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AN OVERVIEW: COMPONENT DEVELOPMENT FOR SOLAR THERMAL SYSTEMS

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1.0 ABSTRACT

In this paper, I review the significant issues and the development of solar concentrators and thermal receivers for central-receiver power plants and dish/engine systems. Due to the breadth of the topic area, I have arbitrarily narrowed the content of this paper by choosing not to discuss line-focus (trough) systems and energy storage. I will focus my discussion on the development of heliostats, dishes, and receivers since the 1970s with an emphasis on describing the technologies and their evolution, identifying some *key* observations and lessons learned, and suggesting what the future in component development may be.

1.1 Keywords: solar thermal power, solar central receiver, dish/engine system, concentrator, heliostat, dish, thermal receiver, heat-pipe receiver, Stirling engine, pool-boiler receiver

2.0 INTRODUCTION

Power tower and dish/engine system designs have historically resided in the research and development arena. The solar concentrators and receivers used to generate solar thermal power have evolved from component designs aimed at demonstrating technical feasibility in the 1970s and early 1980s to the initial designs for commercial solar thermal electric systems in the 1980s and 1990s. In response to the needs of the fledgling solar thermal industry, we research scientists and engineers are being asked to abandon our traditional models for technology development. No longer is it feasible for us to devote years to developing *proof of concept prototype* systems and, once the systems have been thoroughly demonstrated, only then to address commercialization of the designs. The next five-to-ten years represent a critical juncture for the commercialization of power tower and dish/engine systems. The first of these systems to reach the market place will provide a great deal of information on the performance, reliability, and the costs. Industry is looking to the R&D community to provide the next-generation of concepts and components that will take these solar thermal systems beyond initial introduction to the markets and to establishing a sustainable, significant market share. In order to do this, we must work more closely with

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industry to provide a faster turn around time from concept to final, commercial designs. Furthermore, we must employ concurrent engineering and a more complete understanding of user needs at the very beginning of the process.

In the final assessment, the users of solar thermal systems could care less about whether a power tower uses glass-metal or stretched-membrane heliostats and a water/steam or a molten-salt system or whether a dish/engine system uses a Brayton or Stirling engine. What they are concerned with are the answers to the following two questions: *can I use the power when I want it, and what is the unit cost of power over the lifetime of the plant?* The answers to these two questions should guide the direction of our research and establish the criteria that we use in comparative evaluations of systems and components.

In this paper, I present examples of solar thermal technologies for central receiver and dish/engine systems, specifically: solar concentrators, heliostats and dishes, and thermal receivers, cavity and central receivers. In each case, I will provide examples of the technology, describe the strengths and weaknesses of the designs in terms of the potential user's needs, and describe what I see as the near-term future for these components.

3.0 HELIOSTATS

Heliostats are the nearly-flat mirrors that are used to focus the solar energy on a central power tower receiver. The trends in heliostat development over the last fifteen to twenty years have been from smaller to larger heliostats and from smaller to larger optical facets, to benefit from larger scale. Initial heliostats, such as the Martin Marietta (U.S.) heliostats used at Solar One and the SPP 5 Russian power plant, and the CIEMAT array (Spain) at Cesa Uno [1, 2, and 3] are glass-metal designs with 12 facets on each 40 m^2 unit. An example of this technology is shown in Figure 1, which is a picture of the heliostats used at the Soviet SPP 5 power plant in the Crimea. The SPP 5 heliostat has 45 flat glass facets (total area 25 m^2) mounted on a support structure so that they can be canted to focus the heliostat at any distance. The azimuth/ elevation drive is representative of

Figure 1. Soviet SPP 5 Heliostat in the Crimea

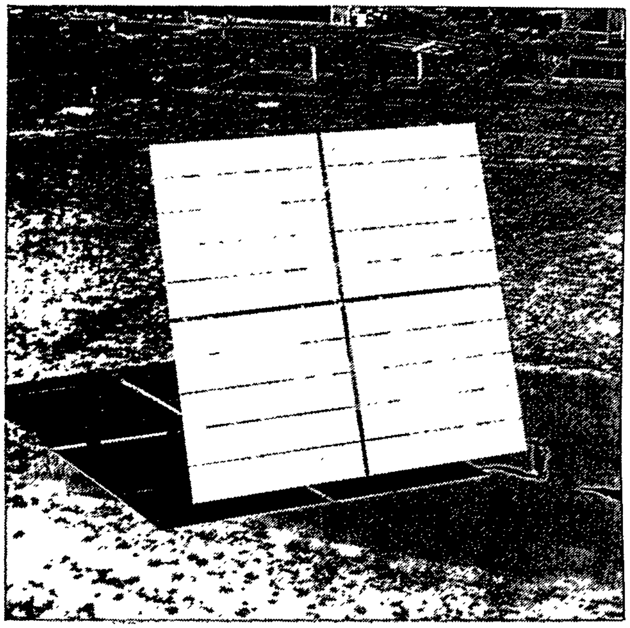

Figure 2. ATS 150 m^2 Heliostat

the other glass-metal heliostats built during this period. Two unique features of the SPP 5 heliostat design are its concrete pedestal and an optical sensor, located in front of the heliostat, that provides a closed-loop control signal for tracking the heliostat onto the centrally-located receiver [4, 5].

Glass-metal heliostats of this era have many facets that require costly field alignment and the small-area heliostats do not make efficient use of the expensive drives. ATS (Advanced Thermal Systems) and Solar Power Engineering Company (SPECO) responded to these two issues (U.S.) [6]. SPECO designed and built a 200 m^2 heliostat with 64 facets and ATS designed and built a 150 m^2 heliostat with 100 facets. The ATS heliostat utilized mirror assemblies of five facets each to reduce the field alignment to twenty modules. Although, this is not a great improvement in the number of heliostat modules requiring field alignment, it does represent an economy of scale that has already reduced the cost by a factor of 4 over the initial glass-metal designs. The ATS 150 m^2 heliostat is shown in Figure 2.

Advanced stretched-membrane heliostats have been built by the Germans, the Spanish, and the Americans. Two stretched-membrane heliostats are shown in Figures 3 and 4. A stretched-membrane heliostat makes use of two metal membranes attached to a ring to form the optical element of the heliostat. Glass or a polymer film can be attached to one of the membranes to form the reflective surface. The heliostat is focused by drawing a slight vacuum in the plenum space between the two metal membranes. A heliostat of this design has a large range of adjustable focal lengths and does not require that a number of small facets be aligned during assembly in the field. Figure 3 is a picture of the German 50 m^2 stretched-membrane heliostat with a glass surface [7]. Figure 4 is the SAIC Dual-Module heliostat (U.S.), which uses a polymer reflective film [8].

The current state-of-the-art heliostat is the ATS 150 m^2 design. The size of the unit is limited by wind loads and the slant range of the heliostat (i.e., the size of the receiver and the distance from the tower). The near-term development of heliostats will probably be in the direction of larger, curved facets for a 100 to 150 m^2 heliostat. Because of their lower parts count and simplicity, longer-term heliostat development will probably build on stretched-membrane heliostat designs. However, since large heliostat optical elements must be assembled and/or fabricated in the field, large stretched-membrane heliostats will become commercial units only if field fabrication and assembly costs can be minimized. A more likely scenario is that large stretched-membrane optical

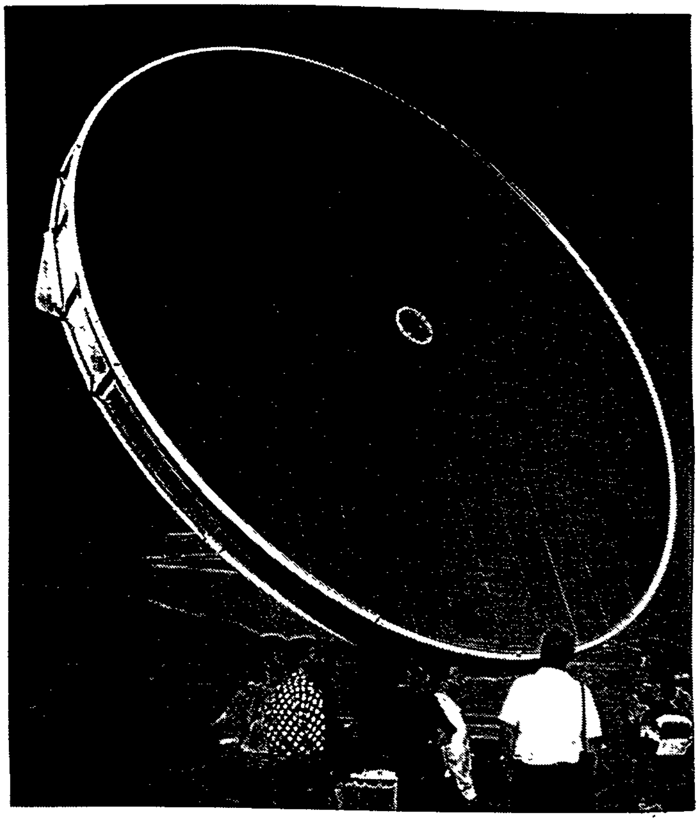

Figure 3. German SM Heliostat

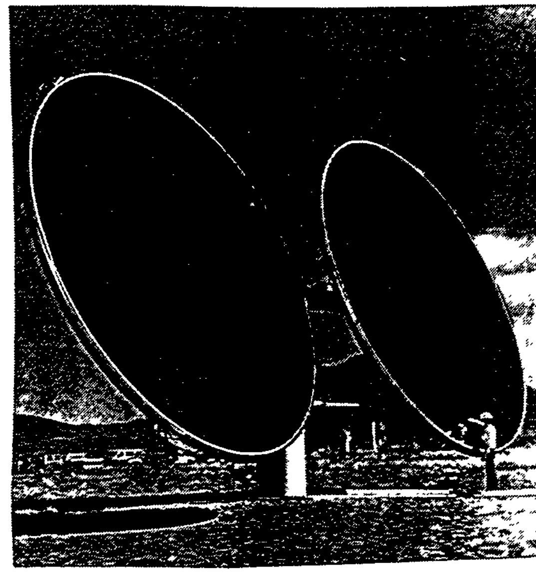

Figure 4. SAIC SM Heliostat

elements, perhaps similar to those used for the faceted stretched-membrane dish, will be adapted to a heliostat design.

4.0 DISH CONCENTRATORS

There are subtle differences in the way in which dish concentrators and heliostats must carry wind loads [9]. In addition, dish concentrators must also carry the cantilevered load of the thermal receiver and power conversion system so that the contour of the dish does not change with elevation, sometimes referred to as *clam shell.* In addition to wind loads, the size of the dish is determined by the output and efficiency of the power conversion system. Current power conversion systems generally range in size up to about 30 kW_e and are about 25% efficient, resulting in dishes up to 100 m^2 total area.

Figure 5. The McDonnell Douglas Dish

Some early dish concentrators evolved from satellite communications antenna designs and, much like heliostats, the current state-of-the-art is a glass-metal design, the McDonnell Douglas (U.S.) dish shown in Figure 5.

The McDonnell Douglas dish comprises 82 silvered glass facets with

The McDonnell Douglas dish comprises 82 silvered glass facets with six different facet focal lengths and the facets are aligned in the factory for a total area of 91 m^2 [11]. The dish is an azimuth over elevation drive and utilizes the weight of the concentrator to balance that of the power conversion system at the drive. Eight solar concentrators were originally manufactured and have undergone nearly 27 years of accumulated testing, evaluation, and routine operation. The dish has a geometric concentration ratio of 2793 (the ratio of the dish-to-receiver aperture areas) and a reported efficiency of about 88% [12]. The system is installed in one and one-half days.

A second glass-metal dish design that is nearing commercialization is the German Schlaich, Bergermann und Partner stretched-membrane dish. Three of these dishes are currently running a Stirling engine at the Plataforma de Solar in Almeria, Spain. The dish, which is shown in Figure 6, is 7.5 meters in diameter (to provide power for a 9 kW_e pcs) and is made of a single preformed, stainless steel stretched membrane with glass tiles bonded to the steel to form optical surface of the dish [10, 13]. The membrane is preformed using a combination of uniform and nonuniform loading to shape the dish contour. A slight vacuum in the plenum space is used to maintain this shape. The drum that supports the front and back membranes is mounted in a polar tracking arrangement. This dish offers good potential for scale-up (several 17-m diameter dishes of this design have been made).

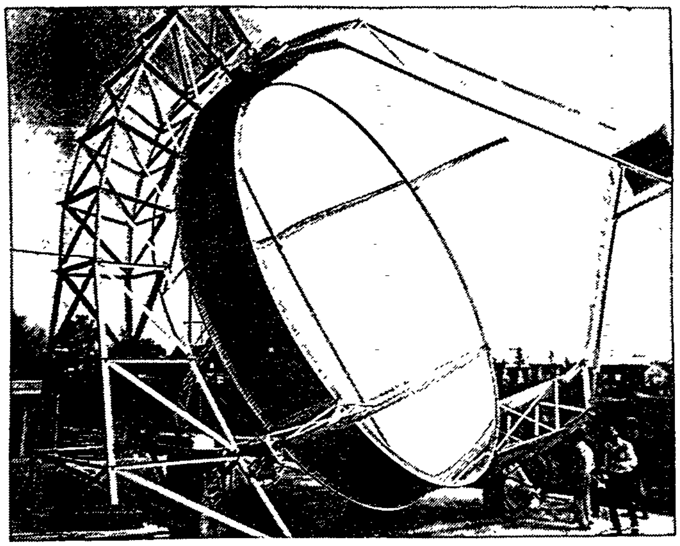

Figure 6. The German SBP Dish

Faceted stretched-membrane dishes have been designed and built by Cummins Power Generation (U.S.) and, as part of the DOE Solar Thermal Program, by Science Applications International Corporation. SAIC has developed the next-generation of a faceted dish based on the DOE design. The DOE Faceted Stretched-Membrane Dish is shown in Figure 7.

The Faceted Stretched-Membrane Dish is made of 12, 3-m diameter stretched-membrane facets for a dish area of about 85 m^2 [14, 15, 16]. The power delivered to a 0.3-meter diameter aperture by the faceted dish is 70 kW_t. The dish that is shown in the Figure uses a polymer film as the reflective surface for the facets. The SAIC design uses thin glass as the reflective surface.

The future of dish concentrator development will be strongly influenced by the ability to manufacture as much of the dish as possible in the factory and ship it to the site for assembly. Since installations can range from one to hundreds of dishes at any given site, dish costs are even more sensitive to field fabrication and assembly than are those of heliostats. Monolithic stretched-membrane dish designs, which require substantial field fabrication, will be at a cost disadvantage relative to faceted dish designs that can be fabricated in the shop and shipped to the site for installation.

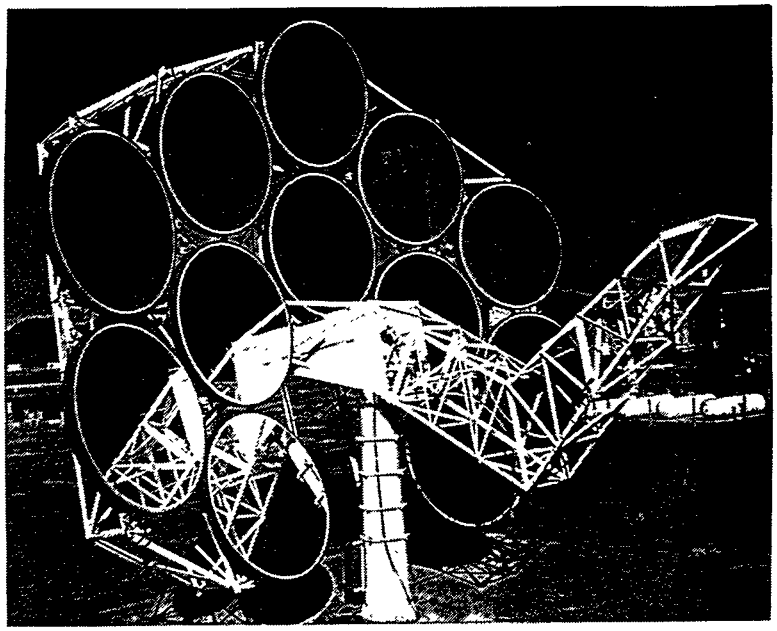

Figure 7. DOE Faceted SM Dish

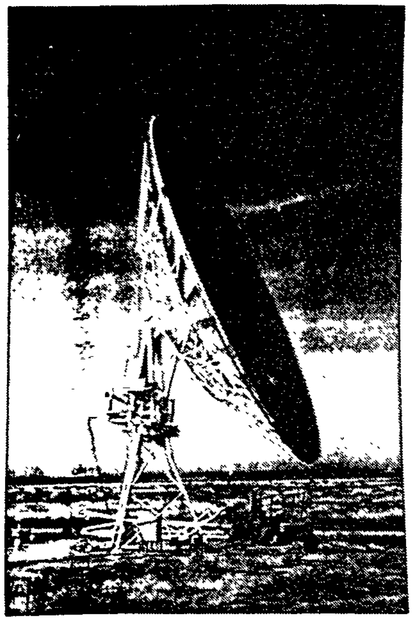

Figure 8. The Acurex Innovative Concentrator

Another concept that holds great promise, but has never been proven, is the monolithic monocoque design in which the assembled structure provides both the optical contour and carries the wind loads to the pedestal. This concept is shown in the Acurex Innovative Concentrator (U. S.) [17] pictured in Figure 8. Unfortunately, a weld in the pedestal failed and severely damaged the dish before the dish could be tested. Cummins Power Generation (U. S.) is currently evaluating a variation of this concept for their advanced concentrator design.

5.0 CENTRAL (POWER TOWER) RECEIVERS

Central receivers for power-tower applications are of three generic configurations -- tubular water/steam receivers, tubular molten-salt receivers, and volumetric air receivers. Two tubular water/steam receivers were designed, built, and operated in the mid 1980s in the United States [18] and in the Crimea of the former Soviet Union [4, 5]. These two receivers are shown in Figures 9 and 10.

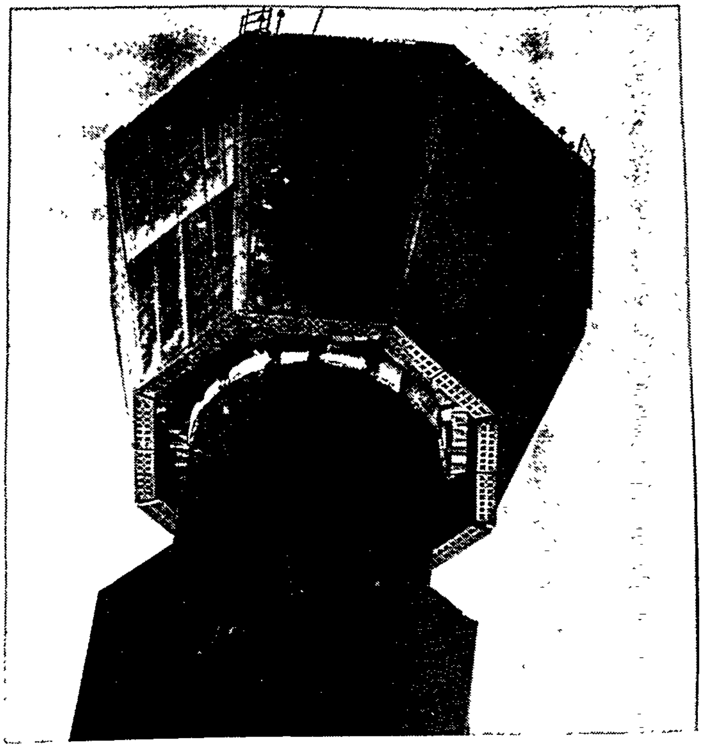

Figure 9. The Russian SPP 5 Receiver

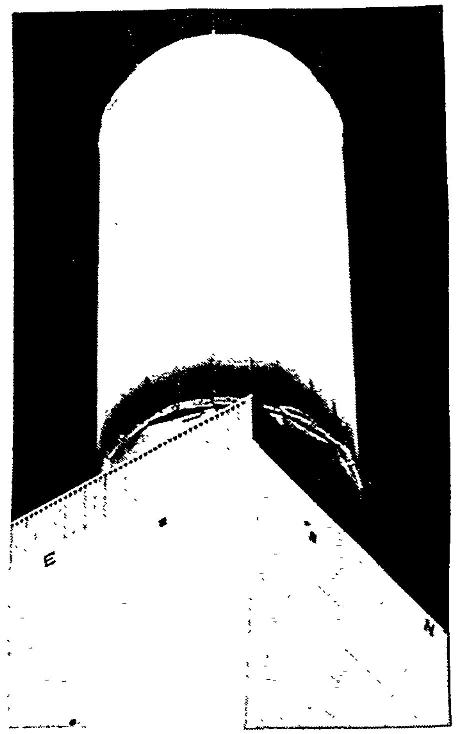

Figure 10. The U. S. Solar One Receiver

The SPP 5 solar receiver was designed to provide 21 MW_t. The geometry is a 16-sided polyhedron that is 7 meters high and about 7 meters in diameter with a total surface area of 157 m^2. The sixteen panels are made of vertical tubes, fourteen of the panels are the evaporator and two of the panels make up a south-facing economizer.

The U. S. Solar One receiver, which was built by Rockwell, is a single-pass-to-superheat boiler designed to provide about 43 MW_t of throughput power. The receiver is 13.7 meters high and 7 meters in diameter. The outer surface of the receiver is made up of 24 panels (each about 1 meter wide), six of the panels are feedwater heaters and the remaining eighteen are boiler panels. The total absorber area is 302 m^2. Test results showed a receiver efficiency at rated power of about 77% and the absorptivity of the Pyromark™ painted surface decreased by about 4% over the three-year testing period. Receiver tube leaks resulted in increased maintenance requirements. Also, because the steam passed directly from the receiver to the turbine, plant operations was very sensitive to cloud transients.

Another central-receiver concept that is proposed for the PHOEBUS Technology Program Solar Air Receiver [19, 20]. A 2.5 MW_t volumetric receiver has been designed by L&C STEINMULLER (Germany) and tested at the Plataforma Solar de Almeria, Spain. by the DLR and PSA. This concept uses a wire-mesh matrix to absorb the incident solar radiation and recirculation of warm and cold air as the working fluid for the receiver. A major advantage of this concept is that the working fluid is air, simplifying many elements of receiver design. Test results reported for May to December 1993 proved the technical feasibility of the concept by demonstrating that air outlet temperatures of 700 C could be achieved at an average flux density of 0.3 MW/m^2; and that the air flow distribution in the absorber could be matched to the incident flux distribution. A schematic diagram of the volumetric receiver is shown in Figure 11.

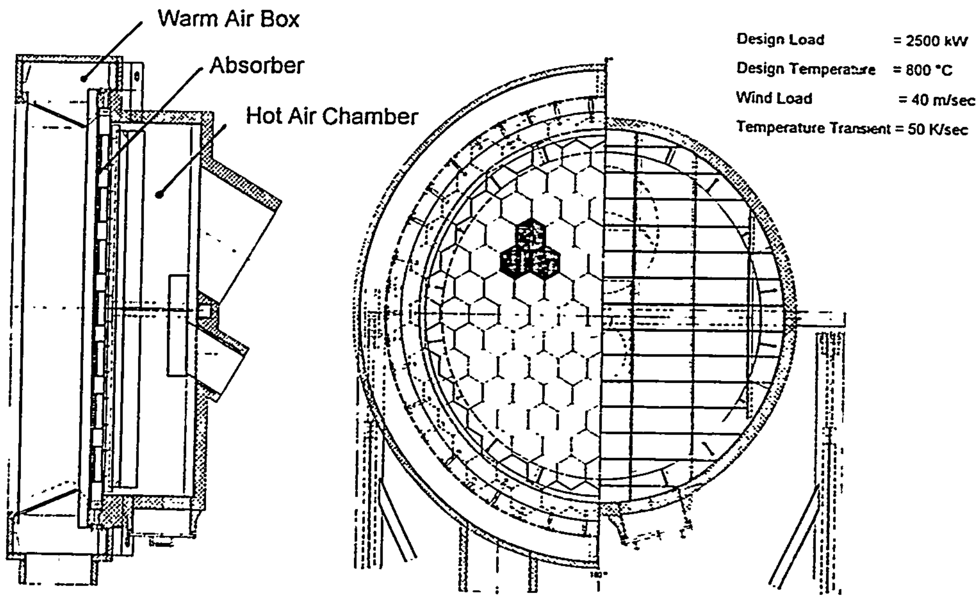

Figure 11. The FDE Volumetric Air Receiver

A third type of central receiver concept has been designed by Rockwell International [21] for the prototype commercial plant Solar Two in the United States. The receiver will use a molten nitrate salt as the working fluid and as thermal storage. The rated power throughput of the receiver is 42.2 MW_t. The receiver, a picture of the model is shown in Figure 12, is 5.5 meters in diameter and 6.7 meter high. It comprises 12 panels with 32 serpentine flow tubes per panel. The receiver will be used to heat the molten salt from a nominal temperature of about 750 C in the *cold* tank to 1050 C in the hot tank.

Clearly, each of the three major concepts has unique advantages that may apply to systems with particular characteristics and for specific applications. It is worthy of note that for the volumetric and molten-salt receiver designs engineers have made noticeable efforts to address manufacturing and user concerns. More of this type of thinking must be incorporated into future designs if they are to be successful.

6.0 DISH (CAVITY) RECEIVERS

A cavity receiver absorbs the solar energy that is reflected from the dish and transfers the thermal energy to the working fluid of the power conversion system. These receivers must operate in a severe environments -- at temperatures from 700 to 800 C and at solar flux intensities from 40 to about 80 W/cm^2. For a 25 kW$_e$ dish/Stirling system, the receiver must have a throughput of 80 or 90 kW$_t$. The working environment and cyclical operating conditions due to clouds and the diurnal solar cycle are a severe test for materials. While the operation of a cavity receiver is simple and their costs are not the major driver for the system costs, achieving reliable, long-term operation is a technological challenge.

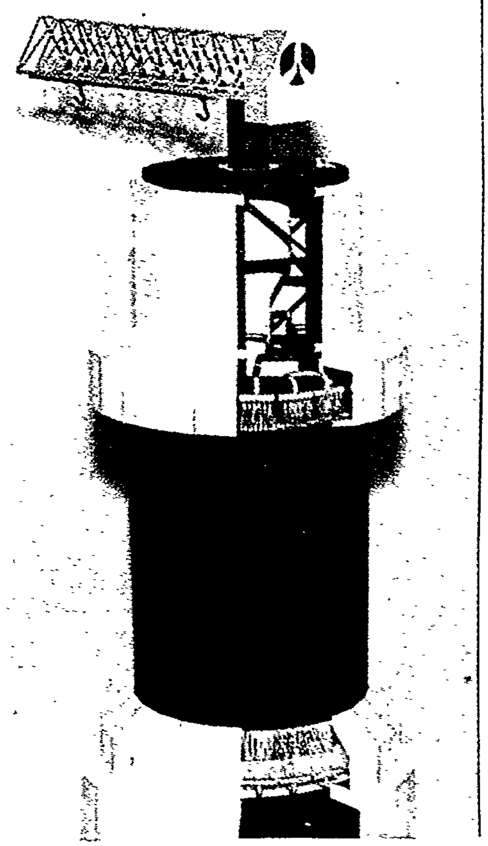

Figure 12. Solar Two Molten-Salt Receiver (Picture Provided by Rocketdyne)

The first type of receiver that was used on a dish/Stirling system is the direct illumination receiver or DIR. The DIR was used on the Vanguard and McDonnell Douglas (U.S) dishes [12, 23] and is currently the baseline receiver for SAIC's (U.S.) dish/Stirling system. The STM DIR is shown in Figure 13.

A DIR is simply a set of tubes that are connected to the Stirling engine's heater head and carry the engine working fluid (hydrogen or helium) to and from the engine. The volume of gas in the receiver must be minimized because additional *dead volume* has a deleterious affect on the engine's performance. In a multi-cylinder engine, sections of the tube bundle are connected to individual cylinders. In this case, the solar flux distribution should be balanced among the cylinders or the engine performance will be compromised by the lowest

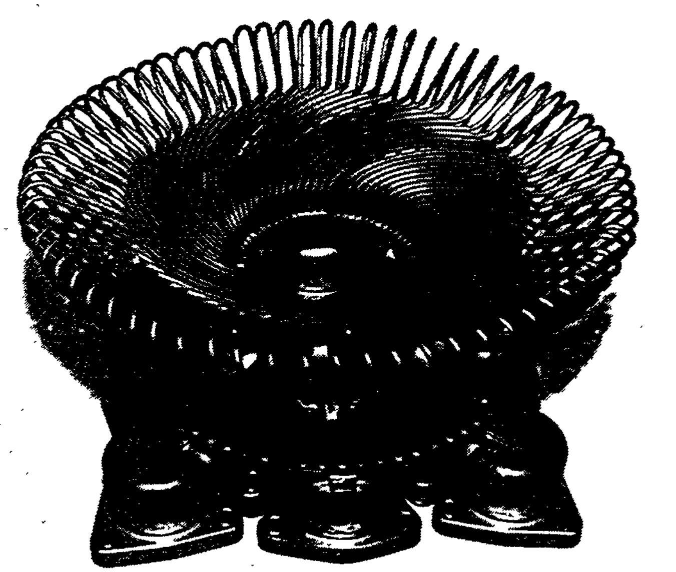

Figure 13. STM DIR Cavity Receiver

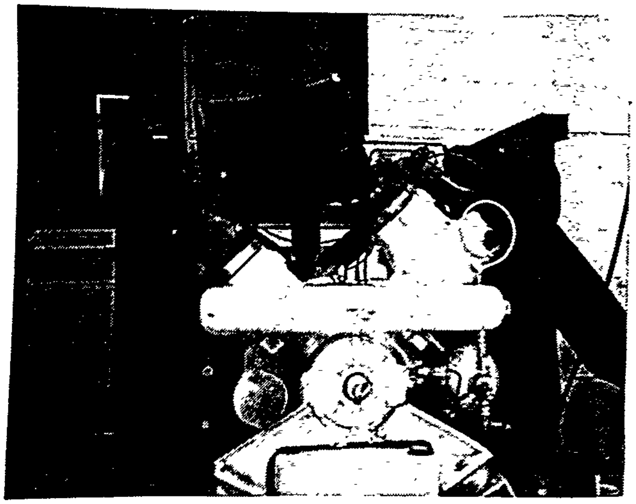

Figure 14. DIR Receiver on the SBP Engine

temperature cylinder. During tests on the Vanguard dish/Stirling system, a number of the N-155 (a ferrous alloy) tubes failed due to thermal fatigue. In more recent DIR receivers, the tubes are made from Inconel 625 and thermal fatigue has not been a problem. A second DIR receiver, this one on the former Stirling Power Systems engine (now being manufactured by Solo Kleinmotoren) on the SBP dish/Stirling system (Ger), is shown in Figure 14 [10].

Liquid-metal (Na or NaK) receivers have been developed and used on dish/Stirling systems in Russia [23], Germany [24], and the U. S. [25, 26]. These receivers are of two general types -- pool boilers and heat pipes. These receivers have the potential of providing a uniform flux, through condensation of the liquid metal, to the heater head of the engine, thereby eliminating one of the major problems of the DIR receiver. A schematic diagram of a pool boiler receiver is shown in Figure 15. In a pool-boiler receiver the back side of the receiver surface is flooded with liquid metal. As the surface is heated, the liquid metal boils, passes to the condenser end of the receiver (the engine heater head), condenses, and *refluxes* or flows back into the pool. A heat-pipe receiver is similar to a pool boiler except that it uses a wick on the back of the absorber surface to lift a small amount of liquid metal over the absorber by capillary action. The inventory of liquid metal is smaller in a heat-pipe solar receiver than in a pool boiler.

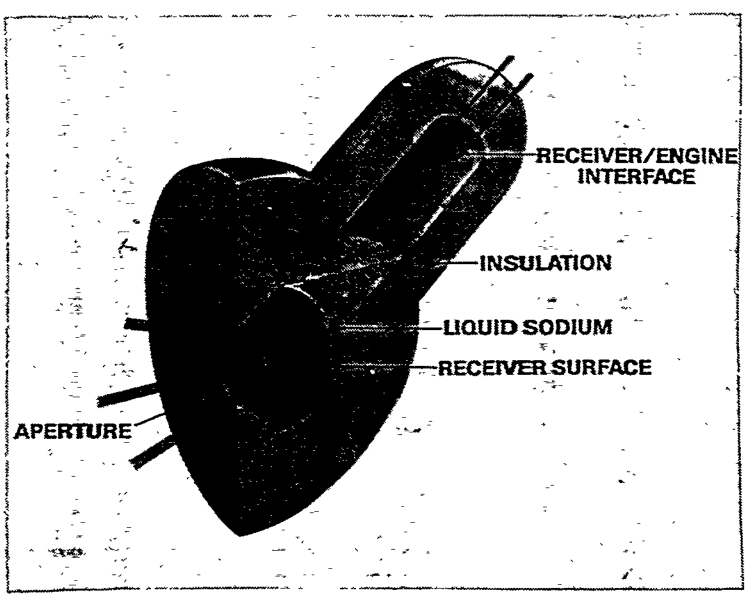

Figure 15. Schematic Diagram of a Liquid-Metal Pool-Boiler Receiver

A third type of cavity receiver for a dish/engine system is the VOBREC receiver developed by the DLR, the German Aerospace Research Establishment, for use with Northern Research Corporation's Brayton engine [27]. The receiver is a volumetric air receiver. Air flows through the receiver at low velocity where it passes through a solar-irradiated foam matrix. In the foam matrix, the air temperature is increased by about 200 C. After exiting the absorber, the air passes through a conventional combustor where additional heat may be added if required. Because the receiver is pressurized (250 to 300 kPa), the air must be contained with a fused silicon dioxide window covering the aperture. Brayton cycles must also have a recuperator to reclaim waste heat before the air is exhausted to the atmosphere. The quartz window and recuperator increase the complexity and cost of a Brayton system, but the advantage of hybridization may offset this additional cost. A schematic diagram of the VOBREC receiver is shown in Figure 16.

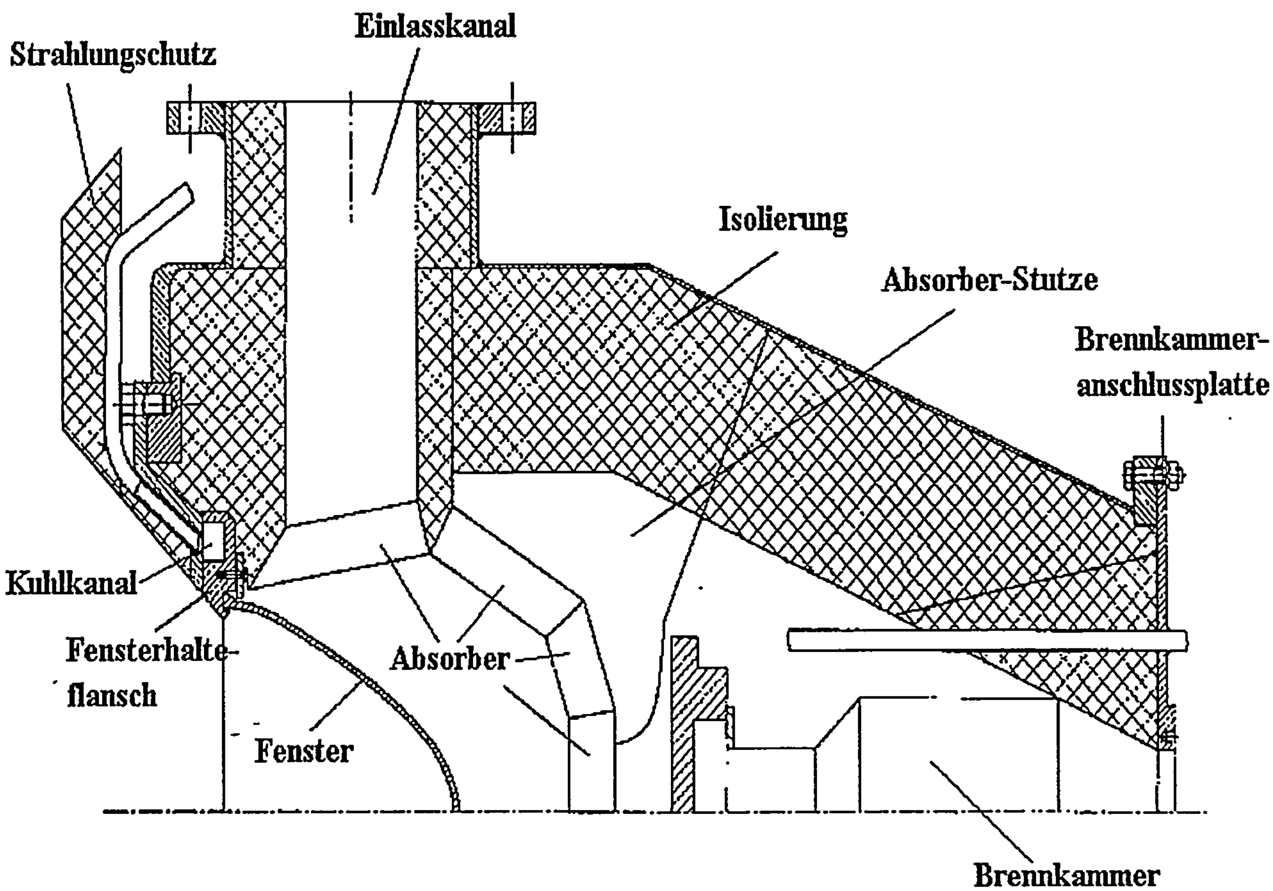

Figure 16. The DLR VOBREC Receiver

Because one of the key user requirements for solar thermal systems is to have them available when they are needed and thermal storage is not a viable option for dish/engine systems, they will likely have to be hybrid. Hybridization of DIR and liquid-metal receivers is a formidable task. The fact that the VOBREC/Brayton system is hybrid gives it an advantage in meeting user needs. In the near-term, the most likely receiver is the simplest concept - the one that can provide reliable operation for an extended period of time. The DIR and heat-pipe receivers are likely to be the choices for dish/Stirling systems over the next five to ten years. The major design challenges for these receivers will be hybridization and achieving long-term reliable operation.

7.0 SUMMARY

The solar power industry is at a critical juncture in its development. During the next five to ten years, power towers and dish/engine systems will be introduced to the commercial market place. The next generations of solar concentrators and thermal receivers for use in power tower and dish/engine systems are very important because their success could mean that solar power will be able to define a sustainable market share. Industry is looking to the R&D community to provide these next-generation components. To meet this challenge, we must redefine our traditional design cycles to be shorter and to incorporate sooner user needs and design for manufacture.

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