay Firor

PROA
4019 Edith Blvd. NE
Building 23
Albuquerque, NM 87107
Attn: Conrad Seagroves

PV ENERGY SYSTEMS
2401 Childs' Lane
Alexandria, VA 22308
Attn: Paul D. Maycock

PVI PUBLISHING
2250 N. 16th Street
Suite 103
Phoenix, AZ 85006
Attn: Mark Fitzgerald

PACIFIC GAS & ELECTRIC COMPANY
3400 Crow Canyon Road
San Ramon, CA 94583
Attn: Keene M. Matsuda

POLYDYNE
1230 Sharon Park Drive
Suite 61
Menlo Park, CA 94025
Attn: Peter Bos

POLYTECHNIC INSTITUTE OF NEW YORK
333 Jay Street
Brooklyn, NY 11201
Attn: Ann-Christine Albertson

PUBLIC SERVICE ELECTRIC & GAS CO.
80 Park Plaza
Floor 16A
P. O. Box 570
Newark, NJ 07101
Attn: Harry Roman

PUBLIC SERVICE CO. OF COLORADO
P. O. Box 840 Room 420
Denver, CO 80201
Attn: Jim Wilson

PUBLIC SERVICE CO. OF NEW MEXICO (2)
Alvarado Square
Albuquerque, NM 87158
Attn: Frank Burchan
Don Martinez

PURDUE UNIVERSITY (2)
Potter Bldg. Rm 322
West Lafayette, IN 47907
Attn: Geraldine Vest
Robert Vest

QUEENSLAND FINANCIAL GROUP
350 S. Figueroa, #498
Los Angeles, CA 90071
Attn: Warren Shoun

RJR TECHNICAL COMPANY
1100 Reynolds Blvd.
Winston-Salem, NC 27102
Attn: Peter Valenti

RSA ARCHITECTS
5011 Mac Farland Lane
Woodland Hills, CA 91364
Attn: Richard Schoen

RESEARCH TRIANGLE INSTITUTE
P. O. Box 12194
Research Triangle Park, NC 27709
Attn: M. F. Lamorte
RESOURCE PLANNING ASSOC.
50 Church Street
Cambridge, MA 02138
Attn: James Levitt

RICHWAY ENTERPRISES
6752 Rockglen Ave.
San Diego, CA 92111
Attn: Richard L. Quincey

RICHWAY ENTP., INC.
C/O Pacific Locations
250 First Street, Suite 250
Claremont, CA 91711
Attn: Jack D. Richway

RIDGEWAY ENTERPRISES
8181 Tapin Via
R. Cucumonga, CA 91730
Attn: Francis J. Van Stralen

SALT RIVER PROJECT
P. O. Box 1980
Phoenix, AZ 85001
Attn: Steve Chalmers

SAN DIEGO GAS ELECTRIC CO.
110 W. A Street
Box 1831
San Diego, CA 92112
Attn: Wes Goodwin

SAN DIEGO STATE UNIVERSITY
Dept. of Physics
San Diego, CA 92182
Attn: Alan R. Sweedler

SCIENTIFIC ANALYSIS, INC.
4249 Lomac Street
Suite C
Montgomery, AL 36106
Attn: Allen Gunn

SERI (4)
1617 Cole Blvd.
Golden, CO 80401
Attn: Richard DeBlasio
L. Kazmerski
T. Surek
E. Witt

SOLAR ELECTRIC CO. OF NM
2700 Espanola NE
Albuquerque, NM 87110
Attn: Steve Verchinski

SOLAR ENERGY INDUSTRY ASSN.
1156 15th Street NW
Suite 520
Washington, DC 20005
Attn: Charlie Gay

SOLAR INITIATIVE
Citicorp Plaza, Suite 900
180 Grand Avenue
Oakland, CA 94612
Attn: Jerry Yudelson

SOLAR INVERTER
8480 Cliffridge Lane
LaJolla, CA 92037
Attn: James Ross

SOLAR UTILITY NETWORK
P. O. Box 4590
Fort Worth, TX 76106
Attn: S. A. Varnoos

SOLAREX CORPORATION (2)
1335 Piccard Drive
Rockville, MD 20850
Attn: Daniel Bumb
Hal Macomber

SOLAVOLT INTERNATIONAL
3646 E. Atlanta
Phoenix, AZ 85040
Attn: Bruce Larson

SOLEC INT'L INC.
12533 Chordon Avenue
Hawthorne, CA 90250
Attn: George McClure
David R. Lillington
Ishaq Shahryar

SOLLOS, INC.
1519 Comstock Avenue
Los Angeles, CA 90024
Attn: Milo Macha

SOUTHERN CAL EDISON
P. O. Box 800
Rosemead, CA 91770
Attn: N. Patapoff
SPECIALTY CONCEPTS, INC.
9025 Eton Ave, Ste D
Canoga Park, CA 91304
Attn: Tom B. Philp

SPECTROLAB, INC.
12500 Gladstone Avenue
Sylmar, CA 91342
Attn: Alex Garcia

SPIRE CORPORATION
Patriots Park
Bedford, MA 01730
Attn: Anthony Armini
Roger C. Little
Mark B. Spitzer

SPRINGBORN LABORATORIES, INC.
10 Springborn Center
Enfield, Conn 06082
Attn: Bernard Baum
Paul B. Willis

STANDARD OIL COMPANY (Ohio)
1608 Midland Bldg
Cleveland, OH 44115
Attn: Toby K. Alfred

STANDARD OIL COMPANY (Ohio)
4440 Warrensville Center Rd.
Cleveland, OH 44128
Attn: Ronald C. Cull

STRATEGIES UNLIMITED
201 San Antonio Circle
Suite 205
Mt. View, CA 94040
Attn: Robert Steele

SUNELCO CORP.
1619 South Rancho Santa Fe Rd.
San Marcos, CA 92070
Attn: Ed M. Baldwin
Fred Nobile
Robert A. Shade, Jr.

SUPERWAVE TECHNOLOGY
2895 Northwestern Pky.
Santa Clara, CA 95125
Attn: Bruce Minaee

SYSTEMS DEL SOL
10933 Los Alamitos Blvd
Los Alamitos, CA 90720
Attn: Craig P. Boyd

TENNESSEE VALLEY AUTHORITY
715 Market St.
Chattanooga, TN 37401
Attn: Dexter Stanphill

TEXAS INSTRUMENTS, INC.
P. O. Box 225536, M/S 147
Dallas, TX 75265
Attn: Jules D. Levine

THE GRINDELWALD LETTER
P. O. Box 70
Mammoth Lakes, CA 93546
Attn: Alfred H. Canada

THE PASADENA PROJECT
3858 East Colorado Blvd.
Pasadena, CA 91107
Attn: Andrew O. Jensen
Edward A. Sequeira

UHL & LOPEZ ENGRS.
213 Truman NE
Albuquerque, NM 87108
Attn: Dave Penasa

USAF
P. O. Box 5400
Albuquerque, NM 87115
Attn: John Hanson

UNION CARBIDE CORPORATION
Old Ridgeburn Road
Danbury, CT 06817
Attn: James L. Young

UNION CARBIDE CORPORATION (2)
3333 Index Street
Washougal, WA 98671
Attn: Sridhar K. Iya
Hiroshi Morihara

UNIVERSITY OF CALIFORNIA,
LOS ANGELES (2)
Electrical Engineering Department
7732 Boelter Hall
Los Angeles, CA 90024
Attn: Fred Allen
Patricia D. Sparks

UNIVERSITY OF FLORIDA
Electrical Engineering
Gainesville, FL 32611
Attn: Fredrik A. Lindholm