Volumetric Receivers in Solar Thermal Power Plants with Central Receiver System technology: A review

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1. Abstract

Deployment of the first generation of grid-connected plants for electricity production, based on Solar Thermal Power Plants with Central Receiver System technology using large heliostat fields and a solar receiver placed on the top of a tower, is currently being boosted by the first commercial plants in Spain, PS10, PS20, and Gemasolar.

Therefore one of the main goals of solar technology research is the study of existing receivers and development of new designs to minimize heat losses.

In this context, volumetric receivers appear to be the best alternative to tube receivers, mainly due to their functionality and geometric configuration. They consist of a porous material that absorbs concentrated radiation inside the volume of a structure and transfers the absorbed heat to a fluid passing through the structure. Solar radiation is first converted into thermal energy or chemical potential, and then at a later stage, into electricity.

This volumetric receiver technology has been under development since the early 1990's in various research and development projects. This paper is a chronological review of the volumetric receivers of most interest for electricity production, identifying their different configurations, materials and real and expected results, and pointing out their main advantages and conclusions based on the multitude of international and national projects reports and references.

This study also deals with other important issues surrounding the volumentric receiver, such as the basic plant configuration, flow stability phenomenon and the main problems of a windowed design for pressurized receivers.

Keywords: Absorber; ceramic materials; metallic materials; state of the art; volumetric receivers; central receiver system.

Nomenclature

p	pressure
x	coordinate in the flow direction
μ	dynamical viscosity
K_1	viscous permeability coefficient
K_2	inertial permeability coefficient
ρ	density of the fluid
υ	velocity of the fluid
β	correction factor
σ	Stefan Boltzmann constant ($5.67 \cdot 10^{-8}$ W·m^{-2}·K^{-4})
T_0	inlet temperature
Subscript	
th	thermal
e	electrical
crit	critical

2. Introduction

The increasing problems of CO_2 emissions and energy security concerns have strengthened interest in alternative, nonpetroleum-based sources of energy. Solar Thermal Power Plants (STPP) with optical concentration technologies are important candidates for becoming a major clean, renewable energy resource in the medium-term. Although solar radiation is a high-quality energy resource due to the high temperature and exergy of its source, the low flux density at the Earth's surface makes it unable to extract work or heat a Heat Transfer Fluid (HTF) to temperatures adequate for industrial applications (Sizmann 1991). Hence, the use of STPP unequivocally requires optical concentration. In the framework of Central Receiver Systems (CRS), incident solar radiation (rays) is redirected by large two-axis tracking mirrored collectors called heliostats, in order to concentrate sunlight at a focal point on the absorber surface at the top of a tower where the energy is transferred to the HTF by radiative/convective mechanisms. Reflective solar concentrators are usually used to attain the temperatures required to operate thermodynamic cycles (Mancini et al. 1997).

Solar radiation is converted into thermal energy or chemical potential in the receiver, and at a later stage, into electricity the same way as in conventional fossil fuel plants.

CRS can operate in hybrid configurations with convectional power plants or alone, generating electricity with high annual capacity factors by using thermal energy storage. With storage, CRS plants can operate for over 4500 hours per year at nominal power (Kolb 1998). The main characteristics of CRS plants are summarized in Table 1.

Table 1. Characteristics of Solar Thermal Power Plants with Central Receiver System technology, adapted from (Romero et al. 2002)

Typical Size	10 – 200 MW*
Operating Temperatures - Rankine - Brayton	 ~ 600 ºC ~1000 ºC
Annual Capacity Factor	20-77%*
Peak Efficiency	23%*
Annual Net Efficiency	12-20*
Commercial Status	PS10 (11 MW) PS20 (20 MW) Gemasolar (17 MW)
Technology Development Risk	Medium
Storage available	Pressurized water thermal tanks for saturated steam receivers Nitrate salt for molten salt receivers Ceramic bed for air receiver
Hybrid designs	Yes
Investment cost - €·W^{-1} - €·W^{-1**}	 3.83-2.16* 2.09-0.78*

€·W^{-1} cost per Watt installed

* Values indicate changes over the 2000-2030 time frame

** €·W^{-1} removes the effect of energy storage or solar multiple.

Although most of the new solar thermal power plants built in Spain use parabolic-trough collector technology, higher plant efficiencies and lower electricity production costs still require innovations allowing operation at higher temperatures and higher solar fluxes, as CRS already does.

2.1. Receiver Development

The technical feasibility of CRS has been considered sufficiently mature since the demonstration plants built mostly during the 80s (DeMeo and Galdo 1997; Falcone 1986; Grasse et al. 1991; Mancini et al. 1997), and the wide variety of receivers tested to date. Moreover, several HTFs such as liquid sodium, saturated or super-heated steam, nitrate molten salts and air, have been tested in those plants. The majority of these tests were carried out by European projects at Plataforma Solar de Almeria in Spain (Grasse et al. 1991) and in the USA (Pacheco and Gilbert 1999).

In the USA, the technology was based mainly on solar-only operation with large storage capacities using molten salts as the HTF. This was the case of Solar Two (Radosevich and Skinrood 1989), which is the basis of the nearly completed Gemasolar commercial demonstration plant (Fuentes de Andalucia, Spain). On the other hand, Europe and Israel strongly focus on volumetric receivers with air technology operating in either closed loop for efficient integration into gas turbine cycles, or open loop for intermediate storage and/or hybrid solutions, both backed by such notable projects as Phoebus-TSA, SOLAIR and DIAPR.

In today's context, receivers working with air as the HTF are again being considered an option. Challenges not fully solved in the past, like absorber durability, receiver efficiency and the specific cost, still remain to be solved. Nevertheless, the associated advantages of the air receiver (such as availability of the fluid, no trace heating necessary, non-toxic, 3-5 hours of thermal storage, etc) allow higher-efficiency thermodynamic cycles, and the receiver thermal efficiency may be >75% due to the volumetric effect which reduces thermal radiation losses.

At present, even though this technology has not yet been commercially developed, in Jülich, Germany, a 1.5-MW_e pre-commercial demonstration power tower plant with ceramic volumetric receiver and thermal storage, has been in operation since 2009 (Hennecke et al. 2008). The continuous research and development in volumetric receivers and the first complete power plant built in Jülich make this technology a promising power tower alternative. This paper is therefore an overview of the progress of this emerging energy-efficient technology.

3. Volumetric Receivers

The USA pioneered study of solar energy technologies (Becker and Böhmer 1987; Sander_Associates_Inc. 1979), first with the development and use of tube receivers and later, with Europe (Fricker 1983), searching for alternative receivers based on other concepts, such as the volumetric receiver that were simpler, cheaper, more efficient and had better thermal properties.

Research and development focused on new receivers for future plants with a smaller aperture to minimize heat loss, allowing higher solar flux compared than technologies in use at the time (tube receiver).

Volumetric receivers are more flexible than tube receivers due to their functionality and three-dimensional configuration (volumetric) compared to the quasi-two-dimensional tube.

3.1. Operating principles

The basics principles of a volumetric receiver are:

- A multitude of porous interlocking shapes, knit-wire packs, foam, or foil arrangements, made of metal, ceramic or other adequate materials with a specific porosity are installed in a volume inside the receiver so the solar concentrated radiation is absorbed in the depth of the structure.
- The concentrated solar radiation heats the material in the volume. At the same time, the working fluid passes through the volume and is heated up by forced convection, transforming the solar radiation into thermal energy. Fig. 1 compares absorption in tubular and volumetric receivers.
- Heat is transferred to the working fluid on the surface which is heated up by the incoming radiation.
- Finally, the volumetric effect causes the temperature on the irradiated side of the absorber to be lower than the outlet temperature.

3.2. Absorber Materials

The highly porous structure of volumetric receivers may be metal or ceramic. Since ceramics are the most appropriate materials for achieving the highest air temperatures, this is the most suitable option when temperatures above 800ºC are necessary. Volumetric receivers are capable of producing high outlet air temperatures:

- With metals, a minimum of 800ºC and maximum of 1000ºC are achievable
- 1200ºC are achievable with SiSiC ceramics and 1500ºC with SiC
- Other ceramics with higher temperature ranges, such as alumina ceramics, with a melting point of around 2000ºC, may also be used. Their main disadvantage is that they are white, but they can be doped or coated to increase their absorptivity, retaining their good mechanical properties.

Fig. 2 shows the temperature ranges of various metal and ceramic absorber materials. Note that even metal absorbers can produce outlet air temperatures of up to 1000ºC. The upper temperature limit for SiSiC is given by silicon which melts at around 1400ºC. SiC can reach temperatures of 1400ºC, but is limited to about 1700ºC.

3.3. Flow Stability

In the flow through a porous sample, the mass flow density is determined by the pressure difference between the two sides of the sample. The pressure drop is produced by a blower. Instability occurs when a pressure drop causes different mass flow densities, and can therefore be related to different outlet temperatures.

The poor performance of some receivers is cause for concern. The prediction of outlet air temperatures of over 1000ºC for a variety of absorbers has not been completely fulfilled. (Kribus et al. 1996) predict unstable gas flow through volumetric receivers leading to local overheating and thus poor performance and local failures, such as melting or cracking.

The pressure drop across the structure is described by the Forchheimer extension to Darcy's law:

$$-\frac{dp}{dx} = \frac{\mu}{K_1}\cdot\upsilon + \frac{\rho}{K_2}\cdot\upsilon^2 \qquad (1)$$

Where p denotes pressure, x the coordinate in the direction of the flow, K_1 the viscous permeability coefficient, K_2 the inertial permeability coefficient, μ dynamical viscosity, ρ fluid density and υ fluid velocity. Coefficients K_1 and K_2 are characteristics of the absorber geometry (Pitz-Paal et al. 1996).

In general, an increase in the air outlet temperature can be achieved at a given flux level by reducing the mass flow, which is generally linked to a lower pressure loss. If the flow is unstable, a lower mass flow rate can be linked to a higher pressure loss. This is what happens when there is a linear relationship in the structure between the pressure drop and velocity (Kribus et al. 1996), that is $K_2 = \infty$, where the equation (1) becomes simpler and the graph of the quadratic pressure difference versus the temperature shows what happens with instability. In Fig. 3 constant pressure drop lines intersect the curves with high flux at three points. Therefore, some parts of the absorber may have low mass flow through them and other parts high mass flow, which can generate small sections of local overheating, since the temperature may be beyond the melting point of the absorber material. A slight perturbation, like a local variation in wind pressure or of incident radiation, might be sufficient to switch from one point to other point and vice versa.

Fig. 3 shows the quadratic pressure drop for different solar fluxes and a material with a purely linear pressure drop characteristic ($K_2 = \infty$). It may be seen that there is only instability above a certain solar flux. The critical flux above which instabilities can occur is described in (Becker et al. 2006) and can be calculated with the following equation:

$$I_{0,crit} = 1694 \cdot \beta \cdot \sigma \cdot T_0^4 \qquad (2)$$

Fig. 4 shows the quadratic pressure drop difference for several K_2 at constant solar flux. A change in the characteristics of the absorber (K_1 and K_2) has an important influence on the curves. The lower K_2 is, the less likely instabilities are.

Therefore instability is found only in highly porous honeycomb structures (Pitz-Paal et al. 1996), while in other absorber types (wire mesh, ceramic low-porosity foam honeycomb) the pressure loss characteristic is dominated by a quadratic coefficient, so their behaviour is stable.

3.4. Basic Power Cycle Principles

There are two basic power plant principles in volumetric receiver applications:

- Open loop receiver system with a Rankine cycle; where the atmospheric air is heated up through a metal or ceramic volumetric receiver and then used to produce steam in a heat recovery steam generator with separate superheater, reheater, evaporator and economizer sections, for the Phoebus-TSA scheme, feeding a Rankine turbine-generator system (Romero et al. 2002). The design of an open loop receiver system may include an air return system that would improve receiver efficiency by using the cold air flow leaving the steam generator for two purposes, to cool the receiver support structure and to reuse the enthalpy of the return air. The process flow diagram is summarized in Fig. 5.
- Closed loop receiver system with Brayton cycle; where the introduction of solar energy, with pressurized volumetric receivers, into the gas turbine of Combined Cycle systems (CC) offers significant advantages over other solar hybrid power plant concepts. A very promising system that would fully exploit the potential of the solar/CC combination is solar preheating of the compressor outlet air before it enters the combustor of the gas turbine (Kribus et al. 1998). The solar air preheating system is depicted in Fig. 6.

  Solar air preheating offers better performance, as the solar energy absorbed in the air is converted directly with the high efficiency of the CC plant. For a certain annual solar share, this leads to a reduced heliostat field size and lower investment in the solar part compared to solar steam generation. Moreover, this concept could be applied to a wide power range (1-100MW$_e$). At lower powers, highly efficient recuperated gas turbine cycles can be used instead of CC. The solar share can be chosen quite flexibly by the receiver outlet temperature, which could be higher than with other hybrid concepts (e.g. solar combined cycle system with parabolic troughs) (Buck et al. 1998; Romero et al. 2002).

4. Classification of volumetric absorbers

As mentioned above, volumetric absorbers are the most promising, with a simpler design and on the verge of commercial receiver development.

Due to the great number of absorbers proposed for thermal applications, some reports and papers have made attempts at their classification by geometry, material, application type, prototype power, etc.

This paper, rather than using any previous classification, proposes a new one, based on the combination of two important factors, pressurization and material, resulting in four subgroups with a representative receiver defining each type:

- Phoebus-TSA type: open loop volumetric receiver with metallic absorber
- SOLAIR type: open loop volumetric receiver with ceramic absorber
- REFOS type: closed loop volumetric receiver with metallic absorber
- DIAPR type: closed loop volumetric receiver with ceramic absorber

4.1. Open loop volumetric receiver with metallic absorber (Phoebus-TSA type)

Under the initiative of H.Fricker (Fricker 1983), the metal absorber volumetric receiver technology development emerged. The main metal absorber designs are briefly described below. For further details see Table 2.

4.1.1. Mk-I

A promising concept was presented in Europe in 1983 (Fricker 1983) consisting of a mesh of thin wires, over which cooling atmospheric air is drawn. In order to test this concept, a prototype with a 62-mm outer diameter which delivered a power of 3 kW_{th} at an average flux density of 1 MW/m^2 was constructed in the Swiss Alps in 1985. It was tested in a parabolic 2.7-m dish and produced hot air at up to 842ºC (Fricker 1986) without damaging either the absorber or the structure. Thermal efficiencies around 70 to 90% were estimated. Having met the goals set for this receiver, its simple design, low cost and easy operation, ensured further development of this idea some years later with Sulzer 1.

4.1.2. Sulzer 1

This was the next generation of the Mk-I, hence its name, Mk-II (Winkler et al. 1989). Its main purposes were to demonstrate the capability and feasibility of the wire pack concept, determine receiver efficiency, to study its dynamic performance and to acquire operating experience (Becker and Böhmer 1987).

The 875-mm inner diameter receiver, designed for a 200-kW_{th} output power, had a wire absorber consisting of a ring-shaped 1.65-mm wire mesh made of 0.40-mm diameter stainless steel (oxidized AISI 310) wires. A metal sheet with predetermined perforations behind the absorber ensured the correct air mass flow corresponding to the local flux intensity.

The receiver was demonstrated at the Plataforma Solar de Almeria (PSA), achieving air outlet temperatures of 780ºC, outlet power of 200 kW_{th} with a quick, predictable response to changing load conditions. The thermal efficiency at 550ºC predicted by Hotair code (Skocypec et al. 1989) was 80%, but was measured at only 68% (Becker and Sánchez 1989).

The main disadvantage was the geometric design of the absorber which caused distortion in the structure, making it difficult to maintain the absorber geometry, and producing insufficient cooling of some absorber areas, which resulted in lower than expected efficiencies.

4.1.3. Sulzer 2

A second absorber, the Sulzer 2, tested at the PSA in spring of 1988, consisting of coiled knit wire, was designed with the aim of improving the errors found in the previous absorber. Tests demonstrated its simplicity of design and operation, and the knit-wire absorber was more efficient than the Sulzer 1. Mean thermal efficiency at 550ºC was 79%. The maximum flux in the absorber was 757 kW/m^2 at an air temperature of 689ºC (Becker and Sánchez 1989).

The main disadvantages were that the absorber was sensitive to hot spots, the volumetric effect was not totally satisfied, and there was still insufficient support of the absorber, producing the aforementioned distortion effect.

The main conclusions after testing the Sulzer 1 and Sulzer 2 were that they were able to produce hot air at temperatures between 550-800ºC, their easy operation, good controllability and quick transient response. The receiver evaluation (Becker and Sánchez 1989) concluded with the feasibility of extrapolating the Sulzer 2 receiver to commercial sizes. This proposal led to the formation of the Phoebus consortium (Grasse 1988) and the subsequent development of a 2.5-MW_{th} prototype (Haeger et al. 1994) and design studies for a 30 MW_e plant in Jordan (De Laquil et al. 1990).

4.1.4. Catrec 1

Interatom built a metal foil volumetric receiver based on Emitec´s catalyst converters. It was installed in Sulzer´s test bed at the PSA and tested from November 1988 to March 1989.

The absorber which was made up of five modules, had a total diameter of 940 mm, and was 90 mm deep. The channel openings in the metal honeycomb absorber structure were approximately 1.6 mm^2 with a 0.05-mm wall thickness. The stainless steel ($X_5CrAl_2O_5$+Ce) foil material has a high melting point at 1470ºC (Meinecke and Unger 1989). The maximum output power could not go above 200 kW_{th}, due to limitations of the Sulzer´s test bed set up.

The main innovations in the Catrec design were that it had a small solid front area, high surface-to-volume ratio, modularity and employed standard materials with low thermal inertia.

The results showed an overall efficiency of about 80% for mean air outlet temperatures up to 570ºC (Becker and Böhmer 1990). The air outlet temperatures measured were not as high as theoretically expected, because of different cold bypass possibilities in the Catrec receiver arrangement. Measured absorber matrix material and air outlet temperatures were up to 1070 and 826ºC at 844 kW/m^2 maximum solar flux.

In spite of some deficiencies with the volumetric metal foil receiver, its promising efficiency, high thermal load endurance and rather high air outlet temperatures recommended further development. Some of the improvements proposed for Catrec 2 were to design a module with hexagonal absorber elements and to avoid gaps from thermal deformation.

4.1.5. TSA

Since the Sulzer project tests were successful, the Phoebus-TSA (Technology Program Solar Air Receiver) project was promoted as the indispensable intermediate step towards the envisaged 115 MW_{th} capacity (Heinrich et al. 1992) of the Phoebus receiver concept. It consisted of a 2.5 MW_{th} volumetric air receiver together with a thermal storage and steam generator. The receiver design included an air return system to improve receiver efficiency.

The absorber was made up of 280-mm diameter by 50-mm deep cups which were hexagonal to avoid gaps between them (Fig. 7). As in the Sulzer 2, the absorber consisted of coiled knit-wire knitted packs.

The main result of the tests carried out in 1993 was the ability to achieve the design absorber efficiency of 85% at 700ºC receiver air outlet temperature at an average flux density of 0.3 MW/m^2 and an air return ratio of 60%. Moreover, the nominal receiver power output of 2934 kW$_{th}$ was recorded several times (Meinecke et al. 1994). A mean absorber temperature of 750ºC was reached in less than 30 minutes after start-up and approximately 30 minutes later the receiver air outlet temperature stabilized at 700ºC.

The main conclusions (Meinecke and Cordes 1994) from the tests were that it was able to produce sufficient and constant, useful-quality steam (480-540ºC and 35-150 bar), system control was able to maintain air outlet temperatures constant, the modular design would facilitate future plant scale-up, the ability to match the air flow distribution of the absorber with the incident flux distribution and the flexibility of the process.

The experience of the Phoebus-TSA receiver with the aforementioned absorber was a success, but unfortunately, the Jordan plant designed by the Phoebus consortium was unable to acquire the necessary subsidies and funding and was never built (Romero et al. 2002).

4.1.6. Bechtel 1

In 1993, the New Mexico State University designed and built an experimental 67-mm diameter cylindrical receiver (Hellmuth et al. 1994) composed of a 54-mm-deep multi-layered wire mesh absorber with 17 circular screens (Hellmuth and Matthews 1997). The first nine screens had one layer each of 0.11-mm-diameter wire mesh, and the remaining eight screens had four layers each of 0.21-mm-diameter wire mesh with a 3.2-mm separation between them. The wire mesh layers were made of knitted oxidized nichrome (80 % Ni - 20 % Cr alloy) resistance wire.

The experimental receiver was tested under an average incident solar flux on the front face of the absorber of 660 kW/m^2. This flux varied from approximately 890 kW/m^2 at the centre to 400 kW/m^2 at the edge. Total power on the receiver aperture was typically 2.3 kW$_{th}$ during testing. Air entering the experimental apparatus at approximately 25ºC was heated by a Pyrex globe from 100ºC to 200ºC before it entered the absorber. Efficiency ranged from 80% to 69% at outlet air temperatures of 320ºC to 820ºC, respectively.

After reasonable results in lab-scale tests, it was planned to scale up to a 250-kW$_{th}$ prototype to be tested at the PSA (Chavez et al. 1994).

4.1.7. Bechtel 2

Bechtel, with the assistance of Sandia National Laboratories, fabricated a 250-kW$_{th}$ receiver in 1993 (Hellmuth et al. 1994).

The volumetric array, consisting of a stack of 15 screens rings (875-mm diameter), was contained in a 304 stainless steel housing. The first five screens contained one layer of mesh made of 0.11-mm-diameter wire, the sixth and seventh screen rings contained two layers of 0.11-mm-diameter wire mesh. The remaining screen rings, each contained four layers of mesh made of 0.2-mm-diameter wire. All 41 receiver mesh layers, were made of knitted nichrome (80% Ni - 20% Cr alloy).

Testing was begun in July 1993. The maximum mean outlet air temperature reached was 563 ºC, with a peak temperature of 656 ºC in the centre. Absorber thermal efficiencies ranged from 90% at 200ºC to 66% at 563ºC, in contrast to the expected thermal efficiency of 90% at 700ºC (Hellmuth 1995).

There are several reasons for these lower thermal efficiencies:

- The temperature data from the individual rings showed an unbalanced air flow resulting in significantly higher air temperatures in the centre ring than in the outer rings.
- The "hot spot" was observed to move with the wind in the wire pack showing probable susceptibility to wind effects due to its high porosity.
- Some white ceramic paint flaked off the inner walls, which caused the receiver housing to heat up leading to additional thermal losses.

This idea was not developed any further, by Sandia, after these unexpected results.

4.1.8. Catrec 2

A second generation Catrec prototype was fabricated in 1993 and tested from May 1994 to May 1995 at the PSA. The following improvements were incorporated in Catrec 2 (Meinecke et al. 1996):

- The absorber consisted of 7 identical 240-mm wide by 90-mm thick hexagonal elements made of the same material as the Catrec 1.
- Special care was taken during installation to avoid any gaps between the absorber and the concentric adapter behind it.
- A different pressure drop was achieved in the perforated sheet behind the absorber, which allowed different mass flow rates at different locations in the receiver.

The main results of the tests were the maximum absorber temperature of 1069ºC, and maximum average outlet air temperature of 460ºC, which was clearly below the expected 700ºC (Pitz-Paal 1996). During the attempt to reach higher air outlet temperatures, a module was irremediably burnt.

The main reason for its poor performance was that the air flow distribution through the absorber was unstable (Kribus et al. 1996; Pitz-Paal et al. 1996). These effects of flow instability were detected for the first time in Catrec 2. Furthermore, DLR recommended major improvements in the flux measurement equipment after finding that it was in bad condition.

4.1.9. Sirec

CIEMAT-PSA designed and tested a volumetric air receiver called SIREC in 2001. The absorber`s modularity followed the Bechtel receiver approach, with a stack of 15 screen rings. Each screen ring contained one layer of 0.2-mm-diameter wire in a 0.72-mm mesh. The separation between screens was of 10 mm to withstand thermal expansion. Alloy 230 wire mesh was used because its content in rare earth elements provided good properties.

The prototype diameter was 875 mm, and 190 mm deep, but due to the configuration of the cool-air return system, the effective aperture diameter was reduced to 760 mm. The same improvements made in the Catrec 2 for distribution of the mass flow rate were applied to keep the incident solar flux uniform and achieve the same temperature all over the receiver.

The main results reported were (Téllez et al. 2001):

- The maximum outlet air temperature in the centre of the absorber was 973ºC with a gradient of around 500ºC over the external parts.
- The average air outlet temperature of 710ºC was achieved with an average inlet power of 300 kW_{th} and thermal efficiency of 48 %.
- Efficiencies of 85% were achieved with an average outlet air temperature of 500 ºC.

- The mean air return ratio varied from 42 to 45 %.

The conclusions arrived at from testing were:

- Difficult control of radial distribution of the air mass flow rate, resulting in high thermal gradients in the absorber and problems for surpassing 600ºC in the outer ring or an average of 760ºC in the receiver.
- The reduction of the effective surface of the absorber (around 24%) due to poor cooling system design, produced an unexpected cooling effect over the external elements of the receiver.

4.2. Open loop volumetric receiver with ceramic absorber (SOLAIR type)

The interest in ceramic absorbers emerged from the limitation placed on the maximum outlet air temperature achievable by metal absorbers, which in the TSA was 700ºC. Thermodynamically, the higher temperatures in the HTF, the higher overall power plant performance is. Other arguments for the selection of this new concept were its greater durability, mechanical tolerance, resistance to higher solar thermal fluxes and higher thermal gradients and the possibility of reducing the receiver aperture and thus the infrared losses. The main ceramic absorber designs are briefly presented below. For further details see Table 2.

4.2.1. Sandia Foam

Some developments with a matrix solar receiver by Sanders Assoc. (Becker and Böhmer 1987) were first tested at the USA Army Heat Furnace at White Sands, New Mexico, next in the Jet Propulsion Laboratory in the California Institute of Technology and finally the program was completed with a 250-kW_{th} prototype tested at the Georgia Institute of Technology. This open cavity central receiver was operated with a 1100ºC outlet temperature using a silicon carbide honeycomb material (Sander_Associates_Inc. 1979).

After this step forward, an absorber using a porous ceramic material was designed by the University of Colorado with the Hotair volumetric receiver code (Skocypec et al. 1988), and later built by Sandia (Chavez 1988) and tested on the test bed at the PSA. The porous ceramic absorber was made up of 17 30-mm-thick pieces made of 92% alumina with 80% porosity and 20 ppi (Chavez and Chaza 1991) and coated with Pyromark 2500 flat black paint to increase their absorptivity.

The absorber was tested at flux peaks up to 824 kW/m^2 and mean flux of 410 kW/m^2. The maximum average outlet air temperature was 730ºC with 54% efficiency and material temperature of 1350ºC. With medium outlet air temperatures of 550 ºC, the absorber material temperature was up to 350ºC higher than the outlet air temperature, and the efficiency was only 65% (Becker et al. 1990), although the expected efficiency at 550ºC was 80-85%.

There are a few reasons for the lower than expected efficiencies: the optical density of the material was too high, the Pyromark paint used was too thick blocking many pores of the absorber, and finally, due to the insulation, the area of the absorber was reduced by around 5%.

The results of this foam, similar to those of the Sulzer, were considered positive, taking into account that it was a first attempt. Furthermore, in spite of the lower efficiencies, there was no degradation of the ceramic absorber material.

4.2.2. CeramTec

An absorber designed by DLR and fabricated by Hoechst-CeramTec was tested at the PSA (Böhmer and Chaza 1991) in 1989 and 1990. The receiver had a diameter of 950 mm and a depth of 100 mm. Interatom´s (Freudenstein and Karnowsky 1987) thermodynamic calculations resulted in channel and rod cross sections of 3 x 3 mm and a foil thickness of 0.75 mm. Silicon-infiltrated silicon carbide (SiSiC) was selected as the absorber material for its good thermal properties.

It was attempted to decrease the front reflective losses in this volumetric receiver by reducing the surface of the absorber by means of a "staggered front design" which implied that every second layer of the foil and every second rod was 10 mm shorter (Böhmer and Meinecke 1991).

The receiver produced air at 500ºC with an efficiency of 89% and an power output of 234 kW_{th} (Becker et al. 1991). The maximum air temperature was 782ºC with an efficiency of 59% and a material temperature of 1320ºC measured in the centre of the absorber, which delivered a total output power of 330 kW_{th}. During the tests, two larger pieces of the absorber broke off due to a combination of mechanical and thermal stresses. Nevertheless, this failure did not influence the performance of the absorber, which is one of the advantages of volumetric receivers. The receiver did not achieve mean outlet air temperatures over 800ºC because of test bed limitations.

4.2.3. Conphoebus-Naples

Hoechst-CeramTec built a SiSiC absorber based on multicavity geometry. The complete absorber was made of nine pieces assembled by groove-and-tongue joints. The 150-mm-thick channels had a 9 x 4.8 mm cross section. The vertical walls were 5 mm thick, and the horizontal ones were 1.6 mm thick. The front face was shortened 10 mm in an alternating pattern to reduce radiative losses and increase the convective heat coefficient at the aperture (Reale et al. 1991).

The prototype tested provided a maximum average outlet air temperature of 788ºC with an associated 60% efficiency for a maximum incident solar flux of 917 kW/m^2 (Carotenuto et al. 1993). For medium air outlet temperatures of 550ºC, thermal efficiency reached 70%.

After 30 days under operation there was no evidence of any structural damage. There was fair agreement between calculated and measured results, which proved the good performance of the physical model (Carotenuto et al. 1991).

4.2.4. Selective Receiver

In 1992, HOECHST-CeramTec fabricated an absorber made of SiSiC (40 % porosity) for DLR, which consisted of square ducts with a 3-mm cross section and 3 and 0.8-mm-thick vertical and horizontal walls respectively (Becker et al. 1990). This material was used for its reliable behaviour in previous tests (Böhmer and Chaza 1991). Due to production constraints, the thickness of the vertical walls could not be reduced, so a 30º ridge profile was used to minimize reflection losses (Pitz-Paal et al. 1991b).

The ceramic structure was covered by a quartz glass structure (Fig. 8). This material is highly transparent to solar radiation but partly absorbs the thermal radiation emitted by the ceramic structure. Receiver emissive losses could thus be reduced. The idea of using a ceramic receiver with a glass cover was first introduced by Flamant (Flamant et al. 1988; Menigault et al. 1991) who investigated a packed SiC pellets bed absorber covered with a second slab of glass pellets. As the glass is more transparent to solar radiation than to thermal radiation emitted by the absorber, emission losses should be reduced. Moreover, the packed bed can be used only in a horizontal position, which complicates its application in CRS. The selective idea was taken up by (Pitz-Paal et al. 1990) and adapted to CRS.

In order to quantify the improvement in efficiency, a physical model was developed comparing results with and without the quartz glass at 1 MW/m^2 solar flux, 0.7 kg/s air flow rate and ambient temperature (Pitz-Paal et al. 1991a). The results of the model evaluated were an outlet air temperature of 997ºC with 75% efficiency for the selective receiver (glass + ceramic) and a temperature of 919ºC with 68.5% efficiency for the pure ceramic receiver (without glass).

The receiver was tested with and without the glass structure under similar conditions showing that (Pitz-Paal and Fiebig 1992):

- For temperatures below 600ºC the receiver without the glass cover performed better. This was explained by the additional reflection losses caused by glass turbidity from manufacturing.
- At higher outlet temperatures this effect was diminished by the expected reduction of emission losses due to the quartz glass cover. 62% efficiency was achieved for an average outlet air temperature of 620ºC with the quartz glass cover, and there was poor agreement between calculated and measured data as can be seen for the wide difference in the results.

4.2.5. HiTRec I

The HiTRec I (High Temperature RECeiver) was born in 1995 during comparative testing of different ceramic materials in the DLR solar furnace (Hoffschmidt et al. 2001).

A group of modular hexagonal ceramic cups formed the front of this receiver, and the back was a stainless steel structure. The cups were free to move or expand because a space in between them kept them from touching. The idea of separating the absorber modules by a space, made it possible for the front to be fed by return air from the waste heat recovery boiler on the one hand, and on the other hand, made module replacement easy.

The receiver was composed of 37 modules with a 120-mm horizontal diameter and a 0.49 m^2 aperture. Each module consisted of a hexagonal absorber structure and a SiSiC cup. The absorber honeycomb structure was made of recrystallized SiC with a normal open porosity of 49.5%.

The tests were carried out without problem (Hoffschmidt et al. 1999) and the experimental results showed good correspondence with the predicted design values. At an outlet air temperature of 800 ºC, the measured thermal efficiency was in the range of 75 to 80%, and 79% was predicted for 800ºC by the theoretical model. The maximum outlet air temperature of 980ºC was reached with a thermal efficiency of 68%. The temperature difference across all the absorber modules was less than 150ºC with no hot spots, and finally, the receiver demonstrated short start-up times and easy operability.

The main problem during the test was deformation of the stainless steel structure due to an error in design of the air cooling system which, although it did not affect operability, is not acceptable for a large receiver.

4.2.6. HiTRec II

Encouraged by the test results of the HiTRec I, in 1998, Ciemat, Inabensa and DLR, started the development of the HiTRec II (Hoffschmidt et al. 2001). The goals of this project were to solve the problems in the stainless steel structure and to demonstrate that the failure was due to a design error.

The receiver was assembled from 32 140-mm-diagonal cups in hexagonal ceramic modules (Fig. 9). Cup and the absorber materials were the same as HiTRec I with a total aperture area of 0.41 m^2. The metal receiver structure was made of Incoloy 800, a steelnickel alloy especially recommended for high working temperatures and just right for this design, because the expansion coefficients of Incoloy 800 and SiSiC materials are quite similar.

With no damage to the structure after 38 days and 155 hours of tests, receiver evaluation concluded that the main goal of the project, the demonstration of a more durable stainless steel construction, had been achieved (Hoffschmidt et al. 2003b). Moreover, thermal efficiency at a 700ºC outlet air temperature was 76% while at 800ºC, it was 72%. The measured air return ratio of up to 45% for receiver loads under 50% were reasonable. Higher loads could not be achieved due to thermal restrictions of the blower.

Several questions like types, sizes and shapes of the absorber structure, materials, etc., had not been fully investigated, so a follow-up, the SOLAIR project was begun.

4.2.7. SOLAIR 200

The goals of the SOLAIR 200 project were the design and testing of a modular, highly efficient and durable open volumetric high-flux receiver, which could be easily and safely operated at mean outlet air temperatures of up to 800 ºC (Hoffschmidt et al. 2001). The project was carried out in two stages. In the first, an advanced 200-kW_{th} receiver called the SOLAIR 200 with a 0.62-m^2 aperture was designed and tested. In the second stage, several modules were assembled in a 3-MW_{th} receiver (Hoffschmidt et al. 2002).

The test campaign started in 2002, with a receiver with 36 131-mm square SiSiC cups and three different absorber materials:

- Configuration 1: 36 recrystallized SiC cups with 49.5% open porosity.
- Configuration 2: 18 recrystallized SiC cups and 18 SiSiC cups installed in the top half of the receiver.
- Configuration 3: 2-mm thick porous fibre plates were placed in front of the eastern half of the receiver. This configuration allowed four different configurations to be tested: re-SiC and SiSiC; both with or without the porous fibres.

The 50-day test campaign showed that performance goals were accomplished, with temperatures over 800ºC achieved for the first two configurations on five test days.

At 800ºC mean thermal efficiency was 74% for Configuration 2 and, 75% for Configuration 1. Efficiency at 700ºC was 81±6% for absorber Configuration 1 and 83 ±6% for Configuration 2. Thus it was concluded that Configuration 2 showed the best performance for temperatures below 750ºC (Téllez 2003), while Configuration 3 did not achieve the expected mean outlet temperature of 800ºC. The air return ratio during the tests was assumed constant at 40%.

4.2.8. SOLAIR 3000

This receiver continued the same approach of the previous 200-kW_{th} receivers (HiTRec-I, HiTRec-II and SOLAIR-200) and was an intermediate step in scaling up. The SOLAIR 3000 consisted of a modular ceramic absorber, a supporting structure and an air-return system (Fig. 10). One of the advantages of using ceramics was that even though the absorber surface (2.6 x 2.2 m) was reduced by around 20% with respect to the TSA receiver, it could still receive the same thermal power (Hoffschmidt et al. 2003a). It was designed to provide a 680 to 800ºC average outlet air temperature and to withstand temperatures of up to 1000ºC. Testing at the PSA started in June 2003, accumulating 115 test hours under concentrated radiation.

The receiver was a modular absorber assembled from 270 140-mm-wide square ceramic cups made of SiSiC. The honeycomb structure was made of recrystallised SiC with an open porosity of 49.5%. The measured solar power incident on the receiver aperture achieved a maximum of 2950 kW_{th}.

The main conclusions observed after the testing were (Téllez et al. 2002):

- At nominal conditions of about 750ºC and mean solar fluxes in the range of 370 to 520 kW/m^2, efficiencies varied in the range of 70 to 75%.
- The measured air return ratio varied between 49±4% and 52±4% for a wide range of air mass flow and wind speed conditions.
- Temperature differences over the absorber aperture, at nominal conditions, were up to 450ºC.
- Over dynamic performance, the response time ranged between 10 to 14 minutes.

In June 2006, it was decided to build a central receiver plant with volumetric receiver (SOLAIR 3000 technology) and thermal storage in Jülich, Germany. It consists of a solar thermal power tower plant with 1.5-MW_e high-temperature air receiver. Receiver operation was begun in early 2009, and the first solar electricity was delivered to the grid in April 2009 (Koll et al. 2009). The aim of the project was to demonstrate this technology in a complete pre-commercial power plant for the first time. The receiver is four times larger than the SOLAIR 3000 tested at the PSA and has an aperture of about 23 m^2. The receiver consists of over 1000 ceramic absorber modules mounted at a tower height of 55 m (Hennecke et al. 2008).

4.3. Closed loop volumetric receiver with ceramic & metallic absorber (DIAPR & REFOS type)

Since only one pressurized metal absorber has been tested, both the closed-loop ceramic and metal absorbers are reviewed in this section. For further details see Table 2.

Several studies (Kribus et al. 1998; Price et al. 1996) have shown the advantages of introducing solar energy into a CC over other hybrid solar plants. Solar energy could be an effective high-temperature heat source for driving a CC. Because of this, pressurized volumetric receivers appear to be an alternative to fossil fuels (Kribus et al. 1999). Closed cycles for gas turbines usually envision hybrid operation (fuel saver) rather than a stand-alone solar plant that replaces fossil fuel completely. However, high-pressure operation makes it necessary to equip the receiver with a transparent window. The purpose of the window is to separate the receiver cavity from the ambient air and enable high-pressure operation, minimizing reflection, reradiation and convection losses.

Many studies (Abele et al. 1996; Anikeev et al. 1992; Buck 1990; Buck et al. 1996; Posnansky and Pylkkänen 1991; 1992; Pritzkow 1991) have demonstrated that the window poses a difficult design problem because of the limitations in size and the specific requirements in optical properties, mechanical strength, high variable working temperature, stress-free installation and sealing and cooling capability (Karni et al. 1998a).

Therefore, a suitable window, able to withstand higher pressure and temperature over a long period of operation constitutes the main goal of the directly irradiated volumetric receiver.

Due to the importance of the window design concept, the following sections provide additional information on the window designs available for each volumetric receiver and, in some cases, the main difficulties found and solutions proposed.

Several projects, apart from the ones proposed here, attempt to find windows design solutions, even with another possible application based on gas-phase solar chemistry (Buck et al. 1994; Buck et al. 1992; Buck et al. 1991; Flamant and Olalde 1983).

4.3.1. PLVCR - 5

In 1989, DLR designed a Pressure Loaded Volumetric Ceramic Receiver (PLVCR) with a foam absorber and 5 kW_{th} power (Pritzkow 1989), which was later tested at the Sandia solar furnace. The system worked as follows: compressed air was blown into the pressure vessel ring channel. Once the air was spread over the window, it was blown through the Si_3N_4 (SIRCON) ceramic foam absorber coated with Pyromark. The window was a 100-mm diameter and 3-mm thick domed watch-glass type quartz glass window with a water-cooled frame. The domed window has two advantages compared to a flat window: reflection losses can be reduced considerably (Heller 1991), and it is better suited to withstand the pressure inside the receiver (Buck et al. 1992).

The first tests showed that the watch-glass window was not able to withstand the 10-bar design pressure. Scratches and bad grinding reduced the maximum loading capacity, especially near the frame. As a result, a new elliptically shaped window was fabricated. A finite element calculation showed that the maximum bending stress was only 1/10 of the permissible, and like the watch-glass type windows, the highest stress was no longer reached in the area near the frame. The receiver was tested with these new windows, and in this stage, the highest pressures and outlet air temperatures were reached.

After 14 tests and over 8 hours of operation, the main results were a pressure of 4.2 bar, a power output of 2.5-3.7 kW_{th}, and 71% efficiency at outlet air temperatures of 1050ºC (Pritzkow 1991). The expected working pressure of 10 bar could not be achieved due to a sealing problem between the cold metal and the hot ceramic structure, although, this would not be a problem if the receiver were used in a high-pressure closed loop. Despite this, a larger prototype, PLVCR-500, was scheduled to be constructed and tested.

4.3.2. PLVCR - 500

This receiver was designed as an alternative modular system with a secondary concentrator at a power of 500 kW_{th}. The design focused on heating up air from ambient temperature to 1000ºC at pressures up to 10 bar (Pritzkow 1993). The design flux was up to 3.5 MW/m^2, produced by the heliostat field and the secondary concentrator.

It consisted of a pressure vessel with a spherical quartz-glass window in front of the concentrated solar radiation coming from the secondary concentrator which entered the receiver as shown in Fig. 11. The 10 and 12-mm windows, respectively, were produced by Heraeus Quarzschmelze. The window was set into a 610-mm diameter water-cooled frame. The absorber (SIRCON 20 ppi Si_3N_4 foam with a special black SiC coating) was a 650-mm-diameter truncated pyramid.

The tests at the PSA were divided in three stages (Leuchsner 1993). During the first stage, temperatures up to 700ºC were reached working at pressures of 3.6 bar and delivering a power of 100 kW_{th}. The main problem was the window (10 mm). After each test, a growing number of tear-shaped bulges were noticed, and finally the window cracked through the centre. The most likely reason was poor distribution of the air entering the receiver. This caused convective cooling of the window to be too strong in some places, and resulted in steep temperature gradients and thermal stresses. During the next test period, the new window (12 mm) was mounted with a more flexible frame to compensate movement of the window. Air distribution was also better. The second test stage was used for testing the secondary concentrator. The measured input flux distribution was more suitable for operating the receiver than the measured output flux distribution. Because of these results, all the following tests were done without the secondary concentrator, and the final stage was used to test the receiver alone. The maximum outlet air temperature achieved was 960ºC delivering 92.4 kW_{th}, with an efficiency of 57.3% working at 4.15 bar. During the tests, cracks appeared in the window and no pressure over 4 bar was reached due to the leaks.

Receiver efficiencies were rather low for two main reasons:

- The average flux density on the absorber was very low (150 to 500 kW/m^2). The theoretical study showed that good efficiencies could be achieved with flux of 1 MW/m^2, which could be reached with a secondary concentrator.
- Optical analysis of the black coating sprayed on the absorber showed that it was highly reflective in the infrared band, resulting in higher reradiation loss and a higher front-surface temperature as well.

The conclusions reported that the window frame was the Pressure Loaded Volumetric Ceramic Receiver`s biggest problem. It is very important for the window frame to be flexible to avoid jamming and to allow relative movement of the window and the frame due to the different thermal expansion coefficients. Steep temperature gradients should be avoided. One possible solution is to use hot gas at the receiver inlet (Leuchsner 1993).

4.3.3. DIAPR 30-50

The first DIAPR was built by the Weizmann Institute of Science (WIS) and Rotem Industries in 1992. The first tests were performed in the WIS solar furnace (Karni et al. 1997) with an 11-kW$_{th}$ power input. Later, a modified version was tested in 1994-1996 at the WIS solar tower, with a 30-50 kW$_{th}$ power input (Kribus et al. 2001). Fig. 12 shows the receiver cross-section. The inlet aperture diameter was 0.1 m, and the outer receiver dimensions were 0.42 m diameter by 0.35 m long. The absorber elements were made of Pythagoras alumina-silica (60% Al_2O_3) tubes, (Karni et al. 1998b). The receiver had three main components: i) Porcupine volumetric absorber, ii) a frustum-like high pressure window and, iii) secondary concentrator.

The fused-silica window design is shown in Fig. 13. The main purpose of the window is to separate the receiver cavity from the ambient air and allow high-pressure operation, while minimizing reflection losses. Analyses and tests showed that this window could withstand a pressure of over 50 bar. The window did not fail during more than a hundred hours of solar tests with the DIAPR, at a pressure of 10 to 30 bar. The tests proved that the window was not sensitive to local temperature gradients due to the settling of contaminants, such as dirt, ceramic insulation, etc., on its surface. Contamination was observed to increase overall window temperature somewhat, but did not generate local-hot spot failure. Ray-tracing calculations showed that window reflection losses of the window were only about 1%, since several reflections were necessary for incoming rays to escape (Kribus 1994). The window was only 2.25 mm thick, and since fused silica is highly transparent to solar radiation, energy loss from sunlight absorption was negligible (Karni et al. 1997).

After around 250 hours of solar tests had been carried out, the most remarkable results were that the DIAPR was capable of producing mean outlet air temperatures of 1200ºC, working at 17-20 bar with an incident solar flux varying between 3600-5300 kW/m^2. Overall efficiencies were in the range of 70 to 80%. For the first time, a receiver was able to produce continuous mean outlet air temperatures above 1000ºC, and the window sustained its design working conditions with receiver pressures of up to 30 bar (Karni et al. 1998a).

Based on the technology developed at the WIS and combined with the design by Haim Dotan Ltd. Architects, Aora erected a modular hybrid solar-thermal power plant with 30-m-high solar tower in the Arava desert in southern Israel. This receiver unit forms a single power module, capable of generating 100 kW_e power in addition to 170 kW_{th} power (Augsten 2009).

4.3.4. DIAPR Multistage

In 1996, the WIS designed a receiver whit the aperture divided into two separate stages according to the irradiance distribution, to minimize the thermal loss (see Fig. 14) (Kribus et al. 1999). The working fluid was gradually heated as it passed through a sequence of receiver elements while the irradiance level was increasing. Partitioning was matched to the radiation from the heliostat field, with higher flux at the centre and lower further from the centre.

The design consisted of four preheaters with the respective secondary concentrators around the centre (high temperature) stage. The estimated average inlet flux on the receiver aperture was between 2500 to 4000 kW/m^2 and entering the preheaters varied from 850 to 1400 kW/m^2.

The preheaters were designed as cavity tubular receivers with an Inconel 600 absorber tube made of and the high temperature receiver stage was a DIAPR with a porcupine absorber (Karni et al. 1998b). The DIAPR cavity was closed by a fused-silica window (Fig. 13) (Karni et al. 1998a). In this receiver the air was divided into two streams. The main one, distributed to the preheaters and then collected in a single pipe and conveyed to the high temperature receiver and the second stream blown for cooling the quartz DIAPR window.

The test included about 40 hours of operation, achieving a maximum outlet air temperature of 1000ºC with the preheaters supplying about 650-750ºC air at the inlet of the DIAPR. Output power ranged from 30 to 60 kW_{th}, and operating pressures were 16 to 19 bar.

4.3.5. REFOS

In 1996, the REFOS project started to demonstrate the feasibility of introducing solar energy into the gas turbine of Combined Cycle systems. The technical goals of the REFOS receiver system demonstration were (Buck et al. 2002):

- Absorbed thermal power for a single module: 350 kW_{th}
- Air outlet temperature of up to 800 ºC
- Absolute operating pressure: 15 bar
- Receiver efficiency (with an improved secondary concentrator): 80 %

The volumetric absorber, installed in a pressure vessel, consisted of several layers of heat-resistant wire screens (Inconel 600), and was closed off by a domed quartz window as shown in Fig. 15. The window was elliptical with a 620-mm diameter at the open end and a height of 420 mm. The wall was 8 mm thick. In-depth analyses were made on the quartz window to determine low-stress geometry (Uhlig 1998). Before installation, the window was certified up to a pressure of 19.5 bar (Buck et al. 1998). It should be mentioned that for successful operation of fused-silica windows, it is important for them to have clean, defect-free glass surfaces. Care must be taken to avoid contaminants on the glass during mounting, and appropriate cleaning procedures and frequencies must be defined (Hofmann et al. 2009).

Testing started with the evaluation of the secondary concentrator, which resulted in a measured optical efficiency ranging from 74.5 to 79%. After installation in the receiver testing continued. Project goals were demonstrated, with lower than expected efficiencies of 67% at 800ºC due to reflection losses in the secondary concentrator and insufficient insulation of the receiver. The receiver withstood overload conditions up to

400 kW_{th} without damage. One important advantage of the volumetric receiver was the low 18-mbar pressure drop achieved, which was important for hook up to gas turbines.
After demonstration of the robust, low-risk construction of the secondary concentrator, an improved one was built that better approximated a circle with the utilization of curved mirrors (Buck et al. 1998). The optical efficiency of the new concentrator improved from 75% in the previous one to 86%. The main reason for the improvement was the enlargement of the acceptance angle.
First tests with quartz windows have proven their feasibility and have shown good mechanical and optical characteristics, but even though these tests were short compared to lifetime requirements, they have already revealed the first signs of degradation of the window surface (Hofmann et al. 2009).

4.3.6. SOLGATE

The Solgate project started in 2001 with the main goal of developing a solar receiver cluster able to provide pressurized air at 1000 ºC to feed a conventional gas turbine system. The pressurized solar receiver system consisted of three 400-kW_{th} modules each with a secondary concentrator. The modules, which were connected in series, had a hexagonal aperture.
The top module, Fig. 16, was the low temperature receiver. The concept was a multi-tube coil attached to the secondary concentrator. The module in the middle was the medium temperature receiver (Refos receiver), and finally, the high temperature module (another Refos receiver), where the metal wire mesh absorber had been replaced with a ceramic absorber, the temperature was to rise to 1000ºC. The ceramic absorber was made of SiC with 20 ppi porosity coated with a silica layer and tempered to increase absorption to 96%. The solar receiver cluster was designed to increase the temperature by around 200 to 250ºC in each module (Heller et al. 2004).
Testing was divided into two parts. The first stage, intended to demonstrate the ability of the gas turbine along with the receiver and reach design operating conditions of 800ºC. In the second stage, the receiver outlet air temperature was to be increased to 1000ºC by replacing the metal-wire mesh absorber in the high temperature receiver by a ceramic absorber. This was assisted by active outer window cooling, as particularly at high temperatures, there was evidence of possible danger of recrystallization of the quartz glass. Due to structural changes in the recrystallization phase during temperature changes, chipping and cracking of the quartz glass can occur, which may damage the receiver window. Hence, overheating the window above 800ºC had to be avoided.
During the first test stage, at the end of March 2003, the temperature reached 800ºC and the system delivered 230 kW_e to the grid without major problems. In the second stage, the temperature rose to 960ºC with about 770 W/m^2 direct normal irradiation and 70% efficiency. Under these conditions, the solar fraction was close to 70% (Heller et al. 2006).
With the results found, it was demonstrated that volumetric pressurized receivers were able to produce 1000ºC air to drive a gas turbine. All the components were successfully tested and the cost and performance appeared promising for future solar power generation.

5. Assessment on the Research and Development Activities

The above review of volumetric receivers shows that a great effort has been made in the USA, Europe and Israel to study the performance of a wide variety of receivers, tested in different research institutions worldwide during the last three decades.

Most of the prototypes have been tested in the lab or small-scale test bed, but others, like the Phoebus-TSA and SOLAIR-3000, have had medium-scale development. DLR and the PSA have had a very important role in the development of this technology at their facilities.

Before commercial application of CRS with volumetric receivers is possible, there are some issues that need to be solved for the technology to be successful, i.e the development of control and plant management strategies, further improvement of the performance and reliability of key components, materials durability under high solar fluxes and system performance under fluctuating irradiation conditions. With the construction of a significant precommercial demonstration plant in Jülich, the aforementioned open questions and the demonstration of the complete system in commercial-like operation over a long period of time should be solved in the near future. Moreover, the Jülich plant has shown that CRS with atmospheric air might be the next technology to be deployed on an industrial scale.

On the other hand, CRS based on closed-loop volumetric receivers have been tested, in some cases, showing reasonable performance, but they are nowhere near maturity, especially because of the problems related to window design and certification. The domed quartz (REFOS) and fused-silica (DIAPR) windows with water-cooled frame and a more flexible frame to compensate movement of the window, are the directions to be followed for solving design problems. Moreover, further research and development of windows size are necessary, because current limitations force several receiver-modules to be used in order to achieve high power production.

However, some of the different volumetric receivers tested did not achieve the predicted design temperatures without local damage or structural cracks mostly from thermal shock, material defects and poor operating conditions. In order to correct these faults, DLR started to focus on better understanding the thermal and fluid dynamic performance of volumetric receivers, and an innovative modular design consisting of a volumetric absorber with an orifice at the exit, was developed. On the one hand, this design makes it possible to select a particular orifice diameter, depending on the expected local flux density in order to assure homogeneous outlet temperature. On the other hand, the pressure loss due to the orifice dominates that of the absorber itself, and it is designed in such a way that pressure changes affected by local wind effects will not disturb the flow, preventing flow instability. The new generation of modular volumetric receivers, i.e., HiTRec and SOLAIR, ensures stable receiver operation and should be further investigated. Furthermore, the same numerical study was applied to volumetric receivers with a highly porous honeycomb absorber structure, i.e., Catrec 1 and 2, which showed unstable operation under certain conditions due to the flow distribution (Pitz-Paal et al. 1996).

After evaluation of the receivers tested, the question of which material is the most suitable for different temperatures remains unanswered. It can generally be said that:

- For temperatures below 800ºC, some stainless steels and especially base-nickel alloys with high chrome content are the most suitable for volumetric receivers due to their capacity to form oxides, which are black and highly absorptive.
- For temperatures above 800ºC, the most suitable materials are the oxide ceramics. Al_2O_3 is the ideal material because of its good properties and price, but its main disadvantage is that it is white, which results in poor optical performance. Nevertheless, there are several coating techniques which can improve optical behaviour while retaining good mechanical properties. Other good materials are non-oxide ceramics, which are not rust proof. The best material is SiC, which has better optical properties and absorptivity than Al_2O_3.

Volumetric receivers have huge potential for producing thermal energy at very high temperatures, and can therefore cover a wide field of solar applications. Ceramic absorbers are able to produce very high gas (air) temperatures (>800ºC) for industrial process heat, gas turbines, and chemical processes. Direct chemical processes are also feasible with windowed receivers. A receiver output air temperature of 700-800ºC is sufficient for power generation with a steam turbine cycle, and therefore, the open air volumetric receiver is a promising alternative receiver concept (Becker et al. 1989). Finally, the main applications of volumetric receivers may be classified as (Freudenstein and Karnowsky 1987):

- Medium temperature (< 800ºC) open-loop receivers for steam generation for Rankine cycle electricity production or industrial process heat.
- High temperature (> 800ºC) open-loop receivers for indirect Brayton cycle power production and industrial process heat.
- High temperature (> 800ºC) closed-loop receivers for a wide variety of uses, from direct Brayton cycle power production (CC) to chemical processes.

Despite the research and development already carried out, the current investment required for the commercialisation of this technology with medium risk make subsidies necessary for its deployment on the electricity market.

6. Conclusions

During the last three decades of study, the state-of-the-art of volumetric receivers is similar to tube receivers. This paper has provided a brief overview of more than 20 volumetric receiver types tested in the USA, Europe and Israel.

They were classified in four subgroups: Phoebus-TSA, SOLAIR, REFOS and DIAPR, based on the air pressure used and the type of material (ceramic or metal).

All the receivers were described, including their structure (configuration, geometry, dimensions, material, etc), expected and real results (efficiencies and temperatures) and the overall system performance.

A great number of receivers have surpassed 800ºC in quasi-stationary state (HiTRec I and II, SOLAIR, etc.). The SOLGATE receiver supplied air at 960ºC to a gas turbine and the DIAPR air outlet temperatures were around 1200ºC at 20 bar.

Most of the prototypes have been demonstrated in the lab or small-scale test bed, but others have achieved medium-scale development. There is also a precommercial demonstration plant in Jülich which will probably answer some of the factors, such as operating control, plant management strategies, possibilities for improving performance under fluctuating conditions, etc. present unknown in the near future.

Nevertheless, despite their high technical and economic potential for use in CRS and dishes, there are still unresolved questions (i.e. window design, materials durability) that require further studies and research.

With the development of the CRS PS10, PS20 and Gemasolar plants only one type of power tower technology, CRS with volumetric receiver technology, has not been marketed yet.

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8. References

Abele, M., Bauer, H., Buck, R., Tamme, R., and Woerner, A. (1996). "Design and test results of a receiver-reactor for solar methane reforming." *International Solar Energy Conference*, 339-346.

Anikeev, V. I., Bobrin, A. S., and Kirillov, V. A. (1992). "New Conception of Catalytic Volumetric Reactor-Receiver." *Proc. 6 International Symposium on Solar Thermal Concentrating Technologies*, Mojacar, Almería, 387-394.

Augsten, E. (2009). "Make the desert bloom." *Sun & Wind Energy*, 9/2009, pp. 2052-2055.

Becker, M., and Böhmer, M. (1987). "Proceedings of the Third Meeting of SSPS - Task III - Working Group on "High Temperature Receiver - Technology", Nº 2/87, Alburquerque, N.M., USA."

Becker, M., and Böhmer, M. (1990). "Volumetric Metal Foil Receiver CATREC - Development and Tests- SSPS Technical Report No. 1/90." *SSPS-TR*.

Becker, M., Böhmer, M., and Cordes, S. (1991). "Report of the DLR / CeramTec Volumetric Ceramic Foil Receiver, SSPS TR -1/91, DLR, MD-ET."

Becker, M., Böhmer, M., and Meinecke, W. (1990). "Proceedings of the Fifth Meeting of SSPS - TASK III - Working Group on "High Temperature Receiver Technology", SSPS TR 2/90, Davos, CH."

Becker, M., Böhmer, M., Meinecke, W., and Unger, E. (1989). "Volumetric Receiver Evaluation." DLR, Cologne.

Becker, M., Fend, T., Hoffschmidt, B., Pitz-Paal, R., Reutter, O., Stamatov, V., Steven, M., and Trimis, D. (2006). "Theoretical and numerical investigation of flow stability in porous materials applied as volumetric solar receivers." *Solar Energy*, 80(10), 1241-1248.

Becker, M., and Sánchez, M. (1989). "Report of the Wire Pack Volumetric Receiver Tests Performed at the PSA in 1987-1988. Technical Report 2/89." *SSPS T.R. Nº 2/89*, DLR - Ciemat-PSA, Almería.

Böhmer, M., and Chaza, C. (1991). "The ceramic foil volumetric receiver." *Solar Energy Materials*, 24(1-4), 182-191.

Böhmer, M., and Meinecke, W. (1991). "Proceedings of the Volumetric Receiver Workshop. IEA SSPS Tasks III and VII. SSPS Technical Report No 2/91, Köln."

Buck, R. (1990). "Test and calculations for a volumetric ceramic receiver." *Solar Thermal Technology - Research Development and Applications, Proceedings 4th International Symposium.*, B.P.Gupta and W.H.Traugott, eds., Hemisphere, New York, pp. 279-286.

Buck, R., Abele, M., Bauer, H., Seitz, A., and Tamme, R. (1994). "Development of a volumetric receiver-reactor for solar methane reforming." *ASME-JSES-JSME International Solar Energy Conference*, 73-78.

Buck, R., Abele, M., Kunberger, J., Denk, T., Heller, P., and Lüpfert, E. (1998). "Receiver for Solar-Hybrid Gas Turbine and Combined Cycle Systems." *Proc. of 9th SolarPACES Int. Symp. on Solar Thermal Concentrating Technologies*, Font-Romeu, France, 537–544.

Buck, R., Biehler, T., and Heller, P. (1992). "Advanced Volumetric Receiver/Reactor for Solar Methane Reforming." *Proceedings of the 6th Int. Symp. on Solar Thermal Concentrating Technologies*, Mojacar, 395.

Buck, R., Brauning, T., Denk, T., Pfander, M., Schwarzbozl, P., and Tellez, F. (2002). "Solar-Hybrid Gas Turbine-based Power Tower Systems (REFOS)." *Journal of Solar Energy Engineering*, 124(1), 2-9.

Buck, R., Heller, P., and Koch, H. (1996). "Receiver development for a Dish-Brayton system." *Proceedings of ASME Solar Engineering 1996, The 1996 International Solar Energy Conference*, ASME, New York, 91-96.

Buck, R., Muir, J. F., and Hogan, R. E. (1991). "Carbon dioxide reforming of methane in a solar volumetric receiver/reactor: the CAESAR project." *Solar Energy Materials*, 24(1-4), 449-463.

Carotenuto, A., Reale, F., Ruocco, G., Nocera, U., and Bonomo, F. (1993). "Thermal behaviour of a multi-cavity volumetric solar receiver: Design and tests results." *Solar Energy*, 50(2), 113-121.

Carotenuto, A., Ruocco, G., and Reale, F. (1991). "Heat exchange in a multi-cavity volumetric solar receiver." *Solar Energy*, 46(4), 241-248.

Chavez, J. M. (1988). "Design and Testing of a New Volumetric Receiver Absorber." Sandia National Laboratories. Memorandum dated 7/15/1988, Alburquerque, NM.

Chavez, J. M., and Chaza, C. (1991). "Testing of a porous ceramic absorber for a volumetric air receiver." *Solar Energy Materials*, 24(1-4), 172-181.

Chavez, J. M., Lessley, R., and Leon, J. (1994). "Design, Fabrication, and Testing of a 250 kWt Knit-Wire Mesh Volumetric Air Receiver." *Proceedings of the ASME-JSES-JSME International Solar Energy Conference*, Publ by ASME, San Francisco, CA, USA, 605-610.

De Laquil, P., Ettischer, C., Geyer, M., Meinecke, W., Fricker, H., Vidal, R., and Mateos, J. (1990). "PHOEBUS project. 30 MWe solar central receiver plant conceptual design." Publ by American Soc of Mechanical Engineers (ASME), Miami, FL, USA, 25-30.

DeMeo, E. A., and Galdo, J. F. (1997). "Renewable Energy Technology Characterizations." *TR-109496 Topical Report*, U.S. DOE-Washington and EPRI, Palo Alto, CA.

Falcone, P. K. (1986). "A Handbook for Solar Central Receiver Design." *SAND 86-8009*, Sandia National Laboratories, Livermore, CA.

Flamant, G., Menigault, T., and Schwander, D. (1988). "Combined Heat Transfer in a Semitransparent Multilayer Packed Bed." *Journal of Heat Transfer*, 110(2), 463-467.

Flamant, G., and Olalde, G. (1983). "High Temperature Solar Gas Heating Comparison Between Packed and Fluidized Bed Receivers- I." *Solar Energy*, 31(5), 463-471.

Freudenstein, K., and Karnowsky, B. I. G. (1987). "Volumetric Ceramic receiver cooled by open air flow. Feasibility study." In: *Solar Thermal Energy Utilization*, Springer, Berlin, 1-54.

Fricker, H. W. (1983). "Proposal for a novel type of solar gas receiver." *Proceedings of the International Seminar on Solar Thermal Heat Production, Stuttgart, German Aerospace Center (DLR), Pfaffenwaldring 38–40, D-70569 Stuttgart*.

Fricker, H. W. (1986). "Tests with a small volumetric wire receiver." *Proceedings of the Third International Workshop on Solar Thermal Central Receiver Systems,*, Springer-Verlag; 1986 ISBN 3-540-17052-9, Konstanz, Berlin, Heidelberg, New York.

Grasse, W. (1988). "PHOEBUS - the European solar tower project." *Phoebus - das europaeische Solarturmprojekt*

Brennstoff-Waerme-Kraft, 40(10), 395-398.

Grasse, W., Hertlein, H. P., and Winter, C. J. (1991). "Thermal Solar Power Plants Experience." In: *Solar Power Plants. Fundamentals, Technology, Systems, Economics*, L. L. Vant-Hull, ed., Springer-Verlag, Berlin, 215.

Haeger, M., Keller, L., Monterreal, R., and Valverde, A. (1994). "PHOEBUS technology program solar air receiver (TSA): experimental set up for TSA at the CESA test facility of the Plataforma Solar de Almeria (PSA)." *ASME-JSES-JSME International Solar Energy Conference*, Publ by ASME, San Francisco, CA, USA, 643-650.

Heinrich, P., Keintzel, G., and Streuber, C. (1992). "Technology Program Solar Air Receiver - 2.5MWt System Test on Volumetric Air Receiver Technology." *Proceedings of the 6th International Symposium on Solar Thermal Concentrating Technologies*, 1, 247-261.

Heller, P. (1991). "Optimization of windows for closed receivers and receiver-reactors: enhancement of optical performance." *Solar Energy Materials*, 24(1-4), 720-724.

Heller, P., Pfander, M., Denk, T., Tellez, F., Valverde, A., Fernandez, J., and Ring, A. (2004). "Test and Evaluation of a Solar Powered Gas Turbine System." *Proceedings of 12th SolarPACES International Symposium on Concentrated Solar Power and Chemical Energy, Technologies*, Oaxaca, Mexico. October/2004.

Heller, P., Pfänder, M., Denk, T., Tellez, F., Valverde, A., Fernandez, J., and Ring, A. (2006). "Test and evaluation of a solar powered gas turbine system." *Solar Energy Solar Power and Chemical Energy Systems (SolarPACES'04)*, 80(10), 1225-1230.

Hellmuth, T. E. (1995). "Experimental Characterization, Modeling and Optimum Design of a Wire Mesh Solar Volumetric Air Receiver, PhD Thesis," New Mexico State University, Las Cruces, NM.

Hellmuth, T. E., and Matthews, L. K. (1997). "Modeling and Optimum Design of a Wire Mesh Solar Volumetric Air Receiver." *Journal of Solar Energy Engineering, Transactions of the ASME*, 119(3), 208-213.

Hellmuth, T. E., Matthews, L. K., J.M., C., and Hale, C. A. (1994). "Performance of a Wire Mesh Solar Volumetric Air Receiver." *Proceeding of the 1994 ASME/JSME/JSES International Solar Energy Conference*, 573-578.

Hennecke, K., Schwarzbözl, P., Alexopoulos, S., Hoffschmidt, B., Göttsche, J., Koll, G., Beuter, M., and Hartz, T. (2008). "Solar Power Tower Jülich - The First Test and Demonstration Plant for Open Volumetric Receiver Technology in Germany." *Proceedings of the 14th Biennial CSP SolarPACES Symposium*, Las Vegas, USA, March 4-7, 2008.

Hoffschmidt, B. (1997). "Vergleichende Bewertung verschiedener Konzepte Volumetrischer Strahlungsempfanger, DLR Forschungsbericht pp. 97-35."

Hoffschmidt, B., Fernández, V., Beuter, M., Stobbe, P., and Téllez, F. (2003a). "Test results of a 3 MW solar open volumetric receiver." *Proceedings of ISES Solar World Congress 2003*.

Hoffschmidt, B., Fernández, V., Konstandopoulos, A. G., Mavroidis, I., Romero, M., Stobbe, P., and Téllez, F. (2001). "Development of Ceramic Volumetric Receiver Technology." *Proceedings of 5th Cologne Solar Symposium*, Forschungsbericht 2001-10, DLR, Germany, 51–61.

Hoffschmidt, B., Fernández, V., Pitz-Paal, R., Romero, M., Stobbe, P., and Téllez, F. (2002). "The development strategy of the HiTREC volumetric receiver technology—up-scaling from 200kWh via 3MWh up to 10 MWel." *Proceedings of the 11th SolarPACES International Symposium on Concentrated Solar Power and Chemical Energy Technologies*, Zürich, Switzerland.

Hoffschmidt, B., Pitz-Paal, R., Böhmer, M., Fend, T., and Rietbrock, P. (1999). "200 kWth open volumetric air Receiver (HiTRec) of DLR reached 1000 °C average outlet temperature at PSA." *J. Phys. IV France*, 09(PR3), Pr3-551-Pr553-556.

Hoffschmidt, B., Tellez, F. M., Valverde, A., Fernandez, J., and Fernandez, V. (2003b). "Performance Evaluation of the 200-kW[sub th] HiTRec-II Open Volumetric Air Receiver." *Journal of Solar Energy Engineering*, 125(1), 87-94.

Hofmann, A., Schenk, C., and Uhlig, R. (2009). "Optical quartz glass windows for high concentrated thermal power plants." *Proceedings of 15th SolarPACES International Symposium on Concentrated Solar Power and Chemical Energy, Technologies*, Berlin, Germany. September/2009.

Karni, J., Kribus, A., Doron, P., Rubin, R., Fiterman, A., and Sagie, D. (1997). "The DIAPR: A high-pressure, high-temperature solar receiver." *Journal of Solar Energy Engineering, Transactions of the ASME*, 119(1), 74-78.

Karni, J., Kribus, A., Ostraich, B., and Kochavi, E. (1998a). "A high-pressure window for volumetric solar receivers." *Journal of Solar Energy Engineering, Transactions of the ASME*, 120(2), 101-107.

Karni, J., Kribus, A., Rubin, R., and Doron, P. (1998b). "The "Porcupine": A novel high-flux absorber for volumetric solar receivers." *Journal of Solar Energy Engineering, Transactions of the ASME*, 120(2), 85-95.

Kolb, G. J. (1998). "Economic evaluation of solar-only and hybrid power towers using molten-salt technology." *Solar Energy*, 62(1), 51-61.

Koll, G., Schwarzbozl, P., Hennecke, K., Hartz, T., Schmitz, M., and Hoffschmidt, B. (2009). "The Solar Tower Jülich - A Research and Demonstration Plant for Central Receiver Systems." *Proceedings of the 15th SolarPACES Conference*, Berlin, Germany, September, 2009.

Kribus, A. (1994). "Optical Performance of Conical Windows for Concentrated Solar Radiation." *Journal of Solar Energy Engineering*, 116(1), 47-52.

Kribus, A., Doron, P., Rubin, R., Karni, J., Reuven, R., Duchan, S., and Taragan, E. (1999). "A Multistage Solar Receiver:: The Route To High Temperature." *Solar Energy*, 67(1-3), 3-11.

Kribus, A., Doron, P., Rubin, R., Reuven, R., Taragan, E., Duchan, S., and Karni, J. (2001). "Performance of the Directly-Irradiated Annular Pressurized Receiver (DIAPR) Operating at 20 Bar and 1,200[degree]C." *Journal of Solar Energy Engineering*, 123(1), 10-17.

Kribus, A., Ries, H., and Spirkl, W. (1996). "Inherent limitations of volumetric solar receivers." *Journal of Solar Energy Engineering*, 118, 151-155.

Kribus, A., Zaibel, R., Carey, D., Segal, A., and Karni, J. (1998). "A solar-driven combined cycle power plant." *Solar Energy*, 62(2), 121-129.

Leuchsner, V. (1993). "The PLVCR 500 and HCPC. Tests and Results. DLR-Mitteilung 93-04."

Mancini, T. R., Kolb, G. J., and Prairie, M. (1997). "Solar Thermal Power." In: *Advances in Solar Energy: An Annual Review of Research and Development*, K. W. Boer, ed., American Solar Energy Society, Boulder, CO, 1-42.

Meinecke, W., Böhmer, M., and Becker, M. (1996). "Proceedings of the Seventh Task III - Meeting within IEA SolarPACES on "Solar Technology and Applications", Nº III - 1/96, PSA, Almería."

Meinecke, W., and Cordes, S. (1994). "Phoebus Technology Program Solar Air Receiver (TSA)- Operational Experience and Test Evaluation of the 2.5MWth Volumetric Air Receiver Test Facility at the Plataforma Solar de Almeria."

Proceeding of the 7th International Symposium on Solar Thermal Concentrating Technologies, 943-957.

Meinecke, W., Cordes, S., and Merten, I. (1994). "PHOEBUS Technology Program Solar Air Receiver (TSA) - Final Report on Test Evaluation." DLR (MD-ET), Köln.

Meinecke, W., and Unger, E. (1989). "Volumetric Receiver Evaluation - Preparatory Material and Evaluation Report of Experts Meeting. Technical Report 3/89." Cologne.

Menigault, T., Flamant, G., and Rivoire, B. (1991). "Advanced high-temperature two-slab selective volumetric receiver." *Solar Energy Materials*, 24(1-4), 192-203.

Pacheco, J. E., and Gilbert, R. (1999). "Overview of Recent Results for the Solar Two Test and Evaluations Program." *Proceedings of the ASME International Solar Energy Conference 1999: Renewable and Advanced Energy Systems for the 21st Century*.

Pitz-Paal, R. (1996). "Evaluation of the CATREC II Receiver Test." IEA Solar PACES Technical Report, No. III-2/96.

Pitz-Paal, R., and Fiebig, M. (1992). "First Experimental Results From the Test of a Selective Volumetric Air Receiver." *Proceedings of the 6th International Symposium on Solar Thermal Concentrating Technologies*, Mojacar, Almería, 277-289.

Pitz-Paal, R., Hoffschmidt, B., Böhmer, M., and Becker, M. (1996). "Experimental and numerical evaluation of the performance and flow stability of different types of open volumetric absorbers under non-homogeneous irradiation." *Solar Energy*, 60(3-4. Oxford, United Kingdom), 135-150.

Pitz-Paal, R., Morhenne, J., and Fiebig, M. (1990). *Solar Thermal Energy Utilization*, Becker, M. (Ed.), Vol. 5, Springer Berlin, p.273-308.

Pitz-Paal, R., Morhenne, J., and Fiebig, M. (1991a). "A new concept of a selective solar receiver for high temperature applications." *Solar energy materials*, 24(1-4 New York, NY, United States), 293-306.

Pitz-Paal, R., Morhenne, J., and Fiebig, M. (1991). "Optimization of the Surface Geometry of a Volumetric Foil Receiver." *Solar World Congress. Proceedings of the Biennial Congress of the International Solar Energy Society*, Denver, Colorado, USA.

Posnansky, M., and Pylkkänen, T. (1991). "Development and testing of a volumetric gas receiver for high-temperature applications." *Solar Energy Materials*, 24(1-4), 204-209.

Posnansky, M., and Pylkkänen, T. (1992). "High Temperature Volumetric Gas Receiver - Results of the Development and Testing of the Atlantis Ceramic Receiver." *Proceedings of the 6th International Symposium on Solar Thermal Concentrating Technologies*, Mojacar, Almería, 291-298.

Price, H. W., Whitney, D. D., and Beebe, H. I. B. (1996). "SMUD Kokhala power tower study." *International Solar Energy Conference*, 273-279.

Pritzkow, W. (1989). "The Pressure Loaded Volumetric Ceramic Receiver (5 kW Version). DLR-Mitteilung 89-17."

Pritzkow, W. (1991). "Pressure loaded volumetric ceramic receiver." *Solar Energy Materials*, 24(1-4), 498-507.

Pritzkow, W. (1993). "The Pressure Loaded Volumetric Ceramic Receiver 500 kW Version Design and Construction. DLR-Mitteilung 93-02."

Radosevich, L. G., and Skinrood, A. C. (1989). "Power production operation of Solar One, the 10 MWe Solar Thermal Central Receiver Pilot Plant." *Journal of Solar Energy Engineering, Transactions of the ASME*, 111(2), 144-151.

Reale, F., Ruocco, G., Carotenuto, A., Nocera, U., and Bonomo, F. (1991). "Final design of a multi cavity volumetric solar receiver." *Solar Energy Materials*, 24(1-4), 284-292.

Romero, M., Buck, R., and Pacheco, J. E. (2002). "An Update on Solar Central Receiver Systems, Projects, and Technologies." *Journal of Solar Energy Engineering*, 124(2), 98-108.

Sander_Associates_Inc. (1979). "1/4-Megawatt Solar Receiver. Final Report. , INC. DOE/SF/90506-1, Oct."

Sizmann, R. L. (1991). "Solar Radiation Conversion." In: *Solar Power Plants. Fundamentals, Technology, Systems, Economics*, Springer-Verlag, ed., Berlin, 17-83.

Skocypec, R. D., Boehm, R. F., and Chavez, J. M. (1988). "Heat transfer modeling of the IEA/SSPS volumetric receiver." *AIChE Symposium Series*, Publ by AIChE, Houston, TX, USA, 146-153.

Skocypec, R. D., Boehm, R. F., and Chavez, J. M. (1989). "Heat transfer modeling of the IEA/SSPS volumetric receiver." *Journal of Solar Energy Engineering, Transactions of the ASME*, 111(2), 138-143.

Téllez, F. (2003). "Thermal Performance Evaluation of the 200 kWh SolAir Volumetric Receiver." Ciemat-PSA, Madrid.

Téllez, F., Romero, M., Heller, P., Valverde, A., Reche, J. F., Ulmer, S., and Dibowski, G. (2002). "Thermal performance of ‘‘SolAir 3000 kWh’’ ceramic volumetric solar receiver." *Proceedings of 11th SolarPACES International Symposium on Concentrated Solar Power and Chemical Energy, Technologies*, Zürich, Switzerland.

Téllez, F. M., Romero, M., and Marcos, M. J. (2001). "Design of "SIREC-1" Wire Mesh Open Volumetric Solar Receiver Prototype." *International Solar Energy Conference*, Washington, DC, 357-364.

Uhlig, R. (1998). "Analyse eines Quarzglasfensters unter Druck- und Temperaturbelastung mit Hilfe der Methode der Finiten Elemente." Diplomarbeit Fachhochschule für Technik Esslingen, Juni 1998.

Winkler, C., Fricker, H. W., Silva, M., and Garcia, G. (1989). "Tests with the volumetric wire receiver Mk II. report no. TM-51-89-18. [in German]." Paul Scherrer Institute (PSI), CH5232 Villigen-PSI.

9. Figures

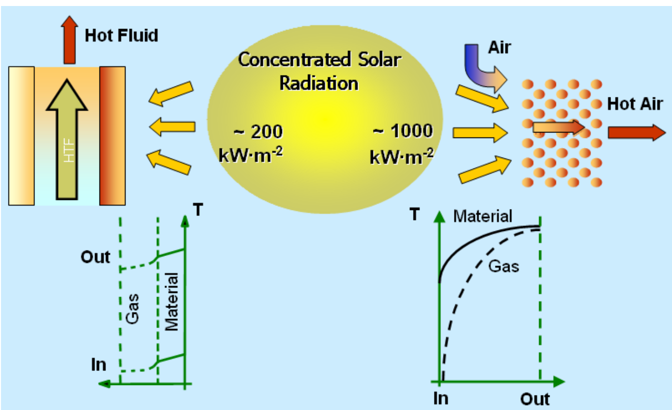

Fig. 1. Performance scheme across a tubular and a volumetric receiver (Hoffschmidt 1997)

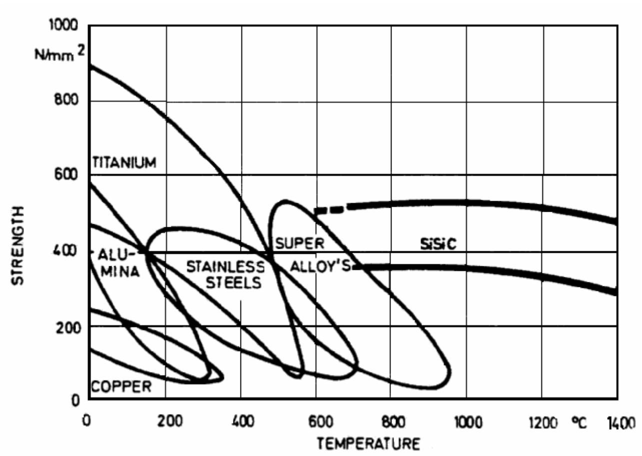

Fig. 2. Bend strength of different material versus the material temperature (Becker et al. 1989)

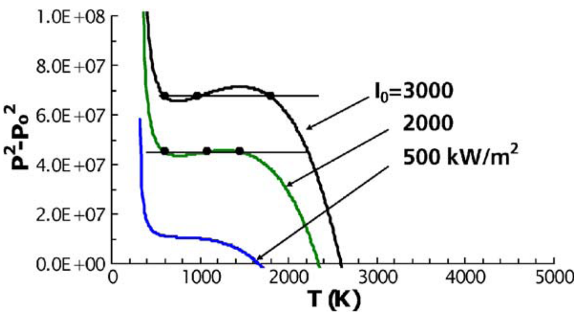

Fig. 3. Quadratic pressure drop versus the air temperature for different solar fluxes (Becker et al. 2006)

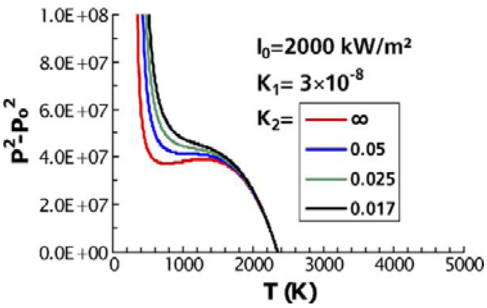

Fig. 4. Quadratic pressure drop difference as a function of the air outlet temperature for several values of the inertial coefficient (Becker et al. 2006)

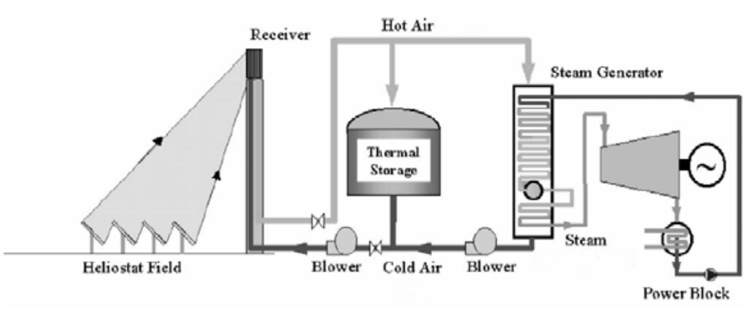

Fig. 5. Schematic plant concept

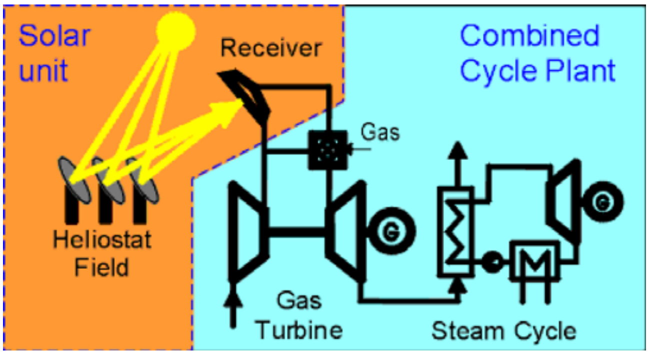

Fig. 6. Scheme of a solarized combined cycle power plant


Fig. 7. Detail of the hexagonal shape cups of the TSA project

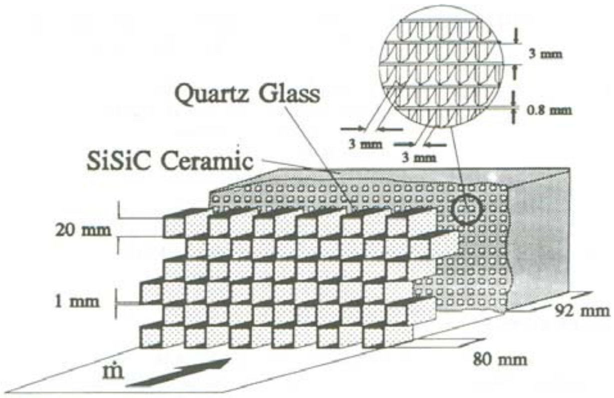

Fig. 8. Artist view of the foil receiver with the quartz cover (Pitz-Paal et al. 1991a)

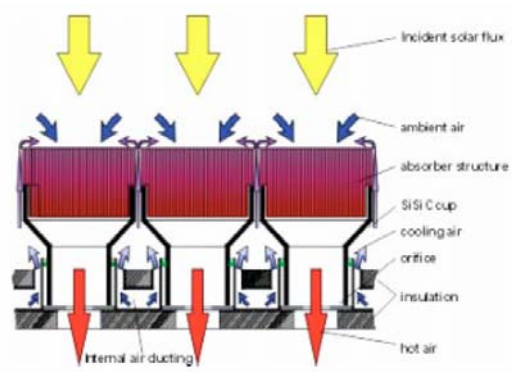

Fig. 9. Performance of HiTRec receiver

Fig. 10. Assembly Solair 3000

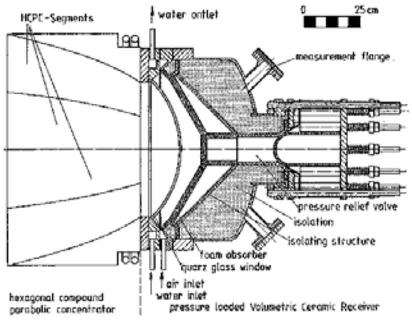

Fig. 11. Scheme of PLVCR 500 receiver (Pritzkow 1993)

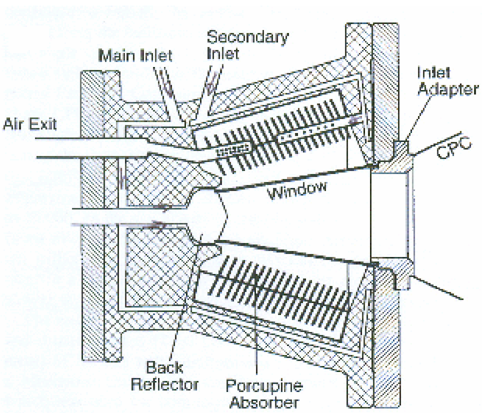

Fig. 12. Schematic cross-section of the DIAPR tested at WIS in 1996 (Kribus et al. 2001)

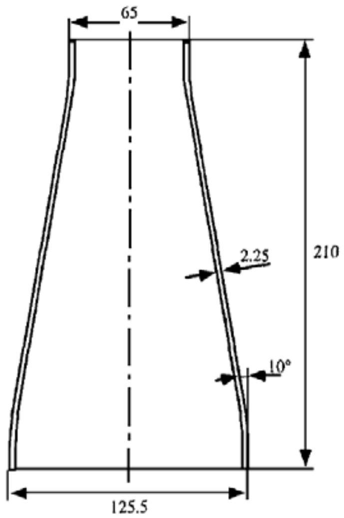

Fig. 13. Design of the frustum-like high pressure window. Dimensions are in millimetres

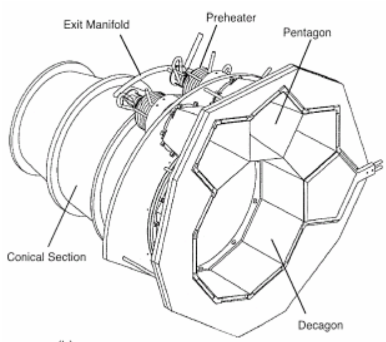

Fig. 14. Assembly of the concentrator array and preheaters over the central stage. (Kribus et al. 1999)

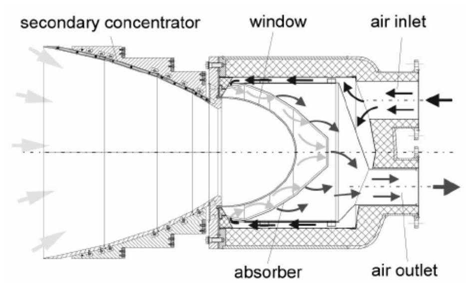

Fig. 15. Refos receiver module (Buck et al. 2002)

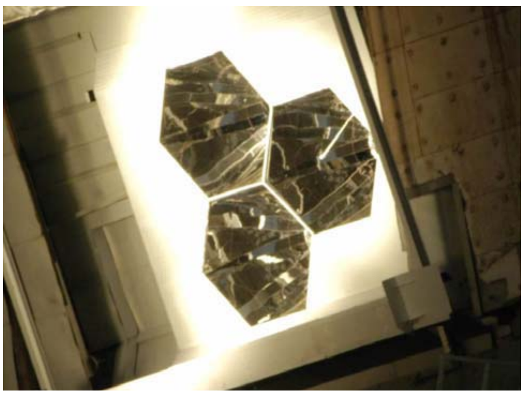

Fig. 16. Solgate solar receiver cluster

Table 2. Main characteristics of solar receivers with volumetric absorber.

Name	Material	Air return ratio, (%)	Thickness, (mm)	Diameter, mm	Average Flux (kW/m^2)	Peak Flux (kW/m^2)	Average Outlet Air Temperature (ºC)	Maximum Outlet Air Temperature (ºC)	Maximum Material Temperature (ºC)	Efficiency (%)	Gas Temp. ºC	Tested in	Power, kW
Mk-I	AISI 310	-	-	62	1000	-	--	-	-	70-90	842	Swiss Alps	3
Sulzer 1	AISI 310	-	-	875	265	960	780	830	-	68	550	PSA	200
Sulzer 2	AISI 310	-	-	875	218	757	689	800	-	79	550	PSA	200
CATREC 1	$X_5CrAl_20_5$+Ce	-	90	940	254	844	570	826	1070	80	570	PSA	200
TSA	Inconel 601	60	50	280-cups	300	800	700	950	-	79	700	PSA	2500
Bechtel 1	Nichrome 80/20	-	54	67	660	-	820	-	-	69	820	New Mexico State University	2.3
Bechtel 2	Nichrome 80/20	-	-	875	-	-	563	656	-	66	563	PSA	200
CATREC 2	$X_5CrAl_20_5$+Ce	-	90	756	-	-	460	560	1069	70	460	PSA	200
SIREC	Alloy 230	45	190	875	300	-	710	973	-	48	710	PSA	250
SANDIA FOAM	Al_2O_3	-	30	875	410	824	550	730	1350	54	730	PSA	200
CeramTec	SiSiC	-	100	950	330	840	500	782	1320	59	782	PSA	200
Conphoebus Naples	SiSiC	-	150	706	255	917	550	788	1238	60	788	PSA	200
Selective Receiver	SiSiC	-	92+80	835	600	750	620	750	1400	62	620	PSA	200
HiTRec I	re-SiC	-	-	Hexagonal shape	600	-	800	980	-	68	980	PSA	200
HiTRec II	re-SiC	45	-	Hexagonal shape	450	900	700	800	1000	72	800	PSA	200
SOLAIR 200	re-SiC / SiSiC	40	-	Square shape	450	620	700	815	-	75	800	PSA	200
SOLAIR 3000	re-SiC	52	-	Square shape	500	800	750	-	-	75	750	PSA	3000
PLVCR-5	SIRCON	-	18	150	300	470	-	1050	-	71	1050	Sandia	3
PLVCR-500	SIRCON	-	25	650	420	550	625	960	-	57	960	PSA	500
DIAPR 30-50	Alumina-silica	-	350	420	3600	5300	-	1200	-	71	1200	Weizmann	50

												Institute Sciences	
DIAPR Multistage	Alumina-silica	-	350	420	2500	4000	900	1000	-	-	1000	Weizmann Institute Sciences	50
REFOS	Inconel 600	-	-	-	350	600	800	900	-	67	800	PSA	350
SOLGATE	Inconel 600 and SiC	-	-	-	550	800	800	960	-	70	960	PSA	400