Plataforma Solar de Almería

Annual Report 2003

Table of Contents

Introduction

The activity of the Plataforma Solar de Almería in 2003 was structured along three main lines of work: solar thermal electricity generation technologies, use of solar radiation for environmental applications and activities publicizing and disseminating these technologies on as large a scale as possible.

At the time of writing, the research activity of the PSA is structured differently than it was in 2003 and is currently organized into three R&D Programs called Medium-Temperature Solar Thermal Energy, High-Temperature Solar Thermal Energy, and Environmental Applications of Solar Energy and Characterization of Solar Radiation. However, given that our activities in 2003 were carried out under the previous model of organization, we think it is more appropriate to keep that organization in the structure of this report.

In the area of parabolic-trough collectors, we continue to focus on the consolidation of the direct steam generation technology, which is expected to reduce the costs of electricity production with parabolic-trough collectors by about 30%. The most important milestone this year, under the European INDITEP project, was the erection and commissioning of two new ET-100 parabolic-trough collectors in the DISS direct steam generation loop. These two new collectors have increased the steam production capacity of the solar field to 1 kg/s.

Also related to electricity generation, Central Receiver Technology Group activities were marked by tests carried out in the 3 MW-SOLAIR and SOLGATE projects. The SOLAIR project demonstrated the feasibility of the modular volumetric technology concept, the receiver tested at the PSA being the basic unit which would make up a commercial receiver in the tens-of-MW range. The SOLGATE project, has successfully advanced in the integration of solar energy in a gas Brayton cycle for electricity generation in an adapted conventional turbine.

Our activity in environmental applications have focused on wastewater detoxification and seawater desalination. An important milestone was the commencement of work on the world's first commercial solar detoxification plant installed for treatment of rinse water in a pesticide bottle recycling plant. This project is promoted by the 'Albaida Recursos Naturales y Medioambiente[1]' company and is based on scientific and technological developments at the Plataforma Solar de Almería in recent years.

The first steps in setting up an 'Associated European Solar Energy Laboratory' (SolLAB) were also taken this year. This virtual laboratory would be made up of the main European concentrated solar energy research institutes, that is, IMP-CNRS in Odeillo (France), the Deutsche Zentrum für Luft-und Raumfahrt e.V. (DLR) Solar Energy Division (Germany), the Swiss Federal Institute of Technology's Renewable Energy Laboratory in Zürich and the

[1] Albaida Natural Resources and Environment

CIEMAT itself. The agreement is expected to be signed at the beginning of 2004 and it is hoped that new partners will soon be joining.

Moreover, the continued and intense collaboration with the University of Almería (UAL) was strengthened and consolidated with the creation of a mixed CIEMAT-UAL center for joint research in solar energy applications. This collaboration will be physically located in a new building, financed by the EC ERDF program on the UAL campus. Construction is due to begin at the beginning of 2004.

Training and divulgation activities continued to take strong strides forward, as we are aware that we must not neglect the facet of informing society about the existence of this renewable energy option. Educational agreements with several different universities are maintained and participation in access programs for researchers promoted by the European Commission have continued.

I should not like to end this brief introduction without a word of appreciation for the support and fine work of all the PSA personnel during my first year as Director.

Diego Martínez Plaza
Director of the Plataforma Solar de Almería

General Presentation

The PSA as a Large Solar Facility: General Information

The Plataforma Solar de Almería (PSA), a dependency of the Center for Energy, Environment and Technological Research[2] (CIEMAT), is the largest center for research, development and testing of concentrating solar technologies in Europe. PSA activities form an integral part of the CIEMAT Department of Renewable Energies as one of its lines of R&D.

The objectives that inspire its research activity are the following:

- Contribute to a sustainable, clean, world energy supply.
- Contribute to conservation of European energy resources, climate and environment.
- Promote market introduction of solar thermal technologies and derived solar chemical processes.

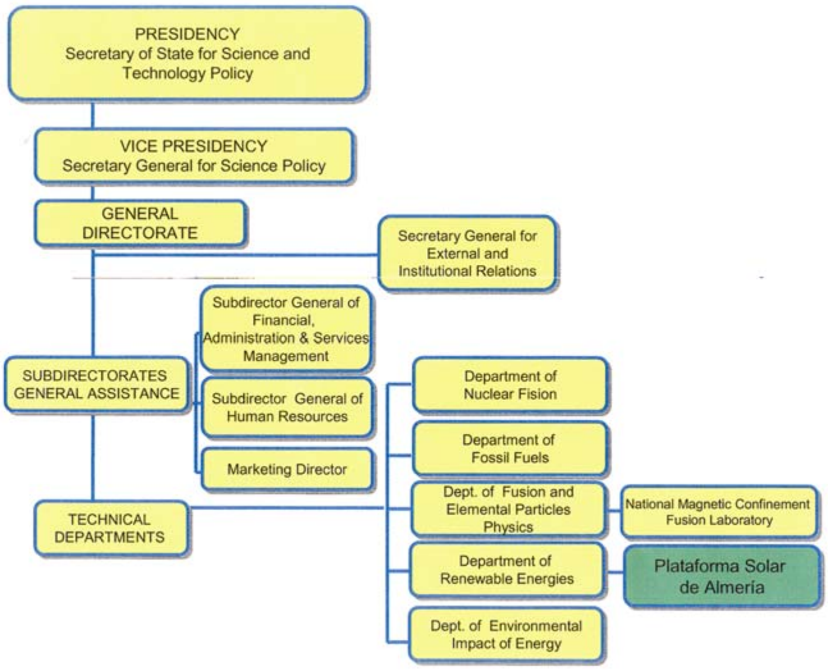


Figure 1. Integration of the PSA in the CIEMAT organizational structure

[2] Centro de Investigaciones Energéticas Medioambientales y Tecnológicas

Figure 2. Aerial view of the Plataforma Solar de Almería

- Contribute to development of a competitive European solar thermal export industry.
- Reinforce cooperation between the business sector and scientific institutions in the field of research, development, demonstration and marketing of the solar thermal technologies.
- Boost cost-reducing technological innovation, thus contributing to increased market acceptance of the solar thermal technologies.
- Promote North-South technological cooperation, especially in the Mediterranean Area.
- Assist industry in identifying market opportunities related to the solar thermal technologies.

Organization and Functional Structure

Research carried out at the Plataforma Solar de Almería is structured around four main projects: "Parabolic-Trough Collector Technology", "Central Receiver Technology", "Solar Chemistry" and "Training and Access to the Plataforma Solar de Almería". The first two are devoted to the development of new and improved ways to generate solar thermal electricity. The third to exploring the possibilities of solar chemistry, especially with regard to its potential for detoxification of industrial effluents, the synthesis of fine chemicals and the desalination of water; finally, the goal of the fourth is to make the PSA infrastructure available to the national and international scientific community and train young researchers in the technologies under development here.

To assist the R&D projects mentioned above, the PSA also has the corresponding areas of management and services which, given the variety and complexity of the facilities, are extraordinarily important to daily operation in all the center's lines of work.

Each R&D project has a Project Leader and a technical staff whose work follows the master lines of PSA scientific activity and technological development, while remaining quite independent in the execution of their budget, planning of scientific objectives and technical management of their resources. Nevertheless, the four R&D projects all share a great deal of PSA resources, services and infrastructures, so that they must maintain fluent communication with the technical support and administration units at all times, through the Directorate, which must assure that the capacities, infrastructures and human resources are efficiently distributed. It is also the Directorate that channels requirements to the various Subdirectorates for General Assistance located at the CIEMAT in Madrid.

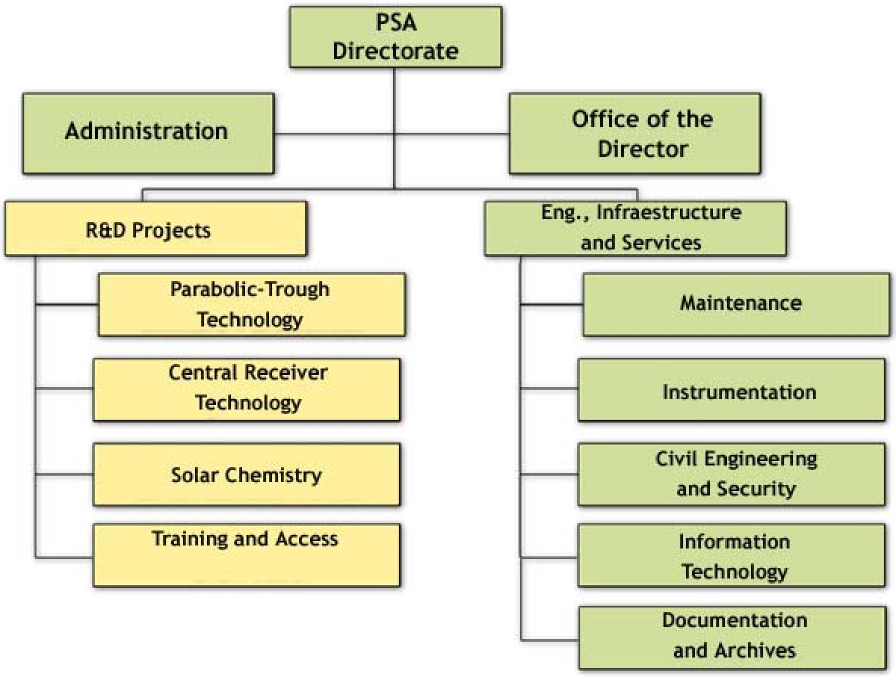


Figure 3. PSA Organization Chart 2003. Directorate, Technical and Administrative Service Offices are indicated in green.

Human and Economic Resources

The scientific and technical commitments of the PSA and their associated workload are undertaken by a team of 93 persons who, as of December 2003, made up the permanent staff that lends its services to the Plataforma Solar. Moreover, in addition to this permanent staff, there is a considerable influx of trainees and visiting researchers who are handled through the Training and Access Project described later.

Of the 93 persons that work daily at the PSA, an important part come from auxiliary services, operation and maintenance contracts (29 persons). The auxiliary contracts are for 8 administrative and secretarial staff 2 user information service technicians and five security guards. The O&M contracts are for 8 facility operators, 5 operating watchers and 13 persons for mechanical, electrical and electronic maintenance and 3 cleaners. The rest of the personnel are composed of the 37 persons on the CIEMAT-PSA staff and the 12 who make up the DLR permanent PSA delegation that result from the current commitments of the Spanish-German Agreement.

The PSA R&D staff of 37 is still small. 24 of them are in Almería and 13, while integrated in

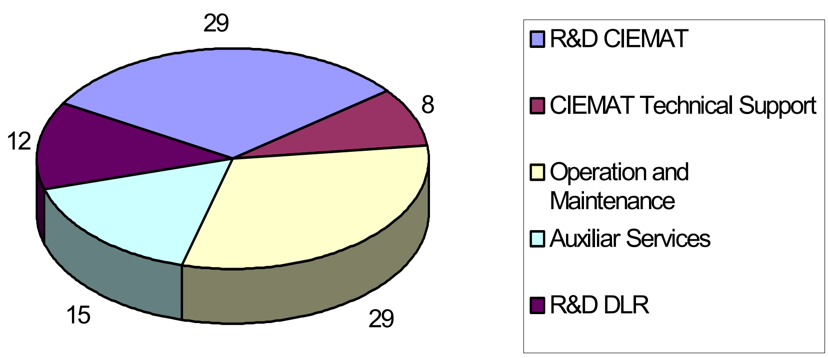


Figure 4. Distribution of PSA permanent personnel as of December 2003.

PSA R&D projects, work at the CIEMAT in Madrid. Another 12 DLR delegation staff members also work in R&D, for a total of 49 persons devoted to R&D at the PSA.

In the PSA budget, it is clear that in spite of the withdrawal of DLR from the basic budget for O&M expenses, the upward trend has been maintained, thanks in good measure to more revenues being received and to the CIEMAT itself, which has assumed the greater part of the budget previously absorbed by the Spanish-German Agreement.

Successfully raising external revenues, mainly from the European Commission, has been an outstanding contribution of DLR. The proposal of a good number of new joint projects to the EC has allowed DLR to remain at the PSA in a new relationship based on specific projects. The fruit of this success is the relevancy of the German PSA delegation.

The PSA budget reached 4.96 million Euros in 2003 (not including the cost of R&D personnel). The CIEMAT contribution was increased to be able to undertake the activities approved in the PSA infrastructure plan. These improvements were begun in 2002 with considerable new construction, such as the new visitors building, new office building, installation of the new meteorological station, replacement of the solar furnace, repairs in the DCS field and improvements in the heliostat fields.

Scope of Collaboration

As mentioned above, since 1987, the Spanish-German Cooperation Agreement with the DLR, commonly known as the CHA, has been maintained at the PSA. At the present time, the relations and Annex IV of this Agreement includes a Delegation at the PSA in 2003, 2004 and 2005. 2002 was a transition year in which new conditions and their extent were set for collaboration under the CHA. In 2003, the new Annex IV of this Agreement has been carried out to the great satisfaction of both parties.

Altogether, the scope of cooperation in which the PSA moves is very broad. In the sphere of international relations, the PSA actively participates in Tasks I, II and III of the IEA-SolarPACES program, under which information is exchanged and cost-sharing tasks are carried out with similar centers in other countries (USA, Mexico, Brazil, Germany, France, UK, Switzerland, South Africa, Israel, Russia, Australia, Algeria and Egypt).

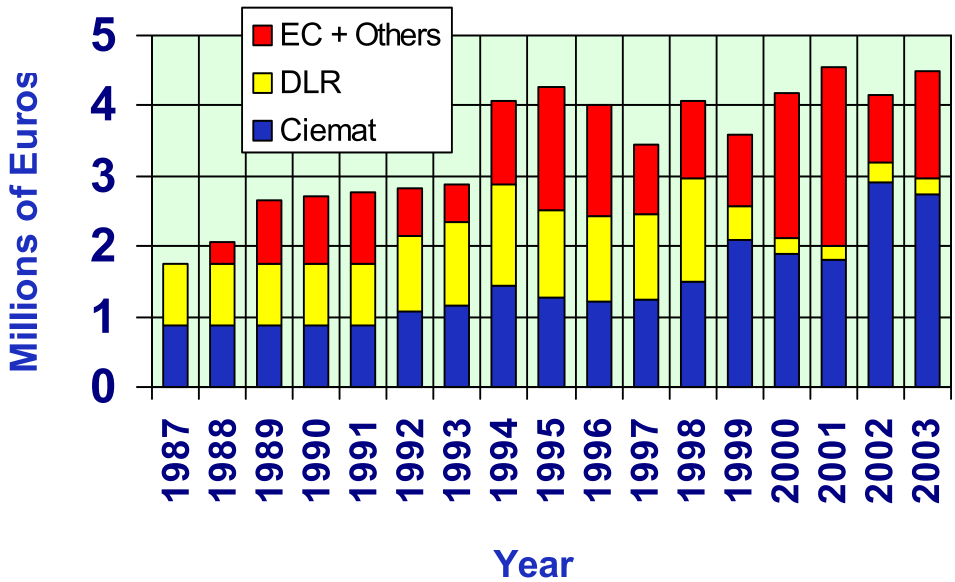


Figure 5. Evolution of PSA budgeted expenses and distribution of source of financing

In 2003, the first steps were taken toward the founding of an Associated European Solar Energy Laboratory (SolLAB). This virtual laboratory will be made up of the major European concentrated solar energy research institutes, that is, IMP-CNRS, Odeillo (France), the solar energy division of the DLR (Germany), the renewable energies laboratory of the Federal Technology Institute of Zurich (Switzerland) and the CIEMAT itself. The agreement is expected to be signed at the beginning of 2004.

Under the Training and Access Project, as one of the large scientific installations selected by the EC Directorate General for Research in the IHP (Improving Human Potential) program, the PSA maintains relations with over 60 research teams and universities from different European countries. There is also an agreement for joint management of grants with the University of Almería, as well as educational agreements to receive students from universities all over Europe. The PSA also forms part of the European EUROCARE Network for Solar Energy and Advanced Combustion Projects.

The Parabolic Trough Technology Area maintained a wide scope of collaboration both in national and European projects, with the universities of Seville, Malaga and Almería, and European research centers such as DLR, Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW) and the Fraunhofer Institute for Solar Energy Systems (ISE). The list of collaborators in private business includes Spanish (ABENGOA, IBERDROLA, Ingeniería Consultoría, Gamesa Energía and INITEC), as well as foreign companies (FLAGSOL, SBP and SIEMENS). This wide range of collaboration will be extended considerably in 2004 with PSA participation in the DISTOR project, in which 12 European entities of recognized prestige, including the CNRS, DEFI Systemes, EPSILON Ingénierie, SGL Technologies GmbH, the WIS and the Bulgarian Academy of Sciences will be collaborating.

In the national scope of central receiver technology, the PSA collaborates in projects with SOLUCAR, IBERESE and SERLED and universities such as the University of Sevilla, Almería and the UNED[3]. Under the umbrella of the 5th Framework Program's Energy Program and the Spanish German Agreement, collaboration with the DLR has been intense in several projects with other European institutions and companies such as ORMAT (Israel), TUMA (Switzerland), Heron (Netherlands), FICHTNER (Germany), STC (Denmark), Forth-Cperi (Greece) and Saint Gobain Ceramics (Germany).

In 2003, the Chemical Applications of the Solar Radiation Project kept up the high level of collaborative relations reached in previous years. A list of the institutions with which formal activities have been carried conveys the idea well. In fact, as of December 31, 2003, the list of current contractual relationships extends to all the possible spheres, from local (Univ. de Almería, DSM Deretil, Cajamar, Coexpal, Comunidad de Regantes Cuatro Vegas) to national (Grupo Abengoa, Ecosystem, Aragonesas Agro, Emuasa, Indoor Air Quality, Caucho-Metal Products, Fundación Inasmet, ICP-CSIC, Hospital de San Carlos in Madrid and the Autónoma de Barcelona, Complutense, Alcalá and La Laguna Universities), European (Weir-Entropie, Ao Sol, Hellenic Saltworks, Trailigaz, Janssen Pharmaceutica N.V., Ahlstrom Paper Group, IPM, Protection des Metaux, and ETH, NTUA, INETI, EPFL, Claude Bernard Lyon 1, Poitiers, L'Aquila, universities, etc.) and in the rest of the world where we have collaboration contracts with institutions in México, Argentina, Perú, Colombia, Venezuela, Morocco, Egypt and Tunisia.

[3] Universidad Nacional para Educación a Distancia (National University for Education by Correspondence)

Facilities and Infrastructures

General Description of the PSA

The PSA is located in southeastern Spain in the Desert of Tabernas at 37º05'27.8" north and 2º21'19" west. It receives a direct annual insolation above 1900 kWh/(m²·year) and the average annual temperature is around 17ºC.

The capacity to offer researchers a place with climatic and insolation conditions similar to those in developing solar-belt countries (where the greatest potential for solar energy is found) but with all the advantages of a large scientific installation in the most advanced European countries, makes the PSA a privileged site for evaluation, demonstration and transfer of solar technologies.

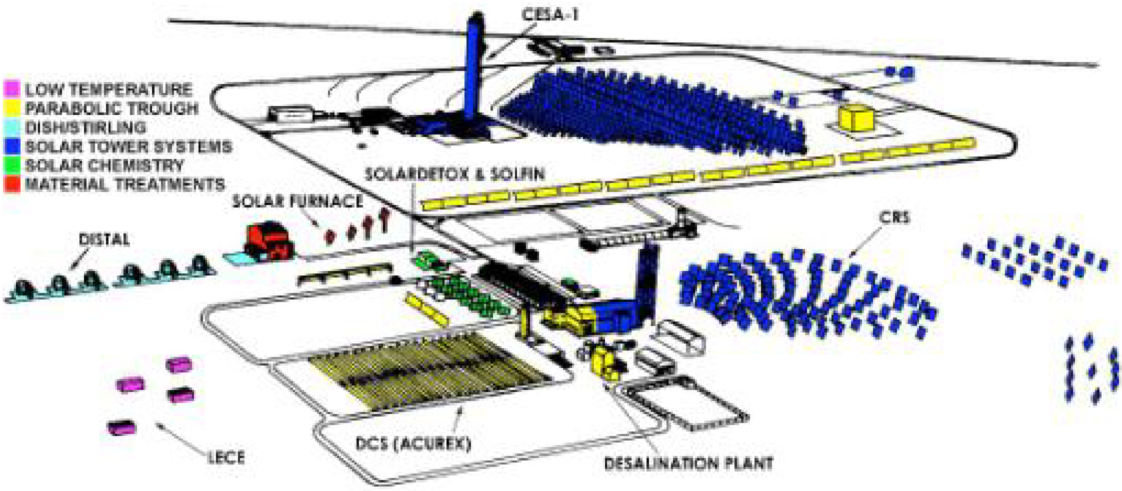


Figure 6. Location of the main PSA test facilities

At present, the main test facilities available at the PSA are [SolarPACES, 1996]:

- CESA-1 and SSPS-CRS central receiver systems, 7 and 2.7-MWt respectively.
- SSPS-DCS 1.2-MWt parabolic-trough collector system, which has an associated thermal storage system and water desalination plant.
- The 1.3-MWt DISS test loop, which is an excellent experimental system for two-phase flow research and direct steam generation for electricity production.
- The HTF test loop, which has a complete oil circuit that allows evaluation of new components for parabolic trough collectors.

- A facility with 6 dish/Stirling systems called 'DISTAL'.
- A 60-kWt solar furnace for thermal materials treatments.
- A multiple facility for solar detoxification applications consisting of a parabolic-trough loop with two-axis tracking and three CPC photoreactors for different types of trials.
- The Laboratory for Energy Testing of Building Components[4] (LECE).
- A meteorological station.

Central Receiver Facilities: CESA-1 and CRS

The PSA has two exceptional facilities for the testing and validation of central receiver technology components and applications. The CRS and CESA-1 enable projects to be undertaken and technologies validated in the hundreds of kilowatts range. They are outdoor laboratories specially conditioned for scaling and qualifying systems in the phase prior to commercial demonstration.

They are also used for other applications that require a high photon concentration on a relatively large surface, such as high temperature chemical processes, surface materials treatments or astrophysics experiments.

7-MW_T CESA-I FACILITY

The CESA-I project, inaugurated in May 1983, was promoted by the Spanish Ministry of Industry and Energy to demonstrate the feasibility of central receiver solar plants and enable the development of the necessary technology. At present, the CESA-1 does not produce electricity, but is operated as a very flexible test facility for subsystems and components such as heliostats, solar receivers, thermal storage, solarized gas turbines, control systems and concentrated solar radiation high flux measurement instrumentation.

The facility collects direct solar radiation by means of a field of 300 39.6-m^2-surface heliostats distributed in a 330-x-250-m north field into 16 rows. The heliostats have an average nominal reflectivity of 90%, the solar tracking error on each axis is 1.2 mrad and the reflected beam image quality is 3 mrad. The CESA-1 facility has the most extensive experience in glass-metal heliostats in the world, with first generation units manufactured by SENER and CASA as well as second generation units with reflective facets by ASINEL and

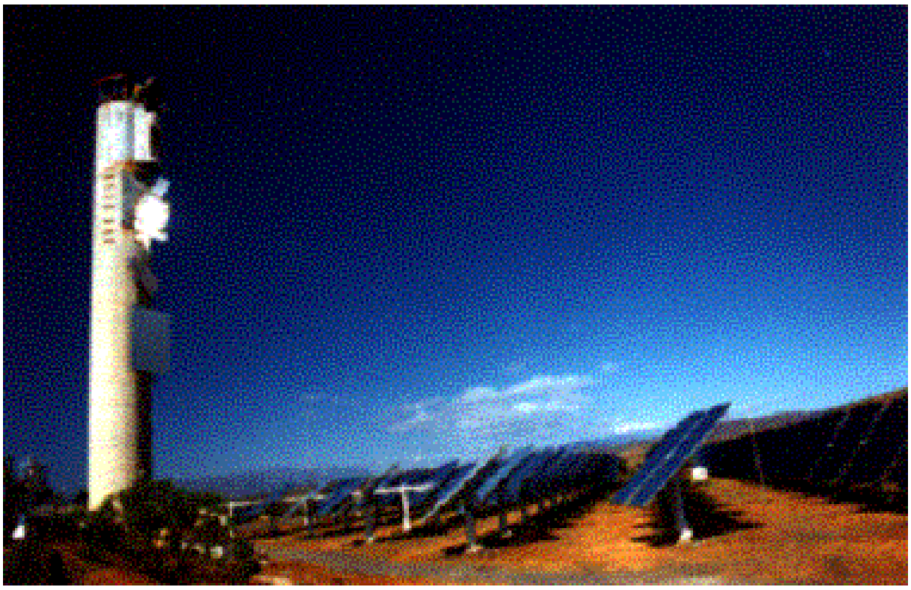


Figure 7. Side view of the CESA-I facility with heliostat rows focusing on the medium-height test level (60 m.)

[4] Laboratorio de Ensayo Energético de Componentes de la Edificación

third generation facets and prototypes developed by CIEMAT and the SOLUCAR company. In spite of its over 20 years of age, the heliostat field is in optimum working condition due to a strategic program of continual mirror and facet replacement and drive mechanism component repair. To the north of the field are two additional areas used as a test platform for new heliostat prototypes, one located 380 m from the tower and the other 500 away. The maximum thermal power delivered by the field onto the receiver aperture is 7 MW. At a typical design irradiance of 950 W/m², a peak flux of 3.3 MW/m² is obtained. 99% of the power is focused on a 4-m-diameter circle, 90% in a 2.8-m circle.

The 80-m-high concrete tower, which has a 100-ton load capacity, has three test levels:

- A cavity adapted for use as a solar furnace for materials testing at 45 m, which has been used very successfully in reproducing the heat ramp on test pieces of the ceramic s hield for space shuttles during their reentry into the atmosphere and also for surface treatment of steels and other metal compounds.
- A cavity with a calorimetry test bed for pressurized volumetric receivers at 60 m. At the present time this cavity houses the SOLGATE project infrastructure, which includes three volumetric receivers with a total incident power of nearly 1 MW and 250-kW solarized turbine, to which the corresponding electric generator, air loop, heat rejection system and thermal shield.
- The 2.5-MW TSA volumetric receiver test facility at the top of the tower at 80 m.

The tower is complete with a 5-ton-capacity crane at the top and a freight elevator that can handle up to 1000-kg loads. Finally, for those tests that require electricity production, the facility has a 1.2-MW two-stage turbine in a Rankine cycle designed to operate with 520°C 100-bar superheated steam

THE 2,7-MW$_T$ SSPS-CRS FACILITY

The SSPS-CRS plant was inaugurated as part of the International Energy Agency's SSPS project (Small Solar Power Systems) in September 1981. Originally, it was an electricity production demonstration plant, and used a receiver cooled by liquid sodium that also acted as the thermal storage medium. At the present time, as with the CESA-I plant, it is a test facility devoted mainly to testing small solar receivers in the 200 to 350-kW thermal capacity range. The heliostat field is made up of 91 39.3-m² first generation Martin-Marietta units. A second field north of it has 20 52-m² and 65-m² second generation MBB and Asinel heliostats that can be used as support. The CRS heliostat field has recently been improved with the replacement of all the reflective facets, which now have a lightweight structure and low-iron glass. The most innovative feature is that in 2003, all of the heliostats were converted into completely autonomous intelligent units, communicated by radio and powered by photovoltaic energy according to the concept developed and patented by PSA researchers. At the present time, the CRS facility has the first autonomous heliostat field which does not require the use of channels or cabling thanks to the financial assistance of the Ministry of Science and Technology's PROFIT program.

The nominal average reflectivity of the field is 87%, the solar tracking error is 1.2 mrad per axis and the optical reflected beam quality is 3 mrad. Under typical conditions of 950 W/m², total thermal capacity of the field is 2.7 MW and peak flux obtained is 2.5 MW/m². 99% of the power is collected in a 2.5-m-diameter circumference and 90% in a 1.8-m circumference.

The 43-m-high metal tower has two test platforms. The first is a two-level open area at 32 and 26 m prepared for testing new receivers for chemical applications. The second is at the top, at 43 m, and houses an enclosed room with crane and calorimetric test bed for the evaluation of small atmospheric-pressure volumetric receivers.

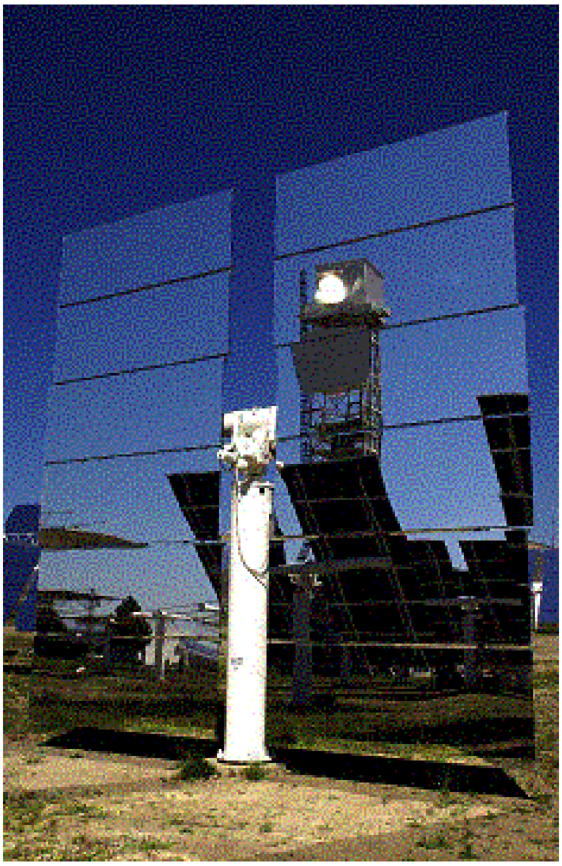


Figure 8. A CRS field heliostat reflecting the tower

Figure 9. Front view of the 200-400-kW volumetric receiver test bed in the CRS tower.

The tower infrastructure is completed with a 600-kg-capacity crane and a 1000-kg-capacity rack elevator.

The test bed (Figure 9)consists of a air-recirculation circuit with axial fan and 40-kW electric heater to control the air-return temperature as well as instrumentation to measure the temperature, pressure and flow rate. Absorber outlet air is cooled by a water-cooled heat exchanger used as an indirect method of thermal balance. The calorimetric bench has been successfully employed since 1986 with the logical improvements and updating, for the evaluation of all kinds of metal and ceramic volumetric absorbers.

Two PROHERMES II (Programmable Heliostat and Receiver Measuring System II) measurement systems are used to measure the flux of the concentrated solar radiation on both towers. For this, the concentrated incident solar beam is intercepted by a lambertian target, located on a plane parallel and immediately in front of the receiver aperture, at which moment a high-resolution CCD camera records the image.

After exhaustive treatment of the image (removal of electronic background noise, correction of aberrancies produced by the viewing equipment and geometric rectification), the gray-scale value associated with each pixel undergoes a transformation called calibration. This operation consists of experimentally finding a specific rule or criterion that unmistakably associates each value given the solar irradiance (W/cm^2) at a specific point on the target to a gray-scale value for the pixel corresponding to the same position previously obtained with the camera. Once the pixel map has been calibrated and the area that they represent individually on the target is found, the total power can be integrated, and the calculation of the rest of the magnitudes of interest, such as peak irradiance or distribution, is possible.

Linear focusing facilities: DCS, DISS, EUROTROUGH and LS3

The PSA has several parabolic-trough solar collector facilities. Some of them, such as the SSPS-DCS, were pioneers in Europe, while other more modern facilities, such as the DISS experimental plant, are unique worldwide and place the PSA in a privileged position for research and development of new parabolic-trough collector applications. The main characteristics of these facilities are briefly explained below.

THE DISS EXPERIMENTAL PLANT

This facility was erected and put into operation in 1998 for experimenting with direct generation of high-pressure high-temperature (100 bar/400°C) steam in the parabolic-trough collector absorber tubes. The DISS experimental plant is the only facility in the world where two-phase flow water/steam processes in parabolic-trough collectors can be studied under real solar conditions. It is very appropriate not only for the study and development of control schemes, but also for the study and optimization of operating procedures, that must be implemented in direct steam generation solar fields. Other possible applications of this plant are the study of the heat transfer coefficients in horizontal tubes through which the two-phase water/steam flow circulates, and testing of components for parabolic-trough solar collector fields with direct steam generation in the absorber tubes.

The DISS plant consists of two subsystems: the Solar Field of parabolic-trough collectors, and the Power Block. In the solar field, the feed water is preheated, evaporated and converted into superheated steam as it is circulated through the absorber tubes of a 650-m-long row of parabolic trough collectors having a total solar collecting surface of 3,838 m^2. The installation of two new collectors in 2003 has increased the nominal superheated steam flow rate that the DISS collector row can produce to 1 kg/s.

Superheated steam generated in the solar field is condensed, processed and reused again as feed water for the solar field (closed-circuit operation) in the power block.

Facility operation is highly flexible and can work at three different pressure levels: 30, 60 and 100 bar and in any of the three basic direct steam generation modes: Recirculation, Injection and Once-Through, or any combination thereof. Furthermore, it is provided with a complete range of instruments that allows complete system monitoring.

Figure 11 shows a simplified diagram of the DISS loop in which the solar field is shown as one row of 13 parabolic-trough collectors with north-south-oriented rotating axes. The collectors are composed of 12-m-long by 5.76-m-wide reflective parabolic-trough modules.

Figure 10. View of the DISS plant solar field in operation

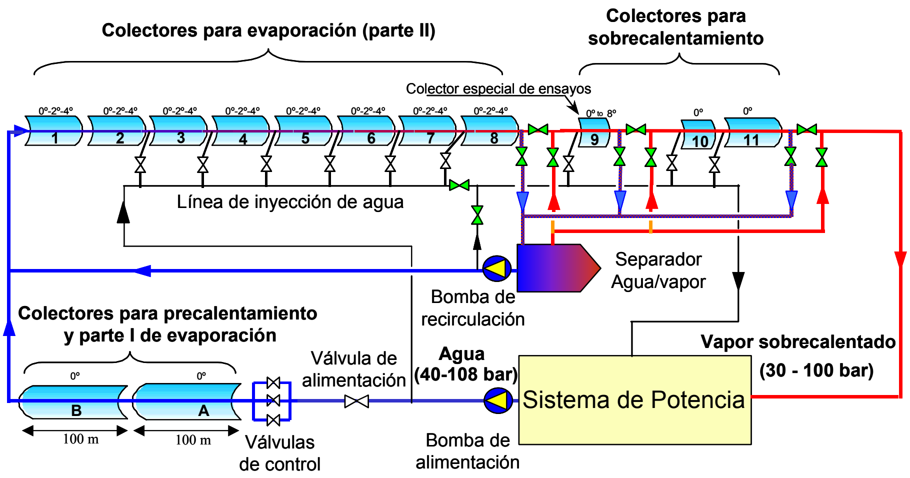


Figure 11. Simplified diagram of the PSA DISS plant

The solar field consists of two parts, the preheating/evaporating section and the superheating section. At the end of the preheating/evaporating section there is a recirculation pump and a water/steam separator which augments the operative flexibility of the system.

The power block consists of water/steam separators, condensers, chemical dosing system, preheaters, degassing system and water pumps.

One of the most important characteristics of the DISS plant is the possibility of measuring the thermal gradient in the cross sections of the parabolic-trough solar collector absorber tubes.

THE LS-3 (HTF) TEST LOOP

The LS-3 test loop, also called the HTF test loop, which was erected in 1997, is an ideal facility for evaluating parabolic-trough collector components under real solar energy operating conditions. Mirrors, absorber tubes, solar tracking systems, etc., can be installed and evaluated in this facility, which is provided with the appropriate measurement and monitoring instrumentation.

The facility consists of a closed thermal oil circuit connected to a solar collector made up of four 12-m-long by 5.7-m-wide LS-3 parabolic-trough modules with a total collecting surface of 274 m^2. The thermal oil used in this facility (Syltherm 800) has a maximum working temperature of 420°C, and a freezing point of –40°C. The rotating axis of the solar collector is oriented east-west, which increases the number of hours per year in which the angle of incidence of the solar radiation is less than 5°. The facility's oil circuit, which has a maximum working pressure of 16 bar, is made up of the following elements:

- 1-m^3-capacity oil expansion tank, with automatic nitrogen inertization system
- Oil circuit sump tank
- Mechanical draft oil cooler, with air speed control and 225-kW maximum cooling.
- Centrifugal oil pump, with a flow rate of up to 2.8 liters per second
- 40-kW, 3-x-380 V electric oil heater.

In the HTF test loop, and in parallel to its solar collector, is the EUROtrough collector prototype. The EUROtrough collector design was developed by a European consortium which, with the financial aid of the European Commission, designed, built and erected it at the PSA and evaluated it under real conditions. The new parabolic-trough collector is apt not only for solar thermal power plants, but also for other large applications, such as desalination of seawater or industrial process heat in the 150°C-425°C range. At the conclusion of the EUROtrough project, the partners in the project donated this first prototype to CIEMAT for its operation and maintenance, which now forms part of the PSA parabolic-

Figure 12. General view of the LS-3

trough collector facilities. With the installation of the EUROtrough HTF loop, the system's collecting area has increased to 685 m^2.

SSPS-DCS PLANT WITH SOLAR DESALINATION SYSTEM

This 1.2 MW$_t$-capacity facility, as shown in the diagram below (Figure 13), consists of four main subsystems:

- A solar field made up of 40 ACUREX 3001 parabolic-trough collectors in 10 parallel rows of 4 collectors connected in series. Its total solar collecting surface is 2,672 m^2 and the rotating axis of the collectors is oriented east west. The fluid used by this collector field is Santotherm 55 oil, which has a maximum working temperature of 300ºC. The collector absorber tubes are not evacuated and have a black chrome selective coating. This solar field has an overall performance of 50%, with peak power of 1.3 MW$_t$ for direct solar radiation of 950 W/m^2. The average daily thermal energy delivered is 6.5 MW$_t$.
- A 5-MWh$_t$-capacity thermal storage system consisting of a 140-m^3 thermocline oil tank for charging/discharging temperatures of 295º/25ºC with automatic fire-

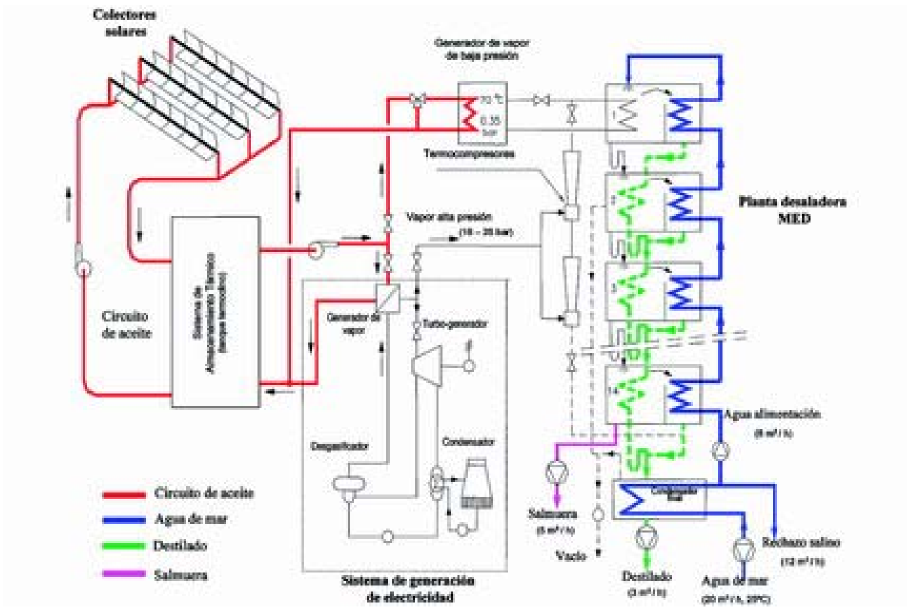


Figure 13. General diagram of the SSPS-DCS plant

extinguishing system, automatic venting valves and volatile-condensing system. It also has a water-cooled oil cooler for quick cooling during transient testing.

- A 500-kWe water/steam Rankine cycle electricity generating system consisting of a steam generator fed by the hot oil delivered by the solar field and/or storage tank; degasifier; steam turbine; electric generator and mechanical draft closed-loop cooling tower.
- The MED desalination plant, called the SOL-14, consists of a 14-stage multi-effect distillation plant, which is connected to the thermal storage system described above. For a nominal production of 3-m³/h distillate, plant consumption is 190 kW_t, with an efficiency factor (number of kg of distillate produced for every 2,300 kJ of energy consumed) over 9. The saline concentration of the distillate is around 50 ppm. The nominal temperature gradient between the first and last stages is 40°C, with an operating temperature of 70°C in the first stage. The vacuum system, made up of two hydroejectors fed by seawater at 3 bar is used evacuate the air from the unit at the beginning of operation and to compensate for the small amounts of air and gas released with the feedwater, as well as any slight losses in the various connections.

A double-effect (LiBr – H_2O) absorption heat pump is the first real prototype of a device of its kind for this application. Heat loss recovery with this pump in the last condenser increases the performance ratio of the MED plant to 20 over operation without it.

Capacity:	3 m^3/hour
Number of effects:	14
Feed water:	Seawater (35,000 ppm)
Product:	Distillate (≤50 ppm)
Recovery Factor:	38%
Feedwater flow rate:	8 m^3/hora
Thermal consumption (FR):	63 kWh/m^3 (>9)
Electricity Consumption:	3 kWh/m^3
Solar field capacity:	1.2 MWp
Solar field performance:	50%
Collector surface:	2762 m^2
Type of collectors:	ACUREX 3001 (CCP)
Storage:	5 MWh (Therminol 55)
Maximum oil temperature:	300°C

Figure 14. Technical specifications of the PSA SOL-14 solar desalination plant and aerial view with ACUREX field in foreground, thermal storage tank at upper left and MED upper right

Dish/Stirling Systems: DISTAL and EURODISH

PRINCIPLES

A dish/Stirling system consists of a wide-diameter parabolic mirror with a Stirling-type external combustion motor installed in its focal area. The parabolic dish-mirror continuously tracks the sun, so that the sun's rays are reflected onto its focal plane, obtaining a Gaussian-shape concentrated solar energy map and several tens of kW. The Stirling motor is an external combustion motor that employs the thermodynamic cycle of the same name and that has two advantages that make it appropriate for this application:

- Combustion is external, that is, the energy contribution may from sunlight collected by the parabolic dish and concentrated on its focal zone.
- It is a high-performance thermodynamic cycle.

An alternator is connected to the Stirling motor, so that the luminous energy can be transformed into electricity or delivered to a nearby application for direct consumption right in the same block at the focus of the concentrating dish.

The most obvious application of dish/Stirling systems is the production of electricity for self-producers in remote areas or rural communities where there is no grid, for pumping water, etc.

The optimum niche on the energy market would be a power range of a few tens of kilowatts, where it would compete with the already commercial photovoltaic systems or diesel generators.

Since the beginning of activities in 1992, three generations of prototypes have been erected and routinely operated at the PSA for their technical evaluation, DISTAL I, DISTAL II and EUROdish.

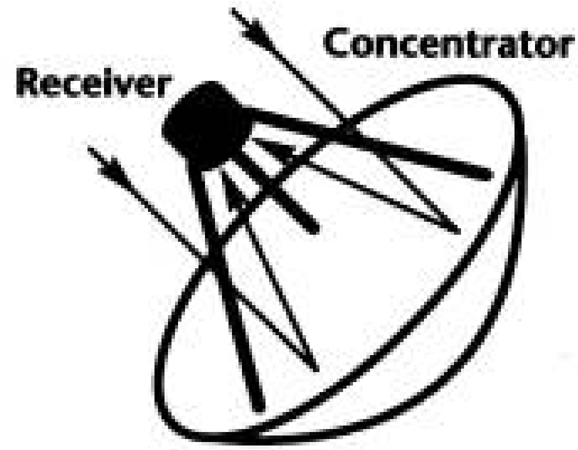


Figure 15. Schematic diagram of a parabolic dish with Stirling motor at the focus

DISTAL I

In operation since 1992, this installation initially consisted of 3 7.5-m-diameter parabolic dish units capable of collecting up to 40 kW_t energy with a SOLO V160 9-kW_e Stirling motor located in its focal zone.

The concentrator prototype was made using the stretched membrane technique, which maintains the parabolic shape with a small vacuum pump. It has 94% reflectivity and can concentrate the sunlight up to 12,000 times in its 12-cm-diameter focus. It has a focal distance of 4.5 meters and polar solar tracking. Two DISTAL I units were disassembled in the year 2000 and replaced by third generation EUROdish units.

Figure 16. A DISTAL I dish in operation

DISTAL II

The DISTAL II was a first attempt at a system with better features and per-kWe cost. Three new stretched-membrane prototypes were erected and put into routine operation in 1996 and 1997. Their slightly larger 8.5-m-diameter delivers 50 kW_t to the motor. The focal distance is 4.1 m and the maximum concentration is 16,000 suns at the focus. The Stirling motor, which had also evolved, is now a 10-kW_e SOLO V161 and the tracking system is azimuth-elevation, which allows automatic sunrise-to-sunset operation.

Figure 17. DISTAL II unit

EUROdish

The second and latest attempt to make this technology economical is the Spanish-German EUROdish project. Two new prototypes were designed and erected with the following goals:

- Reduce the price of components by using standard industrial elements.
- Develop a new dish manufacturing system discarding the stretched-membrane technology and applying a composite-material molding system.
- Develop a new optimized system assembly procedure that uses new specially developed tools.
- Remote control and monitoring over the WWW.

Figure 18. New Stirling motor receiver cavity absorber tubes.

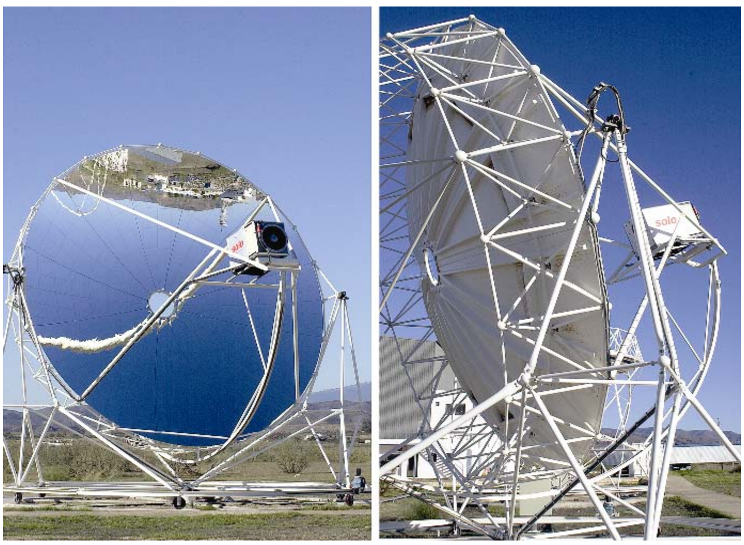


Figure 19. Front and back views of the EURODishes.

- Improve the Stirling SOLO V161 motor, especially those components used in the receiver cavity.
- Test pre-commercial units as reference systems.

Solar Furnace

GENERAL DESCRIPTION AND PRINCIPLES OF OPERATION

Solar furnaces reach the highest energy levels obtainable with a solar concentrating system, having attained concentrations over 10,000 suns. Their main field of application is materials testing, either in ambient conditions, controlled atmosphere or vacuum, and solar chemistry experiments using chemical reactors associated with receivers.

The solar furnace essentially consists of a continuously solar-tracking flat heliostat, a parabolic concentrator mirror, an attenuator or shutter and the test zone located in the concentrator focus [Martínez and Rodríguez, 1998].

The flat collecting mirror, or heliostat, reflects the parallel horizontal solar beams on the parabolic dish, which in turn reflects them on its focus (the test area). The amount of incident light is regulated by the attenuator located between the concentrator and the heliostat. Under the focus there is a test table movable in three directions (East-West, North-South, up and down) that places the test samples in the focus with great precision.

HELIOSTATS

The reflective surface of the heliostats is made up multiple flat non-concentrating facets that continually track the solar disk and reflect its parallel horizontal beams onto the optical axis of the concentrator.

The PSA solar furnace has four heliostats arranged on two levels, each one of which focuses on a fourth of the concentrator, so that complete illumination of the concentrator is assured during the operating period. The heliostats have 16 3.35-m^2 sandwich-type facets, for a total of 53.58 m^2. Each one is made up of two mirrors with 90% reflectivity held to a supporting frame by 30 suction cups.

CONCENTRATOR

The concentrator disk is the main component of the solar furnace. It concentrates the incident light from the heliostat, multiplying the radiant energy in the focal zone. Its optical properties especially affect the flux distribution at the focus. It is composed of 89 spherical facets with a total surface of 98.5 m^2 and 92% reflectivity. Its focal distance is 7.45 m. The parabolic surface is achieved with spherically curved facets, distributed along five radii with different curvatures depending on their distance from the focus.

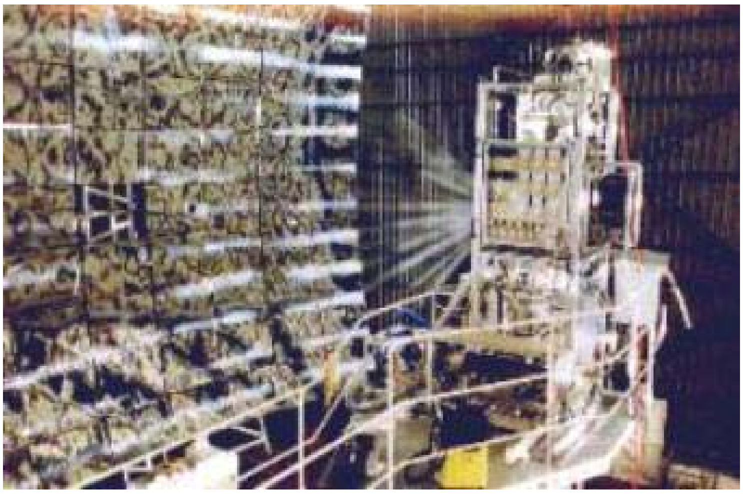


Figure 20. Solar Furnace: Concentrator (left) and receiver in operation at the focus (right).

ATTENUATOR

The attenuator consists of a set of horizontal louvers that rotate on their axes, regulating the amount of entering sunlight incident on the concentrator. The total energy on the focus is proportional to the radiation that passes through the attenuator.

It is composed of 20 louvers arranged in two columns of 15. In closed position the louvers form a 55° angle with the horizontal and 0° when open.

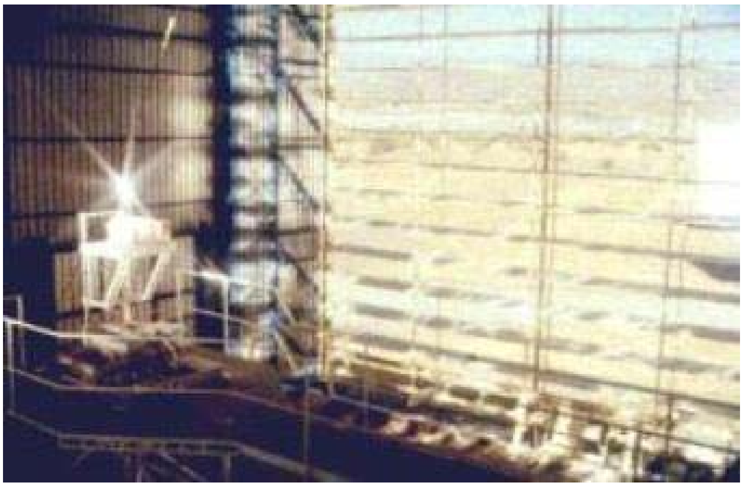


Figure 21. The focus and the test table on the left. On the right, the attenuator, completely open, allows the rays from the heliostats outside to enter.

TEST TABLE

This mobile support is located under the focus of the concentrator. It moves on three axes (X, Y, Z) perpendicular to each other and positions the test sample with great precision in the focal area.

DISTRIBUTION OF THE FLUX DENSITY IN THE FOCUS

The concentration and distribution of the flux density in the focus characterize a solar furnace. This distribution usually has a Gaussian geometry and is characterized by a CCD camera hooked up to an image processor and a lambertian target. The characteristics of the focus with 100% aperture and solar radiation of 1000 W/m^2 are: peak flux, 3000 kW/m^2, total power, 58 kW and focal diameter, 23 cm [Neumann, 1994].

FACILITY IMPROVEMENT

After 12 years in operation, the four MBB heliostat facets had been deteriorated by corrosion and some that were broken had no replacement, and so the conditions in the furnace worsened day by day. It was therefore decided to replace the four furnace heliostats with a single large reflective surface placed as close as possible to the concentrator, that would operate with advantage over the four previous ones, since it would produce just one focus and therefore, higher concentration.

Installation of the new GM-140 heliostat 28 m from the attenuator, was completed in July, concentrating all the energy of the furnace on only one focus instead of four, one for each of the four old heliostats, on which it had been concentrated previously.

This new heliostat consists of 32 3.22-m x 1.36-m flat facets with a 140-m^2 area providing the largest reflective surface now operating at the PSA. Although it has not yet been measured, the total optical error σ of the heliostat is expected to be less than 2 mrad.

Figure 22. New GM-140 heliostat

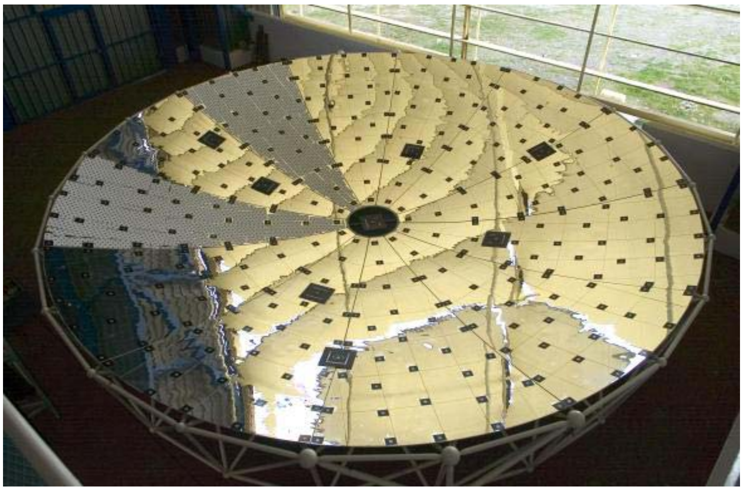


Figure 23. New EURОdish parabolic concentrator

A new arm, facets and facet-support structure were fabricated, while pedestal and head of the old GM-100 Solucar heliostat were used for the new heliostat. The entire control panel and software were made at the PSA.

On the other hand, it has always been a goal of the PSA Materials Group to improve the solar furnace's concentrating factor, since, although it's 60-kW power is considerable for this type of facilities, its peak concentration is only 3000 suns, which is insufficient for certain tests that require high instantaneous energy to attain a steep thermal gradient or a very high temperature (2000ºC), so it was decided to acquire a parabolic concentrator such as those manufactured by the German company Mero Gmbh for use in the dish/Stirling-EURОdish systems.

The **new EURОdish parabolic concentrator** has 12 curved fiberglass sections (petals) attached to each other with a two-component glue and a strip of fiberglass providing a lightweight, rigid parabolic surface. The front face of the reflective surface is made up of thin 0.8-mm-thick films. All of this is supported by a ring-shaped structure of tubes joined by small knot-like balls.

Although, the flux of this new 56-m^2 concentrator has not yet been measured, it is expected to attain concentrations of over 6000 suns, which would be sufficient for testing at very high temperatures and steep gradients that up to now have been out of reach of the PSA furnace.

Figure 24. New vertical-axis solar furnace tower

The concentrator was erected in November in the furnace test bay. It is built on a movable structure in front of the present concentrator in such a way that the two dishes can be used interchangeably depending on the type of test to be done.

Moreover, the 18-m high tower with a 5 x 5 m base that supports the new vertical axis of the furnace was erected on the outside of the southern face of the bay. 15 m from ground level is the attenuator with horizontal blades. A new 25-m^2 heliostat already manufactured, called the HT-25, is to be installed in the center of the base of the tower. The new 3.5-m–diameter vertical axis concentrator will be at the top, and below it over the attenuator, the test table.

Solar Chemistry Facilities

DETOX/SOLFIN FACILITIES FOR SOLAR PHOTOCHEMICAL APPLICATIONS

The first pilot plants with reactors for solar decontamination at the Plataforma Solar de Almería were developed at the beginning of the nineties. The present configuration of the photochemistry parabolic-trough collector pilot plant is composed of four two-axis solar-tracking parabolic trough solar collectors with a total collecting surface of 128 m^2. The concentrating factor achieved is 10.5 suns. Each "Heliomans" solar collector consists of a column supporting 32 mirrors in four parallel parabolic troughs for a total area of 32 m^2. The working flow may be varied between 500 and 4000 L/h. All the piping, tanks and accessories are HDPE (high-density polyethylene), a material highly resistant to the majority of chemicals. The module absorber tubes (56-mm-diameter, 2-mm-thick borosilicate glass) are each 16 m long, totaling 64 linear meters of photochemical reactor.

Later, other CPC (Compound Parabolic Collector) pilot plants were installed that can use diffuse radiation as well as direct. The CPC reflectors are made of anodized aluminum. At the PSA there are now three such plants. The largest has two modules, each with a 3-m^2 surface tilted 37° (local latitude) from the horizontal. The complete includes a pump, tank and connecting piping. The total system volume is approximately 250 L and the absorber tube (illuminated) volume is 108 L. In 2002, a new 15-m^2 collector was installed that increased the volume to 300 L. This collector is the most advanced model developed in recent years and treatment plants to be developed in several different projects are expected to be based on it. Furthermore, two twin prototypes are also available for parallel experiments. Each reactor is made up of three modules of eight glass tubes each. The three modules (3.08 m^2) of each reactor are mounted on a fixed platform also tilted 37°. The total reactor volume is 40 L, of which 22 L is the total irradiated volume and the rest is in the piping and tank.

There are also three sensors for measuring ultraviolet solar radiation, one with a solar tracking unit for direct radiation and two horizontal units tilted 37° (the same angle as the CPCs) to the earth's surface for global. All the data are sent to a computer where they are stored for their later evaluation. At the end of 2003, due to the completion of SOLFIN (Solar Synthesis of Fine Chemicals) activities, the facility was disassembled.

The PSA Solar Chemistry Laboratory is a 75-m^2 building designed to hold all the conventional chemical laboratory equipment: work tables, gas extractor fan hood, storeroom for

Figure 25. General view of the CPC Solar Photochemical Facilities with the new collector in the foreground

small amounts of chemicals, central distribution of technical gases, UPS, safety systems (extinguishers, shower, eyewash, etc.) precision-scale workbench, water ultra-purification system, ultrasound bath, centrifugal vacuum distillation system, as well as many other systems normally used in a chemistry laboratory. Furthermore, it has the following analytical equipment, all of them related to Environmental Chemistry: Liquid chromatograph (quaternary pump with automatic injector and diode detector), gas chromatograph (FID and TDC) with purge and trap system (analysis of volatiles dissolved in water), ion chromatograph, TOC analyzer (with automatic injector), UV-visible spectrophotometer, COD and BOD. All these systems are completely computerized and networked. Furthermore, it has the only Andalusian network (14 stations) node in Almería for UVB/UVA/PAR measurement

SOLAR CHEMISTRY TEST BED

This test bed, located in the CIEMAT's Department of Renewable Energies (Madrid), enables laboratory-scale experimentation to determine the feasibility of processes that will later be carried out in the various solar facilities mentioned above. The use of this test bed has basically been to determine process thermodynamics and kinetics. The facility consists of Pyrex photoreactors that operate in recirculation or batch mode and use a solar simulator with a 1000-W Xenon lamp as the light source. It has an automatic temperature, pH, oxygen concentration and CO_2 measurement control system that works by means of probes. Furthermore, the HPLC, GC, etc., analytical techniques available enable precision determination of all the parameters now being studied at laboratory scale, among which the following are the most important:

Figure 26. Solar Chemistry Project test bed

- Feasibility of Fe^{+2}-H_2O_2-concentrated solar radiation system for treatment of effluents.
- Technical feasibility of certain solar photocatalytic storage processes, e.g., photo-assisted reduction of CO_2 using RuO_2-TiO_2 catalysts.

GAS PHASE DETOXIFICATION LABORATORY

The Gas-Phase Detoxification Laboratory is located in Madrid in the Department of Renewable Energies Building. Any Volatile Organic Compound (VOC) can be tested in it under controlled conditions of contaminant concentration, pressure, temperature and flow rates, of both gases and radiants and destruction efficiencies can be determined for it. The energy source can be either solar or UV lamp, individually or combined, on different types of catalysts and reactors. For this there is a gas intake and mass control system, real solar radiation test bed located on the laboratory roof, and an indoor test bed with xenon lamp solar simulator. The analytical instrumentation is basically GC and GC-MS associated with a thermal desorption system, as well as continuous SO_2 and CO_2 analyzers.

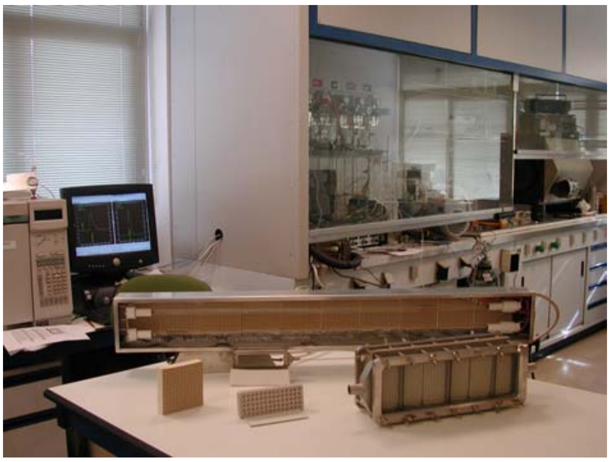


Figure 27. Different types and configurations of reactors and catalysts–flat, monolithic, tubular-tested in gas phase.

Other Facilities

STATIONARY SOLAR COLLECTOR TEST BED

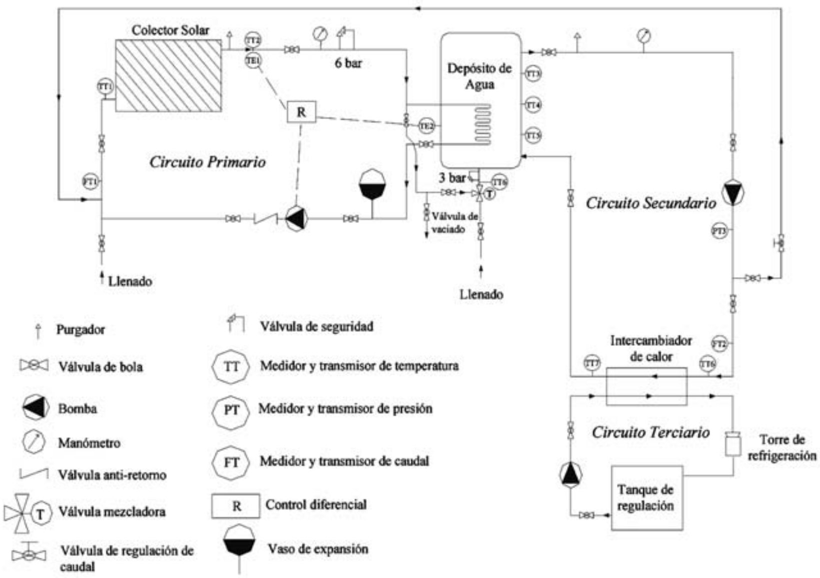


Figure 28. General schematic diagram of the stationary solar collector test bed.

This facility was erected in 2002 to offer additional services to the scientific research community, among which is the energy characterization of stationary solar collectors, especially their possible application to solar desalination.

The facility has three independent hydraulic circuits. In the primary circuit, the liquid (water or mixture of water and anti-freeze) is heated as it passes through the solar collector, delivering the energy acquired to the water deposited in a storage tank. In the secondary circuit, the water from the tank is pumped to a heat exchanger for transfer of the energy to the tertiary tank. This heat exchanger simulates the hot water entering the first cell of a multi-effect distillation plant. Finally, the water in the tertiary circuit is pumped to a cooling tower where the energy acquired from the secondary loop is dissipated into the ambient.

Figure 29. View of the stationary solar collector test bed

METEOROLOGICAL STATION

The Plataforma Solar de Almería meteorological station is located on the property. Although originally in the southeast, it has now been moved to the south west, further from the influence of reflection from nearby devices. This station has been taking solar radiation measurements at this site, as well as numerous other meteorological variables, since 1988. Among the variables recorded are: global, direct and diffuse radiation, atmospheric temperature at 2 and 10 m, wind speed at 2 and 10 m, wind direction at 10 m, relative humidity at 2 and 10 m, atmospheric pressure and cumulative precipitation. Although from 1988

Figure 30. New Meteorological Station at the PSA

to 1998, the 5-minute average, maximum and minim of each channel was measured, as of 1999, the value of each channel has been recorded every two seconds.

ENERGY TESTING OF BUILDING COMPONENTS LABORATORY (LECE)

The Energy Testing of Building Components Laboratory (LECE) is another of the facilities at the PSA. This laboratory is part of the Bioclimatic Architecture R&D program of CIEMAT's Renewable Energies Department and is managed directly by it. It participates in the PASLINK EEIG, a network of European laboratories with similar characteristics, which is of economic interest. The laboratory consists of four fully instrumented test cells for testing conventional and passive solar building components and furthermore makes use of the excellent infrastructure conditions at the PSA for solar applications.

The purpose of the LECE is to contribute to the knowledge on the energy quality of building elements through experiments determining the thermal properties of closures, such as the global heat transfer coefficient, the solar gain factor or system response times. It also performs other types of tests among which are important because of the climatic conditions in Spain, with regard to ventilation phenomena. The knowledge of those properties can be used to improve building design for increased energy savings without loss of comfort and predicting their thermal behavior. LECE activities may be classified as:

- Experimental support for preparation of standards and regulations.
- Experiments in the CIEMAT Bioclimatic Architecture R&D program.
- Collaboration with and services for building materials and component manufacturers.

Figure 31. Views of the LECE: Cells,reference buildings and solar chimney

R&D Projects

Introduction

In 2003, R&D activity at the PSA was structured as shown in Figure 32, with three CIEMAT Projects clearly focused on aspects and applications of concentrating solar technology and a fourth Project, complementary to the other three, devoted to publicizing our activities and acting as a catalyst for possible new collaboration through access to use of our facilities by research groups from other institutions.

In central receiver technology, two air-cooled volumetric receiver systems, SOLAIR and SOLGATE, were tested in 2003, which permitted the qualification of the atmospheric and pressurized air technologies at a pilot-plant scale of a few MW.

The PSA also reinforced its activity in the development and testing of new heliostat concepts. Specifically, a new 120-m^2 prototype for the future Sanlúcar Solar plant was validated and the entire CRS field was reconverted to the "stand-alone heliostat field" concept under the PCHA project. Other new projects in this field have been MEGAHELIO, SPACE-CIL and the Monocentric Solar Concentrator, all of them with national financing, and exploring innovative ideas for cost reduction.

Parabolic-trough technology activity during 2003 was based mainly on the European INDITEP project. This project is the logical technical continuation of the DISS project, which demonstrated the technical feasibility of the Direct Steam Generation (DSG) process in parabolic-trough collectors. The next logical step, which is the purpose of INDITEP, is optimization of the process and its essential components, as well as undertaking the detailed design of a first commercial solar thermal power plant with direct steam generation in the

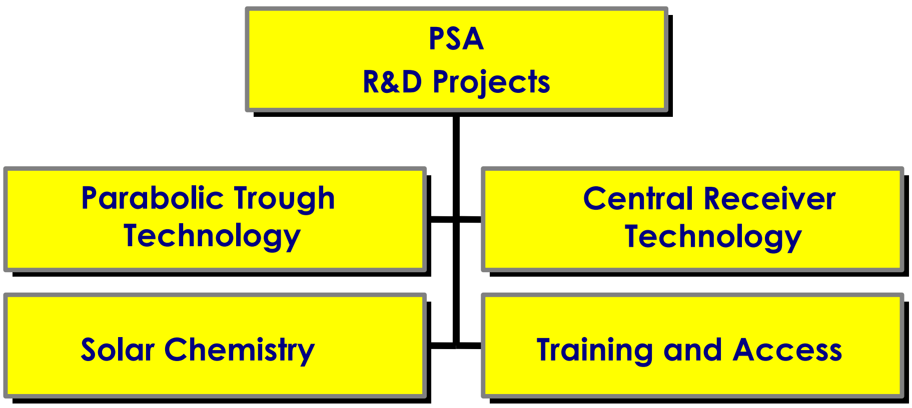


Figure 32. Projects that comprise PSA R&D activity

solar field.

In 2003, PSA-CIEMAT activities mainly focused on three areas:

1. Participation in the detailed engineering of a 5-MWe DSG plant
2. Improvement of the PSA DISS solar field, leading to superheated steam production of up to 1 kg/s
3. Development of new selective Solgel coatings

The improvement of the DISS field represented a huge assembly, commissioning and characterization effort. Once erection of the two new collectors was completed in July, pressure tests at 180 bar were performed and thermal insulation was installed. The first operating tests with the new collectors took place in October. At present the system is completely operative.

The nationally oriented PREDINCER project is partly financed by the Ministry of Science and Technology. Under this project, CIEMAT collaborates with Research Groups from the Universities of Almería and Seville in the development and evaluation of new predictive control algorithms for processes with bounded uncertainties applicable to parabolic-trough solar collector fields.

Under this project, modeling and identification techniques are analyzed and developed for the specific case of bounding DISS plant uncertainties so they can be taken into account in the control of this plant's different operating modes.

This year the Solar Chemistry Project consolidated enlargement of the sphere of its activity, passing from basically photochemical applications to another much wider one in which much deeper problems of global interest are undertaken.

The beginning of the AQUASOL, CADOX and SOLWATER (along with its twin AQUACAT) projects, all of them coordinated by the PSA, was at the same time an important challenge for the management and leadership abilities of the Solar Chemistry Group and a notable opportunity to move the nucleus of the Project's activities from photocatalytic degradation of pollutants (in aqueous and gas phase) to more diversified, complementary activities, basically focusing on solving water problems: degradation of pollutants, treating drinking water and desalinating seawater, all with solar energy-based processes.

All of the recent reports published by the various agencies of the United Nations concur in pointing out that water is going to be one of the most important problems of our century due to its impact on a very large part of the world's population. The strong synergy that exists between solar radiation and applications associated with water processes, permits us to predict that significant activity in this field will be kept up during the coming years.

R&D activities at the PSA are supplemented by a Training and Access Project that basically revolves around the PSA classification as a Large Scientific Installation under the European Commission's IHP (Improving Human Potential) program. Thanks to this project, from 2000 to 2003, 60 European research groups have had access to the PSA facilities.

In general, R&D activity during 2003 was highly satisfactory, with clear consolidation of the lines of work in solar receivers and concentrators, thermal storage, desalination, detoxification of effluents and the appearance of new activities in solar thermochemical hydrogen production This allows us to forecast a stable work environment, consolidated projects and clear objectives, with commitments that in some cases have an R&D activity horizon in 2006.

In the national context, the PSA has been keeping up close collaboration with the majority of the companies working in solar concentration for electricity, thermal and chemical applications and with universities, such as the University of Seville, University of Almería and the UNED.

The PSA has human resources and infrastructure unique in solar concentrating technology which means that any solar thermal power plant development or project in Spain counts on CIEMAT participation.

In the international sphere, we should point out our participation in Tasks I, II and III of the International Energy Agency (IEA) SolarPACES program, where information is exchanged and task costs are shared with similar centers in Germany, Switzerland, Australia, Russia, Israel, France, etc. At present SolarPACES is the only network of experts in solar thermal concentrating technology and systems. Under the umbrella of the 5th Framework Program in its Energy Program and the Spanish-German Agreement, there is intense collaboration with the German Aerospace Agency (DLR) with which the traditional participation in joint projects is maintained.

Central Receiver Technology

Tower systems, or central receiver technology (CRT), consist of a large field of heliostats or mirrors that track the sun's position at all times (elevation and azimuth) and direct the reflected beam on the focus located at the top of a tower. As it is a fixed focus, the optics are off-axis, making optical-energy analysis and optimization more complicated. Solar concentration is on the order of 200 to 1000 suns with unit capacities of from 10 to 50 MW, less than in parabolic-trough plants. They can operate with a wide variety of thermal fluids, such as saturated steam, superheated steam, molten salts, atmospheric air and pressurized air, with operating temperatures in the range of 300ºC to 1000ºC. The PSA has a long tradition of research in this technology and has two absolutely privileged facilities, the CESA-1 and CRS, with very flexible test beds for the testing and validation of components and subsystems.

Due to the high incident radiation flux (typically from 300 to 1000 kW/m^2), high working temperatures are possible and it can be integrated in more efficient cycles from Rankine cycles with superheated steam to integration in Brayton cycles with gas turbines, easily admitting hybrid operation in a wide variety of options, and with thermal storage can generate electricity with high capacity factors, already surpassing 4500 equivalent hours per year.

Central receiver systems, after scale-up and concept demonstration, are today at the gates of commercial operation. To date, more than 10 experimental facilities have been tested around the world. They are generally small 0.5 to 10 MW systems, and the majority were operated during the eighties. That experience demonstrated the technical feasibility of the concept and its ability to operate with large thermal storage systems. The most intense experience was in the projects carried out at the Plataforma Solar de Almería and in the Solar One and Solar Two plants in Barstow (California). The various technological development projects that have taken place since then have enabled components and procedures to be improved, so that today, system solar-to-electricity conversion efficiency forecasts are for 23% at design point and 20% annual. In spite of all this, the great challenge remaining for central receiver systems is to start up a first generation of commercial plants operating under market grid dispatch conditions. The first three commercial plants now underway are based on technologies using molten salts, saturated steam and air-cooled volumetric receivers.

The high cost of capital is still an obstacle for making full use of its commercial potential [Romero, Buck y Pacheco, 2002]. The first commercial applications that are about to be born still have costs of around 0.18 to 0.20 Euro/kWh. A cost reduction in the technology is therefore essential to extend potential deployment and the number of commercial applications. Aware of this problem, the PSA maintains a permanent CRT R&D program focused on the technological development of components and systems for their cost reduction and efficiency improvement.

The goal it is intended to achieve in this line of R&D is to facilitate market penetration of central receiver solar thermal systems. This general goal is structured around the following specific objectives:

- Improve overall profitability by reducing costs and increasing component performance and durability, especially those that most affect plant cost (heliostat field, receiver and control), and simplification of associated O&M.
- Improve central receiver system integration by developing advanced components to make production more efficient, both in electricity generation and industrial processes.
- Facilitate the development and consolidation of a domestic industry, by technology transfer, market studies and defining action tending to eliminate the non-technological barriers impeding penetration of this technology.

These goals will be achieved through a strategy based on three essential elements:

- Technological consolidation and cost reduction.
- Development of advanced components and integration concepts.
- Technology transfer and strengthening feasibility.

The research activity carried out by the PSA CRT group in 2003 took place around a nucleus of publicly financed R&D projects:

1) Project: "PS10: 10 MW Solar Thermal Power Plant for Southern Spain"; Ref. NNE5-1999-00356. Announcement: 1999/C 77/13. Financing: EC-DG RTD (ENERGIE Programme). Senior Researcher: Rafael Osuna (SOLUCAR). Participants: CIEMAT, SOLUCAR (E), DLR, Fichtner (D). Period: July 2001/July 2004.
2) Project: "Megahelio – Large Reflective Surface Heliostat Tracking System for Solar Thermal Power Plants" Ref. FIT-120102-2002-19. Announcement PROFIT-2003, Ministry of Science and Technology. Senior Researcher: Juan Enrile (SOLUCAR). Participants: CIEMAT and SOLUCAR Period: January 2003/April 2004.
3) Project: "Space-Cil Cylindrical Heliostat for Solar Thermal Power Plants". Ref. FIT-120100-2003-62. Announcement PROFIT-2003, Ministry of Science and Technology. Senior Researcher: Valerio Fernández (SOLUCAR). Participants: CIEMAT and SOLUCAR. Period: January 2003/April 2004.
4) Project: "PCHA: First Stand-Alone Heliostat Field-Phase II"; Ref. FIT-120100-2003-54. Announcement PROFIT-2003, Ministry of Science and Technology. Senior Researcher: Ginés García (CIEMAT). Participants: CIEMAT. Period: January/December 2003.
5) Project: "The Monocentric Solar Concentrator: Search for a Modular Competitive Alternative". Ref. FIT -120100-2003-47. Announcement PROFIT-2003, Ministry of Science and Technology. Senior Researcher: Marcelino Sánchez (CIEMAT). Participants: CIEMAT. Period: January/December 2003.
6) Project: "SOLAIR: Advanced Solar Volumetric Air Receiver For Commercial Solar Tower Power Plants"; Ref. NNE5-1999-10012 Announcement: 1999/C 77/13. Financing: CEC-DG RTD (ENERGIE Programme). Main participants: CIEMAT, SOLUCAR, IBERESE (E), STC (DK), DLR (D) and FORTH/CEPRI (GR). Senior researcher: Rafael Osuna (SOLUCAR). Period: February 2000/June 2004.
7) Project: "SOLGATE: Solar Hybrid Gas Turbine Electric Power System"; Ref. ENK5-2000-00333. Announcement: EC- DG RTD (ENERGIE Programme). Participants: ORMAT (IL), INABENSA, CIEMAT (E), DLR (D), Heron (NL) and TUMA (CH). Coordinator: C. Sugarmen (ORMAT). Period: January 2001/September 2003.
8) Project: "HST: Hocheffiziente Solarturm-Technologie – High Efficiency Solar Tower Technology"; Ref. Z II 6 (D) -46040 - 1/3.3. Announcement: BMU-German Ministry of the Environment -2001 and Kreditanstalt für Wiederaufbau-KfW. Participants: CIEMAT (E), DLR, KAM, G+H, Isolite (D). Coordinator: R. Buck (DLR). Period: January 2002/September 2004.
9) Project: "Desarrollo de Sistemas y Herramientas de Control para Plantas Termosolares". Collaboration Agreement CIEMAT-University of Almería. Senior Researchers: Manuel

Romero (CIEMAT) and Manuel Berenguel (UAL). Period: November 2002/October 2005.

10) Project: SOLPRO - Proceso para la Integración de Energía Térmica Solar y de Combustible Biomásico en Planta de Generación Eléctrica de Alta Eficiencia. Ref. FIT-120100-2003-57. Announcement PROFIT-2003, Ministry of Science and Technology. Senior Researcher: Valerio Fernández (SOLUCAR). Participants: CIEMAT and SOLUCAR Period: January/December 2003.

These projects may be grouped in three large areas of action:

a) Component Development:
   - Solar Receivers
   - Heliostats
   - Control
b) Feasibility studies and demonstration projects
c) Software and measurement tools development and testing

THE PS10 PROJECT

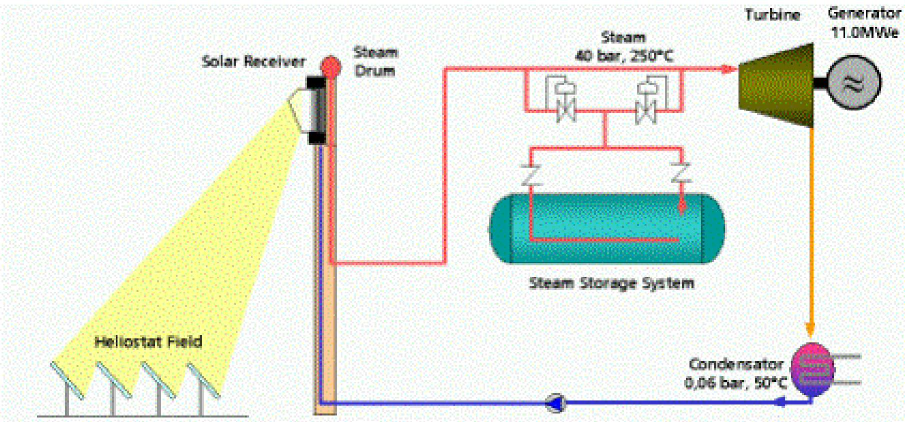
The PS10 project is today the only initiative with successful perspectives for design and construction of a central receiver solar power plant. Since the pioneering facilities of the seventies and eighties, no new large solar thermal electric project has been carried out, although several attempts were made in Spain under the GAST, SOLGAS, COLON SOLAR and Solar Three Initiatives. The PS10 project, initiated in 1999, has come a long way and has awakened numerous expectations in the solar community, since it is the prior stage to the self-sustaining commercial implantation of these technologies. For the PSA, the PS10 project is enormously important, because it is the required reference focusing research and development on central receiver technologies and a way for channeling feedback between industry, in this case SOLUCAR, and a public research institution such as CIEMAT, in which strategies in heliostat design, advanced concentrators, solar receivers, software codes and tools, and thermal storage are jointly defined; and these subjects are in turn the generators of many other projects that have been financed by the Spanish Ministry of Science and Technology's PROFIT Program.

The main goal of the PS10 project (Planta Solar 10), also known as Sanlúcar Solar, is the design, construction and commercial operation of a solar thermal electric plant with tower system and heliostat field and a nominal capacity of 10 MW. This plant is to be erected within the municipal limits of Sanlúcar la Mayor in the province of Seville. The plant is promoted by Abengoa, through its operating company, Sanlúcar Solar, and coordinated by SOLUCAR. The project has received a subsidy of five million Euros from the European Commission and two million Euros from the Andalusian Government. CIEMAT, DLR and Fichtner Solar are also partners in the European project.

At first, the project was based on the Phoebus scheme which uses pressurized atmospheric air as the thermal fluid and a volumetric solar receiver. During 2003, the project required a complete technical revision. The requirements set by the promoting company at the beginning of the project, 3000 €/kW and annual production of 24 GWh, were difficult to achieve with the air technology for a first small-scale commercial plant. Because of these limitations, the basic plant scheme was modified and now uses a saturated steam solar receiver (Figure 33). The system includes a field of glass-metal heliostats (Sanlúcar-120 heliostat), a saturated steam cavity receiver, steam thermal storage and a saturated steam turbine.

The system has a total of 624 121-m² heliostats developed by the SOLUCAR company and a 90-m-high tower. A cavity-type solar receiver was selected to reduce radiation and convection losses, with which it achieves a thermal efficiency of 92%. The absorber panel is made up of independent vertical flexible tubes to absorb the thermal expansion and mechanical deformation without breakage or leakage (Figure 34). The receiver produces saturated steam at 40 bar and 250°C, which is fed to a boiler that increases the system thermal inertia. The steam is then sent to the turbine where it expands to produce work and electricity. At the outlet of the turbogenerator, it is sent to a water-cooled condenser, working at a pressure of 0.06 bar. The condenser outlet is preheated by the turbine exhaust. A moisture separator is installed between the high and low-pressure components of the turbine to increase the steam quality in the last stages of expansion.

With all these procedures, a power block working with saturated steam at 250°C and a nominal conversion to electricity of 30.7% is achieved. The thermal efficiency of the system at design point is estimated at 21.7% with an annual average of 16.3%. In this regard, the challenge of finding a simpler, more economical technology, with improved efficiency has been met.



General Description		
Emplacement	Sanlúcar M. (Sevilla), Lat 37.4°, Lon 6.23°	
Nominal Power	11.02MWe	
Tower Height	90m	
Receiver Technology	Saturated Steam	
Receiver Geometry	Cavity180°, 4 Pannels 5m x 12m	
Heliostats	624 @ 121m2	
Thermal Storage Technology	Water/Steam	
Thermal Storage Capacity	15MWh, 50min @50% Rate	
Steam Cycle	40bar 250°C, 2 Pressures	
Electric Generation	6.3kV, 50Hz -> 66kV, 50Hz	
Land	60Has	
Annual Electricity Production	24.2GWh	
Nominal Rate Operation		
Optical Efficiency	77.0%	67.5MW -> 51.9MW
Receiver and Heat Handling Efficiency	92.0%	51.9MW -> 47.7MW
Thermal Power to Storage		11.9MW
Thermal Power to Turbine		35.8MW
Thermal Pow. -> Electric Pow. Efficiency	30.7%	35.8MW -> 11.0MW
Total Efficiency at Nominal Rate	21.7%	
Energetical Balance in Annual Basis		
Mean Annual Optical Efficiency	64.0%	148.63GWh(useful) -> 95.12GWh
Mean Annual Receiver&Heat Handling Efficiency	90.2%	95.12GWh -> 85.80GWh
Operational Efficiency (Starts Up/Stops)	92.0%	85.80GWh -> 78.94GWh
Mean Annual Thermal Ener. -> Electric Efficiency	30.6%	78.94GWh -> 24.2GWh
Total Annual Efficiency	16.3%	

Figure 33. Flow chart and general description of the PS10 Plant with a saturated steam solar receiver .

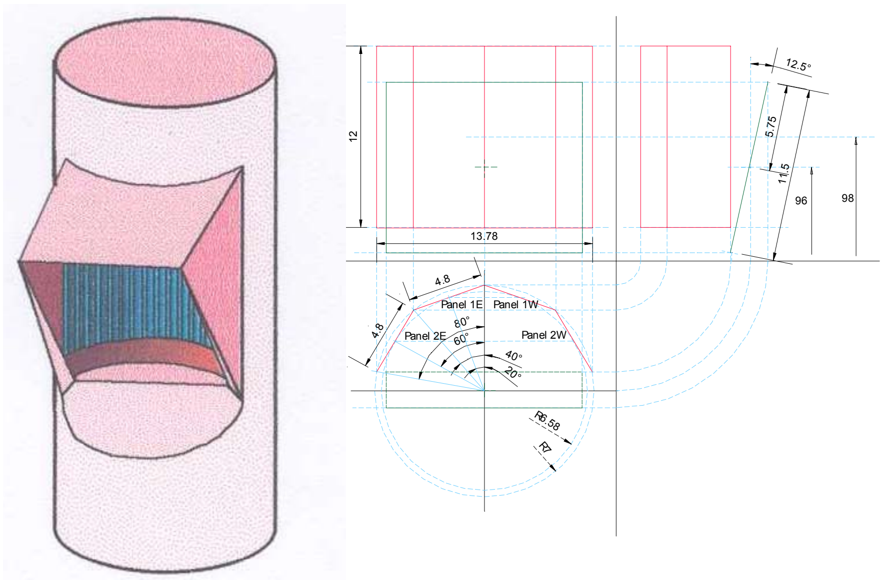


Figure 34. Design of the cavity receiver with saturated steam

The third and last preheater is fed by steam coming directly from the receiver. This way the water temperature is increased up to 245°C. Once mixed with the water returned from the boiler, the water enters the receiver at 247°C. The steam receiver is continually purged to avoid any accumulation of precipitants from salts on the bottom of the evaporator. For cloud transients, the plant incorporates a 15-MWh saturated steam storage system which provides 50 minutes of operation at 50% turbine load.

In 2003, the PSA collaborated with Solucar in redefining the project, basically in reviewing the new solar receiver designed by the Tecnical company, a direct flux measurement system on the inside of the cavity, the validation of the procedure for optimizing the heliostat field (using a comparison between the SOLVER and STC codes), and in the evaluation of the Sanlúcar-120 heliostat. The heliostat is characterized by its horizontally rectangular shape (9575 x 12925 mm), with a total of 28 3.21-m-x-1.35-m facets in 7 rows and four columns. Optical testing at the PSA in August verified a reflected beam image quality of 2.1 mrad, although highly elliptic at other than the midday hours (Figure 35).

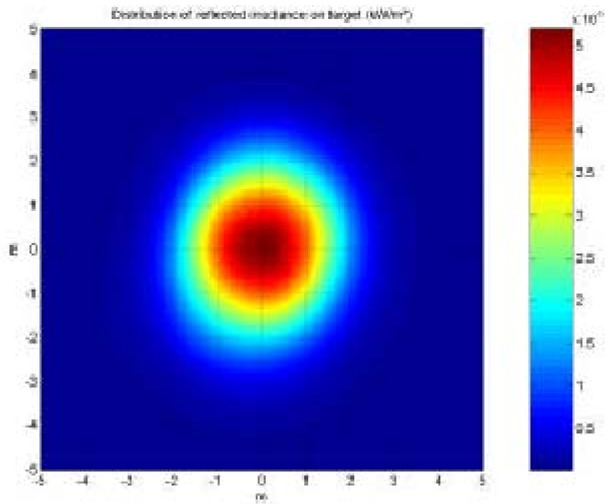


Figure 35. Projection of the sun on the CESA-1 target by the Sanlúcar 120 heliostat (Day: 01/08/2003; Time: 12:30 UT)

The change from air to saturated steam technology was presented to the EC in 2003 and accepted, which meant modification of the contract, which now includes the new scheme in its technical annex

HELIOSTAT DEVELOPMENT (MEGAHELIO AND SPACE-CIL PROJECTS):

The Sanlúcar-120 heliostat represents the most mature and commercial reference at the present time. SOLUCAR estimations place its cost at less than 180€/m^2 for a production of about one thousand units (150€/m^2 with improved drive mechanism). This goal has, however, slowed down during the execution of the PS10 Project.

The PSA has carried out two projects financed by PROFIT funds in 2003, also in collaboration with the SOLUCAR company, for new alternatives that will allow successive improvements in production costs to be achieved. Fruit of that collaboration came out of the Megahelio and Space-Cil designs. The purpose of the Megahelio project was to develop a new prototype tracker for a heliostat with a useful surface of around 200 m^2 for solar thermal plants, which improves the reference cost of the Sanlúcar-120 heliostat up to 30%. The Megahelio Prototype is characterized by its large width/height ratio.

The technically and economically optimum configuration of the mirror distribution is shown in the photo below (Figure 36). All together there are 48 3220-mm x 1355 mm mirrors for a total reflective area of 209.43 m^2. This is the net reflective surface, but the total surface exposed to the wind is larger, around 215 m^2. In the support structure the almost 26-meter-long horizontal metal lattice girder (in blue) is outstanding. Another innovation in the design is the two-legged support, one of them fixed and the other movable along a semicircular rail. Although the Megahelio design achieves the estimated price goal of less than 180€/m^2, with a potential further reduction of almost 30%, this also seems possible with the Sanlúcar-120 heliostat with possible improvements in the drive mechanism. For this reason, it was decided not to continue into construction and testing of a prototype.

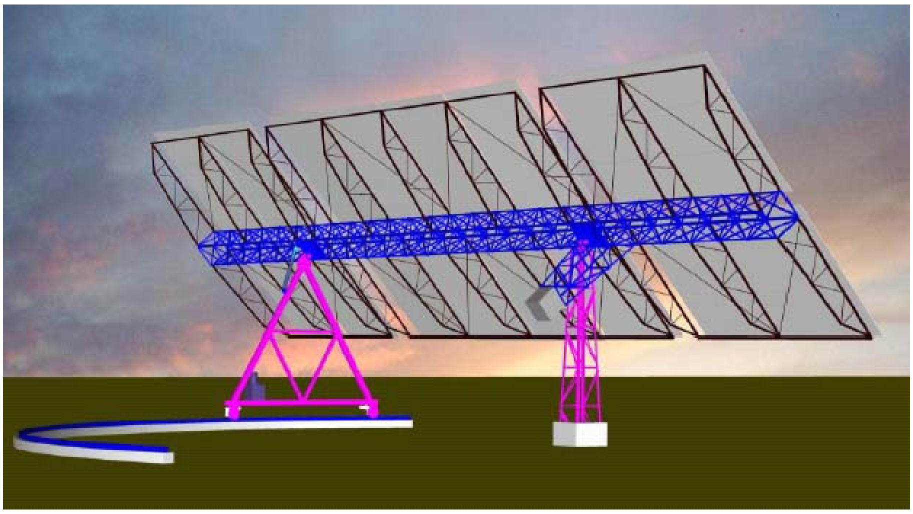


Figure 36. Artist's view of the 200-m^2 Megahelio heliostat (Design by SOLUCAR)

The Space-Cil heliostat emerged from a different strategy. In this case, it is made more economical by using a cylindrical heliostat with the apparent advantages of this system over the present shaped and canted spherical type. However, the main contribution of this innovation is with regard to the simplified operation of the plants where they are employed, one of the most complicated aspects of making use of high temperature solar thermal energy. At present, all the conventional heliostat concepts use parabolic or spherical curves, both for facets and canting. However, in practice, a heliostat field does not aim at a single point on the receiver. Control algorithms strategically disperse the radiation that has been so dearly concentrated by each individual heliostat. This essentially contradictory fact, and its questionable success, has led to consideration of the advisability of revising the heliostat design parameters, so that their individual distribution of irradiance on the solar receiver is in harmony with what is demanded afterwards of the set of all the heliostats that make up the field, so the aiming-point strategy control is minimized or even eliminated. That is why a conceptual heliostat design change has been proposed. This conceptual change is integral since it affects the optics, the aiming mechanism and the orientation of its placement in the heliostat field. The flux delivered by cylindrical heliostats is directly redistributed over the vertical surface facing it. Thus aiming strategies can be eliminated, and the plant can be operated throughout the year with the same control philosophy.

The cylindrical heliostat concept patented by CIEMAT in 2003 (P200401270) was developed jointly with SOLUCAR under a PROFIT project. The heliostat proposed (Figure 37) consists of a cylindrical or parabolic-trough reflective surface (1) that is rotated on two orthogonal axes called the main (3) and the secondary (5) by drive mechanisms (4) and (6) and is governed by a control system (8). The main axis is parallel to the straight axis of the vertical of the cylindrical reflective surface. The mechanical assembly that enables movement of this surface must be able to guarantee the orientation of the secondary axis (5) in a well defined direction which is achieved by a) the orientation α of the arm (7) with regard to the zenith axis (9) and b) by rotation β of the whole around that zenith axis.

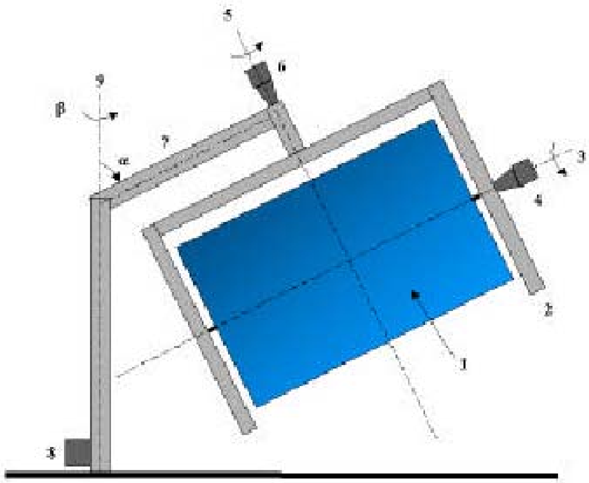


Figure 37. Confined line-focusing cylindrical heliostat

SOLUCAR carried out the detailed engineering for a 7-m-high 22-m^2 surface based on the above concept. Material supply and construction were completed by the end of 2003 and installation and testing at the PSA are planned for 2004.

PROJECT: FIRST STAND-ALONE HELIOSTAT FIELD (PCHA):

One of the objectives pursued in recent years at the PSA is evaluation of the technical and economic feasibility of using intelligent autonomous units. These heliostats have an autonomous photovoltaic power system for the control ad solar tracking drivers that use panels integrated in the heliostat, and a wireless communications system for governing the heliostat field, both during emergency and safety operations and routine operation. This autonomous concept has been patented by the PSA (P9901275).

The autonomous concept implies that this heliostat, equipped with a specially designed local control, can function without the aid of any other external device, and can perform the axis calculation and guiding functions by itself, keeping the focus controlled while caring for its own integrity and security. It can perform these functions either individually, or as is more usual, as a component of a field of heliostats with a power tower. This means that by employing photovoltaic energy to independently power each heliostat and wireless communications over commercial radio channels, it can be installed any-

- Completely autonomous heliostat
- Mirror surface: 40m^2
- PV Panel: 55Wp, 12 Vcc
- Battery: 60Ah, 12 Vcc
- 2 Motors: 70 W, 12 Vcc
- 2 Speeds: AZ: H=8,5°min, L=3,4°min
  EL: H=10,5°min, L=4,2°min
- Daily consumption: 50 Wh minimum
- Days autonomy: 12 maximum
- Radio-modem 430 Mhz, 9 channals, 38 Kbs
- Magnetic wind switch
- 2 incremental coders: 20000 bits
- Angular resolution : 0,3 mRad (Az y El)
- Accuracy of the astronomic algorithm: 0,5 min

Figure 38. Most relevant technical characteristics of the PCHA heliostat

place without electrical, wiring or channel infrastructure requirements. Thus, the most important innovation introduced by the autonomous concept is that it can be successfully applied to the heliostat fields of future power tower solar plants, in an attempt, among other things, to lower the costs of civil engineering work by eliminating the network of channels and power, communications and signals cabling.

After several tests with prototypes and mini-series since 1995, a PSA research team has carried out the ambitious project of converting the entire CRS field of 92 heliostats into a stand-alone field controlled entirely by radio, which is without doubt a worldwide milestone. The project, begun in 2002, at a total cost of 650,000€, is partly subsidized by the Spanish Ministry of Science and Technology PROFIT Program. PCHA (Primer Campo de Helióstatos Autónomos[5]) project activity is structured in three perfectly differentiated phases or milestones. The first phase, carried out in 2002, included the electronic and computer design tasks. Also in 2002, the materials and equipment supply necessary for the assembly of local controls to be erected in 2003 was begun. In the second phase, carried out in 2003, a pre-series of heliostats were manufactured and erected as well as their later cloning in 92 units with outside assistance. The third and last phase of the project is being carried out in 2004, with the configuration and startup of the full field already completed at the time of writing.

In March 2002, the heliostat pre-series was erected and commissioned as a first step to fabrication of the complete field of 92 units. The low daily electrical consumption of 52 Wh, which is sufficient to assure operation during cloudy periods up to 12 days long is to be emphasized. Field assembly began in October 2003 and was finished in December 2003, at which time 22 units were commissioned.

PROJECT: THE MONOCENTRIC SOLAR CONCENTRATOR

The purpose of this project, financed with PROFIT funding, is to design and optimize a monocentric solar concentrator with a mobile receiver and fixed concentrator, developed from a spherical concept to find the optimum configuration and compare such a system with conventional fixed receiver and mobile concentrator systems. It is an innovative project searching for a concept that is radically different from the usual central receiver concentrator. These designs can be adapted to any topography, without additional cost and, as the mirror field is stationary, the only movable part is the solar receiver, which obviously involves a considerable associated cost reduction. Therefore, the purpose is to see whether it is possible to produce electricity with a simple, modular system at a competitive price.

In 2003, CIEMAT carried out the initial optical design and system optimization phase, for which it adapted its own SCT (Solar Concentration Toolbox) Matlab® environment software. The optimum configuration for a total mirrored surface of 1000 m^2 at a latitude of 37.4 degrees for the case of Seville, is a concentrator with three different curved zones, tilted 28 degrees south and with a 5.5-m-long cylindrical receiver suspended at a height of 10 m. The annual costs estimated per kWh produced are similar to those of other solar concentrating technologies (comparison made with data from the PS10 project and cost estimations made by Solucar Solar for the optimized prototype), since although movable parts are drastically reduced, so is the energy collected per square meter of reflector. Nevertheless, the land use ratio is up to 3.5 times better than conventional systems and the initial investment cost is reduced, given its modularity, which minimizes the risk. Furthermore, radiation flux on the receiver is greater than the equivalent in other linear receivers, which makes foreseeable thermal losses also lower.

The final objective of the project is to design and erect a pilot facility to demonstrate the technical and economic feasibility of solar thermal electricity generation with autonomous modules having unit capacities in the range of 100 to 500 kWe. The modular

[5] First Autonomous Heliostat Field

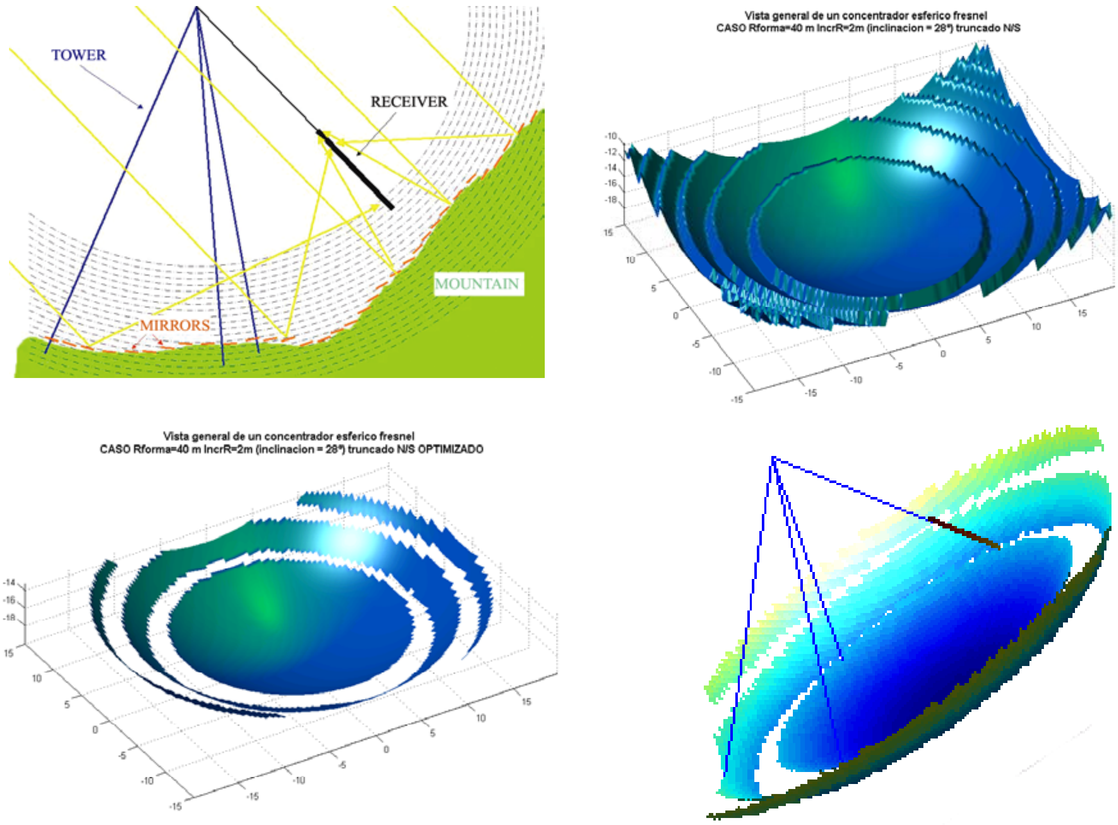


Figure 39. Flow diagram of a monocentric solar concentrator and representation of its optimized structure .

concept offers extraordinary perspectives compared to development paths undertaken up to now in this field, which has not been able to advance sufficiently on the road to the market. It is therefore hugely strategic to the sector, since if results foreseen by the studies are achieved, it would mean a viable, economically profitable alternative for commercial solar thermal electricity generation.

THE SOLAIR PROJECT

The receiver, which is the authentic nucleus of any power tower system, is the most technologically complex component, because it must absorb the incident radiation with the lowest losses and under very demanding concentrated flux conditions. Among the different options for thermal fluids and configurations of heat exchangers, the PSA has been focusing its research since 1986 on the development of air-cooled volumetric receivers. Volumetric receivers are specifically conceived to optimize heat exchange with air as the thermal fluid, the illuminated absorber being a matrix or porous media (metal knit or ceramic monolith), through which the cooling gas flows.

The purpose of the SOLAIR project is to design a volumetric air receiver with a ceramic SiC absorber able to produce hot air at 700ºC, using a modular concept easily scalable to large plants. The use of a ceramic matrix makes the absorber more resistant and its design in modular cups eliminates the uncontrolled fluidodynamic instabilities of previous designs. Finally, it incorporates a new air recirculation system which leads to recirculation ratios near 70%. The SOLAIR project is a European project with EC financing and participation of CIEMAT, SOLUCAR and IBERESE (E), HelioTech (DK), DLR (D) and CPERI (GR). CIEMAT has a very active role in this project, leading prototype testing and evaluation, performing air recirculation system analyses and optimization using fluid dynamics codes such as FLUENT®, selecting the geometry of the ceramic heads, and performing thermomechanical structural analyses with the ANSYS® code.

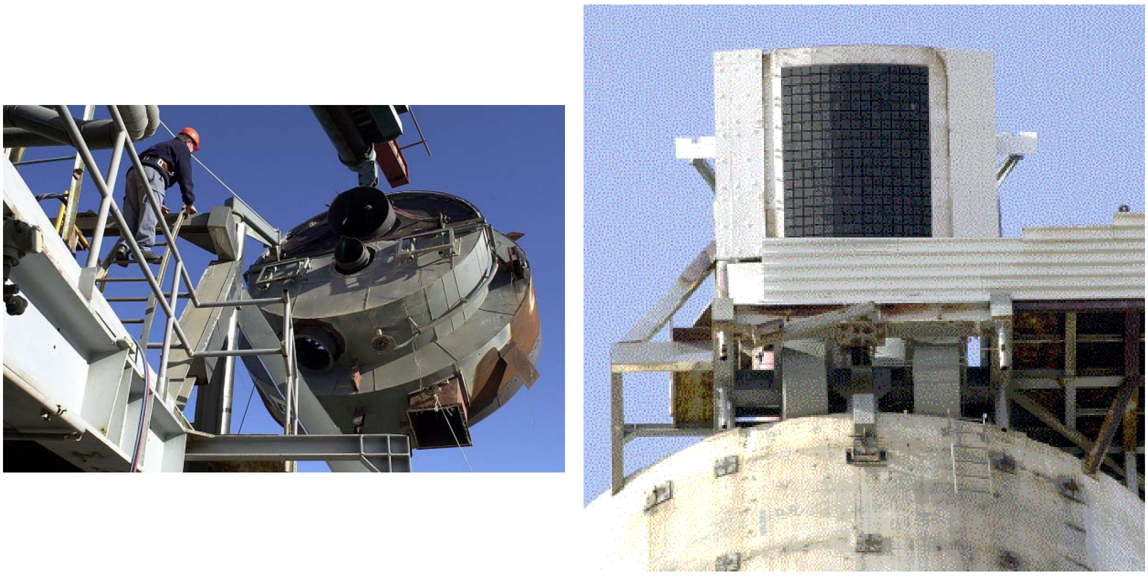


Figure 40. The metal absorber TSA receiver being lowered from the tower in March 2003 (left) and front view of the new Solair-3000 receiver in the CESA-I tower.

The SOLAIR project began in 2000, and in 2000 and 2001 the most appropriate ceramic material was chosen and mechanically and thermally qualified in the DLR solar furnace in Cologne, and the first ceramic cups were designed and fabricated. In 2002, a 200-kW prototype installed at the PSA was successfully tested, proving concept feasibility.

In 2003, construction and assembly at the PSA of the 3-MW prototype was completed. The new receiver was installed in the TSA test bed, for which the metal receiver was taken down by the PSA operating and maintenance personnel in March. Work on the adaptation of the test bed to the new receiver, which required important modifications in control room support structures, adapting the heliostat field control software and the data acquisition system was intense throughout the first half of 2003.

Systematic low-temperature testing at 600 and 650°C began in October. Testing at the end of 2003 still had not reached nominal operating conditions, so the project has received an extension to July 2004 from the EC in order to complete its evaluation. The tests had to be interrupted during several periods due to the partial breakage or ungluing of some of the ceramic cups from the SiC absorber. The incidents were explained by deficient gluing of some of the parts of the cup/absorber sets.

The most peculiar trait of the Solair 3000 receiver design is it's complete modularity in

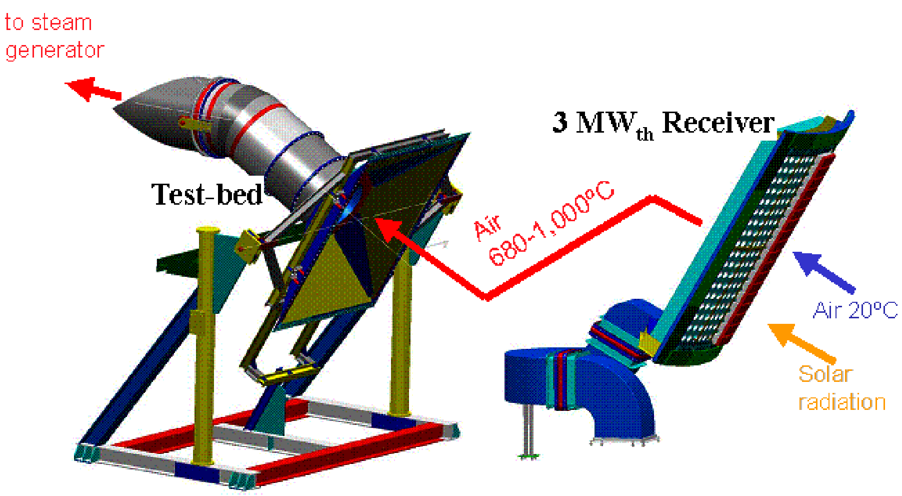


Figure 41. SOLAIR 3000 Test bed component parts showing solar radiation flux input

such a way that the 3-MW modular testing phase would be replicated dozens of times to form a cluster on a commercial plant receiver. In this respect, technical and operational qualification of the current model would enormously reduce the risk of scaling up to high capacities. The KAM company in Munich (Germany), has publicly expressed its interest in the SOLAIR concept for its application in future projects of solar thermoelectric plants.

SOLGATE AND HST PROJECTS

The SOLAIR receiver is open to the atmosphere and therefore produces hot air at atmospheric pressure. In this case, the intended reference use is integration in a Rankine cycle with steam superheated by heat exchange in a steam generator. In addition to this option, a second line of longer-term research uses pressurized volumetric receivers in a Brayton cycle with a gas turbine. This alternative has hybrid solar/gas turbine plants as its main objective. Hybrid solar thermal plants have an important potential for reducing costs up to 30% over solar-only plants. A great step forward along this line of research is the SOLGATE project. The SOLGATE project is the first successful initiative in connecting a pressurized solar receiver with a combustion turbine. SOLGATE is financed by the EC, DLR and CIEMAT with participation of ORMAT (IL), SOLUCAR (E) and TUMA (CH).

The system combines a 250-kW turbine and a 1-MW receiver cluster made up of three modules connected in series. The OST3 turbine supplied by ORMAT has been adapted to receive air preheated in the solar receiver so it can operate in hybrid mode (solar-fossil) or in fossil-only mode. The three solar receiver modules can reach 1000°C. The first of the modules (low temperature) is made up of 16 directly irradiated metal tubes connected in parallel, in order to reduce costs. The configuration of the other two modules is a cavity with a quartz window and volumetric absorber.

The first two SOLGATE system solar tests took place at the PSA in December 2002. In a first phase, during a period ending in March 2003, a high-temperature receiver with a metal absorber was tested attaining a maximum operating temperature of 800°C. Later, this module was replaced by a module with a honeycomb SiC ceramic foam absorber to work at 1000°C and thereby increase the solar share. To achieve this temperature, it was necessary to incorporate cold air ducts to cool the outside of the window. Once these new components had been installed, testing was restarted in June 2003. The maximum temperature reached was 960°C. Under these maximum temperature conditions, receiver performance was inferred based on the radiation flux measurement. The thermal efficiency of the solar receiver was 68-79%. The load loss was 120 mbar in the receiver, which meets design expectations. The solar share achieved was 70% at 960°C, as shown in Figure 42.

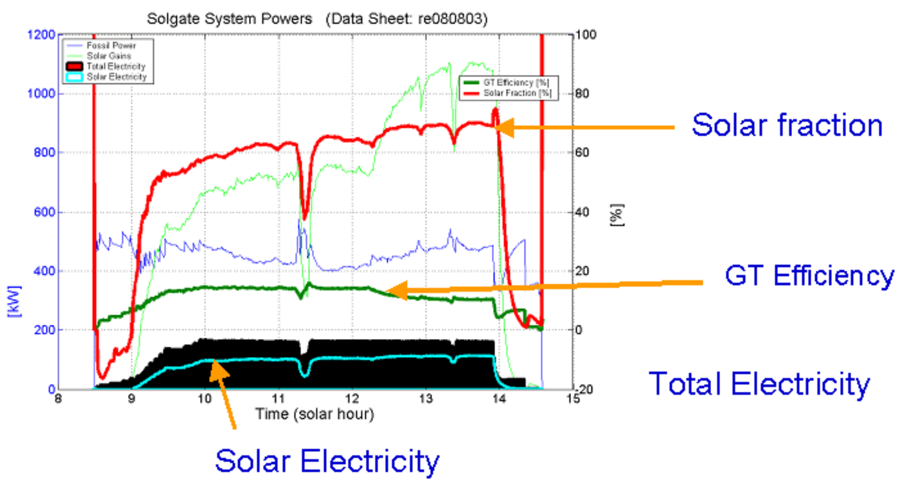


Figure 42. **Results of operating the SOLGATE system on August 8, 2003 (Maximum temperature 960ºC)**

During this second test campaign, there were operating failures in the turbine and it had to be dismounted for repair and maintenance outside of the PSA. The turbine is to be reinstalled and high-temperature testing (1100ºC) will be continued in May 2004. Once the SOLGATE project is completed, testing will begin again with a new ceramic receiver under the HST (Hocheffiziente Solarturm-Technologie - Tecnología de Torre Solar de Alta Eficiencia) project, financed by the German BMU. CIEMAT also participates in this project, coordinated by DLR, which began in January 2002. It is due to be completed in September 2004.

DEVELOPMENT OF ADVANCED CONTROL SYSTEMS (UAL)

A fruitful line of research in developing control systems is maintained based on a scientific cooperation agreement signed with the University of Almería (UAL) in 2002. Under this agreement, important work has been carried out in cooperation with the Automatics, Electronics and Robotics Research Group at the University of Almería. This agreement includes the development of a new real-time heliostat field control system to be implemented in the PSA CESA-1 and CRS fields and integration of control environments, acquisition and evaluation of results in power tower solar receiver testing.

A significant advance has been achieved in the first of the objectives, development of a Control System for Heliostat Fields, in control schemes for the CESA and CRS fields. As the CRS field communications system is being reconverted at present, its development has been delayed due to the conceptual differences between the Central Control of Autonomous Heliostat Fields and the traditional CESA-I type. It should be emphasized that for the development of the software for these Control Systems, technologies are being used that not only offer a solution to the local problem of PSA heliostat field control, but are also scalable to commercial solar thermal power tower plants. Specifically, standardized distributed object technologies are being used in which the real-time determinism of the software component behavior is guaranteed by the use of Real Time Operative Systems (RTOS). CORBA® is being used with LynxOS® RTOS in this project for the development of control systems for both heliostat fields.

In spite of having been planned only for the last quarter of 2003, the task of integrating control environments, acquisition and evaluation of test results with solar tower receiver fields lasted all year long. Two basic objectives have been achieved for following work packages:

- Design and development of a Control System for the Receiver Block, Storage and Air Circuit based on LabView®. This system will be perfectly integrated with the Heliostat Field Control System as well as other computers in the CIEMAT network (in the PSA subnetwork and in the CIEMAT-Moncloa subnetwork in order to provide an environment for real time analysis of the experiments carried out at the PSA. This Environment has already been used satisfactorily in the latest SOLAIR project test campaigns.
- A dynamic model for the Receiver/Storage/Circuit system is in a very advanced state of development. The dynamic Solar Furnace model is being developed with object oriented modeling technologies using Dymola/Modelica ® tools. Development of models of this type is necessary for optimized control algorithms for the facility. Figure 43 shows a view of the different components of the power plant (solar receiver, storage tank, heat exchanger, water pump, etc.).

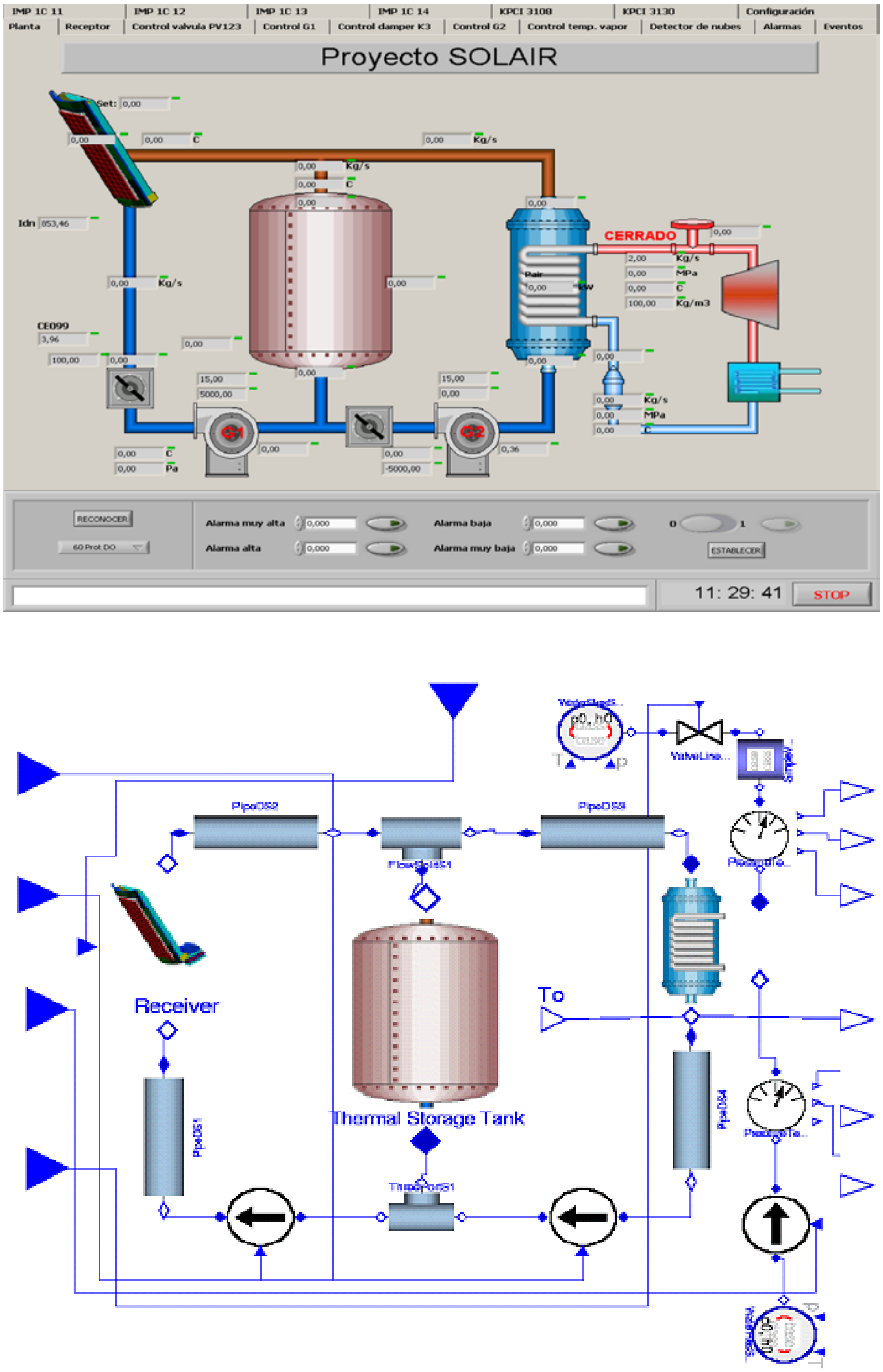


Figure 43. Graphic environment developed in Labview® for the new SOLAIR facility control system (arriba) y Dynamic model of the new SOLAIR facility control system using Dymola/Modelica® (abajo)

OTHER ACTIVITIES (SOFTWARE AND MEASUREMENT SYSTEMS)

In addition to the activities directly related to the projects mentioned above, the PSA, as a large facility for testing and characterization of central receiver systems, has continued devoting part of its effort to the improvement and development of new computerized tools for design and evaluation, and concentrated solar radiation flux measurement systems.

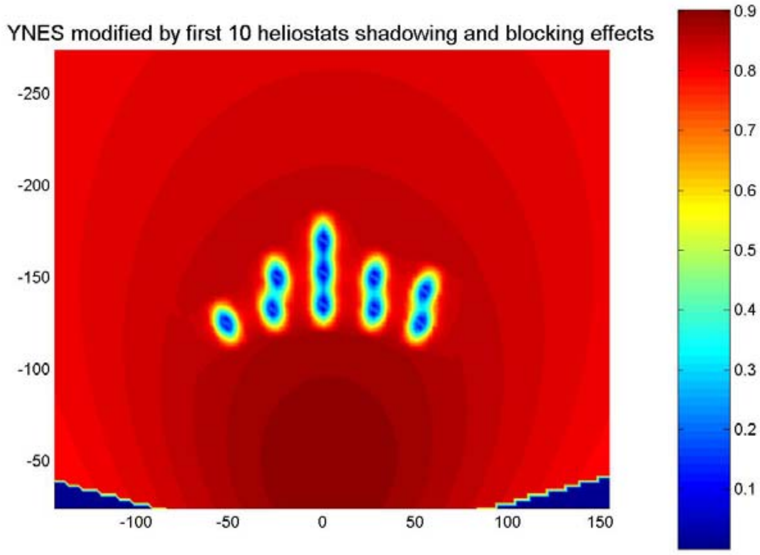


Figure 44. Example of an YNES after being modified with the distribution of the first 10 heliostats. The blue spots represent shading and blocking caused. The coordinates are expressed in meters from the tower (0.0).

Work has continued on software tools with the improvement of models using the FIAT-LUX and SCT codes. In the particular case of FIAT-LUX, the code developed at the PSA for the characterization and optical simulation of solar concentrators, a special effort has been made in the use of genetic algorithms for the optimum parameterization of sources of errors that define the real optics of a heliostat. The procedure implemented has permitted demonstration of the applicability of genetic algorithms for approximation of a model of the real optics, enabling reliable prediction of the irradiance on the solar receiver aperture. Similarly, the use of genetic algorithms has also been tested for generating optimized heliostat field layouts. A comparative study with SCT in collaboration with the Federal Polytechnic School of Lausanne (Switzerland) demonstrated its feasibility.

In 2003, a new procedure using a standard factor called the YNES (Yearly Normalized Energy Surface) was also developed for the optimization of heliostat fields. Yearly available land efficiency can be mapped using this factor. The procedure proposed sets up a first stage in which a YNES is generated for the land with those factors, such as cosine, atmospheric attenuation and intercept factor, which are independent of heliostat geometry and position. Then the YNES is updated by incorporating heliostats in iterations which generate "molecules" with energy maps that include the effect of shading and blocking. With this procedure, packages better than those obtained with conventional methods based on radial three-leaf distribution for equivalent efficiencies. The heliostat distribution optimization technique based on the YNES is highly flexible and generates layouts for terrains that are complex or have geometric restrictions. It has been validated for the PS10 field by comparison with the procedures used by SOLUCAR with its SOLVER code.

Measurement of the solar power incident on the receiver aperture is another of the subjects that is under constant improvement at the PSA. There are many factors affecting its measurement and that make it necessary to improve its precision. This uncertainty is propagated in the final solar plant design and consequently, in its price. That is why the causes for distortion in the measurement of the incident power have to be analyzed to significantly reduce the uncertainty. The definition of a calibration procedure for the sensors (calorimeters) used in measuring very concentrated solar radiation, as well as the design of a new calorimeter mitigating the deficiencies of those existing are the main objectives of a new project called MEPSOCON: Measurement of concentrated solar power in central receiver power plants". The MEPSOCON project, which began December 1, 2003 and ends on November 30, 2006, is financed by the National R&D program through its Industrial Design and Production Program. MEPSOCON and the development of radiometers and calorimeters is the subject of collaboration with the Center for Energy Research of the Autonomous National University of Mexico, among the objectives of which are the design, construction and characterization of a cavity calorimeter for measuring concentrated radiative flux on solar concentrating systems.

NEW PLANT SCHEME (SOLPRO PROJECT)

SOLPRO is a project that begins the short-term development of a new concept in solar thermal power generation based on optimized integration of proven technological components. It deals with the start up of a 1.5-MW capacity solar thermal power plant connected to the grid and located right on the PSA. The project takes advantage of incorporating a large part of the infrastructure already existing in the CESA-1 field at the Plataforma Solar de Almería. The project is financed by the Ministry of Science and Technology's PROFIT program and in 2003 performed the comparative analysis of several solutions for solar integration based on the use of steam receivers, volumetric air receiver or combinations thereof. The scheme selected consists of an air receiver working at maximum temperatures of 450°C, which increases performance and durability is guaranteed, with the support of a saturated steam receiver and a biomass boiler for transients. This concept helps reduce the technological risk currently associated with volumetric receivers that work at air temperatures above 700°C and it also has advantages with regard to the its high performance and the limited risk of a saturated steam receiver at 250°C based on the experience already available from the PS10 project and the volumetric receivers technology.

Based on the results of the feasibility study, a proposal has been submitted to PROFIT for 2004 which concerns the detailed plant engineering pending solution.

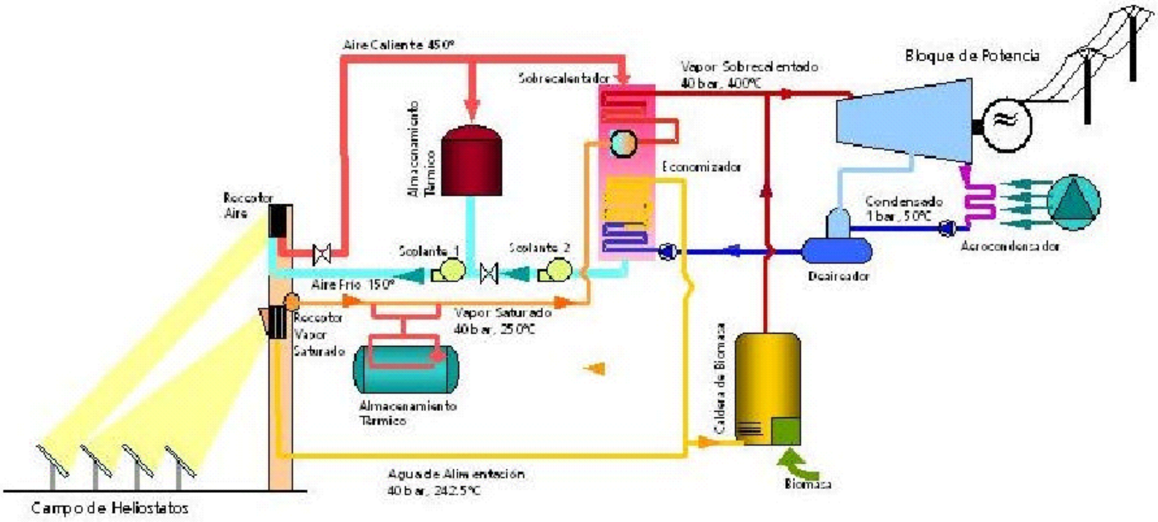


Figure 45. Schematic diagram of the 1.5-MW SOLPRO plant proposed for the PSA.

Parabolic-Trough Collector Technology

Parabolic-trough collectors (PTC) are linear-focus concentrating solar devices that convert direct solar radiation into thermal energy and are ideal for working in the 150°C-400°C-temperature range. The concentrated direct solar radiation incident on the aperture plane of the collector efficiently raises the temperature of the working fluid to about 425°C. Such temperatures make the PTC ideal for integration in a large number of industrial processes in the mid-temperature range.

A PTC is basically made up of a parabolic-trough-shaped mirror that reflects direct solar radiation concentrating it on a receiver tube located in the focal line of the parabola. This concentrated radiation heats the fluid that circulates through the tube, thus transforming the solar radiation into thermal energy in the form of the sensible heat of the fluid [Zarza, 2001]. Figure 46 shows a PTC and how it works.

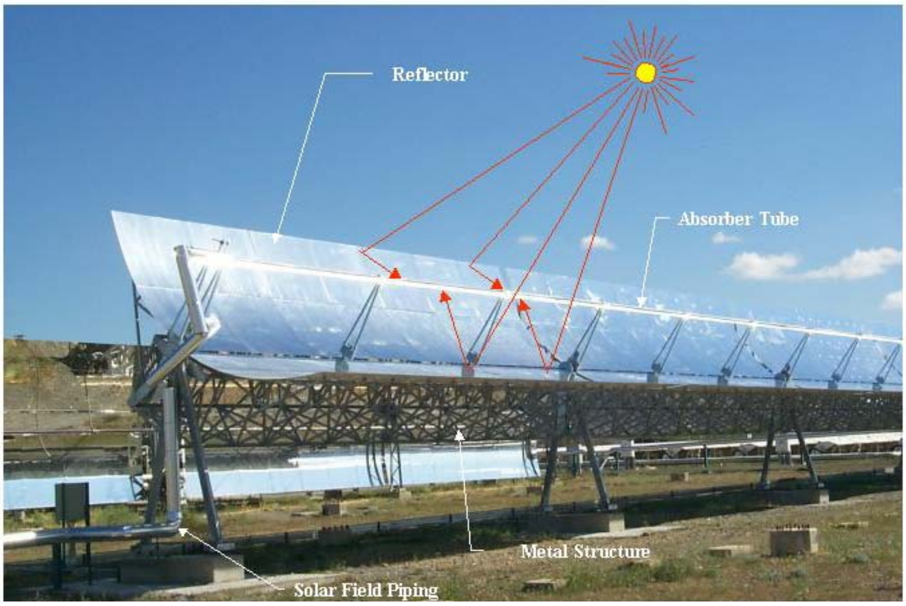


Figure 46. The parabolic-trough collector principle

The PSA has a complete parabolic-trough collector technology R&D program aimed at developing a new generation of PTC solar thermal power plants with three main points:

1) Development and implementation of improved components for parabolic-trough collectors (new absorbers, mirrors, lighter-weight structure designs, new solar tracking systems, etc.).
2) Development of the *direct steam generation (DSG) technology* to eliminate the thermal oil which is currently used in this type of solar thermal plants as a heat transfer medium between the solar collector field and the power block.
3) Overall optimization of STP plant design to improve the solar system connection to the power block.

Given the complexity and reach of each of these three points, the activities developed by the PSA in parabolic-trough collectors are grouped in several different projects that each have its own group of partners, budget and planning. The final result pursued in this set of projects is increased competitiveness of parabolic-trough collector solar systems, which would favor commercial implantation of this technology. In electricity generation, a 26% reduction in the cost of electricity generated by this type of solar thermal plants is sought. Furthermore, activities in developing new mirrors and optical coatings provide a series of interesting byproducts, for example: selective mirrors for photovoltaic energy, anti-diffusion coatings, colored glass for buildings, etc.

Finally, both the improved components for parabolic-trough collectors and the direct steam generation technology being developed at the PSA, can be applied not only to electricity generation, but also to any other industrial heat process in the medium range of 150°C – 400°C).

The activities performed by the PSA in 2003 under the Parabolic-Trough Collector Technology R&D Program were mainly under three projects: *INDITEP*, *DISS* and *PREDINCER*. Of these three projects, INDITEP has absorbed most of the resources and work carried out, due to the significant participation of the PSA in that project. In order to open new projects that assure the continuity of the lines of work defined in this R&D program, in 2003 we also devoted a great effort to the preparation and management of new projects. Below the most relevant results obtained in 2003 by the PSA in the *INDITEP*, *DISS* and *PREDINCER* projects are briefly described. At the end. the activities carried out with regard to other projects and new national and European project proposals presented in 2003 are also presented.

INDITEP PROJECT

The 36-month INDITEP project officially began on July 1, 2002. It receives financial assistance from the European Commission (contract nº ENK5-CT-2001-00540) and the activities planned under the project constitute the logical technical continuation of DISS project activities. Once the technical feasibility of the direct steam generation (DGS) process had been demonstrated in the DISS project, the next logical step had to be optimization of the process and its essential components at the same time that the detailed design of a first commercial solar thermal power plant with DSG in the solar field could be undertaken.

The INDITEP project has four basic objectives:

1) Detailed design of a first commercial 5-MWe DSG plant
2) Optimization and development of advanced components to make the DSG technology more competitive (compact economical water/steam separators, thermal storage for DSG, etc.)
3) Characterization under real solar conditions of the most important components for DSG solar fields.
4) Socioeconomic study of DSG technology

Most of the Partners in the INDITEP project (IBERDROLA, ABENGOA, CIEMAT, DLR, Flachglas Solar, GAMESA, INITEC, SIEMENS and ZSW) also participated in the DISS project, assuring perfect continuity of activities between the two projects. CIEMAT participation in INDITEP focuses on the following activities:

- Participation in detailed engineering of a 5-MWe DSG plant
- Improvement of the PSA DISS solar field to increase steam production to 1 kg/s.
- Operate and maintain the DISS plant in order to elaborate operation and maintenance procedures for commercial DSG plants, as well as evaluate new water/steam separators, thermal storage systems and new reflectors.
- Improve the PSA DISS solar field regulation and control system
- Analyze stress produced in DISS collector absorber tubes after more than 4000 hours of operation.
- Develop new selective coatings able to support temperatures of up to 550ºC.

In 2003, CIEMAT-PSA activities mainly focused on three subjects:

1) Participation in the detailed engineering of a 5 MWe DSG plant.
2) Improvement of the PSA DISS plant solar field to increase superheated steam production to 1 kg/s
3) Development of new selective Solgel coatings.

The activities carried out by the PSA with regard to each of these three points are described below.

Detailed Engineering of a 5 MWe DSG plant:

In this area, the PSA designed the solar field concept for the plant, according to the requirements of the power block designed by INITEC and the turbine selected by the partners in the project. Figure 47 below shows the solar field designed by CIEMAT, which is made up of seven rows of 10 ET-100 collectors connected in series. The eight first collectors of each row are devoted to preheating and evaporating the feed water, while the last two superheat the steam. A water/heater separator at the end of the evaporation section in each row assures that the superheating section is fed only saturated steam. There is also a water injector at the inlet of the last collector in each row, to assure good control of the temperature of the superheated steam supplied by each row.

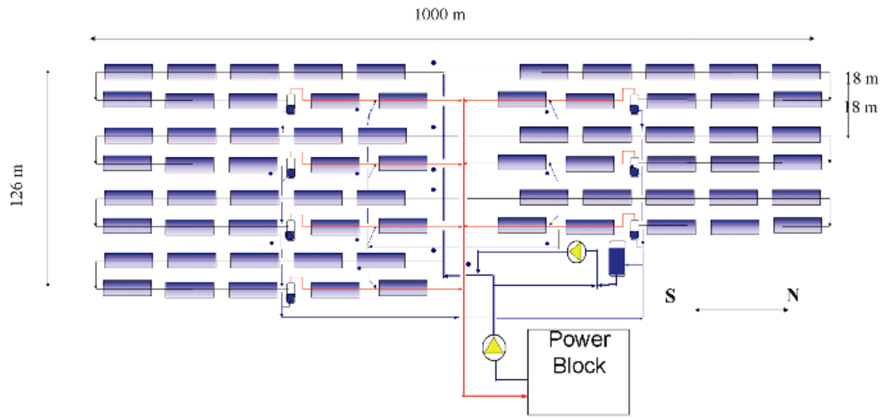


Figure 47. Simplified diagram of the INDITEP plant solar field designed by CIEMAT.

All the water/steam separators connected to the various rows drain into a final recirculation water tank. A recirculation pump sends to the inlet of the solar field the water accumulated in this tank. To avoid the possibility of cavitation during aspiration by the recirculation pump, the recirculation water is cooled down a little by mixing it with a small amount of cold water supplied by the main solar field pump.

Table 1 gives the main parameters of the ET-100 collector used in the design, while Table 2 shows the parameters for the design point and temperature, pressure and flow rate in the solar field design.

Table 1: ET-100 collector specifications

Aperture width (m)	5.76
Total length of collector (m)	98.5
Total length of each module (m)	12.27
Number of modules	8
Outer diameter absorber tube (m)	0.07
Inner diameter absorber tube (m)	0.055
Length of each connecting tube (m)	4
90º elbows in each interconnection	8
Mirror aperture area (m^2)	548.35
Peak optical efficiency	0.765
Dirt Factor	0.97
Absorber pass-through area (m^2)	2.40xE-03
Height of absorber-tube grain (m)	4.0xE-05
Relative absorber-tube roughness	7.23xE-04

The PSA has also simulated annual solar field behavior, calculating the superheated steam production that takes place at any given moment depending on the environmental data (direct solar radiation and ambient temperature).

For the design and simulation of the INDITEP solar field, several software tools were developed, such as the EXCEL work sheet "*Dimensioning a DSG Plant* " (González, 2003), which enables pre-dimensioning (under nominal conditions) of solar fields with parabolic trough collectors that work with direct steam generation and with the LS-3 or EUROtrough collector models. A FORTRAN program called *"Simcampo.for",* was also created to simulate the behavior of a north-south EUROtrough-type parabolic-trough collector field with direct steam generation. This program can calculate, among other factors, the thermal power generated in the solar field during the year and the steam flow rates delivered by the solar field at any given moment during the year.

Table 2: Design-point data and nominal temperature, pressure and flow rate parameters

Direct solar radiation	875 W/m^2
Solar date and time	June 21st; 12:00h
Ambient temperature	20 °C
Angle of incidence	13.7°
Water temperature at BOP outlet	127.7 °C
Average collector row inlet water temperature	115 °C
BOP inlet steam temperature	400 °C
Average collector row outlet steam temperature	410 °C
Nominal BOP steam flow rate demand	7.22 kg/s
Over-sizing Factor	1,15
Steam flow rate delivered by the solar field at design point in summer	8.3 kg/s
Average feedwater pressure in each collector row	81 bar
Average steam pressure at each collector row outlet	71 bar
Steam pressure at BOP inlet	65 bar

Dimensioning of the solar field was completed with the design of the control scheme required to assure good operation and pressure and temperature stability of the superheated steam supply. The work done in 2003 by the PSA related to detailed engineering of the INDITEP plant will be completed in 2004 with the preparation of the specifications of all the necessary instrumentation, as well as for solar field startup and shut down operating procedures.

Improvement of the PSA DISS Plant

Another important share of PSA participation in the INDITEP project in 2003 was devoted to improve the solar field of the experimental DISS plant to increase the nominal 100bar/395°C steam flow rate to 1 kg/s. To do this, the collecting area of the DISS plant solar field collector row had to be increased. Two ET-100 collectors were connected in series to the row of 11 collectors installed during the DISS project in 1998, increasing the row's collecting area by 1096 m^2. Figure 48 shows a simplified schematic diagram of the solar field after installation of the two new collectors.

As seen in Figure 48, the two new collectors have been installed in series and connected to inlet of the collector row installed in 1998. Figure 49 shows a view of the new ET-100 collector concentrator module structures during assembly, and Figure 50 shows how the connection between the two new collectors installed in 2003 and the collectors installed in 1998 is in the shape of a "U".

Once assembly of the two new collectors had been completed in July, 180 bar pressure tests were carried out and then thermal installation was installed. The first operating tests of the new collectors took place in October 2003. At present the system is completely operative.

At the same time as the two new collectors were being assembled, DLR installed one of the two compact water/steam separators to be evaluated during the INDITEP project.

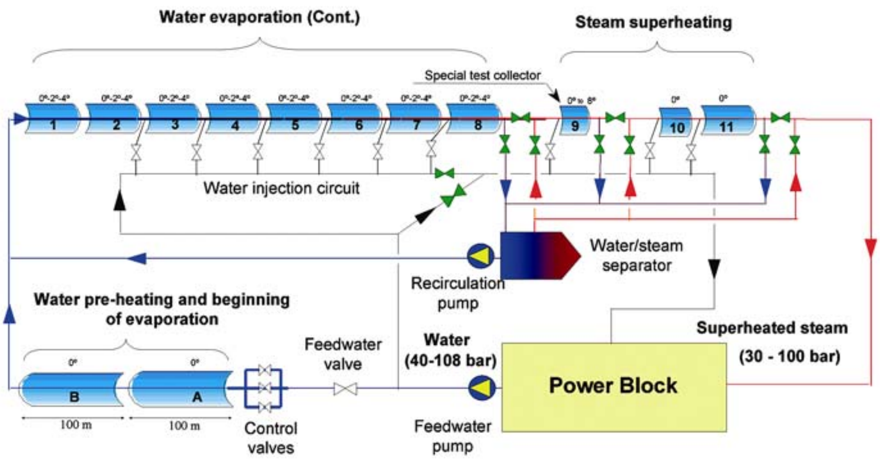


Figure 48. Schematic drawing of the DISS plant solar field after improvement of the solar field

Figure 49. View of the metal structures of the two new collectors installed in the DISS plant.

Figure 50. View of the "U-shape" connection between the two new collectors and the row installed in 1998.

In addition to the assembly of the two new collectors, the PSA fabricated its solar tracking local controls and prepared all the technical specifications for assembly of associated instrumentation. Another of the PSA tasks carried out was modification of the data acquisition system and regulation of the DISS plant to include the new instrumentation and introduce the new collectors in the system graphic displays.

Development of new Solgel coatings:

Following the line of work initiated more than seven years ago by CIEMAT in the development of new Solgel coatings, the PSA continued working in the second half of 2003 on antireflective coatings for glass and selective coatings for absorber tubes. During the first half, research was slowed down because the laboratory used for this activity was out of service while all the furnishings were replaced and new instruments were acquired.

Solgel activities in 2003 focused on two fields: a) antireflective coatings for glass and b) selective coatings for solar absorbers. In continuation the achievements in these two fields are described.

Antireflective coatings for glass: An antireflective porous silica film on borosilicate glass, the material used in the fabrication of the glass cover that protects the parabolic-trough collector absorber tubes was optimized. The antireflective properties were observed to improve when in a dense silica film was placed between the glass and the porous silica layer (see Figure 51).

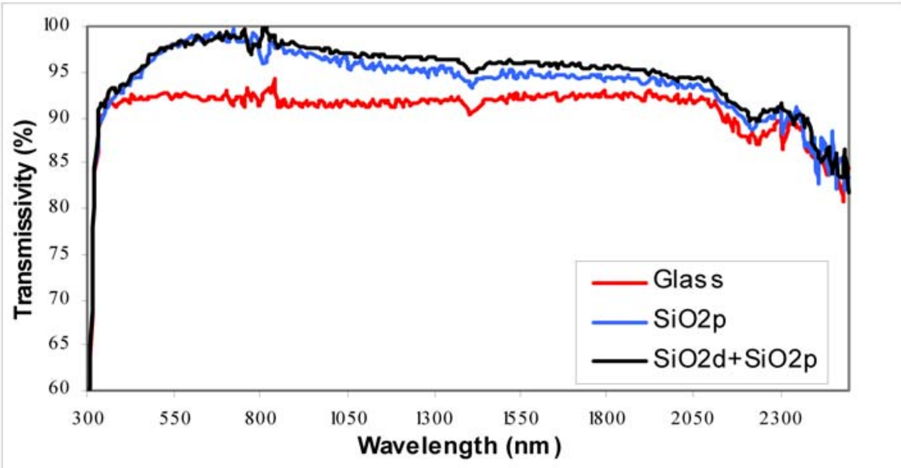


Figure 51. Solar transmittance of borosilicate glass with no coating, with porous silica coating and with a dense silica and another porous layer.

The solar transmittance (AM1.5) of the borosilicate glass used in the tests (0.923) increased to 0.953 with the layer of porous silica and to 0.959 with the two layers of silica.

Tests carried out by the German company, Schott, on a sample of the antireflective coating developed by the PSA showed excellent mechanical and optical properties, which will enable it to be used outdoors. The average transmittance was 95.85.

Furthermore, the problem of steam absorption by the silanols (Si-OH) in the antireflective porous silica coating was solved by dipping the sample in a solution of alkoxides, which replace–OH silanol radical avoiding absorption of water and conferring the coating clearly hydrophobic behavior. However, in 2004, work will attempt to improve the long-term behavior of the antireflective coating developed, since its optical properties could become diminished over time, and the transmissivity drop from 95.85 to 94.

Selective coatings for solar absorbers:

A selective coating stable in contact with 550º air with a carbon steel substrate, the material used in the absorber tube, is being developed in the INDITEP project. These requirements have made it necessary to make significant changes in the selective absorbent developed by the PSA for stainless steel tubes at 450ºC.

The selective coating now under development at CIEMAT under the INDITEP project is made up of two alumina/platinum cermet coatings, with different metal content on a thin reflective platinum film. Different protective barriers and/or anti-diffusers and an antireflective coating are used between the layers.

The higher operating temperature means the Solgel films produced at 550-600ºC have to be denser to avoid continued absorbent thickening during collector operation, with the consequent reduction in layer thickness and the change of optical properties of the coating. And, as the increased temperatures also cause greater diffusion of the layers, anti-diffusion barriers need to be denser and have better properties.

Direct generation of steam requires that carbon steel be used in the absorber tube. Since carbon steel has lower chemical and thermal stability, the material must be protected with some kind of coating that permits the Solgel film deposition and thermal densification treatments. It is not possible to use protective dense silica films on stainless steel or aluminum because they cause strong oxidation of the substrate at temperatures as low as 200ºC. To solve this problem, nickel-tungsten films are being deposited by electrolysis, which is showing high thermal stability and allows densification at temperatures over 500ºC.

At the end of 2003, samples of the complete absorbent on the carbon steel substrate began to be prepared for evaluation of their thermal stability at 550ºC air temperature. The individual films were sintered at 600ºC in air for thirty minutes to achieve better densification. The optical properties of the selective coatings obtained up to now are: absorptivity = 0.94 and emissivity_{400C} = 0.14.

DISS PROJECT

The main purpose of the DISS project is to develop the direct steam generation technology (known as DSG), by which high pressure high temperature steam is produced right in the parabolic-trough collector absorber tubes, which eliminates the oil traditionally used in solar plants with parabolic-trough collectors as the working fluid in the solar collectors. The first phase of the DISS Project began in January 1966 and was completed in November 1998 with the startup of what is today the only real-scale experimental plant for GSD process research under real solar conditions. This PSA-DISS experimental plant was operated during the second phase of the project (December 1998-December 2001) to obtain experimental data clarifying technical uncertainties of direct steam generation.

Although the DISS Phase 2 contract signed by the European Commission and the project partners (CIEMAT, Abengoa, DLR, ENDESA, IBERDROLA, Flabeg Solar International and ZSW) officially terminated in December 2001, CIEMAT has continued its activity in this project in the following years for two reasons: a) continue evaluating the experimental data obtained during Phase 2 and b) completing the results obtained in additional experiments carried out during the second phase of the project.

In 2003, the study of the thermal gradients in the absorber tubes of the DISS collectors was completed and the results were published in a doctoral dissertation entitled ""*Generación Directa de Vapor con Colectores Solares Cilindro Parabólicos. Proyecto DISS*[1]" defended at the School of Engineering of Seville in November 2003. The work studied three different zones in the collector row during direct steam generation:

[1] Direct Steam Generation with Parabolic-Trough Solar Collectors. The DISS Project.

a) Water preheating zone
b) Evaporating zone, and
c) Superheated steam zone.

Since both in the preheating and superheating zones there is monophase flow of either water or steam, depending on which, the study of thermal gradients in these two employed a similar methodology. The main conclusions that were obtained for these two zones are the following [Zarza, 2003]:

All the maximum circumferential temperature differences measured in the absorber tubes were much lower than the 70ºC adopted as the limit that would guarantee absorber tube endurance.

The thermal gradient and the maximum pressure measured under the worst working conditions found in the preheating and superheating zones are quite a bit lower than the maximum admitted t 10 MPa by the ANSI/ASME B31.1, 1983 code. Specifically, the maximum pressure obtained in the preheating zone was $8 \cdot 10^7$ N/mm^2, while in the superheating zone it was $11 \cdot 10^7$ N/mm^2, which is equivalent to 47% and 67% of the maximum admitted by the Von-Mises criterion. Therefore, the integrity of the metal absorber tube is guaranteed. Figure 52 shows the evolution of the circumferential temperature profiles and the thermal gradient for the worst case found in the water preheating zone, which was in a test made on May 29, 2002.

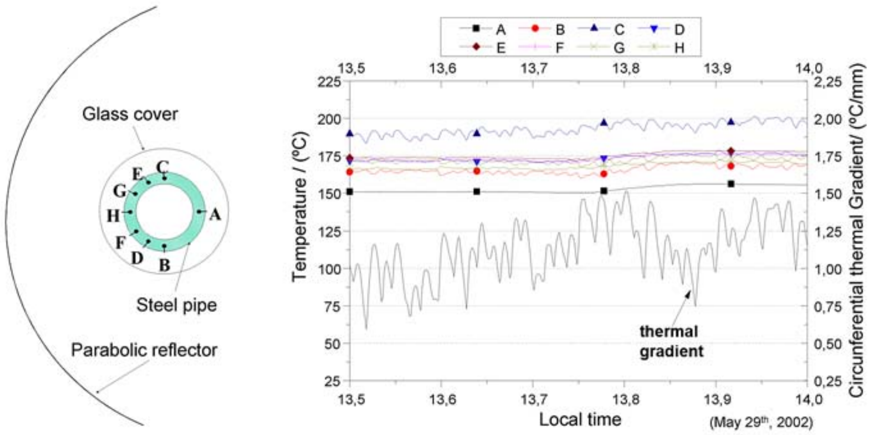


Figure 52. Temperature profile and thermal gradient in the most unfavorable case found in the water preheat zone.

The one-pass-through operating mode is not advisable for commercial DSG plants because of the strong fatigue produced in the interphase between the evaporation and superheating zones.

In the evaporating zone, the over 900 experimental data evaluated have made it clear that the thermal gradients in this zone are also much lower than the maximum admissible for ensuring the integrity of the absorber tubes. It has been shown that in practice, the most unfavorable operating conditions assumed in the DISS project theoretical studies never occur simultaneously. Thus, for instance, it was demonstrated that there is never a low angle of collector axis rotation and high direct solar irradiance at the same time.

The feedwater flow rates that cause stratification in the liquid phase in the evaporating zone were also found in the 2003 study depending on the working pressure. These minimum flow rates are: 0.8 kg/s at 10 MPa; 0.55 at 6 MPa y 0.4 at 3 MPa. It was also observed that the most critical segment in the evaporating zone is within the steam quality range of $0.3 \le x \le 0.5$. This means that stratification, if it appears, will always begin in this segment of the evaporation zone.

Another important conclusion of the study is that when there is liquid-phase stratification in the evaporating zone, the maximum circumferential temperature differences increase considerably with working pressure as do the rest of the operating parameters.

Figure 53 shows typical evolution of maximum circumferential temperatures in the absorber tubes in the evaporating zone of the DISS collector row, as a function of steam quality in the two-phase flow. The tendency shown in Figure 53 is qualitatively very similar to the GUDE project (Goebel, Hennecke, 1997)(Köhler, Herbst y Kastner, 1996).

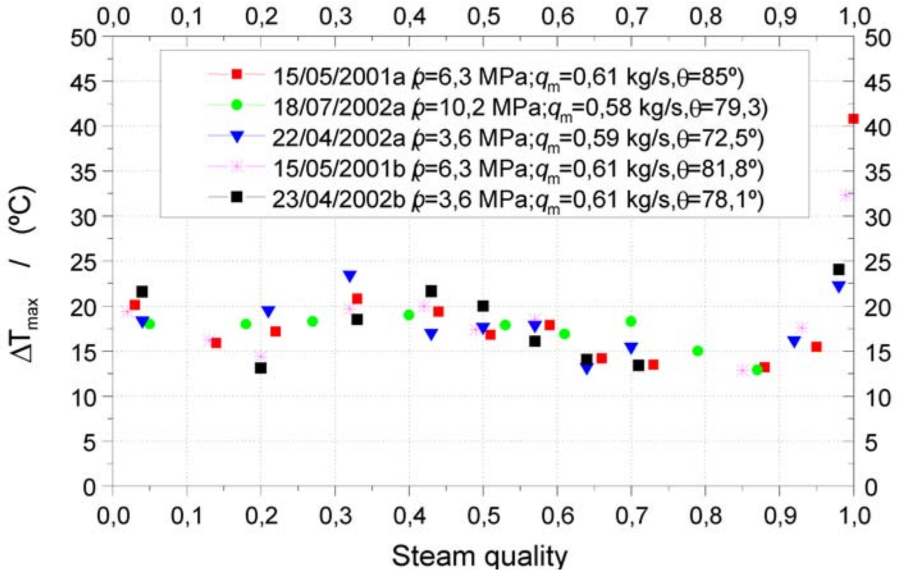


Figure 53. Measured values of the maximum circumferential temperatures in the absorber tube evaporating zone, depending on the steam quality.

The 2003 study also showed a series of interesting phenomena that were previously unknown:

a. The profile of concentrated solar radiation flux incident on the absorber tube is very irregular and shows high flux lines that are even visible to the eye. The intensity and position of these lines changes rapidly with the relative positions of the sun and the collector. Although the cause of these high flux lines is not yet clear, it seems that they may be due to a combination of factors (parabolic mirror shape error, assembly tolerances, etc.). Figure 54 shows a photograph of a DISS collector absorber tube in operation, in which the high flux lines mentioned can be seen.

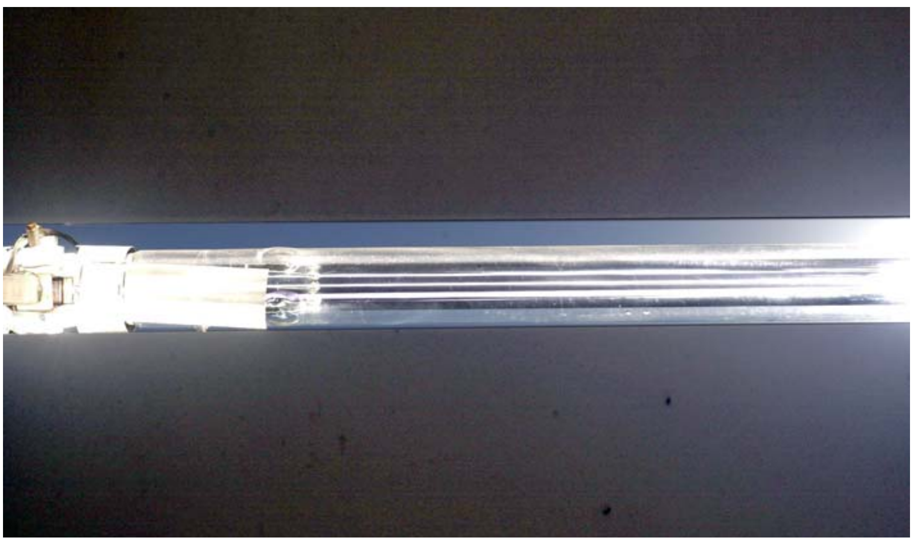


Figure 54. High flux lines on DISS absorber tubes

b. It was also found that the separations between adjacent modules in a collector and between vertical rows of mirrors within a same parabolic-trough module cause shading of the absorber tube, so if there are any thermocouples measuring the absorber tube temperature in that zone, the temperature reading is significantly lower than when there is no shading. Therefore, the location of thermocouples installed in parabolic-trough collector absorber tubes will have to be studied in detail (Zarza, Sanchez, 2002).

In 2003, a comparison of data for the surface convective heat transfer coefficient measured in the evaporating zone of the PSA DISS collectors with the predicted by Kandlikar (1990), Goebel (1998), Chen (1996), Shah (1976) and Gungor and Winterton (1986), which are the most widely upheld today, concluded that the calculation of the surface heat transfer coefficient is very sensitive to small variations in temperature so that even a 1°C variation in temperature can produce variations of as much as 50% in the heat transfer coefficient obtained. Since it is impossible to assure that the temperatures measured by the thermocouples installed in the DISS absorber tubes are error-free to 1°C, the temperatures measured by those thermocouples cannot be used to calculate the convective heat transfer coefficient inside the absorber tubes in the evaporating zone. Figure 10 shows the comparison between values obtained with the DISS experimental data and those obtained for those same working conditions by the Goebel correlation (1998).

In the first half of 2003 the study for the improvement of heat transfer on the inside wall of the parabolic-trough collector absorber tubes during direct steam generation. This work produced as the final result the doctoral dissertation "*Mejora de la transferencia de calor en flujo horizontal bifásico. Aplicación a colectores solares cilindro-parabólicos*[2]", presented in June at the College of Physical Sciences of the Complutense University, Madrid in its Atomic, Molecular and Nuclear Physics Department. This dissertation was the culmination of one of the lines of research initiated during the DISS project by CIEMAT-PSA.

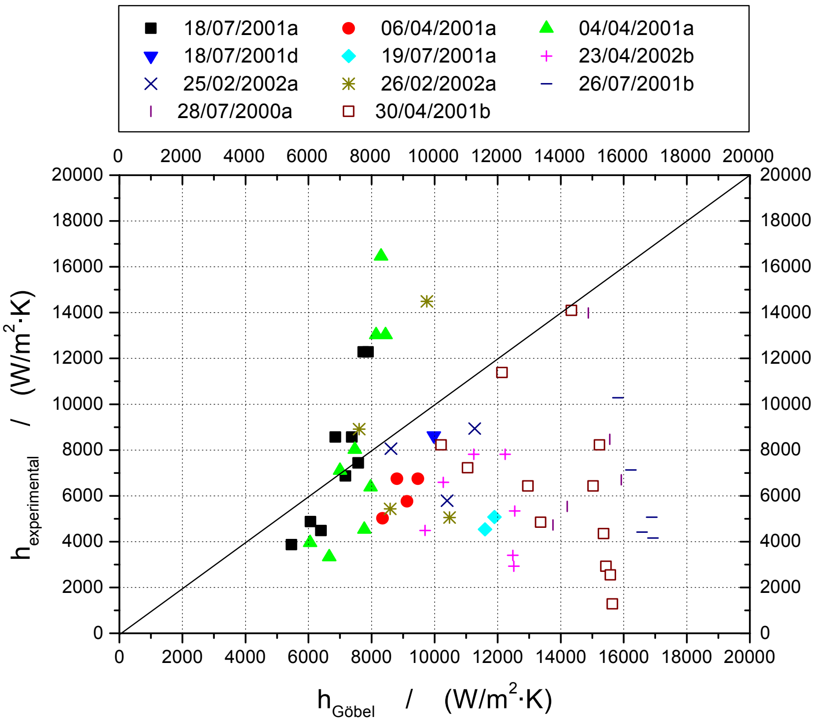


Figure 55. Comparison of the Goebel (1998) correlation and the surface convective heat transfer coefficient values obtained from the DISS experimental data.

[2] Improvement of heat transfer in two-phase horizontal flow. Application to parabolic-trough solar collectors.

PREDINCER PROJECT

The PREDINCER project is a coordinated national R&D project that receives partial financing from the Ministry of Science and Technology. In this project, CIEMAT collaborates with research groups from the universities of Almería and Seville, in the development and evaluation of new predictive control algorithms for processes with bounded uncertainties applicable to parabolic-trough collector solar fields. This project began in September 2002 and lasts 36 months.

In 2003, in analysis and development of modeling and identification techniques, structural analyses of linear models were begun and the boundaries of the uncertainties in the specific cases of the PSA DISS plant operating modes are now being studied. For this system, first low-order linear models were obtained and the experimental data available for the system were analyzed. After a first analysis of the data, a series of specific tests were proposed for the system to be carried out in 2004 that would produce sufficiently dynamic data.

Work was also done on improvement of a dynamic simulator for the DISS plant that was developed when the first system theoretical studies were carried out. The availability of this simulator is going to enable modeling and simulation of predictive control structure designs that are made of this system with bounded uncertainties.

As fruit of the collaboration of researchers in this group with the others in the coordinated project, the following results have been obtained, both in the scope of this project and in other previous collaborations.

- L. Valenzuela, E. Zarza, M. Berenguel, E.F. Camacho. Feedforward control for a once through solar boiler. *IEEE Control System Magazine*, 2003, in printing.
- L. Valenzuela, E. Zarza, M.Berenguel, E.F. Camacho. Control concepts for direct steam generation process in parabolic troughs. *ISES Solar World Congress*, Göteborg, Sweden, June 2003.
- L. Valenzuela, M.Berenguel, E. Zarza, E.F. Camacho. Control schemes for direct steam generation in parabolic solar collectors under recirculation operation mode. Sent to *Solar Energy* for possible publication, 2003.

OTHER ACTIVITIES IN 2003:

In addition to the activities in the INDITEP, DISS and PAREDINCER projects, the PSA has carried out other activities in parabolic-trough solar collector technology in 2003.

An important effort was made in the preparation and planning of new projects for continuation of the main lines of work defined by the PSA in the field of parabolic-trough collectors. As a result of this activity, the PSA participated in two proposals presented to the European Commission in the first announcement of the 6th Framework Programme in 2003. These two proposals were the following.

- DISTOR: the purpose of which is development of a thermal storage system for solar plants with direct steam generation. This proposal, coordinated by DLR, has a long list of partners: DLR, SGC, FSOL (D), CNRS, EPSILON, DEFI (F), CIEMAT, INASMET, SISCALOR, IBERINCO, SOLUCAR (E), Weizmann Inst. of Science (IL) and the Bulgarian Academy of Science (Bulgaria). The proposal was approved and activity in the 42-month project will begin at the beginning of 2004.

- NEW-AGE-PV: the purpose of which is development of procedures and facilities for accelerated testing of photovoltaic modules. The proposal was coordinated by Fraunhofer ISE (D) with the participation of CIEMAT (E), PSE, Solon. Isovolta (D), National Testing and Research Institute (S) and the University of Louvain (Aus). This proposal was unsuccessful in the evaluation phase.

In December 2003, two proposals for national projects were also presented. One of them was presented in collaboration with research groups from the universities of Malaga and Seville (GEDIVES Project), for the development of design and simulation tools for parabolic-trough solar fields with direct steam generation. The second proposal for a national project was presented to the PROFIT program in collaboration with several Spanish companies and the University of the Balearic Islands, for the study of two new designs for linear focus collectors apt for integration in buildings or in industrial processes with low or medium thermal energy consumption in the range of 125ºC – 300ºC. These two new solar collector developments fit in with the interests of the International Energy Agency and its recently created Task 33/4 SHIP (‘*Solar Heat for Industrial Processes*’), in which the PSA participates.

In 2003, the PSA also participated in several AndaSol project meetings, in which we are already involved. However, our contribution to this project is still modest because the main PSA contribution to AndaSol will take place during the plant installation and startup phases.

The final reports on CIEMAT-PSA’s participation in the European *EUROtrough-II* project, which was completed in December 2002, were written at the beginning of 2003.

Finally, we also continued in 2003, within the limitations that the few persons in the parabolic-trough program allow, to provide assistance to Spanish companies interested in the field of parabolic-trough collectors.

Solar Chemistry

INTRODUCTION

In 2003, CIEMAT underwent an external evaluation of its lines of activity which to that time had been called “CIEMAT Projects”, by outstanding scientists with acknowledged international prestige in the related fields of activity. As a result of that evaluation, in the second half of 2003, the CIEMAT profiled, defined and considerably reorganized its activity, which, in the case of the “Chemical Applications of Solar Radiation” Project will involve a series of important changes as of January 1, 2004.

The first of these changes is that, starting in 2004, the “Chemical Applications of Solar Radiation” “*Project*” will become a “Program” called “Environmental Applications of Solar Energy and Solar Radiation Characterization”. The term “*Program*” implies certain characteristics in wider areas of activity than those previously assigned to “*Projects*”. The reason for this change can be found in the basically environmental nature of the many initiatives that the Solar Chemistry Project has carried out in recent years.

These changes do not mean, however, that the lines of activity have been carried out in recent years at the PSA are to be abandoned or even modified and in all cases, have been focused on the development, both scientific and technological, of different chemical or photochemical processes with primary use of solar radiation. On the contrary, all of these activities will be maintained and strengthened, but noticeably reinforced by others that will augment growth of the group’s activity, as it reaches a critical mass sufficient to allow its consolidation as a group of worldwide reference in the development of solar technologies and their application to specific processes.

This is the case for example of the processes associated with the use of solar radiation to approach different water issues. The significant experience accumulated in the field of solar photocatalysis for detoxification of water has been very useful for promoting other types of initiatives, in principle totally different, such as solar desalination of sea water. More recently, the Solar Chemistry Group has also taken the step of approaching disinfection of drinking water, with basic application to isolated rural environments in developing countries.

In all these cases, the environmental issue related to water is very clear, with significant public awareness associated. All the international organizations recognize that the scarcity or lack of water is one of the main challenges to be faced by Mankind in the 21st century. All of which leads to the important opportunities and potential currently and, certainly, in the future, for the development of environmentally benign technologies that offer effective solutions.

Another important field of activity is and will continue to be photocatalytic treatment of gases, for which there is already some equipment on the market, although they use light generated by electric lamps. In 2003, growing interest was observed in certain Spanish companies in the possibilities of solar technology for the elimination of odors and gaseous contaminants in general.

However, the most conspicuous result of CIEMAT's reorganization is the incorporation of the group devoted to measurement and characterization of solar radiation from satellite images, which was previously in the CIEMAT "Evaluation of Renewable Energy Resources "Project". The possibilities and potential that this has for the entire group are very important, since, in addition to the relevance that characterization of the solar resource has in and of itself, analysis and modeling of solar radiation available for specific spectrum bands, i.e., ultraviolet radiation, is of the strongest interest to photocatalytic processes.

Among the lines of research ending is "Solar Synthesis of Fine Chemicals" which was completed at the end of 2003. This activity, carried out since the middle of the nineties in close collaboration with our colleagues from DLR-PSA, in 2004 will be suspended awaiting new projects and opportunities.

The very outstanding milestones achieved in 2003 have been many, however, if any of them stands out among them, we would have to cite two as the most relevant. The first is the startup of work on the first commercial solar detoxification plant in the world to be erected for the treatment of rinse water from recycling of empty pesticide containers; this project is promoted by the Albaida Recursos Naturales y Medioambiente company and is based on the scientific and technological developments achieved at the Plataforma Solar de Almería in recent years. The second of the milestones is the startup of the "*Solar Thermochemical Application for CO_2-Free Production of Syngas + H_2 from Heavy Crude Oil*" promoted and financed by Petroleos de Venezuela S.A., for the solar production of hydrogen and syngas from heavy crude waste. With an initial budget of nearly US$7 million in its first phase, this initiative means a very serious decision in favor of the development of solar fuels".

Finally, among the most outstanding results obtained in 2003, the satisfactory conclusion of a doctoral dissertation in the Solar Chemistry Group, a total of 15 publications in international journals with scientific impact rating, 1 international patent, publication of 3 books (one of them by an international publisher), 2 chapters in books (international publisher) and 21 communications to congresses (13 of them oral and almost all of them international). This ample intense scientific activity, kept up during recent years, has given the Solar Chemistry group its present high prestige and its labors are recognized internationally [Blanco y Malato, 2003a]. in the sections below, the main projects and activities carried out in 2003 are briefly described.

1) <u>Solar detoxification of liquid effluents</u>
2) <u>Gas-phase solar detoxification</u>
3) <u>Solar disinfection of drinking water</u>
4) <u>Solar desalination of sea water</u>
5) <u>Access to the PSA as a Large European Installation. Solar-chemistry-related activities</u>
6) <u>Other environmental solar chemistry processes.</u>

1) SOLAR DETOXIFICATION OF LIQUID EFFLUENTS

DESIGN AND OPTIMIZATION OF A PILOT PLANT FOR INTEGRAL TREATMENT OF RESIDUES IN PESTICIDE CONTAINERS FOR RECYCLING

The TREN-AGRO project, financed by the Ministry of Science and Technology (Call for R&D projects, BOE March 8, 2000, Project PQ2000-0126-P4-05), began in November 2001. In this project the Plataforma Solar participates along with the Analytical Chemistry Department of the University of Almería (coordinator), Aragonesas Agro S.A., Cooperativa de Exportadores de Frutas y Hortalizas de la Provincia de Almería[3] and the Chemical Engineering Department of the University of Alcalá.

The work proposed is intended to develop a process for the treatment of residues in pesticide containers for their recycling and other applications in the plastics industry. The process has two basic steps, each consisting of several operations (i) one for the containers themselves: shredding, washing, drying and compacting to sufficiently inertize the residues and (ii) and one for the water: physical-chemical treatment (AOPs, advanced oxidation treatment) that totally eliminates the toxic components such as pesticides and their transformation products.

In 2003, it was demonstrated that both photocatalysis with TiO_2 and photo-Fenton are viable treatments for purifying and detoxifying water polluted by pesticides (Figure 56). The photo-Fenton process has been shown to be more efficient than TiO_2 not only for degradation of pesticides, but also for mineralization of TOC and reduction of toxicity [Agüera et al., 2003; Cáceres y col, 2003]. Degradation products identified by GC-MS, GC-AED and LC-MS in both photocatalytic treatments are similar. The solid phase extraction (SPE) method applied has been very useful in obtaining "cleaner" chromatograms in GC-AED and GC-MS. No information of interest is lost with it while avoiding the use of liquid-to-liquid extraction (LLE), a sample preparation procedure that is usually tedious, expensive and damaging to the environment (use of solvents).

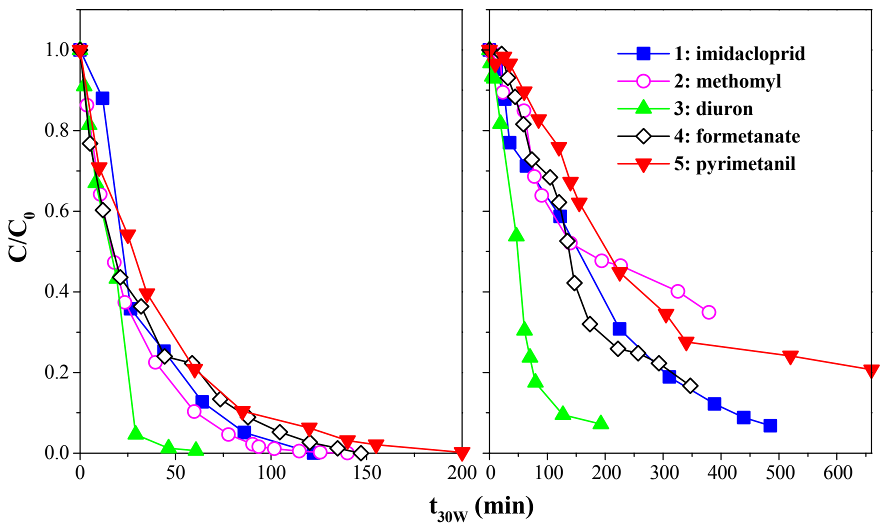


Figure 56. Degradation (left) and mineralization (right) of several pesticides at C_0 = 50 mg/L using TiO_2 (200 mg/L).

The combined use of AED/MS in GC detection has been shown to be one of the most powerful alternatives for identifying and quantifying unknown compounds. Specifically, GC-AED with compound independent calibration has proven a very useful tool for the identification and quantification of photocatalytic treatment DPs. With the use of LC-MS, with an atmospheric pressure ionization (API) interface, information on the appearance

[3] The Fruit and Vegetable Export Cooperative of the Province of Almería

and evolution of DPs formed during water treatment is acquired quickly and in detail. The use of LC-ES-MS in positive ion mode provides evidence of the pesticide degradation path in photocatalytic processes. An ion trap (IT) analyzer in tandem with MS-MS is a good tool for detection of a large number of DPs and confirmation of structures using the mass spectra of the product ions. Furthermore, mass spectra generated by LC-MS/MS are unaffected by signal background noise. Evaluation of DPs using LC-ES-MS by direct injection avoids sample preparation procedures required with LLE and SPE and, without preconcentration when the concentration is sufficient, analytes of interest are not lost.

PDs or mixtures there of that are generated during the photocatalytic degradation processes can be more toxic than the original components. No clear correlation has been observed between the results obtained from the toxicity bioassays and TOC in the two AOPs employed. The fact that the TOC is a parameter that cannot easily be correlated with toxicity may be due to the different PD formation rates and thereby, to their relative concentration at any given moment. Therefore, there is a clear need to make bioassay batteries to obtain conclusive results (Figure 57). It was demonstrated that the design of a photocatalytic treatment plant unavoidably requires pilot plant experimentation and not just at laboratory scale, since these can give rise to results that are difficult to extrapolate and with the resulting problems for scaling up. This is also because every case behaves differently, making it necessary, if possible, to use pilot plants to obtain design parameters. The treatment costs not only depend on the degradation rate. The amount and type of catalyst, the use of oxidants, pH adjustment before and after treatment, etc., have considerable relevance in cost calculations. This is one more reason why photocatalytic water treatment requires a detailed case study for the design of every treatment plant [Malato et al., 2003b-d].

Plaguicida	**Bioensayo**	**$t_{30W, TOX}$ min**		**$C_{T, TOX}$ $m^3\ m^{-2}\ year^{-1}$**	
		TiO_2	*Photo-Fenton*	*TiO_2*	*Photo-Fenton*
Methomyl	*Daphnia Magna*	297	133	6.4	14.3
	Vibrio Fishcheri	355	146	5.4	13.0
	Selenastrum Capricornotum	86	109	22	17
Diuron	*Daphnia Magna*	108	1.1	18	1780
	Selenastrum Capricornotum	52	51.	37	37

Figure 57. Treatment capacity of the two photocatalytic methods used (corrected with the average UV available) for reaching EC_{50} with two of the pesticides tested.

ENVIRONMENTAL COLLECTION AND RECYCLING OF PLASTIC PESTICIDE CONTAINERS WITH SOLAR PHOTOCATALYSIS

This project focuses on problems that originate in intensive greenhouse agriculture, a sector that has been growing exponentially in recent years in the Mediterranean Basin. There are currently over 200,000 hectares of greenhouses, most of them in EU countries. This type of agriculture requires up to 200 times more pesticides than conventional agriculture (Figure 58). The environmental problems are one of the greatest disadvantages for the development of this economic sector. One of these problems is the uncontrolled dumping of plastic pesticides containers, which usually still contain residues. This is a serious risk of pollution for soil and ground water. The solution is to selectively collect these containers for recycling. But before the plastic can be recycled, it must be washed and the water used for it becomes polluted by the pesticides. This water must be treated before it is discharged. Therefore, the development of a simple clean treatment process for this water in the place where it is produced is necessary. At the present time there is no such technology [Blanco, 2003 f; Malato et al., 2003i]. The ALBAIDA company and CIEMAT presented a project entitled "Environmental Collection and Recycling of Plastic Pesticide Bottles using Advance Oxidation Process driven by Solar Energy" to the European LIFE-ENVIRONMENT program, which was approved and began in October 2001. At this time, the definitive plant is under construction and is expected to be operable in spring 2004.

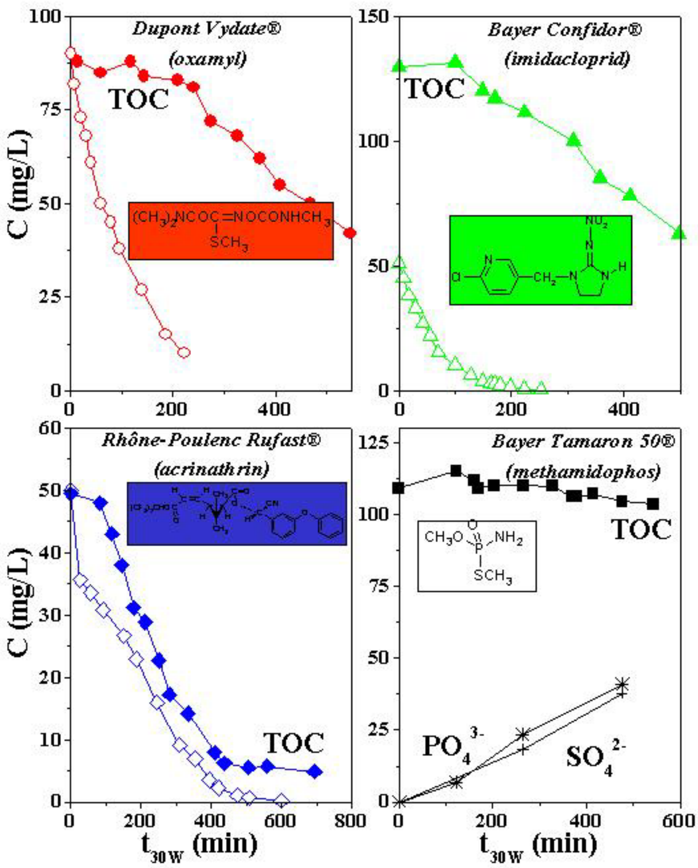


Figure 58. **Photocatalytic degradation of four commercial pesticides widely used in greenhouse agriculture.**

The 12,915-m² lot where the pesticide container treatment plant is to be located is in the municipal limits of La Mojonera (Almería). The plant will have a 180-m² storage bay for receiving and handling the plastic containers as they arrive. It also will have a solar field where the water from the washing unit with all the organic residues from the containers will undergo photocatalytic treatment for degradation of the pollutants. There will also be a 15-m² office space and another 25 m² for a laboratory facility. As the truckloads of containers arrive at the plant they will be dumped into a hopper at the unloading dock where 500 containers/hour will be transported on a 2 x 0.4-m² carrier belt to the storage bay.

The plastic container recycling must start with shredding and then industrial washing of the shredded plastic, which produces water polluted with a highly toxic persistent compounds in total organic carbon concentrations of a few hundred mg/L. The shredded plastic is sent to a series of three baths of the same size. It is important for the selection of containers to be well done, since it is very common for the grower to throw away any kind of used or useless container and this plant is exclusively for plastic. Therefore, on arrival, any other kind of container (glass, steel, etc.) or those that do not have pesticide residues, such as detergents or other nonhazardous products used in the agricultural sector, have to be detected.

The containers that are not going to be treated in the Plant will have to be given a different specific treatment; that is, deposit them as they appear in a container designated for that purpose, and later send them to an authorized agency. This is where the separation of the plastic and the wash water would begin. The wash water would be drained from each of the baths, at floor level and go to a storage tank. This water would carry the dissolved organic matter that was in the washed pesticide containers and is therefore considered a hazardous toxic product. As the water must be continuously recycled and reused, the contaminants must be treated (Figure 59).

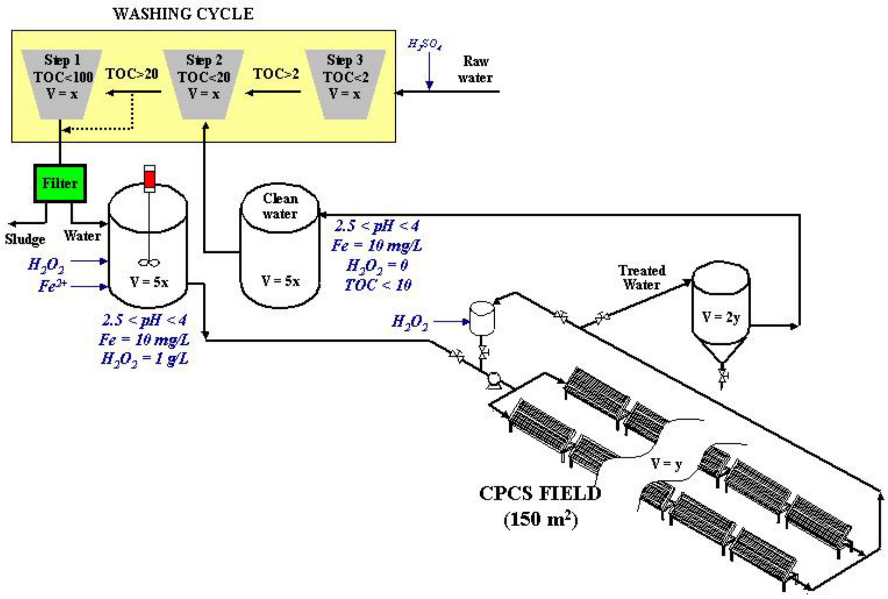


Figure 59. Schematic diagram of the container washing and photocatalytic water treatment plant concept

Before entering the solar field, the contaminated water is treated physically and chemically. The water will still contain solid waste, which is eliminated by a rough screen and then to another tank where reactives needed for the photocatalytic reaction are added. Once the sample is prepared, it enters the solar field of several photoreactors connected in series through which the water flows from one to the other (Figure 60). When the water leaves the solar field, it will have to be tested to see if the process has considerably diminished the TOC concentration in the treatment water. If not, it is sent back through the solar field again to undergo the solar detoxification process in the solar collectors. When the TOC measurement is sufficient, the water is reused, reentering the washing unit in the container storage bay. When the water has recirculated four or five times, it can be filtered by an active carbon filter where any substance resistant to the solar process would be retained, and discharged into a storage pool for later reuse.

Figure 60. Partial view of the plant solar collector field during erection

TREATMENT OF WATER CONTAINING PERSISTENT ORGANIC POLLUTANTS BY A COMBINATION OF ADVANCED OXIDATION AND BIOLOGICAL PROCESSES.

Since the first European Directive in 1975, progress has been made in the fight against sources of contamination of European water. However, it has been necessary to continually revise and improve the EC legislation on this matter, for example, in the field of water policy, a list of Priority Hazardous Substances was written up (European Parliament Decision nº 2455/2001/EC of November 20, 2001) as an improvement to the Water Framework Directive 2000/60/EC (known as the WFD). Human health is threatened by high concentrations of pesticides, heavy metals, hydrocarbons, chlorated hydrocarbons, etc., dissolved in water, usually from industrial waste sources that contain PHS at low-to-medium (<500 mg/L) concentrations. In this context, European Directive 96/61/EC also requires the development of specific industrial technologies and management practices to minimize contamination and increase reuse of the water. Due to the lack of treatment technologies available on site, a large number of industrial activities included in the Annex to Directive 96/61/EC do not sufficiently treat waste water. As a result, simple, low-cost treatment technologies are very much in need. For this reason, the Plataforma Solar de Almería applied to the EC (EC-DG Research; Energy, Environment and Sustainable Development; Sustainable Management and Quality of Water) for the CADOX project "A coupled advanced oxidation-biological process for recycling of industrial wastewater containing persistent organic contaminants", (http://www.psa.es/webeng/projects /cadox/index.html), to develop an appropriate technology to satisfy this demand. This proposal was favorably evaluated and work began in February 2003. CIEMAT is the coordinator with many European participants (ECOSYSTEM-Spain, AOSOL-Portugal, Universitat Autónoma de Barcelona-Spain, INETI-Portugal, TRAILIGAZ-France, Janssen Pharmaceutica-Belgium, Ecole Politechnique Fedérale de Lausanne-Switzerland and DSM-Deretil-Spain). The CADOX technology has basically focused on pesticides and non-biodegradable chlorated solvents (NBCS) considered PHS by the EC. At the same time, funding was applied for and obtained for the "Combined Photocatalysis-Ozonization Treatment for water detoxification. Design of a solar facility" Project with the Autonomous University of Barcelona from the Ministry of Science and Technology (Call for R&D Projects, Order of January 11, 2002, MCYT, PPQ2002-04060-C02-02). This project began in December 2002. This project is intended to complement and enlarge the tasks included in the CADOX Project.

The Advanced Oxidation (AOPs) is characterized by generating hydroxyl radicals ($^{\bullet}OH$), a highly oxidizing species, and although the high potential of the AOPs in the treatment of water containing persistent pollutants is widely recognized, it is also known that their operating costs for the complete oxidation of toxic organic compounds are very high, when compared to biological treatments. In any case, its use as a pretreatment stage to increase the biodegradability of such water can be justified if the bio-treatment is capable of degrading the intermediate AOP results.

The main innovation of the CADOX project is in the integration of the different technologies that have been developed separately to treat this kind of waste water [Blanco et al, 2003d; Fernández et al., 2003c; Rodríguez et al., 2003] (Figure 61).

The objective of the CADOX Project is commercial development of a combined AOP-Biological Treatment Process for industrial waste water polluted with organic compounds for reuse. To develop each of these two processes, the following scientific and technological objectives must be achieved.

The scientific objectives are:

1. Demonstrate that combined AOP (TiO_2, photo-Fenton and ozone photocatalysis) and biological treatment is an appropriate procedure for the decontamination of waste water containing 7 pesticides with medium-to-high solubility considered PHS by the EU (Alaclor, Atrazine, Clorfenvinphos, Diuron, Isoproturon, Lindane y Pentachlorophenol). Should the EU include other medium-to-high solubility or NBCS pes-

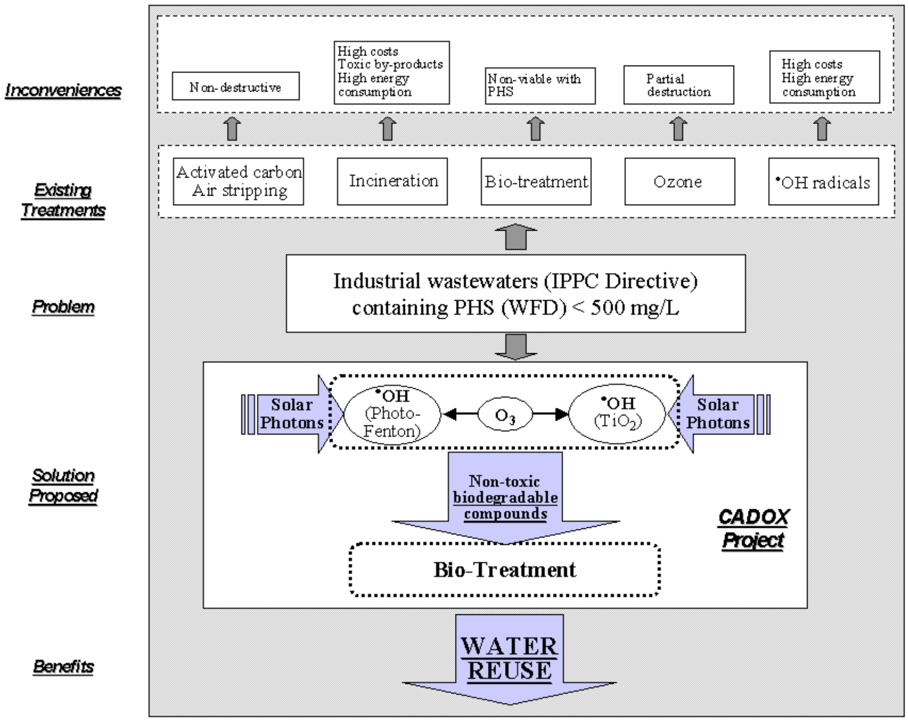


Figure 61. Innovative aspects of the CADOX project and schematic summary of alternative technologies

ticides in the PHS category, CADOX would automatically include them also as target compounds.

2. Definition of the best combination of AOPs to optimize treatment.
3. Develop new solar collectors to carry out the photocatalytic process with TiO_2 and photo-Fenton.
4. Build and test two small prototypes for the combined technologies mentioned above.

The technological objectives are the focus and main innovation in this project:

1. The construction and testing of a demonstration plant for the treatment of pesticides and NBCS based on the results obtained in the two prototypes.
2. The conceptual design and economic evaluation of an industrial-scale treatment plant.
3. Detailed analysis of the applicability of this technology in European sources of PHS at low-to-medium concentrations (<500 mg/L).

This Project attempts to demonstrates that the treatment cost of water containing persistent contaminants can be drastically reduced [Farré et al., 2003; Malato et al., 2003a, 2003f-h; Maldonado et al, 2003a, 2003b].

2) GAS PHASE SOLAR DETOXIFICATION

- The Photocatalytic destruction of precursors and generators of foul odors in sanitary waste water facilities was concluded successfully (MCYT- PROFIT Project).
  The following projects are underway:
- Elimination of persistent organic contaminants in gas effluents by advanced photooxidation (MCYT FOTOCOP Project).
- Development and evaluation of a photocatalytic treatment system for deodorization and disinfection of air inside buildings (CAM Project).

DESTRUCTION OF ORGANIC CONTAMINANTS IN AIR

Elimination of H_2S

The "Photocatalytic destruction of precursors and generators of foul odors in sanitary waste water facilities" project (financed by the MCYT- PROFIT: FIT-140100-2001-158 and 2002-84) was formally completed in December 2002, with a small extension during the first quarter of 2003. This project, jointly developed by the CIEMAT Department of Renewable Energies, the ICP-CSIC and the Aguas de Murcia S.A. company, has demonstrated the feasibility of photocatalysis for the destruction of hydrogen sulfide.

Figure 62 shows how starting out with a concentration of 27 ppm_v of H_2S, immediately after applying photons by turning on an 8W lamp under controlled laboratory conditions, total destruction of the compound is reached in the first 24 hours. This level of destruction progressively diminishes with regard to the poisoning of the catalyst due to formation of sulfates on its surface, which obstructs the active centers until the total deactivation of the catalyst within a few days. This process is reversible by successive washing with distilled water which allows optimistic proposals for the use of photocatalysis for the elimination of H_2S in water treatment plants.

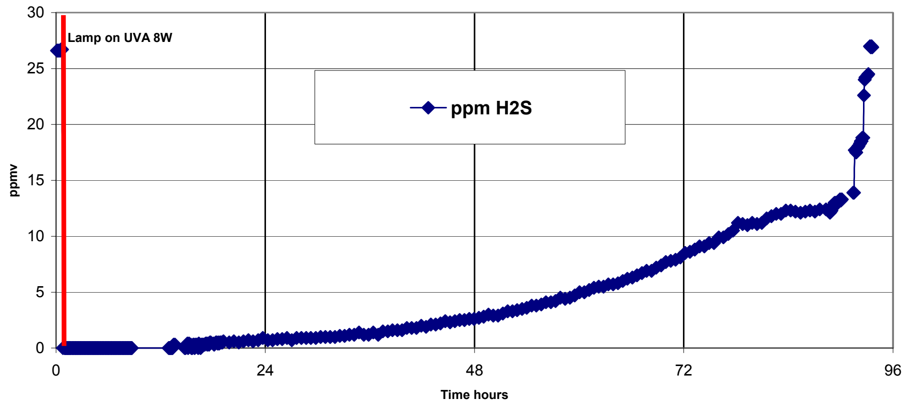


Figure 62. Destruction of 27 ppm_v of H_2S and its evolution over time

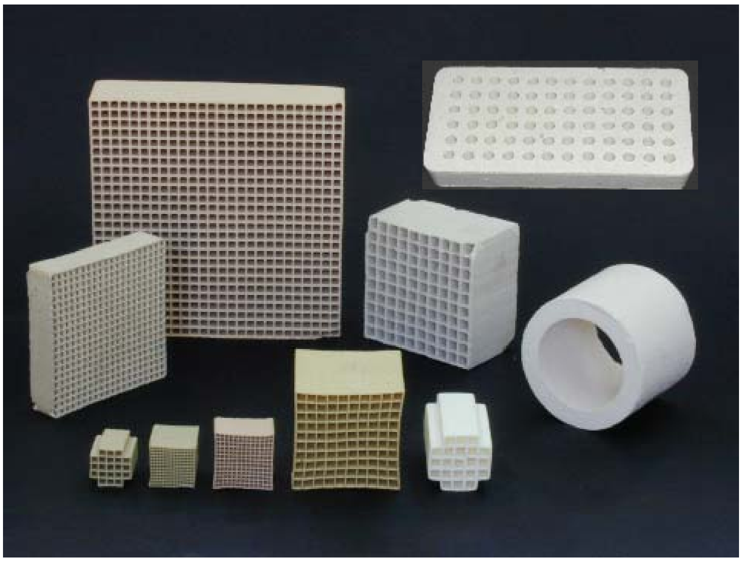
Photocatalytic treatment of dioxins and furanes

The project "Elimination of persistent organic contaminants in gas effluents by advanced photooxidation (FOTOCOP) Project, financed by the Spanish Ministry of Science and Technology continued in 2003.

The main goal of this project is the development, construction and testing under pilot plant conditions of a first prototype photocatalytic reactor which alone or in association with a conventional adsorption system, can destroy persistent organic compounds (POCs) in exhaust gases from waste incineration systems, such as dioxins and furanes.

To achieve this goal, several different monolithic catalysts and supports impregnated with titanium dioxide by different techniques – impregnation, solgel, spray, and determination of the activity of the different supports on a laboratory scale.

The results showed that the massic catalysts had the best efficiencies. Although the massic catalysts contained a greater amount of TiO_2 than the other techniques, much of this TiO_2 is not photoactive because it is hidden from the light inside the mass of the support. The larger BET surface and porosity of these monoliths with regard to impregnated or solgel catalysts should also be emphasized. This phenomenon is the consequence of interpenetration of the TiO_2 particles among the magnesium silicate fibers in the massic preparation phase. On the other hand, in impregnated monoliths or solgel-treated (dip coating) the surface area is less due to the obstruction of pores by TiO_2 particles deposited



Catalyst Samples	Method of Preparation	TiO_2 (wt%)	BET Surface Area (m^2g^{-1})	Pore Volume ($cm^3\ g^{-1}$)
Support	Extrusion	0	88	0.74
“Massic”	Extrusion	44.5	98	0.70
“Impregnated”	Washcoated	2.3	84	0.62
“Sol-Gel”	Sol gel - dip coating	4.5	82	0.61

Figure 63. Catalyst support shapes, such as monoliths, plates and ceramic plaques for photovoltaic testing of preparations made by ICP-CSIC

on the support surface. See Table in Figure 63 above. The greater activity of the solgel treated monolith in comparison to the impregnated support may be the result both of the greater amount and the smaller surface of the particular TiO_2 present in them.

The other target task during this period was the development of a methodology for sampling and analysis of dioxins and furanes before and after photocatalytic treatment, for which a collection system was designed and developed. The sample extraction and purification system and the detection system were optimized, as well as quantification by isotopic dilution.

Starting out with a first low-cost prototype photoreactor, controlled-emission pilot tests are expected to be performed next year under real solar radiation conditions.

Deodorization and disinfection of air in interiors

The “Development and evaluation of a photocatalytic treatment system for deodorization and disinfection of air inside buildings” project, financed by the Regional Government of the Community of Madrid (CAM), has continued evaluating the concentrations of VOCs, microbe load of saprophytes and pathogens in hospital ambient air. See Figure 64.

As in the previous project, special attention was given the efficiency of the different supports and catalysts – massic, solgel and impregnation in the treatment of VOCs. A modular reactor was developed and tested using two-component mixtures. In them, the massic catalysts were more efficient for the reasons given above. See Figure 65. An important task will be to check its efficiency in the treatment of colonies the results of which can be extrapolated to pathogenic colonies.

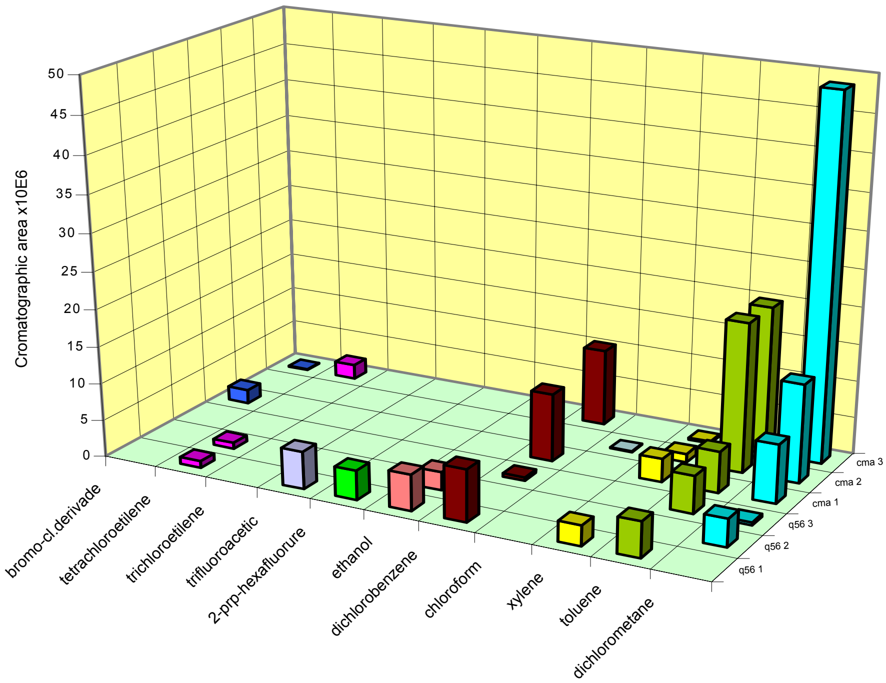


Figure 64. VOCs detected in different hospital atmospheres

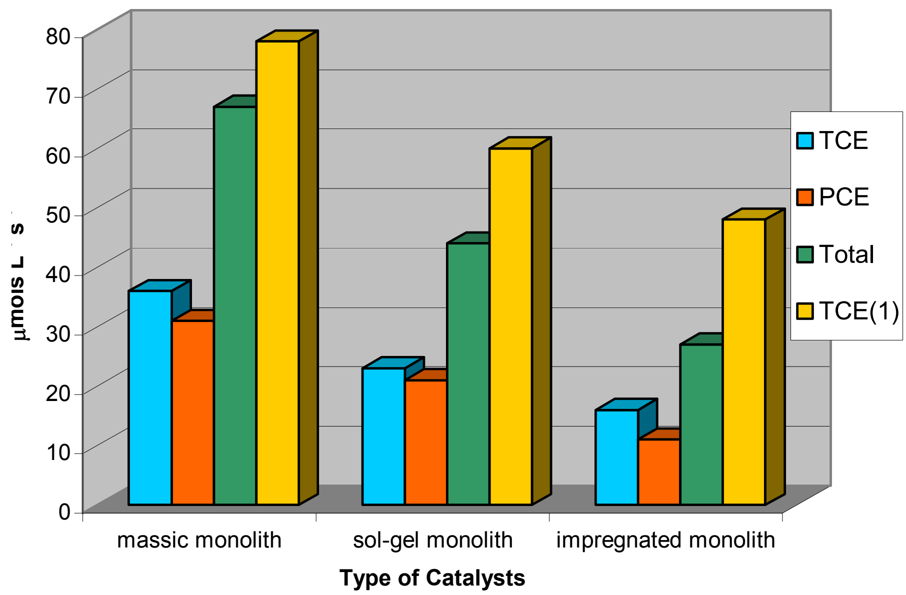


Figure 65. Photodegradation response in two-component mixtures

3) SOLAR DISINFECTION OF DRINKING WATER

The disinfection of water is a decisive process for the development of the population. It is important to emphasize that the lack of drinking water in a large number of countries is one of the most important problems on the planet. This reality is the cause of contagion of disease in water in many regions of the planet, that usually coincides with lower social and economic development. This causes a health problem that must be solved with efficient, economically feasible technologies. The methods traditionally employed for disinfection of water are chemical flocculation, granular filtration and chlorination. Membrane filtration techniques are very expensive, impeding their generalized use in treating large amounts of water. Disinfection by chlorination is the most commonly used. Gaseous chlorine or dissolved as hypochlorite, which is efficient against viruses and bacteria. However, these methods generate highly toxic sub-products, such as trihalomethanes and other carcinogenic compounds. Furthermore, traces of other halogens present in chlorine additives can form sub-products that are also toxic and the residues of chlorine present in water treated entail an additional problem with these methods. Additional disadvantages are the risks involved in their production, storage, transport and handling in chlorine treatment plants, as well as to the environment. Therefore, new disinfection technologies, including UV radiation (254 nm) and ozonization, have been developing for nearly 20 years.

The bactericide power of ultraviolet radiation (wavelength 254 nm) has been known since the beginning of the 20th century. But only recently has it been used as an efficient tool for disinfection, avoiding the generation of harmful sub-products. However, its lack of oxidizing power and the impossibility of working with natural light, make such disinfection expensive. Furthermore, operating problems, along with the high cost of O&M compared to disinfection by chlorination, have kept this type of treatment from growing noticeably among drinking water treatment methods. Furthermore, treatment with ozone is of great interest because of its high capacity for oxidation. At the present time, this technology is employed in the United Kingdom for disinfection of drinking water in spite of the high cost of ozone production, and it is taking hold more and more firmly in developed countries because it is more efficient than UV radiation. However, ozone tends to escape from water and cannot be stored, so ozonization treatment plants are potentially dangerous. Ozone can also generate toxic bromate ions in water rich in bromide. This, along with its oxidative selectivity, complicates its use as a water treatment technology.

In the sphere of advanced oxidation processes, is heterogeneous photocatalysis with TiO_2, Al_2O_3, ZnO, etc., catalyst which, under sufficiently energetic radiation in the presence of water is able to generate hydroxyl radicals. This type of process has been known and investigated since 1976. Its applicability to treatment of water containing pollutants in solution has been demonstrated for a large number of organic substances: phenols, halogenated compounds, pesticides, dyes, etc., and microorganisms. Therefore, the use of this kind of photocatalyst is a subject of research in the field of disinfection. Normally, when drinking water is disinfected, microorganisms and organic compounds are present simultaneously, which makes photocatalysis more effective because radicals of those compounds that are also bactericide are formed [Blanco, 2003b, 2003c; Fernández 2003a, 2003b; McLoughlin et al. 2003a, 2003b].

The problem of lack of water and the progressive increase in demand for it make the development of efficient technologies that are respectful of the environment more and more important. Competitive methods that constitute a clear alternative to those now available must therefore be developed. This is the reason why the Plataforma Solar has been working since November 2002 in the project entitled, “Cost effective solar photocatalytic technology to water decontamination and disinfection in rural areas of developing countries” (SOLWATER)”, EC-DG Research contract nº: ICA4-CT-2002-10001, under its “Confirming the International Role of Community Research for Development Program”. The PSA Solar Chemistry Group is the coordinator of this project, with European participants Ecosystem (E), Aosol (P), Complutense University of Madrid (E), National Technical Univ. of Athens (GR) and Ecole Polytechnique Federale de Lausanne (CH) and from South America, Instituto Mexicano de Tecnología del Agua, Comisión Nacional de Energía Atómica (ARG), Universidad Nacional de Ingeniería-Perú and TINEP-Mexico. Moreover, the Solar Chemistry Group participates in another European Project conceptually linked to SOLWATER, called "Detoxification of waters for their recycling and potabilisation by solar photocatalysis in semi-arid countries " (AQUACAT, ICA3-CT2002-10016) coordinated by the University of Lyon-1.

The main objective of both of these projects is the development of a stand-alone solar system for the disinfection and degradation of traces of organic pollutants in drinking water in remote locations without the use of chemical additives. The final system treats water based on photocatalytic processes activated by solar energy. Two reactor prototypes are to be obtained. One is based on the generation of hydroxyl radicals by TiO_2 fixed to an inert matrix. The other is based on the production of singlet oxygen from a photosensitizer fixed to a polymeric matrix. The prototypes obtained within the frame of the SOLWATER project will be applied in isolated areas in three very different locations in South American, Argentina, Peru and Mexico. And those obtained in the AQUACAT project will be tested in communities in the Mediterranean basin, such as Egypt, Morocco, Greece and Tunisia.

The Solar Chemistry Group has demonstrated photocatalytic degradation with TiO_2 on Ahalstrom® paper [Guillard et al., 2003ª, 2003b] of a model organic pollutant, gallic acid ((Figure 66, left), and inactivation by photocatalysis of *E.Coli* bacteria (Figure 66, right) making use of the CPC solar reactors at the Solar Chemistry facility.

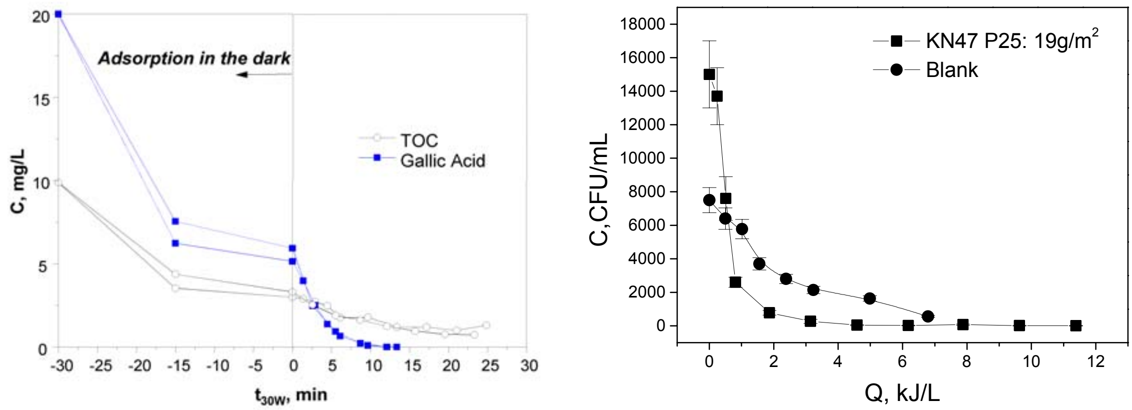


Figure 66. Left: Photocatalytic degradation of gallic acid with TiO_2 deposited on Ahlstrom type NW-10 paper (C_0= 20 mg/L). Right: Deactivation of E. Coli con TiO_2 deposited on Ahlstrom type KN-47 paper (C_0= 10^4 CFU/mL). Both carried out in a CPC solar reactor.

Furthermore, the first reactor prototype for disinfection was designed based on a fixed TiO_2 photocatalyst (Figure 67, left). This reactor provides double photocatalyst availability, concentric on the glass reactor tube itself (Figure 67, right), and a thin flat sheet inserted vertically inside the reactor tube. These reactors are to be erected and evaluated during the experimental phase of the project that will be carried out in 2004.

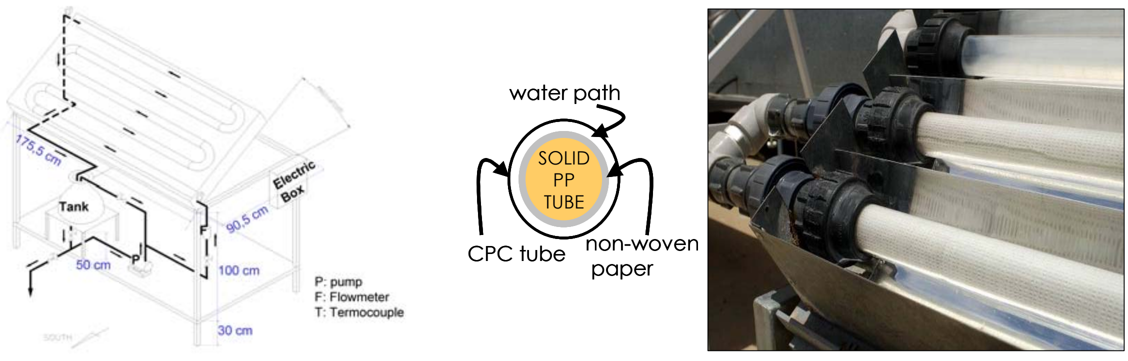


Figure 67. Photoreactor for disinfection by photocatalysis (left) and solar concentric arrangement of Ahlstrom paper with TiO_2 (right).

4) SOLAR SEAWATER DESALINATION

At the present time, the PSA Solar Chemistry Group research projects are being carried out in the field of solar seawater desalination, one Europea (AQUASOL Project: Enhanced Zero Discharge Seawater Desalination using Hybrid Solar Technology) and another national (SOLARDESAL Project: Advanced Hybrid Solar-Gas Desalination Technology with Stationary Solar Collectors).

The participants in the SOLARDESAL project are: CIEMAT (coordinator), University of la Laguna, INABENSA and ECOSYSTEM. The three-year project started in November 2001.

The AQUASOL Project participants are: CIEMAT (coordinator), INABENSA (Spain), Ao Sol Energias Renováveis (Portugal), National Technical University of Athens (), INETI (Portugal), Cajamar (Spain), Hellenic Saltworks (Greece), Comunidad de Regantes Las Cuatro Vegas de Almería (Spain) and Weir-Entropie (France). This four-year project is divided into two phases: in a first phase of research to last two and a half years and a second demonstration phase to last one year and a half. The project began in March 2002.

The goal of both projects is to develop a hybrid solar/gas seawater desalination technology based on multi-effect distillation (MED) that is energy efficient, low-cost and with no discharge.

The AQUASOL project in particular focuses on technological development of:

1) Incorporation of a high-efficiency, low-cost hybrid solar/gas energy supply with compound parabolic solar collectors (CPC).
2) Development of a double-effect absorption heat pump (LiBr/H_2O) optimized for coupling to the MED process that reduces the energy consumption by half.
3) Reduction to zero of any type of discharge from the distillation process by recovering the salt from the brine.

Figure 68 shows the configuration chosen for coupling the subsystems that make up the AQUASOL Project desalination system. Design of the subsystems (double-effect absorption heat pump, CPC solar collector field, thermal storage tanks, gas boiler and solar dryer) was completed in 2003.

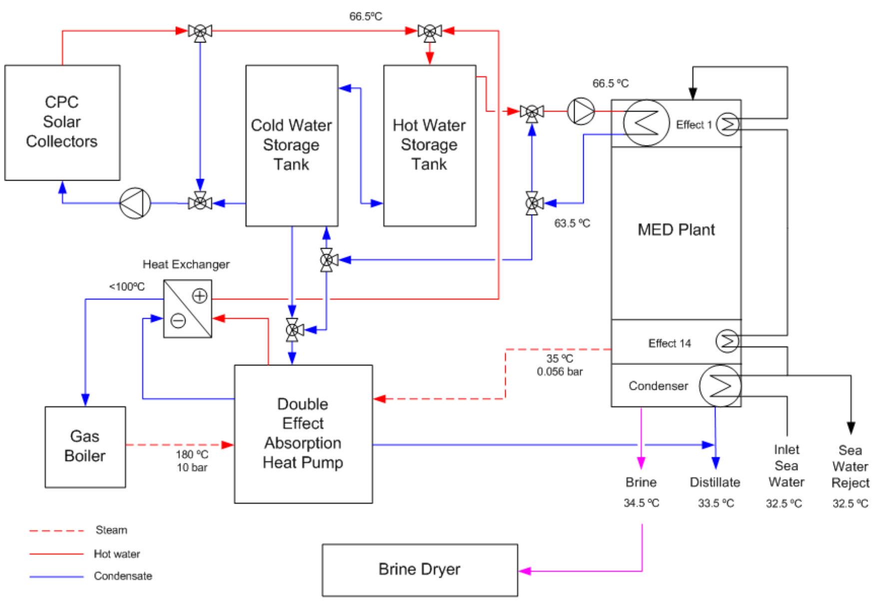


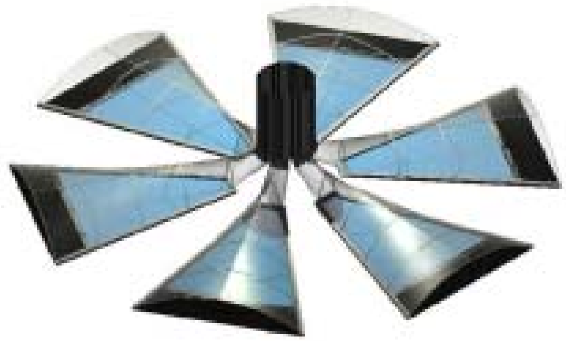
Figure 68. Final configuration of the desalination system to be erected in the AQUASOL Project.

66.5ºC water is supplied to the first effect of the MED plant directly from the storage tank, which is in turn supplied either by the solar collector field, or by the double-effect absorption heat pump. Operation at that temperature presents two clear advantages: in the first place, it considerably reduces the risk of crusting on the heat exchangers in the distillation plant, reducing the consumption of chemical additives; in the second place, the energy efficiency of the stationary solar collectors increases as the difference between the water temperature and the ambient temperature decreases. Connection in series of two storage tanks allows system controllability to be improved, as well as the temperature difference necessary for efficient operation of the heat pump.

Due to the maximum temperature limitation that can be obtained with standard CPC solar collectors, the only way the double-effect heat pump can be operated is using high–pressure steam (180ºC, 10 bar) from the gas boiler. Therefore, the plant performance factor (kg distillate produced /2300 KJ energy contributed to the process) oscillates between 10 (solar-only mode) and 20 (gas-only mode). Study of the hybrid operating modes in which the heat pump can function at a partial load (20%-100%) along with a share from the solar field is planned in this project [*Alarcón et al., 2003] [Blanco et al., 2003e]*.

The solar field is made up of 252 stationary solar collectors (CPC Ao Sol 1.12x) with a total surface area of approximately 500 m^2. The collectors are arranged in four rows of 63 collectors. In each of these rows, groups of three collectors are connected in parallel, and these in turn are connected in series to another group of three collectors. These groups of six collectors are finally connected in parallel to a general pipe for each row. The collectors are tilted 35º and oriented toward the south.

The purpose of the advanced solar dryer is to increase the concentration in the brine until it has reached the saturation point of calcium carbonate (16ºBe, Baumé scale). This drier consists of six evaporation channels with an air preheat section at the inlet, which converge on a solar chimney located in the center for exhaust by convection of air in the channels. For a first evaluation of the behavior of materials to be used in construction of the final prototype, two small prototypes with just one channel have been installed at the INETI and at the National Technical University of Athens (NTUA) (Figure 69).



Courtesy of INETI

Courtesy of NTUA

Figure 69. Design of the advanced solar dryer (left) and 1-channel prototype (right)

5) ACCESS TO THE PSA AS A LARGE EUROPEAN INSTALLATION. SOLAR CHEMISTRY ACTIVITIES

Under the European Commission's IMPROVING HUMAN POTENTIAL Program, the "Transnational Access to the Plataforma Solar de Almería: The European Solar Thermal Test Centre" project ran from February 1, 2000 to the end of 2003. This project consisted of making the Plataforma Solar de Almería available to European research groups for testing in solar energy, with consulting and cooperation by the PSA scientific staff. Solar photochemistry is one of the most successful areas in this project, with a large amount of scientific production [Gernjak y col, 2003a-e; Kositzi y col, 2003a-c; Mailhot et al., 2003; Malato et al., 2003e]. In 2003, it was broadened to include seawater desalination, converting the Solar Chemistry Group in a European reference in the field. In fact, in 2003, 15 different groups were received in 9 testing periods (4 in detoxification, 2 in Solfin and 3 in desalination), which is very similar to this project's activity in 2001.

Photocatalytic detoxification testing in 2003, basically in water decontamination, was:

1) University of Calabria / University of Palermo (Italy). *Photocatalytic treatment of effluents containing antibiotics and separation of catalyst with membranes*. In hospitals and operating rooms, a wide variety of substances are used in diagnosis and disinfec-

tion. After use, many of them are dumped with waste water. These compounds are also dumped in a similar way in veterinary medicine, stock raising and fish farms. One very typical compound is tetracycline, and many TiO_2 photocatalytic degradation tests have been carried out with it. Furthermore, this treatment has been tested coupled with a catalyst membrane separation process. (Figure 70).

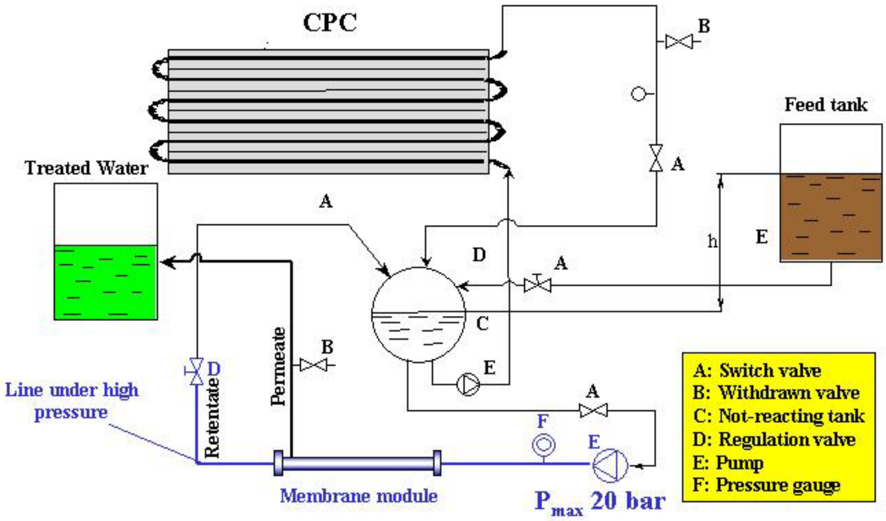


Figure 70. Conceptual diagram of the membrane system coupled to a CPC photoreactor

2) J. Heyrovský Institute of Physical Chemistry, Academy of Sciences of the Czech Republic (Czech Republic)/ Laboratoire de Photochimie Moléculaire et Macromoléculaire, UMR CNRS Université Blaise Pascal n°6505 (France). *Fe(III) and Q-TiO_2 Photocatalyst Efficiency Study*. Use of complete aqueous Fe(III) combined with TiO_2 (nanocrystalline anatase) for the elimination of monuron (pesticide). A clear synergy was observed between the two photocatalytic systems during tests carried out in the PSA CPC pilot plant, in which use of Fe(III), TiO_2 (P-25) and Q-TiO_2 alone was compared.

3) UMR 6503 CNRS "Catalysis and Organic Chemistry", University of Poitiers (France)/ Environmental Biotechnology Laboratory of the Swiss Federal Institute of Technology in Lausanne (Swiztzerland). *Degradation of model compounds by photo-Fenton with supported Fe/C and Fe/Nafion/C catalysts*. Fe catalysts supported on carbon have been tested for the degradation of orange II (dye) and gallic acid. The results were compared to those obtained by photo-Fenton in homogeneous solutions. This could be a strong advantage of the photo-Fenton process, since the pH of the water need not be reduced when Fe is supported, because it is active at neutral pH.

4) Pharmaceutical Chemistry & Medical Physics Department of The Royal College of Surgeons/ Civil, Structural & Environmental Engineering Department of The University of Dublin (Ireland). *Small-scale photocatalytic disinfection of water containing pathogens and their possible application in developing countries*. Comparison of the SODIS (Solar Disinfection) process and Solar photocatalysis in the degradation of 2-propanol and Malathion (pesticide), as well as inactivation of *E. coli*. The efficiency of borosilicate glass and PET bottles into which a piece of flexible plastic with adhered TIO_2 had been inserted was tested and this system was demonstrated to be 20%-25% more effective than the SODIS process in inactivating E. coli. This technique can be of great interest in the Third World [Duffy et al., 2003; McLoughlin O.A. et al., 2003c]. Furthermore, the efficiency of different CPC collectors was also tested for the same application. $1x10^6$CFU/ml de *E. Coli* (K-12) was deactivated in 60 minutes. (Figure 71).

Tests in the SOLFIN facility in 2003, basically for the synthesis of compounds using solar radiation, were the following.

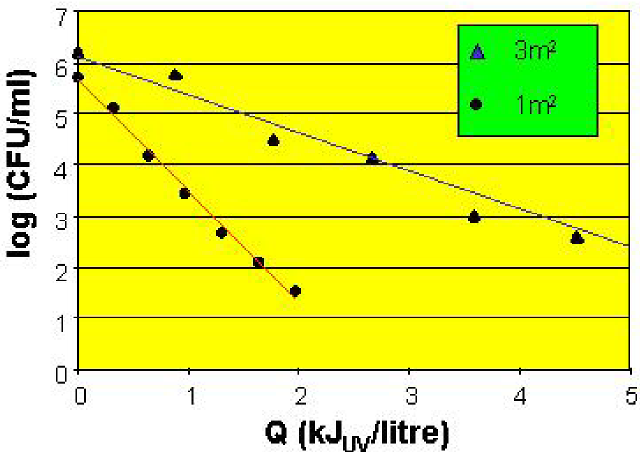


Figure 71. Inactivation of *E.coli* (log(CFU/ml)) as a function of solar UV solar collected in CPCs with 1 and 3 m² collector surfaces

1) <u>Faculty of Chemistry, Nicolaus Copernicus University, Torun, Poland.</u> *Influence of UV radiation on biomaterials derived from collagen*. The influence of UV radiation on the properties of new materials derived from synthetic and natural polymers was studied. To do this, these materials were exposed both to solar radiation and radiation from artificial light to compare both results by UV-VIS and FTIR spectroscopy. Solar UV radiation was shown to cause changes in the conformation of the collagen molecule (main component of the skin) as well as in polymers derived from it (Figure 72).

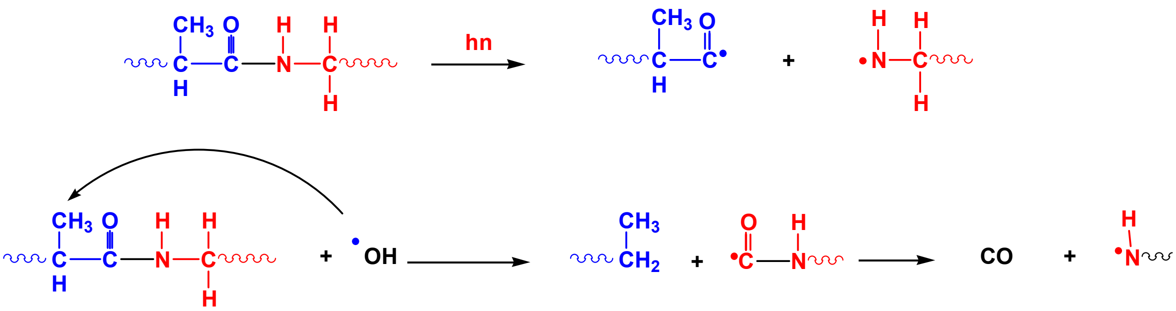


Figure 72. Possible mechanisms of transformation of collagen induced by solar radiation

2) <u>Dipartimento di Chimica dell'Università di Ferrara / ICCOM CNR, Florencia, Italia.</u> *Photochemical activation of hydrides in transition metals.* Several tests were carried out to check whether organometallic compounds such as [(triphos)RuH_2(L)] (L = CO, RCN, PR_3, AsR_3, etc) subjected to solar radiation were susceptible to photo-elimination of the H_2 molecule, giving rise to fragments that could react with organic substances. The influence of solar radiation on the reactivity of allenylidene Re complexes, such as [Re{C=C=CPh_2}CO_2(triphos)]Otf was also studied.

In 2003, activities in desalination were also carried out under the European "Improvement of Human Potential" program (IHP).

1) <u>Mechanics and Aeronautics Dept., University of Rome "La Sapienza" (Italy)</u>. Testing of the Ao Sol CPC 1.5x prototype solar collector for a TRYNSYS simulation model of it
2) <u>Dept. of Energy Supply, Univ. of Rousse/SIKA, (Bulgaria).</u> Installation and evaluation of a prototype collector the main innovation of which is the incorporation of an absorptive liquid jointly developed by this university and Bulgarian firm.
3) <u>Metallurgy and Mining Engineering Dept., National Technical University of Athens (Greece).</u> Study of the of the PSA multi-effect distillation plant operation and implementation of a code in Visual Basic to simulate stationary state behavior.

6) OTHER SOLAR CHEMISTRY ENVIRONMENTAL PROCESSES

SELECTIVE CATALYZED FUNCTIONALIZATION OF TERMINAL ACETYLENES BY MEANS OF COORDINATION COMPLEXES IN AN AQUEOUS MEDIUM

Catalysis in homogeneous media has a series of disadvantages that could be remedied if it were done in two phases (aqueous/organic). In this way, the fact that the catalyst is dissolved in water and the reaction products dissolved in the organic phase or are insoluble in water make them easily separated and recovered for their later use.

A project proposal submitted and approved by the Spanish Ministry of Science and Technology (P2000-1301) to develop and study this idea started in December of 2000. The participating groups are the Plataforma Solar de Almería, the University of Almería (coordinator), DLR-PSA and the Dept. of Organic Chemistry of the University of La Laguna.

One of the project goals is the synthesis and characterization of new water-soluble bonds as well as new allenylidene and ruthenium carbene complexes soluble in water that act as optimum catalysts in two-phase systems. Another objective proposed was the use of solar radiation as a source of energy in synthetic reactions [Mañas, 2003; Richter et al., 2003; Saoud et al., 2003]. New solar photoreactors were developed to carry out these synthetic reactions and all of the parameters (temperature, radiation, etc.) were controlled to make the system selective, economical and ecological.

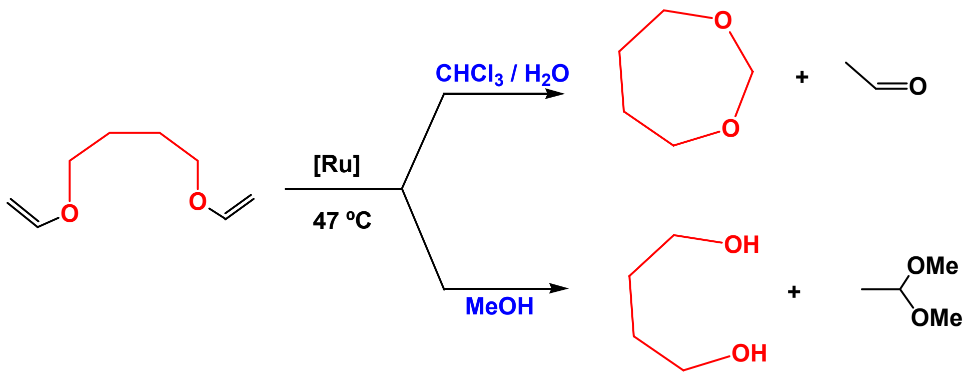


Figure 73. Selective catalytic transformation of 1,4-vinyl ester-butanediol in monophase (MeOH) and biphase ($CHCl_3$ / H_2O) media under mild conditions

An example of the processes performed is catalytic transesterification by vinyl ester Ru(II) coordination complexes soluble in water to form organic, acetal and aldehyde compounds (Figure 73). A system for photochemical synthesis of various inorganic compounds, such as those derived from phosphoric acid, using solar radiation as the energy source was also developed. Finally, how solar UV-VIS radiation influences the synthesis of organometallic compounds with thiopurine bonds, such as [RuH(PPh_3)$_3$(8-MTT-κ^2*N7O6*)], cis-[Ru(PPh_3)$_2$(8-MTT-κ^2*N7O6*)$_2$], etc., was also studied.

SOLAR ENERGY STORAGE PROCESSES WITH ENVIRONMENTAL IMPACT

In recent years, there has been an international effort in solar energy storage by photo-assisted processes, such as the growing environmental concern for anthropogenic CO_2 greenhouse gas emissions that has stimulated systematic research on CO_2 reduction in fuel production. The application of photocatalysis to selectively promote the reduction of CO_2 represents an application of great interest for the development of sustainable organic chemical compound, fuel and materials production systems as these processes would avoid the use of conventional fossil fuels and thereby, more CO_2 in the atmosphere.

First results obtained with commercial materials such as TiO_2 P-25 and laboratory preparations of TiO_2 doped with metal oxides were very promising. Modification of the catalyst by doping with ruthenium oxide was demonstrated to cause a considerable improvement in the net conversion efficiency of chemically storable solar energy. The products formed would mainly be CH_3OH, CH_3-CO-CH_3 and CH_3-CH_2OH (Figure 74).

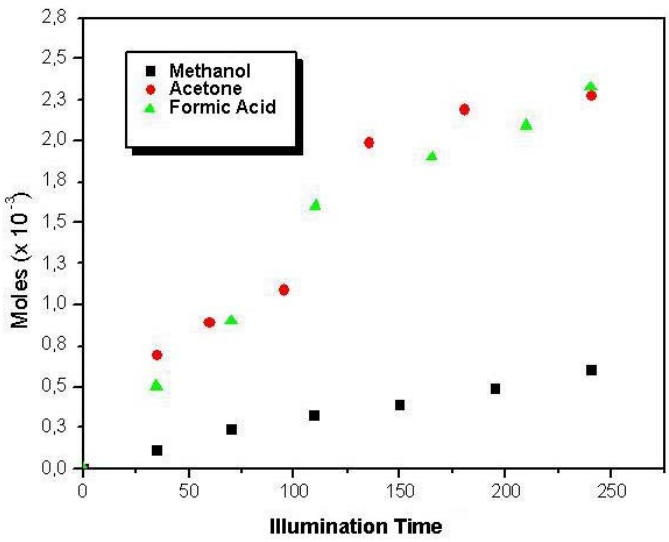


Figure 74. Formation of methanol, acetone and formic acid during the CO_2 reduction process. Experimental conditions: 100 ml/min CO_2; pH = 1; TiO_2-Ru (0.1%).

As these products could be used as fuels, the reduction of CO_2 using this type of process makes this path of the greatest interest for conversion of solar energy. Solar energy-to-chemical energy conversion performance near 5% has been achieved, a rather acceptable value considering the net efficiency of real conversion systems is not over 12-13%.

PRODUCTION OF H_2 AND SYNGAS FROM HEAVY CRUDE OIL WASTE BY SOLAR THERMOCHEMICAL PROCESSING WITH NO CO_2 GENERATION

Toward the end of 2002, an agreement was signed by CIEMAT, the Swiss Federal Institute OF Technology Zurich (Switzerland) and Petroleos de Venezuela-INTEVEP (Venezuela) for the "*Solar Termochemical Application for CO_2-Free Production of Syngas + H_2 from Heavy Crude Oil*" project.

This project, which started at the beginning of 2003, is to last 5 years and has a total estimated budget of U.S.$6.9 million. The purpose is to develop a solar technology which,

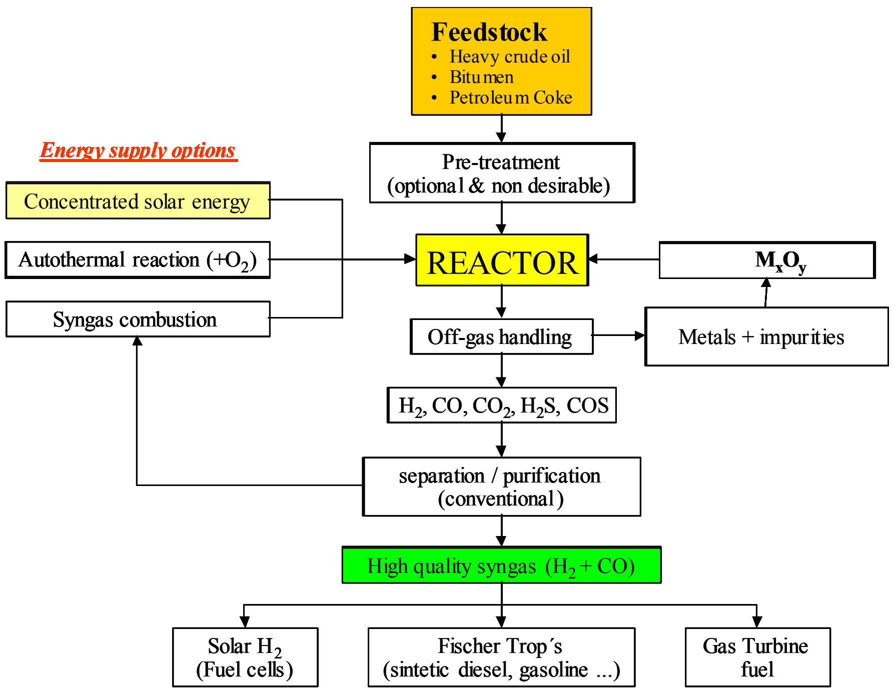
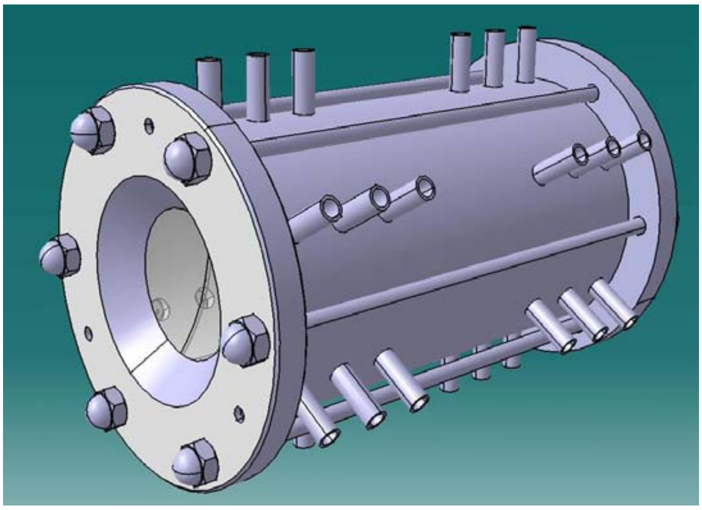


Figure 75. Flow diagram of the process to be technologically developed

based on central receiver tower systems and direct solar irradiation, will produce high-quality syngas and/or hydrogen from heavy crude oil waste by high-temperature thermo-chemical gasification.

The first phase of the project is underway, mostly at the ETH Zurich, where very promising results have been obtained in their solar simulator. Based on these experiments, design of the reactor where the process will take place in a first phase at 5 kW and later scaled up to 500 kW to demonstrate the concept at the PSA. The final phase of the project will include the feasibility analysis of the technology at a commercial scale of around 200 MWth. The process patent application has already been submitted to the U.S. Patent Office [Domingo, et al., 2003].

In 2003, the CIEMAT has focused its efforts on the study of two essential aspects of the process engineering: the analysis of fluid dynamic behavior of the solar reactor that is being designed by ETH (Figure 76) for which the FLUENT code was used (Figure 77) and in the second place, the optimization of the solar flux concentration strategy for the 500-kW pilot plant design to be tested at the PSA.



Courtesy of ETH (Zurich, Switzerland)

Figure 76. Artists view of the experimental reactor designed for the first phase (5 kW) of the project.

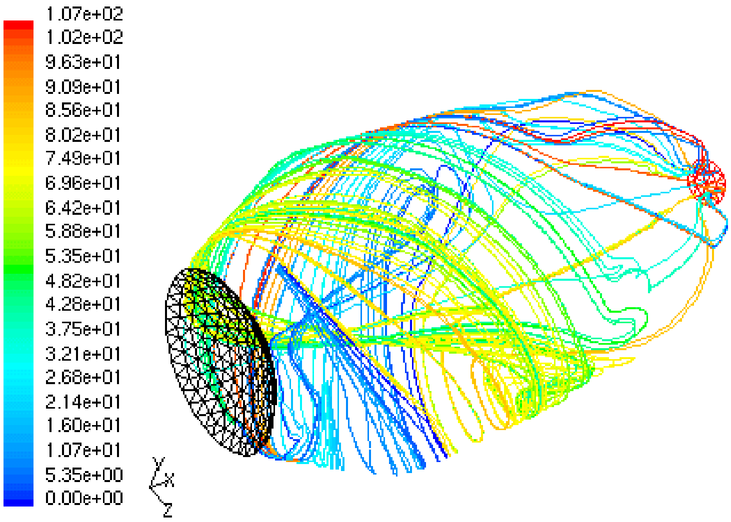


Figure 77. "FLUENT" code modeling of particle flux inside the reactor. Analysis conditions: Flux by injector = 2 Ln/min = 4.0833 x 10^{-5} kg/s Total flux = 12 Ln/min; Theoretical mean residence time = 4.72 s. Injectors = 1A, 2A,3A,4A,5A,6A; Tangential injection (a=0,ß=90)

Training and Access

The objectives of this project may be considered to be among the priority activities of CIEMAT itself. **Participation in access programs** contributes to dissemination of the possible applications of solar thermal energy among the international scientific community, so that an ever-greater number of research groups dedicate their time and resources to exploring this option.

The results thus favor penetration of the renewable energies in general, and of solar thermal energy in particular, into the industrial and economic structures of society, which is defined as one of the basic objectives of the Department of Renewable Energies.

Another no less important objective of PSA participation in access to large installations programs, is that it contributes to the optimized use of its facilities by taking advantage of otherwise idle periods in which the research infrastructure is not required for PSA projects.

The purpose of these access programs, aimed especially at benefiting young researchers, is usually the transnational movement of researchers and their **training. This is the same principle behind the Plataforma Solar de Almería's own training program**. Around thirty students of different nationalities are admitted to this program each year, thus giving new generations of professionals the experience of the Plataforma Solar in solar thermal technologies accumulated during twenty years of experimentation.

Finally, as an international "large scientific installation", the PSA assumes the following functions:

- Preparation of proposals in response to announcements or actions that concern the center as a large scientific installation
- Quality Management of technical and scientific services, including both to users or third party customers and the center's services to CIEMAT's own projects
- Public awareness activities

'IMPROVING HUMAN POTENTIAL' (IHP) PROGRAM ACTIVITIES

The 'Improving Human Research Potential' Program (IHP) is a concerted activity of the European Commission Directorate General for Science, Research and Technology Devel-

Figure 78. IHP Users Meeting at the PSA

opment (DG-RTD). Its main objective is to give the European scientific community an opportunity to use any large research infrastructure, in whatever member country it may be located.

Given that one of the general objectives of the CIEMAT and of the PSA in particular, is to contribute to spreading knowledge on the possible applications of solar thermal energy, this program is an excellent tool for that purpose.

Therefore, the PSA has been participating almost without interruption in the successive research and technology development programs that can generically be called ‘Access to Large Scale Installations’ promoted by the DG-RTD since 1990.

Participation in the IHP program is for two years from March 2002 to February 2004. The PSA offers eight facilities for access and 18 research groups will have been received in them by the end of the two-year period.

As the first activity of the year, the independent expert User Selection Panel met at CIEMAT-Moncloa on February 11, 2003, selecting a total of 18 research groups from other European countries to be awarded free access to the PSA’s test facilities during the year.

All the groups selected were then invited to a first meeting at the PSA to present the IHP program and the test facilities on March 10th.

THE ‘EUROCARE’ SCIENTIFIC INFRASTRUCTURES NETWORK

In its desire to advance toward the unification of efforts and optimization of resources dedicated to research, the European Commission is promoting a series of infrastructure networks grouped by subject matter. The Psa is part of the ‘EuroCARE’ network with those centers that study energy.

Apart from the PSA, other members of EuroCARE’ are:

- University of Whales-Cardiff (coordinator-United Kingdom)
- ENEL Produzione (Italy)
- International Flame Research Foundation (Netherlands)
- Federation of Aerothermodynamics and Propulsion Studies (France)
- Institute des Materiaux et Procedes (France).

This is also a horizontal IHP program and within it, the tasks are structured around three study panels:

- First: Measurement and diagnostic techniques in high-temperature processes.
- Second: Future research requirements. This is an especially interesting task, since the final document will be sent to the European Commission for its consideration when it is preparing the basic outline of the 6th Framework Program for Community research and technological development.
- Third: Industrial training in the context of large installations.

Figure 79. www.euro-energy.net

The meetings are held twice yearly, and this year, for various different reasons, both meetings were held in Velsen Noord (NL) in February and June.

The network has a website where it publicizes the contents of the study panels and the opportunities related to the access programs carried out by each of the participants. This page may be visited at www.euro-energy.net.

EuroCARE’s 6th Framework Program objective includes the expansion of its activities, by including new members and cooperating in depth on common subjects of research.

TRAINING ACTIVITIES

The European Commission DG RTD's access programs normally have as their argument the transnational mobility of researchers and their training, with special emphasis on young researchers.

This is also the principle governing the **Plataforma Solar's own training program**. Through this program, around thirty students of different nationalities are admitted every year, thus contributing to the transmitting to new generations of graduates, the knowledge on solar thermal technology accumulated at the Plataforma Solar de Almería during twenty years of experimentation.

As our goal within this project, we intend to continue with this activity and even reinforce it if possible. Such training activities are also CIEMAT priorities.

Training program activities consisted of:

- Management of the grants given by annual agreement with the University of Almería (UAL).
- Management of the 'Leonardo da Vinci' agreement grants.
- Management of several specific educational collaboration agreements with other centers to accept students at the PSA.

In 2004 it is expected that the agreement with UAL for PSA grant management and also the 'Leonardo da Vinci' program for foreign students will be renewed.

TESTING IN THE SOLAR FURNACE

In 2003, the solar furnace was devoted mainly to materials testing under the EC 5th Framework Programme, Improvement of Human Potential (IHP), and also continued testing in the PSA Materials Group's own line of research.

The PSA Materials Group, in collaboration with researchers from the Ceramic Materials Department of the Electric Industry Research Institute (ARI) of Bucharest (Romania) and researchers from the Austrian Research Center (ARC) in Seibersdorf in association with the Technical University of Riga (RTU), tested samples in the MiniVac (Mini Vacuum Chamber) in controlled argon atmospheres for the ARI Institute of Bucharest and in a nitrogen atmosphere for the ARC Seibersdorf, on both horizontal and vertical planes. The PSA is working on its own line of research based on thermal treatment of steel powder metallurgy samples, foaming of aluminum samples and sintering of copper wire bundles.

The **ARI Institute of Bucharest** is studying the effect of the Zircon content (+CaO o +MgO) on the temperature, sintering times, density and mechanical resistance of alumina-zirconia composites. These materials are pre-sintered in an electric furnace at different temperatures and then exposed to temperatures of around 200°C in the solar furnace. Afterward, the results obtained are compared with those obtained under similar conditions in a conventional electric furnace. The very high temperatures reached in the solar furnace make it an ideal tool for sintering these composites, as sintering is more complete.For the high temperatures foreseen, Type C thermocouples (5%W-Re / 26%W-Re), which have a range of up to 2200°C, and wolfram and molybdene cresols had to be used.

The main problem that came up in these tests was the strong reaction in the MiniVac between the materials inside it, which caused a large amount of smoke and prevented a large part of the energy in the focus from reaching the samples, so that the 2000°C target temperature could not be reached. Support rods and insulating wolfram and molybdene shields will be used in following campaigns to avoid the use of other insulating materials such as graphite, porous alumina or zirconia fabric that could react with the molybdene in the thermocouple cover.

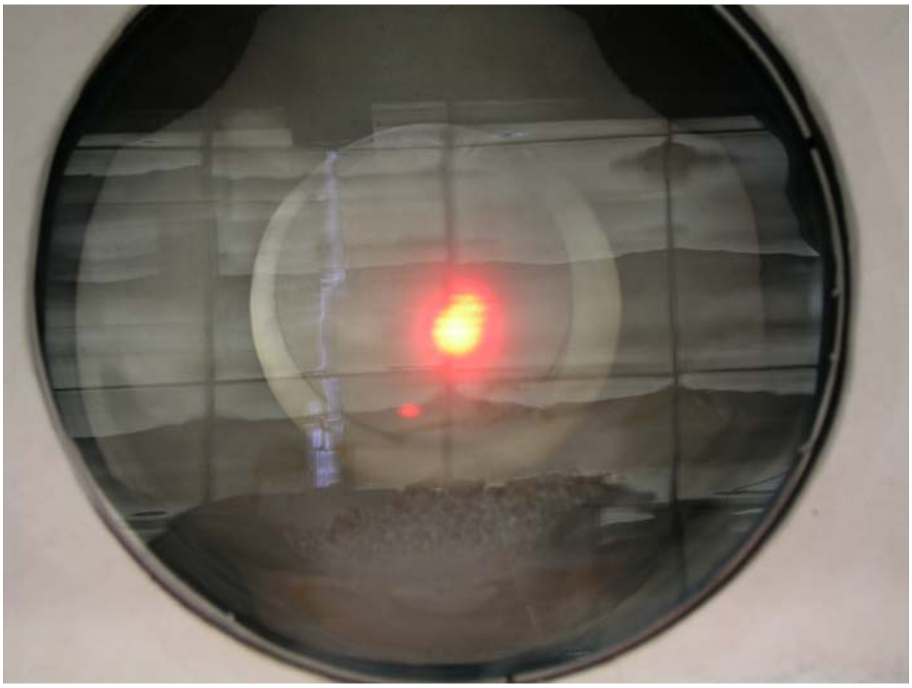


Figure 80. Test crucible in the MiniVac

The testing carried out by the **ARC Research Center Seibersdorf** of Austria in collaboration with the **Technical University of Riga** is for the development of nanostructural materials – materials with a grain size of less than 100 nm. The fabrication of these materials includes the following critical steps: preparation of the nanopowder, its deagglomeration and stabilization, densification and sintering.

The nanopowders from which the nanomaterials are obtained are highly reactive, so the traditional methods of compacting (sintering, hot pressing, gas pressure sintering or hot isostatic pressing) cause the grain to swell, producing a material with a thick grain structure. Fast high-energy thermal treatment must be used to develop this type of materials, so the solar furnace, given its characteristics is the best facility for these treatments.

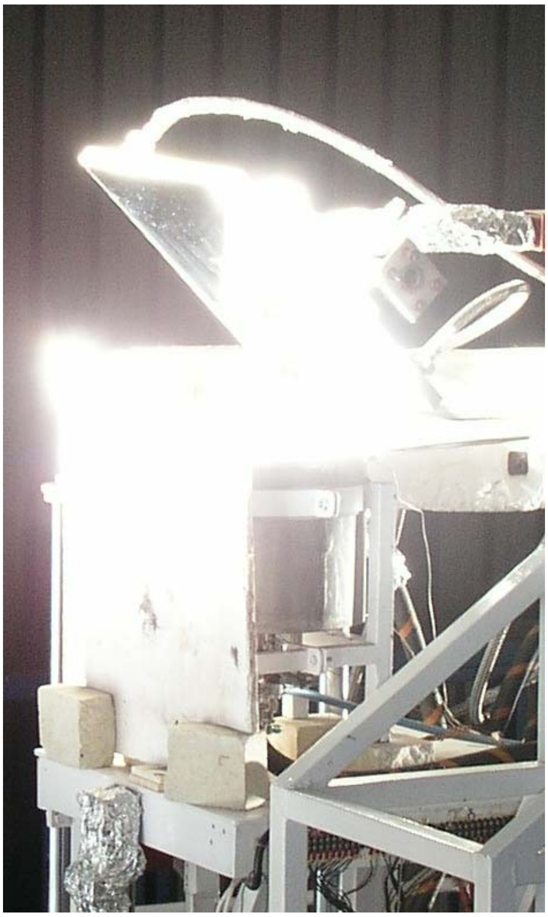


Figure 81. Tilted mirror and MiniVac during testing

The ARC Seibersdorf along with the Institute of Inorganic Chemistry of Riga, is studying the possibilities of using alternative methods of sintering for the development of different types of nanostructural materials, and are also comparing these possibilities with the traditional sintering methods. The basic compounds for research are Al_2O_3, TiO_2, ZrO_2 TiCN, Cu and Si_3N_4 powders with different sintering additives.

Testing coincided with the startup of the new GM-140 heliostat that has replaced the four former MBB heliostats, so only a few tests could be carried out and the rest of the tests planned for 2003 had to be left for a future campaign.

THE PSA MATERIALS GROUP

The PSA Materials Group is involved in different lines of research based on the application of concentrated solar energy to powder metallurgic processes. The particular conditions of sintering metal particles that must be done at high temperatures and in controlled atmospheres or in vacuum, can be obtained in solar furnaces since these facilities are designed to reach very high energy concentrations and temperatures, admitting the use of vacuum chambers with gas preparation systems.

In this sense collaborations have been established with different universities to advance in the application of concentrated solar energy to this type of processes, with particular emphasis on the advantages that solar furnaces have over conventional furnaces, since the application of this renewable thermal energy to thermal treatment processes, in addition to not requiring transformation, provides controlled high energy flux densities over a wide spectrum of wavelengths, reaching very high-speed irradiation and temperatures up to 3500°C.

At the present time there are three lines of research open: *Sintering of copper in solar furnace* in collaboration with the Department of Mechanical Engineering and Materials at the School of Industrial Engineering of the University of Seville and *Structural study of powder metallurgical steels after their thermal treatment in solar furnace* and *Aluminum foaming by concentrated solar energy*, both in collaboration with the Department of Materials Engineering of the School of Mining Engineering of the Polytechnic University of Madrid.

Throughout 2003, in the solar furnace there have been several different test campaigns for each one of these lines of work, obtaining satisfactory results and showing in all of them the feasibility of the processes.

References and Documentation

[1] Agüera A., Fernández-Alba A.R., Piedra L., Mézcua M., Hernando D., Malato S., Cáceres J.. Use of Chemical and Biological techniques in the Evaluation of Pesticide degradation by Solar Photocatalytic processes. *7th Int. Conf. Solar Energy Storage and Applied Photochemistry 4th Int. Workshop on Environmental Photo*chemistry. Luxor, Egypt, February 23 – 28, 2003. *Book of abstracts*, Poster 6. 2003.

[2] Alarcón D., Blanco J., Malato S., Maldonado M.I., Sánchez, B., Solar thermal seawater distillation activities at the Plataforma Solar de Almería: Increasing the thermo-economic process efficiency. Proceedings of the *4th European Congress in Chemical Engineering*. September 21-25, 2003. Granada, 2003.

[3] Ballestrín J., S. Ulmer, A. Morales, A. Barnes, L.W. Langley, M. Rodríguez (2003) "Systematic error in the measurement of very high solar irradiance", Solar Energy Materials & Solar Cells 80, 375–381.

[4] Blanco Gálvez J., Malato Rodríguez S. *Solar Detoxification*. UNESCO Publishing, France. ISBN 92-3-103916-4. 190 pag. 2003a.

[5] Blanco J. "Energia solar y tecnologias del agua". In "Seminario internacional sobre tecnologías económicas para la descontaminación y desinfección de agua" of the "*X Seminario Peruano de Energía Solar*", Cusco, November. 17 – 22, 2003. Oral communication. 2003b.

[6] Blanco J. "Energía solar y tecnologías del agua". *International Workshop Nuevas tecnologías para la desinfección y descontaminación del agua* organized by IPEN, Lima, November 14, 2003. Oral communication. 2003c.

[7] Blanco J. Desarrollo de colectores solares CPC para aplicaiones fotoquímicas de degradación de contaminantes en agua". Editorial CIEMAT, España. ISBN: 84-7834-442-X. 277 pag. 2003f.

[8] Blanco J., Malato S., Vidal A., Cardona A. I., Alarcón, D., Cáceres, J., Maldonado, M. I., Applied Studies in Solar Photocatalytic Detoxification: an Overview. *ISES Solar World Congress* 2003, Göteborg, Sweden, 14-19 June 2003. Book of abstracts, Oral 05-42. 2003d.

[9] Blanco J.; Hublitz A.; Alarcón D.; Sánchez B.; Malato S. Techno-economical comparison of different solar-assisted heat supply systems for a seawater multi-effect distillation unit. *Proceedings of the ISES Solar World Congress* 2003. June 14-19, 2003. Göteborg, Sweden. 2003e.

[10] Cáceres J., Malato S., Fernández-Alba A.R. Evaluación analítica y optimización de procesos de oxidación avanzada en planta piloto solar. Editorial CIEMAT, Madrid, ISBN 84-7834-436-5. 336 pp. 2003.

[11] Chen, J.C. Correlation for Boiling Heat Transfer to Saturated Liquids in Convective Flow. *Ind. Eng. Chem. Process Design and Develop,* Vol. 5, Nº 3, 1966: pp. 322-339.

[12] Domingo Rodriguez, P., Morales A., (PDVSA-INTEVEP), Blanco, J., Romero, M. (CIEMAT), Steinfeld, A. (ETH). Process for the conversion of heavy crude oils and petroleum coke to syngas and hydrogen using an external source of radiation. Registro No. 60/508,064 de la Oficina de patentes de Estados Unidos (01-10-2003).

[13] Duffy E.F., F. Al Touati, S.C. Kehoe, O.A. McLoughlin, L.W. Gill, W. Gernjak, I. Oller, M.I. Maldonado, S. Malato, J. Cassidy, R.H. Reed, K.G. McGuigan. A novel TiO2-assisted solar photocatalytic batch-process disinfection reactor for the treatment of biological and chemical contaminants in domestic drinking water in developing countries. Submitted, *Solar Energy*. 2003.

[14] Farré M.J., Maria Isabel Franch, Sixto Malato, José Antonio Ayllón, José Peral and Xavier Domènech. Degradation of some biorecalcitrant pesticides by Homogeneous and Heterogeneous Photocatalytic Ozonation. Submitted to *Chemosphere*. 2003.

[15] Fernández J. (2003). "Análisis estadístico de la reflectividad de un campo de helióstatos. Aplicación al campo de helióstatos CRS de la Plataforma Solar de Almería". Informes Técnicos CIEMAT- 1023. Sept. 2003. Ed. CIEMAT.ISSN: 1135-9420.

[16] Fernández, P. "Procesos de Fotocatálisis Solar para la Detoxificacion y Descontaminación de Aguas". International Workshop on "Nuevas tecnologías para la desinfección y descontaminación del agua" organized by IPEN, Lima, Nov. 14, 2003. Oral communication. 2003a.

[17] Fernández P. "Procesos de Fotocatálisis Solar para la Detoxificacion y Descontaminación de Aguas". En "Seminario internacional sobre tecnologías económicas para la descontaminación y desinfección de agua" X *Seminario Peruano de Energía Solar*, Cusco, Nov. 17 – 22, 2003. Oral communication. 2003b.

[18] Fernández-Ibáñez P., Blanco, J., Malato, S., de las Nieves, F. J., Application of the colloidal stability of TiO2 particles for recovery and reuse in solar photocatalysis. *Wat. Res*., 37, 3180-3188, 2003c.

[19] García G., "First Autonomous Heliostats Field, PCHA project", Proceedings of SolarPaces Tasks Meetings, Göteborg, Sweden, June 17, 2003. Eds. M. Romero, A. Steinfeld and V. Quaschning. Pub. CIEMAT. ISBN: 84-7834-455-1.

[20] García G., A. Egea. M. Romero, "First Autonomous Heliostat field. PCHA project", ISES SOLAR WORLD CONGRESS 2003, June 14-19, 2003 Göteborg, Sweden. ISBN: 91-631-4740-8

[21] Gernjak W., Axel Mentler, Raquel Rodríguez, Maria Fürhacker, Sixto Malato. Photo-Fenton treatment of a pesticide mixture simulating real wastewater and 4-nonylphenol. In: The Improving Human Potential Programme. Research Results at Plataforma Solar de Almería within the Year 2002 Access Campaign. CIEMAT, ISBN 84-7834-446-2. pp. 43-50, 2003a.

[22] Gernjak W., M. Fürhacker, M.I. Maldonado, I. Oller, L. Yebra and S. Malato. Systematic investigation of the photo-fenton method at pilot plant scale. 3rd Scientific Meeting of the Spanish Society of Chromatography and Related Techniques. 3rd Waste Water Cluster (WWC) European Workshop. Almería, Spain. 19-21 November 2003. Book of Abstracts, OP-12. 2003b.

[23] Gernjak W., M.I. Maldonado, S. Malato, J. Cáceres, T. Krutzler, A. Glaser and R. Bauer. Degradation of polyphenolic content of Olive Mill Wastewater (OMW) by solar photocatalysis. IWA 3rd Conference on Oxidation Technologies for Water and Wastewater Treatment Germany, Goslar 18- 22 May 2003. A. Vogelpohl (Ed.), pp. 879-884. 2003c.

[24] Gernjak W., M.I. Maldonado, S. Malato, J. Cáceres, T. Krutzler, A. Glaser and R. Bauer. Pilot-Plant treatment of Olive Mill Wastewater (OMW) by solar photocatalysis and solar photo-Fenton method. Submitted, Solar Energy. 2003d.

[25] Gernjak, W., Krutzler, T. Glaser, A., Malato, S., Cáceres, J., Bauer, R., Fernández-Alba, A. R., Photo-Fenton treatment of water containing natural phenolic pollutants. *Chemosphere*, 50, 71-78, 2003e.

[26] Goebel, O. Wärmeübergang in Absorberrohrenn von Parabolrinnen-Solarkraftwerken. Stuttgart, *VDI-Fortschrittsberichte*, Sección 6 (Energietechnik), Nº. 402. ISBN: 3-18-340206-8.

[27] Goebel, O.; Hennecke, K. Investigation of thermohydraulics in a parabolic trough absorber tube with direct steam generation (DSG). *In* BECKER, M. and BÖHMER, M. *eds.* Proceedings of 8th International Symposium on Solar Thermal Concentrating Technologies celebrado en Colonia (Alemania) del 7 al 11 de octubre de 1996. C.F. Müller Verlag, Heidelberg, Alemania 1997: pp. 787-814. ISBN 3-7880-7616-X.

[28] González, L. "Manual *de "Dimensionado Planta-DSG*". Herramienta para el diseño de plantas de colectores solares cilindro parabólicos con Generación Directa de Vapor".Informe técnico INDITEP-SC-SF-01. Plataforma Solar de Almería, May 2003.

[29] Guillard Ch., J. Disdier, Ch. Monnet, J. Dussaud, S. Malato, J. Blanco, M. I. Maldonado, J.M. Herrmann. Solar efficiency of a new deposited titania photocatalyst: chlorophenol, pesticide and dye removal applications. Appl. Catal. B: Environ., 46, 319-332. 2003a.

[30] Guillard Ch., Disdier, J. Herrmann, J.-M., Monnet, C., Dussaud, J., Malato S., and Blanco, J., Solar efficiency of a photocatalytic nonwoven: dye removal applications. In: *The Improving Human Potential Programme. Research Results at Plataforma Solar de Almería within the Year 2002 Access Campaign*. CIEMAT, ISBN 84-7834-446-2. pp. 59-66, 2003b.

[31] Gungor, K.E.; Winterton, R.H.S. A General Correlation for Flow Boiling in Tubes and Annuli. *International Journal of Heat and Mass Transfer*, Vol.29, No. 3, 1986: pp. 351–358.

[32] Hoffschmidt B., Téllez F., Valverde A., Fernández J., Fernández V. (2003), "Performance evaluation of the 200-kWth HiTRec-II Open Volumetric Air Receiver". Int. J. of Solar Energy Engineering 25, 87-94.

[33] Kandlikar, S.G. A General Correlation for Saturated Two-Phase Flow Boiling Heat Transfer Incide Horizontal and Vertical Tubes. *Journal of Heat Transfer*, Vol. 112, 1990, pp: 219-228

[34] Koehler, W.; Herbst, O.; Kastner, W. Thermal design of solar absorber tubes with direct steam generation. *In* Becker, M. and Böhmer, M. *eds.* Proceedings of 8th International Symposium on Solar Thermal Concentrating Technologies held in Cologne, October 7 – 11, 1996. C.F. Müller Verlag, Heidelberg, 1997: pp. 767-786. ISBN 3-7880-7616-X.

[35] Kositzi M., A. Antoniadi, I. Poulios, I. Kiridis, S. Malato. Solar photocatalytic treatment of simulated dyestuff effluents. In: The Improving Human Potential Programme. Research Results at Plataforma Solar de Almería within the Year 2002 Access Campaign. CIEMAT, ISBN 84-7834-446-2. pp. 67-74, 2003a.

[36] Kositzi M., A. Antoniadis, I. Poulios , I. Kiridis , S. Malato. Solar Photocatalytic Treatment of Simulated Dyestuff Effluents. Submitted, Solar Energy.2003b.

[37] Kositzi M., I. Poulios, S. Malato, J. Caceres, A. Campos. Solar Photocatalytic Treatment of Synthetic Municipal Wastewater. Water research, in press, 2003c.

[38] Mailhot G., J.Cáceres, S. Malato and M. Bolte. Fe(III) solar light induced degradation of Diethylphthalate (DEP) in aqueous solution. In: The Improving Human Potential Programme. Research Results at Plataforma Solar de Almería within the Year 2002 Access Campaign. CIEMAT, ISBN 84-7834-446-2. pp. 35-42, 2003.

[39] Malato Rodríguez S., Blanco Gálvez, J., Fernández Ibáñez, P., Alarcón Padilla, D., Collares Pereira, M., Farinha Mendes J. and Correia de Oliveira, J., Engineering of Solar Photocatalytic Collectors. Submitted, Solar Energy. 2003a.

[40] Malato S., A. Agüera. Detoxification of pesticides in water using solar photocatalysis. In: Pesticide decontamination and detoxification. ACS Symposium Series 863. Jay J. Gan, Peter C. Zhu, Steven D. Aust, Ann T. Lemley (eds.). Am. Chem. Soc., Washington D.C., USA. ISBN-0-8412-3847-2. pp. 113-126, 2003b.

[41] Malato S., Albanis T., Piedra L., Agüera A., Hernando D., Amadeo Fernández-Alba. LC-MS and LC-MS/MS strategies for the evaluation of pesticide intermediates formed by degradative processes. photo-Fenton degradation of diuron. In: Liquid Chromatography/mass Spectrometry, MS/MS and Time-of-flight MS. ACS Symposium Series 850. I. Ferrer and E.M. Thurman (eds.). Am. Chem. Soc., Washington DC, USA. ISBN 0-8412-3825-1. pp. 66-95. 2003c.

[42] Malato S., Cáceres J., Fernández-Alba A. R., Piedra L., Hernando M. D., Agüera A., Vial J.. Photocatalytic treatment of diuron by solar photocatalysis: evaluation of main intermediates and toxicity. Env. Sci. Technol., 37, 2516-2524, 2003d.

[43] Malato S., J. Blanco, A. Campos, J. Cáceres, C. Guillard, J.M. Herrmann and A. R. Fernández-Alba. Effect of operating parameters on the testing of new industrial titania catalysts at solar pilot plant scale. Appl. Catal. B: Environ., 42, 349-357. 2003e.

[44] Malato S., J. Blanco, A. Vidal, D. Alarcón, J. Cáceres, M. I. Maldonado. Photocatalysis in Plataforma Solar de Almería: applied studies in environmental detoxification. 7th Int. Conf. Solar Energy Storage and Applied Photochemistry 4th Int. Workshop on Environmental Photochemistry. Luxor, Egypt, February 23 – 28, 2003. Book of abstracts, Oral presentation. 2003f.

[45] Malato S., J. Blanco, M. I. Maldonado, I. Oller, W. Gernjak, D. Alarcón, P. Fernández. Solar advanced oxidation processes applied to wastewater treatment. A step forward: CADOX project. 3rd Scientific Meeting of the Spanish Society of Chromatography and Related Techniques. 3rd Waste Water Cluster (WWC) European Workshop. Almería, Spain. 19-21 November 2003. Book of Abstracts, IL-7. 2003g.

[46] Malato S., M. I. Maldonado, J. Blanco, J. Cáceres, W. Gernjak, and D. C. Alarcón. Photocatalytic water treatment: practical applications with solar energy. IWA 3rd Conference on Oxidation Technologies for Water and Wastewater Treatment Germany, Goslar 18- May 22, 2003. A. Vogelpohl (Ed.), pp. 221-226. 2003h.

[47] Malato S., J. Blanco, A. Vidal, D. Alarcón, M. I. Maldonado, J. Cáceres, W. Gernjak. Applied studies in solar photocatalytic detoxification: an overview. Solar Energy, 75, 329-336, 2003i.

[48] Maldonado M. I., I. Oller, S. Malato, W. Gernjak, J. Blanco, D. Alarcón, P. Fernández. A coupled advanced oxidation-biological process for reciclyng of industrial wastewater containing persistent organic contaminants. Results of photo-Fenton preliminary experiments. 3rd Scientific Meeting of the Spanish Society of Chromatography and Related Techniques. 3rd Waste Water Cluster (WWC) European Workshop. Almería. 19-21 November 2003. Book of Abstracts, P-56. 2003a.

[49] Maldonado Rubio M.I., S. Malato Rodríguez, J. Blanco Gálvez, D. Alarcón Padilla, W. Gernjak, Wastewater treatment by solar photocatalysis: an overview. I Jornadas Ibéricas de Fotoquímica. Santiago de Compostela, 18-20 Septiembre 2003. Libro de Resúmenes. Comunicación C-24, pg. 58. 2003b.

[50] Mañas S. Estudio de la Reactividad de Fósforo Blanco y Metales de Transición. Doctoral dissertation, 2003.

[51] McLoughlin O.A., P. Fernandez, W.Gernjak, S.Malato, L.W.Gill. Feasibility of solar disinfection of water using low cost compound parabolic collectors. 3rd Scientific Meeting of the Spanish Society of Chromatography and Related Techniques. 3rd Waste Water Cluster (WWC) European Workshop. Almería, Spain. 19-21 November 2003. Book of Abstracts, P-60. 2003a.

[52] McLoughlin O.A., P. Fernandez, W.Gernjak, S.Malato, L.W.Gill. Photocatalytic Disinfection of Water Using Low Cost Compound Parabolic Collectors. Submitted, Solar Energy. 2003b.

[53] McLoughlin O.A., S.C.Kehoe, K.G.McGuigan, E.F. Duffy, F. Al Touati, W.Gernjak, I. Oller, S.Malato, L.W. Gill. Solar Disinfection of Contaminated Water: a Comparison of Three Small-Scale Reactors. Submitted, Solar Energy. 2003c,

[54] Monterreal R. and Gimenez A. (2003). "Search for a Real Model of Heliostat Optics Using Genetic Algorithms". Proc. ISES Solar World Congress, Göteborg, Sweden, June 2003. ISBN: 91-631-4740-8

[55] Monterreal R., "The solar diameter as a calibration source for a proper CCD camera image scale", Proceedings of SolarPaces Tasks Meetings, Göteborg, Sweden, June 17,2003. Eds. M. Romero, A. Steinfeld and V. Quaschning. Pub. CIEMAT. ISBN: 84-7834-455-1.

[56] Palero S., Romero M., Estrada C., Castillo J.L. (2003), "Experimental investigation in small scale volumetric solar receivers to study the mass flow instability and its comparison to theoretical models". Proc. ISES Solar World Congress, Göteborg, Sweden, June 2003. ISBN: 91-631-4740-8

[57] Richter C., A. Romerosa, S. Mañas, M. Peruzzini, S. Malato. Photochemical Oxidation of P4 to Obtain phosphorus Derivates. 7th Int. Conf. Solar Energy Storage and Applied Photochemistry 4th Int. Workshop on Environmental Photochemistry. Luxor, Egypt, February 23 – 28, 2003. Book of abstracts, Poster 67. 2003.

[58] Rodríguez M., Sixto Malato, Jaime Giménez, David Curcó, Cesar Pulgarin and Santiago Espulgas. Mineralization of phenol by means of solar photo-Fenton treatment: influence of different types of reactors. 4th European Congress of Chemical Engineering. Granada, 21-25 September 2003. Book of Abstracts 4, P-4.3-081. 2003.

[59] Romero M. (2003). "Hybrid CSP systems as an intermediate step from fossil fuels to solar". Proceedings of International Forum for Technology on Heavy and Extra-Heavy Crude Oils. 21st Century Vision. Oct. 09-11, Puerto la Cruz (Venezuela). Ed. PDVSA. Oct. 2003.

[60] Romero M., "Task I working group", Proceedings of SolarPaces Tasks Meetings, Göteborg, Sweden, June 17, 2003. Eds. M. Romero, A. Steinfeld and V. Quaschning. Pub. CIEMAT. ISBN: 84-7834-455-1.

[61] Romero M., Buck R., Pacheco J.E. (2002), "An Update on Solar Central Receiver Systems, Projects, and Technologies.", Int. J. Solar Energy Eng., Vol. 124, pp. 98-108.

[62] Romero M., Zarza E. (2003). "Desarrollo tecnológico e implantación de las centrales eléctricas termosolares en España". *Energía. 168, 60-66.*

[63] Sánchez M., Romero M. (2003), "Optimisation of heliostat field layout in central receiver systems based in yearly normalized energy surfaces". Proc. ISES Solar World Congress, Göteborg, Sweden, June 2003. ISBN: 91-631-4740-8

[64] Sánchez, B., Candal, R., Cardona, A., Ávila, P., Rebollar, M., "Photocatalytic oxidation of chlorinated hydrocarbons with TiO_2 on magnesium silicate monoliths". 18^{th} North American Catalysis Society Meeting. June 1-6, 2003. Cancún, México

[65] Saoud M., Antonio Romerosa, Sonia Mañas Carpio, Luca Gonsalvi, and Maurizio Peruzzini. Eur. J. Inorg. Chem, 2003, 1614-1619. 2003.

[66] Shah, M. A new correlation for heat transfer during boiling flow through pipes. *Transactions of the American Society of Heating, Refrigerating and Air-Conditioning Engineers*. *(ASHRAE),* Vol. 82, 1976: pp. 66-86.

[67] Sugarmen C., Ring A., Buck R., Heller P., Schwarzbözl P., Tellez F., Marcos M. J., Enrile J., Solar-Hybrid Gas Turbine Power Plants – Test Results and Market Perspective. Proc. ISES Solar World Congress, Göteborg, Sweden, June 2003. ISBN: 91-631-4740-8

[68] Téllez F. (2003), "Thermal performance evaluation of the 200kWth Solair Volumetric Solar Receiver". Informes técnicos CIEMAT-1024. Ed. CIEMAT. Madrid. Sept. 2003. ISSN: 1135-9420.

[69] Valenzuela, L., Berenguel, M., Zarza, E., Camacho, E.F., Control schemes for direct steam generation in parabolic solar collectors under recirculation operation mode. Sent to Solar Energy for possible publication, 2003.

[70] Valenzuela, L., Zarza, E., Berenguel, M., Camacho, E.F., Control concepts for direct steam generation process in parabolic troughs. ISES Solar World Congress, Göteborg, Sweden, June 2003.

[71] Valenzuela, L., Zarza, E., Berenguel, M., Camacho, E.F., Feedforward control for a once through solar boiler. IEEE Control System Magazine, 2003, in printing.

[72] Valera P., A. Esteban, M. Carrillo, R. Osuna, P. Menna, R. Gambi, P. Helm, M. Grottke, M. Geyer, F. Dobón, J. Monedero, A. Lugo, M. Romero, F. Chenlo, M. Alonso, M. Sánchez, J. Artigas, A. Fresneda (2003) "SOLAR ENERGY: Comparative analysis of solar technologies for electricity production". Proceedings World Conference on Photovoltaic Energy Conversion - WCPEC-3, Osaka, Japón, May 11-18, 2003

[73] Zarza, E. "Generación Directa de Vapor con Colectores Solares Cilindr Parabólicos. Proyecto DISS". Doctoral dissertation presented at E.S.I.I., Seville. November 2003.

[74] Zarza, E.; Sánchez, R, Influencia de la posición que ocupan las Secciones Transversales de Ensayos (S.T.E.) de los colectores DISS con respecto a los espejos reflectores. Informe técnico DISS-SC-SF-31. Almería, Plataforma Solar de Almería. November, 2002.

List of Acronyms

ANSI	American National Standards Institute (USA)
ASME	American Society of Mechanical Engineers (USA)
AOP	advanced oxidation process
ARI	Bucharest Institute of Research for the Electrical Industry (Romania)
ASINEL	Asociación para la Investigación Eléctrica
BMU	German Ministry of the Environment
BOE	Boletín Oficial del Estado (Official State Bulletin) (E)
BOP	Balance of Plant
CASA	Construcciones Aeronáuticas S.A.
CCD	charge-coupled device
CESA-1	Central Eléctrico Solar Almería-1
CFU	colony forming units
CIEMAT	Centro de Investigaciones Energéticas Medio Ambientales y Tecnológicas (E)
CPC	Compound Parabolic Collector
CRS	central receiver system
CRT	central receiver technology
DCS	distributed collector system
DEAHP	double effect heat absorption pump
DER	Renewable Energies Dept. (CIEMAT)
DISS	Direct Solar Steam
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V. (D)
DP	degradation products
DSG	direct steam generation
EC	European Commission
ETH	Swiss Federal Institute of Technology Zurich (CH)
EU	European Union

FID	Flame ionization detector
FTIR	Fourier transform infrared spectroscopy
GC	gas chromatography
GC-AED	gas chromatography with atomic emissions detector
GC-MS	gas chromatograph coupled to mass spectrometry
HDPE	High-density polyethylene
HPLC	High-performance liquid chromatography
HST	Hocheffiziente Solarturm-Technologie (High Efficiency Solar Tower Technology)
HTF	heat transfer fluid
ICP-CSIC	Instituto de Catálisis y Petroleoquímica – Consejo Superior de Investigaciones Científicos (E)
IEA	International Energy Agency
IHP	Improvement of Human Potential (EC)
INETI	Instituto Nacional de Engenharia e Tecnologia Industrial (P)
IPA	atmospheric pressure ionization
IT	ion trap analysis
LC-ES-MS	liquid chromatography with electrospray mass spectrometry
LC-MS	Liquid chromatography coupled to mass spectrometry
LECE	Laboratorio de Ensayo Energético de Componentes de la Edificación
LLE	Liquid-liquid extraction
MBB	Messerschmitt Bolkow-Blohm
MCYT	Ministry of Science and Technology
MED	multi-effect desalination
NBCS	non-biodegradable chlorated solvents
POC	persistent organic compound
PROHERMES II	Programmable Heliostat and Receiver Measuring System II
PSA	Plataforma Solar de Almería
PTC	parabolic-trough collectors
RTOS	Real Time Operative Systems
SENER	Empresa de Ingeniería SENER
SHIP	Solar Heat for Industrial Processes (IEA)
SODIS	Solar Disinfection
SOLFIN	Solar Synthesis of Fine Chemicals
SOLUCAR	Solúcar Energía S.A.
SPE	Solid-phase extraction
SSPS	Small Solar Power Systems project (IEA)
STP	solar thermal power
TCD	thermal conductivity detector

TOC	total organic carbon
TSA	Programa Tecnológico de Receptor Solar de Aire
UAL	University of Almería
UNED	National University for Education by Correspondence (E)
UV-Vis	Ultraviolet-visible spectrum
VOC	volatile organic compound
WFD	Water Framework Directive 2000/60/EC
WIS	Weizman Institute for Science (IL)
ZSW	Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (D)

Plataforma Solar de Almería
Carretera de Senés s/n
P.O. Box 22
04200 TABERNAS (Almería), Spain
Phone: +34 950 387900
Fax: +34 950 365300
e-mail: info@psa.es
web: www.psa.es