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THE DISH-RANKINE SCSTPE PROGRAM
(Engineering Experiment No. 1)

by

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ABSTRACT

Paper summarizes the activities planned for Phase II of the Small Community Solar Thermal Power Experiment (SCSTPE) program. A Dish-Rankine Point Focusing Distributed Receiver (PFDR) solar thermal electric system will be designed and developed and a single power module tested at the JPL Solar Thermal Test Facility, Edwards AFB, California. Major design efforts will include: development of an advanced concept indirect-heated receiver; development of hardware and software for a totally unmanned power plant control system; implementation of a hybrid digital simulator which will validate plant operation prior to field testing; and the acquisition of an efficient organic Rankine cycle (ORC) power conversion unit (PCU). Preliminary performance analyses indicate that a mass-produced Dish-Rankine PFDR system is potentially capable of producing electricity at a levelized busbar energy cost of 60 to 70 mills per KWh and with a capital cost of about $1300 per KW.

INTRODUCTION

FACC will be the Systems Contractor for Phase II of the SCSTPE program, under contract to JPL. The Phase III effort, as currently envisioned, will consist of the fabrication, installation and test of multiple power modules comprising a complete power plant - in the range of 1/4 to 1 MW_e - at a site to be selected by DOE.

The Phase I studies carried out by FACC considered PFDR solar thermal electric systems employing Stirling, Brayton and Rankine cycle engines. Given the benefits of mass production, all of these concepts were shown potentially capable of producing electricity at a cost competitive with the energy cost projected for fossil- and nuclear-fueled plants in the near future. The Dish/Rankine PFDR concept was chosen for the Phase II SCSTPE program primarily because it offered the best performance for the lowest program risk. In general, Rankine cycle engines represent a well-developed technology and should prove to be very reliable equipment. At the module power levels of interest (~20 KW_e) to the SCSTPE program, however, there is a lack of data on representative hardware, and an experimental program is necessary to obtain operating experience and provide a valid data base for accurate projections of performance, reliability and (maintenance) cost of the ultimate commercial systems.

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PROGRAM REQUIREMENTS AND PLANS

The overall milestone schedule for the SCSTPE program is shown in Figure 1. The major constraint is the customer requirement to have the

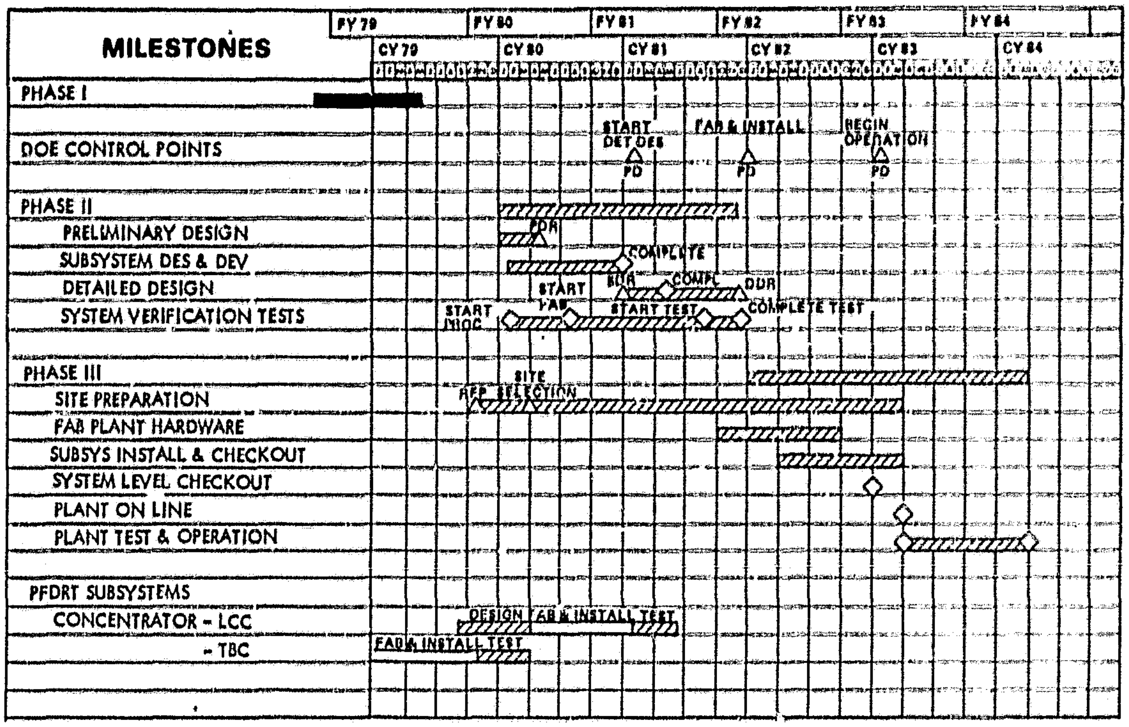

FIG. 1. OVERALL MILESTONE SCHEDULE FOR SCSTPE PROGRAM

plant "on-line" by mid-FY83. The critical path for Phase II is acquisition of the organic Rankine PCU during month 15 for integration with the FACC receiver and subsequent installation into the power module at the JPL Solar Thermal Test Facility. This schedule assumes a 12-month development cycle for the organic Rankine PCU.

The Preliminary Design Review will be held after 4 months; the Systems Design Review after 12 months; and completion of the Phase II program after 23 months. In addition to program schedule and cost considerations, subsystem and component selection will be based on economics of a commercial, mass-produced PFDR system (circa 1990) designed for 1 MW_e rated power without storage. The remote (unmanned) plant will interconnect with a utility grid network. The Barstow, California, site will be employed for preliminary design computation. Subsequent analyses will use the Phase III site currently under source selection.

Effort during design of the major subsystems will address the following key issues:

Concentrator - The General Electric prototype 12-meter Low Cost Concentrator (LCC) will be provided by JPL as the baseline. The JPL/E-System Test Bed Concentrator (TBC) will remain as backup for the System Verification Tests at the JPL Solar-Thermal Test Facility.

Power Conversion Unit - A detailed presentation of this subsystem has been given previously by Mr. Boda. Among the key issues to be addressed are the rather tight development schedule discussed previously and the lack of operating experience on toluene at the desired operating temperature range of 700-800°F. The baseline PCU will be hermetically sealed to avoid leakage, oxide contamination, etc. A parallel steam Rankine engine system is under consideration as program backup.

Receiver - Details of this subsystem were given previously by Mr. Osborn. Key issues relate to the selection of an acceptable secondary working fluid within the relatively short time available prior to the scheduled decision date at PDR. The direct-heated receiver concepts currently under development as a part of the JPL PFDR program remain as backups.

Plant Control - FACC will design the plant control subsystem for remote, unmanned operation. The detailed design of the hardware and software for complete control of a multi-module plant is a major task of the Phase II program. A complete hardware-in-loop system simulator will be constructed so that complete dynamic simulation of plant operation can be achieved; varying solar insolation, start-up, shut-down, transient cloud cover, forced outages and the like will be simulated and thoroughly examined. An additional benefit of this simulator is its applicability to other PFDR systems, regardless of the type of engine employed.

Energy Transport - The Energy Transport subsystem is a conventional DC electrical network. The program decision to go DC is based on extensive studies which show no significant difference in system efficiency between the AC or DC design, whereas the DC network permits an easier interface (one point) with the utility grid, and, if storage were desired, permits a more efficient interface with batteries since the DC-DC interconnection does not require additional conversions.

BASELINE SYSTEM

The baseline system for SCSTPE has been established consisting of the collector subsystem, the energy transport subsystem and a central plant control subsystem. Details of these subsystems are given in the following paragraphs.

Collector Subsystem

The collector subsystem consists of multiple power modules. Each power module contains a 2-axis tracking parabolic dish concentrator, a cavity receiver and an ORC Power Conversion Unit (ORC engine and electrical generator). The control rectifier is also part of the PCU, but is mounted at ground level near the base of the dish concentrator. Figure 2 shows the prototype power module which uses the 12-meter General Electric Co. Low Cost Concentrator (LCC) currently under development as a part of the JPL PFDR program. The LCC is a lightweight, advanced design unit which employs injection-molded plastic dish segments, integral reflector surface, front structural bracing and a wheel/track type of azimuth/elevation mount with the unique capability to achieve an inverted stow position in order to reduce survival wind loads and provide easy access to the power conversion assembly and the reflecting surface. The prototype LCC will use an aluminized plastic reflecting surface; later designs may use silvered glass mirror elements with substantially higher reflectivity and longer life. Sun tracking is accomplished by a combination open loop/closed loop system. A more detailed discussion of the LCC has been given by Mr. Zimmerman of the General Electric Company.

A cutaway view of the power conversion assembly consisting of the receiver, ORC engine, alternator and plumbing is shown in Figure 3. Complete weight of the assembly is 490 Kg (1078 lb); it is 2.60m (8.52 ft) long and fits within a 1-meter-diameter circle. The receiver* is an indirect-heated design based on the pool-boiling or thermosyphon concept thoroughly studied by FACC during the Phase I program. It is essentially a double-walled cylindrical container with a secondary fluid boiling in the annulus. (The leading candidates for the secondary fluid are sulphur mixed with 10-15 percent iodine and a terphenyl organic compound.) The cylindrical container is connected by a short pipe to a heat exchanger which contains the circulating toluene. The vaporized secondary fluid is transported up the pipe by natural convection, condenses on the toluene heat exchanger surfaces and returns to the boiler by gravity.

The PCU has not been selected although preliminary designs have been submitted by a number of firms including Sundstrand, Barber-Nichols, Garrett/AiResearch, Thermo-Electron and General Electric. Both Sundstrand and Barber-Nichols have had contracts from FACC to provide high-performance ORC engine designs. The Barber-Nichols design (Figure 3) has an electrical output of about 16 KW_e at rated power conditions.

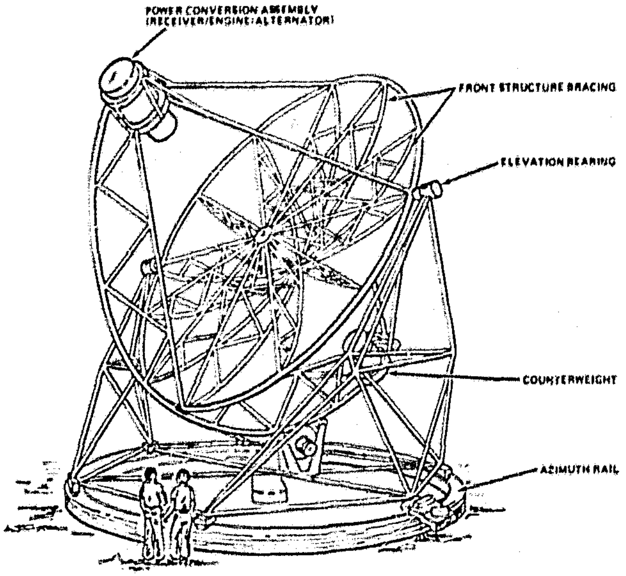

FIG. 2. POWER MODULE INCORPORATING LOW COST CONCENTRATOR AND ORC POWER CONVERSION ASSEMBLY

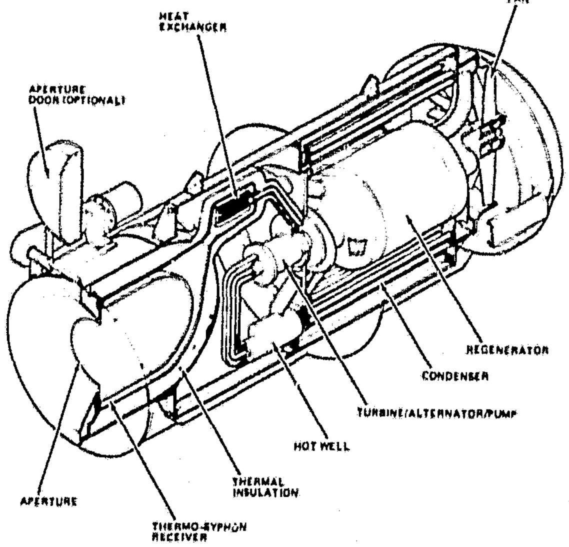

FIG. 3. ORC POWER CONVERSION ASSEMBLY

*Patent Applied For

An air-cooled condenser is packaged concentrically about its turbine/alternator/regenerator components as shown in Figure 3. Toluene operating supercritically is the working fluid with a maximum temperature of 427°C (800°F). Consideration has been given to the effect of the 427°C maximum operating temperature on the long-term stability of toluene. Estimates have been made which indicate that the working fluid will have to be changed only about every 30,000 hours or twice during the 30-year life of the plant. It should be noted that the rate of fluid degradation is low since the bulk of the toluene fluid inventory is at much lower average temperature than the 427°C maximum operating temperature. Note further that the use of a hermetically sealed system minimizes oxide formation and attendant scale deposition on the plumbing.

Energy Transport Subsystem

The overall SCSTPE system schematic shown on Figure 4 illustrates the major elements of the Energy Transport Subsystem. A DC electrical system interconnects the individual power modules and converts the collected energy into AC power by a central inverter. Standard interface

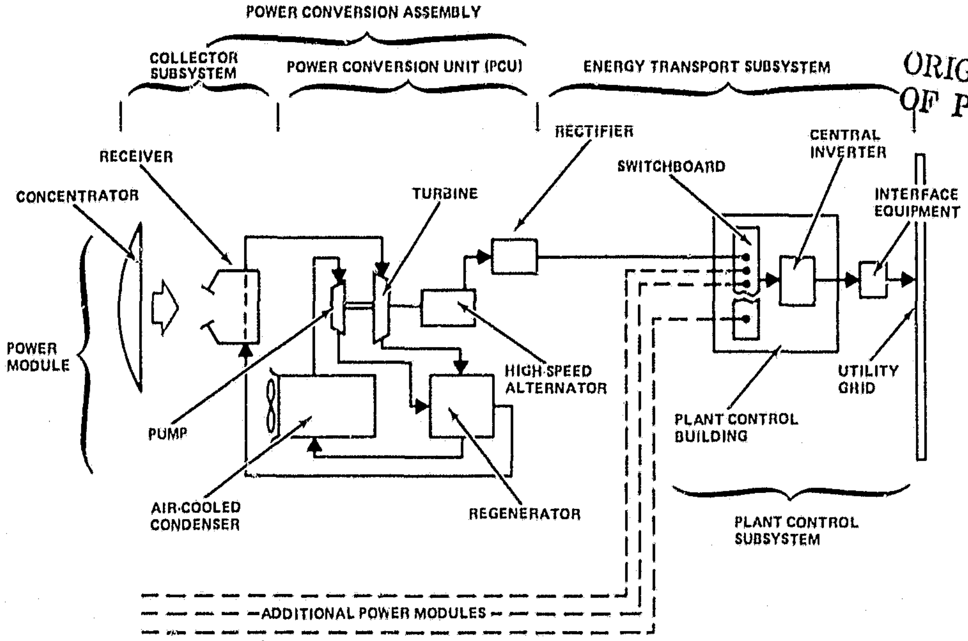

FIG. 4. SCSTPE SYSTEM SCHEMATIC

equipment is used to connect to a utility grid. Overall efficiency of the SCSTPE Energy Transport Subsystem from PCU output to the utility grid is estimated at 93.4 percent. All components are off-the-shelf items with demonstrated performance and minimum risk.

Plant Control Subsystem

The Plant Control Subsystem is designed to permit remote, unmanned operation of the SCSTPE. A central microprocessor serves as the supervisory-level controller and centralized interface for communications among all plant subsystems and the central plant control room. The general functions performed by the control subsystem include

(1) Automatic/Manual control of all plant subsystems.

(2) Coordinated sequencing of plant subsystems for its various operating modes such as: start-up, shutdown, normal operation, intermittent operation and emergency operation.

(3) Plant system protection against failures (grid faults, environmental conditions, etc.) by means of monitoring key measurement variables and commanding automatic emergency sequencing.

(4) Status monitoring of relevant plant variables for control room terminal display and recording.

Most control functions will be implemented as algorithms in the microprocessor software; however, in certain cases local analog electronic control loops may be used and only supervisory level control will be provided. The microprocessor speed and memory have been sized to permit sequential communication with each power module through a serial-multiplexed data bus.

SYSTEM PERFORMANCE

A major variable in the ORC system is the working fluid temperature at the inlet to the engine expander (turbine). Figure 5 shows the influence of turbine inlet temperature (TIT) on the pertinent component efficiencies. Note that overall system efficiency (from sun to electric grid) is maximum ($\sim$21%) at 427°C (800°F), which is the upper limit for the data, corresponding to an upper limit estimated for reliable operation with toluene. As shown later, it is possible to operate at somewhat lower temperature, if an added safety factor is desired, with only a small increase in energy cost. The performance data presented herein, however, have been computed at a temperature of 427°C.

System annual output was determined by calculating performance in 15-minute intervals for a Barstow, CA, site during CY1976; all plant parasitic losses are included. Figure 6 shows the power budget for an individual module as a function of time for a typical Barstow day. Figure 7 shows power delivered to the grid, per module, for three representative days of the year. For a 1 MW_e system, nominally rated at a solar insolation of 800 W/m^2 and an ambient temperature of 27°C (80°F), approximately 68 power modules are required and annual energy output is 54.5 MWH/Dish, for a total system output of 3706 MWh/year. This corresponds to an Annualized Capacity Factor (ACF) of 0.418 without storage and adjusted for computed System Availability.

These computations were carried out for a spatial arrangement of modules corresponding to 25 percent packing fraction, i.e., the ratio of concentrator aperture area to land area. At 25 percent packing fraction, the annual energy loss due to mutual shading/screening of concentrators is negligible (Reference 1) and total system cost, including electrical cabling and land (at $5000/acre) is minimum. Corresponding

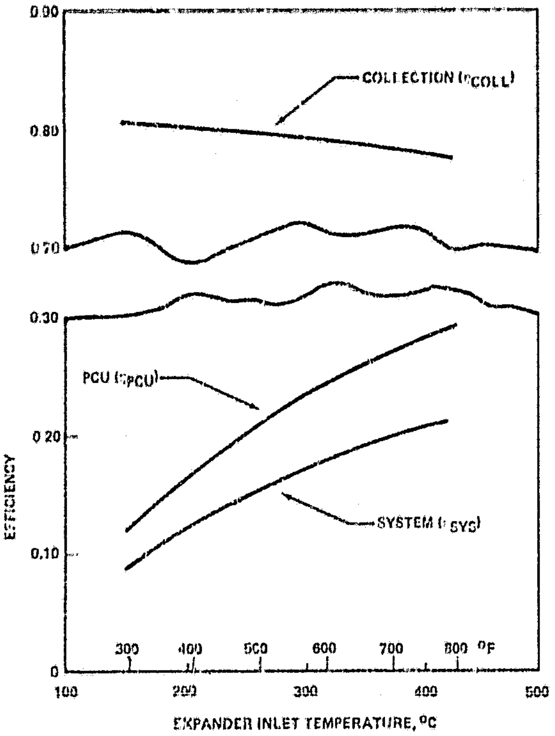

FIGURE. 5. EFFECTS OF TEMPERATURE ON COMPONENT EFFICIENCY (OPTIMIZED 1 MW_e - ORC SYSTEM)

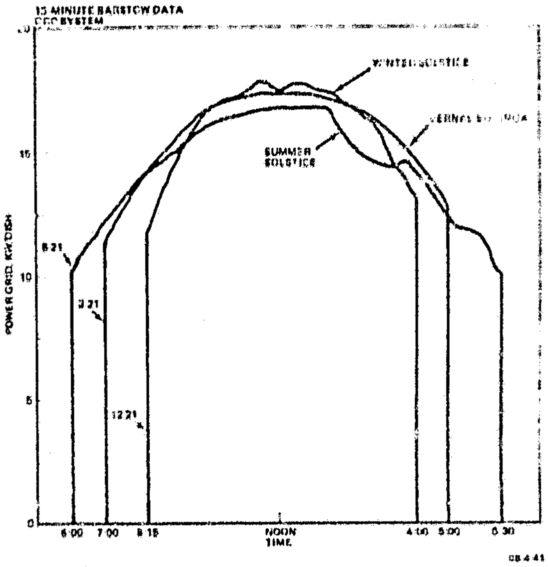

FIGURE. 7. SYSTEM PERFORMANCE BY SEASON (INDIVIDUAL POWER MODULE)

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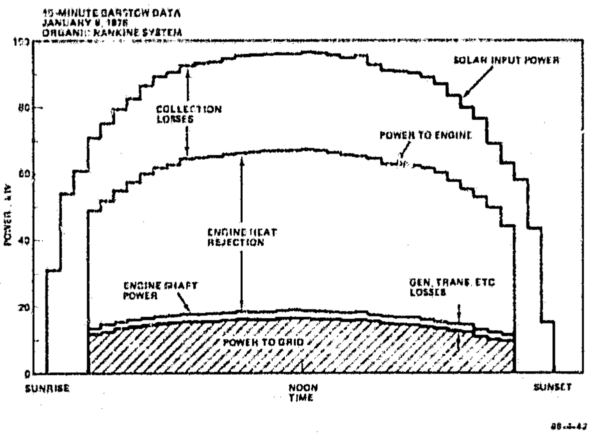

FIGURE. 6. INDIVIDUAL POWER MODULE SYSTEM PERFORMANCE FOR A TYPICAL DAY

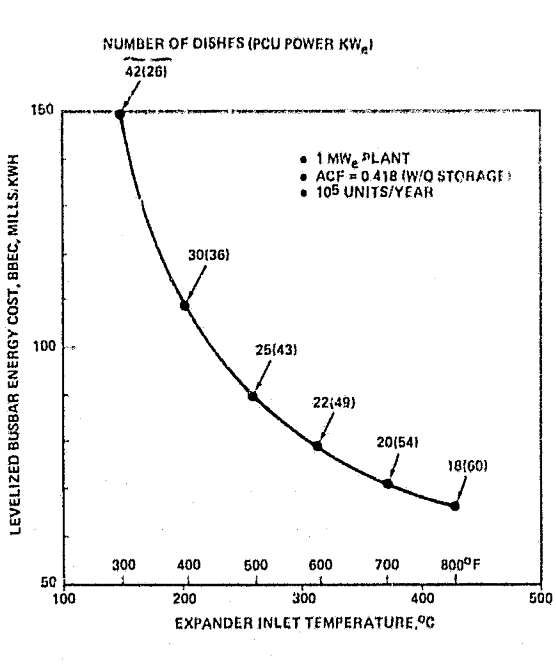

FIGURE. 8. OPTIMIZED ORC SYSTEM PERFORMANCE

land area for a prototype 1 MW_e plant is 7.6 acres. Higher packing fractions are achievable, but with some loss in energy. For example, at 50 percent packing, annual energy loss is about 6 percent, but land costs would have to exceed about $30,000/acre to achieve minimum system cost at this density.

SYSTEM ECONOMICS

A generalized economic analysis was carried out for the Dish-Rankine concept, assuming optimized components* and the benefit of mass production/installation techniques. Life cycle cost analysis techniques (Reference 2) were employed to determine System Levelized Busbar Energy Cost ($\overline{BBEC}$), which is used as the sole comparative parameter. Figure 8 shows the influence of TIT on $\overline{BBEC}$ for a production rate of 100,000 modules/year. The benefits of higher temperature are obvious, but very non-linear since the reduction in $\overline{BBEC}$ for the last 55°C (100°F) difference in TIT is only about 5 mills/kWh (~7%). Note that lowest $\overline{BBEC}$ is on the order of 70 mills/kWh despite use of the relatively conventional FACC concentrator design. Use of more advanced concentrators currently in the design stage could reduce $\overline{BBEC}$ below 50 mills/kWh.

Figure 9 shows the effect of power module production rate on BBEC. Note that modest production rates (~1000/year) result in energy costs low enough to be attractive at the present time for certain special applications, e.g., islands, military facilities and remote sites.

Figure 10 shows the sensitivity of $\overline{BBEC}$ to plant size. For plant rated power on the order of 1/2 MW_e and above, the maximum variation in $\overline{BBEC}$ is only about 10 mills/kWh (~15%). Below 1/2 MW_e there is a substantial increase in energy cost - due primarily to the influence of the fixed cost elements.

CONCLUSION

The Dish-Rankine PFDR concept projects excellent performance; an ACF of 0.418 without storage reflects the very good part-load performance of the ORC engine. The concept also projects very good economic potential, given the benefit of mass-production and the use of optimized components. The SCSTPE program is a challenge, particularly with regard to schedule, but will offer many benefits toward development of the ultimate, operational PFDR small community power system.

REFERENCES

1. Osborn, D. B., "Generalized Shading Analysis for Parabolic Concentrator Fields," ASME Paper 80-RET-33, 1980 Energy Source Technology Conference, New Orleans, 3-7 February 1980.

*An FACC concentrator design was employed since it is the only design for which suitable parametric performance/cost data are currently available.

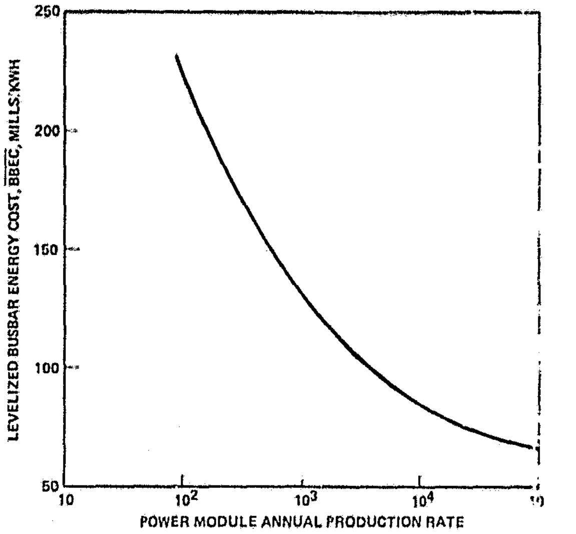

FIGURE. 9. EFFECT OF POWER MODULE ANNUAL PRODUCTION RATE ON (MIN) ENERGY COST

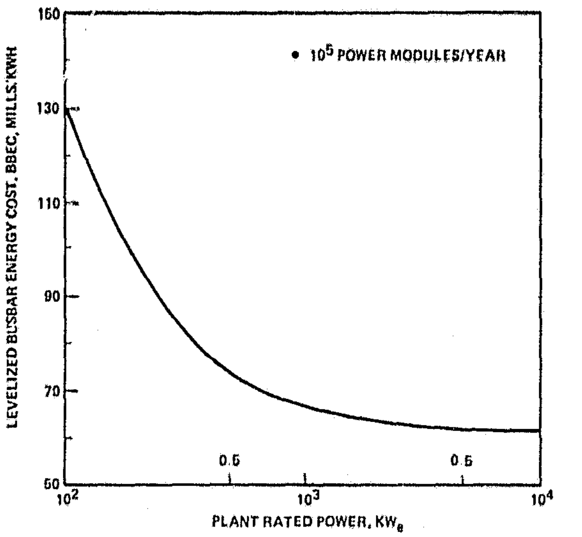

FIGURE. 10. EFFECT OF PLANT SIZE ON SYSTEM ENERGY COST

2. Doane, J. W., et al, "The Cost of Energy from Utility-Owned Solar Thermal Electric Systems" JPL Report 5040-79 ERDA/JEL 1012-76/3, June 1976.