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Dish/Stirling Systems: Overview of an Emerging Commercial Solar Thermal Electric Technology

To be presented at 1995 Annual Meeting of the Mexican Solar Energy Association with the title "SISTEMAS DE PLATO PARABOLICO/STIRLING: PANORAMA DE UNA TECNOLOGIA COMERCIAL TERMOSOLAR EMERGENTE PARA LA GENERACION DE ELECTRICIDAD"

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ABSTRACT

Dish/Stirling is a solar thermal electric technology which couples parabolic, point-focusing solar collectors and heat engines which employ the Stirling thermodynamic cycle. Since the late 1970s, the development of Dish/Stirling systems intended for commercial use has been in progress in Germany, Japan, and the United States. In the next several years it is expected that one or more commercial systems will enter the market place.

This paper provides a general overview of this emerging technology, including

- a description of the fundamental principles of operation of Dish/Stirling systems,
- a presentation of the major components of the systems (concentrator, receiver, engine/alternator, and controls),
- an overview of the actual systems under development around the world, with a discussion of some of the technical issues and challenges facing the Dish/Stirling developers.

A brief discussion is also presented of potential applications for small Dish/Stirling systems in northern Mexico.

INTRODUCTION

Existing and emerging solar thermal electric technologies are being positioned to provide a significant portion of the new electrical generation capacity that will be added around the world in the remainder of this decade and during the first decade of the twenty-first century. The opportunities are particularly favorable in regions of the developing world where there is an abundance of sunshine, where the demand for electricity is growing, and where a central power grid infrastructure is lacking. Moreover, the environmentally benign character of solar thermal electric power places the technology at advantage as concerns for pollution and carbon dioxide generation become an increasingly important criteria in the technology selection process. Technologies which harness sunlight into electricity are expected to play a significant role in the coming two decades and beyond (DLR et al., 1992 and U.S. DOE, 1993). Dish/Stirling technology

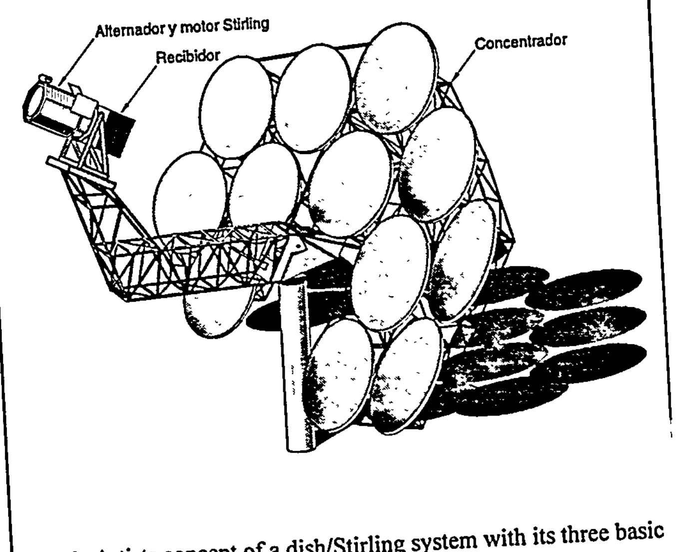

Fig. 1: Artists concept of a dish/Stirling system with its three basic components: concentrator, receiver, and heat engine/generator. (Concepto artístico de un sistema de plato parabólico con máquina Stirling y sus tres componentes básicos: concentrador, receptor, y máquina con generador)

is one of these and is emerging as an exciting and attractive generation alternative for both remote, grid-disconnected regions and for utility generation.

Solar thermal electric technologies can be classified into one of three design architectures:

Line-focus systems concentrate the sun's energy onto a tube or receiver positioned in the line of focus of a parabolic-shaped reflective trough.

A point-focus central receiver (power tower) system employs a large field of sun-tracking reflectors (heliostats) to concentrate sunlight on a receiver situated on top of a tower.

A point-focus dish system uses a parabolic dish to reflect light into a receiver at the dish's focus. The dish/Stirling system fits in this last category.

All three of these solar thermal electric technologies have proven themselves to be technically feasible options for electric power generation. Line-focus concentrators predominate in commercial solar power generation with over 350 MW of installed generating capacity in California. They are the more mature and market experienced of the three technologies. Point-focus concentrator systems, however, can achieve higher conversion efficiencies than can line-focus concentrators because they operate at higher temperatures. Research and development of point-focus central receiver (power tower) technology sponsored by the U.S. Department of Energy at Solar I and Solar II and ongoing work elsewhere promise the availability of commercially-ready power plants in the size range of 100 to 200 MWe in the later part of this decade.

While central receiver systems are projected to reach sizes of 100 to 200 MWe, dish/Stirling systems are smaller, typically about 5 to 25 kWe. At this size, one or few systems are ideal for stand-alone or other decentralized applications, such as replacement of diesel generators in remote rural areas. This technology has been in development since the late 1970's, and has demonstrated a net solar-to-electric conversion efficiency of 29.4%, the highest of any solar thermal electric technology (Stine and Diver, 1994). Dish/Stirling plants with outputs of 1 to 20 MWe are expected to meet moderate-scale grid-connected applications (Klaiss et al., 1991). Small clusters of dish/Stirling systems could be used in place of utility line extensions, and dish/Stirling systems grouped together could satisfy load-center/demand-side power options (<10 MWe). In addition, they can be designed to run on fossil fuels for operation when there is no sunshine. Dish/Stirling systems have been identified as a technology that has the potential of meeting cost and reliability requirements for wide-spread sales of solar electric power generating systems (Stine, 1987)

This paper provides a description of dish/Stirling technology and its components. It summarizes the current development efforts as well as the technical challenges which lie in the path toward commercialization.

SOLAR-POWERED DISH/STIRLING SYSTEMS

There are three principle components or sub-systems in a solar dish/Stirling electric power generation system: a concave parabolic solar concentrator (or dish), a cavity receiver, and a Stirling heat engine coupled with an electric generator or alternator. Fig. 1 provides an artist's illustration of a system. Their roles are described below:

Solar Concentrator: The concentrator's sun-tracking system rotates the solar parabolic concentrator or dish about two axes so to keep the dish's optical axis pointed directly at the sun. The parabolic shape of the dish's reflective surface makes it possible for the sunlight entering the face of the dish to be reflected and concentrated into the cavity receiver positioned in the dish's focal region.

Cavity Receiver: The cavity receiver captures the solar energy, absorbing and converting it from electromagnetic (radiant) energy into thermal energy which is used to heat the working fluid of the Stirling heat engine.

Stirling Engine/Alternator: The Stirling engine is a sealed system with a working gas that is typically hydrogen or helium. The working gas which is continually recycled within the engine is alternately heated and cooled. The gas is expanded when it is hot and compressed when it is cool. Power is generated because more power is produced by the gas' expansion when it is hot than is expended compressing the gas when it is cool. The expansion and compression within the engine produce a rising and falling pressure on the engine's piston, which is converted to mechanical motion and power and utilized in turn by the engine generator or alternator to produce electricity.

A more detailed discussion of these three sub-systems is given in the following sections.

DISH CONCENTRATORS

The size of collectors employed by today's dish/Stirling systems ranges from approximately 7.5 m (24.6 ft) for a system which will produce 7 kW_e under optimal sunshine conditions (1,000 W/m^2) up to 11 m (36 ft) for a 25-kW_e system.

Although a paraboloid is the ideal shape for a point-focus dish collector, it is easier to manufacture small circular facets with spherically-shaped reflective surfaces. With a spherical reflective surface it is possible to produce a focus that closely resembles the parabola provided that the distance from the mirror to the focal region is several multiples or more of the diameter of the mirror itself. Many of today's dish collectors employ a group of spherically shaped mirror facets with slight curvatures i.e. long focal lengths (see Fig. 1).

The reflective surfaces of current designs use aluminum or silver, deposited either on the front or the back surface of glass or plastic. Some solar collector mirror designs are evolving toward lighter weight, lower cost materials as reflected in the growing use of stretched-membranes. Multi-faceted dish collectors are using facets constructed from thin metal or polymer membranes to which a thin, metalized reflective polymer film or thin-glass mirrors have been applied. Membranes are stretched across the front and back of a metal rim or hoop, creating a closed interior space. A partial vacuum is applied to this facet's interior and draws the membrane inwards to produce a nearly spherical curvature. In order to obtain adequate optical performance, the vacuum is adjusted to produce a focal region several times longer that the facet diameter. Improvements continue to be made on thin reflective polymer films, but these materials have yet to achieve the durability that would make them a clear design choice.

For collectors that consist of only one or a few facets (and proportionally shorter focal lengths), the facet surface should be nearly parabolic. This can be achieved by plastically deforming a metal membrane using a combination of vacuum and hydraulic loads during its initial manufacture. The thin reflective polymer film is afterwards bonded to the metal membrane, and during operation the membrane's shape is maintainted by applying a small vacuum to the interior cavity of the facet.

To maintain the sun's energy focused into the dish's receiver, the dish concentrator uses a two axis tracking system in order to follow the sun's path over the course of the day. This can be done with either an azimuth-elevation or a polar tracking system. An azimuth-elevation system rotates the dish about an axis perpendicular to the plane of the earth (azimuth) and about an axis (elevation) that is horizontal to the earth.

In a polar tracking system, the collector rotates at a constant rate of 15 degrees per hour about the polar axis which is parallel to the earth's axis of rotation. The collector's other axis of rotation, the declination drive is adjusted to the earth's declination which varies throughout the year by up to plus or minus 23.5 degrees. The adjustments made by the declination drive insure that the polar axis remains perfectly parallel to the earth's axis.

RECEIVERS

Receivers for dish/Stirling systems are cavities receivers designed to fulfill two functions: to capture and convert the concentrated solar radiation from the collector into thermal energy or heat, and to transfer that heat to the Stirling engine's working gas. The focused solar energy enters the receiver through an aperture which is made large enough to capture most of the beam but small enough to minimize radiative and convective thermal losses. At the back of the cavity is located an absorber which, as its name implies, absorbs the solar radiation, converting it into heat energy. A receiver is generally mounted on a dish so that the energy beam is at its narrowest point (its focus) when it passes through the aperture and so that the beam is somewhat diffused or spread out at the position of the absorber. The walls of the cavity are heavily insulated to reduce thermal losses from the absorber.

Receivers are designed to employ one of two different strategies in order to transfer the captured solar energy to the heat engine. The first approach is called direct illumination and is accomplished by transfering the heat directly from the solar beam into the working gas of the heat engine. This is accomplished by passing the working gas through a network of small tubes positioned in the region of concentrated solar flux. The network of tubes functions as the absorber in the receiver and heats the engine's working gas directly.

The second means for transporting the energy from the receiver to the heat engine is to employ a liquid metal (such as sodium) as an intermediate heat-transfer fluid. The liquid metal is vaporized on the surface of the absorber and then condensed on tubes carrying the engine's working gas. Because the liquid metal vapor condenses and flows back to be heated again, this type of receiver is called a reflux receiver.

An important advantage which reflux receivers have is that the two-phase heat transfer they employ results in nearly isothermal (constant temperature) operation. This promotes

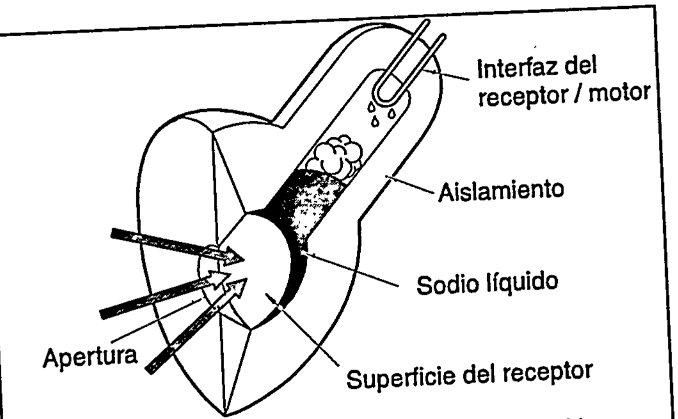

Fig. 2: Receptor de reflujo con caldera sumergida

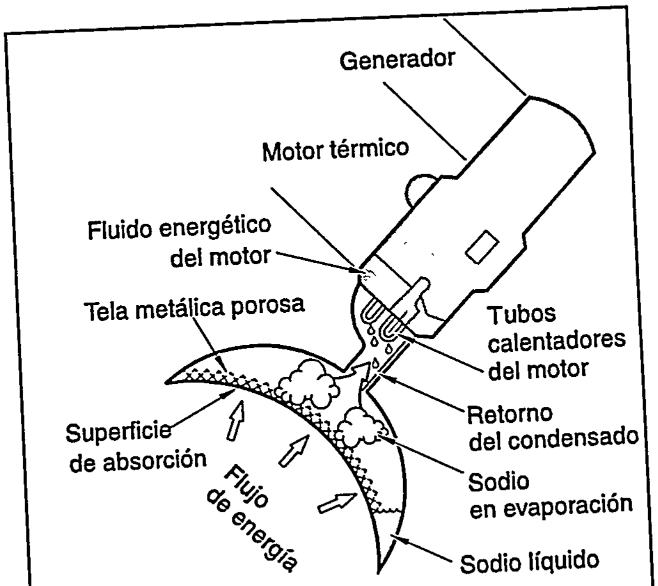

Fig. 3: Receptor de reflujo con caloriducto

longer receiver life and improved efficiency and it makes possible the addition of a gas burner (hybridization) for operation during overcast conditions or at night.

Two types of reflux receivers are being developed for dish/Stirling systems, pool boilers and heat pipes. A pool boiler is designed to keep liquid metal in constant contact with the absorber surface, while a heat pipe employs a wick structure on the back surface of the absorber which by means of capillary forces draws liquid metal over the surface of the absorber where it is evaporated. The two reflux receiver types are illustrated in Figs. 2 and 3.

HEAT ENGINES

The Stirling heat engine, invented by Robert Stirling and patented in 1816, converts heat into mechanical work with the highest theoretical efficiency of any heat engine. The first recorded solar application using the Stirling was by John Ericsson in 1872. Since then, prototype Stirling engines have been developed as trucks, buses, boats, and as underwater power units for submarines.

While the engine has yet to be commercialized on a large scale, in recent times the need for clean and efficient power generation has resulted in intense worldwide development of the concept. At the same time, advances in high-temperature metals and other technology along with Stirling engine innovations such as the free-piston Stirling engine concept have resulted in increased potential to compete with other engines.

Because the Stirling engine has the potential for long life, reliable operation, and reasonable cost, it has emerged as the preeminent power conversion module for dish-electric systems. These advantages along with other unique characteristics have also resulted in increased interest in Stirling engines for other applications. Applications currently under development include domestic heat pumps, automobile engines, refrigeration units, and space power generating units. Most of the U.S. developments are being implemented in programs supervised by NASA Lewis Research Center and Sandia National Laboratories at Albuquerque, NM. Japan is involved in a very intensive development program, and other countries, such as Germany and Sweden, are also active. Parabolic dish technology has accomplished its most significant achievements with distributed systems using the Stirling engine. These modular power systems are suited to both small, remote power as well as utility-scale applications.

Solar concentrators, because they are capable of producing very high temperatures, offer a good match as a heat source for the efficient Stirling engines, which like other heat engines increases in efficiency with increasing operating temperature. The typical temperature range of operation for the dish/Stirling engines is from 650° to 800° Celcius (1,200° to 1,470° Fahrenheit); efficiencies at this temperature are in the 30% to 40% range.

The working gas for a dish/Stirling system is typically hydrogen or helium which have high heat-transfer properties. Hydrogen is thermodynamically a better choice and will generally result in a more efficient engine. However, helium has fewer problems of material compatibility and is safer to work with.

The heat engines maximize their power by operating at high pressures, in the range from 5 to 20 MPa (725 to 2,900 psi). One of the resulting technical challenges is to effectively seal the working gas; this is one area of current design improvement.

There are two types of Stirling engines being designed for solar applications: the kinematic engine and the free-piston engine. In a kinematic Stirling engine (Fig. 4), the power piston and the gas displacer piston are mechanically linked. The output piston is also linked to the rotating output shaft which transfers power to the alternator. In a free-piston engine (Fig. 5), the power piston and the displacer piston are not linked. The displacer is free-moving. The power piston, in many current designs, attaches directly to the magnet of a linear alternator, and slides back and forth in the space containing the working gas and a spring (usually a gas spring). The magnet's linear motion past a stationary coil generates electric power. The frequency and timing between the power and the displacer pistons are determined by the dynamics of the spring/mass system. Other means of extracting power from a free-piston Stirling have been considered, such as driving a hydraulic pump.

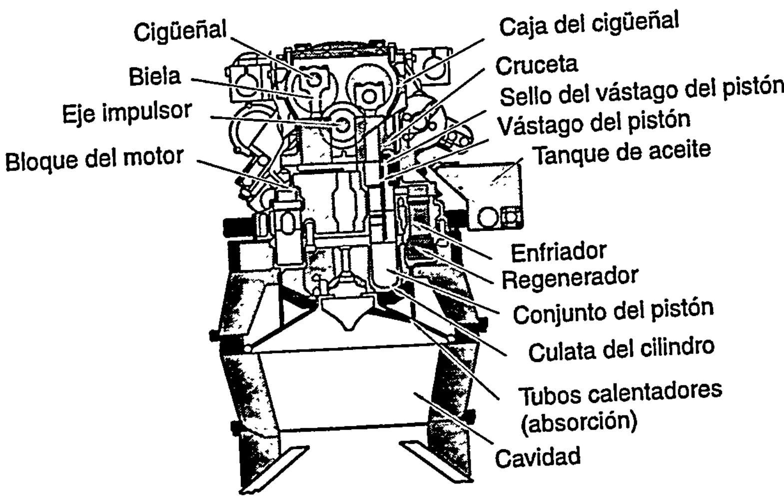

Fig. 4: Kinematic Stirling engine with a directly illuminated tube receiver (Máquina Stirling de tipo cinemático con receptor de tubo de iluminación directa)

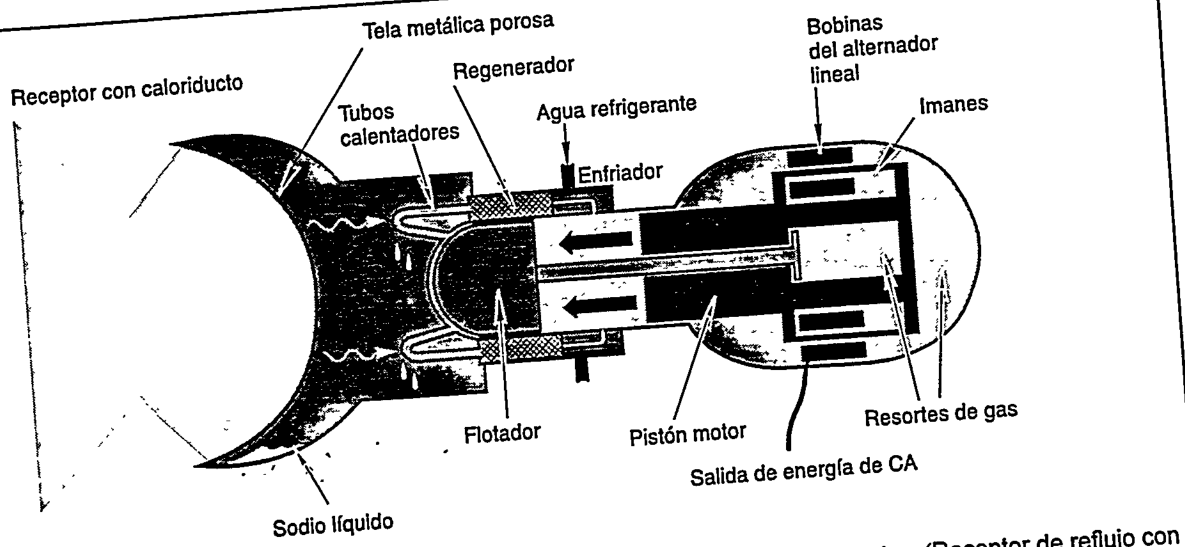

Fig. 5: Free-piston Stirling engine with linear alternator and liquid-metal heat-pipe receiver (Receptor de reflujo con caloriducto)/*

CURRENT DEVELOPMENTS & TECHNICAL ISSUES

Dish/Stirling systems are the least developed of the three solar thermal technologies, and much basic technology development remains. The current interest in dish/Stirling technology is, to a large extent, attributable to the technically successful Advanco and McDonnell Douglas 25-kilowatt systems, which in the mid 1980s demonstrated the potential for very high efficiency. However, maintenance costs remain highly uncertain due to the lack of adequate data. As a result of the drop in the price of oil, McDonnell Douglas divested their interest in dish/Stirling in 1986.

Recently there have been efforts to develop advanced designs for numerous dish/Stirling components including stretched membrane dishes, reflux receivers, and free-piston and kinematic Stirling engines. These new developments are just beginning to be integrated into systems, and a significant amount of uncertainty therefore remains with respect to their promised performance, life, cost, and reliability. In addition, significant capital is required to develop a Stirling engine and provide the infrastructure needed to support commercialization.

Within the past few years, dish/Stirling systems for remote power applications have been advanced in the U.S., Germany, and Japan. In 1989, Cummins Power Generation, Inc. (CPG), a wholly-owned subsidiary of Cummins Engine Company, demonstrated the first dish/Stirling system using a faceted stretched-membrane dish, a reflux receiver, and a free-piston Stirling engine. Through a joint venture with DOE/Sandia, CPG is continuing development of a 7-kW$_e$ dish/Stirling system for remote applications. In June 1992, the first CPG prototype system became operational. However, since then durability problems with the reflective film has forced CPG to abandon their stretched-membrane dish design for a more conventional glass/metal panel construction. In addition, CPG changed free-piston engine designs because of development and manufacturability problems with the original Sunpower, Inc. engine and are now approximately two-years behind their original schedule.

In Germany, Schlaich, Bergermann, und Partner (SBP) has developed and performed system testing of 8-kilowatt systems using a single-element, stretched-membrane dish and directly illuminated cavity receivers. The Stirling Power Systems (SPS) V-160 Stirling engine used in the SBP system is of the kinematic type. Three prototype systems operating in Almeria, Spain, have accumulated nearly 20,000 hours of operation. The SBP system has also demonstrated operation with a reflux receiver. The SPS V-160 Stirling engine has been licensed to Solo Kleinmotoren GmbH, a German small engine manufacturer, who is currently producing the engine in small quantities. Application of the engine to co-generation and heat pumps is being considered. Reducing costs and manufacturability are key to the commercialization of the SBP technology and the application of the Stirling engine to other applications, such as heat pumps, may help.

In Japan, Aisin Seiki Ltd. has been advancing kinematic Stirling engine technology, primarily for heat pump applications. Most of the solar testing of the Aisin engine has been done on a McDonnell Douglas dish. The Aisin engines, derated to 8-kW$_e$, are also being integrated with modified CPG stretched-membrane dishes on Miyako Island, south of Okinawa. A prototype Aisin kinematic Stirling engine is also being integrated into a CPG utility scale system in the U.S.

Larger dish/Stirling systems are being developed for use in utility applications. Cummins Power Generation, Inc. (CPG) and Science Applications International Corporation (SAIC) are developing a 25 and 20-kW_e dish/Stirling systems, respectively, in cooperation with DOE/Sandia. CPG is evaluating free-piston, and kinematic Stirling engines, and a Brayton cycle engine for this system. The SAIC system utilizes the Stirling Thermal Motors STM 4-120 kinematic Stirling engine. Both of these systems, however, still have a long way to go before they reach the level of operational maturity necessary for commercial introduction. CPG's plans currently calls for limited production of their 7 kW_e remote power system for 1997. The 25 kWe utility systems are not scheduled for commercial introduction until after the year 2000.

POTENTIAL APPLICATIONS IN MEXICO FOR DISH/STIRLING SYSTEMS

A study of the potential use of dish/Stirling systems in Mexico (DynCorp, 1994) suggests that they are likely to play a significant role in remote and grid-disconnected regions of this and other fast-developing countries. Ten percent of Mexico's population in approximately 100,000 villages are not served by the country's electric grid, and the revision in 1992 of Mexico's electric power laws opened the door for private power producers. Dish/Stirling systems are likely to find their first commercial success in off-grid applications. In the numerous areas of Mexico that posses an abundant solar resource and are remote from centrally generated electricity, dish/Stirling technology can offer a competitive option, provide water pumping and electricity for rural communities and tourist facilities, water pumping for cattle and for crop irrigation, and electric power for many economically productive rural uses such as water purification and ice-making.

CONCLUSIONS

Dish/Stirling systems are an emerging solar thermal electric technology in the 5 to 25 kW_e size range that is expecteed to enter the world power market in the later part of this decade and at the beginning of the next. Technologists in Japan, Germany, and the United States are actively pursuing the development of systems which incorporate various alternative design concepts:

- multiple facet collectors versus single facet collectors
- thin-film stretched-membrane reflectors versus reflectors made from glass and other materials
- directly illuminated versus reflux receivers
- pool-boiler reflux receivers versus heat-pipe reflux receivers
- kinematic heat engines versus free-piston heat engines.

Critical issues facing the technology's development include 1) durability of thin-film reflective materials for stretched-membrane facets, 2) development of durable and manufacturable Stirling engine designs, and 3) integration of advanced components into low cost and reliable dish/Stirling systems.

Dish/Stirling systems are likely to be a competitive option for power generation in developing regions of the world that have a good solar resource and are distant from the distribution grid for centrally generated electricity. These solar thermal electric systems seem particularly suited to Mexico, with its abundance of sunshine and growing rural economies that are unserviced by the country's central electric grid.

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