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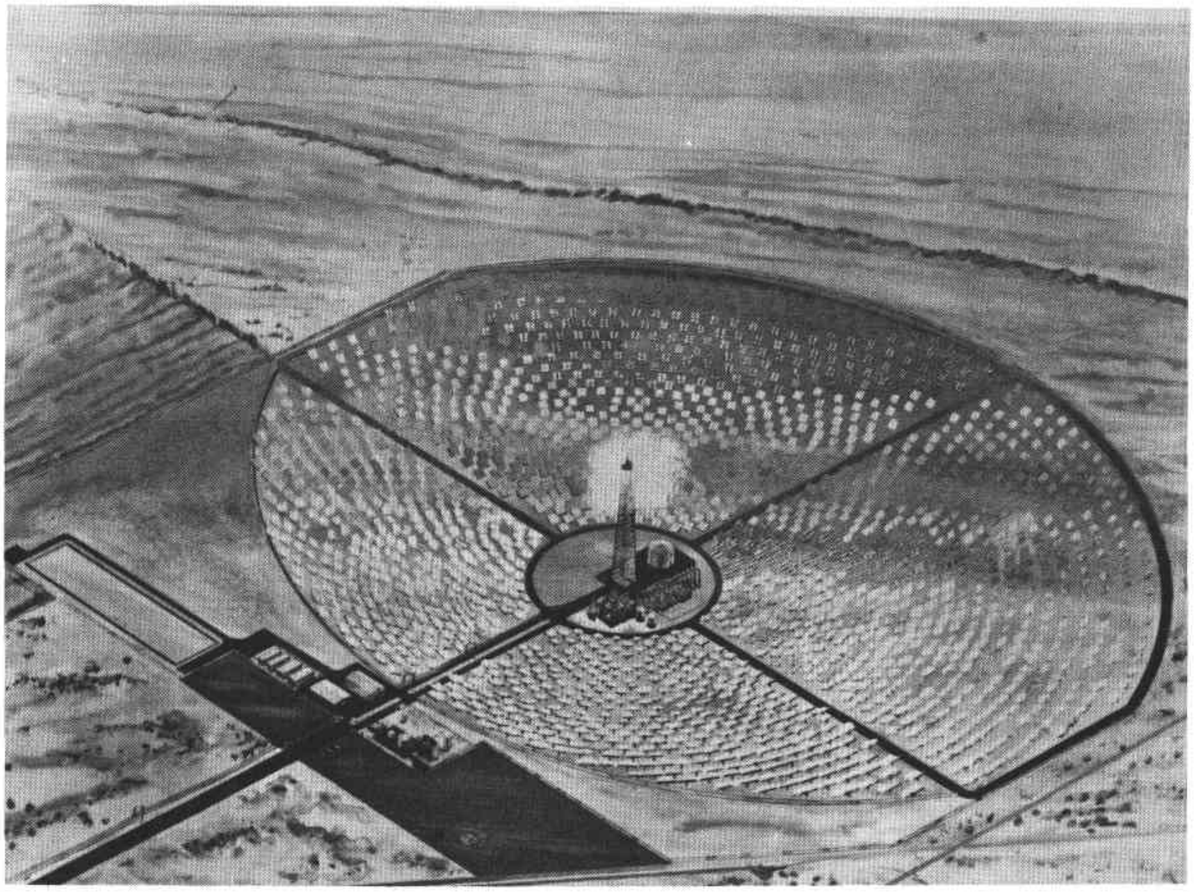
Solar Ten Megawatt
Pilot Plant
Performance Analysis



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SOLAR 10 MEGAWATT
PILOT PLANT PERFORMANCE ANALYSIS

FEBRUARY, 1981

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1.0 INTRODUCTION

The nation's first solar-powered electrical generating plant is being constructed near Barstow, California, by the Department of Energy and a consortium composed of the Southern California Edison Company, the Los Angeles Department of Water and Power, and the California Energy Commission. The principal objectives of this Pilot Plant project are establishing the technical feasibility of a solar power plant of the Central Receiver type and obtaining data on the development, production, and operating costs of such a plant which are scalable to larger, commercial-size plants. A secondary objective is to gather operational and environmental data to both stimulate and enhance utility and public acceptance of solar thermal energy systems which can be used to supplement fossil-powered systems.

The Pilot Plant system is composed of a select number of major elements, as depicted in Figure 1. The operational interaction of the design elements is shown in the simplified schematic diagram in Figure 2.

This document defines the expected performance of the Solar 10 Megawatt Pilot Plant on the basis of design characteristics. The Pilot Plant rating, operational limits, energy output, and efficiency are defined as a function of solar insolation and sun angle, which are a function of time. In developing the performance data, the following ground rules were used:

1. Plant performance calculations are based on subsystems characteristics used in developing the plant baseline design. Plant performance may degrade in time with any degradation of those subsystem characteristics, e.g., heliostat reflectivity, receiver absorbtivity, and the tolerances on the heliostat tracking mechanism.
2. The operating modes were selected to optimize the energy output of the plant.
3. The plant startup operation is based on the generation of useful power once a 15° sun angle is reached.

2.0 ASSUMPTIONS

The assumptions used in this Pilot Plant performance study are summarized

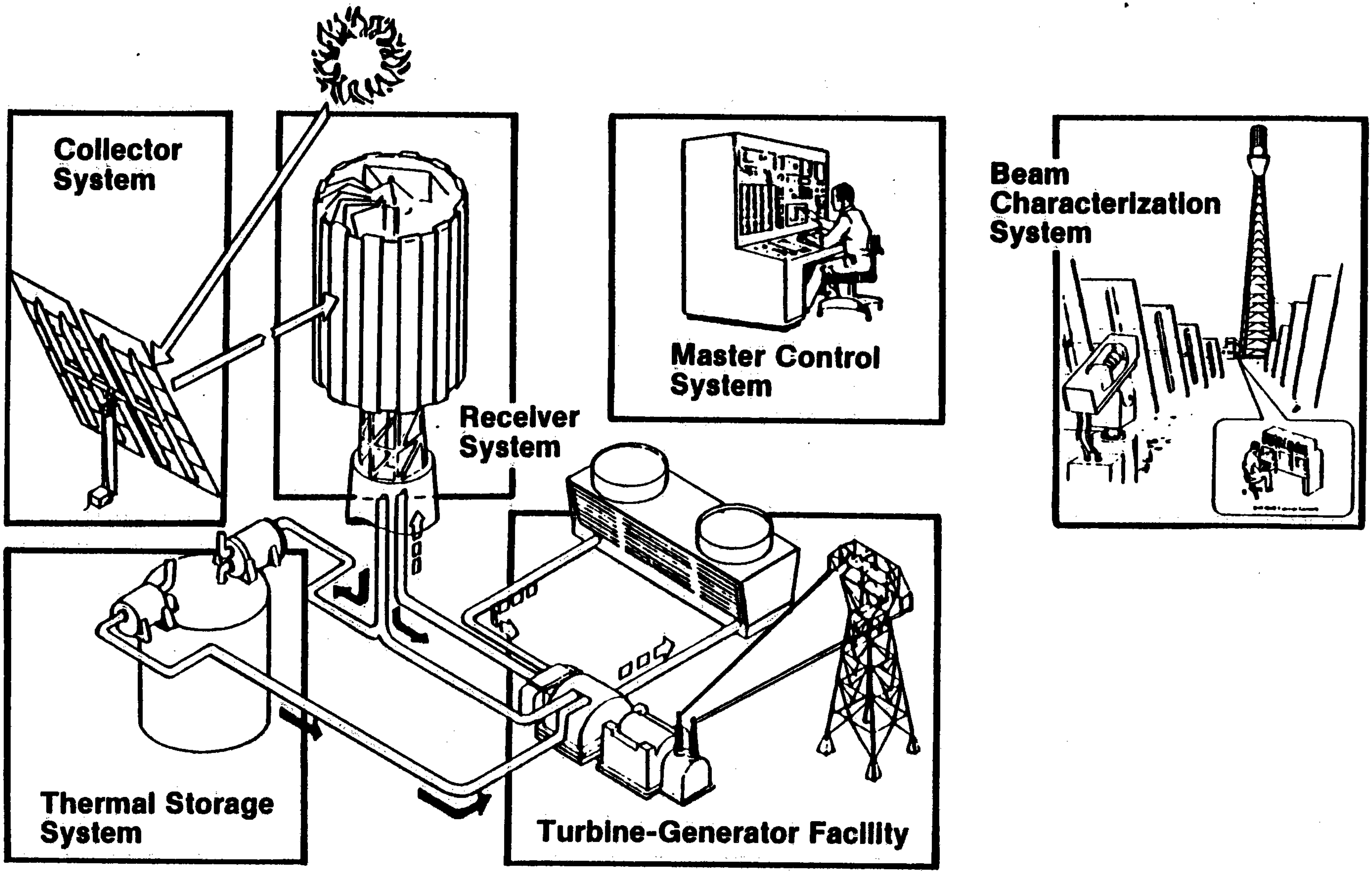

Figure 1. Pilot Plant System Design Elements

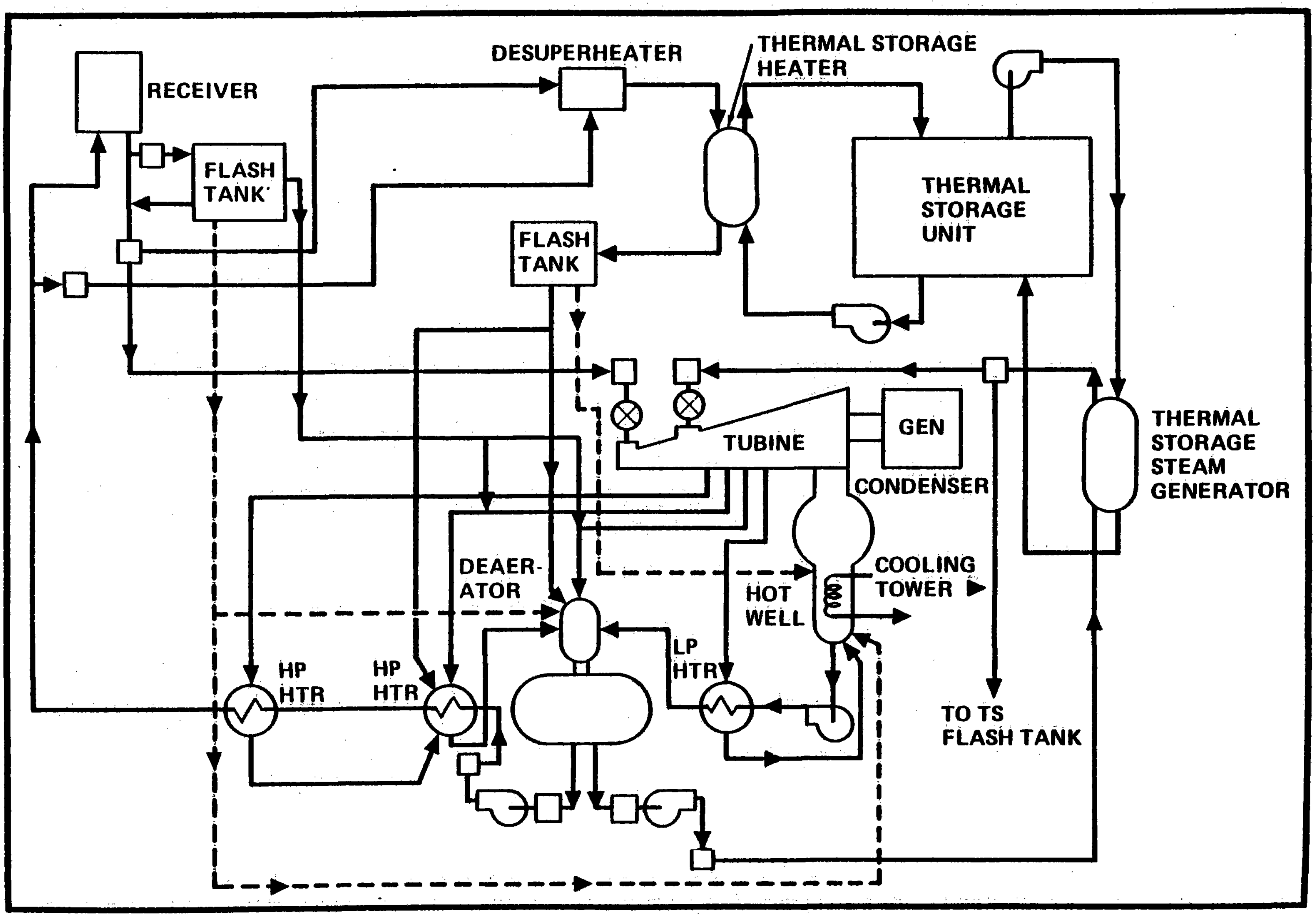

Figure 2. Pilot Plant Simplified Schematic

below. Unless otherwise noted, these assumptions were derived from data used by McDonnell Douglas Company, the Solar Facility Design Integrator (SFDI), in developing the plant baseline design (References 1, 2, 3).

The Pilot Plant operation scenarios are developed from a history of solar energy or insolation data from the plant site. A typical clear day operating scenario is shown in Figure 3.

1. The Barstow 1976 hourly insolation data tape was used for daily and annual insolation data, (Reference 4), along with an experimental observation of the actual insolation at the Plant site measured at 16 second increments (Reference 5).

2. The collector field consists of 1818 heliostats with a total reflector area of 772,125 ft^2.

3. The time-dependent collector field power efficiency for sun cosine angle effect and heliostat blocking and shadowing are summarized in Figure 4.

4. The following plant performance efficiency factors were assumed to be constant throughout the year:

Receiver and tower blocking and shadowing	99.3%
Heliostat reflectivity	89%
Atmospheric attenuation	97%
Receiver intercept (spillage)	97.6%

5. The following receiver loss values were assumed constant during receiver operation:

   Radiation and convection: 4.7 MWt (based on an ambient temperature of 55°F and a wind speed of 8.5 mph)

   Surface absorptivity: 0.95

6. Main steam downcover piping thermal loss of 0.1 MWt.

7. Admission steam piping thermal loss of 0.015 MWt.

8. Thermal storage energy loss of 2% per 20 hour hold.

9. Gross steam cycle electrical conversion efficiencies are based on the following turbine design values provided by the turbine-generator vendor:
   a. Receiver steam only (950°F and 1465 psia) at the turbine stop valve:
      1. Efficiency - 35.19%

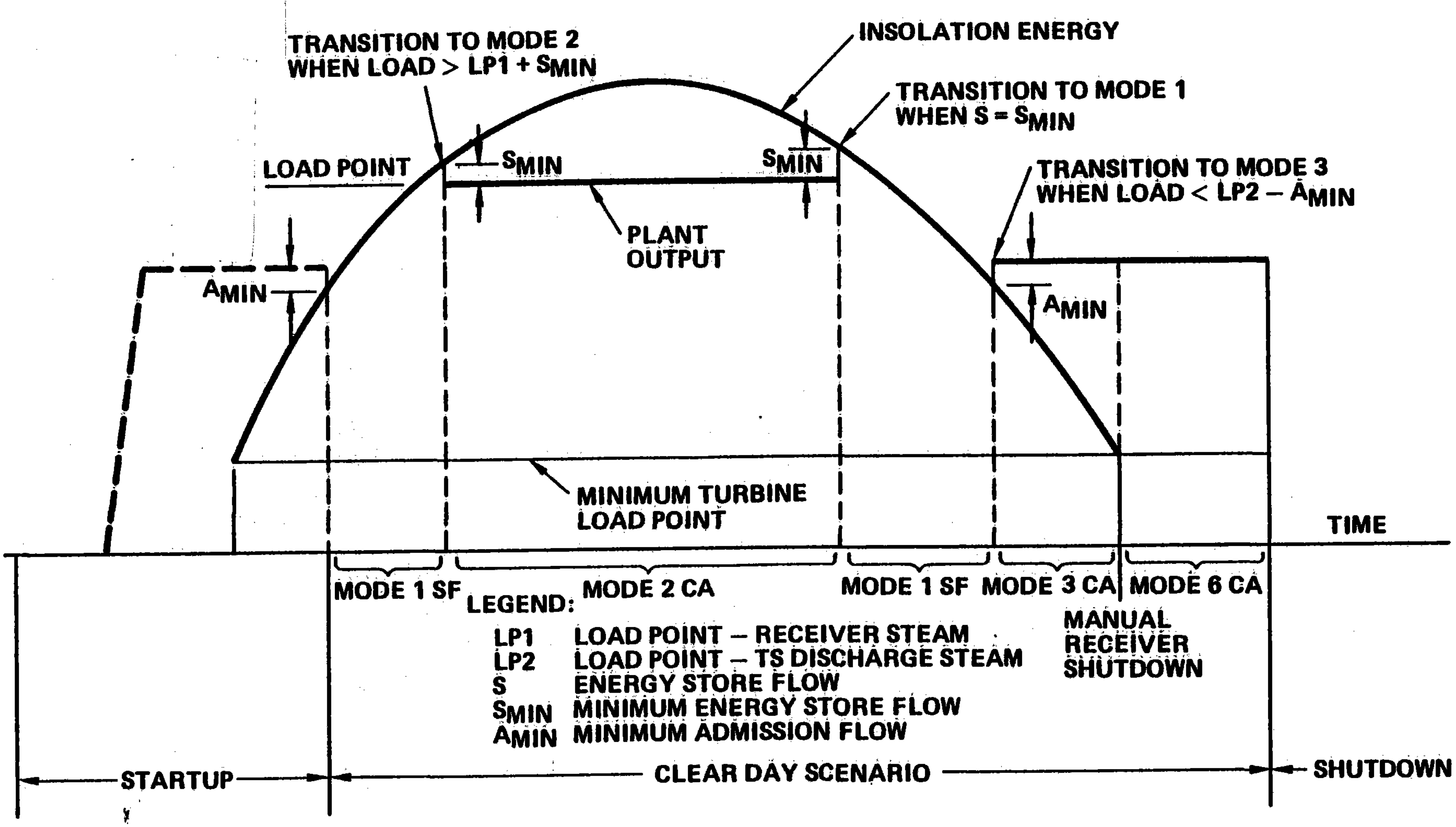

Figure 3. Clear Day Operating Scenario

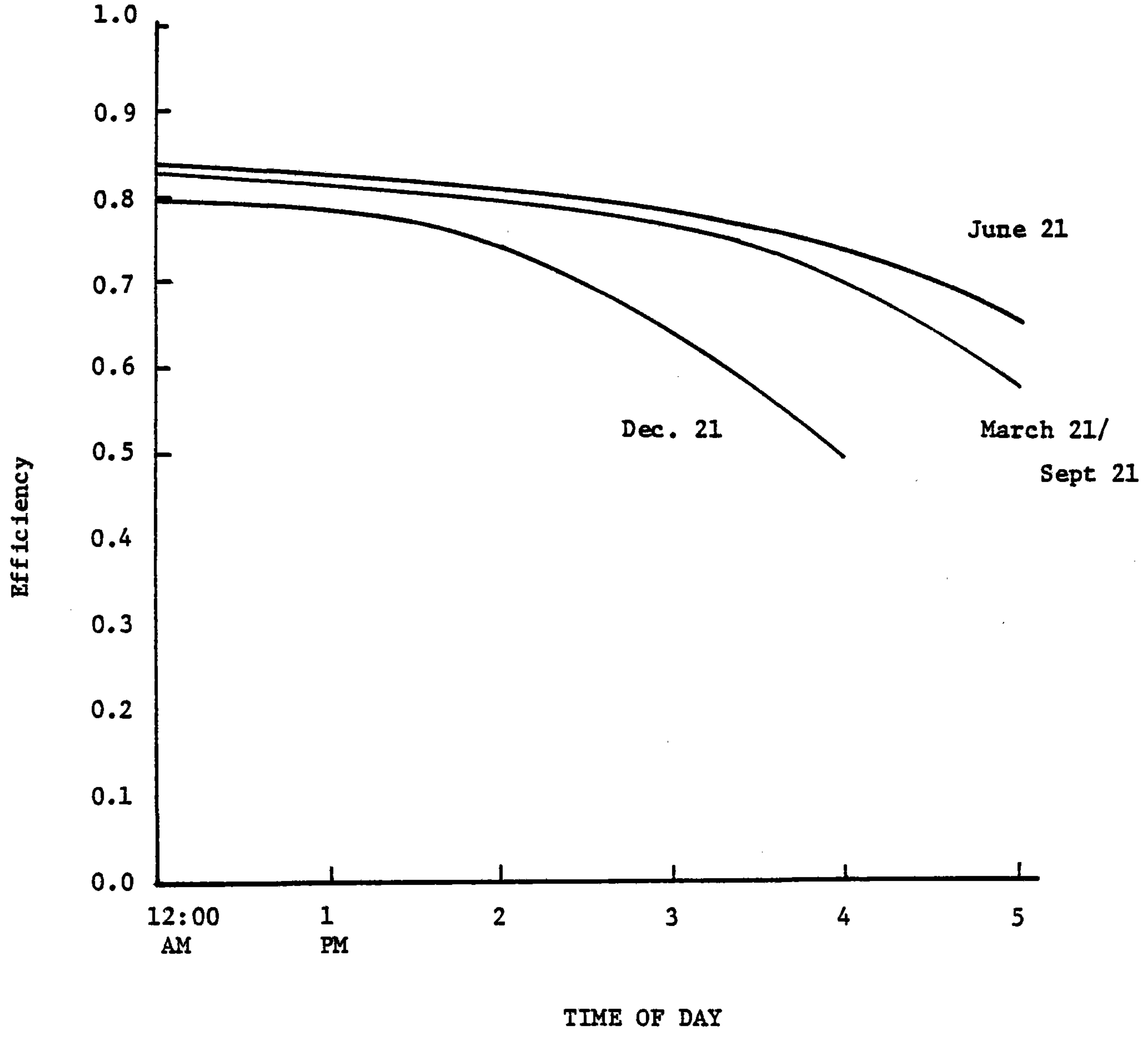

Figure 4. Pilot Plant Collector Field Efficiency for Cosine Effect, Heliostat Blocking, and Shading

2. Gross power output - 12.5 MWe
3. Steam flow rate - 112,140 lb/hr.

b. For admission steam only (525°F and 385 psia) at the turbine admission stop value:
1. Efficiency - 25.36%
2. Gross power output - 8.001 MWe
3. Steam flow rate - 105,000 lb/hr.

c. Combined receiver and admission steam:
1. Efficiency - 30.48%
2. Gross power output - 10.348 MWe
3. Steam flow rate - 57,500 lb/hr
Receiver steam and 57,500 lb/hr admission steam.

10. The parasitic power estimates noted in Table 1 are for full power operation for each operating mode. The plant operating modes are listed in Table 2 and shown schematically in Figure 5.

11. Warm turbine daily startup requires 15 MWt-hr of energy extraction from the Thermal Storage Subsystem.

3.0 ANALYTICAL PROCEDURES

For purposes of this performance analysis, an Aerospace computer program, SEPPEM - Solar Electric Plant Parametric Evaluation Model - was used to determine the plant power output and the daily and annual energy generation. The calculation includes the effects of variation in the sun position throughout all the days of the year and is based on Barstow, California, measured insolation data. The calculations were performed exclusively for optimized plant operation.

The analysis begins by calculating for each hour of the day the power converted into steam, accounting for the variable collector field loss factors and constant receiver thermal losses. The thermal energy absorbed in the steam is then converted into electrical energy using the appropriate operating mode. For this particular analysis, to optimize the amount of electrical energy generated by the power plant, the energy in the receiver is, inasmuch as possible, passed directly to the turbine. Therefore, operating modes 1, 2, and 3 are used extensively.

When the energy absorbed by the receiver in transforming water into steam is in excess of the energy required for the turbine generator to provide the rated

Table 1

PLANT PARASITIC LOAD ESTIMATE (kW)*

	OPERATING MODE							
	1	2	3	4	5	6	7	8
Collector System*	54	54	54	54	54	-	54	-
Motor Control Center (MCC) "A" & "L"								
SCE ROTATING EQUIP.	1097	1097	1220	1220	1097	630	1220	139
SFDI, CONTROL, DAS & EQUIP.	40	40	40	40	40	40	40	40
WAREHOUSE	22	22	22	22	22	22	22	2.8
SCE CONTROL BLDG. A/C, LIGHTING, OTHER	100	100	100	100	100	100	100	100
SCE ADMIN. BLDG.	90	90	90	90	90	90	90	30
Motor Control Center "B" (TSS)	13	337	337	661	337	337	661	38.3
Motor Control Center "C" (Water Tr.)	149.7	149.7	149.7	149.7	149.7	149.7	149.7	185.0
Power Panel A (Receiver)	25.6	25.6	25.6	25.6	25.6	20.0	25.6	44.0
OTHER**	100	100	100	100	100	60	100	50
TOTALS	1691	2015	2138	2462	2015	1449	2462	529

*McDonnell Douglas Data, September 1980

**Includes: Special Data Acquisition System, Beam Characterization System, Weather Station, etc.

TABLE 2

PILOT PLANT STEADY STATE OPERATING MODES

Mode	Description
1. Turbine Direct	All thermal power absorbed by the receiver flows to the EPGS for direct turbine-generator operation
2. Turbine Direct and Charging	Thermal power collected by the receiver is divided between thermal storage (charging function) and the EPGS for direct turbine-generation operation
3. Storage Boosted	All thermal power collected by the receiver flows to the EPGS and is augmented by admission steam power extracted from thermal storage
4. In-Line	All power collected by the receiver flows to thermal storage. Thermal power is extracted from storage for turbine-generator admission steam operation.
5. Charging Only	All thermal power collected by the receiver is used for thermal storage charging.
6. Discharging Only	Thermal power is extracted from storage for admission steam turbine generator operation.
7. Storage Boosted and Charging	Thermal power collected by the receiver is divided between both storage and the EPGS. Thermal power is also extracted from storage and routed to the admission steam input of the EPGS.
8. Inactive	All subsystems are inactive and held in a standby condition during overnight shutdown.

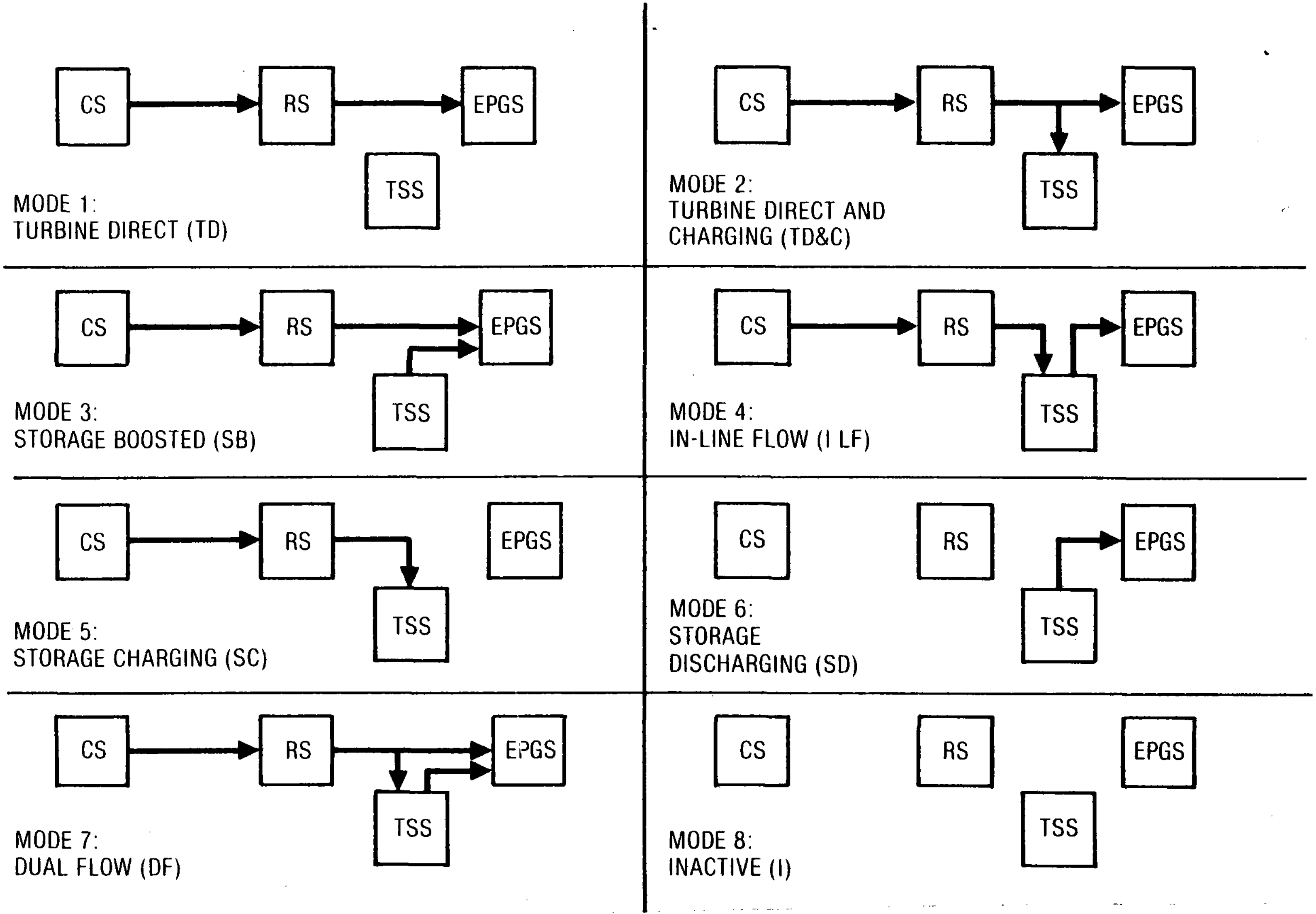

Figure 5. Pilot Plant Steady State Operating Modes

10 MWe net power to the utility grid, the excess energy is diverted to thermal storage for later production of electrical power. (Operating Mode 2). When energy from the receiver is less than that required to generate rated power, the receiver steam is augmented by thermal storage (Operating Mode 3). When less than full rated receiver steam is available but storage is empty, Operating Mode 1 is used. When neither direct solar nor storage energy is available to the plant, it is placed in an inactive mode (Operating Mode 8) and grid power may be used to keep the plant in a standby condition. Modes 4 or 5 are used for transitory conditions only, while Mode 6 is used when storage energy is available and when no energy is available from the receiver. The passage of clouds is not considered in the analysis for obvious reasons but is factored into an availability analysis (Ref. 5).

The program calculates generated and stored thermal energy for each hour of the day. The electrical energy generated through every day of the year is then integrated to yield the total annual energy generation and the plant capacity factor.

4.0 PERFORMANCE CHARACTERISTICS

Computer runs were made to outline the Pilot Plant performance characteristics. The key items of interest are: 1) plant rating or power output, 2) operating time range (how long the plant can deliver rated power), 3) daily and annual total energy output, and 4) plant efficiency. The Pilot Plant performance results are summarized in Table 3, and the individual characteristics are discussed below.

4.1 Pilot Plant Power Rating

4.1.1 Rated Power From Direct Receiver Steam

The Pilot Plant will deliver a minimum of 10 MWe net electrical energy to the Southern California Edison Company distribution grid when the turbine is operating directly from receiver steam (105,000 lb/hr, 950^{o}F and 1465 psia steam conditions at the turbine stop valve). The plant heat and mass balance at these conditions is shown in Figure 6. The power level is the net output of the plant when operating solely from insolation after subtracting all plant electrical parasitic loads.

Table 3

SUMMARY OF PILOT PLANT PERFORMANCE

Plant Rating:	10 MWe for 7.8 Hrs. Summer Solstice plus 10 MWe for 4 Hrs. Winter Solstice 7 MWe net for 4 Hrs. from Thermal Storage
Maximum Power to Grid:	10.8 MWe (Operating mode 1) (12.5 MWe Gross-1.7 MWe Parasitic)
Energy Storage Capacity:	28 MWe-hr net Output plus Seal and Startup steam
Maximum Estimated Daily Energy	112 MWe-hr (June 21) 58 MWe-hr (Dec. 21)
Annual Estimated Energy Generation:	26,000 MWe-hr (365 day operation)
Plant Capacity Factor:	0.3
Plant Efficiency (Net electrical power/ normal insolation) energy	17.4% (June 21, Noon) 15.3% (Dec. 21, 2PM)
Plant Energy Efficiencies: (Net electrical energy/ normal insolation energy)	13.5% (June 21) 11.1% (Dec. 21) 13% (Annual)

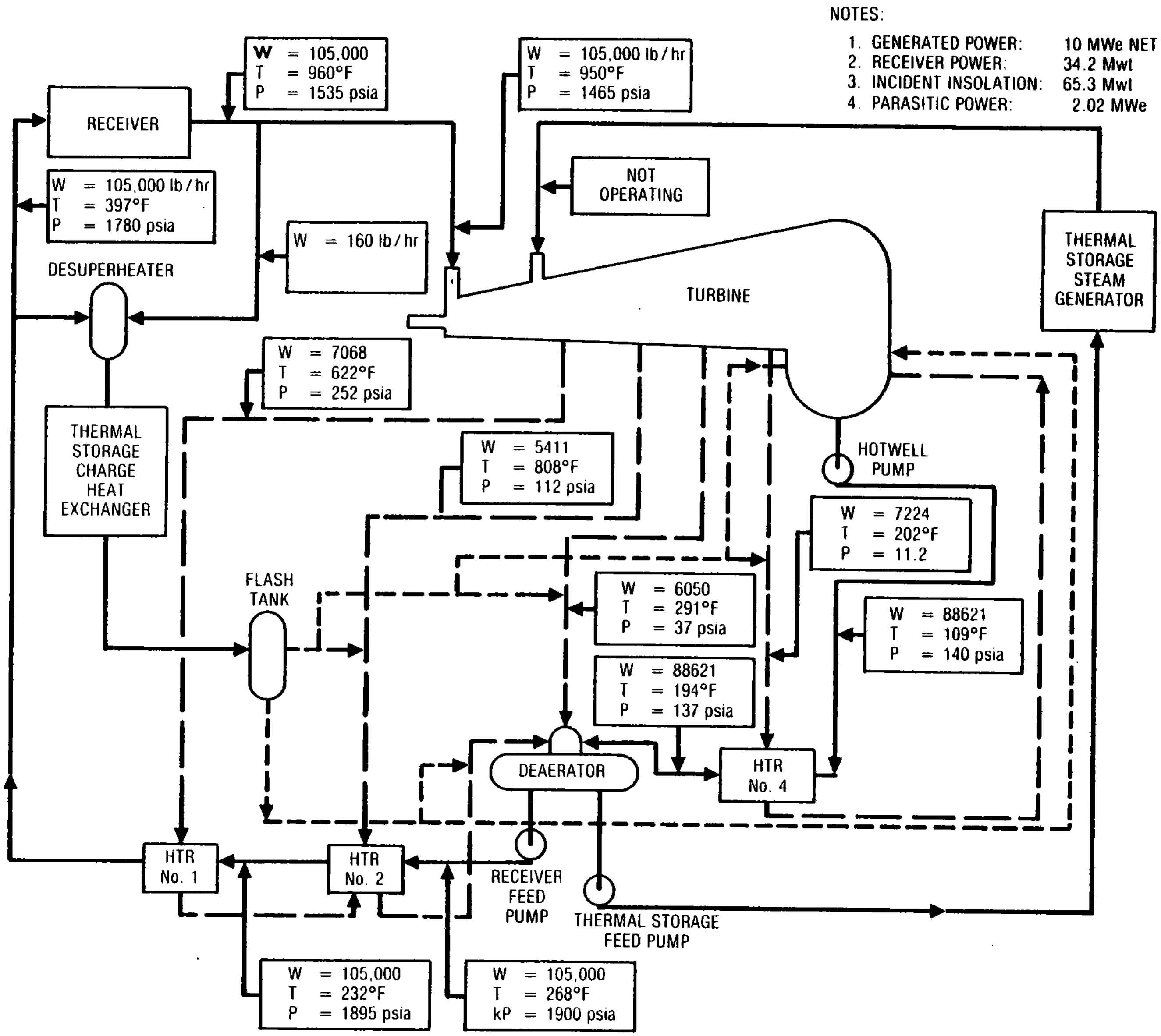

Figure 6. Pilot Plant Heat and Mass Balance for Winter Design Conditions (2PM, December 21)

4.1.2 Maximum Power From Direct Receiver Steam Operation

The maximum direct power delivered by the Pilot Plant when operating directly from receiver steam is 10.8 MWe net electrical (112,300 lb/hr, 950°F, 1465 psia steam conditions). The output power is turbine limited. Required receiver power is 35.7 MWt. (See Reference 3 for detailed heat balance).

4.1.3 Rated Thermal Storage Operation

The Pilot Plant will deliver 7 MWe net electrical power when operating from the thermal storage subsystems (110,000 lb/hr, 525°F, 385 psia steam conditions at the admission stop valve). See Reference 3 for detailed heat balance.

4.2 Operating Range at Rated Power

The amount of solar energy collected by the Pilot Plant on any given day is essentially constant; however, the amount of electricity generated by the Plant depends on the time of day the energy is needed by the utility and the operating mode selected by the operator during that day. The "Plant Design Best Day" is defined as the day of the year when the solar energy incident on the collector field is at a maximum. This peak energy day occurs approximately at summer solstice, June 21. The minimum insolation day, corresponding to the "Plant Design Worst Day," occurs approximately at winter solstice, December 21. On the "Plant Design Best Day" the Plant can deliver a maximum of 112 MWe-hrs, (Section 4.4.1); however, if energy is required during the night, the plant can deliver 7 MWe net for up to four hours from thermal storage steam by limiting daytime electrical generation to 10 MWe net for a period of just under eight hours.

On the "Plant Design Worst Day" the Plant can deliver 10 MWe net for four hours from receiver steam and 7.0 MWe net for some minimal period from thermal storage. If nighttime energy generation is required, the thermal storage operation can be increased up to four hours by reducing daytime 10 MWe generation to three hours or less and diverting the collected energy to storage.

4.3 Energy Storage Operation

The Pilot Plant can store approximately 165 MWt-hr of thermal energy. From that, the Pilot Plant can deliver 28 MWe-hr of electrical energy to the grid and in addition can provide: sufficient steam to maintain equipment in a hot standby condition; a blanketed condition during non-operating periods; and, in addition, provide sufficient thermal energy for turbine startup the next day.

4.4 Pilot Plant Energy Generation

4.4.1 Plant Design Best Day Energy Generation

The Pilot Plant can generate a maximum of 112 MWe-hrs net energy at the best design day assuming full insolation using operating modes which maximize direct operation (receiver to turbine) for maximum plant efficiency and subsequent energy generation. The operational power profiles for this day are shown in Figures 7 and 8. While operating in the extended operations mode, some efficiency is lost by diverting energy through thermal storage, and the total generated energy is only 100 MWe-hrs. net.

4.4.2 Plant Design Worst Day Energy Generation

The Pilot Plant worst day energy generation capability is 58.0 MWe-hr net. With full utilization (28 MWe-hrs) of thermal storage with its efficiency loss, the capability of the plant is 56.4 MWe-hr. The power profiles for maximum power on this day are shown in Figures 9 and 10.

4.4.3 Annual Energy Output

The Pilot Plant is able to generate an annual output of 26,000 MWe-hrs net based on the insolation and environmental data contained in the 1976 insolation data tape for Barstow. This analysis ignores downtime for maintenance, which is assumed to occur at night, or special experimental operation. This output corresponds to a plant capacity factor of 30 percent based on a 10 MWe rated capacity.

The daily energy generation based on the 1976 data tape is shown in Figure 11 for both the maximum energy operating mode and for the full extended operation mode.

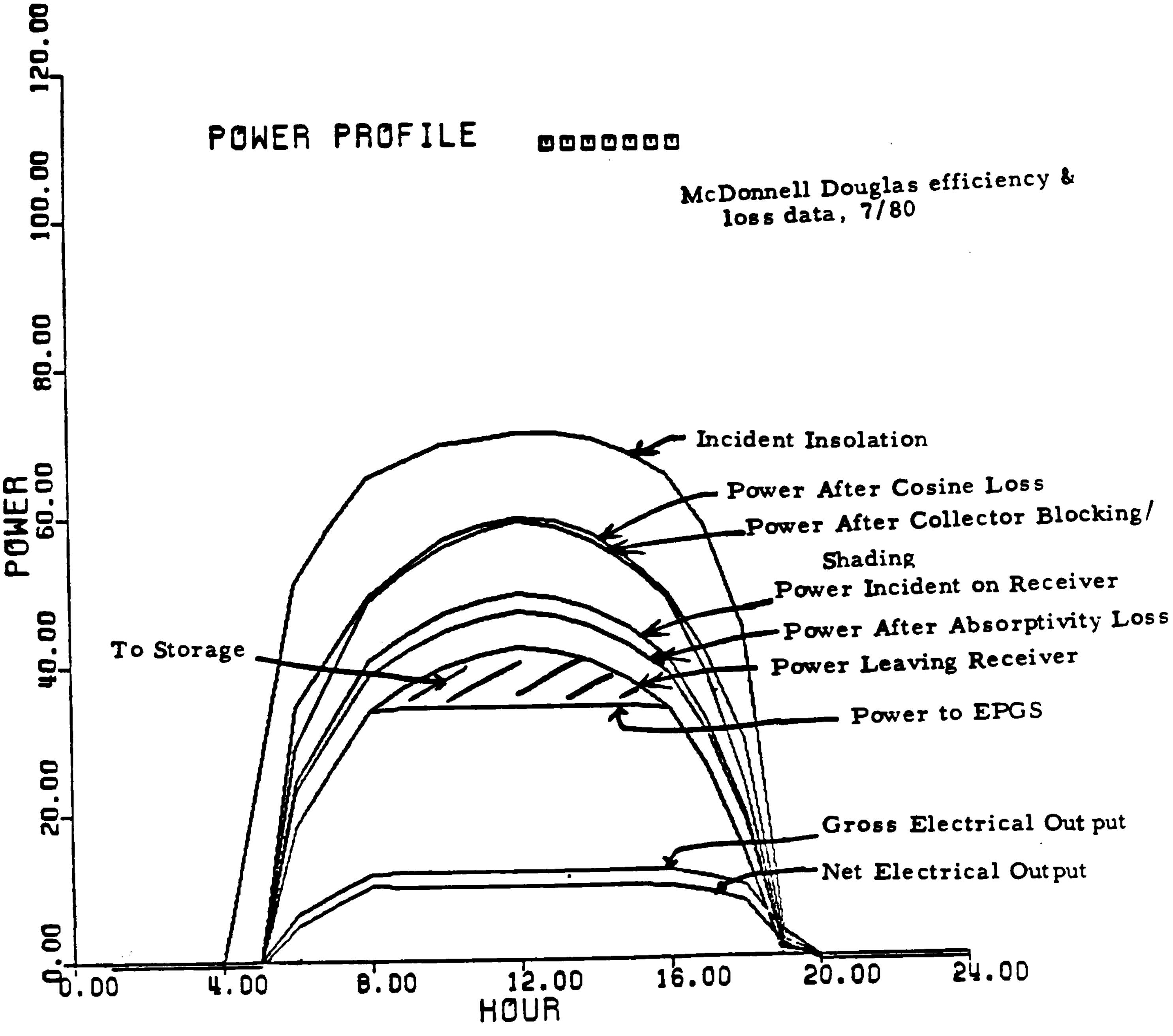

Figure 7. Pilot Plant Best Day Power Profile (June 21)

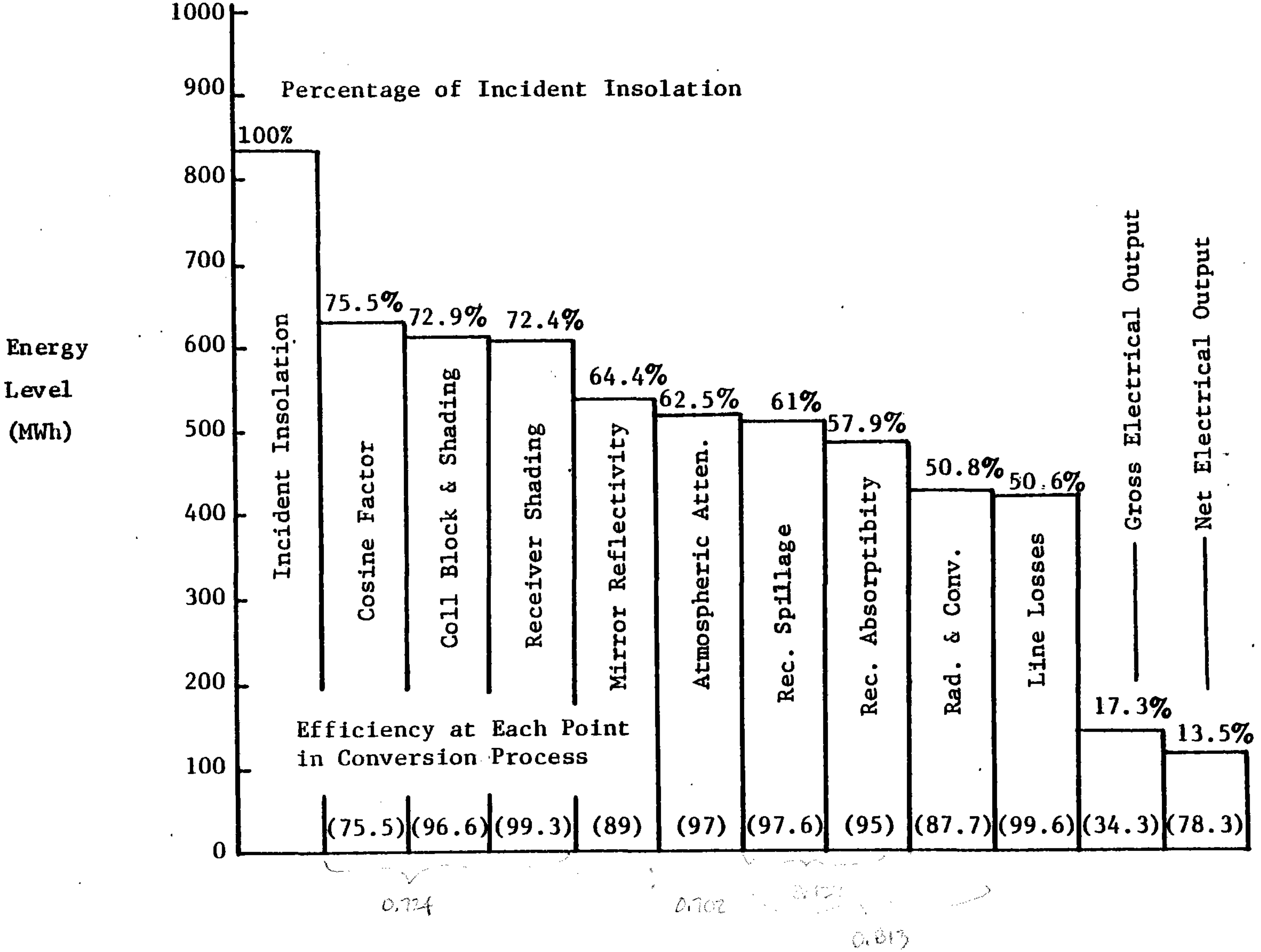

Figure 12. Summer Solstice Energy Efficiency (Daily Average)

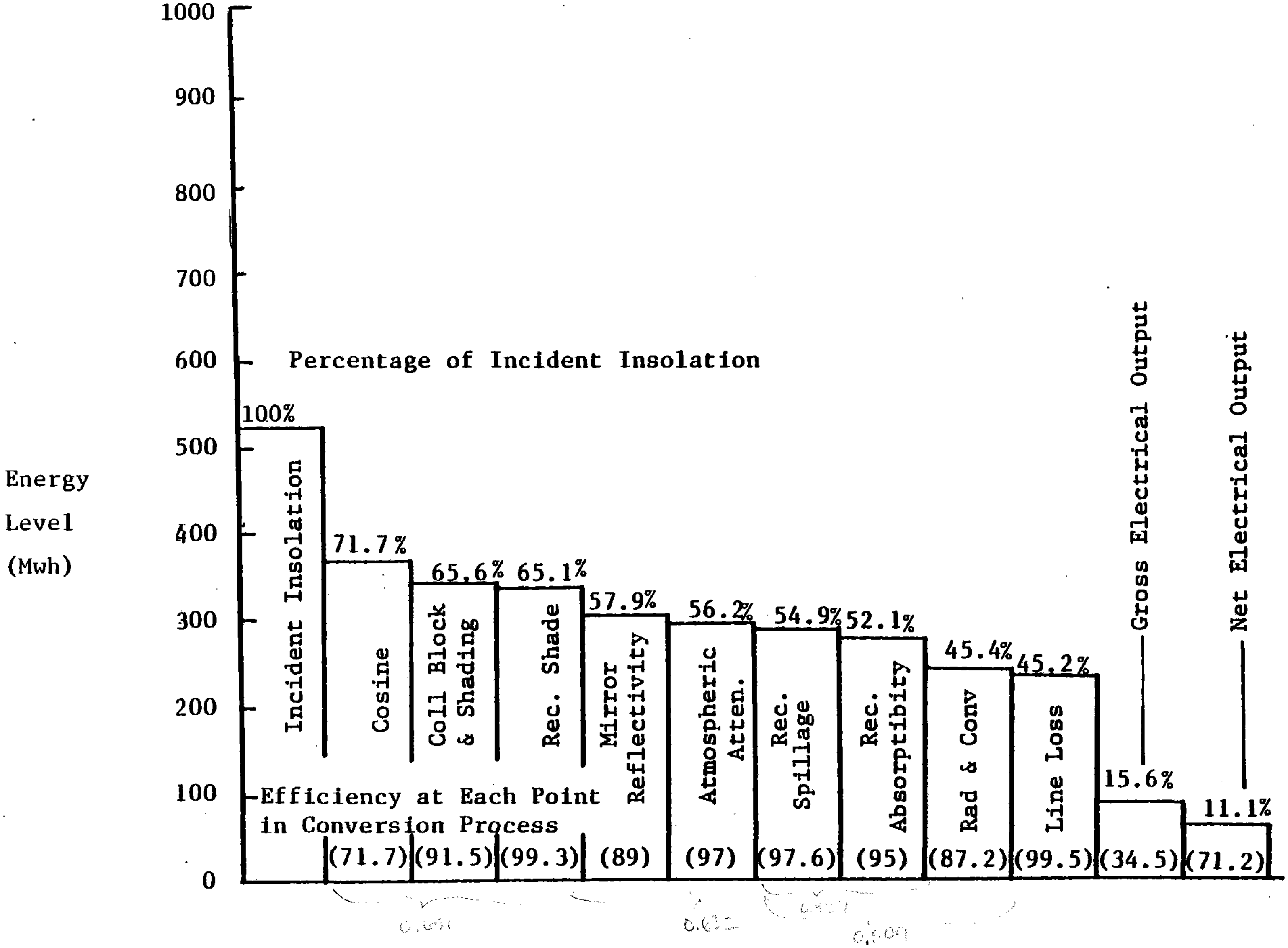

Figure 13. Winter Solstice Energy Efficiency

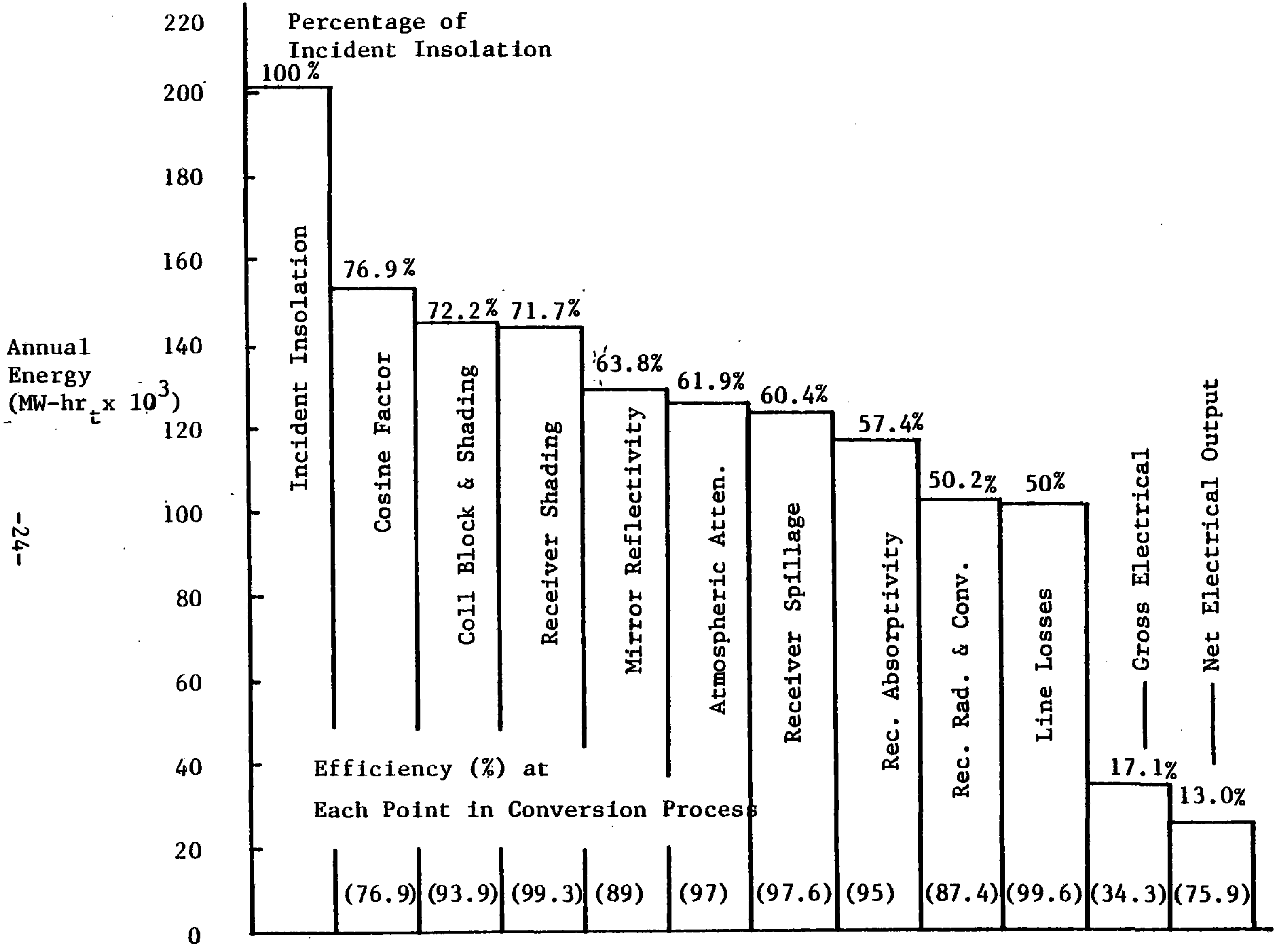

Figure 14. Annual Energy Efficiency (Typical Year)

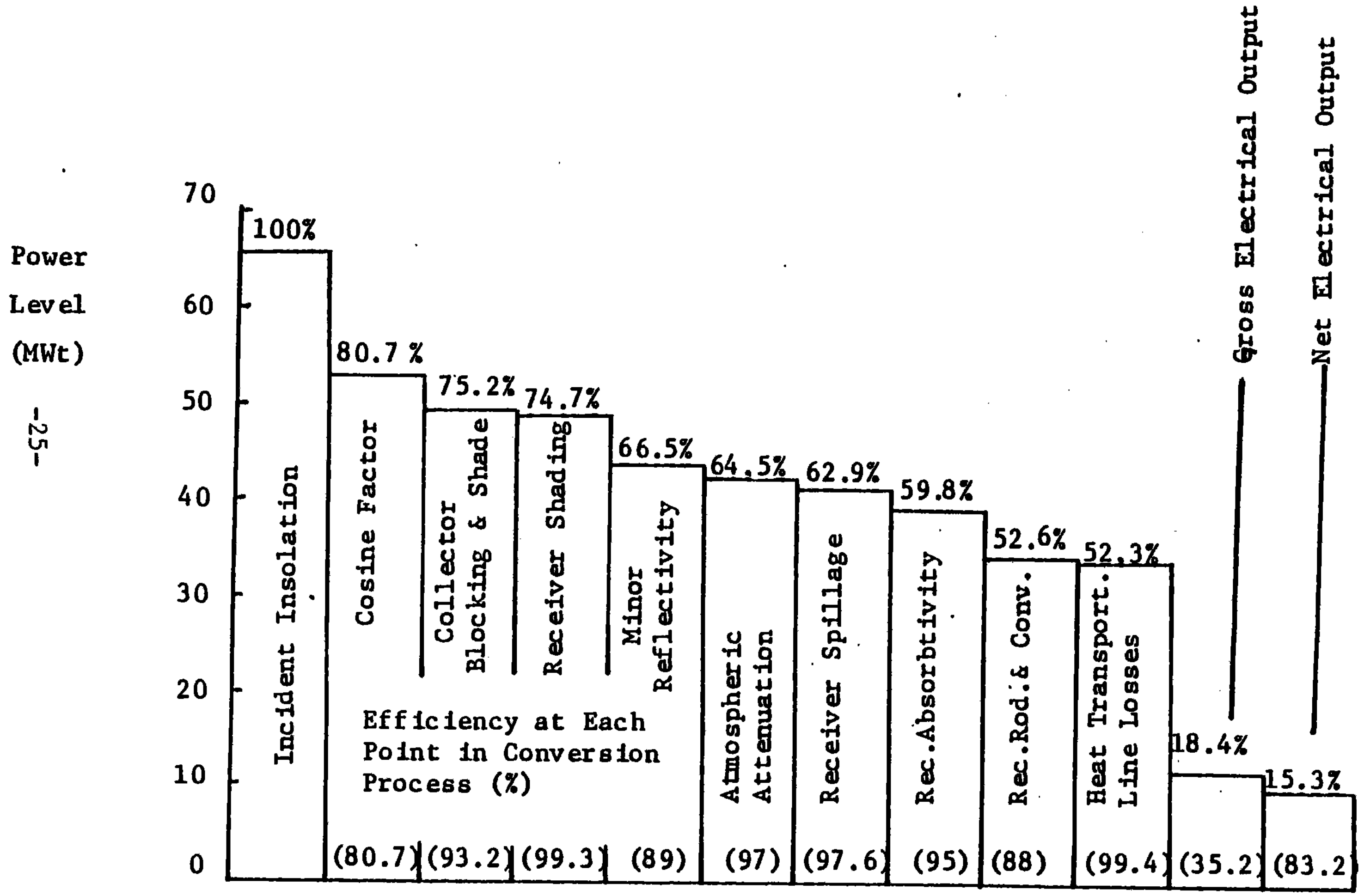

Figure 15. Winter Solstice Design Point Efficiency (2 PM, Dec. 21)

5.0 REFERENCES

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2. "10 MWe Solar Thermal Central Receiver Pilot Plant System Specification (RADL Item 2-3)" Astronautics Company, November, 1979.

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4. Patapoff, N.W., "The West Associates Solar Resource Evaluation Project-Solar Energy Measurements During 1976", Project Manager, Southern California Edison Company, June 1977.

5. "Measurements of Typical Insolation Variation at Daggett, California", Aerospace Report No. ATR-80(7747)-1, Vol. I and Vol. II; C. M. Randall, B. R. Johnson and M. E. Whitson, Jr.

6. Aerospace Technical Audit, Pilot Plant Pressure Drops and Flow Analysis, September 1980.

7. McDonnell Douglas Astronautics Company

6.0 ACKNOWLEDGEMENT

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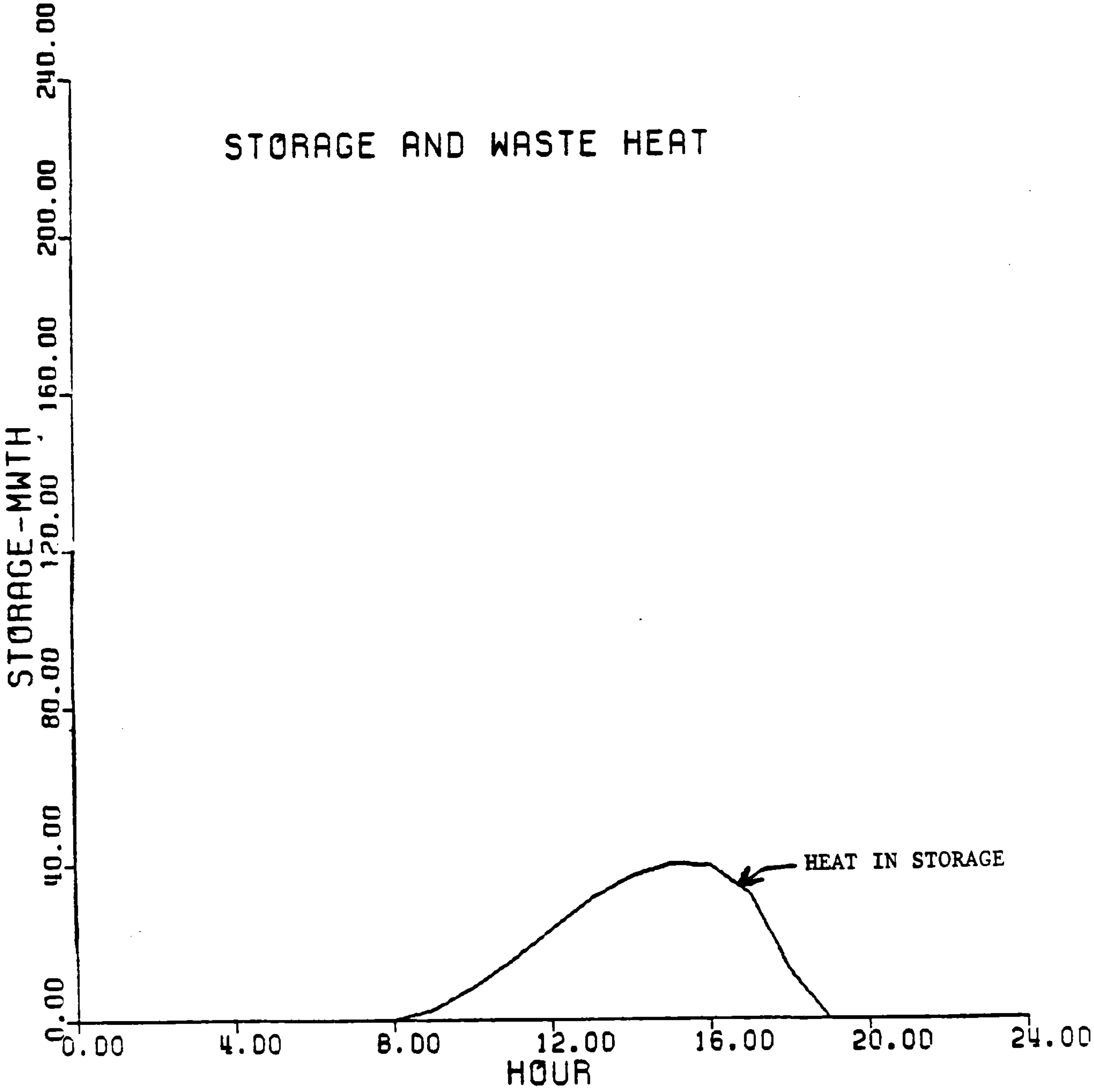

Figure 8. Thermal Storage Operations (June 21)

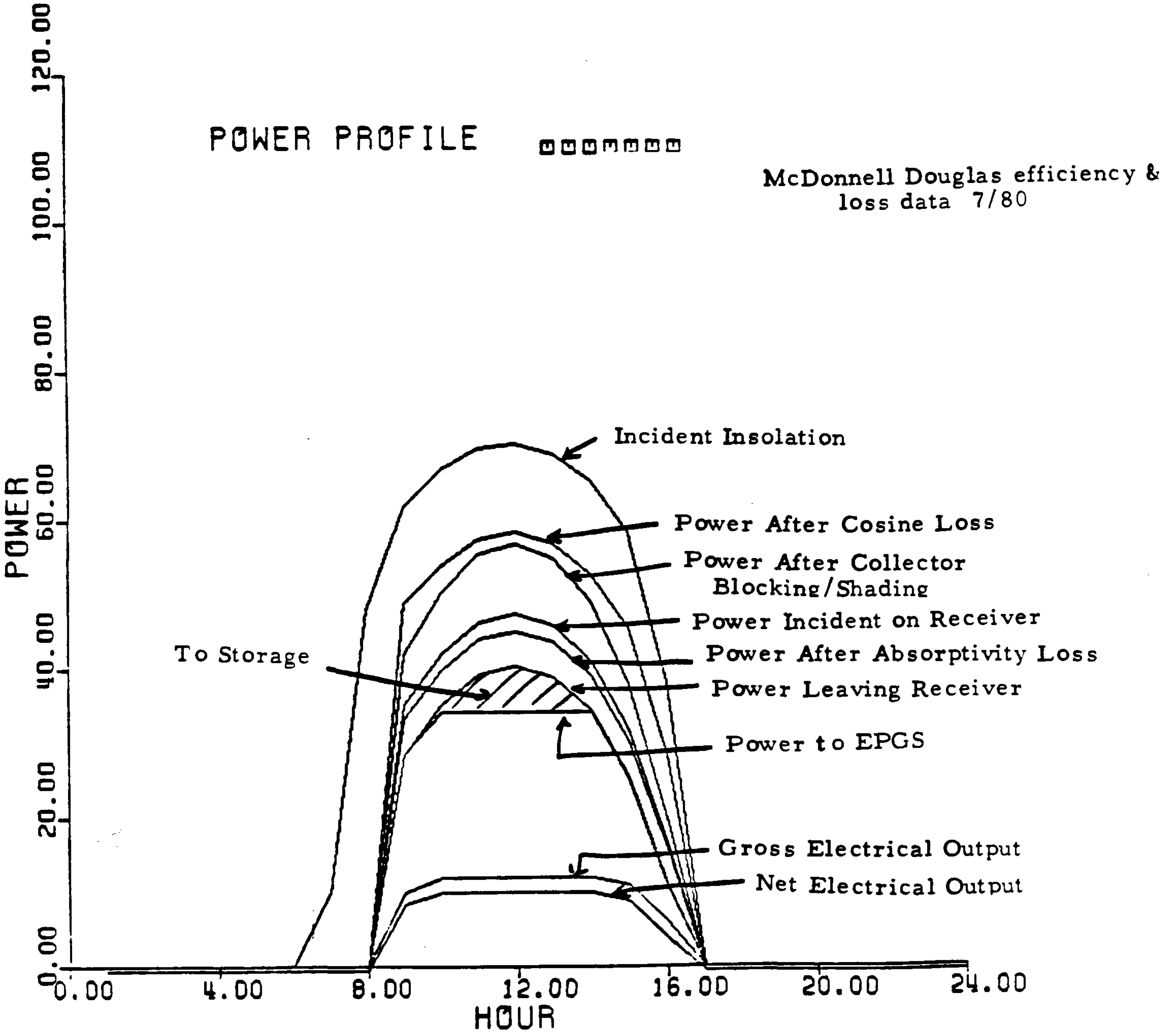

Figure 9. Pilot Plant Worst Day Power Profile (Dec. 21)

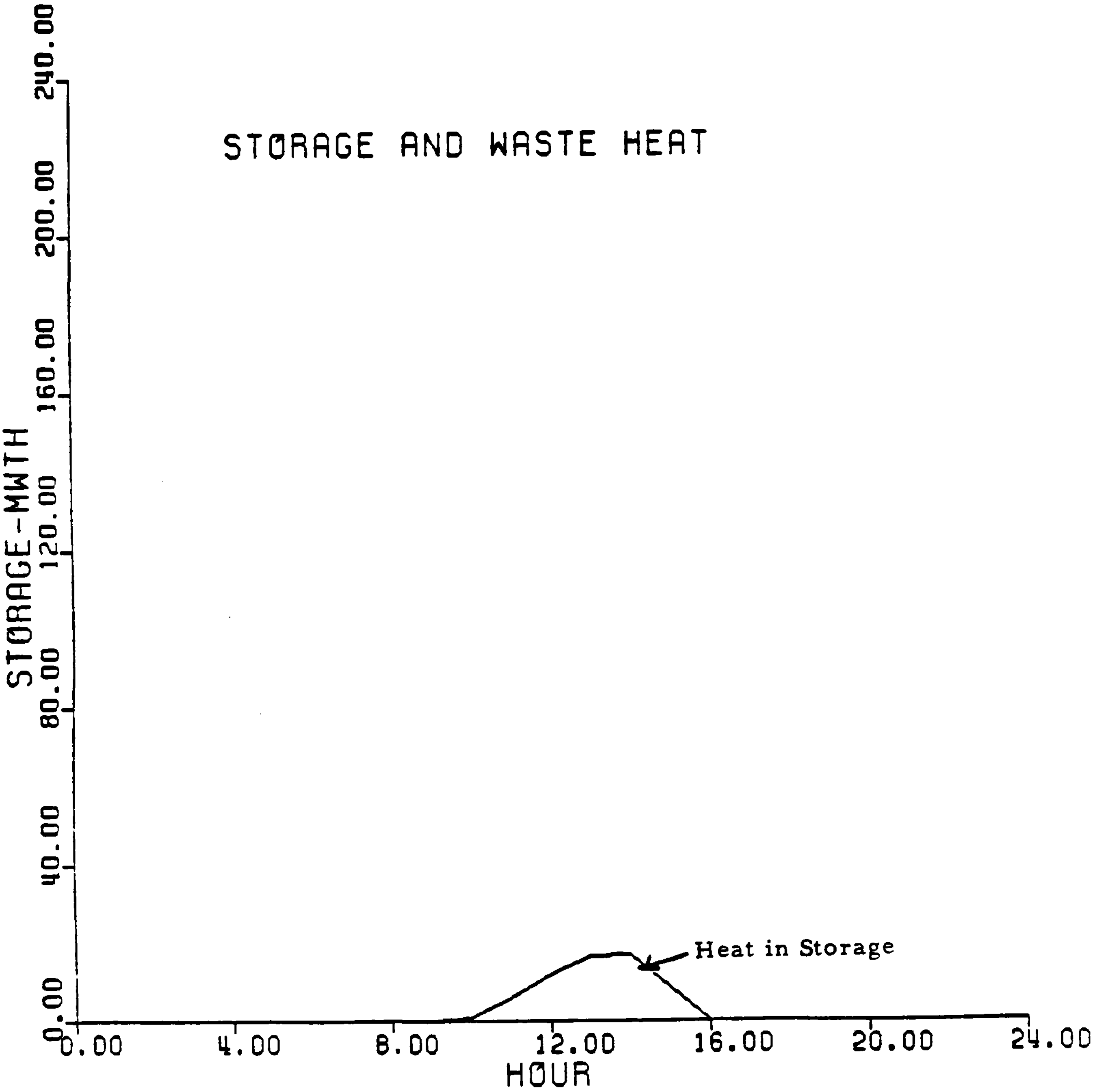

Figure 10. Thermal Storage Operations (Dec. 21)

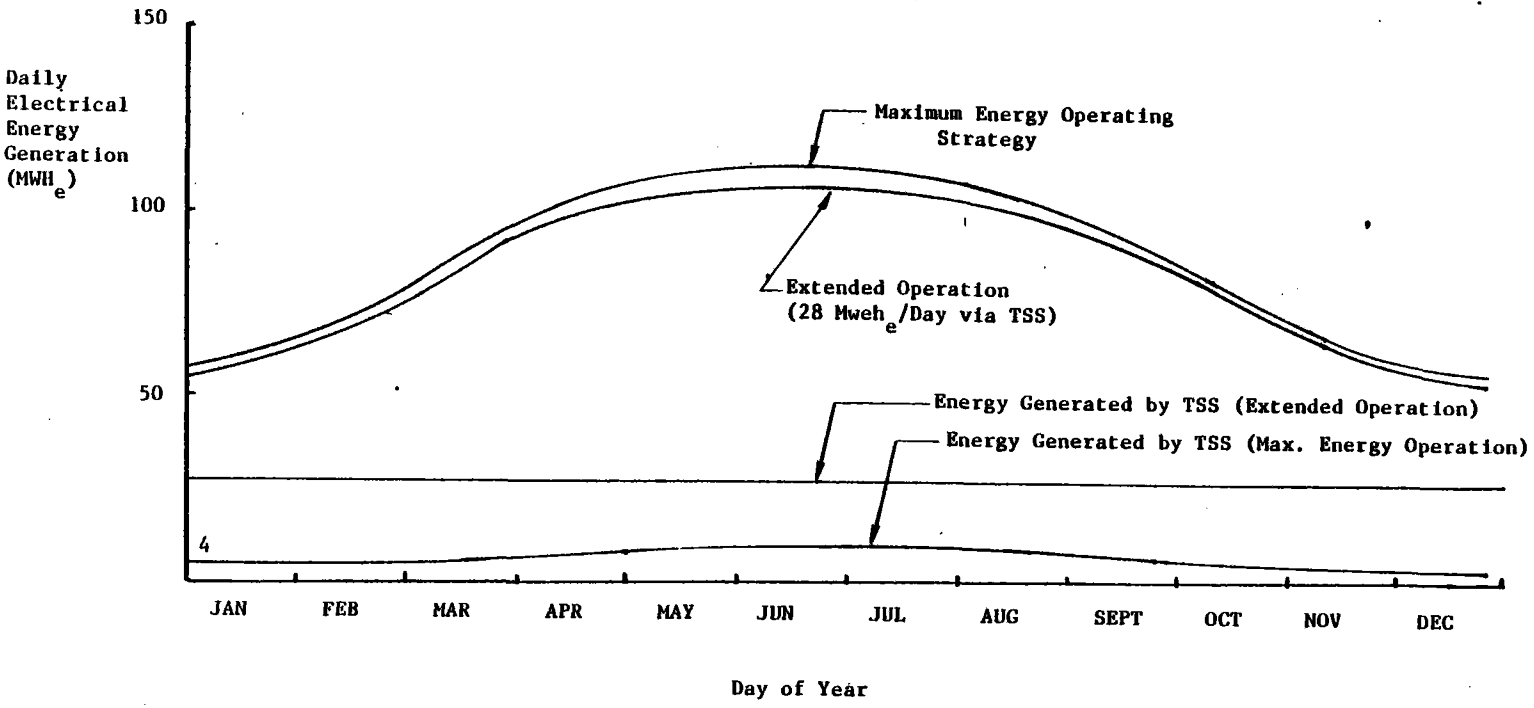

Figure 11. Daily Energy Throughout the Year - 10 MW Pilot Plant

4.5 Pilot Plant Efficiency

4.5.1 Design Best Day Energy Efficiency

The design day energy efficiency is defined as the ratio of the total electrical energy delivered to the grid assuming maximum energy operation to the total thermal energy available to the collector field assuming a full insolation day (mirror area x integrated normal insolation). The best day efficiency is 13.5% as illustrated in Figure 12. Using full storage operation, this efficiency drops to 12%.

4.5.2 Design Worst Day Energy Efficiency

The worst day energy efficiency is 11.1% based on maximum power operation and 10.6% based on full energy storage operation. The energy loss staircase is shown in Figure 13.

4.5.3 Annual Energy Efficiency

The Pilot Plant annual energy efficiency is 12.9% based on available incident insolation of 2.02×10^5 MWt-hr, maximum power operating strategy, and no allowance of shutdown for maintenance. The energy staircase is shown in Figure 14.

4.5.4 Primary Design Point System Power Efficiency (2 PM, Dec. 21)

The design point power efficiency is defined as the ratio of rated power (10 MWe) to that portion of the thermal power available to the collector field,which is directed to support EPGS operation (Exclusive of TSS). This efficiency, shown in Figure 15, is a minimum of 15.3%.

4.5.5 Secondary Design Point System Power Efficiency

This efficiency is defined as the ratio of rated net power (7 MWe) while the plant is operating in Mode 6 (extended operation) to the thermal power extracted from the TSS storage media (oil) by the TSS heat exchanger. This efficiency is a minimum of 20%.