Holmes

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Cost Data Base for Solar Thermal Technologies

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*B. Butler thinks a structurally stabilized Composite membrane will beat all of these.*

*JH 11/11/88*

# APPENDIX A

## DOCUMENTATION ON COST DATA FOR ELECTRICITY GENERATION SYSTEMS BASED ON THE GLASS-METAL DISH CONCENTRATOR

Presented here are long-term costs for the dish-stirling solar generating concept based on a kinematic stirling engine with a glass-metal concentrator. For the long-term estimates, the technology is assumed to be mature and all components are considered to be in mass production. Contingencies associated with these estimates reflect the mature nature and high production levels associated with long-term technologies. The presumed annual production level for the system is $2.5 \times 10^6$ m² of concentrator aperture area per year or the quantity of units required to support $2.5 \times 10^6$ m² of aperture area. It is assumed that the builder of a plant could buy any portion of the annual production level and achieve the same central production facility economies-of-scale benefits.

Presented in Table A.1 are the long-term estimates. The cost data are presented in one of four forms: dollars per square meter of aperture area, as a function of initial capital cost, dollars per kilowatt electric, or total-dollars at several design points (MWe, number of dishes, or m² of aperture area). For cost data given as a function of design points, it is necessary to fit the data to equations which allows the determination of component costs over a range of system sizes and not just at given design points. After the preparation of equations is completed, it is then possible to use the cost data presented to prepare system estimates at the component and subcomponent levels for a wide range of system sizes.

Following Table A.1 there is a subcomponent-by-subcomponent explanation of how the estimates were prepared. In addition to procedural information, a quality judgment of the data is given at the component and subcomponent level. The quality judgment includes a rating of good, fair, or poor and an explanation of weakness and strengths of the data.

TABLE A.1. Long-Term Cost Data Table for Glass-Metal Dish Systems, 1984$

| | | |
|---|---|---|
| Concentrator (glass-metal; based on McDonnell Douglas technology) | | |
| Mirror/Support | | |
| Unit (F.O.B.) | $61 per m$^2$ of aperture area | |
| Transportation | $7 per m$^2$ of aperture area | |
| Field Installation | $16 per m$^2$ of aperture area | |
| Drive | $20 per m$^2$ of aperture area | |
| Controls and Wiring | $760 per dish | |
| Foundation | $9 per m$^2$ of aperture area | |
| Receiver | $1881.59(MWe/0.025 MWe)$^{-0.32068}$ | for 25 kWe unit(s) |
| Transport | 0.025 MW system | $12,400 |
| | 0.05 MW system | $12,800 |
| | 0.125 MW system | $14,900 |
| | 0.25 MW system | $20,500 |
| | 0.65 MW system | $34,700 |
| | 3.875 MW system | $212,600 |
| | 16.25 MW system | $912,800 |
| | 64.75 MW system | $3,707,500 |
| | 323.75 MW system | $18,734,400 |
| Conversion | $4390.39(MWe/0.025 MWe)$^{-0.32068}$ | for 25 kWe unit(s) |

TABLE A.1. (Cont.)

Balance-of-Plant

Land and Site Preparation

| | | |
|---|---|---|
| Basic Land and Site Prep. for access roads, and buildings | 0.025 MW system | $4300 |
| | 0.05 MW system | $4300 |
| | 0.125 MW system | $4300 |
| | 0.25 MW system | $4300 |
| | 0.5 MW system | $18,800 |
| | 2 MW system | $20,700 |
| | 10 MW system | $35,800 |
| | 30 MW system | $39,800 |
| | 100 MW system | $42,200 |
| | 200 MW system | $44,700 |
| Dish-Array Land and Site Prep. | $4.94 per $m^2$ of aperture area | |
| Dish-Array Fencing | $87m^2$ field size | $2,700 |
| | $174m^2$ field size | $3,800 |
| | $434m^2$ field size | $6,100 |
| | $869m^2$ field size | $8,600 |
| | $2,250m^2$ field size | $13,800 |
| | $13,500m^2$ field size | $33,800 |
| | $56,250m^2$ field size | $69,100 |
| | $225,000m^2$ field size | $138,200 |
| | $1,125,000m^2$ field size | $309,000 |
| Excess Land | $0.0247 per $m^2$ of aperture area | |
| Master Controls | 1 dish system | $3,000 |
| | 32 dish system | $29,000 |
| | 100 dish system | $74,000 |
| | 1000 dish system | $497,000 |
| | 10000 dish system | $3,734,000 |
| Structures | 0.025 MW system | $2,000 |
| | 0.05 MW system | $2,000 |
| | 0.125 MW system | $2,000 |
| | 0.25 MW system | $2,000 |
| | 0.5 MW system | $2,000 |
| | 2 MW system | $110,800 |
| | 10 MW system | $185,100 |
| | 30 MW system | $297,100 |
| | 100 MW system | $365,600 |
| | 200 MW system | $431,100 |
| Power Conditioning | 5 MW system | $105,000 |
| | 10 MW system | $130,000 |
| | 30 MW system | $360,000 |
| | 100 MW system | $810,000 |
| | 200 MW system | $1,540,000 |
| Service Facilities | <2 MW system | $0 |
| | 2 MW system | $137,500 |
| | 10 MW system | $217,400 |
| | 30 MW system | $273,200 |
| | 100 MW system | $581,100 |
| | 200 MW system | $1,162,000 |
| Spare Parts | 3% of capital cost of BOP items (excluding land and site prep.) | |
| | 0.6% of capital cost of energy conversion and receiver | |
| | 0.3% of capital cost of collector and transport | |

Operating and Maintenance (annual)

| | | |
|---|---|---|
| Operating | | |
| Security | < 2 MW system | $0 |
| | 2=<=100 MW system | $46,600 |
| | 100 <=200 MW system | $93,200 |
| Service Contract | < 2 MW system | $24/kWe of gross generating capacity |

TABLE A.1. (Cont.)

| | |
|---|---|
| Concentrator Maintenance | 0.20% of concentrator capital cost plus 15% overhead<br>$1.78 per m$^2$ of aperture area plus 15% overhead |
| Receiver Maintenance | lab: $2.24 per m$^2$ of aperture area plus 15% overhead<br>mat: $1.50 per m$^2$ of aperture area plus 15% overhead |
| Conversion System Maintenance | lab: $5.83 per m$^2$ of aperture area plus 15% overhead<br>mat: $3.89 per m$^2$ of aperture area plus 15% overhead |
| Transport System Maintenance | 0.5 MW system 0.75% of transport capital cost plus 15% overhead<br>2 MW system 0.80% of transport capital cost plus 15% overhead<br>10 MW system 0.85% of transport capital cost plus 15% overhead<br>30 MW system 0.90% of transport capital cost plus 15% overhead<br>100 MW system 0.95% of transport capital cost plus 15% overhead<br>200 MW system 1.0% of transport capital cost plus 15% overhead |
| Balance-of-Plant Maintenance | 1.4% of structures, service facilities, power conditioning, and spare parts plus 15% overhead<br>1.6% of master controls plus 15% overhead |
| Indirects | 25% of subtotaled component estimate |
| Contingencies | 10% of subtotaled component estimate |

**COMPONENT: CONCENTRATOR** (glass-metal technology)

QUALITY JUDGMENT: Overall the quality of the concentrator component estimate is "good". Exactly what must be included in the concentrator estimate is quite clear from the available design information. Also, there are a significant amount of cost data which pertain to heliostats that can be applied to dish concentrators.

SUBCOMPONENT: MIRRORS AND SUPPORT

METHOD: This subcomponent was estimated by PNL in three parts: (1) the concentrator unit (F.O.B.), (2) transportation, and (3) field installation (Williams et al. 1987, p. 7.1).

QUALITY JUDGMENT: The quality of this subcomponent estimate is "good". There is good definition of the mirrors and support design requirements enabling the preparation of manufacturing and installation estimates which contain considerable detail and therefore, have a high confidence level. The estimate prepared for transporting the mirrors and support structure from the factory to the site is "good" within the limits of the transportation scenario presumed. If a different method of transportation was to be used, the costs could differ slightly.

DATA: The construction of the mirror module consists of 0.028-inch thick back-silvered fusion glass with copper and protective coatings laminated to a smooth steel sheet (0.015-inch thick) and a stamped aluminized steel sheet (0.015-inch thick). The reflectivity of a new and clean module is 0.94. Design point performance estimates for the concentrator are as follow (Williams et al 1987):

Concentrator Reflectivity (new and clean)--0.94

Reflectivity Degradation (assuming bi-weekly cleaning)--0.95

Concentrator/Receiver Intercept Factor--0.966

Concentrator Design-Point Efficiency→ $0.94 * 0.95 * 0.966 = 0.863$

Concentrator Unit

The F.O.B. cost of the concentrator was estimated by using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table A.2. The concentrator estimate as generated from the algorithm is $5256 per concentrator which translates to $61 per $m^2$ of dish aperture area for the McDonnell Douglas dish which has 86.86 $m^2$ of aperture area.

TABLE A.2. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Mirrors and Support Subcomponent

| | |
|---|---|
| Direct Materials | \$3458 per dish; \$99,528,156 for 28,782 dishes/year[a] |
| Direct Labor | 9.43 hours; 271,327.5 hours for 28,782 dishes/year |
| Capital Equip. | $\$7.1 \times 10^6$ |
| Plant Area | 145,000 sq. ft. |
| Plant Acreage | 9 Acres |

(a) 28,782 dishes per year is equivalent to $2.5 \times 10^6$ square meters of concentrator area which is the assumed production level.

Concentrator Transportation

Module transportation costs were estimated by determining the number of loads required (either weight- or volume-limited) to deliver concentrator subassemblies from the factory to the site and multiplying by an assumed delivery distance of 600 miles and a cost per mile of \$1.45. It was determined that 750 mirror modules (9.15 dishes) could be transported on a weight-limited load. This results in a total transportation cost of \$645 per dish. This cost distributed over the aperture area of the dish and rounded is \$7 per $m^2$ of aperture area.

Concentrator Installation

The field installation was independently prepared by PNL for Williams et al. (1987) and is \$1376 per dish. This figure is based on a PNL estimate of 49.9 manhours for site assembly and installation and a 163-dollar charge per dish for capital installation equipment. The total estimate of \$1376 per dish when distributed over the aperture area of the McDonnell Douglas dish (86.86 $m^2$) yields a rounded unit cost of \$16 per $m^2$ of aperture area.

SUBCOMPONENT: DRIVE

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: This subcomponent estimate is based primarily on a cost and design analysis prepared by Peerless-Winsmith. Since a major focus of Peerless-Winsmith's work was a cost analysis, their bottom line estimate is based on a thorough analysis rather than a cursory one. This tends to give their estimate credibility. It is interesting that Winsmith managed to significantly reduce costs without a significant reduction in weight or predicted performance. The actual performance has yet to be demonstrated. Based on these strengths and weaknesses and also that the drive was intended for heliostats and not dishes, the quality of this subcomponent estimate is rated as "fair".

DATA: Approximately fifteen drive estimates were evaluated to determine the dish system drive cost. Of the drives evaluated, the Winsmith drive is currently the lowest cost drive which could be used for the a glass-metal dish. The Winsmith drive is designed to have low maintenance requirements and a high reliability with low degradation in desert environments. No pointing accuracy data is available yet. No parasitic energy usage is available yet either; however, on a sunny operation day the tracker unit of the Advanco concentrator uses an average of 7.2 kWh which comprises approximately 39% of the total parasitics for that system (Washom 1984 p. 77).

The Winsmith drive has two motorized units, the azimuth drive and the elevation drive. The strengths of these two units are as follows:

| Moment | English Units | SI Units |
|---|---|---|
| Azimuth max. static overturning moment | $2.58 \times 10^6$ in-lbs | $0.292 \times 10^6$ N-m |
| Azimuth static torsional moment | $2.496 \times 10^6$ in-lbs | $0.282 \times 10^6$ N-m |
| Azimuth operational torsional moment | $0.786 \times 10^6$ in-lbs | $0.0888 \times 10^6$ N-m |
| Elevation maximum static moment | $2.64 \times 10^6$ in-lbs | $0.298 \times 10^6$ N-m |
| Elevation maximum operational moment | $0.787 \times 10^6$ in-lbs | $0.0889 \times 10^6$ N-m |

While no data is available on the drive strength requirements for the McDonnell Douglas Dish, there is data on this subject for the Advanco concentrator which is also representative of the glass-metal technology. The Advanco concentrator has a different type of drive unit; however, the stress exerted by wind and gravity on the Advanco drive is approximately the same as the stress the Winsmith heliostat drive can handle. This indicates the low-cost heliostat drive or a similar drive of similar cost should meet dish system requirements.

The cost of the Winsmith unit is estimated to be $1856 (1987-dollars) (Heller 1987). De-escalating to 1984-dollars, a cost of $1696 (1984$) per drive is estimated. This estimate corresponds to the drive cost at a production level of 50,000 units per year. It is estimated the drive would cost approximately the same at a production level of 28,872 units per year, because the additional production economies-of-scale achieved over the production increase from 28,782 to 50,000 units per year is anticipated to be very small, less than five percent. Distributing this cost, $1696, over the aperture area of the McDonnell Douglas dish (86.86 m²), a rounded unit cost of $20/m² of aperture (1984$) is estimated.

SUBCOMPONENT: CONTROLS AND WIRING

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". While there are a significant number of estimates relating to the controls and wiring for heliostats, it is somewhat ill-defined as to how dish controls and wiring would differ. For this reason, some engineering judgments were required to adjust heliostat controls and wiring estimates to dish system estimates.

DATA: Development of the estimate was based on adjustment of heliostat controls and wiring estimates to conform to the system requirements of the dish system. Estimates prepared by ARCO, Martin Marietta, McDonnell Douglas (Norris and White 1982) and PNL (Drumheller 1981) were evaluated for applicability to dish systems. Based on engineering judgment, the estimate presented in Table A.3 was prepared. The total rounded cost per dish is $760 (1984$).

TABLE A.3. Long-Term Cost Estimate for Dish System Controls and Wiring (1984$)

| | | |
|---|---|---|
| Power and Control Cabling[(a)] | $463 | per dish |
| Dish Controller[(b)] | 265 | per dish |
| Dish Array Controller[(c)] | 27.50 | per dish |
| | $755.50 | per dish |

(a) This estimate includes $280 (1980$) for power cabling (Norris and White 1982, p. 94) and $90 (1980$) for control cabling. The control cabling estimate is the average of a Martin Marietta estimate of $63 (Norris and White 1982, p. 94) and a McDonnell Douglas estimate of $120 (Norris and White 1982, p. 94). The total power and control cabling estimate of $370 (1980$) was escalated to $463 (1984$).

(b) The dish controller estimate is based on the average of a McDonnell Douglas estimate of $203 (1980$) (Norris and White 1982, p. 94) and an ARCO estimate of $328 (1980$) (Norris and White 1982, p. 94). The average of $265 was not escalated because electronic components have remained about the same with respect to cost from 1980 to 1984.

(c) The dish-array controller for controlling 3631 dishes was estimated by PNL for Williams et al. (1987) to cost $100,000 (1984$) which on average is $27.50 per dish.

SUBCOMPONENT: FOUNDATION

METHOD: This subcomponent was independently estimated by PNL (Williams et al. 1987, p. 7.1).

QUALITY JUDGMENT: All the tasks necessary to prepare the foundation are typical of standard construction techniques for which good historical cost estimating data is available. For this reason, the quality of this subcomponent estimate is "good".

DATA: Foundation site preparation was estimated as $632 (1984$) and the pedestal was estimated to cost $175 (1984$). The total of $807 was distributed over the dish aperture area of 86.86 $m^2$ to yield a rounded unit cost of $9 per $m^2$ of aperture area.

COMPONENTS: RECEIVER AND ENERGY CONVERSION

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: The quality of the receiver and energy conversion estimate is rated as "fair". There was a good correlation between the three source estimates used as the basis for the final estimate which is a positive aspect. However, none of the estimates include details, which results in some uncertainty in the final estimate.

DATA: The receiver and energy conversion components for the dish are combined in a single power conversion unit (a stirling engine/generator set). The stirling engine used is a 25-kWe 4-95 Solar II Unit. The 4-cylinder engine uses hydrogen as the working fluid, operates at a heater temperature of 750-degrees Celsius, and has a gross efficiency of 0.41 (i.e., the shaft mechanical power as a fraction of heater tube heat input is 0.41.) (Holtz 1987). On a sunny day when the unit produces 227 kWh (gross), the water pump uses approximately 1.7 kWh (9% of the total parasitics), and the fan uses 9.4 kWh (51% of the total parasitics) (Washom 1984 p. 77). Design-point performance estimates for the receiver are as follows (Williams et al 1987):

Flux Entering Receiver→ $0.863 * 950\ W/m^2 * 86.86\ m^2 = 71.2\ kW$

Receiver Absorptivity--0.96

Receiver Thermal Loss--7.42 kW

Receiver Design-Point Efficiency→ $[(71.2 * 0.96) - 7.42] / 71.2 = 0.856$

Stirling cost data from three sources were evaluated. These data are presented in Table A.4. The Vanguard estimates were for installed dish system engines and were reduced by assuming installation, alignment, and testing adds ten percent to the basic cost of the unit. The other estimates reflect only purchase cost. All the units are rated at 25 kWe gross generating capacity.

The data was then fit to two equations. The first of these equations was based on the data points ranging from one to 10,000 units/yr and the second on the data points ranging from 10,000 to 400,000 units/yr. The intersection of these equations is at a production level of 9577. The equations are as follows:

$1 < \text{units/year} < 9577 \qquad \$/kWe = 2020.474 + (-187.509)\ln X$

$9577 < \text{units/year} < 400{,}000 \qquad \$/kWe = 5701.798X^{-0.32068}$

The latter of these two equations was then used to estimate the cost for long-term production levels. An additional 10% was added to the estimating equation to allow for installation, alignment, and testing. The resulting long-term estimating equation for the receiver and energy conversion unit cost is as follows:

$$\$/\text{kWe} = 6271.98X^{-0.32068}$$

"X" is equal to the number of 25 kWe (0.025 MWe) units produced per year. Substituting the plant size in MWe divided by 0.025 MWe for "X" results in the following equation which is equivalent to the one presented above:

$$\$/\text{kWe} = 6271.98(\text{Size, MWe}/0.025\ \text{MWe})^{-0.32068}$$

According to United Stirling, approximately 30% of the unit by cost could be considered the receiver and the balance would fall into energy conversion (Nelving 1985). On this basis the cost equation was split into two equations by multiplying by 0.3 and 0.7 to obtain equations for the receiver and energy conversion components, respectively. These equations are as follows:

$$\text{receiver:}\quad \$/\text{kWe} = 1881.59(\text{Size, MWe}/0.025\ \text{MWe})^{-0.32068}$$

$$\text{conversion:}\quad \$/\text{kWe} = 4390.39(\text{Size, MWe}/0.025\ \text{MWe})^{-0.32068}$$

TABLE A.4. Dish Power Conversion Unit Purchase Cost Data, 1984$

| Source | Production Quantity | Cost/Unit |
|---|---|---|
| United Stirling[a] | 1 | $50,000 |
| | 2,000 | $20,000 |
| | 25,000 | $ 5,500 |
| JPL[b] | 1,000 | $17,576 |
| | 25,000 | $ 5,641 |
| | 100,000 | $ 2,946 |
| | 400,000 | $ 2,539 |
| Vanguard[c] | 1 | $57,878 |
| | 100 | $28,941 |
| | 1,000 | $15,463 |
| | 10,000 | $ 8,700 |

(a) Telephone conversation with Worth Percival, United Stirling.
(b) Fortgang and Mayers (1980, p. 10) prices were escalated to 1984-dollars.
(c) Washom (1984, p. 9) prices were escalated to 1984-dollars and reduced to an uninstalled basis.

## COMPONENT: TRANSPORT

QUALITY JUDGMENT: Overall the quality of the transport estimate is "good". PNL specifically designed and estimated transport costs for dish technology. There is a wealth of estimating data on transport components.

METHOD: This component was independently estimated by PNL (Williams et al. 1987, p. 7.12).

DATA: The items included in this estimate and their respective costs versus field size are presented in Table A.5. The design-point performance for the transport system is a function of power level, because larger fields have longer transmission lines with higher loss. The design-point efficiencies of a dish-stirling transport system are as follows (Williams et al. 1987):

<=3.875 MW -- 0.974
16.25 MW -- 0.972
64.75 MW -- 0.964
323.75 MW -- 0.958

TABLE A.5. Costs for the Dish-Striling Transport System, 1984$

| | 0.025 MW | 0.05 MW | 0.125 MW | 0.25 MW | 0.65 MW |
|---|---|---|---|---|---|
| Disconnect Switches | $ 185 | $ 370 | 925 | $ 1850 | $4,625 |
| Sheet Metal Cubicles | 250 | 250 | 250 | 500 | 1,250 |
| Air Circuit Breakers | 215 | 215 | 215 | 435 | 1,125 |
| Transformer | 9,070 | 9,070 | 10,044 | 13,284 | 20,200 |
| 600 volt UF Cable | 195 | 390 | 970 | 1,950 | 5,036 |
| Closing Dis. Switches | 2,500 | 2,500 | 2,500 | 2,500 | 2,500 |
| Overhead Line #1 | - | - | - | - | - |
| Overhead Line #2 | - | - | - | - | - |
| Poles | - | - | - | - | - |
| | $12,415 | $12,795 | $14,904 | $20,519 | $34,736 |
| Rounded Total | $12,400 | $12,800 | $14,900 | $20,500 | $34,700 |

| | 3.875 MW | 16.25 MW | 64.75 MW | 323.75 MW |
|---|---|---|---|---|
| Disconnect Switches | $ 27,750 | $115,625 | $ 462,500 | $ 2,312,500 |
| Sheet Metal Cubicles | 7,500 | 31,250 | 125,000 | 625,000 |
| Air Circuit Breakers | 6,750 | 28,125 | 112,500 | 562,500 |
| Transformer | 121,200 | 505,000 | 2,020,000 | 10,100,000 |
| 600 volt UF Cable | 30,215 | 125,895 | 503,580 | 2,517,900 |
| Closing Dis. Switches | 15,000 | 62,500 | 250,000 | 1,250,000 |
| Overhead Line #1 | 3,046 | 22,208 | 88,830 | 444,150 |
| Overhead Line #2 | - | 12,282 | 98,992 | 669,392 |
| Poles | 1,100 | 9,900 | 46,200 | 253,000 |
| | $212,581 | $912,785 | $3,707,602 | $18,734,442 |
| Rounded Total | $212,600 | $912,800 | $3,707,600 | $18,734,400 |

**COMPONENT: BALANCE-OF-PLANT**

QUALITY JUDGMENT: The balance-of-plant estimate is judged to be "fair" in quality. The problem with the balance-of-plant category is the requirements are often nebulous. This leads to uncertainty with respect to what should and should not be included.

SUBCOMPONENT: LAND AND SITE PREPARATION

METHOD: Estimated by PNL for Williams et al. (1987) using existing estimates as guidance.

QUALITY JUDGMENT: Because the exact land and site preparation could be very different for any specific site, this subcomponent estimate is given a quality rating of "fair". One particular area which could affect the cost of this subcomponent is the selection of a site with easy access and one where all the land purchased can be used.

DATA: The estimate for land and site preparation was independently estimated by PNL using a number of earthwork estimating manuals. The subcomponent estimate consists of four parts. These include (1) basic land and site preparation for roads and building areas, (2) dish-array land and site preparation, (3) dish-array fencing, and (4) excess land cost.

The first of these parts, basic land and site preparation, is expressed as a function of power level. The unit costs for each element of the land and site preparation estimate are listed in Table A.6. The total cost as presented in Table A.6 is \$9,985/acre, which is equivalent to 2.47/$m^2$ of land area. Combining this information with estimates of the structures and access road land requirements for each plant size, the basic land and site preparation estimate was prepared. This estimate is shown in Table A.7.

Dish-array land and site preparation is a function of the total field size (aperture area). It is estimated that each square meter of aperture area requires two square meters of ground area. This results in a dish-array land and site preparation estimate of \$4.94 per $m^2$ of aperture area.

Fencing for the array is based upon a unit cost of \$51.50 per linear meter of fencing. The dish-array fencing estimates are presented in Table A.8 as a function of field size.

Finally, there is excess land cost. Although this might seem like an extraneous category, many previous site-specific studies show it is an actual cost. This cost arises because land is purchased in sections or other large tracts depending on federal or state regulations or the willingness of private landowners to sell certain parcels. The plant owner is often limited in the ability to purchase exactly the land required. Because excess land must only be purchased

and not developed, it results in an incurred cost of \$500/acre (\$0.124/m² of land area). Although land for solar facilities often ranges from \$500 to \$5000/acre, because dish systems have flexible siting requirements and do not require mainline water connections the low end of the cost range was used. Excess land for a dish system is estimated to be 10% of the dish-array land area. This corresponds to a excess land cost of \$0.0247 (1984\$) per m² of aperture area.

TABLE A.6. Unit Costs for Dish System Land and Site Preparation, 1984\$

| | |
|---|---|
| Land Purchase Cost | \$ 500/acre |
| Rough Grading | 6,300/acre |
| Clear and Grub | 625/acre |
| Survey | 930/acre |
| Roads | 860/acre |
| Ditches | 470/acre |
| Permits | 300/acre |
| | \$9,985/acre |

TABLE A.7. Basic Dish System Site Area Size and Corresponding Cost For Land and Site Preparation, 1984\$

| System Size | Land Area | Cost |
|---|---|---|
| 0.025 MW | 1,750/m² | \$ 4,300 |
| 0.05 MW | 1,750/m² | 4,300 |
| 0.125 MW | 1,750/m² | 4,300 |
| 0.25 MW | 1,750/m² | 4,300 |
| 0.5 MW | 6,800/m² | 16,800 |
| 2 MW | 8,400/m² | 20,700 |
| 10 MW | 14,500/m² | 35,800 |
| 30 MW | 16,100/m² | 39,800 |
| 100 MW | 17,100/m² | 42,200 |
| 200 MW | 18,100/m² | 44,700 |

TABLE A.8. Dish-Array Fencing Costs, 1984\$

| Field Size (aperture area) | Cost |
|---|---|
| 87m² | \$ 2,700 |
| 174m² | 3,800 |
| 434m² | 6,100 |
| 869m² | 8,600 |
| 2,250m² | 13,800 |
| 13,500m² | 33,800 |
| 56,250m² | 69,100 |
| 225,000m² | 138,200 |
| 1,125,000m² | 309,000 |

SUBCOMPONENT: MASTER CONTROLS

METHOD: Adjustment of existing estimates.

QUALITY JUDGMENT: The estimate for this subcomponent is rated as "fair", because there are not independent estimates to support its accuracy and there is no available backup detail for the estimate.

DATA: From a review of six source estimates, an estimate by Advanco (Washom 1984, p. 9) was selected for escalation because it was recently prepared and complete. These controls are for a fully mechanized unattended facility. The source estimate and the adjustments made to generate a final estimate are presented in Table A.9. The smallest master controller unit developed for the Advanco dish system is capable of controlling 32 dishes. For systems smaller than 32 dishes, the use of a standard PC and software is assumed.

TABLE A.9. Dish System Master Control Estimates

| Production Level | Cost/Module (1982$) | Total Cost (1982$) | Total Cost (1984$) |
|---|---|---|---|
| 1 | - | - | $ 3,000[a] |
| 32 | $28,000 | $ 28,000 | 29,000 |
| 100 | 711 | 71,100 | 74,000 |
| 1,000 | 478 | 478,000 | 497,000 |
| 10,000 | 359 | 3,590,000 | 3,734,000 |

(a) Assumes the use of a standard PC.

SUBCOMPONENT: STRUCTURES

METHOD: Independently estimated by PNL for Williams et al. (1987) using existing estimates as guidance.

QUALITY JUDGMENT: This subcomponent estimate is rated as "fair". It is not clear exactly what size the support structures for a dish system would need to be in order to provide necessary support for the dish system.

DATA: The structures subcomponent includes a control room, administration building, warehouse, maintenance building, and fencing around the structures. PNL unit cost estimates for these items are presented in Table A.10. The total cost for these items at various power levels are presented in Table A.11.

As shown in Table A.11., not all types of structures are present at all power levels. At plant sizes below 2 MW, it is assumed a small structure, probably prefabricated and skid-mounted, would be used at each site. This structure would house the controls, instrumentation, and possibly some spare parts or tools. At these small plant sizes, no maintenance or warehouse facilities are present.

It is assumed that below 2 MW the plant is maintained by a service contractor or by a centralized facility operated by the plant's owner; therefore, no costs for maintenance or warehouse facilities are included in the structure subcomponent estimate. However, there is an allowance for a service contract for plants less than 2 MW. It is included in the operating subcomponent and accounts for maintenance and warehouse space.

At very large plant sizes (greater than 100 MW) an allowance is made for approximately one administrative office. This office may or may not be located on site. For plants less than 100 MW, but greater than or equal to 2 MW, a small amount of administration space is included in the estimate. This space represents the plants contribution toward a larger administration facility which handles the administrative duties for several plants.

TABLE A.10. Structure Unit Costs, 1984$

| | |
|---|---|
| Control Building | $700/m² of floor area |
| Maintenance Building | $530/m² of floor area |
| Warehouse | $430/m² of floor area |
| Administration Building | $590/m² of floor area |
| Multi-Purpose Enclosure | $2000 each |
| Fencing | $51.50/linear meter |

TABLE A.11. Dish System Structures Estimates, 1984$

| | 0.025 MW | 0.05 MW | 0.125 MW | 0.25 MW | 0.5 MW | 2 MW | 10 MW | 30 MW | 100 MW | 200 MW |
|---|---|---|---|---|---|---|---|---|---|---|
| Control Building | - | - | - | - | | $ 6,500 | $ 13,000 | $ 26,000 | $ 26,000 | $ 26,000 |
| Maintenance Building | - | - | - | - | | 36,750 | 61,250 | 98,000 | 122,500 | 147,000 |
| Warehouse | - | - | - | - | | 60,000 | 100,000 | 160,000 | 200,000 | 240,000 |
| Administration Building | - | - | - | - | | 1,475 | 2,950 | 2,950 | 5,900 | 5,900 |
| Multi-Purpose Enclosure | $2,000 | $2,000 | $2,000 | $2,000 | $2,000 | - | - | - | - | - |
| Fencing | - | - | - | - | | 6,100 | 7,900 | 10,100 | 11,200 | 12,200 |
| Rounded Total | $2,000 | $2,000 | $2,000 | $2,000 | $2,000 | $110,800 | $185,100 | $297,100 | $365,800 | $431,100 |

SUBCOMPONENT: POWER CONDITIONING

METHOD: Comparison and Adjustment of Existing Estimates

QUALITY JUDGMENT: The quality of this subcomponent estimate is rated as "fair", because it is not clear exactly what should be included in this subcomponent.

DATA: Based on site-specific solar power plant studies, the following assumptions were made with respect to transmission line voltage:

| | |
|---|---|
| <5 MW | 13.8 kV |
| 10 MW | 33 kV |
| 30 MW | 115 kV |
| >100 MW | 230 kV |

Because the transport system boosts the voltage to 13.8 kV, no power conditioning is required for plants less than 5 MW. Based on engineering judgment and transformer cost data (Westinghouse 1981) the estimates in Table A.12 were prepared.

TABLE A.12. Dish System Power Conditioning System Cost Estimates, 1984$

| System Size | Cost |
|---|---|
| 5 MW system | $ 105,000 |
| 10 MW system | 130,000 |
| 30 MW system | 360,000 |
| 100 MW system | 810,000 |
| 200 MW system | 1,540,000 |

SUBCOMPONENT: SERVICE FACILITIES

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

QUALITY JUDGMENT: The quality of this subcomponent estimate is rated as "fair". The "fair" rating was assigned since the exact requirements for dish systems are not well-defined.

DATA: Service facilities estimates for various power levels are presented in Table A.13. The estimate for each power level includes service vehicles, site communication equipment, fire protection, and water systems. Below plant sizes of 2 MW, it is assumed that a service contract is in place or the owner of the plant services the system from a centralized facility. Therefore, no service facilities costs are included in this subcomponent estimate for plants less than 2 MW. Under the operating subcomponent there is an allow made for a service contract for plants less than 2 MW.

TABLE A.13. Dish System Service Facilities Estimates, 1984$

| System Size | Vehicles | Communication | Fire Protection | Water | Rounded Subtotal |
|---|---|---|---|---|---|
| <2 MW | $ 0 | $ 0 | $ 0 | $ 0 | $ 0 |
| 2 MW | 133,000 | 440 | 3000 | 1,040 | 137,500 |
| 10 MW | 195,000 | 2,200 | 15,000 | 5,210 | 217,400 |
| 30 MW | 206,000 | 6,600 | 45,000 | 15,640 | 273,200 |
| 100 MW | 357,000 | 22,000 | 150,000 | 52,120 | 581,100 |
| 200 MW | 714,000 | 44,000 | 300,000 | 104,230 | 1,058,000 |

SUBCOMPONENT: SPARE PARTS

METHOD: Estimated by PNL for Williams et al. (1987) using existing estimates as guidance.

QUALITY JUDGMENT: Nothing can substitute for actual operating experience when attempting to determine the number of spare parts required for a particular plant, subsystem, or piece of equipment. Since there is no good operating experience available, some engineering judgments were required based upon existing heliostat spare parts estimates. For these reasons, the overall quality of this subcomponent estimate is rated as "poor".

DATA: The spare parts estimates include a three-year supply of parts. The primary basis is estimates developed for the repowering of the Saguaro Power Plant (Weber 1982). These estimates for annual spare parts are:

| | |
|---|---|
| Collector Equipment | 0.1% of initial cost/yr |
| Receiver Equipment | 1.0% of initial cost/yr |
| Storage Equipment | 1.0% of initial cost/yr |
| Heat Exchanger Subsystem | 1.0% of initial cost/yr |

Source: Weber 1982, p. G-12

Using these estimates as guidelines, the following estimates were prepared for dish systems:

| | |
|---|---|
| Concentrator Equipment | 0.3% of initial cost |
| Transport Equipment | 0.3% of initial cost |
| Balance-Of-Plant Items (excluding land and site prep.) | 3.0% of initial cost |
| Receiver and Energy Conversion | 0.6% of initial cost |

Centralized components were presumed to have spare parts requirements which are ten times greater than the requirements for distributed components, because failure of a centralized component affects the entire (or major parts) of the system while failure of a distributed component has a limited affect on the whole system. For this reason the transport system which is distributed has the same spare parts allowance as the collector which is also distributed. The balance-of-plant allowance is estimated as ten times higher because it is a centralized component. Exceptions to the rule are the land and site preparation subcomponent which requires no spare parts, and the receiver and energy conversion spare equipment estimate which is presumed to be twice as high as the collector spare parts estimate, because the receiver and energy conversion equipment (i.e., the stirling engine) is expected to require significantly more maintenance than the collectors. Hence, additional spares are required.

## COMPONENT: OPERATING AND MAINTENANCE

QUALITY JUDGMENT: the quality of O&M cost data is rated as "poor", mainly because little operating experience exists which causes estimates to be based largely on conjecture.

### SUBCOMPONENT: OPERATING

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

QUALITY JUDGMENT: This subcomponent estimate is rated as "poor". Although the estimate is good for the assumptions made, there is considerable uncertainty as to what would be the actual requirements.

DATA: Operating personnel for the dish systems at all power levels greater than 100 MW is estimated to be three full-time security personnel. For plants ranging from 2 MW to 100 MW one and one-half full-time security persons are estimated present. Below 2 MW no security personnel are present. The estimated salary per full-time person is $27,000 per year. A 15% overhead charge (Guthrie 1974) is added to this estimate to yield a total operating personnel estimate of $31,050 per full-time person. Therefore, the rounded final estimates are as follows:

| | |
|---|---|
| < 2 MW systems | $0 |
| 2=<=100 MW systems | $46,600 |
| 100 <=200 MW systems | $93,200 |

In addition, plants less than 2 MW are assumed to have either a service contract or be maintained from the owner's centralized maintenance facility which is not on site. Because a service contract is in place for plants less than 2 MW, maintenance, warehouse, administration, and service facilities for these same plants were estimated as zero.

For a 2 MW plant approximately $1385 per 25 kWe dish and $1719 per 25 kWe dish are estimated to be spent on structure and service facilities, respectively; therefore, these costs times the owner's or subcontractor's fixed charge rate is the amount each dish must be charged per year for the capital recovery of the structures and service facilities. The actual parts and labor for this type of arrangement are estimated to be the same as for all other plant sizes (see the maintenance subcomponents).

The fixed charge rate used for buildings is 0.177 which is based on a depreciation period of 20 years, economic life of 20 years, a 10% discount rate, a 38% federal tax rate, and 2% in other taxes. The fixed charge rate used for service facilities is 0.205 which is based on a depreciation period of 5 years, economic life of 10 years, a 10% discount rate, a federal tax rate of 38%, and 2% in other taxes.

Applying these two fixed charge rates to the corresponding estimates above yields an annual service charge of approximately $600 per 25 kWe dish. This is equivalent to $24/kWe of gross generating capacity. Although this cost could be grouped with maintenance costs, because it is a fixed annual expense it is listed as an operating expenditure.

SUBCOMPONENT: MAINTENANCE OF THE CONCENTRATOR

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: Maintenance of the concentrator is broken into two major elements, washing and non-washing maintenance. The washing estimate is fair in quality, being a well understood, relatively straight-forward task. The non-washing estimate is poor due to uncertainty in what is truly required. An overall rating of "poor" is assigned.

DATA: Dish washing costs were assumed 50% higher than heliostat washing costs due to washing complexities caused by the dishes' curved surface. Washing costs for the heliostat are a product of a review of six source estimates. Based on the completeness of the estimates and engineering judgment, estimates by ARCO, and McDonnell Douglas were used as the basis for the final estimates. These estimates are presented in Table A.14. The average material cost for washing is $0.285/m² (1980$) while the average labor cost of washing is $0.16/m² (1980$). However, one-third of the labor is moving from heliostat to heliostat; therefore, the cost of actual washing labor is $0.107/m² (1980$). Because washing costs for the dish were assumed to be 50% greater, due to washing complexities, the cost of actual dish washing was estimated as $0.160/m² (1980$). Adding back the moving cost between dishes and material cost, the total cost for twelve washes per year is $0.498/m² (1980$). To keep the reflectivity to a reasonably high level, the estimate was doubled to allow twenty-four washes per year. Escalating to 1984-dollars, results in an estimate of $1.18 per m² of surface area (1984$). Adjusting the estimate to a dollars-per-square-meter-of-aperture-area basis yields an estimate of $1.24 per m².

TABLE A.14. Heliostat Mirror Washing Cost (12 Washes/Year), 1980$

| | |
|---|---|
| ARCO | 0.48/m² (a) |
| McDonnell Douglas | 0.41/m² (b) |

(a) ARCO (Norris and White 1982, p. 116) estimates $0.18 for washing materials and $0.06 (1980$) for washing labor for 6 washes per year.

(b) MDAC (Norris and White 1982, p. 116) estimates $0.21 for washing materials and $0.20 (1980$) for washing labor for 12 washes per year.

Non-washing costs for the dish are assumed equal to those of the heliostat on a square-meter-of-surface-area basis. Heliostat non-washing cost estimates from four sources were averaged to get estimates of \$0.41 and \$0.20 per square meter of surface area (1980\$) for labor and materials, respectively. These were escalated to \$0.51 and \$0.25 in 1984-dollars, respectively. The source estimates are presented in Table A.15.

TABLE A.15. Heliostat General Maintenance (non-washing) Costs, 1980$

| | Labor | Materials |
|---|---|---|
| ARCO | $0.31/m² | $0.11/m² |
| McDonnell Douglas | 0.38/m² | 0.30/m² |
| Boeing | 0.41/m² | 0.32/m² |
| Martin Marietta | 0.55/m² | 0.06/m² |

Adjusting the non-washing maintenance cost estimates to a dollars-per-square-meter-of-aperture-area basis yields estimates of \$0.54/m² and \$0.26/m² for labor and materials, respectively. Material costs would increase relative to the concentrator capital cost, and are therefore expressed as a fraction of initial capital cost. Dividing the materials estimate of \$0.26/m² of aperture area by the concentrator capital cost of \$122 per square meter of aperture area, results in a yearly non-washing materials concentrator maintenance estimate of 0.20 percent of the initial concentrator cost.

Summarizing, concentrator maintenance has three components, (1) washing costs which are \$1.24/m² of aperture area, (2) non-washing labor costs which are \$0.54/m² of aperture area and (3) non-washing material costs which are 0.20% of the initial capital concentrator cost. In addition, a 15% overhead charge (Guthrie 1974) is added to all of the above estimates.

SUBCOMPONENT: MAINTENANCE OF THE RECEIVER SYSTEM.

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

METHOD: Based on the expert opinion of United Stirling (Percival 1986) and additional data estimated by PNL for Williams et al. (1987).

DATA: Maintenance costs were based on data provided by Worth Percival of United Stirling. PNL estimated maintenance costs to be .625¢/kWh for the receiver which represents the average of a range of costs estimated by United Stirling. Using an annual insolation of 2848 $kWh_t/m^2$ at Barstow, CA (1976), and an average system efficiency of 21%, total annual maintenance costs for the receiver are equal to:

$$\$(0.00625)(2848)(0.21) \text{ per m}^2 \text{ of aperture area}$$

This equation is broken down into a labor and materials components by assuming an a 60/40 labor-materials split (Jelen 1970, p. 348) applies. The final two equations are as follow:

lab: \$2.24 per $m^2$ of aperture area
mat: \$1.50 per $m^2$ of aperture area

In addition a 15% overhead charge must be added to this estimate (Guthrie 1974).

SUBCOMPONENT: MAINTENANCE OF THE CONVERSION SYSTEM

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

METHOD: Based on the expert opinion of United Stirling (Percival 1986) and additional data estimated by PNL for Williams et al. (1987).

DATA: Maintenance costs were based on data provided by Worth Percival of United Stirling. PNL estimated maintenance costs to be 1.625¢/kWh for the conversion system which represents the average of a range of costs estimated by United Stirling. Using an annual insolation of 2848 $kWh_t/m^2$ at Barstow, CA (1976), and a system efficiency of 21%, total annual maintenance costs for the conversion component are equal to:

$$\$(0.01625)(2848)(0.21) \text{ per } m^2 \text{ of aperture area}$$

This equation is broken down into a labor and materials components by assuming an a 60/40 labor-materials split (Jelen 1970, p. 348) applies. The final two equations are as follow:

lab: \$5.83 per $m^2$ of aperture area
mat: \$3.89 per $m^2$ of aperture area

In addition a 15% overhead charge must be added to this estimate (Guthrie 1974).

SUBCOMPONENT: MAINTENANCE OF THE TRANSPORT SYSTEM

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

QUALITY JUDGMENT: Due to the maintenance requirements being quite nebulous, this subcomponent estimate is rated as "poor".

DATA: The estimate as prepared by PNL is presented in Table A.16. It is based on applying engineering judgment to maintenance cost estimates for other electrical operating systems. In addition to the costs presented below an overhead charge of 15% must be added (Guthrie 1974).

TABLE A.16. Dish Transport System Maintenance Cost Estimate

| System Size | Scheduled/ Unscheduled Maint.[a] | Maint. Materials[a] | Total[a] |
|---|---|---|---|
| 0.5 MW | 0.25 | 0.50 | 0.75 |
| 2 MW | 0.30 | 0.50 | 0.80 |
| 10 MW | 0.35 | 0.50 | 0.85 |
| 30 MW | 0.40 | 0.50 | 0.90 |
| 100 MW | 0.45 | 0.50 | 0.95 |
| 200 MW | 0.50 | 0.50 | 1.00 |

(a) The estimates are presented as the fraction of the transport system capital cost required for annual maintenance.

SUBCOMPONENT: MAINTENANCE OF BALANCE-OF-PLANT

QUALITY JUDGMENT: Due to the maintenance requirements being quite nebulous, this subcomponent estimate is rated as "poor".

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

DATA: The estimate as prepared by PNL for the balance-of-plant exclusive of the master controls and land and site preparation is presented in Table A.17. The maintenance estimate for the master controls is 1.6% of the capital cost per year (Weber 1983). In addition an overhead charge of 15% (Guthrie 1974) must be added to these estimates.

TABLE A.17. Dish System Balance-of-Plant Maintenance Cost Estimate

| System Size | Scheduled/ Unscheduled Maint.[a] | Maint. Materials[a] | Total[a] |
|---|---|---|---|
| 10 MW | 0.40 | 1.0 | 1.4 |
| 30 MW | 0.40 | 1.0 | 1.4 |
| 100 MW | 0.40 | 1.0 | 1.4 |

(a) The estimates are presented as the fraction of the balance-of-plant capital cost (excluding the master controls and land and site preparation) required for annual maintenance.

## INDIRECTS AND CONTINGENCIES

METHOD: Comparison and adjustment of existing estimates

DATA: Seven complete system estimates formed the basis for the indirects and contingencies estimate. The source estimates are presented in Table A.18.

TABLE A.18. Source Estimates for Dish System Indirects and Contingencies

| Source | Indirects | Contingencies |
|---|---|---|
| SCE et al. (1982, p. 19) | - | 20 |
| Weber (1983) | - | 23 |
| Easton and Endicott (1982) | 21 | 10.6 |
| Weber (1982) | 24.3 | 17.3 |
| Weber (1980) | 30.7 | 12.2 |
| Joy et al. (1981) | 15.8 | 15 |
| Bloomster et al. (1982) | 25 | 25 |
| Avg. | 23.4 | Avg. 17.6 |

The average indirects estimate was rounded to 25 percent. The contingency estimate was reduced to 10% to reflect a plant representative of mature technology with no extraordinary contingencies. This reduction was based on logic presented in EPRI's TAG (1982, p. 3-3).

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The cost estimates for near-term "Nth plant" dish systems are summarized in Table A.19. "Nth plant" is defined as approximately the fifth to tenth plant built employing a specific dish technology. Although "Nth plant" technology is not in a mature state of development, it has been developed to a significant enough level that extraordinary contingencies don't exist. However, slightly higher contingencies do prevail. The contingency for the near-term components is 15% as opposed to 10% for the long-term estimates. No technology development costs are included in "Nth plant" cost estimates. The annual production level assumed is equal to the production rate that is required to build one "Nth plant."

The cost data are presented in one of four forms: dollars per square meter of aperture area; as a function of initial capital cost; dollars per kWe; or total-dollars at several given design points (MWe, $m^2$ of aperture area, or number of dishes). Unless otherwise specified, kWe and MWe ratings used throughout the estimates refer to gross generation capacity. With the exception of only a few components and subcomponents, the near-term estimates are the same as the long-term estimates. This is because components such as buildings, electrical components, land and site preparation, etc. are already maturely developed; therefore, near-term dish systems will be able to take advantage of the lower mature cost of some items.

Like the long-term estimates a subcomponent-by-subcomponent explanation of how the estimates were prepared is included. In addition to procedural information, a quality judgment of the data is given at the component and subcomponent level. The quality judgment includes a rating of good, fair, or poor and an explanation of weakness and strengths of the data.

TABLE A.19. Near-Term Cost Data Table for Glass-Metal Dish Systems, 1984$

| | | |
|---|---|---|
| Concentrator (glass-metal; based on McDonnell Douglas technology) | | |
| Mirror/Support | | |
| Unit (F.O.B.) | 1 dish system | $177 per $m^2$ of aperture area |
| | 100 dish system | $140 per $m^2$ of aperture area |
| | → 1000 dish system | $80 per $m^2$ of aperture area |
| | 10000 dish system | $67 per $m^2$ of aperture area |
| Transportation | | $7 per $m^2$ of aperture area |
| Field Installation | | $16 per $m^2$ of aperture area |
| Drive | 1 dish system | $48 per $m^2$ of aperture area |
| | 100 dish system | $38 per $m^2$ of aperture area |
| | 1000 dish system | $25 per $m^2$ of aperture area |
| | 10000 dish system | $21 per $m^2$ of aperture area |
| Controls and Wiring | 1 dish system | $3700 |
| | 100 dish system | $1800 |
| | 1000 dish system | $1300 |
| | 10000 dish system | $900 |
| Foundation | | $9 per $m^2$ of aperture area |
| Receiver | | $(666.76 + (-61.878)ln(Size, MW/0.025 MW)) for 25 kWe unit(s) per kWe of gross generating capacity |

TABLE A.19. (Cont.)

| | | |
|---|---|---|
| Transport | 0.025 MW | $12,400 |
| | 0.05 MW | $12,800 |
| | 0.125 MW | $14,900 |
| | 0.25 MW | $20,500 |
| | 0.65 MW | $34,700 |
| | 3.875 MW | $212,600 |
| | 16.25 MW | $912,800 |
| | 64.75 MW | $3,707,600 |
| | 323.75 MW | $18,734,400 |
| Conversion | $(1555.8 + (-144.38)ln(Size, MW/0.025 MW)) for 25 kWe unit(s) per kWe of gross generating capacity | |
| Balance-of-Plant | | |
| Land and Site Preparation | | |
| Basic Land and Site Prep. for access roads, and buildings | 0.025 MW system | $4300 |
| | 0.05 MW system | $4300 |
| | 0.125 MW system | $4300 |
| | 0.25 MW system | $4300 |
| | 0.5 MW system | $16,800 |
| | 2 MW system | $20,700 |
| | 10 MW system | $35,800 |
| | 30 MW system | $39,800 |
| | 100 MW system | $42,200 |
| | 200 MW system | $44,700 |
| Dish-Array Land and Site Prep. | $4.94 per $m^2$ of aperture area | |
| Dish-Array Fencing | $87m^2$ field size | $2,700 |
| | $174m^2$ field size | $3,800 |
| | $434m^2$ field size | $6,100 |
| | $869m^2$ field size | $8,600 |
| | $2,250m^2$ field size | $13,800 |
| | $13,500m^2$ field size | $33,800 |
| | $56,250m^2$ field size | $69,100 |
| | $225,000m^2$ field size | $138,200 |
| | $1,125,000m^2$ field size | $309,000 |
| Excess Land | $0.0247 per $m^2$ of aperture area | |
| Master Controls | 1 dish system | $3,000 |
| | 32 dish system | $29,000 |
| | 100 dish system | $74,000 |
| | 1000 dish system | $497,000 |
| | 10000 dish system | $3,734,000 |
| Structures | 0.025 MW system | $2,000 |
| | 0.05 MW system | $2,000 |
| | 0.125 MW system | $2,000 |
| | 0.25 MW system | $2,000 |
| | 0.5 MW system | $2,000 |
| | 2 MW system | $110,800 |
| | 10 MW system | $185,100 |
| | 30 MW system | $297,100 |
| | 100 MW system | $365,600 |
| | 200 MW system | $431,100 |
| Power Conditioning | 5 MW system | $105,000 |
| | 10 MW system | $130,000 |
| | 30 MW system | $360,000 |
| | 100 MW system | $810,000 |
| | 200 MW system | $1,540,000 |

## TABLE A.19. (Cont.)

| | | |
|---|---|---|
| Balance-of-Plant (Continued) | | |
| Service Facilities | <2 MW system | $0 |
| | 2 MW system | $137,500 |
| | 10 MW system | $217,400 |
| | 30 MW system | $273,200 |
| | 100 MW system | $581,100 |
| | 200 MW system | $1,162,000 |
| Spare Parts | | 3% of capital cost of BOP items (excluding land and site prep.)<br>0.6% of capital cost of energy conversion and receiver<br>0.3% of capital cost of collector and transport |
| Operating and Maintenance (annual) | | |
| Operating | | |
| Security | < 2 MW system | $0 |
| | 2=<=100 MW system | $46,600 |
| | 100 <=200 MW system | $93,200 |
| Service Contract | < 2 MW system | $24/kWe of gross generating capacity |
| Concentrator Maintenance | | 0.20% of concentrator capital cost plus 15% overhead<br>1.78 per $m^2$ of aperture area plus 15% overhead |
| Receiver Maintenance | | lab: $2.24 per $m^2$ of aperture area plus 15% overhead<br>mat: \${666.76 + (-61.87)ln(Size, MW/0.025 MW)}{(1.50) ($m^2$ of aperture area)}/ {1881.59(Size, MW/0.025 MW)$^{-0.32068}$} plus 15% overhead |
| Conversion System Maintenance | | lab: \$(5.83) per $m^2$ of aperture area plus 15% overhead<br>mat: \${1555.8 + (-144.38)ln(Size, MW/0.025 MW)}{(3.89) ($m^2$ of aperture area)}/ {4390.39(Size, MW/0.025 MW)$^{-0.32068}$} plus 15% overhead |
| Transport System Maintenance | 5 MW system | 0.80% of transport capital cost plus 15% overhead |
| | 10 MW system | 0.85% of transport capital cost plus 15% overhead |
| | 30 MW system | 0.90% of transport capital cost plus 15% overhead |
| | 100 MW system | 0.95% of transport capital cost plus 15% overhead |
| | 200 MW system | 1.0% of transport capital cost plus 15% overhead |
| Balance-of-Plant Maintenance | | 1.4% of structures, service facilities, power conditioning, and spare parts plus 15% overhead<br>1.5% of master controls plus 15% overhead |
| Indirects | | 25% of subtotaled component estimate |
| Contingencies | | 15% of concentrator, receiver, and conversion component estimates<br>10% of all other component estimates |

**COMPONENT: CONCENTRATOR** (glass-metal technology)

QUALITY JUDGMENT: Overall the quality of the concentrator component estimate is "fair". Exactly what must be included in the concentrator estimate is quite clear from the available design information; however, there is little information regarding the production economies-of-scale which would occur for near-term manufacturing of the concentrator.

SUBCOMPONENT: MIRRORS AND SUPPORT

METHOD: This subcomponent was estimated by PNL in three parts: (1) the concentrator unit (F.O.B.), (2) transportation, and (3) field installation (Williams et al. 1987, p. 7.1). Determination of the long-term production cost was made, and the production economies-of-scale which would exist for lower near-term production levels were estimated.

QUALITY JUDGMENT: The quality of this subcomponent is "fair". There is good definition of the mirrors and support design requirements which enabled the preparation of a long-term estimate with a high confidence level. Uncertainty arises when trying to determine the production economies-of-scale which would exist before long-term production levels are reached.

DATA: The construction of the mirror module consists of 0.028-inch thick back-silvered fusion glass with copper and protective coatings laminated to a smooth steel sheet (0.015-inch thick) and a stamped aluminized steel sheet (0.015-inch thick). The reflectivity of a new and clean module is 0.94. Design-point performance estimates for the concentrator are as follow (Williams et al 1987):

Concentrator Reflectivity (new and clean)--0.94

Reflectivity Degradation (assuming bi-weekly cleaning)--0.95

Concentrator/Receiver Intercept Factor--0.966

Concentrator Design-Point Efficiency→ $0.94 * 0.95 * 0.966 = 0.863$

The long-term F.O.B. cost of the concentrator was estimated by using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table A.20. The concentrator estimate as generated from the algorithm is $5256 per concentrator which translates to $61 per m² of dish aperture area for the McDonnell Douglas dish which has 86.86 m² of aperture area. This estimate is for a production level of 28,782 concentrators per year.

TABLE A.20. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Mirrors and Support Subcomponent

| | |
|---|---|
| Direct Materials | \$3458 per dish; \$99,528,156 for 28,782 dishes/year[a] |
| Direct Labor | 9.43 hours; 271,327.5 hours for 28,782 dishes/year |
| Capital Equip. | \$7.1 x $10^6$ |
| Plant Area | 145,000 sq. ft. |
| Plant Acreage | 9 Acres |

(a) 28,782 dishes per year is equivalent to 2.5 x $10^6$ square meters of concentrator area which is the assumed production level.

The main differentiating factor between the cost of the near-term and long-term glass-metal dish technologies is production economies-of-scale. In the case of the long-term estimates, 28,782 dishes per year are produced while in the near-term the erection of a 200 MW plant would require only about 8000 dishes and smaller systems would require even less.

Cost versus production level data is nearly non-existent for glass-metal dish concentrators; however, one source (Washom 1982, p. 9) does include this type of information for the Advanco glass-metal concentrator. While the Advanco and McDonnell Douglas concentrators are different and the absolute dollar estimates for the Advanco are not applicable to the McDonnell Douglas technology, because the concentrators are somewhat similar in design the same relative production economies-of-scale estimated by Washom (1984, p. 9) for the Advanco dish can be reasonably be applied to the McDonnell Douglas dish.

The estimates for the Advanco concentrator (Washom 1984, p. 9) as a function of production level were fit to an equation. These estimates are presented in Table A.21. The equation was then used to estimate the cost of the Advanco concentrator at 28,782 units per year. Using this estimate and the source estimates (Table A.21), the additional cost (in fractional form) due to production economies-of-scale for producing less than 28,782 units per year was calculated. These fractions are presented in Table A.22.

TABLE A.21. Advanco Concentrator Estimates, 1982\$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | \$52,797 |
| 100 per year | 41,655 |
| 1000 per year | 23,788 |
| 10000 per year | 19,895 |

TABLE A.22. Advanco Concentrator Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 28,782 Units |
|---|---|---|
| 1 per year | $52,797 | 2.92 |
| 100 per year | 41,655 | 2.31 |
| 1000 per year | 23,788 | 1.32 |
| 10000 per year | 19,895 | 1.10 |
| 28782 per year | 18,057[a] | - |

(a) Cost predicted by the equation $56917X^{0.888489}$ ($r^2 = 0.998$) which is based on a curve fit of the data presented in Table A.21. Where "X" is the annual production level and the predicted cost is the total annual production cost.

These fractions were then applied to the PNL-derived long-term estimate for the McDonnell Douglas concentrator at a production level of 28,782 units per year to determine the cost of the McDonnell Douglas concentrator at production levels of 1, 100, 1000, and 10000 dishes per year. These estimates are shown in Table A.23. Distributing the cost of the concentrator over the aperture area of the McDonnell Douglas dish, 86.86 $m^2$, yields estimates for the production levels 1, 100, 1000, and 10000 dishes per year of $177, $140, $80, and $67 per $m^2$ of aperture area.

TABLE A.23. Estimated Cost of the McDonnell Douglas Concentrator at Production Levels less than 28,782 Units per Year, 1984$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $15,347 |
| 100 per year | 12,141 |
| 1000 per year | 6,937 |
| 10000 per year | 5,782 |
| 28782 per year | 5,256[a] |

(a) Same cost as the long-term estimate

The mirror module transportation costs and the concentrator installation costs are presumed the same as the long-term estimates, $7 per $m^2$ of aperture area and $16 per $m^2$ of aperture area, respectively.

SUBCOMPONENT: DRIVE

METHOD: This subcomponent was estimated by using the long-term drive estimate which corresponds to a production level of 28,782 drives per year and adjusting its cost to reflect the lower production levels associated with near-term systems.

QUALITY JUDGMENT: This subcomponent estimate is based primarily on a cost and design analysis prepared by Peerless-Winsmith. Since a major focus of Peerless-Winsmith's work was a cost analysis, their bottom line estimate is based on a thorough analysis rather than a cursory one. This tends to give their estimate credibility. It is interesting that Winsmith managed to significantly reduce costs without a significant reduction in weight or predicted performance. The actual performance has yet to be demonstrated. An uncertainty driver is the lack of information regarding the increased drive cost for low volume production as opposed to the lower uncertainty associated with the high volume long-term production cost. Based on these strengths and weaknesses and also that the drive was intended for heliostats and not dishes, the quality of this subcomponent estimate is rated as "poor".

DATA: Approximately fifteen drive estimates were evaluated to determine the dish system drive cost. Of the drives evaluated, the Winsmith drive is currently the lowest cost drive which could be used for the a glass-metal dish. The Winsmith drive is designed to have low maintenance requirements and a high reliability with low degradation in desert environments. No pointing accuracy data is available yet. No parasitic energy usage is available yet either; however, on a sunny operation day the tracker unit of the Advanco concentrator uses an average of 7.2 kWh which comprises approximately 39% of the total parasitics for that system (Washom 1984 p. 77).

The Winsmith drive has two motorized units, the azimuth drive and the elevation drive. The strengths of these two units are as follows:

| Moment | English Units | SI Units |
|---|---|---|
| Azimuth max. static overturning moment | $2.58 \times 10^6$ in-lbs | $0.292 \times 10^6$ N-m |
| Azimuth static torsional moment | $2.496 \times 10^6$ in-lbs | $0.282 \times 10^6$ N-m |
| Azimuth operational torsional moment | $0.786 \times 10^6$ in-lbs | $0.0888 \times 10^6$ N-m |
| Elevation maximum static moment | $2.64 \times 10^6$ in-lbs | $0.298 \times 10^6$ N-m |
| Elevation maximum operational moment | $0.787 \times 10^6$ in-lbs | $0.0889 \times 10^6$ N-m |

While no data is available on the strength requirements for the McDonnell Douglas Dish, there is data on this subject for the Advanco concentrator which is also representative of the glass-metal technology. The Advanco concentrator has a different type of drive unit; however, the stress exerted by wind and gravity on the Advanco drive is approximately the same as the stress the Winsmith heliostat drive can handle. This indicates the low-cost heliostat drive or a similar drive of similar cost should meet dish system requirements.

The cost of the Winsmith unit is estimated to be $1856 (1987-dollars) (Heller 1987). De-escalating to 1984-dollars, a cost of $1696 (1984$) per drive is estimated. This estimate corresponds to the drive cost at a long-term production level of 50,000 units per year. It is estimated the drive would cost approximately the same at a production level of 28,872 units per year, because the additional production economies-of-scale achieved over the production increase from 28,782 to 50,000 units per year is anticipated to be very small, less than five percent.

Like the concentrator, the main differentiating factor between the cost of the near-term and long-term drive unit is production economies-of-scale. The limited cost versus production level data available for the drive unit was prepared for the Advanco concentrator drive unit (Washom 1984, p. 9). While the Advanco and McDonnell Douglas drive are different in design, the Advanco information is the only production versus cost data available. Because both units fulfill the same functions and are made of similar materials, the Advanco production economies-of-scale can reasonably be used to generate estimates for the McDonnell Douglas dish.

The estimates for the Advanco concentrator drive (Washom 1982, p. 9) as a function of production level were fit to an equation. These estimates are presented in Table A.24. The equation was then used to estimate the cost of the Advanco concentrator drive cost at 28,782 units per year. Using this estimate and the source estimates (Table A.24), the additional cost (in fractional form) due to production economies-of-scale for producing less than 28,782 units per year was calculated. These fractions are presented in Table A.25.

TABLE A.24. Advanco Concentrator Drive Estimates, 1982$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $13,240 |
| 100 per year | 10,592 |
| 1000 per year | 6,767 |
| 10000 per year | 5,830 |

TABLE A.25. Advanco Concentrator Drive Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 28,782 Units |
|---|---|---|
| 1 per year | $13,240 | 2.46 |
| 100 per year | 10,592 | 1.97 |
| 1000 per year | 6,767 | 1.26 |
| 10000 per year | 5,830 | 1.08 |
| 28782 per year | 5,376[(a)] | - |

(a) Cost predicted by the equation $13985X^{0.906881}$ ($r^2 = 0.999$) which is based on a curve fit of the data presented in Table A.24. Where "X" is the annual production level and predicted cost is the total annual production cost.

These fractions were then applied to the long-term estimate for the Winsmith drive at a production level of 28,782 units per year to determine the cost of the drive at production levels of 1, 100, 1000, and 10000 dishes per year. These estimates are shown in Table A.26. Distributing the cost of the drive over the aperture area of the McDonnell Douglas dish, 86.86 $m^2$, yields estimates for production levels of 1, 100, 1000, and 10000 dishes per year of $48, $38, $25, and $21 per $m^2$ of aperture area, respectively.

TABLE A.26. Estimated Cost of the Winsmith Drive at Production Levels less than 28,782 Units per Year, 1984$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $4,172 |
| 100 per year | 3,341 |
| 1000 per year | 2,137 |
| 10000 per year | 1,832 |
| 28782 per year | 1,696 |

SUBCOMPONENT: CONTROLS AND WIRING

METHOD: Adjustment of the long-term estimate to reflect the lower production levels associated with near-term construction.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". While there are a significant number of estimates relating to the controls and wiring for heliostats it is somewhat ill-defined as to how dish controls and wiring would differ. For this reason some engineering judgments were required to adjust heliostat controls and wiring estimates to dish system estimates. Additionally there is uncertainty with respect to the production economies-of-scale which would occur in the near-term.

DATA: Development of the long-term estimate was based on adjustment of heliostat controls and wiring estimates to conform to the system requirements of the dish system. Estimates prepared by ARCO, Martin Marietta, McDonnell Douglas (Norris and White 1982) and PNL (Drumheller 1981) were evaluated for applicability to dish systems. Based on engineering judgment, the estimate presented in Table A.27 was prepared. The total cost per dish of $755.50 (1984$) is for a production level of 28,782 units per year.

TABLE A.27. Long-Term Cost Estimate for Dish System Controls and Wiring, 1984$

| | | |
|---|---|---|
| Power and Control Cabling[a] | $463 | per dish |
| Dish Controller[b] | 265 | per dish |
| Dish Array Controller[c] | 27.50 | per dish |
| | $755.50 | per dish |

(a) This estimate includes $280 (1980$) for power cabling (Norris and White 1982, p. 94) and $90 (1980$) for control cabling. The control cabling estimate is the average of a Martin Marietta estimate of $63 (Norris and White 1982, p. 94) and a McDonnell Douglas estimate of $120 (Norris and White 1982, p. 94). The total power and control cabling estimate of $370 (1980$) was escalated to $463 (1984$).

(b) The dish controller estimate is based on the average of a McDonnell Douglas estimate of $203 (1980$) (Norris and White 1982, p. 94) and an ARCO estimate of $328 (1980$) (Norris and White 1982, p. 94). The average of $265 was not escalated because electronic components have remained about the same with respect to cost from 1980 to 1984.

(c) The dish-array controller for controlling 3631 dishes was estimated by PNL for Williams et al. (1987) to cost $100,000 (1984$) which on average is $27.50 per dish.

Cost versus production level data for the controls and wiring was prepared by Advanco (Washom 1984, p. 9). For the same reasons Advanco data was used in preparing the concentrator and drive estimates, it was used to determine near-term costs for the controls and wiring.

The estimates for the Advanco controls and wiring (Washom 1982, p. 9) as a function of production level were fit to an equation. These estimates are presented in Table A.28. The equation was then used to estimate the cost of the Advanco concentrator drive cost at a production level of 28,782 units per year. Using this estimate and the source estimates (Table A.28), the additional cost (in fractional form) due to production economies-of-scale for producing less than 28,782 units per year was calculated. These fractions are presented in Table A.29.

TABLE A.28. Advanco Controls and Wiring Estimates, 1982$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $20,000 |
| 100 per year | 9,961 |
| 1000 per year | 6,796 |
| 10000 per year | 4,951 |

TABLE A.29. Advanco Controls and Wiring Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 28,782 Units |
|---|---|---|
| 1 per year | $20,000 | 4.82 |
| 100 per year | 9,961 | 2.40 |
| 1000 per year | 6,796 | 1.64 |
| 10000 per year | 4,951 | 1.19 |
| 28782 per year | 4,146[a] | - |

(a) Cost predicted by the equation $19969X^{0.847201}$ which is based on a curve fit of the data presented in Table A.28. Where "X" is the annual production volume and the predicted cost is the total annual production cost.

These fractions were then applied to the PNL-derived estimate for the controls and wiring at a production level of 28,782 units per year to determine the cost of the controls and wiring at production levels of 1, 100, 1000, and 10000 dishes per year. These estimates are shown in Table A.30.

TABLE A.30. Estimated Cost of the Controls and Wiring at Production Levels less than 28,782 Units per Year, 1984$

| Production Level | Cost per Unit | Rounded Cost per Unit |
|---|---|---|
| 1 per year | $3,738 | $3700 |
| 100 per year | 1,813 | 1800 |
| 1000 per year | 1,272 | 1300 |
| 10000 per year | 899 | 900 |
| 28782 per year | 756[(a)] | 760 |

(a) Same cost as the long-term estimate

SUBCOMPONENT: FOUNDATION

METHOD: It is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent, because minimal learning would be involved and only small production economies-of-scale would exist. The details and basis for the estimate of $9 per $m^2$ of aperture area are included in the long-term documentation.

**COMPONENTS: RECEIVER AND ENERGY CONVERSION**

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: The quality of the receiver and energy conversion estimate is rated as "fair". There was a good correlation between the three source estimates used as the basis for the final estimate which is a positive aspect. However, none of the estimates include details, which results in some uncertainty in the final estimate.

DATA: The receiver and energy conversion components for the dish are combined in a single power conversion unit (a stirling engine/generator set). The stirling engine used is a 25-kWe 4-95 Solar II Unit. The 4-cylinder engine uses hydrogen as the working fluid, operates at a heater temperature of 750-degrees Celsius, and has a gross efficiency of 0.41 (i.e., the shaft mechanical power as a fraction of heater tube heat input is 0.41.) (Holtz 1987).

Based on Advanco tests, on a sunny day when the unit produces 227 kWh (gross), the water pump uses approximately 1.7 kWh (9% of the total parasitics), and the fan uses 9.4 kWh (51% of the total parasitics) (Washom 1984 p. 77). Design-point performance estimates for the receiver are as follows (Williams et al 1987):

Flux Entering Receiver→ $0.863 * 950\ W/m^2 * 86.86\ m^2 = 71.2\ kW$

Receiver Absorptivity--0.96

Receiver Thermal Loss--7.42 kW

Receiver Design-Point Efficiency→ $[(71.2 * 0.96) - 7.42] / 71.2 = 0.856$

Stirling cost data from three sources were evaluated. These data are presented in Table A.31. The Vanguard estimates were for installed dish system engines and were reduced by assuming installation, alignment, and testing adds ten percent to the basic cost of the unit. The other estimates reflect only purchase cost. All the units are rated at 25 kWe gross generating capacity.

The data was then fit to two equations. The first of these equations was based on the data points ranging from one to 10,000 units/year and the second on the data points ranging from 10,000 to 400,000 units/year. The intersection of these equations is at a production level of 9577. The equations are as follows:

$1 < \text{units/year} < 9577 \qquad \$/kWe = 2020.474 + (-187.509)\ln X$

$9577 < \text{units/year} < 400,000 \qquad \$/kWe = 5701.798X^{-0.32068}$

In the near-term, production levels of the stirling engine/generator set will be much lower than in the long-term. Because even a large plant, 200 MWe, will require only about 8000 engines and smaller plants even less, the former of these two equations was used to estimate the near-term cost. The "X" in this equation represents the number of units produced per year. Substituting the plant size divided by the engine size (i.e., MWe / 0.025 MWe), results in an equation which yields $/kWe as a function of plant size. Based on the determination by United Stirling that approximately 30% by cost of the unit could be considered the receiver and the balance is energy conversion (Nelving 1985), the equation can be broken into the two following equations by multiplying by 0.3 and 0.7, respectively.

Receiver $\$/kWe = 606.1422 + (-56.2527)\ln(\text{Size, MWe}/0.025\ \text{MWe})$

Conversion $\$/kWe = 1414.332 + (-131.256)\ln(\text{Size, MWe}/0.025\ \text{MWe})$

Both equations must have an additional 10% added to account for installation, alignment, and testing. Making this adjustment yields the finalized estimating equations.

Receiver $\$/kWe = 666.76 + (-61.878)\ln(\text{Size, MWe}/0.025\ \text{MWe})$

Conversion $\$/kWe = 1555.8 + (-144.38)\ln(\text{Size, MWe}/0.025\ \text{MWe})$

TABLE A.31. Dish Power Conversion Unit Purchase Cost Data, 1984$

| Source | Production Quantity | Cost/Unit |
|---|---|---|
| United Stirling[a] | 1 | $50,000 |
| | 2,000 | $20,000 |
| | 25,000 | $ 5,500 |
| JPL[b] | 1,000 | $17,576 |
| | 25,000 | $ 5,641 |
| | 100,000 | $ 2,946 |
| | 400,000 | $ 2,539 |
| Vanguard[c] | 1 | $57,878 |
| | 100 | $28,941 |
| | 1,000 | $15,463 |
| | 10,000 | $ 8,700 |

(a) Telephone conversation with Worth Percival, United Stirling.
(b) Fortgang and Mayers (1980, p. 10) prices were escalated to 1984-dollars.
(c) Washom (1984, p. 9) prices were escalated to 1984-dollars and reduced to an uninstalled basis.

COMPONENT: TRANSPORT

METHOD: All the transport components are mature in design and already are in mass production. Also, economies-of-scale related to system size are accounted for in the long-term estimates. For these reasons, it is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent. The details and basis for the estimate are included in the long-term documentation.

COMPONENT: BALANCE-OF-PLANT

METHOD: All the balance-of-plant components are mature in design and already in mass production. Also, economies-of-scale related to system size are accounted for in the long-term estimates. For these reasons, it is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent. The details and basis for the estimate are included in the long-term documentation.

COMPONENT: OPERATING AND MAINTENANCE

QUALITY JUDGMENT: the quality of O&M cost data is rated as "poor", mainly because little operating experience exists which causes estimates to be based largely on conjecture.

SUBCOMPONENT: OPERATING

METHOD: The operating subcomponent includes security personnel for plants 2 MW or larger and a service contract for plants smaller than 2 MW. It is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent. In the case of security, staffing levels will be the same in the near-term and long-term. With respect to the service contract, it only accounts for capital recovery of service facilities provided by a subcontractor or centralized service facility. Actual maintenance labor and materials are accounted for in the maintenance subcomponents. Therefore, the operating subcomponent is expected to cost the same in the near-term and long-term. The details and basis for the estimate are included in the long-term documentation.

SUBCOMPONENT: MAINTENANCE OF THE CONCENTRATOR

METHOD: The only significant difference between near-term and long-term concentrator maintenance costs is the non-washing material cost. This cost is expected to be higher in the near-term than in the long-term due to maintenance materials being in lower production. The cost of non-washing materials is estimated to be proportional to concentrator capital cost. Therefore, the relative difference between non-washing materials and concentrator cost will be the same in the near-term and long-term. Consequently, the fraction of initial concentrator capital estimated for long-term non-washing materials applies in the near-term also.

SUBCOMPONENT: MAINTENANCE OF RECEIVER

METHOD: It is estimated that the materials cost element of the receiver maintenance will be higher in the near-term than it will be in the long-term. The labor element of the receiver maintenance is estimated to be approximately the same in the near-term and long-term. To account for the higher near-term material cost, the long-term material costs were scaled based on the ratio of near-term receiver capital cost to the long-term receiver capital cost.

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

DATA: Long-term maintenance costs were based on data provided by Worth Percival of United Stirling. Maintenance costs were estimated to be to be .625¢/kWh for the receiver which represents the average of a range of costs estimated by United Stirling. This estimate is for mature systems and is assumed to correspond to a receiver production level of 28,872 receivers per year. Using an annual insolation of 2848 $kWh_t/m^2$ at Barstow, CA (1976), and average system efficiency of 21 percent, long-term total annual maintenance costs for the receiver are equal to:

$$\$(0.00625)(2848)(0.21) \text{ per } m^2 \text{ of aperture area}$$

This equation is broken down into labor and material components by assuming an a 60/40 labor-materials split (Jelen 1970, p. 348) applies. The resulting two equations are as follow:

labor: \$2.24 per $m^2$ of aperture area
materials: \$1.5 per $m^2$ of aperture area

In the near-term, labor costs are estimated to be relatively equal to the long-term labor costs; however, material costs are expected to be higher in the near-term than in the long-term. Higher near-term material costs are due to the lower production levels of spare parts that are associated with the near-term. Material costs are estimated to be proportional to the cost of the receiver unit.

Using the long-term material estimate as a basis, the near-term materials estimate was prepared by multiplying the long-term estimate by the ratio of the near-term receiver cost to the long-term receiver cost. This ratio is represented by the following equation:

$$\{666.76 + (-61.87)\ln(\text{Size, MW}/0.025 \text{ MW})\} / \{1881.59(\text{Size, MW}/0.025 \text{ MW})^{-0.32068}\}$$

Multiplying this equation by the long-term materials cost estimating equation yields the following near-term receiver maintenance cost estimating equation for a 25 kWe stirling unit:

$$\{666.76 + (-61.87)\ln(\text{Size, MW}/0.025\text{ MW})\}\{(1.5)(\text{m}^2\text{ of aperture area})\}/\{1881.59(\text{Size, MW}/0.025\text{ MW})^{-0.32068}\}$$

In addition a 15% overhead charge must be added to this estimate (Guthrie 1974).

SUBCOMPONENT: MAINTENANCE OF THE CONVERSION SYSTEM

METHOD: It is estimated that the material component of the energy conversion maintenance will be higher in the near-term than it will be in the long-term. The labor component of the conversion maintenance is estimated to be approximately the same in the near-term and long-term. To account for the higher near-term material cost, the long-term material costs were scaled based on the ratio of near-term conversion capital cost to the long-term conversion capital cost.

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

DATA: Long-term maintenance costs were based on data provided by Worth Percival of United Stirling. Maintenance costs were estimated to be to be 1.625¢/kWh for the conversion which represents the average of a range of costs estimated by United Stirling. This estimate is for mature systems and is assumed to correspond to a conversion unit production level of 28,872 units per year. Using an annual insolation of 2848 $\text{kWh}_t/\text{m}^2$ at Barstow, CA (1976), and average system efficiency of 21%, long-term total annual maintenance costs for the conversion unit are equal to:

$$\$(0.01625)(2848)(0.21)\text{ per m}^2\text{ of aperture area}$$

This equation is broken down into labor and material components by assuming an a 60/40 labor-materials split (Jelen 1970, p. 348) applies. The resulting two equations are as follow:

labor: \$5.83 per m² of aperture area
materials: \$3.89 per m² of aperture area

In the near-term labor costs are estimated to be relatively equal to the long-term labor costs; however, material costs are expected to be higher in the near-term than in the long-term. Higher near-term material costs are due to the lower production levels of spare parts that are associated with the near-term. Material costs are estimated to be proportional to the cost of the conversion unit.

Using the long-term material estimate as a basis, the near-term materials estimate was prepared by multiplying the long-term estimate by the ratio of the near-term conversion cost to the long-term conversion unit cost. This ratio is represented by the following equation:

$$\{1555.8 + (-144.38)\ln(\text{Size, MW}/0.025\ \text{MW})\}/\{4390.39(\text{Size, MW}/0.025\ \text{MW})^{-0.32068}\}$$

Multiplying this equation by the long-term materials cost estimating equation yields the following near-term receiver maintenance cost estimating equation for a 25 kWe stirling unit:

$$\{1555.8 + (-144.38)\ln(\text{Size, MW}/0.025\ \text{MW})\}\{(3.89)(m^2\ \text{of aperture area})\}/\{4390.39(\text{Size, MW}/0.025\ \text{MW})^{-0.32068}\}$$

In addition a 15% overhead charge must be added to this estimate (Guthrie 1974).

SUBCOMPONENT: TRANSPORT SYSTEM MAINTENANCE

METHOD: It is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent, because transport system maintenance is already in a mature state of development. The details and basis for the estimate are included in the long-term documentation.

SUBCOMPONENT: BALANCE-OF-PLANT MAINTENANCE

METHOD: It is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent as balance-of-plant maintenance is already in a mature state of development. The details and basis for the estimate are included in the long-term documentation.

## INDIRECTS AND CONTINGENCIES

METHOD: Comparison and adjustment of existing estimates

DATA: Seven complete system estimates formed the basis for the indirects and contingencies estimate. The source estimates are presented in Table A.36.

TABLE A.36. Source Estimates for Dish System Indirects and Contingencies

| Source | Indirects | Contingencies |
|---|---|---|
| SCE et al. (1982, p. 19) | - | 20 |
| Weber (1983) | - | 23 |
| Easton and Endicott (1982) | 21 | 10.6 |
| Weber (1982) | 24.3 | 17.3 |
| Weber (1980) | 30.7 | 12.2 |
| Joy et al. (1981) | 15.8 | 15 |
| Bloomster et al. (1982) | 25 | 25 |
| Avg. | 23.4 | Avg. 17.6 |

The average indirects estimate was rounded to 25 percent. The contingency estimate was reduced to 10% for the mature components (i.e., transport, and balance-of-plant). For other components it was reduced to 15% to be representative of new technology with no extraordinary contingencies and to be consistent with the utility studies (Hillesland et al. 1988).

# APPENDIX B

DOCUMENTATION ON COST DATA FOR ELECTRICITY GENERATION SYSTEMS BASED ON THE STRESSED METAL-MEMBRANE DISH CONCENTRATOR

Presented here are long-term costs for the dish-stirling solar generating concept based on a kinematic stirling engine with a 14-meter diameter stressed metal-membrane concentrator. For the long-term estimates, the technology is assumed to be mature and all components are considered to be in mass production. Contingencies associated with these estimates reflect the mature nature and high production levels associated with long-term technologies. The presumed annual production level for the system is $2.5 \times 10^6$ m² of concentrator aperture area per year or the quantity of units required to support $2.5 \times 10^6$ m² of aperture area. It is assumed that the builder of a plant could buy any portion of the annual production level and achieve the same central production facility economies-of-scale benefits.

Presented in Table B.1 are the long-term estimates. The cost data are presented in one of four forms: dollars per square meter of aperture area, as a function of initial capital cost, dollars per kilowatt electric, or total-dollars at several design points (MWe, number of dishes, or m² of aperture area). For cost data given as a function of design points, it is necessary to fit the data to equations which allows the determination of component costs over a range of system sizes and not just at given design points. After the preparation of equations is completed, it is then possible to use the cost data presented to prepare system estimates at the component and subcomponent levels for a wide range of system sizes.

Following Table B.1 there is a subcomponent-by-subcomponent explanation of how the estimates were prepared. In addition to procedural information, a quality judgment of the data is given at the component and subcomponent level. The quality judgment includes a rating of good, fair, or poor and an explanation of weakness and strengths of the data.

TABLE B.1. Long-Term Cost Data Table for Stressed Metal-Membrane Dish Systems, 1984$

| | | |
|---|---|---|
| **Concentrator (reflective polymer; based on stressed metal-membrane)** | | |
| Mirror/Support | | |
| Unit (F.O.B.) | 2.35 MWe | \$41.6 per $m^2$ of aperture area |
| | 2.35 MWe | \$42.5 per $m^2$ of aperture area |
| Transportation | 2.35 MWe | \$0.9 per $m^2$ of aperture area |
| | 2.35 MWe | \$1.4 per $m^2$ of aperture area |
| Field Installation | 200 MWe | \$2.2 per $m^2$ of aperture area |
| | 100 MWe | \$2.3 per $m^2$ of aperture area |
| | 50 MWe | \$2.5 per $m^2$ of aperture area |
| | 30 MWe | \$4.0 per $m^2$ of aperture area |
| | 10 MWe | \$5.9 per $m^2$ of aperture area |
| | 5 MWe | \$8.3 per $m^2$ of aperture area |
| | 3 MWe | \$7.8 per $m^2$ of aperture area |
| | 2.35 MWe | \$10.2 per $m^2$ of aperture area |
| | 2.30 MWe | \$8.1 per $m^2$ of aperture area |
| | 1 MWe | \$10 per $m^2$ of aperture area |
| | 0.25 MWe | \$20 per $m^2$ of aperture area |
| | 0.1 MWe | \$41 per $m^2$ of aperture area |
| Drive | | \$11 per $m^2$ of aperture area |
| Controls and Wiring | | \$820 per dish |
| Foundation | >=2.35 MWe | \$21 per $m^2$ of aperture area |
| | 2.30 MWe | \$22 per $m^2$ of aperture area |
| | 1 MWe | \$22 per $m^2$ of aperture area |
| | 0.25 MWe | \$23 per $m^2$ of aperture area |
| | 0.1 MWe | \$25 per $m^2$ of aperture area |

## TABLE B.1. (Cont.)

| | | |
|---|---|---|
| Receiver | $3160 per dish for 50-kWe unit | |
| Transport | 0.025 MW system | $12,400 |
| | 0.05 MW system | $12,800 |
| | 0.125 MW system | $14,900 |
| | 0.25 MW system | $20,500 |
| | 0.65 MW system | $34,700 |
| | 3.875 MW system | $212,600 |
| | 16.25 MW system | $912,800 |
| | 64.75 MW system | $3,707,600 |
| | 323.75 MW system | $18,734,400 |
| Conversion | $7370 per dish for 50-kWe unit | |
| Balance-of-Plant | | |
| Land and Site Preparation | | |
| Basic Land and Site Prep. for access roads, and buildings | 0.025 MW system | $4300 |
| | 0.05 MW system | $4300 |
| | 0.125 MW system | $4300 |
| | 0.25 MW system | $4300 |
| | 0.5 MW system | $16,800 |
| | 2 MW system | $20,700 |
| | 10 MW system | $35,800 |
| | 30 MW system | $39,800 |
| | 100 MW system | $42,200 |
| | 200 MW system | $44,700 |
| Dish-Array Land and Site Prep. | $4.94 per $m^2$ of aperture area | |
| Dish-Array Fencing | 87 $m^2$ field size | $2,700 |
| | 174 $m^2$ field size | $3,800 |
| | 434 $m^2$ field size | $6,100 |
| | 869 $m^2$ field size | $8,600 |
| | 2,250 $m^2$ field size | $13,800 |
| | 13,500 $m^2$ field size | $33,800 |
| | 56,250 $m^2$ field size | $69,100 |
| | 225,000 $m^2$ field size | $138,200 |
| | 1,125,000 $m^2$ field size | $309,000 |
| Excess Land | $0.0247 per $m^2$ of aperture area | |
| Master Controls | 1 dish system | $3,000 |
| | 32 dish system | $29,000 |
| | 100 dish system | $74,000 |
| | 1000 dish system | $497,000 |
| | 10000 dish system | $3,734,000 |
| Structures | 0.025 MW system | $2,000 |
| | 0.05 MW system | $2,000 |
| | 0.125 MW system | $2,000 |
| | 0.25 MW system | $2,000 |
| | 0.5 MW system | $2,000 |
| | 2 MW system | $110,800 |
| | 10 MW system | $185,100 |
| | 30 MW system | $297,100 |
| | 100 MW system | $365,600 |
| | 200 MW system | $431,100 |
| Power Conditioning | 5 MW system | $105,000 |
| | 10 MW system | $130,000 |
| | 30 MW system | $360,000 |
| | 100 MW system | $810,000 |
| | 200 MW system | $1,540,000 |

## TABLE B.1. (Cont.)

| | |
|---|---|
| Service Facilities | <2 MW system $0 |
| | 2 MW system $137,500 |
| | 10 MW system $217,400 |
| | 30 MW system $273,200 |
| | 100 MW system $581,100 |
| | 200 MW system $1,162,000 |
| Spare Parts | 3% of capital cost of BOP items (excluding land and site prep.) |
| | 0.6% of capital cost of energy conversion and receiver |
| | 0.3% of capital cost of collector and transport |
| Operating and Maintenance (annual) | |
| Operating | |
| Security | < 2 MW system $0 |
| | 2=<=100 MW system $46,600 |
| | 100 <=200 MW system $93,200 |
| Service Contract | < 2 MW system $24/kWe of gross generating capacity |
| Concentrator Maintenance | ~~0.03%~~ 0.3% of concentrator capital cost plus 15% overhead |
| | 1.84 per m of aperture area plus 15% overhead |
| | $850 every 5th year for optical membrane replacement (present value of these replacements at time zero = $2500) |
| Receiver Maintenance | lab: $2.24 per $m^2$ of aperture plus 15% overhead |
| | mat: $1.50 per $m^2$ of aperture plus 15% overhead |
| Conversion Maintenance | lab: $5.83 per $m^2$ of aperture plus 15% overhead |
| | mat: $3.89 per $m^2$ of aperture plus 15% overhead |
| Transport Maintenance | 5 MW system 0.80% of transport capital cost plus 15% overhead |
| | 10 MW system 0.85% of transport capital cost plus 15% overhead |
| | 30 MW system 0.90% of transport capital cost plus 15% overhead |
| | 100 MW system 0.95% of transport capital cost plus 15% overhead |
| | 200 MW system 1.0% of transport capital cost plus 15% overhead |
| Balance-of-Plant Maintenance | 1.4% of structures, service facilities, power conditioning, and spare parts plus 15% overhead |
| | 1.6% of master controls plus 15% overhead |
| Indirects | 25% of subtotaled component estimate |
| Contingencies | 10% of subtotaled component estimate |

COMPONENT: **CONCENTRATOR** (stressed metal-membrane technology)

QUALITY JUDGMENT: Overall the quality the concentrator component estimate is "fair". The estimate itself is quite comprehensive and is based on a significant amount of detailed cost data which was developed for the stressed membrane heliostat (Solar Kinetics 1987) and other studies. The quality judgment of "fair" is given due to the conceptual nature of the design which results in an estimate with greater uncertainty than an estimate based on detailed engineering drawings.

SUBCOMPONENT: MIRRORS AND SUPPORT

METHOD: This subcomponent was estimated by PNL in three parts: (1) the concentrator unit (F.O.B.), (2) transportation, and (3) field installation.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "good". Although the design is conceptual, there is enough design information and related historical data to generate a "good" manufacturing estimate for the concentrator unit. The transportation estimate is also "good" within the limits of the transportation scenario presumed. If a different method of transportation was to be used, the costs could differ slightly. The field installation estimate is rated as "fair". There is uncertainty as to exactly how some of the site operations would be performed. In particular, the process to hydroform the metal-membrane and the time and equipment estimates for fastening the rear and optical membranes to the ring are uncertain.

DATA: The construction of the stressed metal-membrane concentrator consists of a 14-meter diameter aluminum ring centered around a steel mast. To the back of the ring and base of the mast a vinyl-coated fiberglass rear membrane is attached. To the front of the ring a 0.01-inch thick aluminum membrane is welded. During installation the metal-membrane is hydroformed to an optical shape. Additionally, to the front of the ring an optical membrane is attached. When the plenum between the rear membrane and optical membrane is evacuated the optical membrane is drawn down against the metal-membrane. This forms the optical membrane into the appropriate reflective shape.
Design point performance estimates for the concentrator are as follow:

Concentrator Reflectivity (new and clean)--0.91 (SKI)

Reflectivity Degradation (assuming bi-weekly cleaning)--0.95
-This is the same value that was assumed for the glass/metal concentrator. It is very likely that this value is too high for membrane concentrators; the reasons for this are:

- cleaning will most likely be more difficult, less efficient, and less effective. Due to the very thin metal membrane, high pressure water or brushes will not be able to be used (metal-membrane will be plastically deformed with 0.56 psi). Additionally, the optical surface is thin, stressed polymers will not be able to withstand a cleaning regiment as aggressive as that of the glass/metal concentrator.

- The optical material will suffer permanent degradation over time (the reason for the five-year replacement schedule).

Blocking caused by the center tube support cables--0.986
-There are 24 one-half inch cables. These cables will both shadow the concentrator and block concentrated reflected flux. Considering only the shadowing (or assuming the concentration is very small) the cables will shadow an area equal to:

$$24 * 7m * 0.5 \text{ in.} = 23 \text{ ft}^2 \ (2.13 \text{ m}^2)$$

Shadowing caused by the receiver support structure--0.989
-There are three 3-inch support trusses for the receiver. These trusses will shadow an area of the concentrator equal to:

$$3 * 7m * 3 \text{ in.} = 17.2 \text{ ft}^2 \ (1.60 \text{ m}^2)$$

Concentrator/Receiver Intercept Factor--0.966
-This is the same value that was assumed for the glass/metal concentrator. This value is probably also too high for membrane concentrators; the reasons for this are:

- The optical quality of the concentrator will most likely be less than that of the glass/metal concentrator. Thus, for an intercept factor this high, the receiver aperture would have to be larger which would result in increased receiver thermal losses. Conversely, the aperture could be made small to maintain low receiver losses, but this would increase spillage and thus decrease the concentrator/receiver intercept factor. The optimal value is the one that minimizes the LEC; this value will have to be determined during detailed systems analysis and design.

Concentrator Unit

At the central manufacturing facility; the metal, rear, and optical membranes; the main mast; PCU support tripod; and foundation/drive structure are manufactured. Manufacture of these components is integrated in that foundation parts are cut and painted using much of the same equipment used for the main mast and PCU support tripod. For cost accounting purposes, half of the parts-cutting equipment, paint line, labor, related floor space, and related land area are included in this subcomponent and the remainder in the foundation subcomponent. General factory equipment is divided between these same subcomponents based on the ratio of factory floor space required between the subcomponents.

In addition, for small site sizes (less than 2.35 MWe) it is economically more attractive to manufacture the main concentrator ring at the central manufacturing facility than at the site, as is done for large system sizes. Central facility manufacturing of the ring at small system sizes is desirable, because it is more expensive to set-up the site ring-manufacturing facility and make a small number of rings than it is to centrally manufacture the ring, cut it into eight arched segments and ship it to the site for welding into a uniform ring.

The F.O.B. cost of the concentrator was estimated by using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table B.2 for plant sizes of 2.35 MWe or larger and in Table B.3 for sizes smaller than 2.35 MWe. The concentrator estimates as generated from the algorithm are \$4114 and \$4805 per concentrator for large and small system sizes, respectively. In addition to these costs, \$2125 and \$1572 for burdened materials and working capital allowance for materials used at the site must be added. Making these additions yields estimates of concentrator cost of \$6239 and \$6377, respectively. These estimates translate to \$41.6 per $m^2$ of dish aperture area for systems equal to or larger than 2.35 MWe and \$42.5 per $m^2$ of dish aperture area for system sizes smaller than 2.35 MWe. Both these unit costs are based on a stressed metal-membrane dish which has 150 $m^2$ of aperture area.

Concentrator Transportation

Concentrator transportation costs were estimated by determining the number of loads required (either weight- or volume-limited) to deliver concentrator sub-assemblies from the factory to the site and multiplying by an assumed delivery distance of 600 miles and a cost per mile of \$1.45. For large systems, an average 6.18 dishes can be transported per load. This results in a concentrator transportation cost of \$141. This cost distributed over the aperture area of the dish and rounded is \$0.9 per $m^2$ of aperture area. For small systems shipping of the ring increases transportation costs to \$214 and reduces the average number of dishes per load to 4.07. Small system shipping is rounded to \$1.4 per $m^2$ of aperture area.

Concentrator Installation

The field installation estimates were independently prepared by PNL and are presented in Table B.4. These figures are based on a PNL estimate of 11.9 manhours per dish for site assembly and installation, a \$27.07 charge per dish for capital installation equipment, and a site set-up charge of \$56,740 for systems equal to or larger than 2.35 MWe. Large system site installation progresses at an average output of 159 dishes per week, not including initial site set-up time of one week. For systems smaller than 2.35 MWe, field installation estimates are based on a PNL estimate of 36.10 manhours per dish, a \$111.96 charge per dish for capital installation equipment, and a site set-up charge of \$10,384. Small system site installation progresses at an average output of 4.15 dishes per week, not including initial site set-up time of one week. Table B.5 shows the rounded unit installation cost for stressed metal-membrane dishes are various system sizes.

TABLE B.2. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Mirrors and Support Subcomponent at System Sizes of Greater than 2.35 MWe.

| | |
|---|---|
| Direct Materials | \$2727 per dish; \$45,450,909 for 16,667 dishes/year[a] |
| Direct Labor | 4.91 hours; 81,900 hours for 16,667 dishes/year |
| Capital Equip. | \$9,272,394 |
| Plant Area | 123,891 sq. ft. |
| Plant Acreage | 7.44 Acres |

(a) 16,667 dishes per year is equivalent to $2.5 \times 10^6$ square meters of concentrator area which is the assumed production level.

TABLE B.3. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Mirrors and Support Subcomponent at System Sizes of Less than 2.35 MWe.

| | |
|---|---|
| Direct Materials | \$3200 per dish; \$53,334,400 for 16,667 dishes/year[a] |
| Direct Labor | 5.45 hours; 90,789 for 16,667 dishes/year |
| Capital Equip. | \$9,594,587 |
| Plant Area | 139,891 sq. ft. |
| Plant Acreage | 8.44 Acres |

(a) 16,667 dishes per year is equivalent to $2.5 \times 10^6$ square meters of concentrator area which is the assumed production level.

TABLE B.4. Concentrator Field Installation Estimates, 1984\$

| System Size | Cost per Unit |
|---|---|
| 200 MWe | \$ 333 |
| 100 MWe | 347 |
| 50 MWe | 375 |
| 30 MWe | 413 |
| 10 MWe | 602 |
| 5 MWe | 886 |
| 3 MWe | 1264 |
| 2.35 MWe | 1526 |
| 2.34 MWe | 1222 |
| 1 MWe | 1516 |
| 0.25 MWe | 3073 |
| 0.1 MWe | 6188 |

TABLE B.5. Concentrator Field Installation Estimates, $/m²

| System Size | | Cost per Unit |
|---|---|---|
| 200 | MWe | $ 2.2 |
| 100 | MWe | 2.3 |
| 50 | MWe | 2.5 |
| 30 | MWe | 2.8 |
| 10 | MWe | 4.0 |
| 5 | MWe | 5.9 |
| 3 | MWe | 8.4 |
| 2.35 | MWe | 10.2 |
| 2.30 | MWe | 8.1 |
| 1 | MWe | 10 |
| 0.25 | MWe | 20 |
| 0.1 | MWe | 41 |

SUBCOMPONENT: DRIVE

METHOD: Comparison and adjustment of an existing estimate and the application of a significant amount of engineering judgment.

QUALITY JUDGMENT: The quality of the drive subcomponent estimate is "poor". Basically, this is due to the lack of design requirements for the drive which necessitates a considerable amount of judgment be applied.

DATA: Due to the conceptual nature of the design, the drive design and operational requirements have not been identified by the designers. However, the two basic drive mechanisms have been identified in the conceptual design. These mechanisms include the azimuth drive, and the elevation drive in the form of a screw jack. These components are similar to the components of the Peerless-Winsmith low-cost heliostat drive.

To estimate the cost of the two components of the stressed metal-membrane drive, the costs of these same components from the Peerless-Winsmith drive were used as the basis. At a production level of 50,000 units per year, Heller (1987) estimates the cost of the azimuth drive as $973 (1987$) and cost of the elevation drive as $496 (1987$). Converting these estimates to 1984-dollars and a dollar per m² of aperture area basis yields estimates of $6 and $3 per m² of aperture area for the azimuth and elevation drives, respectively. An additional 25% was added to the cost of both units to account for the production level of the stressed metal-membrane drive units being only 16,667 units per year instead of 50,000 units per year, the presumed level in the Heller estimate, and a small contingency. The extra contingency was added, because it is doubtful the drive could be produced for anything less than $11 per m², and in fact, even $11 may be optimistic. The total installed drive estimate is therefore, $11 per m² of aperture area. At the current stage of the design work, it is impossible to determine exactly what the drive requirements are.

SUBCOMPONENT: CONTROLS AND WIRING

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". While there are a significant number of estimates relating to the controls and wiring for heliostats it is somewhat ill-defined as to how dish controls and wiring would differ. For this reason some engineering judgments were required to adjust heliostat controls and wiring estimates to dish system estimates.

DATA: Development of the estimate was based on adjustment of heliostat controls and wiring estimates to conform to the system requirements of the dish system. Estimates prepared by ARCO, Martin Marietta, McDonnell Douglas (Norris and White 1982) and PNL (Drumheller 1981) were evaluated for applicability to dish systems. Based on engineering judgment, the estimate presented in Table B.6 was prepared. The total cost per dish of $755.50 (1984$) is for a production level of 28,782 units per year.

To adjust this estimate to a production level of 16,667 units per year, a parametric production economies-of-scale relationship was developed. This relationship assumes production economies-of-scale for the Advanco dish controls and wiring are equivalent to the production economies-of-scale associated with the controls and wiring estimate presented here. Based on the four estimates for Advanco controls and wiring presented in Table B.7, the relationship was developed. Fitting a curve to these estimates yields the following equation:

$$Y = 19969.5X^{0.847201}$$

Where "X" equals annual production volume and "Y" equals the total annual production cost. This equation was used to estimate the cost of Advanco controls and wiring at production levels of 16,667 and 28,782 units per year. The ratio of these two costs is 1.09. Multiplying this ratio by the estimated cost for dish wiring and controls of $755.50 at a production level of 28,782 units per year gives an estimated cost for dish controls and wiring of $824 at a production level of 16,667 units per year. This estimate was rounded to $820 per dish.

TABLE B.6. Long-Term Cost Estimate for Dish System Controls and Wiring (1984$)

| | | |
|---|---|---|
| Power and Control Cabling[a] | $463 | per dish |
| Dish Controller[b] | 265 | per dish |
| Dish Array Controller[c] | 27.50 | per dish |
| | $755.50 | per dish |

(a) This estimate includes $280 (1980$) for power cabling (Norris and White 1982, p. 94) and $90 (1980$) for control cabling. The control cabling estimate is the average of a Martin Marietta estimate of $63 (Norris and White 1982, p. 94) and a McDonnell Douglas estimate of $120 (Norris and White 1982, p. 94). The total power and control cabling estimate of $370 (1980$) was escalated to $463 (1984$).

(b) The dish controller estimate is based on the average of a McDonnell Douglas estimate of $203 (1980$) (Norris and White 1982, p. 94) and an ARCO estimate of $328 (1980$) (Norris and White 1982, p. 94). The average of $265 was not escalated because electronic components have remained about the same with respect to cost from 1980 to 1984.

(c) The dish-array controller for controlling 3631 dishes was estimated by PNL for Williams et al. (1987) to cost $100,000 (1984$) which on average is $27.50 per dish.

TABLE B.7. Advanco Controls and Wiring Estimates

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $20,000 |
| 100 per year | 9,961 |
| 1000 per year | 6,796 |
| 10000 per year | 4,951 |

SUBCOMPONENT: FOUNDATION

METHOD: This subcomponent was independently estimated by PNL.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". The estimate is fairly comprehensive. However, because there has not been a detailed design made for the foundation, there is greater uncertainty than is desirable.

DATA: The foundation is manufactured at a central facility in four subassemblies: the kingpost, the sway braces, the a-frame, and the jack link. The F.O.B. cost of the foundation was estimated using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table B.8. The foundation estimate generated from the algorithm is $2824. The four subassemblies are shipped to the site at a cost of $144. Site installation cost estimates are presented in Table B.9. For system sizes equal to or larger than 2.35 MWe field installation estimates are based on a PNL estimate of 0.59 manhours for installation, a $8.13 charge for distributed capital, a fixed set-up charge of $2610, and a $150 charge for installed concrete. Field installation estimates for systems smaller than 2.35 MWe are based on a PNL estimate of 2.55 manhours for installation, a $99.85 charge for distributed capital, a fixed set-up charge of $870, and a $150 charge for installed concrete. The total installed foundation estimates are presented in Table B.10.

TABLE B.8. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Foundation Subcomponent

| | |
|---|---|
| Direct Materials | $1947 per dish; $32,450,649 for 16,667 dishes/year[a] |
| Direct Labor | 1.75 hours; 29,100 hours for 16,667 dishes/year |
| Capital Equip. | $3,437,831 |
| Plant Area | 25,909 sq. ft. |
| Plant Acreage | 1.56 Acres |

(a) 16,667 dishes per year is equivalent to 2.5 x $10^6$ square meters of concentrator area which is the assumed production level.

TABLE B.9. Foundation Site Installation Cost Estimates per dish, 1984$

| System Size | Cost per Unit |
|---|---|
| 200 MWe | $ 173 |
| 100 MWe | 174 |
| 50 MWe | 175 |
| 30 MWe | 177 |
| 10 MWe | 186 |
| 5 MWe | 199 |
| 3 MWe | 216 |
| 2.35 MWe | 228 |
| 2.30 MWe | 331 |
| 1 MWe | 356 |
| 0.25 MWe | 486 |
| 0.1 MWe | 747 |

TABLE B.10. Total Installed Foundation Estimates, $/m²

| | |
|---|---|
| 200 MWe | $ 21 |
| 100 MWe | 21 |
| 50 MWe | 21 |
| 30 MWe | 21 |
| 10 MWe | 21 |
| 5 MWe | 21 |
| 3 MWe | 21 |
| 2.35 MWe | 21 |
| 2.30 MWe | 22 |
| 1 MWe | 22 |
| 0.25 MWe | 23 |
| 0.1 MWe | 25 |

**COMPONENTS: RECEIVER AND ENERGY CONVERSION**

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: The quality of the receiver and energy conversion estimate is rated as "fair". There was a good correlation between the three source estimates used as the basis for the final estimate which is a positive aspect. However, none of the estimates include details which results in some uncertainty in the final estimate. Adding additional uncertainty, the final estimate for a 50-kWe power conversion unit is scaled from costs for a 25-kWe unit.

DATA: The receiver and energy conversion components for the dish are combined in a single power conversion unit (a stirling engine/generator set). The stirling unit used for the 150 $m^2$ stressed metal-membrane dish is assumed to be 50-kWe in size. Although, optimized designs may use a smaller engine.

Cost data on 50-kWe units is unavailable. Therefore, cost data for a 25-kWe 4-95 Solar II Unit is used and scaled accordingly for the difference in size. The 25-kWe engine used as the cost basis is a 4-cylinder engine which uses hydrogen as the working fluid, operates at a heater temperature of 750-degrees Celsius, and has a gross efficiency of 0.41 (i.e., the shaft mechanical power as a fraction of heater tube heat input is 0.41.) (Holtz 1987). It is estimated the 50-kWe engine would have a gross efficiency a few percent higher. However, no detailed data is available. For all available related information refer to the working paper "Stirling Engines in Solar Applications".

Stirling cost data from three sources were evaluated. These data are presented in Table B.11. The Vanguard estimates were for installed dish system engines and were reduced by assuming installation, alignment, and testing adds ten percent to the basic cost of the unit. The other estimates reflect only purchase cost. All the units are rated at 25-kWe gross generating capacity.

The data was then fit to two equations. The first of these equations was based on the data points ranging from one to 10,000 units/yr and the second on the data points ranging from 10,000 to 400,000 units/yr. The intersection of these equations is at a production level of 9577. The equations are as follows:

$$1 < \text{units/year} < 9577 \qquad \$/\text{kWe} = 2020.474 + (-187.509)\ln X$$

$$9577 < \text{units/year} < 400{,}000 \qquad \$/\text{kWe} = 5701.798X^{-0.32068}$$

The latter of these two equations was then used to estimate the cost for long-term production levels. An additional 10% was added the estimating equation to allow for installation, alignment, and testing. The resulting long-term estimating equation for the receiver and energy conversion unit cost is as follows:

$$\$/\text{kWe} = 6271.98X^{-0.32068}$$

"X" is equal to the number of 25 kWe (0.025 MWe) units produced per year. This equation is only valid for 25-kWe units whereas the stressed membrane concentrator requires a 50-kWe unit. Because there is no available data on the production cost of 50-kWe units, the cost data for 25-kWe units was scaled.

Scaling of a unit from 25 to 50-kWe results in some economies-of-scale being achieved. Size economies-of-scale are achieved as the engine size is increased which allows the use of less material and labor hours per kWe of output. A review of several sources indicates size economies-of-scale of exist, but the extent is questionable. The general form of the cost-scaling equation using a cost-size factor (denoted SF) is as follows:

$$\text{Unit Cost}_2 = \text{Unit Cost}_1 * (\text{Size}_1/\text{Size}_2) * (\text{Size}_2/\text{Size}_1)^{SF}$$

Assuming a cost-size factor (SF) of 0.6 and applying the generic cost-scaling equation to the equation generated above for the unit cost of the 25-kWe unit, the following equation results for the unit cost of 50-kWe units:

$$\$/\text{kWe} = (25/50)(6271.98X^{-0.32068})((50/25)^{0.6})$$

Through this transformation "X" changes to the number of 50-kWe (0.05 MWe) units produced per year. Additional information on the derivation of this equation is presented in the working paper "Stirling Engines in Solar Applications."

According to United Stirling, approximately 30% of the unit by cost could be considered the receiver and the balance would fall into energy conversion (Nelving 1985). On this basis the cost equation was split into two equations by multiplying by 0.3 and 0.7 to obtain equations for the receiver and energy conversion components, respectively. These equations are as follows:

receiver: $\$/\text{kWe} = 1425.98(\text{MWe}/0.05\ \text{MWe})^{-0.32068}$

conversion: $\$/\text{kWe} = 3327.29(\text{MWe}/0.05\ \text{MWe})^{-0.32068}$

Using an annual production level of 833.35 MWe which corresponds to the production of 16,667 units, results in the following estimates:

receiver: $3157

conversion: $7365

These estimates were rounded to $3160 and $7400, respectively.

TABLE B.11. Dish Power Conversion Unit Purchase Cost Data, 1984$

| Source | Production Quantity | Cost/Unit |
|---|---|---|
| United Stirling[(a)] | 1 | $50,000 |
| | 2,000 | $20,000 |
| | 25,000 | $ 5,500 |
| JPL[(b)] | 1,000 | $17,576 |
| | 25,000 | $ 5,641 |
| | 100,000 | $ 2,946 |
| | 400,000 | $ 2,539 |
| Vanguard[(c)] | 1 | $57,878 |
| | 100 | $28,941 |
| | 1,000 | $15,463 |
| | 10,000 | $ 8,700 |

(a) Telephone conversation with Worth Percival, United Stirling.
(b) Fortgang and Mayers (1980, p. 10) prices were escalated to 1984-dollars.
(c) Washom (1984, p. 9) prices were escalated to 1984-dollars and reduced to an uninstalled basis.

**COMPONENT: TRANSPORT**

QUALITY JUDGMENT: Overall the quality of the transport estimate is "good". PNL specifically designed and estimated transport costs for dish technology. There is a wealth of estimating data on transport components.

METHOD: This component was independently estimated by PNL (Williams et al. 1987, p. 7.12).

DATA: The items included in this estimate and their respective costs versus field size are presented in Table B.12. While these costs were developed for systems using 25-kWe dishes, transport costs are primarily a function of power rating which allows the same costs to be applied to systems using dishes other than 25-kWe in size. The design-point performance for the transport system is a function of power level, because larger fields have longer transmission lines with higher loss. The design-point efficiencies of a dish-stirling transport system are as follows (Williams et al. 1987):

<=3.875 MW -- 0.974
16.25 MW -- 0.972
64.75 MW -- 0.964
323.75 MW -- 0.958

TABLE B.12. Costs for the Dish-Striling Transport System, 1984$

| | 0.025 MW | 0.05 MW | 0.125 MW | 0.25 MW | 0.65 MW |
|---|---|---|---|---|---|
| Disconnect Switches | $ 185 | $ 370 | 925 | $ 1850 | $4,625 |
| Sheet Metal Cubicles | 250 | 250 | 250 | 500 | 1,250 |
| Air Circuit Breakers | 215 | 215 | 215 | 435 | 1,125 |
| Transformer | 9,070 | 9,070 | 10,044 | 13,284 | 20,200 |
| 600 volt UF Cable | 195 | 390 | 970 | 1,950 | 5,036 |
| Closing Dis. Switches | 2,500 | 2,500 | 2,500 | 2,500 | 2,500 |
| Overhead Line #1 | - | - | - | - | - |
| Overhead Line #2 | - | - | - | - | - |
| Poles | - | - | - | - | - |
| | $12,415 | $12,795 | $14,904 | $20,519 | $34,736 |
| Rounded Total | $12,400 | $12,800 | $14,900 | $20,500 | $34,700 |

| | 3.875 MW | 16.25 MW | 64.75 MW | 323.75 MW |
|---|---|---|---|---|
| Disconnect Switches | $ 27,750 | $115,625 | $ 462,500 | $ 2,312,500 |
| Sheet Metal Cubicles | 7,500 | 31,250 | 125,000 | 625,000 |
| Air Circuit Breakers | 6,750 | 28,125 | 112,500 | 562,500 |
| Transformer | 121,200 | 505,000 | 2,020,000 | 10,100,000 |
| 600 volt UF Cable | 30,215 | 125,895 | 503,580 | 2,517,900 |
| Closing Dis. Switches | 15,000 | 62,500 | 250,000 | 1,250,000 |
| Overhead Line #1 | 3,046 | 22,208 | 88,830 | 444,150 |
| Overhead Line #2 | - | 12,282 | 98,992 | 669,392 |
| Poles | 1,100 | 9,900 | 46,200 | 253,000 |
| | $212,561 | $912,785 | $3,707,602 | $18,734,442 |
| Rounded Total | $212,600 | $912,800 | $3,707,600 | $18,734,400 |

COMPONENT: **BALANCE-OF-PLANT**

QUALITY JUDGMENT: The balance-of-plant estimate is judged to be "fair" in quality. The problem with the balance-of-plant category is the requirements are often nebulous. This leads to uncertainty with respect to what should and should not be included.

SUBCOMPONENT: LAND AND SITE PREPARATION

METHOD: Estimated by PNL for Williams et al. (1987) using existing estimates as guidance.

QUALITY JUDGMENT: Because the exact land and site preparation could be very different for any specific site, this subcomponent estimate is given a quality rating of "fair". One particular area which could affect the cost of this subcomponent is the selection of a site with easy access and one where all the land purchased can be used.

DATA: The estimate for land and site preparation was independently estimated by PNL using a number of earthwork estimating manuals. The subcomponent estimate consists of four parts. These include (1) basic land and site preparation for roads and building areas, (2) dish-array land and site preparation, (3) dish-array fencing, and (4) excess land cost.

The first of these parts, basic land and site preparation, is expressed as a function of power level. The unit costs for each element of the land and site preparation estimate are listed in Table B.13. The total cost as presented in Table B.13 is $9,985/acre, which is equivalent to 2.47/m² of land area. Combining this information with estimates of the structures and access road land requirements for each plant size, the basic land and site preparation estimate was prepared. This estimate is shown in Table B.14.

Dish-array land and site preparation is a function of the total field size (aperture area). It is estimated that each square meter of aperture area requires two square meters of ground area. This results in a dish-array land and site preparation estimate of $4.94 per m² of aperture area.

Fencing for the array is based upon a unit cost of $51.50 per linear meter of fencing. The dish-array fencing estimates are presented in Table B.15 as a function of field size.

Finally, there is excess land cost. Although this might seem like an extraneous category, many previous site-specific studies show it is an actual cost. This cost arises because land is purchased in sections or other large tracts depending on federal or state regulations or the willingness of private landowners to sell certain parcels. The plant owner is often limited in the ability to purchase exactly the land required. Because excess land must only be purchased

and not developed, it results in an incurred cost of $500/acre ($0.124/m² of land area). Although land for solar facilities often ranges from $500 to $5000/acre, because dish systems have flexible siting requirements and do not require mainline water connections the low end of the cost range was used. Excess land for a dish system is estimated to be 10% of the dish-array land area. This corresponds to a excess land cost of $0.0247 (1984$) per m² of aperture area.

TABLE B.13. Unit Costs for Dish System Land and Site Preparation, 1984$

| | |
|---|---|
| Land Purchase Cost | $ 500/acre |
| Rough Grading | 6,300/acre |
| Clear and Grub | 625/acre |
| Survey | 930/acre |
| Roads | 860/acre |
| Ditches | 470/acre |
| Permits | 300/acre |
| | $9,985/acre |

TABLE B.14. Basic Dish System Site Area Size and Corresponding Cost For Land and Site Preparation, 1984$

| System Size | Land Area | Cost |
|---|---|---|
| 0.025 MW | 1,750/m² | $ 4,300 |
| 0.05 MW | 1,750/m² | 4,300 |
| 0.125 MW | 1,750/m² | 4,300 |
| 0.25 MW | 1,750/m² | 4,300 |
| 0.5 MW | 6,800/m² | 16,800 |
| 2 MW | 8,400/m² | 20,700 |
| 10 MW | 14,500/m² | 35,800 |
| 30 MW | 16,100/m² | 39,800 |
| 100 MW | 17,100/m² | 42,200 |
| 200 MW | 18,100/m² | 44,700 |

TABLE B.15. Dish-Array Fencing Costs, 1984$

| Field Size (aperture area) | Cost |
|---|---|
| 87m² | $ 2,700 |
| 174m² | 3,800 |
| 434m² | 6,100 |
| 869m² | 8,600 |
| 2,250m² | 13,800 |
| 13,500m² | 33,800 |
| 56,250m² | 69,100 |
| 225,000m² | 138,200 |
| 1,125,000m² | 309,000 |

SUBCOMPONENT: MASTER CONTROLS

METHOD: Adjustment of existing estimates.

QUALITY JUDGMENT: The estimate for this subcomponent is rated as "fair", because there are not independent estimates to support its accuracy and there is no available backup detail for the estimate.

DATA: From a review of six source estimates, an estimate by Advanco (Washom 1984, p. 9) was selected for escalation because it was recently prepared and complete. These controls are for a fully mechanized unattended facility. The source estimate and the adjustments made to generate a final estimate are presented in Table B.16. The smallest master controller unit developed for the Advanco dish system is capable of controlling 32 dishes. For systems smaller than 32 dishes, the use of a standard PC and software is assumed. While these estimates where originally generated for 25-kWe dishes the master controls cost is estimated to be a function of the number of dishes, not the size of the individual dishes.

TABLE B.16. Dish System Master Control Estimates

| Production Level | Cost/Module (1982$) | Total Cost (1982$) | Total Cost (1984$) |
|---|---|---|---|
| 1 | - | - | $ 3,000[a] |
| 32 | $28,000 | $ 28,000 | 29,000 |
| 100 | 711 | 71,100 | 74,000 |
| 1,000 | 478 | 478,000 | 497,000 |
| 10,000 | 359 | 3,590,000 | 3,734,000 |

(a) Assumes the use of a standard PC

SUBCOMPONENT: STRUCTURES

METHOD: Independently estimated by PNL for Williams et al. (1987) using existing estimates as guidance.

QUALITY JUDGMENT: This subcomponent estimate is rated as "fair". It is not clear exactly what size the support structures for a dish system would need to be in order to provide necessary support for the dish system.

DATA: The structures subcomponent includes a control room, administration building, warehouse, maintenance building, and fencing around the structures. PNL unit cost estimates for these items are presented in Table B.17. The total cost for these items at various power levels is presented in Table B.18.

As shown in Table B.18., not all types of structures are present at all power levels. At plant sizes below 2 MW, it is assumed a small structure, probably prefabricated and skid-mounted, would be used at each site. This structure would house the controls, instrumentation, and possibly some spare parts or tools. At these small plant sizes, no maintenance or warehouse facilities are present.

It is assumed that below 2 MW the plant is maintained by a service contractor or by a centralized facility operated by the plant's owner; therefore, no costs for maintenance or warehouse facilities are included in the structure subcomponent estimate. However, there is an allowance for a service contract for plants less than 2 MW. It is included in the operating subcomponent and accounts for maintenance and warehouse space.

At very large plant sizes (greater than 100 MW) an allowance is made for approximately one administrative office. This office may or may not be located on site. For plants less than 100 MW, but greater than or equal to 2 MW, a small amount of administration space is included in the estimate. This space represents the plants contribution toward a larger administration facility which handles the administrative duties for several plants.

TABLE B.17. Structure Unit Costs, 1984$

| | |
|---|---|
| Control Building | $700/m² of floor area |
| Maintenance Building | $530/m² of floor area |
| Warehouse | $430/m² of floor area |
| Administration Building | $590/m² of floor area |
| Multi-Purpose Enclosure | $2000 each |
| Fencing | $51.50/linear meter |

TABLE B.18. Dish System Structures Estimates, 1984$

| | 0.05 MW | 0.125 MW | 0.25 MW | 0.5 MW | 2 MW | 10 MW | 30 MW | 100 MW | 200 MW |
|---|---|---|---|---|---|---|---|---|---|
| Control Building | - | - | - | | $ 6,500 | $ 13,000 | $ 26,000 | $ 26,000 | $ 26,000 |
| Maintenance Building | - | - | - | | 36,750 | 61,250 | 98,000 | 122,500 | 147,000 |
| Warehouse | - | - | - | | 60,000 | 100,000 | 160,000 | 200,000 | 240,000 |
| Administration Building | - | - | - | | 1,475 | 2,950 | 2,950 | 5,900 | 5,900 |
| Multi-Purpose Enclosure | $2,000 | $2,000 | $2,000 | $2,000 | - | - | - | - | - |
| Fencing | - | - | - | | 6,100 | 7,900 | 10,100 | 11,200 | 12,200 |
| Rounded Total | $2,000 | $2,000 | $2,000 | $2,000 | $110,800 | $185,100 | $297,100 | $365,600 | $431,100 |

SUBCOMPONENT: POWER CONDITIONING

METHOD: Comparison and Adjustment of Existing Estimates

QUALITY JUDGMENT: The quality of this subcomponent estimate is rated as "fair", because it is not clear exactly what should be included in this subcomponent.

DATA: Based on site-specific solar power plant studies, the following assumptions were made with respect to transmission line voltage:

| | |
|---|---|
| <5 MW | 13.8 kV |
| 10 MW | 33 kV |
| 30 MW | 115 kV |
| >100 MW | 230 kV |

Because the transport system boosts the voltage to 13.8 kV, no power conditioning is required for plants less than 5 MW. Based on engineering judgment and transformer cost data (Westinghouse 1981) the estimates in Table B.19 were prepared.

TABLE B.19. Dish System Power Conditioning System Cost Estimates

| System Size | Cost |
|---|---|
| 5 MW system | $ 105,000 |
| 10 MW system | 130,000 |
| 30 MW system | 360,000 |
| 100 MW system | 810,000 |
| 200 MW system | 1,540,000 |

SUBCOMPONENT: SERVICE FACILITIES

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

QUALITY JUDGMENT: The quality of this subcomponent estimate is rated as "fair". The "fair" rating was assigned since the exact requirements for dish systems are not well-defined.

DATA: Service facilities estimates for various power levels are presented in Table B.20. The estimate for each power level includes service vehicles, site communication equipment, fire protection, and water systems. Below plant sizes of 2 MW, it is assumed that a service contract is in place or the owner of the plant services the system from a centralized facility. Therefore, no service facilities costs are included in this subcomponent estimate for plants less than 2 MW. Under the operating subcomponent there is an allow made for a service contract for plants less than 2 MW.

TABLE B.20. Dish System Service Facilities Estimates, 1984$

| System Size | Vehicles | Communication | Fire Protection | Water | Rounded Subtotal |
|---|---|---|---|---|---|
| <2 MW | $ 0 | $ 0 | $ 0 | $ 0 | $ 0 |
| 2 MW | 133,000 | 440 | 3000 | 1,040 | 137,500 |
| 10 MW | 195,000 | 2,200 | 15,000 | 5,210 | 217,400 |
| 30 MW | 206,000 | 6,600 | 45,000 | 15,640 | 273,200 |
| 100 MW | 357,000 | 22,000 | 150,000 | 52,120 | 581,100 |
| 200 MW | 714,000 | 44,000 | 300,000 | 104,230 | 1,058,000 |

SUBCOMPONENT: SPARE PARTS

METHOD: Estimated by PNL for Williams et al. (1987) using existing estimates as guidance.

QUALITY JUDGMENT: Nothing can substitute for actual operating experience when attempting to determine the number of spare parts required for a particular plant, subsystem, or piece of equipment. Since there is no good operating experience available, some engineering judgments were required based upon existing heliostat spare parts estimates. For these reasons, the overall quality of this subcomponent estimate is rated as "poor".

DATA: The spare parts estimates include a three-year supply of parts. The primary basis is estimates developed for the repowering of the Saguaro Power Plant (Weber 1982). These estimates for annual spare parts are:

| | |
|---|---|
| Collector Equipment | 0.1% of initial cost/yr |
| Receiver Equipment | 1.0% of initial cost/yr |
| Storage Equipment | 1.0% of initial cost/yr |
| Heat Exchanger Subsystem | 1.0% of initial cost/yr |

Source: Weber 1982, p. G-12

Using these estimates as guidelines, the following estimates were prepared for dish systems:

| | |
|---|---|
| Concentrator Equipment | 0.3% of initial cost |
| Transport Equipment | 0.3% of initial cost |
| Balance-Of-Plant Items (excluding land and site prep.) | 3.0% of initial cost |
| Receiver and Energy Conversion | 0.6% of initial cost |

Centralized components were presumed to have spare parts requirements which are ten times greater than the requirements for distributed components, because failure of a centralized component affects the entire (or major parts) of the system while failure of a distributed component has a limited affect on the whole system. For this reason the transport system which is distributed has the same spare parts allowance as the collector which is also distributed. The balance-of-plant allowance is estimated as ten times higher because it is a centralized component. Exceptions to the rule are the land and site preparation subcomponent which requires no spare parts, and the receiver and energy conversion spare equipment estimate which is presumed to be twice as high as the collector spare parts estimate, because the receiver and energy conversion equipment (i.e., the stirling engine) is expected to require significantly more maintenance than the collectors. Hence, additional spares are required.

**COMPONENT: OPERATING AND MAINTENANCE**

QUALITY JUDGMENT: the quality of O&M cost data is rated as "poor", mainly because little operating experience exists which causes estimates to be based largely on conjecture.

SUBCOMPONENT: OPERATING

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

QUALITY JUDGMENT: This subcomponent estimate is rated as "poor". Although the estimate is good for the assumptions made, there is considerable uncertainty as to what would be the actual requirements.

DATA: Operating personnel for the dish systems at all power levels greater than 100 MW is estimated to be three full-time security personnel. For plants ranging from 2 MW to 100 MW one and one-half full-time security persons are estimated present. Below 2 MW no security personnel are present. The estimated salary per full-time person is $27,000 per year. A 15% overhead charge (Guthrie 1974) is added to this estimate to yield a total operating personnel estimate of $31,050 per full-time person. Therefore, the rounded final estimates are as follows:

| | |
|---|---|
| < 2 MW systems | $0 |
| 2=<=100 MW systems | $46,600 |
| 100 <=200 MW systems | $93,200 |

In addition, plants less than 2 MW are assumed to have either a service contract or be maintained from the owner's centralized maintenance facility which is not on site. Because a service contract is in place for plants less than 2 MW, maintenance, warehouse, administration, and service facilities for these same plants were estimated as zero.

For a 2 MW plant approximately $1385 per 25 kWe dish and $1719 per 25 kWe dish are estimated to be spent on structure and service facilities, respectively; therefore, these costs times the owner's or subcontractor's fixed charge rate is the amount each dish must be charged per year for the capital recovery of the structures and service facilities. The actual parts and labor for this type of arrangement are estimated to be the same as for all other plant sizes (see the maintenance subcomponents).

The fixed charge rate used for buildings is 0.177 which is based on a depreciation period of 20 years, economic life of 20 years, a 10% discount rate, a 38% federal tax rate, and 2% in other taxes. The fixed charge rate used for service facilities is 0.205 which is based on a depreciation period of 5 years, economic life of 10 years, a 10% discount rate, a federal tax rate of 38%, and 2% in other taxes.

Applying these two fixed charge rates to the corresponding estimates above yields an annual service charge of approximately \$600 per 25 kWe dish. This is equivalent to \$24/kWe of gross generating capacity. Although this cost could be grouped with maintenance costs, because it is a fixed annual expense it is listed as an operating expenditure.

SUBCOMPONENT: MAINTENANCE OF THE CONCENTRATOR

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: Maintenance of the concentrator is broken into three elements, washing maintenance, non-washing maintenance, and optical material replacement. The total estimate is rated as "poor". The washing estimate is poor, because it is unclear what type of cleaning regiment the optical material and thin metal-membrane can withstand. The non-washing estimate is poor due to uncertainty in what is truly required. The optical replacement estimate is relatively good.

DATA: Dish washing costs were assumed 75% higher than heliostat washing costs. Two-thirds of the increase is due to washing complexities caused by the dishes' curved surface. The remaining one-third is for the increased cleaning time required due to a less aggressive approach used when washing the relatively fragile optical material. Washing costs for the heliostat are a product of a review of six source estimates. Based on the completeness of the estimates and engineering judgment, estimates by ARCO, and McDonnell Douglas were used as the basis for the final estimates. These estimates are presented in Table B.21. The average material cost for washing is \$0.285/$m^2$ (1980\$) while the average labor cost of washing is \$0.16/$m^2$. However, one-third of the labor is moving from heliostat to heliostat; therefore, the cost of actual washing labor is \$0.107/$m^2$ (1980\$). Because washing costs for the dish were assumed to be 75% greater, the cost of actual dish washing was estimated as \$0.187/$m^2$ (1980\$). Adding back the moving cost between dishes and material cost, the total cost for twelve washes per year is \$0.525/$m^2$ (1980\$). To keep the reflectivity to a reasonably high level, the estimate was doubled to allow twenty-four washes per year. Escalating to 1984-dollars, results in an estimate of \$1.24 per $m^2$ of surface area (1984\$). Adjusting the estimate to a dollar-per-square-meter-of-aperture-area basis yields a final estimate of \$1.30 per $m^2$ of surface area (1984\$).

Non-washing costs for the dish are assumed equal to those of the heliostat on a square-meter-of-surface-area basis. Heliostat non-washing cost estimates from four sources were averaged to get estimates of \$0.41 and \$0.20 per square meter of surface area (1980\$) for labor and materials, respectively. These were escalated to \$0.51 and \$0.25 in 1984-dollars, respectively. The source estimates are presented in Table B.22. Adjusting the non-washing maintenance cost estimates to a dollar-per-square-meter-of-aperture-area basis yields estimates of \$0.54/$m^2$ and \$0.26/$m^2$ for labor and materials, respectively.

Non-washing material costs would increase relative to the concentrator capital cost, and are therefore expressed as a fraction of initial capital cost. To calculate this fraction, the initial capital cost of a long-term 200-MWe system was used. This assumption gives the most representative results. Dividing the materials estimate of \$0.26 by the concentrator capital cost of \$83 per square meter of aperture area, results in a yearly non-washing materials concentrator maintenance estimate of 0.30 percent of the initial concentrator cost.

TABLE B.21. Heliostat Mirror Washing Cost (12 Washes/Year), 1980\$

| | |
|---|---|
| ARCO | 0.48/m² [(a)] |
| McDonnell Douglas | 0.41/m² [(b)] |

(a) ARCO (Norris and White 1982, p. 116) estimates \$0.18 for washing materials and \$0.06 (1980\$) for washing labor for 6 washes per year.
(b) MDAC (Norris and White 1982, p. 116) estimates \$0.2 for washing materials and \$0.20 (1980\$) for washing labor for 12 washes per year.

TABLE B.22. Heliostat General Maintenance (non-washing) Costs, 1980\$[(a)]

| | |
|---|---|
| ARCO | \$0.42/m² |
| McDonnell Douglas | 0.61/m² |
| Boeing | 0.73/m² |
| Martin Marietta | 0.68/m² |

(a) Materials, labor and repair costs are included (Norris and White 1982, p.116)

Summarizing, concentrator general maintenance has three elements, (1) washing costs which are \$1.30/m² of aperture area, (2) non-washing labor costs which are \$0.54/m² of aperture area and (3) non-washing material costs which are 0.30% of the initial capital concentrator cost. In addition, a 15% overhead charge (Guthrie 1974) is added to all of the above estimates.

Optical material replacement is required every 5 years of the project life. This cost element was estimated by PNL in three parts: (1) F.O.B. optical membrane cost, (2) transportation cost, (3) field installation cost. The F.O.B. cost of the membrane was estimated using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table B.23. The optical membrane estimate generated from the algorithm is \$818.55. The membranes are rolled onto a mandrel at the factory and shipped to the replacement site. Based on a shipping distance of 700 miles, a shipping cost of \$1.45 per mile, and 700 membranes per load, the shipping cost per membrane is \$1.24. Installation is estimated to take 1.08 hours which at \$24.50 per hour is \$26.46. The sum of all these costs is \$846.25. This estimate was rounded to \$850.

TABLE B.23. Inputs to the PNL Manufacturing Cost Algorithm Replacement Optical Membranes

| | |
|---|---|
| Direct Materials | \$576 per dish; \$48,000,960 for 83,335 units/year |
| Direct Labor | 0.167 hours; 13,890 hours for 83,335 units/year |
| Capital Equip. | \$1,328,000 |
| Plant Area | 32,000 sq. ft. |
| Plant Acreage | 2 Acres |

(a) 83,335 units per year

Replacement of the optical membrane could just as appropriately be categorized as a capital replacement cost. If it were categorized as such, it would be expressed as the present value (at time zero) of all the replacements over the project life. Assuming replacement every five years of the thirty year project life, and a discount rate of 3.15% (as per the "Five-Year Plan"), a capital replacement cost of \$2515.59 is estimated. This estimate was rounded to \$2500. Overheads are already included in this estimate.

SUBCOMPONENT: MAINTENANCE OF THE RECEIVER SYSTEM.

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

METHOD: Costs are assumed equivalent on a dollar per $m^2$ basis to estimates prepared for the 25-kWe glass-metal dish.

DATA: Maintenance costs are assumed equal to those estimated for the glass-metal 25-kWe dish on a dollar-per-square-meter basis. There is currently no available data on receiver maintenance for 50-kWe PCUs. The estimated costs are:

labor: \$2.24 per $m^2$ of aperture area plus 15% overhead

materials: \$1.50 per $m^2$ of aperture area plus 15% overhead

SUBCOMPONENT: MAINTENANCE OF THE CONVERSION SYSTEM

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

METHOD: Costs are assumed equivalent on a dollar per $m^2$ basis to estimates prepared for the 25-kWe glass-metal dish.

DATA: Maintenance costs are assumed equal to those estimated for the glass-metal 25-kWe dish on a $ per square meter basis. There is currently no available data on conversion maintenance for 50-kWe PCUs. The estimated costs are:

labor: $5.83 per $m^2$ of aperture area plus 15% overhead

materials: $3.89 per $m^2$ of aperture area plus 15% overhead

SUBCOMPONENT: MAINTENANCE OF THE TRANSPORT SYSTEM

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

QUALITY JUDGMENT: Due to the maintenance requirements being quite nebulous, this subcomponent estimate is rated as "poor".

DATA: The estimate as prepared by PNL is presented in Table B.24. It is based on applying engineering judgment to maintenance cost estimates for other electrical operating systems. In addition to the costs presented below an overhead charge of 15% must be added (Guthrie 1974).

TABLE B.24. Dish Transport System Maintenance Cost Estimate

| System Size | Scheduled/ Unscheduled Maint.[a] | Maint. Materials[a] | Total[a] |
|---|---|---|---|
| 0.5 MW | 0.25 | 0.50 | 0.75 |
| 2 MW | 0.30 | 0.50 | 0.80 |
| 10 MW | 0.35 | 0.50 | 0.85 |
| 30 MW | 0.40 | 0.50 | 0.90 |
| 100 MW | 0.45 | 0.50 | 0.95 |
| 200 MW | 0.50 | 0.50 | 1.00 |

(a) The estimates are presented as the fraction of the transport system capital cost required for annual maintenance.

SUBCOMPONENT: MAINTENANCE OF BALANCE-OF-PLANT

QUALITY JUDGMENT: Due to the maintenance requirements being quite nebulous, this subcomponent estimate is rated as "poor".

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

DATA: The estimate as prepared by PNL for the balance-of-plant exclusive of the master controls and land and site preparation is presented in Table B.25. The maintenance estimate for the master controls is 1.6% of the capital cost per year (Weber 1983). In addition an overhead charge of 15% (Guthrie 1974) must be added to these estimates.

TABLE B.25. Dish System Balance-of-Plant Maintenance Cost Estimate

| System Size | Scheduled/ Unscheduled Maint.[a] | Maint. Materials[a] | Total[a] |
|---|---|---|---|
| 10 MW | 0.40 | 1.0 | 1.4 |
| 30 MW | 0.40 | 1.0 | 1.4 |
| 100 MW | 0.40 | 1.0 | 1.4 |

(a) The estimates are presented as the fraction of the balance-of-plant capital cost (excluding the master controls and land and site preparation) required for annual maintenance.

## INDIRECTS AND CONTINGENCIES

METHOD: Comparison and adjustment of existing estimates

DATA: Seven complete system estimates formed the basis for the indirects and contingencies estimate. The source estimates are presented in Table B.26.

TABLE B.26. Source Estimates for Dish System Indirects and Contingencies

| Source | Indirects | Contingencies |
|---|---|---|
| SCE et al. (1982, p. 19) | - | 20 |
| Weber (1983) | - | 23 |
| Easton and Endicott (1982) | 21 | 10.6 |
| Weber (1982) | 24.3 | 17.3 |
| Weber (1980) | 30.7 | 12.2 |
| Joy et al. (1981) | 15.8 | 15 |
| Bloomster et al. (1982) | 25 | 25 |
| Avg. | 23.4 | Avg. 17.6 |

The average indirects estimate was rounded to 25 percent. The contingency estimate was reduced to 10% to reflect a plant representative of mature technology with no extraordinary contingencies. This reduction was based on logic presented in EPRI's TAG (1982, p. 3-3).

The cost estimates for near-term "Nth plant" dish systems are summarized in Table B.27. "Nth plant" is defined as approximately the fifth to tenth plant built employing a specific dish technology. Although "Nth plant" technology is not in a mature state of development, it has been developed to a significant enough level that extraordinary contingencies don't exist. However, slightly higher contingencies do prevail. The contingency for the near-term components is 15% as opposed to 10% for the long-term estimates. No technology development costs are included in "Nth plant" cost estimates. The annual production level assumed is equal to the production rate that is required to build one "Nth plant".

The cost data are presented in one of four forms: dollars per square meter of aperture area, as a function of initial capital cost, dollars per kWe, or total-dollars at several given design points (MWe, m² of aperture area, or number of dishes). Unless otherwise specified, kWe and MWe ratings used throughout the estimates refer to gross generation capacity. With the exception of only a few components and subcomponents, the near-term estimates are the same as the long-term estimates. This is because components such as buildings, electrical components, land and site preparation, etc. are already maturely developed; therefore, near-term dish systems will be able to take advantage of the lower mature cost of some items.

Like the long-term estimates a subcomponent-by-subcomponent explanation of how the estimates were prepared is included. In addition to procedural information, a quality judgment of the data is given at the component and subcomponent level. The quality judgment includes a rating of good, fair, or poor and an explanation of weakness and strengths of the data.

TABLE B.27. Near-Term Cost Data Table for Stressed Metal-Membrane Dish Systems, 1984$

Concentrator (reflactive polymer; based on stressed metal-membrane)

Mirror/Support

| | | | |
|---|---|---|---|
| Unit (F.O.B.) | 2 dish system | $116 | per $m^2$ of aperture area |
| | 5 dish system | $105 | per $m^2$ of aperture area |
| | 10 dish system | $97.4 | per $m^2$ of aperture area |
| | 20 dish system | $90.1 | per $m^2$ of aperture area |
| | 40 dish system | $83.3 | per $m^2$ of aperture area |
| | 46 dish system | $82.1 | per $m^2$ of aperture area |
| | 47 dish system | $79.9 | per $m^2$ of aperture area |
| | 80 dish system | 75.4 ~~$77.0~~ | per $m^2$ of aperture area |
| | 100 dish system | $73.6 | per $m^2$ of aperture area |
| | 200 dish system | $68.2 | per $m^2$ of aperture area |
| | 600 dish system | $60.3 | per $m^2$ of aperture area |
| | 1000 dish system | $57.0 | per $m^2$ of aperture area |
| | 2000 dish system | $52.8 | per $m^2$ of aperture area |
| | 4000 dish system | $48.7 | per $m^2$ of aperture area |
| Transportation | >= 2.35 MWe | $0.9 | per $m^2$ of aperture area |
| | < 2.35 MWe | $1.4 | per $m^2$ of aperture area |
| Field Installation | 200 MWe | $2.2 | per $m^2$ of aperture area |
| | 100 MWe | $2.3 | per $m^2$ of aperture area |
| | 50 MWe | $2.5 | per $m^2$ of aperture area |
| | 30 MWe | $2.8 | per $m^2$ of aperture area |
| | 10 MWe | $4.0 | per $m^2$ of aperture area |
| | 5 MWe | $5.9 | per $m^2$ of aperture area |
| | 3 MWe | $8.4 | per $m^2$ of aperture area |
| | 2.35 MWe | $14 | per $m^2$ of aperture area |
| | 2.3 MWe | $8.9 | per $m^2$ of aperture area |
| | 1 MWe | $10 | per $m^2$ of aperture area |
| | 0.25 MWe | $20 | per $m^2$ of aperture area |
| | 0.1 MWe | $41 | per $m^2$ of aperture area |

## TABLE B.27. (Cont.)

| | |
|---|---|
| Drive | 1 dish system \$26 per $m^2$ of aperture area<br>100 dish system \$21 per $m^2$ of aperture area<br>1000 dish system \$13 per $m^2$ of aperture area<br>10000 dish system \$11 per $m^2$ of aperture area |
| Controls and Wiring | 1 dish system \$3700<br>100 dish system \$1800<br>1000 dish system \$1300<br>10000 dish system \$900 |
| Foundation | 200 MWe \$24.0 per $m^2$ of aperture area<br>100 MWe \$25.9 per $m^2$ of aperture area<br>50 MWe \$27.8 per $m^2$ of aperture area<br>30 MWe \$29.3 per $m^2$ of aperture area<br>10 MWe \$33.0 per $m^2$ of aperture area<br>5 MWe \$35.5 per $m^2$ of aperture area<br>3 MWe \$37.5 per $m^2$ of aperture area<br>1 MWe \$43.1 per $m^2$ of aperture area<br>2.35 MWe \$38.5 per $m^2$ of aperture area<br>2.3 MWe \$39.4 per $m^2$ of aperture area<br>0.25 MWe \$50.6 per $m^2$ of aperture area<br>0.1 MWe \$57.4 per $m^2$ of aperture area |
| Receiver | \$459.370 + (-42.632)ln(MWe/0.05 MWe) for 50 kWe unit(s) |
| Transport | 0.025 MW system \$12,400<br>0.05 MW system \$12,800<br>0.125 MW system \$14,900<br>0.25 MW system \$20,500<br>0.65 MW system \$34,700<br>3.875 MW system \$212,600<br>16.25 MW system \$912,800<br>64.75 MW system \$3,707,600<br>323.75 MW system \$18,734,400 |
| Conversion | \$1071.863 + (-99.474)ln(MWe/0.05 MWe) for 50 kWe unit(s) |
| Balance-of-Plant | |
| Land and Site Preparation | |
| Basic Land and Site Prep. for access roads, and buildings | 0.025 MW system \$4300<br>0.05 MW system \$4300<br>0.125 MW system \$4300<br>0.25 MW system \$4300<br>0.5 MW system \$16,800<br>2 MW system \$20,700<br>10 MW system \$35,800<br>30 MW system \$39,800<br>100 MW system \$42,200<br>200 MW system \$44,700 |
| Dish-Array Land and Site Prep. | \$4.94 per $m^2$ of aperture area |
| Dish-Array Fencing | 87$m^2$ field size \$2,700<br>174$m^2$ field size \$3,800<br>434$m^2$ field size \$6,100<br>869$m^2$ field size \$8,600<br>2,250$m^2$ field size \$13,800<br>13,500$m^2$ field size \$33,800<br>56,250$m^2$ field size \$69,100<br>225,000$m^2$ field size \$138,200<br>1,125,000$m^2$ field size \$309,000 |

## TABLE B.27. (Cont.)

| | | |
|---|---|---|
| **Balance-of-Plant (Continued)** | | |
| Excess Land | $0.0247 per $m^2$ of aperture area | |
| Master Controls | 32 dish system | $3,000 |
| | 100 dish system | $74,000 |
| | 1000 dish system | $497,000 |
| | 10000 dish system | $3,734,000 |
| Structures | 0.025 MW system | $2,000 |
| | 0.05 MW system | $2,000 |
| | 0.125 MW system | $2,000 |
| | 0.25 MW system | $2,000 |
| | 0.5 MW system | $2,000 |
| | 2 MW system | $110,800 |
| | 10 MW system | $185,100 |
| | 30 MW system | $297,100 |
| | 100 MW system | $365,600 |
| | 200 MW system | $431,100 |
| Power Conditioning | 5 MW system | $105,000 |
| | 10 MW system | $130,000 |
| | 30 MW system | $360,000 |
| | 100 MW system | $810,000 |
| | 200 MW system | $1,540,000 |
| Service Facilities | <2 MW system | $0 |
| | 2 MW system | $137,500 |
| | 10 MW system | $217,400 |
| | 30 MW system | $273,200 |
| | 100 MW system | $581,100 |
| | 200 MW system | $1,162,000 |
| Spare Parts | 3% of capital cost of BOP items (excluding land and site prep.)<br>0.6% of capital cost of energy conversion and receiver<br>0.3% of capital cost of collector and transport | |
| **Operating and Maintenance (annual)** | | |
| Operating | | |
| Security | < 2 MW system | $0 |
| | 2=<=100 MW system | $46,600 |
| | 100 <=200 MW system | $93,200 |
| Service Contract | < 2 MW system | $24/kWe of gross generating capacity |
| Concentrator Maintenance | 0.3% ~~0.03%~~ of concentrator capital cost plus 15% overhead<br>1.84 per $m^2$ of aperture area plus 15% overhead<br>$850 every 5th year for optical membrane replacement (present value of these replacements at time zero = $2500) | |
| Receiver Maintenance | lab: $2.24 per $m^2$ of aperture plus 15% overhead<br>mat: ${459.370 + (-42.632)ln(Size, MW/0.05 MW)}{(1.50) ($m^2$ of aperture area)}/3160 plus 15% overhead | |
| Conversion Maintenance | lab: $5.83 per $m^2$ of aperture plus 15% overhead<br>mat: ${1071.863 + (-99.474)ln(Size, MW/0.05 MW)}{(3.89) ($m^2$ of aperture area)}/7370 plus 15% overhead | |

TABLE B.27. (Cont.)

| | | |
|---|---|---|
| Transport | | 5 MW system 0.80% of transport capital cost plus 15% overhead |
| | | 10 MW system 0.85% of transport capital cost plus 15% overhead |
| | | 30 MW system 0.90% of transport capital cost plus 15% overhead |
| | | 100 MW system 0.95% of transport capital cost plus 15% overhead |
| | | 200 MW system 1.0% of transport capital cost plus 15% overhead |
| Balance-of-Plant | | 1.4% of structures, service facilities, power conditioning, and spare parts plus 15% overhead |
| | | 1.6% of master controls plus 15% overhead |
| Indirects | | 25% of subtotaled component estimate |
| Contingencies | | 15% of concentrator, receiver, and conversion component estimates |
| | | 10% of all other component estimates |

COMPONENT: **CONCENTRATOR** (stressed metal-membrane technology)

QUALITY JUDGMENT: Overall the quality the concentrator component estimate is "fair". The estimate itself is quite comprehensive and is based on a significant amount of detailed cost data which was developed for the stressed membrane heliostat (Solar Kinetics 1987) and other studies. The quality judgment of "fair" is given due to the conceptual nature of the design which results in an estimate with greater uncertainty than an estimate based on detailed engineering drawings. Additionally, there is little information regarding the production economies-of-scale which would occur for near-term manufacturing of the concentrator.

SUBCOMPONENT: MIRRORS AND SUPPORT

METHOD: This subcomponent was estimated by PNL in three parts: (1) the concentrator unit (F.O.B.), (2) transportation, and (3) field installation. The long-term production cost estimate was the basis for the near-term estimate. The production economies-of-scale which would exist for lower near-term production levels were estimated. These production economies-of-scale were then applied to the long-term estimate to generate the near-term estimate.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". Although the design is conceptual, there is enough design information and related historical data to generate a sound long-term manufacturing estimate. Uncertainty arises when trying to determine the production economies-of-scale which would exist before long-term production levels are reached. The transportation estimate is "good" within the limits of the transportation scenario presumed. If a different method of transportation was to be used, the costs could differ slightly. The field installation estimate is rated as "fair". There is uncertainty as to exactly how some of the site operations would be performed. In particular, the process to hydroform the metal-membrane and the time and equipment estimates for fastening the rear and optical membranes to the ring are uncertain.

DATA: The construction of the stressed metal-membrane concentrator consists of a 14-meter diameter aluminum ring centered around a steel mast. To the back of the ring and base of the mast a vinyl-coated fiberglass rear membrane is attached. To the front of the ring a 0.01-inch thick aluminum membrane is welded. During installation the metal-membrane is hydroformed to an optical shape. Additionally, to the front of the ring an optical membrane is attached. When the plenum between the rear membrane and optical membrane is evacuated the optical membrane is drawn down against the metal-membrane. This forms the optical membrane into the appropriate reflective shape. Design point performance estimates for the concentrator are as follow:

Concentrator Reflectivity (new and clean)--0.91 (SKI)

Reflectivity Degradation (assuming bi-weekly cleaning)--0.95
-This is the same value that was assumed for the glass/metal concentrator. It is very likely that this value is too high for membrane concentrators; the reasons for this are:

- cleaning will most likely be more difficult, less efficient, and less effective. Due to the very thin metal membrane, high pressure water or brushes will not be able to be used (metal-membrane will be plastically deformed with 0.56 psi). Additional, the optical surface is thin, stressed polymers will not be able to withstand a cleaning regiment as aggressive as that of the glass/metal concentrator.

- The optical material will suffer permanent degradation over time (the reason for the five-year replacement schedule).

Blocking caused by the center tube support cables--0.986
-There are 24 one-half inch cables. These cables will both shadow the concentrator and block <u>concentrated</u> reflected flux. Considering only the shadowing (or assuming the concentration is very small) the cables will shadow an area equal to:

$$24 * 7m * 0.5 \text{ in.} = 23 \text{ ft}^2 \ (2.13 \text{ m}^2)$$

Shadowing caused by the receiver support structure--0.989
-There are three 3-inch support trusses for the receiver. These trusses will shadow an area of the concentrator equal to:

$$3 * 7m * 3 \text{ in.} = 17.2 \text{ ft}^2 \ (1.60 \text{ m}^2)$$

Concentrator/Receiver Intercept Factor--0.966
-This is the same value that was assumed for the glass/metal concentrator. This value is probably also too high for membrane concentrators; the reasons for this area:

- The optical quality of the concentrator will most likely be less than that of the glass/metal concentrator. Thus, for an intercept factor this high, the receiver aperture would have to be larger which would result in increased receiver thermal losses. Conversely, the aperture could be made small to maintain low receiver losses, but this would increase spillage and thus decrease the concentrator/receiver intercept factor. The optimal value is the one that minimizes the LEC; this value will have to be determined during detailed systems analysis and design.

<u>Concentrator Unit</u>

At the central manufacturing facility; the metal, rear, and optical membranes; the main mast; PCU support tripod; and foundation/drive structure are manufactured. Manufacture of these components is integrated in that foundation parts are cut and painted using much of the same equipment used for the main mast and PCU support tripod.

For cost accounting purposes, half of the parts-cutting equipment, paint line, labor, related floor space, and related land area are included in this subcomponent and the remainder in the foundation subcomponent. General factory equipment is divided between these same subcomponents based on the ratio of factory floor space required between the subcomponents.

In addition, for small site sizes (less than 2.35 MWe) it is economically more attractive to manufacture the main concentrator ring at the central manufacturing facility than at the site, as is done for large system sizes. Central facility manufacturing of the ring at small system sizes is desirable, because it is more expensive to set-up the site ring-manufacturing facility and make a small number of rings than it is to centrally manufacture the ring, cut it into eight arched segments and ship it to the site for welding into a uniform ring.

The long-term F.O.B. cost of the concentrator was estimated by using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table B.28 for plant sizes of 2.35 MWe or larger and in Table B.29 for sizes smaller than 2.35 MWe. The concentrator estimates as generated from the algorithm are \$4114 and \$4805 per concentrator for large and small system sizes, respectively. In addition to these costs, \$2125 and \$1572 for burdened materials and working capital allowance for materials used at the site must be added. Making these additions yields estimates of concentrator cost of \$6239 and \$6377, respectively. These estimates translate to \$41.6 per $m^2$ of dish aperture area for systems equal to or larger than 2.35 MWe and \$42.5 per $m^2$ of dish aperture area for system sizes smaller than 2.35 MWe. Both these unit costs are based on a stressed metal-membrane dish which has 150 $m^2$ of aperture area and an annual production level of 16,667 units per year.

TABLE B.28. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Mirrors and Support Subcomponent at System Sizes of Greater than 2.35 MWe.

| | |
|---|---|
| Direct Materials | \$2727 per dish; \$45,450,909 for 16,667 dishes/year[a] |
| Direct Labor | 4.91 hours; 81,900 hours for 16,667 dishes/year |
| Capital Equip. | \$9,272,394 |
| Plant Area | 123,891 sq. ft. |
| Plant Acreage | 7.44 Acres |

(a) 16,667 dishes per year is equivalent to $2.5 \times 10^6$ square meters of concentrator area which is the assumed production level.

The main differentiating factor between the cost of the near-term and long-term glass-metal dish technologies is production economies-of-scale. In the case of the long-term estimates, 16,667 dishes per year are produced while in the near-term the erection of a 200 MW plant would require only about 4000 dishes and smaller systems would require even less.

TABLE B.29. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Mirrors and Support Subcomponent at System Sizes of Less than 2.35 MWe.

| | |
|---|---|
| Direct Materials | \$3200 per dish; \$53,334,400 for 16,667 dishes/year[(a)] |
| Direct Labor | 5.45 hours; 90,789 for 16,667 dishes/year |
| Capital Equip. | \$9,594,587 |
| Plant Area | 139,891 sq. ft. |
| Plant Acreage | 8.44 Acres |

(a) 16,667 dishes per year is equivalent to $2.5 \times 10^6$ square meters of concentrator area which is the assumed production level.

Cost versus production level data is non-existent for stressed metal-membrane dish concentrators; however, one source (Washom 1982, p. 9) does include this type of information for the Advanco glass-metal concentrator. While the Advanco glass-metal and stressed metal-membrane concentrators are different, the relative production economies-of-scale are anticipated to be similar. For ordinary production operations, production economies-of-scale are about the same for manufactured components using similar materials, equipment, and fabrication techniques. For conceptual estimates such as those presented here, this assumption is quite adequate.

The estimates for the Advanco concentrator (Washom 1984, p. 9) as a function of production level were fit to an equation. These estimates are presented in Table B.30. The equation was then used to estimate the cost of the Advanco concentrator at 16,667 units per year. Using this estimate and the source estimates (Table B.30), the additional cost (in fractional form) due to production economies-of-scale for producing less than 16,667 units per year was calculated. These fractions are presented in Table B.31.

TABLE B.30. Advanco Glass-Metal Concentrator Estimates, 1982\$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | \$52,797 |
| 100 per year | 41,655 |
| 1000 per year | 23,788 |
| 10000 per year | 19,895 |

TABLE B.31. Advanco Concentrator Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 16,667 Units |
|---|---|---|
| 2 per year | 52,684[(a)] | 2.74 |
| 5 per year | 47,566[(a)] | 2.47 |
| 10 per year | 44,028[(a)] | 2.29 |
| 20 per year | 40,753[(a)] | 2.12 |
| 40 per year | 37,722[(a)] | 1.96 |
| 46 per year | 37,139[(a)] | 1.93 |
| 47 per year | 37,050[(a)] | 1.92 |
| 80 per year | ~~36,055~~[(a)] 34844 | ~~1.87~~ 1.81 |
| 100 per year | 41,655 | 2.16 |
| 100 per year | 34,058[(a)] | 1.77 |
| 200 per year | 31,525[(a)] | 1.64 |
| 600 per year | 27,890[(a)] | 1.45 |
| 1000 per year | 23,788 | 1.24 |
| 1000 per year | 26,346[(a)] | 1.37 |
| 2000 per year | 24,386[(a)] | 1.27 |
| 4000 per year | 22,572[(a)] | 1.17 |
| 10000 per year | 19,895 | 1.03 |
| 16667 per year | 19,251[(a)] | - |

(a) Cost predicted by the equation $56917X^{0.888489}$ ($r^2 = 0.998$) which is based on a curve fit of the data presented in Table B.29. Where "X" is the annual production level and the predicted cost is the total annual production cost.

The fractions were then applied to the PNL-derived long-term F.O.B. estimate for the stressed metal-membrane concentrator at a production level of 16,667 units per year to determine the near-term cost of the stressed metal-membrane concentrator. These estimates are shown in Table B.32. Distributing the cost of the concentrator over the aperture area of the stressed metal-membrane dish, 150 $m^2$, yields the estimates presented in Table B.33.

Concentrator Transportation

Concentrator transportation costs were estimated by determining the numbers loads required (either weight- or volume-limited) to deliver concentrator subassemblies from the factory to the site and multiplying by an assumed delivery distance of 600 miles and a cost per mile of $1.45. For large systems, an average 6.18 dishes can be transported per load. This results in a concentrator transportation cost of $141. This cost distributed over the aperture area of the dish and rounded is $0.9 per $m^2$ of aperture area. For small systems (less than 2.35 MWe) shipping of the ring increases transportation costs to $214 and reduces the average dishes per load to 4.07. Small system shipping is rounded to $1.4 per $m^2$ of aperture area.

TABLE B.32. Estimated Central Manufacturing Cost of the Stressed Metal-Membrane Concentrator at Production Levels Less than 16,667 Units per Year, 1984$

| Production Level | Cost per Unit |
|---|---|
| 2 per year | 17,473 |
| 5 per year | 15,751 |
| 10 per year | 14,603 |
| 20 per year | 13,519 |
| 40 per year | 12,499 |
| 46 per year | 12,308 |
| 47 per year | 11,979 |
| 80 per year | ~~11,667~~ 11,293 |
| 100 per year | 11,043 |
| 200 per year | 10,232 |
| 600 per year | 9,047 |
| 1000 per year | 8,547 |
| 2000 per year | 7,924 |
| 4000 per year | 7,300 |
| 10000 per year | 6,426[a] |
| 16667 per year | 6,239[a] |

(a) Same cost as the long-term estimate

TABLE B.33. Estimated Central Manufacturing Cost of the Stressed Metal-Membrane Concentrator at Production Levels Less than 16,667 Units per Year, 1984$

| Production Level | Cost per Unit, $/m^2$ |
|---|---|
| 2 per year | 116 |
| 5 per year | 105 |
| 10 per year | 97.4 |
| 20 per year | 90.1 |
| 40 per year | 83.3 |
| 46 per year | 82.1 |
| 47 per year | 79.9 |
| 80 per year | ~~77.8~~ 75.3 |
| 100 per year | 73.6 |
| 200 per year | 68.2 |
| 600 per year | 60.3 |
| 1000 per year | 57.0 |
| 2000 per year | 52.8 |
| 4000 per year | 48.7 |
| 10000 per year | 42.8[a] |
| 16667 per year | 41.6[a] |

(a) Same cost as the long-term estimate

## Concentrator Installation

The field installation estimates were independently prepared by PNL and are presented in Table B.34. These figures are based on a PNL estimate of 11.9 manhours for site assembly and installation, a $27.07 charge per dish for capital installation equipment, and a site set-up charge of $56,740 for systems equal to or larger than 2.35 MWe. Large system site installation progresses at an average output of 159 dishes per week, not including the initial site set-up time of one week. For systems smaller than 2.35 MWe, field installation estimates are based on a PNL estimate of 36.10 manhours, a $111.96 charge per dish for capital installation equipment, and a site set-up charge of $10,384. Small system site installation progresses at an average output of 4.15 dishes per week, not including initial site set-up time of one week. The total estimates distributed over the aperture area of the stressed metal-membrane dish (150 $m^2$) yields the rounded unit costs presented in Table B.35.

TABLE B.34. Field Installation Estimates, 1984$

| System Size | Cost per Dish |
|---|---|
| 200 MWe | $ 333 |
| 100 MWe | 347 |
| 50 MWe | 375 |
| 30 MWe | 413 |
| 10 MWe | 602 |
| 5 MWe | 886 |
| 3 MWe | 1264 |
| 2.35 MWe | 2092 |
| 2.3 MWe | 1331 |
| 2 MWe | 1256 |
| 1 MWe | 1516 |
| 0.25 MWe | 3073 |
| 0.1 MWe | 6188 |

TABLE B.35. Field Installation Estimates, $/m^2$

| System Size | Cost per Dish |
|---|---|
| 200 MWe | $ 2.2 |
| 100 MWe | 2.3 |
| 50 MWe | 2.5 |
| 30 MWe | 2.8 |
| 10 MWe | 4.0 |
| 5 MWe | 5.9 |
| 3 MWe | 8.4 |
| 2.35 MWe | 14 |
| 2.3 MWe | 8.9 |
| 2 MWe | 8.4 |
| 1 MWe | 10 |
| 0.25 MWe | 20 |
| 0.1 MWe | 41 |

SUBCOMPONENT: DRIVE

METHOD: This subcomponent was estimated by using the long-term drive estimate which corresponds to a production level of 16,667 drives per year and adjusting its cost to reflect the lower production levels associated with near-term systems.

QUALITY JUDGMENT: The quality of the drive subcomponent estimate is "poor". Basically, this due to the lack of design requirements for the drive which necessitates a considerable amount of judgment be applied.

DATA: Due to the conceptual nature of the design, the drive design and operational requirements have not been identified by the designers. However, the two basic drive mechanisms have been identified in the conceptual design. These mechanisms include the azimuth drive, and the elevation drive in the form of the a screw jack. These components are similar to the components of the Peerless-Winsmith low-cost heliostat drive.

To estimate the cost of the two components of the stressed metal-membrane drive, the cost of these same components from the Peerless-Winsmith drive were used as the basis. At a production level of 50,000 units per year, Heller (1987) estimates the cost of the Winsmith azimuth drive as $973 (1987$) and cost of the Winsmith elevation drive as $496 (1987$). Converting these estimates to 1984-dollars and a dollar per $m^2$ of aperture area basis yields estimates of $6 and $3 per $m^2$ of aperture area, respectively for the azimuth and elevation drives. An additional 25% was added to the cost of both units to account for the production level of the stressed metal-membrane drive units being only 16,667 units per year instead of 50,000 units per year, the presumed level in the Heller estimate and a small contingency. The extra contingency was added, because it is doubtful the drive could be produced for anything less than $11 per $m^2$, and in fact, even $11 may be optimistic. At the current stage of design work, it is impossible to determine exactly what the drive requirements are. This results in an estimate of $11 per $m^2$ of aperture area ($1670) for one drive at a production level of 16,667 units per year.

Like the concentrator, the main differentiating factor between the cost of the near-term and long-term drive unit is production economies-of-scale. The limited cost-versus-production-level data available for the drive unit was prepared for the Advanco concentrator drive unit (Washom 1984, p. 9). While the Advanco and the stressed metal-membrane concentrator drive are different in design, the Advanco information is the only production versus cost data available. Because both units fulfill the same functions and are made of similar materials, the Advanco production economies-of-scale can reasonably be used to generate estimates for the stressed metal-membrane drive.

The estimates for the Advanco concentrator drive (Washom 1982, p. 9) as a function of production level were fit to an equation. These estimates are presented in Table B.36. The equation was then used to estimate the cost of the Advanco concentrator drive cost at 16,667 units per year. Using this estimate and the source estimates (Table B.36), the additional cost (in fractional form) due to production economies-of-scale for producing less than 16,667 units per year was calculated. These fractions are presented in Table B.37.

TABLE B.36. Advanco Concentrator Drive Estimates, 1982$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $13,240 |
| 100 per year | 10,592 |
| 1000 per year | 6,767 |
| 10000 per year | 5,830 |

TABLE B.36. Advanco Concentrator Drive Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 16,667 Units |
|---|---|---|
| 1 per year | $13,240 | 2.34 |
| 100 per year | 10,592 | 1.87 |
| 1000 per year | 6,767 | 1.20 |
| 10000 per year | 5,830 | 1.03 |
| 16667 per year | 5,656[(a)] | - |

(a) Cost predicted by the equation $13985X^{0.906881}$ ($r^2$ = 0.999) which is based on a curve fit of the data presented in Table B.35. Where "X" is the annual production level and the predicted cost is the total annual production cost.

These fractions were then applied to the long-term estimate for the stressed metal-membrane drive at a production level of 16,667 units per year to determine the cost of the drive at production levels of 1, 100, 1000, and 10000 dishes per year. These estimates are shown in Table B.38. Distributing the cost of the drive over the aperture area of the stressed metal-membrane dish, 150 $m^2$, yields estimates for production levels of 1, 100, 1000, and 10000 dishes per year of $26, $21, $13, and $11 per $m^2$ of aperture area, respectively.

TABLE B.38. Estimated Cost of the Stressed Metal-Membrane Concentrator Drive at Production Levels less than 16,667 Units per Year, 1984$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $3,908 |
| 100 per year | 3,123 |
| 1000 per year | 2,004 |
| 10000 per year | 1,720 |
| 28872 per year | 1,670 |

SUBCOMPONENT: CONTROLS AND WIRING

METHOD: Adjustment of the long-term estimate to reflect the lower production levels associated with near-term construction.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". While there are a significant number of estimates relating to the controls and wiring for heliostats it is somewhat ill-defined as to how dish controls and wiring would differ. For this reason some engineering judgments were required to adjust heliostat controls and wiring estimates to dish system estimates. Additionally there is uncertainty with respect to the production economies-of-scale which would occur in the near-term.

DATA: Development of the long-term estimate was based on adjustment of heliostat controls and wiring estimates to conform to the system requirements of the dish system. Estimates prepared by ARCO, Martin Marietta, McDonnell Douglas (Norris and White 1982) and PNL (Drumheller 1981) were evaluated for applicability to dish systems. Based on engineering judgment, the estimate presented in Table B.39 was prepared. The total cost per dish of $755.50 (1984$) is for a production level of 28,782 units per year.

Cost versus production level data for the controls and wiring was prepared by Advanco (Washom 1984, p. 9). For the same reasons Advanco data was used in preparing the concentrator and drive estimates, it was used to determine near-term costs for the controls and wiring.

The estimates for the Advanco controls and wiring (Washom 1982, p. 9) as a function of production level were fit to an equation. These estimates are presented in Table B.40. The equation was then used to estimate the cost of the Advanco concentrator controls and wiring cost at a production level of 28,782 units per year. Using this estimate and the source estimates (Table B.40), the additional cost (in fractional form) due to production economies-of-scale for producing less than 28,782 units per year was calculated. These fractions are presented in Table B.41.

The fractions were then applied to the PNL-derived estimate for the controls and wiring at a production level of 28,782 units per year to determine the cost of the controls and wiring at production levels of 1, 100, 1000, and 10000 dishes per year. These estimates are shown in Table B.42.

TABLE B.39. Long-Term Cost Estimate for Dish System Controls and Wiring (1984$)

| | |
|---|---|
| Power and Control Cabling[a] | $463 per dish |
| Dish Controller[b] | 265 per dish |
| Dish Array Controller[c] | 27.50 per dish |
| | $755.50 per dish |

(a) This estimate includes $280 (1980$) for power cabling (Norris and White 1982, p. 94) and $90 (1980$) for control cabling. The control cabling estimate is the average of a Martin Marietta estimate of $63 (Norris and White 1982, p. 94) and a McDonnell Douglas estimate of $120 (Norris and White 1982, p. 94). The total power and control cabling estimate of $370 (1980$) was escalated to $463 (1984$).

(b) The dish controller estimate is based on the average of a McDonnell Douglas estimate of $203 (1980$) (Norris and White 1982, p. 94) and an ARCO estimate of $328 (1980$) (Norris and White 1982, p. 94). The average of $265 was not escalated because electronic components have remained about the same with respect to cost from 1980 to 1984.

(c) The dish-array controller for controlling 3631 dishes was estimated by PNL for Williams et al. (1987) to cost $100,000 (1984$) which on average is $27.50 per dish.

TABLE B.40. Advanco Controls and Wiring Estimates, 1982$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $20,000 |
| 100 per year | 9,961 |
| 1000 per year | 6,796 |
| 10000 per year | 4,951 |

TABLE B.41. Advanco Controls and Wiring Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 28,782 Units |
|---|---|---|
| 1 per year | $20,000 | 4.82 |
| 100 per year | 9,961 | 2.40 |
| 1000 per year | 6,796 | 1.64 |
| 10000 per year | 4,951 | 1.19 |
| 16667 per year | 5,656 | 1.09 |
| 28782 per year | 4,146[a] | - |

(a) Cost predicted by the equation $19969.5X^{0.847201}$ which is based on a curve fit of the data presented in Table B.40. Where "X" is the annual production level.

TABLE B.42. Estimated Cost of the Controls and Wiring at Production Levels less than 16,667 Units per Year, 1984$

| Production Level | Cost per Unit | Rounded Cost per Unit |
|---|---|---|
| 1 per year | $3,738 | $3700 |
| 100 per year | 1,813 | 1800 |
| 1000 per year | 1,272 | 1300 |
| 10000 per year | 899 | 900 |
| 16667 per year | 824[a] | 820 |

(a) Same cost as the long-term estimate

SUBCOMPONENT: FOUNDATION

METHOD: This subcomponent was independently estimated by PNL.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". The estimate is fairly comprehensive. However, because there has not been a detailed design made for the foundation, there is greater uncertainty than is desirable. In addition, data on the production economies-of-scale for the foundation in the near-term are uncertain

DATA: The foundation is manufactured at a central facility in four subassemblies: the kingpost, the sway braces, the a-frame, and the jack link. The long-term F.O.B. cost of the foundation was estimated using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table B.43. The foundation estimate generated from the algorithm is $2824. The four subassemblies are shipped to the site at a cost of $144. Site installation cost estimates are presented in Table B.44. For system sizes equal to or larger than 2.35 MWe, field installation estimates are based on a PNL estimate of 0.59 manhours for installation, a $8.13 charge for distributed capital, a fixed set-up charge of $2610, and a $150 charge for installed concrete. Field installation estimates for systems smaller than 2.35 MWe are based on a PNL estimate of 2.55 manhours for installation, a $99.85 charge for distributed capital, a fixed set-up charge of $870, and a $150 charge for installed concrete.

In the near-term the manufacturing cost of the foundation is expected to be greater than in the long-term. The foundation shipping and installation costs are estimated to be the same. In the near-term the production economies-of-scale for foundation manufacturing are estimated to be the same as those for the Advanco dish concentrator. While these two components appear completely different, the stressed metal-membrane foundation acts as both the foundation and the mirror support structure for the stressed metal-membrane. Table B.45 restates the production economies-of-scale for the Advanco concentrator which are assumed equivalent to the foundation manufacturing production economies-of-scale. Applying these production economies-of-scale to the long-term foundation manufacturing estimate of $2824 yields the near-term estimates presented in Table B.46. Summing these manufacturing estimates with the transportation and installation estimates results in the final installed foundation estimates listed in Table B.47.

TABLE B.43. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Foundation Subcomponent

| | |
|---|---|
| Direct Materials | \$1947 per dish; \$32,450,649 for 16,667 dishes/year[a] |
| Direct Labor | 1.75 hours; 29,100 hours for 16,667 dishes/year |
| Capital Equip. | \$3,437,831 |
| Plant Area | 25,909 sq. ft. |
| Plant Acreage | 1.56 Acres |

(a) 16,667 dishes per year is equivalent to $2.5 \times 10^6$ square meters of concentrator area which is the assumed production level.

TABLE B.44. Foundation Installation Estimates, 1984$

| System Size | Cost per Dish |
|---|---|
| 200 MWe | \$ 173 |
| 100 MWe | 174 |
| 50 MWe | 175 |
| 30 MWe | 177 |
| 10 MWe | 186 |
| 5 MWe | 199 |
| 3 MWe | 216 |
| 2.35 MWe | 228 |
| 2.3 MWe | 331 |
| 1 MWe | 356 |
| 0.25 MWe | 486 |
| 0.1 MWe | 747 |

TABLE B.45. Advanco Concentrator Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 16,667 Units |
|---|---|---|
| 2 per year | 52,684[a] | 2.74 |
| 5 per year | 47,566[a] | 2.47 |
| 20 per year | 40,753[a] | 2.12 |
| 46 per year | 37,139[a] | 1.93 |
| 47 per year | 37,050[a] | 1.92 |
| 60 per year | 36,054[a] | 1.87 |
| 100 per year | 41,655 | 2.16 |
| 100 per year | 34,058[a] | 1.77 |
| 200 per year | 31,525[a] | 1.64 |
| 600 per year | 27,890[a] | 1.45 |
| 1000 per year | 23,788 | 1.24 |
| 1000 per year | 26,346[a] | 1.37 |
| 2000 per year | 24,386[a] | 1.27 |
| 4000 per year | 22,572[a] | 1.17 |
| 10000 per year | 19,895 | 1.03 |
| 16667 per year | 19,251[a] | - |

(a) Cost predicted by the equation $56917X^{0.888489}$ ($r^2 = 0.998$) which is based on a curve fit of the data presented in Table B.30. Where "X" is the annual production level and the predicted cost is the total annual production cost.

TABLE B.46. Foundation Central Manufacturing Cost, (1984$)

| Production Level | Cost |
|---|---|
| 2 per year | $7738 |
| 5 per year | 6795 |
| 20 per year | 5987 |
| 46 per year | 5450 |
| 47 per year | 5422 |
| 60 per year | 5281 |
| 100 per year | 4998 |
| 200 per year | 4631 |
| 600 per year | 4095 |
| 1000 per year | 3869 |
| 2000 per year | 3586 |
| 4000 per year | 3304 |

TABLE B.47. Total Foundation Estimates, \$/m²

| System Size | | Cost |
|---|---|---|
| 200 | MWe | \$ 24.0 |
| 100 | MWe | 25.9 |
| 50 | MWe | 27.8 |
| 30 | MWe | 29.3 |
| 10 | MWe | 33.0 |
| 5 | MWe | 35.5 |
| 3 | MWe | 37.5 |
| 2.35 | MWe | 38.5 |
| 2.3 | MWe | 39.4 |
| 1 | MWe | 43.1 |
| 0.25 | MWe | 50.6 |
| 0.1 | MWe | 57.4 |

COMPONENTS: RECEIVER AND ENERGY CONVERSION

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: The quality of the receiver and energy conversion estimate is rated as "fair". There was a good correlation between the three source estimates used as the basis for the final estimate which is a positive aspect. However, none of the estimates include details which results in some uncertainty in the final estimate. Adding additional uncertainty is the scaling of 25-kWe unit costs to estimate the cost of the 50-kWe engine.

DATA: The receiver and energy conversion components for the dish are combined in a single power conversion unit (a stirling engine/generator set). The stirling unit used for the 150 $m^2$ stressed metal-membrane dish is assumed to be 50-kWe in size. Although, optimized designs may use a smaller engine.

Cost data on 50-kWe units is unavailable. Therefore, cost data for a 25-kWe 4-95 Solar II Unit is used and scaled accordingly for the difference in size. The 25-kWe engine used as the cost basis is a 4-cylinder engine which uses hydrogen as the working fluid, operates at a heater temperature of 750-degrees Celsius, and has a gross efficiency of 0.41 (i.e., the shaft mechanical power as a fraction of heater tube heat input is 0.41.) (Holtz 1987). It is estimated the 50-kWe engine would have a gross efficiency a few percent higher. However, no detailed data is available. For all related available information refer to the working paper "Stirling Engines in Solar Applications".

Stirling cost data from three sources were evaluated. These data are presented in Table B.48. The Vanguard estimates were for installed dish system engines and were reduced by assuming installation, alignment, and testing adds ten percent to the basic cost of the unit. The other estimates reflect only purchase cost. All the units are rated at 25-kWe gross generating capacity.

The data was then fit to two equations. The first of these equations was based on the data points ranging from one to 10,000 units/yr and the second on the data points ranging from 10,000 to 400,000 units/yr. The intersection of these equations is at a production level of 9577. The equations are as follows:

$1 < \text{units/year} < 9577 \qquad \$/\text{kWe} = 2020.474 - 187.509 \ln X$

$9577 < \text{units/year} < 400{,}000 \qquad \$/\text{kWe} = 5701.798 X^{-0.32068}$

In the near-term, production levels of the stirling engine/generator set will be much lower than in the long-term. Because even a large plant, 200 MWe, will require only about 4000 engines and smaller plants even less, the former of these two equations was used to estimate the near-term cost.

"X" is equal to the number of 25 kWe (0.025 MWe) units produced per year. This equation is only valid for 25-kWe units whereas the stressed membrane concentrator requires a 50-kWe unit.

Scaling of a unit from 25 to 50-kWe results in some economies-of-scale being achieved. Size economies-of-scale are achieved as the engine size is increased which allows the use of less material and labor hours per kWe of output. A review of several sources indicates size economies-of-scale of exist, but the extent is questionable. The general form of the cost-scaling equation using a cost-size factor (denoted SF) is as follows:

$$\text{Unit Cost}_2 = \text{Unit Cost}_1 * (\text{Size}_1/\text{Size}_2) * (\text{Size}_2/\text{Size}_1)^{SF}$$

Assuming a cost-size factor (SF) of 0.6 and applying the generic cost-scaling equation to the equation generated above for the unit cost of the 25-kWe unit, the following equation results for the unit cost of 50-kWe units:

$$\$/\text{kWe} = (25/50)(2020.474 + (-187.509)\ln X)((50/25)^{0.6})$$

Through this transformation "X" changes to the number of 50-kWe (0.05 MWe) units produced per year. Additional information on the derivation of this equation is presented in the working paper "Stirling Engines in Solar Applications."

According to United Stirling, approximately 30% of the unit by cost could be considered the receiver and the balance would fall into energy conversion (Nelving 1985). On this basis the cost equation was split into two equations by multiplying by 0.3 and 0.7 to obtain equations for the receiver and energy conversion components, respectively. These equations are as follows:

receiver: $\$/\text{kWe} = 459.370 - 42.632)\ln(\text{MWe}/0.05\ \text{MWe})$

conversion: $\$/\text{kWe} = 1071.863 - 99.474\ln(\text{MWe}/0.05\ \text{MWe})$

TABLE B.48. Dish Power Conversion Unit Purchase Cost Data, 1984$

| Source | Production Quantity | Cost/Unit |
|---|---|---|
| United Stirling[(a)] | 1 | $50,000 |
| | 2,000 | $20,000 |
| | 25,000 | $ 5,500 |
| JPL[(b)] | 1,000 | $17,576 |
| | 25,000 | $ 5,641 |
| | 100,000 | $ 2,946 |
| | 400,000 | $ 2,539 |
| Vanguard[(c)] | 1 | $57,878 |
| | 100 | $28,941 |
| | 1,000 | $15,463 |
| | 10,000 | $ 8,700 |

(a) Telephone conversation with Worth Percival, United Stirling.
(b) Fortgang and Mayers (1980, p. 10) prices were escalated to 1984-dollars.
(c) Washom (1984, p. 9) prices were escalated to 1984-dollars and reduced to an uninstalled basis.

**COMPONENT: TRANSPORT**

METHOD: All the transport components are mature in design and already are in mass production. Also, economies-of-scale related to system size are accounted for in the long-term estimates. For these reasons, it is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent. The details and basis for the estimate are included in the long-term documentation.

**COMPONENT: BALANCE-OF-PLANT**

METHOD: All the balance-of-plant components are mature in design and already in mass production. Also, economies-of-scale related to system size are accounted for in the long-term estimates. For these reasons, it is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent. The details and basis for the estimate are included in the long-term documentation.

**COMPONENT: OPERATING AND MAINTENANCE**

QUALITY JUDGMENT: the quality of O&M cost data is rated as "poor", mainly because little operating experience exists which causes estimates to be based largely on conjecture.

SUBCOMPONENT: OPERATING

METHOD: The operating subcomponent includes security personnel for plants 2 MW or larger and a service contract for plants smaller than 2 MW. It is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent. In the case of security, staffing levels will be the same in the near-term and long-term. With respect to the service contract, it only accounts for capital recovery of service facilities provided by a subcontractor or centralized service facility. Actual maintenance labor and materials are accounted for in the maintenance subcomponents. Therefore, the operating subcomponent is expected to cost the same in the near-term and long-term. The details and basis for the estimate are included in the long-term documentation.

SUBCOMPONENT: MAINTENANCE OF THE CONCENTRATOR

METHOD: The only significant difference between near-term and long-term concentrator maintenance costs is the non-washing material cost. This cost is expected to be higher in the near-term than in the long-term due to non-washing maintenance materials being more costly in lower production. The cost of non-washing materials is estimated to be proportional to concentrator capital cost. Therefore, the relative difference between non-washing materials and concentrator cost will be the same in the near-term and long-term. Consequently, the fraction of initial concentrator capital estimated for long-term non-washing materials applies in the near-term also.

SUBCOMPONENT: MAINTENANCE OF THE RECEIVER SYSTEM.

METHOD: It is estimated that the material component of the receiver maintenance will be higher in the near-term than it will be in the long-term. The labor component of the receiver maintenance is estimated to be approximately the same in the near-term and long-term. To account for the higher near-term material cost, the long-term material costs were scaled based on the ratio of near-term receiver capital cost to the long-term receiver capital cost.

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

DATA: Long-term maintenance costs were estimated as the following:

labor: \$2.24 per $m^2$ of aperture area
materials: \$1.50 per $m^2$ of aperture area

Using the long-term material estimate as a basis, the near-term materials estimate was prepared by multiplying the long-term estimate by the ratio of the near-term receiver cost to the long-term receiver unit cost. This ratio is represented by the following equation:

$$\{459.370 + (-42.632)\ln(\text{Size, MW}/0.5\ \text{MW})\}/3160$$

Where "size" is the gross generating capacity for the plant size being estimated. Multiplying this equation by the long-term materials cost estimating equation yields the following near-term receiver maintenance materials cost estimating equation for a 50-kWe stirling unit:

$$\text{materials cost} = \{459.370 + (-42.632)\ln(\text{Size, MW}/0.05\ \text{MW})\}\{(1.50)(\text{m}^2\ \text{of aperture area})\}/3160$$

In addition a 15% overhead charge must be added to this estimate (Guthrie 1974).

SUBCOMPONENT: MAINTENANCE OF THE CONVERSION SYSTEM

METHOD: It is estimated that the material component of the energy conversion maintenance will be higher in the near-term than it will be in the long-term. The labor component of the conversion maintenance is estimated to be approximately the same in the near-term and long-term. To account for the higher near-term material cost, the long-term material costs were scaled based on the ratio of near-term conversion capital cost to the long-term conversion capital cost.

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

DATA: Long-term maintenance costs were estimated as the following:

labor: \$5.83 per $m^2$ of aperture area
materials: \$3.89 per $m^2$ of aperture area

Using the long-term material estimate as a basis, the near-term materials estimate was prepared by multiplying the long-term estimate by the ratio of the near-term conversion cost to the long-term conversion unit cost. This ratio is represented by the following equation:

$$\{1071.863 + (-99.474)\ln(\text{Size, MW}/0.5\text{ MW})\}/7370$$

Where "size" is the total gross generating capacity of the plant size being estimated. Multiplying this equation by the long-term materials cost estimating equation yields the following near-term conversion maintenance cost estimating equation for a 50-kWe stirling unit:

$$\text{materials cost} = \{1071.863 + (-99.474)\ln(\text{Size, MW}/0.05\text{ MW})\}\{(3.89)(m^2\text{ of aperture area})\}/7370$$

In addition a 15% overhead charge must be added to this estimate (Guthrie 1974).

SUBCOMPONENT: MAINTENANCE OF THE TRANSPORT SYSTEM

METHOD: It is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent, because transport system maintenance is already in a mature state of development. The details and basis for the estimate are included in the long-term documentation.

SUBCOMPONENT: BALANCE-OF-PLANT MAINTENANCE

METHOD: It is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent as balance-of-plant maintenance is already in a mature state of development. The details and basis for the estimate are included in the long-term documentation.

## INDIRECTS AND CONTINGENCIES

METHOD: Comparison and adjustment of existing estimates

DATA: Seven complete system estimates formed the basis for the indirects and contingencies estimate. The source estimates are presented in Table B.49.

TABLE B.49. Source Estimates for Dish System Indirects and Contingencies

| Source | Indirects | Contingencies |
|---|---|---|
| SCE et al. (1982, p. 19) | - | 20 |
| Weber (1983) | - | 23 |
| Easton and Endicott (1982) | 21 | 10.6 |
| Weber (1982) | 24.3 | 17.3 |
| Weber (1980) | 30.7 | 12.2 |
| Joy et al. (1981) | 15.8 | 15 |
| Bloomster et al. (1982) | 25 | 25 |
| Avg. | 23.4 | Avg. 17.6 |

The average indirects estimate was rounded to 25 percent. The contingency estimate was reduced to 10% for the mature components (i.e., transport, and balance-of-plant). For other components it was reduced to 15% to be representative of new technology with no extraordinary contingencies and to be consistent with the utility studies (Hillesland et al. 1988).

## INDIRECTS AND CONTINGENCIES

METHOD: Comparison and adjustment of existing estimates

DATA: Seven complete system estimates formed the basis for the indirects and contingencies estimate. The source estimates are presented in Table B.49.

TABLE B.49. Source Estimates for Dish System Indirects and Contingencies

| Source | Indirects | Contingencies |
|---|---|---|
| SCE et al. (1982, p. 19) | - | 20 |
| Weber (1983) | - | 23 |
| Easton and Endicott (1982) | 21 | 10.6 |
| Weber (1982) | 24.3 | 17.3 |
| Weber (1980) | 30.7 | 12.2 |
| Joy et al. (1981) | 15.8 | 15 |
| Bloomster et al. (1982) | 25 | 25 |
| Avg. | 23.4 | Avg. 17.6 |

The average indirects estimate was rounded to 25 percent. The contingency estimate was reduced to 10% for the mature components (i.e., transport, and balance-of-plant). For other components it was reduced to 15% to be representative of new technology with no extraordinary contingencies and to be consistent with the utility studies (Hillesland et al. 1988).

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# APPENDIX C

## DOCUMENTATION ON COST DATA FOR ELECTRICITY GENERATION SYSTEMS BASED ON THE STRESSED COMPOSITE-MEMBRANE DISH CONCENTRATOR

Presented here are long-term costs for the dish-stirling solar generating concept based on a kinematic stirling engine with a 14-meter diameter stressed composite-membrane concentrator. For the long-term estimates, the technology is assumed to be mature and all components are considered to be in mass production. Contingencies associated with these estimates reflect the mature nature and high production levels associated with long-term technologies. The presumed annual production level for the system is $2.5 \times 10^6$ $m^2$ of concentrator aperture area per year or the quantity of units required to support $2.5 \times 10^6$ $m^2$ of aperture area. It is assumed that the builder of a plant could buy any portion of the annual production level and achieve the same central production facility economies-of-scale benefits.

Presented in Table C.1 are the long-term estimates. The cost data are presented in one of four forms: dollars per square meter of aperture area, as a function of initial capital cost, dollars per kilowatt electric, or total-dollars at several design points (MWe, number per dish, $m^2$ of aperture area). For cost data given as a function of design points, it is necessary to fit the data to equations which allows the determination of component costs over a range of system sizes and not just at given design points. After the preparation of equations is completed, it is then possible to use the cost data presented to prepare system estimates at the component and subcomponent levels for a wide range of system sizes.

Following Table C.1 there is a subcomponent-by-subcomponent explanation of how the estimates were prepared. In addition to procedural information, a quality judgment of the data is given at the component and subcomponent level. The quality judgment includes a rating of good, fair, or poor and an explanation of weakness and strengths of the data.

TABLE C.1. Long-Term Cost Data Table for Stressed Composite-Membrane Dish Systems, 1984\$

| | | |
|---|---|---|
| Concentrator (reflective polymer; based on stressed composite-membrane) | | |
| Mirror/Support | | |
| Unit (F.O.B.) | >= 1.6 MWe | \$53.8 per $m^2$ of aperture area |
| | < 1.6 MWe | \$54.7 per $m^2$ of aperture area |
| Transportation | >= 1.6 MWe | \$0.9 per $m^2$ of aperture area |
| | < 1.6 MWe | \$1.4 per $m^2$ of aperture area |
| Field Installation | 200 MWe | \$1.2 per $m^2$ of aperture area |
| | 100 MWe | \$1.2 per $m^2$ of aperture area |
| | 50 MWe | \$1.3 per $m^2$ of aperture area |
| | 30 MWe | \$1.4 per $m^2$ of aperture area |
| | 10 MWe | \$1.7 per $m^2$ of aperture area |
| | 5 MWe | \$2.3 per $m^2$ of aperture area |
| | 3 MWe | \$3.0 per $m^2$ of aperture area |
| | 1.6 MWe | \$4.5 per $m^2$ of aperture area |
| | 1.55 MWe | \$3.4 per $m^2$ of aperture area |
| | 1 MWe | \$4.0 per $m^2$ of aperture area |
| | 0.25 MWe | \$9.4 per $m^2$ of aperture area |
| | 0.1 MWe | \$20 per $m^2$ of aperture area |
| Drive | | \$11 per $m^2$ of aperture area |
| Controls and Wiring | | \$820 per dish |
| Foundation | >=1.6 MWe | \$21 per $m^2$ of aperture area |
| | 1.55 MWe | \$21 per $m^2$ of aperture area |
| | 1 MWe | \$22 per $m^2$ of aperture area |
| | 0.25 MWe | \$22 per $m^2$ of aperture area |
| | 0.1 MWe | \$24 per $m^2$ of aperture area |

TABLE C.1. (Cont.)

| | | |
|---|---|---|
| Receiver | \$3160 per dish for 50-kWe unit | |
| Transport | 0.025 MW system | \$12,400 |
| | 0.05 MW system | \$12,800 |
| | 0.125 MW system | \$14,900 |
| | 0.25 MW system | \$20,500 |
| | 0.65 MW system | \$34,700 |
| | 3.875 MW system | \$212,600 |
| | 16.25 MW system | \$912,800 |
| | 64.75 MW system | \$3,707,600 |
| | 323.75 MW system | \$18,734,400 |
| Conversion | \$7370 per dish for 50-kWe unit | |
| Balance-of-Plant | | |
| Land and Site Preparation | | |
| Basic Land and Site Prep. for access roads, and buildings | 0.025 MW system | \$4300 |
| | 0.05 MW system | \$4300 |
| | 0.125 MW system | \$4300 |
| | 0.25 MW system | \$4300 |
| | 0.5 MW system | \$16,800 |
| | 2 MW system | \$20,700 |
| | 10 MW system | \$35,800 |
| | 30 MW system | \$39,800 |
| | 100 MW system | \$42,200 |
| | 200 MW system | \$44,700 |
| Dish-Array Land and Site Prep. | \$4.94 per $m^2$ of aperture area | |
| Dish-Array Fencing | 87$m^2$ field size | \$2,700 |
| | 174$m^2$ field size | \$3,800 |
| | 434$m^2$ field size | \$6,100 |
| | 869$m^2$ field size | \$8,600 |
| | 2,250$m^2$ field size | \$13,800 |
| | 13,500$m^2$ field size | \$33,800 |
| | 56,250$m^2$ field size | \$69,100 |
| | 225,000$m^2$ field size | \$138,200 |
| | 1,125,000$m^2$ field size | \$309,000 |
| Excess Land | \$0.0247 per $m^2$ of aperture area | |
| Master Controls | 1 dish system | \$29,000 |
| | 100 dish system | \$74,000 |
| | 1000 dish system | \$497,000 |
| | 10000 dish system | \$3,734,000 |
| Structures | 0.025 MW system | \$2,000 |
| | 0.05 MW system | \$2,000 |
| | 0.125 MW system | \$2,000 |
| | 0.25 MW system | \$2,000 |
| | 0.5 MW system | \$2,000 |
| | 2 MW system | \$110,800 |
| | 10 MW system | \$185,100 |
| | 30 MW system | \$297,100 |
| | 100 MW system | \$365,600 |
| | 200 MW system | \$431,100 |
| Power Conditioning | 5 MW system | \$105,000 |
| | 10 MW system | \$130,000 |
| | 30 MW system | \$360,000 |
| | 100 MW system | \$810,000 |
| | 200 MW system | \$1,540,000 |

## TABLE C.1. (Cont.)

| | |
|---|---|
| Service Facilities | <2 MW system $0<br>2 MW system $137,500<br>10 MW system $217,400<br>30 MW system $273,200<br>100 MW system $581,100<br>200 MW system $1,162,000 |
| Spare Parts | 3% of capital cost of BOP items (excluding land and site prep.)<br>0.8% of capital cost of energy conversion and receiver<br>0.3% of capital cost of collector and transport |
| Operating and Maintenance (annual) | |
| Operating | |
| Security | < 2 MW system $0<br>2=<=100 MW system $46,600<br>100 <=200 MW system $93,200 |
| Service Contract | < 2 MW system $24/kWe of gross generating capacity |
| Concentrator Maintenance | ~~0.03%~~ .3% of concentrator capital cost plus 15% overhead<br>1.84 per $m^2$ of aperture area plus 15% overhead<br><br>$850 every 5th year for optical membrane replacement<br>(present value of these replacements at time zero = $2500) |
| Receiver Maintenance | lab: $2.24 per $m^2$ of aperture plus 15% overhead<br>mat: $1.50 per $m^2$ of aperture plus 15% overhead |
| Conversion Maintenance | lab: $5.83 per $m^2$ of aperture plus 15% overhead<br>mat: $3.89 per $m^2$ of aperture plus 15% overhead |
| Transport Maintenance | 5 MW system 0.80% of transport capital cost plus 15% overhead<br>10 MW system 0.85% of transport capital cost plus 15% overhead<br>30 MW system 0.90% of transport capital cost plus 15% overhead<br>100 MW system 0.95% of transport capital cost plus 15% overhead<br>200 MW system 1.0% of transport capital cost plus 15% overhead |
| Balance-of-Plant Maintenance | 1.4% of structures, service facilities, power conditioning, and spare parts plus 15% overhead<br>1.6% of master controls plus 15% overhead |
| Indirects | 25% of subtotaled component estimate |
| Contingencies | 10% of subtotaled component estimate |

**COMPONENT: CONCENTRATOR** (stressed composite-membrane technology)

QUALITY JUDGMENT: Overall the quality the concentrator component estimate is "fair". The estimate itself is quite comprehensive and is based on a significant amount of detailed cost data which was developed for the stressed membrane heliostat (Solar Kinetics 1987) and other studies. The quality judgment of "fair" is given due to the conceptual nature of the design which results in an estimate with greater uncertainty than an estimate based on detailed engineering drawings.

SUBCOMPONENT: MIRRORS AND SUPPORT

METHOD: This subcomponent was estimated by PNL in three parts: (1) the concentrator unit (F.O.B.), (2) transportation, and (3) field installation.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". Although the design is conceptual, there is enough design information and related historical data to generate manufacturing estimate for the concentrator unit; however, manufacturing techniques related to the fabrication of the composite membrane are not well-defined. The transportation estimate is "good" within the limits of the transportation scenario presumed. If a different method of transportation was to be used, the costs could differ slightly. The field installation estimate is rated as "fair". There is uncertainty as to exactly how some of the site operations would be performed. In particular, the process for fastening the rear, composite, and optical membranes to the ring is uncertain.

DATA: The construction of the stressed composite-membrane concentrator consists of a 14-meter diameter aluminum ring centered around a steel mast. To the back of the ring and base of the mast a vinyl-coated fiberglass rear membrane is attached. To the front of the ring a fiberglass composite-membrane is attached. Conceptual design work identified attachment of the composite to the ring with a rigid attachment as detrimental to performance; however, due to a lack of alternative design information, a clamp attachment is presumed. Additionally, to the front of the ring an optical membrane is attached. When the plenum between the rear membrane and optical membrane is evacuated the optical membrane is drawn down against the composite-membrane. This forms the optical membrane into the appropriate reflective shape.

Design point performance estimates for the concentrator are as follow:

Concentrator Reflectivity (new and clean)--0.91 (SKI)

Reflectivity Degradation (assuming bi-weekly cleaning)--0.95
-This is the same value that was assumed for the glass/metal concentrator. It is very likely that this value is too high for membrane concentrators; the reasons for this are:

- cleaning will most likely be more difficult, less efficient, and less effective. The optical surface is thin, stressed polymers will not be able to withstand a cleaning regiment as aggressive as that of the glass/metal concentrator.

- The optical material will suffer permanent degradation over time (the reason for the five-year replacement schedule).

Blocking caused by the center tube support cables--0.986
-There are 24 one-half inch cables. These cables will both shadow the concentrator and block concentrated reflected flux. Considering only the shadowing (or assuming the concentration is very small) the cables will shadow an area equal to:

$$24 * 7m * 0.5 \text{ in.} = 23 \text{ ft}^2 \ (2.13 \text{ m}^2)$$

Shadowing caused by the receiver support structure--0.989
-There are three 3-inch support trusses for the receiver. These trusses will shadow an area of the concentrator equal to:

$$3 * 7m * 3 \text{ in.} = 17.2 \text{ ft}^2 \ (1.60 \text{ m}^2)$$

Concentrator/Receiver Intercept Factor--0.966
-This is the same value that was assumed for the glass/metal concentrator. This value is probably also too high for membrane concentrators; the reasons for this are:

- The optical quality of the concentrator will most likely be less than that of the glass/metal concentrator. Thus, for an intercept factor this high, the receiver aperture would have to be larger which would result in increased receiver thermal losses. Conversely, the aperture could be made small to maintain low receiver losses, but this would increase spillage and thus decrease the concentrator/receiver intercept factor. The optimal value is the one that minimizes the LEC; this value will have to be determined during detailed systems analysis and design.

Concentrator Unit

At the central manufacturing facility; the composite, rear, and optical membranes; the main mast; PCU support tripod; and foundation/drive structure are manufactured. Manufacture of these components is integrated in that foundation parts are cut and painted using much of the same equipment used for the main mast and PCU support tripod. For cost accounting purposes, the total costs for the parts-cutting equipment, paint line, labor, related floor space, related land area, and general factory equipment are divided between the foundation subcomponent and concentrator subcomponent using the same total dollar division as was used for the metal-membrane system.

In addition, for small site sizes (less than 1.6 MWe) it is economically more attractive to manufacture the main concentrator ring at the central manufacturing facility than at the site, as is done for large system sizes. Central facility manufacturing of the ring at small system sizes is desirable, because it is more expensive to set-up the site ring-manufacturing facility and make a small number of rings than it is to centrally manufacture the ring, cut it into eight arched segments and ship it to the site for welding into a uniform ring.

The F.O.B. cost of the concentrator was estimated by using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table C.2 for plant sizes of 1.6 MWe or larger and in Table C.3 for sizes smaller than 1.6 MWe. The concentrator estimates as generated from the algorithm are \$5840 and \$6531 per concentrator for large and small system sizes, respectively. In addition to these costs, \$2224 and \$1671 for burdened materials and working capital allowance for materials used at the site must be added. Making these additions yields estimates of concentrator cost of \$8064 and \$8202, respectively. These estimates translate to \$53.8 per $m^2$ of dish aperture area for systems equal to or larger than 1.6 MWe and \$54.7 per $m^2$ of dish aperture area for system sizes smaller than 1.6 MWe. Both these unit costs are based on a stressed composite-membrane dish which has 150 $m^2$ of aperture area.

Concentrator Transportation

Concentrator transportation costs were estimated by determining the number of loads required (either weight- or volume-limited) to deliver concentrator sub-assemblies from the factory to the site and multiplying by an assumed delivery distance of 600 miles and a cost per mile of \$1.45. For large systems, an average 6.18 dishes can be transported per load. This results in a concentrator transportation cost of \$141. This cost distributed over the aperture area of the dish and rounded is \$0.9 per $m^2$ of aperture area. For small systems shipping of the ring increases transportation costs to \$214 and reduces the average number of dishes per load to 4.07. Small system shipping is rounded to \$1.4 per $m^2$ of aperture area.

Concentrator Installation

The field installation estimates were independently prepared by PNL and are presented in Table C.4. These figures are based on a PNL estimate of 6.36 manhours per dish for site assembly and installation, a \$21.4 charge per dish for capital installation equipment, and a site set-up charge of \$16,540 for systems equal to or larger than 1.6 MWe. Large system site installation progresses at an average output of 159 dishes per week, not including initial site set-up time of one week. For systems smaller than 1.6 MWe, field installation estimates are based on a PNL estimate of 11.89 manhours per dish, a \$37.74 charge per dish for capital installation equipment, and a site set-up charge of \$5,440. Small system site installation progresses at an average output of 12.5 dishes per week, not including initial site set-up time of one week. Table C.5 shows the rounded unit installation cost for stressed composite-membrane dishes are various system sizes.

TABLE C.2. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Mirrors and Support Subcomponent at System Sizes of Greater than 1.6 MWe.

| | |
|---|---|
| Direct Materials | \$3844 per dish; \$64,067,948 for 16,667 dishes/year[a] |
| Direct Labor | 5.66 hours; 94,400 hours for 16,667 dishes/year |
| Capital Equip. | \$17,202,599 |
| Plant Area | 249,800 sq. ft. |
| Plant Acreage | 14.44 Acres |

(a) 16,667 dishes per year is equivalent to $2.5 \times 10^6$ square meters of concentrator area which is the assumed production level.

TABLE C.3. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Mirrors and Support Subcomponent at System Sizes of Less than 1.6 MWe.

| | |
|---|---|
| Direct Materials | \$4317 per dish; \$71,951,439 for 16,667 dishes/year[a] |
| Direct Labor | 6.2 hours; 103,289 for 16,667 dishes/year |
| Capital Equip. | \$17,524,792 |
| Plant Area | 265,800 sq. ft. |
| Plant Acreage | 15.44 Acres |

(a) 16,667 dishes per year is equivalent to $2.5 \times 10^6$ square meters of concentrator area which is the assumed production level.

TABLE C.4. Concentrator Field Installation Estimates, 1984\$

| System Size | Cost per Unit |
|---|---|
| 200 MWe | \$ 181 |
| 100 MWe | 186 |
| 50 MWe | 194 |
| 30 MWe | 205 |
| 10 MWe | 260 |
| 5 MWe | 343 |
| 3 MWe | 453 |
| 1.6 MWe | 694 |
| 1.55 MWe | 505 |
| 1 MWe | 601 |
| 0.25 MWe | 1417 |
| 0.1 MWe | 3049 |

TABLE C.5. Concentrator Field Installation Estimates, $/m²

| System Size | | Cost per Unit |
|---|---|---|
| 200 | MWe | $ 1.2 |
| 100 | MWe | 1.2 |
| 50 | MWe | 1.3 |
| 30 | MWe | 1.4 |
| 10 | MWe | 1.7 |
| 5 | MWe | 2.3 |
| 3 | MWe | 3.0 |
| 1.6 | MWe | 4.6 |
| 1.55 | MWe | 3.4 |
| 1 | MWe | 4.0 |
| 0.25 | MWe | 9.4 |
| 0.1 | MWe | 20 |

SUBCOMPONENT: DRIVE

METHOD: Comparison and adjustment of an existing estimate and the application of a significant amount of engineering judgment.

QUALITY JUDGMENT: The quality of the drive subcomponent estimate is "poor". Basically, this is due to the lack of design requirements for the drive which necessitates a considerable amount of judgment be applied.

DATA: Due to the conceptual nature of the design, the drive design and operational requirements have not been identified by the designers. However, the two basic drive mechanisms have been identified in the conceptual design. These mechanisms include the azimuth drive, and the elevation drive in the form of a screw jack. These components are similar to the components of the Peerless-Winsmith low-cost heliostat drive.

To estimate the cost of the two components of the stressed composite-membrane drive, the costs of these same components from the Peerless-Winsmith drive were used as the basis. At a production level of 50,000 units per year, Heller (1987) estimates the cost of the azimuth drive as $973 (1987$) and cost of the elevation drive as $496 (1987$). Converting these estimates to 1984-dollars and a dollar per m² of aperture area basis yields estimates of $6 and $3 per m² of aperture area for the azimuth and elevation drives, respectively. An additional 25% was added to the cost of both units to account for the production level of the stressed composite-membrane drive units being only 16,667 units per year instead of 50,000 units per year, the presumed level in the Heller estimate, and a small contingency. The extra contingency was added, because it is doubtful the drive could be produced for anything less than $11 per m² of aperture area, and in fact, even $11 may be optimistic. The total installed drive estimate is therefore, $11 per m² of aperture area.

SUBCOMPONENT: CONTROLS AND WIRING

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". While there are a significant number of estimates relating to the controls and wiring for heliostats it is somewhat ill-defined as to how dish controls and wiring would differ. For this reason some engineering judgments were required to adjust heliostat controls and wiring estimates to dish system estimates.

DATA: Development of the estimate was based on adjustment of heliostat controls and wiring estimates to conform to the system requirements of the dish system. Estimates prepared by ARCO, Martin Marietta, McDonnell Douglas (Norris and White 1982) and PNL (Drumheller 1981) were evaluated for applicability to dish systems. Based on engineering judgment, the estimate presented in Table C.6 was prepared. The total cost per dish of $755.50 (1984$) is for a production level of 28,782 units per year.

To adjust this estimate to a production level of 16,667 units per year, a parametric production economies-of-scale relationship was developed. This relationship assumes production economies-of-scale for the Advanco dish controls and wiring are equivalent to the production economies-of-scale associated with the controls and wiring estimate presented here. Based on the four estimates for Advanco controls and wiring presented in Table C.7, the relationship was developed. Fitting a curve to these estimates yields the following equation:

$$Y = 19969.5X^{0.847201}$$

Where "X" equals annual production volume and "Y" equals the total annual production cost. This equation was used to estimate the cost of Advanco controls and wiring at production levels of 16,667 and 28,782 units per year. The ratio of these two costs is 1.09. Multiplying this ratio by the estimated cost for dish wiring and controls of $755.50 at a production level of 28,782 units per year gives an estimated cost for dish controls and wiring of $824 at a production level of 16,667 units per year. This estimate was rounded to $820 per dish.

TABLE C.6. Long-Term Cost Estimate for Dish System Controls and Wiring (1984$)

| | | |
|---|---|---|
| Power and Control Cabling[a] | $463 | per dish |
| Dish Controller[b] | 265 | per dish |
| Dish Array Controller[c] | 27.50 | per dish |
| | $755.50 | per dish |

(a) This estimate includes $280 (1980$) for power cabling (Norris and White 1982, p. 94) and $90 (1980$) for control cabling. The control cabling estimate is the average of a Martin Marietta estimate of $63 (Norris and White 1982, p. 94) and a McDonnell Douglas estimate of $120 (Norris and White 1982, p. 94). The total power and control cabling estimate of $370 (1980$) was escalated to $463 (1984$).

(b) The dish controller estimate is based on the average of a McDonnell Douglas estimate of $203 (1980$) (Norris and White 1982, p. 94) and an ARCO estimate of $328 (1980$) (Norris and White 1982, p. 94). The average of $265 was not escalated because electronic components have remained about the same with respect to cost from 1980 to 1984.

(c) The dish-array controller for controlling 3631 dishes was estimated by PNL for Williams et al. (1987) to cost $100,000 (1984$) which on average is $27.50 per dish.

TABLE C.7. Advanco Controls and Wiring Estimates

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $20,000 |
| 100 per year | 9,961 |
| 1000 per year | 6,796 |
| 10000 per year | 4,951 |

SUBCOMPONENT: FOUNDATION

METHOD: This subcomponent was independently estimated by PNL.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". The estimate is fairly comprehensive. However, because there has not been a detailed design made for the foundation, there is greater uncertainty than is desirable.

DATA: The foundation is manufactured at a central facility in four subassemblies: the kingpost, the sway braces, the a-frame, and the jack link. The F.O.B. cost of the foundation was estimated using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table C.8. The foundation estimate generated from the algorithm is $2824. The four subassemblies are shipped to the site at a cost of $144. Site installation cost estimates are presented in Table C.9. For system sizes equal to or larger than 1.60 MWe, field installation estimates are based on a PNL estimate of 0.59 manhours for installation, a $8.13 charge for distributed capital, a fixed set-up charge of $2610, and a $150 charge for installed concrete. Field installation estimates for systems smaller than 1.6 MWe are based on a PNL estimate of 0.93 manhours for installation, a $41.93 charge for distributed capital, a fixed set-up charge of $870, and a $150 charge for installed concrete. The total installed foundation estimates are presented in Table C.10.

TABLE C.8. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Foundation Subcomponent

| | |
|---|---|
| Direct Materials | $1947 per dish; $32,450,649 for 16,667 dishes/year[a] |
| Direct Labor | 1.75 hours; 29,100 hours for 16,667 dishes/year |
| Capital Equip. | $3,437,831 |
| Plant Area | 25,909 sq. ft. |
| Plant Acreage | 1.56 Acres |

(a) 16,667 dishes per year is equivalent to 2.5 x $10^6$ square meters of concentrator area which is the assumed production level.

TABLE C.9. Foundation Site Installation Cost Estimates per dish, 1984$

| System Size | Cost per Unit |
|---|---|
| 200 MWe | $ 173 |
| 100 MWe | 174 |
| 50 MWe | 175 |
| 30 MWe | 177 |
| 10 MWe | 186 |
| 5 MWe | 199 |
| 3 MWe | 216 |
| 1.6 MWe | 254 |
| 1.55 MWe | 243 |
| 1 MWe | 258 |
| 0.25 MWe | 389 |
| 0.1 MWe | 650 |

TABLE C.10. Total Installed Foundation Estimates, $\$/m^2$

| System Size | | Cost per Unit |
|---|---|---|
| 200 | MWe | $ 21 |
| 100 | MWe | 21 |
| 50 | MWe | 21 |
| 30 | MWe | 21 |
| 10 | MWe | 21 |
| 5 | MWe | 21 |
| 3 | MWe | 21 |
| 1.6 | MWe | 21 |
| 1.55 | MWe | 21 |
| 1 | MWe | 22 |
| 0.25 | MWe | 23 |
| 0.1 | MWe | 24 |

## COMPONENTS: RECEIVER AND ENERGY CONVERSION

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: The quality of the receiver and energy conversion estimate is rated as "fair". There was a good correlation between the three source estimates used as the basis for the final estimate which is a positive aspect. However, none of the estimates include details which results in some uncertainty in the final estimate. Adding additional uncertainty, the final estimate for a 50-kWe power conversion unit is scaled from costs for a 25-kWe unit.

DATA: The receiver and energy conversion components for the dish are combined in a single power conversion unit (a stirling engine/generator set). The stirling unit used for the 150 $m^2$ stressed composite-membrane dish is assumed to be 50-kWe in size. Although, optimized designs may use a smaller engine.

Cost data on 50-kWe units is unavailable. Therefore, cost data for a 25-kWe 4-95 Solar II Unit is used and scaled accordingly for the difference in size. The 25-kWe engine used as the cost basis is a 4-cylinder engine which uses hydrogen as the working fluid, operates at a heater temperature of 750-degrees Celsius, and has a gross efficiency of 0.41 (i.e., the shaft mechanical power as a fraction of heater tube heat input is 0.41.) (Holtz 1987). It is estimated the 50-kWe engine would have a gross efficiency a few percent higher. However, no detailed data is available. For all available related information refer to the working paper "Stirling Engines in Solar Applications".

Stirling cost data from three sources were evaluated. These data are presented in Table C.11. The Vanguard estimates were for installed dish system engines and were reduced by assuming installation, alignment, and testing adds ten percent to the basic cost of the unit. The other estimates reflect only purchase cost. All the units are rated at 25-kWe gross generating capacity.

The data was then fit to two equations. The first of these equations was based on the data points ranging from one to 10,000 units/yr and the second on the data points ranging from 10,000 to 400,000 units/yr. The intersection of these equations is at a production level of 9577. The equations are as follows:

$1 < \text{units/year} < 9577 \qquad \$/\text{kWe} = 2020.474 + (-187.509)\ln X$

$9577 < \text{units/year} < 400{,}000 \qquad \$/\text{kWe} = 5701.798X^{-0.32068}$

The latter of these two equations was then used to estimate the cost for long-term production levels. An additional 10% was added the estimating equation to allow for installation, alignment, and testing. The resulting long-term estimating equation for the receiver and energy conversion unit cost is as follows:

$$\$/\text{kWe} = 6271.98X^{-0.32068}$$

"X" is equal to the number of 25 kWe (0.025 MWe) units produced per year. This equation is only valid for 25-kWe units whereas the stressed membrane concentrator requires a 50-kWe unit. Because there is no available data on the production cost of 50-kWe units, the cost data for 25-kWe units was scaled.

Scaling of a unit from 25 to 50-kWe results in some economies-of-scale being achieved. Size economies-of-scale are achieved as the engine size is increased which allows the use of less material and labor hours per kWe of output. A review of several sources indicates size economies-of-scale of exist, but the extent is questionable. The general form of the cost-scaling equation using a cost-size factor (denoted SF) is as follows:

$$\text{Unit Cost}_2 = \text{Unit Cost}_1 * (\text{Size}_1/\text{Size}_2) * (\text{Size}_2/\text{Size}_1)^{SF}$$

Assuming a cost-size factor (SF) of 0.6 and applying the generic cost-scaling equation to the equation generated above for the unit cost of the 25-kWe unit, the following equation results for the unit cost of 50-kWe units:

$$\$/\text{kWe} = (25/50)(6271.98X^{-0.32068})((50/25)^{0.6})$$

Through this transformation "X" changes to the number of 50-kWe (0.05 MWe) units produced per year. Additional information on the derivation of this equation is presented in the working paper "Stirling Engines in Solar Applications."

According to United Stirling, approximately 30% of the unit by cost could be considered the receiver and the balance would fall into energy conversion (Nelving 1985). On this basis the cost equation was split into two equations by multiplying by 0.3 and 0.7 to obtain equations for the receiver and energy conversion components, respectively. These equations are as follows:

receiver: $\$/\text{kWe} = 1425.98(\text{MWe}/0.05\ \text{MWe})^{-0.32068}$

conversion: $\$/\text{kWe} = 3327.29(\text{MWe}/0.05\ \text{MWe})^{-0.32068}$

Using an annual production level of 833.35 MWe which corresponds to the production of 16,667 units, results in the following estimates:

receiver: $3157

conversion: $7365

These estimates were rounded to $3160 and $7400, respectively.

Table C.11. Dish Power Conversion Unit Purchase Cost Data, 1984$

| Source | Production Quantity | Cost/Unit |
|---|---|---|
| United Stirling[(a)] | 1 | $50,000 |
| | 2,000 | $20,000 |
| | 25,000 | $ 5,500 |
| JPL[(b)] | 1,000 | $17,576 |
| | 25,000 | $ 5,641 |
| | 100,000 | $ 2,946 |
| | 400,000 | $ 2,539 |
| Vanguard[(c)] | 1 | $57,878 |
| | 100 | $28,941 |
| | 1,000 | $15,463 |
| | 10,000 | $ 8,700 |

(a) Telephone conversation with Worth Percival, United Stirling.
(b) Fortgang and Mayers (1980, p. 10) prices were escalated to 1984-dollars.
(c) Washom (1984, p. 9) prices were escalated to 1984-dollars and reduced to an uninstalled basis.

## COMPONENT: TRANSPORT

QUALITY JUDGMENT: Overall the quality of the transport estimate is "good". PNL specifically designed and estimated transport costs for dish technology. There is a wealth of estimating data on transport components.

METHOD: This component was independently estimated by PNL (Williams et al. 1987, p. 7.12).

DATA: The items included in this estimate and their respective costs versus field size are presented in Table C.12. While these costs were developed for systems using 25-kWe dishes, transport costs are primarily a function of power rating which allows the same costs to be applied to systems using dishes other than 25-kWe in size. The design-point performance for the transport system is a function of power level, because larger fields have longer transmission lines with higher loss. The design-point efficiencies of a dish-stirling transport system are as follows (Williams et al. 1987):

$<=$3.875 MW -- 0.974
16.25 MW -- 0.972
64.75 MW -- 0.964
323.75 MW -- 0.958

Table C.12. Costs for the Dish-Striling Transport System, 1984$

| | 0.025 MW | 0.05 MW | 0.125 MW | 0.25 MW | 0.65 MW |
|---|---|---|---|---|---|
| Disconnect Switches | $ 185 | $ 370 | 925 | $ 1850 | $4,625 |
| Sheet Metal Cubicles | 250 | 250 | 250 | 500 | 1,250 |
| Air Circuit Breakers | 215 | 215 | 215 | 435 | 1,125 |
| Transformer | 9,070 | 9,070 | 10,044 | 13,284 | 20,200 |
| 600 volt UF Cable | 195 | 390 | 970 | 1,950 | 5,036 |
| Closing Dis. Switches | 2,500 | 2,500 | 2,500 | 2,500 | 2,500 |
| Overhead Line #1 | - | - | - | - | - |
| Overhead Line #2 | - | - | - | - | - |
| Poles | - | - | - | - | - |
| | $12,415 | $12,795 | $14,904 | $20,519 | $34,736 |
| Rounded Total | $12,400 | $12,800 | $14,900 | $20,500 | $34,700 |

| | 3.875 MW | 16.25 MW | 64.75 MW | 323.75 MW |
|---|---|---|---|---|
| Disconnect Switches | $ 27,750 | $115,625 | $ 462,500 | $ 2,312,500 |
| Sheet Metal Cubicles | 7,500 | 31,250 | 125,000 | 625,000 |
| Air Circuit Breakers | 6,750 | 28,125 | 112,500 | 562,500 |
| Transformer | 121,200 | 505,000 | 2,020,000 | 10,100,000 |
| 600 volt UF Cable | 30,215 | 125,895 | 503,580 | 2,517,900 |
| Closing Dis. Switches | 15,000 | 62,500 | 250,000 | 1,250,000 |
| Overhead Line #1 | 3,046 | 22,208 | 88,830 | 444,150 |
| Overhead Line #2 | - | 12,282 | 98,992 | 669,392 |
| Poles | 1,100 | 9,900 | 46,200 | 253,000 |
| | $212,561 | $912,785 | $3,707,602 | $18,734,442 |
| Rounded Total | $212,600 | $912,800 | $3,707,600 | $18,734,400 |

COMPONENT: **BALANCE-OF-PLANT**

QUALITY JUDGMENT: The balance-of-plant estimate is judged to be "fair" in quality. The problem with the balance-of-plant category is the requirements are often nebulous. This leads to uncertainty with respect to what should and should not be included.

SUBCOMPONENT: LAND AND SITE PREPARATION

METHOD: Estimated by PNL for Williams et al. (1987) using existing estimates as guidance.

QUALITY JUDGMENT: Because the exact land and site preparation could be very different for any specific site, this subcomponent estimate is given a quality rating of "fair". One particular area which could affect the cost of this subcomponent is the selection of a site with easy access and one where all the land purchased can be used.

DATA: The estimate for land and site preparation was independently estimated by PNL using a number of earthwork estimating manuals. The subcomponent estimate consists of four parts. These include (1) basic land and site preparation for roads and building areas, (2) dish-array land and site preparation, (3) dish-array fencing, and (4) excess land cost.

The first of these parts, basic land and site preparation, is expressed as a function of power level. The unit costs for each element of the land and site preparation estimate are listed in Table C.13. The total cost as presented in Table C.13 is $9,985/acre, which is equivalent to 2.47/m² of land area. Combining this information with estimates of the structures and access road land requirements for each plant size, the basic land and site preparation estimate was prepared. This estimate is shown in Table C.14.

Dish-array land and site preparation is a function of the total field size (aperture area). It is estimated that each square meter of aperture area requires two square meters of ground area. This results in a dish-array land and site preparation estimate of $4.94 per m² of aperture area.

Fencing for the array is based upon a unit cost of $51.50 per linear meter of fencing. The dish-array fencing estimates are presented in Table C.15 as a function of field size.

Finally, there is excess land cost. Although this might seem like an extraneous category, many previous site-specific studies show it is an actual cost. This cost arises because land is purchased in sections or other large tracts depending on federal or state regulations or the willingness of private landowners to sell certain parcels. The plant owner is often limited in the ability to purchase exactly the land required. Because excess land must only be purchased

and not developed, it results in an incurred cost of $500/acre ($0.124/m² of land area). Although land for solar facilities often ranges from $500 to $5000/acre, because dish systems have flexible siting requirements and do not require mainline water connections the low end of the cost range was used. Excess land for a dish system is estimated to be 10% of the dish-array land area. This corresponds to a excess land cost of $0.0247 (1984$) per m² of aperture area.

Table C.13. Unit Costs for Dish System Land and Site Preparation, 1984$

| | |
|---|---|
| Land Purchase Cost | $ 500/acre |
| Rough Grading | 6,300/acre |
| Clear and Grub | 625/acre |
| Survey | 930/acre |
| Roads | 860/acre |
| Ditches | 470/acre |
| Permits | 300/acre |
| | $9,985/acre |

Table C.14. Basic Dish System Site Area Size and Corresponding Cost For Land and Site Preparation, 1984$

| System Size | Land Area | Cost |
|---|---|---|
| 0.025 MW | 1,750/m² | $ 4,300 |
| 0.05 MW | 1,750/m² | 4,300 |
| 0.125 MW | 1,750/m² | 4,300 |
| 0.25 MW | 1,750/m² | 4,300 |
| 0.5 MW | 6,800/m² | 16,800 |
| 2 MW | 8,400/m² | 20,700 |
| 10 MW | 14,500/m² | 35,800 |
| 30 MW | 16,100/m² | 39,800 |
| 100 MW | 17,100/m² | 42,200 |
| 200 MW | 18,100/m² | 44,700 |

Table C.15. Dish-Array Fencing Costs, 1984$

| Field Size (aperture area) | Cost |
|---|---|
| 87m² | $ 2,700 |
| 174m² | 3,800 |
| 434m² | 6,100 |
| 869m² | 8,600 |
| 2,250m² | 13,800 |
| 13,500m² | 33,800 |
| 56,250m² | 69,100 |
| 225,000m² | 138,200 |
| 1,125,000m² | 309,000 |

SUBCOMPONENT: MASTER CONTROLS

METHOD: Adjustment of existing estimates.

QUALITY JUDGMENT: The estimate for this subcomponent is rated as "fair", because there are not independent estimates to support its accuracy and there is no available backup detail for the estimate.

DATA: From a review of six source estimates, an estimate by Advanco (Washom 1984, p. 9) was selected for escalation because it was recently prepared and complete. These controls are for a fully mechanized unattended facility. The source estimate and the adjustments made to generate a final estimate are presented in Table C.16. The smallest master controller unit developed for the Advanco dish system is capable of controlling 32 dishes. For systems smaller 32 dishes, the use of a standard PC and software is assumed. While these estimates where originally generated for 25-kWe dishes the master controls cost is estimated to be a function of the number of dishes, not the size of the individual dishes.

Table C.16. Dish System Master Control Estimates

| Production Level | Cost/Module (1982$) | Total Cost (1982$) | Total Cost (1984$) |
|---|---|---|---|
| 1 | - | - | $ 3,000[a] |
| 32 | $28,000 | $ 28,000 | 29,000 |
| 100 | 711 | 71,100 | 74,000 |
| 1,000 | 478 | 478,000 | 497,000 |
| 10,000 | 359 | 3,590,000 | 3,734,000 |

(a) Assumes the use of a standard PC.

SUBCOMPONENT: STRUCTURES

METHOD: Independently estimated by PNL for Williams et al. (1987) using existing estimates as guidance.

QUALITY JUDGMENT: This subcomponent estimate is rated as "fair". It is not clear exactly what size the support structures for a dish system would need to be in order to provide necessary support for the dish system.

DATA: The structures subcomponent includes a control room, administration building, warehouse, maintenance building, and fencing around the structures. PNL unit cost estimates for these items are presented in Table C.17. The total cost for these items at various power levels is presented in Table C.18.

As shown in Table C.18., not all types of structures are present at all power levels. At plant sizes below 2 MW, it is assumed a small structure, probably prefabricated and skid-mounted, would be used at each site. This structure would house the controls, instrumentation, and possibly some spare parts or tools. At these small plant sizes, no maintenance or warehouse facilities are present.

It is assumed that below 2 MW the plant is maintained by a service contractor or by a centralized facility operated by the plant's owner; therefore, no costs for maintenance or warehouse facilities are included in the structure subcomponent estimate. However, there is an allowance for a service contract for plants less than 2 MW. It is included in the operating subcomponent and accounts for maintenance and warehouse space.

At very large plant sizes (greater than 100 MW) an allowance is made for approximately one administrative office. This office may or may not be located on site. For plants less than 100 MW, but greater than or equal to 2 MW, a small amount of administration space is included in the estimate. This space represents the plants contribution toward a larger administration facility which handles the administrative duties for several plants.

Table C.17. Structure Unit Costs, 1984$

| | |
|---|---|
| Control Building | $700/m² of floor area |
| Maintenance Building | $530/m² of floor area |
| Warehouse | $430/m² of floor area |
| Administration Building | $590/m² of floor area |
| Multi-Purpose Enclosure | $2000 each |
| Fencing | $51.50/linear meter |

Table C.18. Dish System Structures Estimates, 1984$

| | 0.05 MW | 0.125 MW | 0.25 MW | 0.5 MW | 2 MW | 10 MW | 30 MW | 100 MW | 200 MW |
|---|---|---|---|---|---|---|---|---|---|
| Control Building | - | - | - | | $ 6,500 | $ 13,000 | $ 26,000 | $ 26,000 | $ 26,000 |
| Maintenance Building | - | - | - | | 36,750 | 61,250 | 98,000 | 122,500 | 147,000 |
| Warehouse | - | - | - | | 60,000 | 100,000 | 160,000 | 200,000 | 240,000 |
| Administration Building | - | - | - | | 1,475 | 2,950 | 2,950 | 5,900 | 5,900 |
| Multi-Purpose Enclosure | $2,000 | $2,000 | $2,000 | $2,000 | - | - | - | - | - |
| Fencing | - | - | - | | 6,100 | 7,900 | 10,100 | 11,200 | 12,200 |
| Rounded Total | $2,000 | $2,000 | $2,000 | $2,000 | $110,800 | $185,100 | $297,100 | $365,600 | $431,100 |

SUBCOMPONENT: POWER CONDITIONING

METHOD: Comparison and Adjustment of Existing Estimates

QUALITY JUDGMENT: The quality of this subcomponent estimate is rated as "fair", because it is not clear exactly what should be included in this subcomponent.

DATA: Based on site-specific solar power plant studies, the following assumptions were made with respect to transmission line voltage:

| | |
|---|---|
| $<5$ MW | 13.8 kV |
| 10 MW | 33 kV |
| 30 MW | 115 kV |
| $>100$ MW | 230 kV |

Because the transport system boosts the voltage to 13.8 kV, no power conditioning is required for plants less than 5 MW. Based on engineering judgment and transformer cost data (Westinghouse 1981) the estimates in Table C.19 were prepared.

Table C.19. Dish System Power Conditioning System Cost Estimates

| System Size | Cost |
|---|---|
| 5 MW system | $ 105,000 |
| 10 MW system | 130,000 |
| 30 MW system | 360,000 |
| 100 MW system | 810,000 |
| 200 MW system | 1,540,000 |

SUBCOMPONENT: SERVICE FACILITIES

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

QUALITY JUDGMENT: The quality of this subcomponent estimate is rated as "fair". The "fair" rating was assigned since the exact requirements for dish systems are not well-defined.

DATA: Service facilities estimates for various power levels are presented in Table C.20. The estimate for each power level includes service vehicles, site communication equipment, fire protection, and water systems. Below plant sizes of 2 MW, it is assumed that a service contract is in place or the owner of the plant services the system from a centralized facility. Therefore, no service facilities costs are included in this subcomponent estimate for plants less than 2 MW. Under the operating subcomponent there is an allow made for a service contract for plants less than 2 MW.

Table C.20. Dish System Service Facilities Estimates, 1984$

| System Size | Vehicles | Communication | Fire Protection | Water | Rounded Subtotal |
|---|---|---|---|---|---|
| <2 MW | $ 0 | $ 0 | $ 0 | $ 0 | $ 0 |
| 2 MW | 133,000 | 440 | 3000 | 1,040 | 137,500 |
| 10 MW | 195,000 | 2,200 | 15,000 | 5,210 | 217,400 |
| 30 MW | 206,000 | 6,600 | 45,000 | 15,640 | 273,200 |
| 100 MW | 357,000 | 22,000 | 150,000 | 52,120 | 581,100 |
| 200 MW | 714,000 | 44,000 | 300,000 | 104,230 | 1,058,000 |

SUBCOMPONENT: SPARE PARTS

METHOD: Estimated by PNL for Williams et al. (1987) using existing estimates as guidance.

QUALITY JUDGMENT: Nothing can substitute for actual operating experience when attempting to determine the number of spare parts required for a particular plant, subsystem, or piece of equipment. Since there is no good operating experience available, some engineering judgments were required based upon existing heliostat spare parts estimates. For these reasons, the overall quality of this subcomponent estimate is rated as "poor".

DATA: The spare parts estimates include a three-year supply of parts. The primary basis is estimates developed for the repowering of the Saguaro Power Plant (Weber 1982). These estimates for annual spare parts are:

| | |
|---|---|
| Collector Equipment | 0.1% of initial cost/yr |
| Receiver Equipment | 1.0% of initial cost/yr |
| Storage Equipment | 1.0% of initial cost/yr |
| Heat Exchanger Subsystem | 1.0% of initial cost/yr |

Source: Weber 1982, p. G-12

Using these estimates as guidelines, the following estimates were prepared for dish systems:

| | |
|---|---|
| Concentrator Equipment | 0.3% of initial cost |
| Transport Equipment | 0.3% of initial cost |
| Balance-Of-Plant Items (excluding land and site prep.) | 3.0% of initial cost |
| Receiver and Energy Conversion | 0.6% of initial cost |

Centralized components were presumed to have spare parts requirements which are ten times greater than the requirements for distributed components, because failure of a centralized component affects the entire (or major parts) of the system while failure of a distributed component has a limited affect on the whole system. For this reason the transport system which is distributed has the same spare parts allowance as the collector which is also distributed. The balance-of-plant allowance is estimated as ten times higher because it is a centralized component. Exceptions to the rule are the land and site preparation subcomponent which requires no spare parts, and the receiver and energy conversion spare equipment estimate which is presumed to be twice as high as the collector spare parts estimate, because the receiver and energy conversion equipment (i.e., the stirling engine) is expected to require significantly more maintenance than the collectors. Hence, additional spares are required.

COMPONENT: OPERATING AND MAINTENANCE

QUALITY JUDGMENT: the quality of O&M cost data is rated as "poor", mainly because little operating experience exists which causes estimates to be based largely on conjecture.

SUBCOMPONENT: OPERATING

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

QUALITY JUDGMENT: This subcomponent estimate is rated as "poor". Although the estimate is good for the assumptions made, there is considerable uncertainty as to what would be the actual requirements.

DATA: Operating personnel for the dish systems at all power levels greater than 100 MW is estimated to be three full-time security personnel. For plants ranging from 2 MW to 100 MW one and one-half full-time security persons are estimated present. Below 2 MW no security personnel are present. The estimated salary per full-time person is $27,000 per year. A 15% overhead charge (Guthrie 1974) is added to this estimate to yield a total operating personnel estimate of $31,050 per full-time person. Therefore, the rounded final estimates are as follows:

| | |
|---|---|
| < 2 MW systems | $0 |
| 2=<=100 MW systems | $46,600 |
| 100 <=200 MW systems | $93,200 |

In addition, plants less than 2 MW are assumed to have either a service contract or be maintained from the owner's centralized maintenance facility which is not on site. Because a service contract is in place for plants less than 2 MW, maintenance, warehouse, administration, and service facilities for these same plants were estimated as zero.

For a 2 MW plant approximately $1385 per 25 kWe dish and $1719 per 25 kWe dish are estimated to be spent on structure and service facilities, respectively; therefore, these costs times the owner's or subcontractor's fixed charge rate is the amount each dish must be charged per year for the capital recovery of the structures and service facilities. The actual parts and labor for this type of arrangement are estimated to be the same as for all other plant sizes (see the maintenance subcomponents).

The fixed charge rate used for buildings is 0.177 which is based on a depreciation period of 20 years, economic life of 20 years, a 10% discount rate, a 38% federal tax rate, and 2% in other taxes. The fixed charge rate used for service facilities is 0.205 which is based on a depreciation period of 5 years, economic life of 10 years, a 10% discount rate, a federal tax rate of 38%, and 2% in other taxes.

Applying these two fixed charge rates to the corresponding estimates above yields an annual service charge of approximately $600 per 25 kWe dish. This is equivalent to $24/kWe of gross generating capacity. Although this cost could be grouped with maintenance costs, because it is a fixed annual expense it is listed as an operating expenditure.

SUBCOMPONENT: MAINTENANCE OF THE CONCENTRATOR

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: Maintenance of the concentrator is broken into three elements, washing maintenance, non-washing maintenance, and optical material replacement. The total estimate is rated as "poor". The washing estimate is poor, because it is unclear what type of cleaning regiment the optical material and composite-membrane can withstand. The non-washing estimate is poor due to uncertainty in what is truly required. The optical replacement estimate is relatively good.

DATA: Dish washing costs were assumed 75% higher than heliostat washing costs. Two-thirds of the increase is due to washing complexities caused by the dishes' curved surface. The remaining one-third is for the increased cleaning time required due to a less aggressive approach used when washing the relatively fragile optical material. Washing costs for the heliostat are a product of a review of six source estimates. Based on the completeness of the estimates and engineering judgment, estimates by ARCO, and McDonnell Douglas were used as the basis for the final estimates. These estimates are presented in Table C.21. The average material cost for washing is $0.285/m$^2$ (1980$) while the average labor cost of washing is $0.16/m$^2$. However, one-third of the labor is moving from heliostat to heliostat; therefore, the cost of actual washing labor is $0.107/m$^2$ (1980$). Because washing costs for the dish were assumed to be 75% greater, the cost of actual dish washing was estimated as $0.187/m$^2$ (1980$). Adding back the moving cost between dishes and material cost, the total cost for twelve washes per year is $0.525/m$^2$ (1980$). To keep the reflectivity to a reasonably high level, the estimate was doubled to allow twenty-four washes per year. Escalating to 1984-dollars, results in an estimate of $1.24 per m$^2$ of surface area (1984$). Adjusting the estimate to a dollar-per-square-meter-of-aperture-area basis yields a final estimate of $1.30 per m$^2$ of surface area (1984$).

Non-washing costs for the dish are assumed equal to those of the heliostat on a square-meter-of-surface-area basis. Heliostat non-washing cost estimates from four sources were averaged to get estimates of $0.41 and $0.20 per square meter of surface area (1980$) for labor and materials, respectively. These were escalated to $0.51 and $0.25 in 1984-dollars, respectively. The source estimates are presented in Table C.22. Adjusting the non-washing maintenance cost estimates to a dollar-per-square-meter-of-aperture-area basis yields estimates of $0.54/m$^2$ and $0.26/m$^2$ for labor and materials, respectively.

Non-washing material costs would increase relative to the concentrator capital cost, and are therefore expressed as a fraction of initial capital cost. To calculate this fraction, the initial capital cost of a long-term 200-MWe system was used. This assumption gives the most representative results. Dividing the materials estimate of $0.26 by the concentrator capital cost of $93 per square meter of aperture area, results in a yearly non-washing materials concentrator maintenance estimate of 0.30 percent of the initial concentrator cost.

Table C.21. Heliostat Mirror Washing Cost (12 Washes/Year), 1980$

| | |
|---|---|
| ARCO | 0.48/m² [(a)] |
| McDonnell Douglas | 0.41/m² [(b)] |

(a) ARCO (Norris and White 1982, p. 116) estimates $0.18 for washing materials and $0.06 (1980$) for washing labor for 6 washes per year.
(b) MDAC (Norris and White 1982, p. 116) estimates $0.21 for washing materials and $0.20 (1980$) for washing labor for 12 washes per year.

Table C.22. Heliostat General Maintenance (non-washing) Costs, 1980$[(a)]

| | |
|---|---|
| ARCO | $0.42/m² |
| McDonnell Douglas | 0.61/m² |
| Boeing | 0.73/m² |
| Martin Marietta | 0.68/m² |

(a) Materials, labor and repair costs are included (Norris and White 1982, p.116)

Summarizing, concentrator general maintenance has three elements, (1) washing costs which are $1.30/m² of aperture area, (2) non-washing labor costs which are $0.54/m² of aperture area and (3) non-washing material costs which are 0.30% of the initial capital concentrator cost. In addition, a 15% overhead charge (Guthrie 1974) is added to all of the above estimates.

Optical material replacement is required every 5 years of the project life. This cost element was estimated by PNL in three parts: (1) F.O.B. optical membrane cost, (2) transportation cost, (3) field installation cost. The F.O.B. cost of the membrane was estimated using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table C.23. The optical membrane estimate generated from the algorithm is $818.55. The membranes are rolled onto a mandrel at the factory and shipped to the replacement site. Based on a shipping distance of 700 miles, a shipping cost of $1.45 per mile, and 700 membranes per load, the shipping cost per membrane is $1.24. Installation is estimated to take 1.08 hours which at $24.50 per hour is $26.46. The sum of all these costs is $846.25. This estimate was rounded to $850.

Table C.23. Inputs to the PNL Manufacturing Cost Algorithm Replacement Optical Membranes

| | |
|---|---|
| Direct Materials | \$576 per dish; \$48,000,960 for 83,335 units/year |
| Direct Labor | 0.167 hours; 13,890 hours for 83,335 units/year |
| Capital Equip. | \$1,328,000 |
| Plant Area | 32,000 sq. ft. |
| Plant Acreage | 2 Acres |

(a) 83,335 units per year

Replacement of the optical membrane could just as appropriately be categorized as a capital replacement cost. If it were categorized as such, it would be expressed as the present value (at time zero) of all the replacements over the project life. Assuming replacement every five years of the thirty year project life, and a discount rate of 3.15% (as per the "Five-Year Plan"), a capital replacement cost of \$2515.59 is estimated. This estimate was rounded to \$2500. Overheads are already included in this estimate.

SUBCOMPONENT: MAINTENANCE OF THE RECEIVER SYSTEM.

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

METHOD: Costs are assumed equivalent on a dollar per $m^2$ basis to estimates prepared for the 25-kWe glass-metal dish.

DATA: Maintenance costs are assumed equal to those estimated for the glass-metal 25-kWe dish on a dollar-per-square-meter basis. There is currently no available data on receiver maintenance for 50-kWe PCUs. The estimated costs are:

labor: \$2.24 per $m^2$ of aperture area plus 15% overhead

materials: \$1.50 per $m^2$ of aperture area plus 15% overhead

SUBCOMPONENT: MAINTENANCE OF THE CONVERSION SYSTEM

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

METHOD: Costs are assumed equivalent on a dollar per $m^2$ basis to estimates prepared for the 25-kWe glass-metal dish.

DATA: Maintenance costs are assumed equal to those estimated for the glass-metal 25-kWe dish on a $ per square meter basis. There is currently no available data on conversion maintenance for 50-kWe PCUs. The estimated costs are:

labor: $5.83 per $m^2$ of aperture area plus 15% overhead

materials: $3.89 per $m^2$ of aperture area plus 15% overhead

SUBCOMPONENT: MAINTENANCE OF THE TRANSPORT SYSTEM

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

QUALITY JUDGMENT: Due to the maintenance requirements being quite nebulous, this subcomponent estimate is rated as "poor".

DATA: The estimate as prepared by PNL is presented in Table C.24. It is based on applying engineering judgment to maintenance cost estimates for other electrical operating systems. In addition to the costs presented below an overhead charge of 15% must be added (Guthrie 1974).

Table C.24. Dish Transport System Maintenance Cost Estimate

| System Size | Scheduled/ Unscheduled Maint.[(a)] | Maint. Materials[(a)] | Total[(a)] |
|---|---|---|---|
| 0.5 MW | 0.25 | 0.50 | 0.75 |
| 2 MW | 0.30 | 0.50 | 0.80 |
| 10 MW | 0.35 | 0.50 | 0.85 |
| 30 MW | 0.40 | 0.50 | 0.90 |
| 100 MW | 0.45 | 0.50 | 0.95 |
| 200 MW | 0.50 | 0.50 | 1.00 |

(a) The estimates are presented as the fraction of the transport system capital cost required for annual maintenance.

SUBCOMPONENT: MAINTENANCE OF BALANCE-OF-PLANT

QUALITY JUDGMENT: Due to the maintenance requirements being quite nebulous, this subcomponent estimate is rated as "poor".

METHOD: This subcomponent was independently estimated by PNL for Williams et al. (1987).

DATA: The estimate as prepared by PNL for the balance-of-plant exclusive of the master controls and land and site preparation is presented in Table C.25. The maintenance estimate for the master controls is 1.6% of the capital cost per year (Weber 1983). In addition an overhead charge of 15% (Guthrie 1974) must be added to these estimates.

Table C.25. Dish System Balance-of-Plant Maintenance Cost Estimate

| System Size | Scheduled/ Unscheduled Maint.[a] | Maint. Materials[a] | Total[a] |
|---|---|---|---|
| 10 MW | 0.40 | 1.0 | 1.4 |
| 30 MW | 0.40 | 1.0 | 1.4 |
| 100 MW | 0.40 | 1.0 | 1.4 |

(a) The estimates are presented as the fraction of the balance-of-plant capital cost (excluding the master controls and land and site preparation) required for annual maintenance.

## INDIRECTS AND CONTINGENCIES

METHOD: Comparison and adjustment of existing estimates

DATA: Seven complete system estimates formed the basis for the indirects and contingencies estimate. The source estimates are presented in Table C.26.

Table C.26. Source Estimates for Dish System Indirects and Contingencies

| Source | Indirects | Contingencies |
|---|---|---|
| SCE et al. (1982, p. 19) | - | 20 |
| Weber (1983) | - | 23 |
| Easton and Endicott (1982) | 21 | 10.6 |
| Weber (1982) | 24.3 | 17.3 |
| Weber (1980) | 30.7 | 12.2 |
| Joy et al. (1981) | 15.8 | 15 |
| Bloomster et al. (1982) | 25 | 25 |
| Avg. | 23.4 | Avg. 17.6 |

The average indirects estimate was rounded to 25 percent. The contingency estimate was reduced to 10% to reflect a plant representative of mature technology with no extraordinary contingencies. This reduction was based on logic presented in EPRI's TAG (1982, p. 3-3).

The cost estimates for near-term "Nth plant" dish systems are summarized in Table C.27. "Nth plant" is defined as approximately the fifth to tenth plant built employing a specific dish technology. Although "Nth plant" technology is not in a mature state of development, it has been developed to a significant enough level that extraordinary contingencies don't exist. However, slightly higher contingencies do prevail. The contingency for the near-term components is 15% as opposed to 10% for the long-term estimates. No technology development costs are included in "Nth plant" cost estimates. The annual production level assumed is equal to the production rate that is required to build one "Nth plant".

The cost data are presented in one of four forms: dollars per square meter of aperture area, as a function of initial capital cost, dollars per kWe, or total-dollars at several given design points (MWe, m² of aperture area, or number of dishes). Unless otherwise specified, kWe and MWe ratings used throughout the estimates refer to gross generation capacity. With the exception of only a few components and subcomponents, the near-term estimates are the same as the long-term estimates. This is because components such as buildings, electrical components, land and site preparation, etc. are already maturely developed; therefore, near-term dish systems will be able to take advantage of the lower mature cost of some items.

Like the long-term estimates a subcomponent-by-subcomponent explanation of how the estimates were prepared is included. In addition to procedural information, a quality judgment of the data is given at the component and subcomponent level. The quality judgment includes a rating of good, fair, or poor and an explanation of weakness and strengths of the data.

TABLE C.27. Near-Term Cost Data Table for Stressed Composite-Membrane Dish Systems, 1984$

Concentrator (reflective polymer; based on stressed composite-membrane)

Mirror/Support

| | | |
|---|---|---|
| Unit (F.O.B.) | 2 dish system | \$150 per $m^2$ of aperture area |
| | 5 dish system | \$135 per $m^2$ of aperture area |
| | 10 dish system | \$125 per $m^2$ of aperture area |
| | 20 dish system | \$116 per $m^2$ of aperture area |
| | 31 dish system | \$105 per $m^2$ of aperture area |
| | 32 dish system | \$110 per $m^2$ of aperture area |
| | 40 dish system | \$108 per $m^2$ of aperture area |
| | 80 dish system | 97.3 ~~\$101~~ per $m^2$ of aperture area |
| | 100 dish system | \$95.2 per $m^2$ of aperture area |
| | 200 dish system | \$88.2 per $m^2$ of aperture area |
| | 600 dish system | \$78.0 per $m^2$ of aperture area |
| | 1000 dish system | \$73.7 per $m^2$ of aperture area |
| | 2000 dish system | \$68.3 per $m^2$ of aperture area |
| | 4000 dish system | \$62.9 per $m^2$ of aperture area |
| Transportation | >= 1.6 MWe | \$0.9 per $m^2$ of aperture area |
| | < 1.6 MWe | \$1.4 per $m^2$ of aperture area |
| Field Installation | 200 MWe | \$1.2 per $m^2$ of aperture area |
| | 100 MWe | \$1.2 per $m^2$ of aperture area |
| | 50 MWe | \$1.3 per $m^2$ of aperture area |
| | 30 MWe | \$1.4 per $m^2$ of aperture area |
| | 10 MWe | \$1.7 per $m^2$ of aperture area |
| | 5 MWe | \$2.3 per $m^2$ of aperture area |
| | 3 MWe | \$3.0 per $m^2$ of aperture area |
| | 1.6 MWe | \$4.6 per $m^2$ of aperture area |
| | 1.55 MWe | \$3.4 per $m^2$ of aperture area |
| | 1 MWe | \$4.0 per $m^2$ of aperture area |
| | 0.25 MWe | \$9.4 per $m^2$ of aperture area |
| | 0.1 MWe | \$20 per $m^2$ of aperture area |

TABLE C.27. (Cont.)

| | |
|---|---|
| Drive | 1 dish system \$26 per $m^2$ of aperture area |
| | 100 dish system \$21 per $m^2$ of aperture area |
| | 1000 dish system \$13 per $m^2$ of aperture area |
| | 10000 dish system \$11 per $m^2$ of aperture area |
| Controls and Wiring | 1 dish system \$3700 |
| | 100 dish system \$1800 |
| | 1000 dish system \$1300 |
| | 10000 dish system \$900 |
| Foundation | 200 MWe \$24.1 per $m^2$ of aperture area |
| | 100 MWe \$26.0 per $m^2$ of aperture area |
| | 50 MWe \$27.9 per $m^2$ of aperture area |
| | 30 MWe \$29.4 per $m^2$ of aperture area |
| | 10 MWe \$33.1 per $m^2$ of aperture area |
| | 5 MWe \$35.6 per $m^2$ of aperture area |
| | 3 MWe \$37.6 per $m^2$ of aperture area |
| | 1.6 MWe \$40.3 per $m^2$ of aperture area |
| | 1.55 MWe \$40.6 per $m^2$ of aperture area |
| | 1 MWe \$42.6 per $m^2$ of aperture area |
| | 0.25 MWe \$48.9 per $m^2$ of aperture area |
| | 0.1 MWe \$56.9 per $m^2$ of aperture area |
| Receiver | \$459.370 + (-42.632)ln(MWe/0.05 MWe) for 50 kWe unit(s) |
| Transport | 0.025 MW system \$12,400 |
| | 0.05 MW system \$12,800 |
| | 0.125 MW system \$14,900 |
| | 0.25 MW system \$20,500 |
| | 0.65 MW system \$34,700 |
| | 3.875 MW system \$212,600 |
| | 16.25 MW system \$912,800 |
| | 64.75 MW system \$3,707,600 |
| | 323.75 MW system \$18,734,400 |
| Conversion | \$1071.863 + (-99.474)ln(MWe/0.05 MWe) for 50 kWe unit(s) |
| Balance-of-Plant | |
| Land and Site Preparation | |
| Basic Land and Site Prep. for access roads, and buildings | 0.025 MW system \$4300 |
| | 0.05 MW system \$4300 |
| | 0.125 MW system \$4300 |
| | 0.25 MW system \$4300 |
| | 0.5 MW system \$16,800 |
| | 2 MW system \$20,700 |
| | 10 MW system \$35,800 |
| | 30 MW system \$39,800 |
| | 100 MW system \$42,200 |
| | 200 MW system \$44,700 |
| Dish-Array Land and Site Prep. | \$4.94 per $m^2$ of aperture area |
| Dish-Array Fencing | 87$m^2$ field size \$2,700 |
| | 174$m^2$ field size \$3,800 |
| | 434$m^2$ field size \$6,100 |
| | 869$m^2$ field size \$8,600 |
| | 2,250$m^2$ field size \$13,800 |
| | 13,500$m^2$ field size \$33,800 |
| | 56,250$m^2$ field size \$69,100 |
| | 225,000$m^2$ field size \$138,200 |
| | 1,125,000$m^2$ field size \$309,000 |

TABLE C.27. (Cont.)

Balance-of-Plant (Continued)

| | | |
|---|---|---|
| Excess Land | $0.0247 per $m^2$ of aperture area | |
| Master Controls | 1 dish system | $29,000 |
| | 100 dish system | $74,000 |
| | 1000 dish system | $497,000 |
| | 10000 dish system | $3,734,000 |
| Structures | 0.025 MW system | $2,000 |
| | 0.05 MW system | $2,000 |
| | 0.125 MW system | $2,000 |
| | 0.25 MW system | $2,000 |
| | 0.5 MW system | $2,000 |
| | 2 MW system | $110,800 |
| | 10 MW system | $185,100 |
| | 30 MW system | $297,100 |
| | 100 MW system | $365,600 |
| | 200 MW system | $431,100 |
| Power Conditioning | 5 MW system | $105,000 |
| | 10 MW system | $130,000 |
| | 30 MW system | $360,000 |
| | 100 MW system | $810,000 |
| | 200 MW system | $1,540,000 |
| Service Facilities | <2 MW system | $0 |
| | 2 MW system | $137,500 |
| | 10 MW system | $217,400 |
| | 30 MW system | $273,200 |
| | 100 MW system | $581,100 |
| | 200 MW system | $1,162,000 |

Spare Parts

3% of capital cost of BOP items (excluding land and site prep.)
0.6% of capital cost of energy conversion and receiver
0.3% of capital cost of collector and transport

Operating and Maintenance (annual)

Operating

| | | |
|---|---|---|
| Security | < 2 MW system | $0 |
| | 2=<=100 MW system | $46,600 |
| | 100 <=200 MW system | $93,200 |
| Service Contract | < 2 MW system | $24/kWe of gross generating capacity |

Concentrator Maintenance

~~0.03%~~ 0.3% of concentrator capital cost plus 15% overhead
1.84 per $m^2$ of aperture area plus 15% overhead

$850 every 5th year for optical membrane replacement (present value of these replacements at time zero = $2500)

Receiver Maintenance

lab: $2.24 per $m^2$ of aperture plus 15% overhead

mat: ${459.370 + (-42.632)ln(Size, MW/0.05 MW)}{(1.50) ($m^2$ of aperture area)}/3160 plus 15% overhead

Conversion Maintenance

lab: $5.83 per $m^2$ of aperture plus 15% overhead

mat: ${1071.863 + (-99.474)ln(Size, MW/0.05 MW)}{(3.89) ($m^2$ of aperture area)}/7370 plus 15% overhead

TABLE C.27. (Cont.)

| | | |
|---|---|---|
| Transport | 5 MW system | 0.80% of transport capital cost plus 15% overhead |
| | 10 MW system | 0.85% of transport capital cost plus 15% overhead |
| | 30 MW system | 0.90% of transport capital cost plus 15% overhead |
| | 100 MW system | 0.95% of transport capital cost plus 15% overhead |
| | 200 MW system | 1.0% of transport capital cost plus 15% overhead |
| Balance-of-Plant | | 1.4% of structures, service facilities, power conditioning, and spare parts plus 15% overhead |
| | | 1.6% of master controls plus 15% overhead |
| Indirects | | 25% of subtotaled component estimate |
| Contingencies | | 15% of concentrator, receiver, and conversion component estimates |
| | | 10% of all other component estimates |

**COMPONENT: CONCENTRATOR** (stressed composite-membrane technology)

QUALITY JUDGMENT: Overall the quality the concentrator component estimate is "fair". The estimate itself is quite comprehensive and is based on a significant amount of detailed cost data which was developed for the stressed membrane heliostat (Solar Kinetics 1987) and other studies. The quality judgment of "fair" is given due to the conceptual nature of the design which results in an estimate with greater uncertainty than an estimate based on detailed engineering drawings. Additionally, there is little information regarding the production economies-of-scale which would occur for near-term manufacturing of the concentrator.

SUBCOMPONENT: MIRRORS AND SUPPORT

METHOD: This subcomponent was estimated by PNL in three parts: (1) the concentrator unit (F.O.B.), (2) transportation, and (3) field installation. The long-term production cost estimate was the basis for the near-term estimate. The production economies-of-scale which would exist for lower near-term production levels were estimated. These production economies-of-scale were then applied to the long-term estimate to generate the near-term estimate.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". Although the design is conceptual, there is enough design information and related historical data to generate a sound long-term manufacturing estimate. Uncertainty arises when trying to determine the production economies-of-scale which would exist before long-term production levels are reached. The transportation estimate is "good" within the limits of the transportation scenario presumed. If a different method of transportation was to be used, the costs could differ slightly. The field installation estimate is rated as "fair". There is uncertainty as to exactly how some of the site operations would be performed. In particular, the process to hydroform the composite-membrane and the time and equipment estimates for fastening the rear and optical membranes to the ring is uncertain.

DATA: The construction of the stressed composite-membrane concentrator consists of a 14-meter diameter aluminum ring centered around a steel mast. To the back of the ring and base of the mast a vinyl-coated fiberglass rear membrane is attached. To the front of the ring a fieberglass composite-membrane is attached. Conceptual design work identified attachment of the composite to the ring with a rigid attachment as detrimental to performance; however, due to a lack of alternative design information, a clamp attachment is assumed. Additionally, to the front of the ring an optical membrane is attached. When the plenum between the rear membrane and optical membrane is evacuated the optical membrane is drawn down against the composite-membrane. This forms the optical membrane into the appropriate reflective shape. Design point performance estimates for the concentrator are as follow:

Concentrator Reflectivity (new and clean)--0.91 (SKI)

Reflectivity Degradation (assuming bi-weekly cleaning)--0.95
-This is the same value that was assumed for the glass/metal concentrator. It is very likely that this value is too high for membrane concentrators; the reasons for this are:

- cleaning will most likely be more difficult, less efficient, and less effective. The optical surface is thin, stressed polymers will not be able to withstand a cleaning regiment as aggressive as that of the glass/metal concentrator.

- The optical material will suffer permanent degradation over time (the reason for the five-year replacement schedule).

Blocking caused by the center tube support cables--0.986
-There are 24 one-half inch cables. These cables will both shadow the concentrator and block <u>concentrated</u> reflected flux. Considering only the shadowing (or assuming the concentration is very small) the cables will shadow an area equal to:

$$24 * 7m * 0.5 \text{ in.} = 23 \text{ ft}^2 \ (2.13 \text{ m}^2)$$

Shadowing caused by the receiver support structure--0.989
-There are three 3-inch support trusses for the receiver. These trusses will shadow an area of the concentrator equal to:

$$3 * 7m * 3 \text{ in.} = 17.2 \text{ ft}^2 \ (1.60 \text{ m}^2)$$

Concentrator/Receiver Intercept Factor--0.966
-This is the same value that was assumed for the glass/metal concentrator. This value is probably also too high for membrane concentrators; the reasons for this area:

- The optical quality of the concentrator will most likely be less than that of the glass/metal concentrator. Thus, for an intercept factor this high, the receiver aperture would have to be larger which would result in increased receiver thermal losses. Conversely, the aperture could be made small to maintain low receiver losses, but this would increase spillage and thus decrease the concentrator/receiver intercept factor. The optimal value is the one that minimizes the LEC; this value will have to be determined during detailed systems analysis and design.

<u>Concentrator Unit</u>

At the central manufacturing facility; the composite, rear, and optical membranes; the main mast; PCU support tripod; and foundation/drive structure are manufactured. Manufacture of these components is integrated in that foundation parts are cut and painted using much of the same equipment used for the main mast and PCU support tripod.

For cost accounting purposes, total cost for parts-cutting equipment, paint line, labor, related floor space, related land area, and general factory equipment are divided between the foundation subcomponent and the concentrator subcomponent using the same total dollar division as was used for the metal-membrane system

In addition, for small site sizes (less than 1.6 MWe) it is economically more attractive to manufacture the main concentrator ring at the central manufacturing facility than at the site, as is done for large system sizes. Central facility manufacturing of the ring at small system sizes is desirable, because it is more expensive to set-up the site ring-manufacturing facility and make a small number of rings than it is to centrally manufacture the ring, cut it into eight arched segments and ship it to the site for welding into a uniform ring.

The long-term F.O.B. cost of the concentrator was estimated by using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table C.28 for plant sizes of 1.6 MWe or larger and in Table C.29 for sizes smaller than 1.6 MWe. The concentrator estimates as generated from the algorithm are \$5840 and \$6531 per concentrator for large and small system sizes, respectively. In addition to these costs, \$2224 and \$1671 for burdened materials and working capital allowance for materials used at the site must be added. Making these additions yields estimates of concentrator cost of \$8064 and \$8202, respectively. These estimates translate to \$53.8 per $m^2$ of dish aperture area for systems equal to or larger than 1.6 MWe and \$54.7 per $m^2$ of dish aperture area for system sizes smaller than 1.6 MWe. Both these unit costs are based on a stressed composite-membrane dish which has 150 $m^2$ of aperture area and an annual production level of 16,667 units per year.

TABLE C.28. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Mirrors and Support Subcomponent at System Sizes of Greater than 1.6 MWe.

| | |
|---|---|
| Direct Materials | \$3844 per dish; \$64,067,948 for 16,667 dishes/year[a] |
| Direct Labor | 5.66 hours; 94,400 hours for 16,667 dishes/year |
| Capital Equip. | \$17,202,599 |
| Plant Area | 249,800 sq. ft. |
| Plant Acreage | 14.44 Acres |

(a) 16,667 dishes per year is equivalent to 2.5 x $10^6$ square meters of concentrator area which is the assumed production level.

The main differentiating factor between the cost of the near-term and long-term glass-metal dish technologies is production economies-of-scale. In the case of the long-term estimates, 16,667 dishes per year are produced while in the near-term the erection of a 200 MW plant would require only about 4000 dishes and smaller systems would require even less.

TABLE C.29. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Mirrors and Support Subcomponent at System Sizes of Less than 1.6 MWe.

| | |
|---|---|
| Direct Materials | \$4317 per dish; \$71,951,439 for 16,667 dishes/year[(a)] |
| Direct Labor | 6.2 hours; 103,289 for 16,667 dishes/year |
| Capital Equip. | \$17,524,792 |
| Plant Area | 265,800 sq. ft. |
| Plant Acreage | 15.44 Acres |

(a) 16,667 dishes per year is equivalent to 2.5 x $10^6$ square meters of concentrator area which is the assumed production level.

Cost versus production level data is non-existent for stressed composite-membrane dish concentrators; however, one source (Washom 1982, p. 9) does include this type of information for the Advanco glass-metal concentrator. While the Advanco glass-metal and stressed composite-membrane concentrators are different, the relative production economies-of-scale are anticipated to be similar. For ordinary production operations, production economies-of-scale are about the same for manufactured components using similar materials, equipment, and fabrication techniques. For conceptual estimates such as those presented here, this assumption is quite adequate.

The estimates for the Advanco concentrator (Washom 1984, p. 9) as a function of production level were fit to an equation. These estimates are presented in Table C.30. The equation was then used to estimate the cost of the Advanco concentrator at 16,667 units per year. Using this estimate and the source estimates (Table C.30), the additional cost (in fractional form) due to production economies-of-scale for producing less than 16,667 units per year was calculated. These fractions are presented in Table C.31.

TABLE C.30. Advanco Glass-Metal Concentrator Estimates, 1982$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | \$52,797 |
| 100 per year | 41,655 |
| 1000 per year | 23,788 |
| 10000 per year | 19,895 |

TABLE C.31. Advanco Concentrator Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 16,667 Units |
|---|---|---|
| 2 per year | 52,684[a] | 2.74 |
| 5 per year | 47,566[a] | 2.47 |
| 10 per year | 44,028[a] | 2.29 |
| 20 per year | 40,753[a] | 2.12 |
| 31 per year | 38,810[a] | 2.02 |
| 32 per year | 38,672[a] | 2.00 |
| 40 per year | 37,722[a] | 1.96 |
| 80 per year | ~~36,055~~[a] 34,844 | ~~1.87~~ 1.81 |
| 100 per year | 41,655 | 2.16 |
| 100 per year | 34,058[a] | 1.77 |
| 200 per year | 31,525[a] | 1.64 |
| 600 per year | 27,890[a] | 1.45 |
| 1000 per year | 23,788 | 1.24 |
| 1000 per year | 26,346[a] | 1.37 |
| 2000 per year | 24,386[a] | 1.27 |
| 4000 per year | 22,572[a] | 1.17 |
| 10000 per year | 19,895 | 1.03 |
| 16667 per year | 19,251[a] | - |

(a) Cost predicted by the equation $56917X^{0.888489}$ ($r^2 = 0.998$) which is based on a curve fit of the data presented in Table C.29. Where "X" is the annual production level and the predicted cost is the total annual production cost.

The fractions were then applied to the PNL-derived long-term F.O.B. estimate for the stressed composite-membrane concentrator at a production level of 16,667 units per year to determine the near-term cost of the stressed composite-membrane concentrator. These estimates are shown in Table C.32. Distributing the cost of the concentrator over the aperture area of the stressed composite-membrane dish, 150 $m^2$, yields the estimates presented in Table C.33.

Concentrator Transportation

Concentrator transportation costs were estimated by determining the numbers loads required (either weight- or volume-limited) to deliver concentrator subassemblies from the factory to the site and multiplying by an assumed delivery distance of 600 miles and a cost per mile of $1.45. For large systems, an average 6.18 dishes can be transported per load. This results in a concentrator transportation cost of $141. This cost distributed over the aperture area of the dish and rounded is $0.9 per $m^2$ of aperture area. For small systems (less than 1.6 MWe) shipping of the ring increases transportation costs to $214 and reduces the average dishes per load to 4.07. Small system shipping is rounded to $1.4 per $m^2$ of aperture area.

TABLE C.32. Estimated Central Manufacturing Cost of the Stressed Composite-Membrane Concentrator at Production Levels Less than 16,667 Units per Year, 1984$

| Production Level | Cost per Unit |
|---|---|
| 2 per year | 22,473 |
| 5 per year | 20,259 |
| 10 per year | 18,783 |
| 20 per year | 17,388 |
| 31 per year | 16,568 |
| 32 per year | 16,128 |
| 40 per year | 15,805 |
| 80 per year | ~~15,080~~ 14,596 |
| 100 per year | 14,273 |
| 200 per year | 13,225 |
| 600 per year | 11,693 |
| 1000 per year | 11,048 |
| 2000 per year | 10,241 |
| 4000 per year | 9,435 |
| 10000 per year | 8,306 |
| 16667 per year | 8,064[a] |

(a) Same cost as the long-term estimate

TABLE C.33. Estimated Central Manufacturing Cost of the Stressed Composite-Membrane Concentrator at Production Levels Less than 16,667 Units per Year, 1984$

| Production Level | Cost per Unit, $\$/m^2$ |
|---|---|
| 2 per year | 150 |
| 5 per year | 135 |
| 10 per year | 125 |
| 20 per year | 116 |
| 31 per year | 110 |
| 32 per year | 108 |
| 40 per year | 105 |
| 80 per year | ~~101~~ 97.3 |
| 100 per year | 95.2 |
| 200 per year | 88.2 |
| 600 per year | 78.0 |
| 1000 per year | 73.7 |
| 2000 per year | 68.3 |
| 4000 per year | 62.9 |
| 10000 per year | 55.4 |
| 16667 per year | 53.8[a] |

(a) Same cost as the long-term estimate

## Concentrator Installation

The field installation estimates were independently prepared by PNL and are presented in Table C.34. These figures are based on a PNL estimate of 6.36 manhours for site assembly and installation, a $21.4 charge per dish for capital installation equipment, and a site set-up charge of $16,540 for systems equal to or larger than 1.6 MWe. Large system site installation progresses at an average output of 159 dishes per week, not including the initial site set-up time of one week. For systems smaller than 1.6 MWe, field installation estimates are based on a PNL estimate of 11.89 manhours, a $37.74 charge per dish for capital installation equipment, and a site set-up charge of $5,440. Small system site installation progresses at an average output of 12.5 dishes per week, not including initial site set-up time of one week. The total estimates distributed over the aperture area of the stressed composite-membrane dish (150 $m^2$) yields the rounded unit costs presented in Table C.35.

TABLE C.34. Field Installation Estimates, 1984$

| System Size | Cost per Dish |
|---|---|
| 200 MWe | $ 181 |
| 100 MWe | 186 |
| 50 MWe | 194 |
| 30 MWe | 205 |
| 10 MWe | 260 |
| 5 MWe | 343 |
| 3 MWe | 453 |
| 1.6 MWe | 694 |
| 1.55 MWe | 505 |
| 1 MWe | 601 |
| 0.25 MWe | 1417 |
| 0.1 MWe | 3049 |

TABLE C.35. Field Installation Estimates, $/m²

| System Size | Cost per Dish |
|---|---|
| 200 MWe | $ 1.2 |
| 100 MWe | 1.2 |
| 50 MWe | 1.3 |
| 30 MWe | 1.4 |
| 10 MWe | 1.7 |
| 5 MWe | 2.3 |
| 3 MWe | 3.0 |
| 1.6 MWe | 4.6 |
| 1.55 MWe | 3.4 |
| 1 MWe | 4.0 |
| 0.25 MWe | 9.4 |
| 0.1 MWe | 20 |

SUBCOMPONENT: DRIVE

METHOD: This subcomponent was estimated by using the long-term drive estimate which corresponds to a production level of 16,667 drives per year and adjusting its cost to reflect the lower production levels associated with near-term systems.

QUALITY JUDGMENT: The quality of the drive subcomponent estimate is "poor". Basically, this due to the lack of design requirements for the drive which necessitates a considerable amount of judgment be applied.

DATA: Due to the conceptual nature of the design, the drive design and operational requirements have not been identified by the designers. However, the two basic drive mechanisms have been identified in the conceptual design. These mechanisms include the azimuth drive, and the elevation drive in the form of the a screw jack. These components are similar to the components of the Peerless-Winsmith low-cost heliostat drive.

To estimate the cost of the two components of the stressed composite-membrane drive, the cost of these same components from the Peerless-Winsmith drive were used as the basis. At a production level of 50,000 units per year, Heller (1987) estimates the cost of the Winsmith azimuth drive as $973 (1987$) and cost of the Winsmith elevation drive as $496 (1987$). Converting these estimates to 1984-dollars and a dollar per m² of aperture area basis yields estimates of $6 and $3 per m² of aperture area, respectively for the azimuth and elevation drives. An additional 25% was added to the cost of both units to account for the production level of the stressed composite-membrane drive units being only 16,667 units per year instead of 50,000 units per year, the presumed level in the Heller estimate and a small contingency. The extra contingency was added, because it is doubtful the drive could be produced for anything less than $11 per m², and in fact, even $11 may be optimistic. At the current stage of design work, it is impossible to determine exactly what the drive requirements are.This results in an estimate of $11 per m² of aperture area ($1670) for one drive at a production level of 16,667 units per year.

Like the concentrator, the main differentiating factor between the cost of the near-term and long-term drive unit is production economies-of-scale. The limited cost-versus-production-level data available for the drive unit was prepared for the Advanco concentrator drive unit (Washom 1984, p. 9). While the Advanco and the stressed composite-membrane concentrator drive are different in design, the Advanco information is the only production versus cost data available. Because both units fulfill the same functions and are made of similar materials, the Advanco production economies-of-scale can reasonably be used to generate estimates for the stressed composite-membrane drive.

The estimates for the Advanco concentrator drive (Washom 1982, p. 9) as a function of production level were fit to an equation. These estimates are presented in Table C.36. The equation was then used to estimate the cost of the Advanco concentrator drive cost at 16,667 units per year. Using this estimate and the source estimates (Table C.36), the additional cost (in fractional form) due to production economies-of-scale for producing less than 16,667 units per year was calculated. These fractions are presented in Table C.37.

TABLE C.36. Advanco Concentrator Drive Estimates, 1982$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $13,240 |
| 100 per year | 10,592 |
| 1000 per year | 6,767 |
| 10000 per year | 5,830 |

TABLE C.36. Advanco Concentrator Drive Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 16,667 Units |
|---|---|---|
| 1 per year | $13,240 | 2.34 |
| 100 per year | 10,592 | 1.87 |
| 1000 per year | 6,767 | 1.20 |
| 10000 per year | 5,830 | 1.03 |
| 16667 per year | 5,656[(a)] | - |

(a) Cost predicted by the equation $13985X^{0.906881}$ ($r^2 = 0.999$) which is based on a curve fit of the data presented in Table C.35. Where "X" is the annual production level and the predicted cost is the total annual production cost.

These fractions were then applied to the long-term estimate for the stressed composite-membrane drive at a production level of 16,667 units per year to determine the cost of the drive at production levels of 1, 100, 1000, and 10000 dishes per year. These estimates are shown in Table C.38. Distributing the cost of the drive over the aperture area of the stressed composite-membrane dish, 150 $m^2$, yields estimates for production levels of 1, 100, 1000, and 10000 dishes per year of $26, $21, $13, and $11 per $m^2$ of aperture area, respectively.

TABLE C.38. Estimated Cost of the Stressed Composite-Membrane Concentrator Drive at Production Levels less than 16,667 Units per Year, 1984$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $3,908 |
| 100 per year | 3,123 |
| 1000 per year | 2,004 |
| 10000 per year | 1,720 |
| 28872 per year | 1,670 |

SUBCOMPONENT: CONTROLS AND WIRING

METHOD: Adjustment of the long-term estimate to reflect the lower production levels associated with near-term construction.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". While there are a significant number of estimates relating to the controls and wiring for heliostats it is somewhat ill-defined as to how dish controls and wiring would differ. For this reason some engineering judgments were required to adjust heliostat controls and wiring estimates to dish system estimates. Additionally there is uncertainty with respect to the production economies-of-scale which would occur in the near-term.

DATA: Development of the long-term estimate was based on adjustment of heliostat controls and wiring estimates to conform to the system requirements of the dish system. Estimates prepared by ARCO, Martin Marietta, McDonnell Douglas (Norris and White 1982) and PNL (Drumheller 1981) were evaluated for applicability to dish systems. Based on engineering judgment, the estimate presented in Table C.39 was prepared. The total cost per dish of $755.50 (1984$) is for a production level of 28,782 units per year.

Cost versus production level data for the controls and wiring was prepared by Advanco (Washom 1984, p. 9). For the same reasons Advanco data was used in preparing the concentrator and drive estimates, it was used to determine near-term costs for the controls and wiring.

The estimates for the Advanco controls and wiring (Washom 1982, p. 9) as a function of production level were fit to an equation. These estimates are presented in Table C.40. The equation was then used to estimate the cost of the Advanco concentrator controls and wiring cost at a production level of 28,782 units per year. Using this estimate and the source estimates (Table C.40), the additional cost (in fractional form) due to production economies-of-scale for producing less than 28,782 units per year was calculated. These fractions are presented in Table C.41.

The fractions were then applied to the PNL-derived estimate for the controls and wiring at a production level of 28,782 units per year to determine the cost of the controls and wiring at production levels of 1, 100, 1000, and 10000 dishes per year. These estimates are shown in Table C.42.

TABLE C.39. Long-Term Cost Estimate for Dish System Controls and Wiring (1984$)

| | | |
|---|---|---|
| Power and Control Cabling[a] | $463 | per dish |
| Dish Controller[b] | 265 | per dish |
| Dish Array Controller[c] | 27.50 | per dish |
| | $755.50 | per dish |

(a) This estimate includes $280 (1980$) for power cabling (Norris and White 1982, p. 94) and $90 (1980$) for control cabling. The control cabling estimate is the average of a Martin Marietta estimate of $63 (Norris and White 1982, p. 94) and a McDonnell Douglas estimate of $120 (Norris and White 1982, p. 94). The total power and control cabling estimate of $370 (1980$) was escalated to $463 (1984$).

(b) The dish controller estimate is based on the average of a McDonnell Douglas estimate of $203 (1980$) (Norris and White 1982, p. 94) and an ARCO estimate of $328 (1980$) (Norris and White 1982, p. 94). The average of $265 was not escalated because electronic components have remained about the same with respect to cost from 1980 to 1984.

(c) The dish-array controller for controlling 3631 dishes was estimated by PNL for Williams et al. (1987) to cost $100,000 (1984$) which on average is $27.50 per dish.

TABLE C.40. Advanco Controls and Wiring Estimates, 1982$

| Production Level | Cost per Unit |
|---|---|
| 1 per year | $20,000 |
| 100 per year | 9,961 |
| 1000 per year | 6,796 |
| 10000 per year | 4,951 |

TABLE C.41. Advanco Controls and Wiring Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 28,782 Units |
|---|---|---|
| 1 per year | $20,000 | 4.82 |
| 100 per year | 9,961 | 2.40 |
| 1000 per year | 6,796 | 1.64 |
| 10000 per year | 4,951 | 1.19 |
| 16667 per year | 5,656[a] | 1.09 |
| 28782 per year | 4,146[a] | - |

(a) Cost predicted by the equation $19969.5X^{0.847201}$ which is based on a curve fit of the data presented in Table C.40. Where "X" is the annual production level and the predicted cost is the total annual production cost.

TABLE C.42. Estimated Cost of the Controls and Wiring at Production Levels less than 16,667 Units per Year, 1984$

| Production Level | Cost per Unit | Rounded Cost per Unit |
|---|---|---|
| 1 per year | $3,738 | $3700 |
| 100 per year | 1,813 | 1800 |
| 1000 per year | 1,272 | 1300 |
| 10000 per year | 899 | 900 |
| 16667 per year | 824[a] | 820 |

(a) Same cost as the long-term estimate

SUBCOMPONENT: FOUNDATION

METHOD: This subcomponent was independently estimated by PNL.

QUALITY JUDGMENT: The quality of this subcomponent estimate is "fair". The estimate is fairly comprehensive. However, because there has not been a detailed design made for the foundation, there is greater uncertainty than is desirable. In addition, data on the production economies-of-scale for the foundation in the near-term are uncertain

DATA: The foundation is manufactured at a central facility in four subassemblies: the kingpost, the sway braces, the a-frame, and the jack link. The long-term F.O.B. cost of the foundation was estimated using the PNL manufacturing cost algorithm (Williams et al. 1987, p. F.2). The inputs to the algorithm are presented in Table C.43. The foundation estimate generated from the algorithm is $2824. The four subassemblies are shipped to the site at a cost of $144. Site installation cost estimates are presented in Table C.44. For system sizes equal to or larger than 1.6 MWe, field installation estimates are based on a PNL estimate of 0.59 manhours for installation, a $8.13 charge for distributed capital, a fixed set-up charge of $2610, and a $150 charge for installed concrete. Field installation estimates for systems smaller than 1.6 MWe are based on a PNL estimate of 0.93 manhours for installation, a $41.93 charge for distributed capital, a fixed set-up charge of $870, and a $150 charge for installed concrete.

In the near-term the manufacturing cost of the foundation is expected to be greater than in the long-term. The foundation shipping and installation costs are estimated to be the same. In the near-term the production economies-of-scale for foundation manufacturing are estimated to be the same as those for the Advanco dish concentrator. While these two components appear completely different, the stressed composite-membrane foundation acts as both the foundation and the mirror support structure for the stressed composite-membrane. Table C.45 restates the production economies-of-scale for the Advanco concentrator which are assumed equivalent to the foundation manufacturing production economies-of-scale. Applying these production economies-of-scale to the long-term foundation manufacturing estimate of $2824 yields the near-term estimates presented in Table C.46. Summing these manufacturing estimates with the transportation and installation estimates results in the final installed foundation estimates listed in Table C.47.

TABLE C.43. Inputs to the PNL Manufacturing Cost Algorithm for the Long-Term Foundation Subcomponent

| | |
|---|---|
| Direct Materials | $1947 per dish; $32,450,649 for 16,667 dishes/year[a] |
| Direct Labor | 1.75 hours; 29,100 hours for 16,667 dishes/year |
| Capital Equip. | $3,437,831 |
| Plant Area | 25,909 sq. ft. |
| Plant Acreage | 1.56 Acres |

(a) 16,667 dishes per year is equivalent to $2.5 \times 10^6$ square meters of concentrator area which is the assumed production level.

TABLE C.44. Foundation Installation Estimates, 1984$

| System Size | Cost per Dish |
|---|---|
| 200 MWe | $ 173 |
| 100 MWe | 174 |
| 50 MWe | 175 |
| 30 MWe | 177 |
| 10 MWe | 186 |
| 5 MWe | 199 |
| 3 MWe | 216 |
| 1.6 MWe | 254 |
| 1.55 MWe | 243 |
| 1 MWe | 258 |
| 0.25 MWe | 389 |
| 0.1 MWe | 650 |

TABLE C.45. Advanco Concentrator Production Economies-of-Scale

| Production Level | Cost per Unit | Fractional Cost of Producing less than 16,667 Units |
|---|---|---|
| 2 per year | 52,684[a] | 2.74 |
| 5 per year | 47,566[a] | 2.47 |
| 31 per year | 38,810[a] | 2.02 |
| 32 per year | 38,672[a] | 2.00 |
| 60 per year | 36,054[a] | 1.87 |
| 100 per year | 41,655 | 2.16 |
| 100 per year | 34,058[a] | 1.77 |
| 200 per year | 31,525[a] | 1.64 |
| 600 per year | 27,890[a] | 1.45 |
| 1000 per year | 23,788 | 1.24 |
| 1000 per year | 26,346[a] | 1.37 |
| 2000 per year | 24,386[a] | 1.27 |
| 4000 per year | 22,572[a] | 1.17 |
| 10000 per year | 19,895 | 1.03 |
| 16667 per year | 19,251[a] | - |

(a) Cost predicted by the equation $56917X^{0.888489}$ ($r^2$ = 0.998) which is based on a curve fit of the data presented in Table C.30. Where "X" is the annual production level and the predicted cost is the total annual production cost.

TABLE C.46. Foundation Central Manufacturing Cost, 1984$

| Production Level | Cost |
|---|---|
| 2 per year | $7738 |
| 5 per year | 6795 |
| 20 per year | 5987 |
| 31 per year | 5704 |
| 32 per year | 5648 |
| 60 per year | 5281 |
| 100 per year | 4998 |
| 200 per year | 4631 |
| 600 per year | 4095 |
| 1000 per year | 3869 |
| 2000 per year | 3586 |
| 4000 per year | 3304 |

TABLE C.47. Total Foundation Estimates, \$/m²

| System Size | | Cost |
|---|---|---|
| 200 | MWe | \$ 24.1 |
| 100 | MWe | 26.0 |
| 50 | MWe | 27.9 |
| 30 | MWe | 29.4 |
| 10 | MWe | 33.1 |
| 5 | MWe | 35.6 |
| 3 | MWe | 37.6 |
| 1.6 | MWe | 40.3 |
| 1.55 | MWe | 40.6 |
| 1 | MWe | 42.6 |
| 0.25 | MWe | 48.9 |
| 0.1 | MWe | 56.9 |

COMPONENTS: RECEIVER AND ENERGY CONVERSION

METHOD: Comparison and adjustment of existing estimates

QUALITY JUDGMENT: The quality of the receiver and energy conversion estimate is rated as "fair". There was a good correlation between the three source estimates used as the basis for the final estimate which is a positive aspect. However, none of the estimates include details which results in some uncertainty in the final estimate. Adding additional uncertainty is the scaling of 25-kWe unit costs to estimate the cost of the 50-kWe engine.

DATA: The receiver and energy conversion components for the dish are combined in a single power conversion unit (a stirling engine/generator set). The stirling unit used for the 150 $m^2$ stressed composite-membrane dish is assumed to be 50-kWe in size. Although, optimized designs may use a smaller engine.

Cost data on 50-kWe units is unavailable. Therefore, cost data for a 25-kWe 4-95 Solar II Unit is used and scaled accordingly for the difference in size. The 25-kWe engine used as the cost basis is a 4-cylinder engine which uses hydrogen as the working fluid, operates at a heater temperature of 750-degrees Celsius, and has a gross efficiency of 0.41 (i.e., the shaft mechanical power as a fraction of heater tube heat input is 0.41.) (Holtz 1987). It is estimated the 50-kWe engine would have a gross efficiency a few percent higher. However, no detailed data is available. For all related available information refer to the working paper "Stirling Engines in Solar Applications".

Stirling cost data from three sources were evaluated. These data are presented in Table C.48. The Vanguard estimates were for installed dish system engines and were reduced by assuming installation, alignment, and testing adds ten percent to the basic cost of the unit. The other estimates reflect only purchase cost. All the units are rated at 25-kWe gross generating capacity.

The data was then fit to two equations. The first of these equations was based on the data points ranging from one to 10,000 units/yr and the second on the data points ranging from 10,000 to 400,000 units/yr. The intersection of these equations is at a production level of 9577. The equations are as follows:

$1 < \text{units/year} < 9577 \qquad \$/\text{kWe} = 2020.474 - 187.509 \ln X$

$9577 < \text{units/year} < 400{,}000 \qquad \$/\text{kWe} = 5701.798X^{-0.32068}$

In the near-term, production levels of the stirling engine/generator set will be much lower than in the long-term. Because even a large plant, 200 MWe, will require only about 4000 engines and smaller plants even less, the former of these two equations was used to estimate the near-term cost.

"X" is equal to the number of 25 kWe (0.025 MWe) units produced per year. This equation is only valid for 25-kWe units whereas the stressed membrane concentrator requires a 50-kWe unit.

Scaling of a unit from 25 to 50-kWe results in some economies-of-scale being achieved. Size economies-of-scale are achieved as the engine size is increased which allows the use of less material and labor hours per kWe of output. A review of several sources indicates size economies-of-scale of exist, but the extent is questionable. The general form of the cost-scaling equation using a cost-size factor (denoted SF) is as follows:

$$\text{Unit Cost}_2 = \text{Unit Cost}_1 * (\text{Size}_1/\text{Size}_2) * (\text{Size}_2/\text{Size}_1)^{SF}$$

Assuming a cost-size factor (SF) of 0.6 and applying the generic cost-scaling equation to the equation generated above for the unit cost of the 25-kWe unit, the following equation results for the unit cost of 50-kWe units:

$$\$/\text{kWe} = (25/50)(2020.474 + (-187.509)\ln X)((50/25)^{0.6})$$

Through this transformation "X" changes to the number of 50-kWe (0.05 MWe) units produced per year. Additional information on the derivation of this equation is presented in the working paper "Stirling Engines in Solar Applications."

According to United Stirling, approximately 30% of the unit by cost could be considered the receiver and the balance would fall into energy conversion (Nelving 1985). On this basis the cost equation was split into two equations by multiplying by 0.3 and 0.7 to obtain equations for the receiver and energy conversion components, respectively. These equations are as follows:

receiver: $\$/\text{kWe} = 459.370 - 42.632)\ln(\text{MWe}/0.05\ \text{MWe})$

conversion: $\$/\text{kWe} = 1071.863 - 99.474\ln(\text{MWe}/0.05\ \text{MWe})$

Table C.48. Dish Power Conversion Unit Purchase Cost Data, 1984$

| Source | Production Quantity | Cost/Unit |
|---|---|---|
| United Stirling[a] | 1 | $50,000 |
| | 2,000 | $20,000 |
| | 25,000 | $ 5,500 |
| JPL[b] | 1,000 | $17,576 |
| | 25,000 | $ 5,641 |
| | 100,000 | $ 2,946 |
| | 400,000 | $ 2,539 |
| Vanguard[c] | 1 | $57,878 |
| | 100 | $28,941 |
| | 1,000 | $15,463 |
| | 10,000 | $ 8,700 |

(a) Telephone conversation with Worth Percival, United Stirling.
(b) Fortgang and Mayers (1980, p. 10) prices were escalated to 1984-dollars.
(c) Washom (1984, p. 9) prices were escalated to 1984-dollars and reduced to an uninstalled basis.

COMPONENT: **TRANSPORT**

METHOD: All the transport components are mature in design and already are in mass production. Also, economies-of-scale related to system size are accounted for in the long-term estimates. For these reasons, it is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent. The details and basis for the estimate are included in the long-term documentation.

COMPONENT: **BALANCE-OF-PLANT**

METHOD: All the balance-of-plant components are mature in design and already in mass production. Also, economies-of-scale related to system size are accounted for in the long-term estimates. For these reasons, it is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent. The details and basis for the estimate are included in the long-term documentation.

COMPONENT: **OPERATING AND MAINTENANCE**

QUALITY JUDGMENT: the quality of O&M cost data is rated as "poor", mainly because little operating experience exists which causes estimates to be based largely on conjecture.

SUBCOMPONENT: OPERATING

METHOD: The operating subcomponent includes security personnel for plants 2 MW or larger and a service contract for plants smaller than 2 MW. It is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent. In the case of security, staffing levels will be the same in the near-term and long-term. With respect to the service contract, it only accounts for capital recovery of service facilities provided by a subcontractor or centralized service facility. Actual maintenance labor and materials are accounted for in the maintenance subcomponents. Therefore, the operating subcomponent is expected to cost the same in the near-term and long-term. The details and basis for the estimate are included in the long-term documentation.

SUBCOMPONENT: MAINTENANCE OF THE CONCENTRATOR

METHOD: The only significant difference between near-term and long-term concentrator maintenance costs is the non-washing material cost. This cost is expected to be higher in the near-term than in the long-term due to non-washing maintenance materials being more costly in lower production. The cost of non-washing materials is estimated to be proportional to concentrator capital cost. Therefore, the relative difference between non-washing materials and concentrator cost will be the same in the near-term and long-term. Consequently, the fraction of initial concentrator capital estimated for long-term non-washing materials applies in the near-term also.

SUBCOMPONENT: MAINTENANCE OF THE RECEIVER SYSTEM.

METHOD: It is estimated that the material component of the receiver maintenance will be higher in the near-term than it will be in the long-term. The labor component of the receiver maintenance is estimated to be approximately the same in the near-term and long-term. To account for the higher near-term material cost, the long-term material costs were scaled based on the ratio of near-term receiver capital cost to the long-term receiver capital cost.

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

DATA: Long-term maintenance costs were estimated as the following:

labor: \$2.24 per $m^2$ of aperture area
materials: \$1.50 per $m^2$ of aperture area

Using the long-term material estimate as a basis, the near-term materials estimate was prepared by multiplying the long-term estimate by the ratio of the near-term receiver cost to the long-term receiver unit cost. This ratio is represented by the following equation:

$$\{459.370 + (-42.632)\ln(\text{Size, MW}/0.5\text{ MW})\}/3160$$

Where "size" is the gross generating capacity for the plant size being estimated. Multiplying this equation by the long-term materials cost estimating equation yields the following near-term receiver maintenance materials cost estimating equation for a 50-kWe stirling unit:

$$\text{materials} = \{459.370 + (-42.632)\ln(\text{Size, MW}/0.05\text{ MW})\}\{(1.50)(m^2 \text{ of aperture area})\}/3160$$

In addition a 15% overhead charge must be added to this estimate (Guthrie 1974).

SUBCOMPONENT: MAINTENANCE OF THE CONVERSION SYSTEM

METHOD: It is estimated that the material component of the energy conversion maintenance will be higher in the near-term than it will be in the long-term. The labor component of the conversion maintenance is estimated to be approximately the same in the near-term and long-term. To account for the higher near-term material cost, the long-term material costs were scaled based on the ratio of near-term conversion capital cost to the long-term conversion capital cost.

QUALITY JUDGMENT: Maintenance for the stirling unit is highly subjective and until significant operating data is obtained the estimate is rated as "poor".

DATA: Long-term maintenance costs were estimated as the following:

labor: \$5.83 per $m^2$ of aperture area
material: \$3.89 per $m^2$ of aperture area

Using the long-term material estimate as a basis, the near-term materials estimate was prepared by multiplying the long-term estimate by the ratio of the near-term conversion cost to the long-term conversion unit cost. This ratio is represented by the following equation:

$$\{1071.863 + (-99.474)\ln(\text{Size, MW}/0.5\text{ MW})\}/7370$$

Where "size" is the total gross generating capacity of the plant size being estimated. Multiplying this equation by the long-term materials cost estimating equation yields the following near-term conversion maintenance materials cost estimating equation for a 50-kWe stirling unit:

$$\text{materials} = \{1071.863 + (-99.474)\ln(\text{Size, MW}/0.05\text{ MW})\}\{(3.89)(m^2\text{ of aperture area})\}/7370$$

In addition a 15% overhead charge must be added to this estimate (Guthrie 1974).

SUBCOMPONENT: MAINTENANCE OF THE TRANSPORT SYSTEM

METHOD: It is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent, because transport system maintenance is already in a mature state of development. The details and basis for the estimate are included in the long-term documentation.

SUBCOMPONENT: BALANCE-OF-PLANT MAINTENANCE

METHOD: It is estimated that there will not be a significant difference between the long-term and near-term costs for this subcomponent as balance-of-plant maintenance is already in a mature state of development. The details and basis for the estimate are included in the long-term documentation.

## INDIRECTS AND CONTINGENCIES

METHOD: Comparison and adjustment of existing estimates

DATA: Seven complete system estimates formed the basis for the indirects and contingencies estimate. The source estimates are presented in Table C.49.

Table C.49. Source Estimates for Dish System Indirects and Contingencies

| Source | Indirects | Contingencies |
|---|---|---|
| SCE et al. (1982, p. 19) | - | 20 |
| Weber (1983) | - | 23 |
| Easton and Endicott (1982) | 21 | 10.6 |
| Weber (1982) | 24.3 | 17.3 |
| Weber (1980) | 30.7 | 12.2 |
| Joy et al. (1981) | 15.8 | 15 |
| Bloomster et al. (1982) | 25 | 25 |
| Avg. | 23.4 | Avg. 17.6 |

The average indirects estimate was rounded to 25 percent. The contingency estimate was reduced to 10% for the mature components (i.e., transport, and balance-of-plant). For other components it was reduced to 15% to be representative of new technology with no extraordinary contingencies and to be consistent with the utility studies (Hillesland et al. 1988).

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# APPENDIX D

## STIRLING ENGINES IN SOLAR APPLICATIONS

## WORKING PAPER ON STIRLING ENGINES IN SOLAR APPLICATION

### The Stirling Engine

Stirling engines convert heat into useful work through a thermodynamic process using a single phase fluid, usually a pressurized gas. This working fluid is continuously cycled between the hot and cold parts of the engine, in order to cause a work-producing pressure variation. A regenerator, usually made of stacked wire mesh, temporarily stores heat so that high efficiency can be achieved. Heat exchangers that transfer heat into and out of the cycle must be carefully designed.

Stirling engines can be designed in various configurations. The kinematic stirling engine uses pistons and possibly displacers that are mechanically linked to the crankshaft. The free-piston stirling engine has no crankshaft; the piston and displacer motions are governed solely by inertia and pressure changes in the working space. Power from a free-piston engine is removed through a linear motor, or by hydraulic means. The Ringbom stirling engine uses a kinematic piston and a free-displacer, which provide a simple configuration while maintaining the rotary output of the kinematic engine.

The word "stirling" was capitalized in the past, due to it being the last name of the inventor, Robert Stirling. Enough changes to the engine have taken place since then that like diesel, stirling has become a generic term and is not required to be capitalized.

### Current Status / Engine Availability

Although actual testing of stirling engines on solar parabolic dishes has not been funded by the DOE for the past two years, significant progress has been made with stirling engines that can be used in solar applications. Kinematic engines have been further developed by United Stirling in Sweden, Stirling Power Systems, Mechanical Technology Inc. (MTI) and Stirling Thermal Motors in the USA and by Societe' ECA in France. Advanced Stirling Conversion Systems (ASCS), utilizing free-piston stirling engines, are being developed for solar applications by MTI and Stirling Technology Company (STC) through the NASA-Lewis Research Center.

Stirling-related technology in Japan has greatly advanced in recent years. Numerous stirling heat pump system prototypes in the 3 kWe and 30 kWe range have been developed by several Japanese companies and research organizations as part of the Moonlight project. These engines may be adapted to solar power production, but in any case, the technology involved is not significantly different from the technology available in the US.

The engines available today are scarce and expensive, since only research purposes are currently being served. However, some designs already reflect efforts to reduce production costs. Heat exchanger materials have been identified that are low in strategic metals and thus are less expensive.

Power ratings for stirling engines in solar applications tend to be lower than for non-solar stirling engines. For non-solar applications, power density is more important than long life, so the engines are operated at 3000-4000 rpm. For solar applications, long life is more important than power density, so a synchronous speed of 1800 rpm is typically chosen.

Description of Kinematic Engines

The United Stirling (USAB, Malmo, Sweden) Mark II (4-95) 25-kWe engine, shown in Figure 1 (all figures appear at the end of the paper), has been used extensively by McDonnell Douglas, Advanco Corp., Southern California Edison and Georgia Power & Light for solar-stirling research. It is a 4-cylinder double-acting kinematic engine that was originally developed for automotive applications. The crankcase is not significantly pressurized, as the piston rod seals operate between the engine pressure and atmospheric pressure. Minor improvements have been made over the years, and about a dozen have been built for solar applications.

A larger version of the 4-95 engine, the 4-275, has also been built. This engine can produce 118 kWe when hydrogen is used as the working fluid (non-solar applications), and has a gross efficiency of 47%. In solar applications it is rated at 62 kWe and has a net efficiency of 39.5%. Two of the engines were build for solar use in Saudi Arabia, but the major purpose of the engine is for underwater, air-independent applications. In fact, USAB was purchased on October 23, 1987 by Kockums Marine AB, who is a manufacturer of underwater vehicles. It is expected that solar application stirling engines will still be available from the United Stirling division of Kockums Marine AB. While their efforts will obviously center on underwater applications, improvements to the engine will probably lead to improvements in solar-application engines as well.

The Mechanical Technology Inc. (MTI, Latham, New York) MOD II 25-kWe engine was developed for automotive use; a prototype was recently mounted in a Chevrolet Celebrity chassis. This engine, like the MOD I previously developed by MTI, is a descendent of the United Stirling technology, and like the Mark II, it has 4 double-acting pistons and high pressure difference piston rod seals. While the engine produces up to 60 kW in automotive applications, the output in solar applications is currently expected to be 25 kWe (previously estimated at 40 kWe by Holtz). Minor design changes, based on suggestions by a group of manufacturing engineers from John Deere Inc., have been incorporated to reduce the manufacturing cost and improve performance. For solar use the roller bearings in the crankcase would be replaced by journal bearings and the heater tubes would be modified, which is perceived to be a fairly trivial activity. The engine is shown in Figure 2. While DOE funding for the stirling automotive work has essentially stopped, technology transfer efforts to the US Air Force and others continue. While several successful prototypes have been built by MTI, US auto-makers have shown no interest in mass production of the engine.

The Stirling Thermal Motors (STM, Ann Arbor, Michigan) STM4-120 25-kWe engine, shown in Figure 3, is derived from technology licensed from N. V. Philips of Holland. Four double-acting pistons drive a variable angle swashplate that is enclosed in a pressurized crankcase. The most critical seal is the rotating shaft seal at the rear of the engine; the piston shaft seals operate over only the difference between the mean cycle pressure and peak cycle pressure. The heater tubes receive thermal energy through a sodium heat pipe, so the engine is well suited for hybrid operation. A prototype has been built and laboratory testing is underway. Funding is provided by DOE through Sandia National Laboratory.

The Stirling Power Systems (SPS, Ann Arbor, Michigan) V-160 10-kWe engine uses 2 single-acting pistons in two cylinders (alpha configuration) to generate about 10 kWe. The engine, shown in Fig. 4, was developed from United Stirling technology in the late 70's as a cogeneration package for large recreational vehicles, and has since been refined as a residential cogeneration package, as a heat pump and for solar/hybrid applications. The engine is in limited production; 50 standard engines and 10 solar engines will be built this year.

The Societe' ECA (France) stirling engine, shown in Fig. 5, was developed for application in submarines. The lower unit is taken from a Renault automotive engine; the automotive pistons act as crossheads. The crankcase is not pressurized. A prototype for underwater applications has been constructed and testing is underway. Funding is provided by the defense departments of several countries.

Description of Free-Piston Engines

The Sunpower (Athens, Ohio) solar 10-kWe free-piston engine, shown in Fig. 6, is based on a prototype 3-kWe air engine. The addition of tubular heaters and the use of hydrogen as the working fluid is estimated to increase the power output to close to 10 kWe. This conceptual design has not yet been implemented in hardware form, nor is it currently funded.

The Stirling Technology Company (STC, Richland, Washington) 25-kWe STIRLIC engine, shown in Fig. 7, is based on technology developed for the artificial heart program at the Tri-Cities University Center at Richland, Washington. Because the output of the free-piston engine is hydraulic, the generator can be located either with the engine or on the ground. In fact, the output from several dish/stirling units can be coupled to a single, larger generator. Depending on the decision made by NASA-Lewis late in 1987, a prototype may be built from this design.

The MTI 25-kWe free-piston engine, shown in Fig. 8, is essentially a double-scaled version of the Space Power Demonstrator Engine (SPDE). While the SPDE uses 2-12.5 kWe engines to minimize vibration and balancing problems, the solar concept uses a single 25 kWe engine. This concept may be built as a prototype, depending on the decision made by NASA-Lewis late in 1987.

The description of free-piston and kinematic engines cover only the engines that are documented as have been considered for solar applications. However, any stirling engine can be converted to solar applications, so the list above cannot be considered to be complete. It is, however, adequate to cover the range of technologies that are being researched at the present time.

Advances in Materials

After an extensive research program at NASA-Lewis Research Center, alloys CG-27 and XF-818 have been identified as capable of withstanding the rigorous requirements of the Stirling engine (Stephens 1986). These alloys are low in cost and contain a minimum of strategic materials such as cobalt and chromium. Additional requirements include oxidation/corrosion resistance, capability to be fabricated, weldability and long term cycle operation. Alloy CG-27 was chosen for the heater head tubes because of its high strength, achieved by precipitate strengthening, and its resistance to hydrogen permeation, achieved by forming an aluminum-rich oxide on the tube internal diameter. Alloy XF-818 was chosen for the cylinder and regenerator housing because of its good castability, strength, ductility and weldability.

Reliability

There is not sufficient failure rate data from stirling engines in solar applications, or from stirling engines in general for a traditional reliability study to be performed. Some insights into the perceived critical areas are supplied, and opinions are given as to whether suitable reliability for solar applications can be achieved. The required lifetime for solar stirling energy conversion units is estimated to be 50,000 hours, which is equivalent to operating an engine for 1.5 million miles in an automobile that averages 30 mph. It is assumed that stirling engines used in solar applications operate at 1800 rpm, rather than 3600 rpm typical for automotive and some power generation applications.

One of the reliability concerns that has received the most attention involves seals, piston rod seals in particular (Holtz 1987). For the traditional kinematic engine, such as the United Stirling USAB Mark II, the piston rod seal must operate between the mean operating pressure of the engine and essentially atmospheric pressure. Due to the high pressures involved and the sliding nature of the seal, long life of the seal is difficult to achieve. Over 2000 hrs of operation have been achieved for the pumping Leningrader seals typically used; it is expected that a lifetime of 3500 hrs, required for automotive applications, can be achieved. However, it is not likely that this seal will be able to achieve the required lifetime for solar applications. The solution may be to use a pressurized crankcase in order to reduce the huge pressure difference across the piston rod seal. The Stirling Thermal Motors STM4-120 engine uses a pressurized crankcase and the seal that interfaces between mean engine pressure and atmospheric pressure is a rotary type instead of a reciprocating type. A pressurized crankcase can also be used in conjunction with an internal alternator or magnetic coupling, so that the crankcase can be hermetically sealed (Ross 1987). Free-piston engines do not have this concern, since they have pressurized crankcases without piston rods to seal. In conclusion, it appears that the piston rod seal problem can be solved by either using a free-piston engine or by using a kinematic engine with a pressurized crankcase. As a result, lifetimes will be based on bearing life or heated metal-part life, which typically have lifetimes an order of magnitude greater than piston rod seals.

The USAB Mark II engine receives solar energy from the concentrator directly on its heater tubes. Due to imperfections and variations in the reflective degradation across the concentrator, the energy is not received by the heater tubes uniformly, causing tube temperature variation, or "hot spots." This can be treated by lowering the average tube temperature below the optimal operating temperature; if it is not treated the overheated tubes will fail prematurely. Non-uniform heater tube temperatures can be a problem for stirling engines in non-solar applications as well. A recommended solution is to use a thermal buffer between the concentrated solar energy and the heater tubes, such as a sodium heat pipe or a sodium pool boiler arrangement. Although complexity and thermal lag will increase, the heater tube temperatures will be quite uniform, and long life can be expected. The use of heat pipes with stirling engines is under development at Stirling Thermal Motors, Societe ECA and several other organizations.

Precise engine control is essential for unattended solar applications. Power control is typically achieved by varying the mean operating pressure or by varying the displacer or double-acting piston stroke. Stroke control is thought to be more efficient at part loads, but this has not been clearly demonstrated experimentally. Stroke control can be achieved in a kinematic engine by using a swashplate, as is done in the STM4-120. Stroke control can also be achieved by coupling a linear electric motor to the "free" displacer in a free-piston or Ringbom stirling engine.

Downtime of the USAB Mark II solar stirling engine system was largely due to false alarms and failures of the electronic engine control system. Early in the program sensors failed, sensor wiring failed, circuit boards of the control unit failed and the entire control system was affected by variations in the power supply. Most of these problems have been resolved, but the control unit must be further improved for the energy conversion unit to be a reliable performer.

Performance

Efficiency of stirling systems is largely a function of Carnot efficiency, which is based on the temperature difference. As shown in Table 1, gross efficiency (shaft mechanical power as a fraction of heater tube heat input) measurements and estimates vary from 40-50 percent. The key to higher efficiencies is to use indirect heating, such as a sodium heat pipe, so that the engine heater tube temperatures can be uniformly close to the maximum temperatures that the heater tubes can tolerate. The use of ceramics may eventually allow the hot end temperatures to be significantly increased, but in the near term 820°C should be considered to be the maximum heater tube temperature.

TABLE 1. Terrestrial Solar Stirling Engine Performance

| Reference/Company/Engine | Year | Output/Type | Heater Temp | % of Carnot Eff. | Gross Eff. | Net Eff. |
|---|---|---|---|---|---|---|
| Washom / USAB / Mark II | 1984 | 25kWe / Kin | 750°C | 0.59 | 0.42 | 0.36 |
| Holtz / USAB / Mark II | 1987 | 25kWe / Kin | 750°C | 0.58 | 0.41 | |
| Wells / USAB / 4-275 | 1982 | 62kWe / Kin | 720°C | 0.60 | 0.425* | 0.395 |
| Holtz / MTI / MOD I | 1987 | 39kWe / Kin | 820°C | 0.59 | 0.43 | |
| Sterns / MTI / MOD II | 1985 | 25kWe / Kin | 820°C | 0.62 | 0.45 | |
| Holtz / MTI / MOD II | 1987 | 40kWe / Kin | 820°C | 0.59 | 0.43 | |
| Sterns / Societe' ECA | 1985 | 22kWe / Kin | 720°C | 0.64 | 0.45 | |
| Sterns / STM / STM4-120 | 1985 | 27kWe / Kin | 820°C | 0.66 | 0.48 | |
| Holtz / STM / STM4-120 | 1987 | 25kWe / Kin | 800°C | 0.65 | 0.47 | |
| Williams / SPS / V-160 | 1987 | 10kWe / Kin | | | 0.33* | 0.307 |
| Holliday/ Sunpower | 1986 | 10kWe / FPa | 725°C | 0.57 | 0.40 | 0.34 |
| Sterns / Sunpower | 1985 | 25kWe / FPa | 800°C | 0.56 | 0.40 | |
| Shaltens / MTI | 1987 | 25kWe / FPa | 800°C | | | 0.33 |
| Shaltens / STC / STIRLIC | 1987 | 25kWe / FPh | 800°C | | | 0.33 |

Notes: Type refers to kinematic (Kin), free-piston with linear alternator (FPa) and free piston with hydraulic output (FPh). % of Carnot efficiency is the gross efficiency divided by the Carnot efficiency, which is the maximum possible efficiency for a heat engine. The sink temperature is assumed to be 300°K. Gross efficiency is shaft mechanical power as a fraction of heater tube heat input. Net efficiency is electric output as a fraction of shaft mechanical power.
* Parasitic losses other than the generator are included.

Efficiency of free-piston engines are expected to be slightly less than kinematic engines. Free-piston engines may offer better reliability, but the weight of the linear alternator (see Fig. 6 and 8), which overshadows the engine, may detract from the performance of the dish/stirling system.

Net efficiency is typically 6 percentage points lower than gross efficiency due to generator losses (~3%) and parasitic losses. The parasitic losses include the cooling fan (~1%), the water pump (~1%), and the power control system compressor (~1%).

In summary, reasonable performance has been achieved in working engines. While some improvements may be made in engine performance, alternator performance, and parasitic losses, the most critical needs are to reduce costs and increase reliability.

Advanced Concepts

At the present time, the weight of the energy conversion unit, mounted at the focal point of the dish, is not much of an issue, due to the tremendous weight of the dish itself. An energy conversion unit weight of 2000 lb. for an 11-meter dish is currently acceptable. However, future dishes utilizing thin-film coated reflectors may be much lighter, requiring a light-weight energy conversion unit for proper balancing. Linear alternators will probably be too heavy for such applications, so free-piston engines with hydraulic output, or Ringbom and kinematic engines with small, high efficiency rotary alternators will probably be used.

High pressure difference piston rod seals may never achieve the required lifetimes for commercial solar applications. Pressurized crankcases, whether in a free-piston, Ringbom or kinematic design, will probably be required.

Sodium heat pipes or indirect heating of some kind will probably be used on advanced stirling systems. As a result, hybrid operation will be relatively easy to achieve.

Kinematic Stirling PCU Cost Estimate

In general, cost estimates for stirling engines are few in number. Although existing estimates were made in good faith, it is difficult to substantiate the estimates due to a lack of production experience and the "immature" nature of some engine designs. Because engine configurations are essentially the same regardless of the application, the successful solar-stirling engine will probably be used in both solar and non-solar applications. It is also possible that small engines, perhaps even smaller than the common 25-kWe unit could more easily penetrate the market first; then later, as production rises to a significant level, engine production might shift to larger sizes. Alternatively, other production-cost-size relationships unique to the stirling engine might exist. Some of these are discussed in this paper.

Long-term costs for stirling engines will reflect further advances in materials and manufacturing techniques. The use of ceramics could play a major role if ceramic brittleness is reduced and if ceramic/metal interface problems can be resolved. Stirling engines tend to be expensive, due to severe pressure/temperature requirements, but eventually the cost should be only slightly higher than for a comparable diesel engine.

Regardless of the design, two factors which will have a profound effect on the production cost of stirling engines include production and size economies-of-scale. The interaction of these effects can produce interesting results. Understanding the relationship of the effects with each other is required, if the most rapid market penetration of dish-stirling systems is to occur.

Production Economies-of-Scale

Production economies-of-scale are achieved as the production volume is increased, allowing mechanization of the production process, distribution of the capital investment over a larger number of units produced, etc. Stirling engine cost data from three sources was evaluated which compares the cost of a 25-kWe engine/mechanical-to-electric conversion unit as a function of varying production levels. (Hereafter, the combination of a stirling engine with a mechanical-to-electric conversion unit is termed a power conversion unit, PCU.) These data are presented in Table 2. The Vanguard estimates were for installed dish system PCUs and have been reduced to an un-installed cost by assuming installation adds ten percent to the basic PCU cost. The other two estimates reflect only the purchase cost. The data from these sources was fit to two equations; the first of these equations was based on the data points which ranged from one to 10,000 units per year and the second was based on the data points ranging from 10,000 to 400,000 units per year. The intersection of these equations is at a production level of 9577 units per year. A graph of the equations is presented in Figure 9, and the equations are as follows:

| | |
|---|---|
| $1 < \text{units/year} < 9{,}577$ | $\$/kWe = 2020.474 + (-187.509)\ln X$ |
| $9{,}577 < \text{units/year} < 400{,}000$ | $\$/kWe = 5701.798X^{-0.32068}$ |

The goodness of fits ($r^2$) for these equations are 0.970 and 0.943, respectively.

TABLE 2. Kinematic Stirling Power Conversion Unit Cost Data (1984$)

| Source | Production Quantity | Cost/Unit |
|---|---|---|
| United Stirling[(a)] | 1 | $50,000 |
| | 2,000 | 20,000 |
| | 25,000 | 5,500 |
| JPL[(b)] | 1,000 | 17,576 |
| | 25,000 | 5,641 |
| | 100,000 | 2,946 |
| | 400,000 | 2,539 |
| Vanguard[(c)] | 1 | 52,616 |
| | 100 | 26,310 |
| | 1,000 | 14,057 |
| | 10,000 | 7,909 |

(a) Worth Percival of United Stirling, Inc.
(b) Fortgang and Mayers (1980, p. 10) prices were escalated to 1984$
(c) Washom (1984, p. 9) prices were escalated to 1984$ and reduced to represent purchase cost only.

Using the equations from above, Table 3 shows the predicted cost of a 25-kWe unit for various production rates and the fraction of the cost of the first unit. The table shows that at a production rate of just over 30,000 units per year the cost is about 10% of the cost of producing only one unit. At production rates an order of magnitude higher (300,000 units per year), the cost is half-as-much and represents a cost of about 5% of the cost of producing only one unit.

TABLE 3. Production Rate Versus Cost for Kinematic Stirling Power Conversion Units

| Production Rate, Units/yr | Cost, $/kWe | Fraction of Cost of Producing One Unit |
|---|---|---|
| 1 | 2020 | 1.0000 |
| 5 | 1719 | 0.8510 |
| 10 | 1589 | 0.7866 |
| 50 | 1287 | 0.6371 |
| 100 | 1157 | 0.5728 |
| 500 | 855 | 0.4233 |
| 1000 | 725 | 0.3589 |
| 5000 | 423 | 0.2094 |
| 10000 | 297 | 0.1470 |
| 50000 | 177 | 0.0876 |
| 100000 | 142 | 0.0703 |
| 200000 | 114 | 0.0564 |
| 300000 | 100 | 0.0495 |
| 400000 | 91 | 0.0451 |

Size Economies-of-Scale

Size economies-of-scale are achieved as the engine size is increased which allows the use of less material and labor hours per kWe of output. A review of several sources indicates size economies-of-scale do exist, but the extent is questionable. The general form of the cost-scaling equation using a cost-size factor (denoted as SF) is as follows:

$$\text{Unit Cost}_2 = \text{Unit Cost}_1 * (\text{Size}_1/\text{Size}_2) * (\text{Size}_2/\text{Size}_1)^{SF}$$

One difficulty in using this type of an equation is that it is only accurate over a small size range for which a SF has been determined for the piece of equipment to be scaled. Accurate SFs are based either on historical cost versus size data or on a detailed design analysis of the item to be scaled. As a general practice, an equipment cost estimate should not be prepared using a SF, if the SF was derived from cost data for equipment which varies from the size of the unit of which the estimate is being prepared by 50% smaller or 100% larger. This is important because for small size ranges the SF is relatively constant; however, over broad size ranges the SF increases with increasing size. Considering these limitations on the use of a cost-scaling equation, the equation will only provide good data for the power conversion unit if an accurate SF for a size range which includes the 25-kWe unit (the size for which scaleable cost data is available).

Using such an SF, reasonable estimates for PCUs ranging from 50% smaller than 25 kWe (~10 kWe) and 100% larger than 25 kWe (50 kWe) could be prepared. Since there is no existing SF specifically developed for the PCU, and current resources have prevented a detailed analysis, SFs for other pieces of equipment which resemble the power conversion unit, albeit slightly, were used to illustrate what the cost-size relationships for the PCU might be. The SFs used include 0.83, 0.6, and 0.4. The 0.83 factor originated as a cost-scaling factor for un-installed diesel engines ranging from 1000 to 15000 horsepower (750 to 11200 kW) (Boehm 1985 p. VI-18). Obviously, this factor was developed for diesel engines significantly larger than the 25-kWe stirling engines dealt with here; therefore, a more representative factor is probably less than 0.83, but this factor provides an approximate upper bound. Although it was not used in this analysis since it is approximately the same as a SF of 0.83, a reciprocating compressor with motor (1 to 1000 kW) has a SF of 0.79 (Boehm 1985 p. VI-17). The 0.6 factor was selected for three reasons, the majority of scaling factors for all equipment are approximately 0.6 (Miller 1978 Section A.1000 p. 3), the SF for a positive displacement pump without a motor (1 to 70 kW) is 0.52 (Boehm 1985 p. VI-16) (adding a motor tends to raise the SF slightly), and the SF for 10 to 1000 kW generators is 0.66 (Boehm 1985 p. VI-17). The final SF, 0.4 (Jelen 1970 p. 315), is for a 1 to 15 hp (0.75 to 11.2 kW) stainless steel centrifugal pump with motor. The 0.4 SF provides a reasonable lower bound. Using each of these three factors independently and the 25-kWe unit-cost equations, the costs of 10-kWe and 50-kWe power conversion units at various production levels were estimated. Applying the general form of the scaling equation to the previously developed equations for the 25-kWe PCU, the following equations result:

$1 < \text{units/year} < 9{,}577$

$$\text{\$/kWe for 50-kWe engines} = (25/50)(2020.474 + (-187.509)\ln X)((50/25)^{SF})$$

$9{,}577 < \text{units/year} < 400{,}000$

$$\text{\$/kWe for 50-kWe engine} = (25/50)(5701.798X^{-0.32068})((50/25)^{SF})$$

$1 < \text{units/year} < 9{,}577$

$$\text{\$/kWe for 10-kWe engine} = (25/10)(2020.474 + (-187.509)\ln X)((10/25)^{SF})$$

$9{,}577 < \text{units/year} < 400{,}000$

$$\text{\$/kWe for 10-kWe engine} = (25/10)(5701.798X^{-0.32068})((10/25)^{SF})$$

## Estimate Kinematic Stirling PCU Costs

Tables 4 through 6 present the cost/kWe for the different PCU sizes at various production levels using the three scaling factors. Examination of these tables reveals some interesting relationships between economies-of-scale and economies-of-production. For any given number of units, the largest power conversion unit is always the most economical to produce (see Tables 4 through 6). However, at a given power level of production (i.e., the same number of MW/yr produced regardless of size) this is not necessarily true. Tables 7 through 9 illustrate this by comparing the cost per kW for 10, 25, and 50 kWe power conversion units for constant power levels of production. Finally, Tables 10 through 12 list the percentage by which the 50-kWe and 10-kWe power conversion units are cheaper or more expensive than the 25-kWe PCU.

TABLE 4. Production Rate Versus Cost per kWe for Three Sizes of Kinematic Stirling Power Conversion Units Using a Cost-Size Scaling Factor of 0.4

| Units Produced Per Year | 50-kWe ($/kWe) | 25-kWe ($/kWe) | 10-kWe ($/kWe) |
|---|---|---|---|
| 1 | 1333 | 2020 | 3501 |
| 5 | 1134 | 1719 | 2978 |
| 10 | 1048 | 1589 | 2753 |
| 50 | 849 | 1287 | 2230 |
| 100 | 763 | 1157 | 2005 |
| 500 | 564 | 855 | 1482 |
| 1000 | 478 | 725 | 1257 |
| 5000 | 279 | 423 | 734 |
| 10000 | 196 | 297 | 515 |
| 50000 | 117 | 177 | 308 |
| 100000 | 94 | 142 | 246 |
| 200000 | 75 | 114 | 197 |
| 300000 | 66 | 100 | 173 |
| 400000 | 60 | 91 | 158 |

TABLE 5. Production Rate Versus Cost per kWe for Three Sizes of Kinematic Stirling Power Conversion Units Using a Cost-Size Scaling Factor of 0.6

| Units Produced Per Year | 50-kWe ($/kWe) | 25-kWe ($/kWe) | 10-kWe ($/kWe) |
|---|---|---|---|
| 1 | 1531 | 2020 | 2915 |
| 5 | 1303 | 1719 | 2480 |
| 10 | 1204 | 1589 | 2292 |
| 50 | 975 | 1287 | 1857 |
| 100 | 877 | 1157 | 1669 |
| 500 | 648 | 855 | 1234 |
| 1000 | 550 | 725 | 1046 |
| 5000 | 321 | 423 | 611 |
| 10000 | 225 | 297 | 429 |
| 50000 | 135 | 177 | 256 |
| 100000 | 108 | 142 | 205 |
| 200000 | 86 | 114 | 164 |
| 300000 | 76 | 100 | 144 |
| 400000 | 69 | 91 | 131 |

TABLE 6. Production Rate Versus Cost per kWe for Three Sizes of Kinematic Stirling Power Conversion Units Using a Cost-Size Scaling Factor of 0.83

| Units Produced Per Year | 50-kWe ($/kWe) | 25-kWe ($/kWe) | 10-kWe ($/kWe) |
|---|---|---|---|
| 1 | 1796 | 2020 | 2361 |
| 5 | 1528 | 1719 | 2008 |
| 10 | 1412 | 1589 | 1857 |
| 50 | 1144 | 1287 | 1504 |
| 100 | 1028 | 1157 | 1352 |
| 500 | 760 | 855 | 999 |
| 1000 | 645 | 725 | 847 |
| 5000 | 376 | 423 | 495 |
| 10000 | 264 | 297 | 347 |
| 50000 | 158 | 177 | 207 |
| 100000 | 126 | 142 | 166 |
| 200000 | 101 | 114 | 133 |
| 300000 | 89 | 100 | 117 |
| 400000 | 81 | 91 | 106 |

TABLE 7. Cost per kW at Constant Power Production Levels Using a 0.4 Cost-Size Scaling Factor (number of units produced per year is in parentheses)

| Production Rate | 50-kWe PCU | | 25-kWe PCU | | 10-kWe PCU | |
|---|---|---|---|---|---|---|
| 5 MW/yr | $763 | (100) | $1027 | (200) | $1482 | (500) |
| 10 MW/yr | $678 | (200) | $897 | (400) | $1257 | (1000) |
| 25 MW/yr | $564 | (500) | $725 | (1000) | $959 | (2500) |
| 50 MW/yr | $478 | (1000) | $595 | (2000) | $734 | (5000) |
| 100 MW/yr | $393 | (2000) | $465 | (4000) | $515 | (10000) |
| 200 MW/yr | $307 | (4000) | $335 | (8000) | $389 | (24000) |
| 300 MW/yr | $257 | (6000) | $280 | (12000) | $362 | (30000) |
| 400 MW/yr | $221 | (8000) | $256 | (16000) | $330 | (40000) |
| 500 MW/yr | $196 | (10000) | $238 | (20000) | $308 | (50000) |
| 600 MW/yr | $185 | (12000) | $225 | (24000) | $290 | (60000) |
| 700 MW/yr | $176 | (14000) | $214 | (28000) | $276 | (70000) |
| 800 MW/yr | $168 | (16000) | $205 | (32000) | $265 | (80000) |
| 900 MW/yr | $162 | (18000) | $197 | (36000) | $255 | (90000) |
| 1000 MW/yr | $157 | (20000) | $191 | (40000) | $246 | (100000) |

TABLE 8. Cost per kW at Constant Power Production Levels Using a 0.6 Cost-Size Scaling Factor (number of units produced per year is in parentheses)

| Production Rate | 50-kWe PCU | | 25-kWe PCU | | 10-kWe PCU | |
|---|---|---|---|---|---|---|
| 5 MW/yr | $877 | (100) | $1027 | (200) | $1234 | (500) |
| 10 MW/yr | $778 | (200) | $897 | (400) | $1046 | (1000) |
| 25 MW/yr | $648 | (500) | $725 | (1000) | $798 | (2500) |
| 50 MW/yr | $550 | (1000) | $595 | (2000) | $611 | (5000) |
| 100 MW/yr | $451 | (2000) | $465 | (4000) | $429 | (10000) |
| 200 MW/yr | $353 | (4000) | $335 | (8000) | $324 | (24000) |
| 300 MW/yr | $295 | (6000) | $280 | (12000) | $302 | (30000) |
| 400 MW/yr | $254 | (8000) | $256 | (16000) | $275 | (40000) |
| 500 MW/yr | $225 | (10000) | $238 | (20000) | $256 | (50000) |
| 600 MW/yr | $213 | (12000) | $225 | (24000) | $242 | (60000) |
| 700 MW/yr | $202 | (14000) | $214 | (28000) | $230 | (70000) |
| 800 MW/yr | $194 | (16000) | $205 | (32000) | $220 | (80000) |
| 900 MW/yr | $187 | (18000) | $197 | (36000) | $212 | (90000) |
| 1000 MW/yr | $180 | (20000) | $191 | (40000) | $205 | (100000) |

TABLE 9. Cost per kW at Constant Power Production Levels Using a 0.83 Cost-Size Scaling Factor (number of units produced per year is in parentheses)

| Production Rate | 50-kWe PCU | | 25-kWe PCU | | 10-kWe PCU | |
|---|---|---|---|---|---|---|
| 5 MW/yr | $1028 | (100) | $1027 | (200) | $999 | (500) |
| 10 MW/yr | $913 | (200) | $897 | (400) | $847 | (1000) |
| 25 MW/yr | $760 | (500) | $725 | (1000) | $647 | (2500) |
| 50 MW/yr | $645 | (1000) | $595 | (2000) | $495 | (5000) |
| 100 MW/yr | $529 | (2000) | $465 | (4000) | $347 | (10000) |
| 200 MW/yr | $414 | (4000) | $335 | (8000) | $262 | (24000) |
| 300 MW/yr | $346 | (6000) | $280 | (12000) | $244 | (30000) |
| 400 MW/yr | $298 | (8000) | $256 | (16000) | $223 | (40000) |
| 500 MW/yr | $264 | (10000) | $238 | (20000) | $207 | (50000) |
| 600 MW/yr | $249 | (12000) | $225 | (24000) | $196 | (60000) |
| 700 MW/yr | $237 | (14000) | $214 | (28000) | $186 | (70000) |
| 800 MW/yr | $227 | (16000) | $205 | (32000) | $178 | (80000) |
| 900 MW/yr | $219 | (18000) | $197 | (36000) | $172 | (90000) |
| 1000 MW/yr | $212 | (20000) | $191 | (40000) | $166 | (100000) |

TABLE 10. The Cost Relationship of Kinematic Stirling Power Conversion Units Assuming a 0.4 Cost-Size Scaling Factor

| Production Level | 50-kWe PCU | 10-kWe PCU |
|---|---|---|
| 5 MW/yr | -26% | 44% |
| 10 MW/yr | -24% | 40% |
| 25 MW/yr | -22% | 32% |
| 50 MW/yr | -20% | 23% |
| 100 MW/yr | -16% | 11% |
| 200 MW/yr | -8% | 16% |
| 300 MW/yr | -8% | 29% |
| 400 MW/yr | -14% | 29% |
| 500 MW/yr | -18% | 29% |
| 600 MW/yr | -18% | 29% |
| 700 MW/yr | -18% | 29% |
| 800 MW/yr | -18% | 29% |
| 900 MW/yr | -18% | 29% |
| 1000 MW/yr | -18% | 29% |

TABLE 11. The Cost Relationship of Kinematic Stirling Power Conversion Units Assuming a 0.6 Cost-Size Scaling Factor

| Production Level | 50-kWe PCU | 10-kWe PCU |
|---|---|---|
| 5 MW/yr | -15% | 20% |
| 10 MW/yr | -13% | 17% |
| 25 MW/yr | -11% | 10% |
| 50 MW/yr | -8% | 3% |
| 100 MW/yr | -3% | -8% |
| 200 MW/yr | 5% | -3% |
| 300 MW/yr | 5% | 8% |
| 400 MW/yr | -1% | 8% |
| 500 MW/yr | -5% | 8% |
| 600 MW/yr | -5% | 8% |
| 700 MW/yr | -5% | 8% |
| 800 MW/yr | -5% | 7% |
| 900 MW/yr | -5% | 8% |
| 1000 MW/yr | -6% | 7% |

TABLE 12. The Cost Relationship of Kinematic Stirling Power Conversion Units Assuming a 0.83 Cost-Size Scaling Factor

| Production Level | 50-kWe PCU | 10-kWe PCU |
|---|---|---|
| 5 MW/yr | - | -3% |
| 10 MW/yr | 2% | -6% |
| 25 MW/yr | 5% | -11% |
| 50 MW/yr | 8% | -17% |
| 100 MW/yr | 14% | -25% |
| 200 MW/yr | 23% | -22% |
| 300 MW/yr | 23% | -13% |
| 400 MW/yr | 17% | -13% |
| 500 MW/yr | 11% | -13% |
| 600 MW/yr | 11% | -13% |
| 700 MW/yr | 11% | -13% |
| 800 MW/yr | 11% | -13% |
| 900 MW/yr | 11% | -13% |
| 1000 MW/yr | 11% | -13% |

There is a large uncertainty in the estimates presented the tables above due to the fashion in which they were generated and the confidence in the initial data. For this reason it would not be appropriate to draw major conclusions from this data; however, some general conclusions can be made. For a 0.83 scaling factor, the 10-kWe unit has a cost advantage over the 50-kWe and 25-kWe units for all production levels presented. For a 0.4 scaling factor the largest engine is the most economical at all production levels. For most production levels there is a very small difference in the unit-cost between the three PCU sizes for which estimates were prepared using a 0.6 scaling factor. However, it is interesting to note that the 25-kWe units are most economical only at a production level of 300 MW per year.

Cost Conclusions

Considering all this information, and assuming it is accurate, it is apparent that significant cost advantages may be available if the true cost-size-production relationships can be identified and production efforts are directed toward cost-optimized PCUs. Since the PCU accounts for approximately 50% of the levelized energy cost (LEC) of the dish-stirling system (Williams et al. 1987), a 10% reduction in the PCU capital cost reduces the LEC by approximately 5%. The LEC of large dish systems (~100 MWe) has been estimated to be 70 to 80 mills per kWh (Williams et al. 1985), and if significant reductions in the PCU cost can be identified and achieved by using well-planned production approaches, a direct impact on the LEC would result. The result of this approach would be a more rapidly penetrate the market by the dish-stirling system. Of course, the statement above assumes that all other aspects of a dish system's cost remain equal in a relative sense and as we know this is not true. There are significant economies-of-scale in the collector system and additionally as Table 13 shows, engine efficiency increases significantly with size. An accurate cost-scaling factor must be determined to understand the true relationships which exist. There is a strong likelihood that all things considered (engine efficiency, engine cost, collector cost, etc.), the popular 25-kWe engine is not an optimum size for the near-term or long-term dish-stirling system. It is important to realize that these are not specific recommendations of a given engine size, but rather an illustration of the advantages of understanding the cost relationship between production level and engine size.

TABLE 13. Solar Engine Module Efficiency

| Module Electric Output (kWe) | Solar Engine Efficiency (%) |
|---|---|
| 8.74 | 33 |
| 22.8 | 40 |
| 57.7 | 43 |
| 288 | 47 |

Source: Wells et al. 1982

Other Kinematic Stirling PCU Cost Estimates

In addition to the kinematic stirling PCU cost estimates discussed above, two others estimates are available. The first is for the V-160 10-kWe kinematic engine (Williams 1987). This system is estimated to cost $100,000 for the first unit, $36,000 each for 1000 units, and $20,000 each for 10,000 units (all 1987-dollars). There is no information available describing the basis for these estimates. Also, the costs are prohibitively high and the engine is representative of older technology. For these reasons this design was not given further consideration.

The second estimate is for a solarized version of the Mod II automotive engine (MTI 1987). The estimate is based on a production level of 150,000 engines per year for this 25-kWe unit. The estimate of $3500 to $4000 ($140 to $160/kWe) is for a "ready-to-run" engine with the exception of the solar receiver, heat transport system, and the power generator. This cost estimate is the most reliable and accurate estimate for kinematic stirling engines, since the manufactured parts estimates were done by Deere & Company as part of a $1 million study. However, this estimate could not be included in the cost estimating equations generated above because the estimate is for the engine only and not the entire PCU.

To put the MOD II engine estimate in perspective, the cost of a 25-kWe PCU using the previously derived estimating equation was determined to be $261/kWe (1984-dollars) (roughly $287/kWe in 1987-dollars) at a production level of 15,000 units per year. According to United Stirling, the cost breakdown for their PCU is as shown in Table 14. To compare the estimates, it was assumed the solarized-Mod II estimate includes 20 to 30% of the hot part of a PCU, 20 to 30% of the cold part, all of the heat rejection part, and 70 to 80% of the controls, hardware, and support. Thus, the PCU estimate of $287/kWe needs to be reduced by about 40% to 48% to put it on approximately the same basis as the solarized-Mod II estimate. After this adjustment, the PCU estimate is $149 to $172/kWe. Given all the uncertainty, and the significant amount of design improvement the Mod II engine has received in the last three years, the two estimates are remarkably close as shown in Table 15.

TABLE 14. Cost Breakdown of the United Stirling PCU

| Percent of Total Cost | Item |
|---|---|
| 25-30% | Hot part of the system (mainly the receiver) |
| 15% | Cold part of the system (mainly power generator) |
| 15% | Heat rejection and radiator |
| 40% | Controls, Support, and Hardware |

Source: Hans Nelving of United Stirling (1985)

TABLE 15. Comparison of Adjusted PCU Estimate and Solarized Mod II Estimate

| Item | Estimate |
|---|---|
| Adjusted PCU | \$149 to \$172/kWe |
| Solarized Mod II | \$140 to \$160/kWe |

Free-Piston Stirling PCU Cost Estimates

Estimates for the free-piston stirling engine/energy conversion unit are nearly nonexistent. The sole source (additional estimates are forthcoming in the near-term) which had a free-piston engine with a linear alternator estimate suggested they will cost from \$3500-\$4200 for a 10-kWe unit at a production level of 3000 units per year. Based on this limited information, the free-piston engine could cost substantially less than the kinematic engine, perhaps 50 percent of less. Detailed cost estimates of the 25-kWe MTI and STC free-piston engines, yet to be released by Pioneer Engineering, are expected to be more accurate than previous free-piston engine estimates.

Areas for Further Research

While it is clear from the preceding discussion that there are numerous advantages of larger PCUs and dish sizes, there are certain advantages which are inherent to smaller dish sizes (kWe) that could effect the initial and overall market penetration of dish-stirling systems. Smaller dish sizes allow for:

- A lower initial capital cost if only one dish is being installed
- Greater redundancy for small system sizes (e.g., five 10-kWe units versus one 50-kWe--if one 10-kWe unit fails the other four will still operate).
- Reduced cost for spare parts inventory (e.g., for a 50 kWe installation one extra engine would probably be required--one extra 10 kWe PCU will cost less than one extra 50 kWe PCU)
- Modularity--capacity increments could be smaller

- Greater use in remote applications--many remote applications ideally suited for solar power generation (where photovoltaics are currently used) have small power loads (less than 50 kWe).

Even if the minimum LEC dish-stirling system in the long run is a larger dish size (50 kWe or greater) small ones may maintain a market niche in stand-alone applications. The experience in wind energy conversion systems (WECS) has followed the path of starting with smaller turbines and then increasing the size as operating experience is gained and the capital cost is reduced. Table 16 shows that as the capital cost ($/kWe) decreased, the average size of turbines at wind farms increased by 60% in three years.

TABLE 16. WECS Capacity, Capital Cost, and Turbine Size

| Total Installed Capacity (MW) | Installed Costs (1984$/kWe) | Average Turbine Size (kWe) |
|---|---|---|
| 13.0 | 3556 | 49 |
| 96.4 | 2343 | 56 |
| 296.2 | 1971 | 69 |
| 550.7 | 1860 | 78 |

Source: Smith, Watts, and Williams (1985)

While the larger turbine sizes are dominating the wind farm installations, small wind turbines (less then 10 kWe) are still very popular in stand-alone remote power applications.

Determining the optimal stirling engine entry level and long-term size (kWe) and type (kinematic, free-piston, or Ringbom) would best be done by doing a systems and market analysis which would:

- exploring the actual production level economies-of-scale and size economies-of-scale for all dish system components
- determine component and system efficiencies as a function of dish module size
- determine any market niches (high value markets like repeater stations) and the competition (e.g., photovoltaics, wind, diesel, etc.) which would affect the rate of initial market penetration and optimal dish module size.

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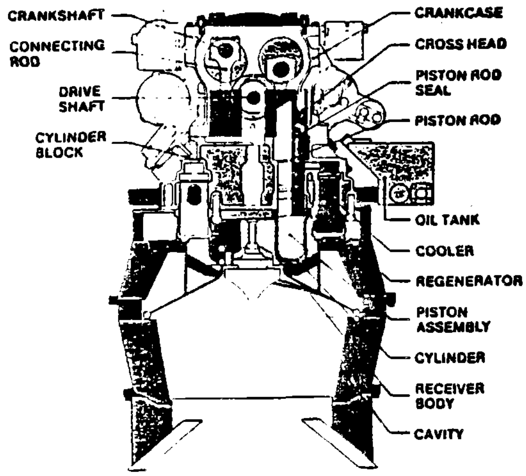



Figure 1. United Stirling USAB Mark II

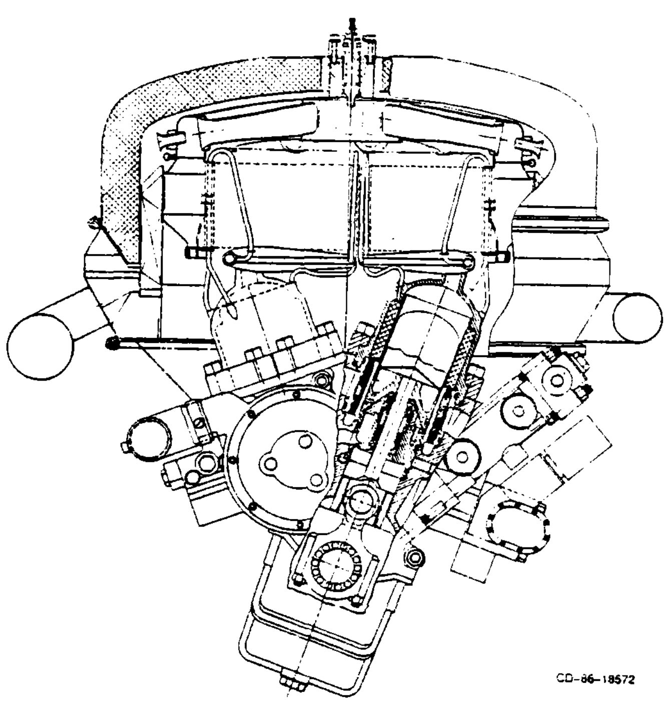



Figure 2. Mechanical Technology Inc. Mod II

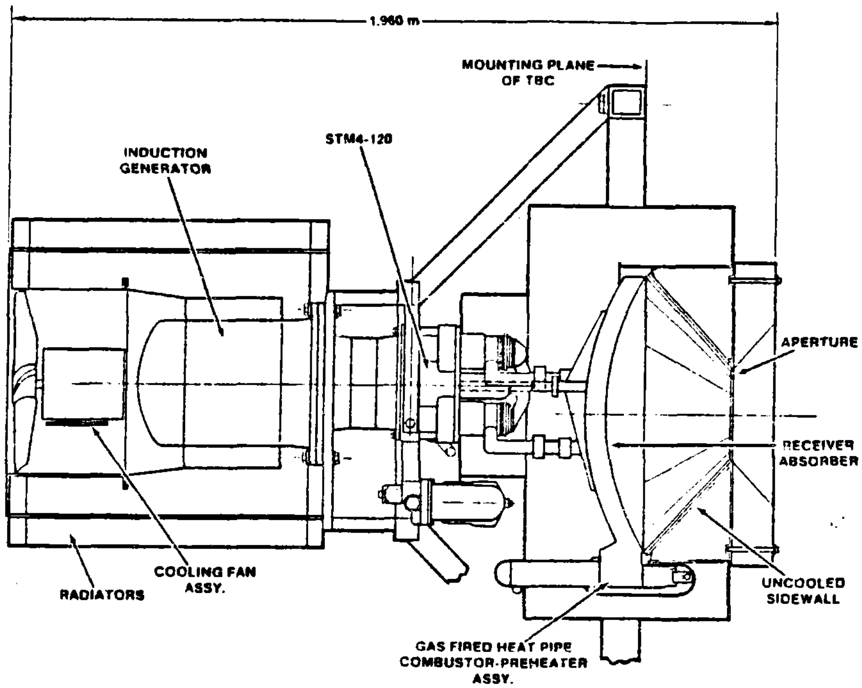



Figure 3. Stirling Thermal Motors STM4-120

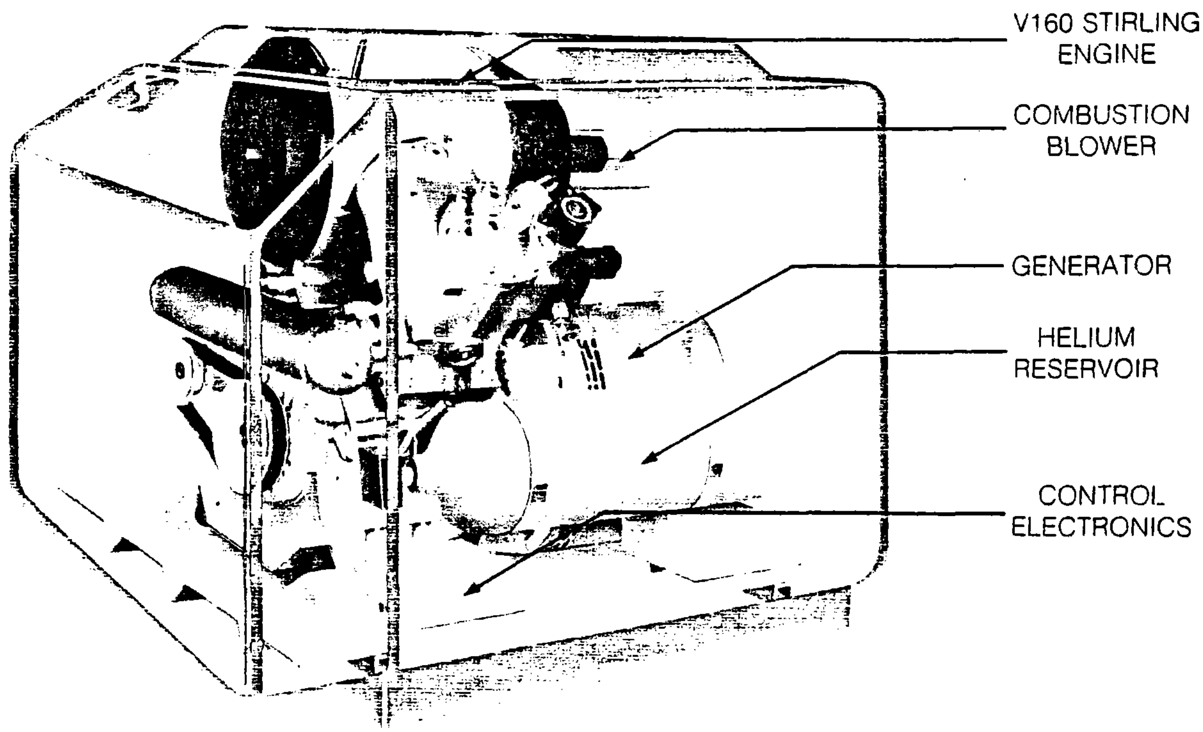



Figure 4. Stirling Power Systems V-160

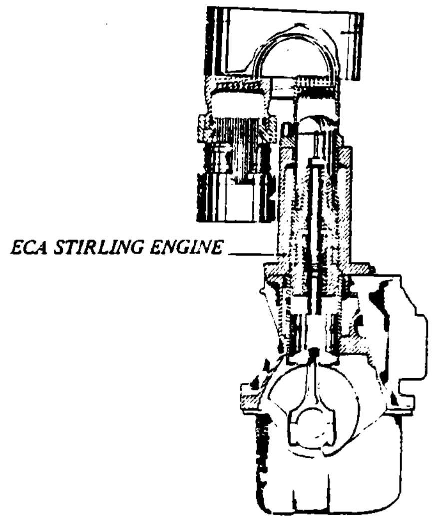



Figure 5. Societe' ECA Stirling Engine

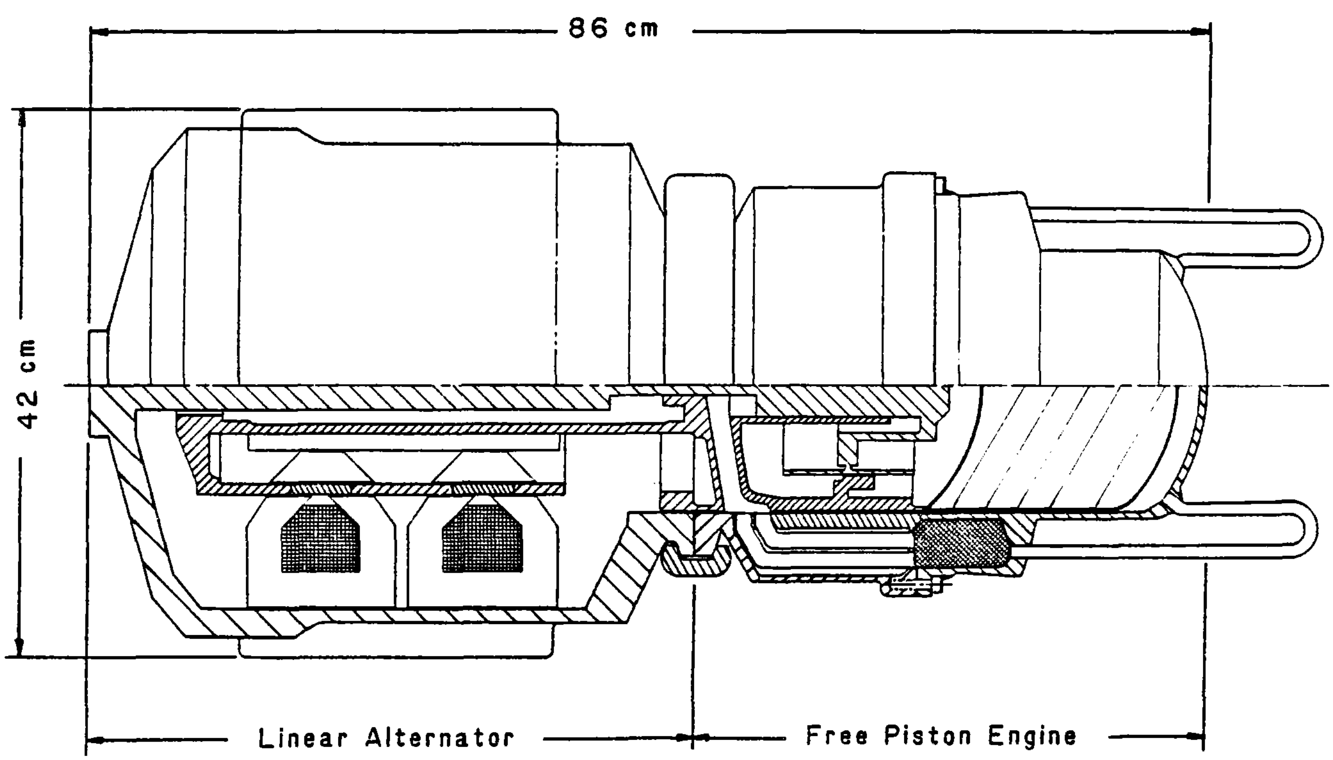



Figure 6. Sunpower Solar Free-Piston Engine

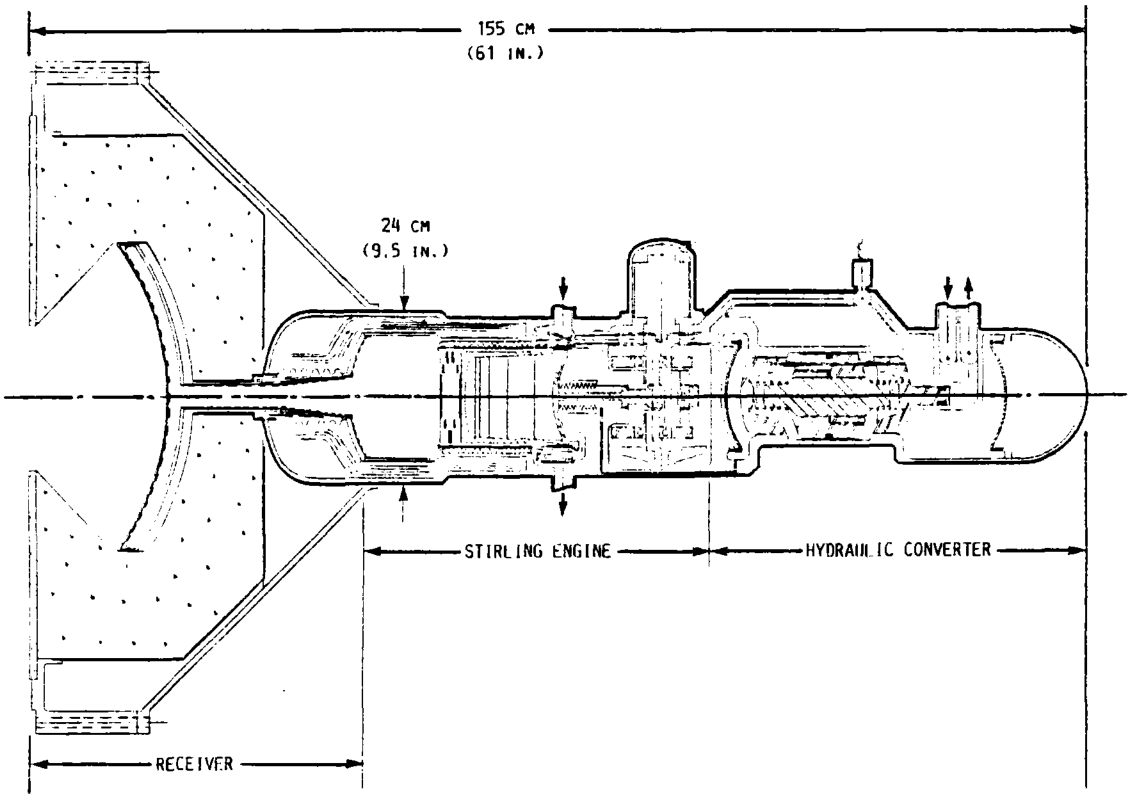



Figure 7. Stirling Technology Company STIRLIC

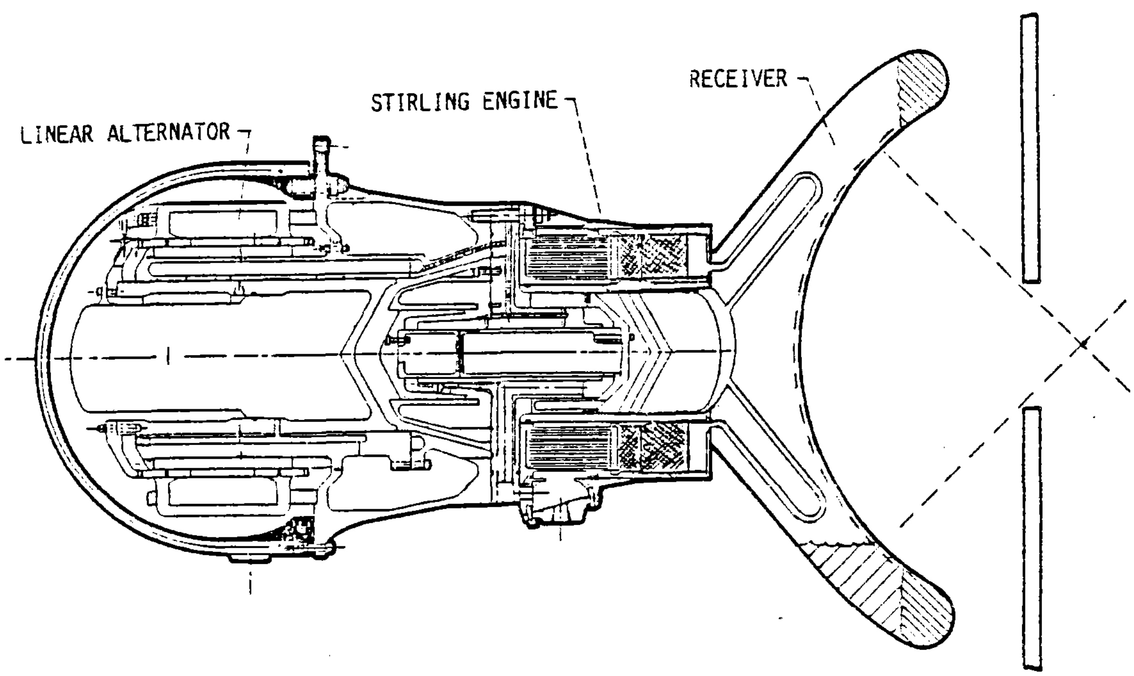
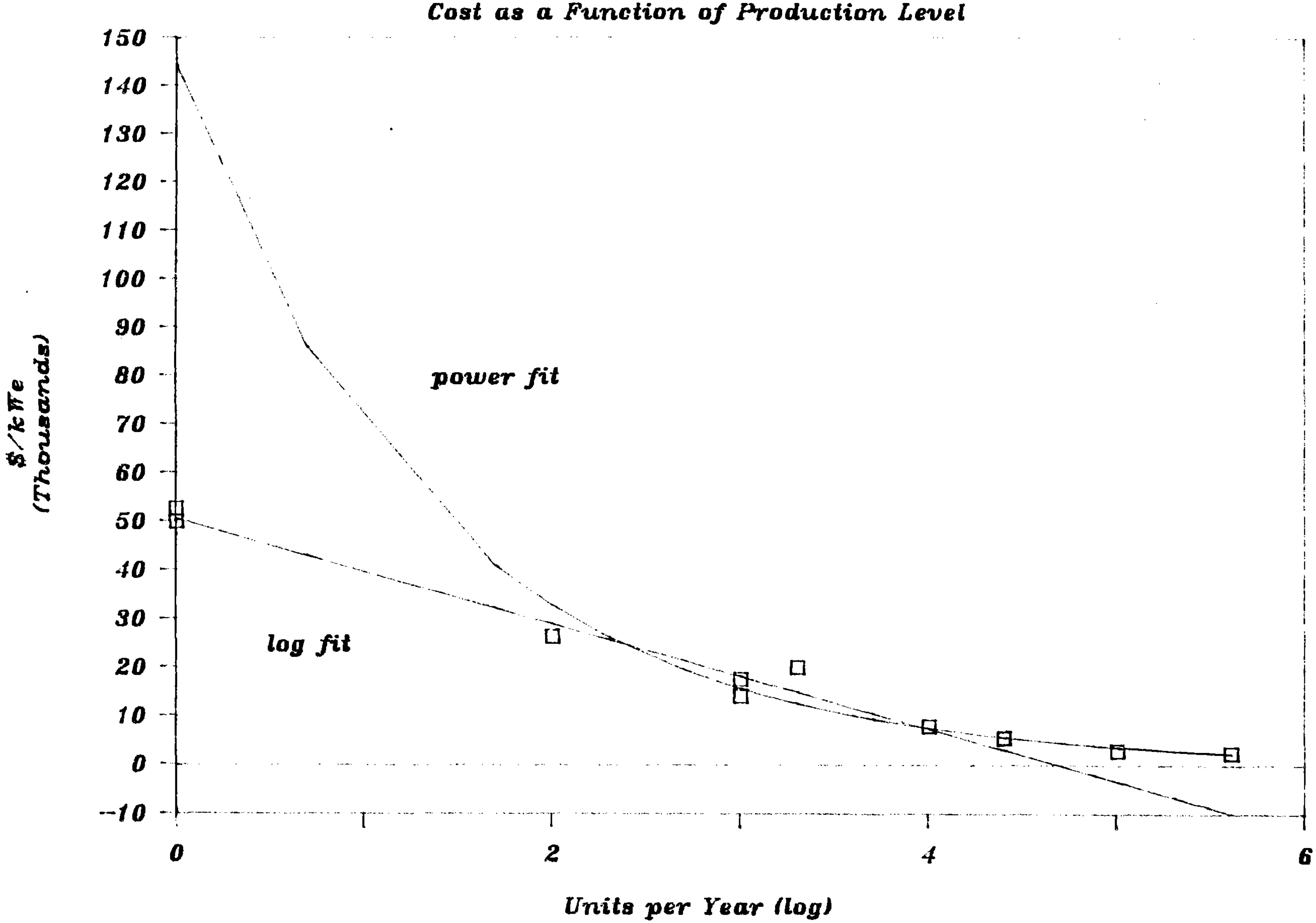



Figure 8. Mechanical Technology Inc. 25 kW Free-Piston Engine

# Figure 9. Stirling Engine Cost



# APPENDIX E

SELECTED CORRESPONDENCE BETWEEN PNL AND SERI

LONG-TERM STRESSED METAL-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 200 MWe (4000 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1535.12 | 1034.00 | 35.50 | 238.55 | 130.39 | 96.67 | 10.23 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3089.94 | 2291.70 | 18.90 | 621.25 | 14.42 | 143.67 | 20.60 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.52 | 655.60 | 17.55 | 202.22 | 4.08 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.59 | 0.00 | 40.77 | 45.82 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5622.15 | 3981.30 | 112.72 | 1107.83 | 148.89 | 271.41 | 37.48 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 1536.91 | 1122.00 | 27.00 | 360.90 | 16.21 (Low?) | 11.80 | 10.25 | 2, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1457.34 | 1251.80 | 0.00 | 110.64 | 94.90 | (a) | 9.72 | 3, 5, 11 |
| 2.3 Optical Material | 867.84 | 633.60 ($4.20/m²) | 10.12 | 172.19 | 50.68 | 1.24 | 5.79 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02[c] | 1947.42[c] | 11.53[c] | 556.94 | 81.32[c] | 3.81[c] | 17.34[c] | 2, 3, 6, 11 |
| SUBTOTAL | 6784.53 | 5257.32 | 48.65 | 1219.60 | 242.11 | 16.85 | 45.23 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 47.76 | 0.00 | 0.00 | 47.76 | 0.00 | 0.00 | 0.32 | 2, 4, 11 |
| TOTALS (Per Dish) | 14124.44 | 10574.62 | 161.38 | 2709.19 | 391.00 | 288.26 | 94.16 | |

Optical material $4.20/m²

LONG-TERM STRESSED METAL-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 100 MWe (2000 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1535.77 | 1034.00 | 35.50 | 239.20 | 130.39 | 96.67 | 10.24 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3090.59 | 2291.70 | 18.90 | 621.90 | 14.42 | 143.67 | 20.60 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.52 | 655.60 | 17.55 | 202.22 | 4.08 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.59 | 0.00 | 40.77 | 45.82 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5623.46 | 3981.30 | 112.72 | 1109.14 | 148.89 | 271.41 | 37.49 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 1538.60 | 1122.00 | 27.00 | 361.12 | 16.68 | 11.80 | 10.26 | 2, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1468.75 | 1251.80 | 0.00 | 119.60 | 97.35 | (a) | 9.79 | 3, 5, 11 |
| 2.3 Optical Material | 867.84 | 633.60 | 10.12 | 172.19 | 50.68 | 1.24 | 5.79 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 | 1947.42(c) | 11.53(c) | 556.94(c) | 81.32(c) | 3.81(c) | 17.34(c) | 2, 3, 6, 11 |
| SUBTOTAL | 6797.63 | 5257.32 | 48.65 | 1228.77 | 246.03 | 16.85 | 45.68 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 48.20 | 0.00 | 0.00 | 48.20 | 0.00 | 0.00 | 0.32 | 2, 4, 11 |
| TOTALS (Per Dish) | 14139.28 | 10574.62 | 161.38 | 2720.11 | 394.92 | 288.26 | 94.26 | |

LONG-TERM STRESSED METAL-MEMBRANE 14M DISH
Gross Reflector Area $M^2$: 150
Production Level 16,667 units/yr - Dollar Year: 1984
System Size: 50 MWe (1000 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1537.07 | 1034.00 | 35.50 | 240.51 | 130.39 | 96.67 | 10.25 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3091.89 | 2291.70 | 18.90 | 623.20 | 14.42 | 143.67 | 20.61 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.52 | 655.60 | 17.55 | 202.22 | 4.08 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.59 | 0.00 | 40.77 | 45.82 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5626.07 | 3981.30 | 112.72 | 1111.75 | 148.89 | 271.41 | 37.54 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 1541.97 | 1122.00 | 27.00 | 361.56 | 19.62 | 11.80 | 10.28 | 2, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1491.57 | 1251.80 | 0.00 | 137.52 | 102.25 | (a) | 9.94 | 3, 5, 11 |
| 2.3 Optical Material | 867.84 | 633.60 | 10.12 | 172.19 | 50.68 | 1.24 | 5.79 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 | 1947.42[c] | 11.53[c] | 556.94[c] | 81.32[c] | 3.81[c] | 17.34[c] | 2, 3, 6, 11 |
| SUBTOTAL | 6823.82 | 5257.32 | 48.65 | 1247.13 | 253.87 | 16.85 | 45.49 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 49.07 | 0.00 | 0.00 | 49.07 | 0.00 | 0.00 | 0.33 | 2, 4, 11 |
| TOTALS (Per Dish) | 14168.96 | 10574.62 | 161.38 | 2741.94 | 402.76 | 288.26 | 94.46 | |

LONG-TERM STRESSED METAL-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 30 MWe (600 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1538.81 | 1034.00 | 35.50 | 242.25 | 130.39 | 96.67 | 10.26 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3093.63 | 2291.70 | 18.90 | 624.94 | 14.42 | 143.67 | 20.62 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.52 | 655.60 | 17.55 | 202.22 | 4.08 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.59 | 0.00 | 40.77 | 45.82 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5629.55 | 3981.30 | 112.72 | 1115.23 | 148.89 | 271.41 | 37.53 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 1546.47 | 1122.00 | 27.00 | 362.14 | 23.54 | 11.80 | 10.31 | 2, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1522.00 | 1251.80 | 0.00 | 161.41 | 108.78 | (a) | 10.15 | 3, 5, 11 |
| 2.3 Optical Material | 867.84 | 633.60 | 10.12 | 172.19 | 50.68 | 1.24 | 5.79 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 | 1947.42 (c) | 11.53 (c) | 556.94 (c) | 81.32 (c) | 3.81 (c) | 17.34 (c) | 2, 3, 6, 11 |
| SUBTOTAL | 6858.75 | 5257.32 | 48.65 | 1271.60 | 264.32 | 16.85 | 45.72 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 50.23 | 0.00 | 0.00 | 50.23 | 0.00 | 0.00 | 0.33 | 2, 4, 11 |
| TOTALS (Per Dish) | 14208.52 | 10574.62 | 161.38 | 2771.05 | 413.21 | 288.26 | 94.72 | |

LONG-TERM STRESSED METAL-MEMBRANE 14M DISH
Gross Reflector Area $M^2$: 150
Production Level 16,667 units/yr - Dollar Year: 1984
System Size: 10 MWe (200 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1547.51 | 1034.00 | 35.50 | 250.95 | 130.39 | 96.67 | 10.32 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3102.33 | 2291.70 | 18.90 | 633.64 | 14.42 | 143.67 | 20.68 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.52 | 655.60 | 17.55 | 202.22 | 4.08 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.59 | 0.00 | 40.77 | 45.82 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5646.95 | 3981.30 | 112.72 | 1132.63 | 148.89 | 284.56 | 37.65 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 1568.97 | 1122.00 | 27.00 | 365.04 | 43.14 | 11.80 | 10.46 | 2, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1674.13 | 1251.80 | 0.00 | 280.88 | 141.45 | (a) | 11.16 | 3, 5, 11 |
| 2.3 Optical Material | 867.84 | 633.60 | 10.12 | 172.19 | 50.68 | 1.24 | 5.79 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 | 1947.42[(c)] | 11.53[(c)] | 556.94 | 81.32[(c)] | 3.81[(c)] | 17.34[(c)] | 2, 3, 6, 11 |
| SUBTOTAL | 7033.38 | 5257.32 | 48.65 | 1393.97 | 316.59 | 16.85 | 46.89 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 56.03 | 0.00 | 0.00 | 56.03 | 0.00 | 0.00 | 0.37 | 2, 4, 11 |
| TOTALS (Per Dish) | 14406.35 | 10574.62 | 161.38 | 2916.62 | 465.48 | 288.26 | 96.04 | |

LONG-TERM STRESSED METAL-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 5 MWe (100 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1560.56 | 1034.00 | 35.50 | 264.00 | 130.39 | 96.67 | 10.40 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3115.38 | 2291.70 | 18.90 | 646.69 | 14.42 | 143.67 | 20.77 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.52 | 655.60 | 17.55 | 202.22 | 4.08 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.59 | 0.00 | 40.77 | 45.82 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5673.05 | 3981.30 | 112.72 | 1158.73 | 148.89 | 271.41 | 37.82 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 1602.72 | 1122.00 | 27.00 | 369.39 | 72.54 | 11.80 | 10.68 | 2, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1902.33 | 1251.80 | 0.00 | 460.08 | 190.45 | 0.00 | 12.68 | 3, 5, 11 |
| 2.3 Optical Material | 867.84 | 633.60 | 10.12 | 172.19 | 50.68 | 1.24 | 5.79 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 | 1947.42(c) | 11.53(c) | 556.94(c) | 81.32(c) | 3.81(c) | 17.34(c) | 2, 3, 6, 11 |
| SUBTOTAL | 7295.33 | 5257.32 | 48.65 | 1577.52 | 394.99 | 16.85 | 48.64 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.78 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 64.73 | 0.00 | 0.00 | 64.73 | 0.00 | 0.00 | .43 | 2, 4, 11 |
| TOTALS (Per Dish) | 14703.10 | 10574.62 | 161.38 | 3134.97 | 543.88 | 288.26 | 98.02 | |

LONG-TERM STRESSED METAL-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 3 MWe (60 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1577.96 | 1034.00 | 35.50 | 281.40 | 130.39 | 96.67 | 10.52 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3132.78 | 2291.70 | 18.90 | 644.09 | 14.42 | 143.67 | 20.89 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.52 | 655.60 | 17.55 | 202.22 | 4.08 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.59 | 0.00 | 40.77 | 45.82 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5707.85 | 3981.30 | 112.72 | 1193.53 | 148.89 | 271.41 | 38.05 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 1647.72 | 1122.00 | 27.00 | 375.19 | 111.74 | 11.80 | 10.98 | 2, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 2206.60 | 1251.80 | 0.00 | 699.01 | 255.78 | 0.00 | 14.71 | 3, 5, 11 |
| 2.3 Optical Material | 867.84 | 633.60 | 10.12 | 172.19 | 50.68 | 1.24 | 5.79 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 | 1947.42[c] | 11.53[c] | 556.94[c] | 81.32[c] | 3.81[c] | 17.34[c] | 2, 3, 6, 11 |
| SUBTOTAL | 7644.60 | 5257.32 | 48.65 | 1822.25 | 499.52 | 16.85 | 50.96 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 76.33 | 0.00 | 0.00 | 76.33 | 0.00 | 0.00 | .51 | 2, 4, 11 |
| TOTALS (Per Dish) | 15098.77 | 10574.62 | 161.38 | 3426.10 | 648.41 | 288.26 | 100.66 | |

LONG-TERM STRESSED METAL-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 1 MWe (20 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1569.55 | 962.50 | 35.50 | 276.92 | 197.96 | 96.67 | 10.46 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3272.55 | 2291.70 | 18.90 | 755.80 | 62.48 | 143.76 | 21.82 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 941.23 | 655.60 | 17.55 | 202.22 | 34.79 | 31.07 | 6.27 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.59 | 0.00 | 40.77 | 45.82 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5869.92 | 3909.80 | 112.72 | 1280.76 | 295.23 | 271.41 | 39.13 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 1991.11 | 1122.00 | 27.00 | 513.64 | 236.67 | 11.80 | 12.74 | 2, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 2224.92 | 1323.30 | 11.99 | 310.47 | 506.66 | 72.50 | 14.83 | 3, 5, 11 |
| 2.3 Optical Material | 921.53 | 633.60 | 10.12 | 172.19 | 104.37 | 1.24 | 6.14 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 | 1947.42[c] | 11.53[c] | 556.94[c] | 81.32[c] | 3.81[c] | 17.34[c] | 2, 3, 6, 11 |
| SUBTOTAL | 7979.99 | 5257.32 | 60.64 | 1572.16 | 929.02 | 89.35 | 53.20 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 180.42 | 0.00 | 0.00 | 180.42 | 0.00 | 0.00 | 1.20 | 2, 4, 11 |
| TOTALS (Per Dish) | 15700.33 | 10574.62 | 173.36 | 3367.34 | 1224.25 | 360.76 | 104.67 | |

LONG-TERM STRESSED METAL-MEMBRANE 14M DISH
Gross Reflector Area $M^2$: 150
Production Level 16,667 units/yr - Dollar Year: 1984
System Size: 0.25 MWe (5 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1700.05 | 962.50 | 35.50 | 407.42 | 197.96 | 96.67 | 11.33 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3403.05 | 2291.70 | 18.90 | 886.30 | 62.48 | 143.67 | 22.69 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 941.23 | 655.60 | 17.55 | 202.22 | 34.79 | 31.07 | 6.27 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.59 | 0.00 | 40.77 | 45.82 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 6130.92 | 3909.80 | 112.72 | 1541.76 | 295.23 | 271.41 | 40.87 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 2579.21 | 1122.00 | 27.00 | 961.24 | 457.17 | 11.80 | 17.19 | 2, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 2722.92 | 1323.30 | 11.99 | 440.97 | 874.16 | 72.50 | 18.15 | 3, 5, 11 |
| 2.3 Optical Material | 921.53 | 633.60 | 10.12 | 172.19 | 104.37 | 1.24 | 6.14 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 | 1947.42(c) | 11.53(c) | 556.94(c) | 81.32(c) | 3.81(c) | 17.34(c) | 2, 3, 6, 11 |
| SUBTOTAL | 9146.09 | 5257.32 | 60.64 | 2150.26 | 1517.02 | 89.35 | 60.97 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 441.42 | 0.00 | 0.00 | 441.42 | 0.00 | 0.00 | 2.94 | 2, 4, 11 |
| TOTALS (Per Dish) | 17388.43 | 10574.62 | 173.36 | 4467.44 | 1812.25 | 360.76 | 115.92 | |

LONG-TERM STRESSED METAL-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 0.1 MWe (2 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1961.05 | 962.50 | 35.50 | 668.42 | 197.86 | 96.67 | 13.07 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3664.05 | 2291.70 | 18.90 | 1147.30 | 62.48 | 143.67 | 24.43 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 941.23 | 655.60 | 17.55 | 202.22 | 34.79 | 31.07 | 6.27 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.59 | 0.00 | 40.77 | 45.82 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 6652.92 | 3909.80 | 112.72 | 2063.76 | 295.23 | 271.41 | 44.35 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3915.41 | 1122.00 | 27.00 | 1856.44 | 898.17 | 11.80 | 26.10 | 2, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 3718.92 | 1323.30 | 11.99 | 701.97 | 1609.16 | 72.50 | 24.79 | 3, 5, 11 |
| 2.3 Optical Material | 921.53 | 633.60 | 10.12 | 172.19 | 104.37 | 1.24 | 6.14 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 | 1947.42[c] | 11.53[c] | 556.94[c] | 81.32[c] | 3.81[c] | 17.34[c] | 2, 3, 6, 11 |
| SUBTOTAL | 11478.29 | 5257.32 | 60.64 | 3306.46 | 2693.02 | 89.35 | 76.52 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 963.42 | 0.00 | 0.00 | 963.42 | 0.00 | 0.00 | 6.42 | |
| TOTALS (Per Dish) | 20764.63 | 10574.62 | 173.36 | 6667.64 | 2988.25 | 360.76 | 138.43 | |

LONG-TERM STRESSED COMPOSITE-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 200 MWe (4000 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1515.73 | 1034.00 | 35.50 | 238.57 | 110.99 | 96.67 | 10.10 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3089.99 | 2291.70 | 18.90 | 621.26 | 14.46 | 143.67 | 20.60 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.63 | 655.60 | 17.55 | 202.24 | 4.17 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.60 | 0.00 | 40.77 | 45.83 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5602.94 | 3981.30 | 112.72 | 1107.89 | 129.62 | 271.41 | 37.35 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3166.09 | 2323.20 | 43.37 | 776.92 | 10.30 | 11.80 | 21.11 | 2, 3, 8, 9, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1486.81 | 1372.80 | 0.00 | 104.45 | 9.56 | (a) | 9.91 | 3, 5, 11 |
| 2.3 Optical Material | 859.85 | 633.60 | 10.12 | 192.10 | 22.79 | 1.24 | 5.73 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 (c) | 1947.42 (c) | 11.53 | 556.94 | 81.32 (c) | 3.81 (c) | 17.34 (c) | 2, 3, 6, 11 |
| SUBTOTAL | 8435.19 | 6579.52 | 65.53 | 1649.33 | 123.96 | 16.85 | 56.23 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 47.85 | 0.00 | 0.00 | 47.85 | 0.00 | 0.00 | 0.32 | 2, 4, 11 |
| TOTALS (Per Dish) | 15755.97 | 11896.82 | 178.25 | 3139.07 | 253.58 | 288.26 | 105.04 | |

LONG-TERM STRESSED COMPOSITE-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 100 MWe (2000 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1516.38 | 1034.00 | 35.50 | 239.22 | 110.99 | 96.67 | 10.11 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3090.64 | 2291.70 | 18.90 | 621.91 | 14.46 | 143.67 | 20.60 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.63 | 655.60 | 17.55 | 202.24 | 4.17 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.60 | 0.00 | 40.77 | 45.83 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5604.25 | 3981.30 | 112.72 | 1109.20 | 129.62 | 271.41 | 37.36 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3167.04 | 2323.20 | 43.37 | 777.14 | 11.03 | 11.80 | 21.11 | 2, 3, 8, 9, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1488.90 | 1372.80 | 0.00 | 105.32 | 10.78 | (a) | 9.93 | 3, 5, 11 |
| 2.3 Optical Material | 859.85 | 633.60 | 10.12 | 192.10 | 22.79 | 1.24 | 5.73 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 (c) | 1947.42 (c) | 11.53 (c) | 556.94 (c) | 81.32 (c) | 3.81 (c) | 17.34 (c) | 2, 3, 6, 11 |
| SUBTOTAL | 8438.24 | 6579.52 | 65.53 | 1649.42 | 125.92 | 16.85 | 56.25 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 48.28 | 0.00 | 0.00 | 48.28 | 0.00 | 0.00 | 0.32 | 2, 4, 11 |
| TOTALS (Per Dish) | 15760.77 | 11896.82 | 178.25 | 3141.90 | 255.54 | 228.26 | 105.07 | |

LONG-TERM STRESSED COMPOSITE-MEMBRANE 14M DISH
Gross Reflector Area $M^2$: 150
Production Level 16,667 units/yr - Dollar Year: 1984
System Size: 50 MWe (1000 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1517.69 | 1034.00 | 35.50 | 240.53 | 110.99 | 96.67 | 10.12 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3091.94 | 2291.70 | 18.90 | 623.21 | 14.46 | 143.67 | 20.61 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.63 | 655.60 | 17.55 | 202.24 | 4.17 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.60 | 0.00 | 40.77 | 45.83 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5606.86 | 3981.30 | 112.72 | 1111.81 | 129.62 | 271.41 | 37.38 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3168.95 | 2323.20 | 43.37 | 777.57 | 12.50 | 11.80 | 21.13 | 2, 3, 8, 9, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1493.09 | 1372.80 | 0.00 | 107.06 | 13.23 | (a) | 9.95 | 3, 5, 11 |
| 2.3 Optical Material | 859.85 | 633.60 | 10.12 | 192.10 | 22.79 | 1.24 | 5.73 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02(c) | 1947.42(c) | 11.53(c) | 556.94(c) | 81.32(c) | 3.81(c) | 17.34(c) | 2, 3, 6, 11 |
| SUBTOTAL | 8444.33 | 6579.52 | 65.53 | 1652.59 | 129.84 | 16.85 | 56.30 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 49.15 | 0.00 | 0.00 | 49.15 | 0.00 | 0.00 | 0.33 | 2, 4, 11 |
| TOTALS (Per Dish) | 15770.34 | 11896.82 | 178.25 | 3147.55 | 259.46 | 288.26 | 105.14 | |

LONG-TERM STRESSED COMPOSITE-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 30 MWe (600 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1519.43 | 1034.00 | 35.50 | 242.27 | 110.99 | 96.67 | 10.13 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3093.68 | 2291.70 | 18.90 | 624.95 | 14.46 | 143.67 | 20.62 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.63 | 655.60 | 17.55 | 202.24 | 4.17 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.60 | 0.00 | 40.77 | 45.83 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5610.34 | 3981.30 | 112.72 | 1115.29 | 129.62 | 271.41 | 37.40 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3171.49 | 2323.20 | 43.37 | 778.15 | 14.46 | 11.80 | 21.14 | 2, 3, 8, 9, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1498.68 | 1372.80 | 0.00 | 109.38 | 16.50 | (a) | 9.99 | 3, 5, 11 |
| 2.3 Optical Material | 859.85 | 633.60 | 10.12 | 192.10 | 22.79 | 1.24 | 5.73 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02(c) | 1947.42(c) | 11.53(c) | 556.94(c) | 81.32(c) | 3.81(c) | 17.34(c) | 2, 3, 6, 11 |
| SUBTOTAL | 8452.46 | 6579.52 | 65.53 | 1655.49 | 135.07 | 16.85 | 56.35 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 50.31 | 0.00 | 0.00 | 50.31 | 0.00 | 0.00 | 0.34 | 2, 4, 11 |
| TOTALS (Per Dish) | 15783.10 | 11896.82 | 178.25 | 3155.09 | 264.69 | 288.26 | 105.22 | |

LONG-TERM STRESSED COMPOSITE-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 10 MWe (200 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1528.13 | 1034.00 | 35.50 | 250.97 | 110.99 | 96.67 | 10.19 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3102.38 | 2291.70 | 18.90 | 633.65 | 14.46 | 143.76 | 20.68 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.63 | 655.60 | 17.55 | 202.24 | 4.17 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.60 | 0.00 | 40.77 | 45.83 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5627.74 | 3981.30 | 112.72 | 1132.69 | 129.62 | 271.41 | 37.52 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3184.19 | 2323.20 | 43.37 | 781.05 | 24.26 | 11.80 | 21.23 | 2, 3, 8, 9, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1526.61 | 1372.80 | 0.00 | 120.98 | 32.83 | (a) | 10.18 | 3, 5, 11 |
| 2.3 Optical Material | 859.85 | 633.60 | 10.12 | 192.10 | 22.79 | 1.24 | 5.73 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 (c) | 1947.42 (c) | 11.53 (c) | 556.94 (c) | 81.32 (c) | 3.81 (c) | 17.34 (c) | 2, 3, 6, 11 |
| SUBTOTAL | 8493.09 | 6579.52 | 65.53 | 1669.99 | 161.20 | 16.85 | 56.62 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 56.11 | 0.00 | 0.00 | 56.11 | 0.00 | 0.00 | 0.37 | 2, 4, 11 |
| TOTALS (Per Dish) | 15846.94 | 11896.82 | 178.25 | 3192.79 | 290.82 | 288.26 | 105.65 | |

LONG-TERM STRESSED COMPOSITE-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 5 MWe (100 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1541.18 | 1034.00 | 35.50 | 264.02 | 110.99 | 96.67 | 10.27 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3115.43 | 2291.70 | 18.90 | 646.70 | 14.46 | 143.67 | 20.77 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.63 | 655.60 | 17.55 | 202.24 | 4.17 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.60 | 0.00 | 40.77 | 45.83 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5653.84 | 3981.30 | 112.72 | 1158.79 | 129.62 | 271.41 | 37.69 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3203.24 | 2323.20 | 43.37 | 785.40 | 38.96 | 11.80 | 21.35 | 2, 3, 8, 9, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1568.51 | 1372.80 | 0.00 | 138.38 | 57.33 | (a) | 10.46 | 3, 5, 11 |
| 2.3 Optical Material | 859.85 | 633.60 | 10.12 | 192.10 | 22.79 | 1.24 | 5.73 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02[c] | 1947.42[c] | 11.53[c] | 556.94[c] | 81.32[c] | 3.81[c] | 17.34[c] | 2, 3, 6, 11 |
| SUBTOTAL | 8554.04 | 6579.52 | 65.53 | 1691.74 | 200.04 | 16.85 | 57.03 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 64.81 | 0.00 | 0.00 | 64.81 | 0.00 | 0.00 | 0.43 | 2, 4, 11 |
| TOTALS (Per Dish) | 15942.69 | 11896.82 | 178.25 | 3249.34 | 330.02 | 288.26 | 106.28 | |

LONG-TERM STRESSED COMPOSITE-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 3 MWe (60 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1558.58 | 1034.00 | 35.50 | 281.42 | 110.99 | 96.67 | 10.39 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3132.83 | 2291.70 | 18.90 | 664.10 | 14.46 | 143.67 | 20.89 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 910.63 | 655.60 | 17.55 | 202.24 | 4.17 | 31.07 | 6.07 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.60 | 0.00 | 40.77 | 45.83 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5688.64 | 3981.30 | 112.72 | 1193.59 | 129.62 | 271.41 | 37.92 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3228.64 | 2323.20 | 43.37 | 791.20 | 58.56 | 11.80 | 21.52 | 2, 3, 8, 9, 11 |
| 2.2 Stretched Membrane/ Ring/Attachment | 1624.38 | 1372.80 | 0.00 | 161.58 | 90.00 | (a) | 10.83 | 3, 5, 11 |
| 2.3 Optical Material | 859.85 | 633.60 | 10.12 | 192.10 | 22.79 | 1.24 | 5.73 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 [c] | 1947.42 [c] | 11.53 [c] | 556.94 [c] | 81.32 [c] | 3.81 [c] | 17.34 [c] | 2, 3, 8, 11 |
| SUBTOTAL | 8635.31 | 6579.52 | 65.53 | 1720.74 | 252.67 | 16.85 | 57.57 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 76.41 | 0.00 | 0.00 | 76.41 | 0.00 | 0.00 | 0.51 | 2, 4, 11 |
| TOTALS (Per Dish) | 16070.36 | 11896.82 | 178.25 | 3324.74 | 382.29 | 288.26 | 107.14 | |

LONG-TERM STRESSED COMPOSITE-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 1 MWe (20 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1414.06 | 962.50 | 35.50 | 276.94 | 42.45 | 96.67 | 9.43 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3175.02 | 2291.70 | 18.90 | 697.90 | 22.85 | 143.67 | 21.17 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 922.81 | 655.60 | 17.55 | 202.24 | 16.35 | 31.07 | 6.15 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.60 | 0.00 | 40.77 | 45.83 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5598.49 | 3909.80 | 112.72 | 1222.91 | 81.65 | 271.41 | 37.32 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3303.46 | 2323.20 | 43.37 | 797.19 | 127.40 | 11.80 | 22.02 | 2, 3, 8, 9, 11 |
| 2.2 Stretched Membrane Ring/Attachment | 1934.52 | 1444.30 | 11.99 | 252.18 | 153.55 | 72.50 | 12.90 | 3, 5, 11 |
| 2.3 Optical Material | 886.06 | 633.60 | 10.12 | 192.10 | 49.00 | 1.24 | 5.91 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02[c] | 1947.42[c] | 11.53[c] | 556.94[c] | 81.32[c] | 3.81[c] | 17.34[c] | 2, 3, 6, 11 |
| SUBTOTAL | 9046.49 | 6579.52 | 77.52 | 1817.33 | 411.27 | 89.35 | 60.31 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 155.41 | 0.00 | 0.00 | 155.41 | 0.00 | 0.00 | 1.04 | 2, 4, 11 |
| TOTALS (Per Dish) | 16470.37 | 11896.82 | 190.24 | 3529.64 | 492.92 | 360.76 | 109.80 | |

LONG-TERM STRESSED COMPOSITE-MEMBRANE 14M DISH

Gross Reflector Area $M^2$: 150

Production Level 16,667 units/yr - Dollar Year: 1984

System Size: 0.25 MWe (5 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1544.56 | 962.50 | 35.50 | 407.44 | 42.45 | 96.67 | 10.30 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3305.52 | 2291.70 | 18.90 | 828.40 | 22.85 | 143.67 | 22.04 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 922.81 | 655.60 | 17.55 | 202.24 | 16.35 | 31.07 | 6.15 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.60 | 0.00 | 40.77 | 45.83 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 5859.49 | 3909.80 | 112.72 | 1483.91 | 81.65 | 271.41 | 39.06 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3515.71 | 2323.20 | 43.87 | 862.44 | 274.40 | 11.80 | 23.44 | 2, 3, 8, 9, 11 |
| 2.2 Stretched Membrane Ring/Attachment | 2146.77 | 1444.30 | 11.99 | 317.43 | 300.55 | 72.50 | 14.31 | 3, 5, 11 |
| 2.3 Optical Material | 886.06 | 633.60 | 10.12 | 192.10 | 49.00 | 1.24 | 5.91 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02 (c) | 1947.42 (c) | 11.53 (c) | 556.94 (c) | 81.32 (c) | 3.81 (c) | 17.34 (c) | 2, 3, 8, 11 |
| SUBTOTAL | 9470.99 | 6579.52 | 77.52 | 1947.83 | 705.27 | 89.35 | 63.14 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 416.41 | 0.00 | 0.00 | 416.41 | 0.00 | 0.00 | 2.78 | 2, 4, 11 |
| TOTALS (Per Dish) | 17416.87 | 11896.82 | 190.24 | 4182.14 | 786.92 | 360.76 | 116.11 | |

LONG-TERM STRESSED COMPOSITE-MEMBRANE 14M DISH
Gross Reflector Area $M^2$: 150
Production Level 16,667 units/yr - Dollar Year: 1984
System Size: 0.1 MWe (2 dishes)

| COST ELEMENT | TOTAL COST ($) | MATERIALS COST ($) | DIRECT LABOR ($) | OTHER COST ($) | SITE INSTALLATION ($) | TRANSPORTATION COST ($) | TOTAL COST ($/m2) | REFERENCES |
|---|---|---|---|---|---|---|---|---|
| 1.0 STRUCTURES | | | | | | | | |
| 1.1 Panel or Mirror Support/ Space Frame | 1805.56 | 962.50 | 35.50 | 668.44 | 42.45 | 96.67 | 12.04 | 2, 4, 7, 11, 12, 13 |
| 1.2 Drive Support | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | |
| 1.3 Base or Stationary Support Structure | 3566.52 | 2291.70 | 18.90 | 1089.40 | 22.85 | 143.67 | 23.78 | 2, 4, 7, 10, 11 |
| 1.4 PCU Support | 922.81 | 655.60 | 17.55 | 202.24 | 16.35 | 31.07 | 6.15 | 2, 4, 7, 11, 12 |
| 1.5 Other | 86.60 | 0.00 | 40.77 | 45.83 | 0.00 | 0.00 | 0.58 | 4, 11, 12 |
| SUBTOTAL | 6381.49 | 3909.80 | 112.72 | 2005.91 | 81.65 | 271.41 | 42.54 | |
| 2.0 CONCENTRATOR | | | | | | | | |
| 2.1 Panels | 3940.21 | 2323.20 | 43.37 | 992.94 | 568.40 | 11.80 | 26.27 | 2, 3, 8, 9, 11 |
| 2.2 Stretched Membrane Ring/Attachment | 2571.27 | 1444.30 | 11.99 | 447.93 | 594.55 | 72.50 | 17.14 | 3, 5, 11 |
| 2.3 Optical Material | 886.06 | 633.60 | 10.12 | 192.10 | 49.00 | 1.24 | 5.91 | 2, 11 |
| 2.4 Edge Pull | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.5 Vacuum System | 321.42 | 302.50 | 0.00 | 18.92 | (b) | (a) | 2.14 | 1, 11 |
| 2.6 Miscellaneous | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | ---- |
| 2.7 Optical Material Replacement | 2601.02(c) | 1947.42(c) | 11.53(c) | 556.94(c) | 81.32(c) | 3.81(c) | 17.34(c) | 2, 3, 6, 11 |
| SUBTOTAL | 10319.99 | 6579.52 | 77.52 | 2208.83 | 1293.27 | 89.35 | 68.80 | |
| 3.0 DRIVE SYSTEM | | | | | | | | |
| 3.1 Azimuth | 1106.25 | 885.00 | (e) | 221.25 | (d) | (e) | 7.38 | 10, swag |
| 3.2 Elevation | 563.75 | 451.00 | (e) | 112.75 | (d) | (e) | 3.76 | 10, swag |
| SUBTOTAL | 1670.00 | 1336.00 | (e) | 334.00 | (d) | (e) | 11.13 | |
| 4.0 GENERAL | 938.41 | 0.00 | 0.00 | 938.41 | 0.00 | 0.00 | 6.26 | 2, 4, 11 |
| TOTALS (Per Dish) | 19309.87 | 11896.82 | 190.24 | 5487.14 | 1374.92 | 360.76 | 128.73 | |

## Footnotes

(a) Transportation is included in the purchase cost of the materials.

(b) Attachment of the vacuum system is included in cost element 1.1, because it is part of general mast assembly.

(c) This cost is the present value of replacement costs in project years 5, 10, 15, 20, and 25 using a real discount rate of 3.15% as per the "Five-Year Plan."

(d) The drive system is an integral part of the support structure; therefore, site installation is included in the support structure cost element (element 1.3).

(e) Portions of the drive cost estimate could not be segregated into separate categories; therefore, this part the drive system cost element is included under direct materials.

## REFERENCES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12. "Thermal Arc Plasma Cutting System." 1987. Thermal Dynamics Corporation, West Lebanon, NH.

13. Piping Manhour Estimating Manual. Page and Nation. Gulf Publishing Company.

Excerpts from Letter dated
March 24, 1988
Revised to Reflect Current Information

Enclosed are cost tables in the format you requested for the long-term stressed metal- and composite-membrane dish concentrators. Also attached are the cost summary tables for these same systems in the near-term. The long-term tables previously sent to you were reviewed and the appropriate changes/additions were made. In addition, long-term tables were prepared for a total of 10 system sizes for each of the two technologies evaluated. These tables were used as a basis for preparing the near-term cost estimates.

The information in this letter covers all four stressed membrane cases you requested in your February 5, 1988 letter to us. As soon as they are completed, we will send you the tables and backup documentation in a format consistent with the previous glass-metal concentrator cost data tables sent to you. For completeness, some of the information sent to you on March 3rd is restated in this transmittal.

Cost tables are included for each of the long-term cases at system sizes of 0.1, 0.25, 1, 3, 5, 10, 30, 50, 100, and 200 MWe. The unit cost per dish decreases as system size increases for several reasons. First, there are fixed site manufacturing set-up costs associated with erecting a system. For larger systems these fixed costs are distributed over a larger number of dishes which reduces the cost per dish. Second, in the long-term for larger system sizes, site manufacturing operations can be mechanized to a greater degree which reduces labor requirements per dish and speeds installation. In addition, for near-term systems larger system sizes allow for a larger central manufacturing operation which reduces the unit cost per dish.

Attached are several tables addressing the assumptions, unit cost, and cost element definitions. The conceptual drawings provided to us lack dimensions for many parts of the concentrator; therefore, the dimensions presented in Table 1 were estimated using engineering judgement. All carbon steel pipe sizes were adjusted to standard sizes to avoid the significant cost penalties associated with non-standard pipe sizes.

In general, the long-term estimates were prepared hypothesizing reasonable manufacturing scenarios and developing estimates at the unit operations level. After determining the material costs, direct labor requirements, and factory

requirements, the PNL manufacturing cost algorithm was used to generate the final estimate. Using this methodology puts these estimates on the same basis as the "Electricity Study" and previous cost data base estimates.
An underlying assumption of the PNL manufacturing cost algorithm is that the long-term production level is equivalent to producing 2.5 x $10^6$ $m^2$ of dish aperture area, because the SKI design is a 150 $m^2$ dish, the assumed production level is 16,667 dishes per year. Some of the unit cost assumptions used to generate these estimates are presented in Table 2.

Every type of concentrator is unique; therefore, it is often difficult to categorize cost elements in an identical manner. To clearly indicate where the boundary of each cost element is drawn, a description of each cost element is presented in Table 3.

Included as an attachment to this letter are the 20 long-term tables, 10 for each technology. In an attempt to anticipate some of your questions regarding why the cost elements of the new estimates are different from the values in the previous draft, Table 4 presents an explanation of all changes which exceed very minor 4 or 5-dollar changes. This explanation compares the March 3 draft table for large metal-membrane systems to the new long-term cost table for 200-MWe metal-membrane systems. The changes in the composite numbers result from similar adjustments and are not discussed due to time constraints.

Near-term systems are defined as approximately the fifth to tenth plant built employing a specific dish technology. Although "Nth plant" technology is not in a mature state of development, it has been developed to a significant enough level that extraordinary contingencies don't exist. However, slightly higher contingencies do prevail; the contingency for near-term components is 15% as opposed to 10% for the long-term estimates. The annual production level assumed is that required to build one "Nth plant."

Consistent with this definition, the costs of central manufacturing operations and replacement optical material manufacturing are expected to be higher in the near-term than in the long-term. Site installation, which is primarily handled the same at any production level, and transportation are not expected to be significantly more expensive in the near-term than in the long-term. The near-term estimates were prepared by applying a parametric production economies-of-scale relationship to the long-term central manufacturing and optical material manufacturing operations while holding site installation and transportation costs constant.

With the exception of the dirve unit, the parametric production economies-of-scale relationship is assumed to be the same as that for glass-metal concentrator manufacturing. The concentrators are different in design; however, for ordinary production operations, production economies-of-scale are about the same for manufactured components using similar materials, equipment, and fabrication techniquaes. The parametric relationship used to estimate near-term drive costs is the same as that used for glass-metal concentrator drive units. For conceptual estimates such as those presented in this letter, these assumptions are quite adequate. Applying this methodology, the near-term estimates for stressed composite- and metal- membrane systems presented in Table 6 were generated.

Finally, as you realize, one of the greatest virtues of this type of estimates is they can be used as a tool for identifying areas for cost control and cost reduction. Next week I will send you a letter briefly discussing aspects of the stressed membrane system which have potential for cost reductions and more importantly, areas where costs must be strictly controlled by optimized manufacturing and installation operations or the system costs estimated in the attached tables will not be achieved.

I think you will find the attached tables very informative. Please contact us with any questions or concerns, and time permitting, we would be glad to be of assistance.

TABLE 1. Material Composition and Dimensional Assumptions

1. Main Mast: 10" NOM. STD. C.S. pipe, 20' long, 10.75" OD, Wall = 0.365"
2. Main Mast Drain Pipe: 3" NOM. STD. C.S. pipe, 10' long, 3.5" OD, Wall = 0.216"
3. Spoke Flange Nut Seat Holders: 2.5" NOM. STD. C.S. pipe, 4.5"/2.5" Miter Cut, 2.875" OD, Wall = 0.203
4. Spherical Nut Seats: 2.875" OD
5. Restraint Flange: Rubber, 48" OD, 10.75" ID
6. Rain Shield Support Rods: 1/4" Diam round bar stock, 42' total
7. Rain Shield Sheet Metal: light C.S., approx 3 mil, 28 sq. $ft_2$.
8. Kingpost Outer Pedestal: 32" OD C.S. pipe, 74" long, Wall = 0.375"
9. Kingpost Inner Pedestal: 28" OD C.S. pipe, 84" long, Wall = 0.375"
10. Drive Pins: 4" OD C.S. Bar Stock, 6" long,
11. Kingpost Axial Joint: 20" OD C.S. pipe, 6" long, Wall = 0.375"
12. Sway Brace Arm: 12" NOM. STD. C.S. pipe, 110" long, Wall = 0.375"
13. Sway Brace Rod: 20" OD C.S. pipe, 120" long, Wall = 0.375"
14. A-Frame Mains: 10" NOM. STD. C.S. pipe, 259" long, Wall = 0.365"
15. A-Frame Cross: 10" NOM. STD. C.S. pipe, 21" long, Wall = 0.365"
16. Jack Link Rod: 10" NOM. STD. C.S. pipe, 90" long, Wall = 0.365"
17. Tripod Main Rods: 2.5" NOM. STD. C.S. pipe, 380" long, 2.875" OD, wall = 0.203"
18. Tripod Cross Rods: 1.25" NOM. STD C.S. pipe, 538" long, 1.660" OD, Wall = 0.140

TABLE 1. Material Composition and Dimensional Assumptions (Continued)

19. Spoke Flange Gussets: 6" x 6" 45-degree, 1/4" C.S. plate

20. Mast Top Flange: 12.75" OD, 10.75" ID, 1/4" C.S. plate

21. Mast Base Flange: 20" OD, 3.5" ID, 1/4" C.S. plate

22. Kingpost Top Cap: 32" OD, 1/4" C.S. plate

23. Kingpost Inner Cap: 28" OD, 20" ID, 1/4" C.S. plate

24. Kingpost Gussets: 6.5" x 6.5" 45-degree, 1/4" C.S. plate

25. Kingpost Base Flange: 41" OD, 1/4" C.S. plate

26. A-Frame End Caps: 10" OD, 1/4" C.S. plate

27. PCU Mounting Flange: 36" OD, 28" ID, 1/4" C.S. plate

28. Spoke Flanges: 48" OD, 10.75" ID, 3/4" C.S. plate29. Flat Kingpost Connecting Arms: 10" x 6", 1/2" C.S. plate

30. Flat Kingpost Connecting Arms: 80" x 10", 1/2" C.S. plate

TABLE 2. Unit Cost Assumptions (1984$)

| | |
|---|---|
| Rear Membrane | 0.33/$ft^2$ |
| Vinyl Cable (.67 lb/ft) | 0.60/lb |
| All C.S. pipe | 0.35/lb |
| All C.S. plate | 0.35/lb |
| Aluminum Plate | 0.17/lb |
| ECP 300 | 0.29/$ft^2$ |
| Restraint Flange | 25.00 ea |
| Nut Seats | 0.50 ea |
| Rain Shield Sheet Metal | 0.40/lb |
| Round Stock | 0.60/lb |
| Ball Joints/Hinges | 1.00/lb |
| Mist. C.S. | 0.35/lb |
| Fan (Vacuum) | 275.00 |
| Cables w/Fixtures | 6.04 ea |
| Attachment Plates | 2.50 ea |
| Attachment Plate Bolts | 0.10 ea |
| Reflective Membrane Clamp | 1.00/ft |
| Metal Membrane | 0.14/$ft^2$ |
| Reinforcing Flange | 25.00 |
| Ring Material | 408.00 |

TABLE 3. Definitions of Cost Elements

1.0 Structures

1.1 Panel or Mirror Support/Space Frame:

Includes the mast and cable system and the entire concentrator once it is assembled.

1.2 Drive Support:

For this concentrator design the drive support is integrated with the Base Support Structure (cost element 1.3); thus the drive support cost is included in cost element 1.3.

1.3 Base or Stationary Support Structure:

Includes the concrete foundation, A-frame, jack link, and kingpost. Also, see cost element 1.5.

1.4 PCU support:

Includes the tripod. Also, see cost element 1.5

1.5 Other

Includes a centralized metal cutting station. Parts cut at this station are used in the construction of cost elements 1.1, 1.3, and 1.4. In addition, a paint line is included.

2.0 Concentrator

2.1 Panels

Includes the rear and metal membranes.

2.2 Stretched Membrane/Ring Attachment

Includes all clamps and hardware used to attach the rear, metal, and reflective membranes to the ring.

2.3 Optical Material

Includes the reflector. The reflector is manufactured, on the same equipment as the rear and metal membranes, therefore, no equipment costs are included in this cost element.

2.4 Edge Pull

There is not an edge pull system for this concentrator as there is for a stressed membrane heliostat. There is a clamping system which is included in cost element 2.2.

TABLE 3. Definitions of Cost Elements (Continued)

2.5 Vacuum System

Includes fan, motor and housing. The Rain Shield is considered part of this mast (cost element 1.1)

2.6 Miscellaneous

No costs are included in this element.

2.7 Optical Material Replacement

The cost presented for this element is the present value of replacement costs in project years 5, 10, 15, 20, and 25 using a real discount rate of 3.15% as per the "5-Year Plan."

3.0 Drive System

3.1 Azimuth

Includes the cost of azimuth drive. Installation and transportation are included in the stationary support structure (cost element 1.3) category because the drive is an integral part of the support structure.

3.2 Elevation

Includes the cost of elevation drive. Installation and transportation are included in the stationary support structure (cost element 1.3) category because the drive is an integral part of the support structure.

4.0 GENERAL

Includes general equipment and floor space which cannot be directly attributed to any single cost element.

The column entitled, "Other Costs" includes land cost, capital equipment cost, G & A costs, working capital, and buildings costs. These costs were estimated using the PNL manufacturing cost algorithm. They were apportioned to each cost element on the following basis: annualized land and buildings costs were distributed proportional to the factory square footage required by the given work element, annualized capital equipment is associated with the cost element using the equipment. G & A is distributed proportional to material and labor cost, and working capital is divided proportionally based on the sum of the material, labor and G & A aspects of the cost elements.

TABLE 5. Near-term Estimates per Dish

| System Size | Metal-Membrane | Composite-Membrane |
| --- | --- | --- |
| 200 MWe | $17,900 | $19,800 |
| 100 MWe | $19,200 | $21,400 |
| 50 MWe | $20,600 | $22,900 |
| 30 MWe | $21,700 | $24,200 |
| 10 MWe | $24,500 | $27,100 |
| 5 MWe | $26,500 | $29,200 |
| 4 MWe | $29,800 | $32,900 |
| 3 MWe | $29,600 | $33,300 |
| 1 MWe | $32,300 | $35,200 |
| 0.25 MWe | $38,500 | $41,300 |
| 0.1 MWe | $45,600 | $47,400 |

March 31, 1988

Mr. Russell Hewett
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401

Dear Mr. Hewett:

To follow up on my letter of March 24, 1988, I am enclosing a short but pointed discussion on some economic aspects of the construction of the stressed membrane dish concentrators. More specifically, we have identified areas where strict cost control is required and areas where there is the potential for cost reduction. Because the design was conceived with low cost in mind, you will find that areas for cost reductions are limited. There are certainly areas for minor improvements; however, many of these will probably be counteracted by minor problems which arise during the detailed design phase (if such a phase is funded).

Aspects of the dish system targeted for cost control are areas where costs must be strictly controlled by optimized manufacturing and installation or the system cost estimated will not be achieved. It is our belief that prioritization of stressed membrane dish concentrator research can be performed using this information. In light of significant budget cuts in the Solar Thermal Program and the stagnation of new solar technologies entering the market-place, we believe program resources should be expended on technologies with the highest commercial potential.

Stressed Metal-Membrane Concentrator

**hydroforming**

Based on a metal-membrane of thickness 0.01 inches, the force necessary for the plastic deformation of the membrane during hydroforming is 0.56 psi. To exert an average force of 0.56 psi over the entire membrane requires approximately 16,000 gallons of water. Theoretically water would be pumped into the plenum between the membrane and a temporary poly-bubble. However, the water must be added "gently" by passing it through some type of diffuser to prevent the uncontrolled deformation of the metal by the force of entering water.

A reasonable flow rate for the entering and exiting water was estimated to be 200 gpm based on engineering judgment. At this rate, filling and emptying requires 160 minutes of unattended operation. To maintain a reasonable installation rate, eleven dishes must undergo hydroforming simultaneously. Although, some would be emptying while others are filling, using such large volumes of water will require a battery of storage tanks and a series of water pumps. If an unattended pumping rate of 200 gpm cannot be maintained or other complicating factors arise, costs could increase substantially (up to $10 per $m^2$). Improvements of the hydroforming operations might result in a cost reduction of a couple dollars-per-$m^2$; however, cost reductions are not likely.

**edge attachment**

It is unlikely the cost of this part of the concentrator can be reduced. It may in fact increase without the proper attention paid to design detail. Edge attachment must be kept simple by using a minimum number of clamps and screws or another simple approach. For the estimates we prepared, unattended clamping by a robot is presumed. If the task turns out to be too complex for a robot, concentrator costs are likely to increase two or three dollars-per-$m^2$.

**main mast**

A simplification of the main mast could reduce costs. In the current design, the main mast includes the main shaft with drilled drain and air holes, a four-piece drain system, two complex spoke flanges, numerous gussets, shaft end plates, and a rain shield. All these parts require a significant amount of welding which is expensive. It may be difficult to simplify the main mast, but at a minimum, optimizing the size and weight will minimize both material and shipping costs.

**support structure**

Like the main mast, the support structure has a large number of cut, welded, and shaped steel parts. These construction techniques result in an expensive support structure; however, this type of design may be necessary to fulfill dish performance requirements in which case optimization will only result in small cost reductions.

**general notes**

The estimated design point efficiency of the stressed metal-membrane concentrator is at least 5% lower (and likely even lower) than that for the glass-metal concentrator. Based on this information alone, it would be necessary for the stressed metal-membrane concentrator to be 5% lower in cost on a per-square-meter-basis to compete with the glass-metal concentrator. Again, this is based only on concentrator efficiency, receiver and conversion efficiency differences may mitigate some of the concentrator efficiency differences.

**future areas of emphasis**

- A large area of emphasis in optimizing the concentrator manufacturing should be the hydroforming operation. Realistic large-scale hydroforming scenarios should be postulated based on test data. In particular the following items should be determined, reasonable flow rates for the forming fluid, how the fluid would be put into the plenum during forming, and how much manual labor is involved in the hydroforming operation. This would not necessarily require an expensive full-scale prototype to be built. Hydroforming is a critical part of the stressed metal-membrane concentrator's construction; and if low-cost, time-efficient methods are not developed, this concentrator design will not be able to compete with glass-metal designs on an economic basis.

- The ability to produce simplistic, relatively air-tight edge attachment systems for the rear and optical membranes should be demonstrated. Ideally, attachment systems should be installed through the use of unattended robots.

- The system efficiency differences due to receiver and energy conversion units of sizes other than the well-characterized 25-kWe units should be addressed.

- Finally, performing engineering design on the mast and support/foundation structure would be beneficial. Keeping parts, welds, weight, and manual assembly to a minimum is an essential part of this work.

## Stressed Composite-Membrane Concentrator

**molding**

The composite membrane avoids the potentially expensive hydroforming process, because it is preformed at the central manufacturing facility. Two disadvantages of the composite are the long processing times required to produce one membrane and large factory floor space requirements. At this stage of the design, how many coats of gelcoat are required, the cure-time for both epoxy and gelcoat, and what type of molds would be used are not well-defined. For estimating purposes, it was assumed all process steps and curing for one concentrator are completed in a 24-hour period. If further investigation shows this is an unrealistic assumption, costs will rise several dollars-per-square-meter. Reduction of drying times or process simplifications might reduce the cost by up to $1 per $m^2$ of aperture area.

**edge attachment**

The cost of this element is uncertain due to a lack of design information. The conceptual design identified attachment of the rigid composite to the ring as detrimental to the optical performance of the concentrator. For lack of better information, a clamp and screw attachment was assumed. Obviously, the proper design will be different; however, the cost is not likely to be lower. Edge attachment for the composite, rear membrane, and optical material must be simple, effective, and preferably automated, or the estimated cost will increase several dollars per square meter.

**main mast, support structure, and general notes**

See stressed metal-membrane comments

**future areas of emphasis**

- Characterization of large scale manufacturing operations for the composite membrane would eliminate much of the uncertainty in this area. In particular, identifying the coating process, curing procedures, mold type, and mold lifetime would be particularly useful in determining the viability of cost-effective mass production.

- Resolving the uncertainty associated with the edge attachment system should be a priority for this design. Unattended installation by robots would probably be the most cost-effective installation method.

- The system efficiency differences due to receiver and energy conversion units of sizes other than the well-characterized 25-kWe units should be addressed.

- Finally, as with the metal-membrane, concentrator engineering design work on the mast and support/foundation structure is necessary.

Since the only way these technologies are likely to be deployed commercially is if they provide superior economics, resolution of the design aspects we have identified above would seem to be the best place for investment of future research dollars. In our opinion, the glass-metal concentrator technology is the benchmark to which all other dish technologies should be compared. If resolution of the design aspects discussed above can be achieved and the stressed membrane technologies can beat, not just compete with, glass-metal technology then these stressed membrane technologies should be developed to their full potential. If these design aspects can not be resolved and superior economics can not be shown, the technologies should be set aside until the U.S. energy outlook changes, Solar Thermal Program funding increases, or other factors make it advantageous to develop these particular stressed membrane technologies.

Sincerely,

Ken Humphreys

Ken Humphreys
Research Engineer

cc: Walter Short
John Thornton