# Development of the Ceramic Volumetric Receiver Technology

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**Introduction**

First experiments in the field of volumetric receivers are reported in the late seventies by the company SANDERS Ass. and the Pacific North West Laboratory of Battelle. Then during the eighties the main activities shifted to Europe. Initiated by the study for a Solar Thermal Power Plant in the Maroz Valley in Switzerland (SOTEL), the metal wire mesh receiver was developed and built by the SULZER-company and (1987 and 1988) tested on the Plataforma Solar de Almeria (PSA) [2]. At the same time a Volumetric Foil Receiver concept was introduced during the SSPS meetings in Atlanta and Winterthur in 1985 and 1986. After a phase of feasibility studies including thermodynamic computer calculations DLR adopted this idea and chose a ceramic foil concept, based on a manufacturing technique, which was developed by Hoechst CeramTec. This was the beginning of the development of ceramic volumetric receivers, which is continuing until today [1,3]. The main reason why ceramic structures became interesting for volumetric receivers is the restriction of the wire mesh receiver to mean temperatures below 750°C due to the limited application temperature of the wires. From the thermodynamic point of view higher mean temperatures would increase the system efficiency and energy density, which leads to an additional cost reduction. However there are further benefits of ceramic absorber structures:

- Support of higher flux densities and gradients, which allow decreasing the receiver aperture and increasing the operation time, which lowers the system costs.
- Extension of the durability and the service time of the absorber.
- Greater tolerance of local overheating due to higher application temperatures.

Following the milestones of the development of the ceramic volumetric receiver technology is summarized.

## Development and tests results of the ceramic open volumetric receivers from 1986-1995

**"CeramTec Receivers" (200kW) 1987 –1991**

As shown in Fig. 1 the receiver was constructed using nine monoliths. The nine monoliths were connected by ploughed-and-tongued joints and mounted on the SULZER test bed of the PSA SSPS tower. The same type of receiver was tested three times. Different hydraulic diameters were tested (3mm and 7mm) and at last a selective glass/ceramic version was assembled and tested by the Ruhr Universität Bochum (RUB). All receivers behaved similar [1, 3, 4, 10].

Results:

- The receivers reached an maximum average outlet temperature between 700°C and 790°C and a maximum mean flux density of 660 kW/m2, while the peak temperature in the center of the receiver rose to higher than 1300°C. Therefore the receiver reached an efficiency of only 58% to 69%.

- Some of the monoliths broke during the tests due to tensile stresses which are automatically generated by the high temperature differences across the monoliths and when a free movement of the monoliths is blocked.

**„Sandia Foam Receiver" (200kW) 1989**

Fig. 2 shows the first ceramic foam test receiver (20 ppi, 80% open porosity) designed from Sandia national laboratory and manufactured for the integration in the Sulzer test bed at PSA. Ceramic foams made of alumina as well as such made of silicon carbide were investigated by Sandia. Alumina was selected because of material properties, time, cost and size limitations. The absorber was assembled from 17 flat pieces and was dipped in black Pyromak paint to enhance the absorption. The absorber design was similar to an arch supported by bolts at the intersections of the pieces [4]. Results:

- Only scarce information about the test results is available.
- The receiver reached a maximum average outlet temperature of 730°C with a corresponding thermal efficiency of 54%. The receiver achieved a maximum mean flux density of 410 kW/m2.

**"CorRec Receiver" (200kW) 1995 –1996**

The CorRec Receiver (Cordierite Receiver) was assembled of square shaped 150 mm extruded cordierite honeycomb blocks (400 cpi), which are used as automotive catalyst carriers. These blocks were connected together like the arch stones of the roof of a gothic cathedral as shown in Fig. 3. Thereby the absorber blocks were held together by their own weight, while the receiver faced down to the heliostat field. The blocks were sealed up only by aluminum oxide fiber layers in-between the blocks. The mass flow distribution across the absorber was adapted by a special flow guiding inside the blocks, which included a mixing chamber and holes from the backside through the mixing chamber which worked like throttles. By the number of the holes the flow through each block could be adapted to the local design flux density. Results:

- Compared to the precursor ceramic open volumetric receivers the CorRec Receiver reached the highest mean outlet temperature of about 880°C and a corresponding thermal efficiency of 79%.
- Although the receiver showed excellent thermal performance, the operation was difficult. In the case of off-design flux distributions onto the aperture the receiver reacted very sensible with critical local overheating.
- Hence local melting of the absorber structure mainly at the sides of the absorber modules happened during operation.
- The blackening of the originally white cordierite material was not satisfactorily solved. The used Pyromak paint degraded and became brighter from test to test.

Fig. 1: Ceramtec Receiver

Fig. 2: Sandia Foam Receiver

Fig. 3: CorRec Receiver

## Lessons learned from ten years of development

The analysis of the results of the described receiver tests can be summarized as follows:

- Ceramic absorbers have the potential to carry higher flux densities than a wire mesh receiver.
- Higher flux densities must not lead to higher average outlet temperatures, if the local mass flow is not adapted well to the local flux density or if the open porosity and heat transfer is too low.
- None of the tested receivers solved the problem of up-scaling for a big receiver design of some hundred square meters of absorber aperture.
- Nearly all of the absorber materials/structures showed breaks in the structure after the test. This is due to the lack of a modular concept, which separates small absorber elements from each other to avoid high tensile stresses, which are automatically generated in bigger ceramic monoliths when heated up highly. Consequently it seems not possible to build big receivers out of only monolithic ceramic materials.

Seen from the state of art today the described five different receiver tests at the PSA SSPS Tower from 1986 to 1996 cannot be classified as real receiver but only as absorber tests. In contrast to this, the development of the wire mesh receiver design from Sulzer and later Steinmüller (TSA Project) focused not only on the absorber material but on the complete receiver system [8]. Especially Steinmüller designed an independent absorber module, which includes the absorber material, its fixing and a set of orifices to adapt the local air mass flow suitably to the local flux density. Based on such module big receivers could be built in the future as we shall see in the PS10 project. During the TSA project Steinmüller worked on many detail problems concerning the connection and sealing of the modules, the problem of how to feed the return air from the waste heat recovery boiler to the absorber front and considerations on the steel structure of the receiver construction. It should be pointed out that a complete receiver technology includes the absorber, a flow device, which adapts the local mass flow to the local flux density, an air return system and an inner construction (steel, ceramic) which carries the weight load of the receiver and connects this to the tower construction. Taking all of this into account DLR started 1995 with the development of a modular receiver system, which is able to carry any ceramic absorber material and at the same time to fulfill all the necessary system requirements.

## Birth of HiTRec receiver technology as an integral receiver design

1995 and 1996 during a systematic comparison campaign of different available ceramic absorber materials in the solar furnace at DLR cologne, it was detected that SiC or SiSiC is the most suitable absorber material (black, highest thermal shock resistance). Especially an extruded honeycomb SiC structure from the company NOTOX showed the best results regarding application temperature, thermal shock resistance and flow stability. During this time Buck, Kribus and Hoffschmidt in parallel found out that highly porous absorber materials show an unstable air flow through the absorber structure under a high solar flux, which usually leads to the destruction (cracks or melting) of the absorber structure by local overheating [7, 5, 11].

From this time on the awareness of flow instability as a major problem, has greatly influenced the whole volumetric receiver development. Without going into details of the physical reason for flow instability, the problem for the volumetric receiver development can be described in a simplified way: the thermal efficiency and a possible flow instability of a volumetric absorber increase with its open porosity, its heat transfer surface and the magnitude of the flux density. That means absorber materials with a high potential of thermal efficiency are blocked from use due to a possible destruction by flow instabilities.

Because of that DLR started to separate the further receiver development from the development of possible absorber materials/structures and created the HiTRec receiver technology. The HiTRec (High Temperature Receiver) receiver technology includes the lessons learned from the previous receiver tests and is able to react to possible flow instability.

In fig. 4 the HiTRec receiver principle is shown. A stainless steel construction forms the basis of the receiver on the backside of a set of ceramic absorber modules (diameter <0,25 m). Similar to a ceramic burner tube the absorber modules are kept from the backside and being free to move or expand in axial and radial direction due to thermal expansion of the modules or movement of the stainless steel construction behind during start up or shut down operation. This is realized by a certain gap in-between each absorber module to avoid any touching of the neighbor modules. The idea to separate the absorber modules not by a sealing but by a gap in-between set free new design and system opportunities. On the one hand the gaps enabled it to feed the return air from the waste heat recovery boiler to the front area, while using the return air to cool the stainless steel construction, on the other hand an easy changing of the modules from the front side became possible, which can lower the maintenance costs. Although both later on described HiTRec receiver tests used nearly the same absorber structure, the HiTRec receiver system is not directly linked to one specific absorber material as long as it can be placed into a ceramic or metallic cup. This means the system is open for any new advanced material or structure, which could arise in the future.

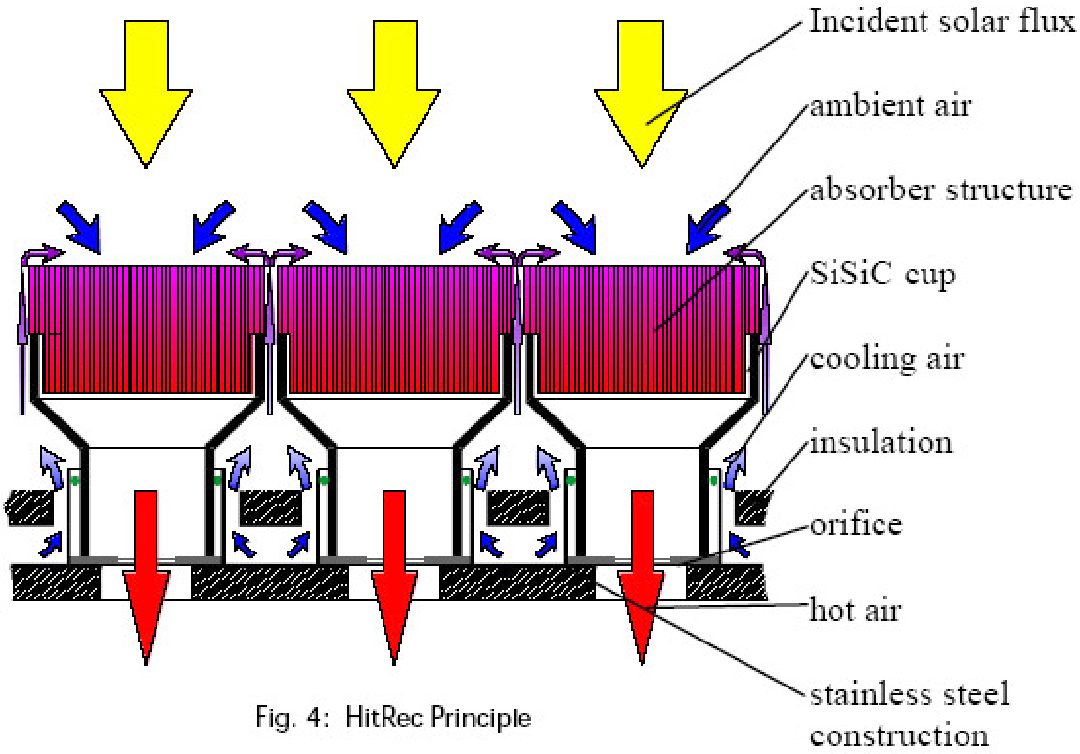


Fig. 4: HitRec Principle

## Development of the HiTRec receiver technology from 1997 up to now

**“HiTRec I” (200kW) 1997 –1998**

In 1996 DLR started the design of the HiTRec I receiver. After the manufacturing (Fig. 5to 7) the receiver was transported to Spain and tested at the PSA test side until 1998. It was planned to use the inner air ducting (see fig. 4 ) to cool the stainless steel construction only with ambient air. The goal was to demonstrate a durable integral receiver system, which is able to operate at average outlet temperatures higher than1000°C. In this time it was the plan of DLR to use this receiver for the feeding of a high temperature heat exchanger, to run a coupled gas turbine [9].

Together with CIEMAT the test was performed successfully. Because of missing founding all further activities at DLR concerning open volumetric receiver tests at the PSA stopped after the tests were finished. Results:- The receiver showed a maximum outlet temperature of 980°C. Higher outlet temperatures were restricted by the Sulzer test bed and not by the receiver system.- The receiver and especially the absorber structure demonstrated easy and friendly operability.- Compared with the previous ceramic receivers the HiTRec receiver demonstrated a good thermal efficiency of 75% at 800°C average outlet temperature (Fig. 8).- Due to an error in design and a missing control element for the mass flow of the cooling air a deformation of the stainless steel structure happened, which did not affect the operability of the test receiver, but is not acceptable for a big receiver.- The retainer devices of the absorber modules did not fix them exactly at the right position. So they were able to move too much.

Fig. 5: HitRec I stainless steel construction

Fig. 6: HitRec I absorber module, monolith and cup

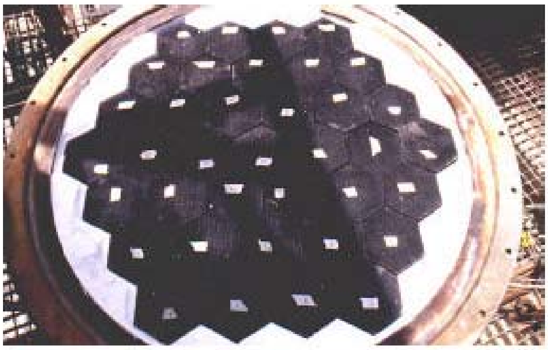

Fig. 7: HitRec I ready for mounting

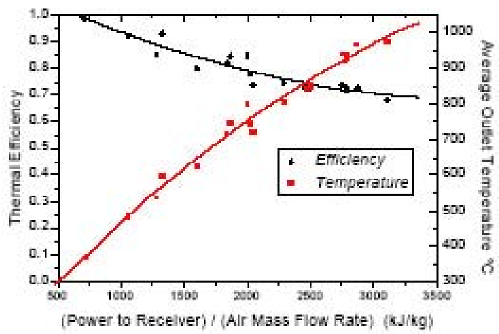


Fig. 8: HitRec I thermal efficiency and temperature versus the energy density

**"HiTRec II" (200kW) 2000 - 2001**

In 1998 CIEMAT managed to arouse the interest of INABENSA ABENGOA in the HiTRec receiver technology. Together with DLR they started a national Spanish funded project to carry on the development of the HiTRec receiver system. The goal was to demonstrate a durable stainless steel construction and to show that the failure of HiTRecI construction was only a design error and not a failure of the receiver principle. In parallel the cooling of the stainless steel construction was planned to be operated with the return air from the heat exchanger of the Sulzer test bed. The absorber modules should be manufactured as closely as possible to a real mass production cycle. Therefore the Danish company Stobbe Tech tried to achieve a simplification in the shape of the absorber monoliths compared with the HiTRec I absorber module design, which were formerly manufactured at DLR lab workshop. INABENSA and DLR optimized the design and worked on an improvement of the retainer device, which keeps the modules in the right position, but enables an easy replacement of the absorber modules. CIEMAT concentrated their activities in the preparation of the test bed, the investigation of an improved air return system and a FEM simulation of the stainless steel construction to detect critical design points.

Results:

- The main goal of the project, to demonstrate a durable stainless steel construction was achieved.
- The simplified retainer device of the absorber modules accomplishes the exact positioning of the absorber modules, but it is highly difficult to replace the modules.
- The air return worked properly for receiver loads lower than 50%. Higher loads could not be achieved due to restrictions of the test bed. For higher loads CIEMAT performed a 3 dimensional simulation with the simulation tool FLUENT. This simulation predicted a maximum air return ratio of 70% at design receiver load, taking small engineering modifications of the absorber modules into account.
- By the simplification of the production of the absorber modules – the monoliths were direct extruded to the final shape of the absorber monoliths the manufacturer missed to hold free the airflow through the channels at the sides of the monoliths. Because of this and due to higher tolerances in the outer shape of the monoliths compared with HiTRec I the sides of the absorber monoliths were overheated and a few of them broke and had to be exchanged.
- HiTRec II reached 5% less thermal efficiency than HiTRec I (Fig. 12). This may be explained by the uncertainties of the flux measurement, which directly influence the measured thermal efficiency, but also the overheating of the side areas of the absorber modules could explain a lower efficiency due to a higher infrared emission to the ambient.

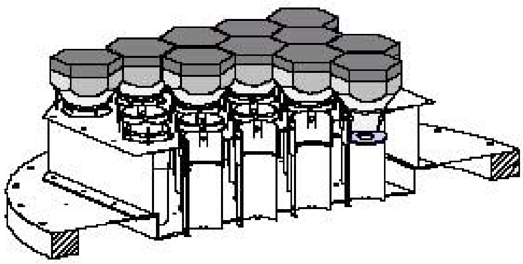

Fig. 9: Cut through the HitRec II receiver design

Fig. 10: Front view of mounted HitRec II receiver

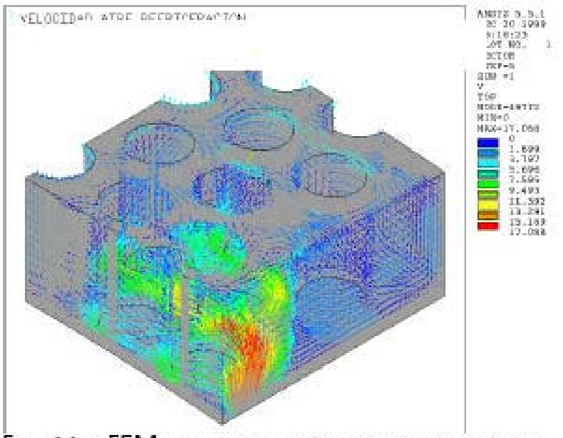

Fig. 11: FEM simulation of the return air flow through the stainless steel construction

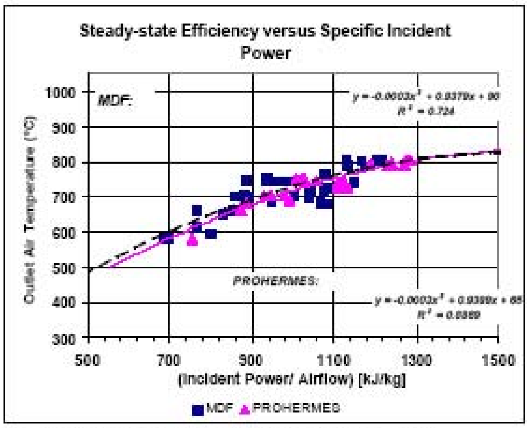


Fig. 12: HitRec I thermal efficiency and temperature versus specific incident power

**SolAir 200kW and SolAir 3MW 2001 to 2003**

In the EU-Project SolAir the next generation of HiTRec receiver technology is currently under design. The SolAir project is carried out by the partners INABENSA (ES), CIEMAT (ES), DLR (D), Stobbe Tech (DK) and CERTH/CPERI (GR). In the first phase of the project an advanced 200 kW HiTRec receiver, which is called SolAir 200 receiver will be designed and tested. After a successful test of this receiver, in a second phase of the project a 3MWth receiver of this type will be erected at the PSA test side. Currently the manufacturing of the SolAir 200 is in progress and it is planned to launch the test at the PSA in July 2001. For SolAir 200 the failures of HiTRec II receiver should be rectified. Stobbe Tech will improve the absorber module design by a better production accuracy of the monoliths and by the introduction of an advanced joining technique of the cups and the monoliths by changing also the material of the cups from SiSiC to re-crystallized SiC. On the base of 3 dimensional simulations at CIEMAT and flow measurements at DLR Stobbe Tech will change the shape of the absorber monoliths to increase the air return ratio. At DLR solar furnace (Fig. 13) different substrates of the absorber material from Stobbe Tech have been tested to choose the most suitable one. Therefore the absorber samples were treated during 2000 cycles with a fluctuating solar load of up to 2 MW/m2. The absorber body temperature varied between 220°C and 1300°C. After the test in the solar furnace none of the substrates showed any visible change. CERTH/CPERI submitted these samples to a detailed material investigation. Afterwards the partners chose that sample for further use, which showed nearly no reaction due to the solar treatment. One main goal of the SolAir 200 receiver is the creation of a receiver module as a subassembly of a big receiver. Therefore the SolAir 200 is build like one single receiver module, to test the thermal performance of the receiver as well as the receiver module behavior. Out of a set of these receiver modules the 3 MWth receiver will be put together. To simplify the joining of the receiver modules the outer shape of the absorber modules is changed from hexagonal to square shape (120mm x 120mm). Because the stainless steel construction showed its durable operation during the HiTRec II test, the partners agreed to build the stainless steel construction of SolAir 200 out of the stainless steel 1.4845 instead of the quite more expensive material Incoloy 800. This will further reduce the costs of a big receiver. Nevertheless the SolAir 200 receiver should demonstrate the same or higher thermal efficiency (75% at 800°C) as HiTRec I.

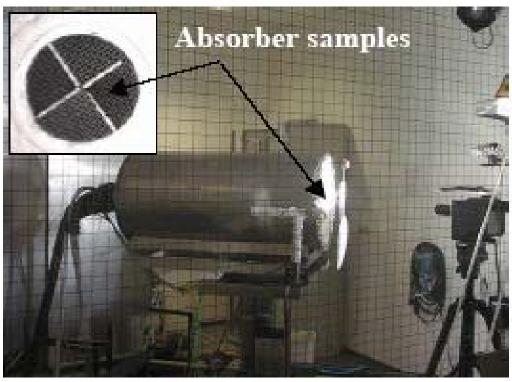


Fig. 13: Cycle test for heliotech absorber materials in the solar furnace at DLR

Fig. 14: Cups for square shaped absorber modules (120mm x 120mm and 250mm x 250mm)

DLR is developing an innovative passive control element, which could replace the ceramic orifice in the absorber module (needed to define the design air mass flow), which is able to reduce the pressure loss significantly when overheating conditions occur. This control element would increase the safe operation of the receiver under hot spot conditions for such an absorber module, because more cooling air will pass through this module. First prototypes show the principle function of such a passive control element. Aiming at a further reduction of costs and of the receiver complexity the SolAir 200 receiver will have an additional absorber area as shown in Fig. 15 to test three big square shaped absorber modules (250mm x 250mm). Such modules would approximately halve the effort for the stainless steel construction, but increase the material requirements for the absorber monoliths.

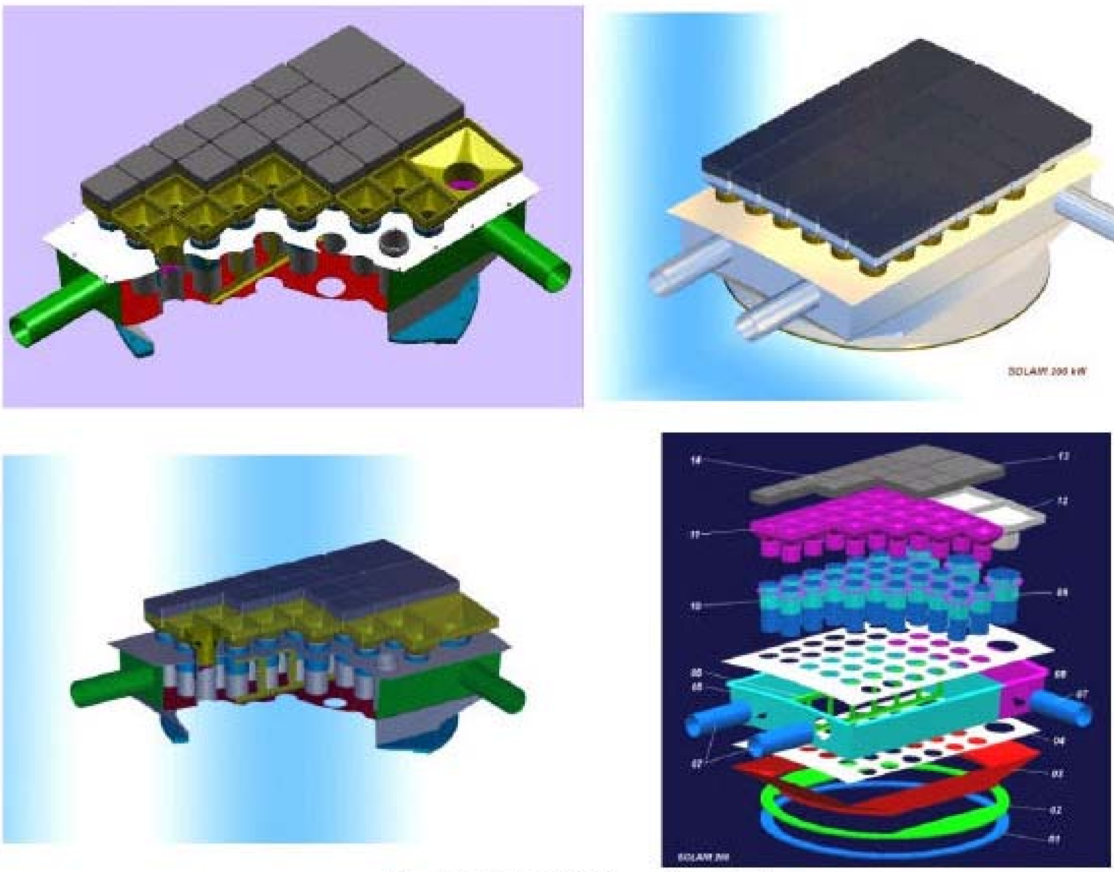


Fig. 15: Solair 200 receiver design

**Absorber development**
The HiTRec receiver technology offered the opportunity to uncouple the development of the receiver from the absorber development. Therefore DLR tested more than 15 different absorbers in the solar furnace from 1994 up to now in order to investigate flow instability and select suitable materials and structures as possible absorber structures. Since 2000 DLR is developing a ceramic high temperature porous structure within two national funded projects, which should increase the thermal efficiency in the range of further 10 to 20 percent points. This structure will not be affected by flow instability. First test results look promising. Fig. 16 shows the thermal efficiency of the new structure compared with the currently used absorber structure as measured in the solar furnace at DLR Cologne.

**Conclusion**
A continuous development of ceramic receivers from 1985 up to now was presented. The first five ceramic receiver tests at the PSA test facilities were described as absorber tests, which did not solve the problem of a possible up scaling. But these tests made available the knowledge to design a fully modular receiver by DLR, which is today called the HiTRec receiver technology. The main advantage of this receiver is, that it is not linked to any specific absorber structure. This offers the opportunity to separate the development of advanced absorber structures and materials from the development of the receiver system. At the same time one became aware of possible flow instabilities inside of highly porous absorber structures, which lead to local overheating of the structure and thereby to cracks in the receiver. Therefore DLR started the first test of the HiTRec receiver (HiTRec I) at the PSA with an absorber structure with relatively low porosity and therefore low potential

of thermal efficiency but with high durability against thermal shocks and high temperature gradients, as was formerly proven at the solar furnace at DLR Cologne. The test showed the feasibility of the receiver principle, but raised some detail problems concerning the stainless steel construction. Encouraged by these test results CIEMAT and the Spanish company INABENSA initiated a national funded project to further improve the HiTRec receiver technology. The test results of the so-called HiTRec II receiver showed a durable receiver system for up to 800°C average outlet temperature and no problems concerning the stainless steel construction by an improved design. The measured thermal efficiency was in the range of 5% lower than for HiTRec I. This could be explained by a less accurate manufacturing of the absorber modules, because it was tried to operate the production very closely to a standard line production. Overlapping with the HiTRec II receiver development INABENSA, CIEMAT, DLR together with Stobbe Tech and CERTH/CPERI got a funding of the SolAir project. In the SolAir project the third generation of the HiTRec receiver technology is addressed. The goal of this current project is to set up and demonstrate a working 3MWth ceramic receiver on the basis of the HiTRec receiver technology. In the first phase of the SolAir project again a 200 kW receiver will be manufactured and tested. The design of the so-called SolAir 200 will be very similar to a receiver subassembly of the 3MWth receiver. To accomplish this a lot of detail investigations and lab tests for air return, absorber module design and inner construction of the stainless steel construction have been carried out by the partners. It is planned to launch the test of SolAir 200 in July 2001. In parallel to the HiTRec receiver development DLR used their solar furnace to develop high advanced ceramic absorber structures, which avoid flow instability and guarantee higher thermal efficiency for the future big receivers.

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