5105-151
Solar Thermal Power Systems
Parabolic Dish Systems Development

Solar Walk-Off Protection

(An Analysis of Cost and Risk Trade-Offs for Walk-Off Protection of Point Focus Thermal Power Systems)

H.I. Awaya
R. Bedard, Jr.

February 1, 1985

Prepared for
Sandia National Laboratories
Albuquerque, New Mexico
Through an Agreement with
National Aeronautics and Space Administration
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SECTION 1
INTRODUCTION AND SUMMARY

1.1 BACKGROUND

A dish concentrator for solar thermal power is pointed at the sun during normal operation so that its concentrated solar beam enters the receiver aperture. A failure of some sort may cause the concentrator to remain fixed while the spot of concentrated sunlight, due to the rotation of the sun relative to the earth, moves slowly across the face of the receiver and the receiver aperture support structure. The intense local heating caused by this event may damage the receiver support structure, and/or nearby equipment such as cables, fluid lines, and instrumentation. This undesired event is called a solar "walk-off."

A solar walk-off is caused by one of three primary failure mechanisms, namely: loss of power to the concentrator drive subsystem, (usually the result of a utility grid failure), failure of the drive subsystem (structurally, electrically or otherwise), or human error.

There have been many design solutions proposed for either preventing the event of a walk-off or protecting the dish module during the walk-off event. All known solutions, however, involve cost and risk trade-offs. One alternative is to accept all the risks of walk-off and spend no money to prevent or protect the dish module from the effects of the intense local heating. Another is to provide only emergency backup power, thus protecting against grid failure, but not against walk-off due to failure in the drive subsystem. Also, protection may be provided for the equipment located in the focal point region thus protecting against both drive subsystem and grid failure. The costs associated with a solar walk-off depend on the cost of walk-off prevention/protection, and the cost to restore the plant to operation following a walk-off event. It is obvious that if an extremely simple, reliable, safe and inexpensive solution to the solar walk-off prevention/protection problem existed, there would be no need for this study. Although there are currently no known solutions that meet these criteria, this is certainly a fruitful area for innovative and creative thinking.

1.2 STUDY OBJECTIVE AND PURPOSE

The objective of this study is to recommend preferred methods of solar walk-off prevention/protection (or no prevention/protection) for a specific assumed generic dish module and electric plant design. A secondary objective is to add clarity to the solar walk-off issue which tends to be somewhat difficult to understand because of its dependence on a multitude of plant, dish module, and site-specific design characteristics.

The purpose of this study is to assist the people at Sandia National Laboratories, who are responsible for developing advanced point focus solar thermal technology, in their development planning activities by identifying further analysis, design or testing needs of promising solar walk-off prevention/protection technologies.

1.3 STUDY APPROACH

The study approach can be summarized as the selection of a baseline solar thermal electric plant design, dish module design and various walk-off protection design alternatives, the gathering of the required cost and risk (probability of a failure causing a walk-off event) data base, the construction of a mathematical representation of the problem and the evaluation of the selected alternatives. The mathematical model must be sufficiently elaborate to capture the essentials of the walk-off cost-versus-risk problem and also must be simple enough to yield computable solutions within the resource constraints of this study. The cost of the baseline case (no walk-off prevention/protection) is first evaluated. It is the initial capital, the recurring operating and maintenance and capital replacement cost of the baseline solar plant and the cost of restoring the plant to operation following a solar walk-off with walk-off events occurring at a frequency depending on grid outage and critical plant component failure rates. The alternative cases (with walk-off prevention/protection) are then evaluated by increasing the solar plant cost as a function of specific walk-off prevention/protection design alternatives and decreasing the cost of walk-off events given the specific level of prevention or protection offered by the alternative cases. The alternative plant designs are then evaluated relative to the baseline and compared against each other by annualizing all costs associated with the plant, walk-off prevention/protection and walk-off events. Based on the evaluation results, conclusions and recommendations are formulated. The overall approach, as described above, is illustrated in block diagram form, in Figure 1-1.

1.4 SCOPE

In addition to stating what this study is, a few statements on what this study is not, will be useful in assisting the reader to understand its scope.

This walk-off study is intended to assess the significant differences among "generic walk-off prevention/protection alternatives" (including no walk-off prevention/protection) for a "generic dish module and electric plant design." It should be clearly understood that it is not the objective of this study to understand all the ramifications of possible dish module, electric plant or walk-off prevention/protection design alternatives. It should also be understood that this study will consider only solar walk-off failure modes and will not consider other dish module failure modes, thermal or otherwise. An example of a nonwalk-off thermal failure mode is loss of circulation caused by a failure of the receiver circulation system.

It should be understood that the cost-versus-risk effectiveness of a specific solar walk-off prevention/protection design alternative is site-dependent, dish module design-dependent, and plant design-dependent. The words "generic dish module and plant" are used to simply mean one that is representative of a typical design that might possibly be considered for application sometime in the future. The word "generic" is not interpreted to mean representative of the entire class of all possible dish module and plant designs. Certainly, for example, it is not possible to select a specific organic Rankine engine that is "generically" representative of the multitude of types of engines, including Stirling and Brayton-cycle engines.

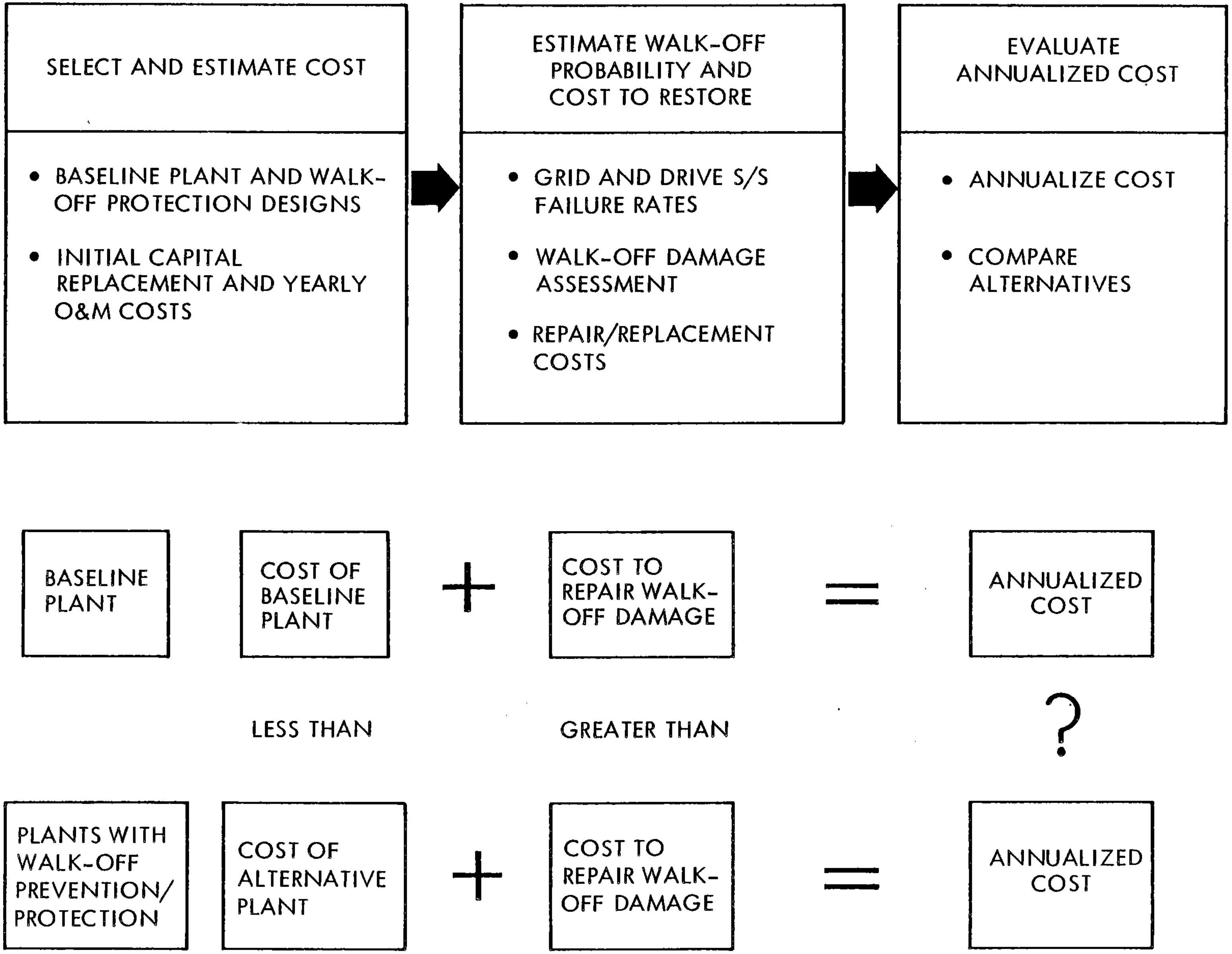

Figure 1-1. Walk-Off Protection Study Approach

1.5 BASELINE SOLAR POWER PLANT

The selected baseline point focus power plant design, as described in Section 2 of this report, is the 1 MWe plant designed by Ford Aerospace and Communications Corporation (FACC) for the Small Community Solar Thermal Power Experiment (SCSE). The most recent description and mass production cost estimate for that plant design is contained in the September 1979 FACC Phase II proposal. Although this design does not represent the latest design in the evolution of that plant, it nevertheless represents typical point focus dish module plant technology sufficient for the purposes of this cost effectiveness study. It should be noted that this study is only evaluating changes relative to a baseline and thus, is not seeking a high degree of absolute accuracy.

The baseline plant design is a grid-connected 1 MWe plant composed of 62 dish modules with each module rated at approximately 22 kWe. Each dish module consists of a parabolic concentrator and a receiver and engine/alternator power conversion unit (PCU). The PCU is located at the focal point of each concentrator. The modules are interconnected by 480 volt cables and are interfaced with the utility grid. The key features of the dish module design are as follows:

(1) Concentrator. An 11-meter diameter General Electric design modified with a mirror glass reflective surface.

(2) Receiver. A cavity-type steam receiver redesigned to operate with toluene by Garrett AiResearch Corporation.

(3) Engine/Alternator Package. An organic Rankine-cycle (ORC) engine with integral electric alternator developed by the Sundstrand Company.

1.6 WALK-OFF PREVENTION/PROTECTION DESIGN ALTERNATIVES

The walk-off prevention/protection design candidates selected for this evaluation are summarized in Table 1-1 and described in Section 3 of this report.

Table 1-1. Walk-Off Prevention/Protection Design Alternatives

Design Alternative	Failure Mode		
	Grid	Drive Motor	Drive Train
Battery Backup Power	Prevention		
Diesel/Gen Backup Power	Prevention		
Graphite Shield		Protection	Protection
Graphite Shield and Shutter	Protection	Protection	Protection
Water-Cooled Shield and Shutter	Protection	Protection	Protection
Gravity Detrack System	Prevention	Prevention	

1.7 COST DATA BASE

The cost methodology and the estimated costs for the baseline plant as well as the walk-off prevention/protection design alternatives are described in Section 4. The selected measure of walk-off prevention/protection cost-effectiveness is an annualized cost discounted cash flow model developed specifically for utility-owned solar power plants.

1.8 WALK-OFF FAILURE RATE AND COST TO RESTORE DATA BASE

The probability of a walk-off occurring as a function of the three primary failure mode causes was assessed. The estimated frequency or rate for the 1 MWe baseline plant is as follows:

(1) One grid failure per year, nominal; however, this is highly site-dependent and could vary from once in 30 years to as much as 10 times per year.

(2) Drive subsystem failure consisting of either a drive motor failure with an estimated frequency of once every three years or a drive structure failure with a frequency of once every 22 years.

(3) A human error-caused walk-off is the third failure mode; however, it was not estimated due to lack of operating experience and a strong dependency on operator experience and skill level.

The cost to restore the plant to operation following a solar walk-off is a function of whether the walk-off is caused by a grid or drive subsystem failure. Grid failures affect all modules whereas drive subsystem failure effects are confined to affected modules only. Further, grid failures damage the receiver support structure and the fluid circulation is lost, whereas in a drive subsystem failure, only the receiver support structure is damaged. Estimates of the costs are contained in Section 5.

1.9 COST-EFFECTIVENESS EVALUATION RESULTS

A summary of the evaluation results is shown in Table 1-2. Detailed discussion of these results is contained in Section 6 of this report. The major evaluation results for the selected baseline plant design is as follows:

(1) It is cost-effective to prevent/protect against grid failure-induced solar walk-offs.

(2) It is more cost-effective to prevent grid failure-induced walk-offs using a diesel/generator set rather than battery backup power.

Table 1-2. Summary of Evaluation Results

	Annualized Cost (AC)			
	Plant Cost (k$)	Walk-Off Protection System Cost (k$)	Cost to Restore Plant After Walk-Offs (k$)	Total Annualized Cost (k$)
Baseline Plant (No walk-off protection)	520	0	613	1133
Alternate #1 (Battery backup)	520	97	1	618
Alternate #2 (Diesel/Gen backup)	520	10	1	531
Alternate #3 (Graphite Shield and Diesel/Gen)	520	16	1	537
Alternate #4 (Graphite Shield and Shutter)	520	8	71	599
Alternate #5 (Water-cooled shield and shutter)	520	21	1	542
Alternate #6 (Gravity Detrack and Diesel/Gen)	520	20	0	540

(3) It is not cost-effective to protect the aperture ring support structure with a graphite shield due to the low frequency rate of drive subsystem failure coupled with the relatively low assumed cost of a drive subsystem walk-off.

(4) It is more cost-effective to prevent grid failure-induced walk-offs, and repair the damage from drive subsystem walk-offs rather than protecting against both failure modes by using either a graphite or water-cooled shield and shutter.

(5) Gravity detrack systems are not cost-effective (for the baseline dish module).

1.10 RECOMMENDATIONS

Recommendations are contained in Section 7 of this report. Major recommendations are as follows:

(1) For future point focus power systems, the following design guidelines are recommended:

    (a) Systems analysis of alternative walk-off prevention/protection methods.

    (b) Walk-off sensing instrumentation.

    (c) Fail-safe sun tracking and control.

    (d) Emergency walk-off control logic.

(2) Develop new, innovative and creative walk-off prevention/protection design concepts using solution approaches such as:

    (a) Moving the receiver away from the focal point (rather than slewing the dish off sun).

    (b) Blocking the reflector from producing the concentrated solar beam (rather than protecting from its intense local heating effects at the focal point).

(3) Conduct preliminary design and analysis and engineering test and evaluation of interesting grid failure walk-off prevention backup power concepts such as:

   (a) Using the dish module electrical output.

   (b) Photovoltaic cells.

(4) Extend the results of this study to include other dish module plant designs of interest.

SECTION 2

BASELINE SOLAR POWER PLANT

A baseline serves as a known starting point for evaluating the effect of change from that starting point. For purposes of this walk-off study, a 1 MWe solar power plant, composed of dish modules with no solar walk-off prevention/protection (P/P), has been selected as a baseline. Various walk-off P/P design alternatives, as described in Section 3 of this report, are evaluated for their cost effectiveness against that baseline.

This section presents and describes the baseline, grid-connected power plant. The plant is composed of a number of dish modules and the necessary electrical transport system for interconnecting to the utility electrical grid. A dish module is comprised of three major subsystems; namely, the concentrator, the receiver (which together are referred to as the collector), and the engine/alternator package.

2.1 BASELINE PLANT SELECTION

The primary criteria used for selecting the baseline plant for this solar walk-off study are twofold; namely:

(1) The plant design must be pre-established and have a referenceable cost data base.

(2) The dish module design must be representative of typical point-focus, distributed-receiver, dish module technology.

Based on a survey of available plant baselines, it became evident that only a single plant candidate existed which satisfied both criteria, namely, the 1 MWe plant designed by Ford Aerospace and Communications Corp. (FACC) for the Small Community Solar Thermal Power Experiment (SCSE).

The most recent description of that plant design is contained in the September 1979 FACC Phase II proposal (Ref. 1). The FACC design is a 1 MWe plant composed of 62 dish module units with each module rated at a nominal

22 kWe. It should be noted that the 62 dish modules exceed that plant nominal rating; however, it is common practice in industry to have more generating capacity than the nominally rated capacity. Each dish module consists of a parabolic concentrator with a receiver and an engine/alternator package for power conversion at the focal point of each module. The modules are interconnected by a 480 volt cable and are interfaced with the utility grid through a high voltage transformer. The key components of the dish module are:

(1) Concentrator - An 11-meter diameter General Electric design modified with mirror glass reflectors.

(2) Receiver - A cavity-type steam receiver redesigned to operate with toluene by Garrett AiResearch Corporation.

(3) Engine/Alternator - An organic Rankine-cycle (ORC) engine with integral electric alternator developed by the Sundstrand Company.

It is recognized that the actual Phase II design evolved in such a way that it differed from the earlier proposed design. Nevertheless, the Phase II proposal represents the latest available documentation and cost estimate for the plant design and for that reason, is used as the baseline.

The following subsections describe the baseline plant, concentrator, receiver, engine/alternator package and tracking control logic. Emphasis of the discussion and description in this section is placed on those attributes which are related to this solar walk-off study.

2.2 BASELINE PLANT DESIGN DESCRIPTION

This subsection describes the selected baseline 1 MWe solar point focus distributed receiver power plant. This plant is grid-connected (supplies its output to and receives power for auxiliary energy needs from the utility grid) and is designed to operate as a fossil fuel energy displacer (thus, it has no provision for storage nor does it need to be hybridized). As noted earlier, each dish module is rated at 22 kW of electric power. Considering parasitic effects and inefficiencies in the system, including optical and thermal losses, as well as electrical line losses, 62 modules are needed to satisfy the nominal 1 MWe plant rating.

The baseline plant layout consists of 16 dish module positions placed north-to-south and 4 dishes placed east-to-west for a total of 64 possible positions. The space for the extra two dishes is used for the plant electrical and control subsystem. Dishes are arranged with a preference for the north-south alignment to minimize losses due to shadow interactions. The modules are interconnected by single-conductor stranded aluminum cables (480 volts). A high-voltage (1250 kVA/1000 kW) transformer with switchboard and instrumentation is provided to interface with a utility grid.

A summary of key baseline plant design features and how those features affect the solar walk-off issue is contained in Table 2-1. The subject of sun tracking and control, both at the central plant and local dish module level, is discussed in Section 2.2.5.

2.2.1 Concentrator

This subsection describes the baseline concentrator design. This design, as illustrated in Figure 2-1, is an 11-meter diameter, single reflection, paraboloidal concentrator. The concentrator dish itself is constructed of injection-molded, glass-reinforced epoxy segments with an integral structural rib pattern on the back side to provide for stiffness and rigidity. Although the original GE design approach utilized an aluminized film as the reflective material, the design is inherently adaptable to a mirror glass reflector. For purposes of this solar walk-off cost-effectiveness study, we have assumed that mirrored glass is used as the reflector in the baseline concentrator. The mount is an elevation over azimuth configuration which allows inverted stow for wind survival, night time storage, and servicing accessibility. The mount design is counterbalanced and thus only inertia, friction and aerodynamic forces need to be overcome by the drive.

Table 2-1. Baseline Plant Design Features

Feature	Effect on Walk-Off Protection
Grid Connected	• Uses grid power for auxiliary needs such as concentrator drives and receiver fluid circulation systems. • A stand-alone design would be capable of providing for its own auxiliary power needs.
Not Hybridized	• A hybrid receiver (uses either solar or fossil fuel energy) design would allow use of dish output without concern about losing grid power during start-up.
No Storage (Buffer or otherwise)	• Plant battery storage could be used to backup grid supplied auxiliary power.
Fossil-Fuel Displacer	• Plant is not responsible for meeting a load requirement. Therefore, there is no reason for backup power other than that needed by the plant itself.

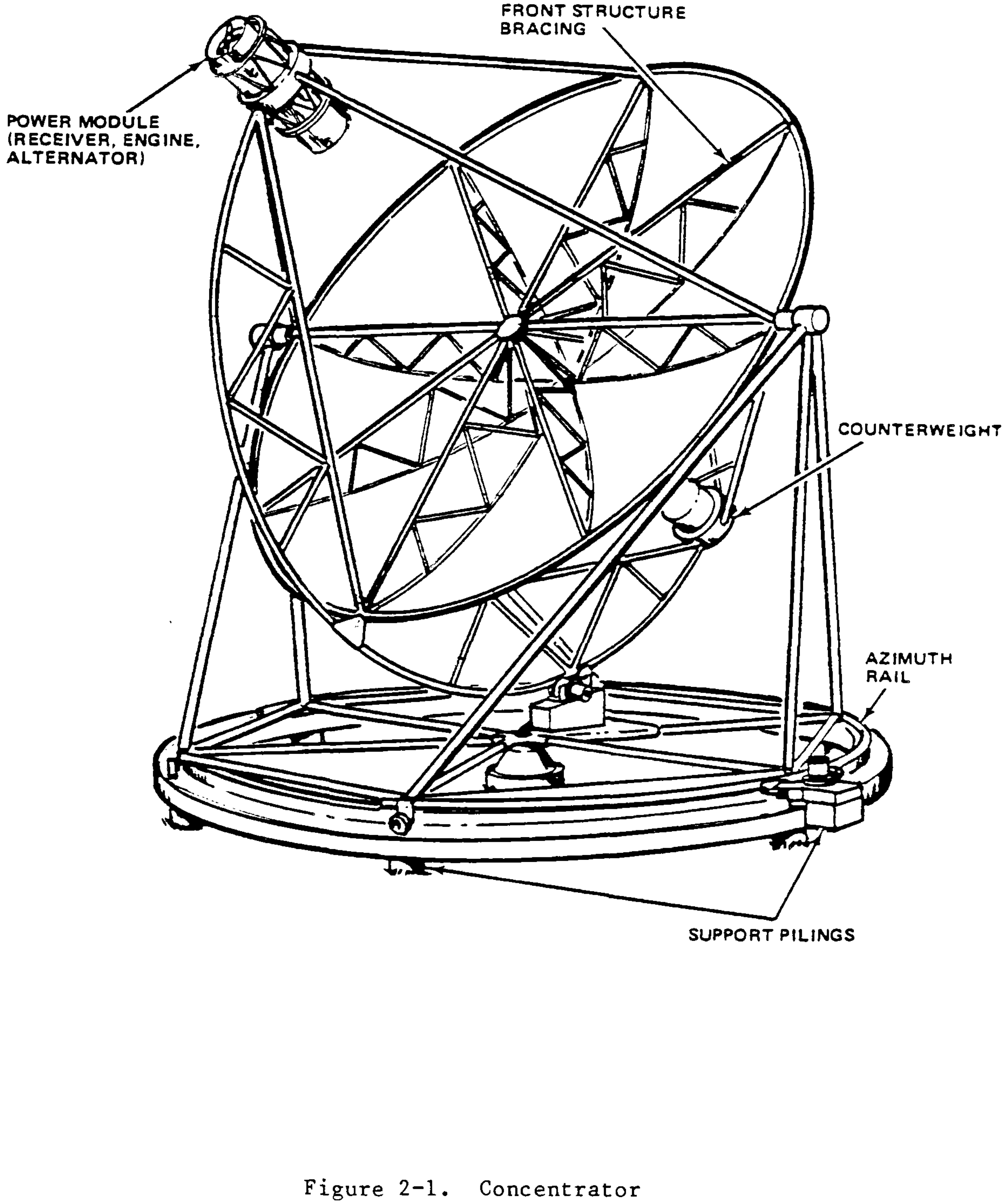

Figure 2-1. Concentrator

The drive subsystem for each axis of the concentrator consists of a cable and drum arrangement. For each drive, an ac motor, geared down to low speed at the output shaft, chain-drives a pair of capstans. The capstans move a steel cable with ends attached to the respective axis frame. The azimuth drive assembly has a stationary ground mount with cable attaching to the azimuth foundation rail. The elevation drive assembly is mounted on the bottom hex cross frame, and its cable lies in the rolled guide between the receiver and counterweight.

Under normal tracking operation, the drive motors operate in an on-off fashion. When commanded by the local tracking controller they drive at 0.5 degree per second until the controller error is within a deadband of ±0.1 degree. Thus the drive system cycles on and off during normal tracking. Cycling time will be in the range of 10 to 100 seconds. Axis drive limit switches will automatically disable drive motion and prevent motor damage in the event of a control failure.

A summary of key concentrator features and how those features affect the solar walk-off protection issue is contained in Table 2-2. The concentrator sun tracking control subsystem, along with master plant control, is discussed in Section 2.2.5.

2.2.2 Receiver

Figure 2-2 shows the baseline, direct-heated, toluene working fluid receiver boiler. The boiler section is a once-through (no reheat) boiler containing helical coils made of stainless steel tubing and surrounded with insulation. A major design consideration which affects walk-off P/P is the choice of whether the engine working fluid is directly passed from the receiver. In theory, direct-heating offers the promise of virtually eliminating the concern of receiver burn-out since the circulation is not dependent upon power outside of the dish module. In practice, however, current direct heated solar receiver/ORC power conversion units are implemented in

Table 2-2. Baseline Concentrator Features

Feature	Effect on Walk-Off Protection
1800:1 Concentration Ratio	• Highly concentrated energy-potential for causing severe damage.
Mirror Glass Reflector	• Breakable optical surface.
24 Reinforced Plastic Molded Dish Segments	• Not easily defocusable.
Elevation Over Azimuth Mount	• Cannot rely on azimuth motion to detrack (get off sun)
Inverted Stow Position	• No concern about walk-off (walk-on, point-off) while in high wind survival stow position.
Counterbalanced	• Low elevation drive torques and balanced elevation moments simplifies drive subsystem.
AC Electric Elevation Drive Subsystem	• Simple and inexpensive drive subsystem allows consideration of providing redundancy.
Aperture Ring-Mounted Fiber Optic Sun Sensors	• Centers receiver to eliminate point-off.

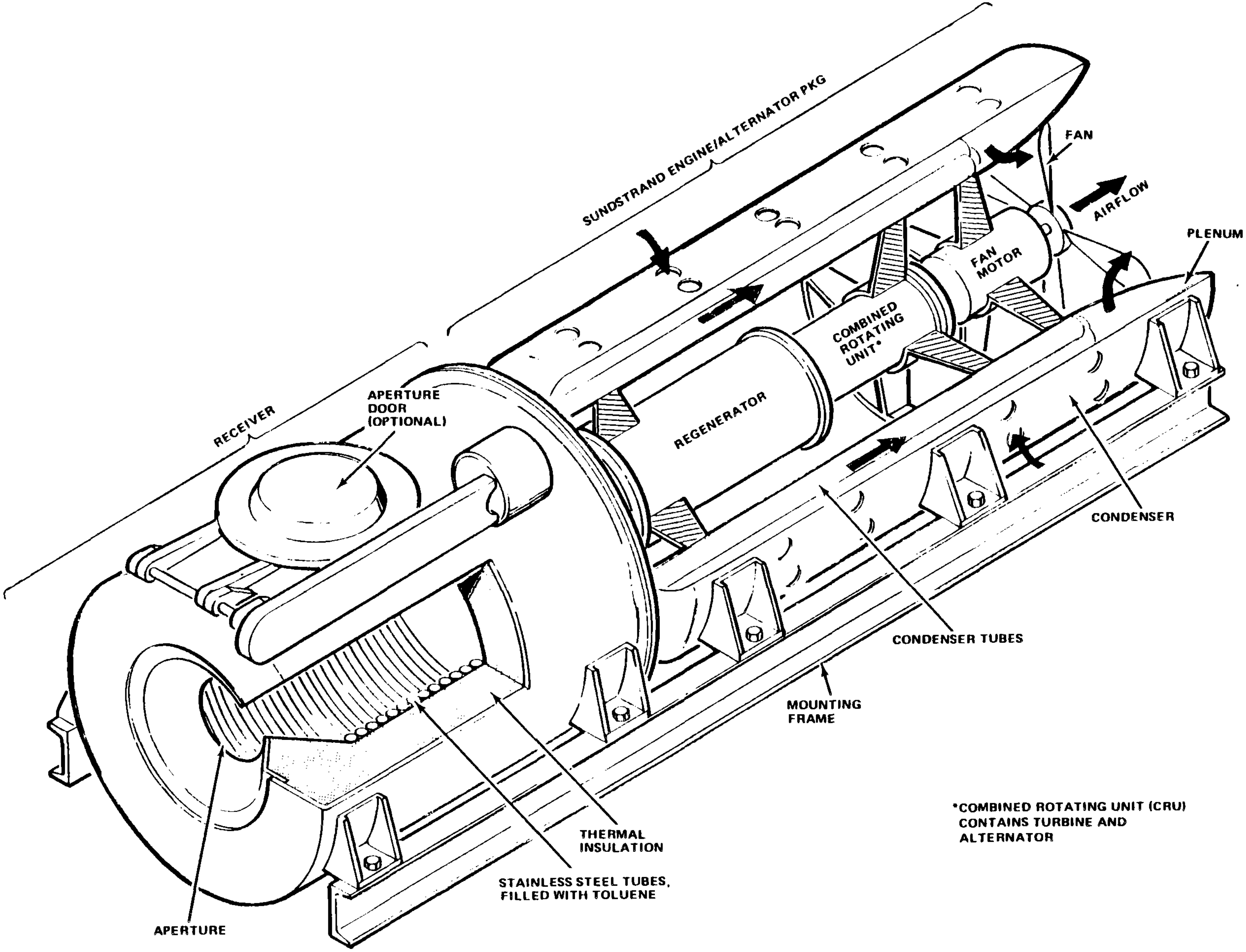

Figure 2-2. ORC Receiver/Power Module

such a way as to require outside auxiliary power for such equipment as booster pumps as well as for start-up. For purposes of this study, we have assumed that loss of outside power (whether from grid or otherwise) results in a burn-out of the receiver.

2.2.3 Engine/Alternator

The baseline engine/alternator package, depicted in Figure 2-2, consists of an organic Rankine-cycle (ORC) engine with integral electric alternator. The engine features a single-stage axial flow turbine which uses toluene as the working fluid. A regenerator preheats the toluene which exits from the receiver. With respect to possible problems raised by walk-off, a brief discussion on the use of toluene is in order. Toluene is considered a "slight-to-moderately" toxic material and is flammable. Since the receiver/ORC is a closed-loop system, FACC believes that the safety aspects of toluene do not constitute a serious obstacle to its use in the ORC. For purposes of this study, we have assumed that a walk-off event causing a receiver burn-out will result in the loss of the working fluid but not added cost as a result of the toxicity or fire hazard.

2.2.4 Electrical Transport System

The electrical transport system consists of the following components:

(1) Electrical cables from each module to the central equipment.
(2) Switchboard.
(3) Transformers.
(4) Switching contactors and miscellaneous equipment.

The major electrical energy transport components and requirements are identified in the electrical one-line diagram shown in Figure 2-3.

Flexible cables are used to carry the generated power across the rotational axis to the ground. A weatherproof box will be put at the base of each concentrator. Typically, this box will enclose the following key components:

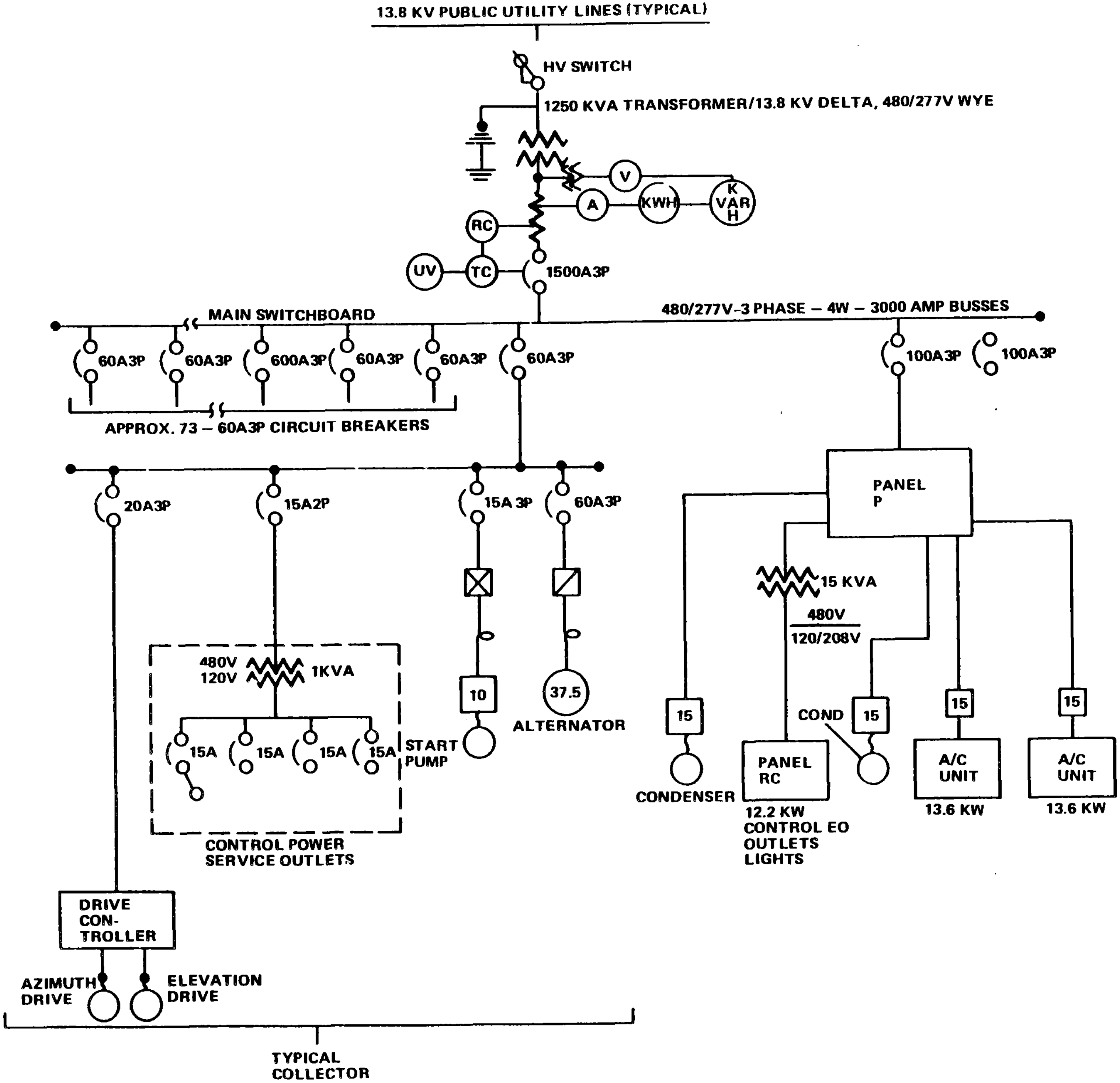

Figure 2-3. One-Line Diagram for Electrical Transport System

(1) AC generator power contactor and circuit breaker.
(2) Engine start pump motor starter and circuit breaker.
(3) Step-down transformer for dish module auxiliary power loads.
(4) Circuit breakers for transformer, panel boards and concentrator drives.

Power cables are run from each dish module and terminate at circuit breakers in the main switchboard located in the central control building. The switchboard also contains breakers for the power to operate the concentrators and the equipment in the control building. A high voltage, step-up transformer is used for matching grid requirements.

2.2.5 Sun Tracking Control

The tracking control is a hybrid system with a position predictive, open-loop mode for coarse control and a fiber optic based closed-loop control on the receiver for fine tracking and receiver positioning.

Each dish module must be accurately positioned to focus the solar image at the receiver aperture. The feedback sensors, drive system and control scheme for tracking the sun and pointing the concentrator must have high accuracy and resolution to provide maximum solar energy to the receiver and to prevent point-off which could result in overheating the receiver lip and receiver support aperture ring. Pointing control of concentrator dishes is performed in part by a local microprocessor at each concentrator and by the central microprocessor. The central microprocessor supplies coarse position tracking commands and sequencing commands for each concentrator while the local microprocessor performs fine sun tracking control and commands the axis drive systems. Commands and automatic tracking are performed in both azimuth and elevation control loops.

A hybrid tracking control scheme is used in which coarse tracking is done by axis angular positional control and fine sun tracking is effected by autonulling of receiver fiber optic signals. Coarse azimuth and elevation position tracking commands are sent from the central microprocessor to each concentrator. These coarse commands consist of ephemeris data which are calculated from central microprocessor algorithms and keyed to the time-of-day. The ephemeris program commands can be modified, if necessary, to correct for known pointing errors caused by gravity sag, pedestal misalignment, angle measuring system nonlinearity and offset, etc.

Fine tracking control is achieved using receiver mounted fiber optics. Two pairs of fiber optics connected to photodiodes are used to generate sun image misalignment signals (one pair aligned for azimuth and the other for elevation). The fiber optics pair differences in each axis represent misalignment errors which are nulled by commanding the axis drive motors. A tracking accuracy error of less than 0.125 degrees is attained with the fine control loops. Thus, fine control and automatic correction of the coarse tracking commands is achieved with the optical loops. Corrections for external disturbances (i.e., concentrator wind motion) are automatically provided.

SECTION 3

WALK-OFF PREVENTION/PROTECTION DESIGN ALTERNATIVES

This section presents and describes the design alternatives selected for evaluation in this solar walk-off cost-effectiveness study. These design alternatives are evaluated in Section 6 relative to the baseline plant with no walk-off prevention/protection (P/P). All walk-off P/P design alternatives result in an increase in capital and maintenance cost due to the P/P device and a reduction in the cost to restore the plant to operation following a walk-off event due to lesser damage and fewer solar walk-off occurrences.

3.1 DESIGN SELECTION

All known walk-off P/P design alternatives (Ref. 2) were considered for evaluation given the one study scope requirement that any alternative to be considered must be developed to at least the conceptual design level. For purposes of this study, the cost of the walk-off P/P design alternatives were estimated and are contained in Section 4 of this report.

A survey of available walk-off protection design alternatives resulted in the following candidates:

(1) Battery Backup Power.
(2) Diesel/Generator Set Backup Power.
(3) Graphite Shield Protection System.
(4) Graphite Shield and Shutter Protection System.
(5) Water-Cooled Shield and Shutter Protection System.
(6) Gravity Detrack System.

3.2 DESIGN DESCRIPTION

This subsection describes the walk-off P/P design alternatives considered and evaluated within this study.

3.2.1 Battery Backup Power

This backup power system operates in the event of an electrical grid failure. Note that this system will not prevent a walk-off in the case of drive subsystem failure (e.g., drive train breakage, motor failure or bearing seizure). This system consists of ten 10 kilowatt lead-acid rechargeable batteries which have ac-to-dc transformers for recharging and five inverters for dc-to-ac conversion to match the 480 volt, 3-phase ac requirements of each dish module. In this concept, the batteries are kept charged at all times. The 10 kilowatt battery units were selected since they are the largest available and thus would benefit from cost economy of scale. The life of the battery is five years resulting in a need to replace the battery set five times in the plant lifetime. This equipment is commercially available.

3.2.2 Diesel/Generator Set Backup Power

This system also provides backup power in the event of grid electrical failure. As in the case of the battery backup system, the diesel/generator set does not prevent walk-offs due to drive subsystem failures. The diesel/generator set consists of a 100 kW diesel engine, a 100 kW generator, and required accessories. The diesel is continuously kept semi-warm to provide a rapid startup (few seconds). Rapid startup is required to quickly get off sun to protect the solar receiver from burning out and to protect the dish module engine from overspeed damage. The diesel system was selected over a conventional gasoline-powered engine because of greater reliability and longer life. High reliability is desirable in a highly automated solar power plant.

3.2.3 Graphite Shield Protection System

This concept uses a grade G-90 graphite shield to cover and protect the receiver lip and support ring. It is identical to the concept described in Section 3.2.4, except that there is no shutter mechanism or assembly which covers the aperture to protect the receiver cavity. In the case of walk-off induced by power failure, since the aperture is not protected, receiver tubes and insulation will suffer damage. In the case of walk-off caused by drive subsystem failure, power is assumed to be available to continue circulating the receiver fluid, thus preventing receiver cavity damage.

3.2.4 Graphite Shield and Shutter Protection System

This design allows the sun to walk across the face of the receiver, the receiver lip and the support structure. This protection system can operate when there is a walk-off due to either grid failure or drive subsystem failure. A shutter mechanism is used to cover the aperture and protect the receiver cavity (tubes and insulation) from damage in the case of loss of power (with resulting loss of circulation). A shield is used to cover and protect the receiver lip and the face of the receiver support ring. The shutter is activated when an emerging walk-off is sensed. The shutter itself is hinged and spring loaded in compression. Both the shield and shutter are made of G-90 graphite. An explosive bolt, releases the spring and closes the shutter over the receiver aperture. Grade G-90 graphite was chosen because of favorable testing results at the JPL Parabolic Dish Test Site (PDTS) facility at Edwards Air Force Base (Ref. 3).

3.2.5 Water-Cooled Shield and Shutter Protection System

This concept is similar to the Graphite Shield and Shutter concept in that protection can be provided regardless of the cause of walk-off. This system utilizes a forced circulation once-through cooling system to keep the shield and shutter from overheating and subsequent damage during either a grid failure or other failure which can cause a walk-off. This system was built and used at the PDTS at Edwards AFB. This concept utilizes a shield and shutter assembly made of welded aluminum which sandwiches an annular region serving as a simple once-through heat exchanger.

Thermal calculations show a flow requirement of 5 gallons of water per minute is sufficient to keep the heat exchanger from experiencing damage. The shutter, which is a rectangular aluminum plate, is actuated by double-acting air cylinders and is supported by ball bearing slides. Along with testing on a periodic basis and frequent inspection, the requirements for maintenance include supply-water quality control to minimize corrosion damage, supply-hose inspection, and occasional inspection and replacement of pumps and of the air/nitrogen actuated double-acting cylinders for the shutter piece.

3.2.6 Gravity Detrack System

This system prevents walk-off in the case of a grid failure or drive motor failure. This system uses gravity-assist in the form of potential mechanical energy to power the existing elevational drive system. Note that this system cannot protect in the case of drive structure (including a bearing seizure) failure as it is designed to operate in conjunction with the existing elevation axis drive structure. The design concept uses a concrete weight and pulley system such that the weight is dropped when an emerging walk-off situation is sensed. Solenoids are de-energized causing the gear of the gravity-assist system to contact the existing elevational drive gear. Simultaneously a microswitch initiates the signal to release the weight. As the weight is dropped, potential energy is converted to power the concentrator drive.

SECTION 4

COST DATA BASE

4.1 COST METHODOLOGY AND ASSUMPTIONS

The cost methodology used in this study employs a discounted cash flow approach detailed in Reference 4. All cash outlays, both nonrecurring and recurring, are "collapsed" into present value amounts. Using specific rates of return and tax structure appropriate for utility-owned power plants, the present value amounts are annualized by a fixed charge rate (FCR) factor for capital or irregularly occurring costs and by a capital recovery factor (CRF) for regularly recurring costs. An example of a capital cost would be the initial cost for an engine when the plant is first constructed. A capital replacement cost would also come under this category since it does not occur regularly. On the other hand, an example of a regularly occurring or recurring cost would be a cost associated with regularly scheduled maintenance such as the annual lubrication of drive motors for the concentrator.

One illustrative way to understand this methodology is to view it as a balancing of costs against revenue. The costs incurred for plant construction, startup, and operation and maintenance over the plant lifetime are added up in terms of present value costs. The sum of these present values would be viewed as the money needed today (or at plant startup) to offset the costs over the plant lifetime. This money is invested at an interest rate equal to the discount rate. To have zero balance at the end of plant lifetime, an economic calculation is made to pay out a uniform amount annually to offset exactly the present value amounts for costs mentioned above.

Table 4-1 shows the baseline economic parameters used for this study. Some of the key items to note are a 30-year system evaluation period or lifetime, a 10% discount factor rate, a 1984 base year, a FCR of 0.177 and a CRF of 0.106.

Table 4-1. Baseline Economic Parameters for Life-Cycle Costing (Nominal Values)

System Operating Lifetime, N	30 years
Miscellaneous Taxes and Insurance Premiums As a percentage of capital investment, q	2.25%
Income Tax Rate, t	40%
Cost of Capital (Discount Rate), K	10%
Rate of General Inflation, G	5%
Escalation Rate for Capital Costs, Gc	5%
Escalation Rate for Operating Costs, Go	6%
Escalation Rate for Maintenance Costs, Gm	6%
Base Year for Constant Dollars, Y_b	1984
Capital Recovery Factor, CRF	0.106
Fixed Charge Rate, FCR	0.177

The construction of the plant is assumed to start in 1986. Plant commercial startup is in 1988. Plant final shutdown (end of life) is 2018. Since this is a comparative study, the absolute value of these economic constants shown in Table 4-1 is relatively unimportant. What is important is that this collection of economic constants form a baseline from which we do not deviate throughout the evaluation of the various walk-off P/P systems.

Table 4-2 presents some of the key costing equations used in this study. Many of the terms in the equations are defined in Table 4-1. The important item to consider is that in the annualized cost equation, FCR modifies the present value of a nonrecurring cost to obtain an annualized nonrecurring cost and the CRF converts the present value of recurring costs to form an annualized recurring cost. The sum of these individual annualized costs is the overall annualized cost (AC). The $(1+G)^{-d}$ factor brings the overall annualized cost to the base year (1984) from the startup year (1988). Thus, these equations form the mathematical basis for annualized costing. The annualized cost is the measure of merit used for purposes of this study.

4.2 BASELINE PLANT COST

Applying the methodology described in Section 4.1 to the baseline plant described in Section 2 of this report resulted in a total AC of approximately $520K. A breakdown by major cost item is shown in Table 4-3. The direct costs for each of the above mentioned items were either cited from or calculated in the Ford Phase II SCSE Proposal (Reference 1). Major assumptions which form the basis for the cost estimates include high volume mass production with extensively automated manufacturing processes. The cost estimates shown in Table 4-3 were converted by the general inflation rate to 1984 dollars from the 1978 dollars estimates given in Reference 1. A further breakdown of concentrator component costs and annualized costs are shown in Table 4-4. The concentrator component costs were taken from the General Electric (GE) Low Cost Point Focus Solar Concentrator Phase I Preliminary Design Report (Ref. 5), with the one modification of substituting glass reflectors for the plastic film at an estimated increased cost of $24/sq. meter. The GE cost was also converted by the general inflation rate to 1984 dollars.

Table 4-2. Important Life-Cycle Costing Equations

$AC = (1+G)^{-d} \left[FCR \cdot CI_{pv} + CRF \left(OP_{pv} + M_{pv} \right) \right]$	(levelized annualized cost)
$CI_{pv} = (1+G_c)^P \sum_t \left[CI_t \left(\frac{1+G_c}{1+K} \right)^J \right]$	(present value of capital investment)
$OP_{pv} = (1+G_o)^P \, OP_t \left(\frac{1+G_o}{K-G_o} \right) \left[1 - \left(\frac{1+G_o}{1+K} \right)^N \right]$	(operational cost present value)
$M_{pv} = (1+G_m)^P \, M_t \left(\frac{1+G_m}{K-G_m} \right) \left[1 - \left(\frac{1+G_m}{1+K} \right)^N \right]$	(maintenance cost present value)
$CRF = K/(1-(1+K)^{-N})$	(capital recovery factor)
$FCR = \frac{1}{1-t} \left(CRF - \frac{t}{N} \right) + q$	(fixed charge rate)

Capital replacement occurs in the $\sum$ term of the CI_{pv} equation

d = time from base year to startup

P = time from price year to startup

J = replacement year minus startup + 1

Table 4-3. Baseline Plant Cost Estimate (Ref. 1)

Item	Cost (1984$)	AC	Percent of Total AC
Concentrator (Capital and Replacement)	$138/m^2 each	$155.1K	30
Receiver (Capital and Replacement)	3000 each	47.8K	9
Engine (Capital and Replacement)	8850 each	147.8K	28
Electrical Transport and Control	391,500 total	72.6K	14
Concentrator Maintenance	252/yr each	32.4K	6
Engine Maintenance	509/yr each	65.4K	13
Total AC (approximate)		$520K	100%

Table 4-4. Baseline Concentrator Capital Cost Estimate Breakdown (Ref. 4)

Item	Direct Capital Cost (1984$)	AC (for 62 Units)
Dish Structure	$ 40/m^2	$43,924
Reflector	$ 24/m^2	$26,354
Mount	$ 23/m^2	$24,890
Drive	$ 12/m^2	$17,968
Control	$ 11/m^2	$11,713
Foundation	$ 16/m^2	$17,570
Assembly	$ 12/m^2	$13,177
Total Concentrator	$138/$m^2$	$155K

The concentrator is assumed to last the entire plant lifetime of 30 years. Major spare parts and component replacement costs are expected to be insignificant (Ref. 1). The one concentrator replacement item which we have assumed for purposes of this study is the electric drive motors (cost of $130 in 1978$ - Reference 3) on a five-year replacement schedule. Regularly scheduled concentrator maintenance includes such items as cleaning of reflector surfaces and lubrication of drives.

The receiver is assumed to have a lifetime of 15 years; thus, a replacement cost is incurred at the start of the 16th year of plant operation. Maintenance is assumed to be insignificant.

The engine/alternator package is assumed to have a 55,000 hour life (15 years at 3660 hours of plant operation per year). Therefore, a replacement cost is incurred at the beginning of the 16th year of plant operation. Regularly scheduled maintenance includes periodically bleeding the organic fluid, cleaning and greasing the bearings of pumps and fans and checking the controllers for proper functioning.

4.3 WALK-OFF PROTECTION DESIGN ALTERNATIVE COST DATA BASE

This section quantifies the capital costs for the walk-off protection design alternatives described in Section 3 of this report. A discussion is also included as to the key assumptions made and references used in estimating the direct costs for the design alternatives. Table 4-5 provides the walk-off protection system cost estimates.

4.3.1 Battery Backup Power Cost

The battery/dc inverter/ac charger set described in Section 3.2.1 was costed by phone survey of battery manufacturers. The battery requirements are derived from baseline plant accessory power requirements for the modules. In this case 10 kWe, 480 volt, 3-phase, 20 amp systems were utilized and costed. Plant requirements necessitated the use of ten batteries and five

Table 4-5. Cost of Walk-Off Protection Systems per 1 MWe Plant

	Capital Cost (1984$)	Yearly O&M Cost (1984$)	Refurbish Cost Per Walk-Off (1984$)
Battery	$153,900	$ 300	-
Diesel Generator	21,400	2,100	-
Graphite Shield	34,200	-	$18,600
Graphite Shield/ Shutter	40,400	-	$24,800
Water-Cooled Shield/Shutter	48,400	5,650	-
Gravity C/W	44,320	1,000	-

inverters. The result of the phone survey showed an average cost of $4100 (1984$) for each 10 kWe and an average cost of $22,500 (1984$) for each inverter unit, making a total of $153,900 (1984$) for the entire plant. If the drive motors were dc-driven, the inverter cost of approximately $112,800 (1984$) would not be required. Battery life is on the order of five years thus requiring five replacements over the 30-year life of the plant. Maintenance is estimated at $300 (1984$) for the plant per year. This assumes weekly inspection and cleaning of terminals and connections.

4.3.2 Diesel Engine/Generator Backup Power Cost

The diesel/generator set described in Section 3.2.2, was costed by referring to a previous JPL cost estimate (Ref. 6). A 100 kWe, 480 volts, 3-phase system is estimated to cost $21,400 (1984$). Operation, which includes the cost of energy to keep the diesel semi-warm,and maintenance, which includes oil and filter changes, is estimated at $2,100 (1984$) per year.

4.3.3 Graphite Shield Protection System Cost

Costs for this system as described in Section 3.2.3 were estimated by JPL. The concept is identical to the concept costed in Section 4.3.4, however, the shutter assembly is deleted. The estimated cost for this system is $552 (1984$) per dish. The cost is not significantly different from the graphite shield and shutter concept because the costs are primarily in the material and the graphite used for the shutter is less than the amount used for the shield.

4.3.4 Graphite Shield With Shutter Protection System Cost

This concept was estimated per the design as presented in Section 3.2.4. The estimated cost is $652 (1984$) per dish. The cost also includes hinges, explosive bolts, sensors, and controls assembly and testing. Maintenance is expected to be insignificant; however, inspection and periodic testing will have to be performed.

4.3.5 Water-Cooled Shield and Shutter Protection System Cost

Drawings and parts lists for the water-cooled shield and shutter assembly designed and built for the Test Bed Concentrators at the JPL PDTS were used for the cost estimation of the system. The estimated cost in mass production quantities is $780 per dish (1984$). Maintenance of this protection system includes periodic testing of the mechanisms and water chemical control to minimize the possibility of corrosion failure. The maintenance is estimated at $91 (1984$) per dish. The maintenance includes weekly water sampling and testing. For purposes of this study, we have assumed that the plant is sited in a location where freezing of the water is not a concern.

4.3.6 Gravity Detrack System Cost

Costs for this system,which is described in Section 3.2.2, was estimated by JPL, based on discussions with Advanco personnel (Ref. 7) with respect to their experience with this walk-off protection device. Including sensors, controls, assembly and test, the estimated cost is $715/dish (1984$).

Maintenance is estimated at $16 (1984$) per year per unit for a total of $1,000 annually for the entire plant.

SECTION 5

WALK-OFF FAILURE RATE AND COST DATA BASE

This section describes the events that can cause walk-off, their probability of occurrence and the estimate of the cost impact of a walk-off occurrence. There are three major causes of a solar walk-off; namely: loss of power to the drive subsystem (for example, an electrical grid failure for the case where the dish module auxiliary power requirements are provided by the utility grid), drive subsystem component failure (for example, a local drive motor) and human error.

In an electrical grid failure, auxiliary power required to drive the dish module following the sun is lost. All modules are affected simultaneously. As the sun continues to move across the sky, the concentrated beam of light produced by the concentrator reflector starts to move out of the focal aperture region and proceeds to walk-off to the lip of the receiver and the structural support. Damage assessment and assumptions are described in Section 5.2. When drive subsystem components, such as drive motors or bearings fail, only the affected module will experience a walk-off. The difference in this failure mode from the grid failure is that only the dish module containing the failed component experiences the solar walk-off, i.e., the entire field is not affected.

The third major potential cause of walk-off involves human operator error. Since there is very little or no commercial operating experience from which we can gather data, for purposes of this study, we will not attempt to quantify its probability. In any case, this source of walk-off is probably strongly dependent upon operator experience and skill level.

5.1 WALK-OFF PROBABILITY DATA BASE

5.1.1 Loss of Grid Power

Table 5-1 shows data gathered for grid power outage frequency. In some cases, the information comes from a published source; in others, direct survey of existing solar plant experience is the source for the power outage information. In all cases, it should be noted that the rate of grid power loss is highly dependent on site-specific factors such as load on the plant, age and type of generating and transmission equipment and storms and winds in the area of the transmission facilities, and thus, is highly variable.

A grid failure rate of one failure per year was chosen as the nominal rate for purposes of this study. However, a sensitivity study was conducted to evaluate the effects of varying the nominal grid failure rate on cost-effectiveness. The results are presented in Section 6. The selected grid failure rate range is one failure for the lifetime of the plant (30 years) to 10 failures per year (Ref. 8).

An important footnote on the subject of grid failure data for solar power plants is that only those grid failures occurring during daylight (power production) hours and when wind speeds are less than the speed which causes the dish to be slewed to its wind survival position (typically 30 mph) cause solar walk-offs. It is obvious that, for the dish to experience a walk-off, it had to be on sun in the first place. The grid outage rates quoted in this study are proportionally adjusted for daylight hours (3660 per year).

5.1.2 Plant Component Failure

Solar power plant components, which upon failure, cause a solar walk-off to occur, for the baseline plant of this study, are described below. Reliability, i.e., failure rate data, for those components are also presented.

For purposes of this study, the assumption is made that the baseline plant and dish modules are sufficiently instrumented so that walk-offs will not occur from failure of tracking control electromechanical equipment (i.e.,

Table 5-1. Utility Electric Grid Outage Frequency Data

Grid Outage Rate	Application	Source
Two per year	National average	IEEE-STD-493 (Ref. 9)
No grid outages while on sun in over 5 years of operation	At Shenandoah Solar Plant, Georgia	Reference 10
Two grid outages since Feb. 1984, one of them while on sun	At Vanguard Solar Test Site, Palm Springs, CA	Reference 11
Three or four per year	At Parabolic Dish Test Site, Edwards, CA	JPL experience

sun sensor, encoders, etc.) or electronic equipment (i.e., microprocessor, integrated circuits, etc.). It is deemed to be good engineering design practice to use the master controller to command a dish to slew to the inverted position upon receipt of instrumentation data that indicates a possible walk-off event (i.e., aperture ring temperature or insolation rise exceeding a set point limit).

Table 5-2 presents the plant component failure rate data selected for use in this study. The failure rate data is given in terms of single time failure rate (occurrences per 10^6 hours) and total failure rate which is the single item failure rate multiplied by the number of the particular items in the entire plant. For the baseline plant, single item failure rates were multiplied by 62, the number of dish modules in the baseline 1 megawatt plant.

For purposes of this study, it is assumed that only plant components which upon failure, cause a walk-off event in the baseline plant are the elevation drive motor and the elevation drive train/structure/bearing mechanisms.

It should be noted that the auxiliary energy stepdown transformer failure mode has the same effect as a failure of the utility grid, i.e., loss of auxiliary power for driving the dish and circulating the receiver fluid. However, since this failure rate is so low compared to the rate of grid failures, it is ignored from further evaluation in this study.

5.2 COST ESTIMATE FOR REPAIRING DAMAGE CAUSED BY SOLAR WALK-OFF

The cost impact, including material and labor, to restore the plant/dish modules to operation following a solar walk-off is described below.

The damage caused by a solar walk-off is at one of two possible severity levels. The severity level is a function of the type of failure. A failure which causes a loss of auxiliary power to both the concentrator drive and the receiver causes the most severe damage. In this instance, for the baseline plant, we have assumed a complete loss of the receiver due to

Table 5-2. Plant Component Failure Rate Data

Item	Failures per Million Hours	Data Source	Number of Items per 1 MWe Plant	Mean Time Between Walk-Offs Per 1 MWe Plant (Yrs)[1]
Elevation Drive Motor	1.24	IEEE Std 493 (Ref. 9)	62	3[2]
Elevation Drive Train Structure/ Bearing	0.20	FACC Phase I SCSE Report (Ref. 12)	62	22[2]
Auxiliary Energy Transformer	6	FACC Phase II SCSE Proposal (Ref. 1)	1	48[3]

NOTES:
[1] Assumes 3660 hours of operation per year.
[2] The walk-off only affects one dish module.
[3] The walk-off affects all 62 dish modules.

overheated tubes, burned-out insulation, destroyed receiver structure and a complete loss of the receiver aperture support ring. A failure, however, which only causes a loss of the concentrator drive (that is, auxiliary power is still available and the receiver circulation system is functioning) produces less severe damage. In this instance, for the baseline plant design, it is assumed that only a loss of the receiver aperture support structure occurred. It should also be noted that it is assumed, for purposes of this study, that no damage or cost occurred as a result of a toluene fire or toxicity hazards.

It should be noted that there is very little actual experience in the assessment of damage due to solar walk-off. The only real experience is a test that was run at Sandia National Laboratories using the Shenandoah collectors (Ref. 13). This test provides a data point for understanding the degree of damage of a walk-off for that specific and rather low concentration ratio (approximately 800) dish design.

With the dish on sun, tracking and the receiver circulation were stopped. The Syltherm 800 fluid inlet temperature was 260°C (500°F) and the outlet temperature was 399°C (750°F). The solar insolation was around 900-950 W/m^2.

After four minutes, the stainless steel receiver coil temperature had risen to 649°C (1200°F), was stable for four minutes, and then started to drop off (the solar beam had walked through the aperture hole).

The damage assessment as a result of this experiment was as follows:

(1) Stainless steel receiver tubes survived.

(2) The insulation between the receiver coil and can lost its binder and had to be replaced.

(3) The east fiber optic sun tracking sensor was destroyed.

(4) The binder was burned out of the astroquartz receiver aperture liner and it had to be replaced.

(5) A few gallons of Syltherm broke down, vaporized, and blew itself out of the system.

(6) The paint on the outside of the stainless steel receiver can was burned.

Table 5-3 summarizes the cost estimate for repairing and replacing the receiver and aperture ring. Both material and labor cost has been estimated. The receiver and aperture ring material cost is that described in the cost data base of Section 4 of this report. The labor estimate is based on estimate for accomplishing the following subtasks:

(1) Replace Receiver and Aperture Ring
  (a) Stow dish.
  (b) Remove receiver/engine/alternator.
  (c) Disconnect receiver from engine/alternator.
  (d) Connect new receiver to engine/alternator.
  (e) Remove damaged ring.
  (f) Replace with new ring.
  (g) Assemble receiver/engine/alternator in ring.
  (h) Recharge with working fluid.
  (i) Checkout.

(2) Replace Aperture Ring
  (a) Stow dish.
  (b) Remove receiver/engine/alternator.
  (c) Remove damaged ring.
  (d) Replace with new ring.
  (e) Assemble receiver/engine/alternator in ring.
  (f) Checkout.

Table 5-3. Cost Estimate for Repairing Damage Caused by Solar Walk-Off

Damage Assessment	Material Cost (1984$)	Labor Cost (1984$)	Total 1984$
1. Replace Receiver and Aperture Ring	$3200	$270 (Two men 4 hours at $34/hr)	$3470
2. Replace Aperture Ring Only	$ 170	$130 (Two men 2 hours at $34/hr)	$ 360

SECTION 6

EVALUATION RESULTS

This section presents the results of the solar walk-off annualized cost evaluations. It compares the added cost of walk-off prevention/protection (P/P) alternatives and the reduced risk of a walk-off event relative to the baseline (no walk-off P/P) plant and relative to each other.

Six candidate plant configurations with various walk-off alternatives were formulated for evaluation against the baseline plant. The six alternatives and the degree of walk-off P/P are listed in Table 6-1. The summary results of the evaluation are shown in Table 6-2. All costs shown in Table 6-2 are annualized using the cost methodology described in Section 4.1 of this report.

6.1 BACKUP POWER

This subsection evaluates the annualized cost of providing backup power to prevent grid failure induced walk-offs. It also evaluates the two candidate backup power systems, namely, battery and diesel/generator.

6.1.1 Nominal Grid Failure Rate

At the nominal rate of one grid failure per year, an examination of Table 6-2 indicates that solar plants must be protected from the effects of walk-off caused by this type of failure. The frequency rate of once per year, the fact that all 62 dish modules within the plant experience a walk-off and that the cost to restore the plant to operation is high because of the complete damage to the receiver, all add up to this strong conclusion. The question of whether it is better to prevent the walk-off (i.e., backup power) or to thermally protect the receiver and the aperture support structure (i.e., graphite or water-cooled shield and shutter), is addressed in Section 6.3.

Table 6-1. No Walk-Off Prevention/Protection Baseline and Walk-Off Prevention/Protection Plant Alternatives

Plant Alternative	Walk-Off Prevention/Protection Offered
Baseline Plant	No walk-off prevention or protection.
Alternate #1 (Battery Backup)	Prevents grid failure walk-offs but does not protect from drive subsystem failures.
Alternate #2 (Diesel/Generator) (D/G)	Same as battery backup.
Alternate #3 (Graphite shield and D/G)	D/G prevents grid failure walk-offs and graphite shield protects structure from drive subsystem failure walk-offs.
Alternate #4 (Graphite shield and shutter)	Graphite shutter protects receiver cavity for grid failure walk-offs, and shield protects structure from either grid or drive subsystem walk-offs.
Alternate #5 (Water-cooled shield and shutter)	Same as graphite shield and shutter.
Alternate #6 (Gravity Detrack and D/G)	Gravity detrack prevents grid failure and drive motor walk-offs. It does not prevent drive structure/bearing failure walk-offs. D/G is needed to assure dish moves to safe position following the limited rotation detrack motion.

Table 6-2. Summary Walk-Off Prevention/Protection Evaluation Results
(Assumed Grid Outage Rate of Once Per Year)

			Cost To Restore Due To				
	Plant Cost (K$)	Walk-Off P/P System Cost (K$)	Grid Failure (K$)	Drive Motor Failure (K$)	Drive Structure Failure (K$)	Total Cost (K$)	Total Cost Less Plant Cost (K$)
Baseline Plant	520	0	610	3	0.2	1,133	613
Alternate #1 (Battery Backup)	520	97	0	0.4	0.1	618	98
Alternate #2 (Diesel/generator)(D/G)	520	10	0	0.4	0.1	531	11
Alternate #3 (Graphite shield and D/G)	520	16	0	0.6	0.1	537	17
Alternate #4 (Graphite shield/shutter)	520	8	70	0.6	0.1	599	79
Alternate #5 (Water-cooled shield/shutter)	520	21	0	0.4	0.1	542	22
Alternate #6 (Gravity Detrack and D/G)	520	20	0	0	0.1	540	20

From among the two candidate backup power systems evaluated, the diesel/generator set was found to be the less costly. The initial capital cost of the battery system is much greater than that of the diesel generator. Further, the required replacement of batteries every five years substantially increases its annualized cost.

6.1.2 Sensitivity to Grid Failure Rate

Section 6.1.1 showed that prevention against grid failure walk-offs at a nominal grid failure rate of once per year is less costly than not preventing grid failure walk-offs. A sensitivity study was conducted to determine whether this conclusion would be true at the low end of the grid failure rate range, that is, once in 30 years. The evaluation results are as follows:

	Annualized Cost	
	Baseline Plant (K$)	Diesel/ Generator Back-Up Plant (K$)
Plant Cost (AC)	520	520
Walk-Off P/P System Cost (AC)	0	10
Cost to Restore (AC)		
• Grid Failure	18	0
• Drive Subsystem Failure	3	0.5
Total Cost	541	530

The results of this sensitivity study show that the conclusion for preventing grid failure walk-off, even at a very low end of the grid outage rate range of once in 30 years, is valid.

6.1.3 Sensitivity to a Simultaneous Grid Outage and Diesel/Generator Set Failure

This sensitivity considers the effect on annualized cost of a simultaneous grid outage and diesel/generator set failure occurrence. If it is assumed that this simultaneous failure occurs once in the 30-year lifetime of the plant (for purposes of this study, at year 15), the annualized cost of the diesel/generator option versus the water-cooled shield and shutter option is as follows:

	Annualized Cost	
	D/G Backup Plant	Water-Cooled Shield and Shutter Protected Plant
Plant Cost (AC)	520	520
Walk-off P/P System Cost (AC)	10	21
Cost to Restore (AC)		
• Grid Failure	18	0
• Drive Subsystem Failure	1	0.5
Total Cost (AC)	549	542

The results of this analysis show the strong sensitivity of AC to even one unprotected grid failure induced walk-off on all dish modules within the plant. Comparing the AC for this case of one simultaneous grid outage and diesel/generator failure to the water-cooled shield and shutter alternative plant shows that the water-cooled shield and shutter would be the preferred option.

6.2 PROTECTION OF THE APERTURE SUPPORT STRUCTURE

Considering that it has been concluded that grid failure walk-offs must be prevented and that prevention vs protection will be evaluated later, whether or not it is cost-effective to protect the receiver support structure with a G-90 graphite shield will now be evaluated.

In this case, walk-off only occurs due to drive subsystem failure on one dish every three years or so (per one MWe plant) and the only damage is assumed to be a burned receiver support ring. The cost of replacing a burned aperture ring is estimated to be $360 (1984$). This expense can be saved by adding a graphite shield but at the cost of spending $300 (1984$) to refurbish the shield after a drive subsystem walk-off. An examination of Table 6-1 results in the conclusion that the use of a graphite shield to protect against damage resulting from drive subsystem failures is not cost-effective.

6.3 COMPARISON OF GRID FAILURE PREVENTION VS PROTECTION

Considering that prevention of grid failure walk-off using backup power is cost-effective relative to no prevention, the next question is whether or not it is more cost-effective to prevent a grid failure walk-off or to protect the receiver and its support structure (i.e., by using a shield and shutter and allowing the walk-off to occur).

As can be seen from examining Table 6-1, backup power prevention is more cost-effective than either the graphite or the water-cooled shield and shutter systems. The water-cooled system is more cost-effective than the graphite.

Although the water-cooled system has higher capital and maintenance cost than the graphite system, it does not require the costly refurbishment after a walk-off event as does that of the graphite systems. This refurbishment, which for grid failure walk-offs, affects all 62 dish modules, turns out to be the dominant factor in the annualized cost trade.

6.4 EVALUATION OF GRAVITY DETRACK

The gravity detrack is somewhat of a unique walk-off prevention system in that:

(1) It can be used to prevent either a grid or a drive motor failure-induced walk-off.

(2) By itself, it does not offer adequate prevention for the baseline elevation over azimuth mount design. Because of limited elevation motion (5 to 10 degrees, or so) it does not guarantee that the dish will be in a safe position for the remainder of the day. Backup power is therefore needed to guarantee that the dish will transverse to a safe position (i.e., a position that guarantees that the dish will never be pointed at the sun).

(3) Is only applicable to balanced mount concentrator designs such as the counterweighted baseline design.

Comparing the cost-effectiveness of the gravity detrack and diesel/generator backup plant versus the diesel/generator backup plant, an examination of Table 6-1 indicates that the additional costs for the gravity detrack system cannot be justified relative to the reduced cost of drive motor walk-offs. The diesel/generator is adequate by itself to prevent grid failure walk-offs. It should be noted that this conclusion applies only to the selected baseline dish module design. It may be possible to design a concentrator mount other than elevation over azimuth in which a limited detrack angular motion might produce a safe position for the remainder of the day. It also may be that, unlike the baseline ORC engine, other engine types, e.g., Brayton or Stirling, may not be able to withstand the short (few seconds) delay before diesel/generator emergency power is available without damage due to overspeed.

6.5 EFFECT OF GRAPHITE REFURBISHMENT ASSUMPTION

The nominal case assumption is that the graphite must be replaced following each walk-off event and that the labor and material cost estimate for the Graphite Shield and Shutter System is $400 (1984$) per refurbishment. A sensitivity study was conducted to determine the crossover point (number of walk-offs until refurbishment) at which the Graphite System would be more cost-effective than the Water-Cooled Shield and Shutter System. The evaluation results are as follows:

	Annualized Cost					
	Graphite Shield and Shutter Number of walk-offs before refurbishment					Water-Cooled Shield and Shutter
	1	2	3	4	5	
Plant Cost	520	520	520	520	520	520
Walk-off P/P Cost	8	8	8	8	8	21
Cost to Restore						
• Grid Failure	70	28	16	12	9	0
• Drive S/S Failure	0.7	0.7	0.7	0.7	0.7	0
TOTAL AC	599	557	545	541	538	541

The Graphite Shield and Shutter Protection System becomes equally cost-effective as the Water-Cooled Shield and Shutter Protection System once the graphite can withstand four walk-offs before replacement. It should be noted that test results of G-90 graphite in a simulated 15-minute walk-off indicated that it most probably will withstand multiple walk-offs before refurbishment is necessary. Oxidation rates varied from 0.008 to 0.3 in. of thickness (Ref. 3). The amount of oxidation varied strongly with the wind speed.

6.6 EFFECT OF WALK-OFF DAMAGE ASSUMPTION

The nominal case assumption of damage due to drive subsystem failure is that only the receiver support ring is damaged and the replacement cost is $360 (1984$). A sensitivity study was conducted to determine the damage level at which the protection of the receiver support ring using a graphite shield (assuming refurbishment after each walk-off), becomes more cost-effective than no protection against drive subsystem failures. The annualized costs were evaluated, assuming a worst case of losing the entire receiver and engine/alternator package as well as the receiver support ring (damage resulting in a replacement cost of $12,700 (1984$)). The evaluation results are as follows:

	Annualized Cost	
	Diesel/ Generator	Diesel/Generator With Graphite Shield
Plant Costs	520	520
Walk-off P/P Costs	0	16
Cost to Restore		
• Grid Failure	0	0
• Drive S/S Failure	12	0.4
Total AC	540	536

The Graphite Shield Protection System becomes cost-effective when the damage caused by a drive subsystem failure approaches $4000 (1984$).

SECTION 7

RECOMMENDATIONS

This section presents solar walk-off related recommendations in two areas; namely, dish module design guidelines and suggested development programs for future funding consideration.

7.1 DISH MODULE PLANT DESIGN GUIDELINES

Dish module plant design guidelines recommendations are made in the areas of system analysis, walk-off sensors, fail-safe sun tracking and control and emergency control logic.

Solar walk-off is a system problem. There is no single most cost-effective walk-off protection solution that is universally applicable. The solution to the walk-off problem lies in the system engineering evaluations that consider the alternative choices given a specific plant, dish module and site selection. It is recommended that for any future dish power plant design, the system designers must provide solar walk-off prevention/protection or justify on a cost-effectiveness (or whatever criteria is in effect) basis, the lack of prevention or protection.

Sensors are needed to detect an emerging walk-off condition. Direct sensing at the aperture, either temperature or insolation, appears to be the most obvious choice, however, some logic may be required to distinguish walk-off from sun acquisition and deacquisition. Other sensors for directly detecting a specific walk-off producing failure situation should probably be used. An example is the sensing of input voltage to the concentrator drive motor. It should be noted that aperture temperature or insolation sensors would also be valuable for alleviating point-off concerns. Point-off is a situation, which for one reason or another, results in the misalignment of the center of the concentrated solar energy beam from the center of the receiver aperture.

Failure of the sun tracking and control system must not result in a walk-off event. It is common sense that failure of inexpensive sun tracking and control equipment must not have the effect of damaging expensive equipment such as dish module receivers and engines. Any failure or any combination of failures in the tracking and control system must result in a situation that is fail-safe from the standpoint of a walk-off event. Note that this statement is not necessarily equivalent to requiring high reliability or availability from the sun tracking and control system. The cost of being unavailable to operate for a short time is not significant. However, as noted earlier, the loss of a receiver or engine is significant and thus must not be allowed to occur because of tracking and control failure.

Emergency logic above and beyond the normal sun tracking and control logic, is needed to translate a signal from a walk-off sensor into actuation of an emergency prevention/protection subsystem. In addition, it needs to have the capability of determining that the emergency subsystem has alleviated the signal which resulted in the original actuation command. Multi-level logic, using two or more thresholds and two or more emergency protection systems may be required.

7.2 DEVELOPMENT PLANNING

Solar walk-off technology development programs suggested for future funding consideration are described in this subsection. Obviously, walk-off technology needs must compete with other solar technology needs for available solar development budgets. At this time, the primary solar walk-off development needs are believed to be in the following three areas:

(1) Generation of new, innovative and creative walk-off solution ideas and preliminary design and analysis of those ideas as well as other currently known walk-off prevention/protection alternatives.

(2) Engineering test and evaluation of promising walk-off prevention/protection designs.

(3) Extension of the results of this study to other solar plants of interest.

The following paragraphs describe these three areas.

A potentially fruitful area for innovative and creative minds is the formulation of new walk-off prevention or protection solutions. Through thinking about the problem in new and different ways, possibly new, reliable, safe and inexpensive solutions can be generated. Instead of thinking about the problem at the aperture with an intensity level of 2000 suns, maybe thinking about solutions at the dish with a benign environment of one sun would be fruitful. Possibly, unfurlable devices or opaque sprayable foam, cleanable with the conventional mirror glass cleaning system, are ideas that should be considered. Techniques for moving the receiver, engine and aperture structure away from the focal point should also be considered.

Preliminary design and analysis efforts should also be expended on some interesting grid failure walk-off prevention backup power ideas such as using the electrical output from the dish modules themselves or using photovoltaic (PV) cells. To use the output from dish modules, it must be understood how to control the engine(s) in load-shedding given the loss of the grid and the added emergency system load requirements. Also, the concern about grid failure during startup must be evaluated. The use of PV cells should also be considered. Unlike diesel/generator sets and batteries which are available any time of the day, PV cells can only supply energy during daylight hours. That limitation, however, is of no concern for grid failure solar walk-off prevention, since a walk-off can only occur during those hours. Maybe a natural match exists.

Once new solutions are designed and analyzed, the most promising of them should be built and tested in a test and evaluation engineering experiments manner.

This solar walk-off study developed an approach and methodology for the conduct of cost-effectiveness comparisons of various walk-off prevention/protection alternatives for a specific plant and dish module design. Extension of these results to other plant and dish module designs might be of interest.

SECTION 8

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