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DEVELOPMENT AND TESTING OF ADVANCED CENTRAL RECEIVERS

James M. Chavez

Sandia National Laboratories
Albuquerque, New Mexico 87185

ABSTRACT

Advanced central receiver concepts are currently being investigated 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. 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 and cheaper than conventional tube-receivers.

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 both the direct absorption receiver and the volumetric receiver are discussed.

1. INTRODUCTION

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. In convential designs, the fluid is contained in 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.

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. The Solar One power plant utilized a water/steam receiver, with a peak flux limit of 0.3 MW/m^2. Solar One successfully demonstrated the feasibility of solar plants but also experienced many of the limitations listed above [1].

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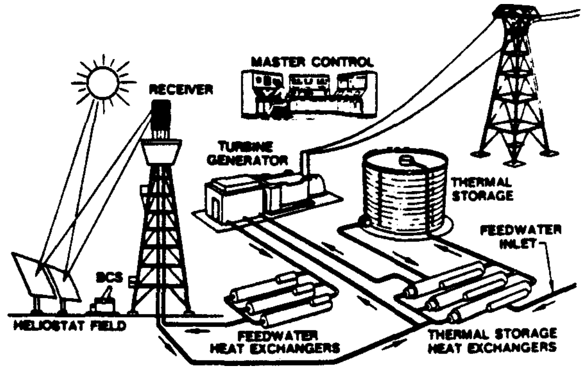

Figure 1. Schematic of Solar One Power Plant, a Central Receiver System

The current state-of-the-art central receiver utilizes molten 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 elevated temperatures. The SIT receiver has a significantly higher flux limit, up to 0.85 MW/m^2, than Solar One. In addition, the SIT receiver can be simpler and more efficient than Solar One. Three scaled-down, 5-MW$_t$ SIT receivers have been tested at the Central Receiver Test Facility (CRTF) in Albuquerque, New Mexico. Even though the flux limit for an SIT receiver was increased over Solar One, the peak flux limit still results in a relatively large receiver which increases both the receiver cost and thermal losses.

In a different economic environment the SIT receiver could be part of a viable solar plant. 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.

2. DIRECT ABSORPTION RECEIVER

2.1 Concept Description

The direct absorption receiver (DAR) is an alternative central receiver design in which the heat transfer fluid (a blackened molten nitrate salt) flows in a thin, wavy film down a vertical panel and directly absorbs the incident solar flux. The DAR concept was originally investigated in the 1970's by Sandia National Laboratories [2]. Figure 2 is an illustration of a DAR in an external cylinder configuration. Both the external cylindrical DAR, with a surround heliostat field, and a north-facing cavity (in a cavity receiver the absorber panel is contained within an enclosure to reduce thermal losses and reduce wind effects) DAR, with a south-facing heliostat field, are being considered in the DAR development program.

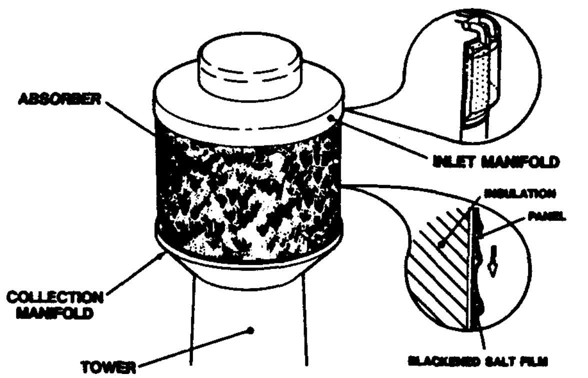

Figure 2. Direct Absorption Receiver

In the operation of the DAR, cold (285°C) 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 (565°C) 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.

2.2 DAR Potential 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. A commercial design of the DAR is shown in Figure 3 [3].

The design and construction of the DAR can be much simpler and more reliable than for a tube receiver. The DAR has no tubes on the absorber, and no drain or purge valves, which simplifies fabrication and operation. Because the DAR is open to the atmosphere the riser and downcomer piping and pumps and valves can be much simpler in the DAR. The heat tracing on the DAR is also less complicated because the flow controllers can reside

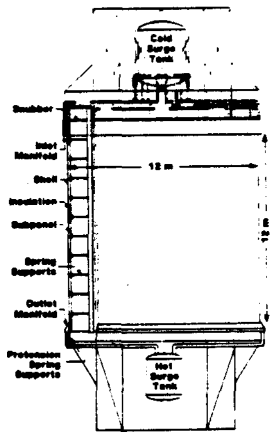

Figure 3. Commercial Design of the DAR

in the flow manifold and do not require stem seals or valve bodies. (Heat tracing is required on all molten salt piping because the salt freezes at approximately 240°C.) Because of these simplifications the system will be more reliable, and it can have significantly decreased O&M costs compared to a SIT receiver.

The DAR has improved efficiency because 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 receivers 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 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.

2.3 DAR Commercial Design Studies and Systems Analysis

Two commercial design studies have been performed on the DAR, one looked at the cavity DAR (100 MW$_t$) [4] and the other looked at the external DAR (320 MW$_t$) [3]. These studies included assessments of design alternatives for absorber panels, stress and deformation, analyses of these designs, mechanical and thermal/hydraulic design, evaluation of fabrication issues, and comparisons of weight and cost to commercial SIT receivers.

Because it is the most recent and most applicable to the ongoing work, only the external DAR design study will be discussed here. The commercial external DAR design, shown in Figure 3, uses a thin, continuous, cylindrical shell. The shell is pretensioned 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 pretensioning of the the shell. This DAR design has the potential to be 40% lighter and 30% less expensive than a comparably sized SIT receiver.

Anticipated DAR cost savings arise from two major areas:

1) substantially lower costs (capital and O&M) for the receiver and some supporting components, and 2) improved system efficiency.

A system study was conducted by Tyner [5] to evaluate the economics of the DAR compared to the SIT receiver. In this study the baseline SIT receiver (0.85 MW/m^2 flux limit) was compared with the DAR (maximum flux of 1.7 MW/m^2). Tyner showed that in the "near term" the Levelized Cost of Energy (LEC) of the DAR could be 17.5% less than the baseline SIT receiver. In the "long term" the DAR could have a 26.2% lower LEC than a SIT. Tyner predicted that the DAR is capable of meeting the DOE cost goals for receivers.

2.4 DAR Development Issues and Testing

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 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) [6]. This research plan called for systems and design studies, materials testing, and small- and large-scale tests of the DAR.

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

Inlet distribution manifolds and collection manifolds were developed and evaluated with the water flow testing. The inlet manifolds uniformly distribute the fluid onto the DAR panel. The manifold design was tested both in the laboratory and on the full-scale test.

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 [7]. Fluid ejection from the roll waves was observed 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 on the 10-m external cylinder at Sandia demonstrated that wind may aggravate the fluid ejection phenomenon.

Since fluid loss on the DAR may be unacceptable, additional water flow testing was conducted at Sandia to evaluate the effect of panel tilt, intermediate manifolds (these stop and redistribute the fluid), and various surface treatments (rougheners, striations, channels, etc) on the wave development and associated fluid ejection. 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 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.

Three molten nitrate salt flow tests of the DAR have been or will be conducted. SERI has tested two DAR panels with salt: one was a 0.6 m long panel [8] for demonstrating the feasibility of the DAR concept, the other was a 5-m long panel used to evaluate the thermal/hydraulic characteristics of the salt flow and to compare these characteristics with the water tests. 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 SERI tests demonstrated the feasibility of the DAR concept with solar testing on the 0.6 m long panel. Testing with simulated solar energy 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. In addition, the fluid ejection phenomenon was observed and the size of waves and amount of fluid ejection was measured [9]. The average salt loss rate is a function of flow rate, salt temperature, and distance down the panel. During the flow testing on the 5-m panel, the panel began to deform due to thermal cycling and the thermal stresses. The panel deformation significantly affected the fluid loss rate and demonstrates the need for a tensioned panel, as discussed earlier in the commercial design study.

The demonstration test of the DAR will be the PRE. An artist's conception of the PRE solar test atop the CRTF tower is shown in Figure 4. 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 and panel design for the PRE are shown in Figure 5. The panel will be tensioned to simulate the commercial receiver design. The location of the intermediate manifold is shown on the drawings.

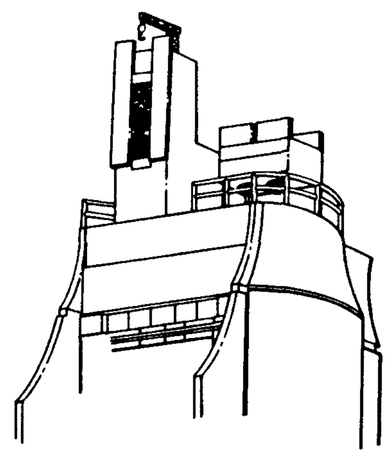

Figure 4. Artists Concept of the PRE

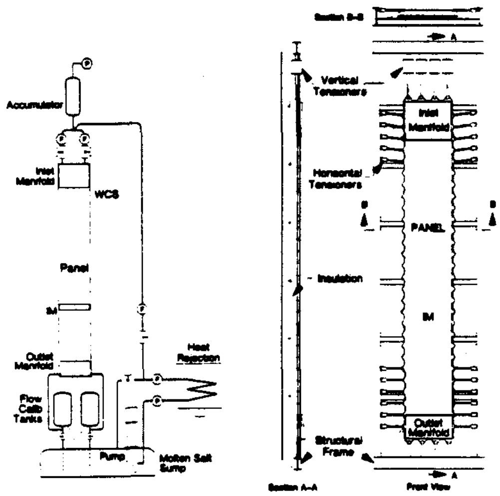

Figure 5. PRE Flow Loop and Panel Design

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. The flow testing will also allow tuning of the control system and flux-off thermal loss testing at various temperatures.

Once the flow testing has been completed, a heat rejection system and water-cooled shielding panels around the PRE will be added, and the receiver will be moved up the tower for solar testing. Testing will include steady-state and transient experiments, thermal loss measurements, responses to severe flux and temperature gradients and high peak fluxes, and optimized operation.

Instrumentation for the PRE will include extensive thermometry, redundant flow measurement, incident solar flux measurement, and high speed photography to view the flowing salt film. If available, an infrared temperature measurement system will be used to determine film surface temperatures. Automated control of the experiment will be performed and monitored with a state-of-the-art distributed-process control system.

2.5 Summary of the DAR Development and Testing

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 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--consequently, very little testing of the salt blackener has been conducted. The PRE, to be conducted at the end of 1989, 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 due to wind effects.

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. VOLUMETRIC AIR RECEIVERS

3.1 Concept Description

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.

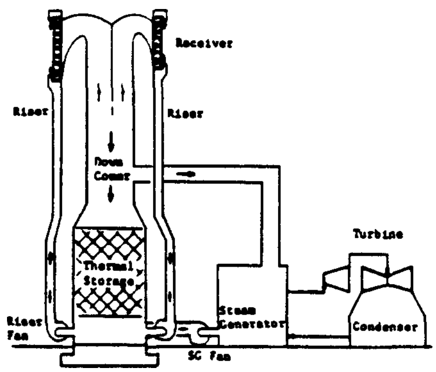

Figure 6. Volumetric Air Receiver System Diagram [10]

The volumetric air receiver was proposed and first tested in the central receiver configuration in the 1970's [11]. In the last few years there has been a renewed interest in the volumetric air receiver. This renewed interest is a result of the formation of the Phoebus consortium (a consortium of European and U.S. companies) which is planning to build a 30 MWe solar power plant by 1995. The Phoebus consortium has expressed an interest in using a volumetric air receiver in the plant.

3.2 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.

Performance benefits of the volumetric receiver are related to the low thermal inertial 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 relatively 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 the air ducting, thermal storage and steam generators will be very large compared to those in a molten salt system. However, these are engineering challenges and not necessarily disadvantages in cost or performance.

3.3 Commercial Design Studies and Systems Analysis

Three commercial design studies and systems analyses of the volumetric receiver have been conducted. The first study was conducted by Drost at Pacific Northwest Laboratories [12] for a solar air heating plant. The first study to evaluate an air system for electric generation was part of the Phoebus study [13], evaluating a 30 MWe plant. A more recent study of a 100 MWe plant [10] was conducted by Bechtel National Inc., in support of the Phoebus consortium.

Because it is the most recent and most applicable to current efforts, only the Bechtel study will be described here. In the Bechtel study 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 the Bechtel volumetric air receiver 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 a small cost advantage over the SIT receiver plant.

3.4 Volumetric Air Receiver Development and Testing

To date very little testing of the volumetric air receiver concept has been conducted. The primary issues related to the volumetric air receiver have been the absorber materials and absorber geometries. Other work on volumetric receivers, besides the system studies, currently includes characterization testing of absorber materials, and modeling of volumetric receivers.

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 [14]. This receiver (designed and built by Sulzer Bros. Ltd, Switzerland) utilized a metallic wire pack absorber. A schematic of the overall receiver design is shown in Figure 7. The absorber fits in the front of the receiver up against a pressure plate. Design conditions for this receiver are to produce 200 kW of power at 80% efficiency at 550°C. In this receiver, the air that is heated in the absorber passes through a water-cooled heat exchanger and then is expelled by a fan. A by-pass valve at the back of the receiver controls the total air flow. The air flow through each of five concentric annular "ring" flow paths is controlled with individually adjusted dampers located directly behind the absorber.

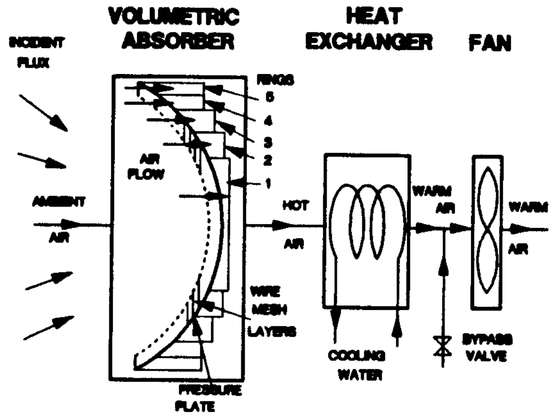

Figure 7. Schematic of the Volumetric Air Receiver

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. 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 [15]. 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 (also built by Sulzer) has been tested on the existing volumetric receiver. This absorber uses a stainless steel wire mesh (0.27 mm diameter wire) wound into a spiral and then wrapped again in a spiral up against the pressure plate. 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 [16]. Additional development of this absorber is being conducted.

A ceramic "foam" porous absorber is currently being tested by Sandia on the volumetric receiver test bed in Almeria, Spain [16]. 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. Preliminary results from the testing of the ceramic foam show that it maintains its integrity in the high temperature-high flux environment. Thermal efficiencies of the ceramic absorber are approximately 80% at 550°C.

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. Other absorber materials and geometries have been proposed for testing, although test results on these absorbers are not yet available. 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.

3.5 Summary of the Volumetric Air Receiver Development

As stated previously, comparatively little development and testing of the volumetric air receiver has been conducted. Most of the testing conducted to date has been feasibility testing of the concept on volumetric receivers in the 200 kWt size. Sandia currently has plans for conducting absorber material characterization and additional modeling of the volumetric receiver. Additionally, the Pheobus 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.

Although much more development and testing is needed, the studies to date have shown that the volumetric air receiver can reduce the cost and increase the reliability of solar central receiver power plants.

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