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THE ADVANCED DISH DEVELOPMENT SYSTEM PROJECT

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ABSTRACT

The objective of the Advanced Dish Development System (ADDS) project is to develop and validate a 9-kWe dish/Stirling solar power system that meets the needs of the remote power marketplace. Key market criteria for concentrating solar power entry into remote power applications such as water pumping and village electrification are reliable unattended operation, minimal and low technology service requirements, and the ability to compete with the cost of alternatives. The Advanced Dish Development System is a test bed for advanced components and systems level testing to address the issues of the remote power market. The ADDS project involves integration and test, at a system level, of advanced dish/Stirling systems. The basic design utilizes the WGAssociates solar concentrator and controls, and the SOLO 161 Stirling Power Conversion Unit. Development has focused on extending the application of dish/Stirling systems to water pumping, reliability improvement and incorporating advanced components such as structural facets, heat pipe receivers, and advanced controls and communications. Testing includes long-term unattended, automatic operation of stand-alone 9-kW_e dish/Stirling solar power generation systems in both on and off-grid modes at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, NM and in the field. In 1999, a first generation (Mod 1) system was fielded at the NSTTF and routine unattended operation initiated. In 2000, a system reliability tracking system was implemented on the Mod 1 system and an upgraded, second-generation (Mod 2) system, including a stand-alone water-pumping capability was developed. To better understand the market and system requirements, field-testing will be conducted at one or more American Indian applications partners test sites in the Southwest U.S. Partnering agreements have been initiated with four tribes and familiarization training completed. In this paper, the ADDS project plan and technical approach are presented. The major system components and features along with test results and project status are also described.

INTRODUCTION

The objective of the Concentrating Solar Power (CSP) program is to develop and validate concentrating solar power technologies that meet the needs of the marketplace. To address the distributed power market, the CSP program is supporting the development of dish/engine systems. A dish/engine system utilizes a tracking paraboloidal concentrator to focus sunlight at a power conversion unit (PCU). The PCU utilizes a heat engine and generator to convert the high-temperature solar heat to electricity. The CSP program has supported a number of industry-led activities aimed at the development of dish-engine systems. (Bean and Diver, 1992, and Gallup and Mancini, 1994) Currently, these activities include cost-shared contracts to develop distributed dish/Stirling systems for utility markets with Boeing/Stirling Energy Systems (Stone, et al.1999) and Science Applications International Corp./Stirling Thermal Motors. (Beninga, et al., 1997) The CSP program also supports receiver and concentrator development activities. (Adkins, et al., 1999)

The Advanced Dish Development System (ADDS) project is a system level development activity aimed at the challenging but extensive remote power market. Studies by industry indicate a vast market for solar-driven remote power systems. In these applications, such as water pumping and village electrification, diesel-engine generators are the established power-generation competition. Key market criteria for entry into remote power applications are reliable unattended operation, minimal and low technology service requirements, and cost relative to the alternatives.

Fig. 1. Photograph of the Mod 1 Advanced Dish Development system at the National Solar Thermal Test Facility in Albuquerque, NM.

The near-term objective of the ADDS project is to field a fully integrated, stand-alone dish/Stirling solar power generation system at a remote, off-grid Native American site in the Southwestern U.S. The Native American remote power application environment provides an ideal test bed for the much larger world markets. In the process of meeting this objective, the ADDS provides a real world test bed for advanced components and systems integration. If successful, the ADDS project has the potential of demonstrating commercially viable proof-of-design hardware that meets the needs of the marketplace while advancing the state-of-the-art of dish/Stirling technology.

PROJECT PLAN

The ADDS project involves the design, fabrication, integration, testing, and refinement of advanced dish systems in automatic, unattended operation both on-grid and off-grid under representative loads. The project builds upon the technology Cummins developed in the Dish/Stirling and Utility-Scale Joint Venture Programs (DSJVP & USJVP) and further developed in the SERDP "Dish/Stirling for DoD Applications" project. (Diver, Moss, et al., 1999) The WGAssociates (WGA) designed concentrator is a scaled-down version of the design used by Cummins in the USJVP. It features a thin-walled tubular space frame with paraboloidal gore shaped facets. The concentrator control system (CCS) was originally developed for remote power applications in the DSJVP. It includes remote monitoring and control capabilities, integral data acquisition, and extensive fault monitoring and response features. The engine is the proven SOLO 161 Stirling PCU, an alpha configuration kinematic Stirling engine, which is being developed for cogeneration applications in Germany. (Baumüller and Schiel, 1997)

In addition to testing at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, NM, the project includes realistic field-testing at one or more American Indian Applications Partners (AP) test sites in the Southwestern U.S -- a realistic test bed for the world markets. By addressing real world applications, we hope to better understand the market and system requirements.

The ADDS project is being conducted in three phases. In phase 1, a first generation (Mod 1) system was designed, fabricated, installed, and testing initiated at the NSTTF. Phase 1 began in October 1998 and by August 1999 system shake down testing was initiated. In phase 2, unattended operation of the system was started in November 1999 and the system was redesigned to incorporate lessons learned from the Mod 1 design and to operate off-grid (Mod 2). Also in phase 2, we established working relationships with Native American Application Partners (AP) and conducted 2-½ day familiarization training sessions on the Mod 1 system at the NSTTF. In phase 3, we intend to field a Mod 2 system on an AP site and continue to improve the reliability and performance of the Mod 1 and Mod 2 systems. We plan to install a Mod 2 ADDS at an AP site during the summer of 2001 and by 2002 to transfer O&M responsibility to the AP, while we continue to monitor system performance and provide follow-on support.

TECHNOLOGY

The Mod 1 ADDS is shown in fig. 1. The system design features the WGA-500 solar concentrator and controls, and the SOLO 161 Stirling cycle power conversion unit (PCU). In order to address remote power markets, the ability to operate autonomously, robust and reliable operation, low capital and installation costs, and maintainability are key system design objectives.

1. Concentrator

The concentrator uses an elevation-over-azimuth tracking space frame dish structure fitted with paraboloidal contour, trapezoidal shaped, glass-metal mirror facets. The concentrator structure comprises two major subassemblies - the tracking structure and the pedestal assembly. Characteristics of the major Mod 1 and Mod 2 concentrator components and key operational and survival specifications are given in table 1. The tracking structure is made up of the dish, including the tracking space frame and mirrors, the PCU support structure, and the transition. The transition provides an interface between the tracking space frame and the PCU support structure. The pedestal assembly includes the pedestal, the drive system, and a yoke, which is affixed to the top of the azimuth drive. The tracking

Table 1. System Characteristics and Specifications

Characteristics/Specifications	Mod 1	Mod 2
Power Output	9 kWe @ 1000 W/m^2 Positive output at 350 W/m^2	9 kWe @ 1000 W/m^2 Positive output at 350 W/m^2
Mirror Projected Area	46.4 m^2 (500 ft^2)	44.7 m^2 (482 ft^2)
Overall Diameter	8.8 m (29 ft)	8.8 m (29 ft)
Elevation Tracking Range	-20 to 84 degrees	-25 to 96 degrees
Elevation & Azimuth Drive Speed	38 degrees/min	38 degrees/min
Focal Length	5.448 m (214.5 in)	5.448 m (214.5 in)
Mirrors and Mounting Hardware	758 kg (1,670 lbs)	502 kg (1,105 lbs)
Tracking Structure Weight	1,275 kg (2,806 lbs)	1,196 kg (2,631 lbs)
Pedestal & Azimuth Drive Assembly	831 kg (1,830 lbs)	783 kg (1,723 lbs)
SOLO 161 Weight	455 kg (1,000 lbs) *	455 kg (1,000 lbs) *
Weight on Foundation	3,320 kg (7,306 lbs) (14.6 lbs/ft^2 aperture)	2,936 kg (6,459 lbs) (12.9 lb/ft^2 aperture)
Operating Wind	Up to 35 mph	Up to 35 mph
Operating Temperature Range	-29°C to 50°C (-20°F to +120°F)	-29°C to 50°C (-20°F to +120°F)
Operating Humidity	100%	100%
Survival Wind any Dish Attitude	Up to 50 mph	Up to 50 mph
Survival Wind at Stow Position	Up to 90 mph	Up to 90 mph
Survival Humidity	100%	100%
Desert Southwest Conditions	Blowing Sand and Dust	Blowing Sand and Dust

* Includes PCU and mounting facilities

structure and the pedestal assembly are connected by the elevation axis axle and drive assembly.

The tracking structure is constructed primarily of structurally efficient thin-wall tubing. Where practicality dictates, such as in the PCU support, square tubing is used. In both the Mod 1 and the Mod 2 designs the structure is fully triangulated for maximum rigidity. In the Mod 1 design the members at each joint intersect at a common work point. This results in no bending moments at the joints and a structure with an exceptionally high stiffness-to-weight ratio. To reduce manufacturing cost in the Mod 2 design, stamped tube ends will be used, resulting in small offsets at some of the joints. These joints have been analyzed and determined to result in minimal deflections. The Mod 2 design will also address installation issues at a remote site. In particular, a Mod 2 objective will be to erect the system without the use of a crane.

The azimuth drive is the field proven, Winsmith, planocentric reducer. In the Mod 1 system, a drive from one of the Cummins CPG-460 concentrators was utilized. It has a gear ratio of about 33,000:1. At the twelve installations employing this drive, it performed reliably with no significant problems reported. To increase drive speed, a 3500-RPM, 1/2 HP, capacitor-start/run induction motor is used instead of the 1750 RPM motor used by Cummins. To allow for use of a 1750 RPM motor on the Mod 2 system, the gear ratio has been halved. The predicted peak loads on the drive are about 20% higher than on the CPG-460 due primarily to the increased dish aperture area. We have, therefore, decreased the allowable go-to-stow wind load, at any dish attitude, from 55 mph to 50 mph.

The elevation drive employs a 10-ton commercial ball screw jack. To facilitate maintenance of the PCU, it is configured to bring the SOLO 161 PCU below the horizon for access from ladders or from the back of a pick-up truck (fig. 2). It is powered by a 1750 RPM, 1/2 HP gear-motor through a secondary worm gear reducer. The overall reduction ratio is approximately 16,000:1, resulting in a dish slew speed of 38 deg./min. The higher slew speed, compared to the CPG-460, is necessary because of the use of a directly illuminated receiver in the SOLO 161. Compared to the heat pipe receivers used by Cummins, the Solo receiver has lower thermal inertia and needs to be taken off sun quicker in the event of an engine fault. The higher slew rate also facilitates system maintenance. Because the Mod 2 system will operate off grid, direct current (DC) drive motors will be used on the Mod 2 system. The drive speed will be comparable to the Mod 1 system and the elevation and azimuth drive motors will be interchangeable.

The mirror facets are glass/metal sandwich-construction structural facets. (Diver and Grossman, 1999) They utilize a sandwich construction consisting of thin-glass mirrors bonded to a sheet-metal membrane. An aluminum honeycomb is bonded with epoxy between the

Fig. 2. Photograph of the Mod 1 Advanced Dish Development System in service position. To facilitate maintenance on the SOLO 161 PCU, the Mod 1 concentrator dips 20 degrees below the horizon.

back of the sheet-metal membrane and a second sheet-metal membrane. The facets have survived exposure to temperatures of 60 C (150 F) and thermal cycling between 54 C and –29 C (130 F and –20 F) with high humidity. The Mod 1 system uses two concentric rows of mirrors, each row consisting of 16 panels. Steel sheet metal (0.6 mm, 24 gauge) membranes are used in the Mod 1 facets. The Mod 2 concentrator utilizes one row of 24 facets. To facilitate the curvature, 1-mm (0.040 inch) thick aluminum sheet metal is used instead of steel. Both designs utilize 1-mm thick, back-silvered, low-iron glass mirrors. Facet mounting to the structure is accomplished by the use of three-point mounting studs that facilitate alignment. Mirrors are aligned by the use of the distant light source technique. (Diver, 1992)

2. System Controls

The Collector Control System (CCS) utilized on the ADDS Mod 1 system is an adaptation of those employed by Cummins at Ft. Huachuca, AZ and other locations. The same basic control system was used to operate ten CPG-460 systems, and an extended version operated the CPG USJVP 25-kW prototype. Together these control systems have over 40,000 hours on-sun tracking and have demonstrated robust, reliable operation.

The CCS provides control and monitoring of the concentrator and the PCU and allows autonomous system operation. It's features and capabilities are summarized in table 2. The CCS has the intelligence needed for all aspects of normal operation, with a network data link for supervisory monitoring and control. Sun tracking uses a hybrid approach consisting of both open-loop and closed-loop tracking. Sun position algorithms based on date, time, and geographic location form the basis for open-loop tracking, and are derived from the U.S. Naval Observatory algorithms. (Maish, 1991) Open-loop tracking is used for the primary tracking mechanism, predicting the motion of the sun and moving the dish in anticipation of those movements. Closed-loop tracking compensates for structural deflection and other indeterminate positioning errors. Closed-loop tracking employs four thermocouples equally spaced around the receiver aperture. Precise closed-loop tracking is accomplished by balancing the temperatures of the four thermocouples. After a day of closed-loop tracking, algorithms automatically derive seven concentrator misalignment parameters - azimuth and elevation offsets (2); pedestal tilt (2); azimuth and elevation gear ratios (2); and orthogonality of the axes, an extension of the SunTrak approach. (Maish, 1991) After the misalignment parameters are "learned", open-loop tracking is close enough for closed-loop tracking to "capture" the focused image without further operator intervention.

Table 2. System Controls Features and Capabilities

• Unattended operation
• Automatic start-up, sun acquisition, tracking, and stowing of the dish
• Automatic detrack on faults
• Failsafe protection against computer failures and loss of grid power
• Automatic stowing during high wind conditions
• Built in remote monitoring, data acquisition, and supervisory control via dial-up modem or direct network connection
• Push, button, handheld terminal, or computer operator interface
• Program and operating data contained in non-volatile memory
• Automatic recovery from grid power failures or power disconnects
• Automatic sun acquisition: Closed-loop capture range of 4 to 6 milliradians allows for low-cost structures and structural alignment methods
• Hybrid tracking methodology: Program tracking corrected by active sun-tracking algorithm based on high-temperature thermocouples
• Automated self-alignment algorithms correct for all critical drive alignment and clock errors

The CCS uses an industrial grade, embedded, single board personal computer (PC) architecture computer and input/output (I/O) cards. The software is written in C++ and compiled into executable machine code. The CCS also contains integral data acquisition functions that enable data collection storage and retrieval of PCU and concentrator parameters. In the event of a computer failure, the system has a fail-safe board that continually queries the computer for a response. If the computer "locks up" or otherwise does not respond, the concentrator is driven in elevation to the vertical limit. The fail-safe also includes a 12 VDC battery and inverter in the event of loss of grid. For fault diagnostics, data acquisition includes a 2 Hz data rate circular file and automatic file archival after a fault is detected. The operator has three ways to interface with the CCS. For routine day-to-day operation, a push button control panel allows an operator to safely send the system on sun, or to any of the defined positions such as offset track, wash, service, or stow position by simply pushing a button. If additional diagnostics are needed, a hand-held terminal can be plugged into the control panel. For detailed diagnostics, including the ability to modify scaling and other engineering data, a computer interface is available. On the Mod 1 system this interface also allows remote monitoring and control though an Internet connection. On the Mod 2 system, we are exploring wireless communications for supervisory control and data acquisition.

The CCS interfaces with the SOLO 161 controls through five 0 to 10 V analog lines and one digital line. The digital line is a relay closure that indicates an engine ready condition. The analog outputs indicate the receiver operating temperature (the highest of the 20 separate receiver temperatures), engine speed, engine pressure, bottle pressure, and engine error code. Along with a detailed description of trouble shooting procedures, the engine error code is invaluable for fault diagnostics. Through a non-disclosure agreement with Schlaich, Bergermann und Partner, license holder of the V-160 technology rights, Sandia National Laboratories (SNL) has obtained copies and is modifying the assembly language source code for the Siemens 80537 microprocessor. For the Mod 1 system we have implemented code changes to resolve over-temperature and over-pressure faults and to simplify helium-filling procedures. For the Mod 2 system, we will modify the controls to communicate with the CCS through RS-232 serial data communications, and to control the engine starter and other auxiliaries.

3. Power Conversion Unit

The ADDS uses a SOLO 161 Power Conversion Unit (PCU). This engine is among the most developed Stirling-cycle engines available and has a proven history of reliable performance. The older model V-160 engines have demonstrated as much as 13000 hours without problems and over 30,000 total on-sun hours on three DISTAL I systems at the Platforma Solar de Almeria (PSA) in Spain. Three DISTAL II systems utilizing the SOLO 161 are currently operating at the PSA. The SOLO 161 engine is being developed primarily for cogeneration applications in Germany and is currently undergoing field-testing. The SOLO 161 utilizes a direct illumination solar receiver and pressure control of the helium working fluid to vary power output. Small helium leaks are automatically made up through an external bottle located on the concentrator tracking structure. The engine is rated at 10 kW_e at 1500 RPM and has a thermal to electric conversion efficiency of 30%. (Baumüller and Schiel, 1997)

The Mod 1 SOLO 161 PCU uses a 3-phase induction motor/generator to supply 3-phase, 480-Volt power to the utility grid. This approach provides power for starting the engine and automatically synchronizes voltage and frequency with the utility grid. In the Mod 2 stand-alone system, a synchronous generator is utilized. Output varies both in voltage and frequency and is used to directly drive an induction motor. Because water pumping is a common need of the Application Partners, the Mod 2 design will drive a conventional 3-phase 480-Volt, 7.5 or 10 HP, submersible water pump. A standard 12-VDC automotive starter is used to start the Mod 2 version of the PCU.

TEST RESULTS

Testing of the ADDS has evolved from concentrator testing early in the project to ongoing system operational, reliability, and performance testing.

1. Concentrator Testing

Following optical characterization of the individual facets with the SunLab Video Scanning Hartmann Optical Test (VSHOT) at the National Renewable Energy Laboratory (NREL), testing of the ADDS concentrator was initiated in July 1999 with Beam Characterization System (BCS) and cold-water calorimetry. The BCS uses a video camera to map flux distributions on a water-cooled target in the focal plane. The BCS and calorimeter results are summarized in fig. 3, which shows the amount of power intercepted by a circular aperture at the focal plane as a function of aperture diameter. The calorimeter results were normalized to a direct normal insolation of 1000 W/m^2. The two BCS curves were normalized to the cold-water calorimeter measurement of 43 kW_t at 18-cm diameter. Results exceeded our objective of 41 kW_t through an 18-cm diameter aperture but were consistent with the exceptional facet optical accuracy measured with the VSHOT. Facet slope errors were in the range of 0.8 to 1.4 milliradians root-mean-square (RMS) and had consistent focal lengths. Based on the results summarized in fig. 3, we are

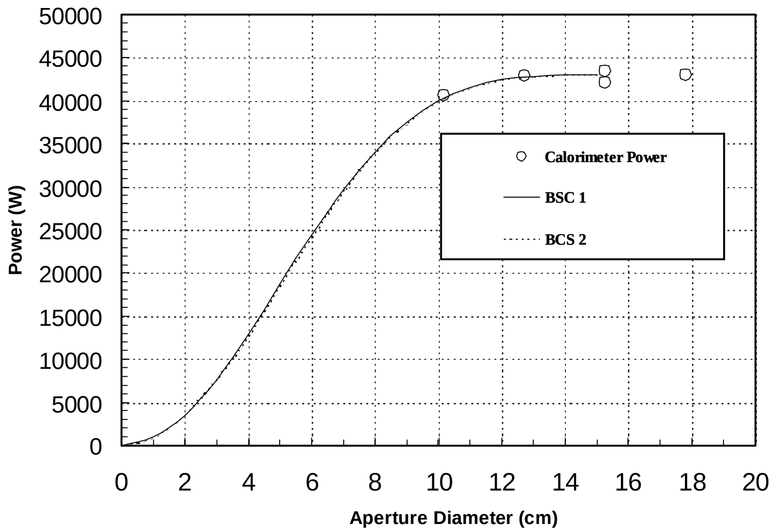

Fig. 3. Intercept curve for the Mod 1 solar concentrator. The plot shows the power intercepted as a function of aperture diameter as measured by the SunLab Beam Characterization System (BCS) and cold-water calorimetry.

utilizing a 14-cm (5.5-inch) diameter aperture. Measured peak concentration ratios in the focal plane are approximately 11,000 suns. Incident peak flux intensities in the receiver plane are 100-110 W/cm^2. Environmental and load testing of the structural facets demonstrated that they are capable of withstanding the operational and survival specifications listed in table 1.

2. Operational and Reliability Testing

System shake down testing was started in August 1999 and involved attended system operation at reduced power levels. Automated system operation was initiated in November 1999 and in early January 2000 we started system reliability testing. As of October 24, 2000 the Mod 1 system had accumulated 2025 on-sun, power-producing hours. Since initiating reliability testing on January 6, 2000, the system has accumulated 1711 on-sun hours and has produced 7.68 MWh (net) of electricity. During this period, insolation was within the system operational specifications 2369 hours, yielding a gross availability of 72.2% (1711/2369). This availability does not account for periods in which wind exceeded operational limits, and down time for tours, AP training, and development.

The Mod 1 system operates automatically and unattended, including weekends and holidays. To determine if conditions are within operational specifications, the system includes an anemometer and a sun sensor. On the Mod 1 system, we have been using the NSTTF site direct normal insolation pyrheliometer. For the Mod 2 system, a low-cost non-tracking, direct normal insolation (DNI) sensor is being developed. After the system detects that DNI is within specifications, it tracks to acquire the sun, starts the PCU, and supplies power to the grid. If the anemometer detects high winds, the system automatically drives to stow where it remains until wind speed returns to a safe level for a specified period of time. When clouds are detected (low DNI), the system drives off sun and continues to offset track. When DNI returns to specified levels the system reacquires the sun and starts the PCU. If the sun does not return within a specified time or if the sun elevation falls below a defined angle, typically 2 degrees, the concentrator stows. If a fault is detected, the system automatically sends the system to stow and notifies the operator though a pager. In many cases, the operator is able to resolve the problem and resume operation remotely.

Routine maintenance involves downloading data, checking the emergency fail-safe system, and checking helium pressure and is currently being conducted weekly on the Mod 1 system. The concentrator drives also require lubrication every six months. Under normal conditions, we have found that the make up helium bottle should last at least a year before needing to be replaced. In the Mod 2 design, we expect to reduce routine maintenance to monthly, mainly for downloading data, and to extend the period between lubrication to one year.

We have been recording incidents in the SunLab Reliability Data System. Most of the incidents thus far have been associated with engine and concentrator controls and have been mostly software related. Engine issues have

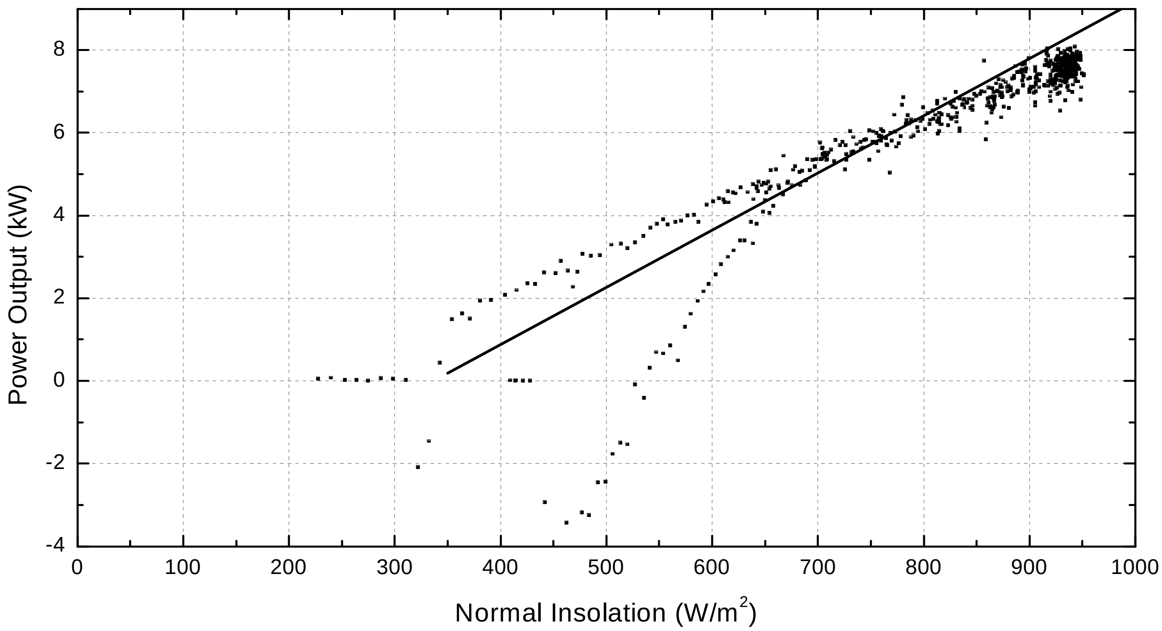

Fig.4. Gross system output of the Mod 1 Advanced Dish Development System on October 20, 2000. The solid line is the specified gross output. Except for the startup, these results are representative of system performance to date. Frost on the mirrors took about ½ hour to melt away and for the system to achieve nominal performance. The system normally produces net positive power within two minutes of going on sun.

primarily been manifested as helium leaks. However, the root cause of the leaks have generally been found to result from improper procedures or from incidents caused by control issues or other faults. For the most part, we have been able to diagnose and resolve the root cause of all of incidents. Repairs to the PCU have been straightforward and similar in technical complexity to standard automotive machinery. We have rebuilt the engine while on the concentrator, including replacement of pistons, cylinders, and solar receiver, in less than ½ day. In addition, as part of the AP familiarization training, Indian personnel completed an engine rebuild in the test cell, including filling the engine with helium, in less than 3 hours. Engine induced vibration remains as a key reliability issue for the ADDS. Its impact on high-temperature insulation materials and the receiver insulation housing are particularly insidious. To address this issue, we are developing new insulation housing designs and are developing and testing a dynamic balancer to reduce vibrations at the source.

3. Performance Testing

System performance has varied, primarily dependent on the receiver cavity design, the amount of soiling on the mirrors, and on the condition of the engine. Figure 4 is a scatter plot showing gross system power as a function of direct normal solar insolation taken at one-minute intervals on October 20, 2000. Except for the startup, the points below the line at the lower insolation levels, it is representative of current system performance. Accounting for parasitic power, which averages about 180 W and includes the engine controls, cooling system water pump and concentrator controls and drives, the system is close to meeting its specified output, the solid line. On this day, the concentrator mirrors were covered with frost at startup and, therefore, required more time than usual for starting the engine. To improve overall system performance and reduce unnecessary stress on the PCU caused by frost, we are developing control algorithms to detect frost conditions and allow the concentrator to offset track until the frost has melted. Similar algorithms are being developed to more intelligently deal with clouds.

We plan to explore the use of hydrogen as an engine working fluid to further improve system output and/or enable a reduction in concentrator area. We are also designing a heat-pipe solar receiver for the SOLO 161. The heat-pipe receiver is expected to improve system performance and reduce the effects of vibration on insulation materials. In addition, the heat-pipe receiver may be a key element of the Mod 2 system. Because of the additional thermal mass from the heat pipe and the ability to start the PCU at higher temperatures, starter motor and battery requirements should also be vastly reduced.

SUMMARY

The Advanced Dish Development System (ADDS) is targeted towards the large but challenging remote power market. The ADDS incorporates some of the best concentrator, controls and Stirling engine technology and has made remarkable progress towards demonstrating performance and reliability, and the ability to operate autonomously in a remote environment. Two system designs, Mod 1 and Mod 2, have been developed for grid-connected and remote water-pumping applications, respectively. The Mod 1 design has performed close to its specifications, has demonstrated autonomous operation, and has been an excellent test bed for reliability and performance improvements. The system is maintainable and has demonstrated minimal and low technology service requirements. The Mod 2 design has been developed to address cost and other issues identified in the Mod 1 system and to address remote, water-pumping applications. Although cost has not been a top priority thus far, the design appears to have the potential to be cost competitive relative to the alternatives. Involvement of American Indian Application Partners has been instructive and has helped us to better understand system requirements and is expected to be an ideal way to test, improve, and ultimately prove the design for the remote power market.

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