FINAL TECHNICAL REPORT

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PROJECT N° : **Proposal No. NNE5-1999-10012**

ACRONYM : **SOLAIR**

TITLE :

Advanced Solar Volumetric Air Receiver for Commercial Solar Tower Power Plants

PROJECT CO-ORDINATOR : **Instalaciones Abengoa SA (INABENSA)**

PARTNERS :

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT)

Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)

HelioTech (formerly: Stobbe Technical Ceramics Aps, STC)

Centre for Research and Technology – Hellas (CERTH, formerly: FORTH)

Iberese SA (IBERESE)

Sanlucar Solar Solucar SA (SASO)

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Part 1: Publishable Final Report **Non Confidential**

1.1. Executive publishable summary

Objectives

Solar thermal power plants in Mediterranean region present an excellent option to contribute to the global objectives to reduce greenhouse gases emissions and to provide a sustainable and secure source of clean energy. The European first solar thermal tower power plant to be operated on a commercial basis is being planned in Southern Spain, an 11 MWe system working on a grid connected mode. One of the technological options considered for this plant was based on a metallic volumetric air receiver, taking a conservative design approach to minimise technical and financial risks. The objective of this project is to develop and demonstrate a new volumetric air receiver technology based on ceramic volumetric absorber modules, which will result in improved reliability and performance with reduced component costs for the next generation of solar tower power plants.

Description of the Work

The project consists of two consecutive phases. During the first phase, the design, manufacturing, treatment and assembly of the ceramic absorber modules is optimised according to specified cost and performance requirements. The absorber module was qualified in small-scale pre-tests. Steel structure supporting the absorber, warm air return system and passive control elements to homogenise the outlet air temperature were developed. The qualified components were assembled and tested at the 200 kW_{th} receiver test bed at the Plataforma Solar de Almería. Material investigations on absorber material degradation were performed with the exposed elements in order to estimate lifetime expectations of these new elements.

The second phase provides the necessary intermediate step in the scale-up to a large scale application, to reduce technical and commercial risks. A 3 MW_{th} scale-up receiver was designed, manufactured and tested in the existing 3 MW solar test bed for volumetric air receivers at the Plataforma Solar de Almería. In order to minimise test costs, a modular design representing a typical section of the prototype power plant was tested, to demonstrate specified performance and reliability criteria, and to gain operation and maintenance experience. In parallel, a detailed optimisation analysis on power plant cycles has been performed to fully exploit the expected benefits of this advanced receiver system.

Results and Exploitation Plans

The results of this project are the detailed design of a modular second generation volumetric air receiver, and the demonstration of the 3 MW_{th} test receiver system, which will enable the consortium to implement this technology. The consortium is expecting to apply this technology after accumulation of some more operation experience in future plants under commercial conditions. In addition, a new optimised cycle design will be available, which takes favour of the improved capabilities of the receiver with respect to high flux levels, large air return ratio and increased air outlet temperature. An overall reduction of solar electricity generating costs by about 10% is projected in comparison to the current volumetric air receiver technology.

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1.2. Publishable Synthesis report

Background

Solar thermal tower power plants exploit the high temperature potential of concentrated solar radiation to generate electricity in a conventional power cycle with high efficiency. The technology developed within this project uses ambient air as the heat carrier, which is heated up by passing through a porous ceramic structure. This structure, a so called volumetric receiver, is located on a tower, where it is irradiated by concentrated sunlight from a field of tracking heliostats. The hot air is transferred to a steam generator which provides steam for a turbine/generator (Figure 1.2-1). Alternatively, a heat storage can be charged with the hot air. The cooled down air is returned to the tower top to be recirculated through the front of the receiver for improved efficiency.

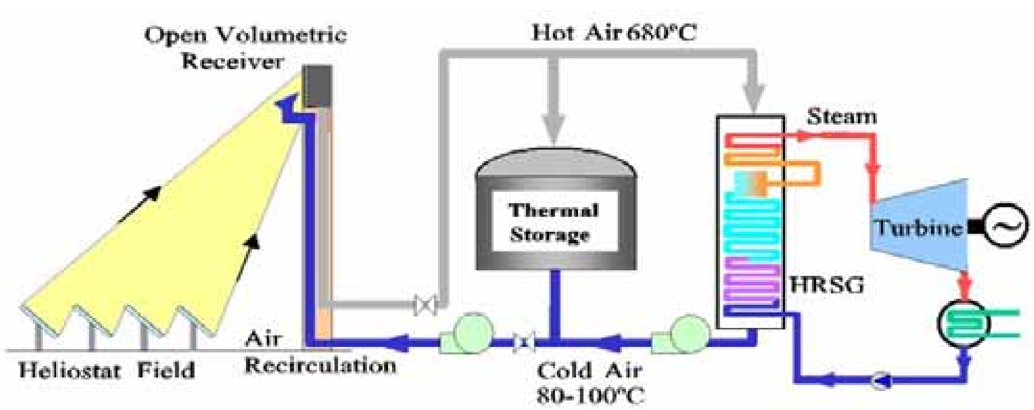

Figure 1.2-1: Solar thermal tower power plant with open volumetric receiver

Current state of the art is to use a wire mesh as the receiver. Such a System, known as TSA, has been tested at the Plataforma Solar de Almeria (PSA) at $3MW_{th}$ scale. It is the aim of this project, to develop an innovative ceramic receiver system which gives a higher safety margin for operation at elevated temperatures and which will withstand higher concentrated flux densities. Consequently, the receiver area can be smaller for the same total power, offering further advantages regarding cost and efficiency. Basis for this system is the HitRec design developed at DLR, which has been tested at the PSA in the 200 kW scale with financial support from the German and Spanish governments. Figures 1.2-2 and 1.2-3 show the design of the HitRec receiver and the ceramic absorber monolith with the cup to assemble an absorber module. Note that the return air is used to cool the steel structure and is then blown out through the gaps between the absorber modules.

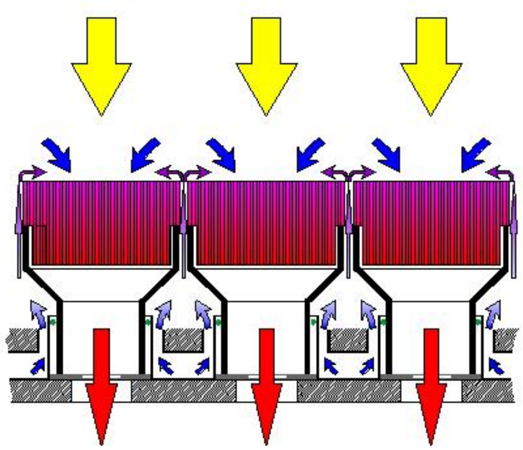

Figure 1.2-2: Schematic of HitRec receiver design

Figure 1.2-3: HitRec ceramic absorber monolith and cup

Project Consortium

The project partnership is composed by the Spanish industrial partner INABENSA leading the consortium, their associated company Solucar aiming to use the technology in commercial applications, and by five European partners covering all the sectors involved in the R&D of the advanced volumetric air receiver project:

- The research institutions in Germany (DLR), Spain (CIEMAT) and Greece (CERTH/CPERI) with scientific capabilities in the field of solar thermal concentrating technologies with special knowledge of R&D of volumetric air receivers in Germany (DLR) and Spain (CIEMAT) including availability of solar test beds on the PSA in South-Spain (CIEMAT).
- The development manufacturing and supply of special ceramic materials by HELIOTECH in Denmark as has been proven in a previous basic ceramic receiver experiment by DLR.
- The cycle optimisation of the next generation of solar tower plants by IBERESE in Spain.

Main scientific and technical goals

1. Development of several subcomponents of the second generation volumetric air receiver with the objectives:
    - to develop a ceramic absorber module, capable to operate at solar flux levels up to 1.5 MW/m² achieving air outlet temperatures more than 750°C with a high safety margin of material limit temperatures and at cost (series production) below 35.000 Euro /m² of receiver aperture area
    - to develop and qualify a connection technology to fix the ceramic structure to the steel supporting structure, fulfils the following requirement: no stress problems, no air bypass and allowance of removal of the structure from the receiver front side at costs of (series production) less than 1000 Euro/m² of receiver aperture area
    - to improve the warm air return system from today 45% air return ratio to 70% air return ratio at the same level of costs
    - to develop a steel supporting structure at costs of 1000 Euro/m² of receiver aperture area
    - to develop and qualify a passive control element which increases the mass flow rate through each module under hot spot conditions at costs of 500 Euro/m² of receiver aperture area.

2. Qualification of the above mentioned sub-components assembled in a small scale 200 kW experimental receiver for testing on an available 200 kW solar test bed at the PSA with the objectives:
    - to demonstrate that the receiver is able to generate air outlet temperature of more than 750°C
    - to prove that the steady state receiver efficiency at 700°C is capable to exceed the receiver efficiency evaluated for the 200 kW metallic wire mesh test receiver at the same 200 kW solar test bed during the test campaign in 1988 by at least 5%
    - to demonstrate that no material failures and no significant degradation will appear.

3. Demonstration of solar operation of a 3 MW scale-up receiver at an available 3 MW solar test bed at the PSA with the objectives:
    - to prove the design, reliability and performance of the receiver system in the scale-up size.
    - to gather experience of operation and maintenance
    - to get a reliable cost basis for receiver subcomponents.
    - to get a lifetime prediction for the ceramic absorber of more than 10 years

4. Optimisation analysis of the next generation power plant cycle using this new receiver technology with the objectives:
    - to analyse effects of system design and costs induced by the advanced receiver technology (improved cycle performance higher upper process temperatures, less safety equipment etc.),
    - to prepare the engineering basis for the next generation power plant using the advanced receiver technology

- to evaluate the overall cost reduction potential induced by the advanced receiver system in detail.

Description of work and main results

After basic considerations about requirements of a modular design for a large scale receiver which resulted in square instead of hexagonal absorber modules, the main task was the development and qualification of the ceramic absorber elements. Different SiC materials varying in wall thickness, porosity in the walls and pore sizes were produced by HelioTech and then tested in the DLR solar furnace. The treated samples were sent to CERTH for characterisation, and based on the results, the material and cell dimensions for the full size absorber monoliths were selected.

Figure 1.2-4: Solar furnace at DLR, Cologne

Figure 1.2-5: Volumetric receiver test bed in the focus of the solar furnace

Figure 1.2-6: Different absorber monolith samples installed in the test bed

Simultaneously, a design for the connection of the ceramic absorber module to the steel structure was developed and tested by DLR. CIEMAT carried out extensive FLUENT simulations to investigate alternatives for an improved air return system. As a result, the outer part of the absorber monoliths was designed with a trapezoidal cross-section to reduce the velocity of the ejected return air. A further option promising air return ratios above 70% would be to use part of the air to create an air curtain from the perimeter of the receiver. Since this concept would be difficult to realise in an upscale design, it was not further pursued in the project. The idea of an self controlled orifice for each absorber module, depending on the air temperature, was found to exceed the budget available for the development within the project. Experience from the later tests of the prototype receivers shows that such elements are not essential for the reliable and efficient operation of the system.

A list of design requirements of the 200kW test bed, and flux distribution profile had been delivered by Ciemat. These input data, joined with the structural analyses, and some other constraint conditions coming from the side of the absorber modules have lead to the design of the receiver, a work developed by both Inabensa and DLR. Figure 1.2-7 shows the conceptual design of the Solair 200 receiver. In addition to the main receiver body with 36 absorber modules of 125x125mm each, the design provides a subreceiver at the top to give the option to test the thermal stability of large (250x250mm) absorber modules.

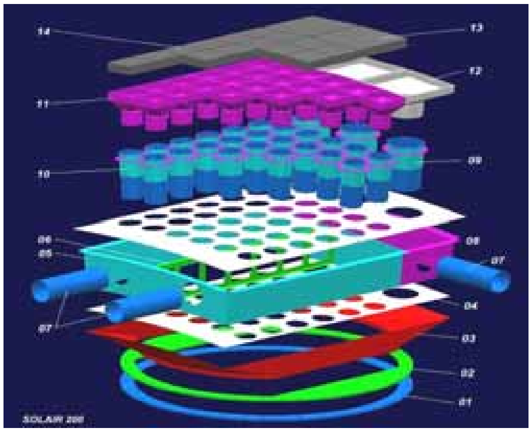

Figure 1.2-7: Conceptual design of 200 kW receiver assembly

Figure1.2-8: Assembled 200 kW receiver

The receiver was manufactured and assembled by Inabensa, and installed at the top of the SSPS-CRS tower at the PSA, which had been completely refurbished by CIEMAT and equipped with a new air return ratio testing device.

The test campaign started in March 2002 and produced fifty data sheets (each corresponding to a test day) and ended in February 2003. During the test phase half of the absorber monoliths were changed to ones made out of SiSiC instead of re-crystallized SiC, which show material degradation due to oxidation of the SiC. In addition, a porous material was fitted in front of the half part of the receiver (covering half of the old absorber material and half of the new SiSiC absorber cups). Thus, three absorber material types (or configurations) have been tested during the test campaign.

The data processing and evaluation results of the Solair 200 receiver show that performance goals for the receiver have been fully accomplished: Temperatures of more than 800ºC were achieved for the first two configurations in five test days. For the two absorber configurations for which incident solar power was measured the estimated efficiency at 700 ºC was 81 (±6)% for configuration 1 and 83 (±6) % for configuration 2 of the absorber. Thus, we may conclude that configuration 2 (that uses different ceramic absorber materials in the upper half part) of the absorber shows better efficiency than configuration 1 for temperatures below 750 ºC. The results also show a good operability and temperature distribution at the receiver outlet with a temperature spread across the absorber modules of <100°C at 750°C mean outlet temperature.

The estimation of the air return rate performance provides rates up to 45%. Finally, thermal efficiency for individual cups was estimated. Configuration 2 of the absorber shows better efficiency than configuration 1 for temperatures below than 750 ºC. Evaluated test results have been used as basis for the development and testing of a 3000 kW receiver.

The design of receiver follows a consistent modular approach as depicted in figures 1.2-9 to 1.2-12, where the 3 MW receiver to be tested at the PSA is designed to represent a module of a future commercial system, whilst it is assembled from smaller subassemblies which carry a set of absorber modules.

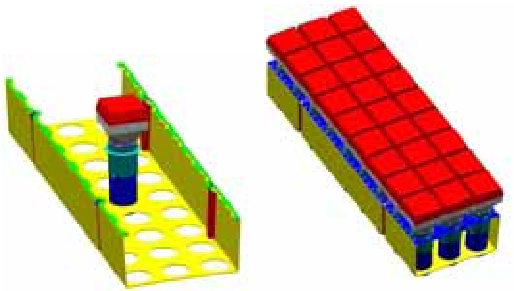

Figure 1.2-9: Absorber module and receiver modules

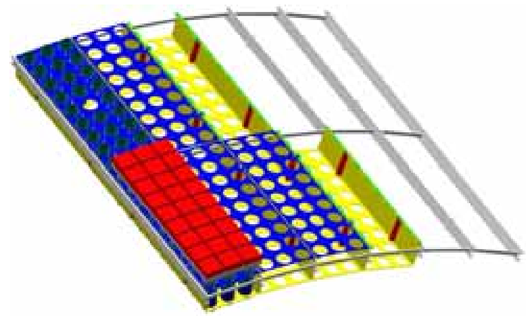

Figure 1.2-10: Receiver modules mounted in frame

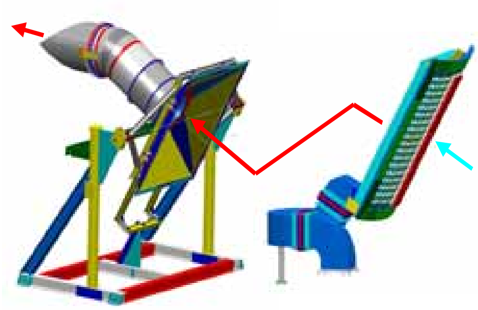

Figure 1.2-11: 3 MW receiver with test bed adaptor

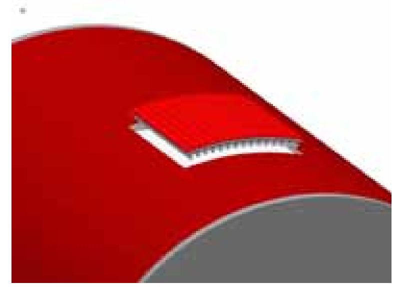

Figure 1.2-12: Multi-MW receiver with 3 MW module

The Solair 3MW receiver steel structure has been manufactured by Inabensa under Solucar engineering and supervision. Materials for adapter and absorbers supporting structure have been delivered by German company KAM (Kraftanlangen Anlagentechnik München). Based on numerical simulations of flux and temperature distributions for different operating conditions of the receiver, orifices for the individual absorber modules were designed to keep the air flow within defined limits. The receiver and assoctiated materials were delivered to the PSA and installed at the CESA1 test facility early 2003.

Figure 1.2-13: Lifting of SOLAIR receiver steel structure on tower

Figure 1.2-14: Receiver installation

Figure 1.2-14: Mounting ceramic absorber modules

Figure 1.2-15: Ceramic orifices and installation pattern

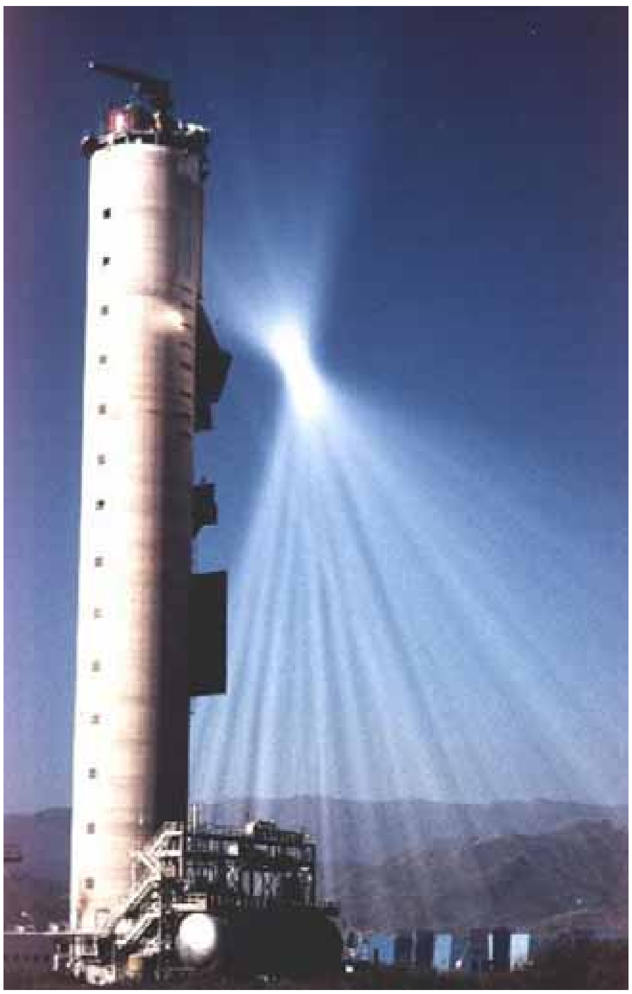

Figure 1.2-16: CESA1 testfacility at PSA

Figure 1.2-17: 3 MW receiver in operation

Figure 1.2-18: Close view of 3 MW receiver

The Solair-3000 receiver was operated on 33 test days between July 2003 and June 2004 accumulating 115 operating hours .The evaluation of receiver performance shows that the majority of the objectives for development, test and evaluation of the Solair-3000 volumetric receiver prototype were probed to be accomplished:

- After a test phase which accumulated operation for 115 hours with concentrated solar radiation on the absorber, the receiver probed its good working and its reliability up to temperatures of 760 ºC (nominal conditions for the prototype).

- At “nominal conditions” of about 750ºC and mean solar flux in the range of 370-520 kW/m^2 (which means incident solar power of 2100-2950 kW) the efficiencies vary in the range of 70 to 75%. Calculations with uncertainty estimates provided steady-state absorber effiencies of (74±9)% at 700ºC and (72±9)% at 750ºC outlet air temperature. These efficiencies exceed the receiver efficiency achieved by the wire mesh receiver in the same test bed.

Several absorber cups breakages occurred during the one year test phase. Subsequent investigation confirmed that a re-design of the connection between absorber monolith and cup should solve that problem.

The power cycle optimisation has been split into two parts:

- Cost optimisation of the steam cycle concepts (simple/advanced steam cycle; simple cycle with reheating) at 30 MWe power level utilising the parameters derived from the test results and earlier system studies.
- Performance evaluation of advanced cycles (open/reverse regenerative cycles; combined cycles; STIG cycles; air-steam mixture cycles; vacuum cycles) utilising receiver parameters that are not yet proven:

It has been concluded that the conventional steam cycle (simple or reheating) are the best alternatives to profit from the state of the art of the SOLAIR receiver and that further development of the receiver should focus on “cavity” solutions to reduce recirculation losses and allow its integration with promising and efficient advanced cycle concepts.

Assessment of the Results and Conclusions

This project has created the basis for future commercial application of the ceramic open volumetric receiver technology. All major project goals have been achieved. In particular, a modular receiver design has been developed and tested which allows scaling of the system to various plant sizes.

Appropriate absorber materials have been selected, and methods for manufacturing and assembly have been developed. Whilst the double membrane design of the receiver steel structure has been proven in both 200 kW and 3 MW scale, the connection between the absorber monolith and the ceramic cup will have to be re-designed since the method applied for the 3 MW system (gluing) leads to excessive thermo-mechanical stress in either the connection or the cup material itself.

In the 200 kW test campaigns, the targeted efficiencies have been demonstrated and even exceeded. The experiments with different absorber configurations indicated the potential for further improvements. It was also shown that reasonable temperature distributions over the receiver surface can be achieved by appropriate design of orifices for the individual absorber modules. The development of a self controlled element, which exceeded the budget allocated to this task within this project, is therefore not to be considered essential for reliable and efficient operation of the receiver.

The 3 MW test campaign was impaired by the absorber failures. Nevertheless, efficiencies close to the target have been achieved and need confirmation by further tests. Continued testing on the 3 MW scale is strongly recommended to gain operation experience for the optimisation of control strategies, and to accumulate load cycles and hours for improved lifetime estimation.

The subsequent step of development should be a small reference power plant to demonstrate the technology in a complete system under real operation conditions. It is envisaged that the technology should be ready for the first “semi”-commercial application within about 3 years after the end of the project.

The investigation of advanced plant designs encourages further developments to exploit the high temperature potential of the ceramic volumetric receiver technology.

Acknowledgements

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