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RESULTS OF THE DESIGN AND TESTING OF A POROUS CERAMIC ABSORBER FOR A VOLUMETRIC AIR RECEIVER*

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ABSTRACT

A new absorber for a volumetric receiver was designed, built, and tested on an existing volumetric receiver test bed (200 kW_t) at the Plataforma Solar de Almeria test facility in Spain. Volumetric air receivers are currently being investigated for use in solar central receiver power plants because of their inherent simplicity. The volumetric air receiver is a unique type of solar central receiver that uses a porous absorber (heat exchanger), on which the solar energy is concentrated and absorbed within its volume. Air flows through the absorber, convectively transferring energy from the absorber to the air. Volumetric receivers have applications in electricity production, industrial process heat, and chemical processing.

We designed this new volumetric receiver absorber to use a porous ceramic. This material was selected because of its structural strength, high temperature capability, and the potential for using smaller pieces to build up an absorber. The ceramic absorber was tested at the Plataforma Solar de Almeria with a solar flux of up to 1200 kW/m^2, and it produced outlet air temperatures of 730°C. The porous ceramic material has exhibited reasonable thermal efficiencies and excellent structural integrity in the high-flux, high-temperature environment.

In this paper we summarize previous tests on the volumetric air receiver and present the current absorber design and test results.

1.0 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 conventional 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.

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 produce high-temperature air (>550°C) at ambient pressure. The volumetric air receiver has applications for electricity production, industrial process heat, and chemical processing. A schematic of a volumetric air receiver power plant system design is shown in Figure 1.

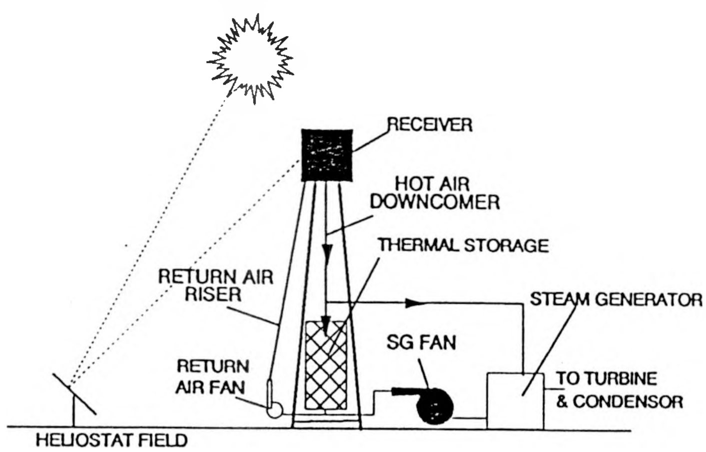

Figure 1
Volumetric Air Receiver System

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Volumetric air receivers are currently being investigated for use in a solar central receiver power plant because of their potential benefits. The major advantages of the volumetric receiver, compared to the current state-of-the-art receiver (these receivers use molten nitrate salt flowing in tubes [2]) are related to the inherent simplicity of using air as the working fluid. Potential performance benefits of the volumetric receiver are related to the low thermal inertial of the receiver, which will allow rapid start-up and response to transient conditions. Also, the thermal losses from a volumetric air receiver can be lower than for the other receivers. 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 radiation losses. The engineering challenges related to the volumetric air receiver are that air is used as the heat transfer fluid. Compared to molten salt, atmospheric pressure air is a relatively poor heat transfer medium (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 because of the power required). 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.

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 composed of European and U.S. companies which is planning to build a 30-MW_e solar power plant by 1995 in Jordan[3]. The Phoebus consortium has expressed an interest in using a volumetric air receiver in the plant. A recent study of a 100-MWe volumetric air receiver plant was conducted by Bechtel National Inc.[1] in support of the Phoebus consortium. In this study the receiver consisted of a quad-cavity atmospheric air receiver utilizing a metal wire mesh for the absorber. Based on this design, Bechtel predicts that the cost of electricity from a volumetric air receiver will be essentially the same as for a state-of-the-art molten salt receiver.

2.0 PREVIOUS DEVELOPMENT AND TESTING

Development and testing of the volumetric air receiver concept has been limited mostly to absorber materials and geometries. This work has consisted of material evaluation and characterization, computer modeling of absorber designs and geometries, and testing of scale model absorbers (200 kW_t).

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 [4]. 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 2. The absorber fits in the front of the receiver up against a pressure plate. Design conditions for this receiver were to produce 200 kW_t 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 by individually adjusted dampers located directly behind the absorber. The absorber size in these tests was 90 cm in diameter.

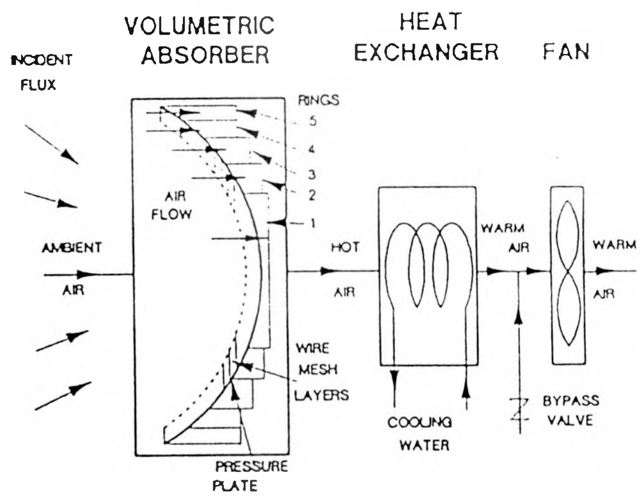

Figure 2
Schematic of the Volumetric Air
Receiver Tested in Spain [4]

The first absorber tested was a metallic wire pack made up of concentric annular layers of stainless steel wire mesh (0.4-mm diameter wire). The thickness of this absorber was approximatly 3 cm. 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 [5]. A computer model of this volumetric receiver was developed by Sandia as a tool for designing and evaluating wire mesh absorbers for volumetric receivers [6]. 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. The results of the model and test did not agree because of the nonuniformity of the absorber and changes in its integrity during the testing.

A second wire mesh absorber (also built by Sulzer) was tested on the existing volumetric receiver. This absorber used 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 [5]. However, there was some degradation of the material in the areas of high flux. Additional development of this absorber is being conducted.

Other absorber materials and geometries have been tested, such as ceramic honeycomb material and thin silicon fibers [7]. However, these materials do not appear to be 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 (through the depth) 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.

3.0 DESCRIPTION OF THE ABSORBER

A new volumetric receiver absorber was designed, built, and tested as part of the International Energy Agency (IEA) solar test program (Task VII) being conducted in Almeria, Spain [8]. The absorber was installed and tested on the previously described volumetric receiver at the Plataforma Solar de Almeria test facility in Spain. Our reason for designing, fabricating, and testing this volumetric receiver absorber was to evaluate materials and structures other than metallic wire mesh for use as an absorber. The purpose of this testing was to investigate the feasibility of using a porous "foam" material as the absorber in a volumetric air receiver. Because it was a first-of-a-kind test, the absorber design was not optimized.

Initially, all types of material were considered for use as the absorber. However, a porous ceramic "foam" made up of 92% alumina was selected for the absorber material because of the material properties, time, cost, and size limitations. The porous ceramic material is structurally stable and has a high-temperature (>1000°C) capability. Furthermore, porous ceramics (both alumina and silicon carbide) are readily available.

The initial design of the absorber was performed by the University of Colorado [9] using the Sandia developed volumetric receiver code "HOTAIR". The code was used to select the geometry and material thickness. However, the HOTAIR code was developed for discrete layers of wire mesh, not a continuous porous ceramic material. In addition, the actual properties (web diameter, heat transfer coefficient, etc.) for the ceramic material were not known. Consequently, the final design of the ceramic absorber obtained was not optimized.

A material of 92% alumina with 80% porosity, 20 pores/inch (20ppi), and a thickness of 3 cm was chosen for the absorber. The thickness of 3 cm was selected based on the model and previous designs. Schematics of the actual absorber design are shown in Figure 3, the absorber was designed to fit into the existing volumetric receiver at the Plataforma Solar de Almeria. The side view, in Figure 3; shows the manner in which the pieces are assembled against the existing pressure plate. The front view shows the 17 individual pieces that make up the absorber and the manner in which they fit together. This absorber was smaller in area than previous absorbers tested because of the method of construction. There are three types of absorber pieces in this design--the center octagon, the first radius trapezoid, and the second radius trapezoid.

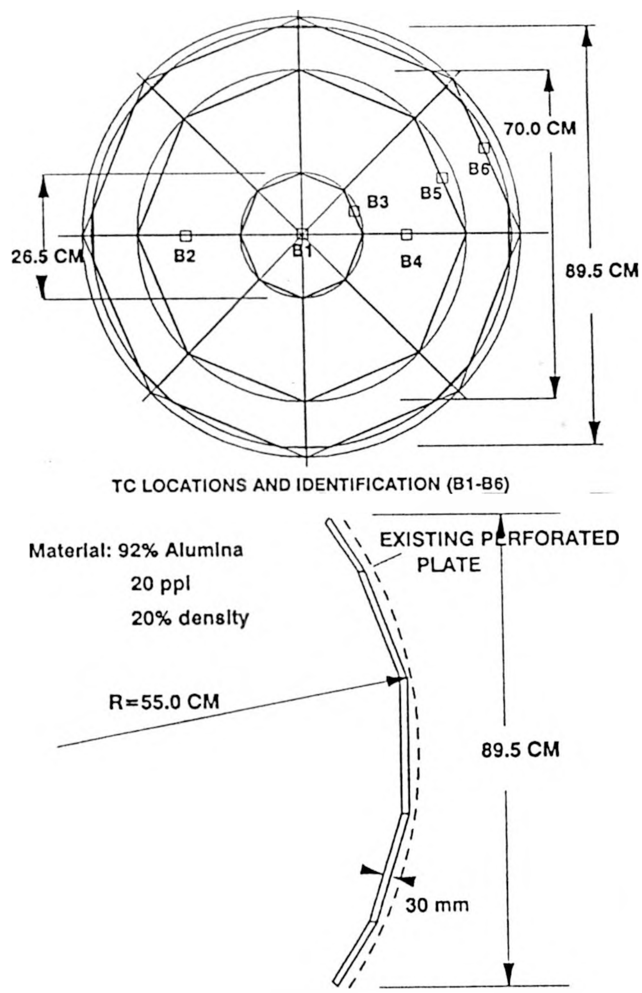

Figure 3
Schematic of the Ceramic Absorber

The individual pieces are flat and tapered at the edges to fit together up against the bowl shaped pressure plate. The absorber holds itself together in the test position (similar to an arch). However, studs were welded to the pressure plate, with washers and nuts holding the pieces at the intersection to facilitate assembly and for safety. The bolts were covered with ceramic cement (to act as an insulator). Ceramic fiber material and ceramic cement were also placed between individual ceramic pieces to act as a gasket. The absorber was assembled on the receiver at the Plataforma Solar de Almeria [10]. Some minor modification of the absorber was required during the final assembly. A picture of the assembled absorber is shown in Figure 4. Note the ceramic cement at all the joints.

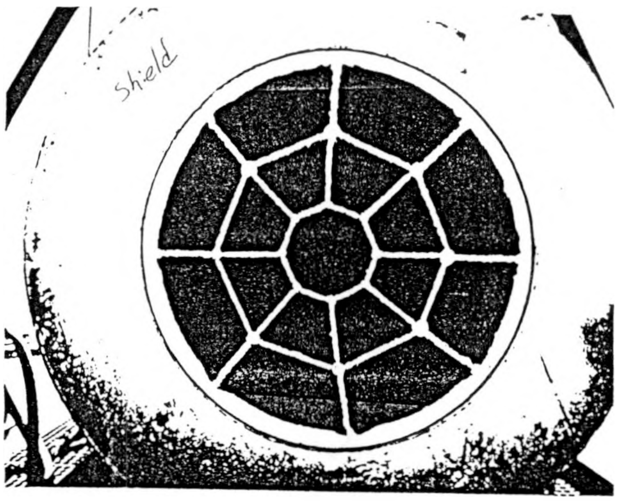

Figure 4
Picture of the Ceramic Absorber

The absorber pieces were painted with Pyromark 2500 flat-black paint by the absorber manufacturer to increase solar absorptivity of the pieces. Unfortunately, the only method of painting the pieces at the time was to dip them in the paint and use an air hose to blow off the excess paint prior to curing them. This method of painting left a very thick layer of paint and blocked many of the ceramic pores. Even so the absorber had an effective absorptivity of 97% [11].

Instrumentation of the absorber included six thermocouples imbedded within in the absorber to measure ceramic material temperatures. The type K, stainless steel sheathed thermocouples were placed in holes drilled 1.5 cm into the absorber. The locations of these six thermocouples are shown in Figure 3.

4.0 DESCRIPTION OF THE TEST BED

A schematic of the test bed is shown in Figure 2. A complete description of the volumetric receiver test bed can be found in Reference 5.

In addition to the absorber instrumentation, other measurements made on the test bed consisted of the following (refer to Figure 2):

- -water cooler inlet and outlet temperature
- -front shield water inlet and outlet temperature
- -cooling water flow rate
- -air temperatures (20 each) at three locations; just behind the pressure plate, in the plenum, and at the fan outlet
- -incident flux at the face of the absorber, with the flux measurement device, 6 calorimeters[5].

These measurements were used to characterize the performance of this absorber.

As stated previously in Section 2, the air flow through the absorber is controlled by five concentric annular "ring" flow paths behind the pressure plate (see Figure 2). The flow rate through each ring is controlled with individually adjusted dampers located directly behind the absorber. The receiver has to be dismantled to adjust them. Before starting this test, the dampers were set to the original setting from the first receiver test [5].

5.0 TEST RESULTS FROM THE POROUS CERAMIC ABSORBER

The testing of this absorber followed the basic test plan used in previous volumetric receiver tests. There were two types of tests; steady-state and transient testing. It should be noted that there was some concern about the rate with which flux is put onto the ceramic material and the resulting temperature shock. Consequently, for the first phase of testing the flux was applied very slowly.

The steady-state tests were designed to determine the steady-state absorber efficiency as a function of air mass flow rate, incident power, and outlet temperature. The steady-state testing started at low outlet temperatures, 200°C, and increased to 800°C. In order, to obtain these temperature increases and reach the desired outlet air temperature, both the incident flux and air mass flow rate were varied. The air mass flow could be modified by adjusting the fan speed control or the butterfly by-pass valve (see Figure 2). Sometimes the aiming strategy of some heliostats were adjusted to achieve a uniform outlet temperature. However, this was not a significant problem as in previous tests [5]. Once a stable outlet air temperature was reached the incident power was measured with the flux measuring device [12].

Absorber efficiency was determined indirectly because there was no air flow measurement available. The absorber efficiency is defined as the power gained by the air flowing through the absorber divided by the power incident on the aperture. Incident power was measured by the flux measurement device for each steady-state test. To determine the power absorbed by the air the air mass flow rate is needed. The air mass flow rate is evaluated by performing an energy balance of the system. The power gained by the heat exchanger and the power lost by the receiver casing are used in the energy balance. That is, the absorber power is equal to the power absorbed by the cooler and that lost by the receiver casing. Once the air flow rate is calculated the air flow rate and enthalpy difference in the air is then used to calculate the absorber power. Measured air temperatures behind each concentric flow ring were weighted to obtain a mean absorber outlet temperature. There is a large uncertainty associated with this method of evaluation of thermal efficiencies [5].

A total of 87 steady-state tests was conducted. The peak mean outlet air temperature was 730°C. The absorber efficiency as a function of mean outlet air temperature is shown in Figure 5. In this plot the effect of increasing outlet air temperature can be seen; because of increased radiation the absorber efficiency decreases. The mean absorber efficiency is on the order of 65% at 550°C. At the absorber peak outlet temperature of 730°C the efficiency was calculated to be 54%. In Figure 6 the absorber efficiency as a function of absorber power is shown. This plot illustrates that at a given temperature the power absorbed by the air increases while the radiation losses remain somewhat constant. These steady-state test results clearly indicate that the absorber is not optimized. This is further demonstrated by the temperature measurements of the absorber. With a mean outlet temperature of 550°C, the absorber temperatures were up to 350°C higher (thermocouples B1 and B4, near the center of the absorber, recorded the highest temperatures) than the outlet air temperature. At the peak mean outlet temperature of 730°C the absorber temperature was measured to be 1350°C at thermocouple B1. However, the material temperature in the center of the absorber should not have been nearly that high. Higher outlet temperatures could not be reached because of limitations of the test bed.

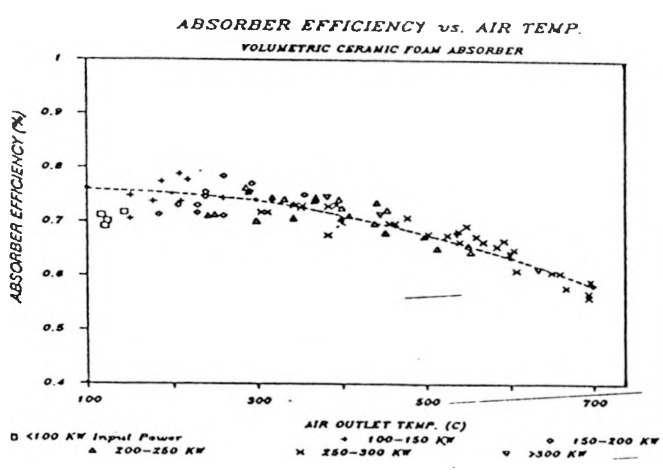

Figure 5
Plot of Absorber Efficiency vs. Outlet Air Temperature

With an optimized absorber we expected an absorber efficiency of 80-85% at 550°C. Since the primary objective of this test was to evaluate the use of porous ceramic as a volumetric air receiver absorber--an optimized design was not an overriding consideration. Yet, there are a few main reasons for the lower-than-expected efficiencies. First of all, the optical density of the material was too high to begin with (too high of density, too many pores per inch). Second, the Pyromark paint used to increase the absorber absorptivity was too thick; the paint blocked many of the pores and micropores, which increases the apparent optical density of the absorber. Finally, the efficiency may be artificially low because the area lost to the ceramic cement and the outside radius covered by insulation was not taken into account. This lost area is approximatly 5% of the absorber area.

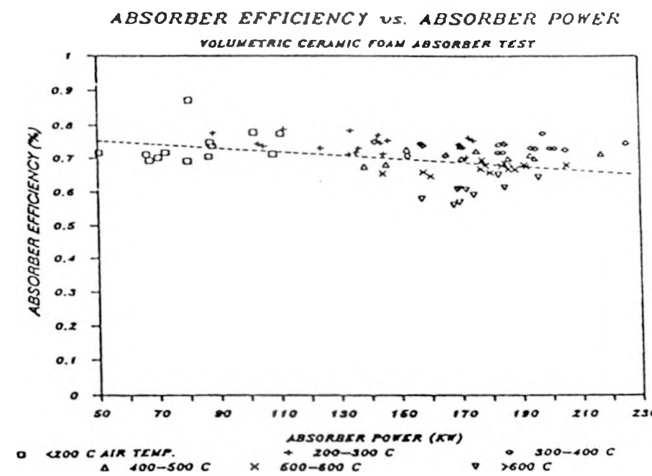

Figure 6
Plot of Absorber Efficiency vs. Absorber Power

Transient testing was conducted to characterize the thermal inertia of the absorber. These tests were conducted by allowing the outlet temperature to reach steady-state, then 20% of the incident power was removed. Once the outlet temperature stabilized again the initial incident power was put back on the absorber. A time constant was determined assuming an exponential temperature change in response to the step change in the input power. At a steady-state outlet temperature of 550°C, the receiver had a time constant of 365 seconds. It should be noted that the shielded thermocouples behind the pressure plate have a slow response, which could affect the results of this test. The time response of the wire mesh absorber previously tested was on the order of 100 seconds [5]. Clearly, the heavier, thicker ceramic material will have a higher time constant than the wire mesh absorber. However, the response time effect on start-up or cloud transients are not significant in either case.

At the beginning of the testing, there were concerns about thermal shocking of the ceramic material; however, there was not any cracking of the absorber pieces. Transient testing demonstrated that the ceramic absorber could handle rapid changes in flux levels. In addition, the absorber was subject to average flux levels as high as 500 kW/m^2, and peak fluxes as high as 1200 kW/m^2. Still there was no cracking or degradation of the absorber at the end of the testing.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The goal of the testing was met by successfully demonstrating that the porous ceramic absorber works well. In the steady-state tests the absorber produced peak outlet air temperatures of 730°C. The absorber efficiencies ranged from 78% at the lower air temperatures to 57% at the higher temperatures. These efficiencies are essentially the same as for the first wire mesh type absorber that was tested [5]. In spite of the lower-than-expected efficiencies, there was no degradation of the ceramic absorber material. Although the absorber was not optimized, it performed well for a first-of-a-kind design.

Two important aspects of the volumetric receiver that we were unable to investigate with this absorber were variable porosity, both radially and laterally, and sizing the pieces to fit the "flow rings" of the receiver. These two aspects could not be designed into the absorber because of time and cost constraints.

As stated previously, comparatively little development and testing of the volumetric air receiver have been conducted. Most of the testing conducted to date has been feasibility testing of the concept on volumetric receivers in the 200-kW_t size. We recommend that the absorber material testing and analysis continue so that an optimized volumetric air receiver absorber design can be obtained.

Other absorber tests are currently planned for the test bed at the Plataforma Solar de Almeria. In addition, Sandia is planning a follow-up test with a porous ceramic absorber with laterally variable porosity at the Plataforma Solar de Almeria in late 1991. Sandia also has plans to conduct absorber material characterization on a solar furnace and additional modeling of the volumetric receiver. The Pheobus consortium is developing a plan to develop 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 testing and studies to date have shown that the volumetric air receiver has essentially the same potential levelized energy cost as the molten salt tubular receiver, but with a simpler working fluid.

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