Solar-Electric Dish Stirling System Development*

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Summary

Electrical power generated with the heat from the sun, called solar thermal power, is produced with three types of concentrating solar systems – trough or line-focus systems; power towers in which a centrally-located thermal receiver is illuminated with a large field of sun-tracking heliostats; and dish/engine systems. A special case of the third type of system, a dish/Stirling system, is the subject of this paper.

A dish/Stirling system comprises a parabolic dish concentrator, a thermal receiver, and a Stirling engine/generator located at the focus of the dish. Several different dish/Stirling systems have been built and operated during the past 15 years. One system claims the *world record* for net conversion of solar energy to electric power of 29.4%; and two different company's systems have accumulated thousands of hours of on-sun operation.

Due to de-regulation and intense competition in global energy markets as well as the immaturity of the technology, dish/Stirling systems have not yet found their way into the marketplace. This situation is changing as solar technologies become more mature and manufacturers identify high-value niche markets for their products.

In this paper, I review the history of dish/Stirling system development with an emphasis on technical and other issues that directly impact the Stirling engine. I also try to provide some insight to the opportunities and barriers confronting the application of dish/Stirling in power generation markets.

Introduction

Dish/Stirling systems utilize a parabolic dish solar concentrator tracking the sun and focusing solar energy into a cavity receiver where it is absorbed and transferred to the Stirling engine/generator. Although Brayton and organic-Rankine cycle engines have been used with dishes, Stirling engines (kinematic and free-piston) have been used for most of the pre-commercial systems under development to date. Stirling engines are preferred for these systems because of their high efficiencies (thermal-to-mechanical efficiencies in excess of 40% have been reported), high power densities (50 kW/liter for solar engines), and their potential for long-term, low-maintenance operation. Dish/Stirling systems are modular, i.e., each system is a self-contained power generator; this is an advantage because they can be assembled into plants ranging in size from a few kilowatts to tens of megawatts. The near-term markets identified by the developers of these systems include remote ower, water pumping, grid-connected power in developing countries, and distributed or end-of-line power conditioning in the United States.

* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

DISCLAIMER

Dish Stirling Systems Development

Over the last fifteen years, a number of different dish/Stirling systems ranging in size from 5 to 50 kW_e have been built in the United States, Germany, Japan, and Russia [Stine, 1993 and 1994]. I will now review the seven most-developed systems whose general characteristics are listed in Table 1 on the following page.

Advanco's Vanguard System

The 25 kW_e Vanguard system, built by ADVANCO in Southern California (1982 - 1985) is shown in Figure 1. The Vanguard dish/Stirling system used a glass-faceted dish 10.5 meters in diameter, a direct insolation receiver (DIR), and a United Stirling 4-95 Mark II kinematic Stirling engine.

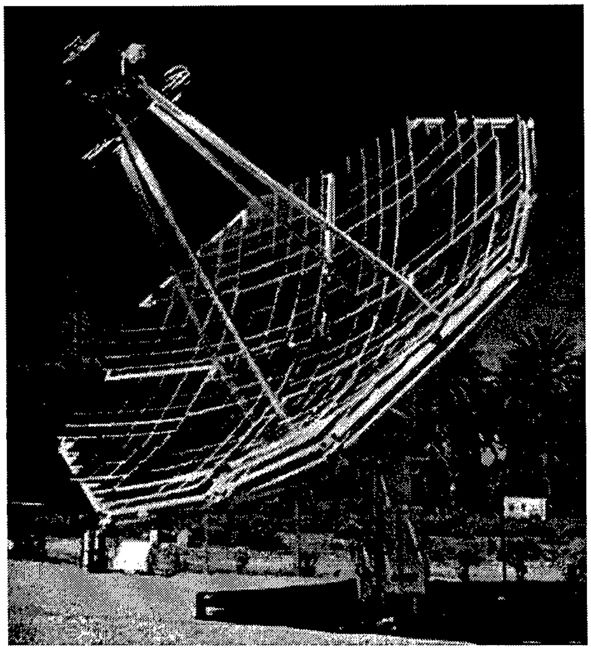

Figure 1. The Vanguard System

During the 18-month operation of the system, two engine overhauls were required for two different reasons. The first overhaul was required due to the failure of a check valve, and the second overhaul was because of a failed oil pump shaft. Other problems, such as excessive noise, vibration, and repeated failure of circuit boards, seem to have been the result of using non-hardened gears. Also, there were substantial hydrogen leaks in the system necessitating the replacement of approximately 0.1 m^3 per hour of system operation. In spite of these problems, the system achieved a reported *World's Record* net solar-to-electric conversion efficiency of 29.4% [EPRI, 1986] and operated for almost 2000 hours during the 18-month test phase.

Schlaich-Bergermann und Partner 50 kW System

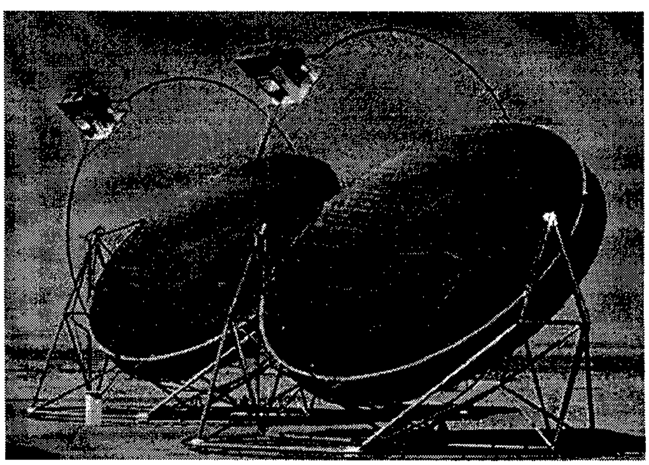

Figure 2. SBP 17-meter D/S Systems

Two 50 kW_e dish/Stirling systems were built, installed, and operated in Riyadh, Saudi Arabia, in 1984 by Schlaich-Bergermann und Partner (SBP) of Stuttgart, Germany [Koshaim, 1986]. The dishes were 17-meter diameter, stretched-membrane concentrators, formed by drawing a vacuum in the plenum space formed by the dish rim and front and back, 0.5-mm-thick stainless steel membranes. The optical surface of the dish was made by bonding glass tiles to the front membrane. The receivers for the SBP dishes were DIRs and the engines were United Stirling 4-275 kinematic Stirling engines.

Table 1. Characteristics of Dish Stirling Systems

Company	Concent Type	Optical Surface	Dish Area (m^2)	Rec Type	Total Hours/ (Nos. of systems)	Engine Company	Engine Type	Rated System Output (kW_e)	Steady, system Output (kW_e)	Steady, system Effic (%)
Advanco Vanguard System	Faceted Glass-Metal	Glass	86.7	DIR	1996 (1)	United Stirling	Double-Acting 4-cyl, KSE	25	~ 20 - 22	23
Schlairch Bergermann und Partner	Stretched Membrane	Glass	227	DIR	NA (2)	United Stirling	Double-Acting 4-cyl, KSE	50	NA	NA
McDonnell-Douglas SES System	Faceted Glass-Metal	Glass	91	DIR	13,852 (7)	United Stirling	Double-Acting 4-cyl, KSE	25	20 - 22	23
Schlaich Bergermann und Partner	Stretched Membrane Parabolic	thin glass	44	DIR	> 27,000 (6)	SOLO Kleinmotoren	2 cylinder KSE	10	~9.0	~ 18.0
Cummins Power Generation	Faceted Stretched-Membrane	aluminum polymer	44	Heat Pipe	> 1000 (4)	Clever Fellows	2 cylinder FPSE	7	5.2	15
Cummins Power Generation	parabolic gore	thin glass	145	Heat Pipe	~ 25 (1)	Aisen Seiki	4 cylinder KSE	25	~ 20	NA
Science Applications Int. Corp.	Faceted Stretched-Membrane	thin glass	107	DIR^+	400 (1)	Stirling Thermal Motors	4 cylinder KSE	20	18.5	22.4

McDonnell-Douglas/Stirling Energy Systems

A third dish/Stirling system was built by McDonnell Douglas Aerospace Corporation (MDAC) in the mid 1980s. In 1986 MDAC discontinued development of the technology because of the status of energy markets and the Company's corporate decision to focus on core competencies. The rights to the system were sold to the Southern California Edison Company (SCE) [Lopez, 1992 and 1993] and, more recently, sold again to Stirling Energy Systems of Phoenix, AZ, USA. SES is upgrading and developing the system for commercial sales.

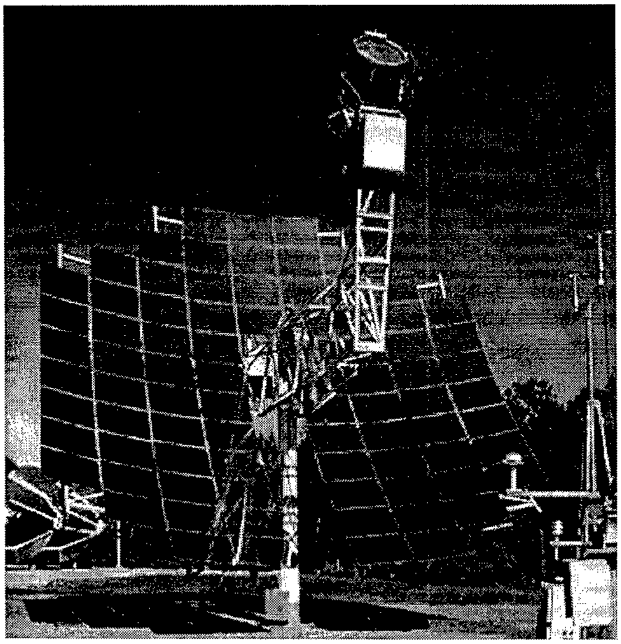

Figure 3. The MDA/SES D/S System

The MDAC/SES dish, shown in Figure 3, is the first dish/Stirling system designed to be a commercial product. The dish is nominally an 11-meter diameter, faceted, glass-metal design with 88 facets. The receiver is a DIR and the engine is the same United Stirling 4-95 Mark II engine that used by Advanco on the Vanguard system.

SCE operated the system from 1985 to 1988 and reported: 13,852 hours of operation of a single system (more than 19.4 operational years were accumulated on seven different systems); 86.5% system availability during the last two months of operation; net power production when the direct-normal insolation exceeded 300 W/m^2; production of 28 kW-net electric power at a solar irradiance of 850 W/m^2; and total production in excess of 720 kWhr of net electrical power per day on a good solar day. Based on their experimental measurements of the dish/Stirling unit, Lopez and Stone developed a predictive model of the system. Their results indicated that a single system operating at Barstow, CA, would produce 50,122 kWhr per year at annual efficiency of 22% (an annual availability of 90% was used in their analysis).

SB und Partner 10-kW System

Schlaich Bergermann und Partner of Stuttgart Germany has developed the 10-kW$_e$ dish/Stirling system, shown in Figure 4, that is nearing commercialization [Schiel, 1994, 1996]. There are now two generations (six systems in all) under test at the Plataforma Solar in Almeria, Spain, the second-generation is a pre-commercial system. This dish/Stirling system comprises a 8.5-meter diameter, stretched-membrane concentrator, a

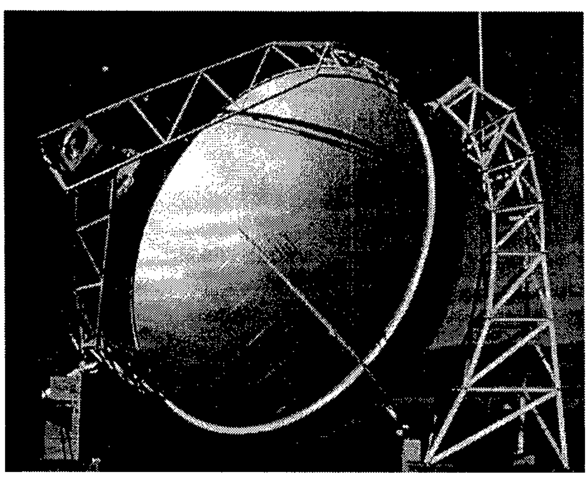

Figure 4. SBP Dish Stirling System

direct-insolation receiver, and a V-161 kinematic Stirling engine, designed by United Stirling of Sweden and now manufactured by SOLO Kleinmotoren GmbH of Stindelfingen, Germany.

The SOLO Stirling engine has a nameplate power rating of 10 kW_e at 1500 rpm and a maximum power rating of 15 kW_e at 3600 rpm. The engine is configured in the alpha arrangement with separate, single-acting compression and expansion pistons.

The first-generation systems have operated for more than 25,000 hours and continue to do so on a daily basis. The three pre-commercial systems started operation in the Spring of 1997. This system is the most tested and nearest to commercialization of the dish/Stirling systems discussed in this report.

Cummins Power Generation 7 and 25 kW_e Systems

During the period from 1991 through 1996, Cummins Power Generation (CPG) was developing two dish/Stirling systems as part of cost-shared projects with the U. S. Department of Energy. In June of 1996, the Cummins Engine Company determined to refocus their development efforts in areas of their core business – diesel engines. They closed CPG and sold the assets to Kombassan of Alanya, Turkey.

CPG 7 kW_e System

CPG's 7-kW_e system, the more developed of the two dish/Stirling systems, is shown in Figure 5. This system comprised a solar concentrator, a heat-pipe thermal receiver, and a free-piston Stirling engine. The solar concentrator utilizes a geodesic space frame, a polar-axis drive, and 24 five-foot-diameter, stretched-membrane, polymer mirror facets. The heat-pipe thermal receiver transfers the absorbed solar heat to the engine by evaporating sodium and condensing it on the tubes of the engine heater head.

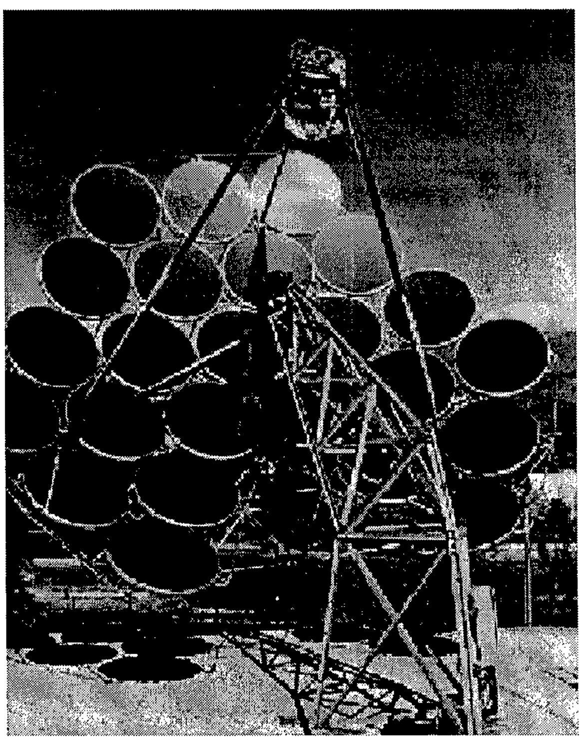

Figure 5. The CPG 7 kW_e D/S System

The baseline engine for the 7-kW_e system was the Clever Fellow's Innovative Consortium (CFIC) free-piston engine [Bean, 1993 and 1995]. The CFIC engine is a twin-opposed configuration that offers the potential of simplicity of design, manufacture, and maintenance. The development of the CFIC engine did not progress as quickly as CPG had anticipated and, as of August 1995, the engine had demonstrated a maximum output of only 5.2 kW_e at an efficiency of 22%. CPG continued to have problems with the engine up to the time that they divested of the technology.

Cummins Power Generation 25 kW System

Through a second DOE cost-shared program, CPG was developing a 25 kW_e dish/Stirling system for grid-connected applications. The 25-kW project started in 1994 and used a new, high performance, solar concentrator design, with a continuous glass surface comprising a number of pie-shaped gores. The dish was designed to provide about 120 kW of thermal power to the receiver. The engine selected for this system was the Aisen Seiki, Japan, kinematic Stirling engine.

The Aisen-Seiki engine is a double-acting, in-line 4-cylinder Stirling engine nominally rated at about 23 kW_e. It operated with helium as the working fluid using variable pressure to control the power output. One of the potential advantages to this engine was that it is based on an automotive engine and, therefore, many of the parts are in mass production.

The CPG 25-kW system operated for a short first time in the Spring of 1996 using a heat-pipe receiver and produced 22 kW_e net power during on-sun operation.

Science Applications International Corporation 25 kW System

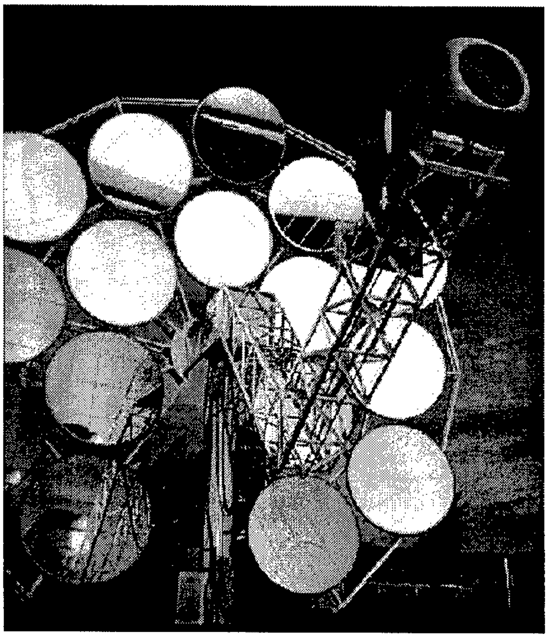

Figure 6. SAIC/STM D/S System

The design/engineering team of Science Applications International Corporation (SAIC) and Stirling Thermal Motors (STM) is currently working on a second-generation dish/Stirling system that utilizes a faceted, stretched-membrane dish, a direct illumination receiver, and Stirling Thermal Motors' kinematic Stirling engine [Beninga, 1995, 1997]. This project, which like the CPG projects is also a U. S. DOE cost-shared program, started in 1993. The first-generation system, shown in Figure 6, produced 21.6 kW_e net at a 24% conversion efficiency and 1000 W/m^2 solar conditions.

The engine for SAIC's dish/Stirling system is the STM 4-120 kinematic Stirling engine, developed by Stirling Thermal Motors, of Ann Arbor, MI. The STM 4-120 Stirling engine is a four cylinder, variable-stroke, kinematic Stirling engine that uses hydrogen as the working fluid. The variable stroke is achieved through the use of a variable-angle swashplate. The SAIC/STM team plans to install five second-generation dish/Stirling systems at various test sites starting in December 1997.

The Future of Dish Stirling Systems

The systems described above have successfully demonstrated the technical viability of dish/Stirling technology for generating electrical power. Commercial development activities target the technical challenges of developing long-life systems capable of producing competitively-priced electrical power.

The potential markets for these systems include: bulk power generation in the U. S. domestic and international arenas; remote power applications; village electrification; and distributed power generation. The systems must exploit their advantages: they are small and modular, and they can be hybridized by adding a fuel burner to the receiver. There are a number of opportunities and barriers to the introduction of these systems into the potential markets. I've listed some of these below.

Opportunities

- *An emerging "green power" market directed at utilizing clean electrical power*
- *Legislated solar mandates/programs in several southwestern states in the U. S. i.e., Arizona, California, New Mexico*
- *Global warming focusing attention on CO_2 emissions and the resulting international pressures for utilization non-fossil fuel approaches for power generation*
- *The Global Environmental Facility support in developing countries for using renewable technologies to generate electrical power*
- *Global warming and the potential for carbon "credits" or permits*

Barriers

- *De-regulation of power markets creating a demand for lowest-cost power*
- *The abundance of inexpensive, fossil fuels for the generation of electrical power*
- *Lack of long-term performance information on dish Stirling systems*
- *High cost of dish Stirling systems and their dependence on other markets to establish the mass production targets required to reduce those costs*

The near-term application of dish Stirling technology will be limited to relatively small-scale demonstrations in niche-type applications. With the uncertainty of the de-regulated electric power markets, it is not likely that dish Stirling systems will penetrate the bulk power markets in significant numbers during the next ten years. Near-term markets will most likely be international with a focus on remote power generation, small-to-modest sized gird-connected power, and take advantage of some of the opportunities presented by the World Bank's Global Environmental Facility.

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M98001305

Report Number (14) SAND--97-2924C
CONF-980211--

Publ. Date (11) 199711
Sponsor Code (18) DOE/EE, XF
UC Category (19) UC-900, DOE/ER

DOE