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Small Power Systems Applications Project

An Overview of Power Plant Options for the First Small Power System Experiment: Engineering Experiment Number 1

SPSA

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Prepared for
Department of Energy
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

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An Overview of Power Plant Options for the First Small Power System Experiment: Engineering Experiment Number 1

A Summary of EE1 Contractor Reports Edited by:
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ABSTRACT

The primary goal of the Small Power Systems Application Project, Engineering experiment No. 1 is to identify suitable technological approaches for small community applications. Three contractors have been selected for Phase I of the experiment based upon their proposed system concepts in three categories of solar thermal electric power plants: central receiver; point focusing, distributed collector, central power conversion; and point focusing, distributed collector and power conversion. Each proposed concept describes a solar thermal electric power plant with a nominal rated power level of 1 MWe, a capacity factor 0.4, a thirty year life and a start-up time of 4.5 years. This report discusses the three selected proposals and some of the Phase I contractor work completed to date.

A selection of one or more of these three concepts will be made for continuation of work through Phases II and III of the experiment which will be to design, fabricate and install a small solar thermal electric power plant in an actual user environment.

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Section I

INTRODUCTION

The primary goal of Engineering Experiment No. 1 (EE1) is to identify suitable technological approaches for small solar thermal power systems in a small community application. One or more small solar thermal electric power plants, based on optimum use of near-term technologies, will be designed, fabricated, and field installed in an actual user environment. Investigation of the performance, functional, operational and institutional interface aspects of such a power plant in a field test environment are additional objectives. It is realized that certain technological developments will be taking place in parallel to this effort in order to advance the state-of-the-art of solar thermal technology. However, it is expected that early experimentation of near-term technology will not only identify specific areas requiring additional technology development, but more importantly identify institutional and operational problems that can be addressed in the appropriate project element of the Small Power Systems Program.

A. The Experiment Program

Engineering Experiment No. 1 is being conducted in three phases: Phase I, consisting of concept definition, Phase II, preliminary design and component/subsystem development/testing; Phase III, detailed design, fabrication, installation, test and evaluation.

Phase I will investigate various system concepts and develop information which will allow selection of the most appropriate system or systems for the first small power system application. Three technology categories will be explored concurrently. These categories are:

Category A:	General (to include, but not be limited to, central receiver and linear-focusing systems);
Category B:	Point-focusing, distributed collector, central energy conversion; and
Category C:	Point-focusing, distributed collector, energy conversion at the collector.

In each category, a contractor will conduct system design and system optimization studies considering plant size, annual capacity factor and start-up time (the time from start of Phase I to the initiation of testing in Phase III) as variables. The primary output of Phase I will be preferred system concepts for each category and start-up time, design and cost data for the systems studied, and Phase II Program Plans for each preferred system concept. Phase I is expected to last ten months.

Depending on information provided by Phase I, and other independent analyses, one or more of the recommended preferred system concepts will be selected for Phase II. The criteria used in selecting a system concept for Phase II will require that a system exhibit high operational reliability, minimum programmatic risk, commercialization potential and low program cost. During Phase II, preliminary design work will be performed for each concept selected. In addition, component, subsystem, and module testing will be performed to provide the basis for a decision with respect to proceeding with detailed design in Phase III. Phase II will be from 8 months to 42 months depending on the program recommended as a result of Phase I.

Phase III will consist of detailed design, fabrication and construction, installation, testing and evaluation. A three-year schedule is anticipated for this phase, with testing to commence during the third year.

B. Selected Contractors

Proposers, responding to the EE1 request for proposals (RFP), selected one of the three technology categories in which to submit technical proposals. Each proposal outlined a baseline system concept within the selected category on which Phase I studies were to be conducted. The design of a system concept was based on a solar thermal electric power plant with a nominal rated power of 1 MWe, a capacity factor of 0.4, a thirty year life, and a start-up time of 4.5 years.

As a result of proposal evaluations, contracts were awarded to three contractors, one in each of the three technology categories. McDonnel Douglas Astronautics Company was selected for Category A, General Electric for Category B, and Ford Aerospace and Communication Corporation for Category C.

This report discusses the three selected concepts for Phase I of Engineering Experiment No. 1 and includes some of the work completed to September 1978. However, due to the nature of Phase I work, where various alternative concepts are being analyzed and tradeoffs are being performed for system optimization, it is highly likely that many of the subsystem designs resulting from the Phase I studies will be different than the subsystems discussed in this report.

Section II

TECHNICAL DESCRIPTIONS

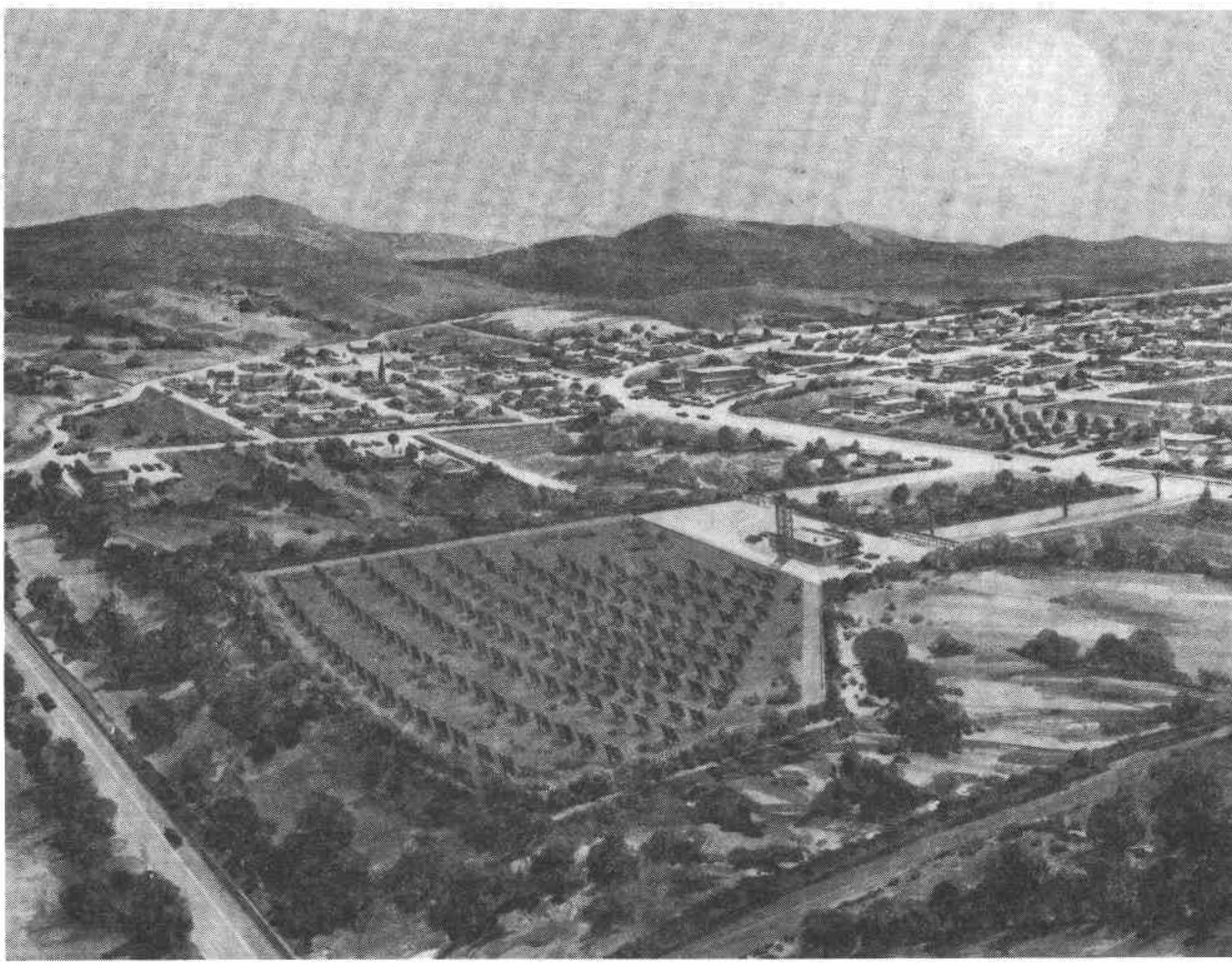

Figure 1

Category A. McDonnell Douglas Astronautics Company

1. Proposed System description

The McDonnell Douglas small central receiver concept is pictured in Figure 1. The complete system is made up of four subsystems, the collector, the power conversion, the energy transport and the energy storage subsystem, as shown in Figure 2.

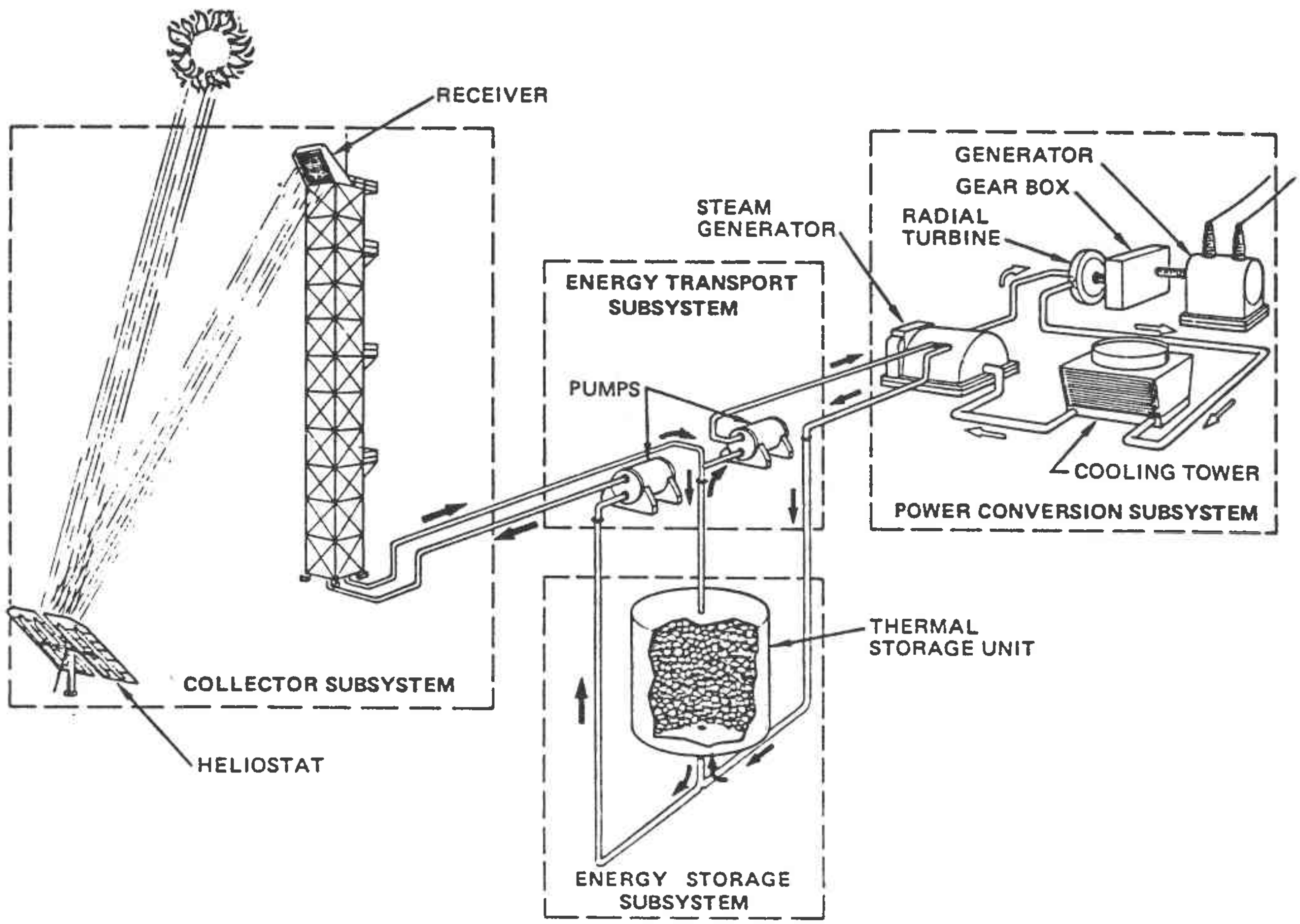

Figure 2. Concept for a Small Electric Power System Module

The collector consists of a concentrator and a receiver. The concentrator is comprised of a field of approximately 160 two-axis tracking reflectors, called heliostats, which direct incident solar radiation to a tower mounted receiver. The heliostat field is located north of the receiver tower, as shown in Figure 3, and requires about 8 acres of land. The heliostat is based on the design being developed by McDonnell Douglas for the DOE Central Power Program, 10 MWe central receiver pilot plant. Each heliostat is mounted on a pedestal with azimuth and elevation drives. The reflecting surface consists of rectangular mirrors mounted on either side of the pedestal, as shown in Figure 2, for a total of 38 square meters of reflecting area for each

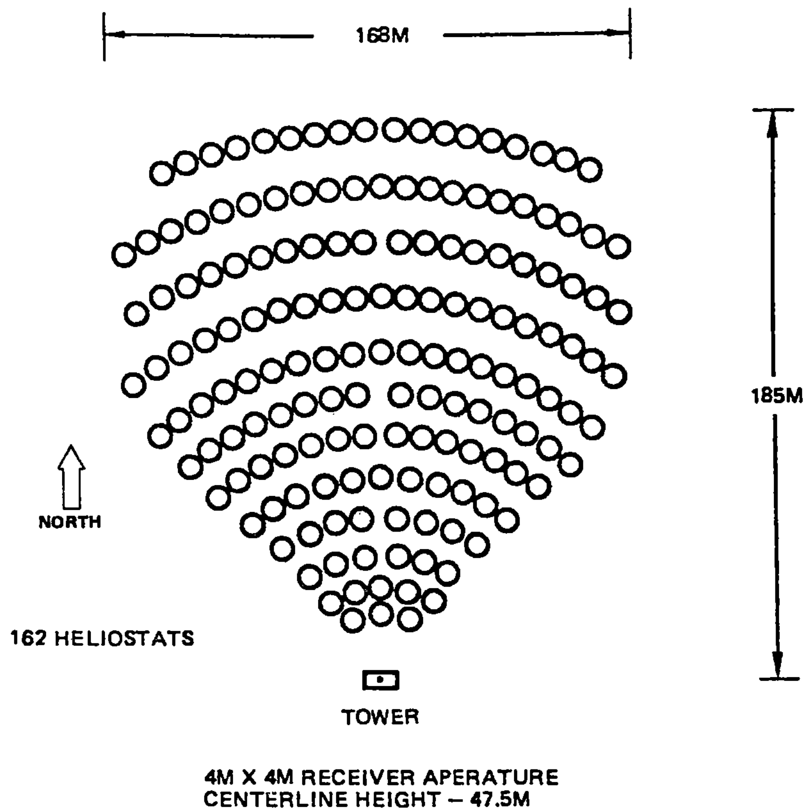

Figure 3. Heliostat Array

heliostat. The heliostat field utilizes an open loop control system to track the sun with each heliostat controlled by the central control unit. The receiver is mounted on a 46 meter open frame steel tower supported by guy wires. Solar radiation concentrated by the heliostat field is absorbed by two series of exposed pipes within the receiver, heating the Hitec fluid used in the energy transport subsystem.

The energy transport subsystem utilizes Hitec fluid, a low melting temperature mixture of salts, to transport thermal energy from the receiver to the power conversion subsystem. As shown in Figure 2, the hot Hitec, at 510°C (950°F), is pumped to either the energy storage unit for use later, or to the steam generator unit to produce steam. Cold Hitec, at 288°C (550°F), is pumped back to the receiver.

Steam produced from the steam generator at 482°C (900°F), drives a steam Rankine cycle radial outflow turbine which in turn drives a gearbox and electrical generator to produce electricity. Waste heat from the turbine is rejected by a wet cooling tower. The nominal output of the power conversion unit is 1.1 MWe of which 0.1 MWe powers parasitic loads, such as pumps and controls. The net output is, therefore, 1 MWe.

The energy storage unit acts as an accumulator, storing thermal energy produced in excess of the energy needed by the power conversion subsystem. The stored energy is used when the power conversion subsystem requires more energy than the receiver can deliver during cloud blockages or at sunset. The storage unit consists of a large tank with 75% of its volume filled with a rock/sand mixture. The sensible heat of the rock/sand mixture stores the thermal energy as the hot Hitec mixture is pumped through the storage tank. The tank, for the baseline system, is large enough to hold 9 MW-hr of thermal energy which can run the solar plant for 3 hours at the rated power of 1 MWe.

As part of Phase I, McDonnell Douglas is considering alternate solar thermal technologies in order to select the preferred system concepts in its general category. Eventually three preferred system concepts will be selected, representing program lengths of 3-1/2, 4-1/2, and 6-1/2 years. Table 1 lists the preliminary concepts identified to date by McDonnell Douglas.

TABLE 1. Preliminary McDonnell Douglas Concepts

COMPONENT	SYSTEM NO. 1	SYSTEM NO. 2	SYSTEM NO. 3
RECEIVER FLUID	Hitec	Hitec	Heat Transfer Salts
TEMPERATURE LIMIT	450°C (842°F)	450-510°C (842-950°F)	510-580°C (950-1076°F)
THERMAL STORAGE	2-Tank	2-Tank	Dual Media Thermocline
PRIME MOVER	Axial Turbine	Radial Turbine (Axial Turbine Backup)	Radial Turbine

2. Proposed System Performance Data

System Data:

rating:	1 MWe
capacity factor:	0.4
availability:	0.96
operating life:	30 years
land used:	8 acres
efficiency:	18.5% at 1 MWe and no storage
type:	162 north field heliostats with tower mounted central receiver

Collector Subsystem:

collector efficiency:	59.5%

concentrator module:

reflecting area:	38 m^2/heliostat, 6160 m^2 total area
error:	3.5 mrad total slope and pointing error
control:	open loop

receiver module:

aperture:	3.4m X 3.4m, 4mx4m with reflector
type:	two zone multipass exposed piping
height:	47.5 meters to centerline of receiver
output:	3.68 MWt at 510°C (950°F)
input:	288°C (550°F)

Power Conversion Subsystem:

type:	rankine cycle radial outflow steam turbine
net output:	1 MWe
parastic loss:	0.1 MWe
inlet temperature:	482°C (900°F)
cooling:	wet cooling tower
efficiency:	31.9%

Energy Transport Subsystem:

type:	steel piping with Hitec transport fluid
efficiency:	97.4%

Energy Storage Subsystem:

type:	dual media rock/sand + Hitec, sensible heat
storage:	9 MWt-hr (3 hours)
max. temp.:	510°C (950°F)
min. temp.:	288°C (550°F)
efficiency:	96%

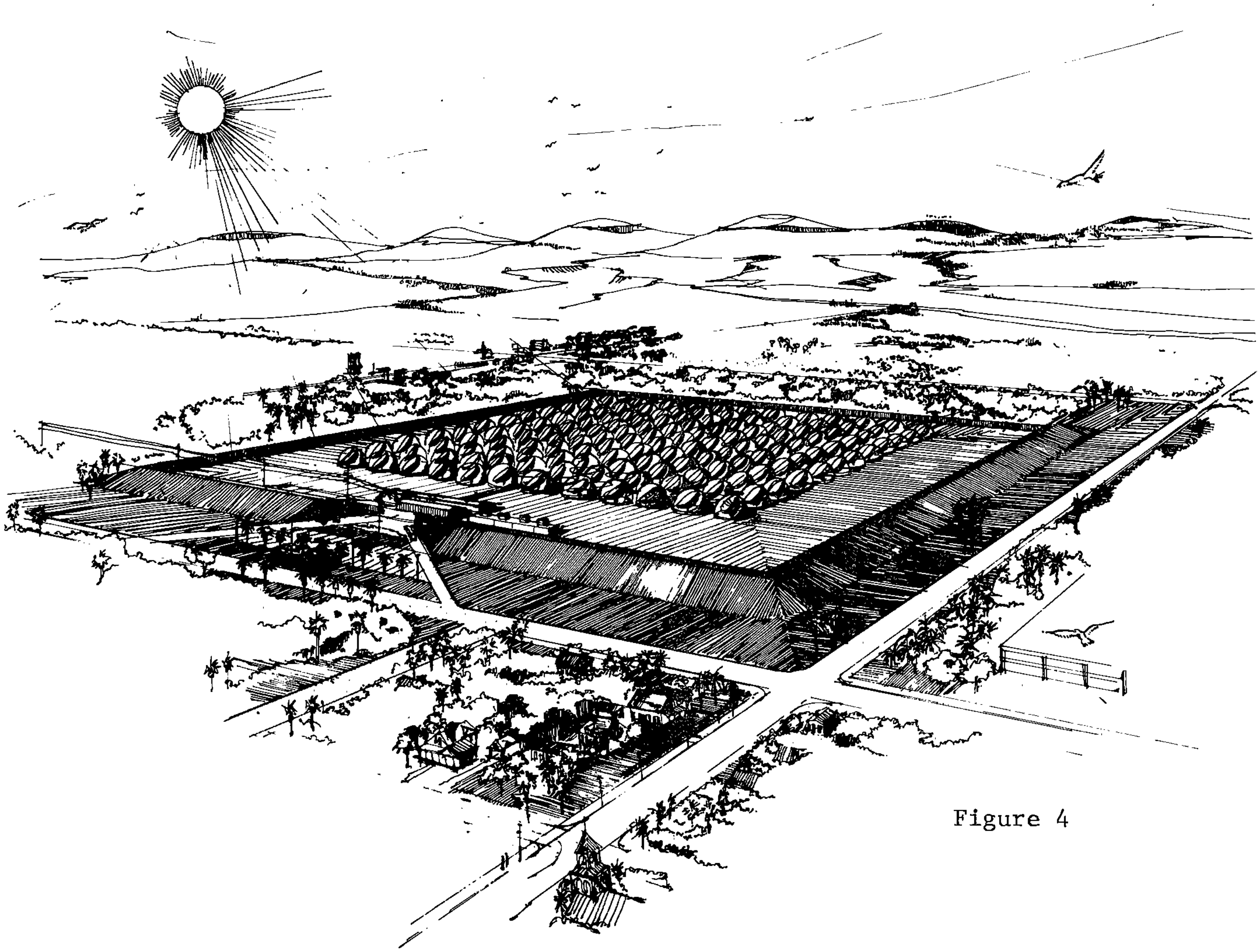

Figure 4

B. Category B: General Electric

1. Proposed System Description

The General Electric system concept, pictured in Figure 4, is comprised of a collector field of approximately 150 two-axis tracking parabolic dish reflecting concentrators. Each concentrator is enclosed within an air-supported transparent enclosure to eliminate wind loading and reduce weather induced mirror degradation on the concentrator. Each dish concentrates incident solar radiation on a ball shaped heat pipe receiver-boiler mounted at its focal point. Steam from the

150 receiver-boilers is transported to the central power conversion unit by vacuum insulated pipes. The General Electric system attempts to minimize field construction costs by reducing the field installation time to 120 days for the entire 1 MWe system.

Each concentrator is mounted on a single pipe pedestal mount at 40 foot intervals and is pivoted through its center of gravity located at its focal point. Figure 5 shows the plant layout of concentrators. Figure 6 shown the construction of a dish. Twenty-eight parabolic segments are mounted on a ring support structure to form a 7.9 meter diameter dish. Each segment is fabricated from a 3/4" aluminum

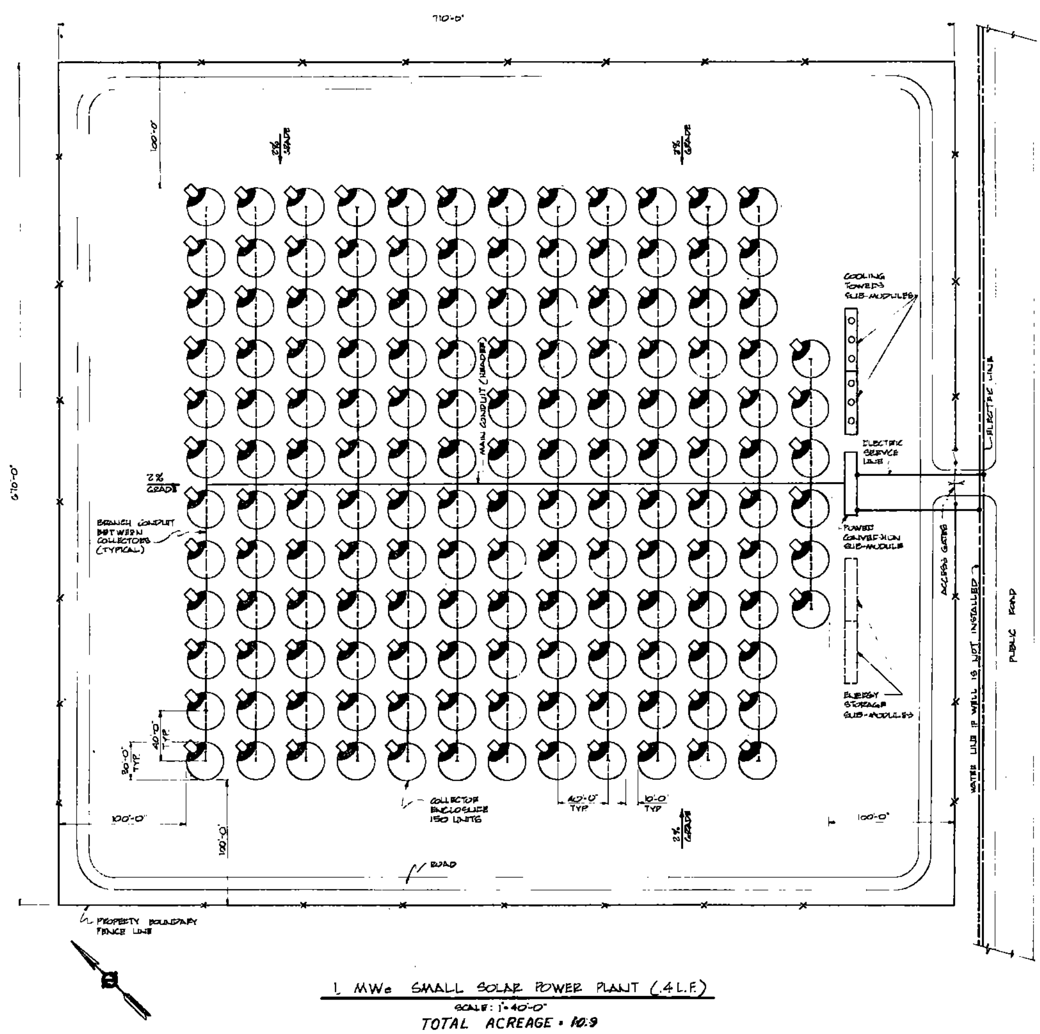

Figure 5. Plant Layout for General Electric Concept

honeycomb sandwich core with a reflecting mylar surface. The total concentrator weight is only 500 lbs. Coarse tracking is controlled by a central computer with a closed loop sun sensor for precision tracking of the sun.

A lightweight dish module is protected from wind loads and weather by a transparent enclosure. The enclosure is constructed of a flexible transparent plastic hemisphere supported by internal air pressure from a small blower. Three tubular step frames provide lightning protection and support during air-system-off periods. Although the enclosures will transmit only 86% of incident solar energy, weight and material costs saved on the concentrators are expected to compensate for the reduced efficiency.

The receiver is mounted in a fixed elevation orientation at the focus of the concentrator, as shown in Figure 6. A potassium heat

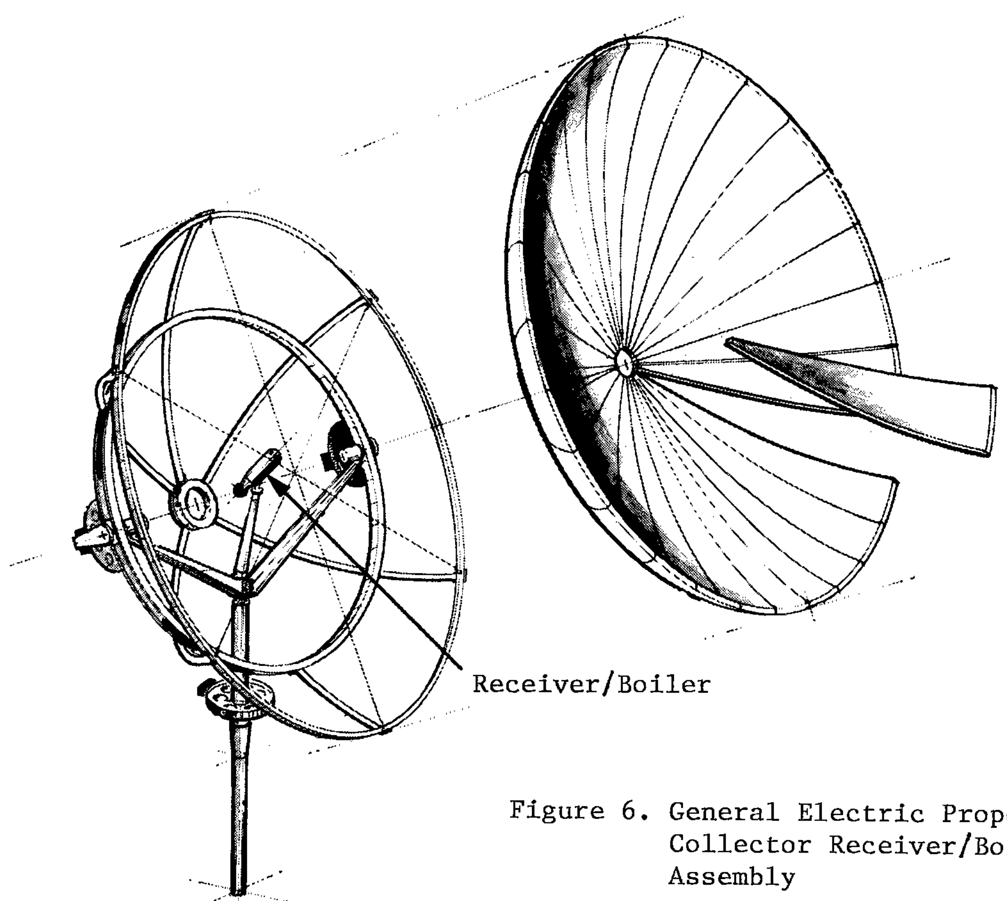

Figure 6. General Electric Proposed Collector Receiver/Boiler Assembly

pipe with an 8" diameter ball shaped absorbing surface at the dish focal point receives the concentrated solar energy. Heat is conducted up the heat pipe to a series of boiler tubes thermally coupled to the heat pipe. Superheated steam, at 510°C (950°F), is produced from the boiler; feedwater to the boiler is at 205°C (400°F).

The energy transport system collects superheated steam from each collector module and transports it to the power conversion unit; feedwater is redistributed back to each module in a similar fashion. To reduce thermal losses on the long runs of piping, 20' feedwater and steam pipe sections are sealed within a long vacuum jacket forming a reflective Dewar-type flask. Figure 7 shows the vacuum piping concept.

The power conversion unit, shown schematically in Figure 8, consists of a 1,235 kW marine type steam turbine, an electrical generator coupled to the turbine through a speed reducing gear box, and all the supporting components. The turbine inlet steam temperature is at 482°C (900°F) with a pressure of 1200 psi.

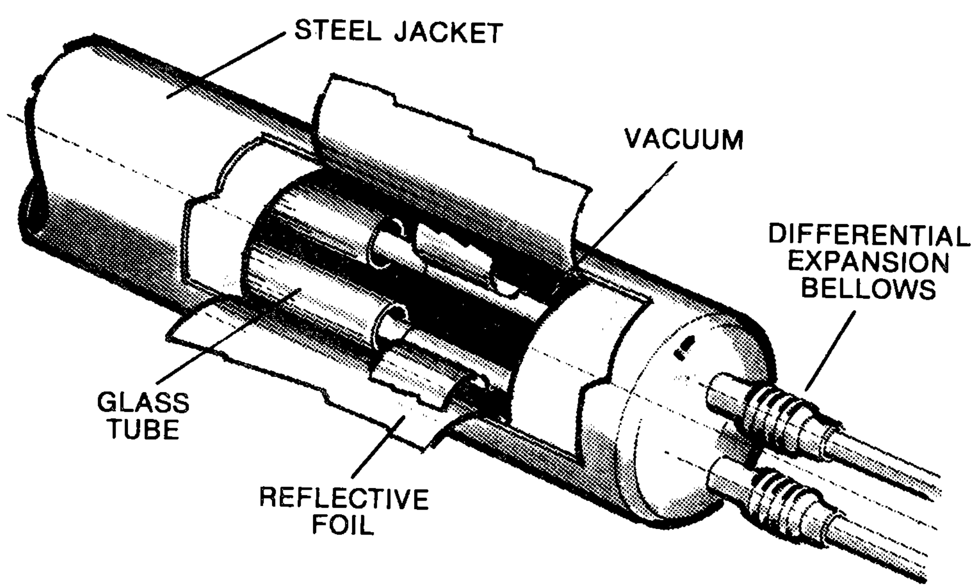

Figure 7. Vacuum Piping Concept Applied to Pedestals, Headers, Laterals, and Expansion Joints

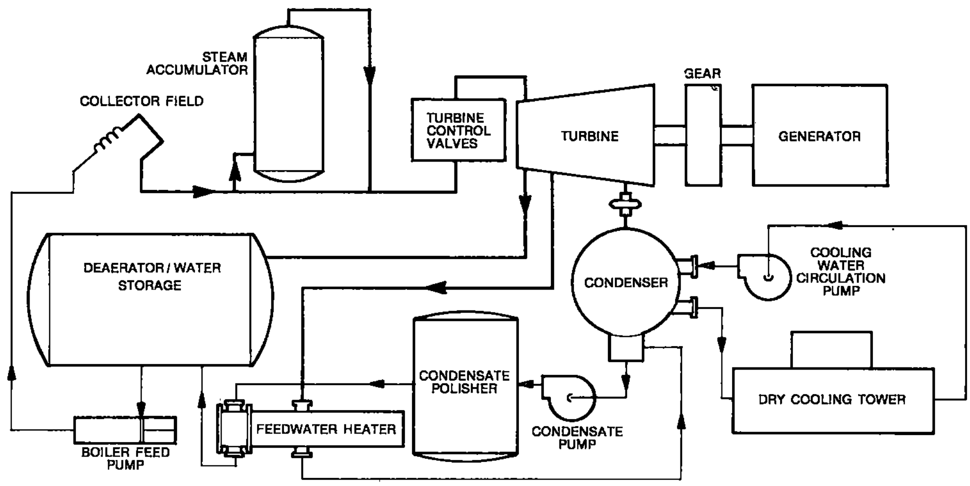

Figure 8. Simplified Process Flow Diagram, 1 MW Power Conversion Subsystem

Electrical output is rated at 1,139 kWe of which 135 kWe is required for parasitic loads to give a net output of 1 MWE. A steam accumulator is used to maintain turbine speed at no-load during intermittent cloud blockages. Waste heat is rejected by a dry cooling tower. The power conversion unit is integrated as a complete submodule as shown in Figure 9.

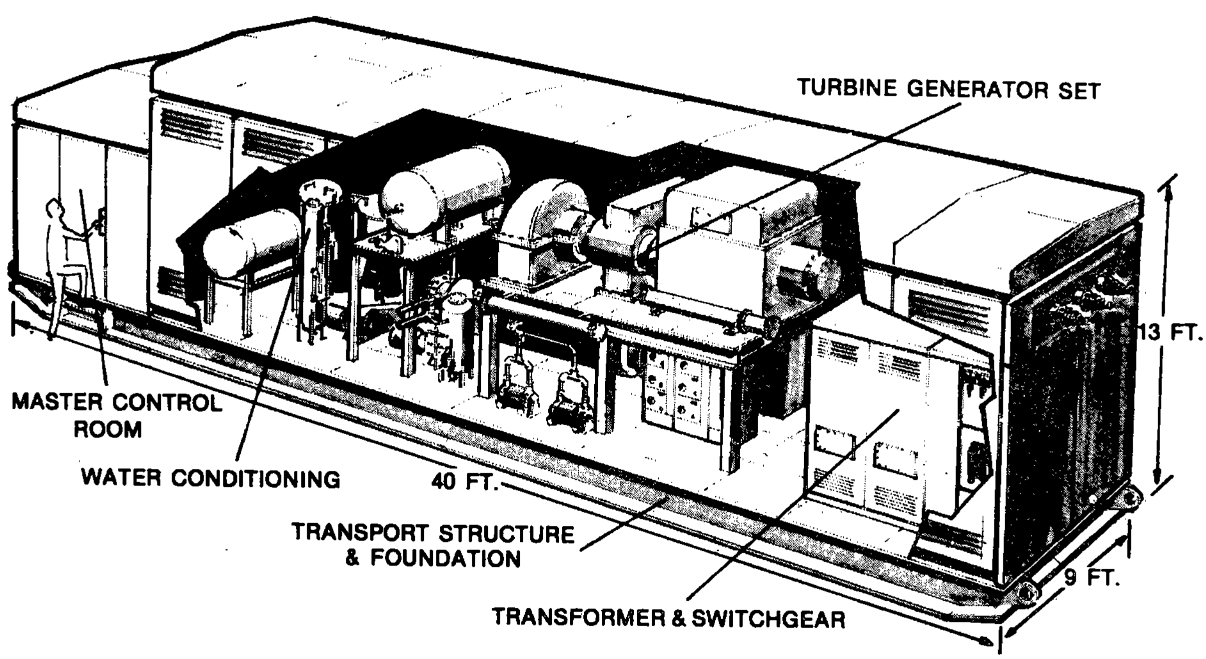

Figure 9. General Electric's Complete Power Conversion Submodule for the 1 MW Plant

The module is rail transportable and skid mounted for quick installation. A battery storage system is used to achieve the required 0.4 capacity factor.

During Phase I, General Electric will investigate three system concepts incorporating a wide range of component options. Table 2 lists the system concepts and components. One of the three concepts will eventually be selected for additional conceptual design work and development planning. The major tradeoffs that are being examined are:

Enclosed vs. Unenclosed Collectors

Cavity vs. Heat Pipe Receivers

Standard Insulation vs. Vacuum Jacketed Piping

Near Term vs. Advanced Technology

Electrical vs. Thermal Storage

TABLE 2. Preliminary General Electric System Concepts

COMPONENT	SYSTEM NO. 1	SYSTEM NO. 2	SYSTEM NO. 3
CONCENTRATOR	Near Term Technology (Shallow Dish-Heavy)	Advanced Lightweight (Shallow Dish)	Advanced Lightweight (Deep Dish)
RECEIVER	Cavity	Cavity	Sphere/Heat Pipe
ENCLOSURE	None	Enclosed	Enclosed
SUN TRACKING DRIVE	Screw Type	Linear Stepping	Linear Stepping
FIELD PIPING	Standard Insulation	Standard Insulation Plus Vacuum Jacketed	Insulation Plus Vacuum Jacketed
ELECTRICAL STORAGE	Lead Acid Batteries	Lead Acid Batteries	Sodium Sulfur Batteries

2. Proposed System Performance Data

System Data:

rating:	1 MWe
capacity factor:	0.4
availability:	0.90 for EE1, 0.95 for mature concept
land used:	11 acres (25% packing factor)
efficiency:	13.88%
type:	150 parabolic reflecting dish-receiver modules with transparent enclosures, central power conversion.

Collector Subsystem:

collector efficiency: 57%

concentrator module:

type:	parabolic point focusing dish, pedestal mounted
diameter:	7.9 meters (26 ft.)
weight:	500 lbs
rim angle:	109°
focal length:	1.4 meters (4.6 ft.)
control:	closed loop, linear stepping motors, microprocessor
error:	slope ± 0.25° pointing ± 0.75°

Enclosure module:

zipper connected transparent panels,
blower unit for each enclosure,
tubular step frame supports
transmission efficiency: 86.4%

Receiver module:

type:	potassium heat pipe with ball shaped hot end at focus of dish; once-thru helical boiler tube on cold end
output:	510°C (950°F) steam
input:	205°C (400°F) feedwater
ball diameter:	8 inches

Power Conversion Subsystem:

type:	skid mounted marine steam turbine-generator
net output:	1 MWe
parasitic losses:	135 kWe
inlet temperature:	482°C (900°F)

steam flow:	3.59 lbs/sec
cooling:	dry cooling
efficiency	28.3%

Energy Transport Subsystem

type:	vacuum jacketed 20' sections of feedwater and steam pipes, rows of concentrators connected to main header on center line of plant.
losses:	100 kWt
efficiency:	97.5%

Energy Storage Subsystem:

type:	lead-acid battery storage for 0.4 capacity factor
efficiency:	73%

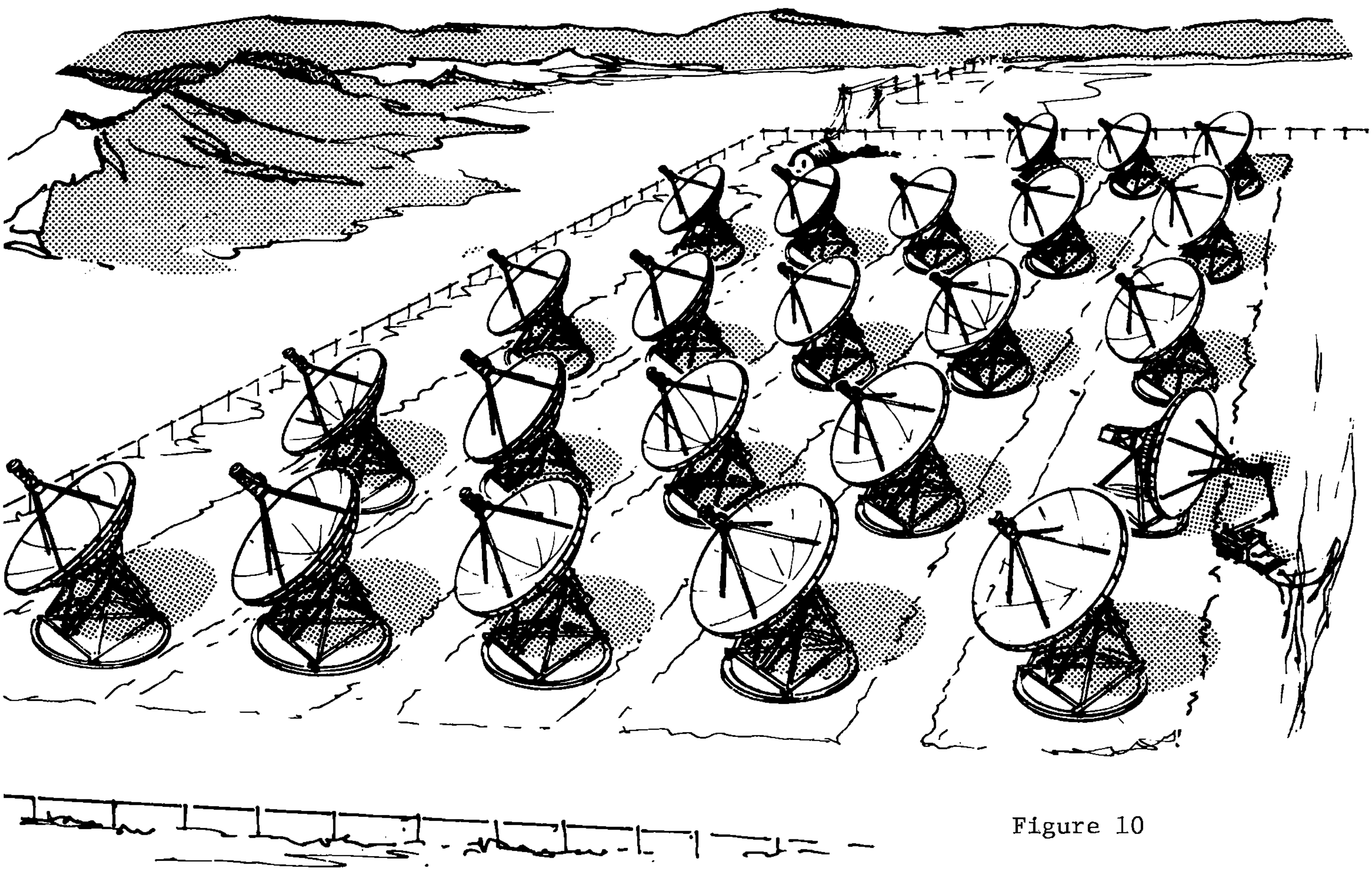

Figure 10

Category C: Ford Aerospace and Communications Corp., Aeronutronics Division

1. Proposed System Description

The Ford Aeronutronics concept, pictured in Figure 10, consists of a collector field of approximately 23 parabolic dish concentrator modules. A receiver unit and a power conversion unit are mounted on each dish near the focus. Figure 11 depicts a Ford Aeronutronics module. Electricity is generated at each collector and transported to the station power conditioning unit providing connection to the utility grid. Figure 12 schematically represents the entire system.

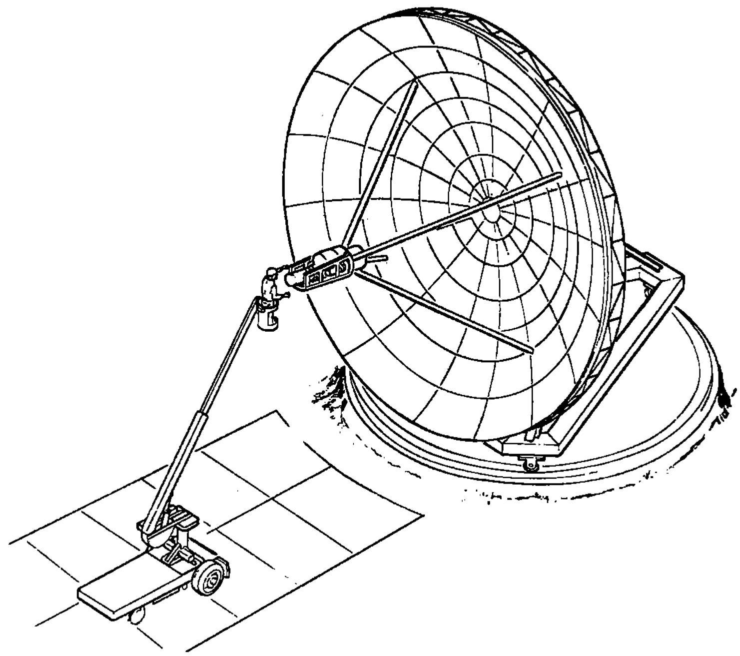

Figure 11. Ford Aeronutronics Power Module

Each concentrator module is 16 meters in diameter and similar in construction to parabolic dish radio antennas. The reflecting surface is an aluminum substrate covered with metallized acrylic tape. The concentrator is mounted on a circular wheeled track for azimuth tracking. A ball and screw jack provides elevation tracking. A sun

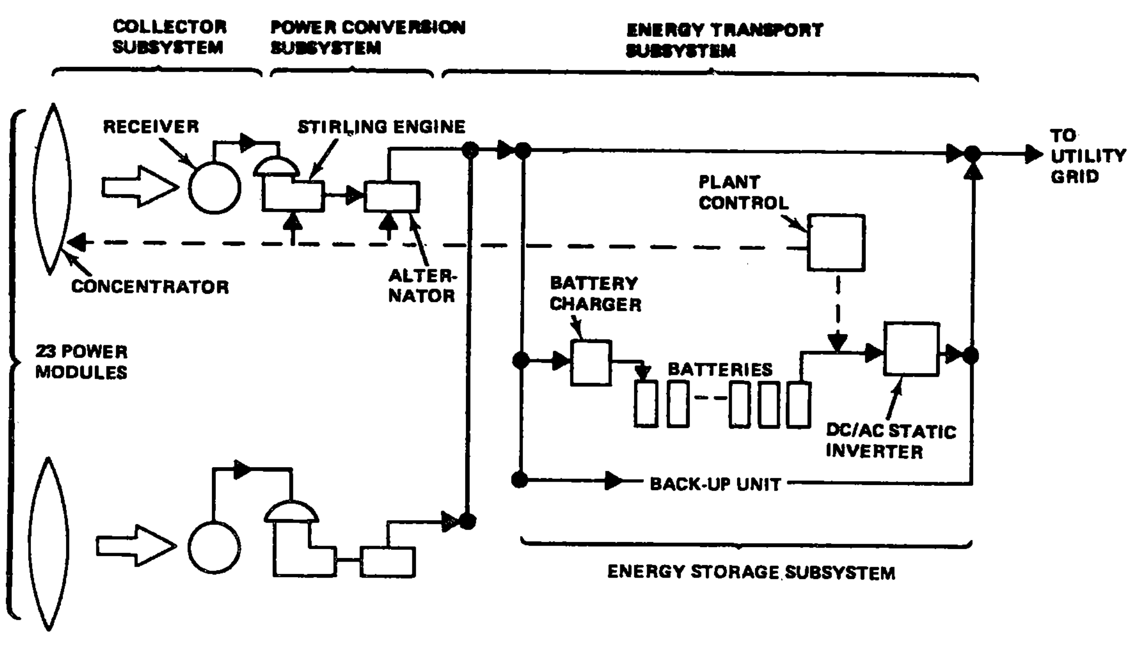

Figure 12. System Schematic

sensor provides closed loop tracking control. Each module is located in the collector field to minimize sun blocking by other collectors. Figure 13 shows the plan view layout of modules.

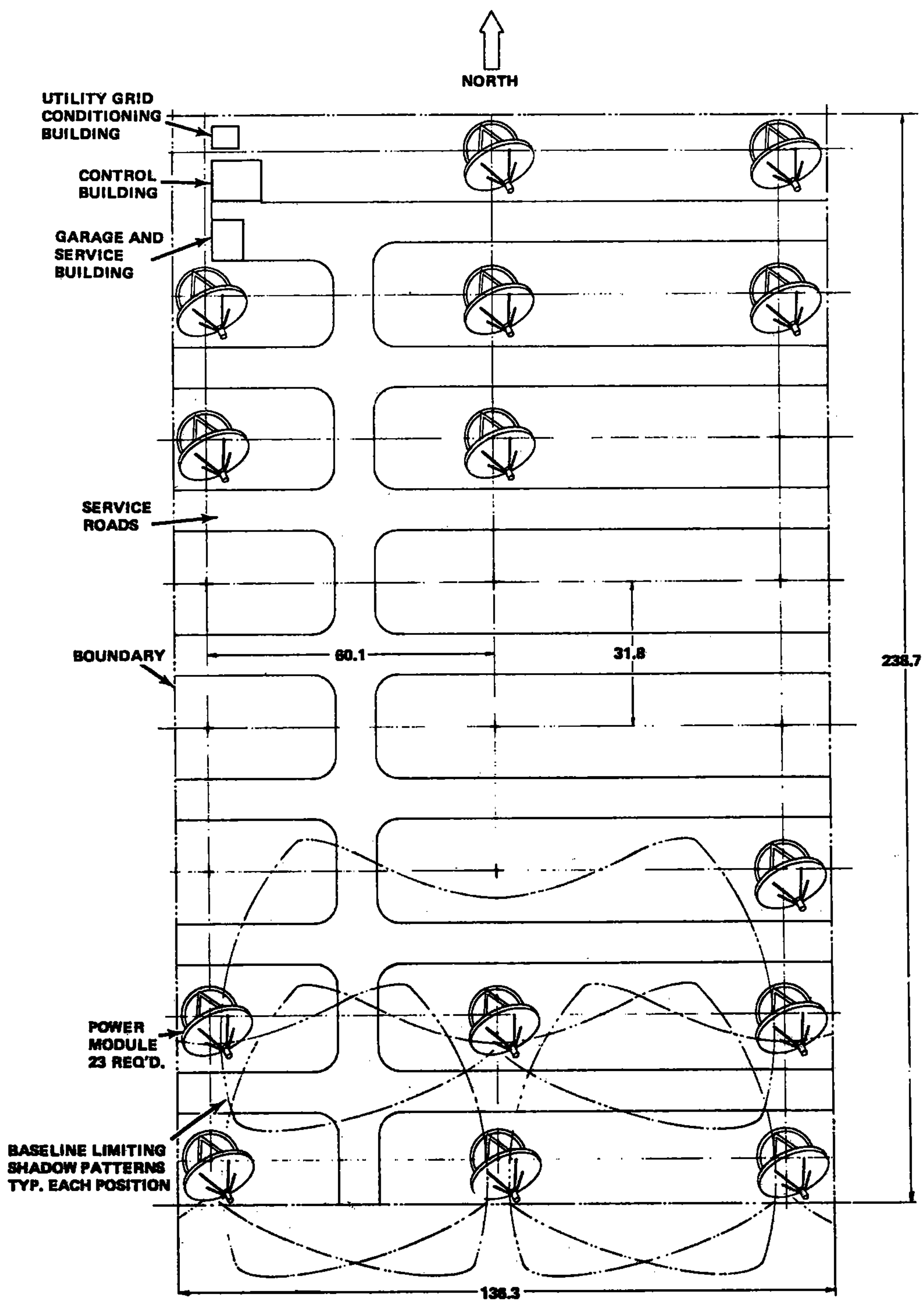

Figure 13. 1 MWe Solar Power Facility Plan View

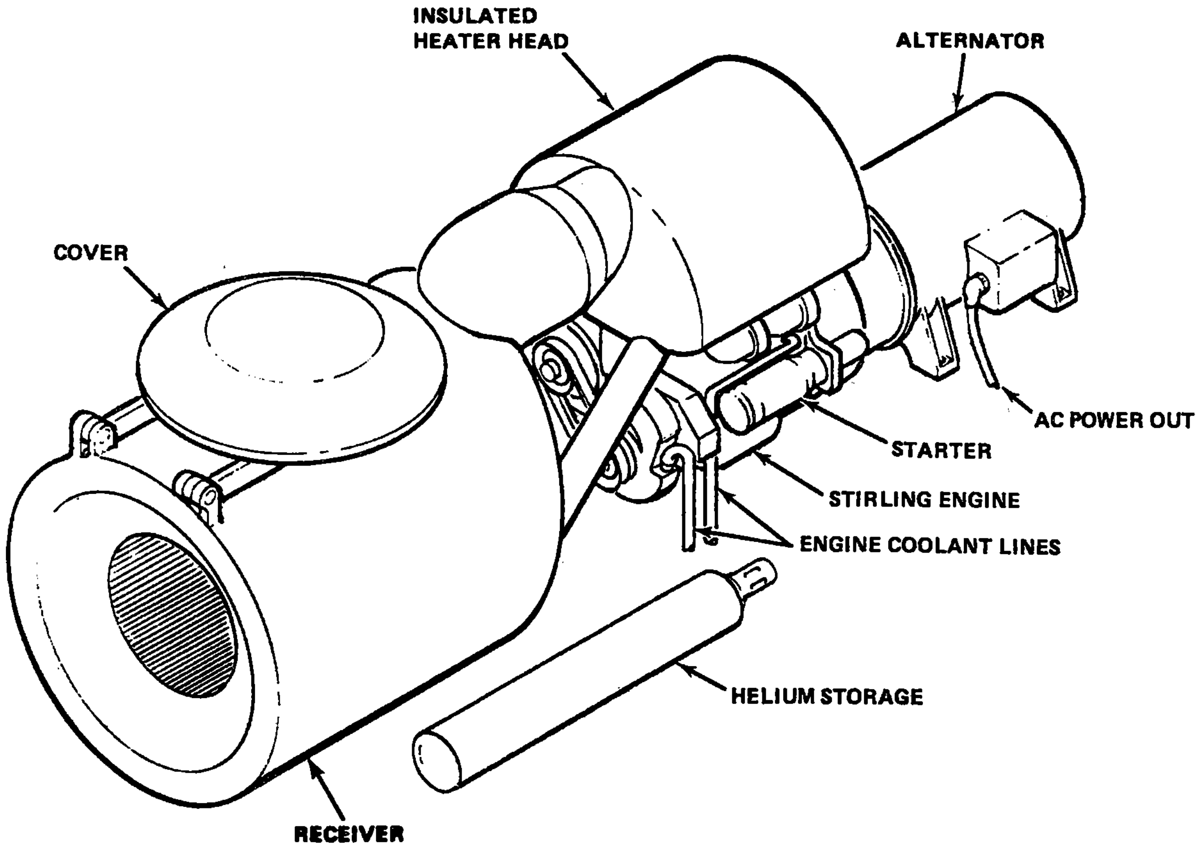

Figure 14. Power Conversion System

The receiver unit and power conversion unit are both mounted near the concentrator focus on a quadripod structure. Figure 14 shows the arrangement of the receiver and power conversion units. The cylindrical cavity type receiver utilizes sodium as a heat transfer medium and operates at 750°C (1382°F).

The power conversion unit consists of a reciprocating Stirling cycle heat engine with gear box and alternator to produce electricity. The heat engine is a P-75 Stirling cycle engine produced by United Stirling of Sweden (USS), modified for a sodium heat source and using helium as a working gas. Waste heat is conducted down the quadripod to a conventional water/ethylene glycol heat exchanger mounted behind the concentrator reflecting surface. The engine operating point efficiency is 39% with a shaft output of 58.5 kWe at 1800 RPM. The alternator is driven by the engine through a 2:1 geared speed increaser. The electrical output is 52.7 kWe a module. Parasitic losses and electrical collection and transportation losses reduce the net output to 50 kWe per module to the utility grid.

Twenty modules are required to achieve rated power of 1 MWe at a capacity factor of 0.371. A 541 kWh lead-acid battery storage subsystem and two additional modules are required to achieve a 0.4 plant capacity factor. AC-DC and DC-AC convertors are used to connect the batteries to the utility grid. An additional module and redundent components in the energy storage subsystem provide a margin allowance.

During Phase I, Ford Aeronutronics is considering alternate subsystem technologies in order to select three preferred system concepts, representing program lengths of 3-1/2, 4-1/2, and 6-1/2 years. These alternate approaches include Brayton and Rankine cycle engines for use in the power conversion subsystem and advanced batteries for energy storage.

2. Proposed System Performance Data

System Data:

rating:	1 MWe
capacity factor:	0.4
operating life:	30 years
efficiency:	22.8% net annualized efficiency
land used:	about 8 acres
type	23 point focusing, parabolic concentrator-receiver-power conversion modules, central power conditioning.

Collector Subsystem:

Collector efficiency:	74.3%

Concentrator module:

type:	parabolic point focusing reflector, radio antenna type construction
diameter:	16 meters
rim angle:	60^{o}
error:	Slope 0.15^{o} pointing 0.10^{o}
control:	closed loop

receiver module:

type:	cavity receiver with tube bundles lining walls of cavity, sodium heat transfer fluid.
output:	$750^{o}C$ ($1382^{o}F$)

Power Conversion Module Subsystem:

type:	USS P-75 reciprocating Stirling cycle heat engine, geared speed increaser and alternator.
net output:	50 kWe/module, including all parasitic loads.
working fluid:	helium
heater head temp:	$720^{o}C$ ($1328^{o}F$)
mean pressure:	1650 PSI
shaft power:	58.5 kWe/module
alternator output:	52.7 kWe/module
efficiency:	39.8%

Energy Transport Subsystem:

type:	underground electrical cables to power conditioning unit.
losses:	126.6 kWe including station power.
efficiency:	98.7%

Energy Storage Subsystem:

type:	lead-acid battery with AC-DC and DC-AC convertors
storage:	541 kWh
efficiency:	72%