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AN OVERVIEW OF ADVANCED CENTRAL RECEIVER CONCEPTS*

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ABSTRACT

Sandia National Laboratories is investigating advanced central receiver concepts as part of the U.S. Department of Energy solar thermal research program. In the last 12 years many studies and test programs have been carried out to develop and demonstrate the viability of central receiver power plants using tube-receivers with molten-nitrate-salt and steam. These receivers are currently the state-of-the-art. However, studies of advanced receiver concepts, such as the molten nitrate salt direct absorption receivers and volumetric air receivers, have shown their potential to be simpler, cheaper, and have better performance than conventional tube-receivers. In order to make central receivers economically competitive these advanced receiver concepts are being investigated.

In a direct absorption receiver, the heat-absorbing fluid (a blackened molten nitrate salt) flows in a thin, wavy film down a flat, vertical panel (rather than through tubes) and absorbs the concentrated solar flux directly. The volumetric air receiver design uses a porous absorber, on which the solar energy is concentrated. Air flows through the absorber, convectively transferring energy from the absorber to the air.

In this paper, the concepts, advantages, status, and test results of the salt-in-tube receiver, direct absorption receiver, and the volumetric receiver are discussed.

1. INTRODUCTION

Sandia National Laboratories is developing central receiver technology for use in producing electricity on a utility scale. In a central receiver power plant, energy from the sun is reflected by a field of heliostats and concentrated on a receiver located atop a tower in the field. The receiver is cooled and the solar energy collected with a heat transfer fluid, typically molten nitrate salt, liquid sodium, steam, or air.

Central receiver power plants are of interest because of the potential for high-efficiency collection of solar energy at very high temperatures. Central receivers can produce superheated steam at the same temperatures and pressures used in conventional power plants. Consequently, these systems can be substituted directly for power plants that burn fossil fuels in a utility boiler. However, central receiver systems

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must be very large in order to be economical. An optimal size for a central receiver power plant that produces electric power is about 200 MW_e. Therefore, any potential for simplification and cost reduction needs to be evaluated.

A schematic of a central receiver power plant is shown in Figure 1, with the basic systems identified. The primary system to be discussed in this paper is the receiver. In conventional central receiver designs, the fluid is contained in tubes (e.g., a boiler design) and the solar flux is directed onto the tubes. Because the concentrated solar energy must pass through the tube wall, tube material constraints limit the size, efficiency, lifetime, and peak flux capabilities of the receiver. In order to optimize the receiver and plant the receiver should be as efficient as possible. To be efficient, the receiver must have a high absorptivity and low thermal losses. The receiver should also be as small as possible in order to reduce costs and energy losses. If the receiver is to be small in size, it must have a high peak flux limit. Finally, the receiver must be simple. Simplicity in the receiver design affects its initial cost, its operation and maintenance costs, its reliability, and its lifetime.

At the present time a number of central receiver concepts have been designed and tested and a pilot power plant has been built and tested. However, there are no central receiver power plants built or planned, because of the current low price of electricity and the lack of demand for new electricity. In a different economic environment, state-of-the-art central receivers could be providing electricity. However, the challenge to develop economically viable solar power systems has become greater with the elimination of tax credits and reduced oil prices. In this paper, we describe the advanced receiver designs that utilize direct absorption and volumetric energy transfer, which can improve the performance and economics of central receivers.

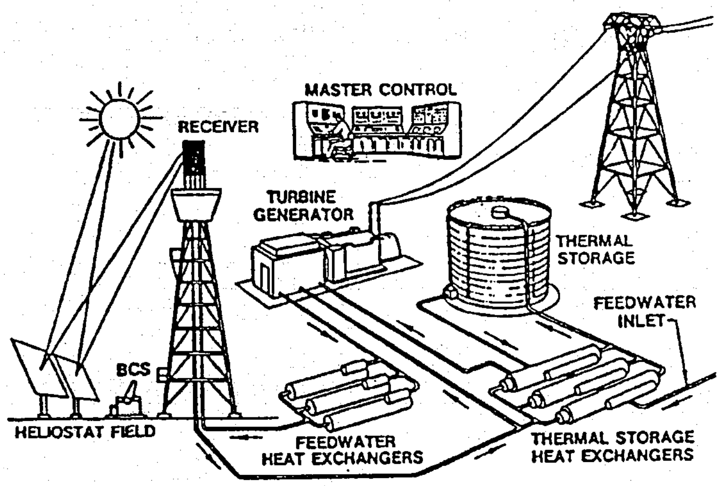

Figure 1
A Central Receiver Power Plant
Solar One Pilot Plant[1]

2.0 STATE-OF-THE-ART CENTRAL RECEIVERS

Solar One Power Plant

Solar One in Barstow, Ca., was the first central receiver solar power plant to be built and successfully tested and operated. A schematic of Solar One is shown in Figure 1. It was tested from 1984 to 1988 and successfully demonstrated the feasibility of central receiver solar power plants[1]. Solar One utilized a water/steam receiver, with a peak flux limit on the receiver of 0.3 MW/m^2. It also experienced many of the limitations listed in the previous section. For example, the receiver was large (because the flux limit was low), its efficiency was approximately 75%, and it was a complex receiver. Because of these and other problems molten nitrate salt was already being investigated as a heat transfer fluid when Solar One was being tested.

State-of-the-Art Receivers

The current state-of-the-art central receiver utilizes molten nitrate salt, contained in tubes, as the heat transfer fluid [this is also called a salt-in-tube (SIT) receiver]. In the last 12 years many studies and test programs have been carried out to develop and demonstrate the viability of molten-salt central receiver power plants. Molten nitrate salt (60% sodium nitrate and 40% potassium nitrate, by weight) is used as the working fluid because its high density and specific heat make it attractive for thermal storage systems, and it is chemically stable at high temperatures [2]. A SIT receiver has a significantly higher flux limit than the Solar One receiver, up to 0.85 MW/m^2, because thin-walled tubing was used. In addition, the SIT receiver can be smaller, simpler, and more efficient than the Solar One receiver. One significant disadvantage of molten salt receivers is that all the piping must be trace heated to keep the piping above the 240°C freezing temperature of the molten salt.

Three 5-MW$_t$ SIT receivers have been tested at the Central Receiver Test Facility (CRTF) in Albuquerque, New Mexico. The 5 MW$_t$ SIT cavity receiver, shown in Figure 2 was recently tested at the CRTF[3]. This receiver utilized a cavity with a door (cavities are used for reducing thermal losses and wind effects). The absorber was fabricated with Alloy 800 tubes painted with a black paint to increase the absorptivity. The molten salt flows in a serpentine path through the receiver.

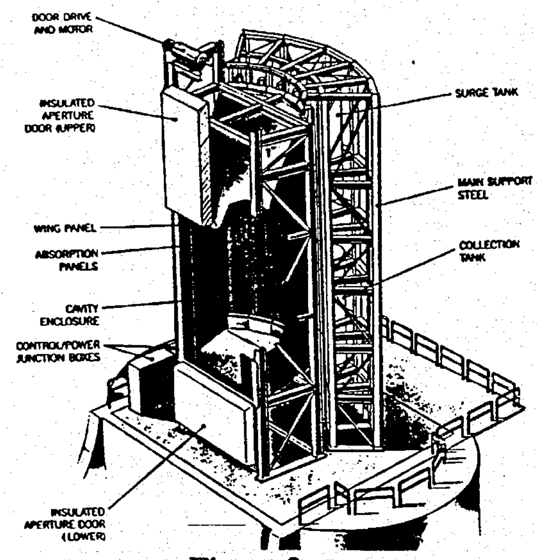

Figure 2
5 MW$_t$ Molten Salt Cavity Receiver

This receiver was designed to test a downscaled prototypical commercial receiver. It was tested for 10 months in 1987 and its performance and capabilities were measured. The receiver had a thermal efficiency of 87% [3] and met all its operating goals.

The SIT technology works and is ready for commercialization. However, the peak flux limit still results in a relatively large receiver which increases both the receiver cost and thermal losses. In addition, the receiver experienced thermal cycling problems and it is still relatively complex. Consequently, any improvements in efficiency and simplification will make central receiver power plants more attractive. Which is why the advanced receiver concepts are being investigated.

3.0 ADVANCED RECEIVER CONCEPTS

3.1 Direct Absorption Receiver

Description of the DAR Concept

The direct absorption receiver (DAR) is an alternative central receiver design in which the heat transfer fluid (a molten nitrate salt, possibly blackened) flows down a vertical panel and directly absorbs the incident solar flux. In the operation of the DAR, "cold"

(285oC) salt is introduced onto the DAR panel at the top of the receiver. The salt flows in a thin, wavy film (typically 2 to 5 mm in average thickness) down the panel surface at velocities of 3 to 5 m/s, through the solar beam which heats the fluid. Hot (565oC) salt is collected at the bottom of the panel and piped down the tower. The ability of the flowing salt film to absorb the incident solar flux depends on the panel design, hydraulic and thermal fluid flow characteristics, and fluid blackener properties. The DAR concept was originally investigated in the 1970's by Sandia National Laboratories [4]. Illustrations of a DAR in an external cylinder configuration and quad-panel configuration are shown in Figure 3a and b, respectively.

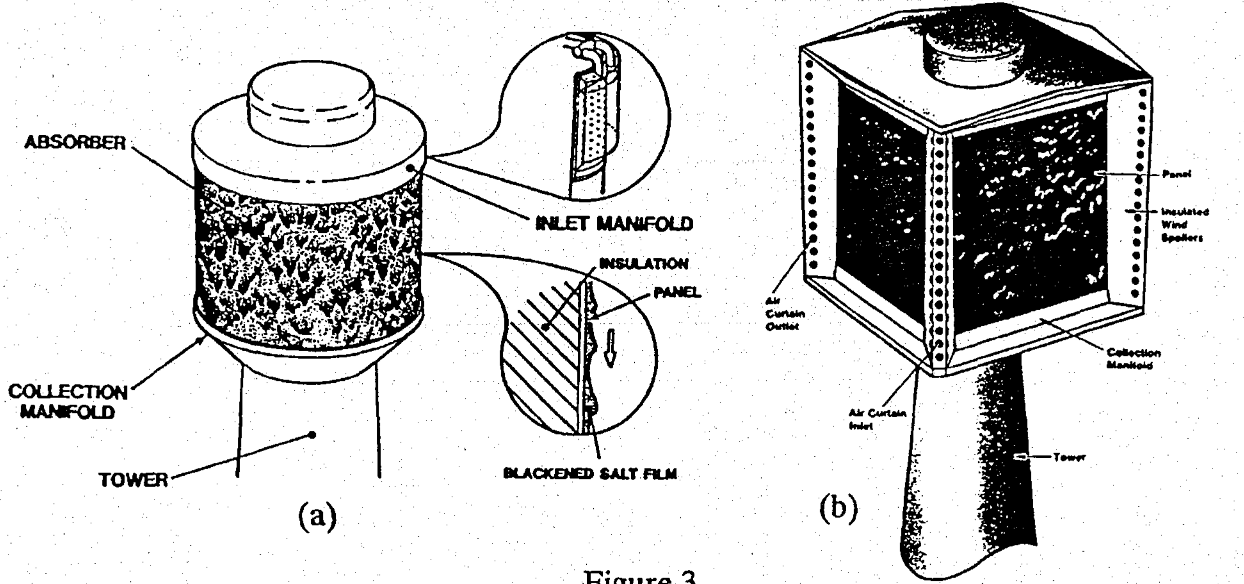

Figure 3
Concepts of Direct Absorption Receivers

A commercial external DAR design [5,6] is shown in Figure 4. It uses a thin, continuous, cylindrical shell, which is pre-tensioned vertically to eliminate potentially damaging compressive stresses and to help absorb wind loading. The shell is also compressively loaded from the inside, though a rigid subpanel and a layer of dense fiber insulation to provide vibration dampening and horizontal pre-tensioning of the the shell.

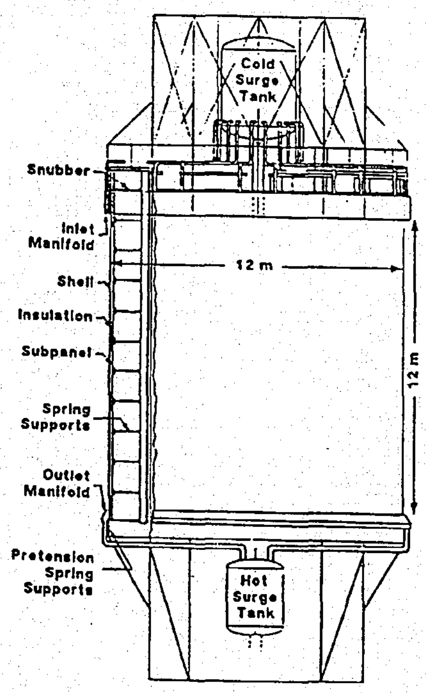

Figure 4
Commercial Design of the DAR

DAR Advantages

Because of its unique design, the DAR offers a number of significant potential advantages over SIT receivers. Potential performance and economic advantages of the DAR include a significantly simplified design, improved thermal performance, increased reliability and operating life, and reduced capital and operating costs. Studies [5,6] have shown that the cost of electricity from a solar power plant utilizing a DAR could be 17-26% less than a plant with a SIT receiver.

The DAR has no tubes on the absorber nor valves for filling or draining the receiver, which simplifies fabrication and operation. Because the DAR is open to the atmosphere, piping, pumps, and valves can be much simpler. The heat tracing on the DAR is also less complicated because of the simplified flow control design. Because of these simplifications the system will be more reliable, and it can have significantly decreased O&M costs compared to a SIT receiver. This DAR design has the potential to be 40% lighter and 30% less expensive than a comparably sized SIT receiver.

The DAR also has the potential for improved efficiency. The increased flux limit of the DAR (the design limit is 2.4 MW/m^2; the actual flux limit may be higher) compared to the SIT (maximum of 0.85 MW/m^2) results directly in decreased receiver size, resulting in decreases in capital costs and lower thermal losses. Thermal losses are also reduced because the surface temperatures of the salt are lower than the corresponding metal surface temperatures in a tube receiver. In addition, because of the reduced thermal mass of the DAR there are smaller thermal losses during startups and transients. Furthermore, because the residence time of the salt on the panel is so small compared to a SIT, the DAR is easier to control.

Development Issues and Test Results

A number of technological uncertainties affecting DAR feasibility require resolution before the concept can be considered a commercial alternative. The key issues that need to be addressed include 1) thermal/hydraulic stability of the flowing salt, 2) DAR panel and component design considerations, 3) salt and blackener chemistry and optical properties, and 4) commercial design and scale-up. A research and development plan to study the DAR was initiated in 1986 by Sandia National Laboratories and the Solar Energy Research Institute (SERI)[7]. This research plan called for systems and design studies, materials testing, and small- and large-scale tests of the DAR.

Water flow testing has been used to evaluate the issues of hydraulic flow stability and panel and component design considerations. Water was used because its flow properties are very similar to those of hot molten nitrate salt, and it is inexpensive and easy to work with. This testing was conducted at Sandia and SERI, on both a laboratory-scale and full-scale.

The greatest concern in the testing of the DAR has been the occurrence of roll waves, which naturally develop in falling liquid films. Water flow testing has shown that these roll waves become increasingly large with distance down the DAR panel [8,9,10]. Fluid ejection from the roll waves occurs at approximately 4.5 m down the DAR panel. The amount of fluid lost by the waves appears to increase with the mass flow rate; the higher the flow rate, the more fluid lost. Water testing at Sandia has also demonstrated that wind aggravates the fluid ejection phenomenon.

To evaluate methods of reducing the roll wave development and the associated droplet ejection, water flow testing was conducted to determine the effect of panel tilt, intermediate manifolds (these stop and redistribute the fluid), and various surface treatments (rougheners, striations, channels, etc). Tilting the panel back 10^o decreases the wave size and fluid loss by half (as compared to the vertical panel). A panel tilt of 20^o decreases the amount of fluid lost even further. The intermediate manifold has been tested and was demonstrated to work satisfactorily and prevent fluid loss. The DAR would be simpler and perform better without tilting the panel or using intermediate manifolds; however, these modifications to the DAR may be needed to limit fluid loss.

The commercial-scale receiver shown in Figures 3a and 4 is not easily modified to incorporate a tilted panel, intermediate manifolds, or some type of wind protection to prevent droplet ejection. Consequently, the alternative concept called the quad-panel DAR configuration, shown in Figure 3b, is currently being studied [11]. In this concept four separate, flat absorber panels, each tilted back 5-10°, are oriented 90° to each other. The panels are separated by wind spoilers. These spoilers also have the capability of having air curtains built in for protecting the fluid flow from the wind and preventing droplet ejection. The cost and performance of the quad-panel DAR are predicted to be similar to the cylinderical DAR concept.

Three molten nitrate salt flow tests of the DAR have been or will be conducted. Thus far the salt flow tests have revealed that the heat transfer coefficient of the salt flowing over the DAR panel may be high enough that the blackener in the salt may not be required. (Orginally, the salt was to be doped with a blackener so that the solar flux would be absorbed directly in the salt; however, because of these results, very little testing of the salt blackener has been conducted). Other salt flow tests demonstrated that the water tests very closely simulate the salt flow. The fluid ejection phenomenon was observed, and the size of waves and amount of fluid ejection were measured [10]. The average salt loss rate is a function of flow rate, salt temperature, and distance down the panel.

To allow large-scale flow testing with molten nitrate salt and to provide a test bed for DAR solar experiments, Sandia has designed and is building a 3-MWt DAR panel research experiment (PRE). The salt flow loop will accommodate a DAR panel 1-m wide by 6-m long with flow conditions typical of a commercial-sized DAR. A diagram of the flow loop for the PRE is shown in Figure 5. The panel will be tensioned to simulate the commercial receiver design.

In addition to providing an opportunity to test all system components and their performance, the PRE salt flow testing will be similar to the laboratory-scale water flow testing, investigating manifold performance, wave phenomena, fluid stability, and fluid loss. Solar testing will include steady-

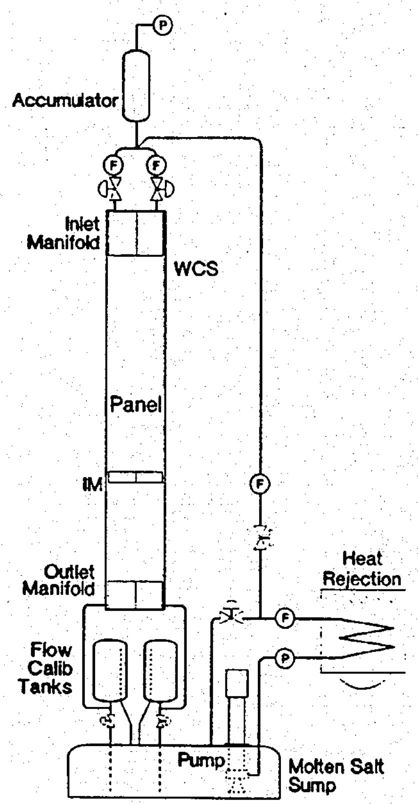

Figure 5
PRE Flow Loop Design

state and transient experiments, thermal loss measurements, responses to severe flux and temperature gradients and high peak fluxes, and optimized operation. This testing will demonstrate the feasibility of the DAR concept and characterize its potential.

The PRE, to be conducted in early 1990, will demonstrate the DAR in a solar environment, with molten salt. This test will also demonstrate whether the intermediate manifold is needed and whether there is a need to make the DAR into a cavity receiver or use wind spoilers or an air curtain due to wind effects on the fluid flow. The DAR represents a significant opportunity to reduce the costs and increase the reliability of central receiver power plants. The testing conducted to date and that yet to be conducted will demonstrate the feasibility and performance of the DAR concept.

3.2 Volumetric Air Receivers

Description of the Volumetric Air Receiver Concept

Volumetric air receivers are also currently being investigated for use in a solar central receiver power plant. A volumetric receiver design is a unique type of solar central receiver that uses a three-dimensional porous absorber (heat exchanger) with a certain volume on which the solar energy is concentrated. The solar energy is absorbed throughout the depth of this volume, instead of on a two-dimensional surface such as a tube surface. Air flows through the absorber, convectively transferring energy from the absorber to the air. A volumetric air receiver can be relatively inexpensive and efficient (the major loss is radiative) and can produce high-temperature air (>550°C) at ambient pressure. A diagram of the volumetric air receiver power plant system design is shown in Figure 6. The volumetric air receiver has applications for electricity production, industrial process heat, and chemical processing. The volumetric air receiver was proposed and first tested in the central receiver configuration in the 1970s [12,13]. In the last few years, there has been a renewed interest in the volumetric air receiver.

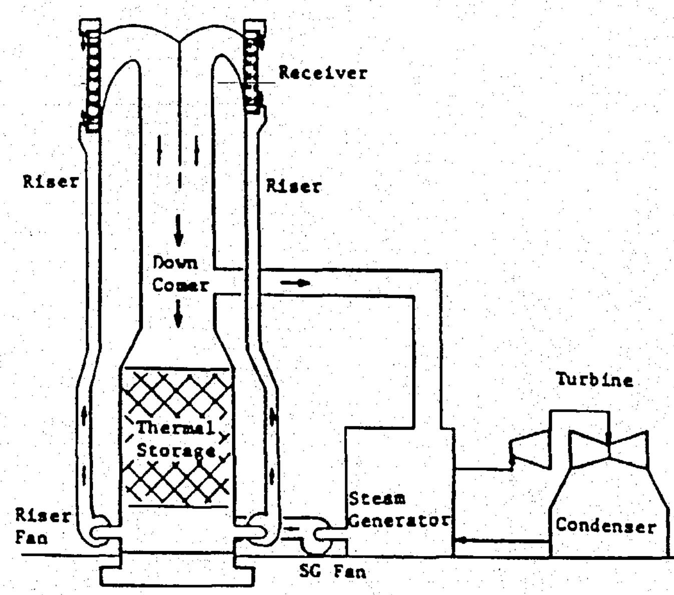

Figure 6
Volumetric Air Receiver System

Advantages of the Volumetric Air Receiver

The major advantages of the volumetric receiver, compared to the SIT and the DAR, are related to the inherent simplicity of using air as the working fluid. The use of air simplifies the heat transport system significantly; no heat trace is required, fluid leaks are not a concern, and there is less auxiliary equipment compared to the molten salt systems. The absorber can also be simpler than an SIT receiver because the absorber material can be either modules of a ceramic material or wire mesh material, which will require some fabrication but no major tube welding like the SIT receiver would require. In addition, the O&M costs of operating a plant with a volumetric air receiver are expected to be lower--in part because the heat transfer medium and absorber materials are easier to work with.

Potential performance benefits of the volumetric receiver are related to the low thermal inertia of the receiver, which will allow rapid startup and response to transient conditions. Also, the thermal losses from a volumetric air receiver should be lower than for the SIT. With the air being drawn into the absorber, there is very little convection loss, and if the absorber is designed correctly, the highest absorber temperature will be at the back of the absorber, thereby minimizing reradiation losses.

The engineering challenges related to the volumetric air receiver are that air is used as the heat transfer fluid. Compared to molten salt, air is a poor heat transfer medium and the air will be at atmospheric pressure (because windows large enough for central receivers are not available, and compressing the air after it is heated is not an option).Consequently, a large volume of air must be used, and the air ducting, thermal storage and steam generators will be very large compared to those in a molten salt system.

Commercial Design Studies and Systems Analysis

In a study by Bechtel National Inc. [14], the receiver consisted of a quad-cavity atmospheric air receiver utilizing a metal wire mesh for the absorber (see Figure 6). The air is heated to 704°C in the receiver and then is drawn into the thermal storage or steam generator. Three important aspects of this volumetric air receiver design are (1) layered metal wire mesh is used as the absorber; (2) the air exiting the steam generator and thermal storage, at 282°C, is returned for the inlet air; and (3) secondary concentrators are used to smooth the flux gradients at the receiver edges and to provide wind protection. Based on this design, Bechtel predicts the volumetric air receiver will be competitive with the SIT receiver plant.

Development and Testing of the Volumetric Air Receiver

The primary issues related to the volumetric air receiver have been the absorber materials and geometries, flux limitation and concerns about the flow phenomena through the absorber. Work on volumetric receivers currently includes characterization testing of absorber materials, modeling, and systems studies.

A volumetric receiver was tested, in the central receiver configuration, at the Plataforma Solar de Almeria in Spain during the summer and fall of 1987 [15]. This receiver utilized a metallic wire pack absorber. A schematic of the overall receiver design is shown in Figure 7. In this 200-kW_t receiver, the air that is heated in the absorber passes through a water-cooled heat exchanger and then is expelled by a fan. A bypass valve at the back of the receiver controls the total air flow.

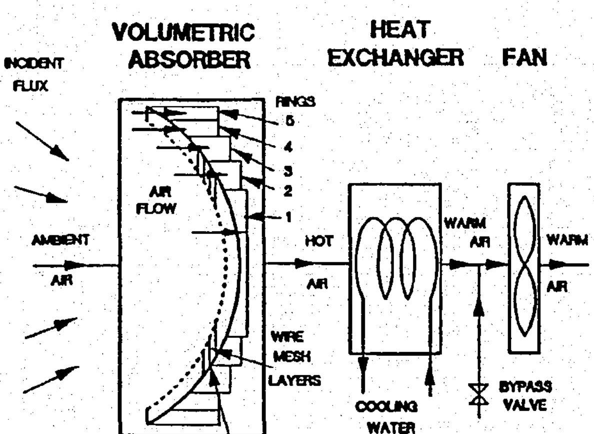

Figure 7
Schematic of the Volumetric Air Receiver

The first absorber tested was a metallic wire pack, which was made up of concentric annular layers of stainless steel wire mesh (0.4-mm diameter wire).

This absorber worked satisfactorily in accomplishing the goal of demonstrating the concept of a central volumetric receiver. However, there were problems in the structural integrity of the absorber and uniformity of the layering of the wire in the absorber. These resulted in nonuniform temperatures and air bypass. Consequently, the testing revealed receiver efficiencies of 65 to 70% at 550°C. A computer model of this volumetric receiver was developed by Sandia as a tool for designing and evaluating wire mesh absorbers for volumetric receivers [16]. Given the flux profiles and the inlet and outlet temperature conditions, the model calculates the convective and radiative energy transfer and determines the air mass flow required. The model also calculates efficiencies for the absorber. An efficiency of 80% was calculated for this volumetric receiver absorber at an air outlet temperature of 550°C.

A second absorber using a stainless steel wire mesh (0.27-mm diameter wire) wound into a spiral was tested in 1988. This absorber performed significantly better than the first absorber in that it was more structurally stable, and test results showed receiver efficiencies of 75-85% at 600°C [17].

A ceramic "foam" porous absorber was tested by Sandia on the volumetric receiver test bed in Almeria, Spain [17]. The ceramic foam is made up of 92% alumina and was selected for the absorber material because it is structurally stable and has a high temperature (>1000°C) capability. Results from the testing showed that the ceramic maintains its integrity in the high temperature-high flux environment. Thermal efficiencies of the ceramic absorber are approximately 65-70% at 550°C. However, this test was only a concept demonstration and the absorber was not optimized.

Other absorber materials and geometries have been tested, such as ceramic honeycomb material and thin silicon fibers. However, these materials are not suitable for use in volumetric air receivers because of practical considerations, mechanical limitations, or because they do not exhibit good thermal performance. A feature that needs to be incorporated into future absorber materials and geometries is to make the absorber with a lateral variable porosity. By making the absorber more porous at the front and more dense at the back, a much more volumetric absorbing effect can be obtained.

Most of the testing conducted to date has been feasibility testing of the concept on volumetric receivers in the 200-kWt size and evaluation of absorber materials and geometries. Sandia currently has plans for conducting absorber material characterization and additional modeling of the volumetric receiver. In addition, a European consortium is developing a plan for the development of the volumetric air receiver. However, a system test of a volumetric air receiver in the megawatt size is not expected until 1992-93.

4.0 SUMMARY OF CENTRAL RECEIVER DEVELOPMENT

Central receiver technology is a valuable resource and can supply a significant portion of our future energy needs. Research and development have provided a sound technical base for the use of central receiver power plants. However, the energy costs from a central receiver using today's technology are about two times higher than those for conventional power plants. Consequently, advanced central receiver technology needs to be investigated and developed to make it a cost-effective, viable energy alternative.

The DAR has the potential to reduce the cost of energy by 26% because of its efficiency and simplicity. As part of the program to develop the molten salt DAR for use in central receiver systems, we have conducted a significant number of tests to evaluate development issues. Although there are some concerns about the potential for fluid ejection from the DAR panel, this phenomenon can be solved with the use of intermediate manifolds, wind spoilers, air curtains, and/or tilting the panel back. Panel designs and manifolds have been developed for use with the DAR. Due to the higher-than-expected heat transfer coefficient of the salt, a blackener may not be needed. A 3-MW_t receiver test will be conducted in the Spring of 1990 to demonstrate the feasibility of the DAR concept.

The volumetric air receiver also has the potential to be simpler than the current central receiver technology. A number of receiver absorber tests have been conducted in Spain. These tests have demonstrated the feasibility of the concept. However, much more development and testing is needed to optimize the receiver and define the remainder of the volumetric air receiver system. The volumetric air receiver development is behind that for the SIT receiver and DAR. A volumetric air receiver system test is expected to take place in 1992 at the Plataforma Solar de Almeria in Spain.

Central receiver power plants will become increasingly attractive as fossil fuels become more scarce and costly and if environmental issues continue to be important.

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