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TERRESTRIAL CENTRAL STATION ARRAY LIFE-CYCLE ANALYSIS SUPPORT STUDY

FINAL REPORT
AUGUST 1978

Work Performed Under

JET PROPULSION LABORATORY Contract No. 954848

for the
PROJECT ANALYSIS AND INTEGRATION AREA
in the
LOW-COST SOLAR ARRAY PROJECT

BECHTEL NATIONAL, INC.
RESEARCH AND ENGINEERING OPERATION
SAN FRANCISCO, CALIFORNIA

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Prepared By

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The JPL Low-Cost Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

ABSTRACT

A study of five basic array designs and design variations was conducted by Bechtel. The purpose of the study was to provide cost data in support of the Life-Cycle Analysis Task being carried out as a part of the Project Analysis and Integration Area of JPL's Low-Cost Solar Array (LSA) Project. The study evaluated total plant designs for a 200 MW (nominal) photovoltaic central station in order to bring to light plant features that may influence module and panel design and vice versa. The level of engineering detail was limited to that needed to identify major life-cycle cost elements.

The five baseline array designs studied are:

- A rack of fixed, latitude-tilted panels
- A tandem design with reflectors and solar panels sharing the array structure
- An array of horizontal panels
- A rack-type design with a seasonally adjusted tilt angle
- A vertical axis tracking array.

Plant elements evaluated included designs for module, panel and array structures, as well as balance-of-plant systems. Installation and maintenance procedures and the impact of site environment were also evaluated.

In terms of the cost of energy produced, the horizontal array configuration was found to be less expensive than the tandem array at latitudes less than 40°. Both of these configurations are less expensive than the rack design. However, the costs of energy for all three configurations are within approximately ±10 percent of each other. For flat plate panels, the seasonally adjusted and tracking array configurations are not economically attractive when compared to the three other designs. Balance-of-plant costs are approximately equal to (goal) module costs. The array structures and foundations are the most expensive items in the balance-of-plant costs.

ACKNOWLEDGMENTS

This study was conducted as a team effort by members of Bechtel National, Inc., Research and Engineering Operation. Overall management responsibility rested with T.E. Walsh, Manager of the Power Technology Group. W.J. Stolte served as the Project Manager. The study was performed under contract to the Project Analysis and Integration (PA&I) Area of the Jet Propulsion Laboratory's Low-Cost Solar Array Project. Dr. W.T. Callaghan was the Manager of the PA&I Area, and Dr. P. Tsou was the Contract Monitor.

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Section 1

SUMMARY

This report presents the results of a study conducted by the Research and Engineering Operation of Bechtel National, Inc. The purpose of the study was to provide input cost data in support of array life-cycle cost analyses being conducted by JPL for utility central station photovoltaic power plant applications. Primary emphasis was on the solar cell modules and arrays, with balance-of-plant concepts developed only as far as necessary to determine their impact on module and array design and vice versa. The level of engineering was directed to be limited to that needed to identify major cost drivers. Detailed design optimizations were not performed. Assessments were made of five alternate array configurations and the impact of parameters such as: site weather, onsite energy storage, system voltage, energy losses within the plant, maintenance requirements and module design.

The plant design used as the baseline for this study is a 200 MW (nominal) central station photovoltaic power plant using 8 by 16 foot flat-plate silicon solar panels comprised of 4 by 8 foot glass superstrate modules. The five alternate array design configurations evaluated were rack, tandem, horizontal, seasonally adjusted and tracking-type arrays. The rack array design consists of panels tilted at the local latitude and supported by inclined back struts and precast concrete block foundations. The tandem array design is similar to the rack design but with reflector panels fastened to the struts. The tilt angles of the solar cell and reflector panels are set as dictated by the optics and site latitude. With the horizontal array design, the panels are horizontal and secured to precast concrete block foundations. This design has no array structure per se. The seasonally adjusted array design is similar to the rack design but with mechanisms added to change the tilt angle of the panels. The tracking array consists of two 8 by 16 foot panels mounted on a pedestal bolted to a concrete caisson foundation. Fixed-tilt panels track the diurnal sun position by rotation about a vertical axis.

For all of the array configurations, dc power at 1500 volts (nominal) is assumed to be brought from several arrays to one of 36 converter units distributed throughout the baseline plant. The converter outputs are collected at 34 kV ac and brought to the plant switchyard for connection to the utility grid at 230 kV. Other balance-of-plant items include instrumentation, buildings, roads and panel maintenance equipment.

Costs were estimated for plants employing each of the five types of arrays in the baseline plant configuration. Since these plants do not produce the same amounts of peak power and energy, their estimated costs are normalized to dollars per watt, dollars per square meter and dollars per kilowatt-hour. On the basis of energy costs, the horizontal array configuration is the least expensive for northern latitudes below 40°. Above this latitude, the tandem configuration is less expensive. Within their optimum latitude ranges, both of these configurations are less expensive than the rack array. However, energy costs from the above three array configurations are generally within ±5 to ±10 percent of each other, depending on site latitude. The seasonally adjusted array is approximately 25 percent more expensive than the average of the rack, tandem and horizontal arrays, and the tracking array is approximately 37 percent more expensive than this average.

The absolute values of these energy costs indicate that further cost reduction through innovation and design optimization will be needed to make such photovoltaic plants economically viable.

Losses in the converters, wiring and switchyard reduce a plant's peak power by approximately 9 percent and reduce its energy output by approximately 7 percent, except for the tracking array where these losses amount to 11 and 10 percent, respectively.

Some reduction in energy cost would come about from lower panel failure rates. Results to date from field applications indicate that preliminary rates postulated by JPL may be unduly pessimistic.

In evaluating panel sizes, it was found that unit material costs (e.g., $/m²) for a 4 by 8 foot panel are less than for an 8 by 16 foot panel. However, other factors, such as installation labor, result in plants using the smaller panel being 10 to

12 percent more expensive. It was also found that plant costs are significantly affected by the structural loads on the panels and arrays. Increasing the loading from 35 psf to 70 psf increases the plant cost by 11 percent for the rack array configuration. Changing the tilt angle results in minor changes to plant cost.

Installed costs were estimated for three and ten hours of onsite energy storage in an advanced battery. The economics of energy storage for photovoltaic plants was not evaluated. However, a cursory assessment did show a lower cost for charging the storage with off-peak utility energy than for charging with solar energy.

The cost of the module is significantly affected by the selected level of dc system voltage. Relationships between module insulation, converter and dc wiring costs show that the lowest cost dc system is for a voltage in the range of 1500 to 2500 volts. The optimum voltage depends on the cost of the module encapsulation.

Performance of the study described in this report has produced cost data that identifies areas of high first and installation costs in the balance of plant and thereby points out the areas in which further design optimization is needed. Also, the data is to be used as input to future life-cycle cost analyses and thereby contribute to identifying areas with the potential to significantly reduce total life-cycle costs and make photovoltaic central station power plants economically viable.

Section 2

INTRODUCTION

There is a growing awareness of the limited reserves of non-renewable energy resources, such as coal, gas and oil, and an increasing environmental concern over their use. This has led to Department of Energy sponsorship of programs intended to develop renewable energy resources, such as solar power. As a part of this effort, the Jet Propulsion Laboratory (JPL) is conducting the Low-Cost Solar Array (LSA) program. The intent of the program is to identify and develop the technologies required for the commercialization of flat-plate silicon photovoltaic arrays and to stimulate commercialization by large purchases. Emphasis has been centered on solar cell and module fabrication techniques. However, assuming the achievement of published national cost and performance goals for both cells and modules, successful commercialization of the technology will require the optimization of overall system design.

The Research and Engineering Operation of Bechtel National, Incorporated has conducted a study to provide cost data in support of the array life-cycle cost analyses being conducted by the Project Analysis and Integration Area in JPL's LSA Project. The study considered first costs (materials), installation (i.e., labor) and operation and maintenance costs, for three fixed array design concepts, a seasonally adjusted rack concept and a tracking array concept. Sensitivities to significant design parameters, such as structural loading and dc system voltage, were also explored. Balance-of-plant system costs were developed where these systems were significantly impacted by plant design parameters. The emphasis of this study was on large-array systems, such as would be used in utility central station generating facilities.

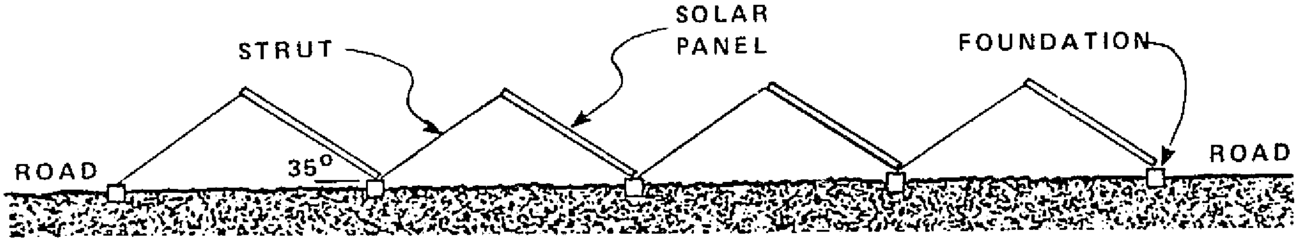
Section 3

PLANT DESIGN FACTORS

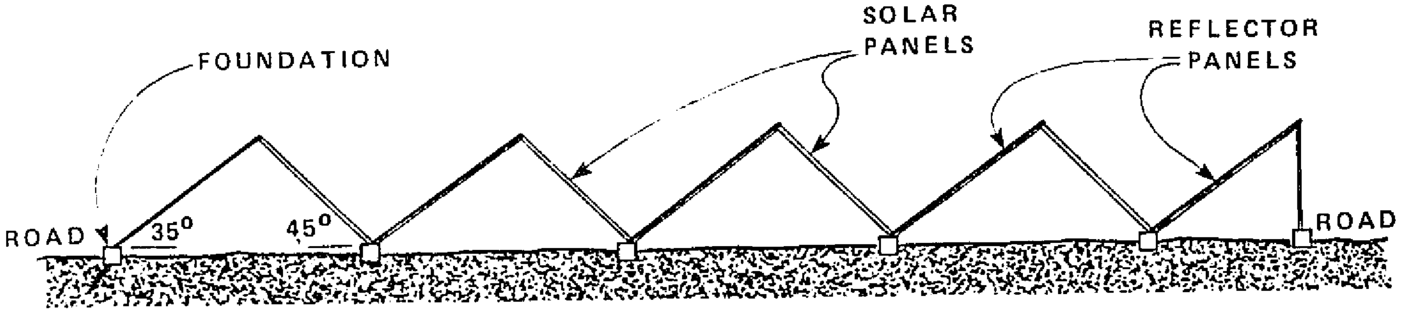
A significant factor in the design and optimization of a central station photovoltaic power plant is in the type of array configuration employed. In order to assess the impact of array configuration on module design and plant life-cycle costs, this study examined plant and system design requirements for five array configurations. The five configurations, which were selected through a collaborative effort between JPL and Bechtel, are shown in Figure 3-1 and are described briefly as follows:

- RACK - Panels are south facing and are supported at a fixed tilt angle equal to the site latitude.
- TANDEM - Panels are south facing, supported at a fixed tilt angle, and are augmented by fixed reflector panels.
- HORIZONTAL - Panels are horizontal, with a small slant angle provided for drainage.
- SEASONALLY ADJUSTED RACK - Same as rack design except tilt angle is adjustable to accommodate seasonal variations in sun angle.
- TRACKING - Fixed tilt panels track the sun on a daily basis about a vertical axis (single-axis tracking).

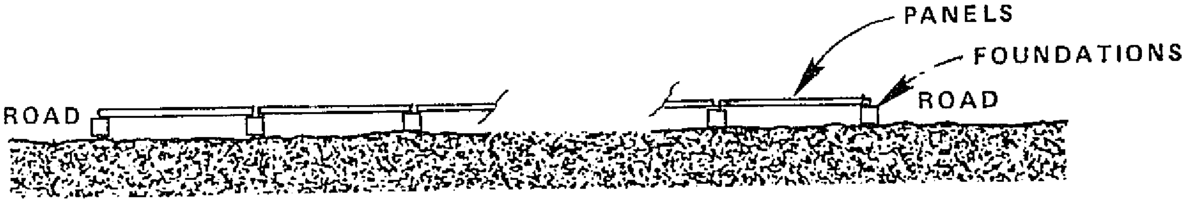
This section discusses the energy collection capabilities and design data for the five baseline collector configurations. Included are descriptions of the impacts of the site environment, civil and electrical design of the central station photovoltaic plant, common design elements of the module and panel, construction aspects, and operation and maintenance. Specific



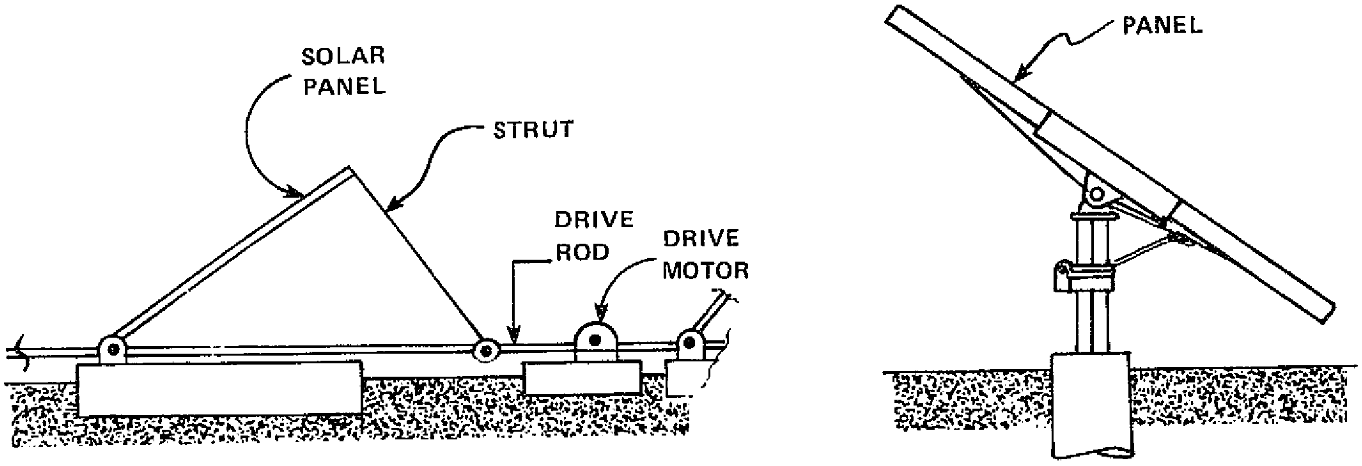
RACK ARRAY



TANDEM ARRAY



HORIZONTAL ARRAY



SEASONALLY ADJUSTED RACK ARRAY

TRACKING ARRAY

Figure 3–1 ARRAY CONFIGURATIONS

design aspects of the five arrays are presented in Section 4, along with the cost basis and detailed costs of each configuration. All costs in this report are presented in terms of 1975 constant dollars. Sensitivities of the array configurations to cost variations are described in Section 5.

3.1 PLANT DESCRIPTION AND TERMINOLOGY

Several previous studies (Refs. 3-1 and 3-2) have broadly outlined the requirements for central station photovoltaic power plants. Basically, the facilities consist of many individual solar cells, electrically interconnected to form modules and panels; these panels are in turn supported on array structures. The panel outputs are collected by a dc wiring system and delivered to a power conditioning unit for inversion to an alternating current. The outputs of several converter units are then collected by an ac wiring system and delivered to the plant switchyard, which is the point of connection to the utility grid. The system design also includes control, instrumentation, and other auxiliary systems, as well as control buildings, shops, warehouses, access roads and all other required facilities.

In order to facilitate their life-cycle cost analyses, the Project Analysis and Integration Area in JPL's Low-Cost Solar Array (LSA) Project has defined seven hierarchical levels of photovoltaic generation, which encompass all elements of a central station photovoltaic power plant. These levels and their associated terminology are illustrated in Figure 3-2.

The cell is the smallest photovoltaic unit manufactured individually and (for silicon) has a nominal 1/2 volt output. Cell design was not considered in this study.

A module consists of a set of cells, electrically connected into an appropriate series/parallel configuration, and physically assembled into a single, handleable unit. Handleability may be achieved by attaching the cells either to a rigid superstrate, such as glass, or to a rigid substrate, such as an insulated metal sheet. The module also includes an encapsulation system which provides suitable environmental protection for the cells during plant operation. Module design is affected by the expected structural loading conditions and dc system voltage.

A panel consists of one or more modules, factory assembled into a single field-installable unit, and contains a single pair of power electrical terminals (plus and minus) and grounding connections. Panel design (e.g., framing requirements) is affected by module size, expected structural loading and array configuration. Block design is in turn affected by panel size.

A block is the smallest individual field-assembled generating unit. It consists of panels, support structures and/or foundations. Block design is affected by array configuration,

HIERACHICAL LEVELS OF PHOTOVOLTAIC GENERATION SYSTEM(1)

CELL - the smallest photovoltaic generation unit manufactured individually.

MODULE - a set of cells physically connected into a single, handleable unit.

PANEL - one or more modules united structurally into a single, field-installable unit.

BLOCK - the smallest field-assembled generating unit, consisting of structures, foundations, and panels.

ARRAY - the smallest field-assembled unit operating at the dc voltage level of the power conditioning unit.

GROUP - a set of arrays, with power conditioning and auxiliary systems, to achieve power output at the ac voltage level of the power conditioning unit.

PLANT - a collection of groups and auxiliary systems to achieve rated power output at the transmission voltage level.

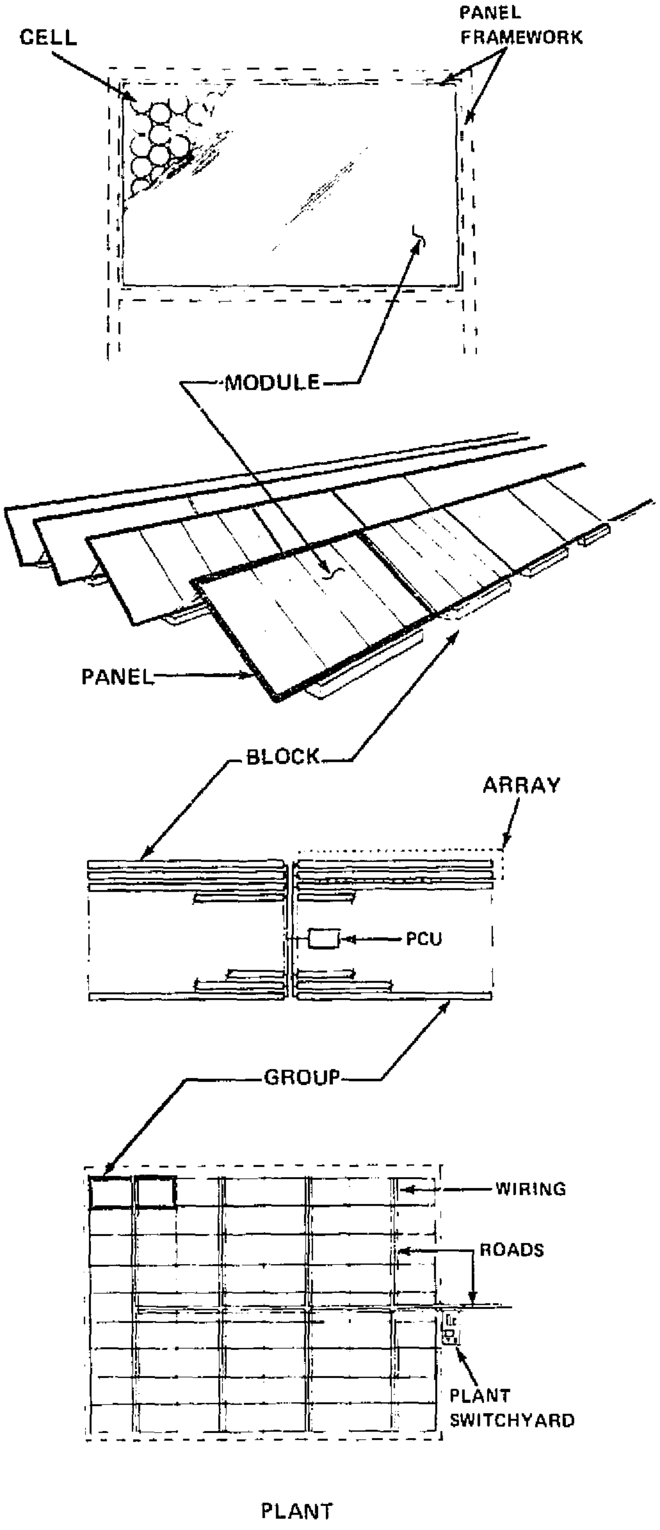


Figure 3-2 DELINEATION OF TERMINOLOGY

(1) As supplied by JPL to facilitate life-cycle cost analyses.

panel size and expected structural loading. Block design affects land and road requirements, as well as both ac and dc wiring systems.

Sets of panels in blocks are electrically connected in series to achieve the dc system operating voltage level. Such sets are called arrays. Each array possesses a single pair of terminals (plus and minus) that operate at the dc system voltage and are connected to the converter bus. Array configuration is affected by orientation and dc system voltage level. Several individual blocks are electrically connected in series (by field installed dc wiring) to form each array.

The term subgroup, although not explicitly defined by JPL, is also useful in describing the system design. A subgroup consists of a number of blocks and/or arrays bordered on both the north and south sides by east-west running maintenance roads.

A group consists of a set of arrays (subgroups) connected in parallel by dc wiring to a power conditioning unit (converter). The output of the converter is three-phase filtered ac power. In addition to the arrays, dc wiring and power conditioning equipment, the group consists of access roads, control and instrumentation systems and other peripheral systems. Group design is primarily affected by array configuration.

Finally, the ac outputs of the groups are collected, via an ac wiring system, and connected to the utility grid at the plant's switchyard. This collection of groups, switchyard, operating and maintenance buildings, roads, fences and all other auxiliary systems comprises the central station photovoltaic power plant.

3.2 SITE ENVIRONMENT

Site environment factors affecting array and plant design are discussed in this section.

3.2.1 Insolation

Insolation topics relevant to this plant design evaluation are briefly described herein.

In each of the designs, one square meter of panel surface will result in a different amount of energy and power. This is illustrated by Figures 3-3 and 3-4. Figure 3-3 shows the yearly average of solar flux at noon incident on a square meter of panel as a function of site latitude. Figure 3-4 shows the theoretical incident energy per square meter of panel for a year of cloudless days. Portions of these curves are from Reference 3-2. Each curve represents the sum of direct normal and diffuse radiation.

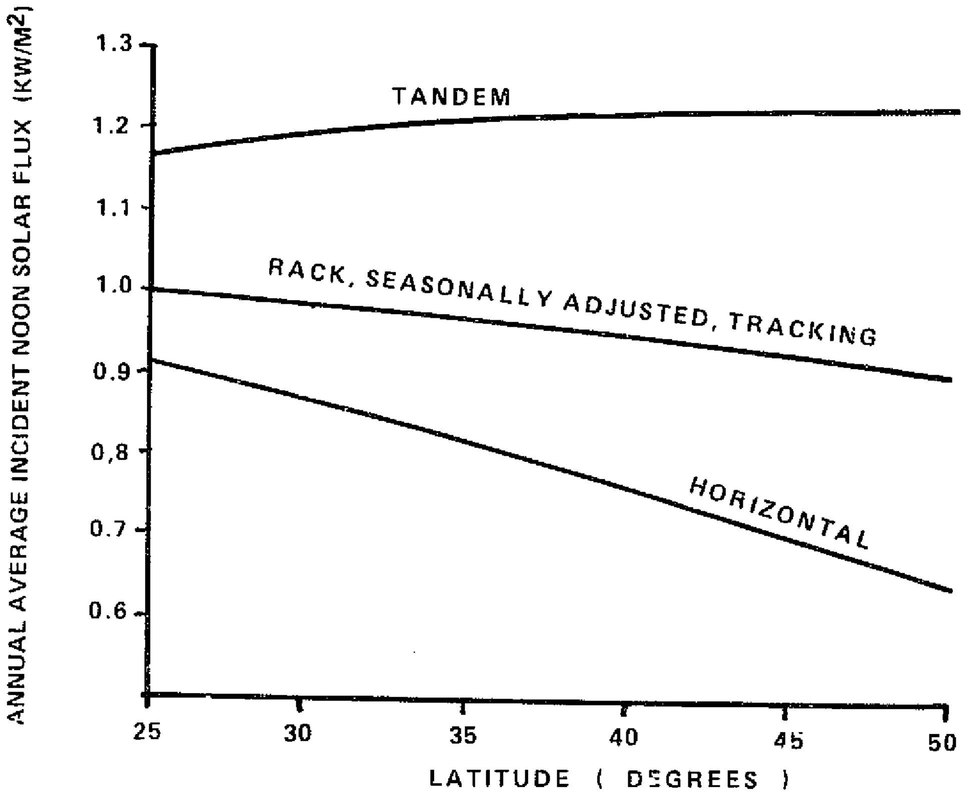


Figure 3–3 AVERAGE INCIDENT NOON SOLAR FLUX VERSUS LATITUDE

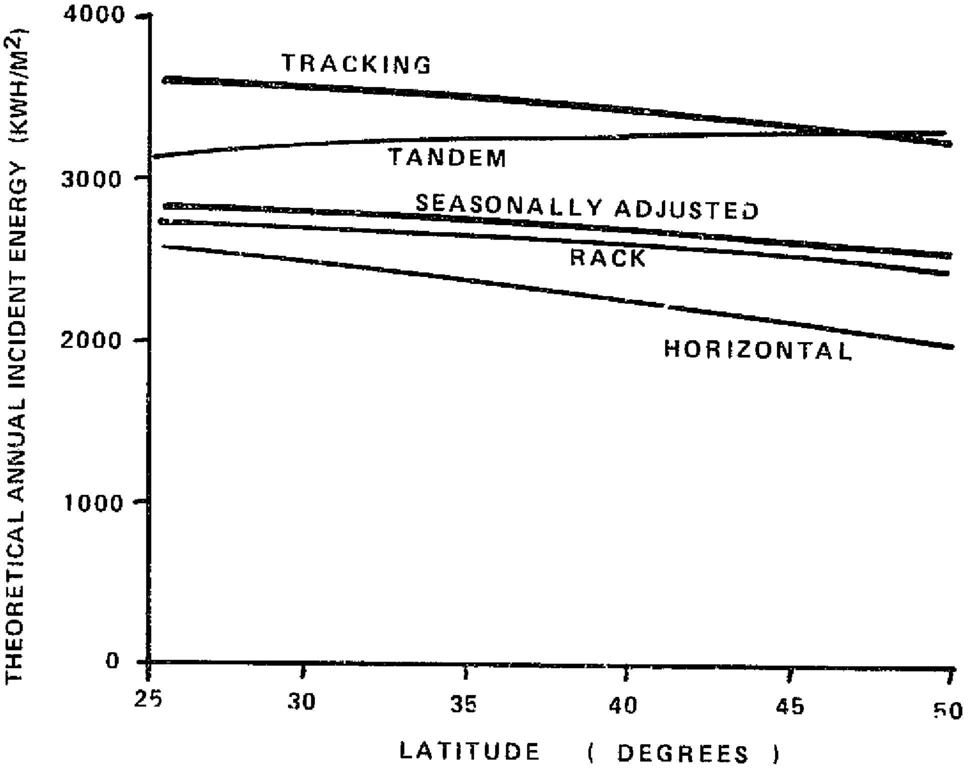


Figure 3–4 ANNUAL INCIDENT ENERGY VERSUS LATITUDE

The actual amount of energy produced is, of course, strongly dependent on the insolation and cloud cover at a site. Thus, the energy produced by identical plants located at the same latitude will vary according to actual insolation at the sites. However, the curves do allow comparison of the five array configurations. It appears that the most logical basis for preliminary comparisons would be plant cost per unit of energy (yearly average), rather than peak power rating. More accurate comparisons will result from the application of life-cycle cost methodology. Detailed evaluations of the value of the energy to a utility must also consider the time of solar energy production in relation to the utility's daily and seasonal load profiles and the characteristics of the other generating equipment or grid interties in the utility's system. These points are discussed further in Section 7.

3.2.2 Wind

Extreme winds are an important factor in specifying loads for array structures. Thus, array structural design and cost are dependent on site wind conditions. The annual extreme fastest mile wind is a standard index used for design and construction. Extreme winds are normally defined in terms of the fastest passage of 1 mile of wind at 30 feet above ground.

Figure 3-5 (Ref. 3-3) shows the annual extreme fastest mile wind associated with a 100-year recurrence interval for the contiguous

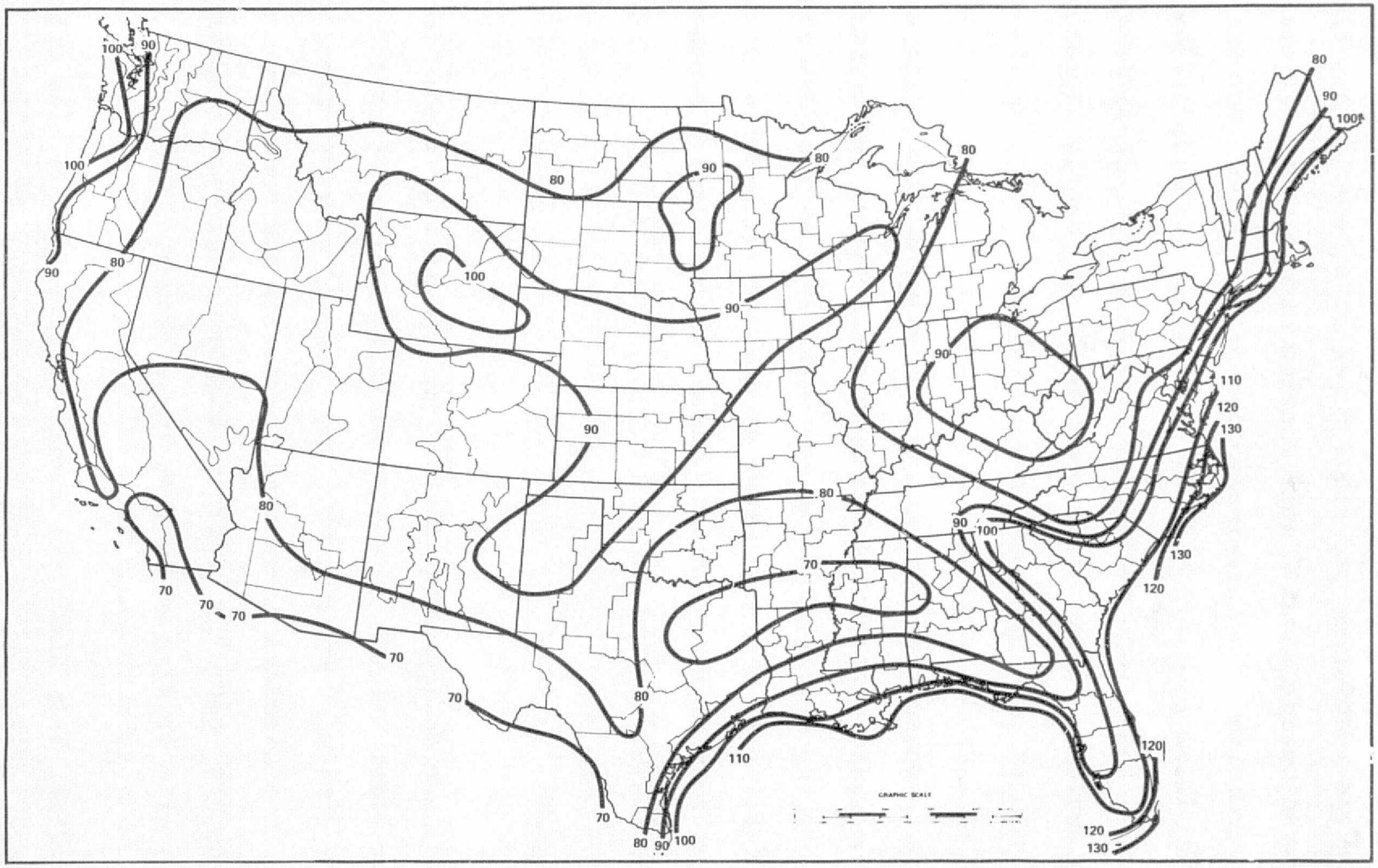


Figure 3–5 FASTEST MILE WIND SPEEDS

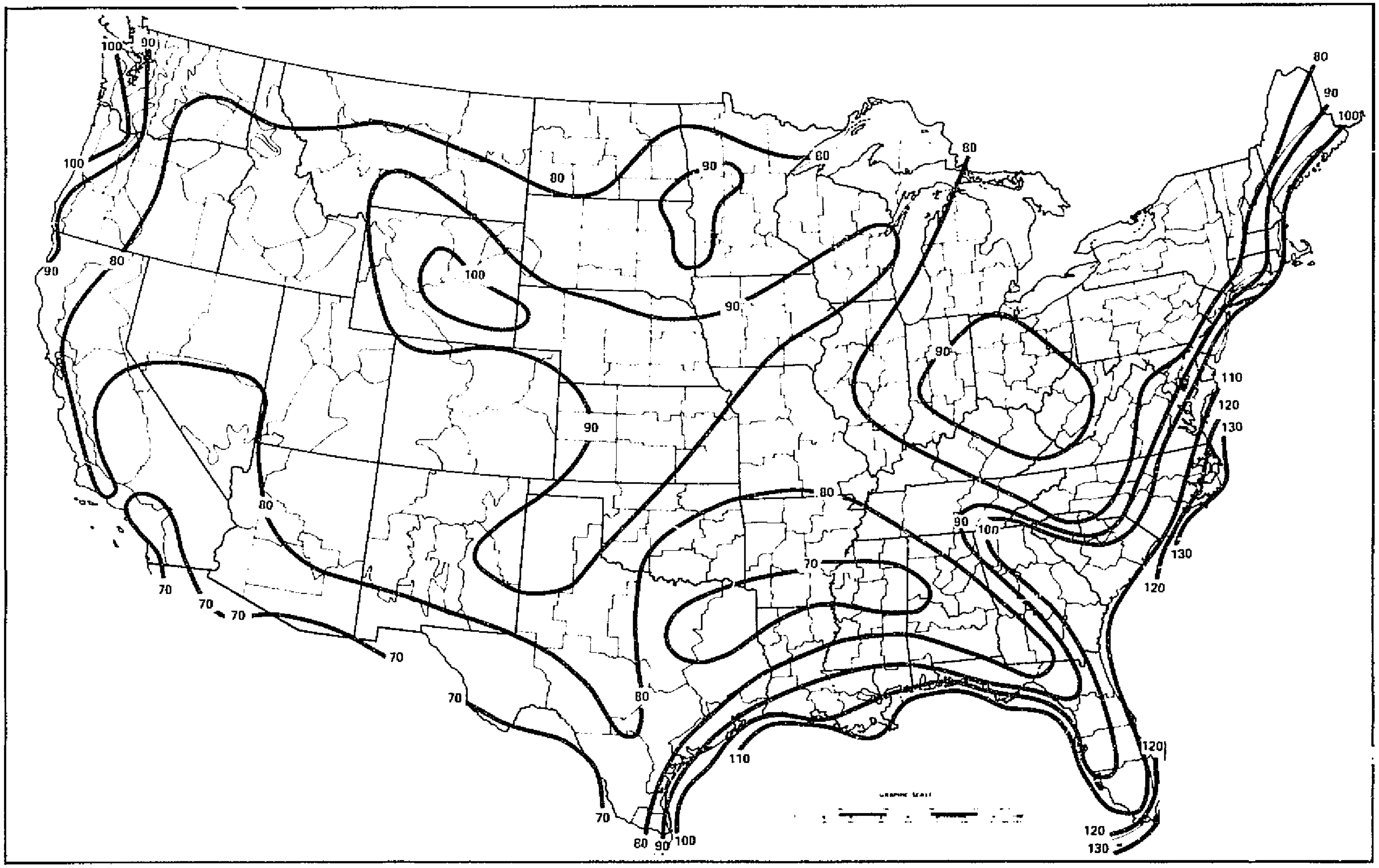


Figure 3–5 FASTEST MILE WIND SPEEDS

United States. Winds in conjunction with tornadoes are excluded from this analysis. Tornadoes are discussed separately in Section 3.2.3. The range of extreme wind speeds varies from about 70 mph in the Southwest and Gulf Interior to about 130 mph along the Atlantic and Gulf Coasts.

It should be noted here that these are regional estimates. Local effects, such as channeling, can necessitate an increase in the extreme wind speed estimates appearing in Figure 3-4.

To calculate the wind load, a basic wind speed is selected from Figure 3-5. This wind speed may then require adjustment if any special local effects exist, including aerodynamically induced vibrations or flutter, vortex shedding and similar phenomena. Next, the basic adjusted or unadjusted wind speed (V) is converted to basic wind pressure (q) according to the following formula:

$$q = 0.00256V^2$$

where

q = basic wind pressure in pounds per square foot, psf

V = basic wind speed in miles per hour, mph

The basic wind pressure (q) should then be converted to effective velocity pressure (Q) to compensate for exposure, height above ground and dynamic response to wind gusts. Q is computed in the following manner:

$$Q = KGq$$

where

Q = effective velocity pressure, psf
K = velocity pressure coefficient
G = gust factor
q = basic wind pressure, psf

The velocity pressure coefficient (K) depends upon the type of exposure and the height above ground. The gust factor (G) is a function of the type of exposure and the dynamic response characteristics of the structure. Table 3-1 (Ref. 3-3) shows the effective velocity pressures for ordinary buildings and structures with exposure to flat, open country. Unusual structures and/or rough terrain require a more complicated analysis.

TABLE 3-1

EFFECTIVE VELOCITY PRESSURES FOR ORDINARY BUILDINGS AND STRUCTURES (psf)*

Height (ft)	Basic Wind Speed (mph)								
	50	60	70	80	90	100	110	120	130
Less than 30	6	7	11	15	20	26	32	39	45
30	8	12	16	21	27	33	40	48	56
50	9	14	18	24	31	38	46	54	64
100	11	16	21	28	35	44	53	63	74
500	16	22	30	40	50	62	75	90	105

*Exposure type is flat, open country

Detailed structural design efforts would account for the probability of several contributing loads (e.g., wind, snow, etc.) acting simultaneously to arrive at the design load for any given site. This is discussed in Section 3.2.10. For purposes of this study, the baseline design load is taken as 50 psf. If this design load were entirely due to wind forces, the first and installation costs for a plant based on the rack array, in $/watt (see Figure 5-2), would vary as 0.89 + 0.003Q, where Q is the effective wind load derived from Table 3-1 and the map in Figure 3-5. Costs for plants based on the other array configurations are expected to vary with loading in a similar manner. However, the horizontal array will likely be less susceptible to wind forces. More precise cost evaluations would take into account the results of wind tunnel tests that are beyond the scope of this present effort.

In addition to governing structural design, average daytime prevailing winds affect module heat transfer. This, in turn, affects cell conversion efficiency so that higher average prevailing winds lead to higher plant output. The effects of temperature on energy output are discussed further in Section 3.2.8.

3.2.3 Tornadoes

Various dangers posed by tornadoes include wind-blown missiles, extreme pressure differentials and extreme wind forces. At present, it does not appear economically possible to design photovoltaic array structures to withstand tornadoes. However, a facility can be located at a site which has a low frequency of occurrence of tornadoes.

No state is completely free from tornadoes; however the frequency of tornadoes varies greatly between different regions of the United States. Figure 3-6 (Ref. 3-6) shows the number of tornadoes reported within the United States by 1° squares for the years 1955-1967. The most notable feature presented here is that nearly the entire western third of the nation was relatively free from tornadoes, while the states of Texas, Oklahoma and Kansas experienced the bulk of the incidents.

Although there have been a number of studies regarding tornado climatology (Ref. 3-4), few have addressed the problem of tornado frequency. Thom (Ref. 3-5) investigated tornado path length and width to determine the probability of a tornado striking a point. This study resulted in the following equation:

$$P = 2.8209\ T/A$$

where

P = the probability of a tornado striking a point in any year in a 1° square

T = average number of tornadoes per year per 1° square (the number appearing in Figure 3-5 divided by 13)

A = area of 1° square

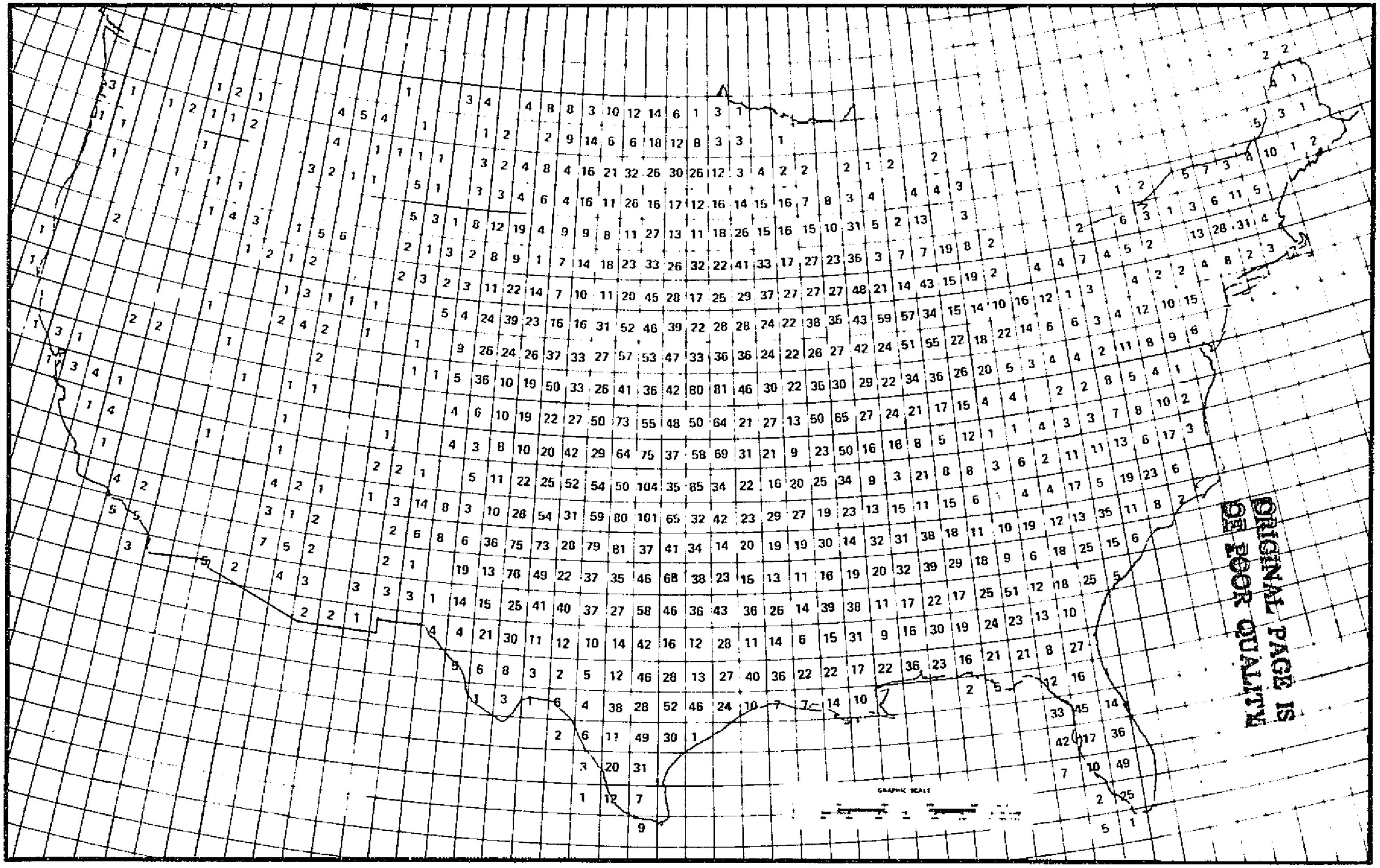


Figure 3–6 NUMBER OF REPORTED TORNADOES BY 1° SQUARES (1955–1967)

The mean recurrence interval (R) is equal to 1/P. For convenience, areas of representative 1° squares are provided in Table 3-2.

TABLE 3-2

AREAS OF 1° SQUARES VERSUS LATITUDE

Latitude (middle of 1° square)	25°30'	30°30'	35°30'	40°30'	45°30'	50°30'
Area (Square Miles)	4300	4109	3887	3634	3354	2983

In order to arrive at the above formula, assumptions have been made regarding the path width and length of a tornado. Also, the number of reported tornadoes is often related to the population density. Therefore, the probability calculated by the above equation includes a degree of uncertainty.

As previously stated, designing a photovoltaic power plant to be tornado proof is not economically feasible and a plant hit by a tornado would be at least partially destroyed. The destruction may be limited to a portion of the plant since the width of a tornado swath is typically less than the dimensions calculated for the 200 MW plants in this study. Further, a part of the loss may be covered by insurance. Insurance against hail damage is discussed in Section 3.8. A similar expense for insurance premiums is expected for tornadoes. The annual premiums are estimated to be on the order of twice the expected loss divided by the mean recurrence interval (in years). Using the data in

Figure 3-6 and the above equation shows that such annual premiums may vary between 0 and $0.004/watt for the plant costs given in Section 4.

3.2.4 Snow

The weight of anticipated accumulations of snow must be taken into account when designing array structures. There are several factors that can significantly modify reported average snow depths and densities that constitute the snow loads. These secondary factors include items such as exposure, icing, structure size, shape and height. Variations in snow loads due to the depth and density are considered first.

Figure 3-7 shows the basic design ground-level snow loads with a 100-year mean recurrence interval for the contiguous United States (Ref. 3-3). The 100-year mean recurrence interval is used when a high factor of safety is desired. Data for areas, such as the Great Lakes and New England, indicate that substantial loads due to snow should be expected. Snow loads in these regions may be as much as 90 pounds per square foot. Snow loads for many western states are not available on a regional basis, as snowfall in this area is strongly influenced by local topography and may vary considerably over short distances. Therefore, a local analysis is necessary to determine the snow load. Buildup of snow drifts due to fence-like action of array structures or the

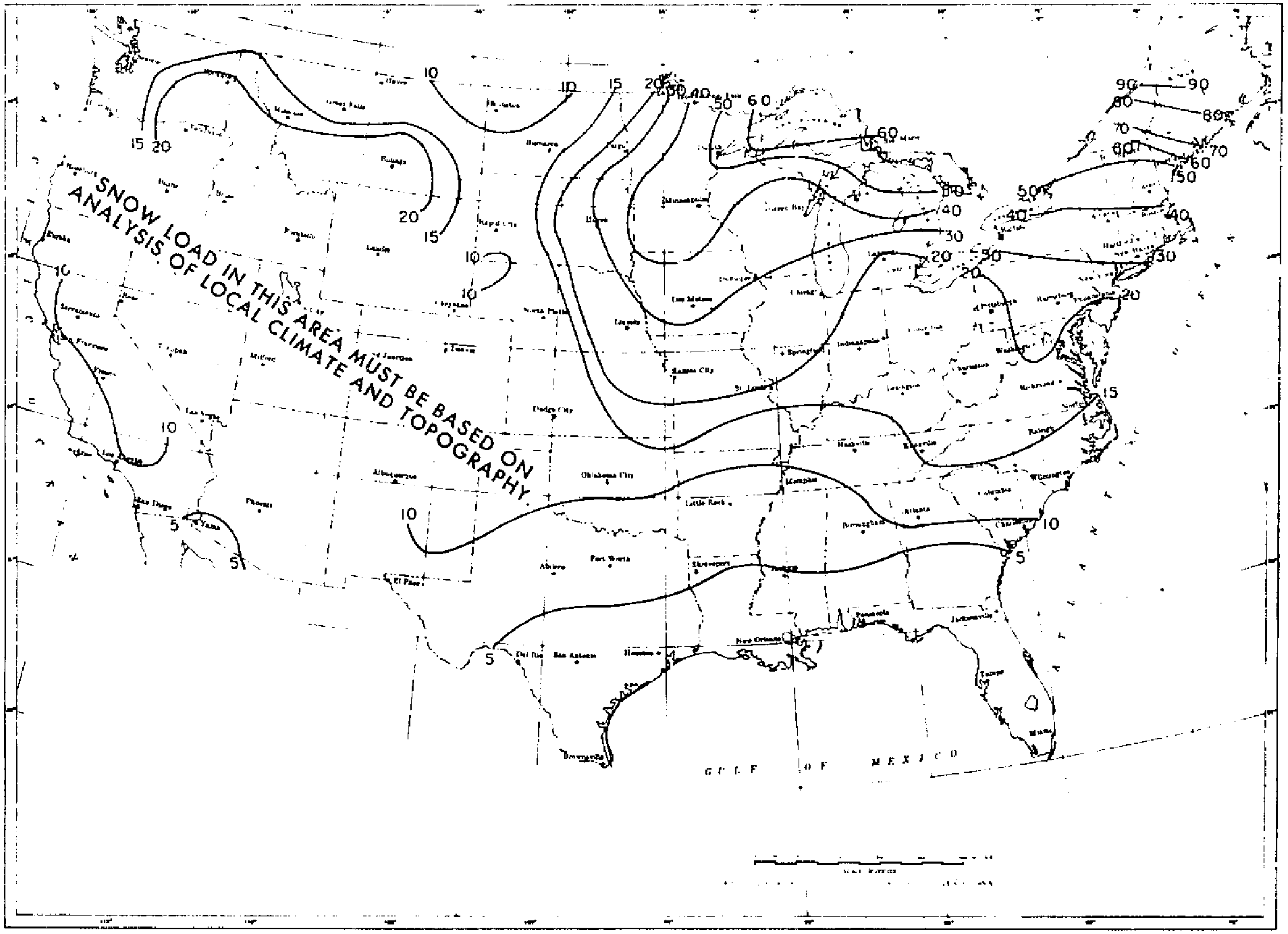


Figure 3–7 SNOW LOADING MAP (PSF)

creation of wind eddies could result in snow loads much higher than those indicated by the 100-year recurrence data.

The ground-level snow loads presented in Figure 3-7 may require adjustment. The basic snow load for elevated surfaces is considered to be 80 percent of the ground-level snow load and may be further decreased or increased depending on the occurrence of the following conditions:

- Decreased load due to slide-off of snow on surfaces with slopes exceeding 30°
- Decreased load due to surfaces having a clean exposure in wind-swept areas
- Increased load in valleys formed by multi-level surfaces (e.g., tandem array)
- Increased load due to snow sliding off sloping surfaces onto adjacent surface areas (e.g., tandem array)
- Increased load for surfaces adjacent to projections due to drifting snow
- Increased load due to icing
- Water content and specific gravity of the snow

A basic snow load of 60 percent may be assumed for elevated surfaces with a sufficiently clear exposure to wind. Surfaces shielded on any side by obstructions within a distance of 10h from the structure, where h is the height of the obstruction above the level of the surface in question, are not considered to have a clear exposure. This criterion is not met by the array groups in the plant.

As mentioned, the baseline design load was not resolved into components such as snow, wind, etc. It is anticipated that plant costs will vary with snow loading in a manner similar to that discussed for wind loading in Section 3.2.2. However, the cost variation for snow will be less than that for wind load because the snow related forces only act in a downward direction and, within the limits of the present study, will not act to increase foundation size.

3.2.5 Hail

Tests conducted by JPL have indicated that photovoltaic modules can be damaged by large hailstones. Thus, the frequency of occurrence and land area covered by hailstorms and the hailstone size distribution should be considered in module design and plant site selection. The occurrence of hail is generally associated with thunderstorms, instability showers, or frontal activity. Spring frontal activity accounts for the majority of hailstorms in the United States. Figure 3-8 shows the reported occurrences of hail 0.75 inch and larger for the years 1955-1967 (Ref. 3-6). A review of this figure will show the mid-section of the country experiences far more hailstorms than either the East or the West.

The size and density of a hailstone, along with other factors, will determine the amount of damage caused. Hailstone diameters vary from about 0.25 inch to as much as 5 inches.

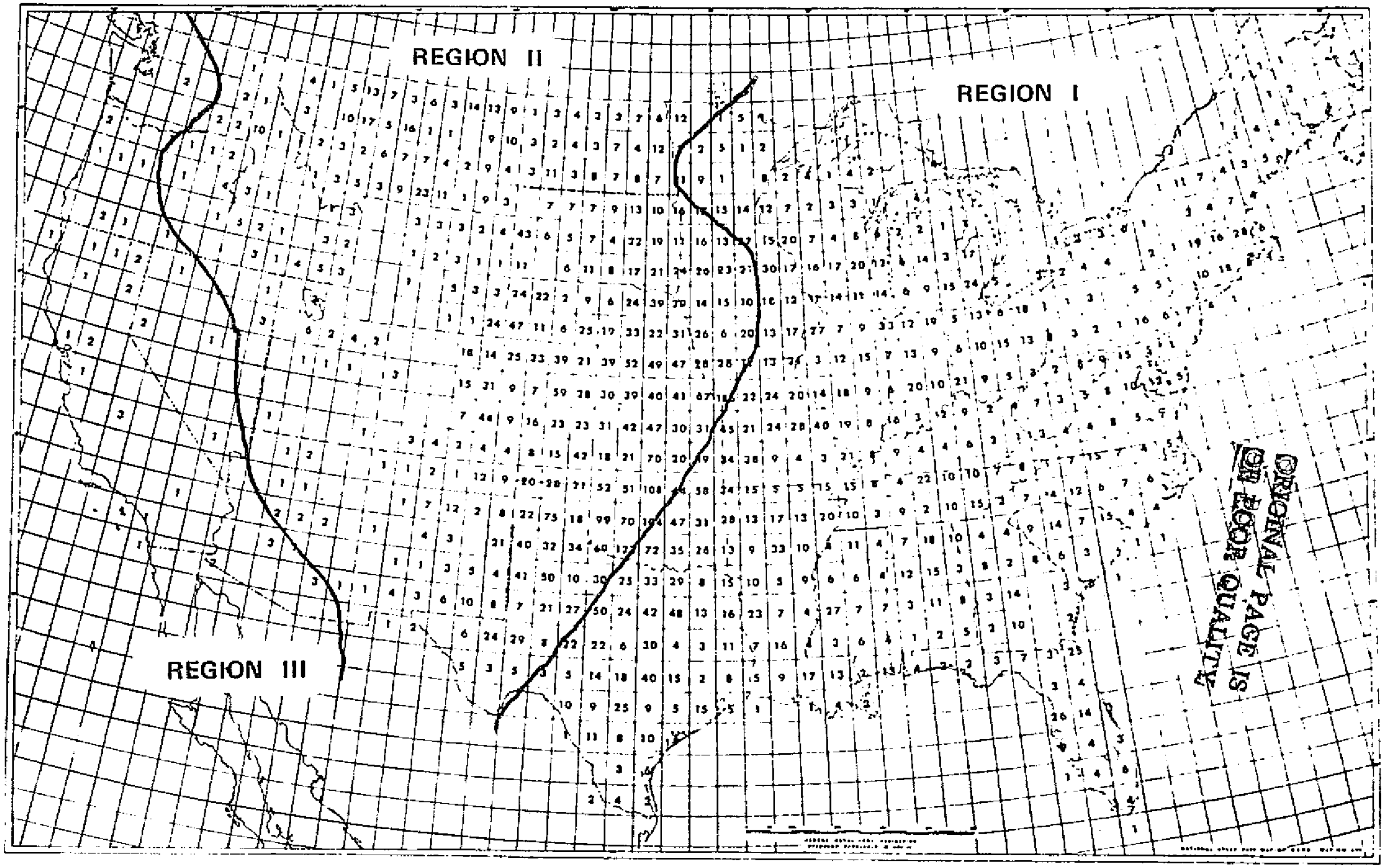


Figure 3-8 REPORTED OCCURRENCES OF HAIL ¾ INCH AND LARGER (1955–1967)

A recent study conducted at the Jet Propulsion Laboratory (Ref. 3-7) has estimated the probability of hailstone size in a hailstorm for three hail regions within the contiguous United States. These regions have been added to Figure 3-8. The results of JPL's work show that region II can expect the largest hailstones given that a hailstorm is occurring. Also, there are very few reports of hailstones greater than 1.0 inch in Region III. The probability of hailstones of one inch diameter or greater is 0.05 in Region III, 0.26 to 0.03 in Region I and 0.40 to 0.15 in Region II.

The thickness of glass or plastic protecting a silicon solar array will determine its immunity to damage from large hailstones. Little data on this subject are currently available.

There are two major cost effects that result from consideration of potential damage by hail. First, the module front cover material may be made thicker to better resist hail damage. This will result in increased material cost and a reduction in plant output due to absorption of light in the thicker cover material. Quantifying this effect requires details of the hail resistance of modules as a function of cover material which are not currently available. The second effect is the cost of insuring against damage by hail. Estimates of this cost are presented in Section 3.8.

3.2.6 Dust

Dust accumulation on the arrays will reduce plant output and necessitate washing operations. The amount of dust suspended in the air and deposited on an array surface is closely related to precipitation, evaporation and wind speed. The amount of dust adhering to the array depends on the array surface, moisture and electrostatic forces. Dry, windy areas, which show the potential for producing excessive dust due to wind erosion, may also represent regions where an array could be adversely affected. In addition to these natural dust producing mechanisms, dust produced as a result of man's activities is perhaps a major factor. However, the lack of moisture and the abundance of wind are the primary ingredients for a dusty environment. Those areas with natural characteristics favorable for wind erosion also indicate places where man's influence on dust emission may be unfavorable both now and in the future.

Figure 3-9 shows the precipitation-evaporation (PE) index developed by Thornthwaite (Ref. 3-8) for state climatic regions. The PE index is defined as the yearly sum of the monthly precipitation/evaporation ratios. Therefore, high numbers indicate moist climates and low values indicate dry climates. Inspection of Figure 3-9 will show that low PE values exist for many regions throughout the West.

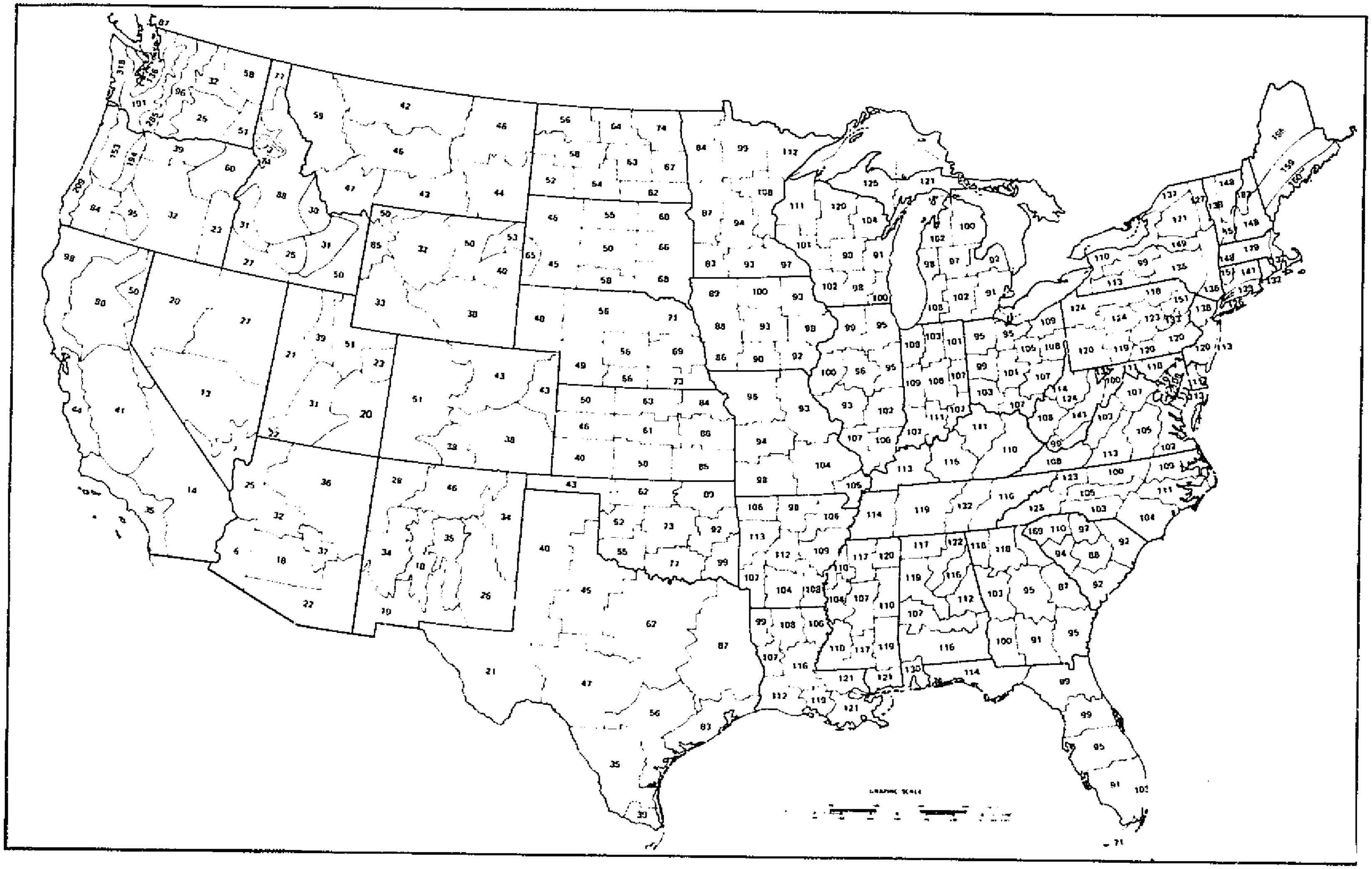


Figure 3-9 PRECIPITATION–EVAPORATION INDEX

Once the PE index for a region has been established, the empirical wind erosion climatic factor (C) can be calculated using the mean wind speed as follows (Ref. 3-9):

$$C = 34.5\,[V^3/(PE)]^2$$

where

V = mean annual wind speed corrected to a standard height of 10 m (30 ft), mph

PE = yearly sum of monthly precipitation/evaporation ratios

This is a standard approach used by the U.S. Department of Agriculture to estimate wind erosion.

C values have been calculated in Figure 3-10 (Ref. 3-24) for the entire contiguous United States with the exception of California, Nevada, Utah and Arizona. The climatic factor could not be computed for these states because wind speed data are generally not available in a reduced form and because of the complicated terrain. However, C values for this area are probably relatively high due to low PE indices. In any case, the eastern half of the nation would appear to experience little wind erosion. Therefore, the dust emission due to erosion should be minimal in the East and relatively significant in the West.

For a more specific region, the type and the extent of man's activities should be considered to determine a qualitative estimate of man-made dust emissions. These man-made or man-related dust emissions will of course have a greater impact in

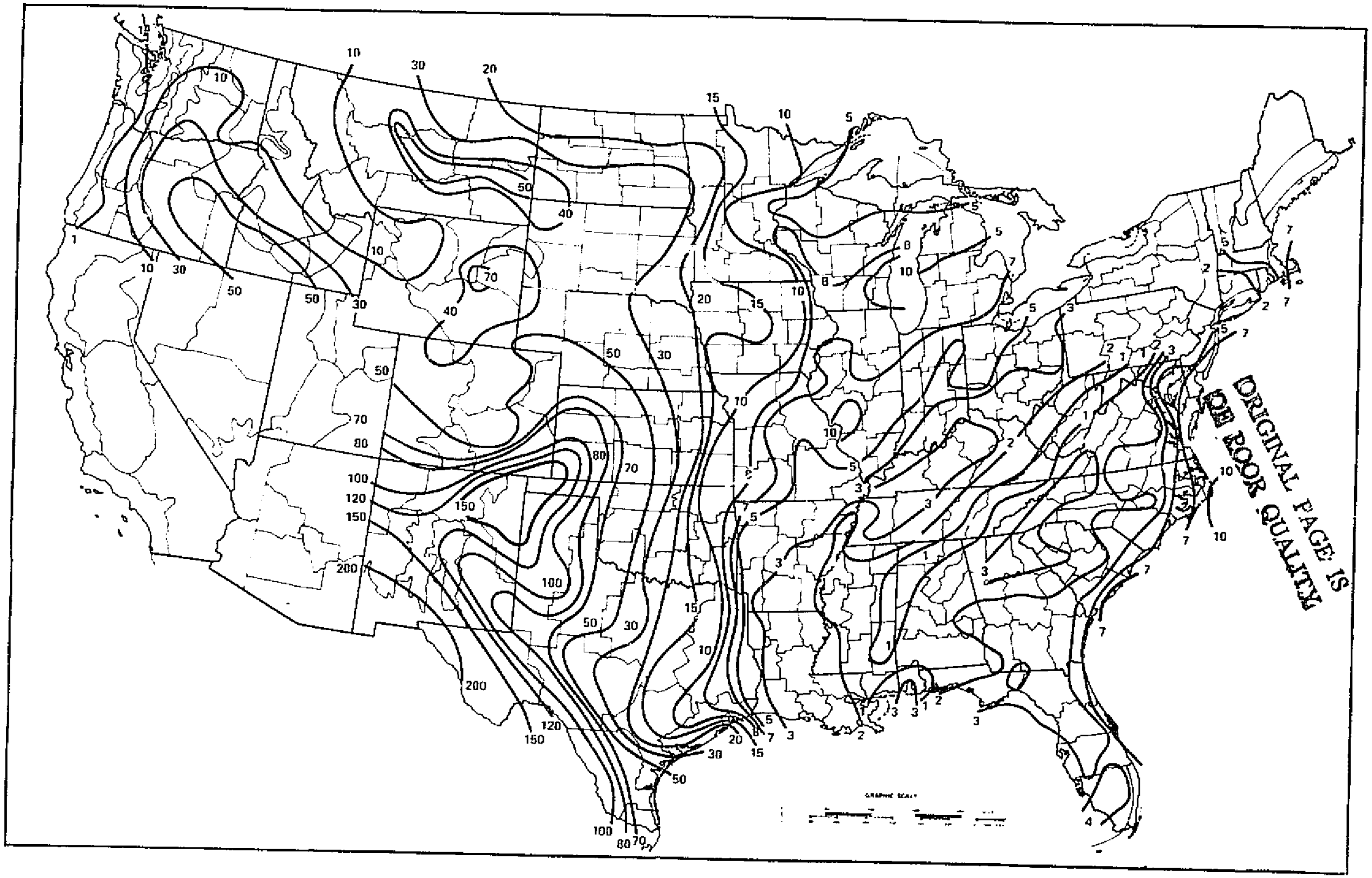


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Figure 3–10 WIND EROSION CLIMATIC FACTOR those areas already identified as zones of significant wind erosion. It should also be of interest in this regard to consider prevailing wind directions and the juxtaposition of dust sources and a solar collection site.

The deposition and retention of dust on solar panels exposed in a rural environment was evaluated for two array configurations. In the first case, the panel is nearly horizontal and for the second case, the panel is tilted at an angle between 25° to 45° from the horizontal.

Considering the dust collection, retention, and residual dust burden for the two cases, the following comments are made:

- The composition of the dust (chemical constituents, particle size frequency distribution, quantity present in the air) varies both by location and month of the year. It also varies on the time scale of hours or days depending on source activity (forest fire, fly ash, plowing and discing, etc.) or on weather (drought, tornado, rain, snow, strong or calm winds).
- The deposition rate of small particles is generally greater than can be accounted for by gravitational fall velocity. Other effects include surface impaction, electrostatic attraction, adsorption and chemical interaction. Furthermore, small dust particles will cling strongly to smooth surfaces due to electrostatic attraction.
- The particle sizes in dust typically range from less than 0.01 micron to 100 micron diameter. There is no standard particle size frequency distribution. This depends on many factors, including nature of source, distance from source, weather and atmospheric dispersion conditions, type of terrain, etc.
- Thanukos, et. al. (Ref. 3-10) finds that wind gusts removed 14 percent of the dust from a high-volume sampler filter left to stand for a period of time before

collection of samples. The particles removed were believed to be greater than 100 micron diameter.

- A panel tilted at 25° will have a horizontal projected exposure of 0.9 that of a horizontal panel. A 45° tilted panel will have 0.7 the exposure of a horizontal panel.

Taking these factors into account, it is believed that the following scenario will qualitatively describe the comparative dirt accumulation on horizontal or tilted panels. Upon initial exposure and continuing for a time scale of a few days to a few weeks, the horizontal panel will have more dust deposited on it than the tilted panel, i.e., the mass/area will be greater for the horizontal panel. Upon further exposure, without precipitation, the effect of wind gusts will remove the larger particles from both the tilted and horizontal panels. To a small and probably insignificant extent more large particles will be removed from the tilted panel, but this would be insignificant because the accretion of smaller dust particles will remain on both panels due to electrostatic forces. Thus, both the horizontal and the tilted panels are expected generally to carry about the same burden of dry dust.

The dust will be disturbed and/or mostly removed by rainfall. The residual dust burden will vary by the amount and intensity of the rain and whether the panel is horizontal or tilted.

The horizontal panel (actually inclined at an angle of 2° for drainage) will exhibit a muddy surface with rivulets if runoff develops when exposed to dew, misting or light drizzle. As the rain increases in intensity or duration, finally most of the dust will be washed away. A very thin film of dirt will remain on the panel when it dries.

In light rain, the tilted panel is expected to clear itself from dust much faster than the horizontal panel. The greater the tilt, the faster it will clear itself, or conversely, a smaller amount of rain is required for dust clearance.

There will be little advantage for adopting tilted panel configuration over horizontal panel as far as dust burden is concerned. The major exception to this conclusion occurs when either configuration is exposed to dew, mist or light drizzle, in which case the tilted panel has an obvious advantage. It is a simple matter to expose a series of test panels at candidate sites in order to obtain quantitative data which would be used in selecting the final site for a solar power plant.

The major cost impact of dust in the area of a photovoltaic plant site will be on the cost of cleaning the modules. However, this cleaning cost is also dependent on other factors such as the amount and types of air pollution present, and the amount, frequency and duration of rain. Cleaning frequency also depends on the price of the energy sold. The question of module cleaning was discussed in detail in a previous Bechtel report (Ref. 3-1). It was found that for the most part cleaning costs would be paid for by the increase in plant output. Cleaning is discussed further in Section 3.7.3.

3.2.7 Precipitation

Precipitation affects the cost, design, and operation of solar plants in several ways. Most significantly, it requires design of a plant storm drainage system and array cleaning operations. Rainfall is generally coincident with winds, but rain by itself does not produce significant structural loadings on the arrays. One exception is that the horizontal arrays (see Section 4.4) must be inclined slightly to prevent accumulations of rainwater which could lead to structural failure of the module (i.e., ponding).

The maximum expected rate of precipitation is an important parameter to be considered in designing drainage systems (see Section 3.3.2), particularly where large areas are covered by non-absorbing material such as solar panels. Of greatest interest in drainage system design is an estimate of maximum rainfalls of short duration. Figure 3-11 (Ref. 3-11) shows the 25-year, 1 hour rainfall for the United States. Such data are used in determining peak runoff and the potential for flooding.

The maximum rainfall is located on the Gulf Coast and tip of Florida. Much lower amounts are indicated throughout most of the West.

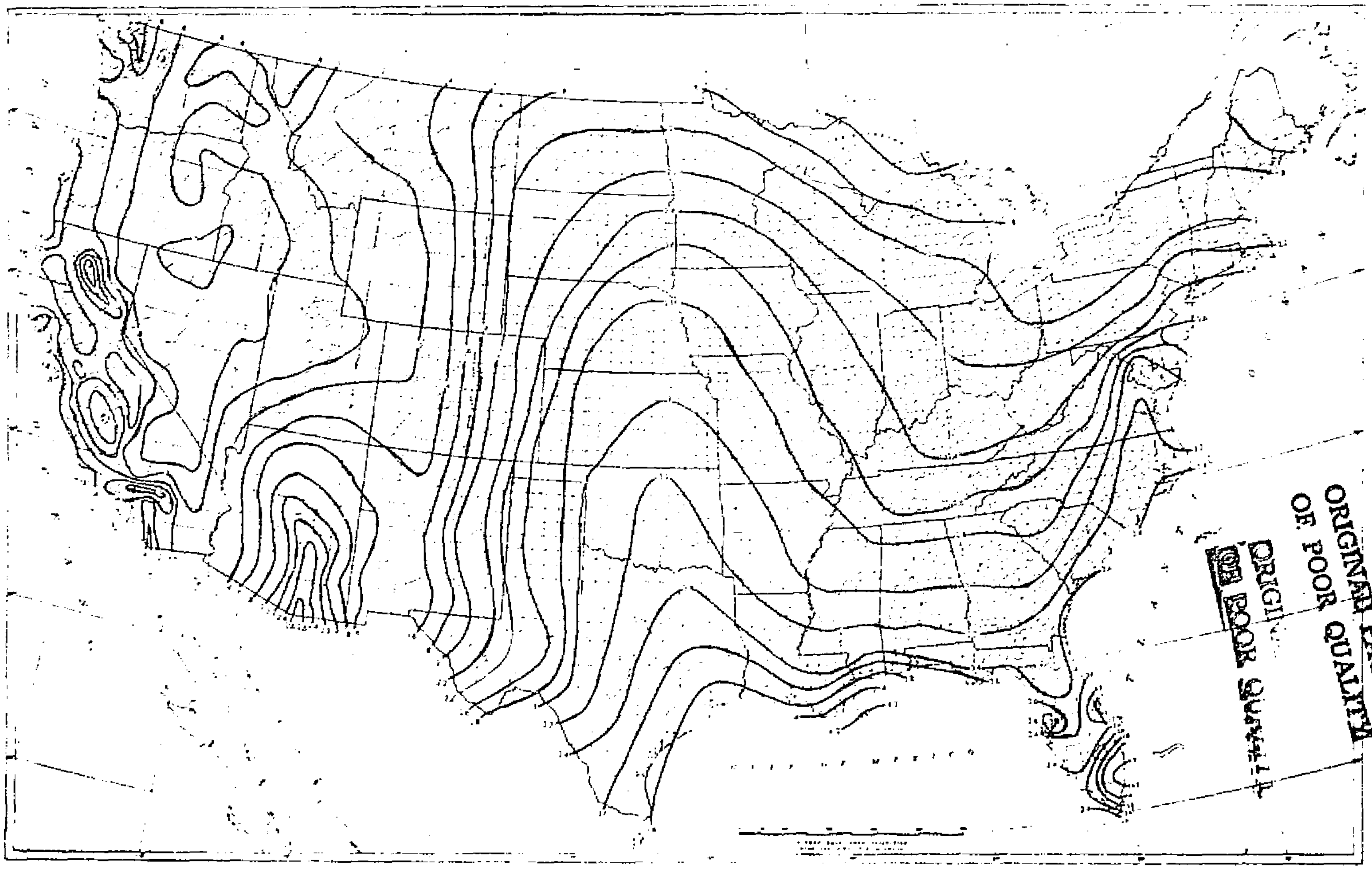


Figure 3–11 25-YEAR 1-HOUR RAINFALL (INCHES)

The reliability of these rainfall estimates is influenced by sampling time, sampling space and the manner in which these maps were constructed. In general, the error may range from a minimum of 10 percent for rainfalls of long duration (24 hours) to as much as 50 percent for rainfalls of short duration (30 minutes) and long return periods (100 years). These errors are especially prominent in regions of rugged terrain.

Maps similar to Figure 3-10 are available for 1/2, 1, 2, 3, 6, 12 and 24 hour periods for 1, 2, 5, 10, 25, 50 and 100 year return periods. Maps showing the annual number of rainy days and monthly and annual precipitation are also available (Ref. 3-11).

Rainfall rates as a function of time of year would be more useful in attempting to determine the optimum frequency and costs of array cleaning. Little detailed information is available on the rate of power loss from arrays due to dirt accumulation and the effectiveness of rain in removing accumulated dirt from various types of module surfaces. The problem of array cleaning was addressed in a previous study by Bechtel (Ref. 3-1). By considering costs for cleaning, sales price for energy and postulated rates of dirt accumulation, an optimum cleaning frequency can be found. Future detailed studies of cleaning might incorporate rain frequency and its effects. Doing this will require further study on the effect of rain on solar panels. For instance rain can deposit dirt or act to cleanse accumulated dirt, depending on the panel's state of cleanliness. Panel surface (e.g., glass, RTV etc.) will also affect the results. Panel cleaning operations are discussed further in Section 3.7.3.

3.2.8 Temperature

For a given insolation level, silicon solar cell conversion efficiency is inversely proportional to cell operating temperature. Data supplied by JPL indicate that module maximum power output decreases by 0.005 watt/watt (0.5 percent) per °C increase in cell operating temperature. Therefore, plant energy output is not only determined by the site latitude and obscurity factors (e.g., cloud cover), but also by ambient temperature conditions. If plants at two different sites receive identical amounts of insolation, but experience different ambient temperature profiles, the plant with a lower ambient temperature will generate more energy.

In order to assess the relative effect of ambient temperature on array efficiency, energy generation was calculated as a function of average yearly ambient air temperature for three site latitudes. Insolation data for the rack array (Ref. Figure 3-4) was combined with average temperature data (Ref. 3-12) under the simplifying assumption that air temperature varies sinusoidally about the average, with the peak displaced three hours past noon. It was further assumed that the difference between cell and air temperature (°C) is equal to 0.3 times the insolation (mW/cm^2). Figure 3-12 shows theoretical annual energy production as a function of annual average ambient air temperature, with site latitude as a parameter. The relative annual energy production in Figure 3-12 is normalized to show energy production relative to a hypothetical site located at 25° latitude with a yearly average ambient air temperature of 0°C. As indicated, potential energy generation is reduced for increasing site latitude and for increasing average ambient air temperature (decrease in array conversion efficiency).

Several specific site locations are indicated on Figure 3-12 for purposes of comparison. It is interesting to note that although Miami, Florida, has a higher theoretical insolation (by virtue of its lower latitude) than does Bismarck, North Dakota, it is

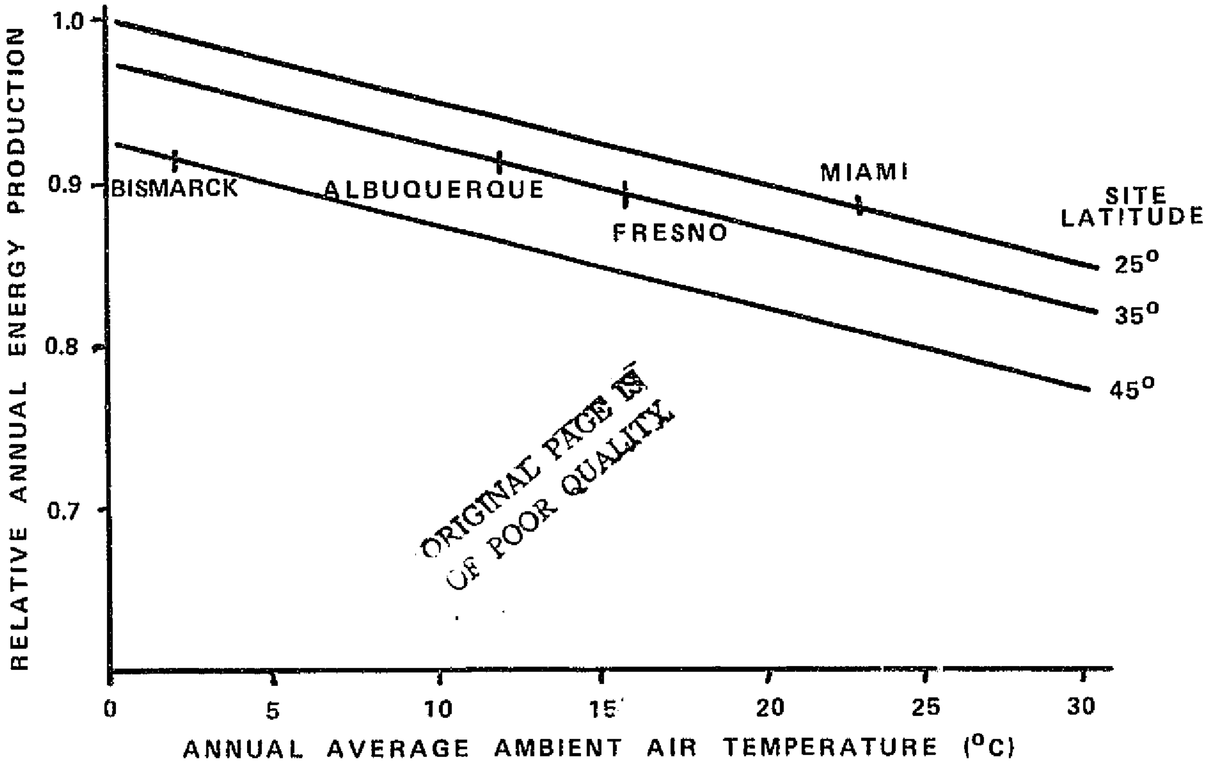


Figure 3–12 RELATIVE ENERGY PRODUCTION VERSUS TEMPERATURE

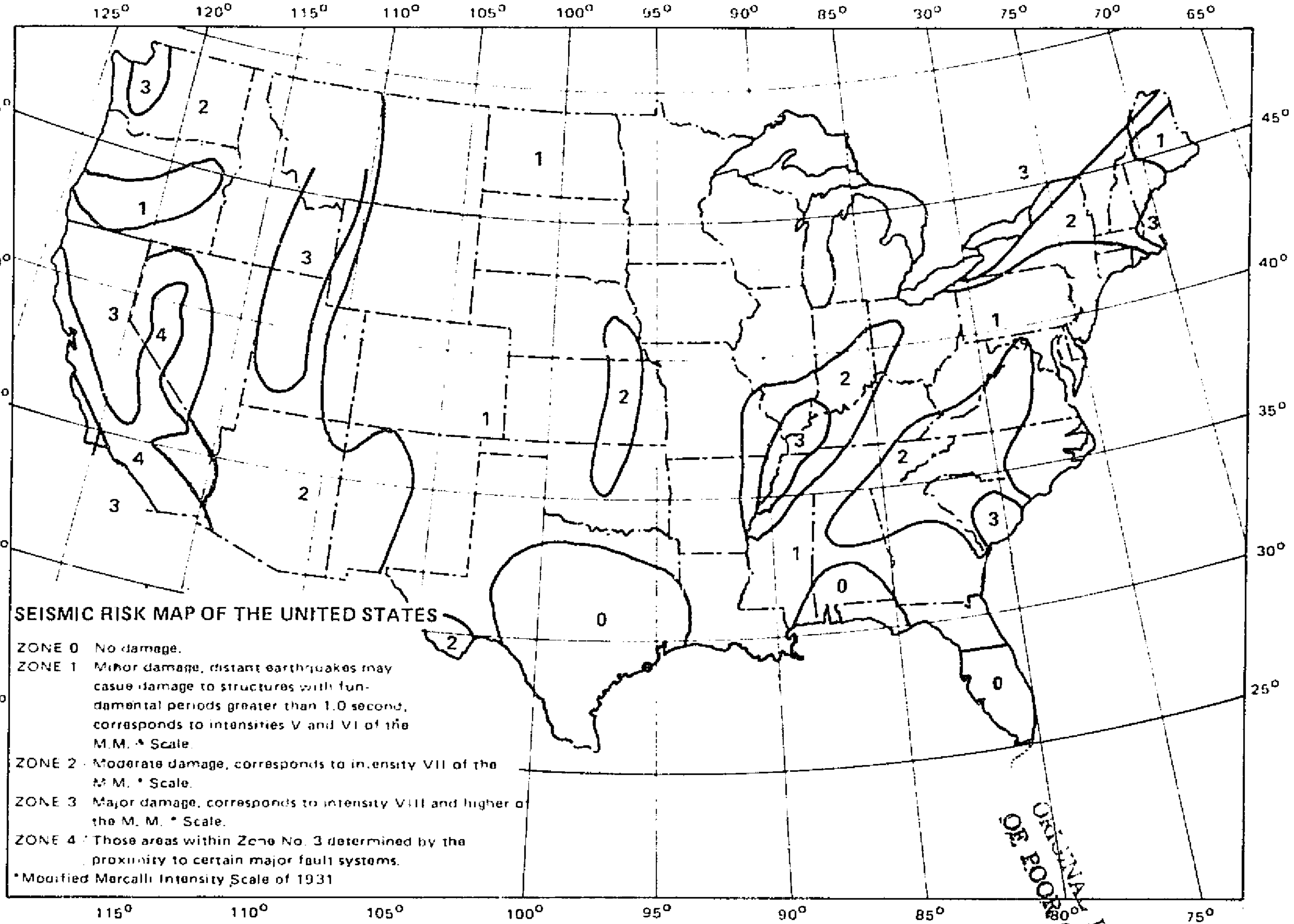
possible that energy generation in Bismarck could be equal to or greater than in Miami for otherwise equivalent plants.

When actual hours of sunshine are considered, this is not found to be the case. However, lower average ambient temperatures do act to increase array energy output.

Although not evaluated quantitatively, similar trends can be expected for array cooling by high prevailing winds.

3.2.9 Seismic Considerations

Failure of a photovoltaic array structure in the event of a major seismic occurrence represents no hazard to public safety. The configurations of the five array designs are such that they generally do not represent a major risk to the safety of plant employees during a seismic occurrence, with the potential exception of the larger size tracking array. However, the design of structures and plant buildings should conform to the applicable requirements of the Uniform Building Code, latest edition. The Seismic Risk Map of the United States (Ref. 3-13) is shown in Figure 3-13. Designing for high risk seismic zones is not expected to produce a major impact on array costs.



SEISMIC RISK MAP OF THE UNITED STATES

ZONE 0	No damage.
ZONE 1	Minor damage, distant earthquakes may casue damage to structures with fundamental periods greater than 1.0 second, corresponds to intensities V and VI of the M.M.* Scale.
ZONE 2	Moderate damage, corresponds to intensity VII of the M.M.* Scale.
ZONE 3	Major damage, corresponds to intensity VIII and higher of the M. M. * Scale.
ZONE 4	Those areas within Zone No. 3 determined by the proximity to certain major fault systems.

*Modified Mercalli Intensity Scale of 1931

Figure 3–13 SEISMIC RISK MAP

3.2.10 Design Loads

It can be expected that various loads resulting from the site environment factors discussed in the preceding sections will occur simultaneously. ANSI Building Code Requirements (Ref. 3-3) contains guidelines on combining the several individual loads to obtain a design load. Since no specific plant site has been selected, the number of possible compositions for any given design load is large. Therefore, for purposes of this study, a baseline design load of 50 psf is used without regard to its composition. However, since loadings of plus and minus 50 psf (normal to the modules) are used, wind loading is implicit. An exception is made for the horizontal array, where greatly reduced wind force can reasonably be expected. For this design, uplift forces are limited to 15 psf, the ANSI minimum for roofs.

The effects of variations in loading are presented in Section 5.

3.3 CIVIL ENGINEERING CONSIDERATIONS

Civil engineering aspects of plant design common to the five array configurations evaluated are discussed in this section.

3.3.1 Site Preparation

Site preparation, drainage and road designs are highly site sensitive. Without a specific site location, assumptions must be made regarding site characteristics that are believed to be representative. The plants require between 505 and 1277 acres of land for a nominal 200 MW peak output rating. Individual plant layouts and areas for each of the five array concepts are discussed in Section 4. It is desirable to have the array groups at approximately the same level, although slight elevation differences between the array groups are acceptable. It is assumed that site topography will be gently sloping, without abrupt changes in contours. A site with a general slope of approximately 3 percent in either the north-south, east-west or diagonal direction is considered acceptable for purposes of this study. This site condition should be reasonably easy to find. Local deviation from the general slope is assumed to be no more than an additional 3 percent. Major natural drainage channels are assumed to exist at the boundary of the plant site.

As to site geology, it is assumed that the soil is a granular, free draining type, containing no more than 30 percent fines (silt and clay). It is also assumed that no rock outcrops or large size boulders (requiring blasting for removal) are present.

Site preparation will include the following operations:

- Clearing and grubbing. Clearing means the removal of all trees, bushes, undergrowth and possibly existing structures or foundations. Grubbing means the removal of all roots over one and one-half inches in diameter and all objectionable organic matters up to 18 inches below the rough grading surface. Clearing and grubbing operation should cover the entire plant area.

- Stripping. Stripping is the removal and stockpiling of topsoil covering the construction area. This operation should cover the areas to be occupied by roads and permanent structures and foundations, as well as excavations and fills associated with the rough site grading operations.

- Excavation. Excavation means the removal of soils over the rough grading elevation of the plant site. It is assumed that excavated material is suitable for fill, therefore, the excess material could be hauled directly to the fill areas.

- Fill. This operation covers the spreading of the hauled fill material to the specified layer thickness (6 inches), moisture conditioning and compaction to the designated density. Ninety percent of maximum density, tested in accordance with ASTM D1557, is normal for structural backfill.

- Moisture control and testing of fill materials. The presence of a qualified soils engineer is mandatory during the excavation and filling operations to insure that the fill material and its moisture conditioning meet specifications and that the minimum density requirements set forth in the specification are met. Continuous field testing of fill materials and sampling of the compacted fill would be the duties of the soils engineer. Fill material judged to be unsatisfactory by the soils engineer should be discarded and replaced with suitable material excavated, if necessary, from designated borrow pits. If excavation reveals local undesirable soil conditions at the plant grade level, the soils engineer would direct the grading contractor to remove this material to a depth below the planned grading level and to replace it with suitable material, compacted to minimum specified density.

Based on the assumptions made for the topographic conditions of the site, it is estimated that an average of approximately 5 million cubic yards of soil will have to be excavated and hauled to the fill areas. The distance between the centers of gravity of excavation and fills is estimated to be approximately one mile.

3.3.2 Drainage

Surface drainage provisions are based on the assumption that drainage from the surrounding tributary area will be collected at the site perimeter in an intercepting ditch system. Any natural drainage channels in the site area will be closed off and the drainage diverted into the peripheral intercept system.

Surface drainage from the plant site proper will be directed to an open trench drainage system by providing slopes in the rough-graded plant area during the site preparation work. The plant area drainage ditches will parallel the plant road system. Setting the maximum slope of the drainage ditches will be based on limiting flow velocity to a maximum of 2 feet per second. This is to prevent excessive erosion of the ditch surfaces during high flow, and thus allowing unpaved ditch surfaces.

At the intersection of the plant roads, flows in the plant drainage ditches will be carried in corrugated metal culverts under the roads. No culvert should be less than 18 inches in diameter. Revetments should be provided at ditch intersections and road crossings.

Adequate space allowances should be provided in clear distances between array groups to accommodate not only the maintenance/access road width but also the surface drainage ditches.

Drainage collected from the plant area will be directed either to natural drainage channels outside the plant area or to the peripheral intercepting ditches at several locations, whichever better suits the site topographical conditions.

3.3.3 Roads

The concept of the central station photovoltaic power plant used herein includes three types of roads:

- A plant access road will connect the plant site to the nearest state or county road or highway.
- Main plant roads will accommodate the movement and the turnaround maneuvering of the washing/maintenance vehicle.
- Plant maintenance roads, running in an east-west direction between the array structures, accommodating the straight-line east-west travel of the washing/maintenance vehicle.

Plant Access Road. The plant access road, if required, will have to be designed and constructed in accordance with the highway standards of the state in which the plant will be located. Pavement width, pavement type (concrete or asphalt), shoulder width and type, culverts, bridges, railings and signs must conform to state highway requirements and regulations. For purposes of this study, it is assumed that the site boundary is adjacent to an existing road. The cost of an access road is not included in the cost estimates.

Main Plant Roads. The main plant roads will be built with 16 foot wide pavement and 4 foot wide shoulders on each side. Although conceivably the washing or maintenance vehicles will be heavy, their use will be intermittent, and the travel speed will be quite low. Public road type concrete or asphalt pouring cannot be economically justified for this type of service, so their use should be limited to turning areas where scrubbing by vehicle tires is a maximum.

In areas where gravel or crushed rock is available, a compacted gravel or crushed rock pavement may be a satisfactory and economic alternative. After finish crowning and compaction of the roads' subgrade, the gravel or crushed rock paving material would be spread evenly, slightly moistened and rolled in place for a finished total thickness of 10 inches.

In areas where gravel or crushed rock is not available within a reasonable hauling distance, a soil-cement pavement should be considered. Soil-cement is a simple, highly compacted mixture of soil, portland cement and water. As the cement hydrates, the mixture becomes a hard, durable paving material. Nearly all soils can be hardened with portland cement. Soil-cement pavements do not need to use well graded aggregates because the stability of the soil-cement mixture results mainly from cement hydration and not from cohesion and internal friction of the materials.

The word "soil" as used in soil-cement means almost any combination of gravel, sand, silt and clay. It includes such materials as cinders, caliche, shale and chat and many waste materials.

Any type of portland cement, complying with the latest ASTM specifications may be used. Types I and IA, normal and air-entraining portland cements are most commonly used. The amount of cement required to produce a good, durable paving surface depends on the soil and is determined by laboratory testing. Using average values for percent of soil pulverization, approximately 35 pounds of portland cement and 7 gallons of water will be required per square yard for 6 inch pavement thickness.

The cost of this type of road is estimated to be approximately $17,000 per mile (1975 $).

Plant Maintenance Roads. For plant maintenance roads, a 10 foot wide pavement with 2 foot wide shoulders will be sufficient. If gravel is used for surfacing, an 8 inch finished thickness would be required. For soil cement pavements, a 4 inch finished thickness will provide adequate strength for the intended use, if the subbase material is adequately firm and stable.

At the intersection of the main plant roads and plant maintenance roads, steel pipe or precast concrete guard posts should be provided at close enough spacing to prevent accidental damage of the array corners by washing or maintenance vehicles.

Passage and crossing the surface drainage under the roads will be accommodated by corrugated metal culverts having a minimum diameter of 18 inches. No large size (multiplate) culverts or bridges are anticipated.

The cost of this type of road is estimated to be approximately $6,700 per mile (1975 $).

3.3.4 Buildings

The plant's office areas and control room will be located in a 1400 square foot single story building. This building will have a prefabricated rigid frame-type steel main structure. The exterior walls and roof will be covered with prefinished insulated sheet metal siding and roofing. Exterior doors will be hollow metal type, standard for prefabricated buildings. Windows will also be in accordance with the manufacturer's standards. The foundations for the building columns will be reinforced concrete spread footings. The office portion will have a 6 inch thick reinforced concrete floor mat on grade.

The control room portion of the building will have an elevated reinforced metal decking floor and structural steel framing supported on a reinforced concrete slab floor to provide for cable spreading and wiring entry to the control panels. Floor finish will be vinyl asbestos floor tile. Interior partitions will be metal stud type covered with decoratively finished panels of the main-fasteners standard type. Lighting, plumbing, lavatory, fire protection and heating, ventilating and air conditioning facilities will provide comfort and safety for the plant personnel.

The plant maintenance and warehouse facilities will be located in another prefabricated, rigid frame type steel structure, having 1400 square feet of floor area. The exterior walls and roof will be covered with prefinished insulated metal siding and roofing, of the manufacturer's standard type. Foundations for the building columns will be reinforced concrete spread footings. The entire building will have a 6 inch thick reinforced concrete floor mat on grade, with steel trowel finish. Building services in the form of lighting, plumbing, lavatory, fire protection, heating and ventilating will be provided. Large equipment doors, permitting the passage of maintenance trucks will be installed, and mobile hoisting devices will ease the handling of heavy items, such as crates of panels. Mechanical electrical and instrumentation areas in the warehouse will be partitioned off by prefabricated partition panels of the manufacturer's standard type.

Electrical equipment, such as converters, switchyard equipment and the main transformers, will be mounted outdoors on reinforced concrete foundation pads.

3.3.5 Other Plant Facilities

An 8 foot high chain link fence topped with three strands of barbed wire, supported by steel pipe posts, will surround the entire plant. Primary access will be provided through the main gate at the entry point of the plant access road. The plant security office will be a part of the control building. Intrusion detection and alarm system signals will also be located here.

It is assumed that the plant will be located outside the area served by the nearest municipal water supply and sewage treatment facility. Accordingly, a drilled well (or wells), equipped with an appropriate pressurization system, is considered for the supply of domestic and array wash water. Equipment to purify the well water is discussed further in Section 3.7.3. The sewage treatment system will consist of a prefabricated aeration unit sized to treat 150 gallons per day per person. The treated effluent is assumed to be absorbed by an appropriately sized leach field.

3.4 ELECTRICAL ENGINEERING CONSIDERATIONS

Electrical aspects of plant design are discussed in this section. The electrical subsystems generally common to all five array configurations include: converters, batteries, dc wiring, ac wiring, switchyard and other balance of plant subsystems such as grounding, lightning protection, station power and control and instrumentation. A brief discussion of equipment and system operating efficiencies is also included. Variations in electrical system design and costs for the five specific array configurations investigated in this study are reported in Section 4.

3.4.1 Converter

The converter system serves as the interface between the dc output of the solar arrays and the ac collection and transmission network. The term converter refers to a bidirectional device capable of both dc to ac (inversion) and ac to dc (rectification) transformations. Equipment of this type is presently under development for use with fuel cells, battery energy storage systems and other dc energy devices. If onsite storage is not included in the facility design, the ac to dc mode of operation is not required (as is the case in fuel cell systems), and the converter system need only be designed to operate as an inverter.

Although several different converter circuit designs are presently being considered, all of them employ solid state switching devices (known as SCRs or thyristors) in bridge circuits similar to those presently used in uninterruptible power supplies (UPS) and high voltace dc transmission (HVDC) systems.

Power Levels. Power levels for this type of equipment can range from only a few kilowatts up to several hundred megawatts. In light of the distributed nature of the solar power generation system, it is anticipated that the converter equipment for a central station photolvoltaic power plant would consist of several modularized units, rated in the 2 to 10 MW range, and dispersed throughout the array field. This modularized approach allows the dc voltage and bus current levels to be maintained at reasonable values.

Current Level. The maximum dc converter bus current level is primarily governed by the ratings of available thyristors and design preference with regard to safety factor and paralleling of devices. Other considerations include I^2R losses and switching and fusing requirements.

Based on an evaluation of available literature, it appears that the optimum dc bus current level will be about 4000 amperes. However, future improvement in thyristor current ratings and development of high speed dc circuit breakers may increase this value.

Voltage Level. Selection of converter voltage level is strongly influenced by converter cost ($/kW) as a function of dc voltage. Selection of the dc voltage level is discussed in Section 3.4.2.

Available data indicate a rapid decrease in converter price for dc voltage up to about 1200 volts, and a more modest price decrease above this voltage. The minimum dc system voltage is therefore strongly influenced by converter costs and appears at this time to be about 1200 volts. The maximum voltage is determined by such parameters as:

- Dc wiring costs
- I^2R losses
- Economics of array and module sizing
- Electrical insulating capabilities of module encapsulating systems

Maximum voltage levels of up to 5000 volts have been proposed, although module encapsulation costs will force somewhat lower voltage levels to be selected (as discussed in Section 3.4.2).

Other Converter Factors. In addition to the thyristor switching devices previously mentioned, the proper operation of the converter system may, depending on design, require some or all of the following:

- Dc filters
- Ac filters

- Transformers
- Power factor correction capacitors
- Surge arrestors
- Fuses and circuit breakers
- Control system

It is anticipated that, with the exception of the output transformer, all equipment will be installed inside a small building or enclosure that can be trucked to the site.

It has been proposed in several studies that energy storage batteries be included in the system design. As discussed in Section 3.4.5, the batteries would be located in conjunction with the converter. Depending on the method of battery connection, impact on converter design can include:

- An increase in available dc fault current
- An increase in required dc voltage operating range
- Increase in complexity of control system

The effect of batteries on the converter cost is dependent on converter design, but will be on the order of a 10 percent increase above a non-storage design (Refs. 3-2 and 3-14).

Converters may be operated either "floating" or with a ground on the dc bus. The floating (ungrounded) configuration is preferred for simplicity of fault detection and for increased reliability.

Converter equipment can introduce voltage transients onto the dc bus. These transients may result from ac system transients, which propagate through the converter, or from dc fault interruption. The magnitude of such transients, although to some extent dependent on converter design, was estimated in a previous Bechtel study (Ref. 3-1) to be in the range of 2.5 to 3 times normal system voltage.

Converter efficiency is not a constant; it is a function of load. Figure 3-14 illustrates the expected variation in efficiency with load for the type of converters needed for photovoltaic central station power plants. As can be seen, energy collected at low powers is reduced by falling converter efficiency. Full load converter efficiency will range from 95 to 97 percent.

3.4.2 Dc System

The dc system interconnects individual solar cell panels and delivers their power output to the converter. The dc system consists of inter-panel connectors, dc wiring and, because it is subjected to the dc system voltage, the module encapsulating system.

Inter-Panel Connectors. As defined in Section 3.1, a panel is the smallest assembly of solar cells delivered to the field. Each panel has a single pair of electrical terminals, which are field connected to the remainder of the system and a ground

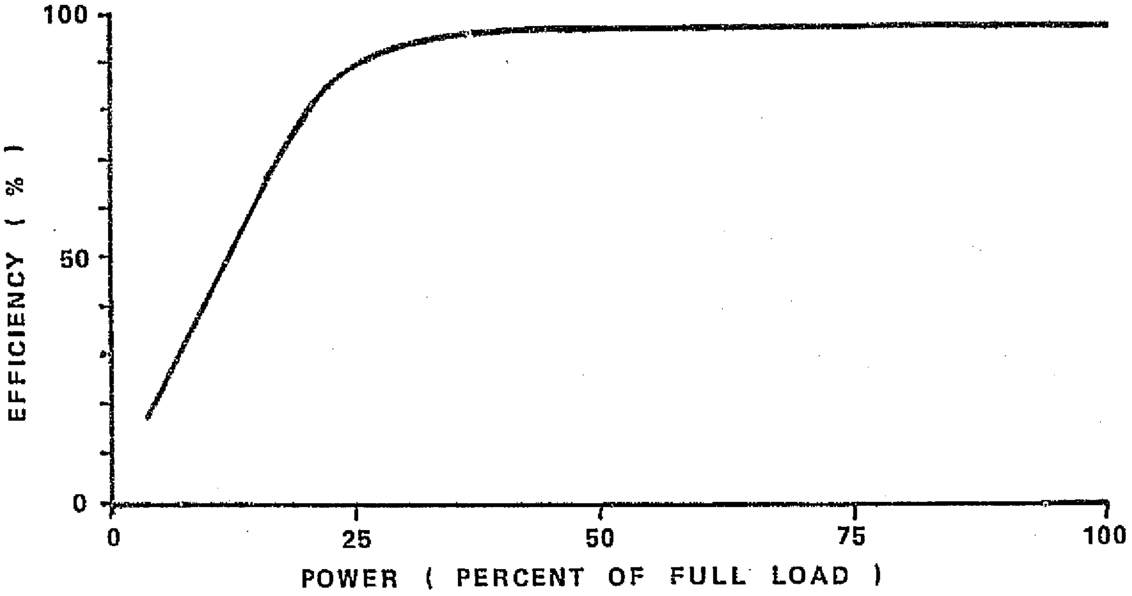


Figure 3–14 CONVERTER EFFICIENCY VERSUS LOAD

connection. It was concluded in an earlier study (Ref. 3-1) that these connectors should be a factory pre-assembled, quick-disconnect type. The connector selected is a scaled-up version of a molded rubber quick-disconnect connector, presently produced commercially for application in truck braking systems. Budgetary cost estimates for such a connector (single contact) were obtained from one manufacturer (ITT Cannon) and are presented in Table 3-3, in constant 1975 dollars.

TABLE 3-3

CONNECTOR COST (1975 $)

Connector Rating (Amperes)	Material Cost ($/mated pair)	Assembly Cost ($/mated pair)	Quantity
10(1)	0.28	0.16	1 x 10^6
25	1.78	0.24	5 x 10^5
100	3.09	0.31	8 x 10^4

(1) Present production model

In addition to the costs presented in Table 3-3, there would be a one time partial tooling charge of $17,500 for each connector type.

The manufacturer has indicated that appropriate voltage ratings can be accomplished by selecting the proper rubber thickness during the initial design phase. It was further indicated that the value of the material involved would be a small percentage of the total connector cost, so that for voltage ratings up to about 5000 Vdc, connector cost would not be significantly affected by voltage rating.

Connectors are attached to the panel leads, at the factory during panel assembly, thus minimizing the field labor required to complete the connection.

Dc Wiring. The dc wiring system connects individual blocks in series (Ref. Figure 3-2) to obtain the dc system voltage and thus form arrays. The wiring then connects the arrays to the converters. The system consists of field installed cables and terminations. The design and costs of the system are dependent on several factors and are therefore difficult to generalize. These factors include:

- Array configuration
- System voltage
- Method of cable installation

During this study, wiring costs were found to range from $0.009/peak watt of ac plant output for the horizontal array, to $0.038/peak watt (ac output) for the vertical axis tracking array. These costs are in constant 1975 dollars, and are for a 1500 volt dc system. Costs for each array type are discussed further in Section 4.

For a constant power level, dc wiring costs tend to decrease with increasing system voltage. It has been estimated (Ref. 3-1) that, within the range of 1000 to 5000 volts, the dc wiring costs vary approximately as voltage to the -0.8 power.

All dc wiring is assumed to consist of insulated conductors installed either underground or directly on the ground. This is done to eliminate clearance problems for construction and maintenance vehicles and to avoid the effects of pole shadows on the arrays.

For this study, it was assumed that all underground wire is installed in open trenches, which are then backfilled and that all terminations are of the standard distribution system type (mechanical crimp lugs installed in the field). An exception is the jumper cable connecting the individual blocks in the tracking array. These cables include factory installed quick disconnect terminations. It is possible that some savings might result from the use of prefabricated wiring harnesses. Such harnesses would consist of pre-cut lengths of cable having factory installed quick-disconnect type connectors, similar to those used for the tracking array. However, time did not permit an analysis of this option for this study. Also, since the dc wiring is not a major cost item (except for the tracking array), the cost impact would not be major.

Module Encapsulating System. During system operation the module encapsulating materials are stressed by a dc electric field. The magnitude of this stress depends on the nominal dc system voltage, solar cell operating temperature, the type of dc system grounding (if any) and the electrical location of the module in the array string. The effect of increasing dc system voltage on the encapsulating system is dependent on the type of module construction and the encapsulating materials employed. Generally, increasing the system voltage increases the required material thickness and, therefore, the encapsulation cost. This is discussed in detail in the final report for another Bechtel study, Reference 3-15.

<u>Selection of dc Voltage Level</u>. The most economic dc system voltage is that which results in the minimum total cost for all components in the dc system (including the converter). Essentially, the only system component costs affected by dc voltage level are the converter, the dc wiring, and the module encapsulation costs. Figure 3-15 presents the behavior of these individual component costs as a function of voltage level. The wiring costs are for the rack type array. The data for Mylar and Tedlar film encapsulants are derived from Reference 3-15 and represent the cost for <u>additional</u> material needed to insulate a module above a voltage of 500 volts dc. The module configuration for this example consists of a soda-lime glass cover sheet, Sylgard 184 cell adhesive and encapsulant and the indicated film material. The results are also applicable to metal substrate modules with glass covers (or other covers capable of withstanding high voltages). As a result of the way the voltage stress divides across a dc insulation system, the only significant effect of voltage on this configuration is to increase the required film thickness. All costs in Figure 3-15 are in constant 1975 dollars.

It can be seen from Figure 3-15 that minimum dc system voltage is governed by converter cost, while the upper limit is determined by encapsulation costs. It is further shown that the optimum voltage level is dependent on the specific module configuration and encapsulating materials selected.

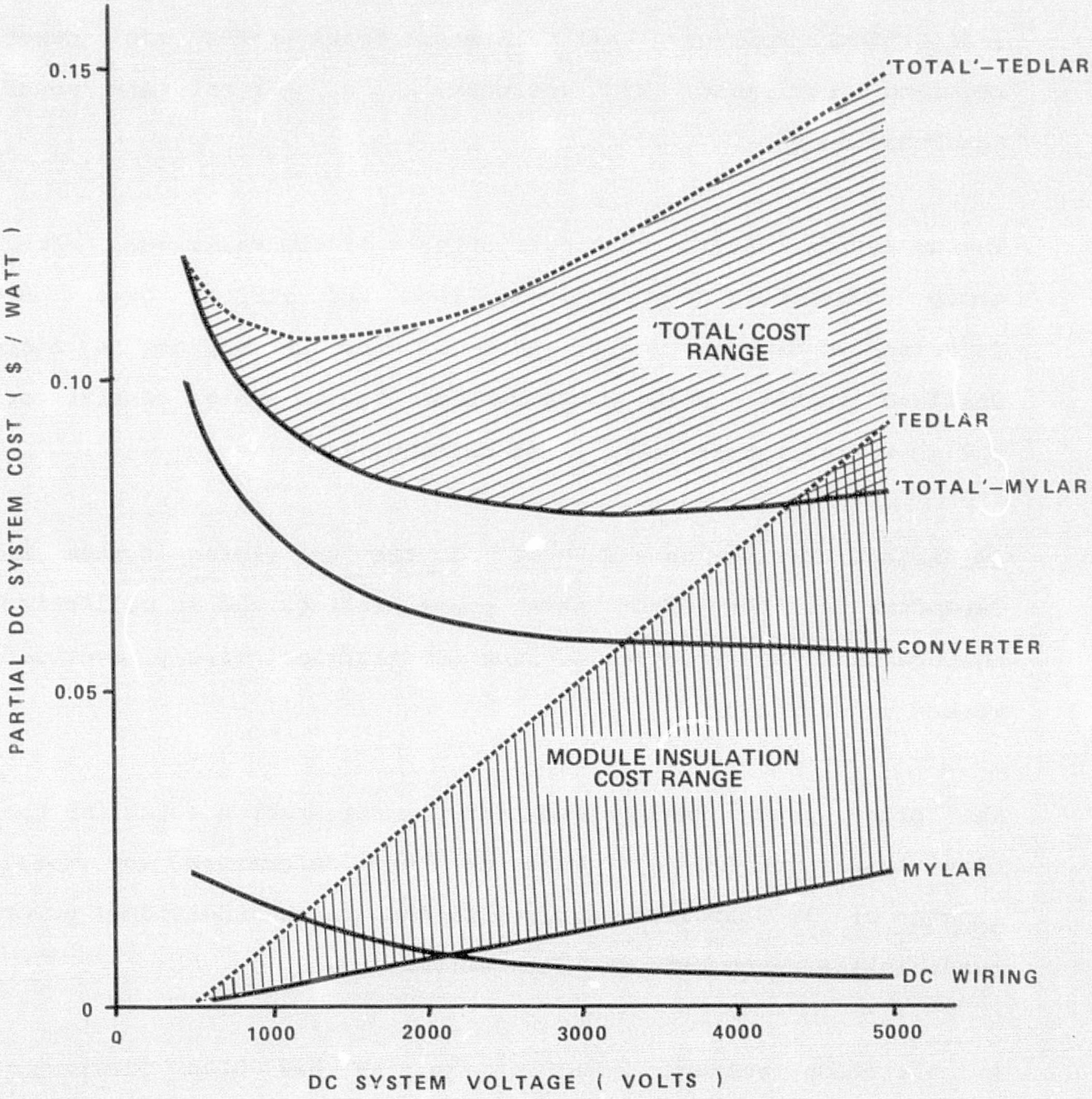


Figure 3–15 COST BEHAVIOR OF DC SYSTEM VERSUS VOLTAGE

3.4.3 Ac System

The output of each power conditioning unit is in the form of filtered three phase ac power at a suitable subtransmission (collection) voltage. All filters, transformers and other required equipment are included as a part of the power conditioning unit.

The ac system collects the power outputs of the individual array group converters for delivery into the utility grid. As discussed in Section 3.4.4, part of the ac system is also utilized in the station power system. The ac system consists of the ac wiring and the main plant switchyard.

Ac Wiring. The design and cost of the ac wiring system is dependent on the plant peak power rating, the ac collection voltage level and the type of line construction (i.e., overhead versus underground).

The plant power rating and array configuration establish the plant land requirements. This in turn determines the total length of ac circuits required to connect the individual power conditioning units with the main switchyard.

A collection voltage level of 34.5 kV has been previously proposed (Ref. 3-2) for plants with peak power ratings in the range of 200 MW. A brief evaluation indicated that any cost differences with ac voltage are beyond the level of detail of this study. Therefore, a voltage level of 34.5 kV was selected for use in this study. Although for plant ratings of perhaps 25 MW or less, a lower voltage level (e.g., 13.8 kV) might be appropriate because of lower switchgear costs at lower voltages. Also, the ac wiring was not found to be a major contributor to plant costs.

The ac circuits can be installed either overhead, using conventional pole line construction, or underground, using established underground cable installation practices.

Ac wiring costs for a 34.5 kV system were estimated for both overhead and underground installation. For a nominal 200 MW plant, these costs were found to be $0.002/peak ac watt for overhead and $0.008/peak ac watt for underground (in constant 1975 dollars). These costs vary with array configuration and plant area. Despite the higher cost, underground installation has two advantages, the elimination of both vehicle clearance requirements and array shadowing, which would result from the use of overhead lines on poles.

<u>Switchyard</u>. The ac collection circuits converge on the main switchyard, which is the central collection point for the output of the array group converters and the point of connection to the utility network.

The switchyard contains transformers, circuits breakers, disconnect switches and other equipment normally found in conventional utility substations. The equipment is outdoor type, pad mounted, and the entire yard is fenced for safety and security.

The estimated cost (1975 $) for the plant switchyard is $0.0073/peak ac watt, for a nominal 200 MW peak output plant. The design is for a 34.5 kV collection voltage and a 230 kV transmission voltage. Voltage levels, and array configuration, do not significantly affect the cost of the switchyard on a dollar per watt basis.

3.4.4 Balance of Plant Electrical Systems

The balance of plant electrical systems include those systems which, while not directly involved with the power generating system, are required for plant operation, maintenance or equipment and personnel safety. These systems include:

- Station power
- Control and instrumentation
- Grounding
- Lightning protection
- Communications
- Security

Station Power. The station power system supplies power to all plant loads, such as the control and maintenance buildings, the power conditioning units and, if required, the array field. It consists of 34.5 kV/480 volt load centers located in the main switchyard, 34.5 kV/480 volt transformers located at each power conditioning unit and required power distribution panels.

During daytime operation, each power conditioning unit station power transformer is energized directly from the high side of the converter output transformer. At night, or during other periods of non-solar generation, the transformers are energized by offsite utility generated power, which is back-fed through the main switchyard and the ac power collection wiring. In the event of loss of all ac power supply to the power conditioning units, the essential loads (i.e., computers and lighting) are supplied by station batteries located at each power conditioning unit.

The system also includes a standby diesel generator and an uninterruptible power supply for essential loads in the main control room area.

The total cost of the station power system, for a nominal 200 MW peak output facility is estimated to be about $240,000 dollars (1975 dollars) or $0.001/peak ac watt. Any changes in station power system costs, which might result from variations in plant rating or array configuration are beyond the accuracy of this study.

Control and Instrumentation. The control and instrumentation systems monitor and display the status of plant equipment, accomplish adjustment of plant configuration (either manual or automatic) to provide optimum operation, detect abnormal system conditions and initiate protective action if required.

The control system includes a central computer, located in the central control room, which is connected by a data link to minicomputers located at each power conditioning unit. To minimize wiring requirements, all microcomputers are paralleled onto a single data bus using multiplexing techniques. Each minicomputer receives information by instrumentation sensors regarding plant operating conditions, such as solar panel temperatures and array voltages, currents and power levels. The minicomputer processes this information and provides input signals to the converter controller. The microcomputer also transmits data to the central computer and receives operating commands from it. Also included in the control system are plant status display panels, switchyard control and protective relaying and required control functions for all other auxiliary systems. The estimated cost of the computers and control panels (exclusive of interconnecting cables) is $0.002/peak watt (1975 dollars). Cabling costs are dependent on array configuration and plant area. They are discussed in Section 4.

It is expected that during the life of the plant certain failures will occur in the array system. These may include open cell interconnects, cracked cells, module, panel and/or array open circuits and ground faults on the dc system. The large quantity of modules/panels required for a central station power plant makes individual monitoring impractical. Therefore, it is likely that failure detection will be limited to the monitoring of larger units such as arrays, or groups. With this scheme, the current levels on the dc array feeders would be monitored.

By comparing the current levels of several adjacent arrays, open circuited module strings may be identified. Using techniques discussed in Section 3.7.2, maintenance crews are then dispatched to locate and, possibly, repair the problem. Monitoring of the dc feeder current levels is accomplished at the point of termination to the converter bus. Therefore, the only additional equipment required are dc current transducers and additional multiplexer channels to connect the current transformers to the existing computer system. The converter bus is also monitored to detect ground faults. The estimated cost of such a monitoring system is $350.00 per channel (1975 dollars), or roughly $0.0007/watt.

The control and instrumentation systems would also include other provisions, such as tracking control, as needed.

Grounding. A grounding system is required for proper equipment operation and to insure plant and personnel safety. All equipment and structures are solidly bonded to the grounding grid. The grid is composed of rebar embedded in the concrete foundations and equipment pads and is supplemented by directly buried bare copper wires and driven ground rods. The grounding system costs for the switchyard, control and maintenance buildings and power conditioning equipment are included with those systems. All of the power conditioning units are bonded together, and to the main switchyard, by bare copper wires installed with the ac power collection circuits discussed in Section 3.4.3. Similarly, to provide for bonding of the arrays to the plant ground, bare copper wires are installed along with the dc wiring circuits discussed in Section 3.4.2.

Array grounding requirements are affected by array design. They are discussed in Section 4.

Lightning Protection. Lightning protection requirements for the array field have yet to be completely defined. It is likely that a system will be included in the plant design for the protection of modules, structures and other equipment.

Traditional methods of lightning protection include overhead ground wires and/or lightning rods. However, these methods are usually applied to much smaller areas. In addition, shadowing problems make such methods less desirable. One type of protection system that has been successfully applied to large areas is the dissipation array. The function of the system is to reduce the electrostatic potential between earth and clouds, thereby preventing the occurrence of lightning strikes within the protected area. Establishment of system costs requires an analysis of system requirements that is beyond the scope of this study. To obtain order of magnitude price estimates, one supplier of such systems (Lightning Elimination Associates) was contacted. They indicated that the installed cost of such a system could be expected to range between about $2500 and $5000 per acre (1975 dollars). Further study in this area is required to more firmly establish system requirements and costs.

Communications. The communication system provides a link between the plant operators and the utility dispatcher, as well as between operation and maintenance personnel within the plant.

The offsite link would likely consist of a transmission line carrier system and a microwave system backup. Onsite communications would consist of mobile and base station radio units, a paging system and telephones.

Based on a previous study (Ref. 3-2), the total installed cost of the communication systems is estimated to be on the order of $300,000 (1975 dollars). This cost is essentially unaffected by array design.

Security. Plant security requirements have not been firmly established yet. Security provisions might include a guard at the plant entrance, automatic intrusion alarms and television cameras. Based on a review of similar, existing security system designs, an estimated cost of $200,000 (1975 dollars) is assumed for this study.

3.4.5 Energy Storage

The output of a terrestrial photovoltaic power system is entirely limited to the daytime and is further subjected to reductions in output due to cloud cover. The use of energy storage in conjunction with photovoltaic power systems can lessen some of these effects by:

- Providing energy during transient disturbances, thereby increasing plant reliability
- Utilizing stored energy to provide system output during extended periods of low or zero insolation (e.g., evenings or overcast days) thereby contributing to utility system load leveling and, possibly, increasing the allowable photovoltaic power plant capacity factor

The overall operation of the utility system is generally not affected by storage subsystem location, with the exception of varying transmission losses. Therefore, depending on the quantity and type of existing offsite storage, and the ratio of solar to non-solar generating capacity, a particular utility may or may not choose to provide onsite storage capacity.

Of the three photovoltaic central station conceptual design studies recently conducted under ERDA sponsorship, one (performed by Westinghouse) assumes that any energy storage will be provided by separate, offsite facilities, and therefore does not include an energy storage subsystem as a part of the photovoltaic facility.

The other two studies, performed by General Electric and Spectrolab (the latter with Bechtel participation), include onsite energy storage in the form of batteries.

The use of batteries for utility load leveling is presently being considered as an alternative to the pumped hydroelectric systems that presently comprise the majority of utility storage capacity (Ref. 3-16), but which have limited application potential due to specific site requirements.

To this end, several programs are currently underway to develop advanced battery designs suitable for service in utility load leveling systems (Ref. 3-17).

Projected costs ($/kWh) and efficiencies for several different battery systems are presented in Figures 3-16 and 3-17, respectively (Ref. 3-18). The present developmental status of many of these battery systems is evident from the wide range of values presented in Figures 3-16 and 3-17. The curves are only intended to show the general range of costs and efficiencies that may be expected for future battery systems.

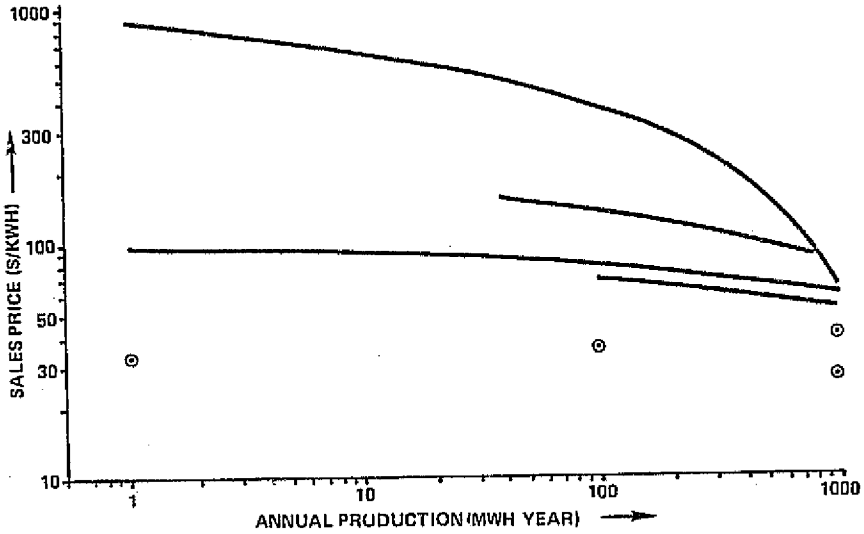


Figure 3--16 BATTERY PRICE VERSUS PRODUCTION RATE

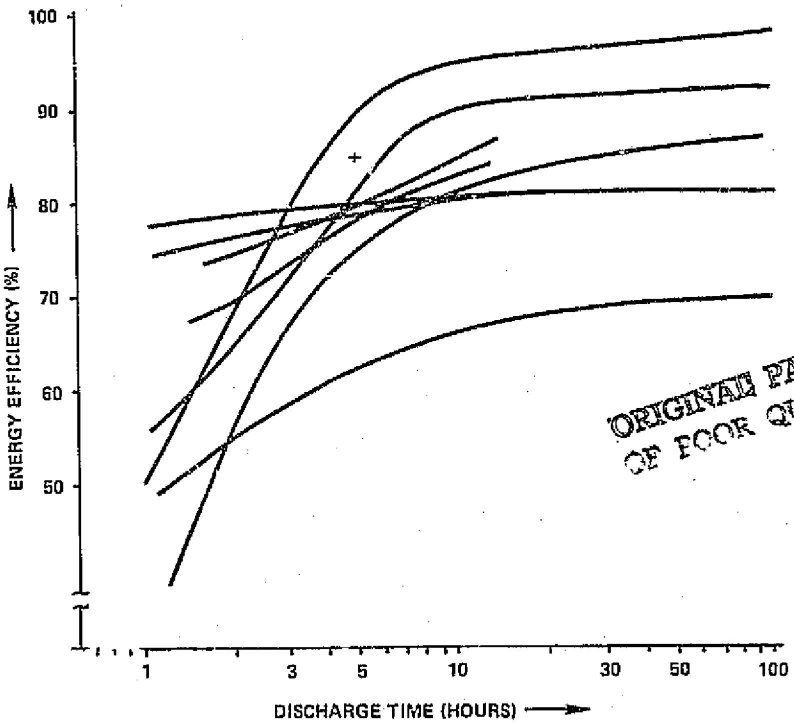


Figure 3—17 BATTERY EFFICIENCY VERSUS DISCHARGE TIME

A battery energy storage system for a nominal 200 MW photovoltaic plant was designed by Bechtel for a previous study (Ref. 3-2). The basic elements of that design are included herein as a basis for estimating the cost of an energy storage system. As mentioned, many types of advanced batteries are currently being developed. The design selected as representative is the lithium-sulfur battery being developed by Argonne National Laboratory. With this design, the batteries and their ancilliary subsystems are housed in prefabricated buildings adjacent to the converter units. Due to the plant layout, no additional land is required. Cost (1975 $) and performance data for this energy storage system are presented in Table 3-4 for both 3 and 10 hours of storage. The battery costs include shipping. The costs of all other equipment items (including the buildings) needed to make a complete, functioning system are included under auxiliaries. Material costs and manhours are normalized to energy capacity. The labor shown is direct labor and the cost of field distributables must be added in arriving at total cost. Also, the estimates shown in Table 3-4 exclude engineering and contingency. The differences in normalized costs between the 3 and 10 hour designs are primarily due to decreases in battery energy capacity with decreasing discharge time.

If a utility system contains both central station photovoltaic generating capacity and battery storage, several factors may favor their co-location. The prime advantage of co-location is that a battery across the array dc bus can respond instantly and

TABLE 3-4

BATTERY SYSTEM COSTS (1975 $) AND CHARACTERISTICS

3 HOUR BATTERY

Item	Material ($/kWh)	Labor (MH/kWh)
Batteries	44.50	0.04
Auxiliaries	3.80	0.17
Converter Modification	1.25	-
Direct "Cost"	49.55	0.21
Salvage Value	6.00	-
Battery Replacement	44.50	0.07

Life - 3000 cycles (9-12 years)
Efficiency - 77%

10 HOUR BATTERY

Item	Material ($/kWh)	Labor (MH/kWh)
Batteries	32.70	0.025
Auxiliaries	2.80	0.125
Converter Modification	0.90	-
Direct "Cost"	36.40	0.150
Salvage Value	5.00	-
Battery Replacement	32.70	0.05

Life - 3000 cycles (9-12 years)
Efficiency - 85%

automatically to transient cloud cover and maintain a constant plant output. Since photovoltaic arrays and batteries are dc devices, their co-location permits sharing of the power conditioning equipment (converters) necessary to interface them with the rest of the utility grid. Other potential advantages include:

- Reduction in the equivalent amount of land required for battery location
- Sharing of operating and maintenance personnel

A potential disadvantage of co-location is an increase in transmission losses if the solar/battery facility is located some distance from both the load and the source of charging power. The inclusion of batteries increases the converter rating requirements, especially with regard to operating voltage range and power factor correction.

The source of charging energy may be the solar arrays, offsite non-solar generated energy, or any combination of the two. The source is determined by an analysis of overall system operating economics. Such an analysis would consider the following points:

- If the period of solar array output coincides with a period of high utility system load demand (on-peak), the cost of energy storage encompasses the cost of the batteries and ancillary systems, plus a penalty for the energy lost due to losses in the battery.
- If sufficient non-solar generating capacity, in the form of relatively low operating cost base-load facilities, is available during periods of low system load demand

> (off-peak), which is typical of many utility's night time load demands, the economics of battery storage can be considerably improved. In this case the batteries are charged with relatively low cost energy generated during off-peak periods, and then discharged back into the grid during periods of peak demand, thereby reducing or eliminating the need for expensive "peaking" capacity (e.g., gas turbines). This mode of operation has been the subject of many recent studies, including Reference 3-19, which seek to demonstrate the economic feasibility of using batteries for load-leveling applications.

The economic viability of battery storage in photovoltaic power plants is determined by such parameters as:

- The value of on-peak generated energy
- The ratio between the values of on-peak and off-peak generated energy
- Efficiency of the storage system

A brief analysis conducted during this study resulted in the battery storage subsystem breakeven costs presented in Table 3-5. The values of on-peak energy were derived by equating the value of the annual facility net energy output with the equivalent annual cost of the facility, using a capital recovery factor of 0.17 and facility capital costs of 1, 0.75 and 0.5 $/peak watt, plus a 5 percent annual charge. A value of $0.010/kWh for off-peak energy was selected based on a review of published literature, which indicates an expected range of from 0.005 to 0.015 $/kWh.

TABLE 3-5

BATTERY STORAGE SUBSYSTEM BREAKEVEN COSTS (1975 $)
200 MW [illegible] OUTPUT, 3 HOURS OF STORAGE

Photovoltaic Facility Capital Cost ($/peak watt)	Value of On-Peak Energy ($/kWh)	Source of Charging Energy	Ratio-Value of On-Peak Energy to Value of Changing Energy	Battery Efficiency (%)	Battery Breakeven Capital Cost ($/kWh)
0.5	0.0358	Arrays(1)	1	75	-24
0.5	0.0358	Arrays	1	90	-8
0.5	0.0358	Utility(2)	3.58	75	41
0.5	0.0358	Utility	3.58	90	46
0.75	0.0537	Arrays	1	75	-36
0.75	0.0537	Arrays	1	90	-12
0.75	0.0537	Utility	5.37	75	77
0.75	0.0537	Utility	5.37	90	82
1.0	0.0716	Arrays	1	75	-47
1.0	0.0716	Arrays	1	90	-16
1.0	0.0716	Utility	7.16	75	113
1.0	0.0716	Utility	7.16	90	118

(1)All energy generated by arrays is assumed to be "on-peak"

(2)All utility derived charging energy is assumed to be generated "off-peak" at a cost of $0.010/kWh

System and subsystem efficiencies are discussed in Section 3.4.6. Breakeven costs include an annual operating and maintenance cost of 0.001 $/kWh for the battery subsystem.

The data presented in Table 3-5 indicate that:

- If array generated energy is utilized for charging, breakeven costs are negative in all cases, implying that an economic penalty is incurred for the inclusion of battery storage. The value of this penalty increases significantly with decreasing battery efficiency and/or increasing value of on-peak energy.
- If off-peak, non-solar generated energy is used, a range of allowable energy storage subsystem costs exists for which onsite battery energy storage can provide economic benefit on an overall system basis. The range of acceptable costs is determined by the value of on-peak energy and the ratio between on-peak and off-peak energy costs, with battery efficiency having only a slight effect.

It should be noted that this analysis assumes that the service lives of both the battery and the solar panels are equal to the useful plant life. In practice, however, it is likely that both solar panels and batteries would be replaced one or more times during the life of the facility. Organizations presently conducting battery development programs are projecting useful lifetimes in the range of 5 to 15 years for load-leveling applications, depending on duty cycle. The data presented in Table 3-5 is intended to illustrate the significant cost drivers involved in the economic evaluation of onsite storage and should not be interpreted as indicating actual breakeven costs.

3.4.6 Efficiency

A portion of the energy generated by the solar cells is consumed by I^2R losses within the plants' power collection and conditioning systems. Therefore, calculations of net plant energy output (to the utility grid) must take into account the magnitude of these losses. Losses occur in:

- Cell interconnects
- Module and panel connectors
- Dc wiring
- Converter equipment
- Ac wiring
- Main switchyard transformers

The following analysis considers all of the loss components listed above except the cell interconnects, which are included within the module efficiency and are beyond the scope of this study.

The magnitude of the loss in any system component is proportional to that component's electrical resistance and the square of the load current. Component resistance is essentially constant, being determined during initial system design. The magnitude of the load current, however, varies both hourly and seasonally in proportion to insolation. The peak power loss for any system design occurs at the time of maximum insolation and, hence, maximum current. Energy loss at a specific power level is proportional to the square of the ratio between the magnitudes of the operating and peak power point currents. In other words, losses at one half peak rated power output are 25 percent of those at full rated output.

The energy lost on a yearly basis and as a percent of gross power generation is determined by integrating the instantaneous power loss over the yearly operating cycle. To simplify the calculation for this study, power losses were calculated for four days representative of the seasonal variations in insolation for each of the five array concepts. Losses within each daily period were calculated at two hour intervals. Insolation data were obtained from Reference 3-2, while the plant designs are as described in Section 4.

Table 3-6 presents peak power loss and yearly energy loss for the five array configurations.

TABLE 3-6

PLANT POWER AND ENERGY LOSSES

Array Type	Peak Power Loss (% Peak Gross Power Generation)	Yearly Energy Loss (% Yearly Gross Energy Generation)
Rack	8.8	6.6
Tandem	9.3	6.7
Horizontal	8.7	6.2
Seasonally Adjusted Rack	8.8	6.6
Tracking	11.1	9.6

It can be seen that energy losses are not significantly affected by array design, except for the tracking array. Increases in both dc wiring length and the percent of total operating time spent at high current levels account for the increased losses of the tracking array system.

Station power loads are a small percentage of plant output, accounting for perhaps one percent of total output. An additional one percent would be consumed by tracking motors in the tracking array case.

3.5 MODULE AND PANEL DESIGN

As mentioned, modules are defined as a set of cells interconnected to form a handleable unit. For purposes of the present study, the modules do not include a frame. Supporting frames are considered as a part of the panel with one or more modules assembled into a frame to form a panel. Module and panel designs are, of course, strongly interdependent from a structural viewpoint. The baseline structural loading was assumed to be 50 psf. Variations in this loading and resultant design changes are discussed further in Section 5 and in conjunction with array types in Section 4.

3.5.1 Module Design

The detailed design of modules is beyond the scope of the present study. Module design is being addressed in detail by several manufacturers in the Automated Array Assembly Task of JPL's LSA program. However, several aspects of module design are addressed herein from a structural viewpoint.

The function of the module is to protect and support assemblies of cells, transmitting wind and other forces to the soil through the panel frame, array structure and foundation. Low-cost designs tend to combine as many functions as possible into a single structural element. Thus, the baseline module design considered herein includes a glass superstrate that functions to both support and protect the cells from the environment.

Several studies have shown glass to be a durable, non-yellowing, and cleanable cover material. It also seems to offer slightly more protection against damage by hail than other designs and is an acceptable electrical insulator. Consideration of the economics of solar energy lost due to absorption in the glass leads to selection of a glass with a low iron content in spite of its price premium. Similar evaluations also favor selection of higher cost but thinner tempered-glass sheets over annealed glass. Calculations based on preliminary non-linear analyses performed at JPL and manufacturers' literature indicate that very thin glass sheets could be used with most of the loads under

C-2

consideration herein. However, present manufacturing capabilities appear to limit the availability of tempered, low iron content glass sheets to thicknesses of about 1/8 inch (nominal) or greater because of problems with handling and heat transfer during tempering. Thus, 1/8 inch thick glass is used for the baseline design.

Module sizes being postulated at present range from about 2 by 4 feet to 4 by 4 feet and are used to form single module panels. A previous Bechtel study (Ref. 3-1) indicated a slightly larger module, e.g., 4 by 8 feet in an 8 by 16 foot panel, will have the lowest cost when panel costs are taken into account. Panel costs increase for larger sizes due to the cost of thicker glass and energy lost in the glass. For smaller sizes, higher panel assembly costs dominated. Large panel sizes are currently being used for solar thermal collectors. As cell manufacturing technology advances and cell costs decrease, the cost of a single, large module will tend to become more acceptable if it must be discarded during manufacturing or after a failure in the field. Since this present study is directed at large central power plants to be built in the post 1986 time frame, a 4 by 8 foot module size is selected for purposes of this study.

The thickness required for a glass (or other material) plate is more dependent on span than on surface area. That is to say, a 4 by 4 foot module and a 4 by 8 foot module will require very nearly the same thickness of glass for the same loading and method of support. Thus, the 2:1 aspect ratio was selected.

For cost estimating purposes, the module is assumed to consist of a sheet of 1/8 inch thick, low-iron, tempered glass, a set of interconnected cells embedded in 0.030 inch of PVB, a back cover of 0.0075 inch Mylar, and a pair of electrical connectors. Since the back cover will not be as exposed to sunlight and weather as would a front cover, Mylar was selected over Tedlar because of its lower cost.

The thickness of the Mylar, and thereby its cost, is set by insulation requirements imposed by the dc system voltage, as discussed in Section 3.4.2. The nominal operating voltage for the dc bus is 1500 volts. The module insulation must be capable of withstanding this voltage level. The glass superstrate will easily withstand this voltage, but the back cover material thickness may be increased over what would be required to provide protection against the weather, particularly for the moderately high voltage likely to be used in large installations. The connectors are a quick-disconnect type (such as the Sure-Seal available from ITT Cannon) in order to facilitate installation. Connector size varies from about 50 to 100 amperes for the various panel and array configurations investigated in this study. The nature of the connector design appears to render any cost differences within this range insignificant.

Other module configurations are being proposed by various manufacturers. These include use of metal or other substrate materials for structural support. For all designs, the encapsulation system must provide adequate electrical insulation. Metal substrate designs must include an insulating sheet between the cells and metal. Although, in this case, the insulator's weatherability is much less important. The top cover must, of course, be a good insulator in addition to having suitable weathering and light transmission properties.

A cursory comparison of the relative costs of glass superstrate and metal substrate module designs can be made as follows. Tempered, low-iron content, 1/8 inch thick glass (e.g., ASG Industries Lo-iron) costs approximately $0.39 per square foot. An equivalent metal substrate would cost approximately $0.38 per square foot (for a 0.050 inch thick steel, stamped to improve plate strength). The cost of adding a protective coating to the steel will add $0.15 to $0.30 per square foot. Cell, adhesive, connector, and assembly cost would be essentially the same for both cases. In addition, the glass module design requires a back cover (e.g., Mylar) while the metal module requires a similar front cover and an insulating sheet between the cells and steel. Thus, the steel substrate module appears to be slightly more expensive in this cursory evaluation. Clever design or manufacturing technology might change this. Also the cost differences would tend to be less for low voltage designs where insulation requirements are less stringent.

The estimated cost of the 4 by 8 foot glass superstrate module is presented in Table 3-7. Portions of the estimate are based on module cost information provided by JPL.

TABLE 3-7

MODULE COST BREAKDOWN (1975 $)

Item	Cost ($/m²)
Cell Assembly [1]	40.00
Glass	4.20
PVB (.030")	7.12
Mylar (.0075")	0.79
Connectors	1.16
Assembly Labor[1]	7.00
Module Cost	60.27

[1] Supplied by JPL

3.5.2 Panel Design

Two panel sizes were evaluated, a 4 by 8 foot panel with a single module and an 8 by 16 foot panel made up of four 4 by 8 foot modules. The basic construction is of lightweight steel sections. Rubber gaskets are used to hold the modules into the panel. A quick-disconnect electrical connector is included to provide a ground connection for the panel frame. The designs presented are workable designs evolved for purposes of this study, but without extensive time spent to optimize them. Further optimization and cost reduction may be possible with future detailed study of module and panel frame design for a particular array concept.

8 by 16 Foot Panel. The basic design of the 8 by 16 foot panel is shown in Figure 3-18. Lightweight steel is used to form the shapes indicated in a manner similar to that used to make metal wall studs. The depth of the sections vary with loading and array design. The rectangular structural tube edge member, shown in section AA, is a channel section for the horizontal and tracking array designs.

Assembly consists of positioning precut frame sections into a jig and welding them. A protective coating is applied to the welded frame and hold-down clamps. Four encapsulated glass modules are fitted with rubber gaskets and placed on the frame. Hold-down clamps are then screwed into place to secure the modules. Assembly is completed by attaching a pair of electrical connectors on short wire leads to the frame to provide for grounding of the frame in the field. This connector is of the same size and type used for the intermodule electrical connectors.

4 by 8 Foot Panel. The basic design of the 4 by 8 foot panel is shown in Figure 3-19. The frame members are made of lightweight steel formed into shaped sections. The thickness of the material varies with loading. Both ends of the two 4 foot members have tabs which are inserted into the 8 foot members and are secured with screws as shown in the corner detail in Figure 3-19.

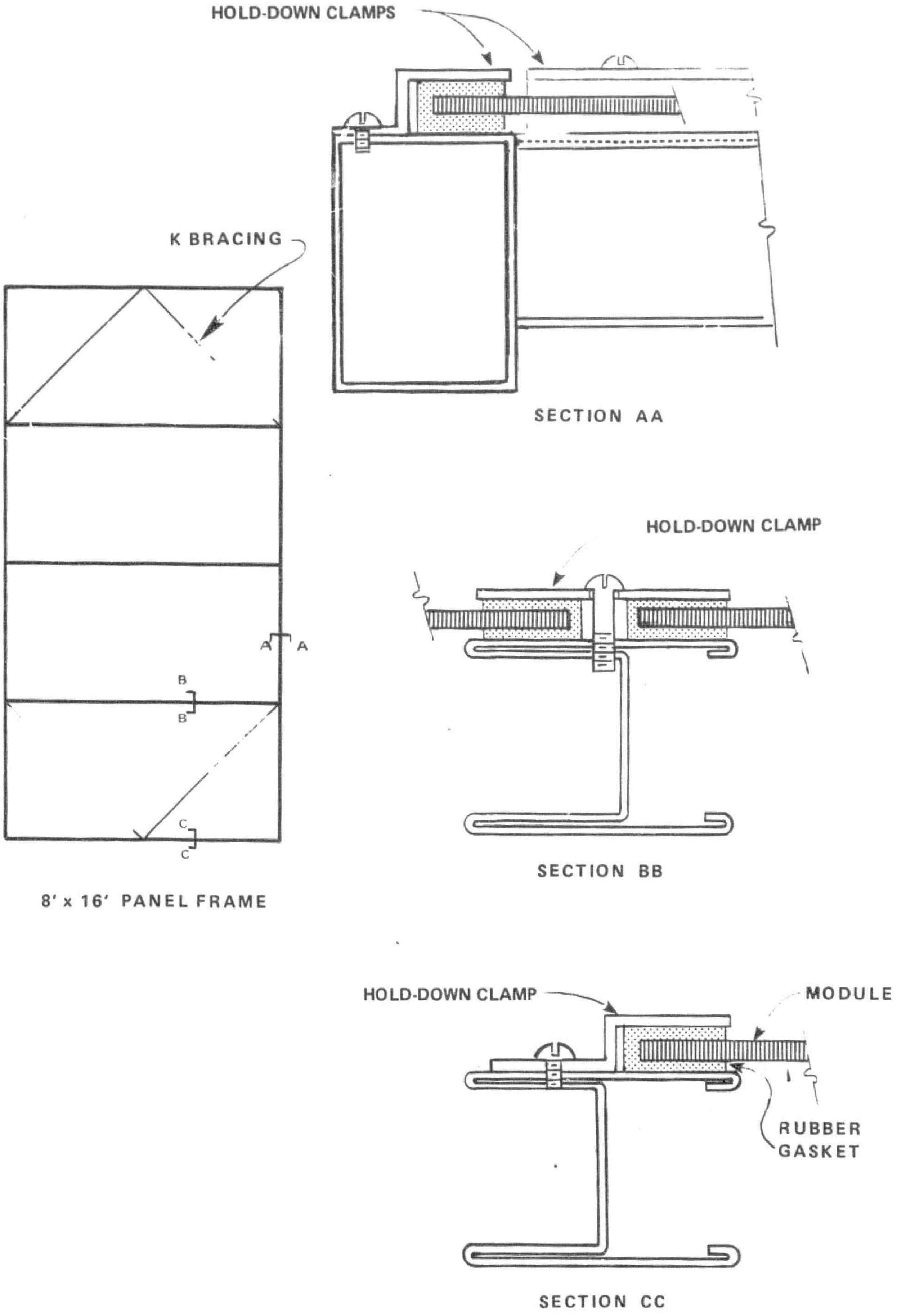


Figure 3–18 8 by 16 FOOT PANEL

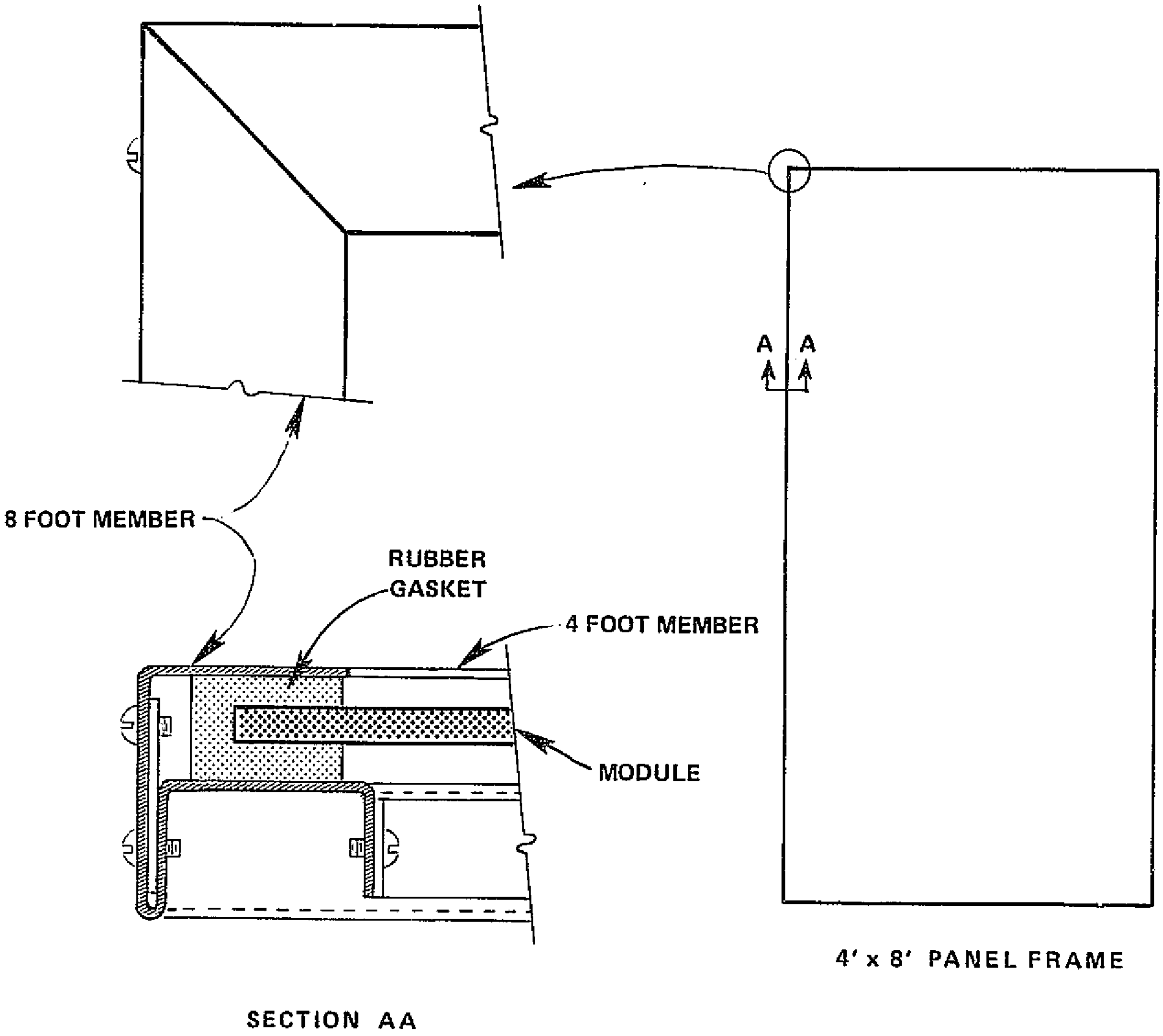


Figure 3–19 4 BY 8 FOOT PANEL

The four frame members are cut, welded, shaped and have a protective coating applied before arriving at the assembly area in the module manufacturing plant. Assembly consists of fitting the four gasket sections and frame members onto a module. The corners are then bolted together and the frame grounding connectors are attached.

Protective Coating. Two types of coatings, inorganic zinc and galvanizing, were evaluated for protection of the panel frames and array structures. Proper application of an inorganic zinc coating on carbon steel requires that the surface be cleaned. Abrasive blast cleaning in accordance with the Steel Structures Painting Council standards, SSPC-SP10, is recommended. The cost of this preparation is about $0.28 per square foot of structural surface (not array surface area). The cost of applying the coating is about $0.085 per square foot, and the cost of the coating material is $0.025 per square foot per mil of thickness. Thus, the total cost is approximately $0.44 per square foot (for a 3 mil coating).

Most coatings of inorganic zinc are applied to a dry film thickness of 3 mils. Inorganic zinc protective coatings can last up to 30 years in a desert environment. Data are not available to indicate whether a coating of half that thickness would result in half the life. Since only a small portion of the total coating cost is associated with the material, it is recommended that the standard thickness be applied. Cutting the coating thickness in half would only reduce the cost by 8.5 percent.

To protect the inorganic zinc, it is recommended that a topcoat of aliphatic polyurethane be applied. This will bring the total protection cost to about $0.55 per square foot of surface protected. This corresponds to approximately $6 per square meter of array surface for the 8 by 16 foot, horizontal array panel framework.

Galvanizing is typically applied with a thickness of 4 mils (2.33 ounces per square foot). Table 3-8 shows an estimate of expected service life (onset of rusting) of such coatings in various environments. Local site conditions will greatly alter these numbers. Galvanizing is sensitive to the presence of industrial pollutants such as sulfur and moisture.

TABLE 3-8

EXPECTED SERVICE LIFE OF GALVANIZED STEEL

Environment	Expected Service Life (years)
Industrial	5-15
Seacoast (>1 mile)	10-25
Rural	40-100

Hot dip galvanizing is typically costed on a weight basis rather than on a square foot basis. Prices range from about $0.08 per pound of steel coated for heavy structural members to $0.17 per pound for very lightweight members in small quantities. Most of the panel and structural members for the designs evaluated herein are lightweight but the quantities are large. A cost of $0.10 per pound is used. This is approximately equivalent to $0.17 per square foot of area coated and translates to $2 per square meter of array surface for the 8 by 16 foot horizontal array panel. Based on the above, the cost of hot dip galvanizing is used for cost estimating purposes. The problem of how to best protect the panel frames and array structures would be addressed in a detailed design study, and final price for protecting the large amount of material need would likely be negotiated.

3.6 CONSTRUCTION

3.6.1 Schedule

The baseline schedule shown in Figure 3-20 can be applied to all five of the array designs evaluated herein, with appropriate changes in manpower loadings to compensate for complexity of design and construction. This schedule represents an estimate of reasonable minimum times required during the several phases in construction to avoid having multiple work crews interfere with each other. However, shorter schedules could be achieved if overtime during construction were programmed. Longer schedules are, of course, possible. The accuracy of the estimated schedule is consistent with the level of engineering detail of this study.

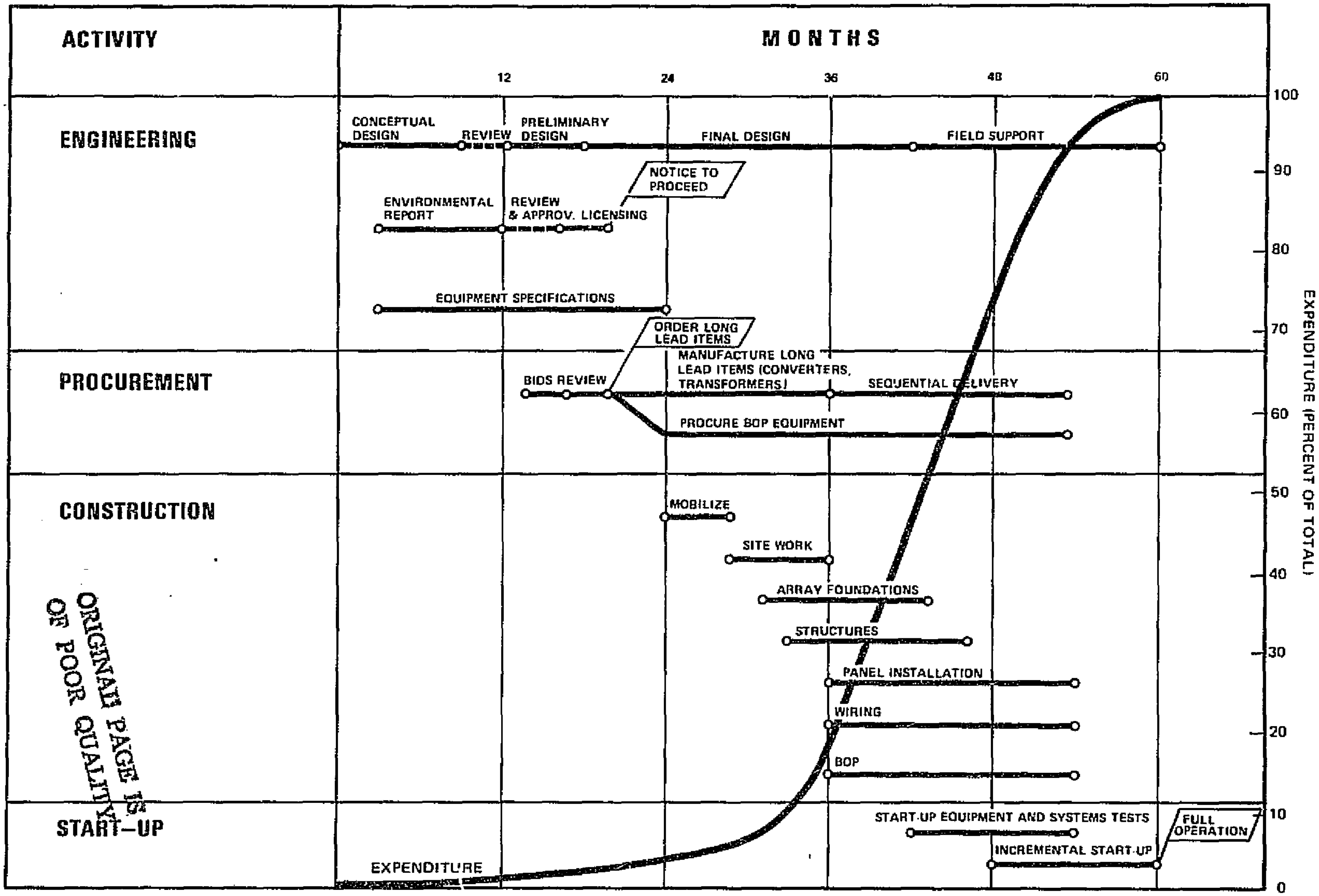


Figure 3–20 ENGINEERING AND CONSTRUCTION SCHEDULE

The following assumptions were included in deriving the minimum-time schedule:

- Site selection is completed at the start of the conceptual design.
- Site soil conditions are similar to those assumed in Section 3.3.1.
- There are no major delays due to licensing and environmental impact report procedures.
- No overtime is included beyond a nominal 5 percent allowance.
- There are no protracted labor disputes or periods of adverse weather.
- Solar panels can be manufactured and shipped to the site at a rate of 130 MW per year with a 12 month lead time.
- All balance of plant equipment (including converters and batteries) are commercially available.
- Equipment deliveries remain on schedule.
- No time-contingency is included in the estimate.
- Labor is nearby, available, and does not require training.

It is also assumed that groups of arrays can be tested and turned over to production of energy as panel installation and wiring are completed. This assumption does not greatly shorten the length of the schedule, but this incremental startup does improve the plant economics by adding revenue during construction.

Further refinement in engineering detail will allow schedules to be estimated with greater accuracy. Knowledge of the site's geology is needed to accurately estimate clearing and grading operations. Similarly, adverse weather conditions at the site can lengthen the estimated schedule. Also, remote or inaccessible site locations will add to the construction schedule and plant cost.

It is possible that the engineering time shown in the schedule may be shortened by several months if current DOE studies and demonstration projects continue. It is anticipated that such efforts will lead to a better definition of array design requirements and optimized array designs for site locations throughout the United States. By the time photovoltaic central station power plants become economically viable, several large photovoltaic plants will likely have been built and standard photovoltaic panels or modules are available. These factors will tend to reduce the amount of engineering effort required for photovoltaic central station power plants.

3.6.2 Installation

The majority of the installation effort will be for the array foundations, structures, and panels. The remaining balance of plant primarily consists of standard items, and their installation is not discussed in this report.

Array installation begins after site preparation has been completed. Installation procedures for the rack array design are described, followed by the variations in installation due to the other array designs. Other scenarios are also possible.

Survey teams will stake out the locations for the concrete foundations. Trenches are excavated for the foundations to provide resistance to the sliding forces resulting from wind loading on the arrays. As a section is completed, the precast foundations are trucked to the point of installation within the plant. Scheduling of the precasting facility is to be coordinated so that trucks arrive at the site and proceed directly to the point within the plant where the foundations are to be placed. This eliminates double handling of the foundations. A supply of precast foundations are stockpiled on site to allow installation to continue in the event of minor scheduling difficulties. A crane is used to remove the foundation from the truck and position it in its surveyed location. A team of four workers sets the foundation into position. This team is comprised of one truck driver, one crane operator, and two ground workers. It is estimated that each foundation will require slightly more than one manhour to place, depending on size. As foundation work is completed in an area, a second team installs the array back support members and panels. Panel installation procedures are illustrated in Figure 3-20. Although an 18 foot trailer is illustrated, 36 foot trailers could be used to carry two crates of panels. Flat-bed trailers are used to carry panels from the manufacturer to the site. As with the precast foundations, delivery schedules are coordinated with installation, and a stockpile of panels on trailers is maintained on site to accommodate variances in schedules. A crane-equipped tractor (see Figure 3-21) is used to tow the trailer to the installation area and is positioned adjacent to the foundations in the roadway between array subgroups.

In addition to the panels, the trailer carries a supply of support members. The crane boom is fitted with a vacuum lift device, such as the Manhandler series available from the C.R. Laurence Company. Control of the crane and lifter is from a man-bucket mounted on the end of the boom. The crew is composed of a driver, a crane operator and two ground workers. Panels are lifted from the shipping crate on the trailer and brought into position for mounting. The two men on the ground first bolt the support members to the foundation and, after positioning, secure the panel in place. The upper edge of the panel is connected first by means of pins through receiver tubes and the back member. As the two workers bolt the holding clamps to the lower edge of the panel, the crane operator repositions the lifter over the next panel to be installed and the cycle is repeated. Electrical connections are made at this time by mating the quick-disconnect panel connectors. Eight panels are installed (four on either side of the road, two panels deep) before the truck is moved forward to the next set of foundations. It is estimated that the total procedure requires approximately one manhour per panel.

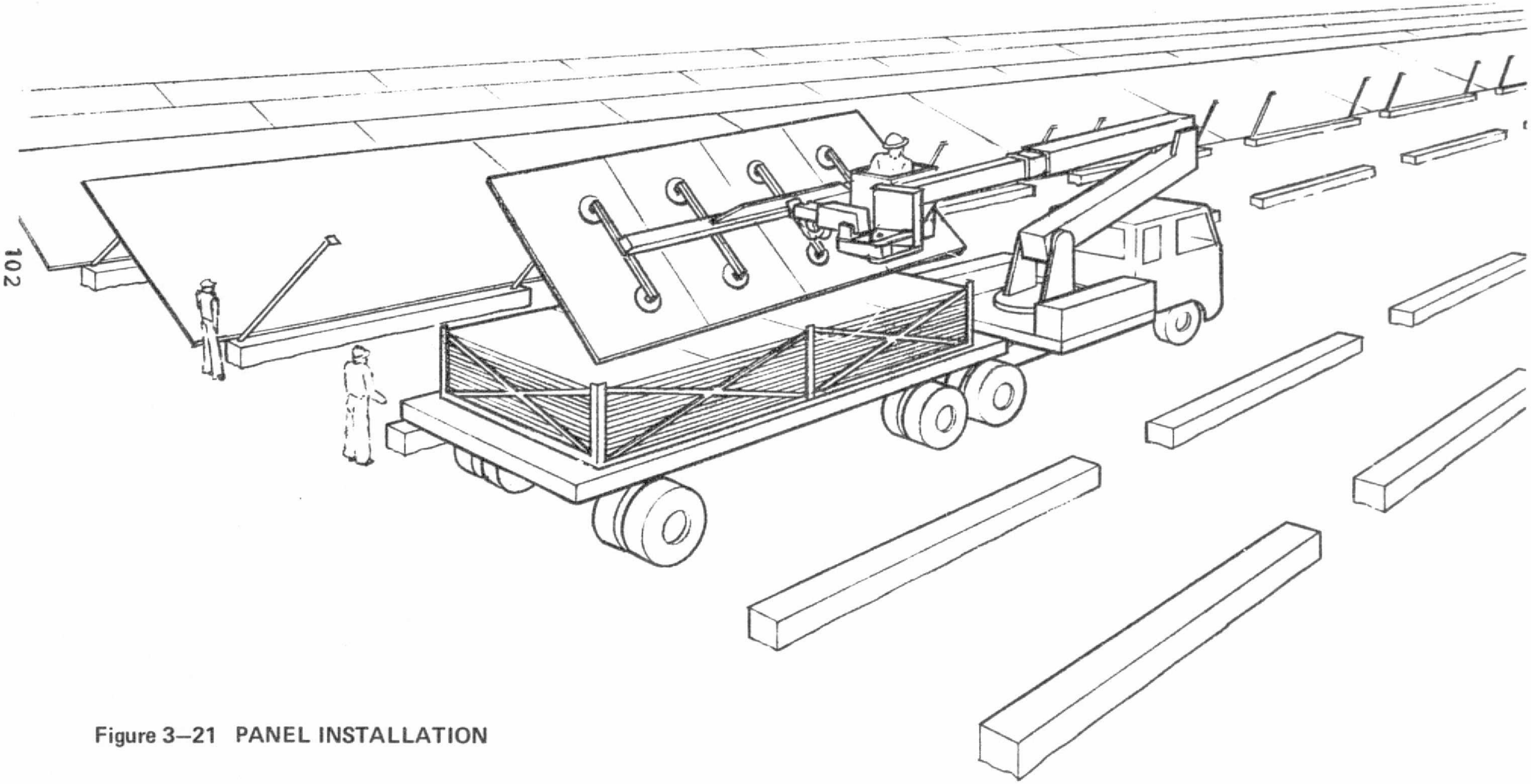


Figure 3–21 PANEL INSTALLATION

Installation for the tandem array proceeds as described for the rack array, except that the truck carries one crate of panels and one crate of 10 by 16 foot reflector panels. The reflector panels are positioned and bolted in place after installation of each adjacent solar cell panel.

Installation for the horizontal array is simpler than for the rack array. Since the horizontal forces are greatly reduced with this design, there is no trenching and the foundations are set directly on the ground. Also, there are no back supports to install. Panel installation is essentially as described above for the rack array.

Installation of the seasonally adjusted arrays is similar to the rack. In this instance, however, the adjusting mechanisms are installed before the panel installation step.

Installation of the tracking array is more involved than the other four designs. As before, foundation locations are surveyed after grading operations are completed. Holes are drilled for a 30 inch diameter, 10 foot deep caisson. Preformed rebar cages are lowered into place, and the concrete is poured. The pipe section which forms the stem is bolted to a baseplate set in the foundation. The upper portion of the stem and tracking mechanism drive are assembled onto the lower stem. The panels are lifted and bolted into place. The panels and tracking drive wiring are completed, and the tilt angle is adjusted to the latitude angle plus 10°.

Installation manhours are also presented in conjunction with the cost data in Section 4.

3.7 OPERATION AND MAINTENANCE

3.7.1 Operation

Operation of a photovoltaic central station is expected to require a minimal amount of onsite operator action. As presently conceived, the operation of the plant could be completely automated. In fact, because of the number of power conditioning units and arrays, an automated system would be the only means to effectively monitor and control the plant. Control of plant operation is primarily by means of an onsite computer and ancillary subsystems, with provisions for operator override.

The control system would provide for:

- Operation of converter equipment when sufficient insolation is present
- Control of real and reactive power flow by preprogrammed course, onsite operators or utility dispatch office
- Monitoring, logging and data reduction of plant operating parameters
- Detecting and logging out of tolerance equipment performance

- Safe shutdown of converter equipment in the event of a fault condition, logging the event, annunciating to the plant operators.
- Maintenance of preset power output and charging of batteries, if onsite energy storage is included
- Control of array tracking (where required)

As presently envisioned, the major functions of the plant operators would include:

- Monitoring and reporting of plant performance data
- Dispatching maintenance crews to correct out of tolerance or fault conditions
- Utilizing weather data to predict plant performance and coordinate operation with the utility dispatch office
- Control plant access and generally supervise plant operation

The number of plant operators required will vary with the practice of the utility system. It is likely that at least two operators will be required during times of plant operation. For plants with onsite energy storage, operation would be on a 24 hour basis, since the batteries would be charged with off-peak utility energy (see Section 3.4.5). An operator will be required on a 24 hour basis in any event (e.g., to supervise night-time array washing operations).

Hours of plant operation will vary with the season of the year and whether onsite storage is included. Several modes of plant dispatch are possible, but most studies seem to agree that solar energy should be dispatched as it is available. As discussed in Section 3.4.5, batteries are most economically charged by off-peak utility energy. Thus, plants with onsite storage would be operated (either dispatching or receiving energy) on a 24 hour basis.

3.7.2 Maintenance

Routine plant maintenance is discussed in this section. Cleaning and total replacement of panels are considered major scheduled items and are discussed separately in Sections 3.7.3 and 3.7.4, respectively.

Panels. It is anticipated that a major maintenance operation will be the replacement of defective panels. Because of the early state of development of large terrestrial arrays, few data are available on the failure rates of panels. However, it has been postulated by JPL (Ref. 3-21) that there will be an initial period of high failure rates (of 10 percent per year), which will taper off in about a half a year to a more or less constant failure rate (about 0.2 percent per year) for the life of the panels. Toward the end of panel life, failure rates will increase. End of life will occur when it becomes more economical to replace groups of arrays or all of the arrays in the entire plant rather than individual panels. Aside from random complete panel failures, end of life for the panels is an economic phenomenon accompanying physical degradation. Thus, end of useful life would also be influenced by technology developing lower-cost, higher-efficiency replacement panels.

It is assumed that panel failures will occur at random locations throughout the plant and that the overall characteristics of the new panels will allow direct replacement for the failed panels.

For the five array designs, panels are wired in series to obtain dc system voltage and form arrays. Thus, complete failure of a single panel would remove the entire array from service. For the rack array, complete failure of a 4 by 8 foot, 430 watt peak module within a panel would remove almost 100 kW from service, making repair an economic necessity. This type of failure would be detected by the instrumentation located at the power conditioning unit and logged by the plant computer system. The plant operator would dispatch a maintenance crew to identify the failed panel. The equipment and procedures used are described in Section 3.4.4 and Reference 3-1. Panel replacement would involve the equipment and procedures used during initial installation (see Figure 3-19 and Section 3.6.3). In this case, however, the old panel would be removed and stored on the truck before the new panel is installed. With the present design, an entire 8 by 16 foot panel would be replaced in the arrays when one of its 4 by 8 foot modules failed. A new module would be installed in the panel in the plant maintenance area. If 4 by 8 foot panels made of 4 by 8 foot modules are used, the single module/panel unit would be field replaced. Defective modules would not be repaired on-site (and likely not at all).

For the majority of the plant life, it is estimated that a single crew of three people will be sufficient to handle module failures. The assumed module failure rate of 0.2 percent per year translates to an average of four modules per (working) day. It is estimated that it will require an average time of 55 minutes (2.75 manhours) to identify and replace a panel. This includes time to:

- Dispatch the crew
- Drive to the affected area of the plant
- Locate the defective array
- Connect the test apparatus
- Locate the defective module
- Drive to the defective module
- Disconnect and remove the defective panel
- Install and connect the new panel

The above estimate does not include time elapsed between occurrence of the failure and dispatch of the crew, or time required to restock the maintenance vehicle and disposition of failed panels.

The horizontal array configuration is compact and thereby reduces the time needed to drive to the affected group and walk along the arrays. However, access to panels in the interior of the group is difficult. Access to tracking arrays is easy, but their spacing requires that greater distances be covered. Within the level of detail for the present study, the repair-time estimate for each array design is considered to be approximately equal.

For higher failure rates (e.g., 10 percent per year during startup) more crews would be needed. Replacement time would be reduced to about 45 minutes because of less dispatch and driving time. A 10 percent failure rate translates to approximately 200 failures per day with all 200 MW installed. Since a phased startup is planned and the initial failure rate is postulated to last for approximately six months, only 5 crews are required during startup. However, crews and equipment dedicated to repair during the phased startup operations would not be available to participate in installing the initial complement of panels. Thus, it is postulated that failed panels be identified during regular working hours (as required by the test methods) and replaced during a swing-shift operation. With this scenario, two 2-person crews are used to identify failed modules or panels and three 3-person crews are used to replace panels.

As the panels approach end of life, the number of crews must be increased to match the increasing failure rate. It appears that by the time complete replacement operations are started five crews will be needed.

Converters. The converter equipment is expected to require a minimal amount of repair and maintenance. Similar solid-state Uninterruptible Power Supply (UPS) systems have mean-time-between-failures of 20,000 hours (Ref. 3-22) to 600,000 hours (Ref. 3-23). Proposed equipment, similar to what would be required in photovoltaic power conditioning units, is estimated to have a mean-time-between-failures of 7000 hours, with a mean-time-to-repair of 1.5 hours (exclusive of time to dispatch the repair crew).

Depending on converter design and site environment, additional maintenance would include changing air filters on the converters' cooling system.

Electrical. Aside from the arrays and converters, all of the remaining electrical systems are comprised of standard equipment. It is esimated that 500 manhours per year will be needed to maintain this equipment.

The ac and dc underground wiring systems are designed to be maintenance free for the life of the plant.

Civil. Road maintenance requirements are highly site sensitive. Local meteorological, topographic and geologic conditions influence the requirements greatly. Assuming average conditions of these site parameters, yearly maintenance cost for the roads and site drainage systems is estimated at $0.50 per square yard for gravel paved surfaces and $0.10 for soil cement surfaces.

Weed Control. Control of the growth of undesirable vegetation is another highly site-sensitive item. The arrid desert region of the Southwest might require little or no effort in weed control. The subtropical Southeast and South on the other hand may require frequent and extensive weed control effort. Uncontrolled vegetation growth in these areas could cause substantial shadowing.

Considering the large areas required by photovoltaic panel fields, the only known effective way of controlling weed growth is soil sterilization by chemical spraying. In areas where precipitation is substantial, the effectiveness of the sterilizing chemicals is shortened by the frequent leaching action of the rain water. Also, the frequent usage of the sterilizing chemicals might be environmentally unacceptable.

Based on current agricultural practice, it is estimated that chemical weed control will cost $200 per acre per year.

3.7.3 Array Cleaning

As discussed in Section 3.2, site environment factors will act to deposit dust and dirt on the module surfaces and thereby reduce plant output. Estimates of power reduction due to this effect range from 5 to 35 percent over periods of a few weeks to several months. This effect is highly site dependent (see Section 3.2.6) and also depends on season and, possibly, the type of module surface (e.g., glass, Tedlar). This problem was addressed in a previous Bechtel study (Ref. 3-1), where it was found to be economic to wash the arrays for almost all expected rates of power degradation and values of energy sold. Thus, provisions for washing the arrays are included herein.

Two types of washing equipment are used: one type for the rack, tandem, horizontal and seasonally adjusted arrays; and one for the vertical axis tracking array. Both of these equipment differ from that previously proposed in Reference 3-1.

The first type consists of a large straddle-carrier (such as available from Drott Manufacturing Division of J.I. Case or Renner Manufacturing Company), spray washing units and ancillary equipment. The spray units are based on data developed by Martin Marietta Corporation for washing float-glass heliostat mirrors in a solar thermal plant (Ref. 3-16). Test results indicated that the glass surface is best cleaned by a spray of hot, demineralized water without detergents or other additives (which tend to leave residues). Based on the above results, a rate of 0.0675 gallons per square foot is used.

Water is assumed to be continuously pumped from an onsite well, processed through a demineralizer unit and stored in a tank. The cost of operating the demineralizer is estimated to be \$0.0017 per square foot of surface washed (\$0.0006 to \$0.003/ft^2 range) for output water with 8 ppm dissolved solids. However, design and operation of a demineralizer unit is critically dependent on the quality of water available at the site.

The carrier straddles a subgroup of arrays, and multiple spray heads are directed onto each array surface. Table 3-9 gives the times required to wash all of the arrays within a plant using one vehicle and a vehicle speed of 100 feet per minute (1.14 mph). If site conditions warrant more frequent washing, another vehicle must be added, thus doubling the washing rate. For the tandem array design, the solar cell panels and reflectors are washed simultaneously. The washing times include time taken to fill the vehicle tanks from the storage tank and drive to the array. One person is needed to drive each vehicle. The cleaning operation is scheduled for after sunset to avoid loss of energy from the array being washed.

TABLE 3-9

ARRAY WASHING DATA

Array Design	Array Area (million ft^2)	Water Required (million gal)	Time Required (8-hr shifts)
Rack	14.9	1.2	23
Tandem	25.9	2.0	31
Horizontal	16.6	1.3	18
Seasonally Adjusted	14.9	1.2	23
Tracking	14.9	1.3	24*

*For 10 washing vehicles

Since the tracking arrays are spread-out, tall, individual units, they are not well suited to cleaning by the method described above for the other array types. The cleaning procedure postulated for the tracking array follows that proposed by Martin Marietta (Ref. 3-16) for their heliostats. However, a small degree of automation is added. As before, cleaning is by a spray of hot demineralized water. The procedure includes parking a truck parallel to an array. Once positioned, the driver electrically tilts a 16 foot long boom parallel to the array surface. The boom travels the length of the array (also 16 feet) on a truck-mounted track mechanism. Spray nozzles on the boom wash the array. Valving of the water is automatic with boom position on the truck. After the wash cycle, the boom is tilted to vertical and then repositioned on the track as the driver proceeds to the next array. For an assumed boom travel speed of 32 feet per minute, the cycle is estimated to take 45 seconds. Driving and parking adjacent to the next array is estimated to average 45 seconds. When the times to refill the truck tank and drive to the array field are added, the total time becomes 1.87 minutes per array. A fleet of ten trucks is then needed to wash the entire array field in twenty-four 8-hour shifts. An advantage for this washing scheme exists in that washing intervals can be decreased in small increments (i.e., add one truck and driver for a 10 percent increase in washing frequency).

As mentioned previously, the actual washing costs will be highly dependent on site environment characteristics. A parametric evaluation of cleaning economics can be found in Reference 3-1.

3.7.4 Panel Replacement

As mentioned in Section 3.7.2, JPL has postulated that the characteristics of solar panel life will require a scheduled replacement of all of the panels at sometime during the life of the plant. The procedure to accomplish this total panel replacement essentially follows that described for initial panel installation in Section 3.6.2, except that the old panels must first be removed. The procedure postulated involves use of flat-bed trailers, as shown in Figure 3-20, to hold one shipping crate of new panels and an empty crate to receive the old panels. The foundations and struts, of course, remain in place. Using the same crew mix as described in Section 3.6.2, the old panels are unbolted and lifted into a crate on the truck. A new panel is then positioned and bolted into place. This procedure is used for rack and seasonally adjusted designs.

With the tandem design, two panels adjacent to the road in a subgroup are removed first and then the two adjacent inner panels are removed to allow better access between reflector panels. This procedure is repeated for panels on the opposite side of the road. Two sets of panels (inner and outer) are then installed, and the truck is moved. Two panels (inner and outer) are removed, two panels are then installed next to the first two panels and the cycle is repeated. A similar procedure is used for horizontal array design.

Access to the tracking arrays is relatively easy. Two old panels are removed and replaced by new panels on each structure.

The estimated labor required for total panel replacement for each of the five array designs is presented in Table 3-10.

TABLE 3-10

TOTAL PANEL REPLACEMENT LABOR

Array Type	Manhours (thousands)
Rack	120
Tandem	100
Horizontal	130
Seasonally Adjusted	120
Tracking	130

3.8 INSURANCE

During the course of this study, attempts were made to evaluate the cost of insuring against hail damage. Similar evaluations apply for other types of environmentally caused damage, such as by tornadoes.

One of the largest companies in the Factory Mutual Group was contacted through the offices of a local insurance broker. Their staff reviewed a previous Bechtel photovoltaic array design (Ref. 3-1) and found the design and design procedures acceptable. The basic plant designs described in this report would also be insurable. However, single event losses would be limited to $10 to $20 million (conservative) to perhaps $50 million (maximum). This may limit plant size.

If all the modules in a plant (at $0.50 per watt) could be destroyed by a single hailstorm event, the plant size would be limited to 100 MW (maximum) in order to be fully insured. As discussed in Section 3.2.5, predicting hailstone distribution and density with available data is difficult. All modules may not be damaged. Thus, plants may be larger than 100 MW and still be insurable against hail damage. Similarly, the swath of a tornado generally will not be wide enough to destroy all sections of the 200 MW (nominal) plants described in this report.

The cost of insuring against hail or other damage after 1986 is difficult to predict. However, based on present rates, the order of magnitude of annual insurance premiums is given by twice the potential loss divided by the recurrence interval (in years) for the damaging event in an area of the plant's size. To put this in perspective, available data were used to calculate a recurrence interval of 640 years for hail 3/4 inch and greater for Cheyenne, Wyoming. Three-quarter inch hail will not damage all modules, and other areas of the country have longer or shorter recurrence intervals. However, for a 640 year interval and 9 percent cost of money, the present worth of 30 years of insurance premiums is about $0.016 per watt. This is a small but significant fraction of module cost and points out a need to continue studies such as described by JPL in Reference 3-7.

Section 4

PLANT DESIGNS AND COST ESTIMATES

This section presents conceptual plant designs and cost data for each of the five array designs being evaluated.

To facilitate the design, cost analysis, and comparison of the five basic arrays, the following design parameters were adopted for the five baseline designs:

- Site latitude is 35°
- Nominal plant rating is 200 MW peak and is composed of 36 array groups each of which is nominally rated 6 MW (actual peak power rating is, of course, determined by the specific array concept employed, site latitude and losses within the plant)
- Nominal dc system voltage is 1500 volts
- Ac collection wiring is installed underground and operates at 34.5 kV
- Panels are 8 feet by 16 feet, and consist of four 4 by 8 foot modules
- Design loading for modules, panels and structures is 50 pounds per square foot
- Overall module conversion efficiency is 14 percent
- Shaddowing effects and attempts to determine the economic optimum interarray spacings are not included
- Peak power output ratings are based on maximum theoretical "best day" insolation, which was derived from Reference 3-2

The general plant configuration is shown in Figure 4-1. Group and subgroup dimensions for the five array designs are summarized

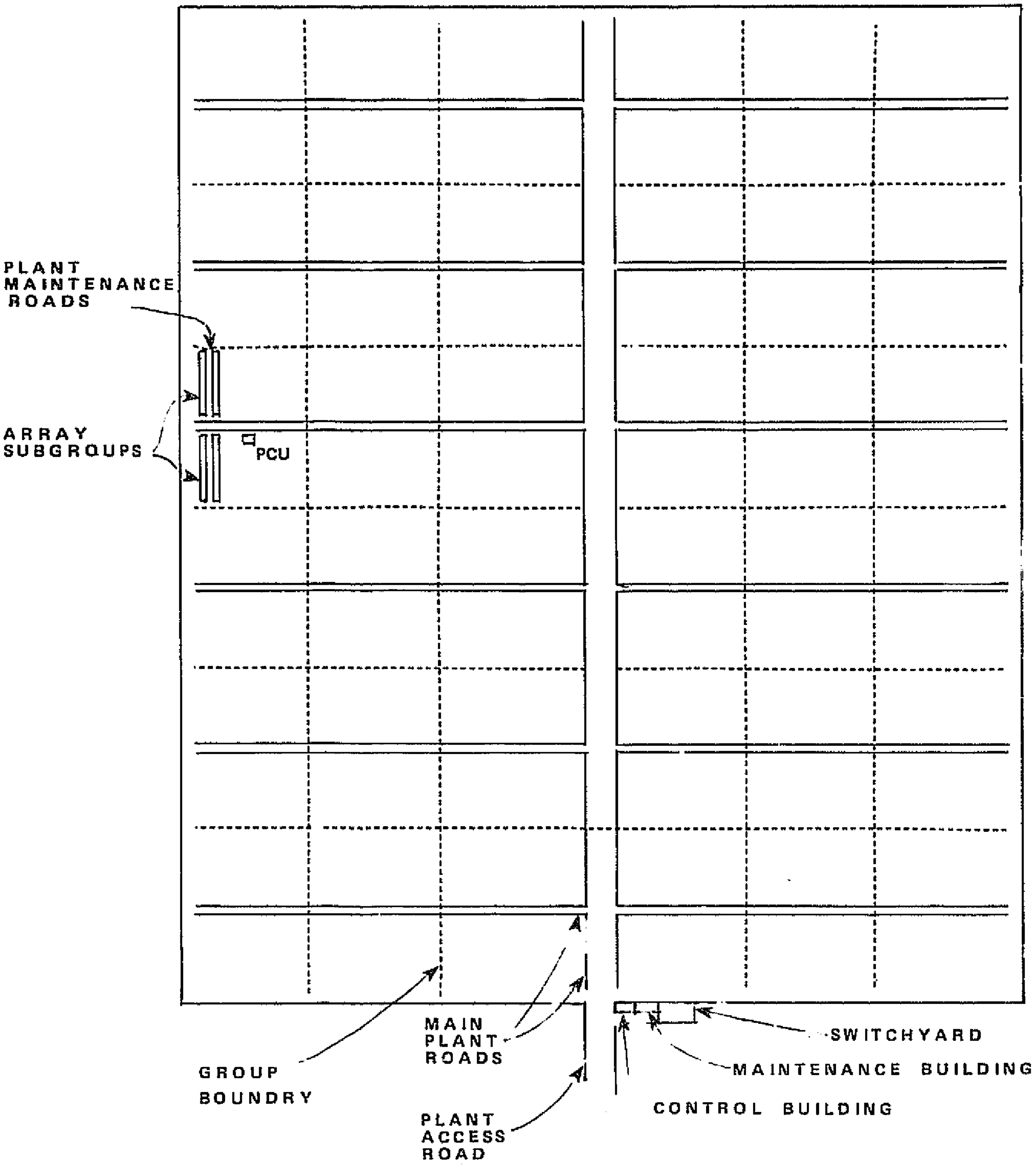


Figure 4–1 GENERAL PLANT LAYOUT

in Figure 4-2. The dimensions of each array and plant are also discussed in conjunction with each array type in the following sections.

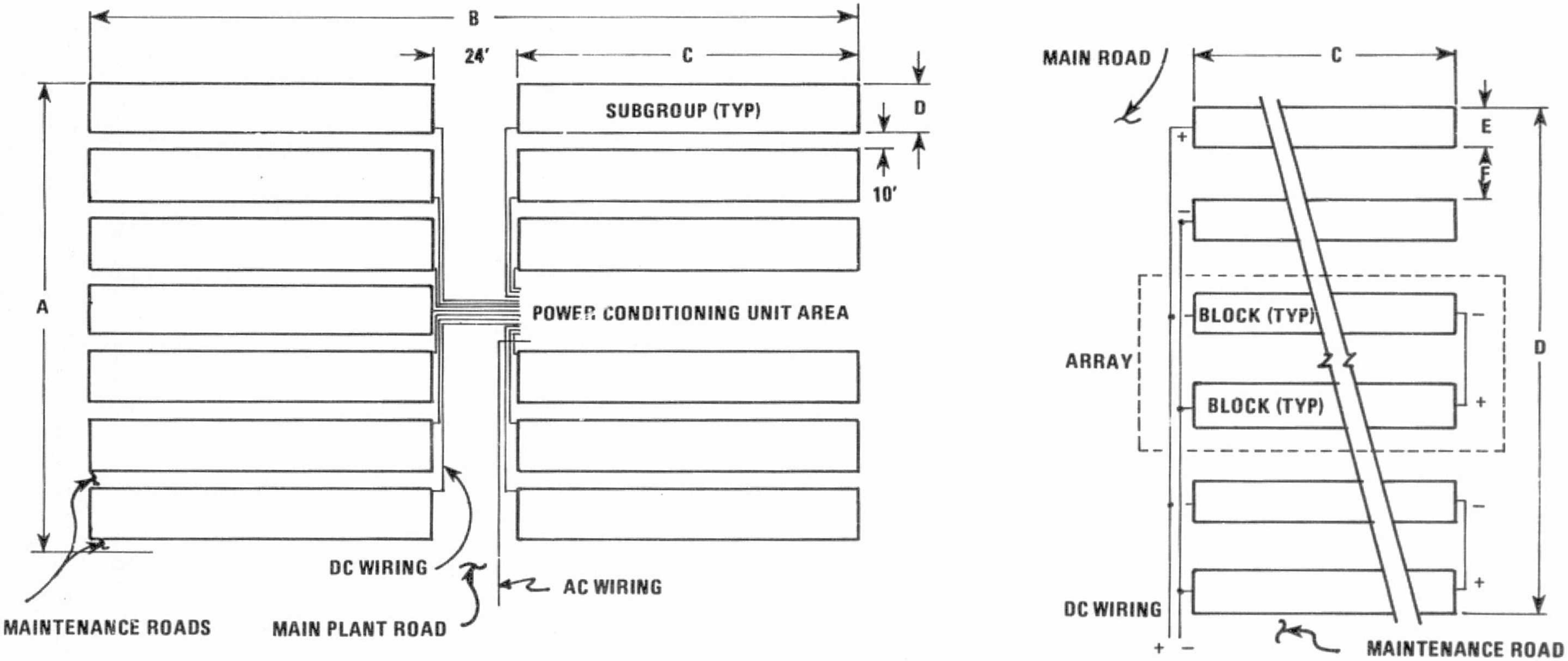
The basis of the cost estimates is presented in Section 4.1. This is followed by a description of each array concept, including the structural design for that concept along with the various elements of plant design affected by the specific array concept. A breakdown of the total plant cost estimate is included for each concept.

The effects of significant design parameters (e.g., structural loading, site latitude, panel size) on plant design and cost are discussed in Section 5.

4.1 COST ESTIMATES

All cost data in this report are presented in terms of first-quarter 1975 dollars. Costs were estimated in first-quarter 1978 dollars and translated into 1975 dollars by using the factor of 1.17 in the LSA Price Deflator Table supplied by JPL. In some instances, this may distort the cost data, since not all material prices have risen by this factor since the first quarter of 1975 (e.g., prices for fabricated steel products).

The code of accounts was derived by JPL to facilitate life-cycle cost analyses by computer.



GROUP

SUBGROUP

ARRAY DESIGN	GROUP				SUBGROUP					
	DIMENSIONS		NUMBER OF SUBGROUPS PER GROUP	MAXIMUM PEAK DC POWER (MW)	DIMENSIONS				NUMBER OF ARRAYS PER SUB-GROUP	NUMBER OF BLOCKS PER SUBGROUP
	A (FT)	B (FT)			C (FT)	D (FT)	E (FT)	F (FT)		
RACK	854	1004	27	5.6	490	51	6.6	6.9	2	4
TANDEM	715	1004	21	6.1	490	55	5.7	8.1	2	4
HORIZONTAL	592	1004	15	6.1	490	64	8	0	4	8
SEASONALLY ADJUSTED	896	1004	27	5.6	490	54	7.3	8.5	2	4
VERTICAL AXIS TRACKING	1728	874	54	5.6	425	48	16	16	1	30

Figure 4-2 GROUP AND SUBGROUP LAYOUTS

The accuracy of the cost estimates is commensurate with the level of detail in the engineering upon which they are based. As requested by JPL, the cost data is presented as the sums of the individual components without rounding off. Thus, the number of significant figures presented herein far exceeds that warranted by the accuracy of the estimates.

Cost data for materials were derived from vendor quotations, literature and in-house data. Cost data for cell assemblies and module and panel assembly costs were provided by JPL. Also, the cost of land was supplied by JPL as being $1710 per acre (1975 $).

Labor quantity estimates were derived from evaluations of the procedures involved and based on similar past construction experience. An average wage rate of $17.00 per hour (1975 dollars) is used for crew mixes considered typical for the types of labor involved. This wage rate includes base rate, normal benefits, and payroll related items such as the employer's contribution to unemployment insurance, social security tax, and workman's compensation insurance. It is assumed that some reduction over standard labor quantities will occur due to a learning curve associated with the repetitive nature and length of construction for certain of the installation operations. No other estimate for variations in productivity was included.

Distributable field costs include the costs of temporary construction facilities; miscellaneous construction services; construction equipment, tools, supplies and utilities; field office costs, preliminary operations and testing; project insurance and other distributable field costs. Temporary construction facilities include temporary buildings, work area roads, fences, power, water and sewage and minor temporary construction. Miscellaneous construction services include surveying, general cleanup, maintenance of tools and equipment, material handling, and watchmen or guards. Construction equipment, tools, supplies, and utilities include construction equipment rental, small tools, consumable supplies and the purchase of construction power, water and fuel. Field office costs include field staff personnel engaged in supervision, engineering, administration, warehousing and purchasing. Preliminary operation and testing include testing, assuring proper installation, adjusting and modification of systems prior to client startup operations. Project insurance includes insurance for public liability, property damage builder's risk, construction equipment, and damage from operation of plant. Other distributables include the costs for non-productive time (e.g., showup and voting time), storm damage preventive measures, repairs not covered by insurance and building permits. For this study, distributable field costs were estimated to be 75 percent of direct labor.

As used herein, engineering costs include costs for design engineering; estimating and cost control; purchasing, expediting and inspection; other home office services; and fees. Design engineering includes all engineering services performed by an architect/engineering/construction management firm. Estimating and cost control include the preparation of cost estimates, budgets, cost studies and similar services. Purchasing, expediting and inspection include purchasing and expediting the delivery of materials and equipment and inspection at a vendor's factory or warehouse. Other home office items include administrative, accounting, labor relations and similar services performed by the firm's home office or regional offices. Salaries, travel expenses, payroll taxes and insurance, vacation, holiday and sick leave pay, blueprints and engineering supplies, stationery and office supplies and telephone and telegraph expenses are included. Fees include all fees payable to the firm for management of the project. For the cost estimates presented in this study, the firm's involvement with solar panels is limited to preparation of structural, electrical, and general performance specifications for bid packages, purchasing, expediting, inspection and supervision of installation. Cell, module and panel designs are specifically excluded from the engineering costs presented herein. Engineering costs for the above services are estimated to be 6 percent of the total field cost. This value is considerably lower than for most conventional facilities due to a limited involvement in solar panel design, and due to the highly repetitive and relatively simple nature of the balance of plant design.

Included in the estimate is a contingency allowance for the uncertainty that exists with the present level of engineering in quantity, pricing or productivity and that is under the control of the constructor and within the scope of the project as defined. Implicitly, this allowance will be expended during the design and construction of the project. It cannot be considered as a source of funds for overruns or additions to the project scope. However, experience shows that it is quite difficult to assess the degree to which future processes are understood in the hardware sense. Thus, if the postulated arrangement of the plant components contains major uncertainties, or the design duty of plant components proves to be more severe than anticipated, or if additional major subsystems are ultimately found to be necessary, then the scope of the project is deemed to have been inadequately defined and this then would not be covered by the allowance. For purposes of this study, a contingency of 20 percent is applied to the balance of plant costs. No contingency is included for the cells, modules and panels.

Owner's costs during construction are variable with utility, site location, type of plant and interest rates. There is no past experience with construction of large photovoltaic plants. The estimate prepared for purposes of this study is a judgmental extrapolation of similar data for other types of plants and is, of course, subject to further refinement. Owner's costs consist of three major elements: interest during construction, other costs, and the cost of replacing panels during startup (see Section 3.7.2). These other owner's costs include startup and operator training; engineering and management; environmental impact report; seismic surveys, soil testing, etc.; licenses, permits and taxes; and insurance. Other owner's costs are estimated to amount to 6 percent of the total plant cost. For purposes of this study, spare parts are not included in the above. Interest during construction is estimated to be 15 percent of the total plant cost based on the construction schedule shown in Figure 3-19 and a 9 percent cost of money. Following Reference 3-21, the panel failure rate during startup is assumed to be 10 percent per year for a six month period (i.e., 0.83 percent per month). Other assumptions as scenarios will change this portion of the owner's costs accordingly.

Costs for photovoltaic plants and components are often presented in terms of dollars per watt or dollars per square meter. However, some of the designs evaluated herein have high peak power ratings in relation to the amount of energy produced. Similarly, for the five array designs evaluated, the same number of square meters of collector surface produces different amounts of power and energy for each design. The most meaningful comparison of the designs is on the basis of life-cycle energy costs. Computer analyses of this type are being conducted by JPL. In order to allow a preliminary comparison of the array designs to be made on the basis of energy costs, an annual fixed charge is used to determine annual costs. This fixed charge includes return on investment, depreciation, ad valorem taxes, income taxes, insurance and administrative and general expenses. Annual charge rates vary with cost of money to a utility and plant life. An annual charge rate of 17.5 percent is assumed for purposes of this study. No allowance for any future solar tax credit is assumed.

Since no site location has been selected, the theoretical insolation at 35° latitude from Figure 3-3 is used to present cost data normalized to energy in the array cost estimate table. Actual energy costs must be derived by multiplying this insolation by the fraction of theoretical insolation received at a site or by use of weather data tapes. Further, owner's costs and operating and maintenance costs must be added to arrive at actual energy costs.

In the above normalizing, the plant's net ac output power and energy are used, since this is what a utility would measure by.

4.2 RACK ARRAY

The rack array design consists of panels tilted at the local latitude. The basic configuration of the arrays for this design is shown by Figure 4-3.

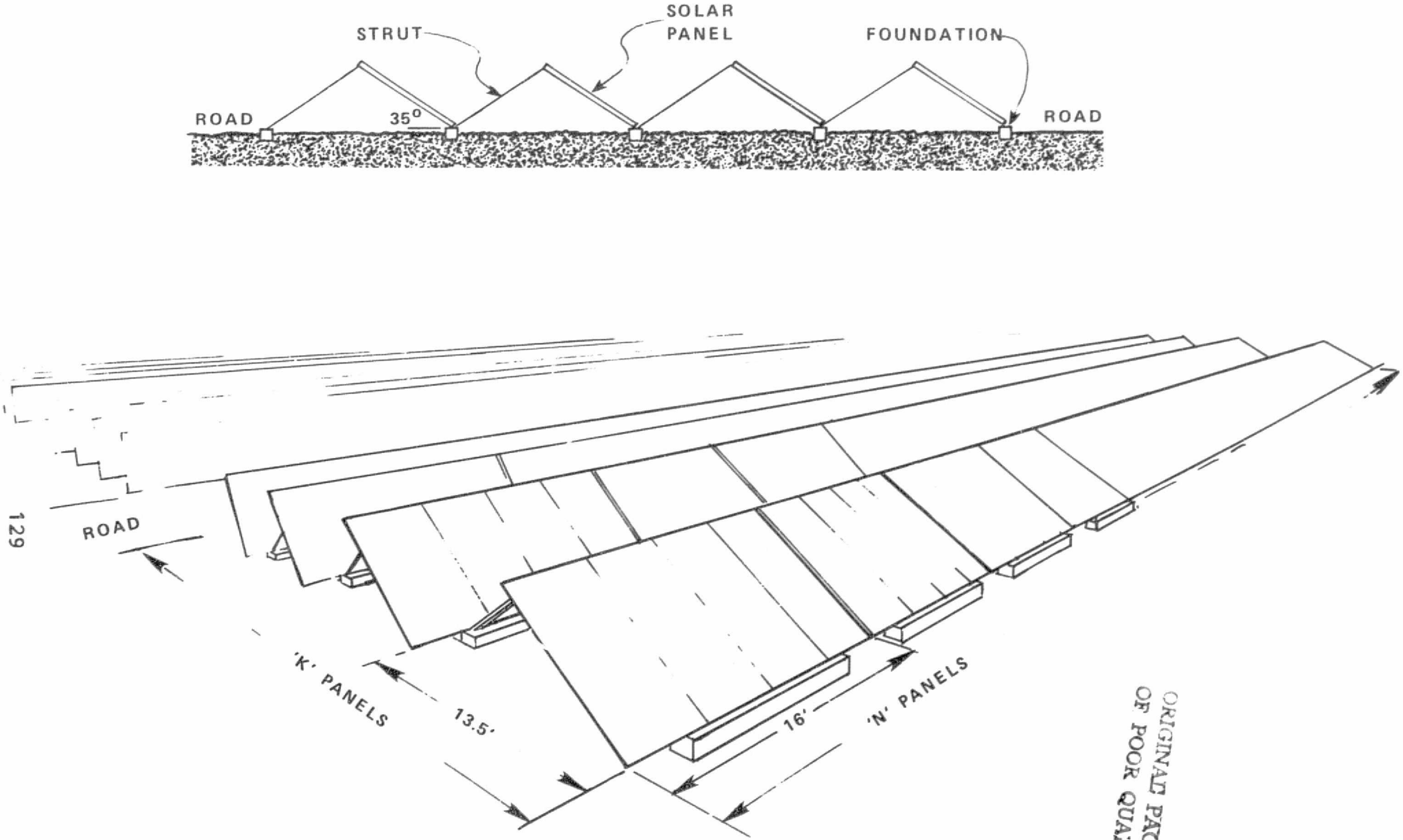


Figure 4-3 RACK ARRAY

4.2.1 Rack Array Design

As shown by Figure 4-3, the rack array consists of 8 by 16 foot panels (as described in Section 3.5.2). The panels are inclined at the local latitude with the 16 foot side horizontal and an 8 foot slant height. The lower edge of the panel is held by clips bolted to a concrete sleeper foundation. The upper edge is supported at two places by back struts sloping down and connected to the adjacent foundation. Thus, the panels share foundations, and a subgroup which is n panels long by k panels wide contains n x k panels and n(k+1) foundations. The struts and hold-down clips are located approximately 20 percent of the distance in from the slanted edges. The foundations are precast concrete sleepers, with threaded inserts for the hold down clips and receivers for the structural steel tubing used for the back struts. These struts are galvanized as discussed in Section 3.5.2 for panel frames. The mass of the concrete is used to resist uplift forces, and the concrete is set in trenches to resist sliding.

Spacing between panel rows, in the north-south direction, is equal to one and one-half times the panel height.

The baseline design is for a 35° latitude and 50 psf loading. The rack design was also investigated for loadings of 20, 35 and 50 psf at 35° latitude and 50 psf at 25° and 45° latitudes. The impact of these changes from the baseline design are presented in

Sections 5.1 and 5.3. No assumptions were made as to the composition of the loads, and the load was assumed to act in both directions. This is a conservative design assumption in terms of uplift forces, i.e., weight of foundations. In the design for uplift, no credit was taken for the panel weight of approximately 3.5 psf or 450 pounds per panel. This difference could effect a foundation weight reduction of between 6 to 19 percent. A more significant reduction would be generated by better defining the uplift forces on arrays at the edge of the plant and ones in the interior. While wind tunnel tests are needed to confirm the following assumption, it is thought that the outer arrays will provide significant sheltering of the interior arrays. This would translate into a lighter foundation design for the interior arrays.

4.2.2 Plant Design (Rack Array)

The baseline plant contains 116,640 8 by 16 foot panels, for a total collector area of 14.9×10^6 ft^2 (1.38×10^6 m^2). Theoretical peak ac power output, at the 230 kV switchyard terminals, is 184 MW for a 35° site latitude. The total land requirement is 722 acres, or 0.171 ft^2/peak watt ac. The plant requires 7 miles of main roads, and 93.5 miles of maintenance roads. Each array group is rated 5.6 MW peak dc output and contains 27 array subgroups. Each subgroup is 30 panels long ($n = 30$), four panels wide ($k = 4$), and contains two complete panel strings (arrays), each of which operates at 1500 volts with a maximum current of 69 amperes. The outputs of each six adjacent arrays (three subgroups) are paralleled onto a single underground dc feeder circuit for connection to the converter bus, as discussed in Section 3.4.2.

Converter design, as well as the ac system, station power, control and instrumentation, lightning protection and other auxiliary systems are as described in Section 3. Control, warehouse and maintenance buildings are also as discussed in Section 3.

4.2.3 Cost Estimate (Rack Array)

The estimated cost for the baseline rack array plant design is presented in Table 4-1. The estimate includes all required equipment and facilities, up to but not including the 230 kV transmission line, as well as engineering, construction and an allowance for uncertainty.

An additional cost estimate breakdown, structured to conform with the hierarchical levels defined by JPL (see Section 3.1), is presented in Table 4-2 in order to assist JPL in their computerized life-cycle cost analyses.

Details of the bases, assumptions and categories in these cost estimates are discussed in Section 4.1.

Table 4-1

RACK ARRAY COST ESTIMATE (1975 $)

(184 MW peak ac output; 1.38 x 10^6 m^2 collector surface;
4.78 x 10^8 kWh/year energy output)

COST ESTIMATE DETAIL			Normalized Cost Distribution		
Component/System	Manhours (Thousands)	Materials ($ Thousands)	$/Wp ac	$/$m^2$	$/kWh ac
Panels					
Fabrication	-	9,721			
Frames	-	11,471			
Frame Protection Coating	-	3,809			
Gaskets	-	1,120			
Modules	-	83,627			
Ground Connectors	-	403			
Subtotal	-	110,151	0.60	80	0.040
Civil and Structual					
Array Foundations	168	13,094			
Array Structures	58	3,775			
Buildings	-	169			
Clearing and Grading	-	6,190			
Roads and Fences	-	877			
Panel Installation	58	-			
Reflector Panels	-	-			
Tracking Mechanisms	-	-			
Other (sewage, well, etc.)	-	67			
Land		1,236			
Maintenance Equipment		394			
Subtotal	284	25,802	0.18	25	0.012
Electrical					
Ac Wiring	24	783			
Converter	30	12,255			
Dc Wiring	42	838			
Grounding and Lightning Protection	3	3,738			
Instrumentation and Control	7	573			
Station Power	3	150			
Switchyard	7	1,115			
Other (communications, security, etc.)	7	348			
Subtotal	123	19,800	0.13	17	0.009

COST ESTIMATE SUMMARY

Item	Costs ($ Thousands)	$/Wp ac	$/$m^2$	$/kWh ac
Materials Cost	155,753			
Direct Labor	+ 6,919			
Direct Field Cost	162,672			
Distributable Field Cost	+ 5,189			
Field Cost	167,861	0.91	122	0.061
Engineering	+10,071	0.06	7	0.004
Subtotal	177,932			
Allowance for Uncertainty	+13,560	0.07	10	0.005
First & Installation Cost Total	191,492	1.04	139	0.070

Bases for the above cost estimate are discussed in Section 4.1.

Table 4-2

RACK ARRAY CODE OF ACCOUNTS

First and Installation Costs (1975 $)				
Level	Code	Accounts	Manhours (Thousands)	Materials (Thousands $)
Plant	1.	Plant Level Subtotal	58	75,799
	1.1	Civil and Structural Subtotal	-	7,905
	1.1.1	Buildings	-	169
	1.1.2	Clearing and Grading	-	6,190
	1.1.3	Fence(1)	-	116
	1.1.4	Land	-	1,236
	1.1.5	Roads	-	127
	1.1.6	Other (parking, sewage, etc.)	-	67
	1.2	Electrical Subtotal	46	6,243
	1.2.1	Ac Wiring	24	783
	1.2.2	Instrumentation and Control	1	159
	1.2.3	Instrumentation and Control Wiring	3	10
	1.2.4	Grounding Grid	3	29
	1.2.5	Lightning Protection	-	3,709
	1.2.6	Station Power	1	90
	1.2.7	Switchyard	7	1,115
	1.2.8	Other (communications, security, etc.)	7	348
	1.3	Engineering Subtotal	-	10,071
	1.3.1	Design	-	5,039
	1.3.2	Construction Support	-	3,019
	1.3.3	Procurement	-	2,013
	1.4	Owner's Cost Subtotal	12	51,193
	1.4.1	Interest During Construction	-	28,699
	1.4.2	Other	-	11,479
	1.4.3	Startup Panel Replacement	12	11,015
	1.5	Maintenance Equipment Subtotal	-	394
Group	2.	Group Level Subtotal	76	14,185
	2.1	Civil and Structural Subtotal	-	634
	2.1.1	Roads	-	634
	2.2	Electrical Subtotal	76	13,551
	2.2.1	Instrumentation and Control	3	290
	2.2.2	Instrumentation and Control Wiring	-	-
	2.2.3	Monitoring Equipment	-	114

Table 4-2 (Continued)

First and Installation Costs (1975 $)

Level	Code	Accounts	Manhours (Thousands)	Materials (Thousands $)
	2.2.4	Converter	30	12,255
	2.2.5	Dc Wiring	41	832
	2.2.6	Station Standby Power	2	60
Array	3.	Array Level Subtotal	1	6
	3.1	Electrical Subtotal	1	6
	3.1.1	Dc Wiring	1	6
Block	4.	Block Level Subtotal	284	16,869
	4.1	Civil and Structural Subtotal	284	16,869
	4.1.1	Foundations	168	13,094
	4.1.2	Panel Installation	58	-
	4.1.3	Reflectors	-	-
	4.1.4	Structures	58	3,775
	4.1.5	Tracking Mechanisms	-	-
Panel	5.	Panel Level Subtotal	-	26,524
	5.1	Fabrication(1)	-	9,721
	5.2	Frame	-	11,471
	5.3	Gasket	-	1,120
	5.4	Protective Coating (frame)	-	3,809
	5.5	Electrical Connector	-	403
Module	6.	Module Level Subtotal	-	83,627
	6.1	Interconnected Cell Assembly(1)	-	55,586
	6.2	Electrical Connector	-	1,614
	6.3	Fabrication(1)	-	9,712
	6.4	Cover	-	5,762
	6.5	Encapsulation Material	-	10,953
		Operating and Maintenance Costs		
System	1.	Operating and Maintenance Subtotal (Annual Cost)	20	1,008
	1.1	Operating Staff	13	5
	1.2	Plant Maintenance	3	521
	1.3	Panel Cleaning	2	312
	1.4	Unscheduled Panel Replacement	1	170
	2.	Complete Panel Replacement (Tenth Year Cost)	120	110,151

(1) Cost supplied by JPL

4.3 TANDEM ARRAY

The tandem array concept is similar to the rack array discussed in Section 4.2. However, in this case the solar cell panels are tilted at an angle equal to the local latitude plus ten degrees, and are augmented by reflector panels tilted at the local latitude. The basic configuration of this design is shown by Figure 4-4.

4.3.1 Tandem Array Design

The tandem array design differs from the rack design in several aspects. The panel tilt angle is 10° steeper. Reflector panels are added, and an additional set of foundations and struts are required to support the reflector panels for the last row of solar cell panels in each array subgroup. Thus, there are n(k + 2) foundations for an array subgroup that is k rows wide and n panels long. Further study might lead to design

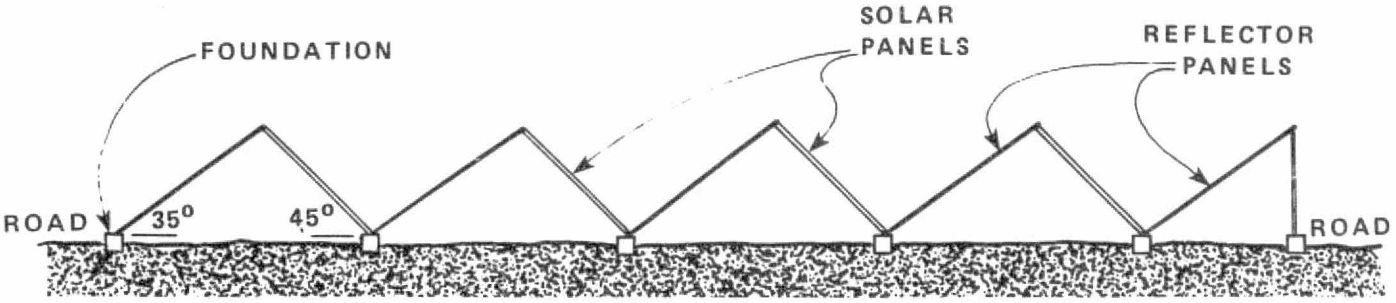


Figure 4–4 TANDEM ARRAY

optimizations wherein the number of rows is increased and the length of the row is shortened to approximately 60 feet (to allow roadway access for installation and maintenance vehicles).

The tandem array configuration was evaluated for 50 psf loading at a 35° latitude, with solar and reflector panels tilted at 45° and 35°, respectively. None of the codes treat wind forces on this type of sawtooth configuration in detail and little technical literature treating this configuration is available. Therefore, for purposes of this study, the tandem array design was treated as being similar to the equivalent rack design. The modules and panels are the same as for the rack array configuration, as discussed in Section 3.5. The foundations are essentially the same, except 16 feet long instead of 11.5 feet, in order to provide additional support for the reflector panels. The back struts are galvanized, rectangular structural-steel tubes.

The reflector panels are 1/2 inch plywood, exterior grade C. Four 4 by 10 foot sheets are factory assembled into a 10 by 16 foot panel by gluing the sheets to impregnated wood stiffeners. Aluminized Mylar is bonded to the plywood at the factory. Holes are pre-drilled to allow bolting of the reflector panels to the array panels, struts and foundation clips during field installation. The panels are assumed to act as a diaphragm and a beam column. These panels also act to stiffen the struts.

4.3.2 Plant Design (Tandem Array)

The baseline plant contains 90,720 8 by 16 foot panels, for a total collector area of 11.6 x 10^6 ft^2 (1.08 x 10^6 m^2). Theoretical peak ac power output at the 230 kV switchyard terminals is 200 MW for a 35° site latitude. The total land requirement is 607 acres, or 0.132 ft^2/peak ac watt. The plant requires 6 miles of main roads and 73.5 miles of maintenance roads. This area requirement might increase if a detailed study indicates spacing between panels in a row is needed to permit better access for maintenance replacement of panels.

Each array group is rated 6.1 MW peak dc output and contains 21 array subgroups. Each subgroup is 30 panels long (n = 30), four panels wide (k = 4) and contains two complete panel strings (arrays), each of which operates at 1500 volts with a maximum current of 97 amperes.

The outputs of each six adjacent arrays are paralleled onto a single underground dc feeder circuit for connection to the converter bus, as discussed in Section 3.4.2.

All other plant systems are as discussed in Section 3.

4.3.3 Cost Estimate (Tandem Array)

The estimated cost for the baseline tandem array plant design is presented in Table 4-3. The estimate includes all required equipment and facilities, up to but not including the 230 kV transmission line, as well as engineering, construction and an allowance for uncertainty.

An additional cost estimate breakdown, structured to conform with the hierarchical levels defined by JPL (see Section 3.1), is presented in Table 4-4 in order to assist JPL in their computerized life-cycle cost analyses.

Details of the bases, assumptions and categories in these cost estimates are discussed in Section 4.1.

Table 4-3

TANDEM ARRAY COST ESTIMATE (1975 $)
(200 MW peak ac output; 1.08 x 10^6 m^2 collector surface;
4.59 x 10^8 kWh/year energy output)

COST ESTIMATE DETAIL			Normalized Cost Distribution		
Component/System	Manhours (Thousands)	Materials ($ Thousands)	$/Wp ac	$/$m^2$	$/kWh ac
Panels					
Fabrication	-	7,561			
Frames	-	8,922			
Frame Protective Coating	-	2,962			
Gaskets	-	871			
Modules	-	65,041			
Ground Connectors	-	314			
Subtotal	-	85,671	0.43	79	0.033
Civil and Structural					
Array Foundations	157	13,718			
Array Structures	68	4,404			
Buildings	-	169			
Clearing and Grading	-	5,888			
Roads and Fences	-	712			
Panel Installation	45	-			
Reflector Panels	45	5,892			
Tracking Mechanisms	-	-			
Other (sewage, well, etc.)	-	67			
Land	-	1,039			
Maintenance Equipment	-	394			
Subtotal	315	32,283	0.21	39	0.016
Electrical					
Ac Wiring	22	727			
Converter	30	13,349			
Dc Wiring	57	1,221			
Ground and Lightning Protection	2	3,143			
Instrumentation and Control	7	546			
Station Power	3	150			
Switchyard	7	1,115			
Other (communications,security, etc.)	7	348			
Subtotal	135	20,599	0.12	23	0.009

COST ESTIMATE SUMMARY				
Item	Costs ($ Thousands)			
Materials Cost	138,553			
Direct Labor	+ 7,650			
Direct Field Cost	146,203			
Distributable Field Cost	+ 5,738			
Field Cost	151,941	0.76	141	0.058
Engineering	+ 9,116	0.04	8	0.003
Subtotal	161,057			
Allowance for Uncertainty	+15,077	0.08	14	0.006
First & Installation Cost Total	176,134	0.88	163	0.067

Bases for the above cost estimate are discussed in Section 4.1.

Table 4-4

TANDEM ARRAY CODE OF ACCOUNTS

First and Installation Costs (1975 $)				
Level	Code	Accounts	Manhours (Thousands)	Materials (Thousands $)
Plant	1.	Plant Level Subtotal	53	67,971
	1.1	Civil and Structural Subtotal	-	7,376
	1.1.1	Buildings	-	169
	1.1.2	Clearing and Grading	-	5,888
	1.1.3	Fence	-	107
	1.1.4	Land(1)	-	1,039
	1.1.5	Roads	-	106
	1.1.6	Other (parking, sewage, etc.)	-	67
	1.2	Electrical Subtotal	43	5,591
	1.2.1	Ac Wiring	22	727
	1.2.2	Instrumentation and Control	1	159
	1.2.3	Instrumentation and Control Wiring	3	9
	1.2.4	Grounding Grid	2	25
	1.2.5	Lightning Protection	-	3,118
	1.2.6	Station Power	1	90
	1.2.7	Switchyard	7	1,115
	1.2.8	Other (communications, security, etc.)	7	348
	1.3	Engineering Subtotal	-	9,116
	1.3.1	Design	-	4,563
	1.3.2	Construction Support	-	2,732
	1.3.3	Procurement	-	1,821
	1.4	Owner's Cost Subtotal	10	45,505
	1.4.1	Interest During Construction	-	26,384
	1.4.2	Other	-	10,554
	1.4.3	Startup Panel Replacement	10	8,567
	1.5	Maintenance Equipment	-	394
Group	2.	Group Level Subtotal	87	15,502
	2.1	Civil and Structural Subtotal	-	499
	2.1.1	Roads	-	499
	2.2	Electrical Subtotal	87	15,003
	2.2.1	Instrumentation and Control	3	290
	2.2.2	Instrumentation and Control Wiring	-	-
	2.2.3	Monitoring Equipment	-	88

Table 4-4 (Continued)

Level	Code	Accounts	Manhours (Thousands)	Materials (Thousands $)
First and Installation Costs (1975 $)				
	2.2.4	Converter	30	13,349
	2.2.5	Dc Wiring	52	1,216
	2.2.6	Station Standby Power	2	60
Array	3.	Array Level Subtotal	5	5
	3.1	Electrical Subtotal	5	5
	3.1.1	Dc Wiring	5	5
Block	4.	Block Level Subtotal	315	24,014
	4.1	Civil and Structural Subtotal	315	24,014
	4.1.1	Foundations	157	13,718
	4.1.2	Panel Installation	45	-
	4.1.3	Reflectors	45	5,892
	4.1.4	Structures	68	4,404
	4.1.5	Tracking Mechanisms	-	-
Panel	5.	Panel Level Subtotal	-	20,630
	5.1	Fabrication(1)	-	7,561
	5.2	Frame	-	8,922
	5.3	Gasket	-	871
	5.4	Protective Coating (frame)	-	2,962
	5.5	Electrical Connector	-	314
Module	6.	Module Level Subtotal	-	65,041
	6.1	Interconnected Cell Assembly(1)	-	43,233
	6.2	Electrical Connector	-	1,255
	6.3	Fabrication(1)	-	7,554
	6.4	Cover	-	4,480
	6.5	Encapsulation Material	-	8,519
Operating and Maintenance Costs				
System	1.	Operating and Maintenance Subtotal (Annual Cost)	20	1,161
	1.1	Operating Staff	13	5
	1.2	Plant Maintenance	3	460
	1.3	Panel Cleaning	3	563
	1.4	Unscheduled Panel Replacement	1	133
	2.0	Complete Panel Replacement (Tenth Year Cost)	100	85,671

(1) Cost supplied by JPL

4.4 HORIZONTAL ARRAY

The horizontal array design consists of 8 by 16 foot panels secured to precast concrete sleeper foundations. There is no array structure per se for this design. The basic configuration for this design is shown in Figure 4-5.

4.4.1 Horizontal Array Design

As mentioned, there is no array structure between the panels and foundations with this design. Since the 16 foot edges of the panels are supported on the foundations for 60 percent of their length, the panels are a lighter-weight construction. Building codes and technical articles do not cover uplift forces due to wind for flat plates close (within 2 feet) to the ground. Therefore, the ANSI A58.1 minimum loading of 15 psf for roofs was used. Also, the dead weight of the panels, approximately 3.5 psf, becomes appreciable in this case, and credit for this weight is taken. Thus, the foundations are smaller than for the rack design. Detailed design would likely use wind tunnel test results to optimize the foundation design.

Since there is little lateral thrust on the panels with the horizontal array design, the foundations are set on the graded surface without the trenching used for the rack and other designs. Aside from being smaller in cross section and lighter in weight, the foundations are precast concrete sleepers similar

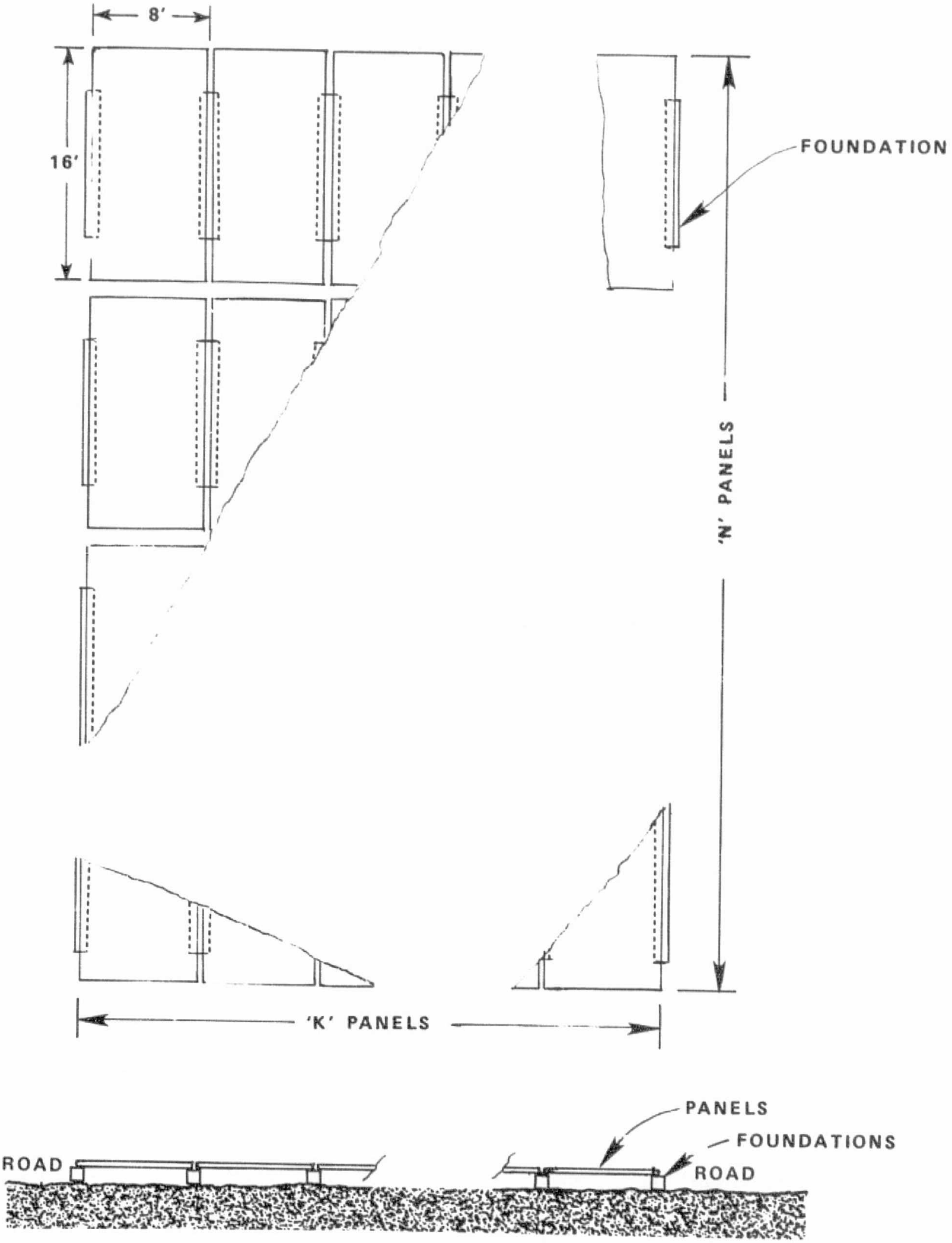


Figure 4–5 HORIZONTAL ARRAY

to those used for the rack design. The sleepers are tapered to give the panels a 2° tilt in order to prevent water accumulation and ponding.

As mentioned, the panel for the horizontal array design is lighter weight construction. The rectangular steel tube shown in section AA of Figure 3-17 is replaced by a channel member. The module hold-down clip along the 16 foot sides (section AA) is omitted because the major loads press the panel down onto the channel. The remainder of the panel design is as shown in Figure 3-17 and discussed in Section 3.5.2. As for all of the panels, the above design is conceptual in nature and subject to verification and optimization during detail design efforts.

4.4.2 Plant Design (Horizontal Array)

The baseline plant contains 129,600 8 by 16 foot panels, for a total collector area of 16.6×10^6 ft^2 (1.54×10^6 m^2). Theoretical peak ac power output at the 230 kV switchyard terminals is 201 MW for a site latitude of 35°. The total land requirement is 505 acres, or 0.109 ft^2/peak watt ac. The plant requires 5.2 miles of main roads and 53.5 miles of maintenance roads.

Each array group is rated 6.1 MW peak dc output and contains 15 array subgroups. Each subgroup is 30 panels long ($n = 30$), eight panels wide ($k = 8$) and contains four complete panel strings (arrays), each of which operates at 1500 volts with a maximum current of 68 amperes.

The outputs of each six adjacent arrays are paralleled onto a single underground dc feeder circuit for connection to the converter bus, as discussed in Section 3.4.2.

All other plant systems are as discussed in Section 3.

4.4.3 Cost Estimate (Horizontal Array)

The estimated cost for the baseline horizontal array plant design is presented in Table 4-5. The estimate includes all required equipment and facilities, up to but not including the 230 kV transmission line, as well as engineering, construction and an allowance for uncertainty.

An additional cost estimate breakdown, structured to conform with the hierarchical levels defined by JPL (see Section 3.1), is presented in Table 4-6 in order to assist JPL in their computerized life-cycle cost analyses.

Details of the bases, assumptions and categories in these cost estimates are discussed in Section 4.1.

Table 4-5

HORIZONTAL ARRAY COST ESTIMATE (1975 \$)

(201 MW peak ac output; 1.54×10^6 m^2 collector surface;
4.85×10^8 kWh/year energy output)

COST ESTIMATE DETAIL			Normalized Cost Distribution		
Component/System	Manhours (Thousands)	Materials (\$ Thousands)	\$/Wp ac	\$/m^2	\$/kWh ac
Panels					
Fabrication	-	10,801			
Frames	-	8,323			
Frame Protective Coating	-	2,623			
Gaskets	-	1,244			
Modules	-	92,906			
Ground Connectors	-	449			
Subtotal	-	116,346	0.58	71	0.042
Civil and Structural					
Array Foundations	146	4,619			
Array Structures	-	-			
Buildings	-	169			
Clearing and Grading	-	4,249			
Roads and Fences	-	553			
Panel Installation	65	-			
Reflector Panels	-	-			
Tracking Mechanisms	-	-			
Other (sewage, well, etc.)	-	67			
Land		865			
Maintenance Equipment	-	394			
Subtotal	211	10,916	0.09	11	0.006
Electrical					
Ac Wiring	21	677			
Converter	30	13,349			
Dc Wiring	38	579			
Ground and Lightning Protection	2	2,617			
Instrumentation and Control	7	584			
Station Power	3	150			
Switchyard	7	1,115			
Other (communications, security, etc.)	7	348			
Subtotal	115	19,419	0.11	15	0.008

COST ESTIMATE SUMMARY				
Item	Costs (\$ Thousands)			
Materials Cost	146,681			
Direct Labor	+ 5,542			
Direct Field Cost	152,223			
Distributable Field Cost	+ 4,157			
Field Cost	156,380	0.78	102	0.056
Engineering	+ 9,383	0.05	6	0.003
Subtotal	165,763			
Allowance for Uncertainty	+ 9,883	0.05	6	0.004
First & Installation Cost Total	175,646	0.88	114	0.063

Bases for the above cost estimate are discussed in Section 4.1

Table 4-6

HORIZONTAL ARRAY CODE OF ACCOUNTS

First and Installation Costs (1975 $)				
Level	Code	Accounts	Manhours (Thousands)	Materials (Thousands $)
Plant	1.	Plant Level Subtotal	55	68,788
	1.1	Civil and Structural Subtotal	-	5,539
	1.1.1	Buildings	-	169
	1.1.2	Clearing and Grading	-	4,249
	1.1.3	Fence	-	99
	1.1.4	Land(1)	-	865
	1.1.5	Roads	-	90
	1.1.6	Other (parking, sewage, etc.)	-	67
	1.2	Electrical Subtotal	42	5,015
	1.2.1	Ac Wiring	21	677
	1.2.2	Instrumentation and Control	1	159
	1.2.3	Instrumentation and Control Wiring	3	9
	1.2.4	Grounding Grid	2	23
	1.2.5	Lightning Protection	-	2,594
	1.2.6	Station Power	1	90
	1.2.7	Switchyard	7	1,115
	1.2.8	Other (communications security, etc.)	7	348
	1.3	Engineering Subtotal	-	9,383
	1.3.1	Design	-	4,698
	1.3.2	Construction Support	-	2,811
	1.3.3	Procurement	-	1,874
	1.4	Owner's Cost Subtotal	13	48,469
	1.4.1	Interest During Construction	-	26,310
	1.4.2	Other	-	10,524
	1.4.3	Startup Panel Replacement	13	11,635
	1.5	Maintenance Equipment	-	394
Group	2.	Group Level Subtotal	72	14,763
	2.1	Civil and Structural Subtotal	-	364
	2.1.1	Roads	-	364
	2.2	Electrical Subtotal	72	14,399
	2.2.1	Instrumentation and Control	3	290
	2.2.2	Instrumentation and Control Wiring	-	-
	2.2.3	Monitoring Equipment	-	126

Table 4-6 (Continued)

First and Installation Costs (1975 $)				
Level	Code	Accounts	Manhours (Thousands)	Materials (Thousands $)
	2.2.4	Converter	30	13,349
	2.2.5	Dc Wiring	37	574
	2.2.6	Station Standby Power	2	60
Array	3.	Array Level Subtotal	1	5
	3.1	Electrical Subtotal	1	5
	3.1.1	Dc Wiring	1	5
Block	4.	Block Level Subtotal	211	4,619
	4.1	Civil and Structural Subtotal	211	4,619
	4.1.1	Foundations	146	4,619
	4.1.2	Panel Installation	65	-
	4.1.3	Reflectors	-	-
	4.1.4	Structures	-	-
	4.1.5	Tracking Mechanisms	-	-
Panel	5.	Panel Level Subtotal	-	23,440
	5.1	Fabrication (1)	-	10,801
	5.2	Frame	-	8,323
	5.3	Gasket	-	1,244
	5.4	Protective Coating (frame)	-	2,623
	5.5	Electrical Connector	-	449
Module	6.	Module Level Subtotal	-	92,906
	6.1	Interconnected Cell Assembly (1)	-	61,762
	6.2	Electrical Connector	-	1,793
	6.3	Fabrication (1)	-	10,792
	6.4	Cover	-	6,401
	6.5	Encapsulation Material	-	12,158
Operating and Maintenance Costs				
System	1.	Operating and Maintenance Subtotal (Annual Cost)	19	1,025
	1.1	Operating Staff	13	5
	1.2	Plant Maintenance	3	482
	1.3	Panel Cleaning	2	359
	1.4	Unscheduled Panel Replacement	1	179
	2.0	Complete Panel Replacement (Tenth Year Cost)	130	116,346

(1) Cost supplied by JPL

4.5 SEASONALLY ADJUSTED RACK ARRAY

The seasonally adjusted rack array concept is similar to the rack array discussed in Section 4.1. However, in this case the panel tilt angle is field adjustable (±10°) to compensate for seasonal variations in sun angle. The basic configuration of this design is shown by Figure 4-6.

4.5.1 Seasonally Adjusted Rack Array Design

As shown by Figure 4-6, the seasonally adjusted rack array consists of 8 by 16 foot panels (as described in Section 3.5.2), oriented with the 16 foot side horizontal and an 8 foot slant height. Each panel is supported on an independent rectangular precast concrete foundation. The lower edge of the panel is attached to the foundation by two hinged joints. Each joint consists of two lugs, one each on the panel and foundation, held together by a pin. The upper edge is supported by two struts, which are connected to the panel via similar hinged joints. As for the rack design, the struts consist of structural steel tubing and are located approximately 20 percent of the distance in from the panel edges. The lower edges of the struts are attached to horizontal activators by hinged joints. The activators consist of structural steel tubing oriented in the north-south direction and anchored to the foundation by guide fixtures. Variation in panel tilt angle results from longitudinal movement of the activators. The activators and

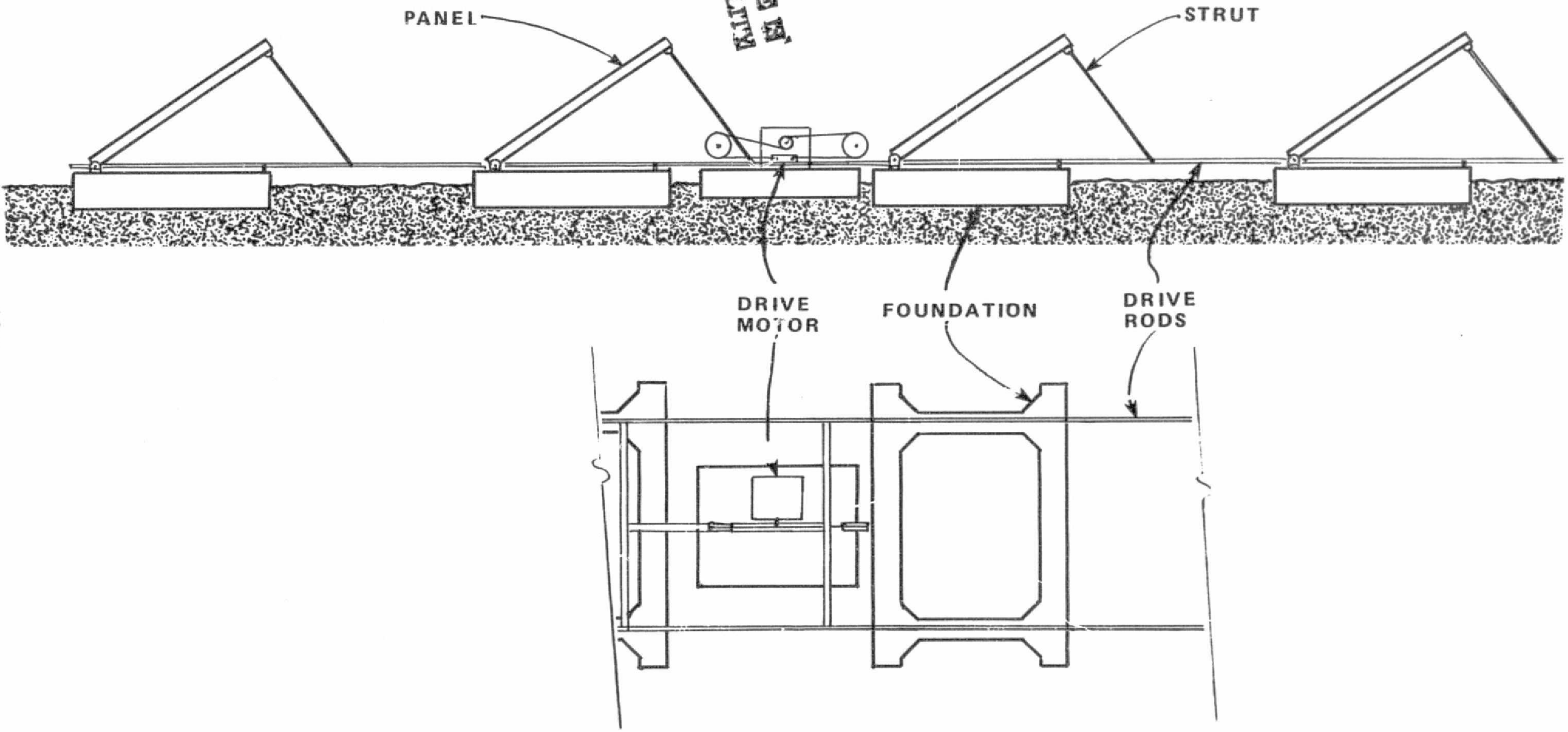


Figure 4–6 SEASONALLY ADJUSTED ARRAY

struts are galvanized as discussed in Section 3.5.2. The mass of concrete is used to resist uplift forces, and the foundations are set in trenches to resist sliding.

Each activator is attached to four panels in the north-south direction and to an actuator mechanism. The actuator mechanism consists of an electric motor, a gear box, and a pulley and cable system, as shown in Figure 4-6.

Spacing between the panel rows, in the north-south direction, is equal to one and one-half times the panel height at the maximum tilt angle.

The seasonally adjusted rack design was investigated for a 50 psf loading and a 35° latitude site.

4.5.2 Plant Design (Seasonally Adjusted Rack Array)

The baseline plant design and power levels for the seasonally adjusted rack array are essentially the same as for the fixed rack array presented in Section 4.1.2. One difference is a 2.5 percent increase in land requirements and main road length.

4.5.3 Cost Estimate (Seasonally Adjusted Rack Array)

The estimated cost for the baseline seasonally adjusted array plant design is presented in Table 4-7. The estimate includes all required equipment and facilities, up to but not including the 230 kV transmission line, as well as engineering, construction and an allowance for uncertainty.

An additional cost estimate breakdown, structured to conform with the hierarchical levels defined by JPL (see Section 3.1), is presented in Table 4-8 in order to assist JPL in their computerized life-cycle cost analyses.

Details of the bases, assumptions and categories in these cost estimates are discussed in Section 4.1.

Table 4-7

SEASONALLY ADJUSTED ARRAY COST ESTIMATE (1975 \$)
(184 MW peak ac output; 1.38 x 10^6 m^2 collector surface;
5.07 x 10^8 kWh/year energy output)

COST ESTIMATE DETAIL			Normalized Cost Distribution		
Component/System	Manhours (Thousands)	Materials (\$ Thousands)	\$/Wp ac	\$/m^2	\$/kwn ac
Panels					
Fabrication	-	9,721			
Frames	-	11,471			
Frame Protective Coating	-	3,809			
Gaskets	-	1,120			
Modules	-	83,627			
Ground Connectors	-	403			
Subtotal	-	110,151	0.60	80	0.038
Civil and Structural					
Array Foundations	140	16,096			
Array Structures	175	12,852			
Buildings	-	169			
Clearing and Grading	-	6,344			
Roads and Fences	-	882			
Panel Installation	58	-			
Reflector Panels	-	-			
Tracking Mechanisms	300	15,921			
Other (sewage, well, etc.)	-	67			
Land	-	1,269			
Maintenance Equipment	-	394			
Subtotal	673	53,994	0.40	53	0.026
Electrical					
Ac Wiring	24	783			
Converter	30	12,255			
Dc Wiring	43	859			
Ground and Lightning Protection	3	3,836			
Instrumentation and Control	29	798			
Station Power	3	150			
Switchyard	7	1,115			
Other (communications, security, etc.)	7	348			
Subtotal	146	20,144	0.13	18	0.008

COST ESTIMATE SUMMARY				
Item	Costs (\$ Thousands)			
Materials Cost	184,289			
Direct Labor	+13,923			
Direct Field Cost	198,212			
Distributable Field Cost	+10,442			
Field Cost	208,654	1.13	151	0.072
Engineering	+12,519	0.07	9	0.004
Subtotal	221,173			
Allowance for Uncertainty	+22,204	0.12	16	0.008
First & Installation Cost Total	243,377	1.32	176	0.084

Bases for the above cost estimate are discussed in Section 4.1.

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Table 4-8

SEASONALLY ADJUSTED ARRAY CODE OF ACCOUNTS

First and Installation Costs (1975 $)

Level	Code	Accounts	Manhours (Thousands)	Materials (Thousands $)
Plant	1.	Plant Level Subtotal	58	89,413
	1.1	Civil and Structural Subtotal	-	8,097
	1.1.1	Buildings	-	169
	1.1.2	Clearing and Grading	-	6,344
	1.1.3	Fence	-	119
	1.1.4	Land(1)	-	1,269
	1.1.5	Roads	-	129
	1.1.6	Other (parking, sewage, etc.)	-	67
	1.2	Electrical Subtotal	46	6,341
	1.2.1	Ac Wiring	24	783
	1.2.2	Instrumentation and Control	1	159
	1.2.3	Instrumentation and Control Wiring	3	10
	1.2.4	Grounding Grid	3	29
	1.2.5	Lightning Protection	-	3,807
	1.2.6	Station Power	1	90
	1.2.7	Switchyard	7	1,115
	1.2.8	Other (communications security, etc.)	7	348
	1.3	Engineering Subtotal	-	12,519
	1.3.1	Design	-	6,265
	1.3.2	Construction Support	-	3,752
	1.3.3	Procurement	-	2,502
	1.4	Owner's Cost Subtotal	12	62,073
	1.4.1	Interest During Construction	-	36,470
	1.4.2	Other	-	14,588
	1.4.3	Startup Panel Replacement	12	11,015
	1.5	Maintenance Equipment	-	394
Group	2.	Group Level Subtotal	99	14,431
	2.1	Civil and Structural Subtotal	-	634
	2.1.1	Roads	-	634
	2.2	Electrical Subtotal	99	13,797
	2.2.1	Instrumentation and Control	4	300
	2.2.2	Instrumentation and Control Wiring	21	215
	2.2.3	Monitoring Equipment	-	114

Table 4-8 (Continued)

Level	Code	Accounts	Manhours (Thousands)	Materials (Thousands $)
		First and Installation Costs (1975 $)		
	2.2.4	Converter	30	12,255
	2.2.5	Dc Wiring	42	853
	2.2.6	Station Standby Power	2	60
Array	3.	Array Level Subtotal	1	6
	3.1	Electrical Subtotal	1	6
	3.1.1	Dc Wiring	1	6
Block	4.	Block Level Subtotal	673	44,869
	4.1	Civil and Structural Subtotal	673	44,869
	4.1.1	Foundations	140	16,096
	4.1.2	Panel Installation	58	-
	4.1.3	Reflectors	-	-
	4.1.4	Structures	175	12,852
	4.1.5	Tracking Mechanisms	300	15,921
Panel	5.	Panel Level Subtotal	-	26,524
	5.1	Fabrication(1)	-	9,721
	5.2	Frame	-	11,471
	5.3	Gasket	-	1,120
	5.4	Protective Coating (frame)	-	3,809
	5.5	Electrical Connector	-	403
Module	6.	Module Level Subtotal	-	83,627
	6.1	Interconnected Cell Assembly(1)	-	55,586
	6.2	Electrical Connector	-	1,614
	6.3	Fabrication(1)	-	9,712
	6.4	Cover	-	5,762
	6.5	Encapsulation Material	-	10,953
		Operating and Maintenance Costs		
System	1.	Operating and Maintenance Subtotal (Annual Cost)	19	1,004
	1.1	Operating Staff	13	5
	1.2	Plant Maintenance	3	500
	1.3	Panel Cleaning	2	329
	1.4	Unscheduled Panel Replacement	1	170
	2.0	Complete Panel Replacement (Tenth Year Cost)	120	110,151

(1) Cost supplied by JPL

4.6 TRACKING ARRAY

The tracking array design consists of panels tilted at an angle equal to the local latitude plus ten degrees. The arrays rotate about a vertical axis to track the sun. The basic configuration of this design is shown by Figure 4-7.

4.6.1 Tracking Array Design

As shown by Figure 4-7, the design consists of two 8 by 16 foot panels (as described in Section 4.3). The panels form a square and are supported on a pedestal type structure at a fixed angle equal to the local latitude plus ten degrees.

Each structure (block) has a 10 foot deep, 30 inch diameter, drilled, reinforced-concrete caisson. The caisson supports an 8 inch diameter schedule 40 pipe extending 51 inches above grade. Attached through a rotating collar is a 10 inch diameter schedule 40 pipe 36 inches long. The cross arms and support frames are connected to the top of the 10 inch diameter pipe. Provisions are made to adjust the tilt to the appropriate latitude.

The pedestal type support increases the panel structural requirements above those of Section 4.4. The additional panel support is provided by a structural steel frame, considered part of the array structure, which supplements the previously described panel frame. The array structural steel is galvanized

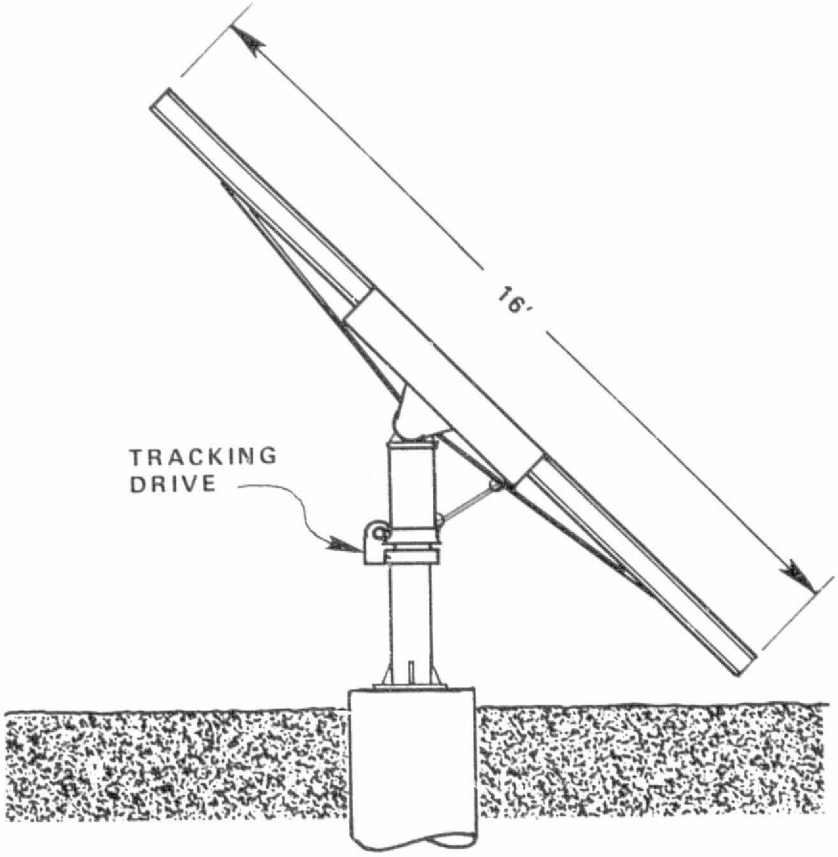

Figure 4–7 TRACKING ARRAY

as discussed in Section 3.5.2 for the panel frame. The panels are held to the array structure by bolted clips.

The tracking mechanism consists of a split-phase fractional horsepower motor and a worm gear drive both mounted on the lower, non-rotating section of the pedestal. These drive a worm gear attached to the upper, rotating, pedestal section.

The single axis tracking design was investigated for a 50 psf loading, a 35° latitude, and an interblock spacing of 1.5 times the height of the structure.

4.6.2 Plant Design (Tracking Array)

The baseline plant contains 116,640 8 by 16 foot panels, for a total collector area of 14.9×10^6 ft^2 (1.38×10^6 m^2). Theoretical peak ac power output at the 230 kV main switchyard terminals is 180 MW for a 35° site latitude. The total land requirement is 1278 acres, or 0.309 ft^2/peak watt ac. The plant requires 12.8 miles of main roads and 162.3 miles of maintenance roads.

Each array group is rated 5.7 MW peak dc output and contains 54 array subgroups. Each subgroup is 15 blocks long and two blocks wide and contains a single array which operates at 1500 volts with a maximum current of 69 amperes.

Interconnection of the dc circuit and panel ground conductors between the individual blocks is accomplished by field installed factory preassembled jumper cables. To facilitate installation, the cables are equipped with quick-disconnect type connectors similar to those described in Section 3.5.1. The outputs of six adjacent arrays (six subgroups) are paralleled onto a single underground feeder circuit for connection to the converter bus, as discussed in Section 3.5.2.

Single phase power for the tracking mechanisms is supplied by the station power transformer located at the power conditioning unit (see Section 3.4.4). Power is distributed to each array by underground feeder circuits installed with the dc wiring and is delivered to each block in an array by a factory preassembled jumper cable similar to that used in the dc and grounding circuits. To reduce the total peak motor load demand, an undervoltage sensor is included as a part of each tracking controller. The sensor prevents motor operation when the system voltage is below a preset limit, thereby providing load sequencing.

All other auxiliary systems are as described in Section 3.

4.6.3 Cost Estimate (Tracking Array)

The estimated cost for the baseline tracking array plant design is presented in Table 4-9. The estimate includes all required equipment and facilities, up to but not including the 230 kV transmission line, as well as engineering, construction and an allowance for uncertainty.

An additional cost estimate breakdown, structured to conform with the hierarchical levels defined by JPL (see Section 3.1), is presented in Table 4-10 in order to assist JPL in their computerized life-cycle cost analyses.

Details of the bases, assumptions and categories in these cost estimates are discussed in Section 4.1.

Table 4-9

TRACKING ARRAY COST ESTIMATE (1975 $)

(180 MW peak ac output; 1.38 x 10^6 m^2 collector surface;
6.06 x 10^8 kWh/year energy output)

COST ESTIMATE DETAIL			Normalized Cost Distribution		
Component/Summary	Manhours (Thousands)	Materials ($ Thousands)	$/Wp ac	$/$m^2$	$/kWh ac
Panels					
Fabrication	-	9,721			
Frames	-	7,664			
Frame Protective Coating	-	2,313			
Gaskets	-	1,120			
Modules	-	83,627			
Ground Connectors	-	403			
Subtotal	-	104,848	0.58	76	0.030
Civil and Structural					
Array Foundations	315	6,710			
Array Structures	233	81,336			
Buildings	-	169			
Clearing and Grading	-	10,923			
Roads and Fences	-	1,392			
Panel Installation	64	-			
Reflector Panels	-	-			
Tracking Mechanisms	58	4,666			
Other (sewage, well, etc.)	-	67			
Land	-	2,188			
Maintenance Equipment	-	459			
Subtotal	670	107,910	0.71	93	0.037
Electrical					
Ac Wiring	31	1,081			
Converter	30	12,473			
Dc Wiring	145	2,609			
Grounding and Lightning Protection	4	6,614			
Instrumentation and Control	52	1,017			
Station Power	3	150			
Switchyard	7	1,115			
Other (communications, security, etc.)	7	348			
Subtotal	279	25,407	0.19	24	0.010

COST ESTIMATE SUMMARY

Item	Costs ($ Thousands)	$/Wp ac	$/$m^2$	$/kWh ac
Materials Cost	238,165			
Direct Labor	+16,133			
Direct Field Cost	254,298			
Distributable Field Cost	+12,100			
Field Cost	266,398	1.48	193	0.077
Engineering	+15,984	0.09	12	0.005
Subtotal	282,382			
Allowance for Uncertainty	+35,507	0.20	26	0.010
First & Installation Cost Total	317,889	1.77	231	0.092

Bases for the above cost estimate are discussed in Section 4.1.

Table 4-10

TRACKING ARRAY CODE OF ACCOUNTS

First and Installation Costs (1975 $)				
Level	Code	Accounts	Manhours (Thousands)	Materials (Thousands $)
Plant	1.	Plant Level Subtotal	68	116,594
	1.1	Civil and Structural Subtotal	-	13,639
	1.1.1	Buildings	-	169
	1.1.2	Clearing and Grading	-	10,923
	1.1.3	Fence	-	162
	1.1.4	Land(1)	-	2,188
	1.1.5	Roads	-	130
	1.1.6	Other (parking, sewage, etc.)	-	67
	1.2	Electrical Subtotal	55	9,421
	1.2.1	Ac Wiring	31	1,081
	1.2.2	Instrumentation and Control	1	159
	1.2.3	Instrumentation and Control Wiring	4	14
	1.2.4	Grounding Grid	4	49
	1.2.5	Lightning Protection	-	6,565
	1.2.6	Station Power	1	90
	1.2.7	Switchyard	7	1,115
	1.2.8	Other (communications security, etc.)	7	348
	1.3	Engineering Subtotal	-	15,934
	1.3.1	Design	-	8,006
	1.3.2	Construction Support	-	4,787
	1.3.3	Procurement	-	3,191
	1.4	Owner's Cost Subtotal	13	77,119
	1.4.1	Interest During Construction	-	47,596
	1.4.2	Other	-	19,038
	1.4.3	Startup Panel Replacement	13	10,485
	1.5	Maintenance Equipment	-	459
Group	2.	Group Level Subtotal	206	16,612
	2.1	Civil and Structural Subtotal	-	1,100
	2.1.1	Roads	-	1,100
	2.2	Electrical Subtotal	206	15,512
	2.2.1	Instrumentation and Control	4	300
	2.2.2	Instrumentation and Control Wiring	43	430
	2.2.3	Monitoring Equipment	-	114

Table 4-10 (Continued)

First and Installation Costs (1975 $)				
Level	Code	Accounts	Manhours (Thousands)	Materials (Thousands $)
	2.2.4	Converter	30	12,473
	2.2.5	Dc Wiring	127	2,135
	2.2.6	Station Standby Power	2	60
Array	3.	Array Level Subtotal	18	474
	3.1	Electrical Subtotal	18	474
	3.1.1	Dc Wiring	18	474
Block	4.	Block Level Subtotal	670	92,712
	4.1	Civil and Structural Subtotal	670	92,712
	4.1.1	Foundations	315	6,710
	4.1.2	Panel Installation	64	-
	4.1.3	Reflectors	-	-
	4.1.4	Structures	233	81,336
	4.1.5	Tracking Mechanisms	58	4,666
Panel	5.	Panel Level Subtotal	-	21,221
	5.1	Fabrication(1)	-	9,721
	5.2	Frame	-	7,664
	5.3	Gasket	-	1,120
	5.4	Protective Coating (frame)	-	2,313
	5.5	Electrical Connector	-	403
Module	6.	Module Level Subtotal	-	83,627
	6.1	Interconnected Cell Assembly(1)	-	55,586
	6.2	Electrical Connector	-	1,614
	6.3	Fabrication(1)	-	9,712
	6.4	Cover	-	5,762
	6.5	Encapsulation Material	-	10,953
Operating and Maintenance Costs				
System	1.	Operating and Maintenance Subtotal (Annual Cost)	40	1,582
	1.1	Operating Staff	13	5
	1.2	Plant Maintenance	3	814
	1.3	Panel Cleaning	23	603
	1.4	Unscheduled Panel Replacement	1	160
			4	
	2.0	Complete Panel Replacement (Tenth Year Cost)	130	104,848

(1) Cost supplied by JPL

Section 5

COST SENSITIVITIES

Variations in estimated costs due to variations in design and other factors are discussed in this section.

5.1 TILT ANGLE

As site latitude changes, the tilt angles for the arrays must be changed. The tilt angle may also be changed to match plant output to seasonal load demand. For purposes of this study, the tilt angles of the rack and tracking arrays are set equal to the latitude angle. The solar panels on the tandem array are set at the latitude angle plus 10°. The tilt angle of the panels on the seasonally adjusted arrays varires about the latitude angle. The tilt angle of the horizontal array, of course, remains at zero (actually 2°) and does not change with latitude.

Table 5-1 shows the plant costs for the array configurations evaluated in this study for latitude angles of 25°, 35°, and 45°. It was found that changing the tilt angle for the rack array did not produce significant changes in plant cost (e.g., <1%). Changes in plant cost for the tandem array were found to be -3.5% at 25° and +6% at 45°. The costs of the seasonally adjusted and tracking arrays are notably higher and it was felt that the engineering effort required to allow estimating of cost changes with latitude was not warranted for these two designs. As the tilt angle is increased, there are increases in land, road, wiring and array structure requirements. The design changes were made with the assumption that loading remains constant at the 50 psf base case value. If wind forces and other load components (see Section 3.2) were to be considered separately, changes with tilt angle would be larger.

TABLE 5-1

EFFECT OF LATITUDE ON PLANT COSTS (1975 $)

Latitude Angle	First and Installation Costs ($ thousands)				
	Rack	Tandem	Horizontal	Seas. Adj.	Tracking
25°	189,919	170,185	175,646	-	-
35°	191,492	176,134	175,646	243,377	317,899
45°	192,378	186,672	175,646	-	-

5.2 SITE LATITUDE

As shown by Figures 3-3 and 3-4, the power and energy produced by a given plant are dependent on site latitude. Figure 5-1 shows how this affects energy costs for the five array designs evaluated in this study by combining the incident energy from Figure 3-4 and the plant cost data from Table 5-1. For purposes of this comparison, only annualized (0.175 annual charge) first and installation cost data normalized to theoretical energy are presented. Actual energy costs will, of course, be made higher by owner's costs, operating and maintenance costs, module degradation and actual insolation. Also, the costs of the

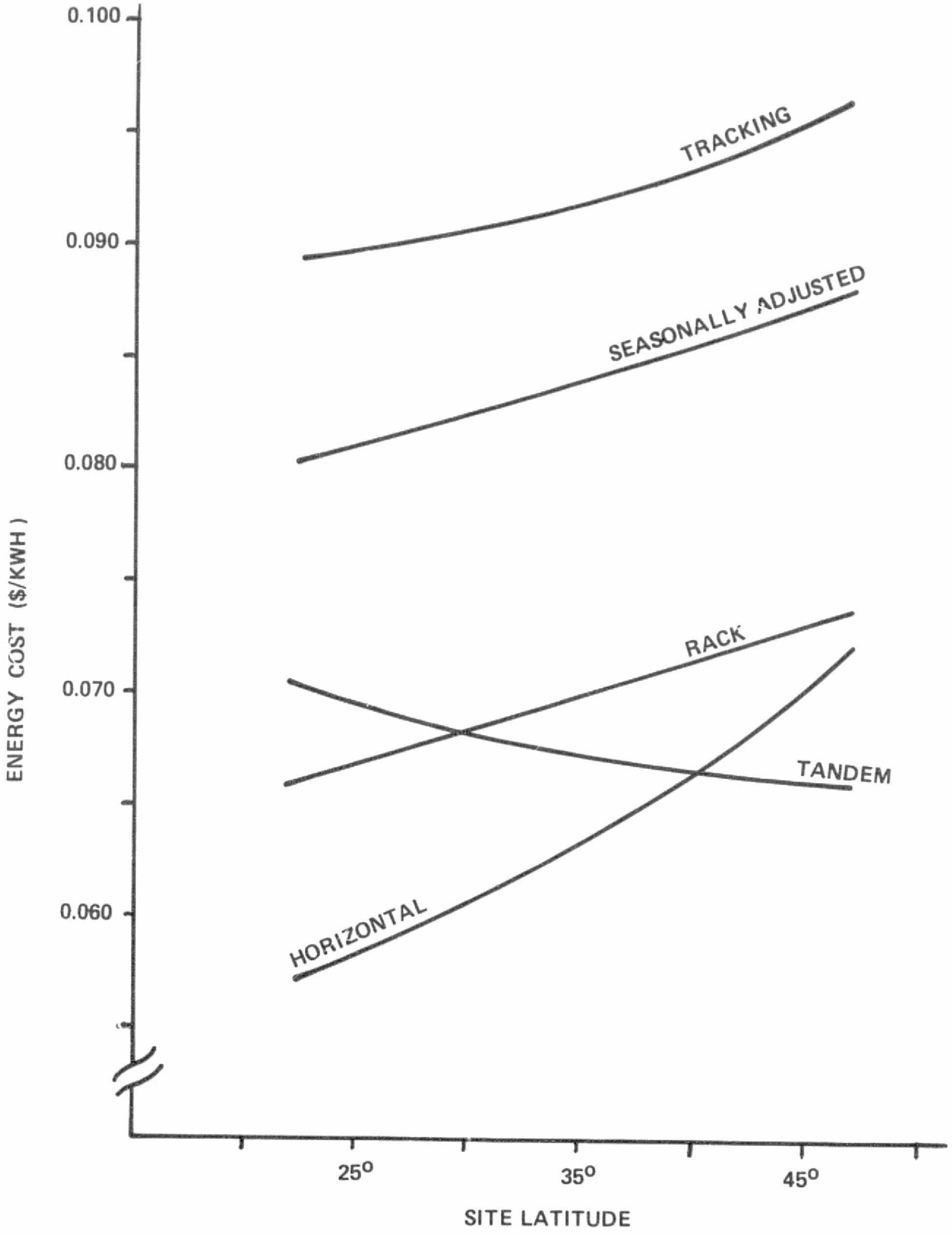

Figure 5–1 ENERGY COST VERSUS SITE LATITUDE

seasonally adjusted and tracking array plants were assumed to remain constant with changes in latitude.

As can be seen from the figure, the horizontal array design results in the lowest cost energy for most latitudes in the United States. The tandem array design is most suitable for northern latitudes. Both of these designs result in lower cost energy than the rack design (at most latitudes). The seasonally adjusted and tracking array designs are clearly more costly and not economic for flat-plate panels.

It must be pointed out that the data in Figure 5-1 are presented on an expanded scale, which tends to magnify the differences between the designs. Also, it is possible that detailed engineering efforts to optimize the array designs could change the juxtaposition of the three lower curves in Figure 5-1. Further, no weight was attached to the match between the plants' energy outputs and daily or seasonal variations in utility load demand.

5.3 LOADING

As would be expected, higher structural design loads increase plant costs. The effect of changes in loading was evaluated for the rack array design. Uniform loadings of 35, 50 and 75 psf were used. As with the base case, no assumptions were made as to the composition of these loads (see Section 3.2.10).

Changing the loading affects array structures and foundations. At 75 psf, a thicker glass superstrate must be used. In going from 35 to 75 psf loading, the array structure and foundation costs approximately double. The effect of loading on rack array plant cost is shown in Figure 5-2, normalized to the same bases as the baseline cost estimate presented in Table 4-1.

As can be seen from the data presented in the figure, loading significantly affects plant costs. Although not evaluated, it is expected that loading will affect the other array designs in a similar manner, with the exception of the horizontal array. Its

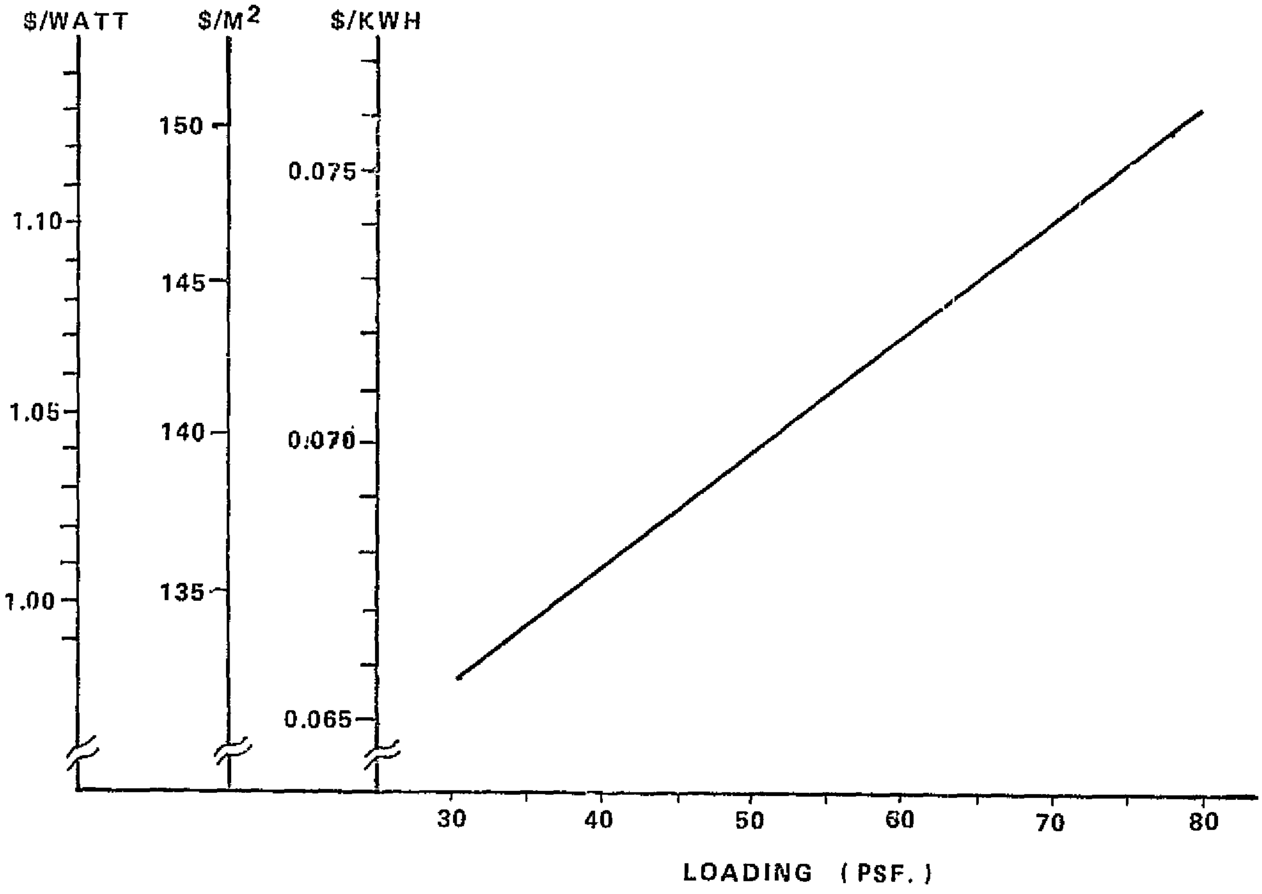

Figure 5-2 COST VERSUS LOADING

wind loading characteristics are significantly different from the other array designs. Further refinement of this type of data should take into account the composition of the loading.

5.4 PANEL SIZE

Two basic panel configurations were evaluated; the 8 by 16 foot baseline design and a 4 by 8 foot design. These designs are shown by Figures 3-17 and 3-18, respectively. The 8 by 16 foot design was used in preparing the cost estimate tables presented in Section 4. The 4 by 8 foot panel was evaluated for the rack, tandem and horizontal array designs. Major cost changes in Tables 4-1, 4-3 and 4-5 resulting from the use of the 4 by 8 foot panel are presented in Table 5-2.

By comparing elements of Table 5-2 with corresponding elements of the tables in Section 4, it can be seen that panel and structure costs decrease for the rack and tandem arrays. Panel costs for the horizontal array increase. In all cases, there is a large increase in installation manhours. The net result is that plants using 4 by 8 foot panels cost 10 to 12 percent more than plants using the 8 by 16 foot panel.

5.5 ENERGY COSTS

As discussed in Section 4.1, energy costs require consideration of utility economic factors, such as annual fixed charge rates on

TABLE 5-2

COST ELEMENT CHANGES FOR 4 BY 8 FOOT PANELS

	Rack(1)		Tandem(2)		Horizontal(3)	
	Manhours (Thousands)	Materials ($ Thousands)	Manhours (Thousands)	Materials ($ Thousands)	Manhours (Thousands)	Materials ($ Thousands)
Panel Frames	—	9,938	—	7,563	—	11,043
Protective Coating	—	3,324	—	2,585	—	3,693
Ground Connectors	—	1,614	—	1,255	—	1,793
Array Foundations	525	13,491	454	14,035	193	8,927
Array Structures	174	2,277	208	[illegible]09	—	—
Panel Installation	187	—	145	—	207	—
Reflector Panels	—	—	145	5,841	—	—
First and Installation Costs	$211,850,000		$197,575,000		$193,780,000	
Net change over 8 by 16 foot panel	+11%		+12%		+10%	

Notes:
- (1) See Table 4-1.
- (2) See Table 4-3
- (3) See Table 4-5.

the plant's capital equipment. Additionally, factors such as owner's costs and maintenance must be considered. Among other things, these factors are strongly dependent on module failure rates and life. It is anticipated that all of the above will be evaluated by JPL in future computer analyses of plant life-cycle costs. Table 5-3 is presented. to show the relative magnitudes of installed equipment costs, owner's costs and operating and maintenance expenses. It should be pointed out that the costs in Table 5-3 exclude replacement of the panels in the tenth year and are based on theoretical insolation. Actual energy cost will vary with insolation at a given site.

TABLE 5-3

ENERGY COSTS ($/kWh)

Item	Rack	Tandem	Horizontal	Seasonally Adjusted	Tracking
Installed Equipment Costs	0.070	0.067	0.063	0.084	0.092
Owner's Costs	0.019	0.017	0.018	0.021	0.022
Operation and Maintenance	0.003	0.003	0.003	0.003	0.004
Energy Costs	0.092	0.087	0.084	0.108	0.118

5.6 OTHER COST SENSITIVITIES

As shown in Section 3.2.8, by influencing cell temperature and conversion efficiency, site temperature can affect plant energy output and, thereby, the cost per watt or kilowatt hour.

Figure 3-14 shows the relation between module insulation (encapsulant), converter and dc wiring costs. Selection of the dc system voltage influences module cost.

The cursory analysis performed in Section 3.4.5 shows that if onsite battery energy storage is included, it is less costly to charge the batteries with off-peak utility energy than with solar energy.

Within the level of engineering allowed for this study, there was no major difference in cost found between metal substrate and glass superstrate module designs.

Section 6

DEPENDENCIES AMONG COST ELEMENTS

JPL has defined cost elements as first cost (i.e., materials), installation costs (i.e., labor) and operating and maintenance costs. Relationships among these cost elements are generally considered as design tradeoffs and are difficult to quantify at the level of engineering of this study.

6.1 FIRST COSTS

The relationships between first and other costs are discussed in this section.

6.1.1 Installation

Quantitative relationships between installation labor and first (i.e., material) costs for the array designs in this study can be obtained by inspection of the cost tables presented in Section 4. However, these relationships should not be interpreted as being generally applicable, since they can change with array design and construction technique.

The amount of installation labor required to install an item of equipment is usually estimated on the basis of past experience with installing similar equipment. On an item by item basis, labor manhours or cost can be quantitatively related to material cost. For expensive materials, such as the converter equipment, installation costs are a small fraction of material cost (on the order of 10 percent). For inexpensive materials, such as concrete, installation cost may approach 50 percent of the material cost. Some items of plant cost, such as site preparation, may consist almost entirely of labor. However, it is common practice to subcontract this type of work and list the cost of the subcontract separately or with materials. Unfortunately, this obscures the amount of labor involved.

Although no major engineering effort was performed to optimize the designs, many design alternatives were considered in arriving at the array designs presented herein. These efforts included consideration of installation procedures and costs. Generally, the approach taken was to have as much assembly labor as possible performed at a factory in order to minimize field labor. Thus, the materials shipped to the field are more expensive by virtue of their factory labor content, but the amount of field installation labor is reduced. Alternate scenarios were not designed for and evaluated so that the material cost could be quantitatively related to installation labor. However, it is felt that the approach taken will result in the lowest installed cost.

One result of the panel size sensitivity evaluation (see Section 5.4) was that even though the smaller panels have a lower material cost, installation labor and other factors resulted in a total plant cost 10 to 12 percent higher than for designs using the large panels.

6.1.2 Operation and Maintenance

Operation. Since there is no fuel cost, the major operating expense will be for the labor required to operate the plant. However, the characteristics of photovoltaic central station power plants are such that the amount of operating labor is minimal. Some material or first costs are associated with the building needed to house the operating personnel, and with the computerized data logging and monitoring equipment used to minimize the staffing requirements. In view of the large number of arrays in the plant, it is felt that some type of automated monitoring system is required. However, tradeoff studies to quantify the relationship between operating labor requirements and the cost of various degrees of automated monitoring were not conducted.

As discussed in Section 3.4.5, if battery energy storage is included, it will be most economically charged with off-peak utility energy. Although it may be possible to accomplish this operation remotely from a utility's central dispatch office, the present study postulates onsite operators to monitor this function. Thus, the cost of the battery system has associated with it a requirement for night-shift operating labor. The question of whether this labor is actually needed will be answered by operation of the Battery Energy Storage Test Facility and utility battery load-leveling installations before photovoltaic central station power plants are constructed.

Maintenance. As discussed in Section 3.7, the major maintenance items will be array cleaning and total panel replacement.

A previous Bechtel study (Ref. 3-1) concluded that manual washing of the arrays was generally more expensive than use of specially designed machines. The expected life of the cleaning machines is greater than one year so that their cost is included with plant capital equipment. First costs associated with array cleaning operations include vehicle(s), water purifying and storage tanks and a well. The magnitude of these costs is dependent on array design and site environment characteristics such as the rate of dirt accumulation and the purity of available water. Design of the washing system is related to array design. The systems described in Section 3.7.3 do not impose a structural load on the arrays. Also, the spread out nature of the tracking arrays necessitates a system that is different from the design for the other four array concepts. Dirt accumulation rates in conjunction with the value of energy sold determine the washing frequency, thereby setting the number of machines needed and cost.

Total panel replacement material cost is equal to the corresponding portion of first cost if it is assumed that the cost of replacement panels is equal to that of the initial set. Actual costs, of course, depend on rates of inflation for the panels, the effect of future production rate on panel cost and the effect of future technology improvements on efficiency (e.g., dollars per watt). This same cost relationship holds true for routine replacement of failed panels during the life of the plant. At present, the amount of additional first cost that must be expended to decrease the panel failure rate and extend life is unknown. Equipment for installation and replacement of panels is included with plant capital equipment.

Galvanizing was selected to protect all panel and array steel for the life of the plant, since the cost to paint the panels in the field would be prohibitively expensive.

No tradeoff studies were conducted to optimize and quantify the relationship between the remaining balance of plant first costs and maintenance costs.

6.2 MAINTENANCE AND INSTALLATION LABOR

As discussed in the preceding section, panel replacement and installation are directly related since they involve the same operation. However, maintenance panel replacement requires almost twice the installation labor, since in this operation, an old panel must first be removed. Replacement labor is slightly less than installation labor because less precision is needed in removing old panels, and combined removal and installation operations require less truck movement.

Section 7

UTILITY PRACTICE

7.1 COST REPORTING

All electric utilities that fall under the jurisdiction of the Federal Energy Regulatory Commission file annual reports containing comprehensive financial and operating information. The form of the reports is based upon the Commission's uniform system of accounts, which is, in all essential respects, identical with the reporting systems prescribed by the various state regulatory commissions. The electric plant cost accounts for production plants are separated into groups for steam, nuclear, hydraulic, and other production plants. Operation and maintenance expense accounts are likewise grouped by the same means of power generation. At this time, a commercial photovoltaic power plant would be placed under the categories of "other production" and "other power generation." Table 7-1 lists the account headings that are used to report costs under these headings (Ref. 7-1).

The cost of construction, which is included in the electric plant accounts, includes both direct and indirect costs including contract work, labor, materials and supplies, transportation, special machine service, shop service, protection, injuries and damages, privileges and permits, rents, engineering and supervision, general administration capitalized, engineering services, insurance, law expenditures, taxes, allowance for funds used during construction, earnings and expenses and training costs. The utilities maintain records of property and property retirements that reflect the service life of property that has been retired to aid in estimating probable service life by mortality, turnover or other methods. Utilities also maintain records to reflect the salvage and removal costs for depreciable electric plant. From these records, annual depreciation on the electric plant is computed and charged as an expense in the income accounts.

TABLE 7-1

UTILITY COST ACCOUNTS

Excerpts From Plant Accounts and Production Expenses

Electric Plant Account - 2D. "Other Production"

340	Land and Land Rights
341	Structures and improvements
342	Fuel holders, producers and accessories
343	Prime Movers
344	Generators
345	Accessory electric equipment
346	Miscellaneous power plant equipment

Operation and Maintenance Expense Accounts - 1D. "Other Power Generation"

546	Operation supervision and engineering
547	Fuel
548	Generation expenses
549	Miscellaneous other power generation expenses
550	Rents
551	Maintenance supervision and engineering
552	Maintenance of structures
553	Maintenance of generating and electric plant
554	Maintenance of miscellaneous other power generation plant

The operation and maintenance expense accounts include labor costs for supervisory and engineering employees engaged in supervising and directing the operation and maintenance of the plant as well as the labor, materials, overheads and other expenses incurred in maintenance work. The work operations applicable to maintenance include:

- Inspecting, testing and reporting on the condition of the plant
- Preventing failure, restoring serviceability and maintaining the life of the plant
- Repairing for reuse materials recovered from the plant
- Testing for, locating and clearing trouble
- Replacing or adding minor items of plant that are not considered retirement units

For the purposes of handling additions and retirements of electric plant, all property is considered to consist of either retirement units or minor items of property. When a retirement item is retired from an electric plant, the remaining book cost of the item is credited to the plant account. After another retirement unit is added to the plant, the cost of the new unit is then added in to the appropriate plant account. If the photovoltaic array modules were to be replaced at least once during the expected life of the photovoltaic plant, they would thus be depreciated over a shorter time than the longer-life structures and components in the plant. This might be the case, for example, for modules with a 10 year design life being used in a facility with an overall 20 year plant life.

7.2 SELECTION OF ALTERNATE FORMS OF GENERATION

The electric power industry is characterized by having very large investments in both plant and equipment, which typically have very long service lives when compared to other industries. A typical utility, for example, must invest close to $5 in capital for every $1 of annual revenue that it receives. This compares with something less than one dollar of capital per annual dollar of revenue for an average manufacturing business. Utilities are also set apart from other industries in operating under regulation with a franchise that obligates them to have sufficient generating capacity to provide service on demand. Over the years of regulation, utilities have developed methodologies of evaluating alternate generating capacity expansion plans to satisfy these primary constraints of cost and reliability.

The traditional planning process that has evolved has been to select the appropriate number and size of new generating units which will be able to serve the utility's total load requirements at an acceptable level of reliability and to then use the criterion of minimizing the total present worth of annual revenue requirements in selecting a particular expansion scheme (Ref. 7-2). In the last decade, the planning process has become increasingly complex due to power plant siting constraints, concern over the long term availability of fuels, rapid escalation of construction costs and fuel prices, the long lead time required for the construction of large plants, and the utility's ability to compete for sources of funds required for financing. The utility system planners have continued to use the same methodology for system expansion as they will likely continue to use when photovoltaic power plants become an available option to them.

The planning practice is typically aided by the use of models to perform reliability evaluations and production and investment costing (Ref. 7-3). Reliability evaluations are made to determine sufficient system generation reserves on a consistent basis. They are ordinarily performed on a single area approach in which transmission systems are not explicitly represented. The analysis compares the system load with the available generation capacity at each point in time. The loss of load probability (LOLP) method is used to determine how much reserve is available and the probability of having more than that reserve out of service on outage. This procedure is continued throughout the year to determine the expected number of days per year that loss of load may occur with the particular generating system being evaluated. Both the reliability and production cost evaluations use load and generation models in the analyses.

A complete reliability analysis would be based on each of the 8760 hours of system operation throughout a year. Historical load data recorded on an hourly basis is usually used to forecast the load shape pattern in the future. Analysis of components of the LOLP index show that the contribution to the total system risk is predominantly due to peak load periods. To reduce computational complexity, the conventional load model is generally simplified to include only weekday peak loads on the entire system.

The introduction of photovoltaic plants will require modification of existing utility planning models to simulate the hourly output of the photovoltaic plant throughout the year. An approach would be to consider the photovoltaic plants as having essentially zero incremental production costs in the same manner as conventional hydroelectric plants. The seasonal hourly data of solar insolation, ambient temperature and wind conditions for a particular site would be used to determine the plant output. This would be further modified by the conditional probability of cloud cover. Thus, the system's hourly load is reduced whenever photovoltaic or hydroelectric power is available.

The generation capacity model is an outage probability table that gives the probability associated with various amounts of capacity on outage. It represents the individual characteristics of thermal units with respect to maintenance scheduling, seasonal ratings, forced outage rates and changes in forced outage rates as units progress from immaturity to seasoned operation.

Utility systems are designed with a reliability criterion of accepting one day's loss of load in a ten year period. The comparison of alternative expansions is done maintaining the LOLP index constant at 0.1 day/year and thereafter minimizing the cost of the expansion. These analyses yield the effective load carrying capability of each generating unit, which is a direct measure of its ability to contribute to the overall system reliability. For a constant LOLP level, the addition of one generating unit to a system will increase the system's peak load carrying ability by an amount equal to the effective capacity of the unit (Ref. 7-4). For large conventional coal or nuclear units, representative values of effective capacity range between 50 to 75 percent of rated capacity. For smaller units such as gas turbines, effective capacity might be 85 to 95 percent of rated capacity. These values are determined by unit size, forced outage rate, maintenance requirements and the system on which the unit is installed.

For a photovoltaic plant the effective capacity is additionally dependent upon the time correlation between system demand and plant output and any dedicated storage. The effective capacity for a photovoltaic plant is quite sensitive to these factors, which makes comparisons of plants by this parameter less meaningful unless all the relevant parameters are specified. Recent studies based upon systems having five percent composition of photovoltaic plant capacity showed a range of effective load carrying capabilities of from 21 to 56 percent for these plants, and corresponding capacity factors ranging from 22 to 30 percent (Ref. 7-5). The lower values of effective capacity require photovoltaic plants to show their merit based upon attractive capital costs and reduced annual production costs throughout the power system by virtue of capacity displacement.

The production costing model simulates the hour by hour operation of the system in order to determine the operating expense involved. These studies involve study periods that range from ten to thirty years into the future. The actual production costing algorithms depend on unit commitment and thermal dispatch. Enough units are committed to service each hour to meet the load and spinning reserve margin of the system determined by the system's commitment policy. The dispatched thermal generating units are called on an equal incremental cost basis to meet the system load not served by hydroelectric or photovoltaic plants. With this model, the system fuel and operating and maintenance costs are directly calculated. This takes into account both forced outage rates, maintenance scheduling, unit heat rates and projected price levels and escalation costs on fuel. Transmission losses are also a part of supplying the requirements of an electric system and must be considered in the production costing. Transmission losses may be determined by means of either power flow studies or transmission loss penalty factors (Ref. 7-6).

The investment costing model determines the annual fixed capital costs of each generating unit on the system including conventional generating plants and the photovoltaic plants. Each unit's annual fixed charges depend upon its initial capital costs and its individual fixed charge rate. The fixed charge rates will vary among different units depending upon their economic life, their location with respect to local taxing jurisdictions and any special income tax treatment that may apply.

With the results of the production and investment costing models applied to specific expansion schemes that meet the reliability criteria of the power pool, the conventional revenue requirements of each scheme are determined. The economic comparison can be made between cases with and without photovoltaic plants by selecting the expansion scheme that has the minimum total present worth of the revenue requirements or the minimum levelized annual revenue requirements.

A brief survey of five utilities (Florida Power and Light, Los Angeles Department of Water and Power, Pacific Power and Light, San Diego Gas and Electric, and Southern California Edison) was made to determine how willing they would be to install photovoltaic plants and what concerns would influence their decisions to do so. Universally, the replies were that the decision would primarily be based on economic factors once the reliability and operational characteristics of photovoltaic plant components are better known. In all cases, the method of selecting a photovoltaic plant from the available resource options would be decided by minimizing the levelized annual revenue requirements. The methods described herein were found to be in the right direction with concern only being expressed on some of the procedures for handling photovoltaic plants in simulations. The treatment of power plant dispatch, for example, and the question of spinning reserve credit for photovoltaic plants with and without energy storage are questions still to be addressed. At the current time a study is being completed refining various computer codes to simulate photovoltaic power plants in utility systems (Ref. 7-7).

Once a utility has selected a photovoltaic plant for an increment of generation, the design question of whether that plant should be more capital intensive to reduce future operating costs was asked of the utilities. In this instance, the technique of minimizing the annual incremental revenue requirements would ideally be the criterion of choice among design alternatives. On the other hand, there would be several factors leaning toward choosing the minimum initial capital cost alternate. Among these are:

- Concern that if the final plant design becomes too expensive, the initial decision to build a photovoltaic plant would have to be reevaluated
- Emphasis on minimizing economic risk in design choices
- Recognizing that while minimizing the revenue requirements is generally paramount, this requirement is always subject to the availability of funds

Section 8

CONCLUSIONS

Major conclusions derived from the conduct of the study described herein are presented in this section.

Balance-of-plant costs are approximately equal to (goal) module costs.

The economics of photovoltaic central stations (and all applications) depend on total plant cost. Thus, reductions in balance-of-plant costs are as important as reductions in cell costs. Unlike cell manufacturing, it is highly doubtful that any reduction in the cost of materials for items in this area will be brought about by advances in technology. Rather, cost reductions for the balance-of-plant will occur from clever and innovative engineering, possibly including the use of unconventional construction materials. At present, it is unknown how many engineering manhours or dollars must be expended to reduce plant cost by some increment.

Module insulation (encapsulation) costs are effected by the dc system voltage and set the upper limit for this voltage.

The horizontal array configuration is less expensive than the tandem array at latitudes less than 40° and both of these configurations are less expensive that the rack design. However, their costs are within approximately ±10 percent of each other.

Seasonally adjusted and tracking array configurations for flat plate panels are not economically attractive when compared to the three other array configurations evaluated.

The site environment affects plant energy costs in several ways including:

- Theoretical insolation varies with site latitude and influences the type of array design selected.
- Lower ambient air temperatures and higher average wind speeds lower cell temperature, thereby increasing conversion efficiency and plant output.
- Array structural and foundation costs increase with increasing fastest mile winds for the site location.
- Array maintenance (washing) costs and energy loss increase with increasing rates of dirt accumulation.
- Insurance costs increase with increasing risk of hail, wind or tornado occurrence and may act to limit plant size to approximately 100 MW.

Except for the tracking array, losses in plant wiring, switchyard and converters reduce the plant's useful energy output by an average of 6.5 percent and reduce peak power at the bus bar by an average of 8.9 percent. Energy and power losses for the tracking array are higher (9.6 and 11.1 percent, respectively) due to longer lengths of dc wiring and percent of time spent at high current levels.

If included, batteries should be charged with off-peak utility energy.

Section 9

RECOMMENDATIONS

The following recommendations are offered to assist JPL and DOE in achieving the goals of the LSA program.

Economic evaluations should account for power and energy losses within the plant and, insofar as possible, the effects of site environment.

The preliminary estimates of module failure rates should be revised or at least evaluated parametrically in life-cycle cost analyses.

In view of the results of this study, further effort should be devoted to optimizing the horizontal and tandem array designs.

Cost goals should be established for balance-of-plant costs. This task will be complicated by the site dependence of plant and energy costs normalized to dollars per watt or dollars per kilowatt hour. However, lower than anticipated costs for optimized plant designs may allow raising cell cost goals or move the time of implementation for photovoltaic central stations closer to the present.

In view of their large contribution to total installed plant costs, a detailed study should be made of distributable,

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engineering and contingency costs for photovoltaic central station plants. The study described in this report drew upon Bechtel's experience on construction projects to define these costs as accurately as possible within the level of engineering allowed. However, further study specific to photovoltaic plants is warranted.

Section 10

NEW TECHNOLOGY

No reportable items of new technology have been identified by Bechtel during the conduct of this work.